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Geological Mapping of the Glenurquhart Complex near Loch Ness, Scotland

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Abstract

The Glen Urquhart complex, northwest of Loch Ness, is a metamorphic complex intruded by a 4 km^2 ultrabasic serpentinite mass. The complex is regarded a Lewisian inlier, enveloped by Moine metasedimentary rocks. The aim of this thesis is to construct a geological map within the northern 12 km^2 of Glen Urquhart complex, and to produce cross-sections from the geological map. The geological map and the cross-sections are then used to evaluate the geological history of the area. Seven different lithologies were observed in the study area, i.e. serpentinite, marble, skarn, metapelite (kyanite schist), gneiss (metasedimentary gneiss and granitic gneiss), breccia and conglomerate. Also, amphibole-rich outcrops were observed, which are included as amphibolite lenticles within the mapped gneiss. The cross-sections show that the lithological units within the study area dip towards the southwest. The strike of the outcrops trends towards the northwest. Previous studies of the characteristics and origin of the complex have been conducted by e.g. Cunningham Craig (1914), Francis (1956, 1958, 1964) and Rock *et al.* (1986). Cunningham Craig suggested that the complex is a Lewisian inlier based on mineralogical and structural evidence. Francis (1958) argued that the area is a part of the Moine rocks that envelope the complex. He also suggests that both the complex and the surrounding Moine rocks have been affected by alkali-metasomatism. Rock *et al.* (1986) suggests that the complex is an independent litho-tectonic unit, the Albynian, which belongs somewhere between the Moine and Dalradian successions. This study favours the hypothesis that a Lewisian inlier forms the Glen Urquhart complex. The cross-sections and field observations suggest thrusting in the area. Future studies could study faults has affected the area. More thorough mineralogical studies of the rocks could be conducted to examine the extent of alkali-metasomatism and to evaluate the resemblance with other inliers and the surrounding Moine rocks.

1. Introduction

The Glen Urquhart complex is a metamorphic complex intruded by a 4 km^2 ultrabasic serpentinite mass, enveloped by Moine rocks (Francis, 1956). The complex lies close to Drumnadrochit, northwest of Loch Ness, Scotland *(Figure 1).*

The Glen Urquhart complex has been examined and discussed throughout time, though there are still controversies regarding the emplacement and the origin of the rocks within the complex. Previous studies within the area of the Glen Urquhart complex have been conducted by e.g. Cunningham Craig (1914), Francis (1956, 1958, 1964) and Rock *et al.* (1986), to investigate the characteristics and the origin of the complex. Cunningham Craig suggested that the complex is a Lewisian inlier based on mineralogical and structural evidence (Francis, 1964). He argued that the complex's resemblance to the metasedimentary rocks in Glenelg, which are considered a Lewisian inlier, together with the presence of hornblendic lenticles, is evidence for a Lewisian origin of the complex. Further, Cunningham Craig states that the differences of strike direction between the complex and the enveloping Moine metasedimentary rocks is evidence that the complex is not a part of the Moine succession (Francis, 1964). Francis (1958), on the other hand, argued that the area is a part of the Moine succession that surrounds the complex. He argued that both the complex and the surrounding Moine rocks has been considerably affected by alkali-metasomatism, and thus are related. He based this hypothesis on his observations of mineral alterations within the complex rocks (e.g. shimmerisation of kyanite schist and granitisation of psammitic gneiss), and the presence of pegmatites, quartz veins and reaction skarns, produced by alkali-metasomatism (Francis, 1958). Francis (1958) discards Cunningham Craig's theory that the complex is a Lewisian inlier, and thus discards Cunningham Craig's mineralogical and structural evidences as invalid. The area was previously regarded as an anticline (Francis, 1958), based on observations that the structurally lowest limestone (marble) was present in the centre of the complex, closest to the serpentinite, whereas higher beds of kyanite schist and psammitic gneiss occurred further away from the serpentinite. Pegmatites, quartz veins and reaction skarns suggest that volatiles were present during the intrusion and that the sediments behaved somewhat plastically (Francis, 1956). Rock *et al.* (1986) disagree with both Cunningham Craig's theory of a Lewisian inlier (Francis, 1958) and Francis' (1958) theory that the complex is a part of the Moine envelope. Rock *et al.* (1986) rather suggests that the complex is an independent litho-tectonic unit, the Albynian, which is thought to belong somewhere between the Moine and Dalradian successions. Rock *et al.* (1986) argues that Francis' (1958) theory of alkali-metasomatism is invalid, as the suggested alkali-injections that would cause the metasomatic alterations of the rocks aren't as extensive as previously believed. Rock *et al.* rather suggests that the shimmerisation and alterations of rocks are due to minor redistributions of material within the complex rocks. Rock *et al.* (1958) also argues against Cunningham Craig's theory of a Lewisian inlier, and thus discards the suggested mineralogical and structural evidence of a Lewisian inlier as well as the presence of hornblendic lenticles. The preserved bedding of the metasedimentary rocks associated with the serpentinite intrusion (i.e. marble and psammitic gneiss), as well as the foliation within the serpentinite intrusion, is taken as evidence for thrusting rather than diapirism. Further, it seems unlikely that an ultrabasic mantle rock should be associated with a young Moine assemblage (Rock *et al.* 1986). There are still controversies regarding the emplacement and the origin of the rocks within the complex i.e. whether the complex belongs to the Lewisian or the Moine succession, or if the area should be regarded as an independent litho-tectonic unit.

1.1 Aim of this Study

The aim of this study is to construct a geological map within the northern 12 km^2 of Glen Urquhart complex, and to produce cross-sections from the geological map. The geological map and the cross-sections should then be used to evaluate the geological history of the area, and how the complex rocks together with the associated serpentinite intrusion were emplaced.

1.2 Geology and Geological History of the Scottish Highlands

Scotland's geology has long been of great interest due to its diversity and complex history. Scotland was during the Precambrian time part of the continent Laurentia. The bedrock has experienced several phases of collision, orogeny, continental extension and uplift (Mendum, R. R *et al.* 2008). The geological succession in Scotland shows that the Moine sediments lie unconformably over Lewisian gneiss and local conglomerates. The Lewisian gneiss is exposed as inliers, surrounded by Moine rocks. These inliers are regarded as thrust slices or antiformal structures (Mendum, R. R *et al.* 2008). The conglomerates are believed to have formed after rifting during the Proterozoic, together with fluvial breccia, sandstone and volcaniclastic material (Mendum, R. R *et al.* 2008). Conglomerates were also deposited during the Early Devonian as alluvial fans on an active fault plane (Mendum, R. R *et al.* 2008).

The Lewisian Complex, formed during Late Archean approx. 2800 Ma, consists of deformed and recrystallized igneous rocks (*p.16,* Gordon, J. E *et al.* 2002). They are regarded as some of the oldest rocks in the world. It is believed that the Lewisian gneiss consists of different units, with slightly different histories and compositions. Parts of the Lewisian gneiss were affected by granulite-facies metamorphism during Late Archean, whereas some parts have been affected by amphibolite facies metamorphism during Early Proterozoic (Mendum, R. R. *et al.* 2008). The rocks have experienced several tectonic events (Wheeler, J. *et al.* 2010), and are thus greatly deformed. The gneiss shows NW-SE trending lineation and folding, which is caused by collisional events (Wheeler, J. *et al.*). The Laxfordian event, 1750 Ma, caused retrogressive amphibolite- and greenschist facies metamorphism, together with migmatization and veining of the Lewisian gneiss (Mendum, R. R *et al.* 2008).

During the Late Proterozoic the Grenvilian Orogeny affected Scotland, and Laurentia and Baltica became a part of the supercontinent Rodinia (Mendum, R. R *et al.* 2008). The Grenvilian Orogeny can be seen in the Glenelg inlier, which shows retrograde Eclogite facies metamorphism (Mendum, R. R *et al.* 2008). After the Grenvilian Orogeny, the Torridon Group and the Moine Supergroup were deposited. The Torridon Group (1000-970 Ma) consists of fluvial red sandstone, whereas the Moine Supergroup (950 Ma) consists of siliciclastic metasedimentary rocks e.g. psammites and pelites (Mendum, R. R *et al.* 2008).

Geikie (1893) suggested that the Torridon Group and the Moine Supergroup could be a part of the same sedimentary succession (Bluck, B. J. 2002). Mendum *et al.* (2008) state that the age of the groups may overlap, but they are not lithological equals.

When the Iapetus Ocean closed 500 Ma, Laurentia and Baltica collided during the Caledonian Orogeny, which caused the Moine Thrust Belt (Mendum, R. R *et al.* 2008). The Moine thrust Belts consists of Moine sediments that has been thrusted over Lewisian gneiss, Torridon sandstone and Cambro-Ordovician quartzites and limestones. The Moine Thrust Belts extends in a SW-NE direction, between the Great Glen Fault and the Moine Thrust (Cowards, M. 1988). The Great Glen Fault is a strike-slip fault between the northern Highland terrane and the southern Grampian terrane. It was formed during the collision between Laurentia and Baltica, and has experienced several phases of movements. The fault moved sinistral (left-lateral) during the Silurian-Devonian and dextral (right-lateral) during the Carboniferous. The movements are possible caused by the different orogenic events that have affected the Scottish Highlands (Strachan, R. A. *et al.* 2002). The fault was reactivated at 400 Ma (Mendum, R. R *et al.* 2008).

The Glen Urquhart complex consists of, possible Lewisian, gneiss and younger metasedimentary rocks associated with a serpentinite intrusion. The Glen Urquhart complex also contains lenticles of breccia-conglomerates approx. 50-400 m thick (*p.228.* Trewin, N. H. *et al.* 2002).

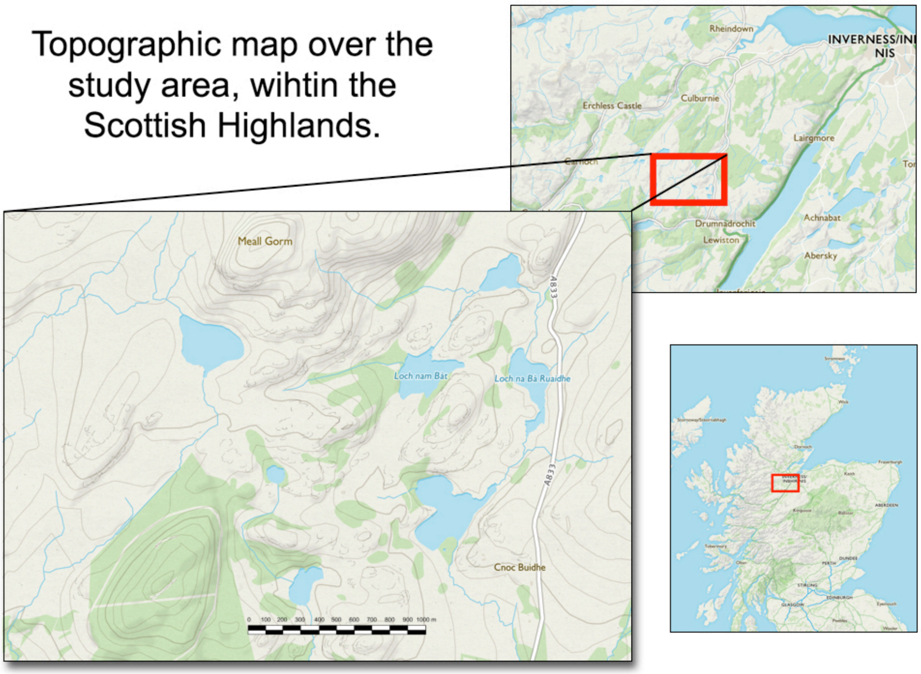

Figure 1: Topographic map over the study area, within the Scottish Highlands. Source: Ordnance Survey, OS Maps.

2. Methods

2.1 Mapping

The mapping was carried out between the 18th of August and the 2nd of September 2015. A topographic map from 'Ordnance Survey, OS Maps' was used to locate outcrops during the fieldwork. A compass clinometer was used to measure dip and dip direction of foliated outcrops. A hand lens was used during the identification of constituent minerals and determination of lithology for the exposed rocks. Diluted Hydrochloric acid (HCl 5%) was used to identify any carbonates present within the rocks. The observed mineralogy and rock characteristics were noted in a field notebook, together with lithology and observations of lithological boundaries within the area. Rock characteristics examined were e.g. mineralogy, colour, foliation, folding, grain size, mineral alignment and reaction to HCl. The lithology of the exposed outcrops was marked on the topographic field map, together with observed boundaries. Some rock specimens were collected for later mineralogical examination to distinguish the lithology for outcrops with uncertainties regarding the lithology.

2.2 Map Interpretation and Cross Sections

The geological map was made from field observations of exposed lithologies and lithological boundaries. For areas with no exposure, interpretations of lithology and boundaries were made by extrapolation. A final geological map was produced, showing interpreted lithology, geological boundaries and measured strikes. Cross sections were constructed from the final geological map. These were used to evaluate the field relationship between the different lithological units within the study area. The relationship between the different lithological units was then used to evaluate the geological history of the area.

3. Results

3.1 Lithology and Mineralogy

Seven different lithologies were mapped in the study area, these were: serpentinite, metalimestone (marble), skarn, metasedimentary (kyanite schist), gneiss (metasedimentary gneiss and granitic gneiss), breccia and conglomerate. Also, amphibole-rich outcrops were observed, which are included as amphibolite lenticles within the mapped gneiss. The lithology of the outcrops was determined by field observations.

3.1.1 Serpentinite

The serpentinite *(Figure 2)* showed a rusty brown to yellow weathered surface, covered with lumps which are pyroxene pseudomorphs, consisting of serpentinite and talc. Fresh surfaces showed a somewhat lustrous, green to dark green colour. The matrix was aphanitic, with 5 - 10 mm large crystals on weathered surfaces. The pyroxene pseudomorphs seemed to be somewhat aligned. Some serpentinite outcrops showed foliation,

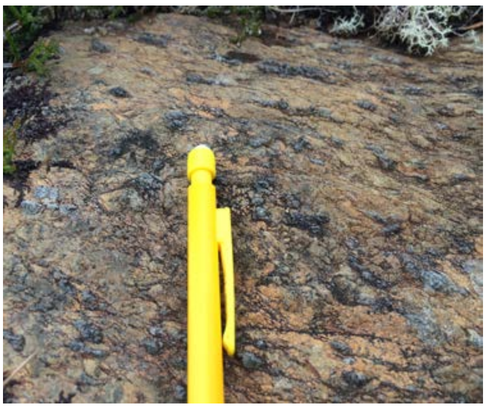

Figure 2: Weathered serpentinite outcrop with visible pyroxene pseudomorph lumps.

however, most of the exposed outcrops were massive and no foliation could be measured. The overall foliation of the outcrops was measured to NW-SE.

3.1.2 Metalimestone (marble)

The marble *(Figure 3)* has a sandy, beige-brown to white-beige appearance. Weathered surfaces had a darker brown-beige appearance, and also showed black spots, whereas fresh surfaces were more leucocratic. Foliation and bedding planes were visible in some outcrops. Large clusters of quartz were present, these were somewhat elongated parallel to the foliation. The presence of calcite within the marble was verified by reaction to a 5% - HCl solution. Areas with pure marble had been quarried.

Figure 3: Weathered marble, with a sandy appearance and quartz blebs, visible bedding tilted to the south-southwest, i.e. with a strike NW-SE.

3.1.3 Metasedimentary (kyanite schist)

The metasedimentary kyanite schist *(Figure 4)* had a rusty yellow to brown appearance, with light blue kyanite porphyroblasts approx. 5 to 10 mm. The shiny appearance of the kyanite schist indicates the presence of mica minerals, such as muscovite and biotite. Some of the kyanite had been altered to form pyrophyllite. Some outcrops showed visible foliation. The strike of the kyanite schist just west of the serpentinite body was measured to NW-SE. Outcrops further away from the serpentinite intrusion, e.g. in the northeastern part of the study area, were more massive and fine grained in appearance with no kyanite porphyroblasts present *(Figure 5)*. These were mapped as metasedimentary rocks based on their shiny appearance, content of mica-minerals and absent of gneissose banding.

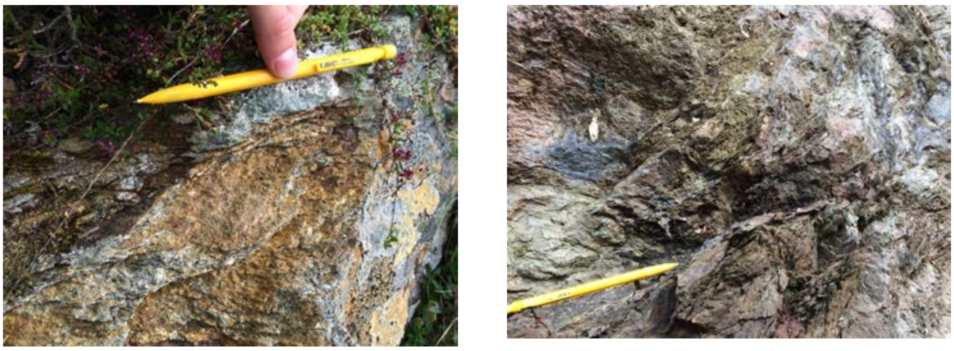

Figure 4: (left) Kyanite schist, with some alteration (shimmerisation) of kyanite.
Figure 5: (right) Metasedimentary rock, in the northeast part of the study area.

3.1.4 Gneiss (metasedimentary gneiss, granitic gneiss)

There were two different types of gneiss visible within the study area, metasedimentary gneiss *(Figure 6)* and granitic gneiss *(Figure 7)*. The metasedimentary gneiss showed a clear banding of leucocratic and melanocratic minerals, together with more or less prominent schistose layers of mica minerals. The mineralogy is appreciated to be quartz, feldspar, pyroxene, garnets and mica minerals. No kyanite is present. Some outcrops were somewhat difficult to attribute a lithology, as they showed a clear schistosity. These were mapped as metasedimentary gneiss based on the presence of leucocratic and melanocratic bands. Mapped gneiss-outcrops may be more or less schistose. Amphibolite outcrops were observed within the gneiss. The granitic gneiss had a more leucocratic appearance, with white and pink banding. The mineralogy is appreciated to be quartz, feldspar, K-feldspar, biotite and garnets. The leucocratic appearance is possible caused by metasomatism and granitization, where elements are substituted within the rock due to hydrothermal fluids. The mica content is considerable lower compared to the metasedimentary gneiss. The granitic gneiss occurred further to the north within the study area, and showed more intense folding. It is likely that there is a gradational transition between metasedimentary gneiss and granitic gneiss.

Figure 6: (left) Metasedimentary gneiss with bands of mica.
Figure 7: (right) Folded granitic gneiss.

3.1.5 Skarn

The observed skarn *(Figure 8)* outcrops were leucocratic, white to grey, with green to dark minerals present. The observed mineralogy is quartz, plagioclase, biotite, epidote and pyroxene (tremolite and actinolite). Some minor garnets are present. The texture is mostly massive and fine grained, porphyroblasts of tremolite or actinolite may occur. The skarn showed some gneissose texture and was therefore mistaken as gneiss during the first day of mapping. It is possible that skarn minerals could be replacing gneiss via metasomatic alterations. Most skarn outcrops were found adjacent or close to marble and metasedimentary rock (i.e. kyanite schist).

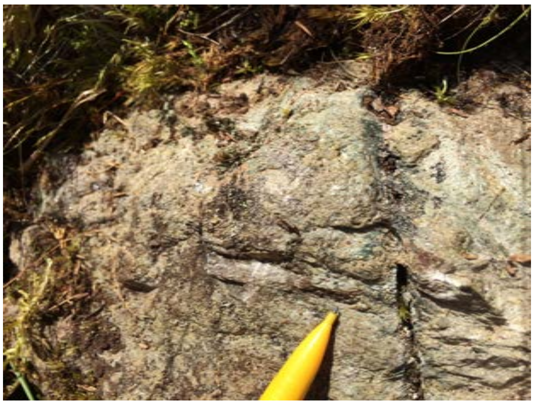

Figure 8: Skarn, with prominent green minerals.

Figure 9: Rock specimen of the Breccia within the north part of the study area.

3.1.6 Fault Breccia

The fault breccia *(Figure 9)* was observed on the slope of Mean Gorm, in the northern part of the study area, just beneath the conglomerate. It has a red to orange appearance, and a clear brecciated texture within an aphanitic matrix. The fault breccia indicates the presence of fault planes.

3.1.7 Conglomerate

The conglomerate *(Figure 10)* was found on the slope of Meall Gorm. It was overlying the breccia, and regarded as the highest observed sequence within the study area. It contains different sized clasts, from pebbles to smaller boulders, within a finer matric. The conglomerate is younger than the complex if the clasts originate from the lithologies within the complex. Clasts of gneiss were observed within the conglomerate, however, the origin of the conglomerate clasts have not been further examined.

Figure 9: Conglomerate.

3.2 Distinguishing between gneiss and metasedimentary rocks

During the mapping there were some difficulties to distinguish whether some outcrops were gneissose schist or schistose gneiss, since the presence of schistose mica layers and the extent of gneissose banding varied. Outcrops were mapped as metasedimentary rocks if they had a shiny appearance, a high content of mica-minerals and no apparent gneissose banding. Outcrops were mapped as gneiss if they showed an apparent gneissose banding, with alternating leucocratic and melanocratic bands, even though they showed a high content of mica-minerals and clear schistose mica layers.

3.3 Outcrop Map

The outcrop map *(Figure 11),* i.e. the topographic field map, shows exposed outcrops and their lithology. Blank areas are areas with no exposure, thus no determination of lithology could be made. Clear boundaries between lithological units are marked on the outcrops map.

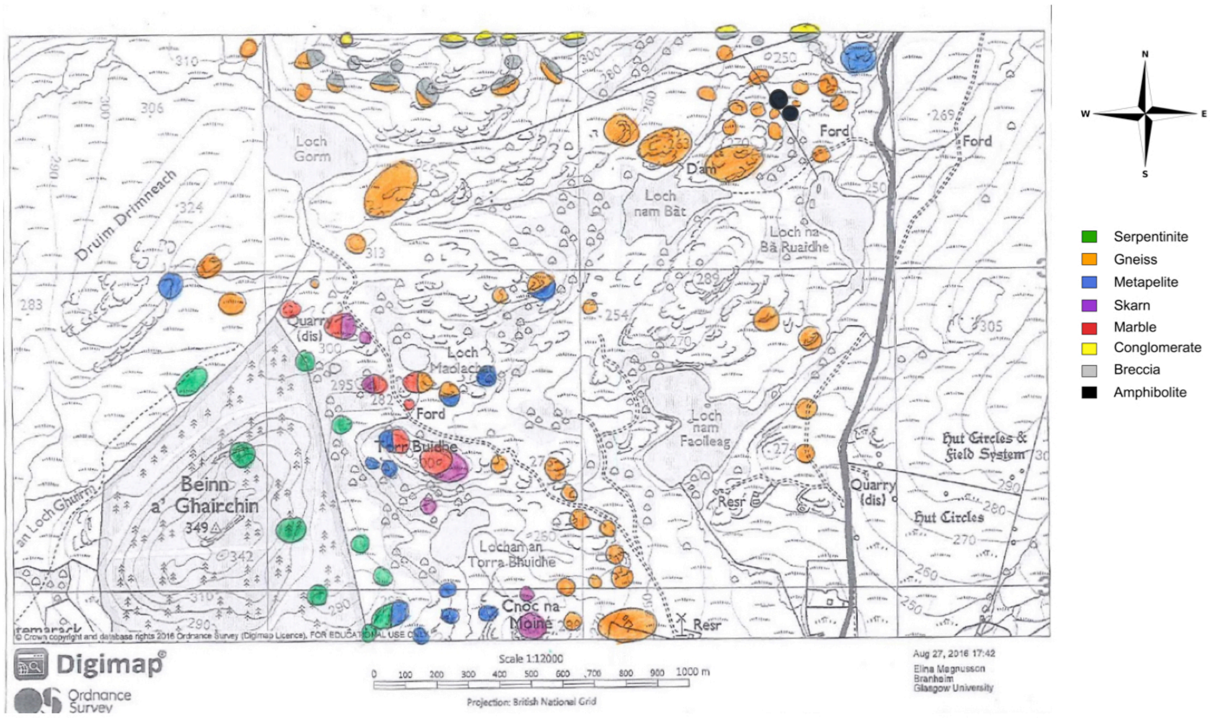

Figure 11: Outcrop map showing localities with exposed lithology.

3.4 Geological Map

The geological map *(Figure 12)* shows interpreted lithology for the study area. Blank areas, showing no exposure in field, has been attributed a lithology based on observations from surrounding outcrops. Boundaries between lithological units, which were clearly seen in field, are marked with a solid black line on the geological map, whereas interpreted boundaries are marked with a dashed line. Strike and dip arrows have been marked on the geological map. Red solid lines represent constructed cross sections.

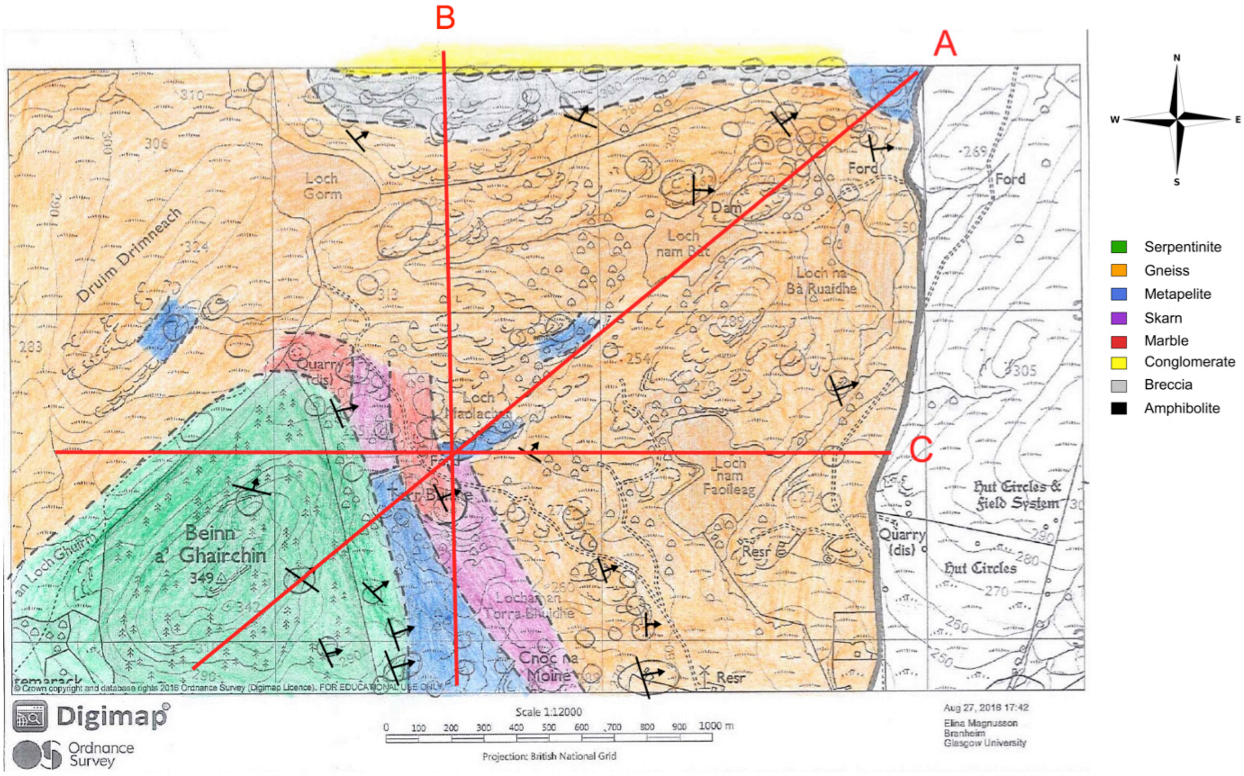

Figure 12: Geological map showing interpreted geology and arrows for strike and dip. Red lines represent constructed cross sections.

3.5 Cross Sections

Cross sections *(Figure 13, 14 and 15)* were constructed from the geological map, and used to evaluate field relationships between the different lithological units. The relationships were then used for the evaluation of the geological history of the area.

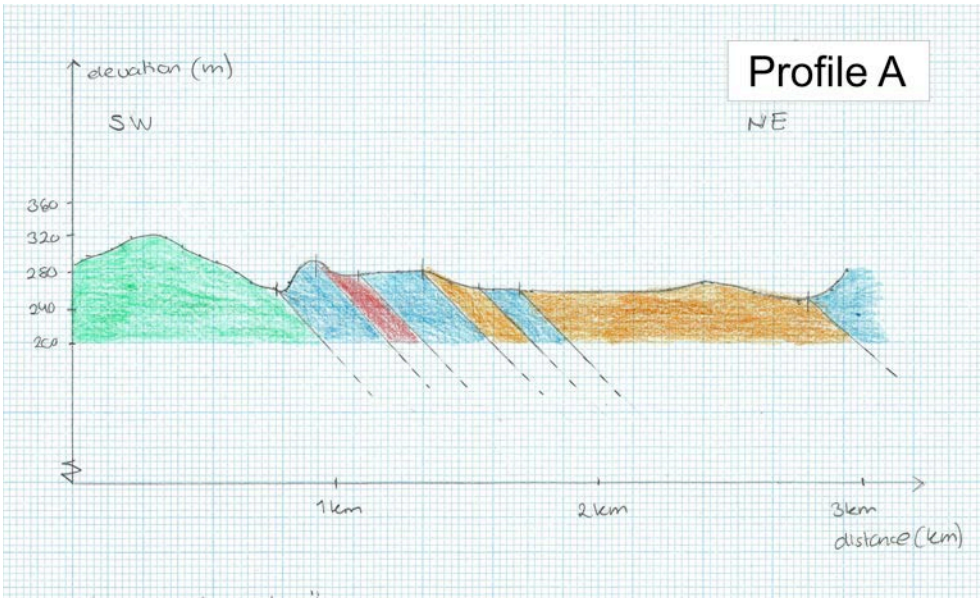

Figure 13: Cross section A, SW-NE.

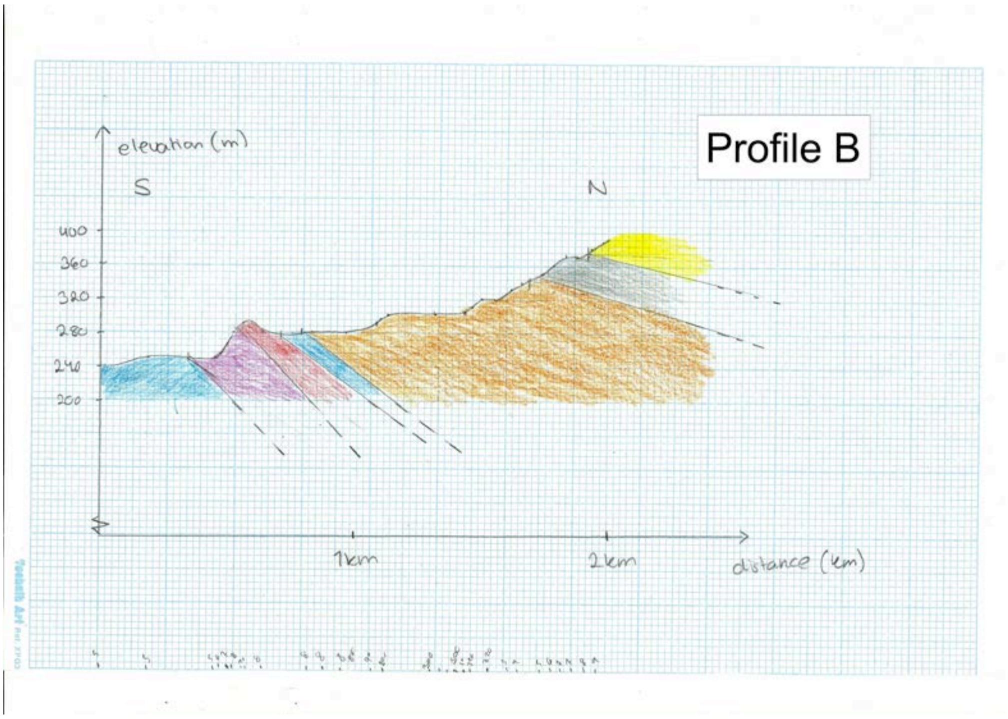

Figure 14: Cross section B, S-N.

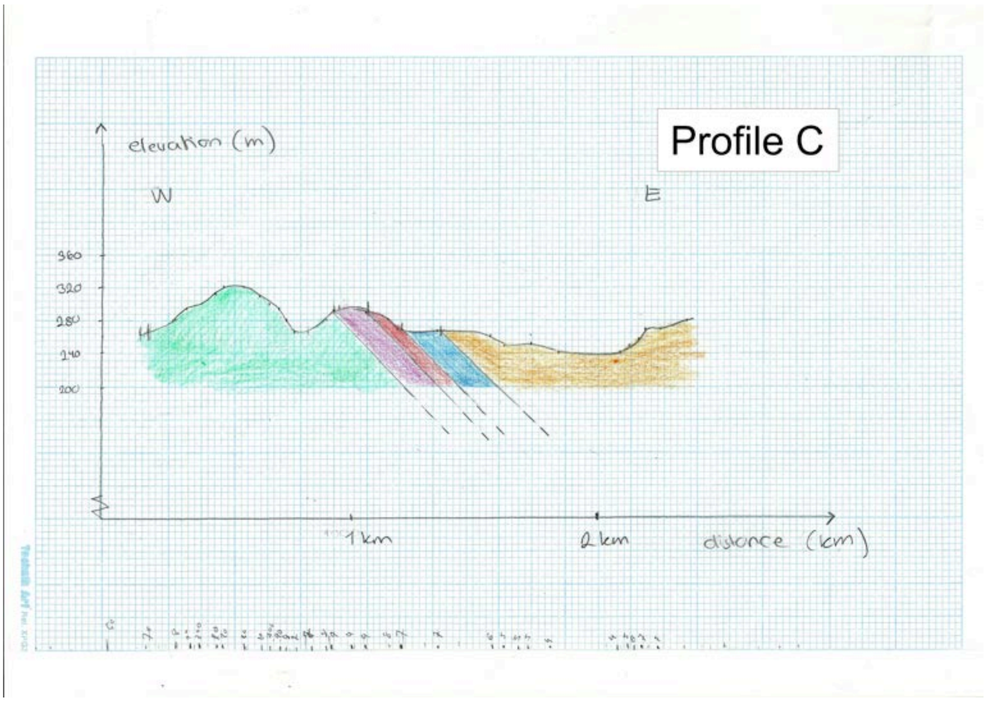

Figure 15: Cross section C, W-E.

4. Discussion

4.1 Previous Work

4.1.1 Cunningham Craig's theory (Francis, 1958, 1964)

In Cunningham Craig's memoir's, described by Francis (1964), Cunningham Craig observe a foliated serpentinite intrusion, which he believed intruded into already folded and metamorphosed sedimentary rocks (Francis, 1956). Cunningham Craig states that the metasedimentary rocks of the complex are older than the enveloping Moine assemblage, and thus should be regarded as a Lewisian inlier (Francis, 1964). Cunningham Craig suggests that the limestone (marble) is the structurally lowest bed, followed by metasedimentary rock and feldspathic gneiss (1956). He regarded the skarns as impurities within the limestone. Further, he noticed that the feldspathic gneiss was the most similar unit to the enveloping Moine rocks (Francis, 1964), but used the presence of hornblendic lenticles as a proof of Lewisian origin.

Cunningham Craig separated the rock within the complex from the enveloping Moine assemblage on lithological and structural grounds (Francis, 1964), which supports his theory of a Lewisian inlier. The structural evidence is based on the observation that the complex is more crystalline than the surrounding Moine assemblage, and that the strike of the complex is trending NW-SE (i.e. normal strike of Lewisian rocks). The lithological evidence is based on the complex's petrological similarity to the metasedimentary rocks in Glenelg, which are regarded as a Lewisian inlier (Francis, 1964). Also, the lithology of the complex is atypical of the Moine succession, which favours the theory of a Lewisian inlier. Cunningham Craig states that the observation of hornblendic lenticles within the gneiss suggests that the rocks are of Lewisian age, as hornblendic lenticles often occur within Lewisian rocks (Francis, 1964). Cunningham Craig therefore used the presence or absence of hornblendic lenticles to distinguish between Lewisian rocks of the complex and the enveloping Moine rocks (Francis, 1964), and to produce a line of unconformity.

Cunningham Craig observe that the structurally lowest rock (limestone with associated skarn) appear in the centre of the complex, whereas the structurally higher rocks (schist and gneiss) appear further away from the serpentinite intrusion. Based on these observations, Cunningham Craig suggests that the complex is an anticline, which exposes the old Lewisian rocks within the Moine succession (Francis, 1964).

4.1.2 Francis (1956)

Francis study (1956) confirms the findings by Cunningham Craig, which state that the ultrabasic serpentinite mass intruded already folded and metamorphosed sediments, since the serpentinite intrusion cuts existing folds in the surrounding wall rock. No apparent contact metamorphism between the intrusion and the country rock can be seen (Francis, 1956). Francis (1956) suggests the serpentinite mass intruded between the limestone (marble) and the kyanite schist, and that the surrounding sediments were somewhat plastic when the ultrabasic mass intruded (Francis, 1956). The reaction skarns were formed by inter-mingling between limestone and kyanite schist, caused by the intrusion of the serpentinite mass. It is believed that the isoclinical folds in rocks just north of the serpentinite (granitic gneiss) were caused by the intrusion of the serpentinite (Francis, 1956).

It is still uncertain how the foliation within the serpentinite were formed, Francis (1956) suggests that the serpentinite intruded as a rather solid mixture of olivine, enstatite and vapour, which would cause foliation of the serpentinite parallel to its direction of movements. Shear stresses are excluded, as the wall rock is unaffected. The intrusion of a fairly solid serpentinite mass would explain the round shape of the serpentinite, and the absence of contact metamorphism (Francis, 1956). Francis (1956) concludes that the serpentinite intrusion was emplaced after the regional metamorphism of the area.

Francis (1956) suggests that a period of alkali-metasomatic injections occurred after the intrusion of the ultrabasic mass, which possible are related to the Older Granite injections in the Scottish Highlands (Francis, 1956). The alkali metasomatism affected both the ultrabasic serpentinite mass and the surrounding metasediment. Francis (1956) states that the skarns are a product of alterations caused by alkali-metasomatic injections.

4.1.3 Francis (1958)

Francis (1958) states that the area suffered metamorphism within the lower amphibolite facies. The ultrabasic serpentinite intrusion intruded into already folded and metamorphosed sediments. The metasediments and the serpentinite intrusion were later affected by alkali-metasomatism. As a result of this, pegmatites and quartz veins were formed, which absorbed materials from the adjacent rocks, e.g. alumina was absorbed from kyanite schist and lime was absorbed from marbles. It is suggested that the quartz veins had an important role during the inter-mingling of the kyanite schist and the limestone to produce reaction skarns (Francis, 1958). Mineralogical studies suggest that there is an increase of lime, alumina and magnesia within the skarns. Further, minerals also show replacement textures, which suggest metasomatic alterations. Francis (1958) disagree with Cunningham Craig's theory of a Lewisian inlier, Francis rather suggests that the complex is a part of the Moine succession.

4.1.4 Francis (1964)

Francis (1964) rejects Cunningham Craig's theory of a Lewisian inlier. He states that Cunningham Craig's proposed unconformity, between the Lewisian complex and the surrounding Moine, is no longer sustained (Francis, 1965). He suggest that the, by Cunningham Craig observed, hornblendic lenticles, are blasto-mylonitic streaks of Moine schist, which can be found both within the complex and within the surrounding Moine succession. Francis (1964) further state that the, by Cunningham Craig observed, differences in strike between the complex and the Moine succession only is a local "swirl" due to the intrusion of the serpentinite. Francis (1964) discards Cunningham Craig's mineralogical and structural evidence for a Lewisian inlier, and rather suggests that the complex is apart of the Moine succession.

Francis (1964) suggests that the degree of alkali-metasomatism increases towards the granitic areas, which are altered kyanite schist. Francis (1964) states that the intrusion of the serpentinite is extremely complicated. Further, he suggests that the serpentinite intrusion is an inclined sill dipping towards the east.

4.1.5 Rock et al. (1986)

Rock *et al.* (1986) suggest that the complex is an allochthon. This is based on its anomalous lithology, the differences between the complex and the surrounding Moine rocks, and its association with an ultrabasic serpentinite intrusion. Rb-Sr isotopic data suggest that the complex was metamorphosed during the later part of the Caledonian Orogeny (459 ± 4 Ma). However, the metasedimentary rock may be older. Rock *et al.* (1986) states that it is likely that several different episodes of folding and metamorphism has affected the area, possible during two or three different orogenies.

Rock *et al.* (1986) suggests that the complex is not a Lewisian inlier. Rb-Sr data suggests that the complex is not related to the Moine or Dalradian succession. This is confirmed by observations that the complex cuts enveloping Moine structures, and that the Moine rocks do not grade into the complex (Rock *et al.* 1986). Further, chemical data show no correlation between the kyanite schist and the limestone to the enveloping Moine rocks. Rock *et al.* (1986) argues that metasomatic alterations are caused by redistribution of elements within minerals, rather than by alkali-metasomatic injections. Thus, the chemical compositions of the rocks have not changed too much from the original composition, and it is not likely that the complex rocks are related to the Moine assemblage. The redistributions have been catalysed by volatiles during the serpentinization, which also produced pegmatites, quartz veins and the reaction skarns.

Rock *et al.* (1986) suggest that the complex should be considered an independent litho-tectonic unit, the Albynian. The Albynian is thought to belong somewhere between the Moine and the Dalradian succession. The serpentinite mass is regarded as anomalous to both the complex rocks and the surrounding Moine succession. This suggests a rather complicated history. Rock *et a*l. (1986) argues that complex rocks intruded tectonically with the intrusion, but are not related to the intrusion. The shallow depth of the complex suggests an antiform structure, or a basement slide separated from its roots (Rock *et al.* 1986).

Rock *et al.* (1986) conclude that Francis' (1964) theory, that the complex is equivalent with the enveloping Moine assemblage, is invalid since the chemical differences are too large. The enveloping Moine rocks are a part of the young Loch Eil Division, thus it is unlikely that this young division would include a Lewisian inlier associated with a serpentinite intrusion (Rock *et al.* 1986). Rock *et al.* (1986) also argues that Cunningham Craig's theory of a Lewisian inlier is invalid, as the resemblance between the complex and the Glenelg Lewisian rocks are not supported. The unconformity between Lewisian complex and the Moine grounds is rejected, as the observed hornblendic lenticles are suggested to be blasto-mylonitic streaks of Moine rocks. These are also found on both sides of the unconformity, which suggests resemblance between the complex and the Moine succession. Rock *et al.* (1986) further state that the complex is not related to the Dalradian succession, as there is no resemblance to these rocks. Rock *et al.* (1986) discards all the previous theories and state that the complex should be regarded as an independent litho-tectonic unit, the Albynian. Present isotopic data suggests that the Albynian is post-Lewisian, and possibly close to the Moine and Dalradian rocks in age. However, Rock *et al.* (1986) attribute the complex as an independent unit, as the complex rocks have no resemblance to either the Moine or the Dalradian succession.

4.2 Present study

The present study states that thrusting has occurred within the area. Rock's *et al.* (1986) theory of a thrust slice is favoured over Cunningham Craig and Francis' (1958) theory of an anticline. This is based on the cross-sections, which shows that the rocks are dipping southeast towards the serpentinite intrusion, and the occurrence of fault breccia within the study area, which is associated with thrusting rather than an anticline structure. A plutonic intrusion or diapirism is rejected, based on the observation of preserved bedding within the limestone, which further favours the theory of thrusting. The observation of preserved bedding indicates that the deformation during the emplacement of the serpentinite intrusion is localised to thrust planes or shear zones, which is evidenced within the study area by observed fault breccia.

It is likely that the serpentinite intruded into already metamorphosed and folded sediments, as Cunningham Craig suggested. Cunningham Craig states that the serpentinite cuts fold structures within the surrounding rocks, which imply that the intrusion was a later structure. No evidence of folds cut by the serpentinite has been observed within this study. However, the absent of folding within the serpentinite compared to the surrounding rocks could imply that the serpentinite intrusion is a later feature. This study can neither confirm nor reject Cunningham Craig's statement that the serpentinite intruded into already metamorphosed and folded sediments. Another theory is that the serpentinite mass is the cause of metamorphism and folding.

Cunningham Craig based his theory of a Lewisian inlier on the structural criterion that the strike of the complex is anomalous to the enveloping Moine rocks, and similar to the Lewisian rocks. The strike in this study is trending NW-SE, which comply with Cunningham Craig's statement. However, the NW-SE trending strike, similar to the strike of other Lewisian rocks, are not a strong enough observation to support or discard Cunningham Craig's statement that the complex is of Lewisian age.

Cunningham Craig suggests that the presence of hornblendic lenticles within the gneiss is evidence of a Lewisian age. Francis (1958) discards this theory. He suggests that the hornblendic lenticles are rather blasto-mylonitic streaks, which may be seen both within the Lewisian complex and the Moine succession. Amphibolite-rich lenticles within the metasedimentary gneiss were observed in this study. These observations favour Cunningham Craig's observations of hornblendic lenticles rather than Francis' statement that the hornblendic lenticles are blasto-mylonitic streaks. However, the observation of amphibolite-rich lenticles within the complex rocks is not a strong enough evidence for Lewisian age of the complex. Further observations of the absent of amphibolite-rich rocks within the enveloping Moine succession would be necessary to prove Cunningham Craig's theory of

Lewisian age for the complex, and thus discards Francis' theory that the complex belongs to the Moine succession.

Francis argued that there is a gradational transition between the complex and the Moine rocks, as well as between the different lithologies within the complex, which he believed to be caused by alkali-metasomatic injections. Some clear boundaries are observed within the complex (e.g. between skarn and marble on Torra Buidhe), however, no contact has been observed between the metasedimentary gneiss and the granitic gneiss. The granitic gneiss, close to the conglomerate and the fault breccia in the north of the complex, shows a more leucocratic and pink colour compared to the metasedimentary gneiss, this might be caused by metasomatic alterations and hydrothermal fluids. Thus, the gradational transition within the gneiss confirms Francis' statement of a gradational transition within the complex due to alkali-metasomatic injections. Rock *et al.* state that Francis' suggested alkali-metasomatic alterations within the complex might not be as pronounced as previously believed, rather he suggests a minor redistribution of element within the complex rocks. However, the gradational transition between metasedimentary gneiss and granitic gneiss, the occurrence of skarns and alteration of kyanite schists (alteration of kyanite to pyrophyllite) suggests that metasomatic alterations have occurred, as Francis suggested. Rock's *et al.* theory of redistribution of elements is neither conformed nor discarded; however Francis theory is favoured. The extent of alkali-metasomatism, or redistribution of elements, could be examined in the future with more thorough mineralogical and petrological studies.

The granitic gneiss within the northern part of the complex is more extensively folded compared to the metasedimentary gneiss. This could be caused by various events of folding by previous tectonic events, as well as more extensive folding due to the close distance to the fault breccia within the complex area, which is believed to be a thrust planes and zone of deformations during the thrusting of the complex.

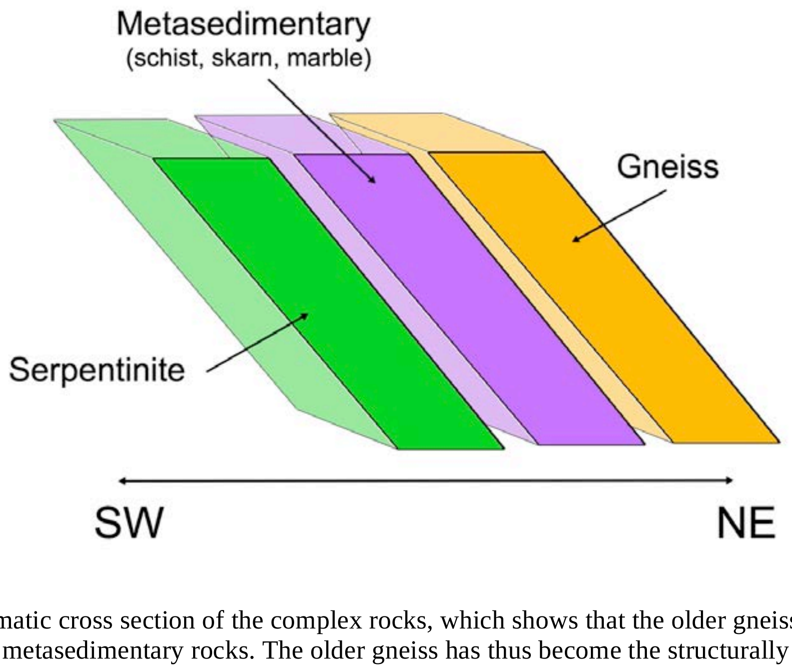

Figure 16: Schematic cross section of the complex rocks, which shows that the older gneiss has been thrusted over the younger metasedimentary rocks. The older gneiss has thus become the structurally highest succession.

Cunningham Craig, Francis and Rock *et al.* all suggest that the limestone (marble) is the structurally lowest bed, followed by kyanite schist and psammitic gneiss. This structural succession was also the foundation for the theory of an anticline, where the structurally lowest limestone has been exposed near the centre of the anticline, with younger rocks further away from the centre. However, this study suggests that the gneiss is the oldest bed, based on the more deformed and folded appearance, and thus should be the structurally lowest. Thrusting of the area could explain why the older gneiss has been placed over the younger metasedimentary rocks *(Figure 16)*. Skarns has within this study been observed between the kyanite schist and the marble. This suggests that they are reaction skarns produced by inter-mingling between the kyanite schist and the limestone together with volatiles from the serpentinite intrusion and elements dissolved within quartz veins, as suggested by Francis (1958).

Rock *et al.* suggests that the complex is neither of Lewisian, Dalradian or Moine age. The rather exotic complex was suggested to be an independent litho-tectonic unit, the Albynian. Rock *et al.* discards Cunningham Craig's theory of relation to the Glenelg Lewisian inlier. He also states that the complex's association with a deep-mantle rock (i.e. the serpentinite intrusion) together with the absent of similarity or gradational transition between the complex and the Moine rocks, rejects Francis' theory the complex resemblance to the Moine succession. Rock's *et al.* theory, that the complex is a thrust slice rather than an anticline, is favoured within this study, and supported by the cross-sections that shows that the older gneiss is thrusted on top of younger metasedimentary rocks *(Figure 16)*. The cross-sections suggest that the units are dipping towards the serpentinite intrusion, and that the thrusting occurred in SW direction. Further, the associated fault breccia could be regarded as thrust plane and zone of deformation during thrusting. The strike of the complex is NW-SE, which is the common strike for the Lewisian gneiss within the Highlands. This would imply that the thrusting occurred during the same time as other tectonic event within the Highlands. The close distance to the Great Glen Fault could imply that the thrusting is related to movements along the Great Glen Fault. The Great Glen Fault has moved several times, both left- lateral and right- lateral. The SW-trending drip of the complex could imply that the thrusting occurred as the fault moved towards the left, i.e. in WSW direction.

The conglomerate observed in the north part of the complex is a later sedimentary structure since it contains clasts from the complex. The conglomerate is believed to have formed during the Early Devonian as alluvial fans on an active fault plane (Mendum, R. R *et al.* 2008). The fault breccia just beneath the conglomerate is believed to have due to thrusting of the area. The close distance to the Great Glen Fault, as well as the common occurrence of faults in the Scottish Highlands, further suggests that the presence of thrust fault within the area.

This thesis concludes that the complex is a Lewisian inlier, which has been exposed within the surrounding Moine succession via thrusting, possible due to the intrusion of a serpentinite body or by other tectonic activities that affected the Scottish Highlands, such as faults. Francis' theory of alkali metasomatic alterations within the complex area is favoured. Evidence for this is the gradational transition between metasedimentary gneiss and granitic gneiss, the occurrence of skarns and the resemblance between skarn and gneiss, which suggests that skarn minerals have replaced gneiss. Rock's *et al.* suggestion that the alteration of rocks are caused by minor redistributions of elements within the rocks may be partly true, however, Francis' theory of alkali metasomatic alterations is favoured. This study favours the theory of thrusting, rather than an anticline structure or diapirism. The cross-sections show that the units are dipping SW towards the serpentinite intrusion, and that the older gneiss has been emplaced above the younger metasedimentary rocks. Further, the associated fault breccia, within the north of part of the study area, is a possible thrust plane, which further suggests that thrusting has occurred. The observation of fault breccia and the displacement of gneiss above metasedimentary rocks discard the theory of an anticline or diapirism. The history of this area is rather complex and the reason for thrusting is not resolved. Previous suggestion is that the intrusion of the serpentinite mass and the thrusting is related, and might be caused by each other. Metamorphism and folding is believed to have occurred throughout various tectonic events during pervious times as well as during the thrusting. The extensive folding of the granitic gneiss in the northern part of the complex, compared with the metasedimentary gneiss, could be explained by the close distance to the fault breccia in the northern part of the complex, which is believed to be the thrust plane and zone of deformation.

4.3 Errors

The entire lithology, and relationship between the different units, are not know since outcrops were not exposed everywhere within the area. The geological map is made by interpretation and extrapolation of lithology and field relationship where no exposure was seen. Lithologies may have been incorrectly mapped in field, which may affect the outcome of the geological map. Since not all the lithological boundaries were exposed, the absolute angles between the rock units are not known. The relationships between the geological units, and thus the thrusting of the area, are based on structural interpretations of the geology.

5. Conclusion

The present study concludes that the Glen Urquhart complex should be regarded as a Lewisian inlier. The alkali-metasomatism suggested by Francis (1958) has been observed as a gradational transition between metasedimentary gneiss and granitic gneiss, the replacement of gneiss by skarn minerals, and the alteration of kyanite schist. Rock's *et al.* (1986) suggestion that the alterations are only minor redistributions within the rocks rather than metasomatic alterations is not supported. Cunningham Craig argues that the presence of hornblendic lenticles is evidence for Lewisian age (Francis, 1964). Amphibolite-rich rocks, rather than blasto-mylonitic streaks as suggested by Francis, have been observed within the complex. However, these observations are not sufficient to confirm or discards neither Cunningham Craig's suggestion of Lewisham age or Francis suggestion of resemblance to the Moine succession. The occurrence of a serpentinite intrusion may suggests Lewisian origin of the complex as other ultrabasic intrusions in the Scottish Highlands are associated with Lewisian rocks, e.g. Glenelg. The theory of thrusting is favoured, rather than the theories of an anticline or diapirism. Cross-sections made from the geological map shows that the rocks are dipping

SW towards the serpentinite intrusion. The fault breccia in the northern part of the mapping area favours the theory of thrusting as it may be regarded as the thrust plane and zone of deformation. Further, the structural succession of the complex, with the old gneiss on top of younger metasedimentary rocks, suggest that thrusting has affected the area and thus displaced the gneiss above the other lithologies. An anticline structure or diapirism would imply that the gneiss is younger than the underlying metasedimentary rock. This is not supported since the gneiss is more deformed and folded than the underlying metasedimentary rocks, thus the theory of an anticline structure or diapirism is discarded. Further, the preserved sedimentary bedding within the marble rejects diapirism, as diapirism would destroy the bedding, whereas thrusting where the stresses are concentrated to the thrust plane would preserve the bedding. It's believed that the thrusting and emplacement of the serpentinite intrusion occurred within already metamorphosed and folded rock, but further caused some metamorphism and folding. The history of the area is complex and the origin of the serpentinite and the thrusting is still not clear. One theory is that the thrusting and emplacement of the intrusion is caused by each other. It is also possible that the thrusting occurred due to other tectonic events that affected the Scottish Highlands, e.g. the Great Glen Fault.

5.1 Future Studies

Future studies within the area could focus on the occurrence of faults and how these have affected the area. More thorough mineralogical and petrological studies of the rocks within the complex would be necessary to examine the extent of alkali-metasomatism within the rocks. Previous petrological studies have not been sufficient to clarify the chemistry of the mineral assemblages within the rocks or fluxes between the rocks (Rock *et al.* 1986). Francis (1964) only used two rock analyses to sustain his theory of alkali-metasomatic alterations within the rocks, which is not enough. Also studies of geochronology of the complex rocks are left for future studies to determine the structural succession within the complex, and the age of the rocks.

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