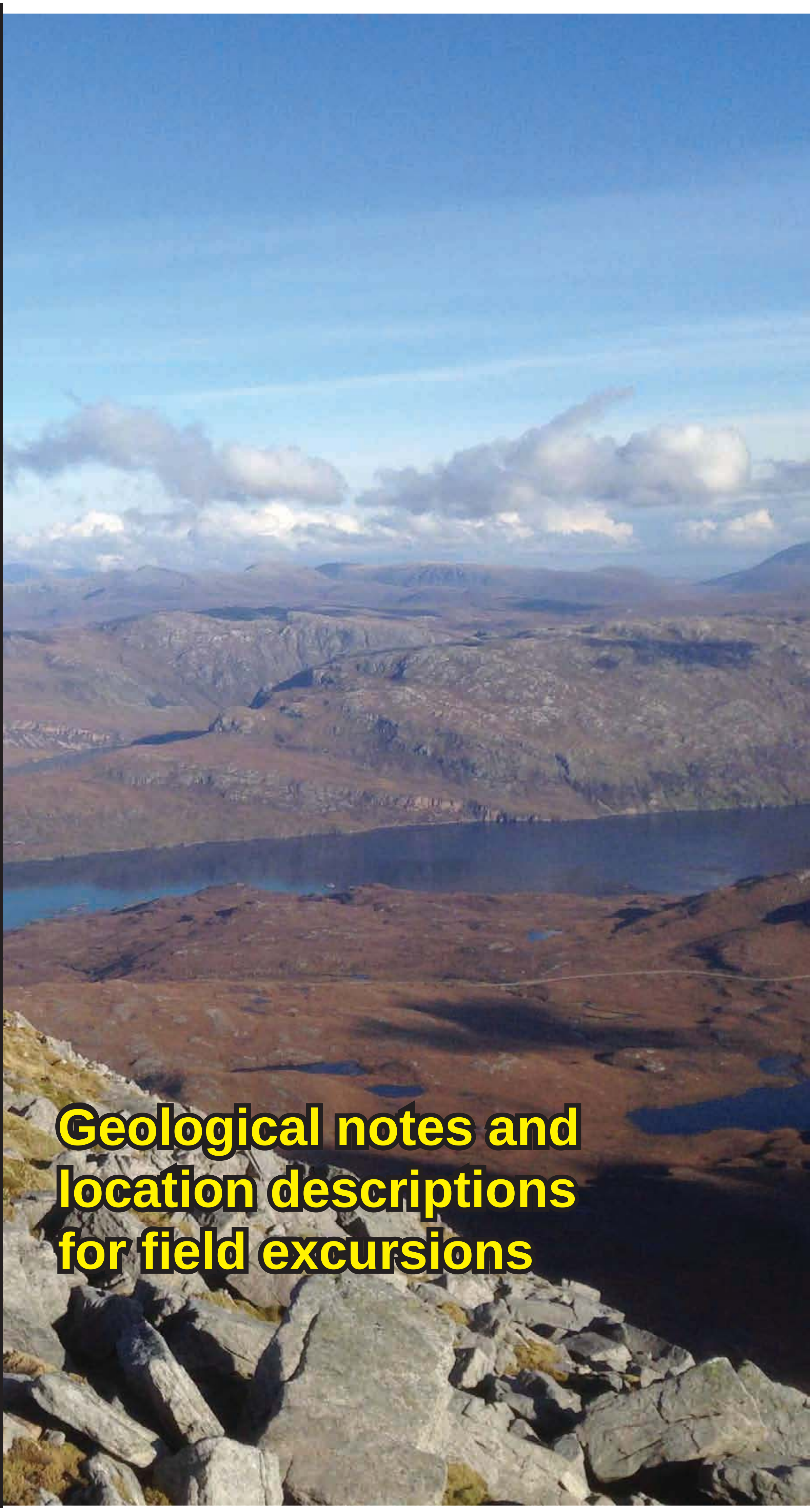
Deformation mechanisms, Rheology and Tectonics 2017

Inverness: 30 April - 7 May



Geological notes and location descriptions for field excursions

*Geological notes**

The crustal evolution and geology of NW Scotland can be considered with reference to the Palaeozoic Caledonian orogeny. This major episode of crustal reworking was associated with the formation of a North Atlantic Craton – suturing the Proterozoic and older crustal blocks of Laurentian and Baltica (together with Avalonia, further south). NW Scotland contains part of the western margin of this orogen (or at least its more intense parts), a tectonic feature termed the Moine Thrust Belt. The foreland to the thrust belt preserves much older geology, exhumed from up to 35-40km depth, that give insight to processes that form, rework and reassemble the continental crust. The Caledonian rocks allow us to follow a transect from exhumed middle crustal sections within the orogen out into the foreland. Collectively these outcrops provide arrays of analogues for crustal geology and deformation structures, and we can use these to promote discussion of their geophysical characteristics when targeted in situ. However, the Caledonian crust, together with its foreland, has seen later deformation associated with the formation of sedimentary basins, chiefly in the immediate offshore. We can also access basin faults and examine not only their individual characteristics but also debate how they may have been influenced by pre-existing structures.

Pre-Caledonian geology

The Lewisian.

The Lewisian forms the oldest basement to the British Isles and has classic Laurentian geology. The key geological markers in the field used to build up a sequence of geological events are a suite of NW-SE-trending metabasic sheets – the Scourie dykes. The age of these intrusions has been controversial but it now seems clear that they were intruded over perhaps a 400 million year period, ending about 2000 million years ago. Where these retain undeformed intrusive relationships we are seeing into a pre-dyke history. Such relationships are found through the core of the Lewisian outcrop on mainland Scotland, defining the so-called Central Block, centred on western Assynt. Current understanding suggests this became a broadly stable part of the continental crust by about 2600 million years ago. Most of the rocks are banded grey gneisses, generally thought to be the deformed and metamorphosed equivalent of extensive plutons. There are thin strips of material that are thought to be of metasedimentary origin. Some of these may represent the material into which the early plutons were intruded. However intense deformation (the "Badcallian") has obliterated all the evidence of this. But what is clear is that the early history of the Lewisian is one of growing continental crust – the growth caused by the repeated injection of magma. The most likely place for this to have happened is above a subduction zone, either as part of a volcanic island arc (e.g. like modern-day Japan) or in an Andean setting. The chemistry of the Lewisian gneisses is in broad agreement with this tectonic model for their origin. The oldest material probably dates from about 3 billion years ago with extensive deformation happening at about 2750 million years ago (an episode called the "Badcallian"). The associated metamorphism was under granulite facies conditions (11-15 kbar, 950-1000 C). This equates to depths of 35-50 km – (over the normal thickness of continental crust). So the Lewisian tells a story of ancient crustal growth and thickening.

The Badcallian gneisses are intruded by widespread NW-SE trending Scourie dykes. In the Central Block these dykes preserve igneous textures – although commonly they contain granulite-facies metamorphic minerals. Elsewhere the dykes have been metamorphosed into amphibolites.

Outside the Central Block, and along some key shear zones within it, large tracts of gneisses with Scourie dykes have been strongly deformed and metamorphosed. In general the metamorphic grade is lower than within the Central Block, characterised by amphibolite facies. In places the redeformed gneisses are invaded by granitic intrusions including coarse-grained pegmatites. It is worth noting however that most of these appear to have been produced by melting pre-existing continental crust. So these late intrusions represent a remobilisation of existing material rather than true growth of new crust. All this activity of deformation, metamorphism and magmatism is generally termed the Laxfordian. The best estimates at present suggest that this happened around 1800-1600 million years ago.

**These notes are modified from the guidebook to the post-conference field excursion for Seismix 2016 – in turn based on material put together for other field excursions including for the 2007 Continental Tectonics (Peach & Horne) meeting. They should be read in conjunction with the main DRT2017 field guides (for illustrations).*

The Central Block, marked by broadly undeformed Scourie dykes, ends at Laxford Bridge in Sutherland. To the north of here dykes and host gneisses are deformed, generally strongly, so that early structures are smeared out. This Laxfordian deformation and its boundary with the Central Block (the "Laxford Front") are generally interpreted as a major zone of crustal reworking of Central Block rocks. However, modern geochemical studies suggest that the two sets of gneisses were derived from continental crust of distinctly different age. Furthermore the northern units contain not a trace of the granulite facies metamorphism that characterises the Central Block. So perhaps the intense shearing relates to displacements that have brought together distinct crustal units. It is interesting to note that almost all the shearing has been taken up by the northern gneisses with little happening to the Central Block. Perhaps this reflects the difficulty of deforming dry granulite rather than hydrated amphibolites – the distribution of Laxfordian deformation being preconditioned by the pre-existing crustal geology.

Note that the southern limit of the Central Block is more complex than at Laxford, but is still marked by a transition into deformed Scourie dykes and host gneisses. In the south there are indications that at least some of the reworking of presumed Central Block material occurred during the emplacement of part of the Scourie dykes, a deformation phase termed the "Inverian". Recent studies have suggested that the Laxford Shear Zone also contains relict Inverian structures, perhaps indicating a polyphase history.

<u>The Torridonian</u>

Suilven, Cul Mor, Cul Beag, Canisp, Coigach and Quinag – all these "mini-mountains" of Assynt are formed from pebbly sandstones - the Neoproterozoic Torridonian rocks. These are the oldest sedimentary rocks in the British Isles, deposited upon the Lewisian and preserved in the Caledonian foreland of NW Scotland. They tell of the erosion of long-gone mountain ranges and of ancient landscapes. Back in the middle 19th century the Torridonian was considered to be of Cambrian age. We now know it to be significantly older – indeed they are different ages. Grouping these sediments together as the Torridonian is itself misleading. In fact there are of at least two distinct packages of sediment. The main sequence is called the Torridon Group that attains an estimated thickness in excess of 6 km. This is dated at around 1000 Ma. The lower part of this Group (the Applecross Formation, named after its type area in Wester Ross) is the classical pebbly sandstone that forms the cliffs and scarps of those great hills. It is chiefly a thick fluvial sequence that was derived from an unroofing Grenvillian and other uplifted orogenic terranes that once lay to the west on the Rodinian supercontinent. But beneath the Torridon Group there are older sedimentary rocks, classically (if erroneously) lumped in with the rest of the Torridonian. This is called the Stoer Group, now dated as 1200-1100 Ma. The Stoer reaches thicknesses in excess of 3 km and, unlike the Torridon Group sediments, was derived from the underlying Lewisian basement. The basin-forming mechanisms that allowed these thick successions to accumulate, and be preserved, are largely unknown. Most workers consider the Stoer Group to be a syn-rift basin sequence. There are no such indications for the Torridon Group. Modern research suggests that it accumulated in a foredeep to the Grenville orogeny and as such it correlates with other Neoproterozoic succesions in the modern North Atlantic region.

<u>The Moine</u>

The Moine comprises a supergroup of Neoroterozoic metasediments, chiefly meta-sandstones (psammites) with sporadic shales (pelites), considered to be shallow-marine or fluviatile. They were deposited across Lewisianoid basement which now form inliers within the main Moine outcrop. The depositional age of the Moine is bracketed by detrital zircon ages (c 950 Ma) and a suite of intrusions (c 870 Ma). The Moine Supergroup is divided into three separate groups (Morar, Glenfinnan, Loch Eil) but these distinctions need not concern us here. The depositional thickness of the Moine is very uncertain because of the intensity of subsequent deformation but probably exceeded 4-5km. The Morar is a candidate lateral equivalent to the Torridon Group (see Krabbendam et al. 2017 for references).

The Moine has been intruded by various igneous rocks. These include basic sheets, dated at around 800-875 Ma, and suites of pegmatitic granites dated at 820-780 Ma). These intrusion events are linked to a Neoproterozoic tectonic episode termed the Knoydartian. This somewhat enigmatic event is also associated with amphibolite-facies metamorphism at garnet growth (dated using Sm-Nd at around 830Ma) and ductile deformation.

Cambro-Ordovician

Regionally the Precambrian rocks of the Caledonian foreland (i.e. Lewisian and Torridonian) are capped by a remarkably planar unconformity which underlies a surprisingly layer-cake succession of Cambro-Ordovician sedimentary rocks. It may be simplified into three distinctive units. The oldest is represented by about 150 m of quartzites (the Eriboll Sandstone Formation), the middle one is a highly differentiated collection of sands, silts, muds (Fucoid Beds Member) and clean quartzites (Saltarella Grit Member: collectively the An t-Sron Formation), and the upper one is a thick (over 1500 m) succession of carbonate rocks (the Durness Group). These units are readily identified, commonly from a great distance, allowing exceptionally complex tectonic interleavings to be unravelled by field geologists. They also provide exposures of thrust and fold structures of unrivalled clarity. The *Skolithos* trace fossils (Pipe Rock Member) in the Eriboll Sandstone Formation are ideal strain markers and have played a key role in the understanding of strain patterns. The Cambro-Ordovician strata presumably represent a regional post-rift steers-head to extensional basins developed to the SE.

Caledonian

Once viewed as a single orogenic "event", with the increased availability of radiometric age determinations, the Caledonian orogeny in NW Scotland is divided into two distinct episodes: the Grampian (c. 460 Ma, Ordovician in age) and the Scandian (c 430 Ma, Silurian). Just how helpful such distinctions are remains to be seen…. Nevertheless, the Caledonian (*sl*) is the major tectonic event the effected the crust of Scotland. We will consider it in a variety of locations.

The Moine Thrust Belt

The Moine Thrust Belt forms the outer edge of the Caledonian Orogenic Belt in the northern mainland of Scotland. It separates the polydeformed and metamorphosed orogenic interior of Moine rocks, to the ESE, from the foreland of Lewisian gneisses with their cover of Torridonian and Cambro-Ordovician sedimentary successions, to the WNW. As such, the thrust belt forms a small segment of the edge of penetrative deformation caused by the Caledonian Orogeny. There are continuations of the belt in northern Greenland and possibly NW Ireland. The Moine Thrust Belt and its extensions are related to the Scandian (Silurian) phase of the Caledonian Orogeny, which resulted from the collision of Baltica and Avalonia against Laurentia, to which Scotland belonged at the time. In Scotland, the thrust belt runs from the north coast near Whiten Head to Sleat on Skye. Northern continuations have been proposed beneath the West Orkney Basin, on the basis of seismic data.

The Moine Thrust Belt has achieved worldwide importance for the development and testing of key concepts in structural geology. Much of our basic understanding of the Moine Thrust Belt comes from research in the 1880s, following the recognition of large-scale thrust surfaces in the Assynt and Eriboll districts by Charley Callaway (1883) and Charles Lapworth (1883). This work settled a famously acrimonious debate in mid-nineteenth century geology between James Nicol and the Geological Survey as represented by Roderick Murchison (both of whom had died by the time the debate was resolved) and later by Archibald Geikie. Murchison's view was that the rock succession in NW Scotland was essentially continuous, while James Nicol contended it was faulted. Lapworth and Callaway's discoveries rendered the Geological Survey's interpretation untenable and led Geikie, then Director of the Survey, to send his most able geologists to complete a major mapping programme. The results of this awesome task eventually appeared in two ground-breaking publications, the NW Highlands Memoir (Peach *et al.*, 1907) and the special 1" geological map of the Assynt district (1923). Oldroyd (1990) has provided an entertaining account of these early researches, together with their socio-scientific fallout and subsequent legacy. The significance of Peach et al.'s (1907) research is discussed by Butler (2007) and underpinned a centenary celebration conference and associated publication (Law et al. 2010).

For over fifty years following the 1907 Memoir, geological research within the thrust belt concentrated upon correlating minor structures, particularly folds and planar fabrics, and relating them to the regional geology. Up until the mid 1970s this research attempted to find structural links between the Moine and its underlying thrust belt (e.g. Barber, 1965; Soper and Wilkinson, 1975). For example, gently inclined and isoclinal to tight folds were linked to a single mylonite-forming event (termed 'D1'). This type of structural analysis received added impetus with the application of radiometric dating techniques to igneous intrusions within the northern Highlands; these age-dates apparently calibrating the relative structural histories built up from field studies (e.g. Woolley, 1970; van Breemen *et al.*, 1979). A review of the evidence from the igneous rocks in Assynt appears in GCR volume 17, *Caledonian Igneous Rocks of Great Britain* (Parsons, 1999).

In the late 1970s, renewed interest in the structural evolution of the Moine Thrust Belt was propelled by the application of analytical techniques developed in the foothills of the Rocky Mountains (e.g. Bally *et al.,* 1966; Dahlstrom, 1970) and the Appalachians of North America (Rich, 1934; Milici, 1975). Elliott and Johnson (1980) pioneered this approach in the NW Highlands. The critical conceptual leap was that thrust belts evolve by individual thrusts growing, linking, moving and then dying. They form in a general foreland-propagating sequence so that higher nappes are carried 'piggy-back' upon lower ones. In the Appalachians, Mitra and Elliott (1980) showed that folds and deformation fabrics could be explained by local thrusting processes rather than by regional tectonic events, prompting a similar re-assessment of minor structures within the NW Highlands. These new approaches led to a major programme of remapping within the thrust belt, in many cases re-examining, for the first time in a hundred years, the geometrical relationships between thrusts and the sheets that they carry. Much of this work confirmed the ideas of Elliott and Johnson (1980), recognizing in particular that many of the structural complexities and bewildering networks of faults originated from the repetition of individually rather simple geometric elements. However, some parts of the thrust belt show fault geometries that are not predicted by Elliott and Johnson's ideas, particularly extensional structures that cut down the stratigraphic section in the direction of transport (Coward, 1982). Controversy remains as to the larger scale tectonic significance of these features, in particular whether they accommodated crustal extension, gravitational collapse or even the locally complex effects of purely compressional tectonics (Coward, 1983; Butler, 2004; Butler *et al.,* 2006, 2007).

The renewed interest in thrust belt structure, particularly in NW Scotland, came when structural geologists began to relate the deformation recorded by mountain belts to plate tectonic processes through integrating surface geology with deep seismic reflection profiles (Soper and Barber, 1982; Brewer and Smythe, 1984). Central to this were attempts to quantify the magnitude of horizontal displacements responsible for stacking up piles of thrust sheets, primarily using balanced cross-sections (as pioneered by Dahlstrom, 1969, in the Canadian Rockies). These constructions are geological profiles drawn parallel to the inferred direction of displacement in such a way that the stratigraphy may be restored graphically to a predicted undeformed state. Although simple palinspastic reconstructions have been made of parts of mountain belts for almost a century, balanced sections are a significant improvement because they attempt to quantify the displacements experienced by all layers, an important part of testing models of structural geometry and evolution for internal consistency. By representing three-dimensional tectonic structure in two-dimensional profiles, balanced cross-sections have a general assumption of plane strain, in that there is no movement of material out of the profile. Notwithstanding this limitation, balanced sections were crucial for providing estimates of almost 60 km for the original width of that part of the Cambro-Ordovician shelf succession now stacked up within the Moine Thrust Belt (Butler and Coward, 1984; Coward, 1985). Estimates for the whole belt suggest some 100 km of subhorizontal displacement (Elliott and Johnson, 1980). These movements have carried the Moine rocks and the intensely metamorphosed part of the Caledonide Orogen, apparently as a relatively thin sheet, by this amount across the foreland Lewisian gneisses.

It is generally accepted that thrust tectonics had ended in NW Scotland by earliest Devonian times (c. 400 Ma), but the evidence for this paradigm is rather sparse. Estimating the timing of displacements within the Moine Thrust Belt relies on radiometric ages from various alkaline igneous intrusions (see below). Direct dating of mylonite formation in the hangingwall to the Moine Thrust implies that ductile movements associated with recrystallization continued until about 410 Ma (Freeman *et al*., 1999). There are no clear indications from geological relationships of the time of final cessation of movement in NW Scotland as there no sedimentary rocks earlier than Triassic age that unconformably overlie the structures.

<u>Ductile thrusting in the Moine</u>

Much of the Moine outcrop, in the hanging-wall to the Moine Thrust, shows intense deformation of Caledonian age. It is this deformation that makes untangling the Proterozoic tectonic history so difficult. Bailey (1910) recognised large-scale stratigraphic inversions with polyphase refolding histories that had closer analogies with the nappe structures then recently deciphered in the Alps than with the strongly localized styles of deformation deduced for the Moine Thrust Belt. The complexity of deformation seen at the outcrop scale meant that debates about the structural geology thereafter centred on the tectonic significance of various structural elements, especially lineations (e.g. Wilson 1953). Thus regions where fold hinge lines had variable orientations or folding was superposed, were the result of complex tectonic shortening patterns. For this paradigm, if structures did not share a common tectonic axis they could not be coeval (McIntyre 1954). For the NW Highlands, it was only in the 1970s that this approach was finally abandoned. Soper & Wilkinson (1975) applied the newly-developed studies of shear zones, especially the development and modification of folds in these settings (e.g. Escher & Watterson 1974). The approach was taken much further by Bob Holdsworth and others in the Moine where they mapped out arrays of folds on all scales, with apparently transport-parallel hinge lines (e.g. Holdsworth *et al.* 2001, Alsop & Holdsworth 2007; see also review by Law & Johnson 2010). However, the general notion of regional structural correlation, based on deformation sequences (D-numbers) remains (e.g. Mendum *et al*. 2009), notwithstanding earlier demonstrations that, within the Moine mylonites, folds only have local significance and there is no spatial-temporal significance in relative chronologies (Butler 1982b).

Impetus for thrust tectonic models was provided by Tanner (1971) in the SW Moine and the recognition of a major shear zone (Sgurr Beag Slide, latterly termed the Sgurr Beag Thrust) that contained thin pips of strongly deformed Lewisianoid rocks. Other ductile thrusts were recognised in the Moine (e.g. Rathbone & Harris 1979), although it remained for Soper & Barber (1982) to propose a "crustal duplex" model for imbrication within the Moine nappe, with reference to the north coast transect. The recognition that the Moine Thrust Sheet did not involve the whole crust of the NW Highlands (Butler & Coward 1984) led to a "thin-skinnned" model for the imbrication of Lewisianoid basement and its cover of Moine metasediments (Butler 1986). Holdsworth *et al.* (1986) argued against this simplification of deformation as characterised by displacement on distinctive thrusts, stressing the importance of folding and distributed shearing. Nevertheless, subsequent work (e.g. Holdsworth et al. 2001) has confirmed and extended the thrust imbrication model, implying substantial displacements within the Moine The notion that the Moine, especially on the Sutherland transect, decoupled along the Moine Thrust raises issues for crustal scale thrust geometry. There is insufficient space beneath the NW Highlands (Fig. 9b) to account for the crust upon which the Moine originally lay. Butler's (1986) models predicted substantial panels of Lewisianoid basement remaining at depth beneath more interior portions of the Caledonide orogeny.

The timing of ductile thrusting in the Moine is intriguing. Given the kinematics and overall similarity with the Moine thrust, allied to the general trend for the synkinematic metamorphic conditions (high grade to low grade from east to west), suggests that the ductile thrusts in the Moine are part of the same system as in the Moine Thrust Belt. However, the migmatitic upper thrust sheets of the Moine yield zircon overgrowth (U-Pb) ages of 467±10 Ma and 461±13 Ma (Kinny et al. 1999). This suggests significant "Grampian" deformation, some 30 Myr earlier than thrusting in the west. Likewise Ar-Ar cooling ages across the northern Moine are 460-470 Ma (Dallmeyer et al. 2001) suggesting ductile deformation had ended by then. More recently however, Kinny et al. (2003) and Kocks et al. 2006) provide synkinematic ages on deformation fabrics in the northern Moine of 420 Ma – 429 Ma, These results may indeed establish that the ductile thrust systems of the Moine are Scandian in age and thus are part of an overall WNW-directed thrust system.

Caledonian intrusions

A suite of syn-to-post kinematic alkali intrusions punch across structures both within the Moine Thrust Sheet and the underlying thrust belt. These include the Ben Loyal Syenite, dated at 426±9 Ma (Halliday et al. 1987). The Loch Borralan intrusion of Assynt, which appears to cut the Ben More Thrust (e.g. Parsons, 1999, 2000), has been dated at 430 ± 4 Ma (van Breemen *et al.,* 1979). The Loch Ailsh intrusion, which is apparently cut by Caledonian structures (see the Ben More GCR site report), has yielded an age of 439 ± 4 Ma (Halliday *et al.*, 1987). In addition, the Canisp Porphyry sills (exclusively locally pre-kinematic), which lie in the foreland immediately west of the thrust belt but are absent from the belt itself, have yieldeda U-Pb TIMS zircon intrusion age of 437 ± 4.8 Ma (Goodenough et al., 2006). Although minor intrusions spatially associated with the Loch Borralan intrusion (e.g. the 'nordmarkite' dykes) are found on both sides of the Moine Thrust, no individual intrusions have been found that definitively suture the thrust belt.

Post-Caledonian geology

The Caledonian and older rocks of NW Scotland form the basement to a set of sedimentary basins. These are well-developed offshore – indeed the modern coast-line is largely controlled by post-Caledonian faults. Rifting began as the Caledonian orogeny ended – most dramatically forming the Orcadian Basin. This hosts Devonian strata, patches outcrop on the mainland in outliers on the north Sutherland coast and in Caithness. The Orkney archipelago comprises Devonian strata. Devonian basins also underlie the Mesozoic strata of the Sea of Hebrides and Inner Moray Firth Basins. The latter includes important oil fields. The continental Old Red Sandstone (ORS) system in a wide variety of sedimentary basins. These have developed on top of a Caledonian orogenic basement that reached shallow crustal levels by c. 430 Ma. The ORS basins contain the detritus from the denuding orogenic belt. It is likely that this deposition occurred across much of the northern Highlands, with just a few outliers remaining. The structure of the ORS basins appears at least locally to have been guided by the orogenic structure of their Caledonian basement. Deep seismic data across the West Orkney Basin (WOB) images an array of Devonian (and Permo-Triassic) basins that are bounded on ESE-dipping normal faults that run into mid-crustal reflective fabrics of the same apparent orientation. Several authors have interpreted these patterns as indicating that Caledonian thrusts have been reactivated under extensional tectonic conditions. There are however issues in tying faults from the WOB with the outcrops on the north Scottish mainland. The rapid change in basin structure implies an important transfer fault system along the coast (e.g. Wilson et al. 2010 and references therein).

The structure of the WOB has been complicated - certainly in its eastern part - by inversion and strike-slip reactivation of basin-limiting faults associated with Carboniferous right-lateral displacements on the Great Glen and related faults. However, the key period for basin initiation around northern Scotland, as elsewhere in NW Europe, was the Permo-Triassic.

The North Coast of Scotland represents the margins of the West Orkney Basin. Although parts of this basin initiated in the Devonian, much of the basin fill and accommodation space was created in the Permo-Triassic. The main Permo-Triassic system appears to have developed to the NW and down the North Minch Basin. The Minches and Sea of Hebrides Basins are the eastern equivalent of the frontier sedimentary basins of the Atlantic continental margin. Although the rifting, subsidence and prospectivity of the Hebridean area is not as great as the deeper-water areas, the outcrops provide valuable analogues for offshore.

During early rifting of the fledgling North Atlantic, NW Scotland experienced a significant episode of magmatic activity associated with the ancestral Iceland hot spot. This is manifest by the Tertiary igneous complexes on the inner Hebridean islands (Skye, Rum, Mull etc). It has little outcrop representation on the NW Scottish mainland. At depth however there may have been significant intrusion of mafic sills – a possible explanation for the seismic reflectivity detected in the deep crust in the BIRPS seismic data.

Further reading

The key volume is:

Special Publication of the Geological Society v 335 *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne*. (eds R.D. Law, R.W.H. Butler, R.E. Holdsworth, M. Krabbendam & R. Strachan), 2010.

This includes review papers:

Wheeler, J., Park, R.G., Rollinson, H.R., & Beach, A. 2010. The Lewisian Complex: insights into deep crustal evolution.

Covers the Lewisian. Try also the paper by Goodenough et al. (The Laxford Shear Zone: an end-Archaean terrane boundary?) in the same volume.

Butler, R.W.H. 2010. The role of thrust tectonic models in understanding the structural evolution of NW Scotland.

Covers the Moine Thrust Belt and its ductile equivalents in the Moine.

Strachan, R. A., Holdsworth, R.E., Krabbendam, M., & Alsop, G.I. 2010. The Moine Supergroup of NW Scotland: insights into the analysis of polyorogenic supracrustal sequences.

Overviews much Moine geology including modern geochronology.

There are two field guides that cover some of the territory:
A Geological Excursion Guide to the North-West Highlands of Scotland (edited by K.M. Goodenough & M. Krabbndam) National Museums of Scotland (2011).
A Geological Excursion Guide to Moine Geology of the Northern Highlands of Scotland (edited by R A Strachan, G I Alsop, C R L Friend & S Miller). National Museums of Scotland. (2010).

The Geological Conservation Review series has abundant information:
Lewisian, Torridonian and Moine rocks of Scotland. (edited by Mendum, J. R, Barber, A. J., Butler, R. W. H., Flinn, D., Goodenough, K. M., Krabbendam, M., Park, R. G. and Stewart, A. D.) Geological Conservation Review Series, volume 34, Joint Nature Conservation Committee, Peterborough, pp. 721. (2009). ISBN 978 1 86107 483 6
There are useful introductory sections on the geological framework of the rock units together with the Moine Thrust Belt. The rest include extensive local information on many of the most important outcrops in NW Scotland (and beyond).

For a very readable account of the 19th century debates and research that led to the fundamental work of Peach, Horne and others – see
Oldroyd, D. R. 1990. *The Highlands Controversy*. Chicago University Press, Chicago.

Web pages
There is information available online –
These sites Google

Assynt's Geology – does what is says… but has general introductory information on NW Highland geology including lots of historical stuff (including Cadell's research). Currently offline.

Moine Thrust Belt web site
www.see.leeds.ac.uk/structure/mtb
Has the virtue of covering a large swathe of the thrust belt. Almost 20 years old, these pages are chiefly based on the GCR sites.

Assynt culmination geological 3D model
http://www.bgs.ac.uk/research/ukgeology/scotland/assyntCulmination.html
BGS's construction with cross-sections and interactive 3D pdf of the classic part of the thrust belt.

Mapping Mountains
http://homepages.abdn.ac.uk/mappingmountains/
A collection of historical maps and further information based on the "clean copies" from the 1880s mapping of the Moine Thrust Belt.

Mid-conference field descriptions

Geoconservation
All sites described (with the exception of the Loch Stack viewpoint) are protected. No materials (including loose rock) can be removed from the locations. The ScourieMore location for example has seen significant damage – not just by drilling but also removal of loose blocks that are important teaching resources). Unsanctioned sampling/hammering etc is illegal!

Finding your way
1:250K OS Travel Map “road” series (green trim).
Sheet 1 – Northern Scotland, Orkney & Shetland. – has all localities.

A series of 1:50K topographic sheets (Landranger series in pink trim). Two maps cover this itinerary:
9 – Cape Wrath
15 – Loch Assynt

There are also excellent 1:25K topographic maps (Explorer series, in orange trim) available. For diagrams and further information please consult the guide included in the other conference materials. The locations here are described in reverse order (F-A) as if driving from the SOUTH. The locations are identified using the UK National Grid Reference (GR) system.

Description
Get to Ullapool. Drive north from Ullapool on the A835 for 12 miles, and park at the well-signed Knockan Crag location (GR NC188091).

Location F: Knockan Crag
The location is the most visited in the Moine Thrust Belt but has been important since 1860 in the early feuds between Murchison and Nicol. Now there is a geological trail and permanent exhibition set up by Scottish Natural Heritage. The visit will involve a 2 km stroll around the trail. The thrust belt above the visitor centre is represented by the Moine Thrust alone. The footwall here is just in Durness limestone. The simple stratigraphic passage up through the foreland stratigraphy, from Pipe Rock, Fucoid Beds, Salterella Grit and into the Durness can be followed on the marked trail north of the visitor centre There are great views onto the foreland – with the Torridonian hills of Cul Beag (south) and Cul Mor (north). The Basal Quartzites of the Cambrian can be seen dipping off these hills towards Knockan.
The Moine thrust plane can be visited in the cliff sections [NC 190093]. The mylonites derived from Moine metasediments in the hangingwall (best seen higher on the tour) are brecciated within about 1m of the thrust plane although the lowest cm or so is made of foliated cataclasites. The underlying carbonates (chiefly dolostones) are brecciated and veined.
A superb viewpoint across Assynt may be reached by breaking up to the knoll [GR NC193094]. An equivalent view is annotated on here to aid location of key places. The visitor trail continues along the top of the escarpment. At the southern end there are some photogenic outcrops of mylonites, before a run of steps leads back to the car-park.

Continue N on the A835, joining the A837 by turning L at Ledmore Junction.
After a further 3 miles, park in the layby (GR NC248204) on the A837 beneath the limestone crag-line.

Location E: Stronchrubie
A viewpoint for imbricated Durness limestones at the lowermost part of the Moine Thrust Belt. The lower part of the escarpment (east of the road) contains Fucoid Beds and Salterella Grit. These units together with the lowermost part of the Durness limestone (with a prominent sill – part of the Assynt Igneous Complex) are apparently horizontal (actually dipping 12 degrees ESE – into the hillside. The overlying limestones (chiefly the Eilean Dubh Formation) are imbricated, as evidenced by the complex dip panels. Cut-offs (=ramps, chiefly footwall) can be identified. This style of tectonic thickening is typical of the lower parts of the thrust belt in Assynt.

Continue for a mile along the A837. Turn north at Skiag Bridge on the A894 and cross the watershed towards Glen Coul. Park at the prominent lay-by with interpretative panel ([GR NC236320]. Note that the location of the thrust is mis-located on the panel (at time of writing). Please refer to the field guide in the conference materials.

<u>Location Dii: Glencoul - Unapool</u>
The two outcrops either side of Kylesku village provide a 3D insight into the structure of the Moine Thrust Belt in northern Assynt together wit the stratigraphic relationships of the foreland. This is the classic panorama into the Glencoul Thrust, with the Stack of Glencoul (Moine Thrust) visible at the head of the valley. The immediate geology around the lay-by is Lewisian of the foreland. The hillside that looms over this site, the northern ramparts of Quinag, is made of Applecross Formation of the Torridonian.

Continue across the Kylesku bridge and up the hill for a mile. Park in the car-park at the top of the hill (GR NC212350).

<u>Location Di: Glencoul - above Kylestrome</u>
The immediate geology to the lay-by is Lewisian of the Central Block (orthogneisses, cross-cut by undeformed Scourie dykes).This viewpoint provides a panorama across the Moine Thrust Belt, described here from left to right (clockwise). On the north side of the Aird da Loch peninsula and up Glen Dhu (looking ESE) the Glencoul Thrust carries a panel (c. 300m thick) of Lewisian gneisses, the first major thrust sheet identified in NW Scotland (Callaway 1883. The Stack of Glencoul (c. 490m) is made of Moine mylonites, carried by the Moine Thrust onto Cambrian quartzites (on the shelf below the Stack). The Sole Thrust forms the base of these with the Cambrian quartzites in the regional footwall forming an ESE-inclined dip-slope running down from the mountain massif of Quinag. The high point of Quinag (Sail Gharbh, 808m) is almost due south of our viewpoint. The northern ramparts of Quinag expose 600m of Torridonian (chiefly Applecross Formation) sandstones, unconformably overlying Lewisian gneisses. The Lewisian forms the low ground around Kylesku and up Glencoul. Despite undulations of 100+m the basal unconformity of the Torridonian is gently inclined here so the Cambrian oversteps onto Lewisian down dip into Glen Coul – the classic “double unconformity” of the NW Highlands.

Continue for 10 miles, and park at the primary school at Scourie More (GR NC151440) do not obstruct parking places for the school when it is in session). The outcrops are 1 km away. Walk up the lane for c 100m and enter the open hillside to the SW via a gate (make sure this is closed after use!). An indistinct path leads W to another gate (again make sure this is left closed) overlooking the promontory with great view out to the Minches (GR NC 14854405). The indistinct path leads down, crossing the broad valley, over a ridge and down to a low headland (Cleit Mhor: GR NC141442).

<u>Location C: Scourie More</u>
These are classic outcrops for understanding crustal growth and the formation of the “Scourian” Central Block crust. The low headland is chiefly formed of Badcallian TTG gneisses with folded and sheared mafic pods. It is cross-cut by undeformed Scourie dykes, best seen on the lower slopes. Look back to the E to see granitic pegmatite crosscutting gneisses. A branch of the intrusion is cross-cut by the Scourie dykes on Cleit Mhor – demonstrating that the magmatism is late Badcallian in age. The pegmatite has spectacular m-sized crystals with graphic textures etc. Apart from TTG gneisses the pegmatite also crosses spectacular coarse-grained mafic and ultramafic granulites. These are deformed by Badcallian structures. The garnet-pyroxene mineralogy is retrogressed adjacent to the pegmatite –the prominent epidotic rims to garnet.

Walk back to vehicles. Continue through Scourie on the A894 for 9km. At the head of Loch Laxford the road continues north as the A838 – take this (it is the continuation, crossing Laxford Bridge. Continue for a few km to the lay-by opposite 4-5m high road-cuts and adjacent to a small lake (GR NC233486).

<u>Location B: Loch na Fiacail aka the “multi-coloured rock stop”.</u>

Stunning road sections of Laxfordianised Lewisian. Take great care with traffic. Until c 20 years ago it was widely assumed that these rocks were simply the deformed equivalents of the Central Belt units. Foliated amphibolite sheets, concordant with the host grey gneisses, are assumed to be deformed Scourie dykes. However, U-Pb zircon ages by Kinny & Friend, (1997) suggest that the protolith to these gneisses is significantly younger (2800-2400 Myr). These results have been used to suggest that the Laxford Shear Zone is a “terrane boundary” although the pre-Laxfordian relationships between “Central” and “Northern” blocks is not clear! Regardless of this controversy, the granitoid sheets offer photogenic examples of synkinematic intrusion and heterogeneous deformation (e.g. flanking folds).

Drive back to Laxford Bridge then take the A838 towards Lairg (turn L straight after the bridge). After 7 km park in the large turn-off just after a crest in the road (GR NC297404), then walk out to the NE about 100m for uninterrupted views over Loch Stack to Arkle.

<u>Location A: Loch Stack</u>
This location shows the front of the Caledonian orogeny – the lower Moine Thrust Belt. It can be contrasted with the other sites. Look N. The low ground running out around Loch Stack (about 35m above sea level) comprises Lewisian gneiss with abundant granite sheets – part of the Laxford Shear Zone. The hillside above leading up to the summit of Arkle (787m above sea level) comprises Cambrian quartzites. The unconformity is evident in the landscape. The quartzites are stacked on low-angle imbricate thrusts that climb section to the WNW. These are evident by low-angle stratal discontinuities and an increase in bedding dip to the ESE. The Moine Thrust lies in the back of the valley (east) with Moine mylonites firming the rounded grassy hills to the NE (see annotated photograph in guide). The thrust belt continues to the south, with the foreland quartzites evident in an E-inclined escarpment just above the forested area. The structure above is significantly different to that on Arkle but is difficult to resolve from here.

Return to vehicles and drive SE on the A838 to Lairg. The Moine Thrust is soon crossed about half way along the side of Loch More. Thereafter the road leads into the Moine and outcrop quickly diminishes. This concludes this one-day itinerary.

Post conference field excursion

This excursion over three days examines a “geotraverse” along the north coast of Sutherland. Consult the post-conference field guide for images, maps etc.
Geoconservation notes apply to all sites here – no hammering, no unsanctioned sampling!

Maps:
Landranger 1:50,000 sheets, Cape Wrath (sheet 9) and Strathnaver (sheet 10) cover it all.
Explorer 1:25,000 sheets, 445, 446, 447 and 448 cover it too.

Day 1

Looking at the regional context of the Moine Thrust, the formation of Moine mylonites (and relationship to other structures in the thrust belt) and subsequent faulting associated with post-Caledonian basin formation.

Drive NW via the A838. Drive into Durness and park at the Sango Sands (GR NC407677).

<u>Location 1.1 Sango bay</u>
This important location lies within a downthrown fault block and preserves the Moine thrust together with the greatest stratigraphic record of its footwall Cambro-Ordovician strata. The age of faulting at Durness and the links to the West Orkney and other offshore basin structures has been the subject of much debate. Wilson et al. (2010) report rare occurrences of red, cavity-filling breccias in the fault rocks around Durness – taken to be Triassic in age. This inference supports the palaeomagnetic dating of hematite cements in these N-S trending fault zones as being Triassic in age (Elmore et al. 2010). Note that Elmore et al. also report that the E-W trending faults at Durness, not studied on this workshop, are Jurassic in age.

The eastern margin of the bay is defined by a WNW-dipping normal fault with a footwall in Durness carbonates (Sailmohr and Sangomore Formations, early Ordovician). The fault plane is spectacularly exposed in the retaining cliff. The hanging-wall consists of Lewisian gneisses which ostensibly implies that the fault is reverse-sense (older on younger). However, these Lewisian rocks are part of a thrust sheet, part of the Moine Thrust system, that over-ran the Durness Group carbonates prior to the development of the steep faults. The contact of the base of these far-travelled basement rocks is found on the promontory on the western edge of Sango Bay (GR NC406680). The best outcrops of fault rocks form the promontory consisting of a lower tier of intensely fractured carbonate (middle Ordovician Durine Group, the youngest part of the Durness system). The upper part of the promontory consists of chloritic phylonites – most probably highly retrogressed and strongly sheared Lewisian gneiss. The base of these phylonites is the Moine Thrust. A thin (2-3m) strip of mylonitic quartzites (highly deformed Cambrian quartzites) lies between the phylonities and the carbonates – here the full representation of the Moine Thrust Belt. We can investigate the subsequent faulting that has offset this tectonic stratigraphy. The cleanest outcrops of carbonate fault rocks can be found in the small cove, forming the western flank of the promontory. Key aspects to note are the entrained veneers of brecciated quartz mylonite and the mineralisation that occludes the fracture porosity in the breccias (carbonate and quartzite). Cataclasis also affects the ductile shear fabrics of the thrust contact. Hippler (1989; Hippler & Knipe, 1990) describe microfracturing and brecciation on all scales in the quartz mylonites at the late fault contacts. Optical and transmission electron microscopy show that fracture patterns on a grain-scale can be influenced by the earlier microstructure of the mylonite.

Back across Sango bay are outcrops of banded quartzo-feldspathic and amphibolitic gneisses. By the big normal fault on the east side of the bay, these outcrops show characteristics of Lewisian rocks but contain penetrative greenschist facies (chlorite, actinolite epidote-bearing) assemblages indicative of significant retrogression. Small chlorite-epidote rich shears cut the gneisses. Passing westwards the degree of retrogression and deformation appears to increase so that outcrops immediately below the public house [GR NC 408677] are unrecognisably of Lewisian origin. At these localities small sea stacks are composed of crenulated chloritic phyllonite with small lensoid belbs of quartz. This is the "oystershell rock" of Peach *et al.* (1907). The quartz blebs contain locally a strong ESE-plunging mineral lineation. The phyllonites generally preserved an intersection lineation defined by the axes of the crenulations. These are dispersed around the quartz lineation. The crenulations themselves are generally extensional with respect to the early foliation and imply a top WNW shear sense.

Drive out of Durness east on the A838 and park up at the large layby above the stunning sandy beach (GR NC443653). Walk down to the sands.

<u>Location 1.2 Ceannabeinne</u>

The outcrops on the western wall of the bay (GR NC442656) display excellent exposures of "Laxfordianized" Lewisian. Amphibolite sheets (?former Scourie dykes) are concordant with the main gneissic banding and are boudinaged with broadly syn/late kinematic granitic pegmatites.

Continue on the A838 along the western side of Loch Eriboll. The slopes on the hills to the west of Eriboll are defined by large panels of gently-ESE-dipping Cambrian quartzites and constitute the foreland to the thrust belt. The ground at the head of the loch contains the Sole Thrust to the Moine Thrust Belt – ground we cover on Day 2.

<u>Location 1.3 Laid</u>

Find a parking spot along the side of the A838 (if in a single car – driving down to Portnancon is an option). Views across Eriboll to set the scene for Kempie – with Ben Hope behind. See annotated photograph in guidebook.

Continue along the A838, around the head of Loch Eriboll (where we cross into the thrust belt) and park up at the layby overlooking Kempie Bay (GR NC444580).

<u>Location 1.4 Kempie</u>

This involves traversing up through the Arnaboll Thrust Sheet to the Moine Thrust. All these rocks lie in the hanging-wall to the Arnaboll Thrust. From the parking site (hinge area of the Ant-Sron anticline) we will walk E 200m along the road, crossing the Kempie syncline to enter its steeply-dipping (slightly overturned) eastern limb. The core of the syncline contains Durness limestone so walking east along the road, down stratigraphic section we cross the Salteralla Grit (very small outcrop), Fucoid Beds and Pipe Rock. The Pipe Rock contains spectacular sheared *Skolithos* that show an eastward vergence, presumably related to folding rather than the regional (WNW-directed) thrusting. A downward-facing imbricate thrust an be found by mapping between the road and shore line that repeats the PR-FB contact.
The route above the road leads steeply through scrub onto open hillsides and into a hanging valley, classic ground for Lapworth and Peach in the 1880s.

The ground above Kempie bay provides an excellent place to examine major folds developed adjacent to the Moine thrust and the ductile reworking of the folds into metre-scale alternations of mylonitic rock types. We will examine this on a transect traversed across strike (starting at GR NC444576).

At the mouth to the hanging valley (about 130m above sea level: GR NC447576) the steep belt of the Kempie syncline terminates at an anticline with moderately E-dipping axial surface. So begins a small fold train that we will cross, continuity east, towards the Moine thrust. Over the next few hundred metres these large-scale folds tighten and the attitude of the axial surface decreases. The units here are Basal Quartzite and Lewisian gneisses. This is accompanied by increased development of shape fabrics in the quartzites until, at the top of the valley, they are mylonitic. The Lewisian gneisses are recrystallised into fine-grained chloritic phyllonites. The quartzites show intense l-s fabrics with a prominent, ESE-plunging mineral lineation and locally developed shear bands. So mylonite development forms part of a progressive deformation manifest by fold tightening. The folds can be mapped laterally (N) where they become more open. These structures can be demonstrated in low deformation state using the cross-bedding in the Basal Quartzite.

From the outcrops above the head of the hanging valley, next objective is a small knoll (219m OD) with outcrops lying along a small escarpment facing the plateau area (GR NC44875726). The upper part of the escarpment consists of distinctive folded mylonites generally considered to be derived from Moine psammites. They contain a strong linear fabric defined by strung out quartz aggregates that plunges towards ESE. The base of the Moine-derived mylonites is considered to be the Moine Thrust. Below lie more mylonites of distinct compositions, arranged in bands of a about a few metres thickness. One type of mylonitic layer is highly quartzitic. Others are essentially chloitic phylonites with thin feldspathic seams. Where evident, these units also show stretching lineations that plunge ESE. These units map laterally into the Lewisian and Basal Quartzite of the folded zone through which we have traversed. Note that the folds (and mylonites) deform thrust structures in the Kempie syncline. Thus discrete (“brittle”) faulting and distributed (ductile) shearing can cycle. The transition in deformation style need not be simply temperature-controlled and uni-directional.

Return to vehicles and drive up to a viewpoint above the small peninsula of Ard Neckie. (GR NC453599).

<u>Location 1.5 Ard Neckie</u>
The layby gives excellent views across the ground at the head of Loch Eriboll that shows the progressive disruption of the Cambrian quartzites as it enters the Moine Thrust Belt. In the distance lies the mountain massif of Foinaven. Originally mapped by H.M. Cadell in the mid 1880s – this ground inspired his “experiments in mountain building”. His cross-sections, reinterpreted by Elliott and Johnson in nearly 100 years later, inspired the type example for hinterland-dipping duplexes. We examine this ground in detail on Day 2.

Day 2

This day provides access to extensive thrust systems and a range of fault rocks – including Lapworth’s type mylonites.

Drive from Tongue west along the A838, bath to the head of Loch Eriboll. Park up near Polla 386546).

<u>Location 2.1 Conamheall and Srath Beag</u>

This is a walking tour through the northern edge of the “Foinaven duplex”. From the parking place follow the (true left) bank of the river until below the prominent east-plunging antiform dropping down from the Conamheall hills. (e.g. GR NC386529). From here head up to rock and take a line up slabs along the fold. There are occasional slabs of weakly deformed *Monocraterion* (trumpet pipes). The slopes to the south contain imbricate slices of Pipe Rock – the leading edges of which wrap over the antiform. While worth exploring, if time is short simply ascend onto the plateau (trend SW) to c NC 369524 to find fully exposed small-scale hanging-wall anticline together with general views of folded imbricate structures.

Continue south, gradually ascending the terrain towards the summit ridge of Conamheall, crossing imbricated Pipe Rock. A couple of tracts of Fucoid Beds and Saltarella Grit lies in stream sections, caught towards the top of the thrust system. Cross the Conamheall ridge and descend to gain good views across to the cliffs on Foinaven (e.g. GR NC 364509). The north facing cliff line overlooking Strath Dionard provides a natural section through the thrust belt, displaying large-scale repetition of the Pipe Rock. Views onto these cliffs provide perhaps the clearest indication of the scale of imbrication within an individual formation. Originally described by Cadell (in Peach *et al.* 1907), this section was later formally interpreted by Elliott & Johnson (1980) as a duplex. Boyer & Elliott (1982) then cited the section as their type example of hinterland dipping duplexes. The section is described in more detail by Butler (2004).

Continue east to the head of a small stream that drains down into Srath Beag (GR NC371509). The western flank of Creag Shomhairle offers a spectacular natural section, 350m deep, normal to the regional thrusting direction. It is an ideal location to examine lateral variations in thrust structures and is critical for establishing the relative timing of various thrusts (Butler, 1982b). Most of Creag Shomhairle consists of Lewisian gneiss similar to that within the analogous Arnaboll thrust sheet. These gneisses are only weakly affected by deformation associated with thrusting. However, they are structurally overlain by Moine mylonites which now lie preserved in a NW-SE-trending synform that crops out on the summit of Creag Shomhairle. On the vertical, SW limb of the synform, the Lewisian of the Creag Shomhairle sheet tapers out . This fold lies on a plinth of gently dipping Pipe Rock with the two units separated by an imbricated package of Fucoid Beds and Salterella Grit. These imbricates wrap a 100m high dome of thin slices of Pipe Rock that has been stacked up by thrusts. These slices, individually less than 5m thick, become progressively steeper towards the hinterland. This is the classic form of an antiformal stack duplex (Boyer and Elliott, 1982; Butler 1987), a geometry that is indicative of 'piggy-back' thrusting.

The stream section at the viewpoint contains excellent cataclastic fault rocks that decorate imbricate thrusts here. Further down the stream line spectacular small scale thrusts in Pipe Rock. Great care is required here.

Otherwise track NE along the hillsides above Srath Beag, gradually descending to the valley bottom – and hence return to vehicles at Polla.

Return on the A838 and drive up to park at the viewpoint above Ard Neckie (Location 1.5).

<u>Location 2.2 Ben Arnaboll</u>

The remainder of the day is devoted to a traverse across to the Arnaboll Thrust, involving a couple of km walk. This is classic ground – the type location for mylonites, as described by Lapworth (1885). It was here that he resolved the “Highlands Controversy and from where Geikie (1884) first coined the term “thrust” in publication. If views of the thrust belt were not possible yesterday then an equivalent panorama looking to the head of Loch Eriboll is available from the layby.

Traverse the low slopes, heading east. The top of the first rise (GR NC 457597) gains imbricated An t-Sron Formation units, with the leading edges of Pipe Rock slices. Cross these, gazing onto the crags ahead (GR NC 458596) that contain: the Arnaboll Thrust, imbricated Pipe Rock in is footwall and the underlying Fucoid Bed sheets. The Arnaboll Thrust is folded and breached.

Ascend the escarpment and head to the northern edge of the hill – overlooking Heilam and the north coast (GR NC461596). Take care when locating the outcrop – it lies below a 5m cliff line! This is the classic outcrop of the Arnaboll Thrust. See sketches and interpretations in the field guide.

Return to vehicles and hence back to Tongue.

Day 3

Today's geology is devoted to ductile thrust tectonics seen in outcrops of the Moine Thrust Sheet. The north Sutherland coast offers the best transect through what is commonly interpreted to be the ductile equivalents to the imbricate thrusts found in the Moine Thrust Belt (Barr et al., 1986; Butler 1986, reviewed by Butler, 2010). The deformation involves the Moine metasediments (chiefly psammites but with local pelitic sections), together with orthogneisses that are now generally considered to be their basement, essentially equivalent to the Lewisian. Minor mafic intrusions exist within the section, of controversial age relative to the deformation. Km-wide ductile shear zones with associated folds interleave Moine and Lewisian rocks. The metamorphic grade decreases form east to west, a trend that continues within the Moine thrust Belt itself. The detailed geology is covered by the BGS memoir to the Tongue area (Holdsworth et al., 2001).

From Tongue cross the causeway on the A836 and turn north through the hamlet of Melness. Park at the cross-roads about 2 km after the small quay (GR NC580643). The crag adjacent to the road fork contains Moine psammites which preserve, locally, cross-bedding. The units are form a N-facing fold pair. The fold hinge line plunge broadly parallel to the regional stretching lineation. Now walk down the lane 700m to Portvasgo (GR NC585650).

<u>Location 3.1 Portvasgo</u>

The coast section running east from Portvasgo is characterised by E-dipping flaggy psammites. Closer inspection reveals the flagginess reflects an intense deformation foliation. The outcrops are a potentially good analogues for mid-crustal shear zones imaged on deep seismic reflection profiles, and for tracts of crust that responsible for seismic anisotropy detected in teleseismic receiver functions.

We can explore this transect. The key components include:

<u>The main linear and planar components</u>. These are best studied on the slabs at Portvasgo itself.

<u>The pod (GR NC586650).</u> This is accessible at low-tide by scrambling along the shore. An eye-shaped pod lies embedded within the foliated Moine psammites – a low-strain lozenge within the shear zone. It contains a prominent mafic sheet that cross-cuts bedded in the psammites but becomes concordant and strongly foliated outside the pod. Holdsworth et al. (2001) interpret this to be a distinct "microdiorite suite" that was emplaced during shearing. The interpretation favoured here is that the basic intrusions pre-date all deformation and that the pod represents a pair of highly developed and modified flanking-folds (i.e. the mafic intrusion deformed heterogeneously and low-strain parts preserve halos of the original intrusive relationships, including only weakly deformed wall-rocks). The mafic units boudinage, implying greater syn-kinematic competence than the surrounding psammites. However, at high strain the mafic units become entrained into a strongly foliated biotite-hornblende schist onto which strain has localised, an example of reaction enhanced ductility.

<u>Intrafolial folds</u>. Take the old track east around the next zawn to cliff-line that faces west (GR NC587650). This has spectacular sets of tight, similar folds, with axial surfaces essentially parallel to the regional deformation foliation. Hinges plunge ESE, down regional stretching lineation.

<u>Garnet micaschist</u>. The bench above the folded psammite contains a thin layer of garnet biotite schist with extensional crenulation cleavage.

Hack up across moorland, passing low outcrops. Traverse the ground to the east to a 3m high crag (GR NC 585645) containing prominent <u>sheath folds</u> (Alsop & Holdsworth, 2004). And then return to vehicles and drive down to the small carpark (GR NC574647) overlooking the sandy bay. Descend to the low outcrops at the back of the beach. Here there are <u>deformed basal Moine conglomerates</u>. In general the shapes are strongly oblate but there is a prominent stretching lineation. This might stimulate discussion about strain state, deformation history and kinematics. If time permits we can head up the hillside to find spectacular quartz-rod linear fabrics.

Return to the A838, pass back through Tongue. Take the minor road north to Torrisdale and park above the bay. Take the path to the Borgie river, crossing the bridge and continuing around to low-lying outcrops beyond the dunes.

Location 3.2 Torrisdale Bay (Druim Chuibhe)
Outcrops of the Naver Thrust Sheet, with highly defomed amphibolite-facies Moine metasediments (plus ?Lewisianoid" basement) with syn-kinematic granitic pegmatite sheets (the Torrisdale Vein Complex; Holdsworth et al (2001). Migmatites here are dated 467±10 Ma (U-Pb SHRIMP zircon ages; Kinny et al. 1999). Ductile fabrics are reworked into a NNW-SSE striking foliation with gently SSE-plunging lineation. We can examine deformation controls on the fractional crystallisation of the pegmatites and their relationship to ductile deformation in the country rocks.

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