Structure of the Northern Moine ~~T~~thrust zone, Loch Eriboll, Scottish Caledonides☆

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☆Submitted to: Tectonophysics Special volume “Style of deformation and tectono-sedimentary evolution of fold-and-thrust belts and foreland basins”.

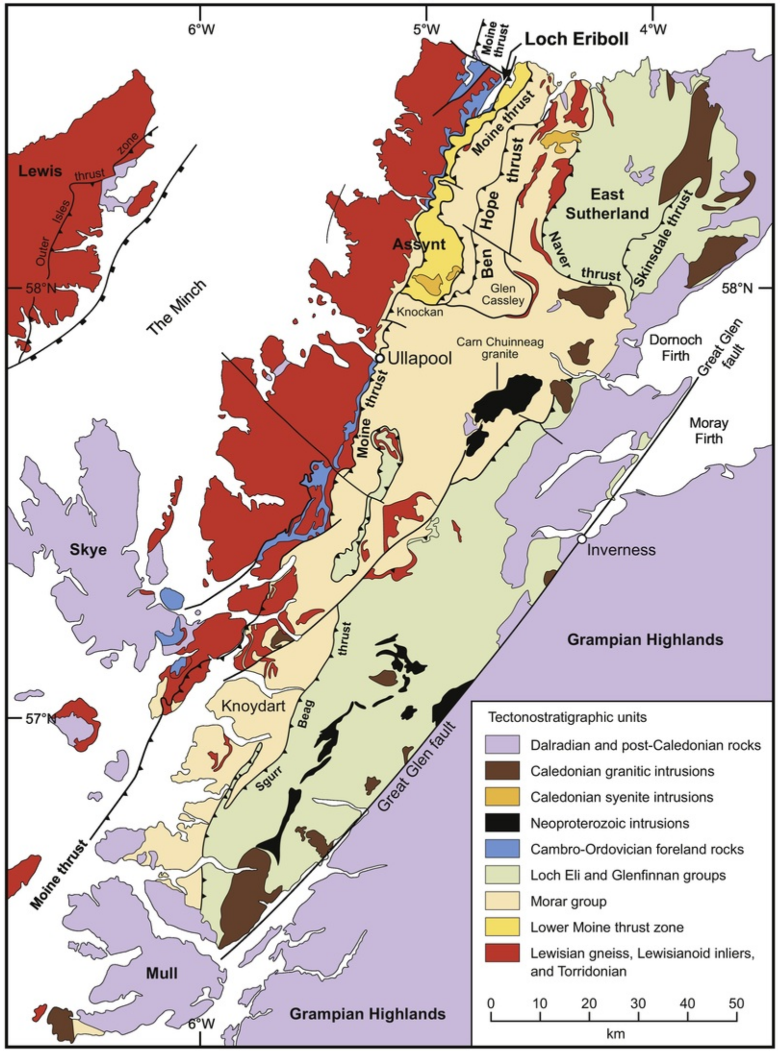
Abstract

This paper reviews the geology of the Late Ordovician - Silurian Caledonian Moine Thrust zone in the Loch Eriboll region, NW Scotland. We present new detailed mapping and balanced/restored cross-sections to examine its structural evolution. This thrust zone comprises four major thrust slices, carried by the Moine, Lochan Riabhach, Arnaboll and Sole thrusts. Ductile mylonites were derived from lithologies in both the hangingwall (Moine schists) and the footwall (Lewisian basement gneisses, Cambrian quartzites, Ordovician dolomites) of the Moine Thrust. The mylonites are bounded by the Lochan Riabhach thrust below and the Moine thrust above. The Arnaboll thrust sheet comprises Lewisian basement gneisses and Cambrian-Ordovician sedimentary rocks over the Sole Thrust sheet, which exposes a spectacular imbricate sequence of Cambrian-Ordovician sedimentary rocks. Although thrusts sequentially propagated in-sequence from higher (Moine) to lower (Sole) thrusts with time, there is evidence for minor out-of-sequence thrusting and breakback thrusting. Thrusts evolve from deep ductile shears where strain is concentrated along mylonite zones up into the brittle field where they become discrete planar thrust faults. The Early Silurian Scandian metamorphism (~435~~-~~–415 Ma) is related to a Himalayan style structure with SSE-directed subduction and WNW directed extrusion of a migmatitic core, which we liken to channel flow.~~-~~ We suggest that two major crustal-scale thrusts that extend down into the upper mantle imaged on seismic profiles across the foreland, the Outer Isles and Flannan thrusts, are unrelated spatially or temporally to the Moine thrust sequence.

Keywords: Moine thrust; Caledonian orogeny; ~~f~~Fold-thrust belt

~~1.~~1 Introduction

The *Moine Thrust zone* (MTZ) in NW Scotland (Fig. 1) forms the western margin of the Caledonian orogeny and crops out for over 250 km from the Loch Eriboll region in the north to the Isle of Skye in the south. The MTZ emplaces the *Moine thrust sheet* comprising regional Barrovian facies metamorphic rocks and granites of the central and eastern Scottish Highlands westwards over the Archean (Lewisian gneiss) and Proterozoic (Torridon Group sedimentary rocks) basement with their Cambrian-Ordovician sedimentary cover sequence in the foreland to the west. The MTZ includes several major thrusts, from top to base the *Moine thrust*, *Lochan Riobhach thrust*, *Arnaboll thrust* and *Sole thrust* (Nicol, 1860; Lapworth, 1883-84, 1885; Peach et al., 1907, 1888; White et al., 1982; McClay and Coward, 1981; Coward, 1984, 1988; Butler, 1982, 1987, 2010a, b, c; Law et al., 1984, 2010; Strachan et al., 2002a, b (omit 'a'); British Geological Survey, 2002; Holdsworth et al., 2006, 2007; White, 2010; Thigpen et al., 2010a, b).



~~Figure 1~~Fig. 1 Simplified geological map of NW Scotland showing the northern part of the Moine Thrust zone after Peach et al. (1907), Butler (2010a, b, c) and others. ST- Sole Thrust; MT- Moine Thrust; BHT- Ben Hope Thrust. Inset map shows major tectonic zones of Scotland; GGF – Great Glen Fault; HBF – Highland Boundary Fault; SUF – Southern Uplands Fault.

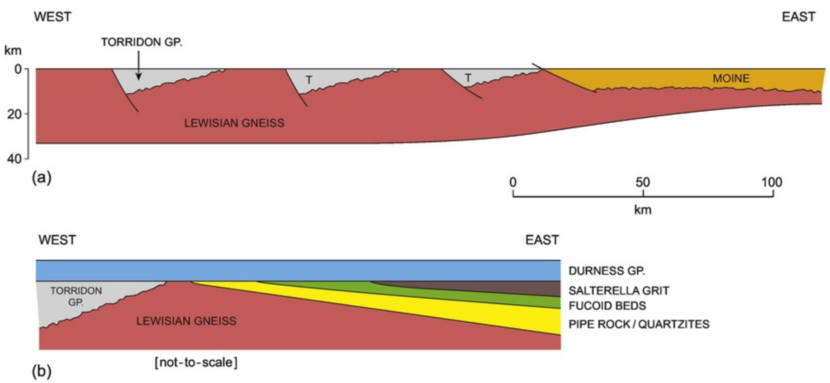
alt-text: Fig. 1

Despite ~~more than~~ >150 years of intense geological study along the MTZ in NW Scotland, the development of recent techniques of balancing and restoring cross-sections, microstructural strain analysis, thermobarometry, and U-Pb dating of metamorphic and magmatic rocks, the tectonic evolution of the MTZ remains somewhat enigmatic. Partially resolved factors include linking the micro- to macro-scale tectonics of the MTZ with structures in the hinterland (Moine metamorphic terrane) and the foreland (Hebrides and the Outer Isles), linking ductile fabrics in mylonites to higher level brittle structures, calculating minimum amounts of shortening and determining the precise sequence of thrusting. Excellent summaries of the history of ideas relating to the MTZ can be found in Law et al. (2010) and Butler (2010a, b).

It was in the Loch Eriboll area, the northernmost exposure of the Moine Thrust belt, that thrust faulting was first proposed to explain the occurrence of deeper, older stratigraphic units emplaced over shallower, younger strata (Nicol, 1860; Callaway, 1883; Lapworth, 1883-84, 1885; Geikie, 1884). Ben Arnaboll mountain is also the type locality of mylonites, where Lapworth (1885) first proposed that these rocks were formed by ductile shearing along thrust planes. These pioneering geologists mapped thrust sheets of allochthonous Lewisian gneiss basement rocks emplaced above Cambro-Ordovician sedimentary rocks in the Arnaboll thrust sheet and proposed that horizontal compressional forces resulted in thickening and shortening of the crust. This discovery was the foundation on which the regional mapping of the Moine Thrust zone in the NW Highlands of Scotland was carried out by the British Geological Survey in the 1880~~-~~–1890s (Peach and Horne, 1884; Peach et al., 1907, 1888). The original Geological Survey maps were first published in the classic Northwest Highland Memoir in 1888. These maps are spectacularly accurate and repeated studies have not found major flaws in their mapping.

Peach et al. (1907) and Soper and Wilkinson (1975) interpreted the structurally lowest thrust, the Sole thrust, to be the oldest, and the structurally highest Moine thrust to be the youngest. It was, however, with the advent of accurate geometric balancing and restoration techniques (Elliott and Johnson, 1980; McClay and Coward, 1981; Coward, 1984, 1988; Butler, 1987) that it became apparent that the opposite must be correct, a foreland-propagating sequence of thrusting. The overall sequence of thrusting from structurally highest to lowest, from the Moine thrust to the Arnaboll thrust to the Sole thrust, from hinterland to foreland, is now widely accepted, and is indeed the norm in most mountain belts.

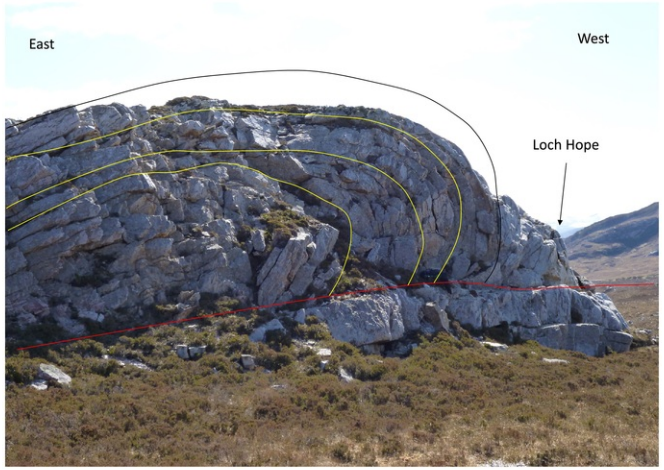
The Loch Eriboll region has been the focus of many detailed structural studies, and the area has been mapped extensively by many previous workers since the 1980s (see Field Guides by Butler (2009, 2010a, b, c)) and Butler et al., 2011) and Mendum et al. (2009). McClay and Coward (1981) made a detailed map of the Heilam – Ben Arnaboll region and favoured the foreland-directed thrust sequence proposed initially by Elliott and Johnson (1980) for the Assynt region. Coward (1984) and Butler (1987) recognised that the Arnaboll thrust was folded and was breached by small-scale imbricates in the underlying thrust sheet, termed breaching thrusts by Wibberley and Butler (2010). Holdsworth et al. (2006, 2007) recognised out-of-sequence thrusts that truncate structures in the footwall and also proposed extensional structures within the Moine thrust zone. Microstructures in the Moine thrust mylonites have been studied extensively by White et al. (1982), Law et al. (1984, 2010), White (2010) and Thigpen et al. (2010a, b). More recently, the British Geological Survey (2002, 2007) published new maps at 1:50,000 scale of the Kyle of Tongue and Loch Eriboll areas. A simplified stratigraphy of the NW Highlands is shown in Fig~~ure~~. 2a and a schematic profile across the Laurentian continental margin prior to Caledonian thrusting is shown in Fig~~ure~~. 2b. The basement units comprise Archean Lewisian gneisses cut by half-grabens infilled with Proterozoic Torridonian sandstones and conglomerates. In eastern Scotland, the protoliths of the Moine schists are dominantly thick psammitic rocks that were time-equivalent facies of the Torridon Group (or Torridonian rocks). The cover sequence shows an eastward thickening series of Cambrian shallow marine sedimentary rocks overlapped by a thick transgressive Ordovician shallow marine dolomite (Durness Group).



~~Figure 2~~Fig. 2 (a) Schematic pre-Cambrian tectonic stratigraphy of the NW Highlands of Scotland, showing the main map units with the Proterozoic Moine sequence as laterally equivalent to the continental Torridonian sandstones; (b) profile across the Ordovician Laurentian continental margin of Scotland, prior to Caledonian thrusting, showing approximate positions of the Lewisian basement thinning towards the east, the Cambrian sediments onlapping the continental margin and thickening towards the east, and the Ordovician Durness Group limestones and dolomites unconformably onlapping and covering all lower units.

alt-text: Fig. 2

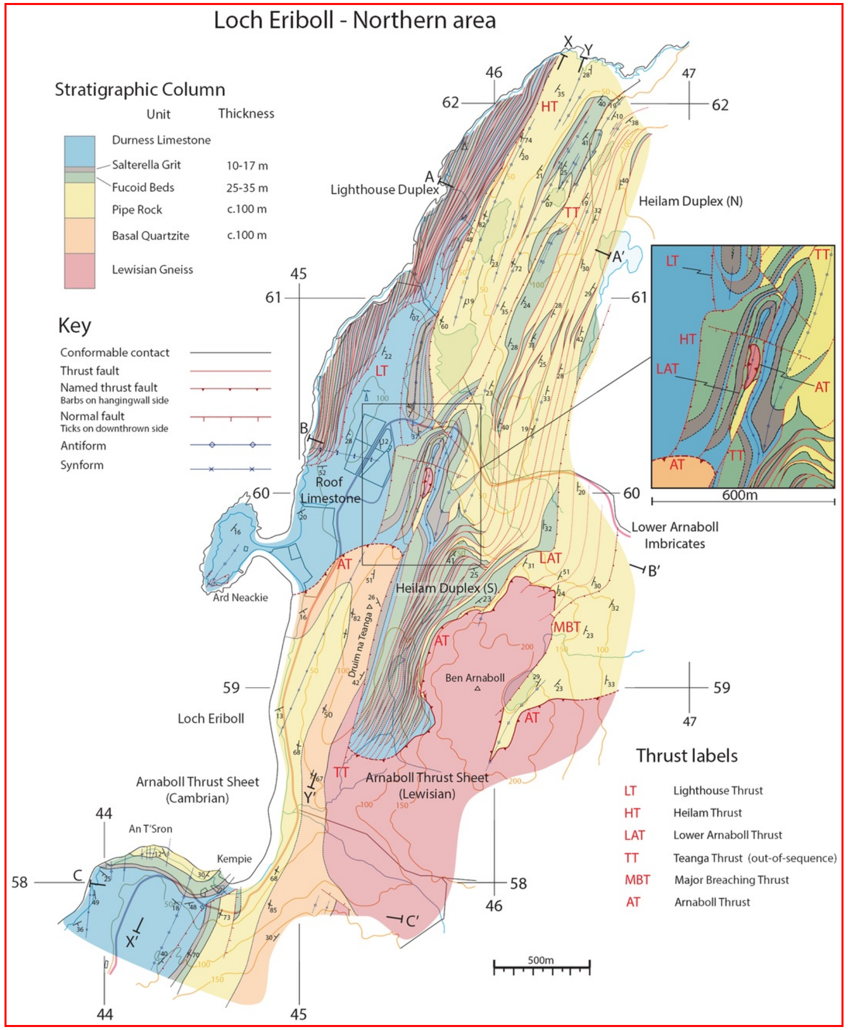
The Loch Eriboll area is one of the classic regions of the Moine Thrust zone showing excellent examples of ductile mylonites along both the Moine and Arnaboll thrusts, classic brittle thrusts and folds (Fig. 3), and a well-exposed imbricate sequence along the northwest coast. We extend our study of the Moine thrust zone to the hangingwall schists, gneisses and migmatites of the hinterland, the Moine Supergroup, and also to the Lewisian foreland to the west. Post-Caledonian normal faults have down-faulted the Moine Thrust zone rocks to the west allowing further constraints on the westward extension of the thrust sheets.



~~Figure 3~~Fig. 3 Photograph of a small-scale west-verging thrust with hangingwall anticline in Cambrian quartzites (Pipe Rock) at Ben Heilam, Loch Eriboll region.

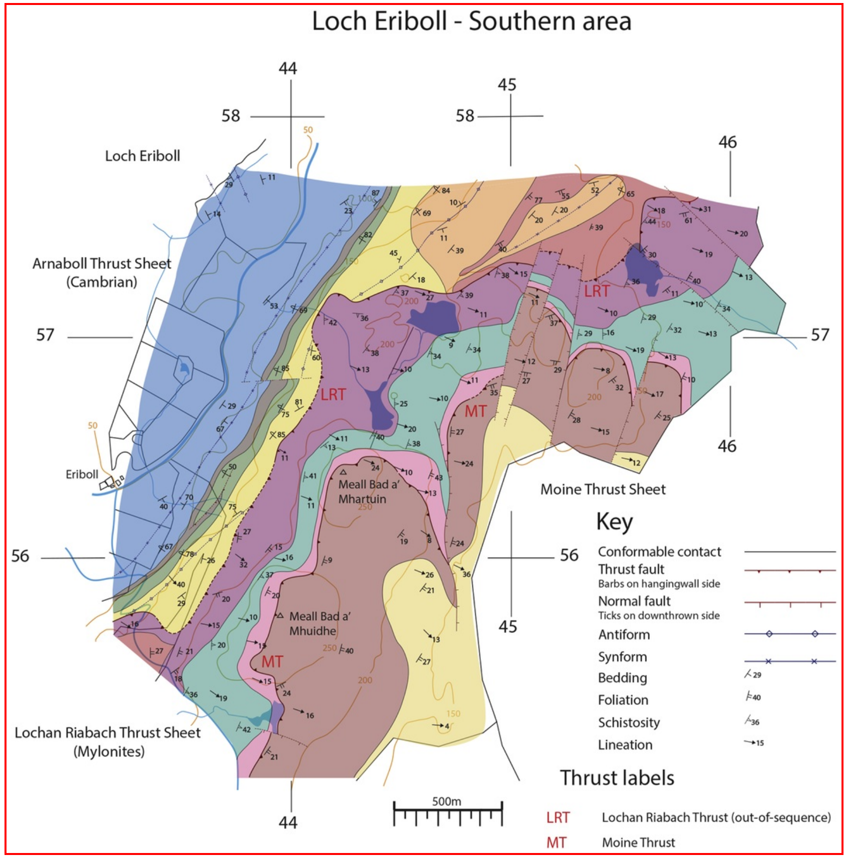
alt-text: Fig. 3

In this paper we attempt to provide deeper insight into the processes of mountain building in NW Scotland. We do this by providing an up-to-date review of the regional geology, alongside presenting results from a new detailed study in one of the key windows into this mountain belt: Loch Eriboll. We present new maps, balanced and restored cross sections from fieldwork at Loch Eriboll (Figs. 4, 5, 6, 7, 8, 9). We also present a cross-section from the Moine thrust hinterland west as far as Sango Bay and Faraid head, the most westerly exposures of Moine mylonites (Fig. 10). We use these maps and sections, together with the numerous earlier mapping studies, to infer geological processes including sequence of thrusting, shortening estimates and regional tectonic implications for this classic fold-thrust belt in the NW Scottish Highlands. Referring to these profiles, we speculate on the origins of the schists of the Moine Supergroup to the east, and the regional significance of the Outer Isles and Flannan thrusts to the west in the Outer Hebrides. Finally, we reflect on the metamorphic sequence overlying the Moine Thrust, and draw parallels to Himalayan style orogenesis.



~~Figure 4~~Fig. 4 Geological map of the Moine Thrust zone in the Loch Eriboll area showing lines of cross-sections in Fig~~ures~~s. 5 and 6.

alt-text: Fig. 4



~~Figure 5~~Fig. 5 Geological map of the southern part of the Loch Eriboll area with balanced cross-section A-A′.

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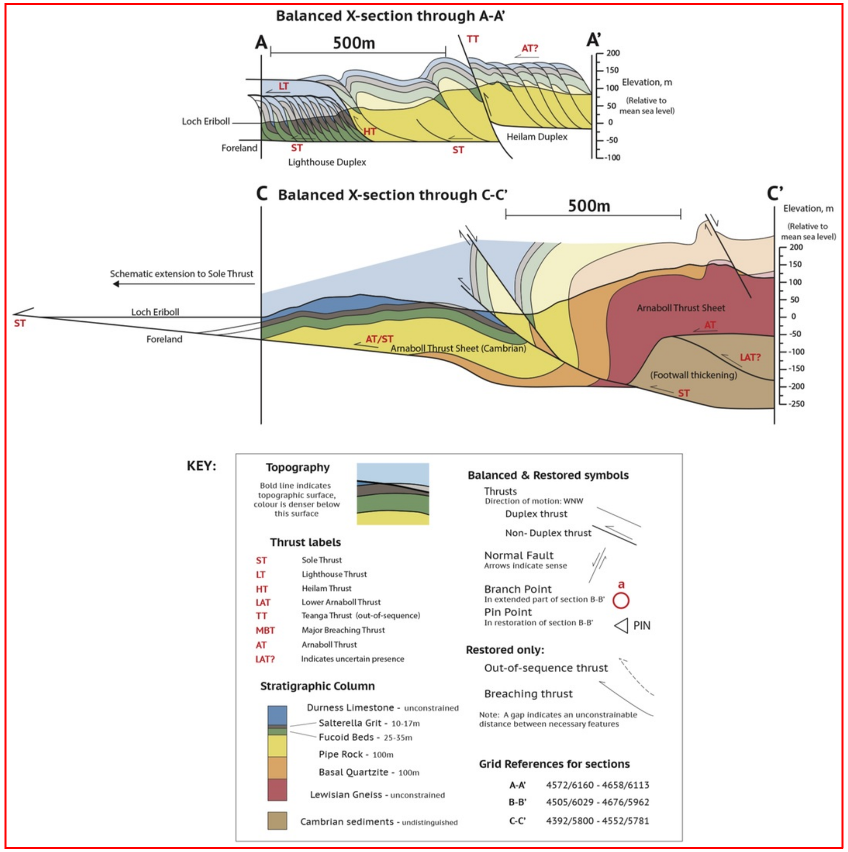

~~Figure 6~~Fig. 6 Balanced cross-sections A-A′ and C-C′ across the northern part of the Loch Eriboll area. See Fig. 4 for line of section.

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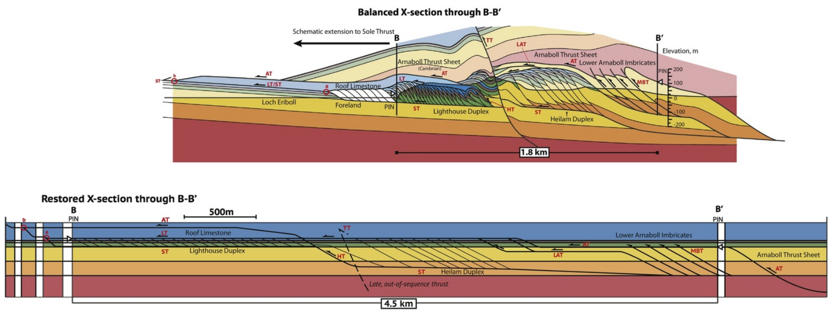

~~Figure 7.~~Fig. 7 Balanced and restored cross-section B-B′ across the northern part of the Loch Eriboll area. See Fig. 4 for line of section. Key is as per Fig. 4.

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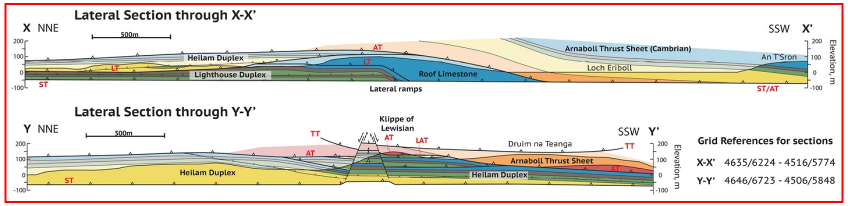

~~Figure 8.~~Fig. 8 Lateral sections X-X′ and Y-Y′ through the northern part of the Loch Eriboll area. See Fig. 4 for line of section. Key is as per Fig. 4.

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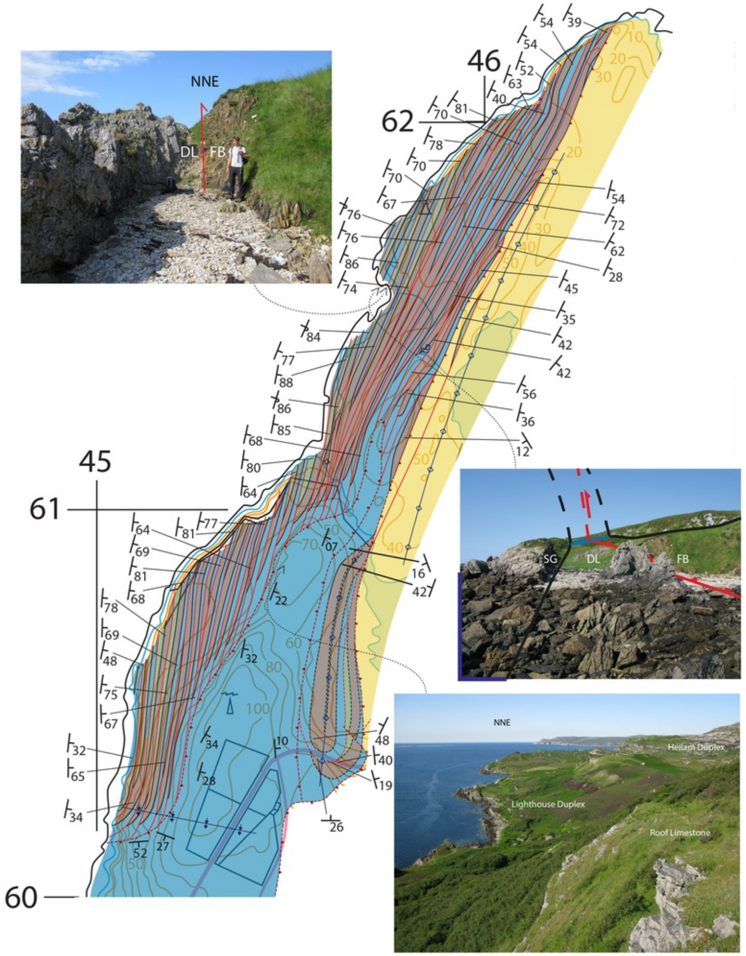

~~Figure 9.~~Fig. 9 Geological map of the coastal imbricate structures, northern part of the Sole Thrust, Loch Eriboll. Photos all looking north showing imbricate structures; FB- Fucoid beds; SG- *Salterella* Grit; DL- Durness limestone.

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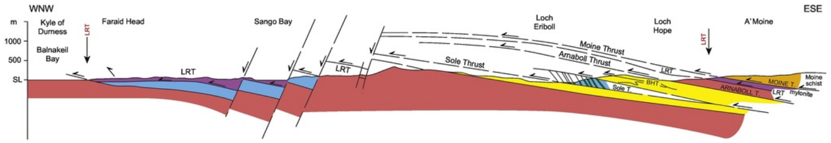


~~Figure 10.~~Fig. 10 Cross-section of the Moine thrust zone from the Kyle of Durness and Faraid Head to Loch Eriboll and A~~-~~'Moine.

alt-text: Fig. 10

~~2.~~2 Regional ~~T~~tectonic setting

After the early breakup of Rodinia at ~670 Ma, NW Scotland was situated along the Laurentian margin to the Iapetus Ocean (Dewey and Shackleton, 1984; Woodcock and Strachan, 2000; Dewey et al., 2015). The Caledonian orogeny resulted from the closing of the Lower Paleozoic Iapetus Ocean and collision of Laurentia with Avalonia and Baltica (Dewey and Shackleton, 1984; Woodcock and Strachan, 2000; Strachan et al., 2002a, ~~b~~(omit 'b'); Dewey and Strachan, 2003; Kinney et al., 2003). The suture zone runs along the Southern Uplands of Scotland, where ophiolites and deep-sea sedimentary rocks are exposed. Folding, thrusting and crustal thickening in the Scottish Highlands resulted in regional Barrovian facies metamorphism in both the Moine Supergroup (NW of the Great Glen Fault) and the Dalradian Supergroup (SE of the Great Glen), both likely part of one contiguous metamorphic terrane prior to strike-slip movement along the Great Glen Fault. U-Pb dating suggests that the Caledonian orogeny comprised two tectonic-metamorphic events: the Grampian (475–460 Ma) and the Scandian (435–415 Ma) events (Oliver et al., 2000; Strachan et al., 2002a, b(omit 'b'); Kinney et al., 2003; Viete et al., 2013; Ashley et al., 2015). In addition, Bird et al. (2013) proposed a Late Ordovician 'Grampian II' event based on Lu-Hf and Sm-Nd garnet ages of 445–450 Ma. The Scandian orogeny ended with numerous granite intrusions and deposition of the Devonian Old Red Sandstone across Scotland beginning at ~416 Ma (Dewey and Shackleton, 1984). There appears to be no evidence for the Scandian event south of the left-lateral Great Glen Fault, and amounts of strike-slip offset along the Great Glen fault remain disputed. Comparison to modern orogens such as the Himalaya and Karakoram (Searle, 2015), suggests that the Caledonian orogeny may have been one continuous, possibly pulsed, metamorphic episode that lasted for ~~more than~~ >50–60 Ma.

Timing of thrusting events along the MTZ in the Assynt region are constrained by U-Pb dating of alkali syenite intrusions within the MTZ at Loch Borralan (429.2 ± 0.5 Ma) and Loch Ailsh (430.6 ± 0.3 Ma) in the Assynt Window (Fig. 1), and the Loch Loyal syenite (~425 Ma) cutting the Moine schists east of Loch Eriboll (Goodenough et al., 2011). Both the Loch Borralan and Loch Ailsh intrusions were emplaced prior to final shearing along the bounding Moine and Ben More thrusts (Searle et al., 2010). The Loch Loyal syenite intrudes the Moine Supergroup above the Moine Thrust. The transfer of displacement from the ductile Moine thrust to the brittle structurally lower thrust sheets must have occurred after 430 Ma (Freeman et al., 1998). Although there are no alkali intrusions in the MTZ in Loch Eriboll, the structural continuity suggests temporal coincidence with the timing of thrusting in Assynt.

~~3.~~3 Tectono-stratigraphic units

The Laurentian foreland includes Archean Lewisian gneiss (2.9–1.75 Ga) unconformably overlain by Proterozoic continental sandstones and conglomerates of the Torridon Group. Several half-grabens across northern Scotland bounded by pre-Cambrian east-dipping normal faults were infilled with Torridon Group sandstones. Cambrian quartzites, with distinctive *Skolithos* trace fossils ('Pipe rock') in the upper part, unconformably overlie both the Lewisian and Torridonian (McKie, 1990). In the area west of Loch Eriboll, the Cambrian sediments thicken outboard towards the east and the Ordovician Durness dolomites unconformably overlap to rest directly on the Lewisian basement around Durness village (Fig. 2). Thin brownish silts (Fucoid beds) and gritty sandstones (*Salterella* grit) overlie the quartzites; the whole sequence is blanketed by an Ordovician marine transgression during establishment of a wide marine shelf carbonate sequence (Durness dolomites, limestones). The protolith of the Moine schists must be a lateral, time-equivalent unit to the Torridonian (Krabbendam et al., 2008; Strachan et al., 2010), but of a more distal, yet still psammitic facies (Fig. 2b). These former passive continental margin sedimentary rocks, together with their basement gneisses and Torridonian cover rocks have been affected by WNW-facing folding and thrusting that has occurred along at least four major thrust sheets.

The Moine Supergroup (Morar Group) schists carried on the Moine thrust comprise a sequence of dominantly psammitic or semi-pelitic schists structurally above inliers of Lewisian basement amphibolite or granulite facies gneisses (Strachan and Holdsworth, 1988; Holdsworth et al., 2001; Strachan et al., 2010). Metamorphic grade decreases down-section from east to west, from sillimanite grade migmatite (Sutherland migmatite complex) to greenschist facies rocks directly above the Moine thrust (Soper & Brown, 1971; Johnson and Strachan, 2006; Thigpen et al., 2013; Ashley et al., 2015). A series of syn- to post-metamorphic ductile shear zones or thrusts within the Moine schists (Skinsdale, Sgurr Beag, Naver, Ben Hope thrusts from upper to lower) place higher grade rocks onto lower grade rocks.

Extensive mylonites along the Moine Thrust are variously derived from Lewisian gneiss, Cambrian quartzite and Moine schists protoliths (Law et al., 1984, 1986). Beneath the mylonites the Moine thrust zone comprises at least three major thrust sheets affecting Lewisian basement gneisses, Torridonian sedimentary cover rocks and Cambro-Ordovician passive margin sediments. The upper thrust sheet beneath the brittle Moine Thrust is the Lochan Riabhach thrust (Holdsworth et al., 2006) that places the various mylonite units over the Arnaboll thrust sheet. The classic mylonite sequence described by Lapworth (1883-84, 1885), lies at the base of the Arnaboll Thrust Sheet, which also comprises Lewisian basement gneisses and Cambro-Ordovician cover. The Arnaboll thrust placed these rocks over the intensely imbricated Cambro-Ordovician sedimentary rocks of the Sole thrust sheet.

The Arnaboll thrust is the along-strike equivalent to the Glencoul or Ben More thrust further south in the Assynt region, all of which carry allochthonous thrust sheets of Lewisian basement above imbricated thrust sheets of Cambro-Ordovician sedimentary rocks beneath (e.g. Peach et al., 1892; Elliott and Johnson, 1980; Coward, 1983; British Geological Survey, Assynt sheet, 2007; Searle et al., 2010). The lowermost Sole thrust is continuous along the length of the Moine thrust zone and forms the basal detachment above the stable foreland to the west.

~~4.~~4 Moine thrust sheet

The hinterland of the Moine thrust is the Moine Supergroup, an extremely thick sequence of monotonous psammites, semi-pelites and pelites, with a migmatite complex (Sutherland migmatites) towards the upper levels, and inliers of Lewisian basement beneath (Strachan et al., 2010). Detrital zircon ages from the Moine Supergroup have Archean to early Neoproterozoic ages and have been interpreted as sediments derived from the erosion of the Grenville-Sveconorweigan orogen (Cawood et al., 2015). Regional Barrovian metamorphism occurred during the earlier Grampian event (~475~~-~~–445 Ma; Ashley et al., 2015) and the later Scandian orogenic event (435~~-~~–415 Ma), both probably part of a continuum during Caledonian mountain building. The presence of bimodal magmatism (gabbros-granites) in the Scottish Highlands suggest a complicated pre-Grampian history. It has been suggested that sillimanite-grade metamorphism leading to formation of the Sutherland migmatites was related to contact metamorphism around the Grampian granites and gabbros (Viete et al., 2013). Given the PT conditions (Ashley et al., 2015) and the regional extent of the classic Barrovian metamorphism it seems far more probable that metamorphism was regional, related to both crustal thickening and heat input from granitic intrusion sources in the deep crust.

Peak conditions immediately above the Moine thrust are 450~~o~~°C and 5.0 kbar with temperature and pressure increasing up-section towards the east to 733~~o~~°C and 9.5 kbar beneath the Naver thrust (Ashley et al., 2015). Several syn- to post-peak metamorphic thrusts have been mapped above the Moine thrust, notably the Ben Hope, Naver, Sgurr Beag and Skinsdale thrusts in ascending structural order. The highest temperatures (>700~~o~~°C) are recorded in the migmatites of the Naver and Skinsdale thrust sheets (Ashley et al., 2015). U-Pb monazite ages of 431 ± 10 Ma have been reported from migmatites above the Naver thrust (Kinney et al., 1999; Friend et al., 2000). The relationship between the Moine rocks NW of the Great Glen fault and the Dalradian complex rocks, SE of the Great Glen fault remains unclear. In contrast to the Moine rocks, U-Pb zircon (SHRIMP) ages of 472~~-~~–471 ± 5.9 Ma to c. 465 Ma are reported for peak metamorphism from the Dalradian complex SE of the Great Glen (Oliver et al., 2000; Viete et al., 2013).

Both deformation and metamorphism in the Moine schists progressed mainly from east (hinterland) to west (foreland) with time. The Ben Hope thrust sheet records PT conditions of 590~~o~~°C and 7.8 kbar followed by prograde burial and heating to 675~~o~~°C and 8.5 kbar (Ashley et al., 2015). At the base of the Moine thrust sheet, PT conditions of 450~~o~~°C and 5.0 kbar reflect the latter emplacement stage of the Moine thrust (Ashley et al., 2015), consistent with temperatures derived from quartz c-axis fabric opening angles (Law, 2014; Thigpen et al., 2010a, b, 2013 (omit 'b')). The Moine thrust is a major tectonic feature, corresponding to a lithological as well as structural break. Whereas temperatures of deformation and metamorphism above the Moine thrust are generally >450~~o~~°C, those at structurally lower levels beneath the mylonites are <275~~o~~°C (Johnson et al., 1985). The overall thermal structure affirms an inverted metamorphic profile across the Moines similar to other large structurally inverted metamorphic sequences associated with large thrust faults such as the Himalayan Main Central thrust (Searle et al., 2008; Streule et al., 2010).

~~5.~~5 Moine, Lewisian and ~~Q~~quartzite-derived mylonites

The Moine Thrust includes a wide variety of ductile deformed mylonites derived from rock facies both above (Moine schists, Lewisian gneiss) and foreland-related lithologies below (Lewisian gneiss, Cambrian quartzites, etc.) the Moine Thrust. Microstructural studies, rigid grain vorticity analyses (e.g. White et al., 1982; Law et al., 1986; Thigpen et al., 2010a, b) combined with deformation temperatures as derived from quartz c-axis opening angle thermometers or Ti-in quartz thermometers (e.g. Kruhl, 1998; Law, 2014) show that most transects show a combination of simple shear and pure shear. Quartz recrystallization microstructures in the mylonites show a transition from small quartz fabric opening angles (Grain Boundary Bulging~~-~~/~~-~~Subgrain Rotation microstructures) within the MTZ to large opening angles (Grain Boundary Migration microstructures) in the upper part of the profiles into the Moines (Law, 2014). Complex changes in deformation temperatures across shear zones, strain rate and fluid (water) weakening all affect the recrystallization microstructures.

Mylonites derived from the mainly psammitic Moine schists above are rich in phyllosilicates and show spectacular S-C fabrics indicative of west-directed simple shear, as well as a significant component of pure shear. S-tectonites show a strong foliation with little or no penetrative stretching lineation; L-tectonites show strong development of stretching lineation with little planar fabric; L-S tectonites show both foliation and lineation development and are assumed to form under conditions of plane strain (Passchier and Trouw, 1996; Thigpen et al., 2010b). Moine thrust mylonites show a strong lineation, well-developed S-C fabrics and strong evidence for both simple shear and pure shear. Lewisian-derived mylonites include gneissic lithologies like the K-feldspar biotite mylonites with rotated porphyroclasts and more enigmatic lithologies such as the 'Oystershell rocks' – chlorite-muscovite phyllonites, seen particularly well at Sango Bay. Lewisian gneiss and mafic intrusions that were subsequently sheared and mylonitized are exposed as rocks showing interlayered orange-coloured quartzo-feldpathic horizons with darker mafic layers composed of actinolite – chlorite mylonites (Holdsworth et al., 2010). Quartz mylonites derived from Cambrian quartzites are monomineralic and particular useful for quartz microstructures and fabric (Law et al., 1984, 1986; Law and Johnson, 2010).

Mylonitisation along the Arnaboll thrust is apparent in the development of a clear high-strain fabric, with mylonitic lineations aligned towards 290°. Quartz is dynamically recrystallized in the fault rocks in the subgrain rotation

(SGR) regime, while feldspars have undergone brittle fragmentation and show undulose extinction. The differing responses of quartz and feldspar offer a good constraint on the temperature conditions during deformation. The above microstructural criteria correspond to temperatures of deformation at between 400 and 450 °C (Passchier and Trouw, 1996). Thigpen et al. (2013) assigned deformation temperatures of ~420 ± 50 °C to samples in the immediate hangingwall of the Moine thrust to the NE of Loch Eriboll, which originated at similar depths to the Arnaboll mylonites.

Mylonites are not restricted to the Moine thrust. Indeed, the type locality from Lapworth (1885) is on the Arnaboll thrust (White et al., 1982; Holdsworth et al., 2007, 2008; White, 2010; Thigpen et al., 2010a, b (omit 'a')), structurally beneath the Moine thrust on Ben Arnaboll in the northern Loch Eriboll area (Figs. 4, 5). These mylonites also show flattening fabrics with well-developed lineations, S-C fabrics indicative of westward transport, and evidence of formation under general shear (a combination of simple shear and pure shear). The restoration of balanced cross sections shows that these mylonites must have formed at a similar depth as the Moine thrust mylonites but in a more foreland position. It is likely that all the deeper hinterland thrusts bearing mylonites initiated from a similar depth.

~~6.~~6 Position of the Moine thrust

The mapped position of the Moine thrust has been the subject of much discussion. The original mapping by Nicol, Clough, Peach, Horne and others in the NW Highland Survey mapped the Moine thrust as following the ductile contact between the Moine (and Lewisian)-derived mylonites above from the mylonitic Cambrian quartzite-derived mylonites beneath. This boundary was used by Law et al. (1986) working in the classic Stack of Glencoul locality and many subsequent workers. However, Johnson (1965) and Johnson (1967) considered the Moine thrust a late brittle feature and therefore mapped it as following the base of the mylonite sequence. Others have mapped regionally significant thrusts within the mylonite sequence, notably the Creagan thrust separating “Oystershell” mylonites above from Cambrian quartzite-derived mylonites below (Thigpen et al., 2010a, b) and the Lochan Riobach thrust separating Lewisian mylonites above from imbricated unmylonisited rocks of the Arnaboll thrust sheet below (Holdsworth et al., 2006).

In reality it may not be universal that the same lithologies underlie a specific thrust along the length of the Moine Thrust zone. Mylonites cannot be used like stratigraphy. Rather they represent ductile shear fabrics superimposed on whatever lithologies the thrust sheet overlies. Thus, as thrusts climb up ramps in the transport direction they will overlay successively different lithological units both across strike and along strike. For these reasons we prefer to map the major mylonite bounding thrusts as regional structures, notably the Moine thrust defining the top of the mylonite section, and the Lochan Riabach thrust the base of the mylonite section, following Holdsworth et al. (2006). Inter-mylonite thrusts, such as the Creagan thrust (Thigpen et al., 2010a, b) may vary along strike as thrusts are progressively following flats and ramps over different footwall units.

The Moine thrust shows a range of different structural levels from deep locations where ductile mylonites are still attached to the base of the Moines, such as at Eriboll, to later sections where out-of-sequence motion has resulted in mylonites resting almost directly on foreland units, such as at Knockan crag in the southern Assynt Window (Elliott and Johnson, 1980; British Geological Survey, 2007; Searle et al., 2010).

~~7.~~7 Arnaboll thrust sheet

The Arnaboll Thrust carries Lewisian basement gneiss and Cambro-Ordovician sedimentary cover over the Sole thrust sheet (Figs. 4, 5). The Lewisian component of the Arnaboll thrust sheet thins to the west, before being cut-off around Druim na Teanga, where the Arnaboll thrust ramp intersects the stratigraphic horizon between the Lewisian and Basal Quartzite. Thickening in its footwall after motion on the Arnaboll Thrust has resulted in folding of the Arnaboll thrust sheet, including a tightly folded klippe that is exposed above Heilam. The thrust sheet is bulged up significantly by thickening in the Heilam duplex, before plunging down to the W in steep-to-overturned beds in Druim na Teanga and east of Kempie (Figs. 4, 6, cross section C). These steep-to-overturned beds are the forelimb of a highly asymmetrical fold, the back-limb of which rises gently west of Kempie in the An T-Sron headland in an open antiform (Figs. 4, 6).

The Arnaboll thrust surface is best exposed around Ben Arnaboll, particularly where it separates Lewisian gneiss above from Cambrian Pipe Rock below. Mylonitisation and retrogression of the dominantly amphibolite facies gneiss to greenschist facies occurred during motion on the Arnaboll thrust, as seen in a band of fault rocks < 2 m thick constituting the thrust surface. Retrogression is evident in the development of phyllosilicates such as sericite at the expense of feldspars and chlorite at the expense of mafic minerals (Wibberley and Butler, 2010). The formation of these retrograde products requires fluid-present reactions. Fluid ingress may have been aided by the creation of a plane of weakness during faulting, while the creation of weak, hydrous products may have promoted the localisation of strain within the narrow zone of retrogression.

The Lewisian gneiss of the Arnaboll thrust sheet is part of the dominantly amphibolite facies rocks of the Laxfordian Complex of NW Scotland. This complex bears the metamorphic and structural overprint of the amphibolite facies Laxfordian event at 1.9 Ga, in which the granulite facies Scourian Complex gneisses intruded by basic dykes of the Scourie Dyke swarm were deformed and retrogressed to amphibolite facies. Pegmatite veins bearing large quartz and K-feldspar phenocrysts intruded the host Lewisian gneiss. Both deformed amphibolite dykes and pegmatite veins are observed intruding gneisses on Ben Arnaboll. The host gneiss is predominantly foliated biotite-bearing syeno-granite, as well as rocks that show a mix of mafic and felsic constituents in strongly gneissic bands.

~~8.~~8 Sole ~~T~~thrust sheet

The Sole thrust sheet is entirely made up of the Cambro-Ordovician succession: Basal Quartzite, Pipe Rock, Fucoid Beds, *Salterella* Grit and Durness Limestone (in stratigraphic order from lowest to highest). Deformation within this tectonic unit was thin-skinned and occurred in the brittle regime; faulting is generally localised onto discrete planes, with cataclasis occasionally apparent in the surrounding few meters of rock.

There is a great deal of structural complexity within the Sole Thrust Sheet in the Loch Eriboll area. Three further structural divisions were mapped within the Sole thrust sheet: the Lower Arnaboll imbricates, the Heilam Duplex and the Lighthouse Duplex (as defined in Coward, 1984).

The Lower Arnaboll imbricates are a series of thrusts that ramp up from a basal flat in the footwall of the Arnaboll thrust, and breach the Arnaboll thrust surface, locally emplacing Cambrian quartzite (Pipe Rock) on top of Lewisian gneiss. The individual thrusts are therefore named breaching thrusts (Wibberley and Butler, 2010). The breaching thrust with the largest offset has created a large asymmetrical antiform in the Pipe Rock and Lewisian above on Ben Arnaboll that explains the notch-like map expression of these two units (Wibberley and Butler, 2010). The foremost of the Lower Arnaboll imbricates is the Lower Arnaboll Thrust. The Lower Arnaboll Thrust surface exhibits oblique to lateral ramps in the Heilam area. In the southernmost part of the Heilam Duplex, the Arnaboll Thrust forms the roof thrust to the Heilam Duplex, juxtaposing Lewisian directly above Durness Limestone. Moving north, however, the Lower Arnaboll Thrust branches off the Arnaboll Thrust, before a lateral ramp satisfies the necessity for a long flat in the Arnaboll Thrust that enables Pipe Rock to underlie the Arnaboll Thrust in the Klippe east of Heilam Cottage (Figs. 4, 7, 8).

The Heilam Duplex comprises thrust slices of Cambrian-Ordovician rocks, with a floor thrust at least as deep as the Pipe Rock, likely cutting shallowly up from within the Basal Quartzite (Fig. 7). The Heilam Duplex is continuous from the Ben Heilam area, where deeper structural levels are exposed, to the area west of Ben Arnaboll, where the upper structural levels are exposed (Figs. 4, 8, section Y). Our interpretation of the structure, differs from that of Coward (1984), who inferred ‘tear faults’ separating the two regions. We argue that such faults are not required, indeed we observe continuity of outcrop around the road section that is good evidence against a tear fault solution (Fig. 4).

The Lighthouse Duplex comprises tightly-packed, steeply dipping thrust slices of Camro-Ordovician sediments (Fig. 9). The floor thrust is in the Fucoid Beds, and thrusts ramp from this floor thrust up through Salterella Grit and branch with a roof thrust in the Durness Limestone. Butler (1982) noted that the siltstones and limestones offered lower resistance horizons, preferentially adopted by flat thrust surfaces. We interpret the overlying thickness of younger Durness Limestone as lying atop a (flat) roof thrust. Thrust slices in the Lighthouse duplex are often as little as several meters wide, and lateral branching occurs in several locations, where new thrust surfaces supersede those that they splay from. We find no evidence for the steeply dipping floor to the Lighthouse Duplex inferred by Coward (1984), indeed the presence of a hitherto unidentified thrust slice at the rear of the duplex, east of the overlying limestone exposures, indicates that the floor thrust must be relatively shallow (Figs. 7, 9). The Lighthouse Duplex rises up to the north on account of lateral ramping that occurs NE of Ard Neackie (Fig. 8). We detect minor extensional faulting in the hangingwall overlying the lateral ramps, consistent with the geometrical expectation that some thinning should occur above the ramps to conserve volume.

9 Devonian and Permian-Triassic normal faulting

Two episodes of post-Caledonian rift-related normal faulting are known from Northern Scotland and the West Orkney basin. Wilson et al. (2010) identified one phase of Devonian ENE-WSW extensional faulting and a phase of Permian-Triassic NW-SE extension. Both these sets of normal faults dip towards the east, in contrast to the well-exposed normal faults exposed on land along the north coast of Scotland, which dip steeply to the west. Examples of these west-dipping normal faults are well exposed at Faraid Head and Sango Bay (Fig. 10). The NNE-SSW aligned fault at Sango Bay shows a brittle fault breccia with angular clasts of all lithologies (Lewisian gneiss, Torridonian and Cambrian sandstones, Durness limestone), including mylonites in a red oxidised-Fe sandy matrix.

The normal faults effectively drop the Moine thrust sheet successively down to the west. Moine thrust zone mylonites are exposed at both Sango Bay and Faraid Head, ~13 km west of the Sole thrust in Loch Eriboll (Fig. 10). Thus, the Moine thrust sheet must have extended at least this far west of its present exposure. Neither the east-dipping Moine thrust nor the post-Caledonian west-dipping normal faults are clearly defined on the MOIST seismic line (see section below).

10 Lithospheric structure

Three major regional seismic lines were shot offshore of the north coast of Scotland during the 1980s for BIRPS (British Institution Reflection Profiling Syndicate). The MOIST (Moine and Outer Isles Seismic Traverse) and WINCH (Western Isles – North Channel) seismic reflection profiles were shot in 1981–1982 and the DRUM line (Deep Reflections from the Upper Mantle) in 1984 (Smythe et al., 1982; Brewer and Smythe, 1984). These seismic profiles show clear reflections of the Moho and the major crustal structures (Fig. 12). The Moho is well imaged as a remarkably flat reflector at ~25 km depth beneath mainland Scotland. A deeper reflector (the ‘W-reflector’) lies at 45–40 km depth within the upper mantle (Snyder et al., 1997), although it is unclear precisely what this seismically reflective horizon represents.

The Moine thrust is poorly imaged on the MOIST reflection seismic profile. It is interpreted to dip at ~20° east at depths of ~5–17 km beneath post-Caledonian sediments in the upper ~5 km offshore northern Scotland (Fig.

12). It is the westernmost of a series of east-dipping reflectors that appear to flatten at 17~~-~~–20 km depth (Brewer and Smythe, 1984; Snyder et al., 1997). This structure is consistent with fold and thrust belt geometry as deduced from surface mapping. Gravity and magnetic signatures suggest that the aut~~h~~ochthonous Lewisian basement, up to 30 km thick beneath the Outer Hebrides and western Scotland mainland, may only extend 20~~-~~–30 km east of the Moine thrust (Watson & Dunning, 1979). However, Lewisian inliers within the Moine schists are known from surface mapping (Holdsworth et al., 2001). Butler and Coward (1984) proposed that some of the east-dipping reflectors are due to imbrication of Lewisian basement in crustal-scale duplexes, which would imply Caledonian age crustal thickening of an originally eastward thinning Lewisian basement.

Two major structures are imaged to the west within the foreland – the Outer Isles thrust (OIT) and the Flannan thrust (FT), both dipping at 25~~-~~–35~~o~~° east. Both thrusts were interpreted as predominantly Caledonian structures because of their similar dip and strike as Caledonian thrust structures, although there is evidence of multiple phases of motion along the OIT which is now thought to have been active during Proterozoic, Carboniferous and Mesozoic time (Imber et al., 2001). The Outer Isles thrust crops out for ~~more than~~ >180 km along the east coast of the Outer Hebrides and dips at 20~~-~~–30~~o~~° east or ESE (Sibson, 1977; Imber et al., 2001). From field and microstructural evidence, Imber et al. (2001) showed evidence for frictional deformation during presumed early Caledonian thrusting to viscous flow during later Caledonian sinistral strike-slip faulting. The Flannan reflector is a well-imaged structure that dips east at an angle of 30~~o~~° extending from ~20 km depth in the crust crossing the Moho into the upper mantle to a depth of 80 km. It is one of the most enigmatic and unique such structures imaged in the upper mantle of any mountain belt, and precisely what structure it is, remains uncertain. Interpretation of the MOIST seismic reflection profile suggests that the fault cuts and offsets the Moho at >25 km depth (Smythe et al., 1982).

Since the Moine Thrust shows the classic thick to thin-skinned thrusting from the eastern hinterland to the western foreland, deep thrusts would not be expected in the foreland region at all, let alone extending down into the mantle beneath the Moho. The OIT, cropping out to the west on the Hebridean foreland, extends down to the upper mantle and the Flannan reflector beneath this extends further down into the upper mantle. We suggest that neither the OIT nor the Flannan reflector (or thrust) has any relationship to the Moine thrust zone, either spatially or temporally. Even in large-scale Cenozoic mountain belts like the Himalaya, there is no evidence for any thrusts extending down into the mantle, and no evidence for any deep thrusts in the foreland region (Searle, 2015). The tectonic significance of either of these major foreland structures remains unexplained in the context of Caledonian thrust tectonics.

~~11.~~11 Discussion: evolution of the Moine ~~T~~thrust zone

~~11.1.~~11.1 Thrust geometry and propagation

The overall sequence of thrusting both across the Moine thrust sheet and the underlying Moine Thrust zone units was mainly a foreland-directed piggy-back sequence (Elliott and Johnson, 1980; McClay and Coward, 1981; Butler and Coward, 1984; Butler, 1987; Holdsworth et al., 2006; Searle et al., 2010). Above the MTZ in the Moine thrust sheet, thrusts developed in-sequence from the Skinsdale, Sgurr Beag, and Naver thrusts in the east that carry sillimanite-grade migmatites and gneiss above, to the Ben Hope thrust that carries amphibolite facies rocks along the Moine thrust and emplaces the hinterland metamorphic rocks over the Laurentian margin sediments (Thigpen et al., 2013; Ashley et al., 2015). Mylonites along the Moine thrust were produced by ductile shearing at depths > 15~~-~~–20 km, and were derived from Lewisian basement gneisses, Cambrian quartzite and Moine psammitic rocks.

In the Moine thrust zone thrusting also propagated in-sequence, down-structural section with time, from the Moine thrust to the Lochan Riabhach thrust to the Arnaboll thrust to the Sole thrust. There is some evidence that the Lochan Riabhach thrust may have had some minor out-of-sequence motion along it at a later stage of thrusting. The Arnaboll thrust also has mylonites (the type section of Lapworth (1883-84)) and has been folded along with its footwall after thrust emplacement. There is some evidence in the Assynt Window for late, final out-of-sequence motion along the Moine thrust with truncated folds and cleavage, for example at Knockan crag in the Assynt Window (Elliott and Johnson, 1980; Coward, 1983; British Geological Survey, 2007), but in the Loch Eriboll area there is no strong evidence for major out-of-sequence thrust motion along the Moine thrust. It could be argued that the Lighthouse thrust, local to the northern part of the Loch Eriboll region, places younger Ordovician Durness limestones/dolomites over older limestones at the top of the Lighthouse Duplex in an out-of-sequence fashion (Fig. 9). However, the westward extent of the Durness limestones above the Lighthouse Thrust may balance the shortening taken up in the duplex structurally below (Fig. 7), meaning that out-of-sequence motion need not be invoked; motion was along a flat. There is also good evidence of late breakback thrusting along the steeply-inclined Teanga thrust (Coward, 1984) that cuts the Sole and Arnaboll duplexes, uplifting the hangingwall by ~100~~ meters~~ m (Figs. 4, 6, 7).

~~11.2.~~11.2 Shortening estimates

Previous estimates of the amount of shortening along the Moine thrust belt include Elliott and Johnson (1980) who, on the evidence of balanced and restored sections across the Assynt Window, concluded that the minimum slip on the Moine Thrust was ~77 km, probably ~~more than~~ >100 km, with >20~~-~~–25 km of slip along the Glencoul thrust and c. 28 km along the Ben More thrust. From our balanced and restored cross-sections, we provide a new estimate for the shortening within the highly complex Sole Thrust Sheet: the minimum amount of shortening in the Loch Eriboll transect is approximately 60% (Fig. 7). This is equivalent to 2.7 km of shortening between the two pin points on the section B-B~~'~~′ (~~fig~~Fig. 7). We do not attempt to restore the ductile deformed upper structural units and mylonites, which we cannot constrain. Added on to the shortening from Loch Eriboll is the 15 km distance between the Moine thrust at Loch Eriboll and the western extent at Faraid Head, where it has been downthrown to the west along several post-Caledonian normal faults (Fig. 10).

~~11.3.~~11.3 Restoration of the Caledonian thrust sheets

Two major phases of post-Caledonian rifting occurred during the Devonian, predominantly east of the Naver thrust, and Permian-Triassic mainly in the west (Wilson et al., 2010). These extensional faults must be restored first in order to infer the geometry of the older Caledonian structures. A schematic restoration of the Caledonian Northern Highlands of Scotland to ~430 Ma is shown in Fig. 11a. Lewisian basement gneisses extend west at least as far as the Outer Hebrides, and east at least 20–30 km east of the Moine thrust. Overlying the Lewisian basement in the east, a thick sequence of Moine metamorphic rocks show normal prograde metamorphic heating and burial with peak PT conditions of 450 °C and 5 kbar above the Moine thrust, increasing up-section to ~730 °C and 9.5 kbar above the Naver thrust (Ashley et al., 2015). The deepest buried and hottest rocks are the 11–12 kbar granulites that occur in the Naver thrust sheet (Friend et al., 2000), where U-Pb zircon ages record a mid-Ordovician Grampian event at ~471 ± 5.8 Ma (Viete et al., 2013) and ~464–461 ± 10 Ma (Kinney et al., 1999). U-Pb monazite ages record a later Scandian migmatisation event at 431 ± 10 Ma (Kinney et al., 1999). Thigpen et al. (2013) showed that the thermal sequence across the Northern Highland was largely intact and resulted from thrust stacking during the Scandian event. The widespread distribution of regional Barrovian metamorphism and PT conditions of Moine metamorphic rocks across the entire Northern Highlands clearly suggest a crustal thickening event and not a contact metamorphic event as suggested by Viete et al. (2013). The highest levels of the Moine series in northeast Scotland the deformed Strath Halladale granite has a U-Pb monazite of 426 ± 2 Ma (Kocks et al., 2006).

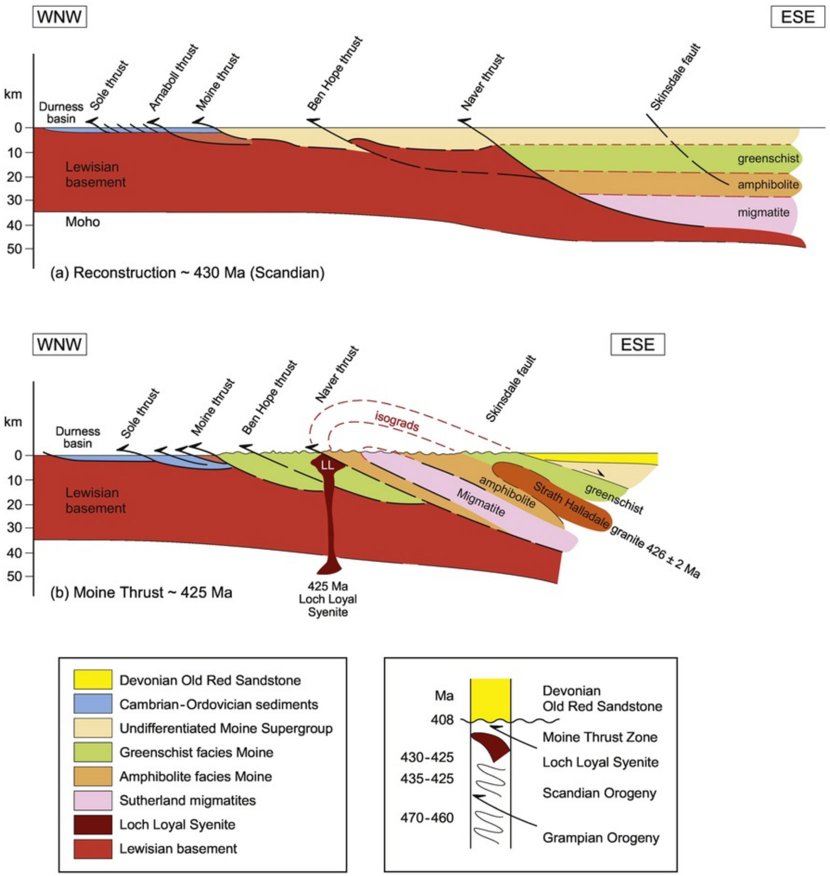
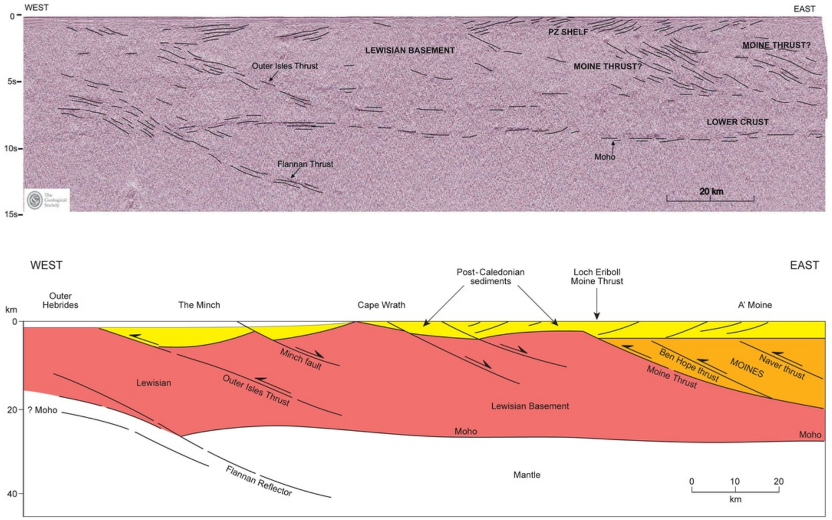


Fig. 11 (a) Reconstruction of the Scandian Moine metamorphic rocks across Northern Scotland and the Moine Thrust zone to ~430 Ma during high grade regional metamorphism and immediately prior to thrusting. Lewisian basement extends east tapering beneath the thick Moine metamorphic series which shows granulite and amphibolite facies rocks buried to depths of 11–12 kbar. (b) Reconstruction of Northern Scotland to ~425 Ma. Westward extrusion of the migmatite core above the Naver thrust is bounded below by the regional Barrovian metamorphic rocks of the Moine and Ben More thrust sheets, and above by the unmigmatised gneisses of the Skinsdale thrust sheet. The upper Moines are buried beneath the Devonian Old Red sandstone molasse sedimentary basin in eastern Caithness. The 425 Ma Loch Loyal syenite intruded up from mantle depths to its present position in the Ben Hope thrust sheet.

alt-text: Fig. 11



~~Figure 12.~~Fig. 12 (a) The MOIST seismic profile across offshore Northwest Scotland, after Snyder et al. (1997), courtesy of the Geological Society, London, and (b) our geological interpretation of the lithospheric profile.

alt-text: Fig. 12

Structural, metamorphic and geochronological data from Northern Scotland show that above the Moine Thrust an inverted PT gradient reaches up structural section to the central migmatite core of the orogeny, above the Naver thrust (Fig. 11b). Fabrics, and thrusts dip towards the ESE and lineations are generally east-dipping. This orogenic structure has remarkable similarities to the inverted metamorphic profile across the southern part of the Greater Himalaya, where the sillimanite-grade migmatite core extruded southward above the Main Central Thrust: the channel flow model (e.g. Searle, 2015). The uppermost part of the Moine Scandian metamorphic succession is buried beneath the unconformably overlying Devonian Old Red Sandstone in Caithness.~~-~~We suggest that some sort of channel flow may have occurred during the Scandian orogenic event (~430~~-~~–425 Ma) and that subduction was directed ~~toward~~towards the ESE during this time. Thus, the Moine Thrust zone and Northern Highlands represent a normal Himalayan-style pro-wedge, and not a retro~~-~~–backthrust zone (e.g. Strachan et al., 2002a, ~~b~~ (omit 'b')).

In the foreland region around Durness, Ordovician Durness limestone-dolomite unconformably overlie Lewisian gneiss. At Loch Eriboll, Cambrian quartzites onlap the basement and dip at a shallow angle (ca 10°) ESE beneath the Sole thrust. Torridonian rocks, a potential unmetamorphosed lateral-equivalent protolith for the Moine psammites are missing, with Cambro-Ordovician sediments lying unconformably directly on Lewisian basement. It is therefore difficult to infer the Moines as direct lateral correlatives with the Torridonian. It must be concluded that the protolith rocks of the Moine Supergroup were more distal, easterly facies equivalent of the Neoproterozoic Torridonian rocks (Fig. 2a).

~~12.~~12 Conclusions

The Loch Eriboll part of the Moine Thrust zone has been the subject of intensive geological mapping and research for over 150 years since the initial field studies of Nicol (1860), Lapworth (1883-84), Peach and Horne (1884), and Peach et al. (1907). Many more recent studies have added new data using modern methods of structural analysis, thermobarometry, geochronology, and seismic profiling. The conclusions drawn from our study are not all new; we integrate new findings from detailed field mapping and our review of the literature, with the most pertinent conclusions from previous work. Our conclusions can be summarised as follows:-

1. The Moine Thrust was initiated not along a plate boundary, but within a continental plate. Lewisian basement gneisses occur in the foreland and as inliers within the Moine Supergroup schists in the hinterland. The reason for initiation of thrusting in this position, far away from a plate boundary remains unknown. The presence of highly alkaline syenite intrusions (Loch Loyal east of Eriboll; Borralan and Loch Ailsh intrusions in the Assynt Window) within or close to the MTZ might suggest an anomalously hot sub-continental mantle might have triggered thrusting.
2. The Moine thrust zone in NW Scotland shows a general foreland-propagating 'piggy-back' sequence of thrusting from east to west with time, from the Moine thrust down structural section to the Lochan Riabhach thrust to the Arnaboll thrust to the Sole thrust (Elliott and Johnson, 1980; Butler and Coward, 1984; Butler, 1987; Coward, 1988; Holdsworth et al., 2007).
3. Mylonites along the Moine thrust are derived from the Moine schists, various Lewisian gneiss lithologies, the Cambrian quartzites and calcareous quartz + muscovite + chlorite phyllonite meta-sedimentary units. The Moine thrust has been

variously assigned to the base of the mylonite sequence (e.g. Soper and Wilkinson, 1975; McClay and Coward, 1981; Butler, 1982, 2004), the middle of the mylonite sequence (Peach et al., 1907; Law et al., 1984) or the upper contact of the mylonites (Holdsworth et al., 2006). Confusion in nomenclature arises because thrusts cut differing lithologies both across strike as they climb ramps and along strike, and mylonites cannot be used as a stratigraphic marker.

4. The Moine thrust oversteps all underlying thrust sheets and extends west, at least as far as Sango Bay and Faraid Head, >15 km west of the outcrop of the Sole thrust in Loch Eriboll. The Moine thrust zone has been down-faulted to the west along a series of steep WNW-dipping normal faults, likely of Devonian age, between Loch Eriboll and Sango Bay (Wilson et al., 2010).

5. The Sole Thrust Sheet exhibits tightly-packed imbricate sequences, in places with as little as several met~~r~~ers between thrust slices. Thrusts are often close to parallel, but some are observed to branch laterally, as a new thrust surface supersedes that which it splayed off. Lateral and/or oblique ramps are evident in parts of the Sole Thrust Sheet and are necessary to explain certain lateral variations in structure. Approximately 60% shortening occurred in the Sole Thrust Sheet.

6. The Sole Thrust Sheet includes examples of breaching thrusts, where underlying imbricate thrusts have cut up through the Arnaboll Thrust surface (Butler, 1987; Wibberley and Butler, 2010).

7. Late-stage breakback thrusts are apparent, for example the Teanga Thrust (Coward, 1984), which cuts steeply across all thrust sheets beneath the Moine and Lochan Riabhach thrusts. These thrusts effectively thicken the wedge during late stage (Sole thrust or later) evolution of the thrust belt.

8. Lewisian gneiss inliers within the Moine schists are similar to foreland Lewisian gneiss. There appear to be no unmetamorphosed equivalents of the Moine schists (dominantly psammites and semi-pelites) beneath the Moine thrust. This presents an unresolved restoration problem for the entire Moine Thrust zone. It has been suggested that the Moine schists might represent metamorphosed equivalents of the Torridonian sandstones and conglomerates, but in the Eriboll area the Cambrian quartzites, thin Fucoid beds, *Salteralla* grits and Ordovician Durness carbonates lie unconformably above Lewisian gneiss with no intervening Torridonian.

9. The Moine schists above the Moine Thrust show inverted metamorphism with grade increasing structurally up-section towards the east from biotite-garnet grade above the Moine Thrust to sillimanite + K-feldspar migmatite grade in the Sutherland migmatite complex (Thigpen et al., 2013; Ashley et al., 2015). We suggest this tectonic inversion is associated with post-metamorphic folding and west-directed ductile shearing of an originally right way-up metamorphic isograd sequence, similar to the Main Central Thrust zone in the Himalaya (Searle et al., 2008; Streule et al., 2010; Searle, 2015).

10. A series of Devonian north-south or NNE-SSW aligned steep, west-dipping normal faults, associated with opening of the West Orkney-Shetland basin, are exposed along the north coast of Scotland. These normal faults drop the Moine thrust and mylonite thrust sheets structurally down to the west (Wilson et al., 2010). Restoration of these post-Caledonian normal faults shows the westward extent of the Moine Thrust ~~more~~ at least 15 km west of Loch Eriboll, as far west as Faraid Head.

11. A final unresolved question is that there appears to be no evidence of a flexural foreland basin west of the Moine Thrust zone. Loading of the Moine thrust hangingwall would be expected to have caused a major flexural basin along western Scotland, for which there appears to be no evidence, unless the entire basin has been eroded. The Sole thrust lies directly on stable Laurentian foreland along the entire length of the Moine thrust zone from Durness south to the Isle of Skye.

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Acknowledgements

We acknowledge with gratitude many discussions on Scottish Highland geology with Rick Law, Rob Strachan, Rob Butler, John Dewey, Marc St-Onge, Bruce Levell, Mike Johnson, Dave Waters, Tony Watts and the late Mike Coward, amongst many others. Thanks to Rob Strachan and Rob Butler for detailed comments on an earlier draft of the paper, to Peter Cawood and an anonymous revie~~w~~wer (reviewer) for their comments, and to Olivier Lacombe for editorial efficiency.

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Highlights

- We present a structural analysis of the Moine Thrust zone Eriboll, NW Scotland based on balanced and restored cross sections, reviews of structures in the Moine Supergroup (Hinterland) and Lewisian foreland and interpretation of deep seismic lines offshore NW Scotland.

Queries and Answers

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Answer: We present new detailed mapping, together with cross-, lateral-, and restored-sections from the northern Moine Thrust zone
Restoration shows that the intensely deformed Sole Thrust Sheet experienced c. 60% shortening at Loch Eriboll
We place this mapping in its regional context and review the structural evolution of the northern Moine Thrust Zone
We review orogen wide data from the Moine Thrust hinterland and compare with Himalayan tectonic architecture
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The citation “Strachan et al., 2002” has been changed to “Strachan et al., 2002a, b” to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

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Citation "Callaway, 1883" has not been found in the reference list. Please supply full details for this reference.

Answer: Callaway, C., 1883. The age of the newer gneissose rocks of the northern Highlands. *Quarterly Journal of the Geological Society, London,* 39,355-422.

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Answer: Peach, B. N., Horne, J., Gunn, W., Clough, C. T., Hinxman, L. W. and Cadell H. M., 1888. Report on the recent work of the Geological Survey in the N.W. Highlands of Scotland, based on the field notes and maps. *Quarterly Journal of the Geological Society, London,* 64, 378-441.

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The citation “Butler, 2011” has been changed to “Butler et al., 2011” to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

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Citation "Soper & Brown, 1971" has not been found in the reference list. Please supply full details for this reference.

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Citation "Kruhl, 1998" has not been found in the reference list. Please supply full details for this reference.

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Query:

Citation "Holdsworth et al., 2010" has not been found in the reference list. Please supply full details for this reference.

Answer: please delete 2010 ref

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Answer: Watson, J. V. and Dunning, F., 1979. Basement-cover relations in the British Caledonides, in *The Caledonides of the British Isles - reviewed* (eds Harris, A. L., Holland, C. H. and Leake, B. E.), *Geological Society of London Special Publications,* 8, 67-91.

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The citation “Lapworth (1883-4)” has been changed to “Lapworth (1883-84)” to match the author name/date in the reference list. Please check if the change is fine in this occurrence and modify the subsequent occurrences, if necessary.

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