The age, geological character and structural setting of quartz-pyrite veins in the Assynt Terrane, Lewisian Complex, NW Scotland.

VERNON, ROWAN,EMMA

The age, geological character and structural setting of quartz-pyrite veins in the Assynt Terrane, Lewisian Complex, NW Scotland.

Rowan Emma Vernon

Thesis submitted for the degree of Masters by Research at Durham University.

Department of Earth Sciences, Durham University

2011

Abstract

A set of previously unrecognised quartz-pyrite veins are present in the Assynt Terrane of the mainland Lewisian Complex, NW Scotland. The veins cross-cut the Badcallian and Inverian fabrics, and the Scourie Dykes. The veins have been reworked by Laxfordian deformation fabrics (ca. 1.8 Ga) and later brittle faults of various ages. Fieldwork analyses suggest that the veins are a multi-modal system of tensile/hybrid fractures which are locally influenced by the existing foliation of the gneisses. They are inferred to have formed during regional NW-SE extension, an orientation that is almost orthogonal to the NE-SW extension direction associated with the intrusion of the Scourie Dykes. Microstructures within the quartz veins suggest that overprinting Laxfordian events reached maximum temperatures of 500°C under moderate strain rates, while pervasive ductile deformation was restricted mainly to the Canisp Shear Zone and was succeeded by brittle deformation as the temperature decreased but strain rates remained high within the shear zone. Re-Os dating of the pyrite within the quartz veins gives an age of 2259±61 Ma, placing the emplacement of the veins after the oldest dates for the Scourie Dykes (2420, 2400 & 2375 Ma) but before the youngest ages (1990 Ma). Sulphur isotope analysis suggests that the pyrite is of primitive mantle origin and may have been either stripped from the crust by fluid circulation or was associated with the intrusion of the Scourie dykes. The presence of the quartz-pyrite veins in both the Assynt and Gruinard Terranes suggest they were amalgamated during or prior to Inverian deformation while the absence of the veins in the Rhiconich Terrane is consistent with the suggestion that this terrane was not amalgamated until the Laxfordian Orogeny. The emplacement of the veins may linked to the formation and/or amalgamation of the Loch Maree Group supracrustal sequence.

Declaration

I declare that this thesis, which I submit for the degree of Masters by Research at Durham University, is my own work and has not been previously submitted at this, or any other, university.

Copyright

Acknowledgements

I would like to thank my supervisors Prof. R. Holdsworth and Dr. D. Selby for their assistance, guidance and expertise throughout my research and Dr. A. Finlay for his assistance with the lab work and analysis for the Re-Os Geochronometer.

I would also like to thank Mr. D. Sales for producing my thin sections and teaching me how to use the rock saw, and Mr. L. Bowen for his assisting with operating the SEM.

My thanks also go to One Northeast who helped to fund my studies and to the Geological Society of London for the Annie Greenly Award which funded my fieldwork.

Finally, thanks to my parents for supporting me and to my aunt and uncle for the loan of their car, as well as to everyone in Ustinov College (particularly Box Tree) for making it such a great year.

Contents **Page Number**

List of Figures **Page Number**

List of Tables **Page Number**

Chapter One – Introduction

1.1 Research Proposal

This project proposes to document the structural and microstructural relationships of a hitherto unstudied regional set of quartz-pyrite veins which occur throughout the Assynt Terrane in the Lewisian Complex, NW Scotland, and to date the formation of these veins using the Re-Os geochronometer. Preliminary field studies by the supervisors of the structural setting of the veins suggest that they cross-cut early Badcallian gneissose fabrics, Inverian reworked fabrics and ca. 2.4 Ga Scourie dykes in the Lewisian. The veins are thought to have been reworked by Laxfordian deformation fabrics (ca. 1.8 Ga onwards) and later brittle faults of various ages. The veins appear to be restricted to the Assynt Terrane and the project will assess whether the absolute age is consistent with the field relationships. There is considerable debate about the application of terrane models to ancient orogenic gneiss complexes like the Lewisian and this project will yield important new insights and potentially recognise a 'signature' event since these veins are apparently restricted only to the Assynt Terrane in NW Scotland.

1.2 Work Carried Out

I began the project with four weeks of field work, from the end of September to the end of October, in the Assynt Terrane of the Lewisian Complex, NW Scotland, based at Inchnadamph Lodge at the southern end of Loch Assynt. My work centred along the Assynt-Lochinver valley where good exposures were known to occur along the shore of Loch Assynt and in road cuts along the Lochinver road, although considerable time was also spent at Clashnessie Bay, Achmelvich Bay and Kylesku. I measured the orientation, thickness, length, lineations and en echelon off-shoots of all the quartz-pyrite veins encountered and studied the relationship of the veins to other structures within the country rocks (e.g. Badcallian, Inverian and Laxfordian foliation, Scourie dykes and later brittle faults). I collected orientated samples of the quartz-pyrite veins from a broad range of locations throughout the terrane to be made into thin sections for optical and SEM analysis, as well as samples of the pyrite within the veins to be dated using the Re-Os geochronometer.

On returning from the field I collated my data into one excel database. I plotted the orientations of the veins onto stereograms using a range of filters (e.g. location, age of country rock, and relationship to Lewisian foliations) to establish any trends in their orientation. Veins containing lineations on their margins were analysed using stress inversion techniques. Using ArcMap, I plotted the positions and orientations of the quartz-pyrite veins onto a geological map and high resolution aerial photographs. With the assistance of D. Selby, I selected six of the samples of pyrite collected in the field to be dated using the Re-Os geochronometer. During November and December I prepared these samples, to be run on the mass spectrometer, in the laboratory under the instruction of A. Finlay, following the method described in the paper (Chapter Two).

During November I began to research and learn about quartz microstructures in preparation to analyse thin sections of the quartz-pyrite veins. I selected twelve orientated samples, which covered a range of settings within the Assynt Terrane, to be made into thin sections, and cut the large samples myself using the rock saw under the instruction of D. Sales. I also began to analyse the microstructures in three existing thin sections of the quartz-pyrite veins.

During late November and December, I made a poster detailing the results of my research to that point, which included field observations, structural analysis, preliminary microstructural analysis of the three existing thin sections, and the results of a pilot Re-Os study carried out by D. Selby on the pyrite within one of the veins. I presented this poster at the annual Tectonic Studies Group Conference at Durham (5th – 7th January 2011), and was awarded runner up in the Postgraduate Poster Competition.

In January D. Selby and A. Finlay helped me to run my prepared pyrite samples on the Mass Spectrometer and to analyse the results using a program they had developed. We then combined these with the results of other pyrite samples from the Assynt Terrane previously analysed by D. Selby, and plotted them on a graph to obtain an isochron, from which a date for the crystallisation of the pyrite could be calculated. Based on the results it was decided to analyse three more pyrite samples for which I conducted the laboratory work under the supervision of A. Finlay. These were run on the Mass Spectrometer shortly before Easter and the results analysed and added to the others. From these results D. Selby assisted me in selecting the results that produced an isochron with the smallest inaccuracy, which is presented in the paper below.

In early February my thin sections were ready and I was able to begin analysing the twelve thin sections of the quartz veins under the optical microscope with the aim of determining their temperature and pressure history post-emplacement to see if this reflected any of the events believed to have occurred in the Lewisian Complex around this time. This work was carried out under the supervision of R Holdsworth. I also analysed the relationships of the pyrite to the quartz in the veins to establish that the pyrite was formed synchronously with the quartz, and thus that the date obtained for the crystallisation of the pyrite was concurrent with the formation of the quartz veins. In addition, I studied the relationship between any other minerals (e.g. muscovite, chlorite and calcite) and quartz grains in the veins to help deduce their history. Following a preliminary analysis of all the thin sections, three were selected to be analysed under the SEM to look more closely at the relationships between the pyrite and the quartz, other minerals and the quartz and shear structures within the quartz. The SEM analysis was conducted during three sessions in late March and April and was carried out in the Physics Department with the assistance of L. Bowen in Carbon Coating the samples and operating the SEM.

After Easter, I collated all my results so far and wrote a first draft of the paper. After reviews by my supervisors it was decided that I should spend another week in the field to gather a bit more data and so during the second week of June I returned to the Assynt Terrane. I concentrated on looking for evidence of the opening directions of the veins primarily around Clashnessie, as there is a wide variation in the orientation of the quartz-pyrite veins in that area, and on gathering some more data from veins which had been affected by the Laxfordian Event within the Canisp Shear Zone. I also collected typical samples of the Badcallian, Inverian and Laxfordian Gneisses.

On returning from the field I selected one sample of each of the Badcallian, Inverian and Laxfordian gneisses to be made into thin sections, as well as two samples of quartz veins containing pyrite. The thin sections were prepared by the end of June and I was able to analyse the microstructures within the gneisses and compare these to the microstructures within the quartz-pyrite veins. I was also able to further establish the relationship of the pyrite to the quartz within the veins. During late June I also added my new structural data to the existing data and analysed this again using stereograms and stress inversion techniques to discover any trends in the orientation and/or distribution of the veins.

By early July I was able to begin writing up my findings from this project into a paper (see below) which will be submitted for publishing to the Journal of the Geological Society of London.

Chapter Two – Quartz-pyrite Veins of the Assynt Terrane

The age, geological character and structural setting of quartz-pyrite veins in the Assynt Terrane, Lewisian Complex, NW Scotland.

*A version of this chapter will be submitted for publishing co-authored by R. Holdsworth[1], D. Selby[1], A. Finlay[1] & T. Fallick[2].

[1] *Department of Earth Science, Durham University, Science labs, Durham, DH13LE.*

[2] *SUERC, Scottish Enterprise Technology Park, Rankine Avenue, East Kilbride, G750QF.*

2.1 Introduction:

Like many regions of continental metamorphic basement, the Lewisian Complex of NW Scotland preserves evidence for multiple episodes of igneous intrusion, ductile and brittle deformation and associated phases of metamorphism and mineralisation (e.g. Wheeler *et al*., 2010, Beacom *et al*., 2001 and references therein). Whilst cross-cutting and overprinting relationships observed in the field and thin section allow relative age relationships to be established on both regional and local scales, only radiometric ages are able to give information concerning the absolute ages of events. Despite the emergence of an increasing number of geochronometers for Earth Scientists, an enduring problem in many basement regions is a relative paucity of material suitable for reliable radiometric dating. This has become a particularly significant problem in the Lewisian Complex since Kinney *et al*. (2005) and Friend & Kinny (2001) proposed that the Lewisian may comprise a number of lithologically and geochronologically distinct tectonic units or terranes.

In this paper, we describe the lithology, field relationships and microstructures of a previously undescribed set of quartz-pyrite veins that are recognised throughout the Assynt Terrane. These display a consistent set of contact relationships relative to regionally recognised igneous, metamorphic and deformational events. We have dated the pyrite in the veins using the Re-Os technique and obtain a consistent set of ages that help to better constrain the geochronology of this important part of the Lewisian Complex in NW Scotland.

2.2. Regional Setting:

The Precambrian rocks of the Lewisian Complex of NW Scotland form a fragment of the continental basement of Laurentia at least as far SE as the Great Glen Fault (**Fig. 1**). The complex underwent a number of major crustal-scale geological events during the Archaean and Palaeoproterozoic and is divided into a number of tectonic regions or terranes which are separated by steep shear zones.

The Assynt Terrane (**Fig. 1**), as defined by (Kelly *et al.*, 2008) comprises grey, banded, tonalitic gneisses which are locally highly heterogeneous in nature ranging from ultramafic to acidic compositions (Sheraton *et al.*, 1973). The orthogneisses are derived from tonalite, trondhjemite and granodiorite plutons intruded at 3030 to 2960 Ma (Macdonald & Fettes, 2007). The depletion of LIL elements is more extensive in the Assynt Terrane compared to adjacent terranes (e.g. Rhiconich, Gruinard) as a result of Badcallian granulite-facies metamorphism (Wheeler *et al.*, 2010) which occurred ca. 2490 Ma (Park, 2005).

The central part of the Assynt Terrane is cut by the major NW-SE-trending, steeply dipping Canisp Shear Zone (CSZ) which has a maximum width of 1.5km (**Fig. 2**). There are also many other NW-SE to WNW-ESE trending minor shear zones cutting the surrounding gneisses (Park & Tarney, 1987). Some of these shear zones, including the CSZ, developed initially during Inverian deformation and amphibolites-facies retrogression which affected substantial parts of the Assynt Terrane ca. 2480 Ma (Love *et al.*, 2004). Mafic to ultramafic Scourie dykes are present throughout the entire terrane. These predominantly cross-cut local Inverian fabrics, although those intruded first are thought to carry Inverian amphibolites-facies assemblages and a weak, steeply-dipping foliation in places (Park *et al.*, 1994). The later main phase Laxfordian event (ca. 1760 Ma) was associated with the widespread retrograde development of phyllosilicate-rich fabrics during lower amphibolite to upper greenschist-facies metamophism (Attfield, 1987, Beacom *et al.* 2001). The effects of Laxfordian reworking in the Assynt Terrane are highly localised, being largely restricted to the central part (ca. 1km wide) of the CSZ and other shear zones, as well as along the margins of pre-existing Scourie dykes. This contrasts with the neighbouring Rhiconich and Gruinard Terranes where this event reached amphibolites facies and was associated with more pervasive ductile shearing and reworking (Droop *et al.*, 1989). This has led to the suggestion that the Assynt Terrane lay at a shallower crustal depth during the Laxfordian event (e.g. Dickinson & Watson, 1976; Coward & Park 1987). **Table 1** provides a summary of the chronology of the Assynt Terrane.

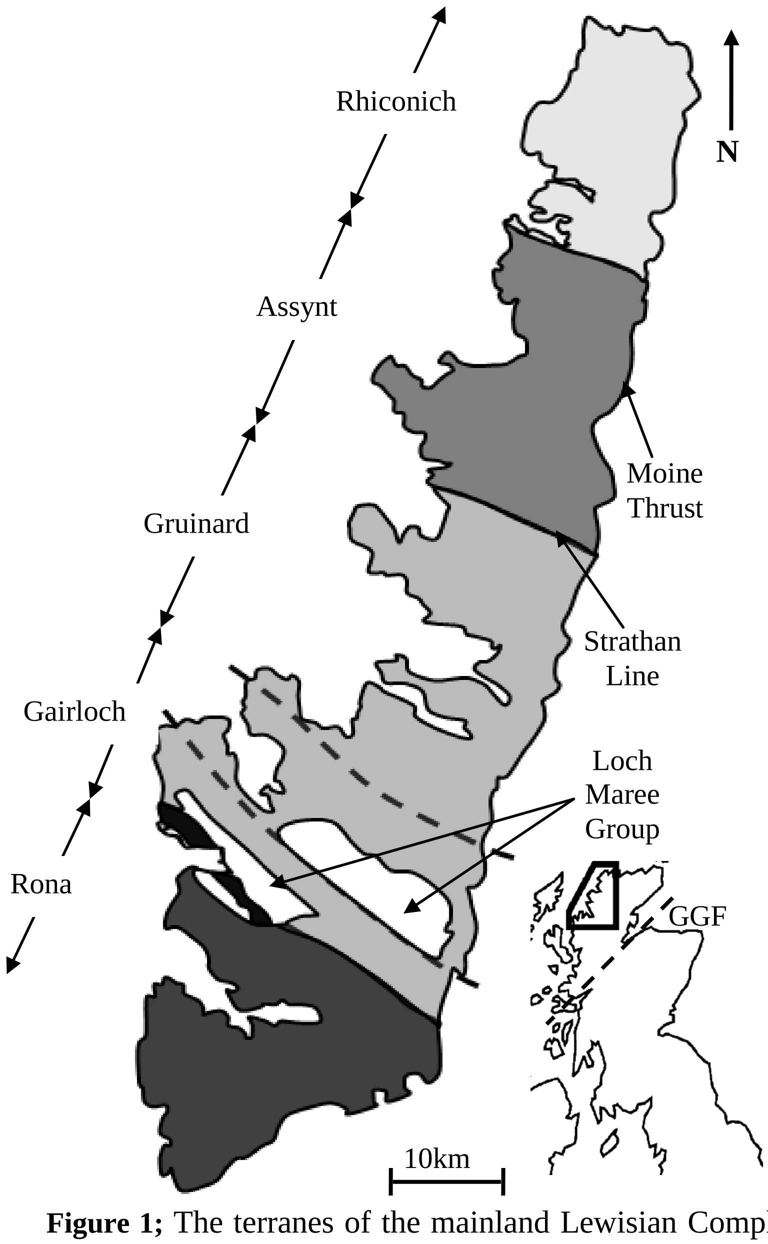


Figure 1; The terranes of the mainland Lewisian Complex (Kelly *et al.*, 2008 & Love *et al.*, 2004). GGF – Great Glen Fault.

Ma	Event	Kinematics
2900 - 2490	Badcallian granulite-facies metamorphism and deformation. NE-SW fabrics and shear zones.	Folding and sub-horizontal thrusting.
2490 - 2400	Inverian amphibolites retrogressive metamorphism and deformation. Steep NW-SE trending shear zones.	Dextral transpression – north-up thrusting with small dextral component.
2400 - 1900	Emplacement of the NW-SE to E-W trending Scourie dyke swarm. Deformation and formation of the Loch Maree Group.	Dextral transtension.
1900 - 1800	Early-Laxfordian amphibolites-facies metamorphism and deformation. NW-SE fabrics and shear zones.	Dextral transtension – on oblique shears and asymmetric shear folds.
1600 - 1400	Mid-Laxfordian upper greenschist-facies metamorphism and deformation. NW-SE fabrics and shear zones.	Dextral transpression – north-up thrusting and upright folds.
1400 - 1200	Late-Laxfordian lower greenschist-facies metamorphism and deformation. NW-SE shear zones and some brittle deformation.	Sinistral strike-slip – steeply plunging asymmetric folds and crush belts.

Table 1; Summary of the chronology of the mainland Lewisian Complex of NW Scotland during the late Archaean and paleao-Proterozoic (Adapted from Beacom, 2001).

2.3. Field relationships of quartz-pyrite veins:

The occurrence of quartz veins is a widely recognised but little described phenomena in the Lewisian Complex of the Assynt Terrane (e.g. Sheraton *et al.*, 1973). Some generally foliation-parallel veins are clearly relatively late features that are closely associated with retrogression and shearing along Laxfordian shear zones and the development of schistose, phyllosilicate-rich high strain zones (Beach 1976; Beacom, 1999). However, the present study has revealed that an earlier, much more widespread and distinctive group of quartz-pyrite veins are present throughout the Assynt Terrane. They are particularly easy to see in fresh road-cut exposures where the pale white colour of the veins stands out markedly from the generally dark-coloured granulite facies Badcallian gneisses. The distribution of the veins throughout the Assynt Terrane does not seem uniform – they typically occur in clusters cutting the gneisses in regions covering areas of tens to hundreds of square metres, with particularly well-defined groups occurring in the Loch Assynt and Clashnessie regions, and along the trace of the CSZ (**Fig. 2**).

The veins typically range from a few millimetres to several tens of centimetres in width (e.g. **Fig. 3a-e**), and are relatively straight and continuous features that can be traced for several metres or, less commonly, tens of metres along strike. They have sharply-defined margins, are occasionally anastomosing and sometimes contain inclusions of country-rock or patches of pink feldspar. Pyrite is not found in all of the veins, but where it occurs it is typically either located along the margins as large crystals (>0.5 mm) or as large clusters (>1cm) of crystals distributed sparsely throughout the veins (**Fig. 3h**). In some cases pyrite clusters have been partially to completely oxidised to red haematite, particularly where they have been exposed at the surface for an extended period; this gives the veins a distinctive localised red staining. Within the CSZ, pyrite crystals are also sometimes found in the sheared gneisses surrounding the vein. In some road cuts, the development of quartz-pyrite veins is additionally associated with a localised yellow-brown sulphurous weathering of the gneisses, e.g. east of Lochinver (NC 1020 2360).

2.3.1 Cross-cutting relationships

The quartz-pyrite veins display a consistent set of cross-cutting relationships with other features in the Lewisian Complex of the Assynt Terrane and can be used to deduce a regionally consistent relative chronology of events. They typically cross-cut the oldest, moderately to shallowly-dipping Badcallian foliations and folds (**Fig. 3a**) in the Assynt terrane, although at Clashnessie, where the foliation is particularly strong and highly variable, the veins are occasionally concordant with the foliation. The veins also consistently cross-cut the steeply-dipping Inverian shear fabrics of the CSZ (**Fig. 3b**) and other minor shear zones within the terrane, as well as most of the Scourie dykes (**Fig. 3c**). Both veins and dykes are consistently overprinted and reworked by dextral shear fabrics related to the Laxfordian event, including the development of the CSZ (**Figs. 3d**). The veins are also cross-cut by late Laxfordian, epidote-bearing small-scale shear zones and fractures (**Fig. 3f**). Many of the larger quartz clasts found in the immediately overlying basal units of the Torridonian sandstones (both Stoer and Torridon Groups) are plausibly derived from the veins. The quartz-pyrite veins are also cross-cut by gouge-bearing post-Torridonian faults (e.g. NC 1020 2360).

These observations collectively suggest that the quartz-pyrite veins post-date both the NW-SE trending Inverian fabrics and Scourie dykes. They appear to pre-date all Laxfordian fabrics and faults and also the deposition of the Torridonian sediments.

2.3.2 Orientation and kinematics

The orientations of 140 quartz-pyrite veins measured in the Assynt Terrane during the present study are shown in **Figs. 4a-c**, and the lineations found on the veins in **Fig. 4d**. A rose diagram plot (**Fig. 4b**) suggests a dominance of NE-SW strikes with subordinate NW-SE, NNW-SSE, and WNW-ESE trends. The regional stereograms (**Figs. 4a & c**) suggest a wide range of vein orientations, with a reasonably strong concentration of planes striking NE-SW and, to a lesser extent NW-SE; dips are quite variable even for veins with similar strike orientations. Note that both NE-SW and NW-SE trending sets display bimodal dip directions (e.g. NW or SE and NE or SW respectively, **Figs. 4a & c**). These observations suggest a generally multimodal pattern of fracture orientations.

In order to try and separate out the possible effects on vein orientation of local country rock fabrics and Laxfordian overprinting, the data have also been plotted according to the localities where well-defined clusters of veins are found. The stereograms for both the Clashnessie and Achmelvich (**Figs. 4e & f)** areas show a wide range of orientations in the strike and dip of the veins and with no clear trends easily distinguished. The Lochinver cluster (**Fig. 4g)** preserves two rough trends striking NE-SW and NW-SE, with the latter dominant. The best defined trends are found in the Kylesku and Loch Assynt (**Figs. 4h & i)** clusters. The Kylesku cluster shows two distinct trends striking NE-SW and NW-SE, whilst at Loch Assynt, there is a very well-defined trend striking NE-SW with the majority of veins dipping steeply NW. In the Scourie cluster (**Fig. 4j)** the veins have shallow dips and the majority strike ENE-WSW.

The vein data have also been plotted according to the local fabrics they cross-cut or are reworked by. In the regions of gneiss dominated by the Badcallian event, both the foliations (**Fig. 4k**) and the veins (**Fig. 4n**) have large variations in their orientations. The foliation shows a slight N-S trend dipping W, whereas the veins show a reasonably strong NE-SW trend of strikes, with bimodal dips to the NW and SE. The Inverian foliation has a strong NW-SE trend with bimodal dip trends (**Fig. 4l**), whereas the veins show a NE-SW trend which mainly dips steeply NW (**Fig. 4o)**. Both the Laxfordian foliation and the veins within the Laxfordian fabrics show a strong NW-SE trend (**Figs. 4m & p)**, reflecting the intensive reworking of fabrics and reorientation of veins into parallelism with those fabrics during overprinting deformation.

The reasons for the observed variations in vein orientation are unclear. The fact that the best defined trends are found in rocks where NW-SE trending Inverian and Laxfordian fabrics are largely absent (e.g. Loch Assynt, Kylesku) may point to the controlling influence of pre-existing foliations and/or later reworking of veins into these orientations elsewhere. It is possible that some variations in orientation are the result of block rotations related to later brittle faults, although we have been unable to conclusively demonstrate the presence of such rotations at any of the localities studied.

The kinematics of the veins are difficult to deduce with any great certainty. Most of the veins appear to be primarily dilational (Mode 1 tensile) features based on observed offsets of markers in the adjacent wall rocks, i.e. the vein opening directions lie at high angles to the vein walls). A few large veins in the Loch Assynt and Lochinver regions display en echelon off-shoots (e.g. **Fig. 3e**) consistent with some degree of shearing during emplacement. Of the seven veins found with such off-shoots, five indicated a sinistral and two a dextral sense of shear. There does not appear to be any obvious orientation control on the shearing directions, and perhaps the shearing may be due to local strains. A few (7) veins display mainly dip-slip slickenline lineations on their outer contacts, but it is unclear whether these are the same age or later than the veins.

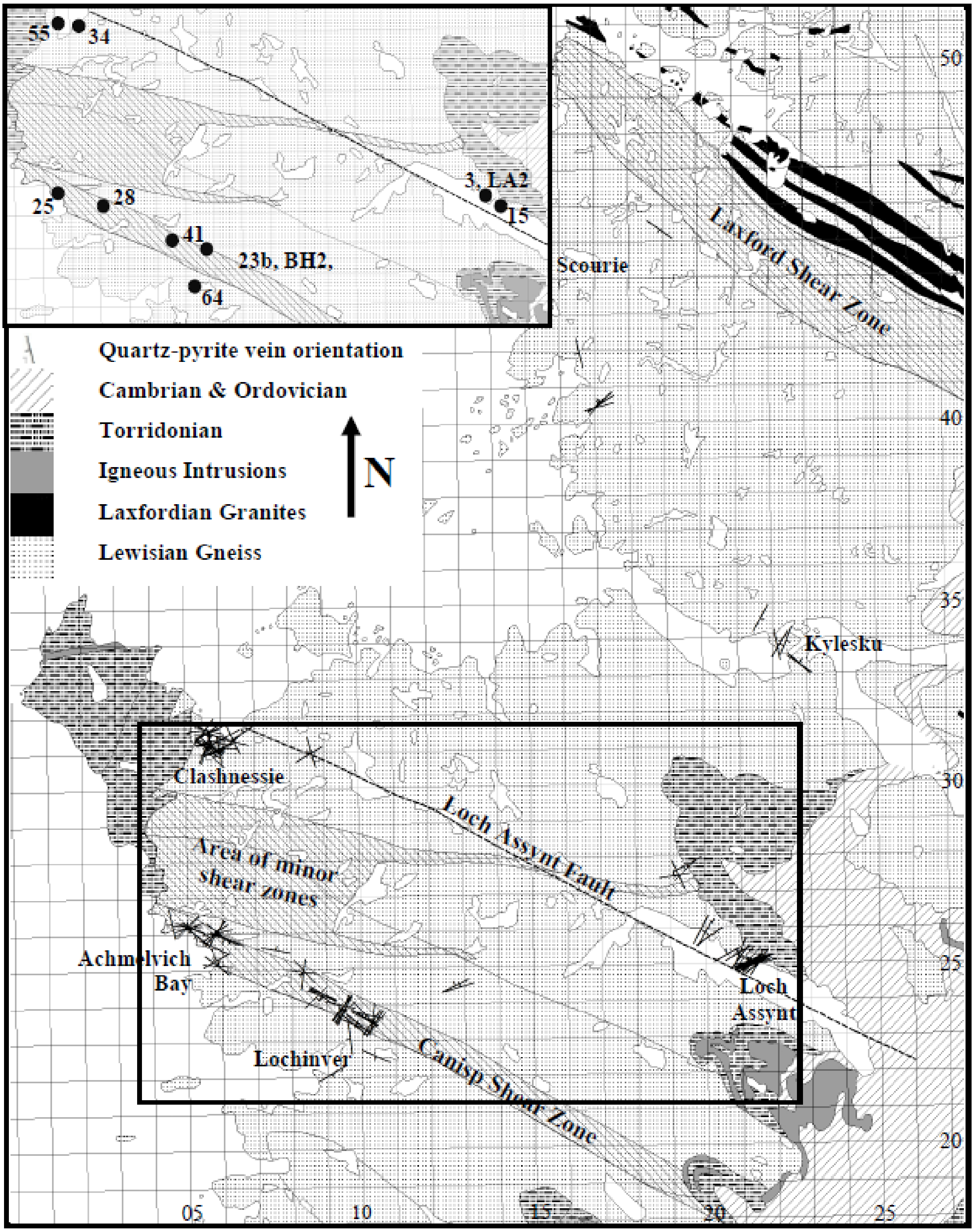


Figure 2: Location and orientation of the quartz veins within the Assynt Terrane of the Lewisian Complex, and the locations of the samples used in optical, SEM and Re-Os analysis (G-Bay is located at Gruinard Bay in the Gruinard Terrane, NC 9530 9077).

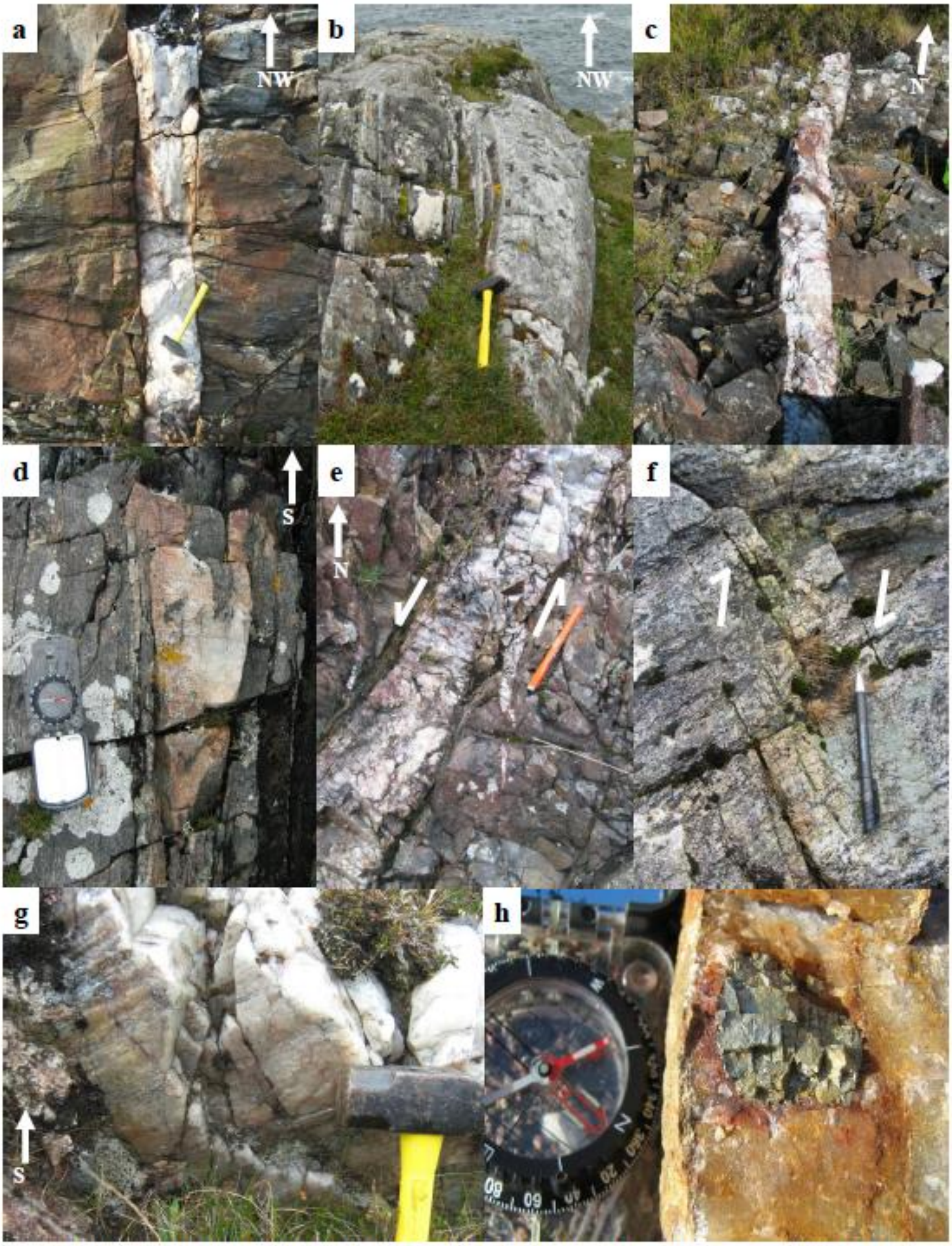


Figure 3; a) Veins cross-cutting Badcallian foliation (NC 0855 3102) and **b)** Inverian foliation (NC 0521 2593), **c)** Vein crosscutting Scourie Dyke (NC 2135 2510), **d)** Vein folded and reworked by Laxfordian fabrics (NC 0515 2620), **e)** Vein with en-echelon off-shoots, indicating sinistral shear (NC 2135 2510), **f)** En echelon fractures filled with epidote in a dextral shear zone (NC 2110 2517), **g)** Shallow lineations on Laxfordianised vein (NC 0606 2580), **h)** Pyrite cluster within a vein (NC1038 2249).

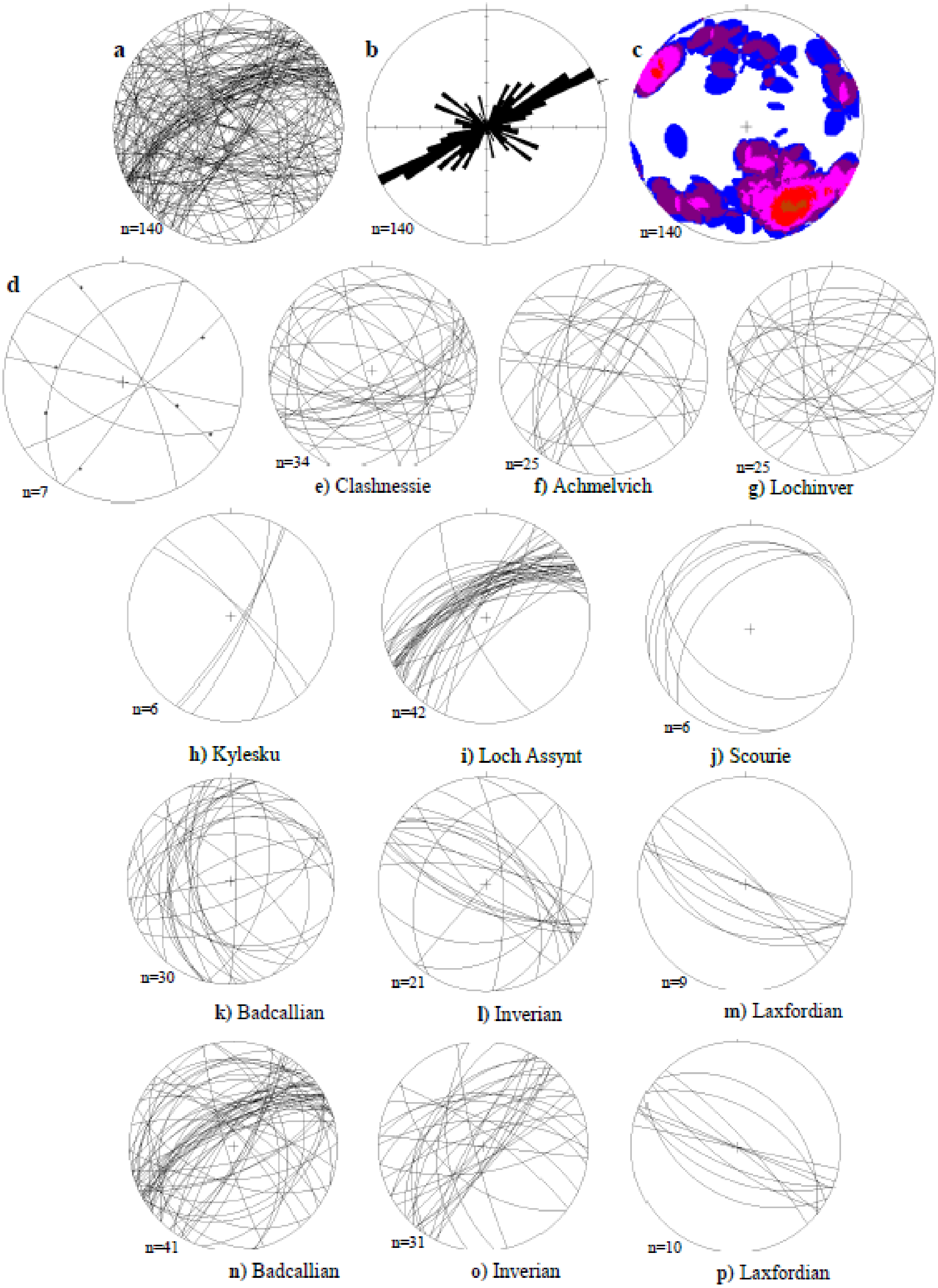


Figure 4; Orientation of the regional vein suite: a) Stereogram, b) Rose diagram, c) Gridded contour density plot, d) Orientations of the veins with lineations, with the lineations plotted, e-j) The orientation of veins within clusters in the Assynt terrane, k-m) The orientations of the three gneissose fabrics within the terrane, and n-p) Orientations of the veins within the gneissose fabrics.

2.4. Microstructure:

2.4.1 Lewisian Gneiss

The Badcallian granulite gneisses of the Assynt Terrane vary considerably in composition from ultramafic to acidic (Sheraton *et al*., 1973). The various compositions of gneiss show foliation on all scales, from millimetres to tens of metres (Sheraton *et al*., 1973), and it is best developed in intermediate gneisses, where it is defined by 0.5 to 5 cm thick layers of contrasting light (plagioclase and quartz) and dark (hornblende and biotite) layers, with individual layers rarely continuing for more than a few metres (Jensen, 1984). Samples of intermediate gneiss from Loch Assynt typically contain 30% quartz, 20% plagioclase, 10% microcline, 10% orthopyroxene and 30% heavily retrogressed material, with occasional relict grains of clinopyroxene. The retrogressed material comprises of fine grained intergrown aggregates of chlorite, epidote, actinolite and hornblende and is probably a product of the later retrograde breakdown of pyroxenes. Holland and Lambert (1975) observe that pure, unregressed granulite is very rare in the Assynt Terrane, with almost all the gneisses containing some secondary amphibole.

The Badcallian gneisses were reworked in shear zones (e.g. the CSZ) during the Inverian, which imposed a new NW-SE foliation in the rocks (Attfield 1987). Deformation within the shear zone is extremely heterogeneous, with lenses of low-strain gneiss enclosed by anastomosing bands of highly deformed, sheared gneiss (Attfield 1987). Intrafolial folds are uncommon but can be found in zones of Inverian deformation (Attfield 1987). Samples of these reworked Inverian gneisses from within the CSZ contain 20% quartz, 40% feldspar (predominantly plagioclase with alteration bands), 5% orthopyroxene, 15% amphiboles (hornblende and some epidote), 15% biotite and chlorite mica, and 5% other minerals such as clinopyroxene. The hornblende, epidote, biotite and chlorite are likely to be a product of the breakdown and hydration of pyroxenes (Beach, 1976) during retrogression first to amphibolite facies during the Inverian Event (~2.5 Ga) and subsequently to upper greenschist facies during the Laxfordian Orogeny (~1.7 Ga). The quartz crystals contain prismatic subgrains and form irregular, sub-parallel ribbons of crystals which are 0.25 - 1mm in size, smaller than in the undeformed Badcallian gneisses, possibly due to syn-tectonic recrystallisation under high strain rates (Jensen, 1984).

The Laxfordian Orogeny reactivated the inner part of the CSZ, producing a new, finer foliation (Sheraton *et al.*, 1973). Commonly, the gneisses which have been reworked in both small and large shear zones have a mineralogy that differs significantly from that of the original gneiss and the extent of the changes that occur appears to be in proportion to the intensity of the deformation (Beach, 1976). A sample of Laxfordianised gneiss from the CSZ contains about 75% quartz, 10% hornblende, 10% biotite and muscovite mica, and 5% feldspar porphyroblasts (typically ~1mm in size). The quartz is banded on a millimetre scale with alternating bands of small quartz grains (<100μm) and larger quartz grains (~500μm to 1mm) which form an anastomosing schistose foliation. The micas are pinned to, and orientated parallel to, the bands of smaller quartz crystals. The quartz crystals themselves are often elongate and contain poorly developed subgrains. Jensen (1984) also recognised the ‘schistose’ fabric within Laxfordian gneisses and finds similar microstrucures and quartz grain sizes within his analysis. Hornblende is surprisingly scarce in the sample analysed and the percentage of quartz is higher than in either the Badcallian or Inverian gneisses. Petrographic analyses of Lewisian gneisses by Beach (1976) show that, during regression, pyroxene is first replaced by hornblende, which is then replaced by biotite in the most intensely deformed gneisses. The analyses also show that an increase in the modal percentage of quartz accompanies the growth of biotite. The Laxfordian reworking occurred in intense zones which anastomosed around lenses of unreworked Badcallian or Inverian gneiss (Sheraton *et al.*, 1973). Tight intrafolial folds are common within the Laxfordianised gneisses and in places Inverian folds have been refolded (e.g. on the coast at Port Alltan na Bradhan; see Attfield, 1987). The Scourie dykes within the CSZ have also been pervasively affected by Laxfordian reworking with shearing particularly concentrated along their margins (Sheraton *et al.*, 1973).

2.4.2 Quartz-Pyrite Veins

The quartz veins display an array of deformation textures resulting from both recrystallisation and shearing processes, suggesting they have experienced a long history of deformation at different temperatures and pressures. A number of overprinting relationships are seen which can be used to reconstruct a relative age sequence. The deformation textures are described with reference to the age of the gneiss fabric which the veins either intrude or – in the case of veins in the CSZ – are overprinted by. **Table 2** summarises the vein samples taken for detailed optical and SEM study and their cross-cutting relationships with features in the host Lewisian Gneisses.

2.4.3 Veins Cutting Badcallian Fabrics

The quartz veins emplaced into the Lewisian Gneisses which have Badcallian age foliations (~2.7 Ga) do not appear to have been significantly reworked or deformed at outcrop scales. Nevertheless they preserve a range of deformation microstructures within the quartz crystals that reflect modest amounts of grain-scale deformation. The seemingly most deformed (e.g. sample 34) contain large quartz crystals (> 1mm, but typically 3 – 7mm) which show sweeping undulose extinction and have highly lobate grain boundaries as a result of the migration of grain boundaries into each other due to differences in the stored strain energy of neighbouring grains during recrystallisation (Stipp *et al.*, 2002). Chessboard subgrains (**Fig. 5a**) within the large quartz crystals are also common and form in response to the migration of dislocations within the crystal lattice into subgrain walls during recrystallisation (Passchier & Trouw, 2005). These structures are a result of grain boundary migration recrystallisation which occurs either at high temperatures (>500°C) or at low strain rates (Hirth & Tullis, 1992). Other deformed veins (e.g. sample 55) also show sweeping undulose extinction, but the boundaries of the large grains are less lobate and relict smaller grains (<100μm) are present along them, a product of grain boundary bulging recrystallisation which occurs under lower temperatures (300 – 400°C) or higher strain rates. As temperature increases or strain rate decreases these small grains are recrystallised to form larger grains. Around 30 percent of the large grains show elongate subgrains. These deformation textures suggest grain boundary migration recrystallisation is beginning to occur, but likely reflect more moderate temperatures (400 - 500°C) and moderate-low strain rates.

The least deformed veins within Badcallian foliation are found on the shores of Loch Assynt (e.g. sample 3). The quartz crystals within these veins also display undulose extinction. The large grains contain deformation lamellae, which are zones of differently orientated crystal lattice separated by dislocations. Grain boundaries have undergone small-scale bulging during recrystallisation and small grains (<100μm) have developed within the bulges and along the deformation lamellae (**Fig. 5b**). Using the sensitive tint plate, it can be seen that the small grains have distinctly different crystallographic orientations to the large grains, and thus they are younger. These structures typically form at lower temperatures (~300°C) or at high strain rates. The development of elongate subgrains in the large grains occurs rarely and indicates temperatures may reached 400°C or that strain rates may have decreased (Hirth & Tullis, 1992).

The range of deformation microstructures observed in the quartz veins suggests that these parts of the Assynt Terrane experienced a moderate temperature (400 - 500°C) event which was characterised by low strain rates, which may have allowed extensive recrystallisation. The veins on the shore of Loch Assynt show considerably lower temperatures (perhaps as low as 300°C) and higher strain rate conditions. This may be the result of later deformation associated with slip on the Loch Assynt fault, to which they are proximal.

2.4.4 Veins Cutting Inverian Fabrics

The veins emplaced into Lewisian Gneiss which has been reworked by Inverian age fabrics within the CSZ also show little obvious deformation at outcrop scale. Like the veins emplaced into Badcallian foliation, they show a range of deformation microstructures - including undulose extinction, deformation lamellae, new grain growth along crystal boundaries, subgrain development and the development of lobate grain boundaries – which are indicative of recrystallisation under low to moderate temperatures (350 - 500°C) and high to moderate strain rates.

Some veins (e.g. sample 23b) contain large (>2mm) quartz crystals with lobate boundaries, formed by grain boundary migration under moderate temperatures and strain rates, which show grain boundary bulging and the development of new, small grains (<250μm) within the bulges, particularly at triple-point grain boundaries (**Fig. 5c**). These structures are typical of recrystallisation under low temperatures (300 - 400°C) or at high strain rates, and indicate a lower temperature event which may have occurred after the main high temperature event. There is little evidence for this event being recorded within the veins emplaced into Badcallian Gneisses, and it may be that it is related to localised later deformation and fluid flow in the CSZ immediately after vein emplacement.

Many of the veins contain small (<10mm), brittle fractures along which chlorite, muscovite, calcite, albite, k-feldspar and spinel can be found. The presence of these minerals is likely to result from fluid flow depositing minerals in spaces within the quartz aggregate (e.g. in sample 25, calcite is found within pull-apart type fractures in the quartz; **Figs. 5d & 6a**). However, it is not clear if these fractures occurred at an early point in the veins' history or during a more recent brittle event.

2.4.5 Veins Reworked by Laxfordian Fabrics

The veins emplaced within the Laxfordian part of the CSZ have been heavily reworked at outcrop scale (e.g. **Figs. 3d & 3g**). Many of the microstructures resulting from the recrystallisation of quartz are similar to those seen in the veins which were emplaced into gneisses with Badcallian and Inverian foliations, but the degree of deformation is much higher due to reworking. In most veins (e.g. sample 64) the larger quartz crystals (>2mm) show sweeping undulose extinction, deformation lamellae, subgrain development and lobate grain boudaries. The majority of small grains have been recrystallised to form large grains, although a few relict ones can still be seen along the boundaries of the large grains. These microstructures indicate deformation under moderate temperatures (350 - 500°C) and strain rates.

In a few samples (e.g. sample 41), the lobate grain boundaries formed by grain boundary migration (moderate temperature and strain rate) show evidence of later grain boundary bulging and the development of new, small grains (<250 μm) along grain boundaries. This lower temperature, higher strain rate overprinting can also be observed in some of the veins in the Inverian part of the CSZ (e.g. sample 23b, discussed above).

The veins reworked by Laxfordian deformation are also characterised by a range of microstructures related to shearing. Many contain discontinuous, sub-parallel bands of reduced crystal size (<100 μm) which are 0.5 - 1mm in width and have no clearly defined margin, creating a mylonitic fabric (**Fig. 5e**) similar to that in the Laxfordian gneiss described above. Some of the larger bands (e.g. in sample 64) contain muscovite and chlorite micas which can be clearly seen in hand specimen. SEM analysis shows many of the micas have kinked lattices (**Fig. 6b**), indicative of deformation under low temperature ductile conditions. SEM analysis also shows the large mylonitic bands contain calcite, albite and k-feldspar amongst, and surrounding, the micas (**Figs. 6b & 6c**). The k-feldspars are frequently stretched out into ribbons parallel to the cleavage within the micas (**Fig. 6b**).

Sub-parallel cataclastic bands of predominantly angular quartz crystals, which have grain sizes that are dramatically smaller (<100 μm) than the surrounding quartz aggregate (0.5 – 3 mm) are present within some quartz veins (e.g. sample 41) (**Fig. 5f**). They are often discontinuous and linked along strike by fluid inclusion trails. The bands are typically less than 250μm in width, although they can be greater than 1mm locally. The narrower bands contain only quartz fragments, while larger bands also contain muscovite and chlorite micas which are often oriented at a high angle to the bands. One such band resembles a large (3mm) fish-shaped structure, which can be seen in hand specimen, and is filled predominantly with angular quartz and mica, but also some plagioclase and pyroxene. The angular nature of the material within the cataclastic bands indicates localised shearing under brittle conditions, although there has been some limited healing and later recrystallisation of the cataclasites.

SEM analysis also reveals a brittle component to the mylonitic zones in Sample 64. Some larger mylonitic zones have well defined sharp margins and some dark, well defined cleavage planes within the kinked micas (**Fig. 6b)** suggesting shearing along these planes under brittle conditions (e.g. sample 64). The mylonitic zones also contain small areas (<100 μm) of intense fracturing with brecciated quartz and feldspar grains which has allowed the formation of micas within the spaces created (**Fig. 6d)**. This suggests that the brittle deformation post-dated the ductile deformation and the shearing continued into the brittle field of the upper crust.

The presence of micas, calcite, plagioclase, k-feldspar and epidote within both the mylonitic and cataclastic fabrics is likely due to fluid flow through the fractures, and the presence of white mica is known to enhance slip (e.g. Mariani *et al*., 2006).

2.4.6 Pyrite

Pyrite can be found in many of the veins in the Assynt Terrane and occurs in a variety of forms. Some samples (e.g. samples 64 and 28) contain large clusters of pyrite crystals up to approximately 1.5cm in diameter which host a number of quartz crystals (0.25mm and 1mm in size) amongst the pyrite (**Fig. 5g**). Small (<100μm), angular fragments of pyrite at the edges of the clusters are inter-grown with the quartz aggregate.

Other samples contain pyrite which is intimately intergrown with quartz (e.g. sample 15) (**Fig. 5h**). SEM analysis shows a smooth-textured, bright white, unaltered pyrite, as well as a local boreal, radial textured variety (**Fig. 6e**). Large areas of smooth texture are unassociated with fractures within the quartz. By contrast, the areas of boreal texture are consistently associated with fracturing which runs through the thin section, and most likely introduced fluids which also caused the oxidation of the pyrite.

The alteration of the pyrite to various iron oxides also occurs at margins and along fractures within some large pyrite clusters (e.g. sample 64). SEM analyses confirm this pattern of breakdown (**Fig. 6f**), with phases of decreasing iron oxide content radiating away from the fractures.

Small (<1mm) pyrite clusters are also associated with the mylonitic zones within the quartz veins (e.g. sample 64), and can also be seen in hand specimen. This pyrite may result from fluid flow associated with deformation after the emplacement of the veins, during a period of raised temperatures and increased strain within shear zones. Small pyrite clusters are also observed in the gneisses, especially in those surrounding veins found within the CSZ, although it is unclear if this is as a result of the emplacement of the veins, or later fluid flow and mineralisation.

2.4.7 Chronology

The evidence from the microstructures within the veins suggests that most of the pyrite grew at the same time as the quartz and that it is a primary mineral phase. The veins then experienced modest amounts of deformation and recrystallisation during a moderate temperature (400 - 500˚C) and strain rate event (the Laxfordian) felt throughout the Assynt Terrane. Laxfordian deformation, especially within the CSZ, resulted in the formation of mylonitic fabrics within the veins to accommodate shearing under ductile conditions. This coincided with a period of high fluid flow and the local introduction of new minerals (muscovite, chlorite, calcite and spinel) into fractures within the veins. There may also have been some limited remobilisation and re-precipitation of pyrite at this time both within the veins and the adjacent sheared gneisses. The shearing continued into the brittle field where deformation was taken up by cataclastic fabrics within the veins and suggests either a decrease in temperature and/or crustal depth.

Sample No.	Latitude	Longitude	Cross-Cutting Relationships	Analysis
64	N 58° 09.049'	W 005°13.357’	Parallel to Badcallian foliation	OM, SEM
28	N 58° 10.640'	W 005° 16.374'	In Scourie Dyke within Inverian foliation	OM
15	N 58° 10.723'	W 005° 02.276'	Cross-cutting Badcallian foliation	OM, SEM
3	N 58° 10.829'	W 005° 02.783'	Cross-cutting Badcallian foliation	OM
55	N 58° 13.613'	W 005° 18.528'	Cross-Cutting Badcallian foliation	OM
34	N 58° 13.654'	W 005° 17.943'	Cross-Cutting Badcallian foliation	OM
23b	N 58° 09.596'	W 005° 13.455'	Cross-Cutting Inverian foliation	OM
41	N 58° 16.387’	W 005°24.626’	Sheared into parallelism with Laxfordian foliation	OM
25	N 58° 10.458'	W 005°18.118'	Cross-Cutting Inverian foliation	OM, SEM

Table 2; Table showing the location, cross-cutting relationships and the type of analysis conducted on each sample. OM = Optical Microscope, SEM = Scanning Electron Microprobe.

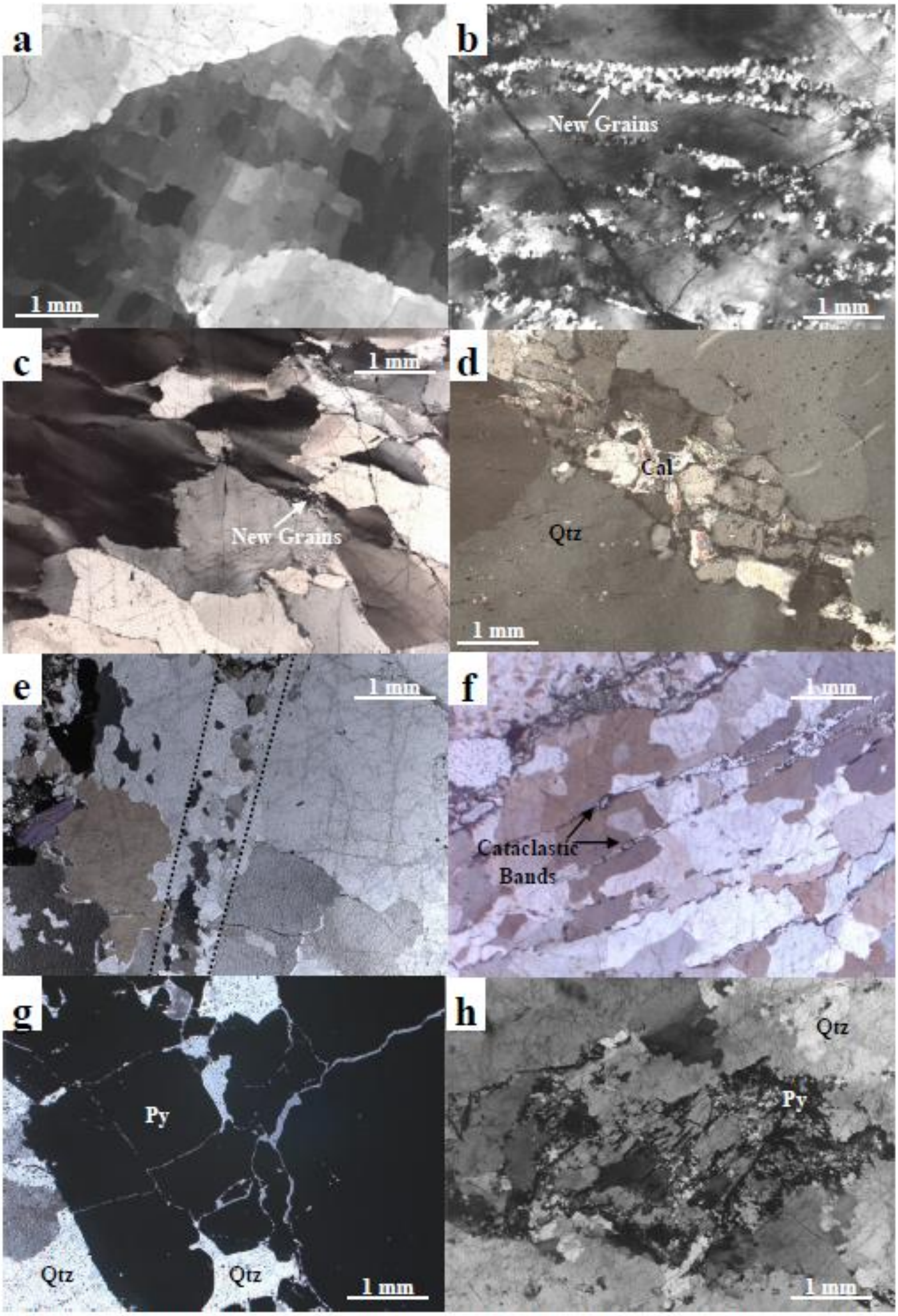


Figure 5); Optical microscopy images: **a)** Chess-board extinction in large quartz crystals, **b)** New grains forming along grain boundaries and deformation lamellae, **c)** Development of new grains at triple junction grain boundaries overprinting high temperature deformation features, **d)** Presence of calcite in spaces created by brittle fracturing, **e)** Ductile band of reduced size quartz crystals, **f)** Cataclastic bands, **g)** Quartz within pyrite cluster, and **h)** Intergrowth of pyrite crystals and quartz.

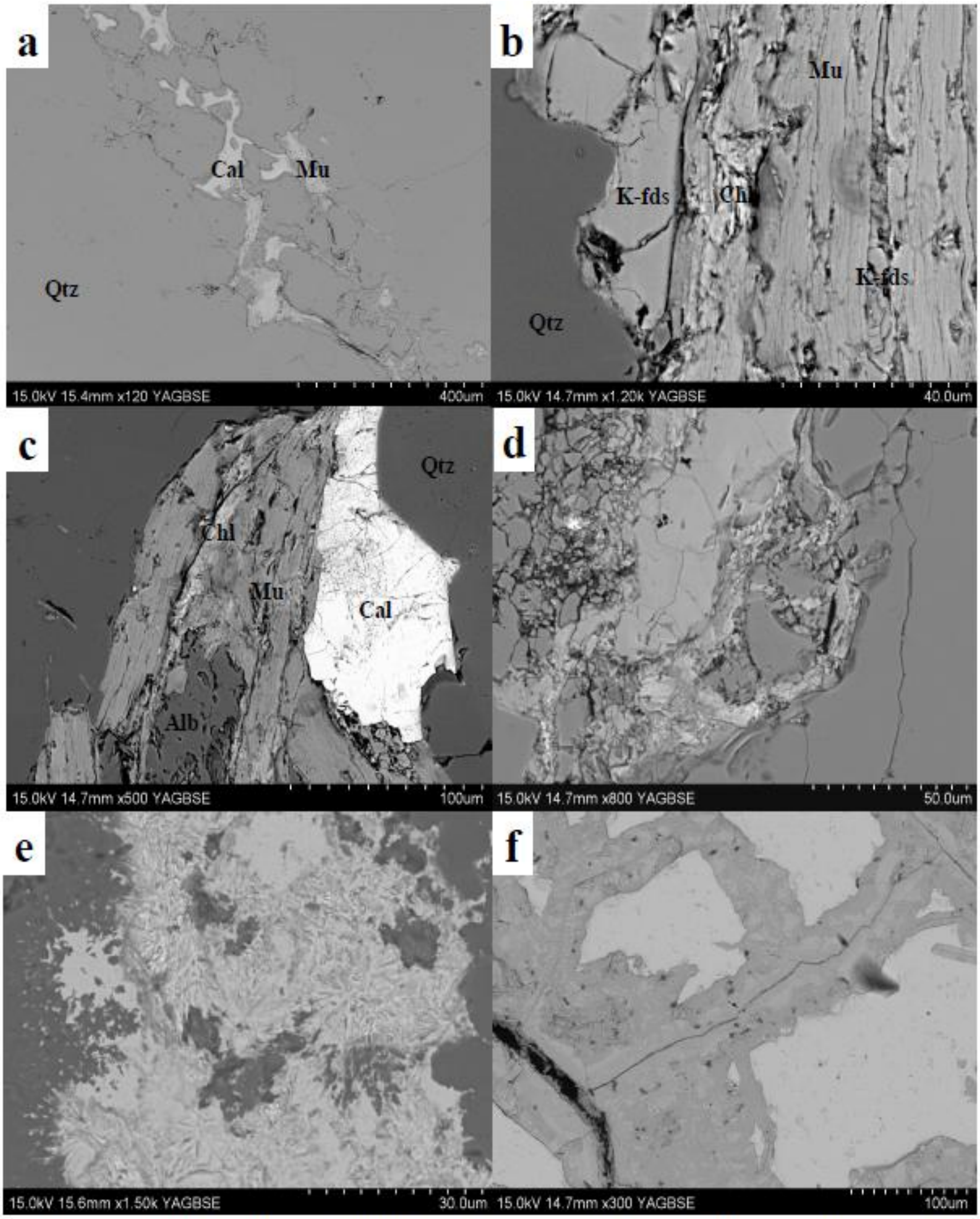


Figure 6; SEM analysis: **a)** Pull-apart fractures filled with calcite and micas, **b)** Bent mica lattices within mylonitic zones, brittle fracturing of K-feldspar ribbons, and well developed cleavage planes within the micas, **c)** Muscovite, chlorite, k-feldspar, albite and calcite within a mylonitic zone with limited brittle influence, **d)** Brittle fracturing of the quartz and k-feldspar within a mylonitic zone, **e)** Smooth and boreal pyrite textures intermixed, and **f)** Alteration of pyrite to iron oxides along fractures.

2.5. Rhenium-Osmium Geochronology:

2.5.1 Analytical Methodology

Six pyrite samples co-genetic with quartz veining were analyzed for their rhenium (Re) and Osmium (Os) abundances and isotopic compositions. The analyses were conducted at the Total Laboratory for Source Rock Geochronology and Geochemistry at the Northern Centre for Isotope and Element Tracing (NCIET) at Durham University. The pyrite sample set represent five locations (Gruinard Bay, Lochan Sgeireach, Waterworks, Lochinver, Loch Assynt) across the field area (see above; **Fig. 2**; **Table 3).**

The pyrite samples were isolated from the quartz vein by crushing, without metal contact, to a < 5 mm grain size. After this stage > 1 g of pyrite was separated from the crushed vein by hand picking under a microscope to obtain a clean mineral separate. The Re and Os analysis reported in this study followed the analytical protocol of Selby et al. (2009). In brief, this involved loading ~ 0.4 g of accurately weighed pyrite into a carius tube with a known amount of a ^{185}Re and ^{190}Os tracer (spike) solution and 11 ml of inverse *aqua regia* (3 ml 11N HCl and 8 ml 15 N HNO_3). The carius tubes were then sealed and placed in an oven at 220°C for 24 hrs. Osmium was isolated and purified from the acid medium using $CHCl_3$ solvent extraction and micro-distillation, with Re separated by anion exchange column and single-bead chromatography. The Re and Os fractions were loaded on Ni and Pt filaments, respectively and analyzed for their isotope compositions using negative-ion mass spectrometry on a Thermo Electron TRITON mass spectrometer. Rhenium isotopes were measured statically using Faraday Collectors, with the Os measured in peak hopping mode using the Secondary Electron Multiplier. Total procedural blanks for Re and Os are, 2.7 ± 1.1 pg and 0.4 ± 0.4 pg, respectively, with an average $^{187}Os/^{188}Os$ of 0.37 ± 0.17 (n = 2, 1 SD). The Re and Os uncertainties presented in **Table 3** are determined by the full propagation of uncertainties from the mass spectrometer measurements, blank abundances and isotopic compositions, spike calibrations, and the results from analyses of a Re and Os standards. The Re standard data together with the accepted $^{185}Re/^{187}Re$ ratio (0.59738; Gramlich et al., 1973) is used to correct for mass fractionation. The Re and Os standard solution measurements performed during the two mass spectrometry runs were 0.5982 +/- 0.0012 (Re std, n = 2) and 0.1608 +/- 0.0002 (DROsS, n = 2), respectively, which agree with the values reported by Finlay et al. (2011) and references therein.

2.5.2 Results

The total Re and Os abundances of the pyrite samples range from 6.8 to 25.8 ppb (parts per billion) and 298.8 to 660.5 ppt (parts per trillion; **Table 3**), respectively. The majority of the Os within the samples is radiogenic ^{187}Os (> 92 %; **Table 3**). Four of the samples (G-Bay, BH2, BH5, LA2) possess > 99 % radiogenic ^{187}Os (**Table 3**). As a result the $^{187}Re/^{188}Os$ values are high to very high (265.6 to 17531), with the accompanying $^{187}Os/^{188}Os$ values being very radiogenic (11.04 to 675.2). The predominance of radiogenic ^{187}Os ($^{187}Os^{r}$) in the pyrite samples defines them as Low Level Highly Radiogenic (LLHR; Stein et al., 2000; Morelli et al., 2005). To account for the high-corrected uncertainties between the $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ data we present the latter with the associated uncertainty correlation value, *rho* (Ludwig, 1980), and the 2σ calculated uncertainties for $^{187}Re/^{188}Os$ and $^{187}Os/^{188}Os$ (**Table 3**). The regression of all the Re-Os data using *Isoplot V. 3.0* (Ludwig, 2003) and the ^{187}Re decay constant (λ) of $1.666\times10^{-11}a^{-1}$ (Smoliar et al., 1996) yields a Model 3 Re-Os age of 2259 ± 61 (2.9 %) Ma, with an initial $^{187}Os/^{188}Os$ of 0.9 ± 9.0 (2σ, Mean Squared Weighted Deviates [MSWD] = 22; **Fig. 7a**). Using this initial $^{187}Os/^{188}Os$ value, including the uncertainty, from the regression of the Re-Os data the abundance of $^{187}Os^{r}$ can be calculated from the total ^{187}Os (common plus radiogenic) in the pyrite samples (**Table 3**). The $^{187}Os^{r}$ is a result of decay of ^{187}Re and can be used to calculate model Re-Os dates for each sample. The model Re-Os dates, with the exception of sample 64.1, all agree within uncertainty with the Re-Os isochron age (**Table 3**; **Fig. 7a**). Sample 64.1 yields a model date of 1597.6 ± 1371.2 Ma. Although this date is within uncertainty of the other model ages and the Re-Os isochron age its nominal age is significantly younger than for the other five pyrite samples. As such, sample 64.1 may represent a separate, distinct quartz and sulphide mineralization event. If we consider this to be the case and regress the $^{187}Re/^{188}Os$ vs $^{187}Os/^{188}Os$ data without sample 64.1, a Re-Os isochron age of 2249 ± 77 Ma, with an initial $^{187}Os/^{188}Os$ of 3 ± 13, is produced (2σ, MSWD = 15; **Fig. 7a**). This Re-Os isochron age is within uncertainty of that determined from all the Re-Os data, however the degree of scatter about the isochron is less (MSWD of 15 vs 22), which may be attributed to sample 64.1 and thus suggest that it is not part of the main quartz vein and sulphide mineralization at ~ 2.2 Ga.

Isochron ages can also be determined by the regression of ^{187}Re vs $^{187}Os^{r}$ plus their uncertainties. The regression of all ^{187}Re and $^{187}Os^{r}$ data yield a date of 2230 ± 140 Ma, with an initial ^{187}Os (common) of 6 ± 24 ppt (**Fig. 7b**; MSWD = 1.2). Excluding sample 64.1 an identical age is determined (2220 ± 140 Ma, initial ^{187}Os = 7 ± 24; MSWD = 1.3; **Fig. 7b**). Finally, if we calculate the $^{187}Os^{r}$ using the initial $^{187}Os/^{188}Os$ value (3 ± 13; **Table 3**) determined from the $^{187}Re/^{188}Os$ vs $^{187}Os/^{188}Os$ isochron without sample 64.1 (**Fig. 7a**) a ^{187}Re vs $^{187}Os^{r}$ isochron date of 2170 ± 180 Ma is determined (**Fig. 7c**, initial ^{187}Os = 15 ± 31, MSWD = 0.56).

Batch/Sample	Location (Lat/Long)	Re (ppb) total	±	Os (ppt) total	±	$^{187}Re/^{188}Os$	±	$^{187}Os/^{188}Os$	±	rho	^{187}Re (ppb)	±	$^{187}Os^r$ (ppt)[1]	±	$^{187}Os^r$ (ppt)[2]	±	%$^{187}Os^r$	Model age	±	$\delta^{34}S$
Gruinard Bay																				
RO297-2/G-Bay	57°51.567' N / 005° 27.121' W	25.2	0.1	602.1	45.1	12670.5	627.9	473.6	27.4	0.851	15.86	0.06	591.6	21.1	589.0	24.1	99.8	2198.5	78.9	3.0
Lochan Sgeireach																				
RO297-3/28	58°10.640' N / 005°16.374'W	6.8	0.0	298.8	26.9	265.6	21.2	11.04	1.4	0.636	4.27	0.02	163.1	145.7	129.3	209.8	91.8	2249.4	2010.2	1.1
Waterworks																				
RO297.5/64.1	58°09.049' N / 005°13.357' W	8.0	0.0	242.8	33.9	395.1	49.5	11.56	2.2	0.663	5.02	0.02	135.5	116.3	135.5	116.3	92.2	1597.6	1371.2	-2.2
Lochinver																				
RO143-1/BH2	58°09.599' N / 005°13.530'W	25.8	0.1	660.5	23.3	4762.4	123.4	186.3	4.9	0.963	16.22	0.06	631.7	30.9	624.6	44.4	99.5	2293.0	112.5	1.9
RO143-4/BH5	58°09.599' N / 005°13.530'W	23.8	0.1	623.8	20.0	4041.8	96.9	160.8	3.8	0.974	14.98	0.06	592.5	33.4	584.7	48.2	99.4	2328.7	131.7	1.8
Loch Assynt																				
RO194-2/LA2	58°10.703' N / 005°28.471' W	14.6	0.1	358.2	49.4	17531.0	1729.3	675.2	66.6	0.998	9.19	0.04	353.8	5.0	352.7	7.0	99.8	2265.5	32.9	0.9

Table 3; The results of Re-Os analysis and isotopic sulphur analysis. All uncertainties are determined by error propagation of uncertainties in Re and Os mass spectrometer measurements, blank abundances, isotopic compositions and spike calibrations, and reproducibility of standard Re and Os isotopic values; $^{187}Os^r$ presented are calculated using initial $^{187}Os/^{188}Os$, plus its uncertainty, from regression of data using $^{187}Re/^{188}Os$ vs. $^{187}Os/^{188}Os$ isochron plot; rho is the error correlation; $^{187}Os^{r1}$ is determined from an initial $^{187}Os/^{188}Os$ of 0.9 ± 9.0; $^{187}Os^{r2}$ determined from an initial $^{187}Os/^{188}Os$ of 3 ± 13; percentage of all measured ^{187}Os determined from the radiogenic decay of ^{187}Re; model age can be directly calculated using $^{187}Os^r/^{187}Re = e^{\lambda t}-1$

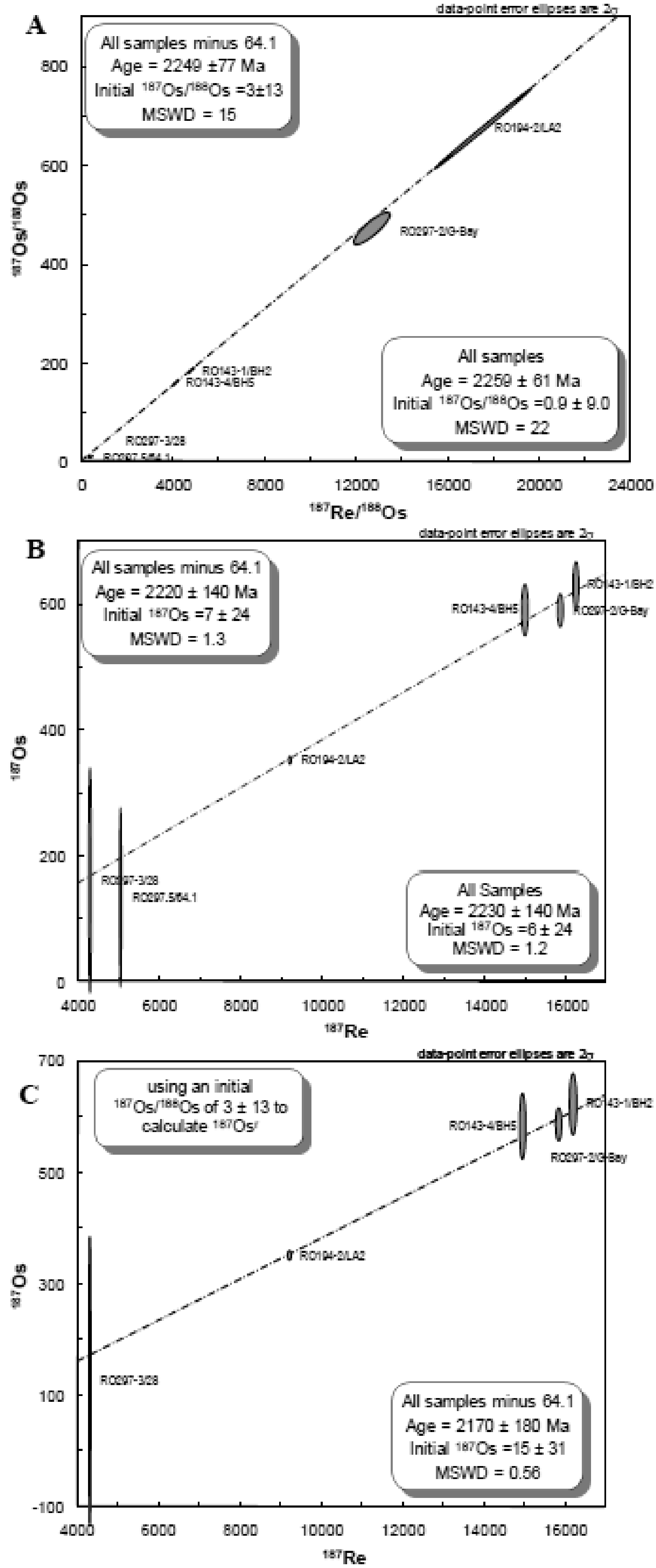


Figure 7; Re-Os isochron plots showing the age of the quartz-pyrite veins.

2.6. Sulphur Isotope Analysis

2.6.1 Analytical Methodology

The isotopic composition of sulphur was determined using standard techniques. Samples of the sulphide were taken from the quartz veins at several locations (**Table 3**) throughout the Assynt terrane and were also used for the Re-Os, along with an additional sample, 60-A, which is taken from a shallowly dipping vein in a road cutting between Scourie and Kylesku.

Under the microscope, the least oxidised grains were handpicked for each sample and 0.01g weighed out for analysis. Sulphur was extracted as SO_2 from the sulphides by fusing samples under vacuum at 1076°C in a Cu_2O (200mg) matrix (Wilkinson *et al*., 2005). The method of Coleman & Moore (1973) was followed for extracting sulphur from SO_2 from sulphates and analysed on a VG SIRA II mass spectrometer to obtain values for $\delta^{66}SO_2$ which were converted to $\delta^{34}S$. Standard correction factors were then applied (Craig, 1957). Results are given in conventional $\delta^{34}S$ notation relative to the Vienna Canon Diablo troilite standard (V-CDT). The reproducibility based on full replicate analyses of internal laboratory standards was ±0.2 per mil (1σ).

2.6.2 Results

All the samples from the sulphur isotope analysis yielded high amounts of $\delta^{34}S$. The lowest yield was 82% from samples 64.1 and BH5, while the highest yield was 97% from sample 28. The $\delta^{34}S$ from the sulphides ranges from +3.0 to –2.2. All the samples are greater the 0.0 except for sample 64.1, which also had the joint lowest yield percent of $\delta^{34}S$. Leaving aside sample 64.1 the lowest $\delta^{34}S$ is 0.1 from sample 60-A.

A $\delta^{34}S$ range of between +3.0 and -2.2 encompasses the primitive mantle value of 0.0 $\delta^{34}S$ (Rollinson, 1993). Thus, this indicates that the sulphur of the pyrite contained within the quartz veins is likely all derived from the primitive mantle.

2.7. Discussion:

The simplest types of natural veins are Mode 1 fractures which open in the direction of the minimum principle stress and have strike orientations perpendicular to this (e.g. Peacock & Mann, 2005). The general NE-SW strike orientation of the quartz-pyrite veins in the Assynt Terrane, implies a NW-SE opening direction, although the veins show a wide range of other orientations which are attributed to a number of factors: the presence of highly variable foliation or strongly banded gneisses (Wheeler *et al.*, 2010); the presence of pre-existing fractures, the formation of Inverian shear zones throughout the complex (Park & Tarney 1987), or to the reworking of veins by Laxfordian fabrics. Limited amounts of shearing during emplacement resulted in the local development of veins which formed en echelon arrays or with en echelon offshoots, probably due to the opening directions of the veins being at an angle to the principle direction of extension (Peacock & Mann, 2005). These may represent veins which are influenced by a local stress field (Mandal, 1995) or are exploiting pre-existing, obliquely oriented fractures during their emplacement, as this requires less energy than forming new fractures. It may be that some of this shearing during emplacement represents a crust which was still under strain, although it is commonly thought the Inverian shearing ended shortly after the intrusion of the early Scourie dykes (ca. 2.4 Ga), and that the fractures opened during vein emplacement provided a way for this to be taken up.

Veins form by the precipitation of fluids circulating through the crust into dilating fractures (Davies & Reynolds, 1996), and are more likely to form in zones of high fluid flow. Faults and shear zones may have influenced the clustered distribution of the quartz-pyrite veins as several vein clusters are related to the presumably Inverian CSZ and the more minor Stoer Shear Zone (see **Fig. 2**). The distribution may also be influenced by the highly heterogeneous nature of the gneisses within the terrane, where foliation is best developed in intermediate gneisses (Sheraton *et al.*, 1973), and perhaps fluid flow was more likely to occur in areas of well developed foliation.

The field relationships seen in the Assynt Terrane suggest that the quartz-pyrite veins are younger than the Scourie dykes. Furthermore, the principle NE-SW orientation of the quartz-pyrite veins lies at almost 90˚ to the NW-SE orientation of the Scourie Dykes, requiring a major change in the regional extension vector for dyke intrusion versus vein emplacement. Temporally the situation is more complex. The Re-Os isochron age for the veins (2259±61 Ma) falls within the broad range of ages obtained from the Scourie dyke swarm across the entire Lewisian Complex (2418 Ma to 1991 Ma; Heaman & Tarney, 1989; Cohen *et al.*, 1988; Waters *et al.*, 1990). Haeman & Tarney (1989) proposed two episodes of dyke intrusion, with ages concentrated around 2418 Ma and 1992 Ma, although only a small sample of dykes were dated by the authors. More recently, Davies *et al.* (2009) have proposed at least four separate periods of dyke intrusion (2420 Ma, 2400 Ma, 2375 Ma and 1990 Ma), with distinct mantle sources tapped during each event. The idea that there are multiple dyking episodes is consistent with some geological field relationships. It is known, for example, in the southern region of the Lewisian Complex that some Scourie dykes cut the Loch Maree Group metasediments and metavolcanics, which were formed in oceanic basins and accreted to the continental crust through subduction between 2.1 and 1.9 Ga (Park *et al.*, 1994). If there are multiple episodes of Scourie dykes, with some pre-dating and some post-dating the quartz-pyrite veins, this implies that there were significant changes in the orientation of regional stress vectors during the 500 Ma period between 2.4 – 1.9 Ga.

The heterogeneity of the crust in the Assynt Terrane is demonstrated not only by the clustered distribution of the quartz-pyrite veins, but also by the varying extent of recrystallisation experienced by quartz within the veins. Recrystallisation, through a range of processes and under a range of temperature and strain rate conditions, has overprinted most primary features associated with the precipitation of quartz within the veins, e.g. fibrous textures, although some quartz-pyrite intergrowth features are preserved (e.g. **Fig. 5h**). The Laxfordian Orogeny (1.8 Ga) may have locally raised the temperature of the crust to amphibolite facies conditions (Park, 1994) allowing subgrain rotation and grain boundary migration recrystallisation to operate within the quartz and facilitated the formation of upper regime two to regime three microstructures (Hirth & Tullis, 1992). The presence of upper Regime Two and Regime Three (Hirth & Tullis, 1992) microstructures in veins across the Assynt Terrane demonstrates that the increase in temperature associated with the Laxfordian event was felt throughout the terrane, although the extensive reworking which characterises the Laxfordian in the Rhiconich and Gruinard terrranes (Macdonald & Fettes, 2007) is absent. An increase in strain rate associated with extensive shearing and the reactivation of major shear zones during the Laxfordian (Attfield, 1987) caused the formation of the schistose and mylonitic fabrics within the Laxfordianised gneiss and the quartz-pyrite veins. Over-printing of high temperature quartz microstructures in veins within the CSZ by low temperature and/or high strain rate microstructures indicates that the Laxfordian was not just a single event but contained at least two separate events. Park (1994) suggested there were two tectono-thermal events within the Laxfordian; the earlier at ~1.87 Ga associated with peak granulite to amphibolites facies metamorphism, and the latter at ~1.74 Ga associated with highly variable amphibolites to greenschist facies retrogression (Park, 2005). As the overprinting features are limited to the quartz veins within major shear zones, it is proposed that the second event may have been restricted to these zones within the Assynt Terrane. The presence of cataclastic bands within veins affected by Laxfordian shearing gives further evidence to the presence of a second, lower temperature, event during the Laxfordian which operated under brittle conditions. The pressure-temperature range of the Laxfordian orogeny, deduced from the quartz microstructures, fits well with the pressure-time and temperature-time plots based on geochronological, palealothermal and palaeobaric studies suggested by Wynn *et al.* (1995) (**Fig. 8**).

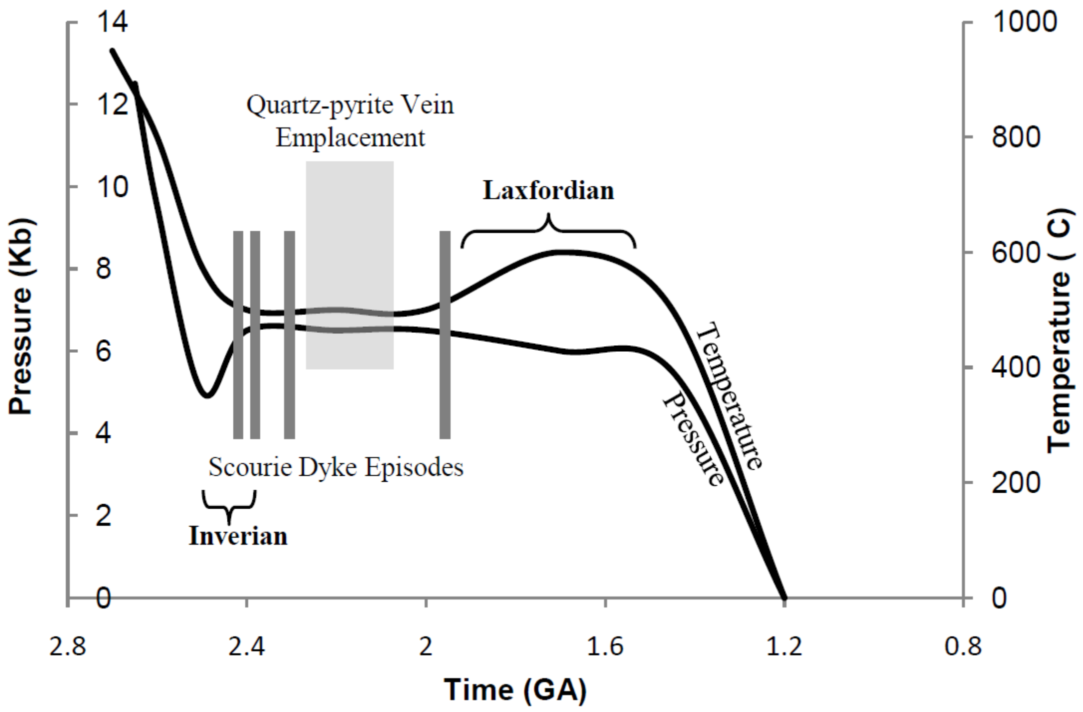


Figure 8; The PT conditions during the Late Archaean and Early Proterozoic, showing the Scourie dyke episodes and the vein emplacement period (Based on Wynn, 1995).

The sulphur isotopic analysis gives $\delta^{34}S$ values which are of primitive mantle derivation (Rollinson, 1993). Sulphide minerals are often introduced into the crust during the crystallisation of mafic magmas Cameron (1994), and thus are present in the Lewisian Gneisses. The type of sulphide observed in the gneisses depends on the degree of retrogression they have undergone, as pyrrhotite is particularly susceptible to alteration to pyrite. Fluids associated with retrogression would thus also have been able to strip sulphide minerals from the crust and concentrate them in solution. Wheeler *et al.* (2010) suggests that post-Inverian autometamorphism was operating during the intrusion of the Scourie Dykes, where the rocks were still hot (300 to 500°C), causing the early dykes to be metamorphosed to amphibolites facies (Tarney, 1973) and enabling the continuation of fluid migration through the crust. However, the presence of feldspars within some veins raises the question of whether pyrite is the only auxiliary mineral within the veins. The veins may be the result of highly concentrated fluids associated with the intrusion of the Scourie Dyke Suite which only retained a very small amount of other minerals present in the Scourie Dykes. However the large difference in the orientation of the veins compared to the dykes casts doubts on this suggestion, unless there was a break in time and change of stress directions before these fluids circulated through the crust.

The Re-Os model age of sample 64.1 (1597.6 ± 1356 Ma) is considerably younger than the model ages for the other samples (2198.5 – 2328.7 Ma), and has a very large uncertainty as well as the lowest Os count of (242.8 ± 33.9 ppb) of all the samples; it is also the only sample with $\delta^{34}S$ less than zero (-2.2). Although this is still close enough to zero to suggest it is derived from the primitive mantle, like the other samples, it suggests that the sulphide within the vein may have a different origin to that within other veins, or that it may have been affected by different processes following emplacement, perhaps related to its location south of the CSZ within the Assynt Terrane. The small-scale, through-going fractures within some of the quartz veins could have provided potential pathways for fluid migration and enabled the introduction of new minerals into the veins (Wheeler *et al*., 2010). Therefore, two ore forming events are possible; the first occurring simultaneously with the emplacement of the veins and the second occurring during a period of high levels of fluid flow associated with the Laxfordian Orogeny (Sills, 1983). The second event, associated with later brittle deformation, may also have oxidised any pyrite formed during the vein emplacement. However, further fieldwork and dating would be needed to verify and constrain this second ore forming event.

2.7.1 Implications for Terrane Models

Dating of the TTG protoliths suggests that the gneisses of the Gruinard terrane are at least 100 Ma younger than those of the Assynt Terrane and underwent granulite metamorphism at 2730 Ma, as opposed to 2490 Ma in the Assynt Terrane (Love *et al*., 2004 & Park, 2005). Thus they are thought to belong to separate terranes which amalgamated along the Strathan Line, south of Lochinver, during Inverian folding and retrogression (Fig. 1, Love *et al.*, 2004). The presence of quartz-pyrite veins within both the Assynt and Gruinard terranes is consistent with amalgamation during the Inverian, and prior to the emplacement of the veins.

The Inverian (2490 – 2480 Ma) metamorphism is strongly prevalent in the Central region but is milder, or entirely absent, in the Northern region. However, the Laxfordian metamorphism was much more intense in the Northern region than the Central region, suggesting these regions had different accretionary and early metamorphic histories and were juxtaposed tectonically along the Laxford Front after the Inverian Event but before, or during, the Laxfordian orogeny (Kinny & Friend, 1997). Friend & Kinny (2001) thus proposed that the Lewisian Complex was amalgamated from separate crustal blocks – terranes – and does not represent one contiguous block of mid-Archaean crust which was been variably reworked. They proposed that the Assynt and Rhiconich terranes were separate crustal blocks that were only finally juxtaposed by a major episode of shearing during the Laxfordian (Friend & Kinny, 2001 & Park, 2005). The apparent absence of 2259 Ma quartz-pyrite veins in the Rhiconich terrane is certainly consistent with the suggestion that the latter is a crustal block that has experienced a different history prior to Laxfordian shearing along the Laxford front.

2.7.2 The Loch Maree Group

The supracrustal Loch Maree Group (LMG) outcrops at two locations within in the Gruinard Terrane, at Gruinard Bay and northeast of Loch Maree, and is bounded on both sides by Lewisian gneiss (Park et al., 2001). The supracrustal rocks include amphibolites of volcanic and volcaniclastic origin (Love *et al.,* 2010) and terrigenous metagreywackes, with subordinate marbles, graphite schists, calc-schists and banded iron formations (Droop *et al.*, 1989). There have been a range of interpretations regarding the formation of the group. Many authors have interpreted the LMG to have been formed in an intracontinental extensional rift basin (e.g. Floyd *et al.*, 1989 and Park *et al.*, 1994) which received clastic detritus from adjacent uplifted basement as well as from internal and volcanogenic sources (Floyd *et al.*, 1989). Floyd *et al.* (1989) also suggests the LMG may be a minor relic of a rift system which once stretched from Canada to Finland. More recent interpretations, however, suggest the LMG formed in a trench or back-arc setting at a continental margin (Park *et al.*, 2001; Park, 2002; Wheeler *et al.*, 2010) as a result of the accretion of oceanic plateau rocks and oceanic sediment to the base of the over-riding plate during subduction (Love *et al.*, 2010). Deformation of the rocks then occurred during accretion and the later Laxfordian Orogeny (~1.9 – 1.7 Ga) (Park *et al.*, 2001).

Park (2005) suggests that a SE plate may have been subducting underneath a NW plate (containing the currently outcropping Lewisian gneisses). If subduction zone roll-back occurred in the upper plate in the period 2.2-2.3 Ga, this would lead to NW-SE extension consistent with the stress field associated with the emplacement of the quartz-pyrite veins. Although the accretion of the LMG is estimated at 2.0 – 1.9 Ga based on Sm-Nd studies and detrital zircon ages (Park *et al*., 2001), the subduction zone could have been operating prior to this, within the broad Re-Os age range for the formation of the quartz-pyrite veins (2259±61 Ma).

It may be that initiation of the subduction zone changed the stress field within the crust from that present during the early episodes of Scourie Dyke intrusion (2420 – 2375 Ma). When the oceanic plateau, which would form the LMG, collided with the subduction zone the zone would have become jammed and subduction may have ceased (Park *et al.*, 2001), perhaps causing a reversion to the pre-subduction stress field. As a result the dykes intruded during the 1990 Ma Scourie dyke episode have a similar orientation to the earlier dykes. Laxfordian deformation then resulted in the inclusion of the LMG into the Gairloch Shear Zone, causing extensive deformation and changing the orientation relationship with the surrounding gneisses to that observed in the present (Park, 2005).

2.8. Conclusions

- A hitherto unrecognised set of quartz pyrite veins have been identified in the Assynt and Gruinard Terranes of the Lewisian complex. The veins consistently cross-cut Badcallian and Inverian structures in the gneisses, as well as the majority of Scourie dykes. They are reworked during Laxfordian shearing events and are also cross cut by a range of later brittle faulting events.

- The dominant strike direction of the quartz-pyrite veins suggests emplacement during NW-SE extension of the crust.

- The Re-Os date of 2259±61 Ma for the pyrite within the veins confirms the field relationships. In absolute terms, the veins are younger than the Badcallian and Inverian events as well as the three of the episodes of Scourie dyke intrusion, and are post-dated by the last episode of Scourie dyke intrusion as well as Laxfordian fabrics.

- The primitive mantle origin of the sulphur suggests the pyrite in the veins was either stripped from the Lewisian crust or was a product of the early intrusion of Scourie dykes, although stripping from the crust is more likely as it is known that there is significant sulphur content in the gneisses which would originally have been derived from the primitive mantle and fluid flow through the crust would have been promoted during the Inverian Event that may have continued afterwards.

- There is a marked change in the extension direction between the early Scourie Dykes and the quartz-pyrite veins, and again between the veins and the later Scourie Dykes suggesting periods of NE-SW extension associated with the intrusion of Scourie dykes were interrupted by an event, or several events, which imposed a NW-SE extension direction on the crust.

- The presence of the quartz-pyrite veins in both the Assynt and Gruinard Terranes confirms their amalgamation prior to 2259±61 Ma, most likely during the Inverian event. The apparent absence of the veins in the Rhiconich Terrane suggests it may not have been amalgamated with the Assynt and Gruinard Terranes until the Laxfordian Orogeny.

- The emplacement quartz-pyrite veins may have been related to roll-back-related extension above a NW-dipping subduction zone located to the SE of the Assynt and Gruinard Terranes which later accreted the Loch Maree Group volcanics and sediments into the Lewisian crust.

2.9. References

- Attfield, P., 1987. The structural history of the Canisp Shear Zone, In: Park, R.G. & Tarney, J. (eds), *The early Precambrian rocks of Scotland and related rocks of Greenland*, Department of Geology, Keele, Pp. 165-174.

- Beach, A., 1976. The interrelations of fluid transport, deformation, geochemistry and heat flow in early Proterozoic shear zones in the Lewisian complex, *Philosophical Transactions Royal Society London A*, **280**, Pp. 569-604.

- Beacom, L.E., 1999. The Kinematic Evolution of Reactivate and Non-Reactivated Faults in Basement Rocks, NW Scotland, Queens University, Belfast, Thesis Unpublished.

- Beacom, L.E., Holdsworth, R.E., McCaffrey, K.J.W. & Anderson, T.B., 2001. A quantitative study of the influence of pre-existing compositional and fabric heterogeneities upon fracture-zone development during basement reaction, In; Holdsworth, R.E., Strachan. R.A., Magloughlin, J.F. & Knipe, R.J, (eds). The Nature and Tectonic Significance of Fault Zone Weakening, *Geological Society Special Publications*, London, **186**, Pp.195-211.

- Cameron, E.M., 1994. Depletion of gold and LILE in the lower crust: Lewisian Complex, Scotland, *Journal of the Geological Society*, **151**, Pp.747-754.

- Cohen, A.S., Waters, F.G., O'Nions, R.K. & O'Hara, M.J., 1988. A precise crystallisation age for the Scourie Dykes, and a new chronology for crustal development in north-west Scotland.

- Coleman, M.L. & Moore, M.P., 1978. Direct Reduction of Sulfates to Sulfur Dioxide for Isotopic Analysis, *Analytical Chemical Society*, **50**, Pp. 1594-1595.

- Coward, M.P. & Park, R.G., 1987. The role of mid-crustal shear zones in the Early Proterozoic evolution of the Lewisian, In; Park, R.G. & Tarney, J. (eds), Evolution of the Lewisian and Comparable Precambrian, *Geological Society Special Publications*, London, **27**, Pp. 127-138.

- Craig, H., 1957. Isotopic standards for carbon and oxygen and correction factors for mass-spectrometric analysis of carbon dioxide, *Geochimica et Cosmochimica*, **12**, Pp. 133-149.

- Davies, J.H.F.L., Haemand, L.M., DuFrane, S.A. & Muehlenbachs, K., 2009. Geochronology and isotope geochemistry of the Scourie dykes, Scotland (abs), 6th International Dyke Conference, Varanasi, India.

- Davies, G.H. & Reynolds, S.J., 1996. *Structural geology of rocks and regions*, Wiley, New York, P.204-210.

- Dickinson, B.B. & Watson, J., 1976. Variations in crustal level and geothermal gradient during the evolution of the Lewisian Complex of Northwest Scotland, *Precambrian Research*, **3**, Pp. 363-374.

- Droop, G.T.R., Fernandes, L.A.D. & Shaw, S., 1989. Laxfordian metamorphic conditions of the Palaeoproterozoic Loch Maree Group, Lewisian Complex, NW Scotland, *Scottish Journal of Geology*, **35**, Pp.31-50.

- Finlay, A. J., Selby, D., Osborne, M., 2011. Re-Os geochronology and fingerprinting of United Kingdom Atlantic Margin oil: Temporal Implications for regional petroleum systems, *Geology*, **39**, Pp.475-478.

- Friend, C.R.L. & Kinny, P.D., 2001. A reappraisal of the Lewisian Gneiss Complex: geochronological evidence for its tectonic assembly from disparate terranes in the Proterozoic, *Contribution to Mineralogy and Petrology.*, **142**, Pp.198-218.

- Floyd, P.A., Winchester, J.A. & Park, R.G., 1989. Geochemistry and Tectonic Setting of Lewisian Clastic Metasediments from the Early Proterozoic Loch Maree Group of Gairloch, NW Scotland, *Precambrian Research*, **45**, Pp.203-214.

- Gramlich, J.W., Murphy, T.J., Garner, E.L. & Shields, W.R., 1973. Absolute isotopic abundance ratio and atomic weight of a reference sample of rhenium, *Journal of Research of the National Bureau of Standards*, **77A**, Pp. 691–698.

- Haeman, L.M. & Tarney, J., 1989. U-Pb baddeleyite ages for the Scourie dyke swarm, Scotland: evidence for two distinct intrusion events, *Nature*, **340**, Pp.705-708.

- Hirth, G. & Tullis, J., 1992. Dislocation creep regimes in quartz aggregates, *Journal of Structural Geology*, **14**, Pp. 145-159.

- Holland, J.G. & Lambert, R.S.J., 1975. The chemistry and origin of the Lewisian Gneiss of the Scottish mainland, the Scourie and Inver assemblages and sub-crustal accretion, *Precambrian Research*, **2**, Pp.161-188.

- Jensen, L.N., 1984. Quartz microfabric of the Laxfordian Canisp Shear Zone, NW Scotland, *Journal of Structural Geology*, **6**, Pp. 293-302.

- Kelly, N.M., Hinton, R.W., Harley, S.L. & Appleby, S.k., 2008. New SIMS U-Pb zircon ages from the Langavat Belt, South Harris, NW Scotland: implications for the Lewisian terrane model, *Journal of the Geological Society*, **165**, Pp.967-981.

- Kinny, P.D., Friend, C.R.L. & Love, G.L., 2005. Proposal for a terrane-based nomenclature for the Lewisian Gneiss Complex of NW Scotland, *Journal of the Geological Society*, **162**, Pp.175-186.

- Love, G.J.L, Kinny, P.D. & Friend, C.R.L., 2004. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisiand Gneiss Complex:

comparisions with the Assynt Terrane and implications for terrane accretion, *Contributions to Mineralogy and Petrology*, **146**, Pp.620-636.

- Ludwig, K.R., 1980, Calculation of uncertainties of U-Pb isotope data: *Earth and Planetary Science Letters*, **46**, Pp. 212–220.

- Ludwig, K.R., 2003, Isoplot/Ex, version 3: A geochronological toolkit for Microsoft Excel: Berkeley, CA, Geochronology Center Berkeley.

- Macdonald, R. & Fettes, D.J., 2007. The tectonomagmatic evolution of Scotland, *Transaction of the Royal Society of Edinburgh: Earth Sciences*, **97**, Pp.213-295.

- Mandal, N., 1995. Mode of development of sigmoidal en echelon fractures, *Proceedings of the Indian Academy of Science (Earth Planet. Sci.)*, **104**, Pp. 453-464.

- Mariani, E., Brodie, K.H. & Rutter, E.H., 2006. Experimental deformation of muscovite shear zones at high temperatures under hydrothermal conditions and the strength of phyllosilicate-bearing faults in nature, *Journal of Structural Geology*, **28**, Pp.1569-1587.

- Morelli, R.M., Creaser, R.A., Selby, D., Kontak, D.J. and Horne, R.J., 2005, Rhenium-Osmium arsenopyrite geochronology of Meguma Group gold deposits, Meguma terrane, Nova Scotia, Canada: Evidence for multiple gold mineralizing events, *Economic Geology*, **100**, p. 1229–1242.

- Park, R.G., 1994. Early Proterozoic tectonic overview of the northern British Isles and neighbouring terranes in Laurentia and Baltica, *Precambrian Research*, **68**, Pp.65-79.

- Park, R.G., 2005. The Lewisian terrane model:a review, *Scottish Journal of Geology*, **41**, Pp.105-118.

- Park., R.G. & Tarney, J., 1987. The Lewisian Complex: a typical Precambrian high-grade terrane?, In: Park, R.G. & Tarney, J. (eds), *Evolution of the Lewisian and*

Comparable Precambrian High Grade Terranes, Geological Society, London, Pp.13-26.

- Park, R.G., Cliff, R.A., Fettes, D.J. & Stewart, A.D., 1994. Precambrian rocks in northwest Scotland west of the Moine Thrust: the Lewisian Complex and Torridonian, In: Gibbons, W. & Farris, A.L., *A Revised Correlation of Precambrian Rocks in the British Isles*, Geological Scoiety, London, Special Report, **22**, Pp.6-22.

- Park, R.G, Tarney, J. & Connelly, J.N., 2001. The Loch Maree Group: Palaeoproterozoic subduction-accretion complex in the Lewisian of NW Scotland, *Precambrian Research*, **105**, Pp.205-226.

- Passchier, C.W. & Trouw, R.A.J., 2005. *Micro-Tectonics*, Springer Berlin Heidelberg, New York, P. 25-66.

- Peacock, D.C.P. & Mann, A., 2005. Evaluation of the controls on fracturing in reservoir rocks, *Journal of Petroleum Geology*, **28**, Pp. 385-396.

- Rollinson, H., 1993. *Using Geochemical Data: evaluation, presentation, interpretation*, Longman Group UK Ltd, Harlow, P.303-306.

- Selby, D., Kelley, K.D., Hitzman, M.W. & Zieg, J., 2009. Re-Os sulphide (Bornite, Chalcopyrite, and Pyrite) systematic of the Carbonate-hosted copper deposits at Ruby Creek, Southern Brooks Range, Alaska, *Economic Geology*, **104**, Pp. 437-444.

- Sheraton, J.W., Tarney, J., Wheatley, T.J. & Wright, *A.E., 1973*. The structural history of the Assynt district, In: Park, R.G. & Tarney, J. (eds), *The early Precambrian rocks of Scotland and related rocks of Greenland*, Department of Geology, Keele, Pp. 31-44.

- Sills, J.D., 1983. Mineralogical changes occurring during the retrogression of Archaean gneisses from the Lewisian Complex of NW Scotland, *Lithos*, **16**, Pp. 113-124.

- Smoliar, M.I., Walker, R.J., & Morgan, J.W., 1996. Re-Os isotope constraints on the age of Group IIA, IIIA, IVA, and IVB iron meteorites, *Science*, 271, Pp. 1099–1102.

- Stein, H.J., Morgan, J.W. & Schersten, A., 2000. Re-Os of Low-Level Highly Radiogenic (LLHR) Sulphides: The Hurnas Gold Deposit, Southwest Sweden, Records Continental-Scle Tectonic Events, *Economic Geology*, **95**, Pp. 1657-1671.

- Stipp, M., Stunitz, H., Heilbronner, R. & Schmid, S.M., 2002. The eastern Tonale fault zone: a 'natural laboratory' for crystal plastic deformation of quartz over a temperature range from 250 to 700°C, *Journal of Structural Geology*, **24**, Pp. 1861-1884.

- Sutton, J. & Watson, J., 1950. The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the north-west Highlands, and its bearing on the chronological classification of the Lewisian, *Quarterly Journal of the Geological Society*, **106**, Pp. 241-307.

- Tarney, J., 1973. The Scourie dyke suite and the nature of the Inverian event in Assynt, In: Park, R.G. & Tarney, J. (eds), *The early Precambrian rocks of Scotland and related rocks of Greenland*, Department of Geology, Keele, Pp. 31-44.

- Waters, F.G., Cohen, A.S., O'Nions, R.K. & O'Hara, M.J., 1990. Development of Archaean lithosphere deduced from chronology and isotope chemistry of Scourie Dykes, *Earth and Planetary Science Letters*, **97**, Pp.241-255.

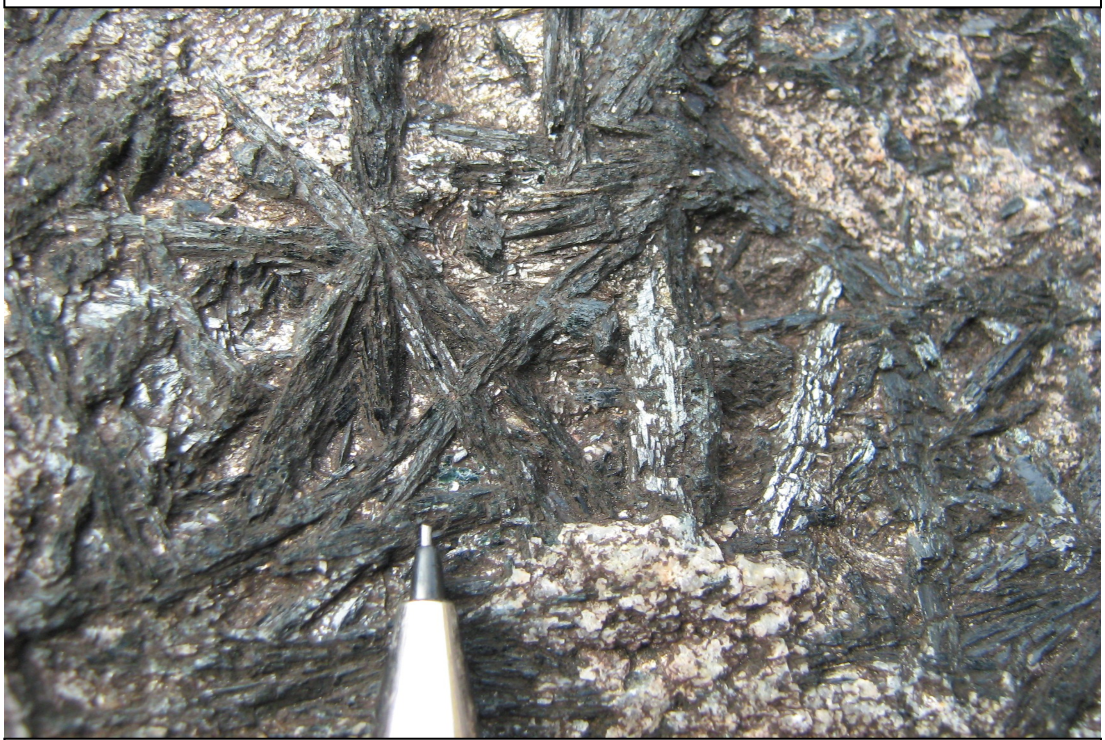
- Wheeler, J., Park, R.G., Rollinson, H.R. & Beach, A., 2010. The Lewisian Complex: insights into deep crustal evolution, In: Law, R.D., Butler, R.W., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds), *Continental Tectonics and Mountain Buildings: The Legacy of Peach and Horne*, Geological Society, London, Special Publications, **335**, Pp.51-79.

- Wilkinson, J.J. & Wyre, S.L., 2005. Ore-Forming Processes in Irish-Type Carbonate-hosted Zn-Pb Deposits: Evidence from Mineralology, Chemistry, and Isotopic Composition of Sulphides at the Lisheen Mine. *Economic Geology*, **100**, Pp. 63-86.

- Wynn, T.J., 1995. Deformation in the mid to lower continental crust: analogues from Protereozoic shear zones in NW Scotland, IN; Coward, M.P. & Ries, A.c. (eds), *Early Precambrian Processes*, Geological Society Special Publications, **95**, Pp. 225-241.

Appendix A – Field Photographs

Tight folds in the Badcallian foliation of the Lewisian Gneisses at Clashnessie Bay (NC 0585, 3099)



Radial hornblendes on the foliation planes in the Badcallian Gneisses at Clashnessie Bay (NC 0573, 31251).

Garnets in the Badcallian Gneisses at Kylesku (NC 2199, 3393).

Tight folds in the Inverian Gneisses below the Lewisian-Torridonian contact to the west of Guinag (NC 1950, 2780).

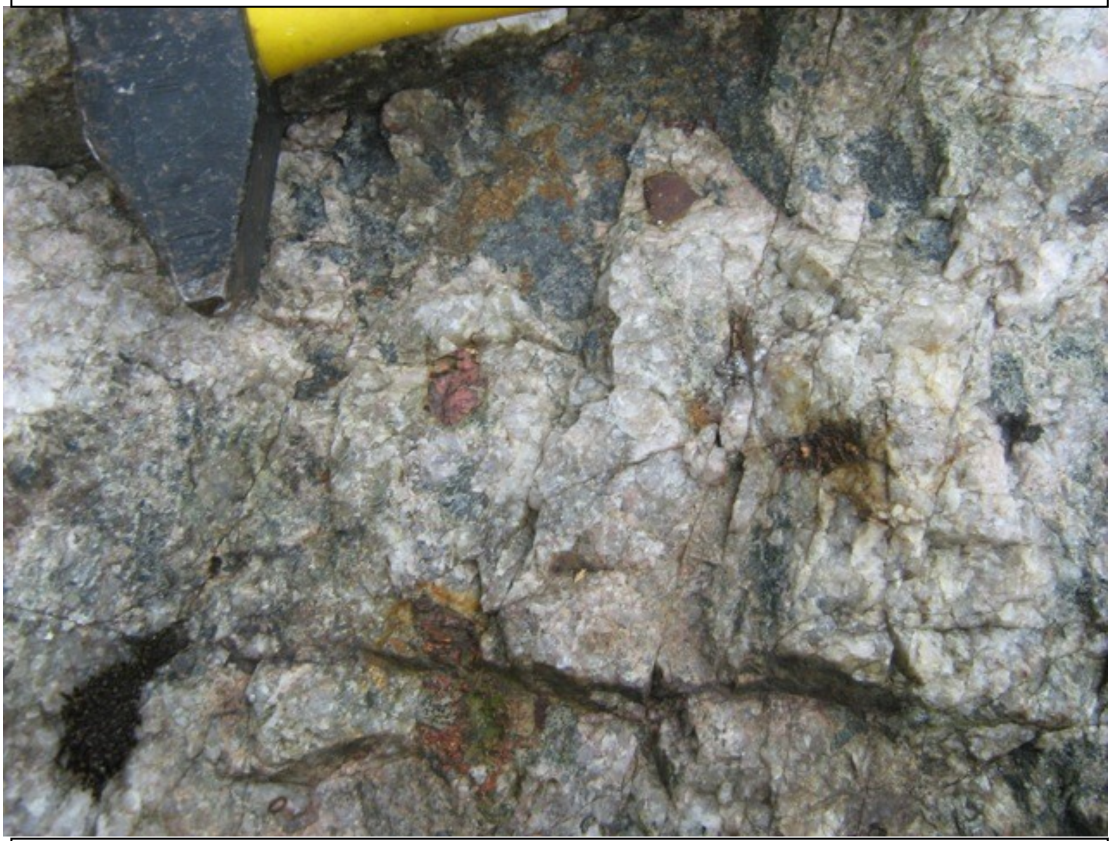
Quartz-pyrite veins cutting each other on the NE shore of Loch Assynt (NC 2140, 2510).

Quartz-pyrite vein emplaced into a thick ultra-mafic band in the Badcallian Gneisses at Clashnessie Bay (NC 0585, 3099).

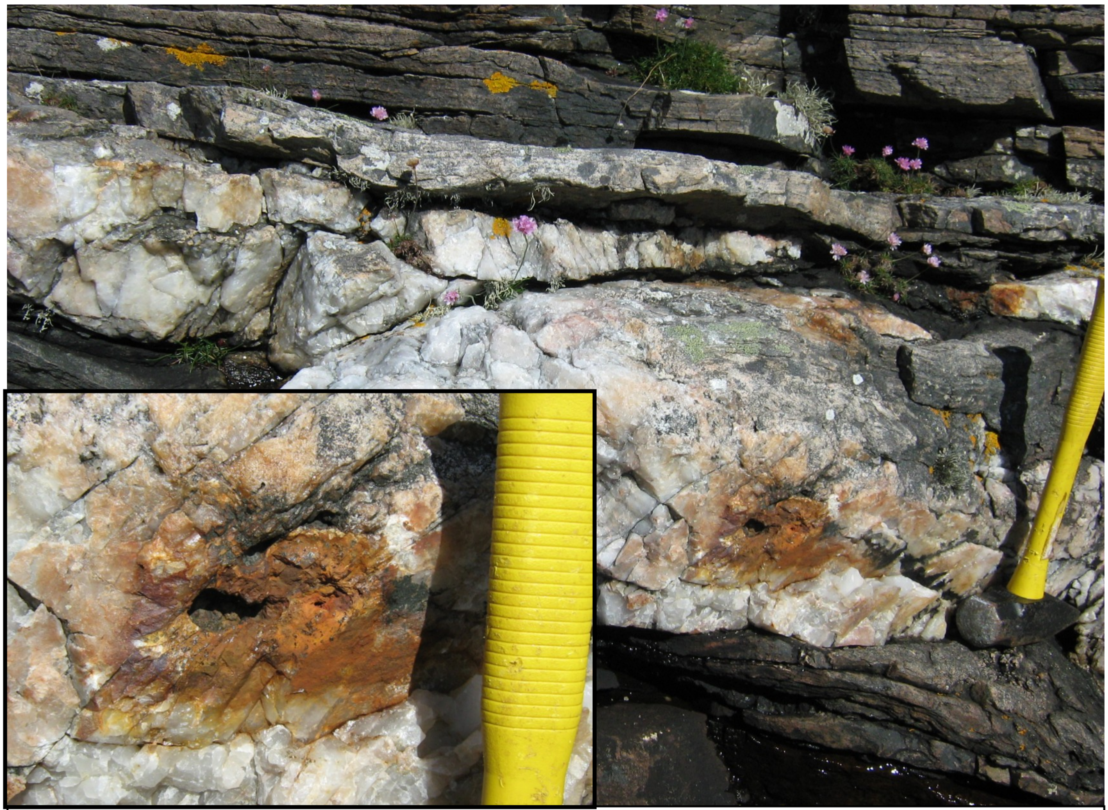
Quartz-pyrite vein concordant with the strong Badcallian foliation at Clashnessie Bay (NC 0604, 3103).

Pink feldspars are occasionally found in the quartz veins (ONC 1025, 2360).

Clean, non-weathered pyrite found in a quartz vein in a road cutting between Kylesku and Scourie (NC 1711, 4054).



Weathered pyrite clusters in a vein in a road cutting between Kylesku and Scourie (NC1711, 4054).



Typical yellow-orange stain found where pyrite in the veins has been weathered and broken down into iron oxides (NC 0570, 3147).

Localised bands of more intensely deformed gneisses associated with Laxfordian shearing inside the Canisp Shear Zone (NC 0831, 2497).

Quartz-pyrite vein which has been reworked by Laxfordian shearing and deformation in the Canisp Shear Zone (NC 0831, 2497).

Tightly folded foliation in the Laxfordian part of the Canisp Shear Zone at Achmelvich Bay (NC 0515, 2620).

Large block (light coloured) of Badcallian gneiss in the Canisp Shear Zone which has been unaffected by Inverian and Laxfordian shearing, surrounded by darker, intensely deformed and anastomosing Laxfordian gneisses (NC 0881, 2416).

Quarzt-pyrite veins reworked into concordance with the foliation by intense Laxfordian deformation (NC 0515, 2620).

Quarzt-pyrite vein folded with the Gneisses during Laxfordian shearing and deformation in the Canisp Shear Zone at Achmelvich Bay (NC 0515, 2620).

Gouge along the margin between a quartz-pyrite vein and the Lewisian country rock (NC 0855, 3102).

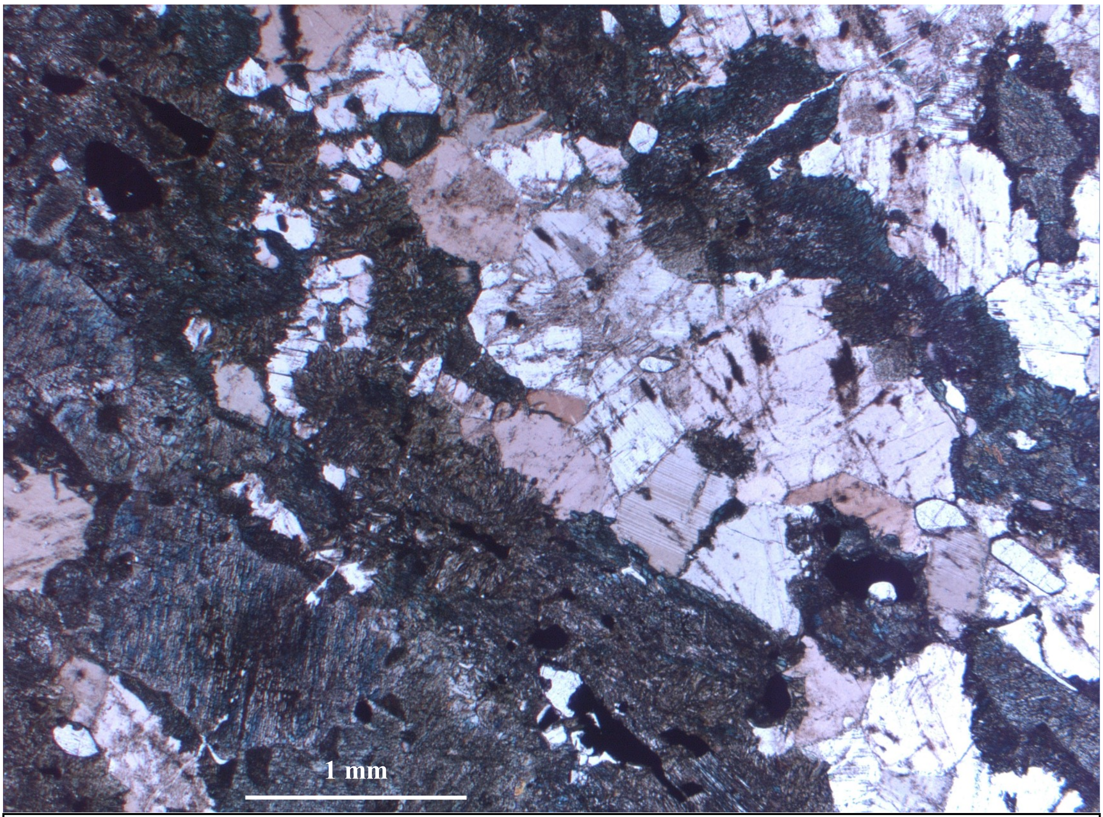
Small-scale shear zone developed perpendicular to the foliation of the Laxfordian gneisses in the Canisp Shear Zone at Achmelvich Bay. Potentially related to late Laxfordian deformation (NC 0577, 2552).

Small-scale crush belt orientated perpendicular to the foliation in the Laxfordian gneisses in the Canisp Shear Zone at Achmelvich Bay. Potentially relater to the small-scale shear zone above and to late Laxfordian deformation (NC 0577, 2552).

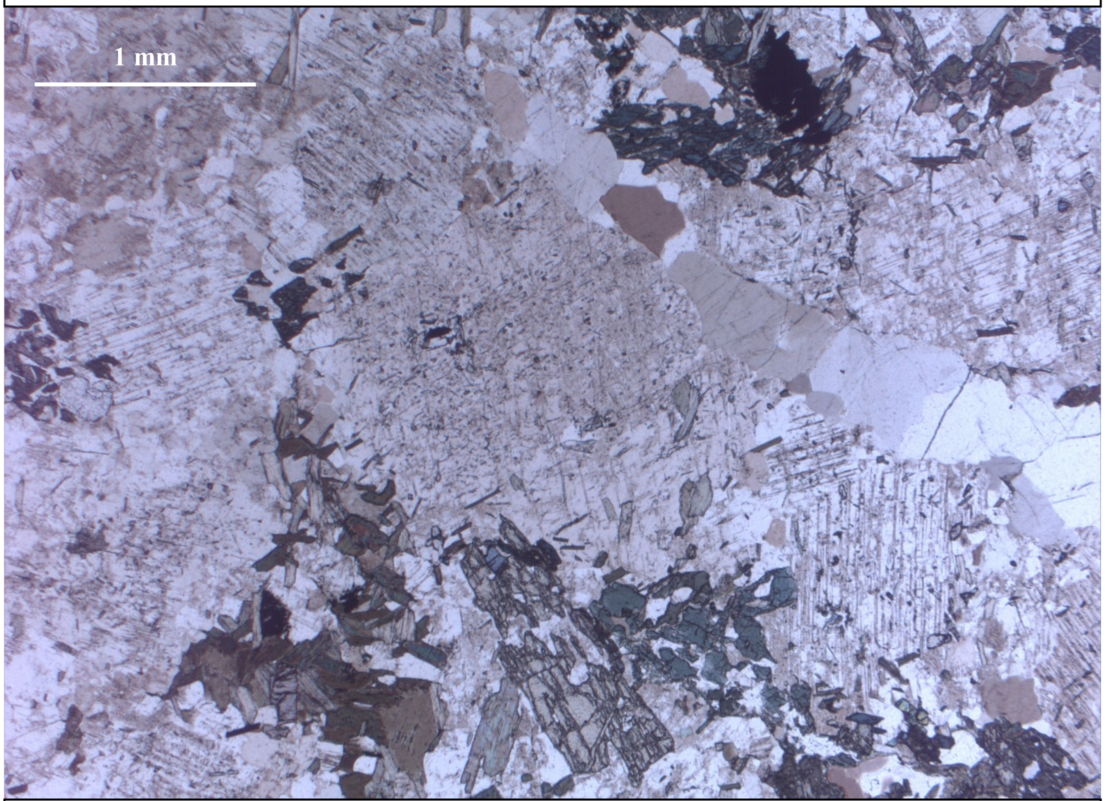
Epidote-filled minor shear zone which cross-cuts the quartz-pyrite vein (NC 2130, 2500).

Quartz-pyrite vein cut and offset by a post-Laxfordian fault in a road cutting near Lochinver (NC 1020, 2360).

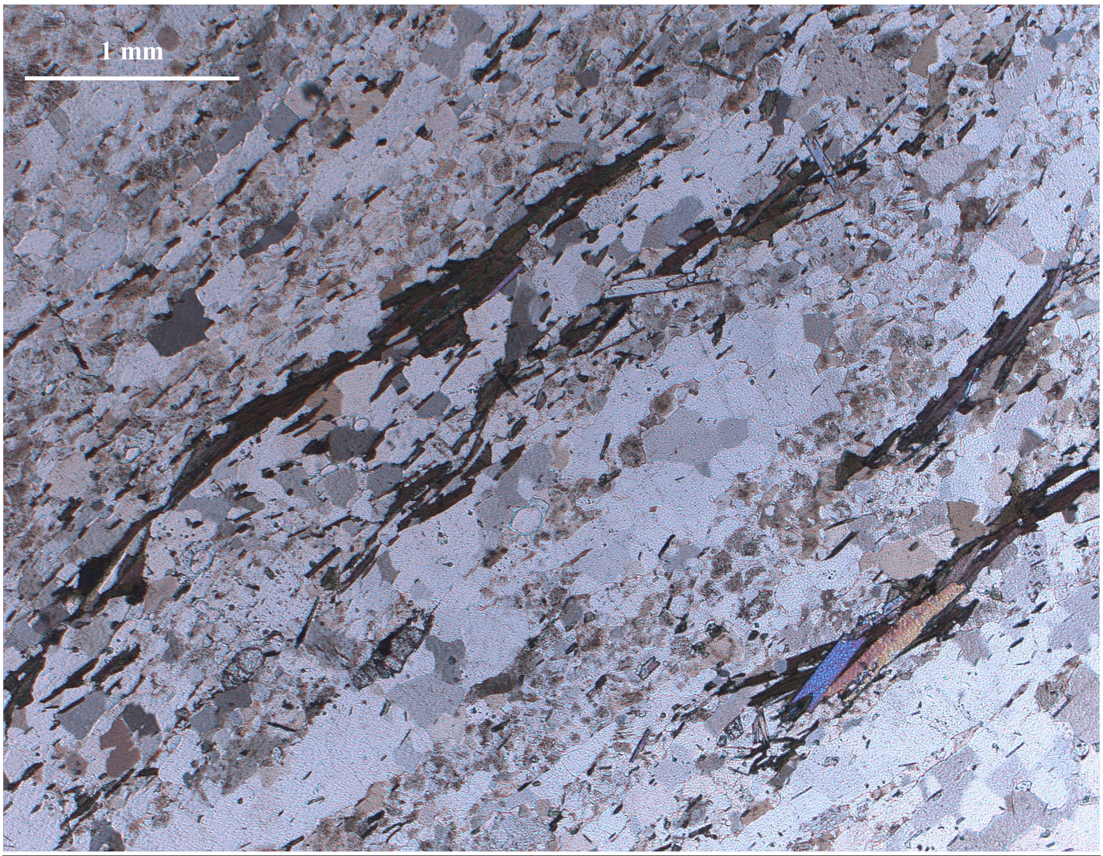
Appendix B – Microstructure Optical Analysis



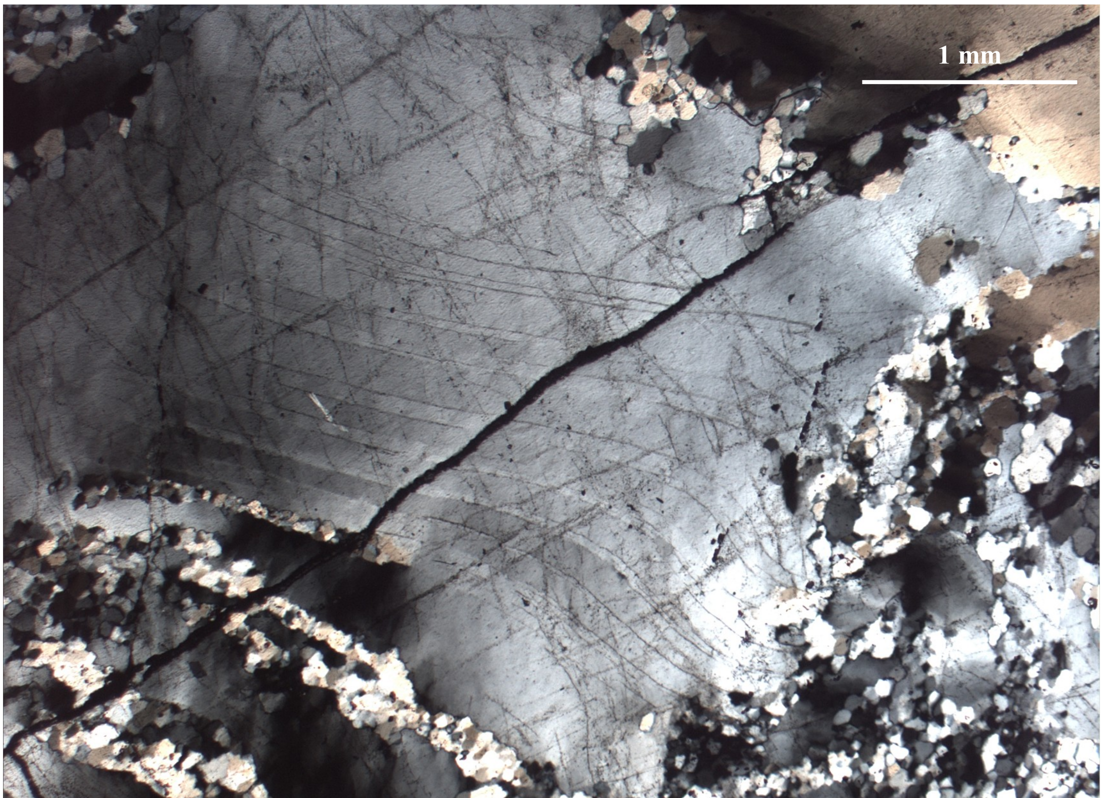
Badcallian gneiss from Loch Assynt.



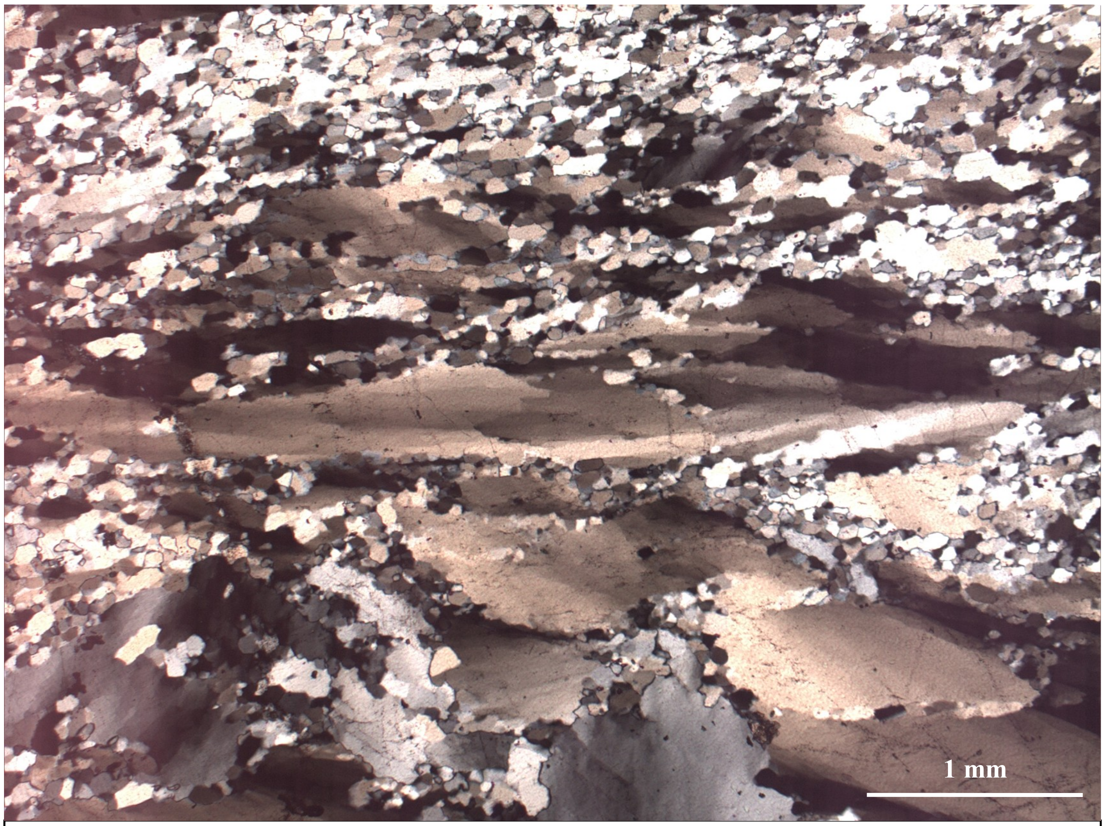
Inverian gneiss from the Canisp Shear Zone at Achmelvich Bay.



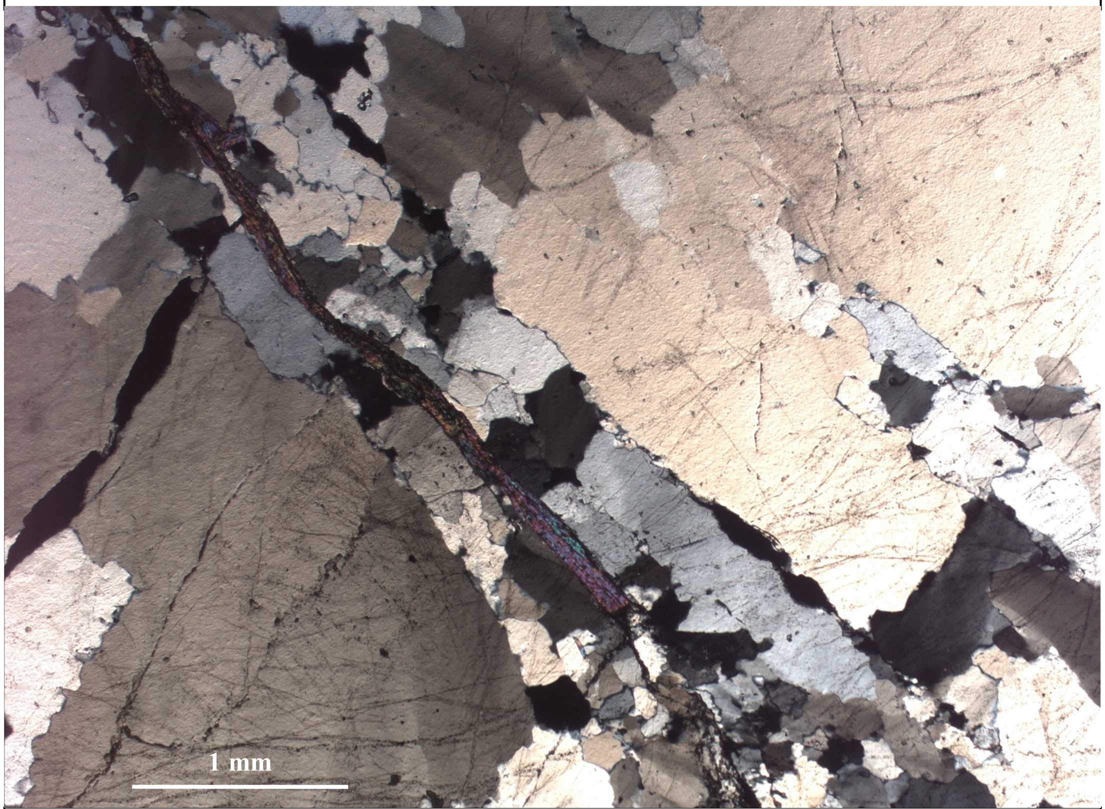
Laxfordian gneiss from the Canisp Shear Zone at Achmelvich Bay.



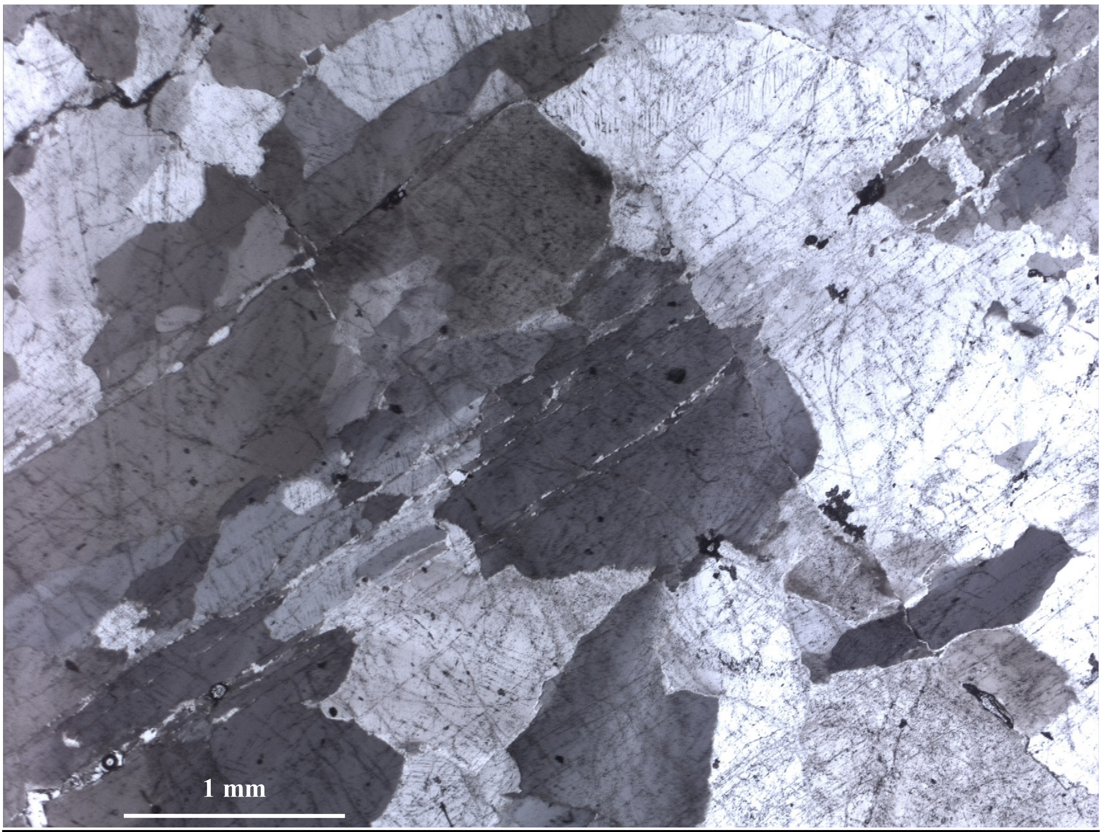
Sample 3: Deformation lamellae within the large quartz crystals.



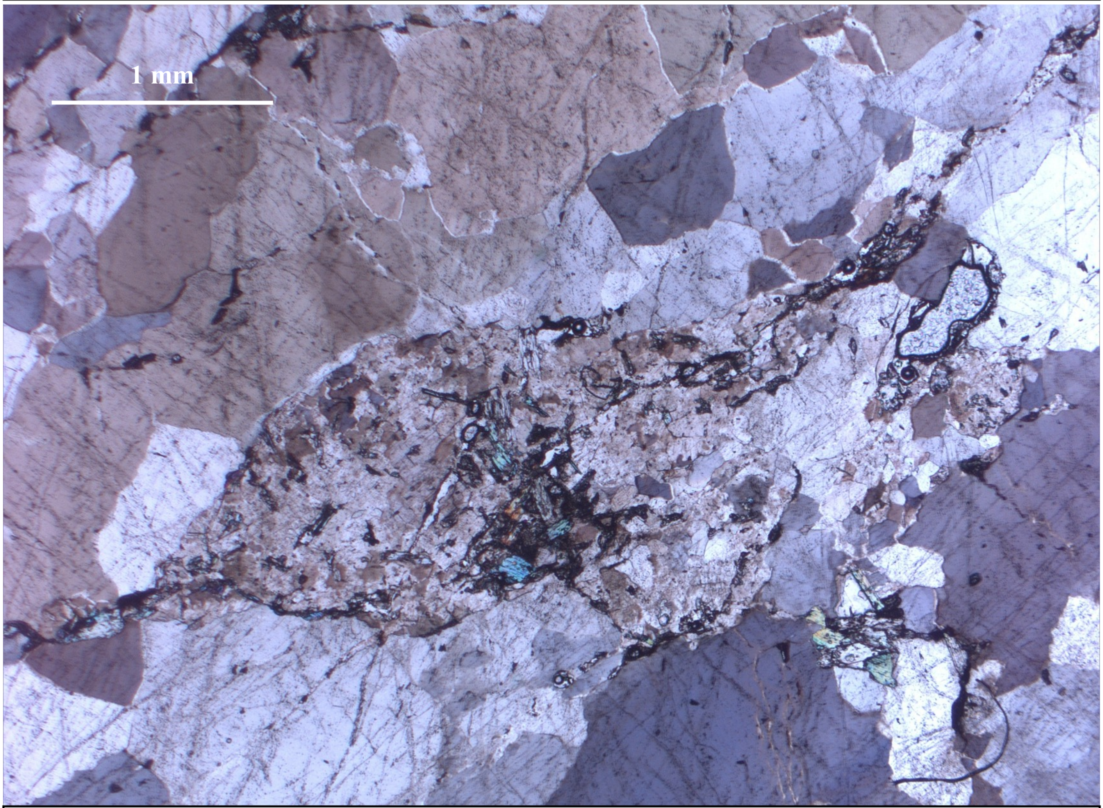
Sample 3: Elongate subgrains within large quartz grains formed through subgrain rotation recrystallisation, and surrounded by a mass of smaller quartz grains.



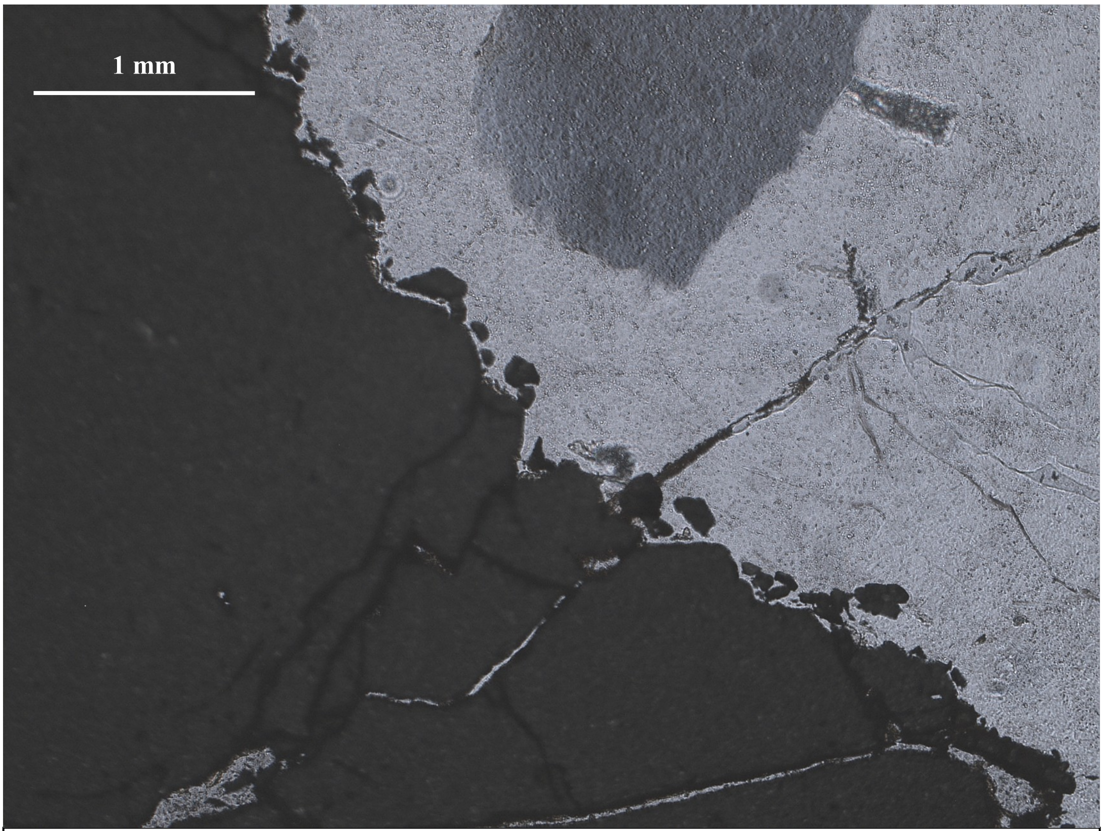
Sample 64: Muscovite and chlorite mica present along a mylonitic band. Edges of the band of reduced grains size are well defined and contain black areas, suggesting may be a brittle component of deformation post-dating the ductile deformation.



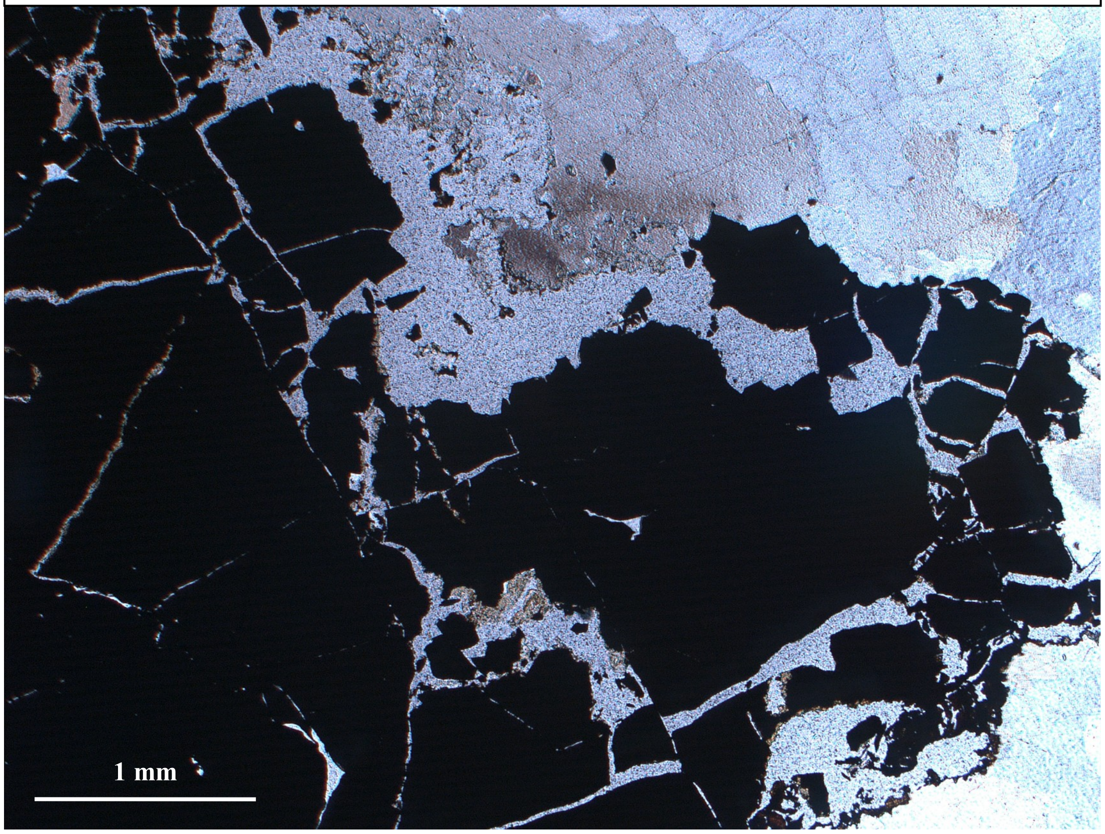
Sample 41: Small angular crystals with cataclastic bands which cut across the crystals, indicates deformation under a brittle regime.



Sample 41: A fish structure associated with the cataclastic bands, containing quartz, mica and feldspar.

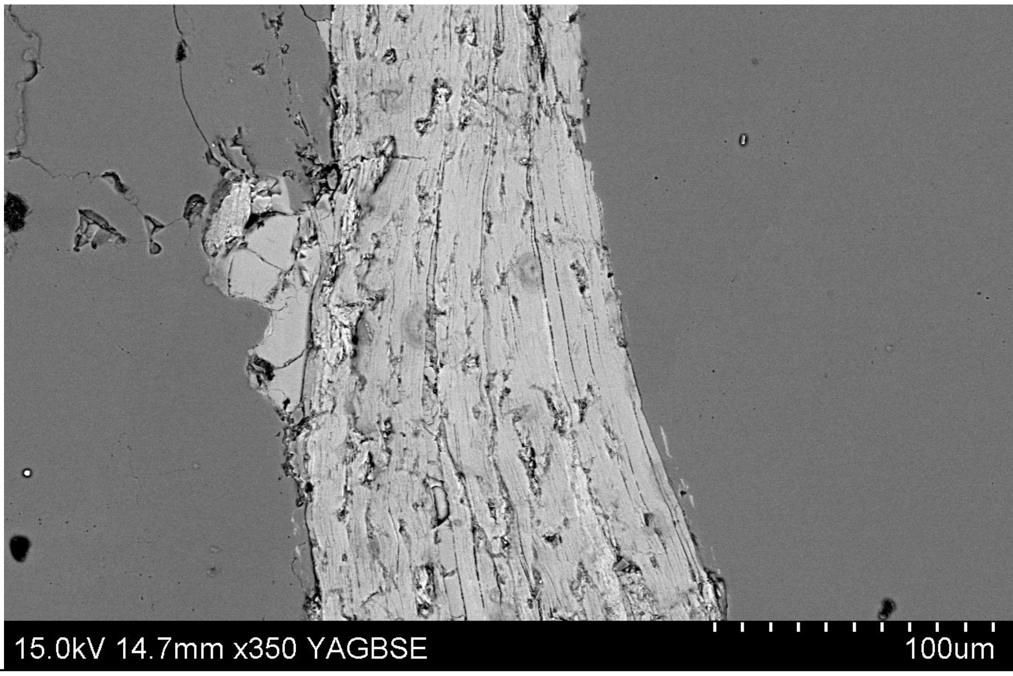


Sample 64: Angular pyrite at the edge of a cluster interspersed with the quartz mass.

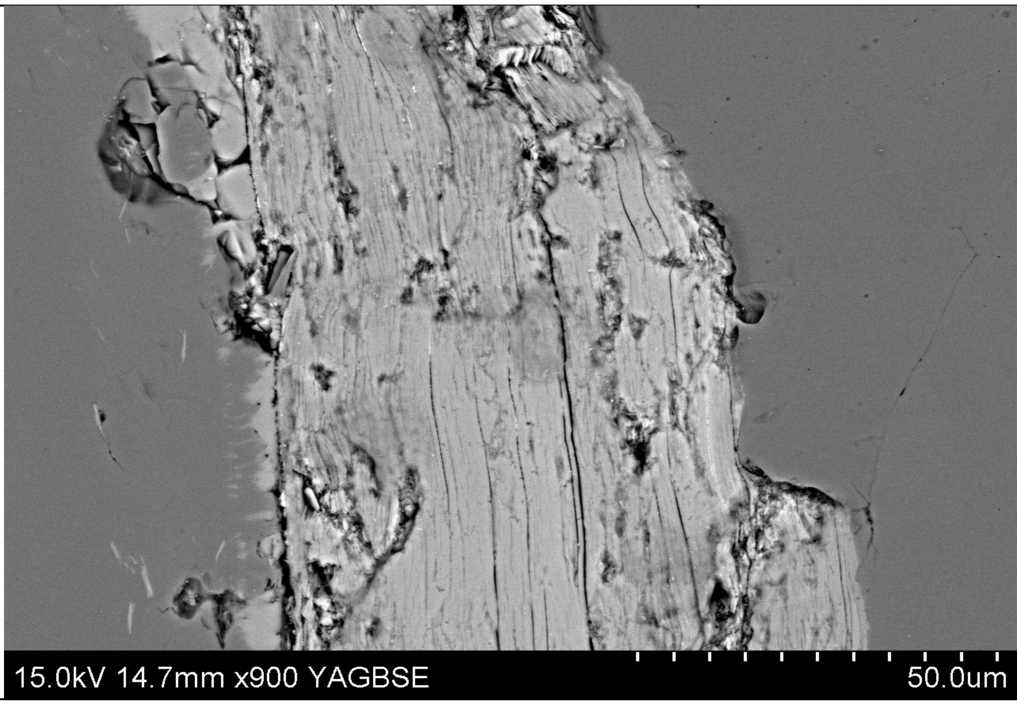


Sample 64: Angular pyrite at the edge of a cluster interspersed within the quartz mass.

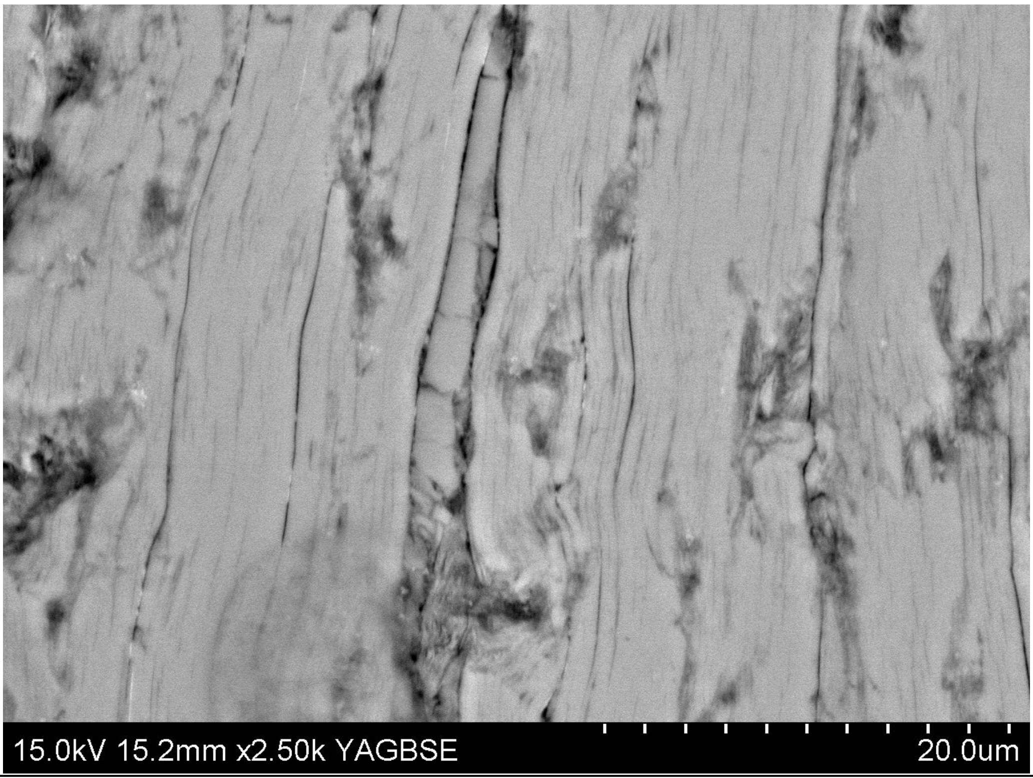
Appendix C – Microstructure SEM Analysis



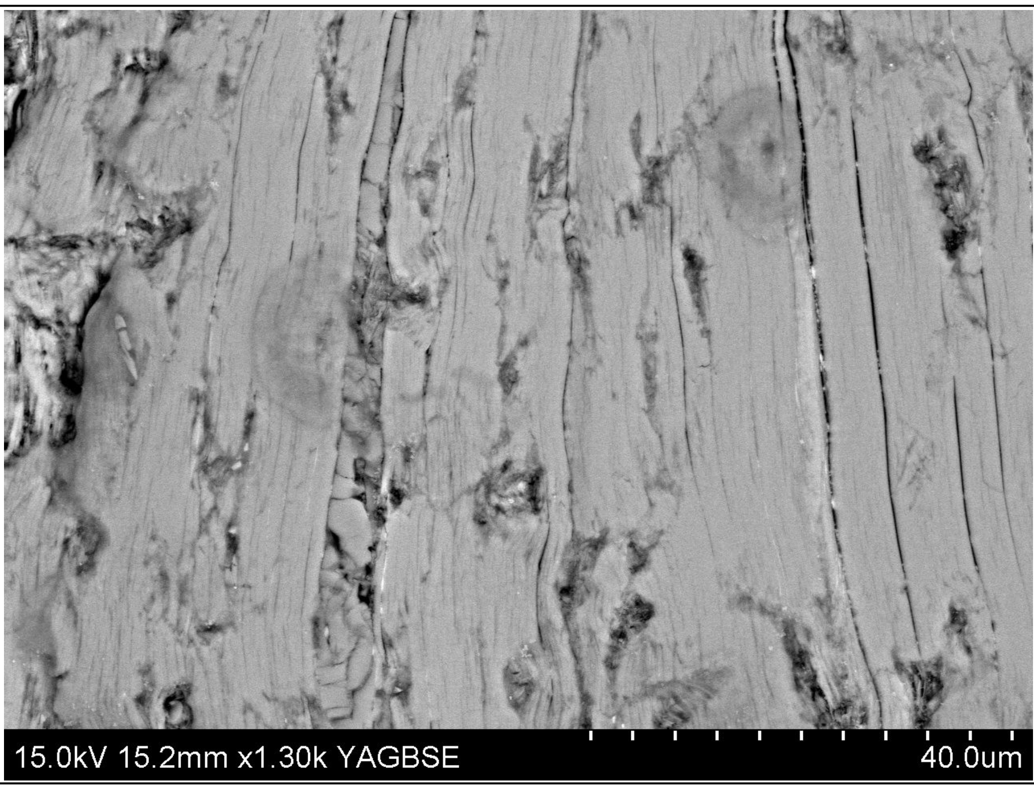
Sample 64: Predominantly muscovite mica with some chlorite mica (lighter colour), some well developed cleavage planes, and K-Feldspar ribbons strung out along the cleavage planes as well as present along the edges of the mica.



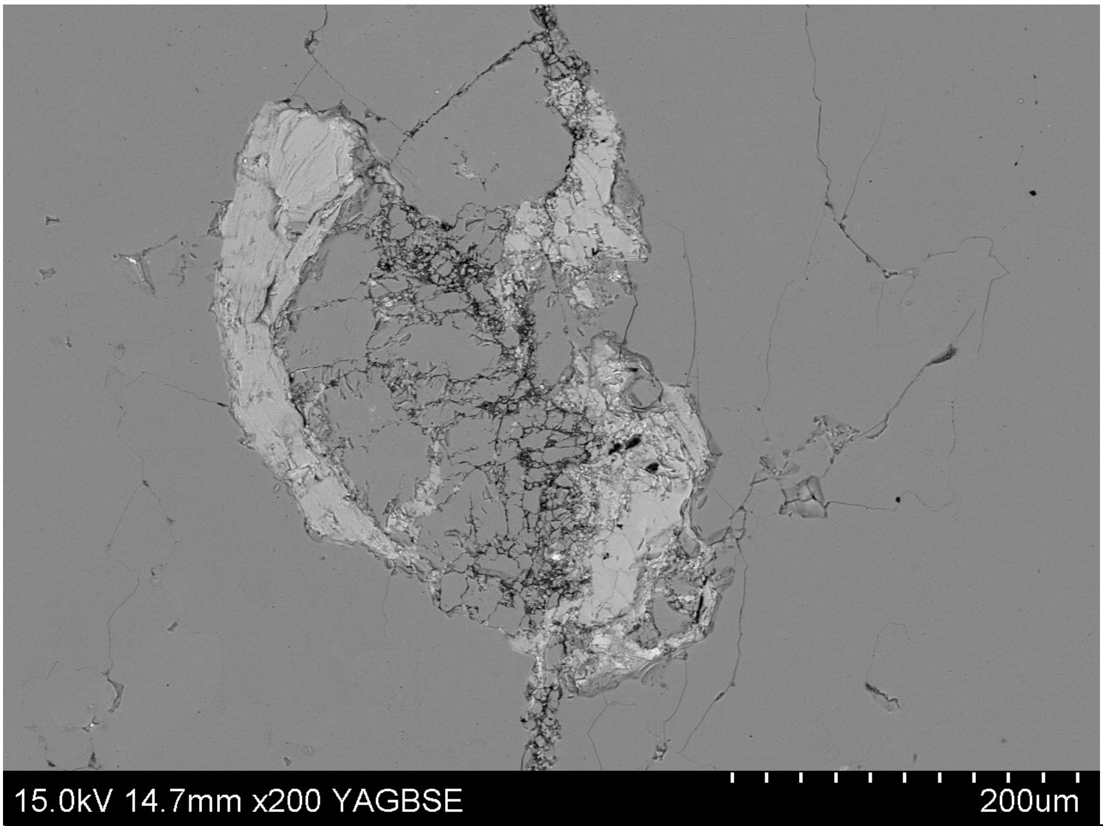
Sample 64: Predominantly muscovite mica with some chlorite mica (lighter colour), kinked mica lattices suggest the minerals have been subject to shearing, K-Feldspar present along the edges of the mica, and corona structures along the edges of the micas (left) which are of K-Feldspar composition.



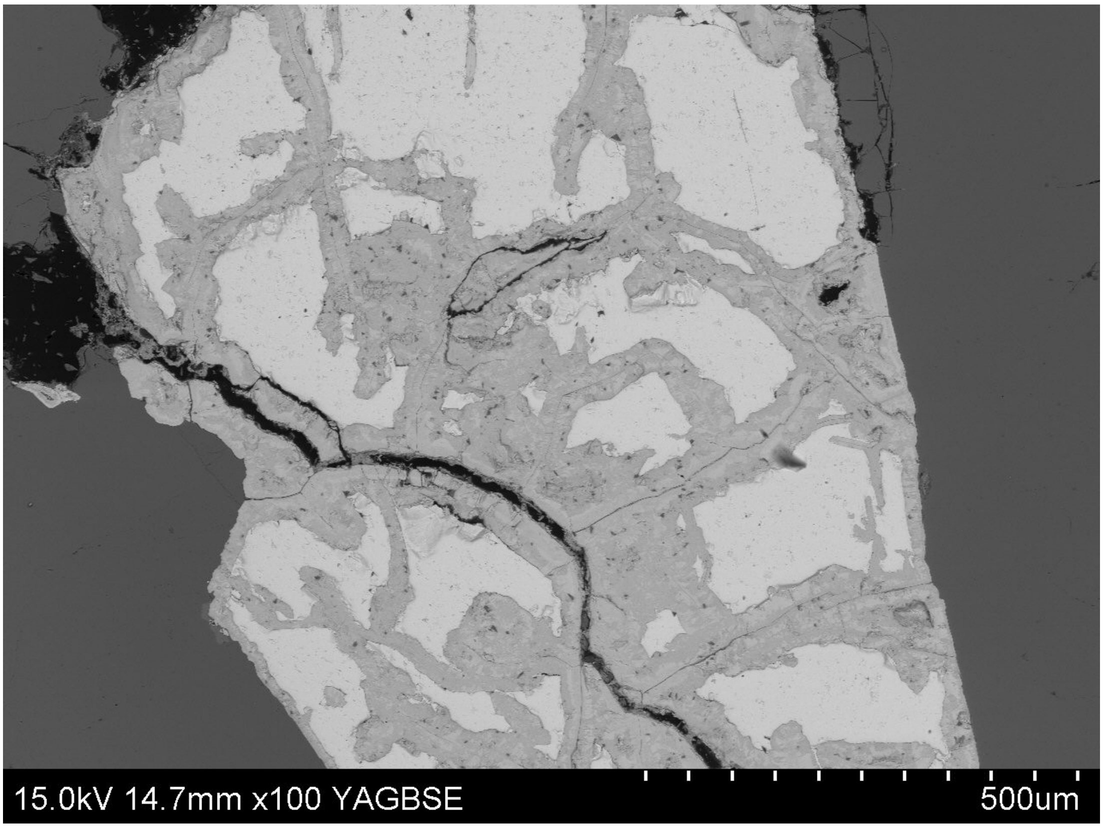
Sample 64: Muscovite micas with some well developed cleavage planes, suggesting brittle movement along these planes, and ribbons of K-feldspar parallel to the cleavage planes.



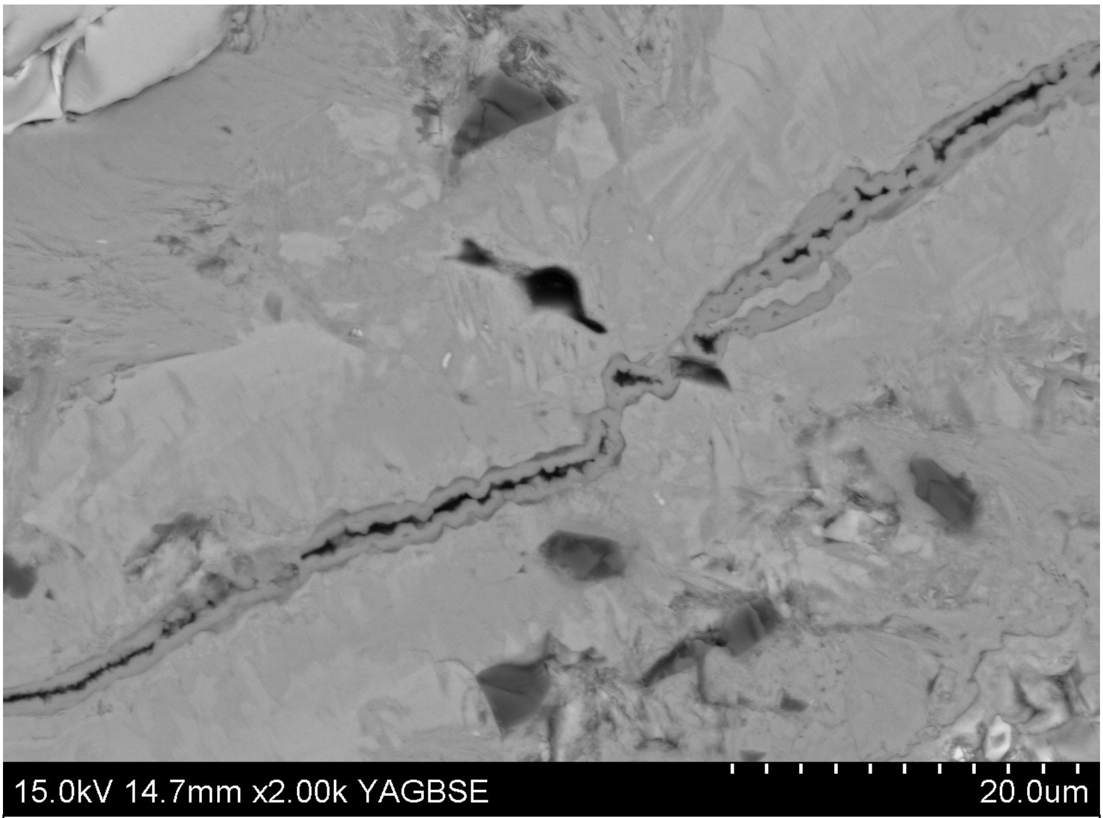
Sample 64: Predominantly muscovite mica with some chlorite mica (lighter colour), some well developed cleavage planes, and K-Feldspar ribbons strung out along the cleavage planes as well as present along the edges of the mica.



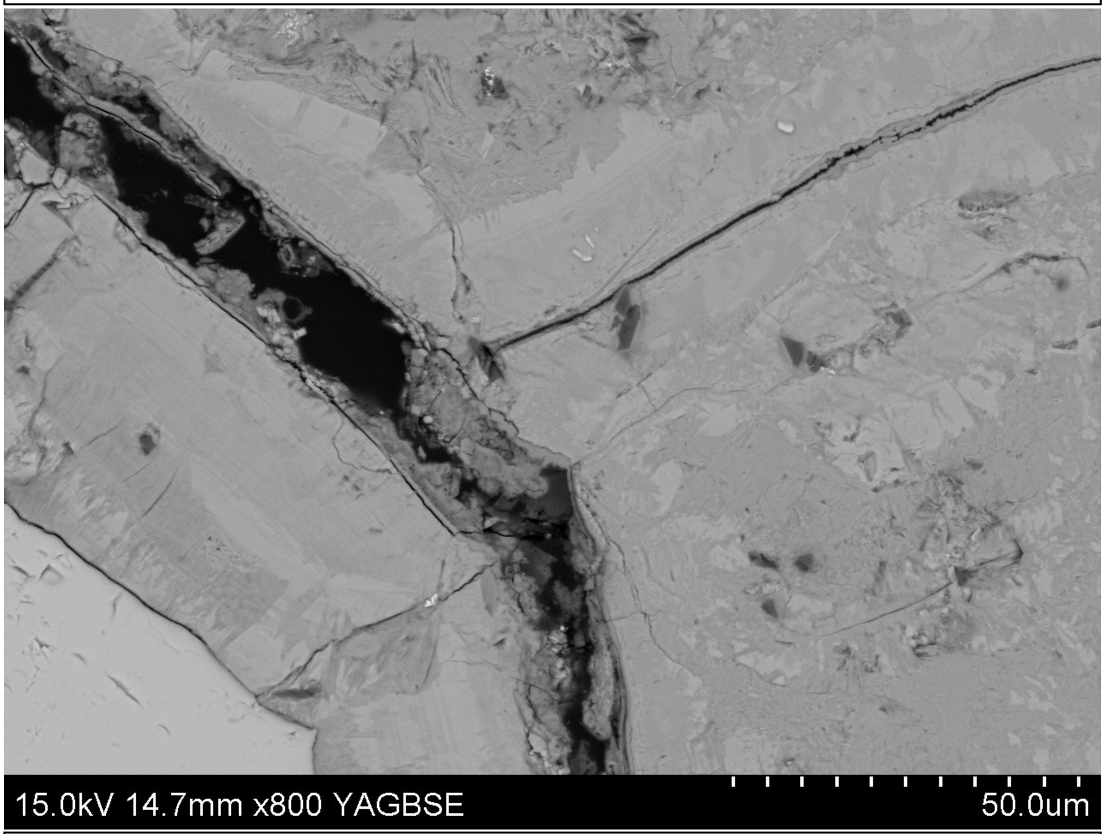
Sample 64: Brittle fracturing of the mica and K-feldspar as well as the quartz.



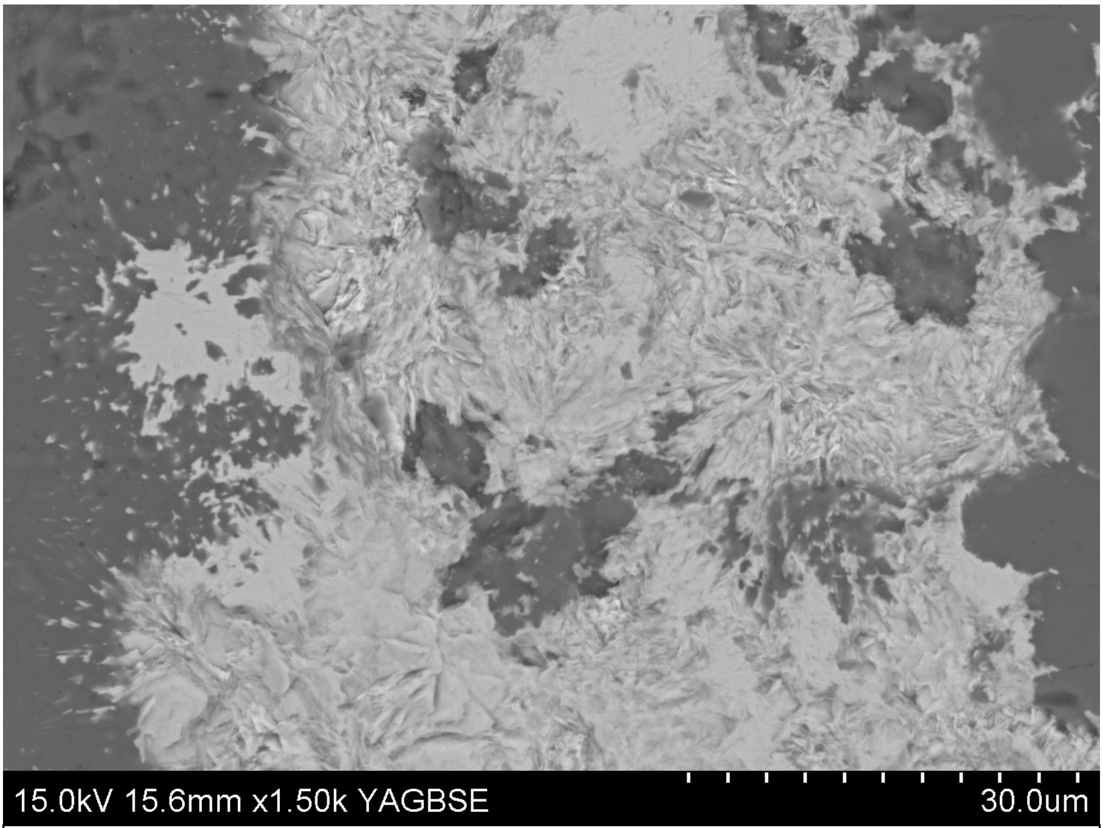
Sample 64: The breakdown of pyrite into iron-oxides centred along fractures within the pyrite, the unaltered pyrite is the brightest white colour.



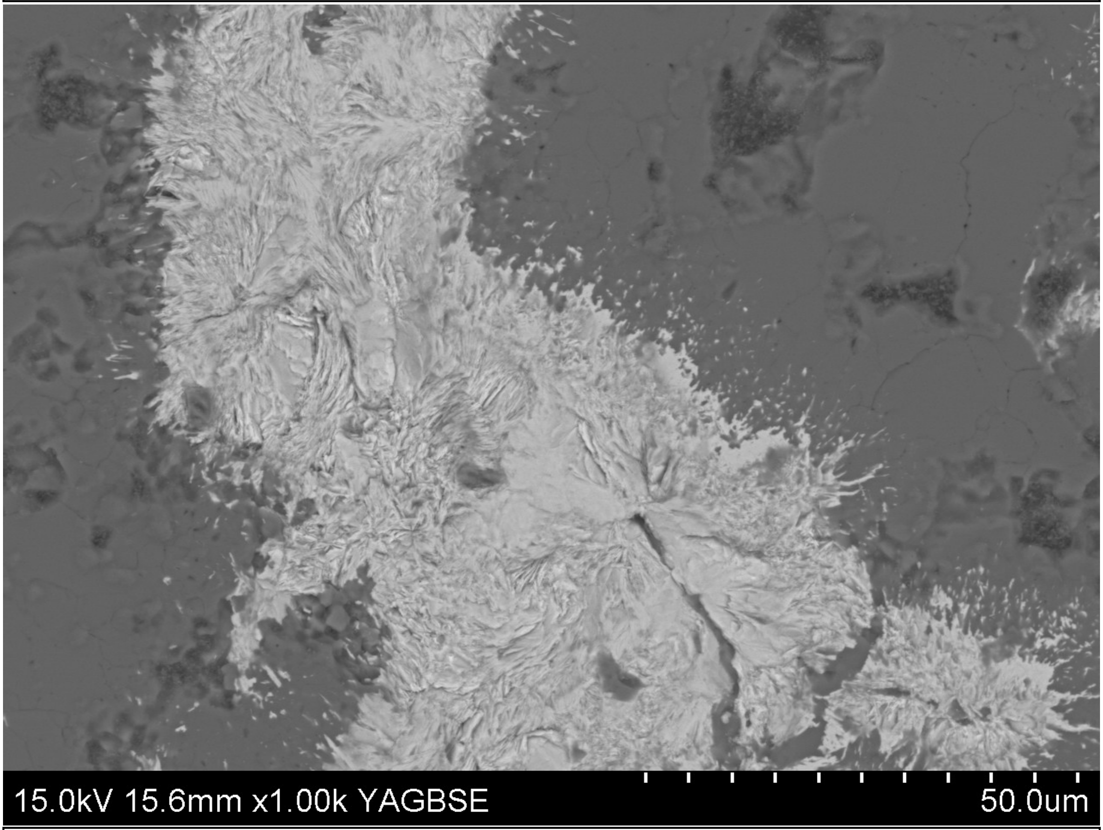
Sample 64: Formation of iron oxides centred along fractures resulting from the breakdown of pyrite, phases can be seen radiating out from the fractures.



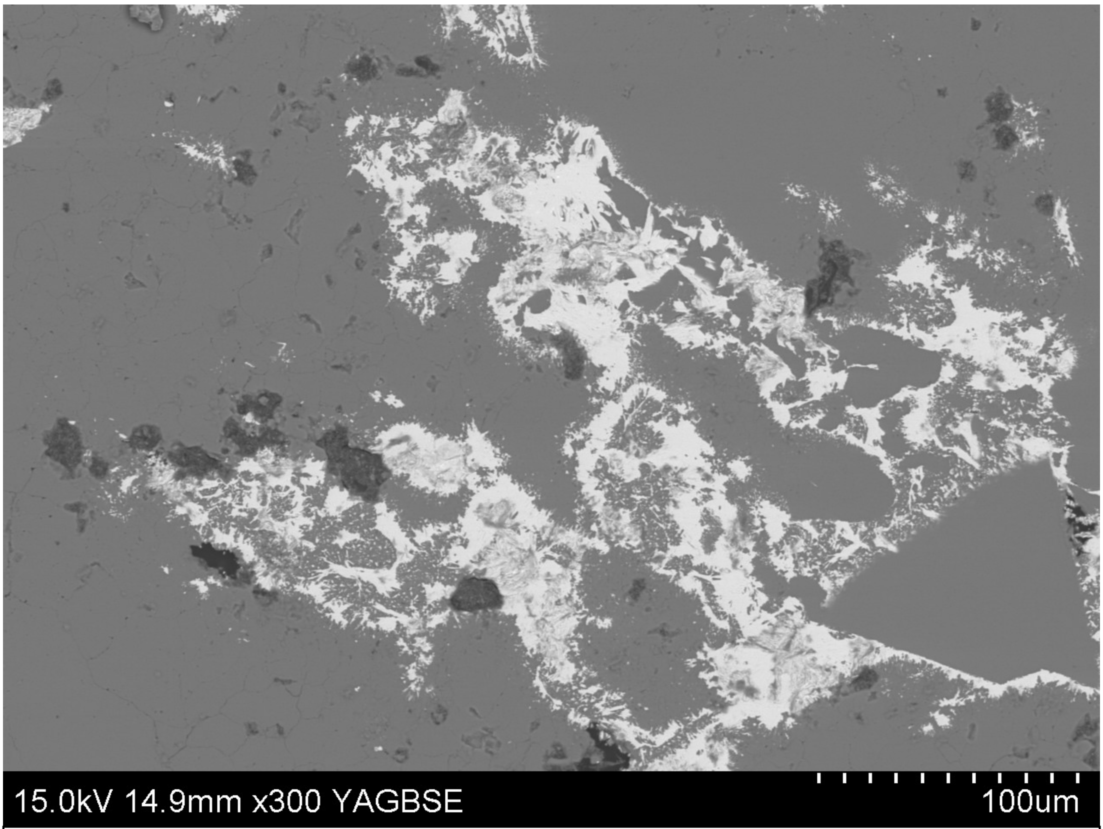
Sample 64: Formation of iron oxides from the breakdown of pyrite centred along fractures can be seen forming new phases (different shades of grey).



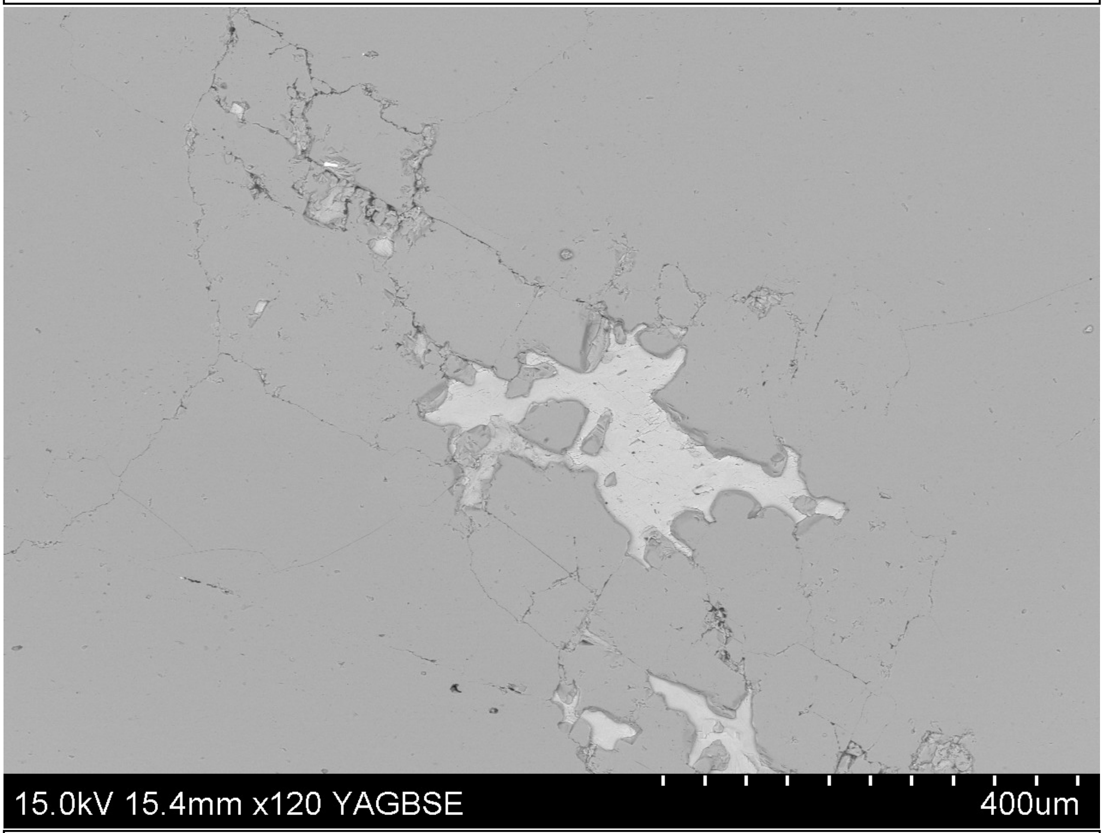
Sample 15: Areas of smooth textured pyrite and boreal textured of the iron oxide (haematite) formed from the breakdown of pyrite.



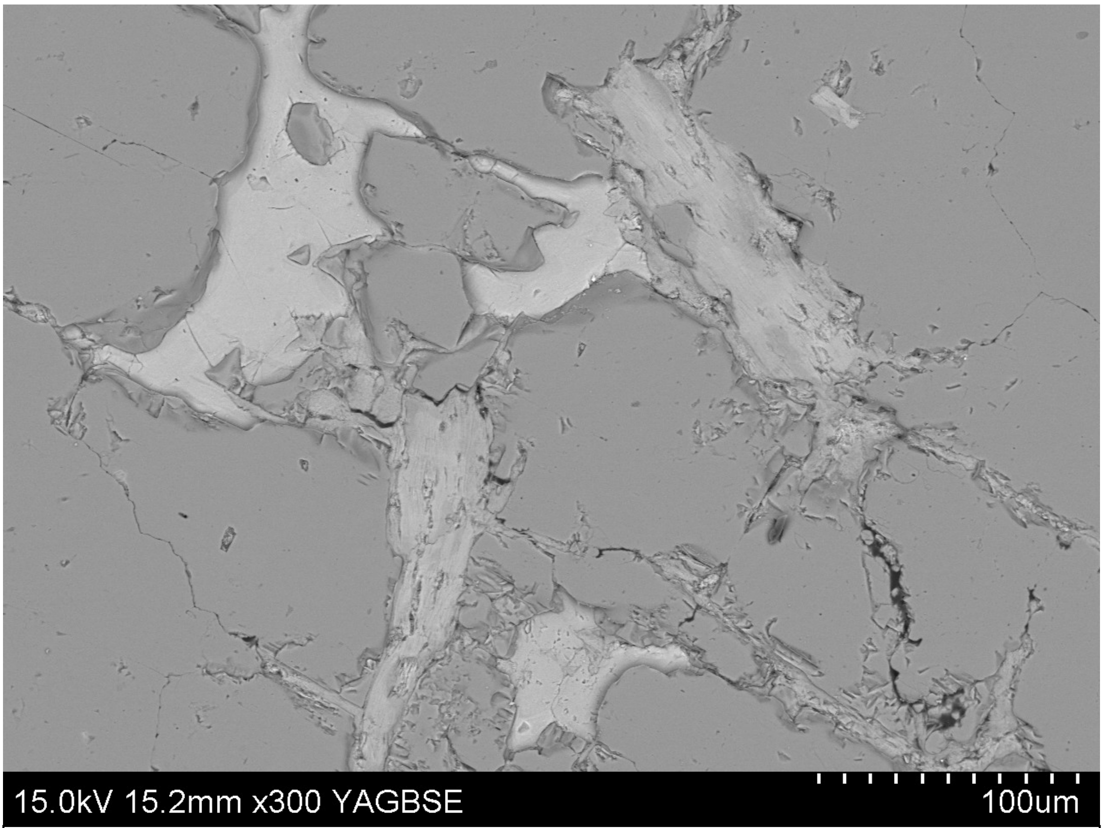
Sample 15: Boreal texture of the iron oxide (haematite) formed from the breakdown of pyrite.



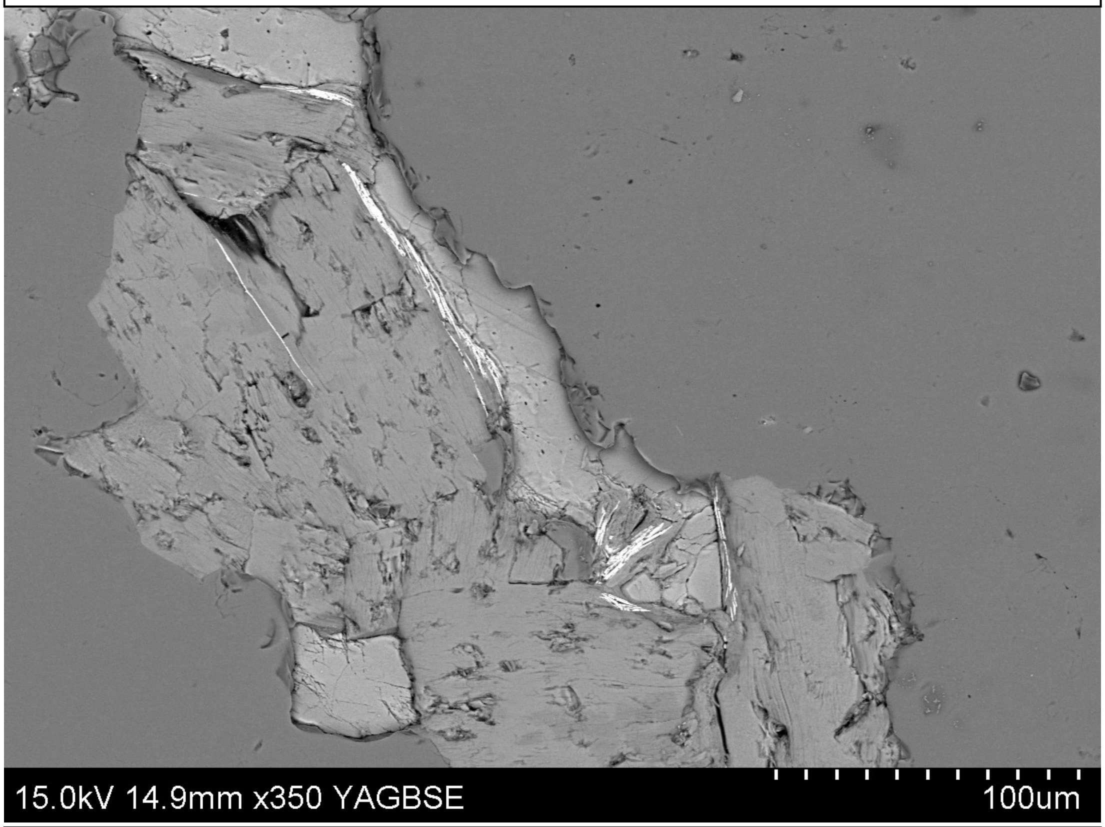
Sample 15: Smooth textured areas of pyrite with some areas of boreal texture, indicating limited breakdown of pyrite into iron oxides (i.e. haematite).



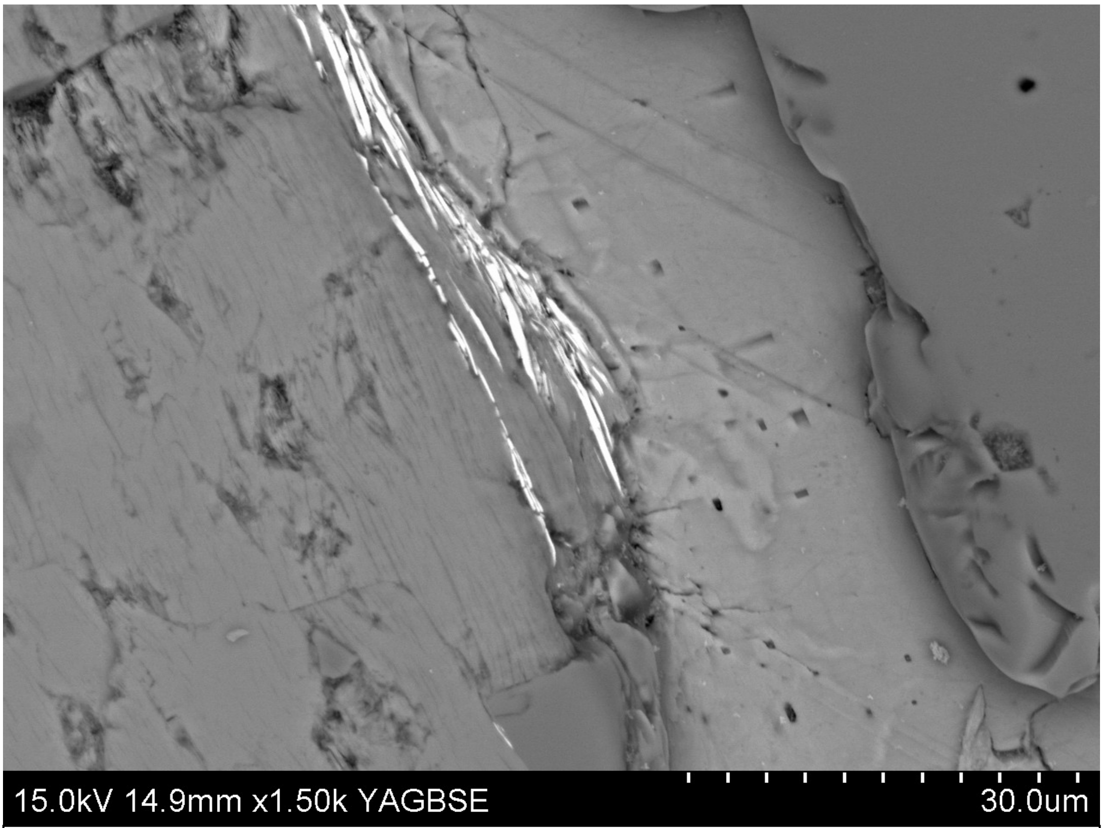
Sample 25: Calcite formed in pull-apart-type fractures within the quartz.



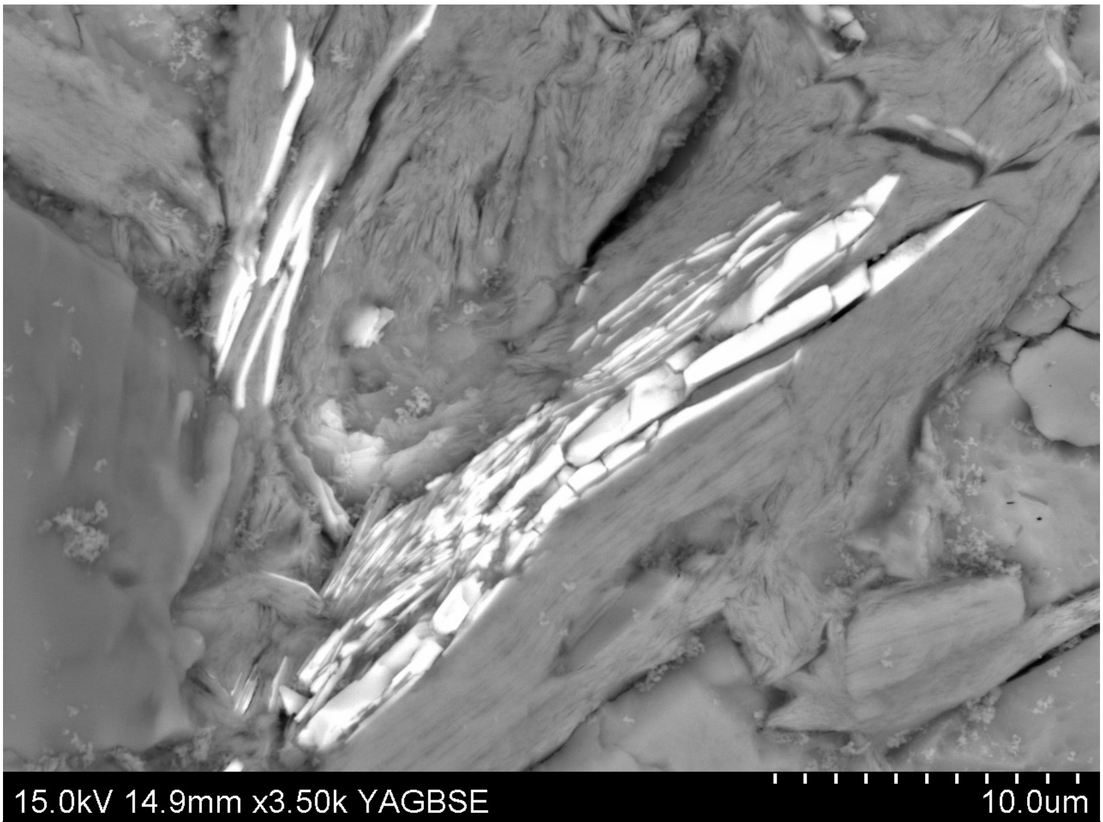
Sample 25: Calcite and muscovite mice formed in pull-apart-type fractures within the quartz.



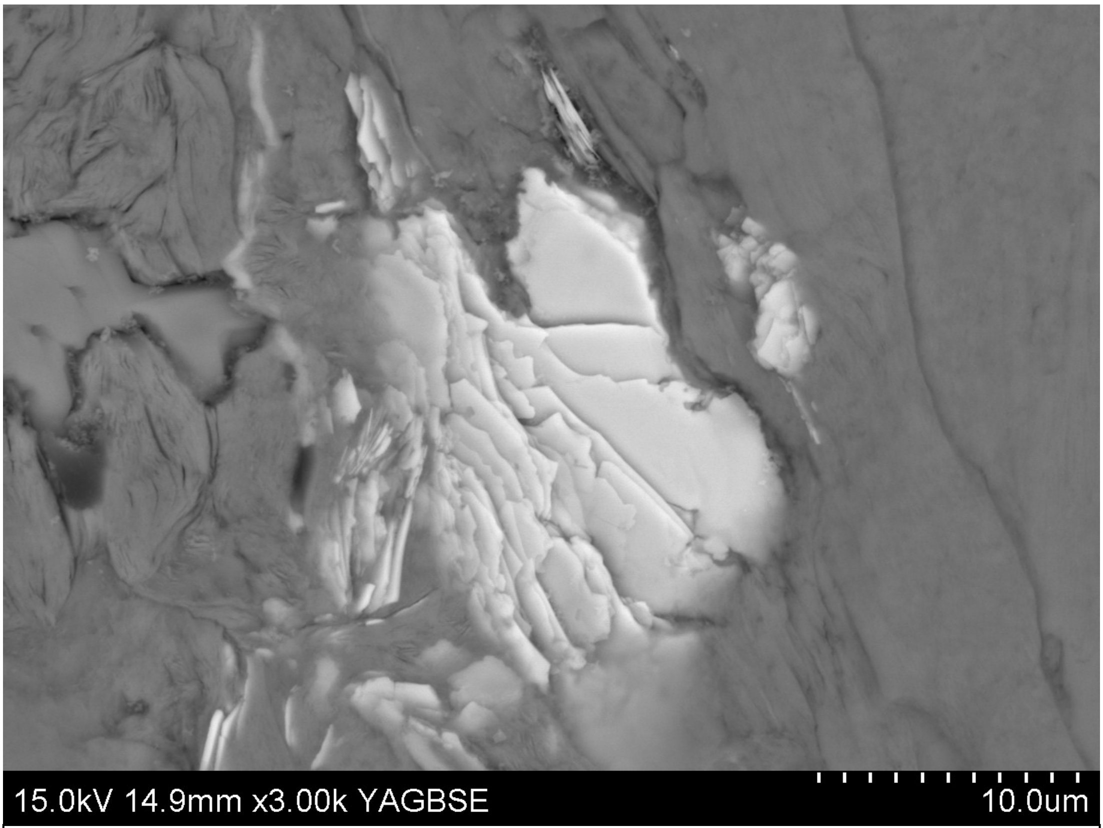
Sample 25: Calcite, muscovite and chlorite micas grown together along a fracture in the quartz. Long, white, platy spinels interspersed within the muscovite and chlorite micas.



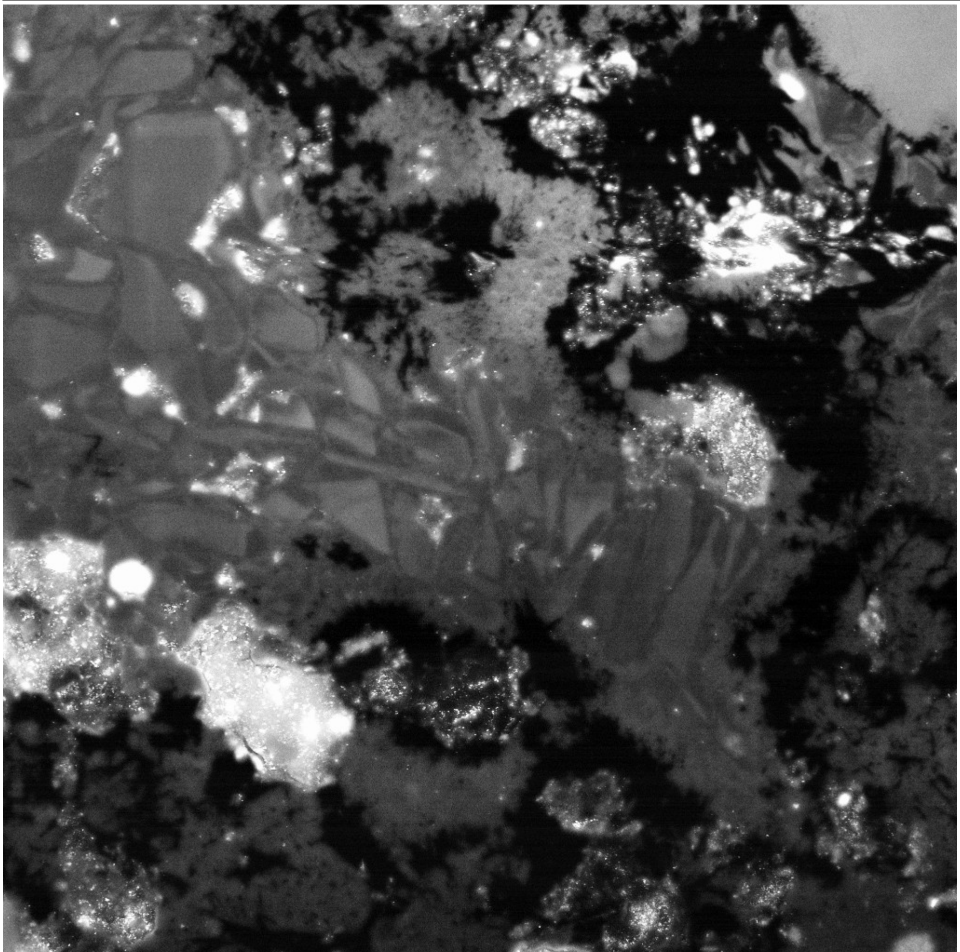
Sample 25: Calcite, muscovite and chlorite micas grown together along a fracture in the quartz. Long, white, platy spinels interspersed within the muscovite and chlorite micas.



Sample 25: Long, white, platy spinel interspersed with muscovite alongside calcite.



Sample 25: White, platy spinel within the muscovite micas.



Sample 25: CL of quartz, showing difference phases of overgrowth.

Appendix D – Geological Society Progress Report (31/12/2010)

The Age, Geological Character and Structural Setting of Quartz-Pyrite Veins in the Assynt Terrane, Lewisian Complex, NW Scotland.

Rowan Vernon

Annie Greenly Fund - £600

Regional Setting

The far northwest of Scotland is one of the most beautiful parts of the UK, it also has some of the most varied and exciting geology in Britain. As you drive northwards through Scotland you notice that you are gradually leaving society behind and entering a land of mountains, lochs and deer. This part of northwest Scotland contains some of the oldest rocks in the world; the Lewisian Complex. In a thin coastal strip stretching from Cape Wrath in the north to Loch Torridon in the south, a section through different crustal depths of an Archaean craton is exposed (**Figure 1**).

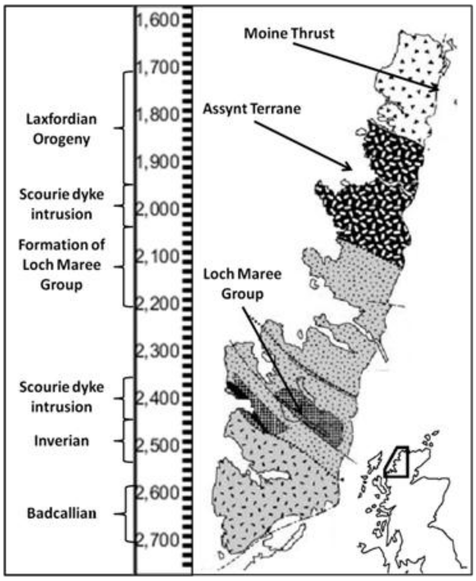


Figure 1: The location of the mainland Lewisian Complex, and the geochronology of the complex (Love *et al.*, 2004 & Kelly *et al.*, 2008).

Some of these rocks are over 3.0 Ga old. They were initially supracrustal rocks which were intruded with voluminous amounts of TTG magmas. The Badcallian event (2.7 Ga), metamorphosed the rocks to granulite facies and imposed the strong foliation shortly after emplacement. Retrogression to amphibolites facies conditions, through hydration reactions (Sills, 1983), occurred during the Inverian event (2.6 – 2.5 Ga) and the amalgamation crustal blocks created major crustal shear zones. The intrusion of the first episode of Scourie dykes, at 2.4 Ga, marks the beginning of a period of crustal extension. During this period the Loch Maree Group of supracrustal rocks was formed in an arc setting and dated at around 2.2 Ga (Floyd *et al.*, 1989). The second major episode of Scourie dykes were intruded around 2.0. The Laxfordian orogeny occurred as minor ocean basins closed and continents moved together, causing many of the major Inverian shear zones to be reactivated.

Within the Assynt Terrane of the Lewisian Complex are a set of hitherto undocumented quartz-pyrite veins. The pyrite within them has been dated at 2250±150 Ma, using the Re-Os geochronometer, in a pilot study by D. Selby at Durham University. Consequently, this project seeks to understand the structural relationships of these veins to fabrics within the complex, the conditions under which the veins were emplaced, the age of the pyrite within the veins and the implications for the geochronology of the Lewisian Complex.

Work carried out

- Fieldwork in the Assynt Terrane during October 2010, which was supported by the fund money. During 4 weeks I collecting data on the characteristics of the quartz-pyrite veins, the structural relationships of the veins and the nature of the country rock around the veins. I also collected samples of pyrite and orientated samples of the quartz from within the veins.
- Produced stereonets and rose diagrams to analyse the structural and kinematic data.
- Prepared 12 orientated samples of quartz from the veins to be cut for thin sections, which will be used for microstructural analysis to constrain the P-T conditions during emplacement and overprinting events. The thin sections are currently being made by the technician.
- Analysed three existing thin sections of vein quartz to establish P-T conditions at emplacement.

- Isolated eight samples of pyrite and carried out Rhenium tests on the samples. The samples are processed and awaiting mass spectrometry.
- Prepared a poster detailing my research so far to be presented at the Tectonic Studies Group conference on the 5th-7th January.

Results

The quartz-pyrite veins are present throughout the Assynt Terrane, normally in loose clusters. They range in width from five centimetres to seventy-five centimetres. The majority of the veins cross-cut the Badcallian (**Figure 2**) and Inverian fabrics as well as the first episode of Scourie dykes, but are reworked by Laxfordian fabrics. Small-scale epidote-bearing shear zones are found cross-cutting the veins, and are probably formed under greenschist facies conditions during the Late Laxfordian. In places post-Laxfordian fractures also cross-cut the veins. En echelon off-shoots and lineations were also found on the veins, and indicate shear and opening directions.

Figure 2: Photograph of a quartz-pyrite vein cutting Badcallian foliation at Lagg Fisheries.

The quartz-pyrite veins have a polymodal distribution with three dominant trends (**Figure 3**). The main trend strikes NE-SW, with secondary trends striking NW-SE and NNW-SSE. Thus the main trend suggests an opening direction NW-SE, which is perpendicular to the orientation of the Scourie dykes. The secondary trend is parallel to the direction of the Scourie dykes but has probably been influenced by the strong Badcallian and Inverian foliation within the Lewisian gneisses.

Three existing thin sections of quartz from within the veins show bulging grain boundaries, subgrain growth, deformation lamellae and sweeping undulose extinction. These are features of metamorphism at temperatures above 300°C and perhaps above 500°C (Passchier & Trouw, 2005) which is consistent with mid-crustal emplacement of the veins under amphibolites facies conditions. This agrees well with the geochronology, as the Scourie dykes intruded at 2.4 Ga were also emplaced under amphibolites conditions (Weaver & Tarney, 1981).

The Re-Os age of 2250±150 Ma for the pyrite within the quartz veins is important as it places the emplacement of the veins between the ages of 2.4 and 2.1 Ga. This overlaps with the intrusion of the Scourie dykes and the beginning of formation of the Loch Maree Group.

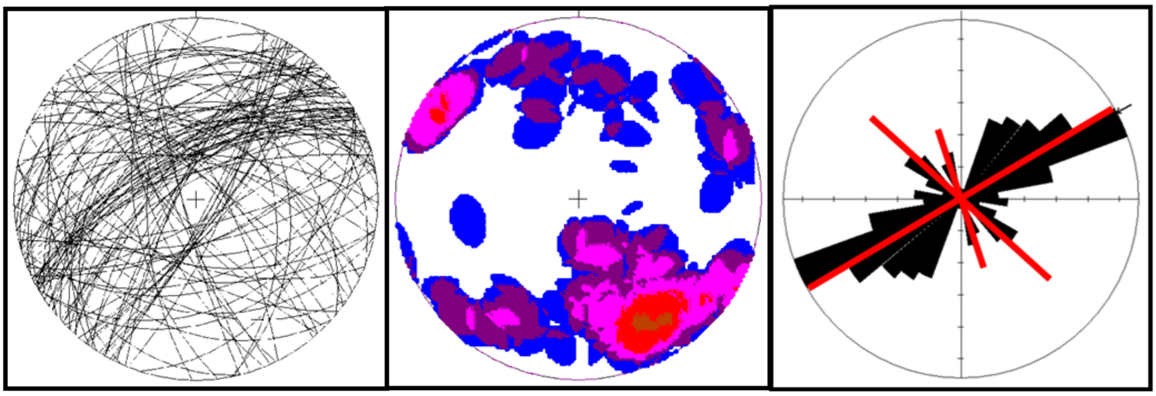


Figure 3: Stereonet, gridded contour density and rose diagram showing the distribution and dominant trends of quartz-pyrite vein orientation in the Assynt Terrane.

Conclusions so far

The structural relationships from the field establish a geochronology to which the Re-Os age of the pyrite within the veins conforms, and further analysis will provide more model ages. The predominant strike orientation of the quartz-veins lies at high angle to the Scourie dykes which were intruded into the gneisses both before and after the veins. However, there is a marked change in the extension direction between the intrusion of the Scourie dykes and the emplacement of the quartz-pyrite veins. Consequently, it is likely that the emplacement of the veins may be related to the beginning of the formation of the Loch Maree Group in an arc setting near the margin of the Assynt Terrane. The microstructures within the veins record amphibolites facies conditions, consistent with emplacement at mid-crustal depths and further studies hope to further constrain the P-T conditions during emplacement and during subsequent overprinting events.

References

- Floyd, P.A., Winchester, J.A. & Park, R.G. (1989). Geochemistry and tectonic setting of Lewisian clastic metasediments from the Early Proterozoic Loch Maree Group of Gairloch, NW Scotland. *Precambrian Research.*, **45**, Pp. 203-214.
- Kelly, N.M., Hinton, R.W., Harley, S.L. & Appleby, S.K., (2008). New SIMS UPb zircon ages from the Langavat Belt, South Harris, NW Scotland: implications for the Lewisian terrane model, *Journal of the Geological Society*, **165**, Pp.967-981.

- Love, G.J., Kinny,. P.D. & Friend, C.R.L., (2004). Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: comparisons with the Assynt Terrane and implications for terrane accretion, *Contrib Mineral Petrol*, **146**, Pp.620-636.
- Macdonald, R. & Fettes, D.J. (2007). The tectonomagmatic evolution of Scotland, *Transactions of the Royal Society of Edinburgh: Earth Sciences*, **97**, Pp. 213–295.
- Passchier, C.W. & Trouw, R.A.J., 2005. Micro-tectonics, 2nd edition, Springer, New York, P. 56-57.
- Sills, J. D. (1983). Mineralogical changes occuring during the retrogression of Archaean gneisses from the Lewisian complex of NW Scotland, *Lithos*, **16**, Pp. 113-124.
- Weaver, B.L. & Tarney, J., 1981. The Scourie Dyke Suite: Petrogenesis and Geochemical Nature of the Proterozoic Sub-Continental Mantle, *Contrib Mineral Petrol*, **78**, Pp. 175-188.