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Geological mapping of the Glenurquhart Complex near Loch Ness, Scotland

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Abstract West of Loch Ness, Scotland, lies a 4 km^2 serpentinite body flanked by a metamorphic complex of uncertain origin, the Glenurquhart Complex. It is an anomaly among the Moine Schists. The aim of this study was to compose a geological map covering 12 km^2 of the complex and serpentinite, and to construct one cross section across the study area to help elucidating the geological history of the formation. Six different lithologies were observed in the field; serpentinite, metasedimentary schist, metasedimentary gneiss, granitic gneiss, marble, and skarn. All sequences were dipping gently northeast. The character of the complex has been investigated by three works throughout the 20th century. Cunningham Craig (1914) claimed the gneiss was Lewisian based on crystallinity, comparisons to bedrock in Glenelg, and the presence of hornblende-schist. Francis (1958) claimed it was an area of extensive K-metasomatism based on observations of gradual contacts between lithologies in the area. Rock *et al.* (1986) disagrees with both models. Instead, they propose that the complex originates from the 'Albynian', a sequence lying between the Moine and Dalradian Supergroups. Francis' (1958) model is deemed unlikely due to observations of the spatial distribution of metasedimentary gneiss and schist, which is considered to be significantly inconsistent with respect to the inferred K source. Rock *et al.*'s (1986) claim that the complex could not be Lewisian was based around the controversy surrounding the Glenelg formation, but in light of findings of hornblende-gneiss, this conclusion is considered premature and their 'Albynian' model might thus be unnecessary. The model of a Lewisian inlier associated with the Glenurquhart Complex serpentinite is preferred in this study. The character of the serpentinite sequence indicates it is possibly a sill or a thrust slice. Thrusting is believed to be more likely due to the presence of the deep-rooted Lewisian rock and observed preserved bedding in the marble. It has previously been considered that the complex constitutes an anticline, but the gentle north-eastern dip of the local layers and their low lateral extension is deemed incompatible with this theory, furthermore it was claimed the marble made out the structurally lowermost sequence, which is considered unlikely because of the shallow character of the marble outcrops. Folded outcrops are used to support claims of folding in the area, however it is not excluded that this might be due to deformational events occurring before the bedrock was emplaced in its current location. Poor exposure and extensive farming are sources of error, which has led to the position of the metasedimentary schist-gneiss contact and its dip angle to be especially uncertain. Investigation of possible faulting in the area is proposed for future work.

1. *Introduction*

Northeast of Glenurquhart near Inverness, Scotland, a c. 4km^2 body of serpentinite crops out. It is associated with a sequence of metasedimentary rocks that are unlike the enveloping bedrock; the Moine Schists. The characteristics of this complex, its origin, and mode of emplacement, have been investigated by Cunningham Craig (1914), Francis (1958), and Rock *et al.* (1986). There is currently no consensus about the origin of these rocks.

The aim of this study was to map the southern 12 km^2 of the complex and to construct a cross section across the study area to help towards elucidating its geological history.

1.1. Geological Background

The age of the bedrock in Scotland ranges from Archean to Tertiary. There are five main terranes; the Hebridean terrane in the northwest, separated from the Northern Highland terrane by the Moine Thrust Zone, which is separated from the Grampian Highland terrane further south by the Great Glen Fault. The Highland Boundary Fault separates the Grampian Highlands from the Midland Valley terrane, and the Southern Upland Fault separates the Midland Valley from the Southern Uplands. In the south the Southern Uplands abuts on to the Iapetus Suture (Trewin and Rollin, 2002).

1.1.1. NW Mainland Geology (Northern Highlands)

The Lewisian is exposed mainly in northwest mainland Scotland and in the Hebrides. It comprises a crystalline complex of gneissose bedrock forming the basement of north-western Scotland, probably as far east as the Great Glen Fault (Watson, 1983). The Lewisian of mainland Scotland consists of two main units; the older Scourian gneisses (2.75 to 3.12 Ga), and the Loch Maree Group (2.49 to 2.19 Ga) (Park *et al.* 2002). The Scourian consists of banded to massive grey gneisses of mostly felsic igneous origin. The Loch Maree Group is made up of two metasedimentary belts together with mafic sheets. The metasediments are mainly composed of semipelitic schists, psammites, carbonates, and quartzites, and the mafic sheets are metamorphosed to hornblende schists (Peach *et al.* 1907; Park *et al.* 2002).

The Moine Thrust marks the western boundary of the Moine Schists. It extends from Loch Eriboll in the north to the Sleat peninsula in the south (Peach *et al.* 1907). The Moine Schists are the main geological unit in the Northern Highland terrane (Trewin and Rollin, 2002). This unit consists of 1 Ga quartz-schists, quartz biotite granulites, garnetiferous muscovite-biotite schists, with occasional Lewisian inliers.

The Moine Thrust separates the Moine Schists from the underlying Cambrian complex of dolomites, fossiliferous limestone, fossiliferous grit, fucoid beds, quartzites with worm-casts and grits believed to originate from the Iapetus Ocean. An unconformity below the Cambrian sedimentary sequence marks the top of the c. 1.2 Ga to 950 Ma Torridonian Group of red arkosic sandstones, micaceous shales, grits, conglomerate and shales with calcareous bands (Johnson, 1983; Trewin and Rollin, 2002). Separating the Torridonian sandstones and the Lewisian gneisses and schists is another unconformity (Peach *et al.* 1907).

The Grampian Highland terrane is dominated by the Dalradian Supergroup. This group is composed of 800 to 470 Ma quartzites, pelites, semipelites, psammites, striped psammites, turbidites, carbonates, tillites and volcanic rocks (Strachan *et al.*, 2002; Trewin and Rollin, 2002).

1.1.2. The Great Glen fault

Just east of the Glenurquhart Complex lies the Great Glen and Loch Ness, marking the surface trace of the Great Glen fault. It is the largest fault among a set of NE-SW trending sinistral faults in the Scottish Highlands (Harris, 1983). Since the Caledonian-Orogeny, fault motion has mainly been sinistral (Strachan *et al.* 2002). Displacement along the fault is uncertain, but Harris (1983) stated that movement doubtless amounts to tens to a few hundred kilometres. Strachan *et al.* (2002) concluded that there has been less than 200-300 km of lateral motion on the fault with support from Briden *et al.* (1984). The Great Glen Fault is a crustal scale fault that might have affected the upper mantle (Harris, 1983).

1.1.3. The Glenurquhart Complex

The Glenurquhart Complex is situated beneath the moorland northeast of Glenurquhart. The complex flanks one of the largest serpentinite bodies of the Highlands (Rock *et al*. 1986), and consists of pelitic schist interlayered with metalimestone and skarn. These rocks are found between the serpentinite body to the southwest and garnetiferous gneiss to the northeast. All of these rocks are of uncertain origin. Cunningham Craig (1914) argued in the memoir ‘the Geology of the country around Beauly and Inverness’ for the gneiss to be of Lewisian character and thus a Lewisian inlier, whilst Francis (1958), Brook and Rock (1983) and Rock *et al.* (1986) argue for a non-Lewisian origin. Even so, Francis (1958) and Rock *et al.* (1986) disagree on the characteristics of the complex, the process of emplacement, and the source of the rock complex. Francis (1958) claims that the metasediments are potash-metasomatised Moine gneisses and that the serpentinite is a sill, whereas Rock *et al.* (1986) argues that the metasedimentary schist has an exotic heritage and that it was tectonically emplaced together with the serpentinite. They claim that the schist is neither Lewisian nor Moine, but instead classify it as ‘Albynian’, a sequence lying between the Moine and Dalradian Supergroups.

It is beyond the scope of this study to ascertain which model is correct. However, this study aims to contribute to the debate by investigating the mechanism whereby the anomalous metasediments and associated serpentinite came to be emplaced among the Moine Schists.

1.1.3.1. Age

Brook and Rock (1983) dated the pegmatites intruding the Glenurquhart Complex using Rb-Sr analyses on biotite, which constrained the minimum complex age to 423 Ma. Whole rock analyses of intruding metabasites are consistent with pre-Caledonian formation, *i.e.* pre-Ordovician (Rock *et al.* 1985).

This does not disprove any of the previously mentioned theories as the Dalradian, Albynian, Moine and Lewisian groups are all older.

2. *Methods*

2.1. Mapping

Mapping of the study area, northeast of Glenurquhart (see figure 1) was done between August 24 and September 2, 2015. For each outcrop, location was determined using a terrain and elevation map from EDINA Digimap, as well as a standard map and compass.

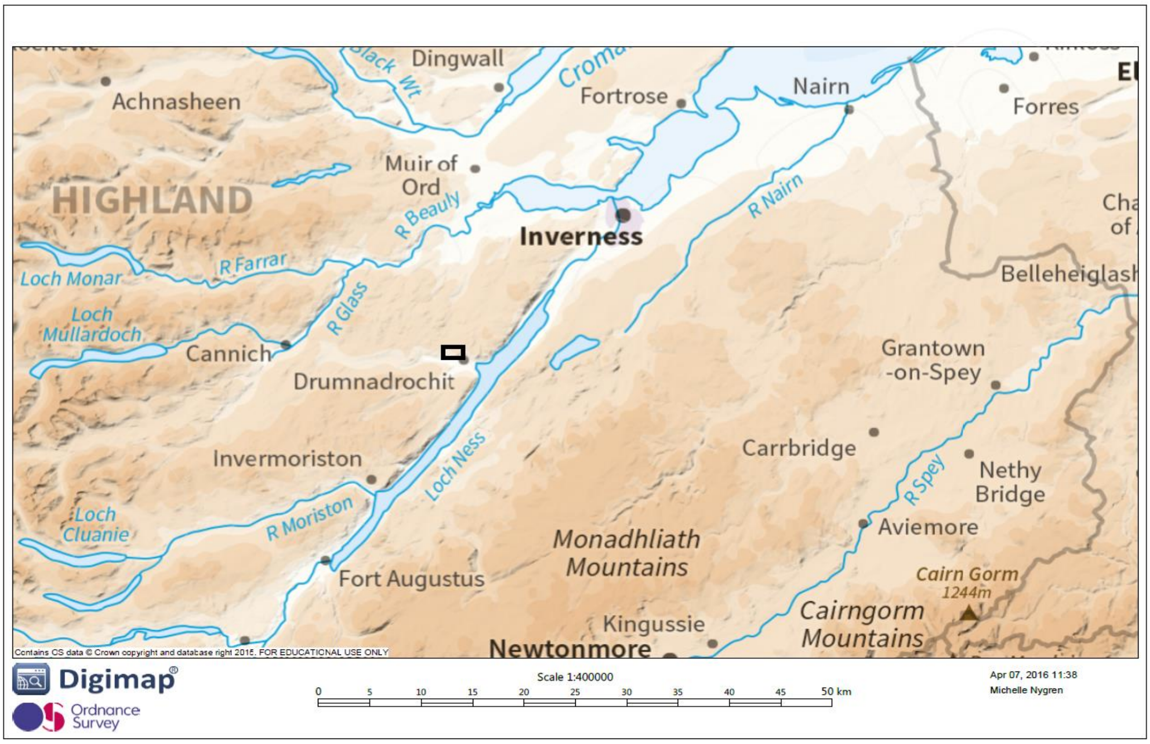


Figure 1: elevation map of a part of Scottish Highlands, the black rectangle indicates the study area of this thesis. Source: EDINA Digimap.

Lithology was identified mainly on site using a hand lens for observation, and 5 % hydrochloric (HCl) acid to determine the presence of carbonate in the rock. Systematic observations were recorded in a field notebook and on a field map. In some cases where the lithology was uncertain, samples were collected for further study and evaluation. Bedrock characteristics recorded were; crystallinity, crystal/grain size, colour, type of foliation, mineral alignment, reaction to HCl, and mineralogy. Dip direction and dip angle of foliations were measured with a compass and clinometer in non-folded outcrops. Mineral alignment, however, was noted but not measured.

2.2. Digitalising

The final scanned map was digitalised using CorelDRAW X5 graphic design. The cross sections were drawn using topographical data from EDINA Digimap. Contact dip directions and angles were approximated using information given by the interpretational geological map of the study area, such that general dip direction and general character of the contact line gradients should be reliable for interpretation.

3. *Results*

3.1. Map of Outcrops of the study area

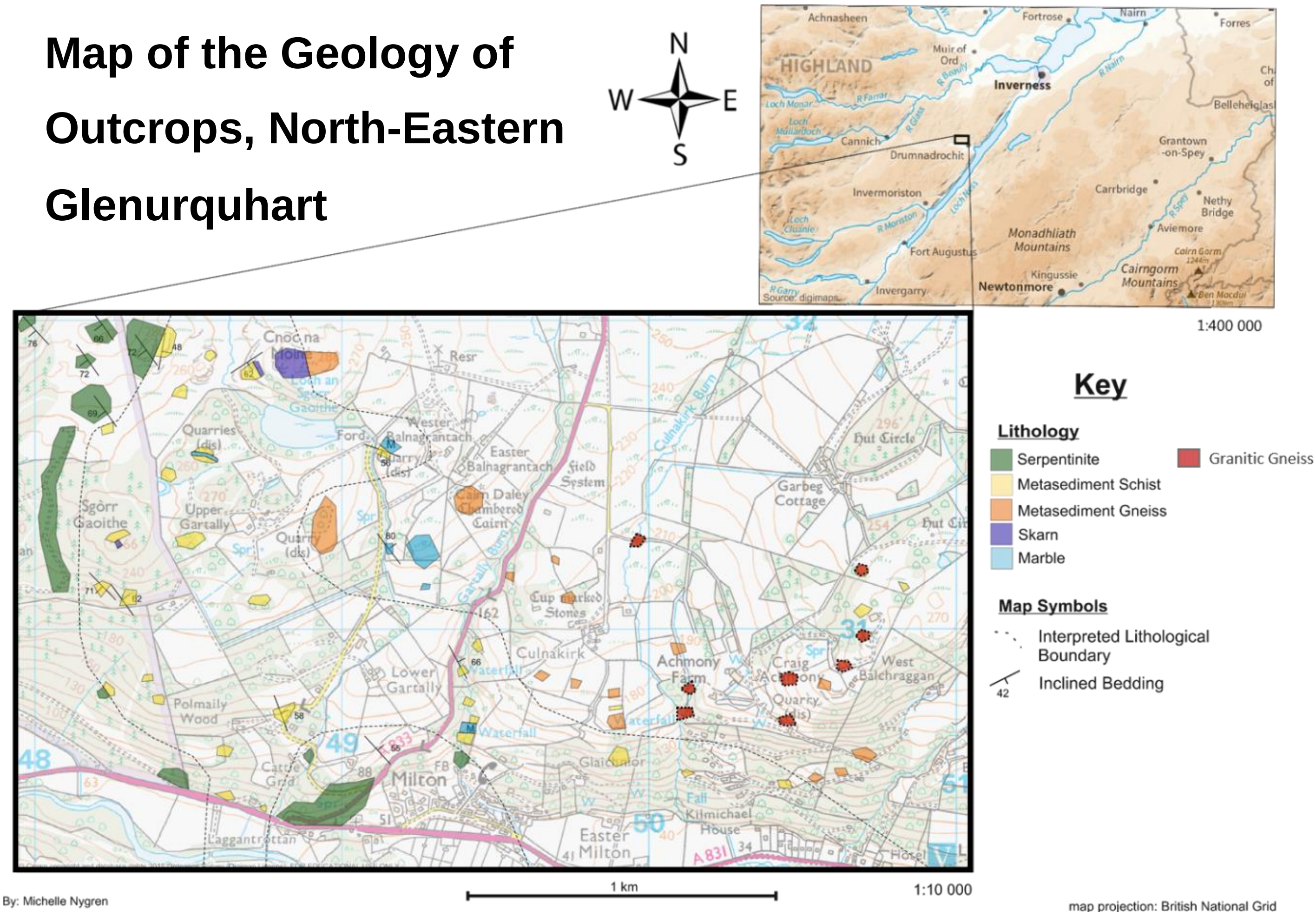


Figure 2: Map of the observed lithology of outcrops in the study area.

3.2. Interpretational Map and Schematic Cross Section

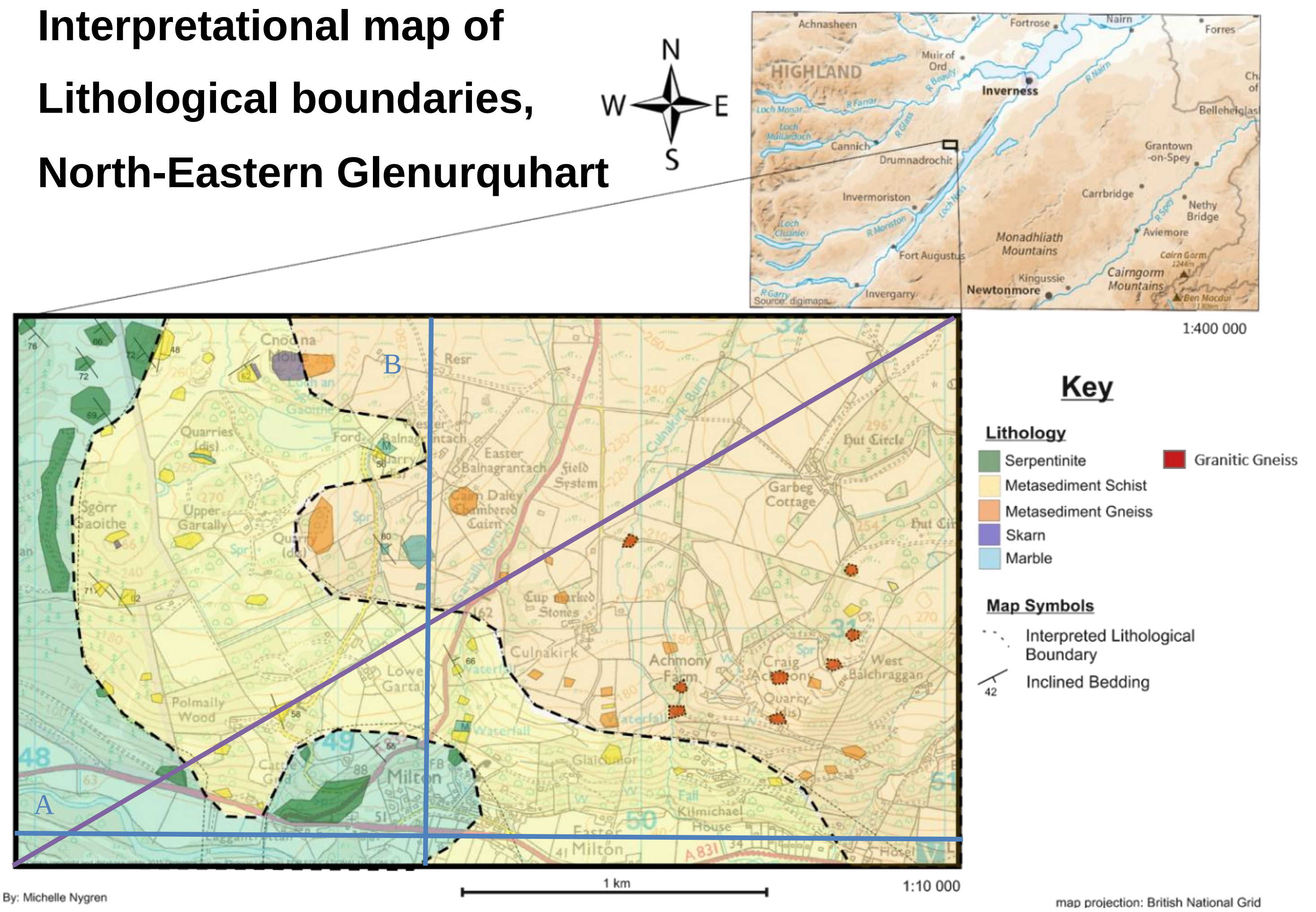


Figure 3: Interpretational map of lithological boundaries in the study area, drawn using information given by the outcrop map. The blue lines show the location of the cross sections according to scale, the purple line shows the location of the schematic cross section.

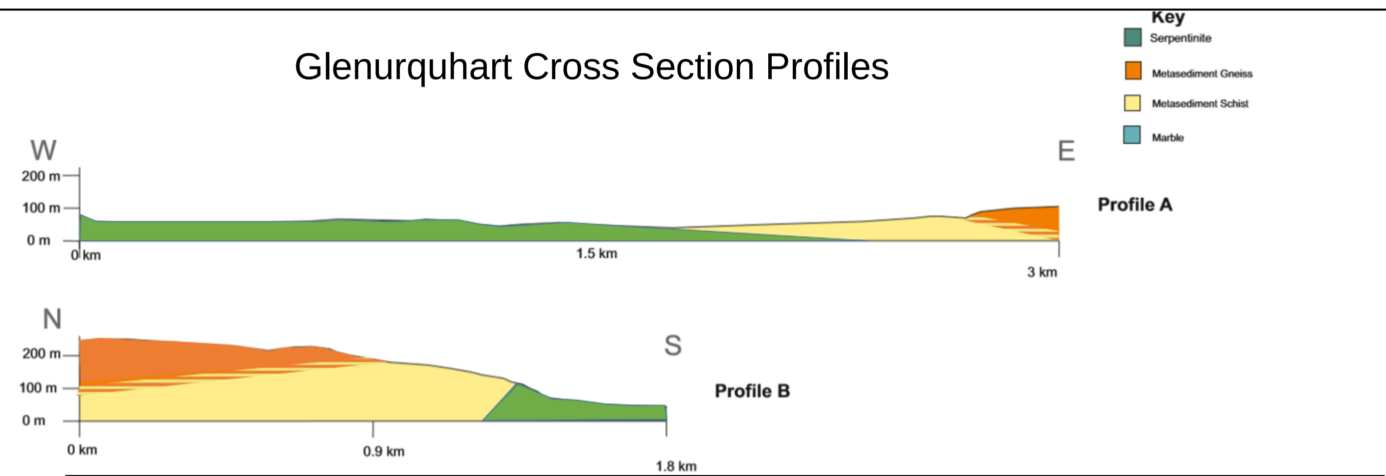


Figure 4: Topography profiles according to scale, cross sections inferred from relation between elevation and contact lines. Profile A is from W to E, Profile B is from N to S.

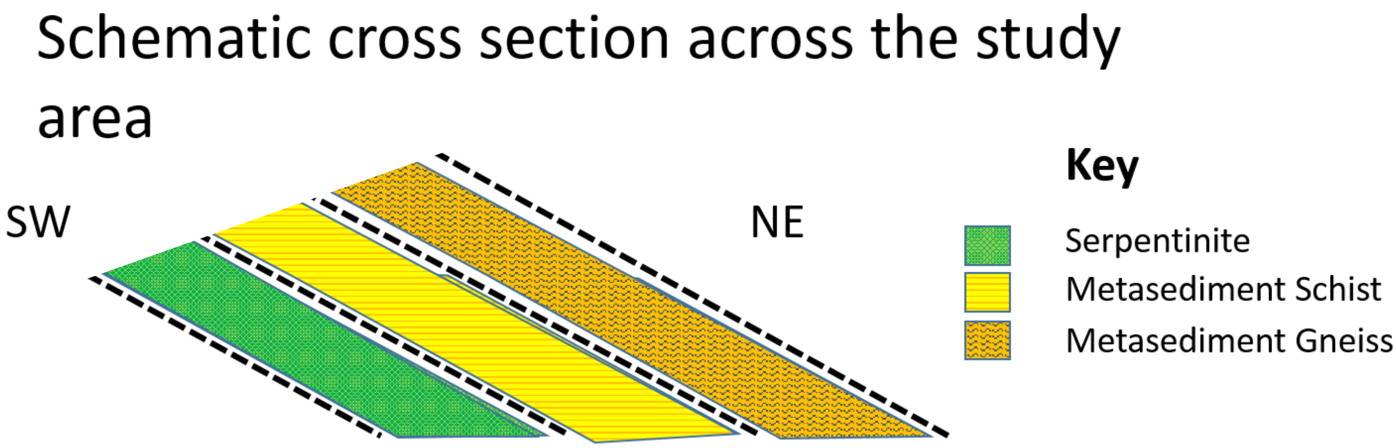


Figure 5: Simplified schematic Cross Section drawn from information given by the interpretational map.

Figure 2 and 3 show outcrop and interpreted maps of the study area. Interpolated contacts fit well with the outcrop data with the exception of two metasedimentary schist outcrops between Craig Achmony and West Balchraggan. These were disregarded in the interpreted map because it is not certain if they are in situ and/or simply a less gneissose part of the metasedimentary gneiss unit (figure 3).

Figure 4 shows accurate W-E and N-S cross sections and figure shows a simplified SW-NE cross section which illustrates the interpreted structure of the area. The accurate cross sections were constructed using interpolated contacts. Contacts are generally dipping gently NE, which can be inferred from the outcrop and interpretational map (figure 2 and 3). However, in some instances, the contacts might dip more steeply. The dip angles and directions have been deduced and drawn by connecting elevation lines of the topographical map to interpret the orientation of contact surfaces.

Figure 6: a serpentinite outcrop N of Lower Gartally, the person is 158 cm tall.

3.3. Lithologies

Six main lithological units were observed, defined and differentiated by either texture/foliation and/or mineralogy. They are; 1. serpentinite, 2. metasedimentary schist, 3. metasedimentary gneiss, 4. granitic gneiss, 5. marble, and 6. skarn.

3.3.1. Serpentinite

The serpentinite was variably foliated or massive. In the northwestern part of the mapping area the weathered surfaces showed pseudomorphic pyroxenes now consisting of aphanitic serpentine and talc, *i.e.* the minerals of the matrix, which here made the foliation very pronounced. The oxidised surface of the pyroxene pseudomorphs located north of Upper Gartally were aligned N-S. The outcrops in the southern parts of the study area (see figure 6) were mostly massive and lacked the preserved pseudomorphs found in the north. The outcrops west of Milton had a weak foliation. The pyroxene pseudomorphs thus made it easier to see the foliation, but ultimately it was defined by the serpentine and talc. The strike of the measureable folded outcrops was generally NW-SE.

3.3.2. Metasedimentary schist

The main minerals in the schistose metasediments were quartz, muscovite, biotite, kyanite which was wholly or partly pseudomorphed to pyrophyllite porphyroblasts (c. 3-15 mm) and garnet porphyroblasts (c. 1-20 mm), see figure 7b. The sequence also contained thin layers of more carbonate-rich rock types, *i.e.* marble and skarn, and sometimes the composition was richer in quartz and poorer in the Al-rich minerals.

The foliation was delineated by platy minerals, *i.e.* muscovite and/or biotite (figure 7a), where they were abundant, and the kyanite was weakly aligned parallel to the foliation defined by the mica minerals. In some locations thicker layers of mica gave the rock a gneissose appearance, and occasionally the schist was folded as well. Altogether, the schistose character was dominant and therefore the layer is defined as being metamorphosed sediment with schistose foliation.

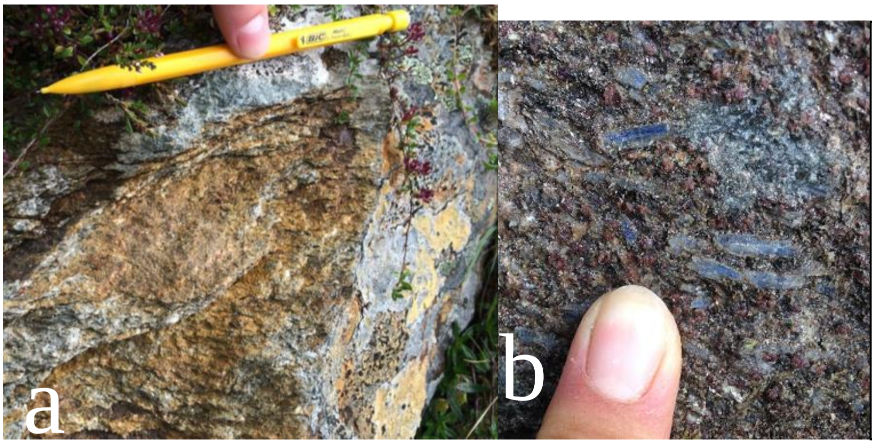


Figure 7: a) kyanite schist W of Cnoc na Moine, the pen is 14 cm long b) garnet kyanite schist with porphyroblasts of key minerals NW of Kilmichael, the fingernail is 1 cm wide.

3.3.3. Metasedimentary Gneiss

The metasedimentary gneiss was similar to the metasedimentary schist, although it contained less muscovite and kyanite, and pyrophyllite did not occur. Instead quartz and feldspar were abundant, and garnet also appeared regularly. Due to the occurrence of carbonates in the gneissose sequence the term metasedimentary was applied here as well. The relationship between the gneiss and the three marble outcrops found, just east of where the contact between gneiss and schist is drawn in the centre of the study area, is uncertain. The gneissose rocks were tightly folded (figure 8a, 8b), and largely the foliation was found to be defined by bands of biotite and amphibole or pyroxene in the melanocratic layer and quartz and feldspar in the leucocratic layer.

Figure 8: a) feldspathic gneiss E of Cnoc na Moine, the fingernail is 1 cm wide. b) garnetiferous feldspathic gneiss, between Achmony Farm, Culnakirk and Glaichmor, the pen is 13 cm long.

3.3.4. Granitic Gneiss

Among the metasedimentary gneisses in the eastern part of the study area, a gneiss of differing mineralogy was sometimes identified (figure 9). It contained a significant amount of feldspar, especially K-feldspar with quartz and some minor biotite. It lacked muscovite, garnet, kyanite, and pyrophyllite. The melanocratic layers contained amphibole and the leucocratic layers were made up largely of K-feldspar. It was also folded, but to a much lesser extent relative to the metasedimentary gneiss (see the orange lines in figures 8a and 8b, and 9 respectively, following the folding in the outcrops and hand sample).

Figure 9: Granitic gneiss S of Craig Achomony. The hand sample comes from a folded outcrop, the pen is 15.5 cm long.

3.3.5. Marble

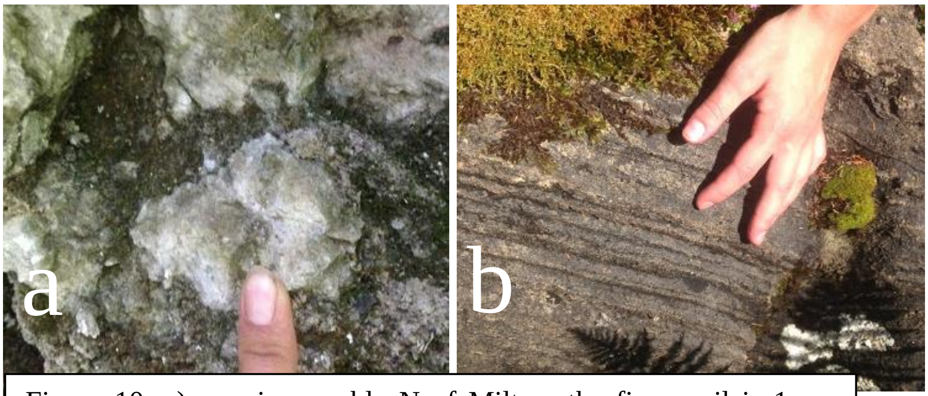


Figure 10: a) massive marble N of Milton, the fingernail is 1 cm wide b) sandy coloured marble N of the study area, showcasing variation in layering, the thumb fingernail is 1.3 cm.

The marble consisted mainly of calcite and quartz crystals, of which the former reacted strongly with the HCl solution. The weathered surface often had a sandy, orange/black mottled appearance, whereas fresh surfaces were white or light grey banded and crystalline with a grain size c. 1 mm. The marble was sometimes massive (figure 10a), and in some instances, a regular variation in crystal size of the minerals was observed (1 mm sized crystals versus 3 mm sized crystals) north of the study area, this was presumed to reflect original bedding (see figure 10b).

3.3.6. Skarn

The skarn had a gneissose appearance, with green melanocratic and white leucocratic bands. It consisted of biotite, quartz, plagioclase, epidote, pyroxene, tremolite, actinolite, and rarely garnet. Occasionally, especially in the northern skarn outcrop, a higher abundance of biotite in melanocratic bands gave the rock a schistose appearance. Elsewhere, gneissose banding was diffuse in appearance. Some skarns, contained large actinolite porphyroblasts or "pockets" containing dark green fibrous masses of actinolite crystals (see figure 11a, 11b).

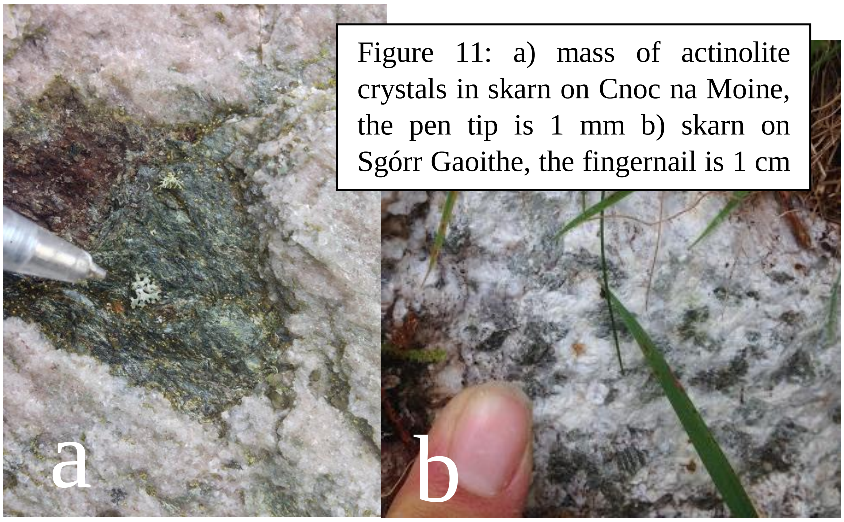


Figure 11: a) mass of actinolite crystals in skarn on Cnoc na Moine, the pen tip is 1 mm b) skarn on Sgórr Gaoithe, the fingernail is 1 cm

Neither the marble nor the skarn occurred as continuous mappable layers. Instead, lenses occurred within the metasedimentary schist and gneiss.

4. *Discussion*

4.1. Geological History

4.1.1. Previous Theories and the Origin of local Metasediments

The geological history of the Glenurquhart complex is a subject of contention and the matter has been investigated and discussed in three works throughout the 20th century. In the following sections, the hypotheses discussed in these works will be considered and compared to each other and observations made during field work for this thesis, in order to justify the selection of a preferred hypothesis.

4.1.1.1. Work of Cunningham Craig (1914):

Cunningham Craig (1914) was of the opinion that the gneiss in the area is Lewisian. He bases his conclusion on lithological and structural grounds, namely discordance of strike and an inferred tectonic boundary with the surrounding Moine rocks.

He made observations about differences in strike between the Moine Schist and the anomalous assemblage, and noted that the two rock units are folded together at the junction between them.

As evidence supporting his theory of a Lewisian inlier, he cites the following observations; the anomalous series is much more highly crystalline than the surrounding Moine, it follows the normal strike of Lewisian gneiss (NW-SE), and the petrology is similar to the petrology of an area in Glenelg, mapped as a Lewisian inlier. Furthermore, Cunningham Craig (1914) used the presence of hornblende-schist as proof of a Lewisian origin.

Cunningham Craig (1914) measured fold axes to trend northwest with a steep plunge. He found no evidence of folding of the serpentinite. The order of succession according to Cunningham Craig (1914) is limestone (*i.e.* the marble) as the lowermost structural unit, followed by 'Rusty micaceous gneiss with kyanite' and 'Felspathic banded gneisses with basic patches and lenticles'. He claims that the structurally lowest rocks are located only in the centre of the inferred inlier and the higher ones at its flanks, which he uses as evidence to draw the conclusion that the area comprises an anticline exposing Lewisian rocks within the Moine Schists.

4.1.1.2. Work of Francis (1956) and Francis (1958):

Francis (1958) argued that the strong differences between the local bedrock to be found in the Glenurquhart area and the Moine were due to potash metasomatism, "granitisation". He based his interpretation on the presence of pegmatites, pegmatitic stringers, quartz veins, as well as gradational transitions from schist to granitic-gneiss, limestone to skarn, amphibolite to biotite skarn and serpentinite to amphibole-biotite skarn. He went on to describe injection structures, and he claimed that the absence of limestone in the nearby Moine schist was for structural reasons. He also claims the overall structure was an anticline and that the limestone, now marble, is the lowermost structural unit in the area.

Francis was also sceptical about the theory of a Lewisian inlier on the basis of its stratigraphical position in the Moine, *i.e.* in the upper psammitic belt (which is exposed in the Glenurquhart area) as all other Lewisian inliers were mapped nearer to the mountain front and lower in the Moine sequence.

Francis (1956) attributed the serpentinite to the intrusion of an ultramafic igneous body together with volatile water which contributed to the serpentinisation of the body, into already folded and regionally metamorphosed Moine bedrock. Francis (1958) described it as a sill intrusion with underlying 'foot' rock west of the serpentinite body and overlying 'hanging' rock east of the serpentinite.

4.1.1.3. Work of Rock *et al.* (1986):

Rock *et al.* (1986) describes the Glenurquhart Complex as lithologically unique, noting that no other similar occurrence is found within the Moine Supergroup. Additionally, they state that the serpentinite is among the largest in the Highlands. They disagree with both Cunningham Craig's (1914) and Francis' (1958) conclusions stating that Cunningham Craig's

Lewisian/Moine contact is 'illusory' and that the correlation to the Glenelg inlier is irrelevant as they disagree with its classification as Lewisian. They did not support Francis' model of potash metasomatism since, according to their work, chemical differences between the Moine and the foreign complex are too large.

They agreed with Cunningham Craig regarding the bedrock in the area being anomalous based on their own observation that the lithological boundary of the complex cross-cuts the Moine host and other lithologies within the formation. Furthermore Rock *et al.* (1986) state that the contact between the complex and the Moine is not gradational based on observations of sharp contacts between the limestone and other rocks within the complex as evidence. Moreover, they argue that the Glenurquhart metasediments are closely associated with the serpentinite intrusion and claim that this is further evidence of a non-Moinian origin. It is suggested in their work (1986), that the complex is either a syncline or a basement slice.

They disagree with Cunningham Craig regarding a Lewisian origin of the metasediments and assign the complex to a new 'Albynian' group, which could either lie stratigraphically between or be diachronous with the Moine and Dalradian Supergroups.

4.1.2. Deductions

4.1.2.1. Arguments for and against the work of Cunningham Craig (1914)

Cunningham Craig (1914) claims that the serpentinite does not show evidence of folding, and although my findings showed the serpentinite was foliated, no evidence of folding was observed, so this claim is not opposed.

The Lewisian Loch Maree Group consists of metasediments and metamorphosed mafic intrusions (see 1.1.1. NW Mainland Geology (Northern Highlands), page 2). One point Cunningham Craig (1914) used to defend his conclusion of a Lewisian origin for the complex was the presence of hornblende-schist. Accordingly, a large, seemingly intrusive, body of hornblende-gneiss was found north of the study area (Magnusson Branheim, E., in preparation).

The structural grounds which Cunningham Craig (1914) further based his conclusion on was not investigated during field work for this thesis and can thus not be compared with personal findings. However, as per the map made by Baynefield Carto-Graphics (1984), 'Solid Geology of the Glenurquhart Serpentinite-Metamorphic Complex and its Moine envelope, West of Loch Ness', the Moine and serpentinite-metamorphic complex are folded together in accordance with Cunningham Craig (1914), although the map shows no difference in strike between the Moine and the complex. However, according to my observations, the contact between schistose and gneissose rocks was gradational, which does not support their conclusions.

The succession suggested by Cunnginham Craig (1914) *i.e.*; "limestone (*i.e.* the marble) as the structurally lowermost unit, overlain by 'Rusty micaceous gneiss with kyanite' [here mapped as metasedimentary schist] and 'Felspathic banded gneisses with basic patches and lenticles' [here mapped as metasedimentary gneiss]" (page 11), partly corresponds with what can be inferred from the map and schematic cross section presented in this thesis, with the exception that the marble does not appear to be the structurally lowermost unit, given that it was found as near horizontal layers at points of higher elevation (see 4.1.4. Folding, pages 15-16). Together with the small size of the complex, it appears unlikely that it is an anticline.

4.1.2.4. Arguments for and against the works of Francis (1956) and Francis (1958)

Francis (1958) made a case for a gradual contact between the Moine Schist and the anomalous rocks. To support this he described transitional contacts from schist to granitic gneiss, limestone to skarn, amphibolite to biotite skarn and serpentinite to amphibole-biotite skarn in the complex.

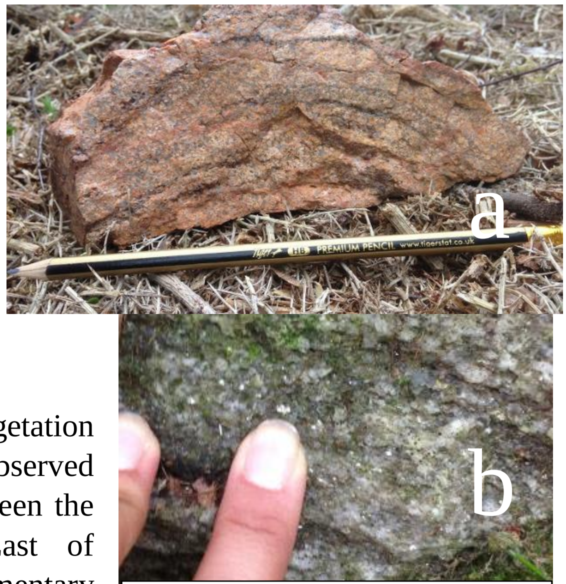


Figure 12: a) granitic gneiss from a folded outcrop S of Craig Achmony, the pen is 15.5 cm long b) folded siliceous gneiss with mica flakes NE-E of Kilmichael house, the fingernail is 1 cm.

Observing contacts was made difficult by land use and vegetation in the study area. For this reason, no contact was observed between the schist and metasedimentary gneiss, nor between the metasedimentary gneiss and the granitic gneiss. East of Kilmichael House, a gradual transition from metasedimentary schist (figure 12a) to granitic gneiss (figure 12b) northwards, to Craig Achmony, was observed. Furthermore, the fact that it was difficult to pinpoint where the change from schist to gneiss occurs also supports the theory of a gradual contact.

Francis (1958) suggested the serpentinite may be a sill intrusion, which fits with the structure observed in the area (see schematic cross section, 3.2. Interpretation Map and Cross Section, page 6).

The model of potash metasomatism (Francis, 1958) is based on the gradual transition between layers which he claims to relate to the spreading of K-rich fluids from a source, which is suggested to be in the area of the granitic gneiss, where the rocks are considered to have undergone full transformation by metasomatism. If another layer is to be added to the

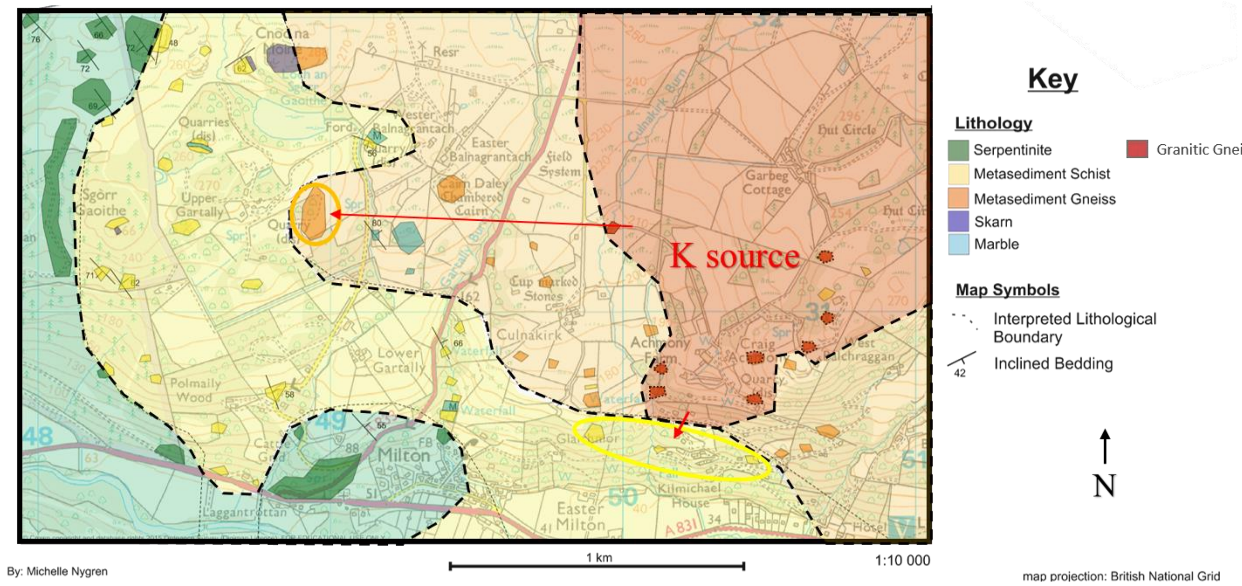
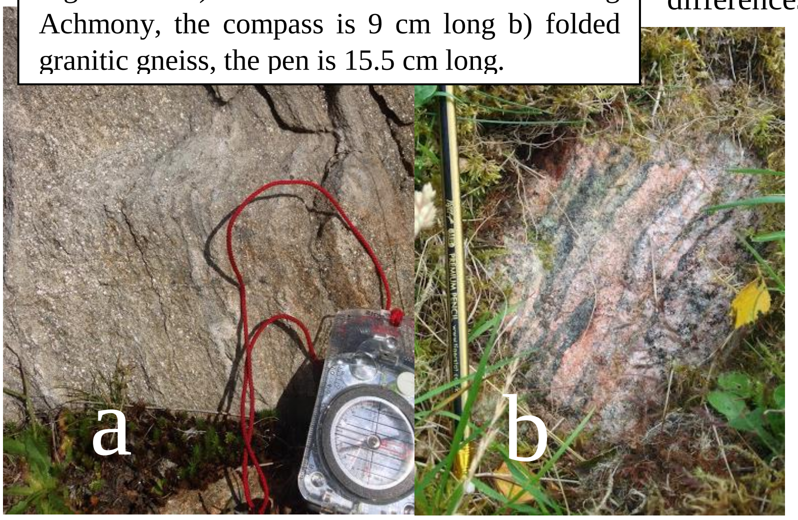


Figure 13: Interpretational map, with a fourth layer added; the granitic gneiss. Here it is assumed the granitic gneiss continues NE, although there are no outcrops in this area. The circles indicate the location of lithologies of interest, and the arrows are suggestions for simple fluid pathways from the source to the receptor.

interpretational map, incorporating the granitic gneiss (figure 13), a possible location for the source may be better visualised.

Granitic bedrock was found in the east. Metasedimentary gneiss was found as far west as Upper Gartally's southeast quarry (the orange circle in figure 13), whereas schist was found quite close to the granitic gneiss, by Glaichmor (the yellow circle in figure 13). It seems unlikely granitisation would be this intermittent in its distribution. Furthermore, there was a marked shift in composition between nearby outcrops of granitic gneiss (compare figures 14a and 14b). These outcrops are both within the area in figure 13 which is interpreted as granitic gneiss. This indicates that, if Francis' (1958) theory was correct, metasomatism was not evenly distributed and fluid flow was localised. Additionally, neither biotite skarn nor amphibole-biotite skarn were observed, thus their transitioning from amphibolite and serpentinite respectively is not supported by data collected in this thesis. However, it cannot be excluded that these rocks may occur outside my study area. Therefore the transformation of Moine Schists by potash metasomatism, as a model to explain the anomaly this complex represents, is deemed unconvincing. Also, large differences in mineralogy were observed between the metasedimentary gneiss and the granitic gneiss. This is in agreement with Rock *et al.*'s (1986) claim of large chemical differences between the anomalous complex and the Moine Schists.

Figure 14: a) micaceous schist NW of Craig Achmony, the compass is 9 cm long b) folded granitic gneiss, the pen is 15.5 cm long.



4.1.2.3. Arguments for and against the work of Rock *et al.* (1986)

Rock *et al.* (1986) used, inter alia, the presence of the serpentinite, one of the largest in the Highlands of Scotland, to support a non-Moinian origin for the complex because serpentinite is usually of mantle origin. However, his other grounds for support of the model include a non-gradational contact between the metasediments of the complex and the Moine, which is not supported by field observations made in this study. They also claim that the contacts between limestone and pelite is non-sedimentary. While possible, it was noted in the field that some contacts were gradational in appearance; *e.g.*, calcite could be detected in small amounts by using the HCl solution south of the marble outcrop west of the river Gartally Burn.

Their disagreement with Cunningham Craig's (1914) argument for the origin of the Glenurquhart complex was based on the controversy surrounding the identification of the Glenelg formation as a Lewisian inlier (Barber and May, 1976; Rock *et al.* 1986). This prompted their suggestion of and Albynian inlier instead.

They proposed that the complex constituted a downfold of rocks or a basement slice to explain the anomaly it represents. They argued that it is unlikely that a syncline could explain the occurrence of deep-rooted Lewisian rocks in the complex and therefore proposed that the rocks belonged to a previously unrecognised unit, *i.e.* the Albynian. This, however, gives the impression the serpentinite body is independent of the complex, which appears to contradict their claim of a close association between the metasediments and the serpentinite. A basement thrust slice is deemed to be a more suitable explanation (see 4.1.3. Emplacement of the Serpentinite body, page 15).

The Albynian model has not been investigated further, and since field work for this thesis support Cunningham Craig's (1914) arguments for a Lewisian inlier model, Rock *et al.*'s (1986) "Albynian" is considered unnecessary. This study consequently supports Cunningham Craig's (1914) Lewisian inlier interpretation, and it might be possible the complex' association with a piece of mantle can justify why it is so far east, which may also explain the small size of the Glenurquhart inlier.

Figure 15: a folded outcrop of metasedimentary gneiss, the pen is 12 cm long.

4.1.3. Emplacement of the Serpentinite body

Francis (1956) and (tentatively) Rock *et al.* (1986) suggest that the serpentinite represents a diapiric intrusion of mantle rocks in the area, independent of the inlier. However, the low dip angle of the serpentinite (see interpretational map and schematic cross section, 3.2. Interpretation Map and Cross Section, page 6) does not support the theory of a plutonic or dyke-like, upwards-directed intrusion (Halbouty, 1968). Alternatively, the serpentinite body might be a shallow sill (Francis, 1958). This interpretation fits with the observations made in this study of the gentle dip of the serpentinite body. However, thrusting seems a more likely model than magmatic activity, to explain the presence of the deep rocks (the serpentinite, the inlier, and the metasediments), the metamorphic foliation of the serpentinite, and why the original bedding of the limestone has sometimes been preserved, *i.e.* because deformation was localised to specific high strain zones.

4.1.4. Folding

Fold structures are known to be associated with Lewisian inliers (Rathbone and Harris, 1979; Rathbone and Harris, 1980), and Cunningham Craig (1914) and Francis (1958) made comments regarding an anticline in the area, and seemed to agree that the marble was the lowermost structural unit. Field observations however, show that marble occurs at points of raised elevation (the marble in the Gartally Burn River is an exception) and contacts observed were generally near horizontal and shallow. Additionally, my findings show that the marble is spatially associated with the serpentinite. However, the dip angle of the gneiss-schist and serpentinite-schist contacts vary across the study area (figure 16). Coupled with findings of several folded outcrops (see figure 15, and figures 8a, 8b, and 9 on page 9), this indicates folding was part of the geological history of the area.

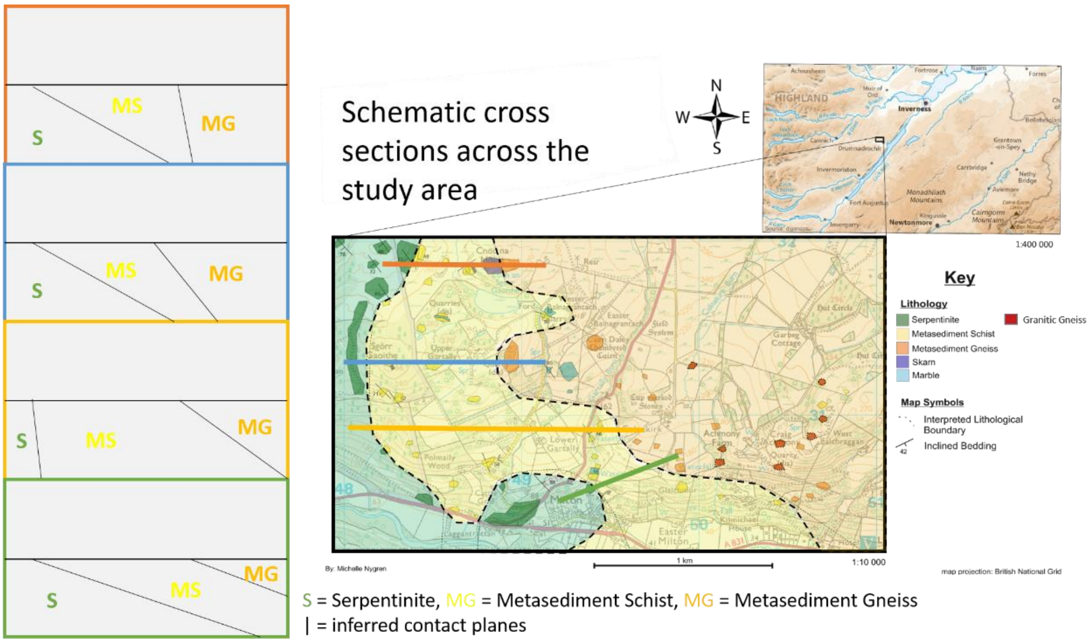


Figure 16: schematic cross sections with their corresponding locations on the map, showcasing changing dip angles between different lithologies N to S in the study.

Alternatively, the complex could have been deformed before emplacement in Glenurquhart; the degree of folding varied greatly between the metasedimentary schist, the metasedimentary gneiss and the granitic gneiss. This may be due to compositional differences and not necessarily because of different levels of stress. In this study, it was found that the serpentinite showed a metamorphic fabric. However, foliation alone is not sufficient evidence to support folding of the serpentinite. Thus folding may have occurred before the serpentinite was introduced to the complex. Notwithstanding, the foliation of the serpentinite indicates it underwent some sort of differential stress before emplacement in its current location. Hence, if the complex and the serpentinite are a lithotectonic unit (*i.e.* a slice of basement), it may be possible that the deformation of the metasedimentary gneiss, and perhaps the metasedimentary schist, occurred before the serpentintie, schist and gneiss were juxtaposed.

4.2. Errors

Due to poor exposure (especially in the centre and northeast of the study area, see outcrop map on page 5), extensive farming, and irregular and transitional contacts, many parts of the contact lines on the map produced by this study are extrapolated. The schist-gneiss contact was obscure and covered by vegetation or soil, thus the position of this contact and its dip angle is especially uncertain; *i.e.* slight changes in the position of the contact line between the metasedimentary schist and the metasedimentary gneiss on the map prompted quite drastic changes in the inferred dip angles of the contacts.

5. *Conclusion*

The results of this study favour the model proposed by Cunningham Craig (1914), that the Glenurquhart Complex represents a Lewisian inlier. This conclusion has been reached after consideration of several factors involving the complex. Since serpentinite commonly originates from the mantle, its presence in close association with the metasedimentary rocks supports an exotic origin. Also, mineralogical differences, reflecting a differing chemical composition, between the Moine and the complex suggest that the complex belongs to another group and not the Moine Schists. Findings of hornblende-gneiss were observed during field work north of my study area (Magnusson Branheim, in preparation) and they are considered to be evidence for a Lewisian origin.

Evidence of folding in the area has been observed. Previously the marble was considered to compose the lowermost structure in an anticline (Cunningham Craig, 1914; Francis, 1958). This has been refuted on the basis of the occurrence of the marble at higher elevations than surrounding rock units and its low dip angles. It is not precluded that the folding could be structures formed before emplacement of the complex in the area.

Igneous dyke or pluton formation as the mechanism for serpentinite emplacement is not supported due to the low dip angles of the serpentinite bodies. Instead, sill formation (suggested first by Francis, 1958) or thrusting are proposed as possible mechanisms. The thrusting model is further supported by the presence of deep rocks, additionally it provides an explanation for why original bedding is sometimes preserved in the marble, *i.e.* if it has been transported as part of a thrust slice.

For future studies, an investigation of faulting in the area is suggested, where *e.g.* the occurrence of fault fabrics and possibly fault planes (if they are exposed) could help to increase the understanding of the Glenurquhart Complex.

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