Flow characteristics of lower crustal rocks: Comparing two polyphase rock types

Vicki A. Beecher

Thesis presented to the Department of Earth and Planetary Sciences, Faculty of Science in partial fulfilment of the requirements for the degree of Bachelor of Science (Honours)

Macquarie University

2013

STATEMENT OF ORIGINALITY

All the work submitted in this thesis is the original work of the author except where otherwise acknowledged. No part of this thesis has been previously submitted to any other university or institution.

________________________________ _____________________

Vicki A. Beecher Date

Acknowledgements

I would like to take this opportunity to formally thank Sandra Piazolo for her gentle encouragement, understanding and pragmatic attitude. She has been an inspiration and a friend and I thank her. To Nathan Daczko - for making geology exciting and intriguing and his endless support thank you so much. Simon George, Tracy Rushmer and Kelsie Dadd, your persistent belief that I could do this even when I didn't believe have convinced me to complete. All of the PhD candidates thanks for your laughter and lunches – I've enjoyed every minute of it. Everyone at Macquarie University from the staff in the Geo chem labs to the administration staff – I thank you.

My fellow honours students – you have all shared my experiences either as your own or through my eyes. This has been the hardest thing to complete – I don't fully understand why but it has been a journey and a half. Tina Gordon – thanks especially for your encouragement and support.

Cait Stuart – you get your very own paragraph. Without you I wouldn't have slightest idea how to write a simple list of 'to do' jobs for myself. Your endless cups of coffee, technical support (think illustrator, excel, power-point even word), friendship, laughter, love, cooking and yoga have sustained me. Your encouragement to 'make this mine' has seen me through the hardest times and your never ending patience it's a gift that I thank you for. I am so happy that this acknowledgement more than any other has made it to print.

To my all my friends Mia, Kate, Carrie, Johanna, Ruth, Karl and everyone else - at the hardest times you said something that gave me just that little bit more to keep going. Took care of my children without any fuss and accepted that I had daily/weekly breakdowns. I have gratitude for you guys and appreciate that you guys are in my life.

To my family – my wonderful gorgeous children Tammy, Reece and Charlie- thank you so much for your seemingly insatiable patience while I have been busy with this thing we have all called THE THESIS. Your acceptance and understanding that I had something important to do and that I couldn't play, run, swim or just be with you for a few months is very much appreciated – Thanks you guys. To my partner Sheldon, your support has been such a gift. Stepping in to my shoes at home and being there for the kids helped so much. I appreciate you being my sounding board and listening to me see saw about whether I would hand in or not and not judging me either way. Your gentle encouragement was, as always, a gift. Thanks.

I am so happy that this experience is over. I enjoyed the topic, the field trip (that was amazing) data collection, and even analysis and am grateful for all of the skills I have learnt. At times this thesis became much more – my nemesis. I cannot recall the number of times I have boxed up all of the associated information and said 'no more' However, here is it in all its glory – enjoy the read.

Abstract

Keywords: Regional geology, flow dynamics/rheology of polyphase minerals, deformation mechanisms

How do polyphase rocks deform? How do they perform to each other? Classically, deformation mechanisms which govern the rheology of a rock (i.e flow properties) are predicted from monomineralic experiments. However, how can science apply laws for one system to another? Is it valid?

At the same time, when looking at deforming rocks science uses interpreted deformation mechanisms of individual phases as indicators for conditions of deformation. Again, based on monomineralic experiments. To ascertain if these predictors are valid I am considering different rock types with different modal percentages that have undergone the same PT conditions.

Individual grains and their “neighbourhoods” would need to be analysed in order to ascertain different deformation mechanisms.

The rocks in this study have been sampled from Fiordland, New Zealand in rare outcrop of lower crustal rocks that have been deformed and recrystallised at PT conditions with that of eclogite facies and then exhumed passively with no further metamorphic or tectonic overprinting.

Observed relationships in the field of Omphacite granulite and Breaksea eclogite indicated that the rocks were co magmatic. The Breaksea eclogite was found within lenticular/elongate pods form mm, cm, 10cm scale within the Omphacite granulite.

SEM EDS analysis revealed three main phases present feldspar, omphacite and garnet throughout the samples collected with varying amounts of strain.

EBSD mapping of high and low strain samples of three phases' feldspar, omphacite and garnet within the two lithologies was able to ascertain the deformation mechanism of each mineral relative to adjacent minerals. Contour pole figures indicated Lattice preferred orientation of minerals that had deformed via dislocation creep.

The deformation mechanisms observed indicate that monomineralic flow laws are not a suitable tool and cannot be used as a reliable predictor of deformation mechanisms of polyphase rocks.

List of Figures

List of Tables

Chapter 1: Introduction

Determination of a rocks rheology (flow characteristics) is ascertained using existing flow laws mainly based on monomineralic experiments. In addition when studies are carried out on deforming rocks, contemporary science uses interpreted deformation mechanisms of individual phases as indicators for conditions of deformation. Again, this is based on monomineralic experiments. However, polymineralic rock types (rocks with more than one mineral) have multiple scenarios that may influence the rheology of the sample depending on the minerals and their location with respect to each other. Is it valid to assume that the minerals will behave in the expected manner regardless of adjacent minerals or the quantity of those minerals? To answer these questions analysing different rocks types with different modal percentages of the same minerals that have undergone deformation at the same PT conditions is expected to provide some answers.

Located in Fiordland, South Island, New Zealand there exists a unique window to study various lower crustal rocks that have been deformed and recrystallized at PT conditions consistent with that of Eclogite facies and then exhumed passively - that is to say without further tectonic overprinting. The samples are from within a unit identified by the Geological and Nuclear Sciences (GNS), New Zealand as the Breaksea Orthogneiss (BOG). The BOG is itself comprised of Omphacite Granulite (OG), and Breaksea Eclogite (BE), Hornblende peridotite (HP), and a cognate layered mafic unit Layered garnetite Pyroxenite (LGP) (De Paoli et al., 2012).

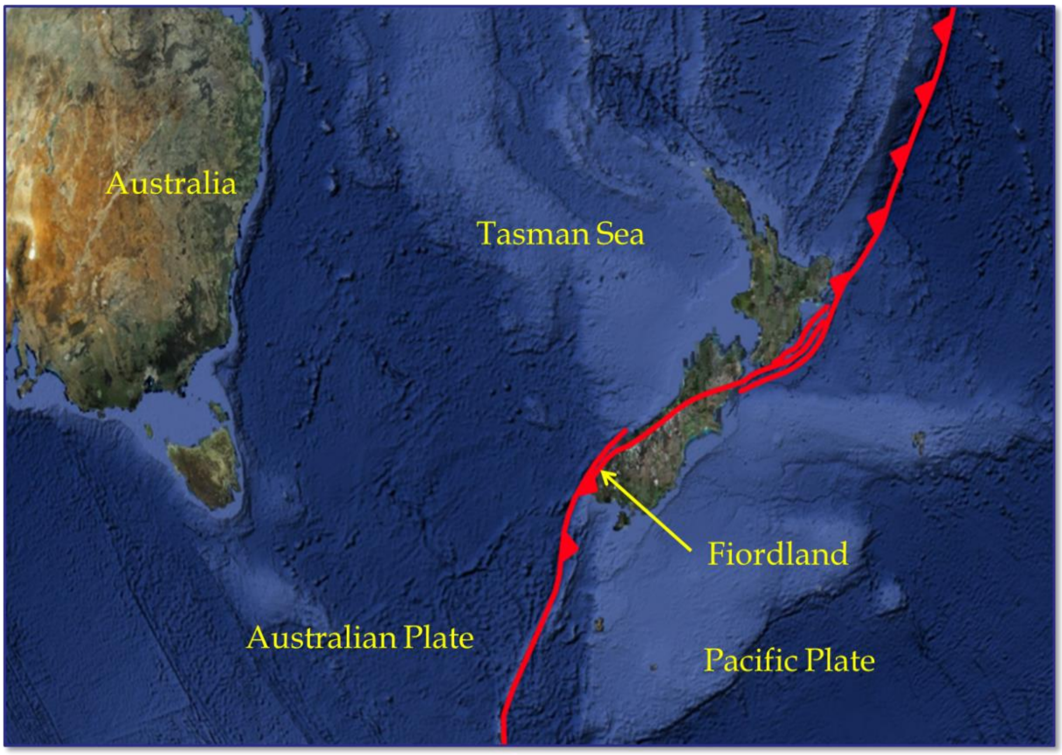

Figure 1.1 Regional Geology of Fiordland.
Illustrating relationship of Median Batholith to Western and Eastern Provinces.

Classically Eclogite is made up of equal parts of Garnet and Omphacite however as this eclogite is from a suite of rocks that are comagmatic the eclogite found here is a cumulate.

1.1 Aims

The aim of this study is to look at the specific rheology/flow dynamics and deformation mechanisms of polyphase minerals contained within the host monzodiorite orthogneiss – BE and OG . As such it is part of a larger study to investigate the lower crust and to assess if existing flow laws/dynamics - typically from experiments on monomineralic rocks – are a suitable predictor of deformation mechanisms.

Questions:

- How does the lower crustal rock deform specifically an Omphacite Hornblende Eclogite relative to Omphacite Granulite?
- Does the percentage of individual phases (mineral types) influence deformation mechanisms in the individual phases e.g. does the deformation mechanism for Omphacite adjacent to Garnet differ to the deformation mechanism for Omphacite adjacent to Garnet with Plagioclase present? Furthermore is the deformation of garnet influenced by the local vicinity of garnet, Omphacite and/or feldspar?

In order to achieve this, quantifying the microstructures present in samples from each of the rock types in the field location, and within degrees of strain is essential. To answer the questions posed earlier I am considering different samples with different modal percentages of 3 main phases - feldspar, garnet and pyroxene that have undergone deformation at the same PT conditions. A natural laboratory!

1.2 Flow characteristics/rheology

Currently science uses existing flow flaws to unravel the story of a rocks history and journey. The flow laws used may be ineffective if they do not pertain to poly mineralic rocks. For example flow laws indicate that garnet will

1.3: Short summary of deformation mechanisms of garnet, omphacite and feldspar

Dynamic recrystallization occurs within a crystal during deformation in an effort to reduce free energy. There 6 deformation mechanisms they are as follows:

1) Shape of grain change (via dislocation or diffusion creep)
2) Sub grain formation and recovery
3) Small grains – Rotational Recrystallization
4) Small grains – Recrystallization by nucleation
5) Grain Boundary migration
6) Grain boundary sliding

The mineralogy of a grain in addition to its crystallographic orientation will determine how that grain will behave/deform. As this study focuses on three main phases, the deformation mechanism for each phase is briefly discussed briefly below.

Garnet

At Granulite-Eclogite facies garnet deforms via dislocation creep and recovery in addition to sub-grain rotation at the highest strains which when grains are recrystallised they are able to deform via diffusion creep assisted by grain boundary sliding with associated rotations (STOREY and PRIOR, 2005)

Omphacite

Crystal lattice defects such as undulose extinction, twinning and sugbrain development are common results of deformed omphacite. Most studies of deformed omphacite focus on development of lattice preferred orientations and what causes the resultant LPO types. A lattice preferred orientation is the ordering of the crystallographic axis of a mineral (McNamara, 2012).

Feldspar (High grade- >500°C)

The dominant deformation mechanisms for feldspars at high PT are dislocation creep and subgrain rotation (Rybacki and Dresen, 2004) in addition to semi brittle floe at the expense of power law creep. Dry plagioclase (as seen in the rocks within this study) require temperatures of ~250°C greater the wet plagioclase (Rybacki and Dresen, 2000, Dimanov et al., 1999).

Chapter 2: Regional Geology

2:1 Regional Setting of Fiordland New Zealand

The extensive Western Fiordland Orthogneiss (WFO) was emplaced and metamorphosed between 126-113 Ma, (Scott et al., 2011, Allibone et al., 2009, Klepeis et al., 2007, Klepeis et al., 2004, Daczko and Halpin, 2009, Hollis et al., 2004). The WFO is host to the youngest and deepest pluton to emerge: the Breaksea Orthogneiss, a high *P* (1.8GPa) High T (850°C) composite (Figure 2.1).

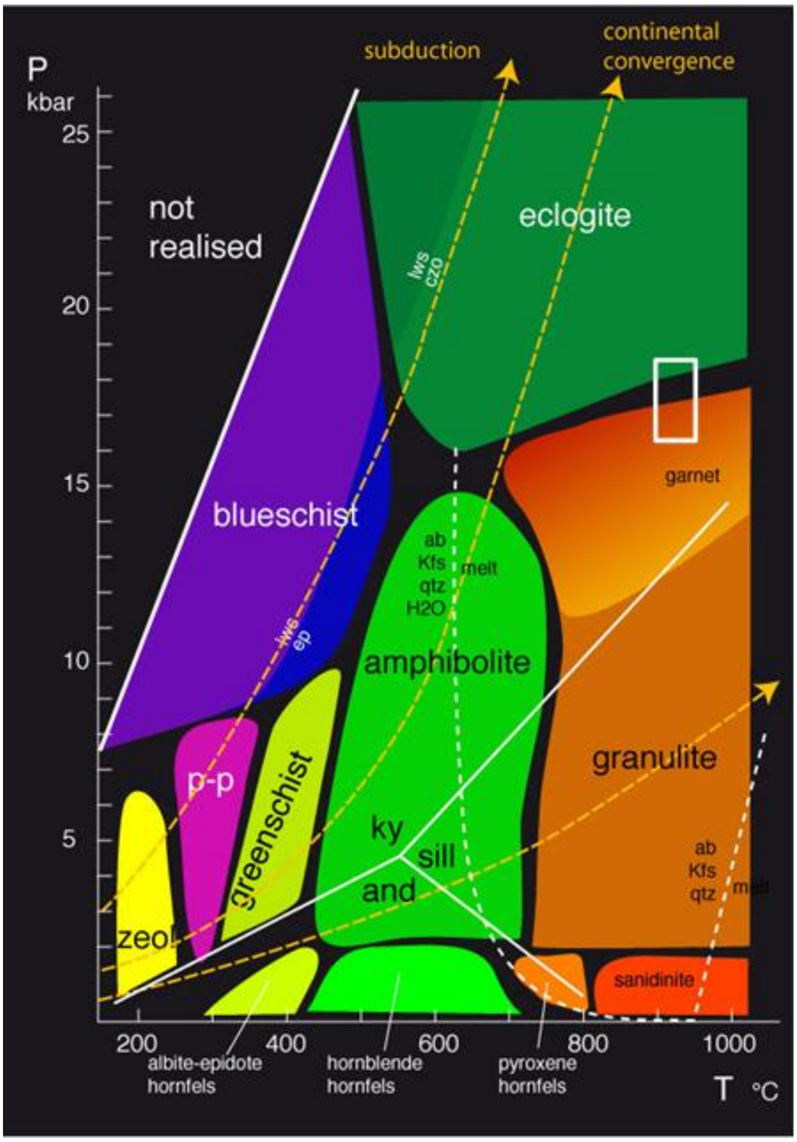

Figure 2.1 PT diagram illustrating Omphacite Granulite and Eclogite analysed in this study were recrystallised at ~18 kbars (1.8GPa) and T 850°C, see inset white box.

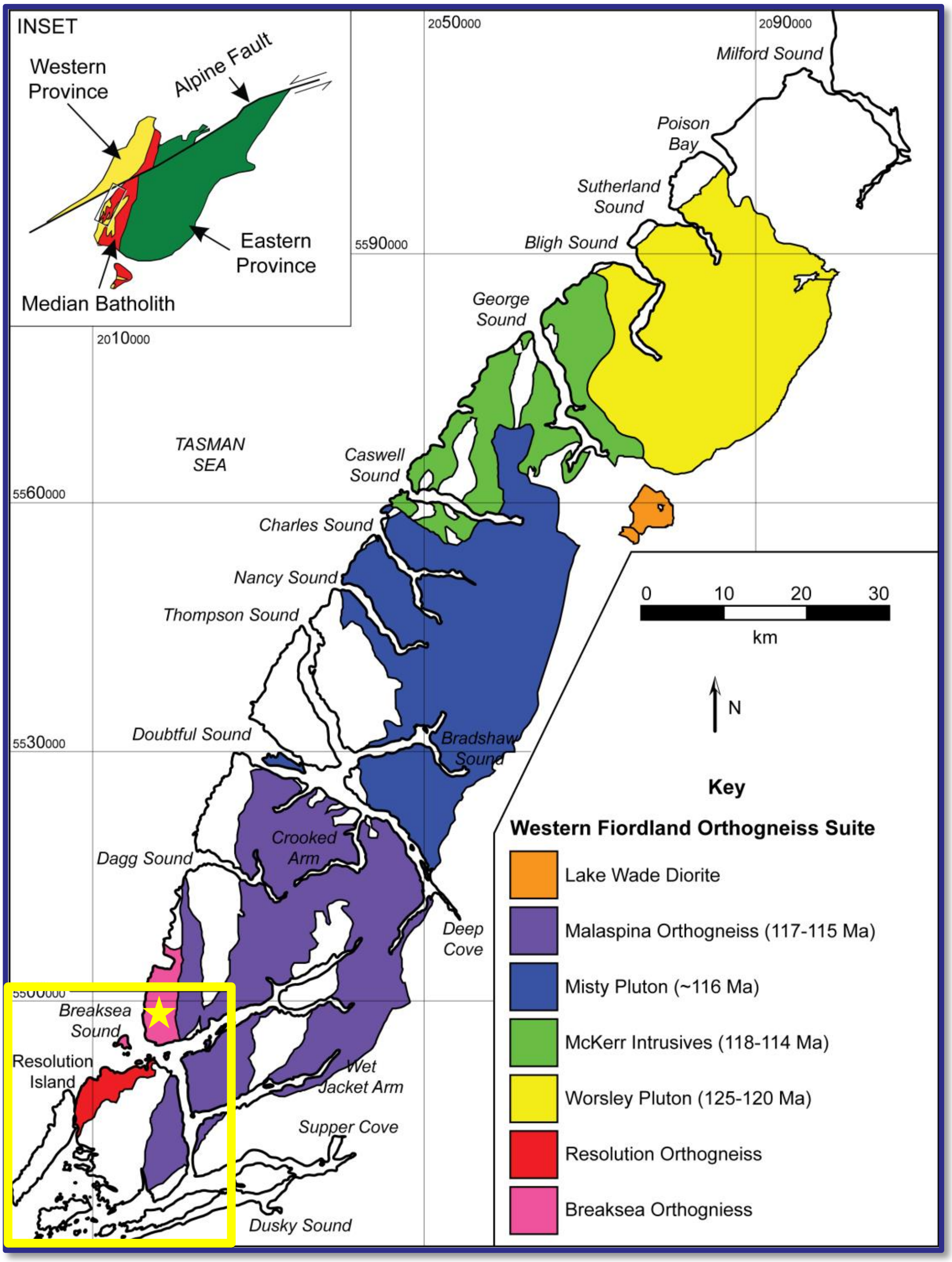

Figure 2.2 Geological map of the Western Fiordland Orthogneiss illustrating the location of the Breaksea Orthogneiss within. The yellow star denotes the field site.

Units within the Breaksea Orthogneiss preserve an intense S_1 foliation: primarily Omphacite Granulite (OG) – the pale monzodioritic host and Breaksea Eclogite (BE) – darker peridot gabbroic layers and pods (DePaoli et al., 2009, De Paoli et al., 2012). OG from the Breaksea Orthogneiss is a coarse grained plagioclase - rich

Omphacite granulite and the darker layers are predominantly coarse grained Omphacite- garnet- rich eclogite that may or may not have orthopyroxene, (De Paoli et al., 2012). In addition hornblende peridotite symplectite and a cognate layer of the Breaksea Orthogneiss itself identified by Meischer *et al* (2010) are found within the Breaksea Orthogneiss. The Breaksea Orthogneiss is extensively recrystallised however it odes maintain its original compositional layering evidenced by centre – meter scale rhythmic banding, (De Paoli et al., 2012)

Chapter 3 Fieldwork

3.1: Site selection

The Breaksea Orthogneiss is a heterogeneous unit that is dominated by dioritic orthogneiss termed Breaksea Omphacite Granulite (BOG). Minor components, in order of abundance are: Omphacite Granulite (OG), Breaksea Eclogite (BE), Layered Garnetite Pyroxenite (LGP) and Hornblende Peridotite (HP). The BOG has been examined in two primary areas – Breaksea Sound and Breaksea Tops, a region located between Breaksea Sound and Coal River, approximately 3 km south of Coal River (Figure 3.1).

This field site was chosen due to the minimal amount of structural and metamorphic overprinting on the BOG, allowing a rare view into the lower crust. Rocks within the BOG are comagmatic and therefore are known to have been deformed as a “package”.

Between 23rd March – 1st April 2012 fieldwork was undertaken in the most accessible location of the Breaksea Orthogneiss - the Breaksea Tops locality (Figure 3.1). Base camp was at GPS coordinates 26727662, within the Breaksea Tops area. Nathan Daczko, Sandra Piazolo, Geoff Clarke, Tim Chapman and I were present. Breaksea

Tops is accessed by helicopter from Te Anau, the nearest serviceable township to field location.

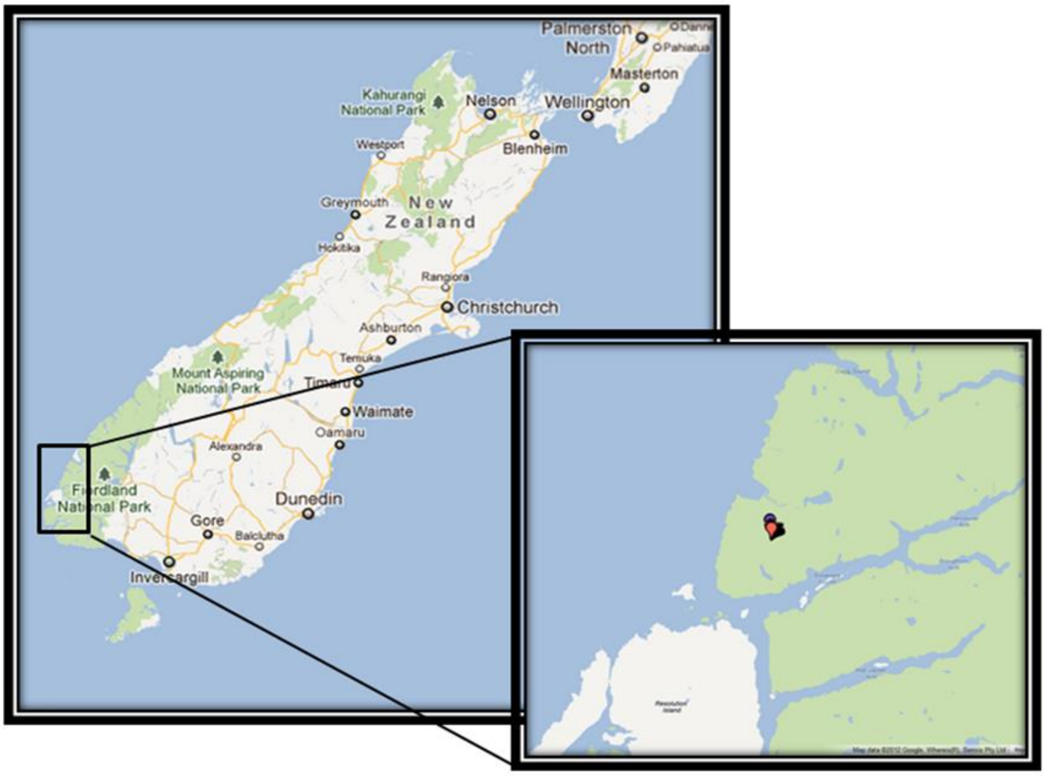

Figure 3.1 Field site, Fiordland, South Island, New Zealand. Cutaway indicating sample location

3.2: Sample selection

The main aim of the fieldwork was to identify field relationships between the various lithologies that make up the Breaksea Orthogneiss. Samples of each lithology were collected other than the layered Garnetite Pyroxenite, with an emphasis on collecting samples of different strain (Figure 3.2). The collected samples were carefully targeted to be representative of the observed range of composition and foliation intensity (Table 3.1) The greatest variation appeared to be in the BOG and BE, therefore these were selected for further study

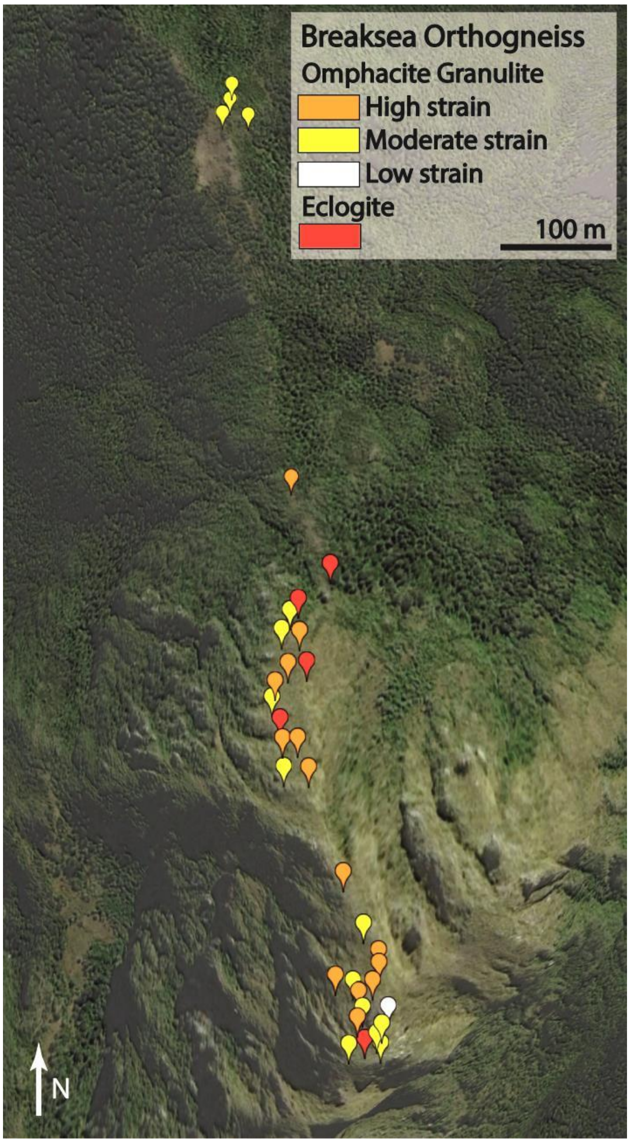

Figure 3.2 Google map of field site with sample collection locations. Samples are categorised by composition and strain.

Table 3.1: All samples used for analysis in this study selected out of a range of 26 samples

Sample	**Unit**	**Strain**	**Geochemical analysis technique**	
BS0904D	Omphacite Granulite	moderate	EMP-EDS	
BS0905B	Omphacite Granulite	low	EMP-EDS	EMP-EBSD
BS1202	Omphacite Granulite	low	EMP-EDS	EMP-EBSD
BS1204	Omphacite Granulite	moderate	EMP-EDS	
BS1205A	Breaksea Eclogite	low	EMP-EDS	
BS1212A	Omphacite Granulite	high	EMP-EDS	EMP-EBSD
BS1212A	Breaksea Eclogite	high	EMP-EDS	EMP-EBSD
BS1212C	Omphacite Granulite	high	EMP-EDS	
BS1212D	Breaksea Eclogite	low	EMP-EDS	
BS1217B	Breaksea Eclogite	moderate	EMP-EDS	EMP-EBSD

Field analysis of shape and composition of different rocks types included tracing, where possible, the boundaries of the different lithologies, recording intensity of foliation, measurements of foliation orientation and establishing if there was notable deflection of the host rock (Omphacite Granulite) around any of the three additional rock types on either cm, m or 10m scale (Figure 3.3).

Figure 3.3 Field relationships of rock units, orientation and dips. Eclogite area indicates lenticular pods of Eclogite which were found within the Garnet Granulite.

3.3: Field relationships

Observations in the field showed that BOG is the primary lithology with apparent pods of BE, Hornblende Peridotite (HP) and layered Garnetite Pyroxenite (LGP) found within (Figure 3.4). Further field observations indicated that the BE deformed at temperatures and pressures quite similarly to the BOG, as foliation did not appear to be deflected around the eclogite.

All samples were taken to Otago University for initial processing. They were cut and cleaned in preparation for transport to Macquarie University.

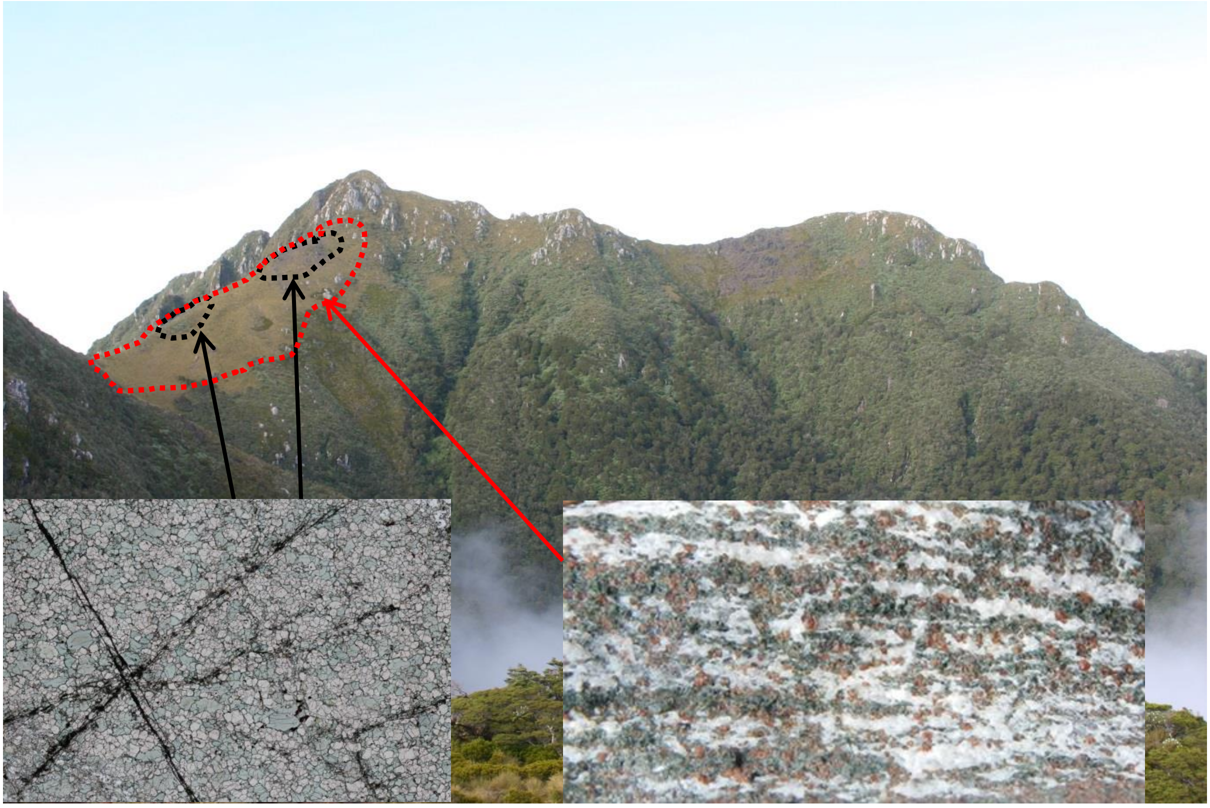

Figure 3.4 Rock sample collection locations. View is towards the South. The BOG was found to be the primary lithology with apparent pods of Breaksea Eclogite (left inset) found within the Omphacite Granulite (right inset)

Chapter 4 – Methods

Part 1: Physical Analysis

This chapter aims to describe representative samples from the selected lithologies for further study: OG and BE. All physical aspects of the samples including Petrography (visual technique), Microstructure (visual technique), crystallographic orientations (electronback scatter diffraction (EBSD)) and strain (visual technique based on foliation).

4.1.1: Petrography

This section examines the petrography of 2 phases of the Breaksea Orthogneiss within carrying degrees of strain. The petrography identifies changes to mineral assemblages and microstructures that are consistent with identification of the phase and that identify the type of deformation that has occurred. Whilst specific thin sections are examined they are used a representative of the phase and therefore detailed analysis of each thin section are found within the appendix.

Analytical Method

Twenty six thin sections have been made from rocks collected in the field. Samples were cleaned and cut in preparation for transport at Otago University, Dunedin, New Zealand. Samples were mounted on glass slides and polished to approximately 30 µm at Macquarie University, Sydney. These were then examined using a Nikon Eclipse E400 POL Petrographic microscope using PPL, XPL in addition to a gypsum plate. A representative description of Breaksea Eclogite and Omphacite Granulite is given below. As this study focuses on three phases these are what is described. Of the twenty six thin sections made, four were selected for more detailed analysis these samples are described below.

Omphacite Granulite

Mineral modal percentages have been estimated via visual inspection of thin sections in addition to ImageJ software. Omphacite granulite consists of plagioclase feldspar (~35%), omphacite (~32%), and garnet (~ 25%). In addition to rutile, ilmenite, haematite, kyanite, orthoclase and apatite.

Omphacite granulite was observed to be varied in composition with greater modal percentages of garnet relative to omphacite observed depending on field relationship and location relative to nearby rock units.

What was thought to be secondary garnet was observed only when omphacite was observed adjacent to plagioclase within the omphacite granulite, see sample BS1212A (Omphacite Granulite area) in addition to what is observed as primary garnet being present.

Breaksea Eclogite

Modal percentages have been estimated via visual inspection of thin sections in addition to the use of ImageJ software The Breaksea Eclogite was observed to have consistent modal percentages regardless of strain. BE is comprised of garnet (~45-50%) and omphacite (~45-50%) accessory minerals are rutile, ilmenite, haematite with minor plagioclase and biotite.

Typically granoblastic in texture. Garnets are blocky to rounded and range in size from 0.15- 1.0mm. Omphacite is more rounded on edges and tend to be smaller and elongate on average, Range in size from 0.14-0.17mm.

1212A High strain Omphacite granulite and Breaksea eclogite

As discussed in section 3 .2 BE was found in the field in pods varying in size from mm-cm-10cm, of elongate-lenticular shape within outcrops of OG in addition to independent outcrops.(Figure 4.1) Sample 1212A was taken from an outcrop of OG and BE and therefore has regions of both compositions. It is a high strain sample

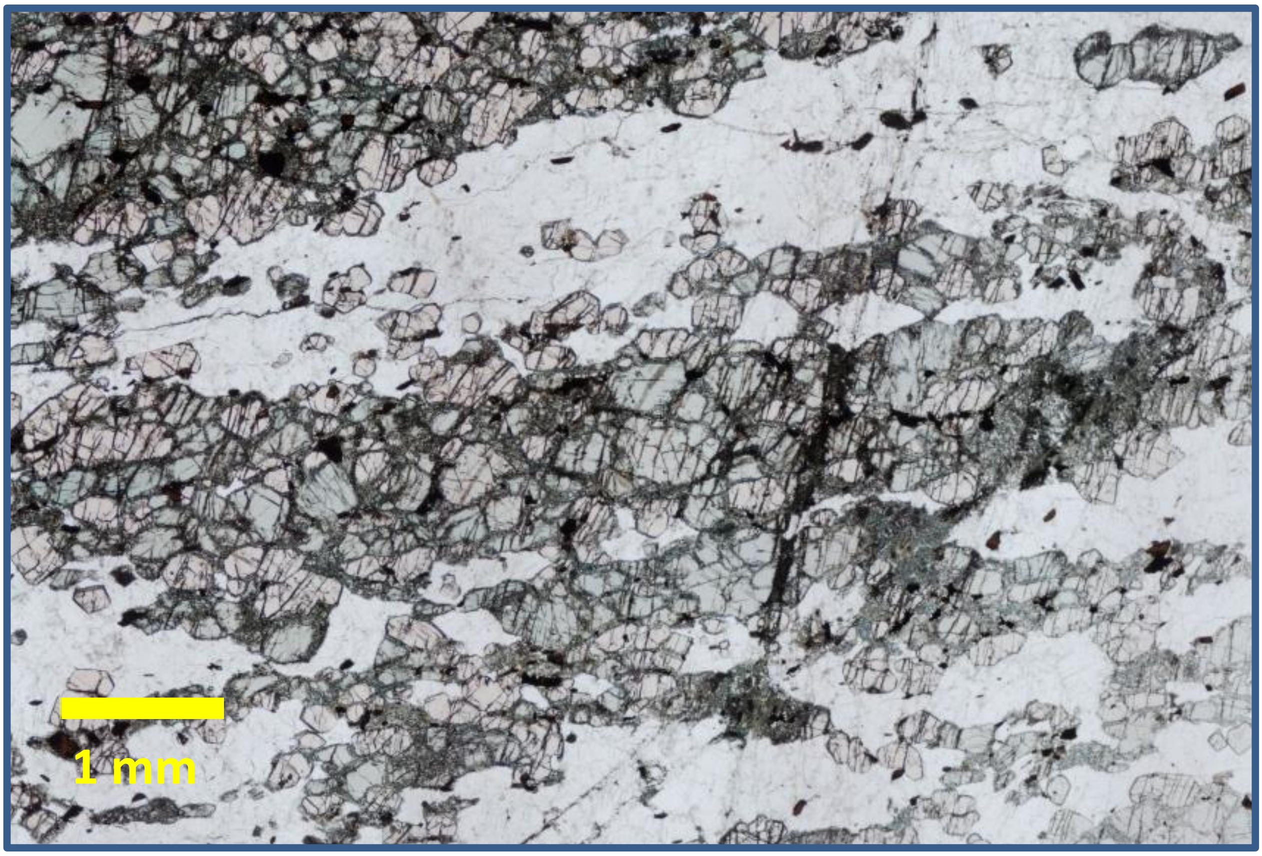

Figure 4.1 Sample 1212A High strain Granulitic texture with eclogite pods which appear strung out. Crystals edges are anheadral.

Sample 1217B Lower strain Breaksea eclogite

Grains are much smaller and tend to be rounded on the edges (Figure 4.2)

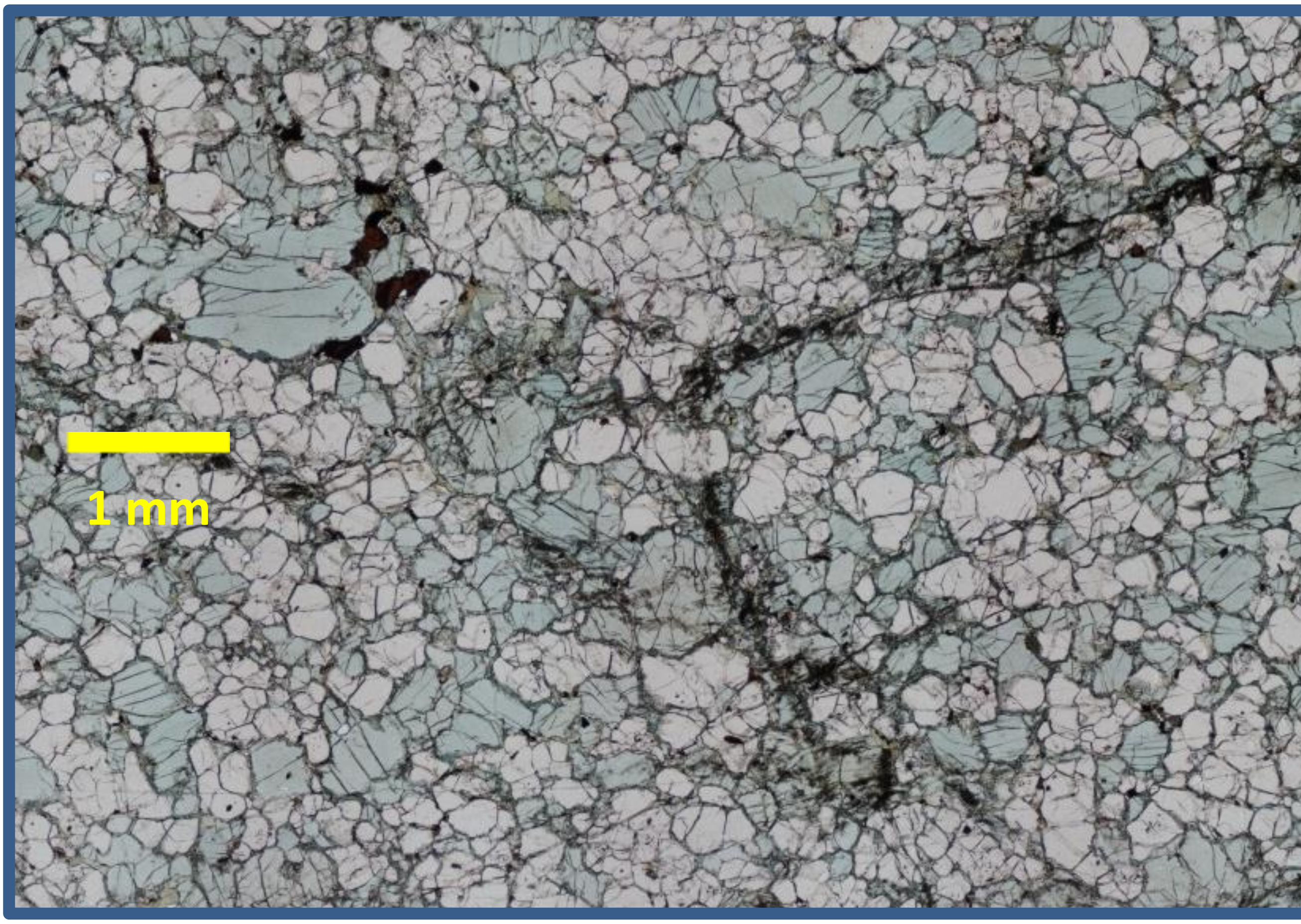

Figure 4.2 Sample 1217B Lower strain Breaksea Eclogite.

Sample 1202 Omphacite granulite

Edges of garnet appear sharp with curves, grains on average are ~500µm. Omphacite is lozenge shaped with recrystallization at tails. Garnets and Omphacite appear to define weak foliation. (Figure 4.3)

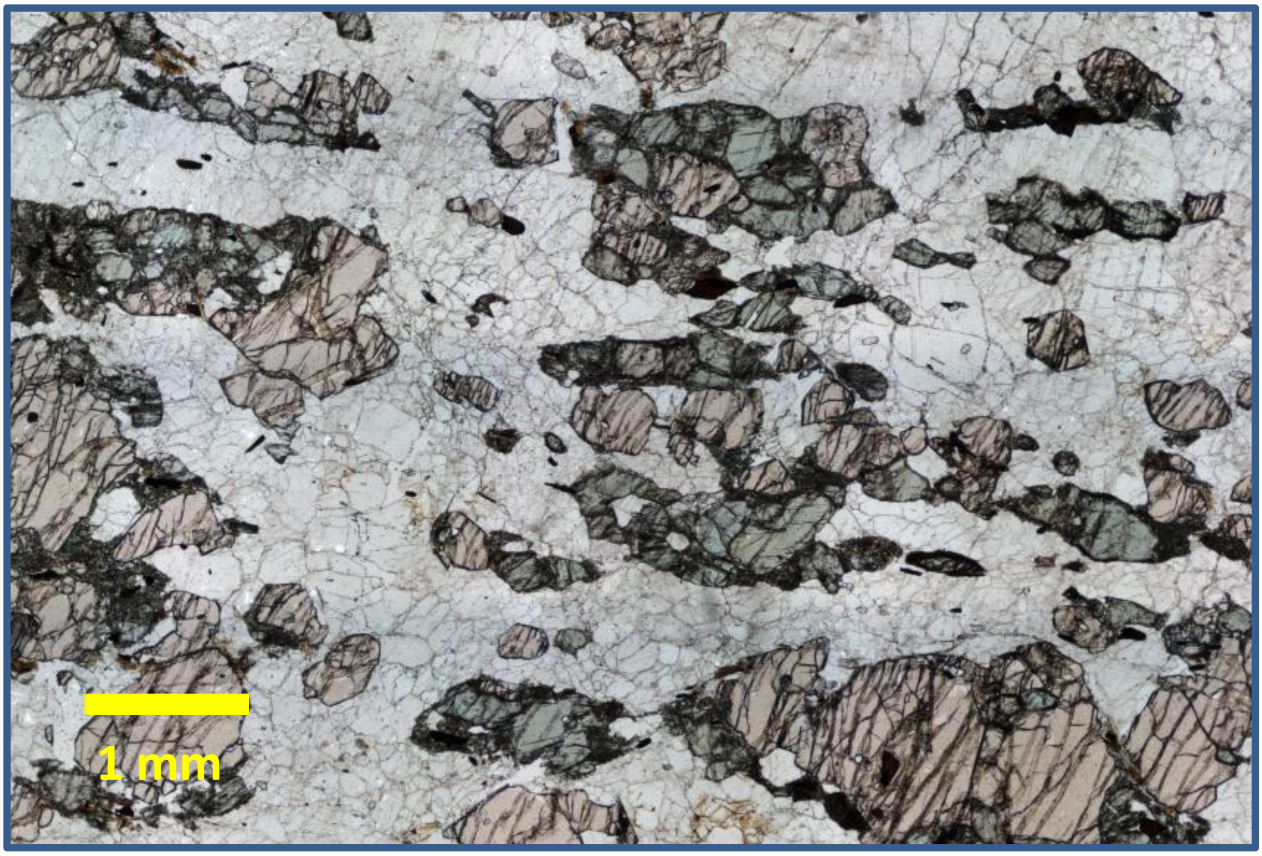

Figure 4 3 Sample 1202 Low strain Omphacite granulite

4.1.2: Strain

The aspect ratio of randomly selected grains within each this section plotted against modal percentage indicates a continuing trend with high strain samples consistently increasing in aspect ratio for both BE and OG, although BE does demonstrate greater variation Figures 4.4-4.6.

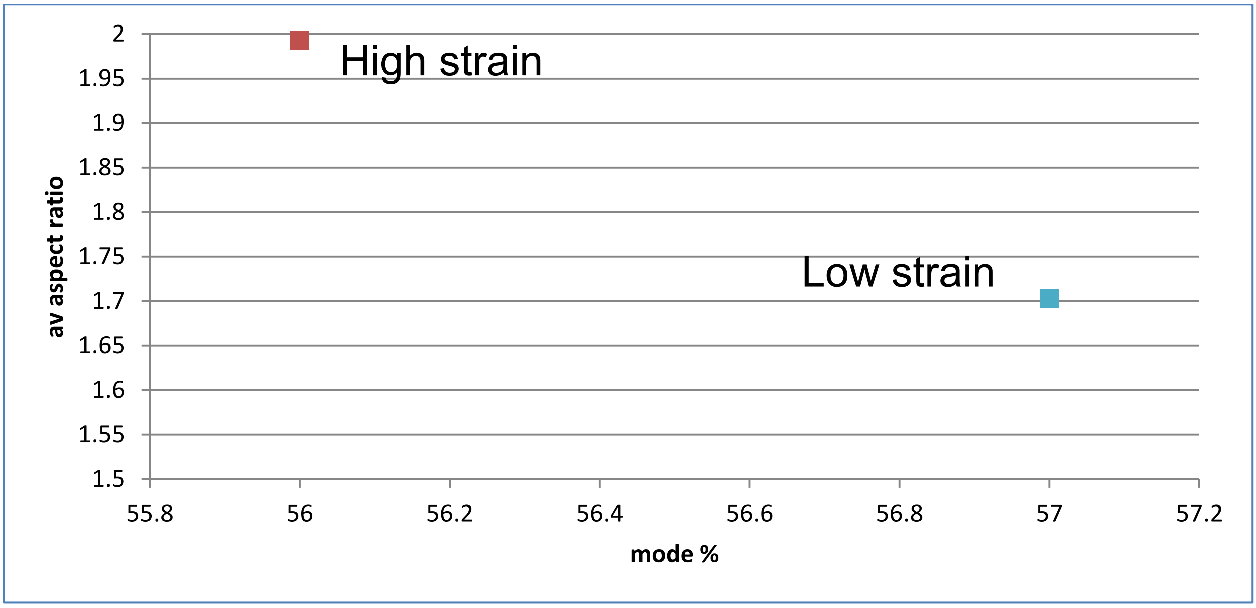

Figure 4.4 Aspect ratio: modal percentages for feldspar for all samples illustrating the relationship between aspect ratio and strain. The higher the aspect ratio the higher the strain.

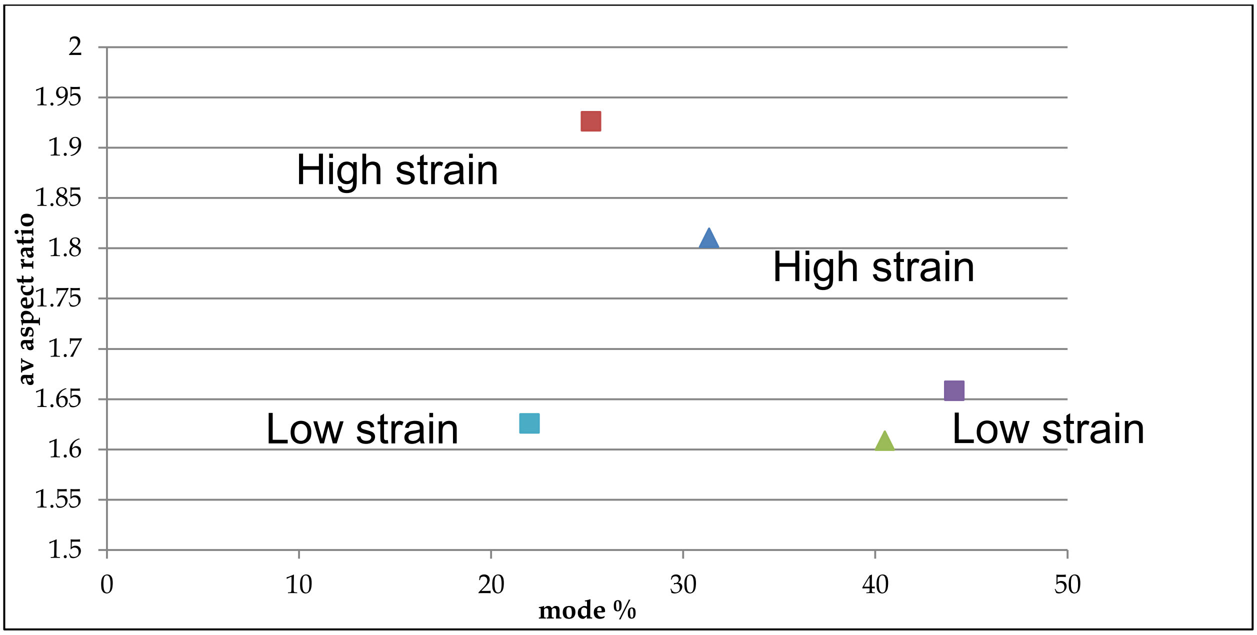

Figure 4.5 Aspect ratio: modal percentages for garnet for all samples illustrating the relationship between aspect ratio and strain. The higher the aspect ratio the higher the strain.

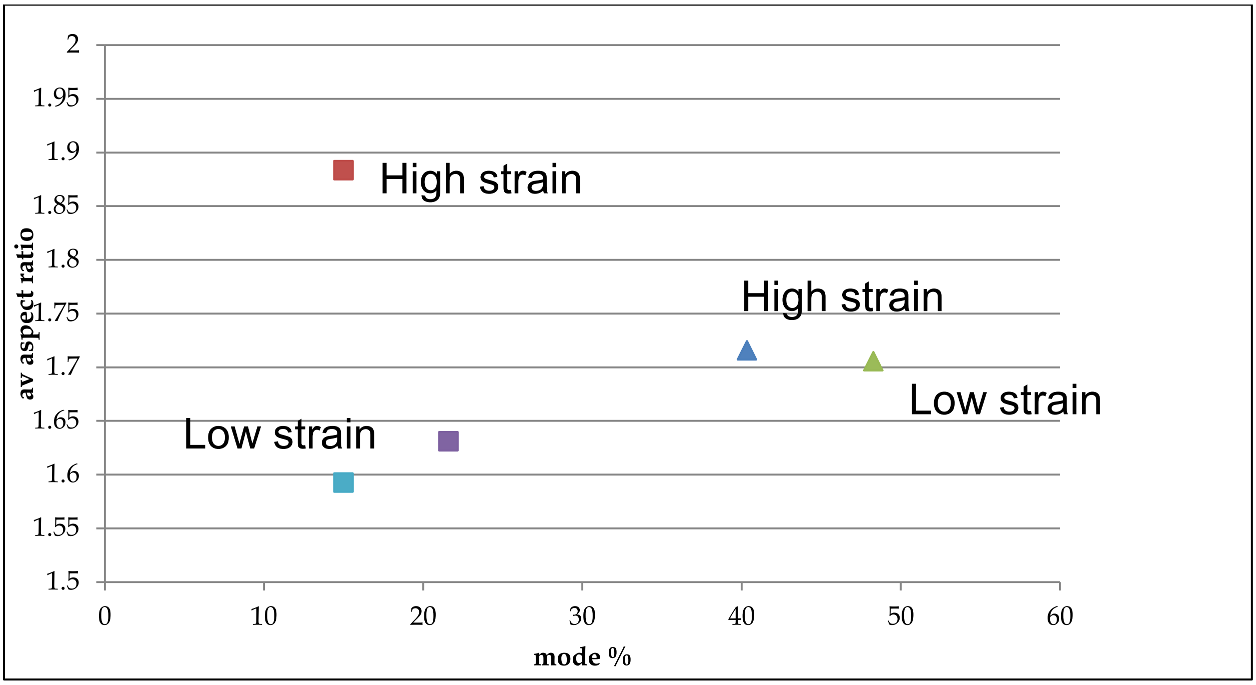

Figure 4.6 Aspect ratio: modal percentages for pyroxenes for all samples illustrating the relationship between aspect ratio and strain. The higher the aspect ratio the higher the strain.

4.1.3 Crystallographic Orientations: EBSD

Electron Backscatter Diffraction analysis was undertaken on a Zeiss EvVO MA15 Scanning Electron Microscope (SEM) with a HKL NordleysNano high sensitivity EBSD detector, using the HKL CHANNEL5 analysis software from Oxford Instruments. Data was collected from mechanically polished thin sections with a final mechanochemical polish using colloidal silica in alkali solution. Thin sections were subsequently coated with a ~3nm of carbon. The SEM was run at a high vacuum with an accelerating voltage of 20kV, a beam current of 8.0nA, and with an aperature of 30µm. The sample was tilted to an angle of 70°.with a tilt correction applied in the Zeiss SEM software. EBSD was then moved to a working distance of ~12-15mm from the stage. EBSPs were processed with 2 frame averaging, 4x4 binning, ~55 theoretical reflectors and 8-11kikuchi bands.

Data was further processed using HKL CHANNEL5 software. Step 1 is to remove all artificial noise and 'clean' the sample – the removal of non-systematic data points (Prior et al., 2002). Once cleaned data is interrogated using the software, initially data is displayed as band contrasting illustrating the data acquisition (Bestmann et al., 2005) Crystallographic orientation of minerals are then viewed via maps that visually represent lattice bending (deformation via dislocation creep), using pole figures determination of a strong Lattice preferred orientation (LPO) is ascertained.

Following are photomicrographs images taken using a Prior microscope located at Macquarie University illustrating the EBSD sample locations on selected samples. Figures 4.9-4.12. Not all maps resulted in viable data due to technical issues and user error. The most representative maps have been chosen for inclusion within this paper. They follow below the location maps.

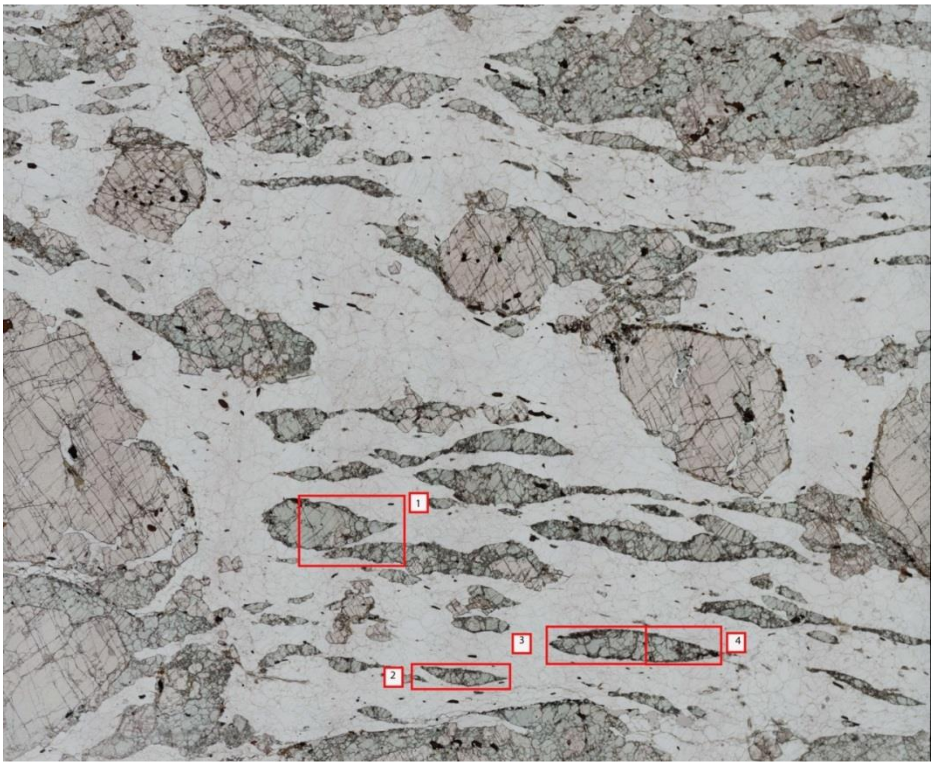

Figure 4.7 1202: Low strain OG, red boxes indicate EBSD map locations. field of view is 50mm

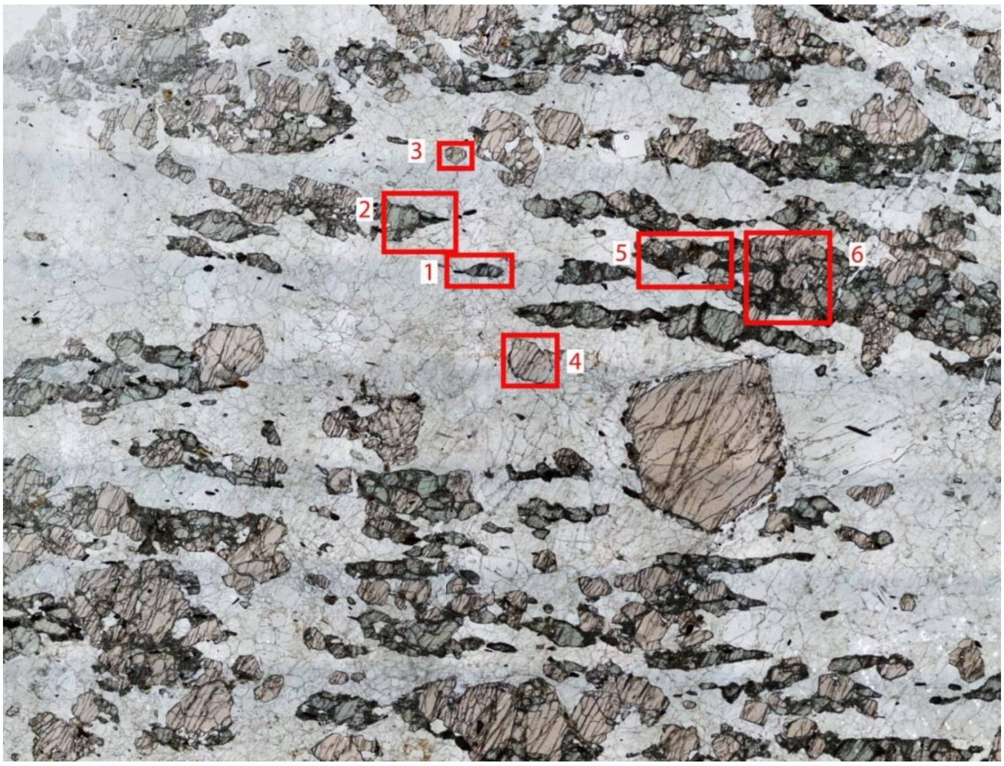

Figure 4.8. 0905b Mid strain OG, red boxes indicate EBSD map locations. field of view is 50.0mm

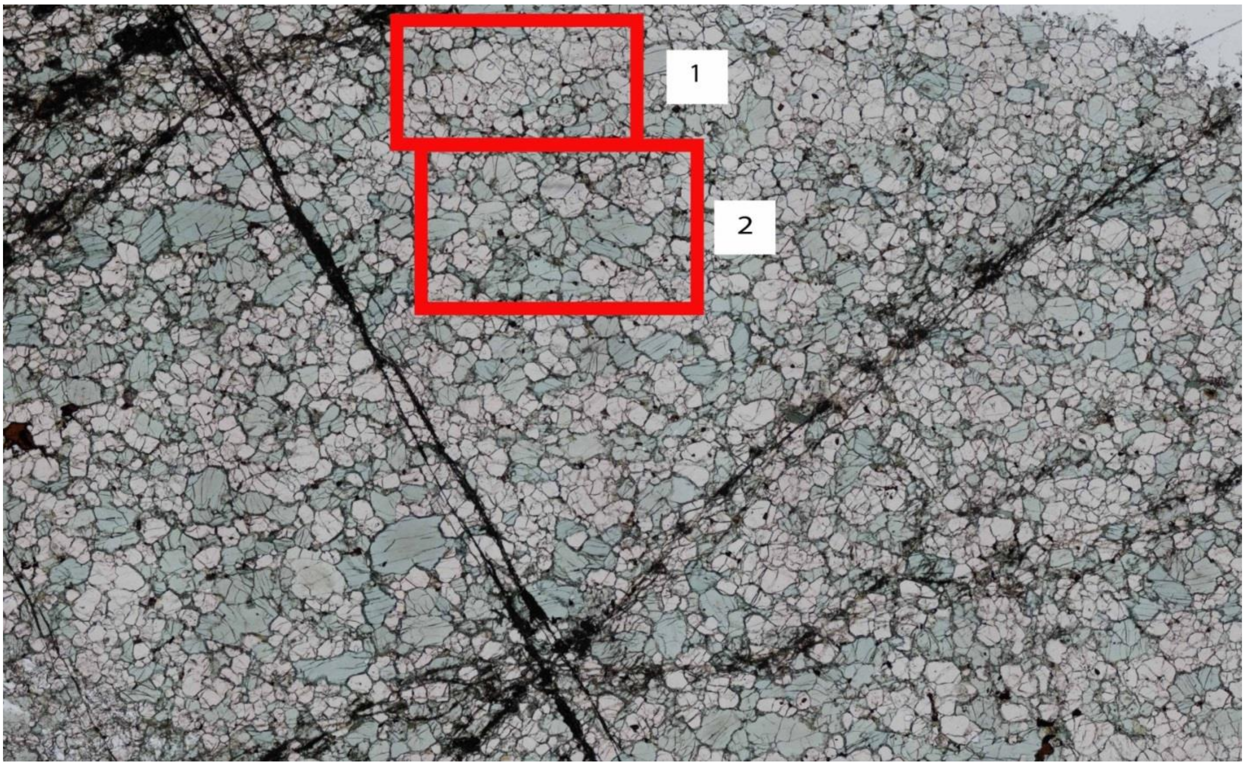

Figure 4.9. 1217 Lower strain BE. Red boxes indicate EBSD map locations. field of view is 50.0mm

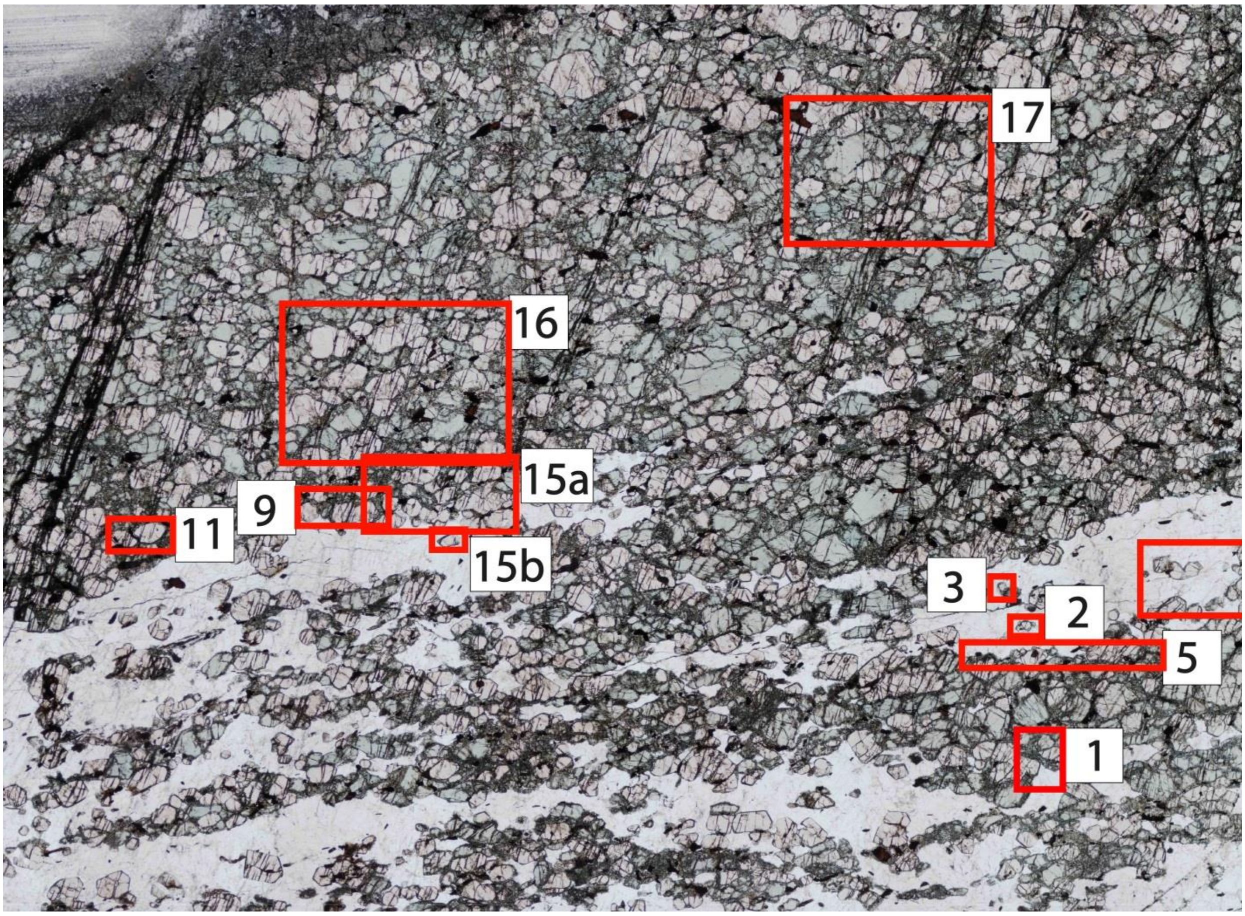

Figure 4.10. 1212a High strain BE (upper filed) and High strain OG (lower field) have been analysed from this sample. Marked boxes indicate EBSD map locations. field of view is 50.0mm

Internal deformation with regard to adjacent minerals or location within the neighbourhood of surrounding minerals is able to be seen via EBSD. The flowing maps illustrate how minerals influence each other during deformation.

This is illustrated via relative orientation changes within individual grains from a reference orientation (coloured blue on the maps see scale on Figure 4.13(the scale remains the same throughout all maps)) to a maximum change in orientation in red of 5 degrees. Figures 4.13 – 4.20 illustrate the deformation of minerals relative to their neighbours and neighbourhoods. Descriptions are within each caption.

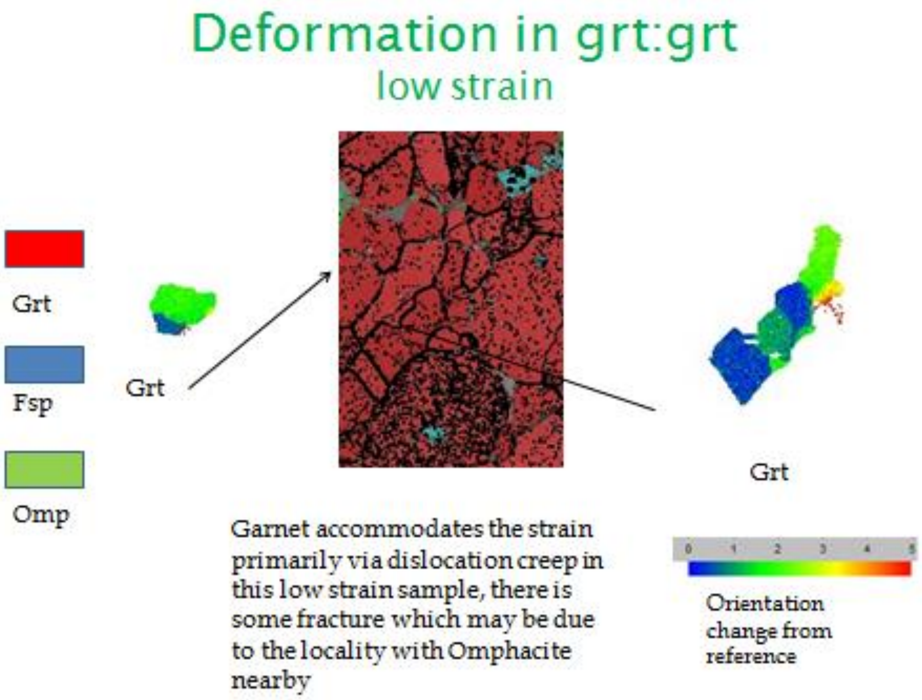

Figure 4.11. EBSD imaging of garnet: garnet in a low strain sample illustrating deformation via dislocation creep in addition to some fracturing which may be due to omphacite in close proximity

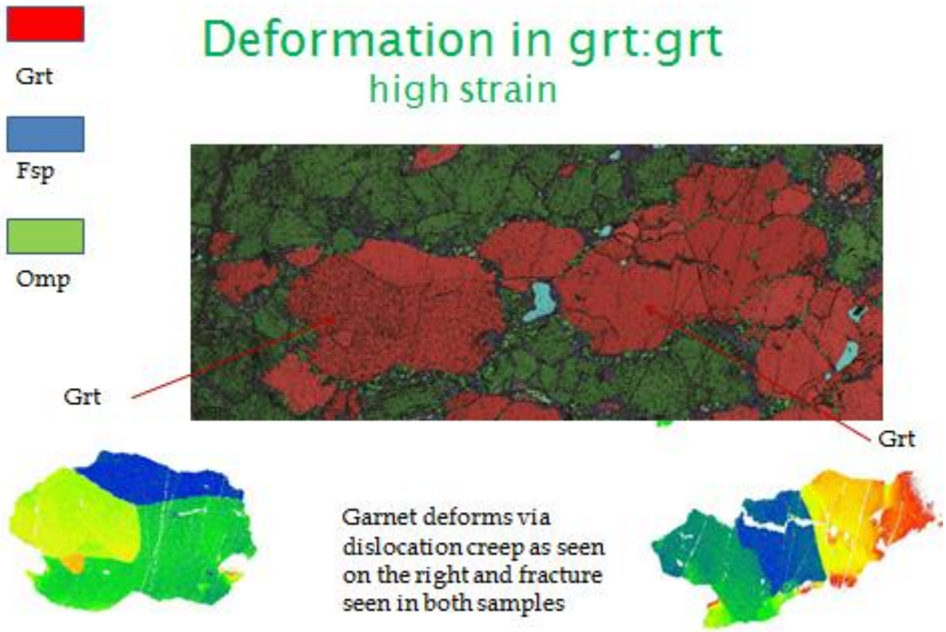

Figure 4.12. EBSD imaging of garnet: garnet in a high strain sample illustrating deformation via dislocation creep which is clearly shown via the bending of the lattice crystals denoted via change in colour from blue to red (representing a 5 degree change)

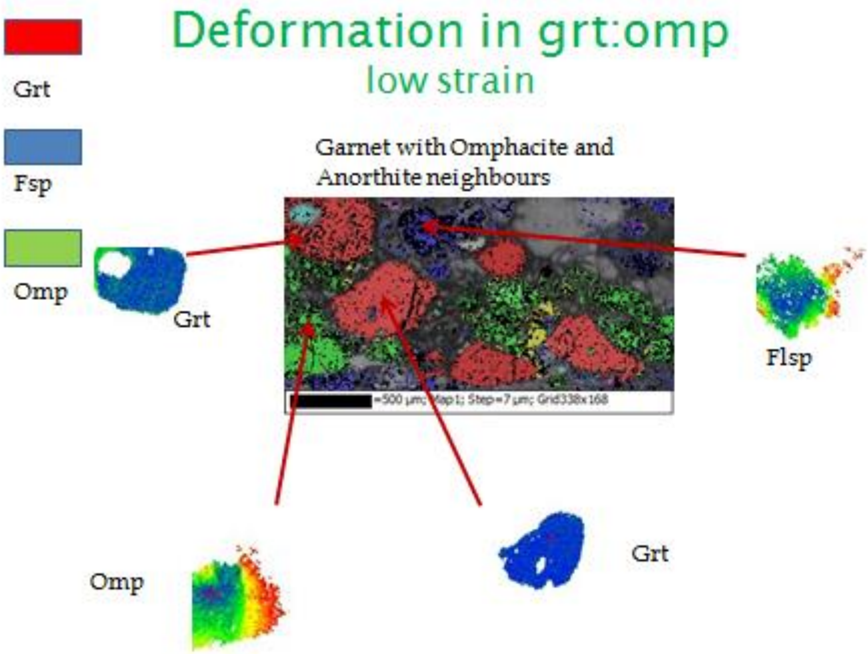

Figure 4.13. EBSD imaging of garnet: omphacite in a low strain sample illustrating both feldspar and omphacite are deforming via dislocation creep.

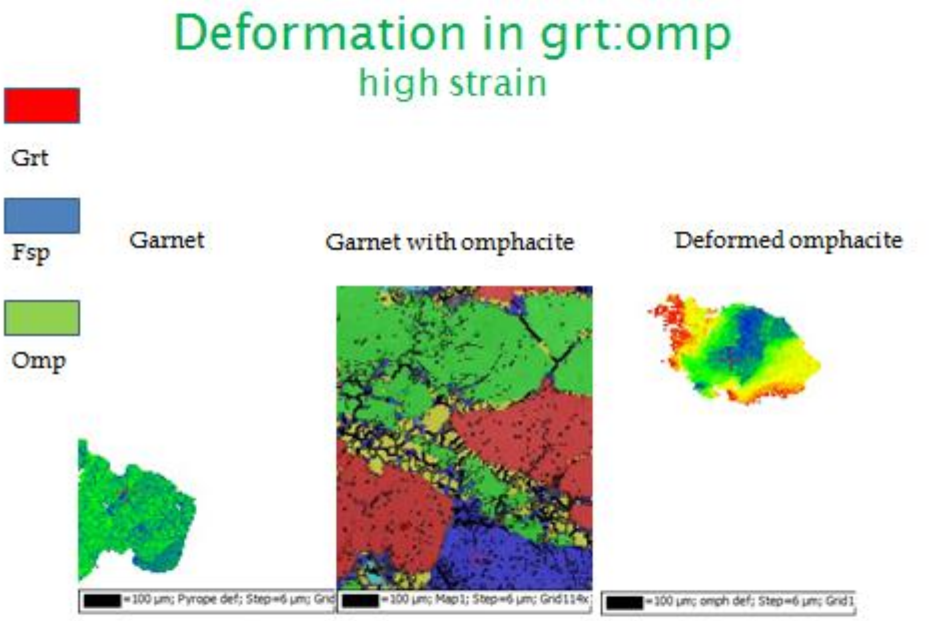

Figure 4.14. EBSD imaging of garnet: omphacite high strain sample illustrating deformation via dislocation creep of the omphacite whereas there is no deformation observed within the garnet

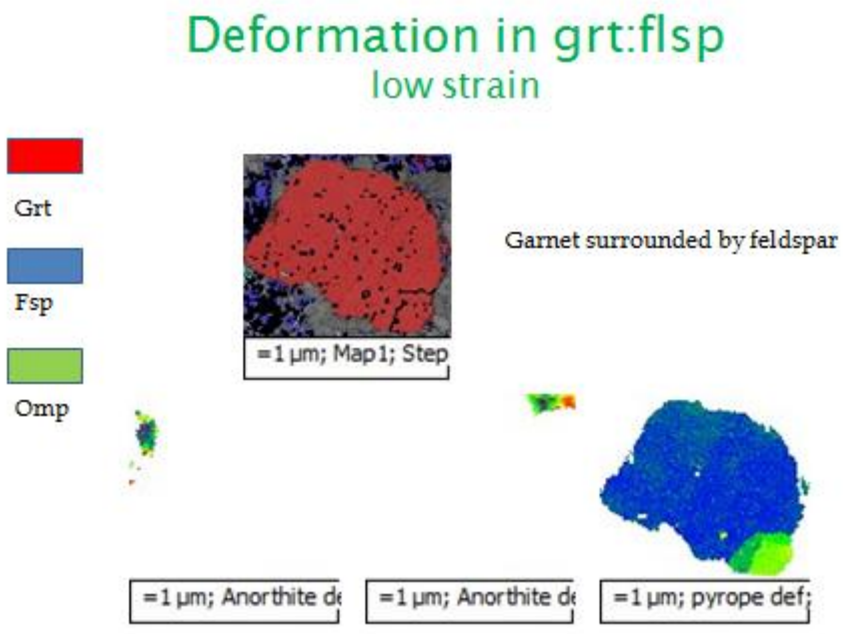

Figure 4.15. EBSD imaging of garnet: feldspar low strain sample illustrating deformation via dislocation creep of the feldspar. No deformation is evident in the garnet.

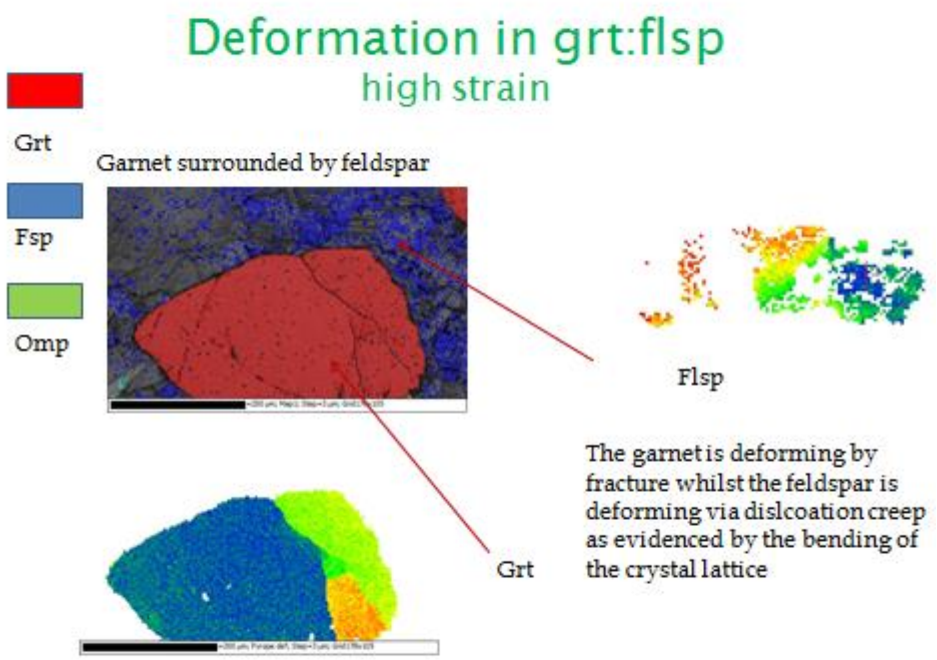

Figure 4.16. EBSD imaging of garnet: feldspar high strain sample illustrating deformation via dislocation creep of the feldspar. Deformation is evident in the garnet via fracture

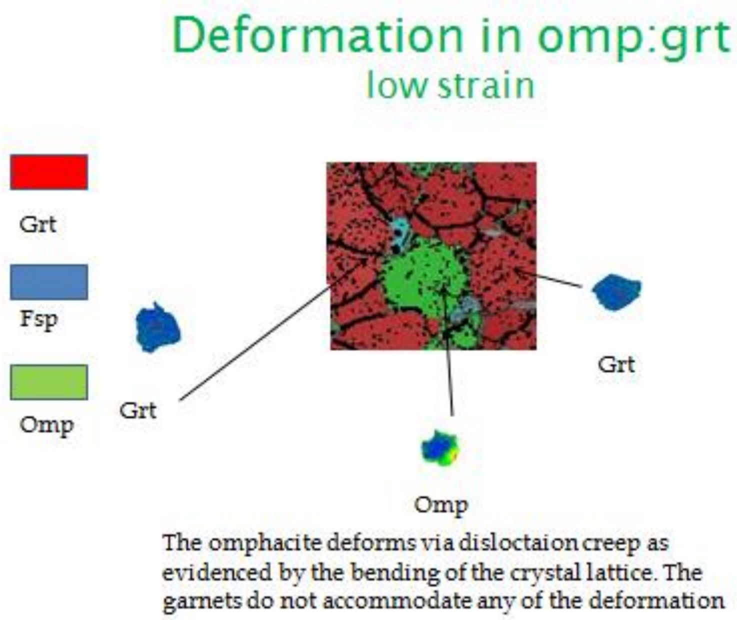

Figure 4.17. EBSD imaging of Omphacite: garnet low strain sample illustrating deformation via dislocation creep within the omphacite

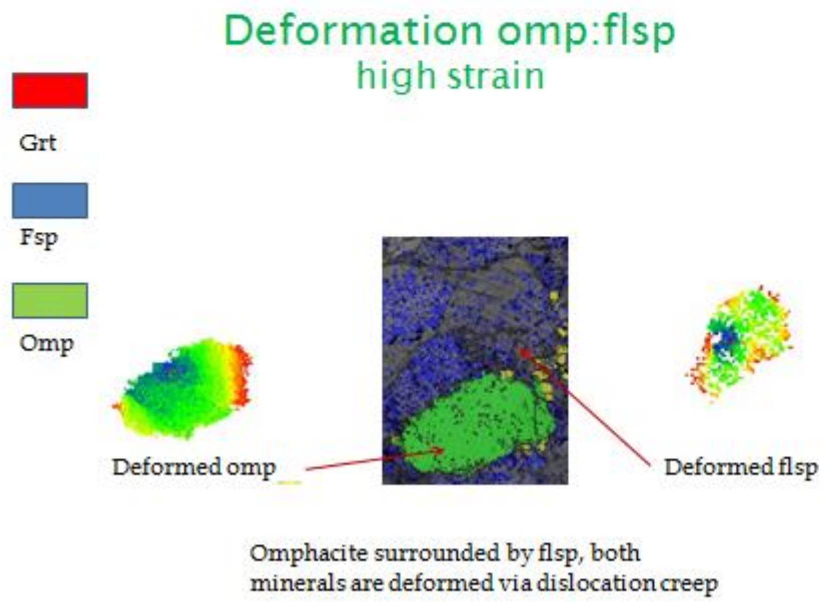

Figure 4.18. EBSD imaging of omphacite: feldspar high strain sample illustrating deformation of both minerals via dislocation creep as evidenced via bending of the crystal lattice

Pole figures can be used to illustrate the Lattice Preferred Orientation (LPO) within a sample with each figure representing the orientation of an axis of a specific mineral. Pole figures are displayed with X axis of a sample as horizontal, Y axis is vertical and Z axis is perpendicular to the page. Preferred orientations are represented as clusters of data around a point (point maxima) or in a band (a girdle).

The three phases this study focused on have different crystallographic systems, therefore different pole figures were plotted for each phase they are as follows; Feldspar (triclinic) <100>, <010>, <001>, Garnet (Cubic) {100},{110},{111}, Omphacite (monoclinic) {100},{110},{111}.

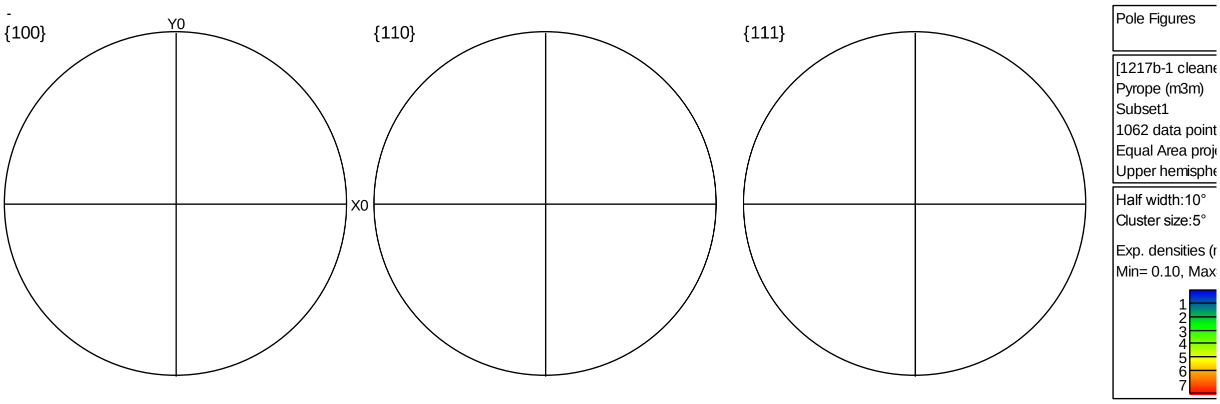

Figure 4.19. Contoured pole figure of garnets within sample 1217b Map 1 illustrating the preferred orientation of garnet relative to garnet. The {100} axis has 3 cluster points

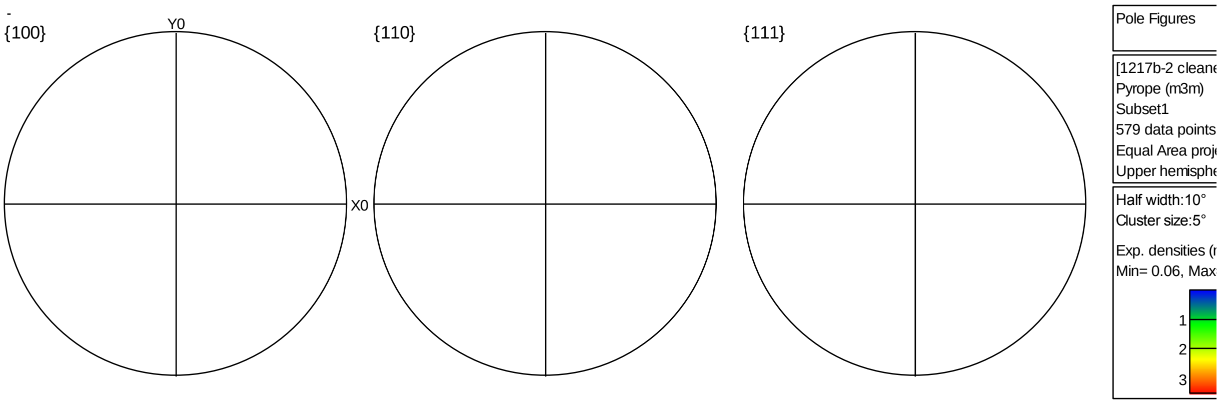

Figure 4.20. Contour pole figure of garnets within sample 1217b map 2.

The {100} axis has 2 main cluster points showing 3 areas together resulting in a weaker LPO relative to 1217b Map 1. Garnet relative to Omphacite

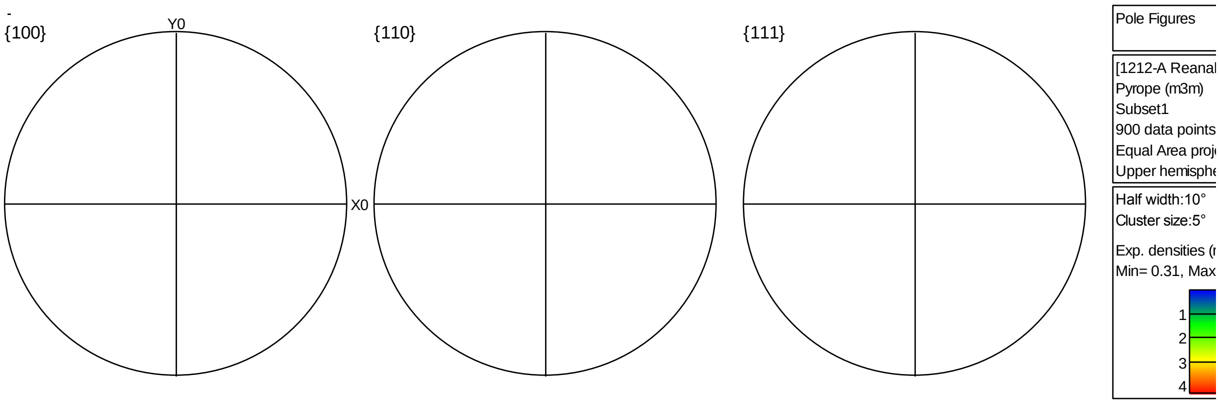

Figure 4.21. Contour pole figure 1212-A Map 3 -
The 100 axis has 3 main cluster points indication a preferred orientation garnet relative to garnet

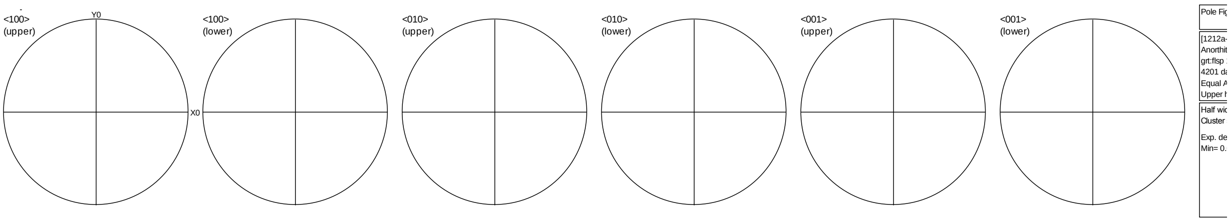

Figure 4.22. Contour pole figure 1212a Map 6 High strain sample
Pole figure for feldspar relative to grt with one cluster point at plane <100> (upper), <010> (upper)and <001> (upper)

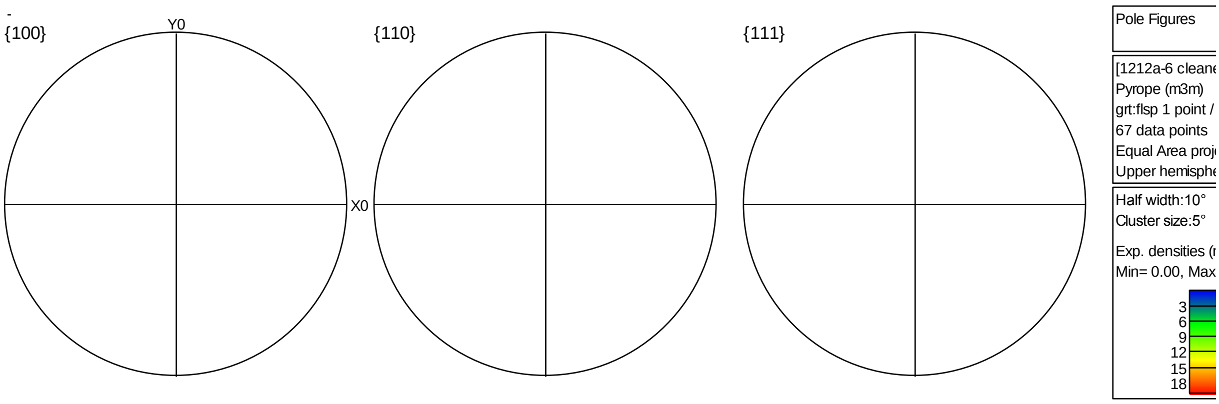

Figure 4.23. Contour pole figure 1212a Map 6 -high strain sample
Pole figure garnet relative to feldspar from same region as sample above A preferred lattice orientation is evidenced at {100} with one cluster point

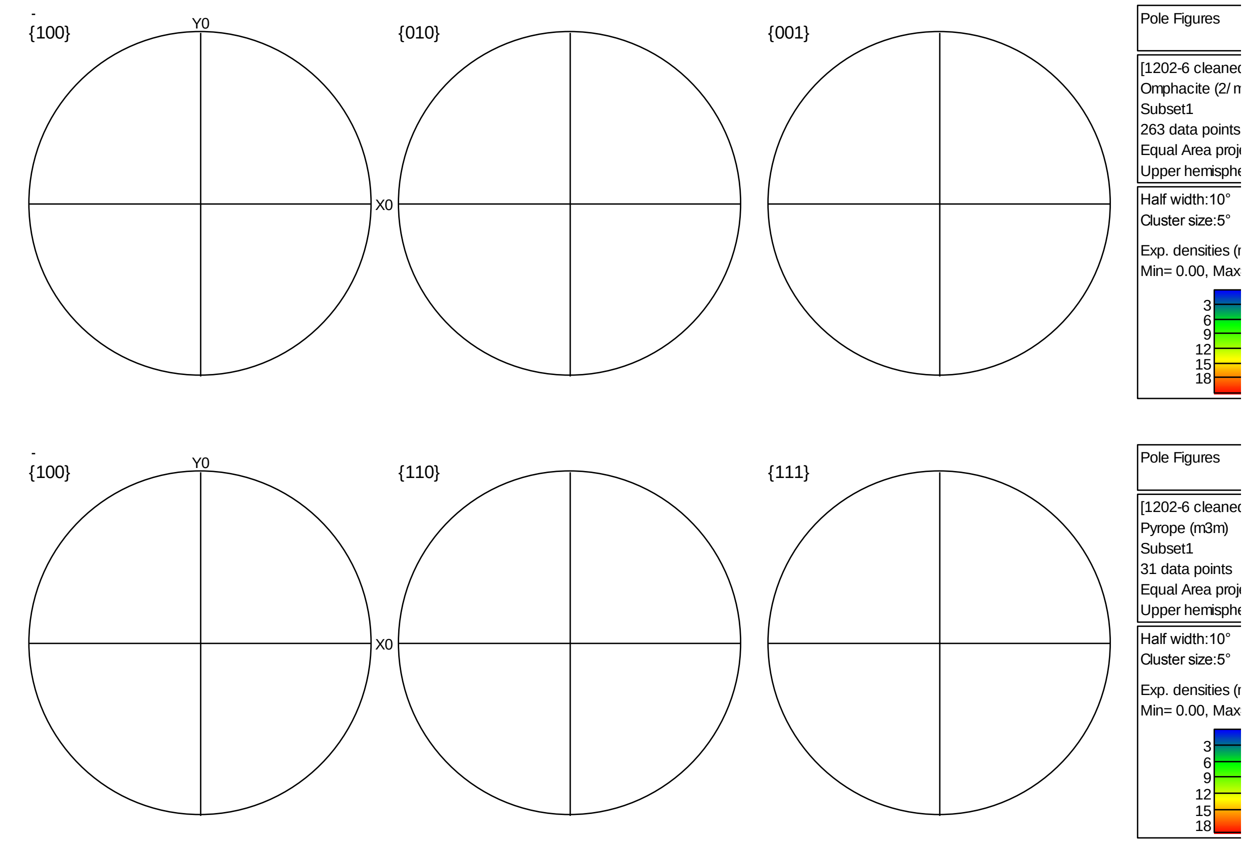

Figure 4.24. Contour pole figure 1202 Map 2 Low strain Omphacite Granulite
Illustrating LPO for Omphacite in {100},{110}and {111}(top pole figure) and garnet in {100} (lower pole figure)

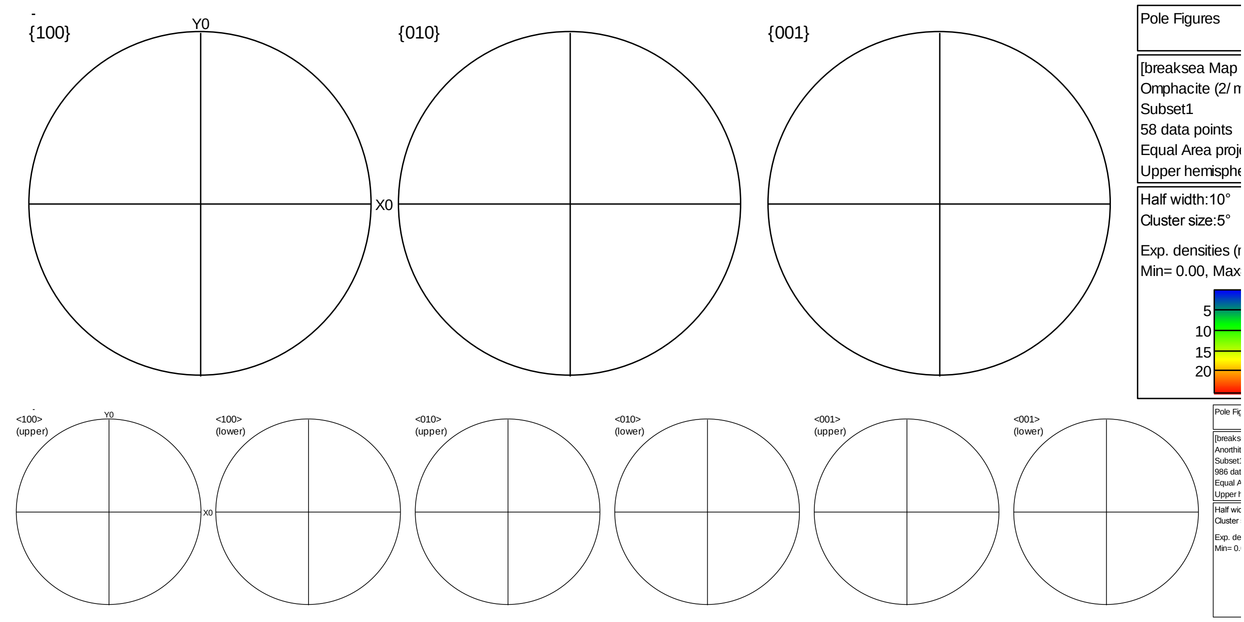

Figure 4.25.Contour pole figures for sample BS0905B Map 1
Illustrating LPO for Omphacite {100}, {010} and {001}(top pole figure) and feldspar in <010> (upper) (lower pole figure)

Part 2: Chemical Analysis

This chapter aims to describe and quantify the mineral chemistry of the three phases found within the Breaksea Eclogite and the Omphacite Granulite examined in this study.

4.2.1 SEM – EDS (note this has two aspects, EDS while EBSD was collected and just EDS (with BSE imaging).

Methods

10 samples were chosen for chemical analysis – BE both high and low strain and OG both high and low strain. Sample locations for BE and OG are shown in Figure 3.4.

SEM-EDS

Selected mechanically polished thin section samples were carbon coated (~10nm) in preparation for mineral chemistry analysis using the Zeiss EVO MA15 scanning electron microscope (SEM) located within Macquarie University. Energy Dispersive Spectrometry (EDS) values for three phases were targeted, they are Garnet, Pyroxene (Omphacite) and Feldspar (Plagioclase). Major element oxides for the selected phases were obtained after which the data was quantified using Oxford Instruments HKL Aztec software The SEM was run at a high vacuum with an accelerating voltage of 20kV, bean current 8.0-10.0nA, and aperature of 30µm. samples were set at a working distance of 11-13mm, 1024 channels with 10eV per channel. An automated count time was used as acquisition continues until enough counts have been collected for quantification.

SEM-EBSD

Four samples were selected for further analysis using SEM-EBSD (explanation of EBSD method and technique is described in section 4.1.3. EBSD gives both crystallographic data and elemental data via elemental maps.

Results

Feldspars Feldspars for all samples plotted as either K feldspar or Plagioclase within Oligoclase – labradorite. Samples trended toward Anorthite with increased strain.

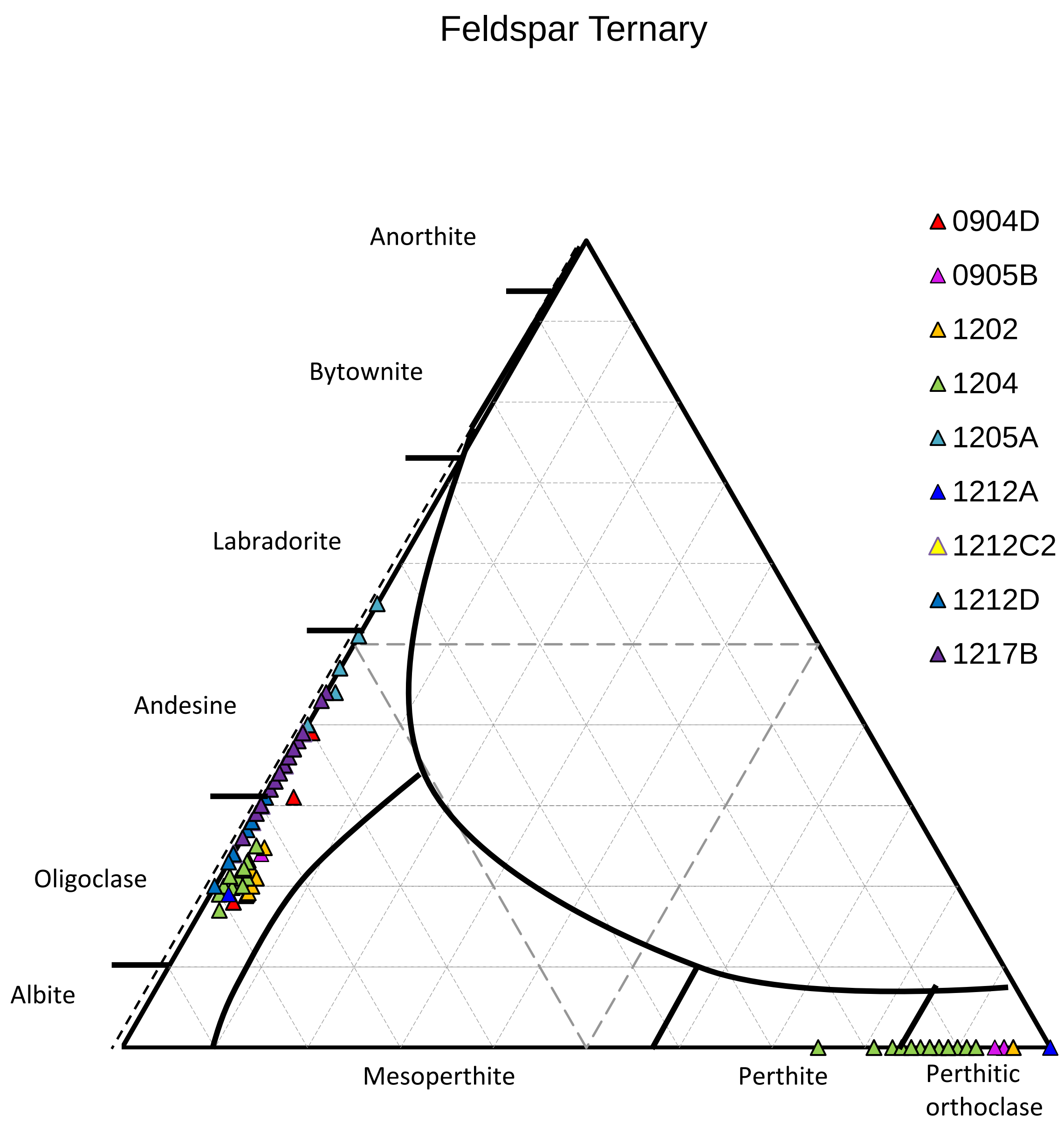

Figure 4.2.1 Feldspar ternary plot for all samples OG.samples both high and low strain.

Further analysis was carried out on samples representative of extremes of low to high strain. The feldspars analysed show a range in feldspar composition with two main populations from the low strain OG plotting within the Oligoclase field whilst the feldspars analysed from the high strain OG plot from Oligoclase _ Andesine migrating into the Anorthite field.

Feldspar Ternary Garnet Granulite

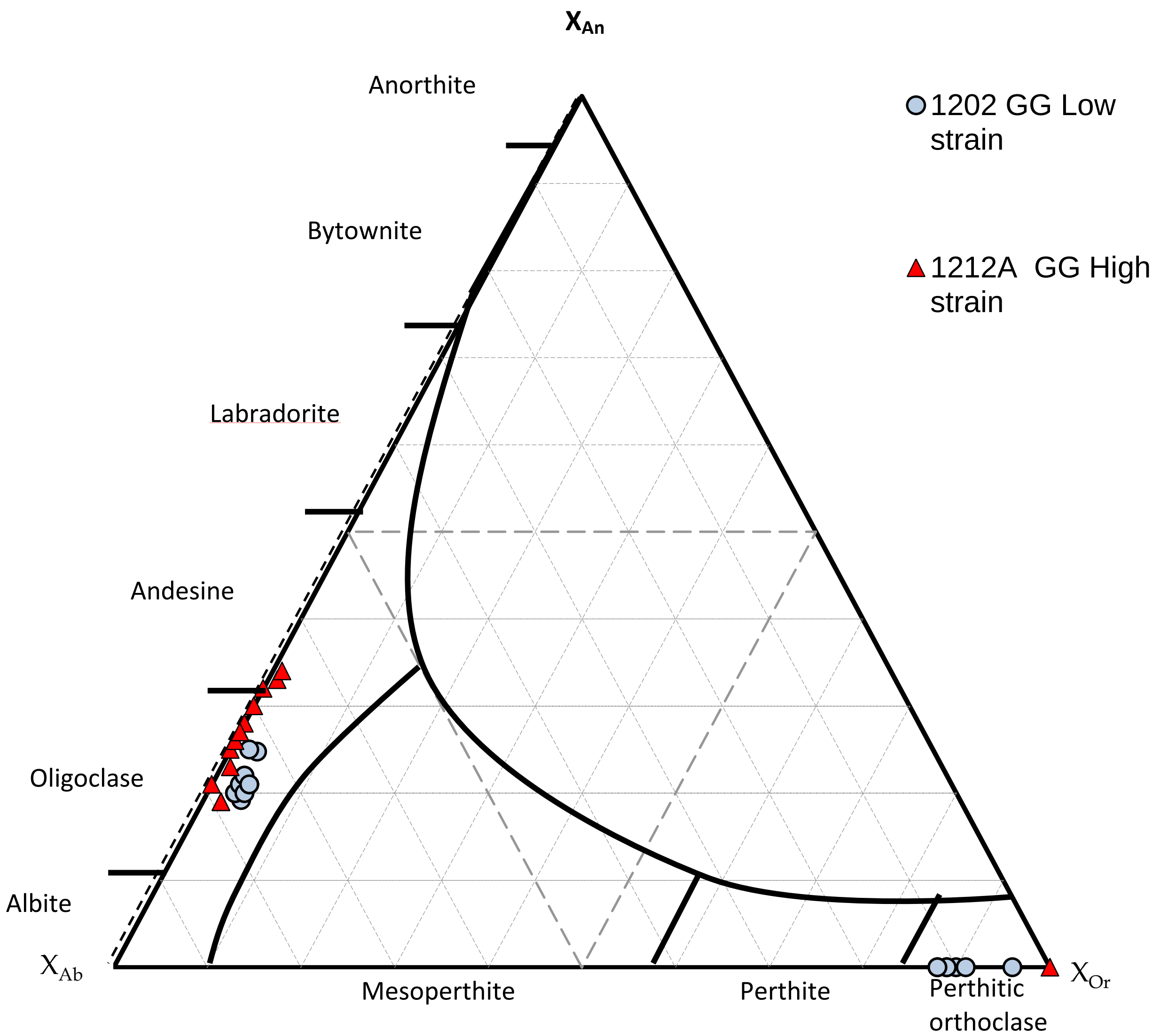

Figure 4.2.2 Feldspar ternary plot for selected Omphacite Granulite.

Garnet

Garnets from all samples both BE and OG plotted within a cluster

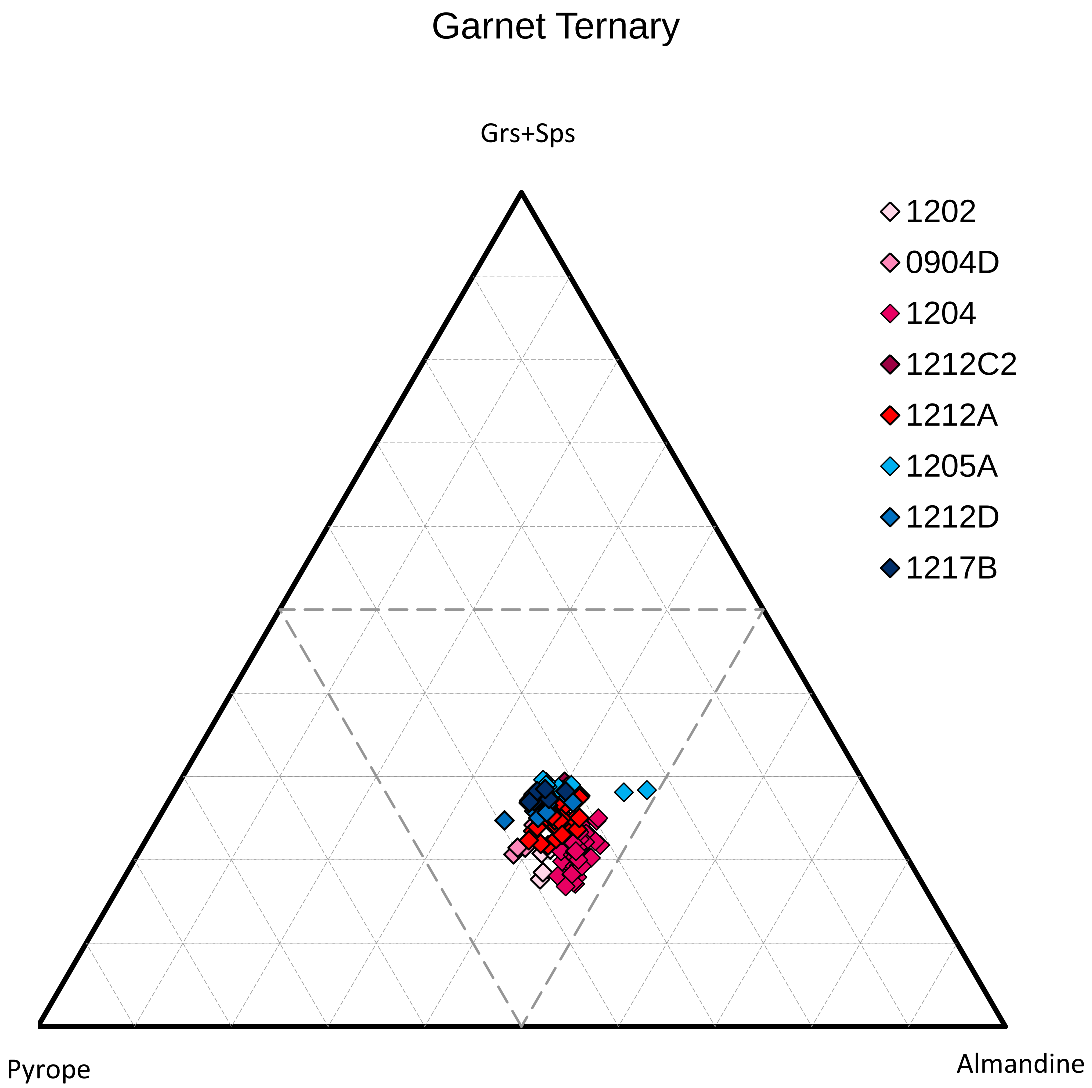

Figure 4.2.3 Garnet ternary plot for all samples.

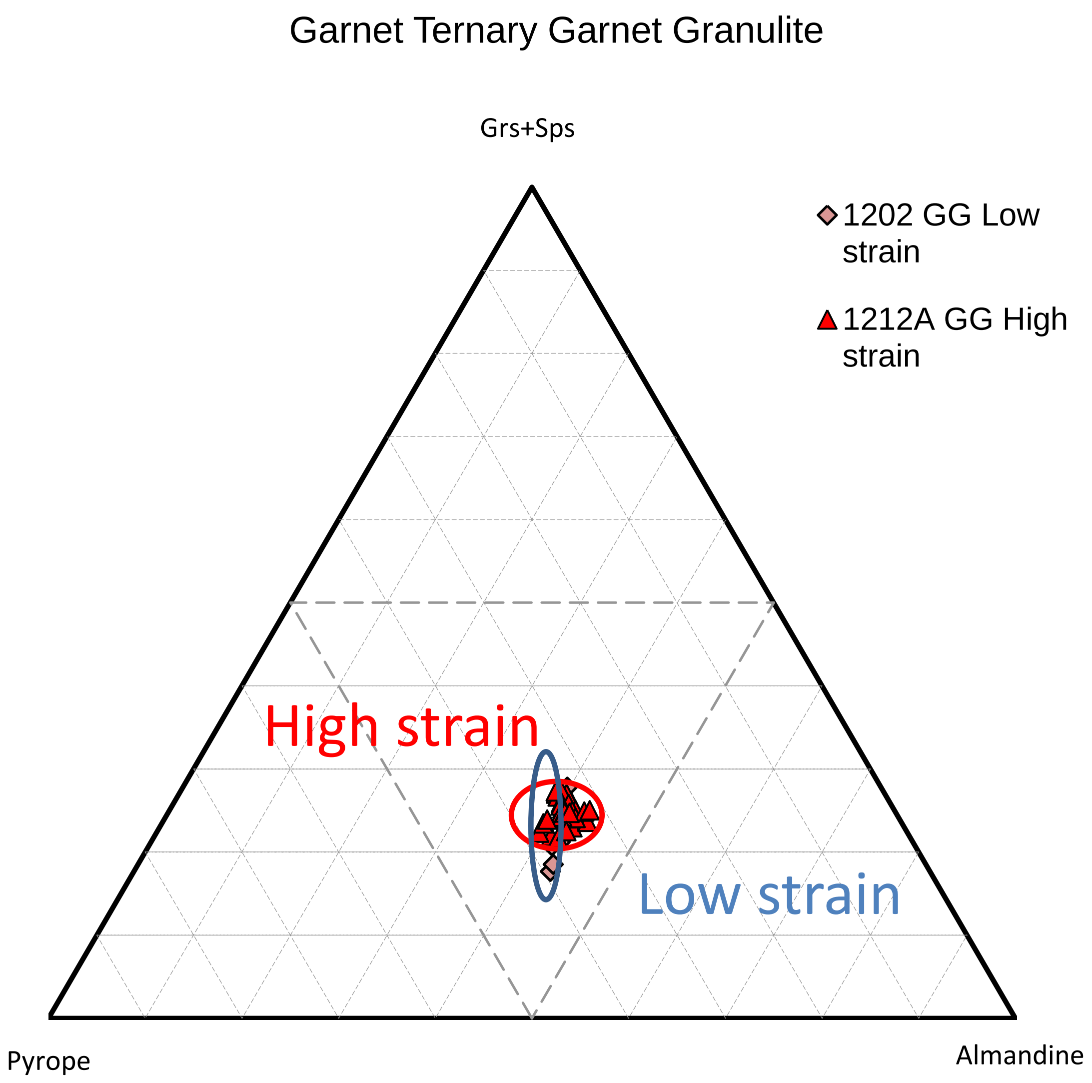

Figure 4.2.4 Garnet ternary plot for selected Omphacite Granulite.

Pyroxenes

Observed Pyroxenes from both BE and OG plotted as Omphacite (Figure 4.2.3). High strain BE seems to accommodate what has been interpreted to be recrystallised Omphacite.

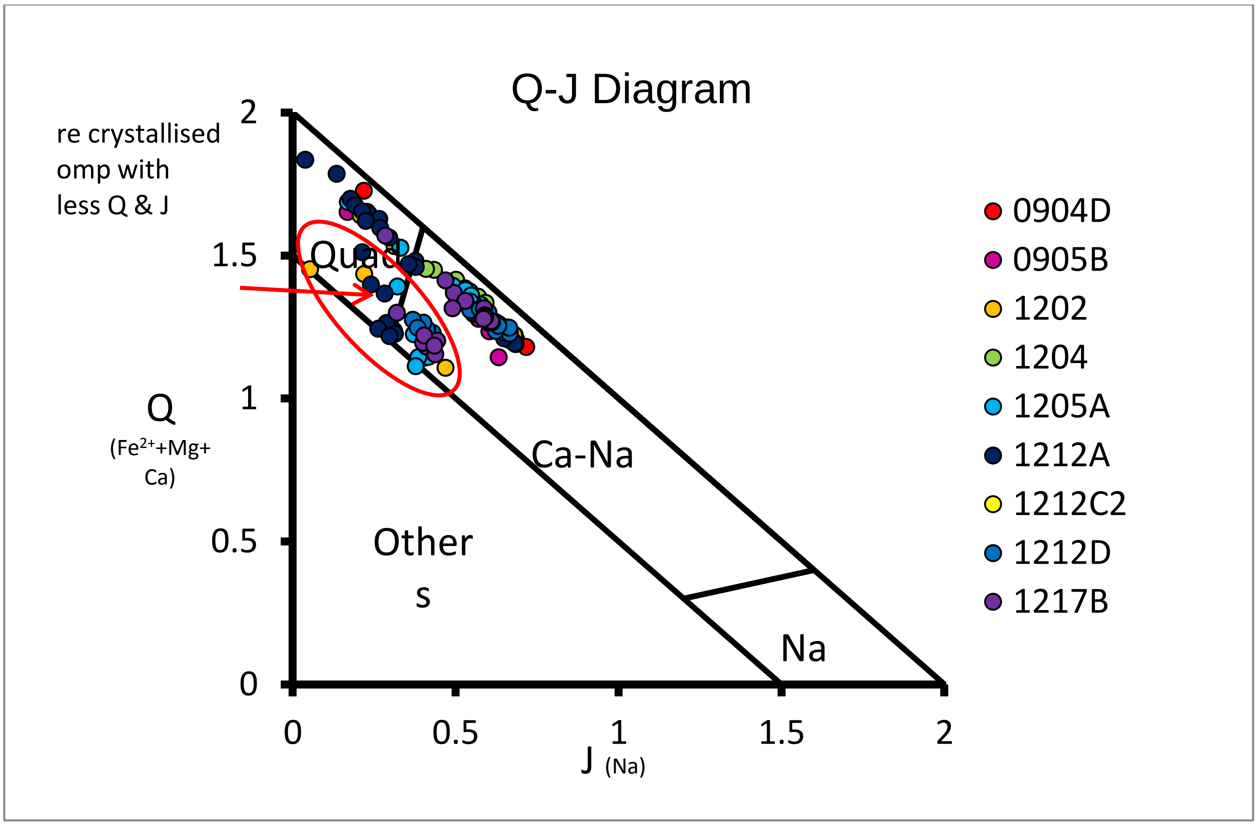

Figure 4.2.5 Garnet ternary plot for selected Omphacite Granulite

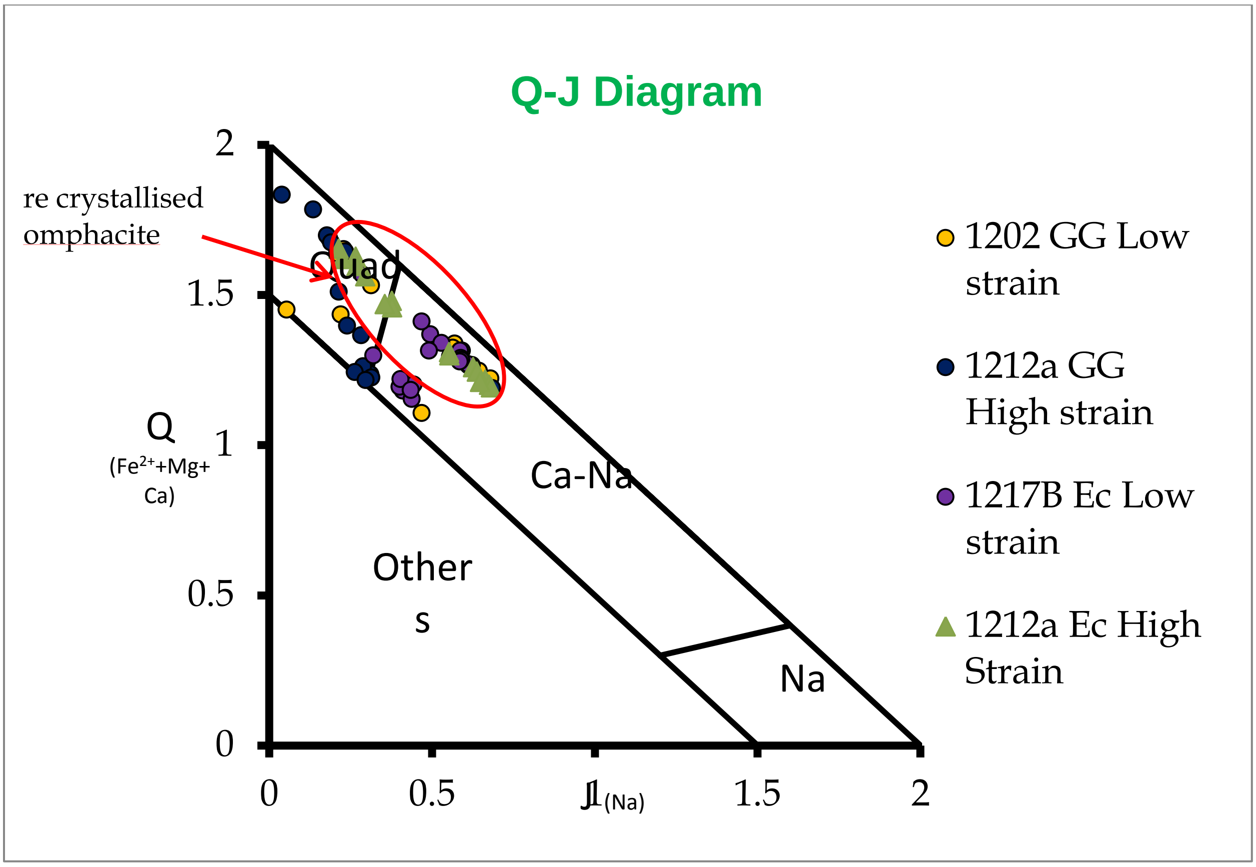

Figure 4.2.6 Garnet ternary plot for selected Omphacite Granulite.

Part 3: Interpretation

As the main aim of this paper is to determine if existing monomineralic flow laws are accurate when applied to polyphase rocks observed chemical variation coupled together with observed crystallographic data from ebsd

Observed chemical change allows the tracking of recrystallization in both feldspar and Omphacite. Garnet does not show any major elemental change

Depending on adjacent mineral Garnet will either undeform/ fracture – typically seen when garnet is surrounded by phases that deform easily. However when a garnet mineral is adjacent to another garnet mineral or in a neighbourhood dominated by garnet minerals then dislocation creep +- recrystallization is observed as evidenced by a strong LPO

Chapter 5 Discussion

Achievement of aims

To answer the research question posed individual grains and the neighbourhoods they were found in were analysed in order to ascertain the different deformation mechanisms. The deformation mechanism for a variety of mineralic comparisons is listed in Table 4.1. EBSD data is able to illustrate in a quantitative way the phases that deform relative to their neighbours.

Deformation mechanisms observed were

- Dislocation creep – undulose extinction, strong LPO, slip systems
- Sub grain migration – small area of the crystal twisting in place in order to reduce strain, in EBSD mis-orientation profiles can be used to ascertain the angle between the grains typically this is very small ~ 5-10 °. Visually looking for small grains within the minerals/at the edge of them.
- Fracture and cataclasis- triple point boundaries observed in smaller sub grains, indication of attempt to reach equilibrium by the mineral.

Regardless of neighbourhood or adjacent mineral feldspars deformed readily consistently accommodating the maximum strain via dislocation creep and sub grain rotation as evidenced via the LPO observed in the pole figures. Omphacite deformed via dislocation creep/sub grain rotation again regardless of adjacent mineral or neighbourhood however the intensity of the deformation was increased in the BE this is thought to be due to the absence of feldspar present to accommodate the majority of the deformation. When in the vicinity of omphacite or feldspar garnet remained undeformed/fractured. However when adjacent to another garnet grain garnet will deform via dislocation creep +- recrystallization (high strain) Table 4.1.

Table 4.1 Deformation mechanism dependance on neighbourhood.

Phase and neighbourhood Mineral 1: Mineral2	Strength 1 (weakest) - 10 (strongest) Mineral 1	Deformation mechanism (mineral 1)	Deformation mechanism (mineral 2)
Fldsp : Grt	1	Dislocation creep, subgrain rotation	Undeformed/ fractured
Fldsp : Omp	3	Dislocation creep, subgrain rotation	Dislocation creep, subgrain rotation
Grt : Omp	5	Undeformed/ fractured	Dislocation creep, subgrain rotation
Omp: Grt	5	Dislocation creep, subgrain rotation	Undeformed/fractured
Grt : Grt	6	Dislocation creep +- recrystallization (high strain)	Dislocation creep +- recrystallization (high strain)
Omp : Fldsp	7	Dislocation creep, subgrain rotation	Dislocation creep, subgrain rotation
Grt : Fldsp	9	Undeformed/ fractured	Dislocation creep +- recrystallization

Chapter 6 Conclusions

At lower crustal conditions eclogite and granulite deform similarly, as evidenced by little to no chemical variation of garnet and Omphacite from samples of each composition.

This was unexpected as other field examples show a difference of rheology of eclogite: granulite, this is interpreted to be due to an artefact of later tectonic overprinting.

When soft feldspar is not present garnet will accommodate strain however omphacite it consistently the primary carrier of deformation if the two phases – garnet and omphacite – are present.

The local neighbourhood of phases can govern the deformation mechanisms that are activated.

Data from monomineralic rocks cannot be used as a proxy for monomineralic rocks, they simply behave differently.

The data collected in this study show that polyphase rocks deform differently depending on what phases are present and in what quantities. With that in I believe that the data within this study illustrates that polyphase rocks deform differently to monomineralic rocks. In addition the data used to provide deformation indicators for polyphase rocks that are based on flow laws for monomineralic rocks is not adequate. My research questions were:

- How does the lower crustal rock deform specifically an Omphacite Hornblende Eclogite relative to Omphacite Granulite?

- Does the percentage of individual phases (mineral types) influence deformation mechanisms in the individual phases e.g. does the deformation mechanism for Omphacite adjacent to Garnet differ to the deformation mechanism for Omphacite adjacent to Garnet with Plagioclase present? Furthermore is the deformation of garnet influenced by the local vicinity of garnet, Omphacite and/or feldspar?

I believe that I have answered both.

Chapter 7 Implications

The results from this study represent a small part of a bigger research problem. The question of 'How does the lower crust deform?". All data and results from this study will contribute to the discovery of a new deeper understanding of the lithosphere.

Information and data obtained about rheological properties of lower crustal rocks adds to the 'tools' available for more realistic large scale numerical geodynamic modelling.

There are direct implications for economic and resource management.

References

ALLIBONE, A. H., JONGENS, R., TURNBULL, I. M., MILAN, L. A., DACZKO, N. R., DEPAOLI, M. C. & TULLOCH, A. J. 2009. Plutonic rocks of Western Fiordland, New Zealand: Field relations, geochemistry, correlation, and nomenclature. *New Zealand Journal of Geology and Geophysics,* 52**,** 379-415.

BESTMANN, M., PIAZOLO, S., SPIERS, C. J. & PRIOR, D. J. 2005. Microstructural evolution during initial stages of static recovery and recrystallization: new insights from in-situ heating experiments combined with electron backscatter diffraction analysis. *Journal of Structural Geology,* 27**,** 447-457.

DACZKO, N. R. & HALPIN, J. A. 2009. Evidence for melt migration enhancing recrystallization of metastable assembledges in mafic lower crust, Fiordland, New Zealand. *Journal of Metamorphic Geology,* 27**,** 167-185.

DE PAOLI, M., CLARKE, G. & DACZKO, N. 2012. Mineral Equilibria Modeling of the Granulite–Eclogite Transition: Effects of Whole-Rock Composition on Metamorphic Facies Type-Assemblages. *Journal of Petrology,* 53**,** 949-970.

DEPAOLI, M. C., CLARKE, G. L., KLEPIS, K. A., ALLIBONE, A. H. & TURNBULL, I. M. 2009. The Eclogite-Granulite Transition: Mafic and Intermediate Assembledges at Breaksea Sound, New Zealand. *Journal of Petrology,* 50**,** 2307-2343.

DIMANOV, A., DRESEN, G., XIAO, X. & WIRTH, R. 1999. Grain boundary diffusion creep of synthetic anorthite aggregates: The effect of water. *Journal of Geophysical Research: Solid Earth,* 104**,** 10483-10497.

HOLLIS, J. A., CLARKE, G. L., KLEPEIS, K. A., DACZKO, N. R. & IRELAND, T. R. 2004. The regional significance of Cretaceous magmatism and metamorphism in Fiordland, New Zealand, from U–Pb zircon geochronology. *Journal of Metamorphic Geology,* 22**,** 607-627.

KLEPEIS, K., KING, D., DEPAOLI, M. C., CLARKE, G. L. & GEHRELS, G. 2007. Interaction of strong lower and weak middle crust during lithospheric extension in western New Zealand. *Tectonics,* 26**,** 3-27.

KLEPEIS, K. A., CLARKE, G. L., GEHRELS, G. & VERVOORT, J. 2004. Processes controlling vertical coupling and decoupling between the upper and lower crust of orogens: results from Fiordland, New Zealand. *Journal of Structural Geology,* 26**,** 765-791.

MCNAMARA, D. D. 2012. Omphacite—a mineral under pressure! *Geology Today,* 28**,** 71-75.

PRIOR, D. J., WHEELER, J., PERUZZO, L., SPIESS, R. & STOREY, C. 2002. Some garnet microstructures: an illustration of the potential of orientation maps and misorientation analysis in microstructural studies. *Journal of Structural Geology,* 24**,** 999-1011.
RYBACKI, E. & DRESEN, G. 2000. Dislocation and diffusion creep of synthetic anorthite aggregates. *Journal of Geophysical Research: Solid Earth,* 105**,** 26017-26036.
RYBACKI, E. & DRESEN, G. 2004. Deformation mechanism maps for feldspar rocks. *Tectonophysics,* 382**,** 173-187.
SCOTT, J. M., COOPER, A. F., TULLOCH, A. J. & SPELL, T. L. 2011. Crustal thickening of the Early Cretaceous paleo-Pacific Gondwana margin. *Gondwana Research,* 20**,** 380-394.
STOREY, C. D. & PRIOR, D. J. 2005. Plastic Deformation and Recrystallization of Garnet: A Mechanism to Facilitate Diffusion Creep. *Journal of Petrology,* 46**,** 2593-2613.