TSG Outer Hebrides Fieldtrip

16th – 22nd June 2015

TSG
Tectonic Studies Group

Acknowledgements

This field guide was written with the invaluable knowledge and assistance of John Mendum (BGS) and Bob Holdsworth (Durham University).

All photos taken by Lucy Campbell if otherwise uncited.

Useful Info:

Hospitals:

- *Western Isles Hospital,* MacAulay Road, Stornoway, Isle of Lewis HS1 2AF. 01851 704 704
- *Uist and Barra Hospital*, Balivanich, Benbecula HS7 5LA. 01870 603 603.
- *St Brendan's Hospital,* Castlebay, Isle of Barra HS9 5XE. 01871 812 021.

Emergency Services:

- Dial 999 for all, including coastguard/mountain rescue.

Outdoor access information:

- Sampling/coring : http://www.snh.gov.uk/protecting-scotlands-nature/safeguarding-geodiversity/protecting/scottish-core-code/
- Land Access Rights: http://www.snh.org.uk/pdfs/publications/access/full%20code.pdf

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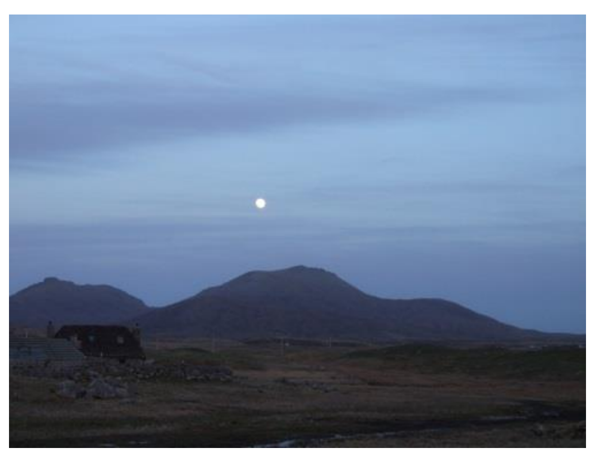
Contents

Introduction

The Outer Hebrides (also known as the Western Isles, or Na h-Eileanan Siar, and sometimes also Innse Gall - isles of strangers - or even just Long Island) form a narrow archiplelago off the northwest coast of mainland Scotland and comprise the large islands of Lewis and Harris, North Uist, Benbecula, South Uist and Barra as well as numerous smaller isles.

One of the few regions of the UK where Scottish Gaelic is still spoken by a majority, and crofting remains an important way of life. The landscape changes from sweeping sandy beaches in the west across low-lying bog to the rugged hills on the rocky east coasts, with Lewis and Harris providing higher and more numerous hills (and larger bogs!). The islands have a wealth of archaeological remains including the 5000-year-old Callanish stone circle, as well as plenty of birds and wildlife.



Trip Itinerary

Day 1: Tuesday 16th June
Ferry travel: departs Oban 1340 (check in by 1255), arriving Castlebay (Barra) 2040
Accommodation will be in Castlebay (Dunard Hostel)

Day 2: Wednesday 17th June
Localities: Barra
1730 ferry Barra – Eriskay (South Uist)
Accommodation – Uist bunkhouse, Daliburgh, South Uist

Day 3: Thursday 18th June
Localities: The Uists
1655 ferry Berneray – Leverburgh (North Uist – Harris)
Accommodation for two nights in Tarbet, Harris - 'The Backpackers Stop'

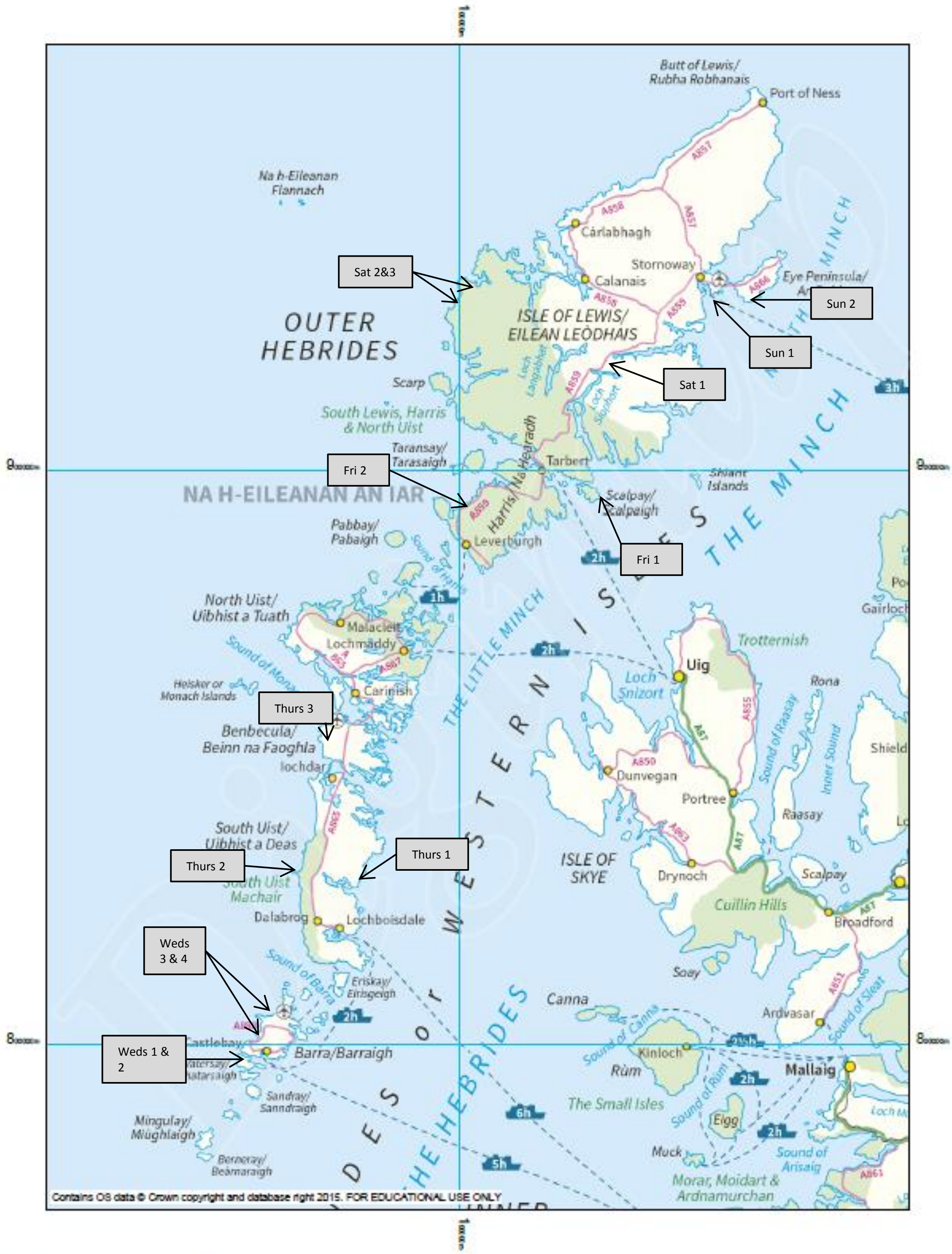
Day 4: Friday 19th June
Localities: Harris
Accommodation in Tarbert as Thursday

Day 5: Saturday 20th June
Localities: SE and W Lewis
Accommodation in Laxdale Bunkhouse, near Stornoway

Day 6: Sunday 21st June
Localities: E Lewis
Ferry: 1430 ferry (check-in by 1345), arriving in Ullapool 1700
Arrive Oban ~2100
Accommodation: Oban SYHA

Day 7: Monday 22nd June
Localities: Kerrera

Trip Itinerary: Localities



Geological Context

The Outer Hebrides expose a predominantly Archean crystalline basement which shows more affinity to the gneisses of Greenland than to the Scottish mainland just across the water. Scotland was initially part of the continent of Laurentia, along with Greenland and much of North America. These gneisses are also exposed in the NW of the mainland, but whatever structure is needed to produce the chemical discontinuity between them and the island rocks remains enigmatic. The signature of collision between Laurentia and other continents including Avalonia (containing England and part of Europe) is clear in the structures of the Outer Hebrides Fault Zone – the islands form part of the Caledonides. Many older tectonic events are also preserved, both rifting and collision. The age of the gneiss also means that it’s formation is significant in understanding the generation of the early crust.

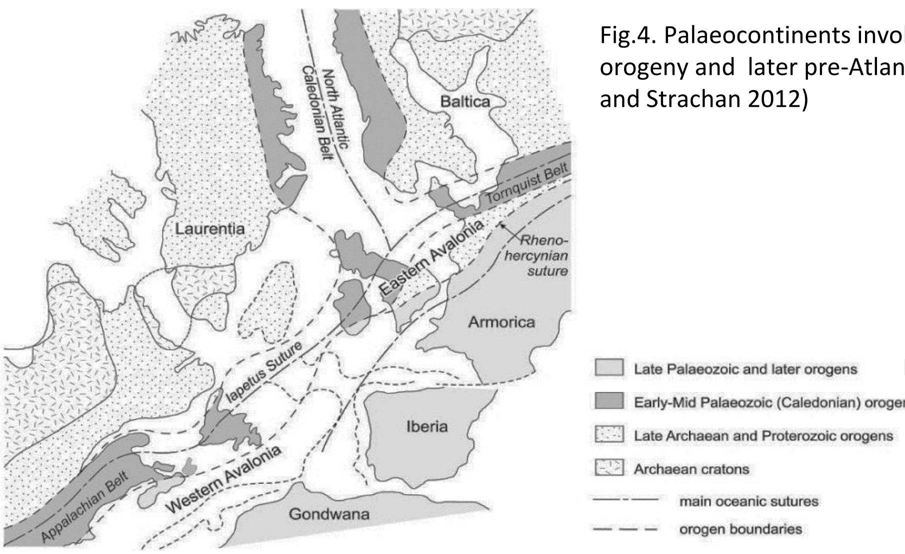
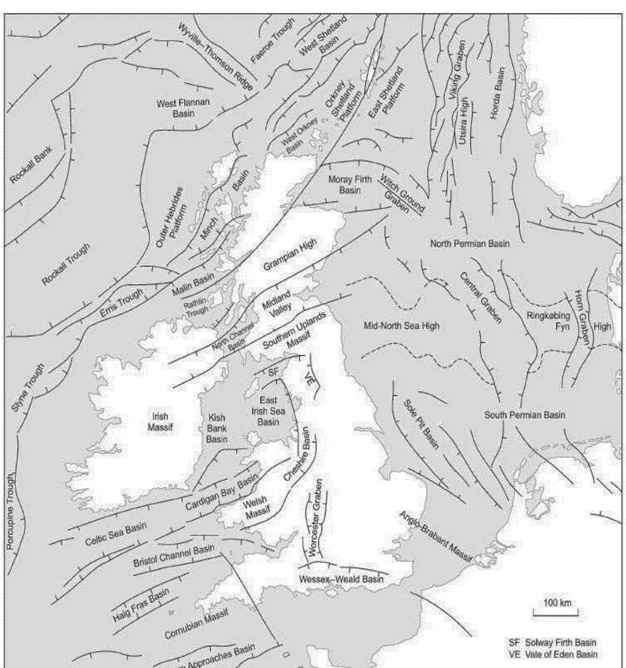
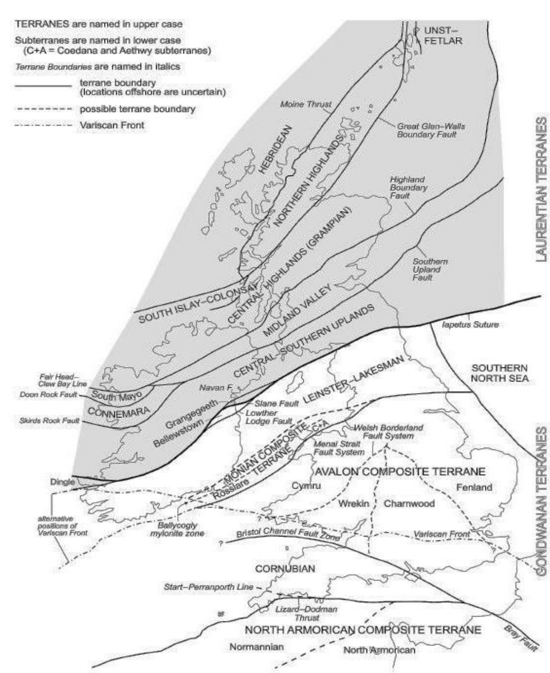


Fig.4. Palaeocontinents involved in the Caledonian orogeny and later pre-Atlantic rifting events (Woodcock and Strachan 2012)

Fig.5. (below left) major faults, basins and highs in the post-Variscan British Isles (Woodcock and Strachan 2012)

Fig.6. (below right) Palaeozoic terrane map of British Isles (Woodcock and Strachan 2012)





Maps

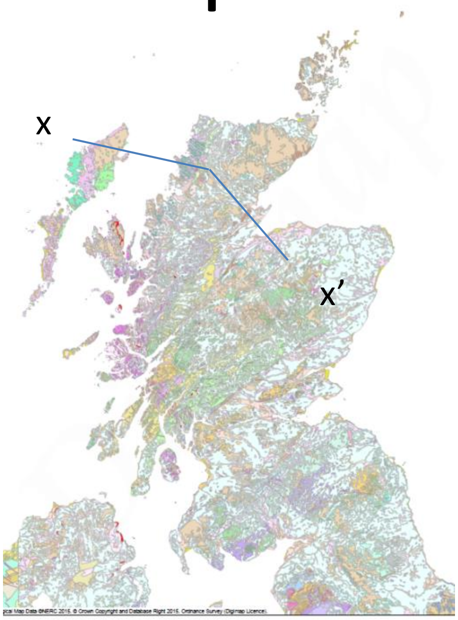
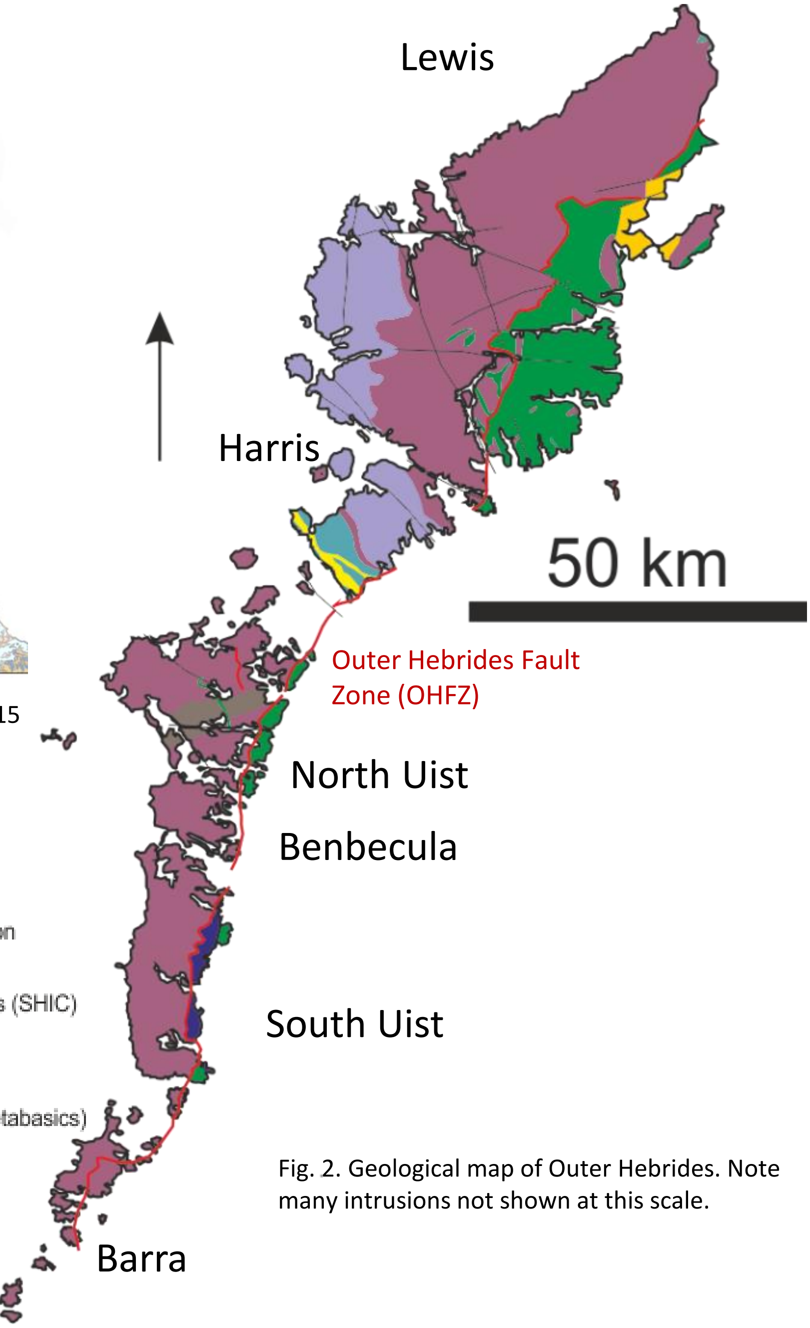


Fig.1. Geological map data © NERC 2015



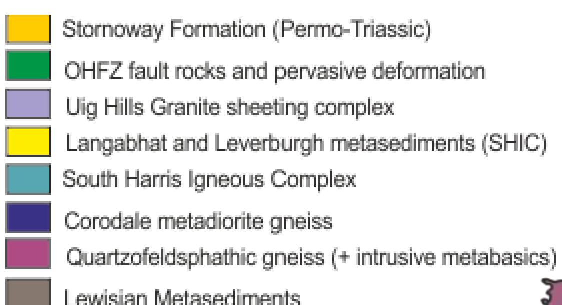


Fig. 2. Geological map of Outer Hebrides. Note many intrusions not shown at this scale.

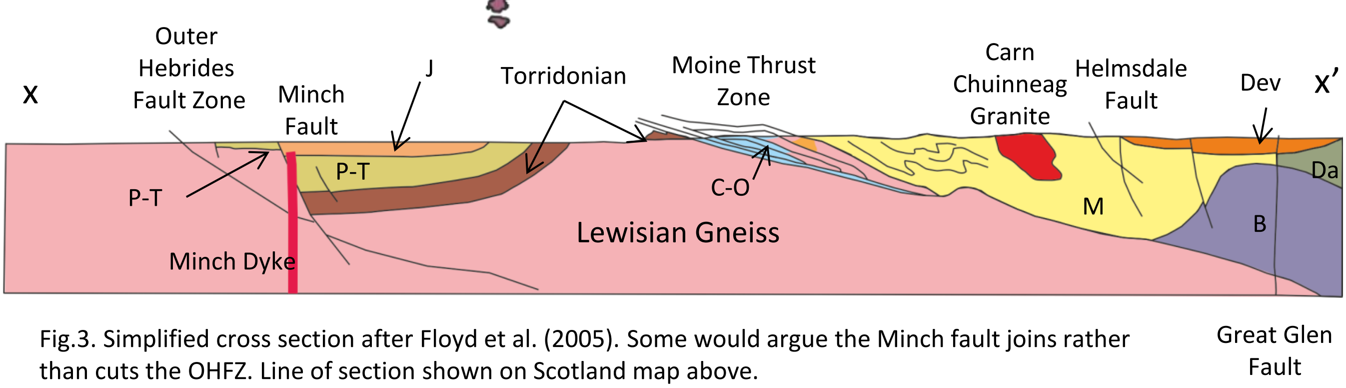


Fig.3. Simplified cross section after Floyd et al. (2005). Some would argue the Minch fault joins rather than cuts the OHFZ. Line of section shown on Scotland map above.
B = Proterozoic basement; M = Moine metasediments; Da = Dalradian metasediments; C-O = Cambro-Ordivician sediments; Dev = Devonian sediments; P-T = Permo-Triassic sediments, J = Jurassic sediments.

Structural History

2700 Ma

Scourian deformation: High grade metamorphism and deformation probably accompanied the generation of the igneous protoliths of the Lewisian Gneiss, forming a gneissic fabric and compositional banding.

2600 Ma

Late Scourian structures: asymmetrical folding of the earlier banding and a few major high strain zones (West Lewis, Nis, Leverburgh belt) which were probably reactivated during the Laxfordian.

2040 Ma

Intrusion of the Younger Basics

1890 Ma

Intrusion of SHIC diorite and norite, and early fabric development here.

Earliest Laxfordian (D_{Lax1}) NW trending fabrics created

Early Laxfordian (D_{Lax2}): Widespread folding of Scourian foliation, folding and boudinage of Younger Basic dykes, creation of weak axial planar foliation (locally). New fabrics and recrystallization occur. High strain zones picked out by tight folding. Typically low-angle axial planes trend NW-SE. Shearing particularly along SHIC boundaries.

1700 Ma

Later Laxfordian (D_{Lax3}, D_{Lax4}): more spatially variable than D_{Lax2}. D_{Lax3} sees the intrusion of the Uig Hills granite complex, whereas migmitisation affected the South Uist gneisses during D_{Lax4}. Broad folds separated by NW-SE high strain zones dominate the Uists and suggest that here, D_{Lax3} rather than D_{Lax2} was the more significant deformation phase. D_{Lax3} axes tend to be steeper than $D_{Lax2,}$ still trending NW-SE. Lewis however has several instances of NNE-SSW shear zones and axial planes.

1680 Ma

Latest Laxfordian: Pegmatite intrusion, mostly striking E-W. Localised brittle cataclastic deformation.

1100 Ma

Grenvillian: Uplift and erosion of Lewisian. Restricted heating and recrystallization north of Langabhat Shear Zone – possible reactivation. Potential genesis of Outer Hebrides Fault Zone (OHFZ).

Caledonian: OHFZ activity through variety of kinematic regimes

1. Top-to-NW ductile thrusting, greenschist to lower amphibolite facies, extensive mylonitisation in the northern section and perhaps local in the south.
2. Top-to-NW brittle thrusting (430 Ma)
3. Top-to NW left lateral (± right lateral) strike slip with phyllonite development, greenschist facies. (420 Ma?)
4. Down-to-SE brittle extension and later phyllonite reactivation/development

~260 Ma to ~145 Ma

Mesozoic faulting: Dating from late Permian, extensional reactivation of deeper OHFZ and formation of Minch (and associated) faults as hanging-wall shortcuts. Opening of Minch basins as well as others in the Hebrides Shelf and west-of-Orkney areas (to W, N and NE of Outer Hebrides)

Lithologies of the Outer Hebrides

Lewisian Complex

The 'Lewisian Complex' encompasses the typical Archean 'grey gneiss' along with basic and ultrabasic intrusions, the dioritic Corodale Gneiss unit, the metasediments and meta-igneous rocks of the South Harris Igneous Complex, other localised metasediment bands and the Uig granites, pegmatites and other late-Laxfordian intrusions. The divisions 'Scourian' and 'Laxfordian' are sometimes used for units respectively pre- and post-dating the Younger Basic (Scourie) dyking episode ~2400 Ma. On the Scottish mainland, different tectonothermal histories recorded in the Lewisian at different localities have led to various evolutionary models, of which the 'terrane' model has more recently taken precedence. This explains the variation by differentiating a number of terranes - crustal slices with varying histories - that were juxtaposed at certain times along shear zones. The Outer Hebrides fits within this and is ascribed three terranes (Tarbet, Roineabhal, Nis) but it is also clear that the Lewisian in the Outer Hebrides is more easily correlated with the Archean gneisses of Greenland than the mainland Lewisian (Friend and Kinny 2001). Certain field relationships do not support these terrane divisions (Mason and Brewer 2004) – but a useful emphasis of the terrane model is that several episodes of crust production may have combined to form the Lewisian.

Grey Gneiss

The dominant rock type in the Outer Hebrides is a quartzofeldspathic gneiss, with additional components of biotite, hornblende and K-spar, with the more mafic phases defining the foliation. Although often mapped as 'undifferentiated gneiss', it may be highly variable on a local scale. The oldest protolith ages yet found come from South Harris, 3125 ± 14 Ma (Friend and Kinny 2001), with more at 2744 ± 1Ma (North Harris), 2760 ± 2 Ma (Benbecula) and 2763 ± 1Ma (South Uist, all Mason et al. 2004). Protoliths for the Grey Gneisses are inferred to be felsic igneous bodies of tonolite-trondhjemite-granodiorite composition, typical of many early-crustal rocks. Metamorphism of the Grey Gneisses prevalently record Laxfordian amphibolite facies conditions , but some relict areas of (presumably Scourian) granulite assemblages hint at localised absences of water precluding later retrogression (Fettes et al. 1992). A set of basic and ultrabasic-basic layered intrusions known as the 'Older Basics' form lenses and concordant dykes within the Grey Gneiss and are dated at 2585 Ma (Francis et al. 1971), hence broadly sharing the structural and metamorphic history of the host.

Corodale Gneiss

The Corodale gneiss is found only in the hangingwall of the Outer Hebrides Fault Zone (OHFZ) in South Uist, and only tectonic contacts exist between it and the Grey Gneiss. Its granulite-facies assemblage consists of clinopyroxene - orthopyroxene – garnet – hornblende – plagioclase, with a dioritic igneous protolith. The Sm-Nd and Pb-Pb ages of 2770 ± 140 Ma and 2900 ± 100 Ma show a similar Archean age of generation to the Grey Gneisses, as opposed to the younger Proterozoic meta-igneous bodies seen in South Harris (Whitehouse 1993).

Younger Basic intrusions

The Younger Basics are a suite of basic and ultrabasic igneous intrusions, often forming dyke-like swarms. They are more discordant and less migmatised than the Older Basics, though the amphibolite mineralogy is similar. Dating of these bodies gives minimum crystallisation ages of 2049 +78/–100 Ma and 2039 +99/-100 Ma (Mason et al. 2004) and metamorphism at 1625-1660 Ma (Cliff et al. 1998) – hence they post-date the Archean Scourian event but were affected by Paleaoproterozoic Laxfordian tectonism. As for the Scourie Dykes on the mainland with which they are traditionally correlated, the Younger Basics form useful markers to discriminate between these deformation periods. However, the Younger Basics in the footwall of the Outer Hebrides Fault Zone (OHFZ) are chemically different from the Scourie suite and are more similar to Greenland dyke swarms of similar age (Mason and Brewer 2004).

South Harris Igneous Complex (SHIC) and metasediments

The Langabhat and Leverburgh metasedimentary belts contain semi-peites, pelites, marbles and amphibolites with other meta-igneous inclusions. The Leverburgh belt is given a maximum age of 2400 Ma (Cliff 1989) and is thought to have undergone granulite facies metamorphism during the Laxfordian accretion and intrusions of the South Harris Igneous Complex. There is some debate on whether the Langabhat belt is related – Mason and Brewer (2004) regard the Leverburgh Belt as amphibolite, rather than granulite grade. The Langabhat Shear Zone lies predominantly within the Langabhat metasediments.

South Harris consists of four igneous suites intruded into and sheared against the Leverburgh and Langabhat metasediment belts. These bodies are traditionally termed gabbro, anorthosite, diorite and norite in order of intrusion, although assemblages have been altered by a series of metamorphic events ranging from granulite to greenschist facies. The anorthosite is roughly 600 Myrs older than the diorite and norite, which share an age around 1890Ma (Mason et al. 2004). This implies that the gabbro-anorthosite body might represent the basement to the younger sediments, whereas the norite and diorite were truly intrusive. Overall, this sequence is interpreted as a Palaeoproterozoic collisional island arc. There are parallels in this with some mainland sequences, notably the Loch Maree Group around Gairloch, Wester Ross. Metamorphism across South Harris peaked at granulite facies soon afterwards, with peak conditions dated in the range of 1870 ± 30 Ma and 1790 ± 130 Ma (Cliff et al. 1998). Amphibolite facies retrogressive assemblages may be found along the boundaries of each unit and are associated with Laxfordian deformation.

The deformation seen in the bodies of the SHIC has been divided up into several phases (e.g. Coward et al. 1970). An initial development of foliation in the igneous rocks, accompanied by small-scale tight folds and some migmitisation, is possibly linked to the intrusion of further magmatic bodies. Next, the main phase of Laxfordian deformation (‘D_{Lax2}’, Fettes et al. 1992) caused many of the marginal shear zones along unit boundaries and possibly the folding of the meta-anorthosite and metagabbro into a NW plunging antiform. Further folding, or at least tightening of exisiting structures, occurred on a larger scale during D_{Lax3}. Later sets of shear zones are attributed to both D_{Lax3} and D_{Lax4}, both of which are estimated to be late-Laxfordian phases .

Uig Hills – Harris Granite Complex

Granite sheeting and 'granitised' (altered and homogenised) gneisses form ~420km^2 of outcrop through western Lewis, Harris and parts of South Harris, bordering the northern edge of the SHIC. Ages of these rocks have been derived as 1710 ±35 Ma from Rb-Sr isochrons and 1715 +20 -10 Ma from U-Pb results (van Breemen et al. 1971), bringing intrusion of the granite into the late-Laxfordian tectonothermal period. The complex is thought to represent a dome structure, the upper limit of granite veining being traceable in the higher hills of North Harris, and zoned with regard to veining size and density, and also the presence of alteration in the host gneiss (Myers 1971). The size of the veins or sheets ranges from centimetres to hundreds of metres in width. Cross-cutting relationships of different intrusion phases may be observed, althought he composition tends to be consistently quartz - plagioclase - K-spar - biotite (Fettes et al. 1992). A suite of leucogranite pegmatites usually forms the latest phase.

An increase of migmatisation in west Harris and heightened recrystallization of the gneiss near to the granite complex led to some interpretations that the intrusion process had partially melted and/or chemically altered the host rock in a 'granitisation' process (Myers 1971). However, it has since been noted that recrystallized gneisses are not always present in regions of granite veining (e.g. Dail Beag, Lewis [NB 235 453]) but may also occur without nearby granites at all (Fettes et al. 1992). The heat source for the granitic melts and the recrystallisation of the gneiss may have been the same but a direct link between them seems likely to be coincidental.

Post-Lewisian

Intrusions: Caledonian and later

Caledonian appinite dykes have been found in the west of Lewis and North Uist, with a coarse grained amphibole rich rock with additional pyroxene, feldspar and biotite (Fettes et al. 1992). There is some chemical and age correlation of these dykes to similar ones on the mainland. K/Ar dating of biotite and hornblende has produced ages of 431 ± 10 Ma and 477 ± 11 Ma.

In Barra and South Uist, a Permo-Carboniferous suite of quartz-dolerite dykes trend between E-W and SE-NW. The overall crustal extension calculated from all known occurrences of these intrusions (~10) is around 3% (Fettes et al. 1992). An additional Permo-Carboniferous dyke set, dated 330 - 230Ma, are potassic lamprophyes containing plagioclase-amphibole-titanaugite or olivine-titanaugite-hornblende. Dykes from this suite are found in Barra, South Harris and Lewis, and can be tracked across the Minch to mainland swarms (Rock 1983).

The final group of intrusions are the most widespread through the isles and are related to the Tertiary opening of the North Atlantic, as part of the British Tertiary Igneous Province. Particularly dense swarms in South Harris and Barra can be linked through matching mainland swarms to the igneous centres of the Cuillin (Skye) and Mull. These intrusions are crinanites (olivine-dolerites with analcite), olivine-dolerites and dolerites (Fettes et al. 1992).

Permo-Triassic Sedimentation and faulting

The Stornoway Formation is the only record left of post-Caledonian bedrock deposition. It consists of a series of alluvial conglomerates with associated sandstones and silt layers and has an apparent thickness of 4km, although its true thickness is probably less (Steel and Wilson 1975). Exposure is limited to the northeast of Lewis, around Stornoway. The unit sits unconformabley on the Lewisian, with clasts being predominantly gneissic and occasionally showing pseudotachylyte veins indicating that the Lewisian was exposed at the surface at this time. Faulting controls the western boundary of the formation. Six alluvial fan sequences are identified by Steel and Wilson (1975) which are inferred to represent syn-tectonic fault scarp fans joined by overbank floodplain and braided stream sequences.

Jurassic sediments are found onshore in the Shiant Islands to the east, largely shales now rather altered by contact metamorphism from Tertiary sills. These are analogous to the Jurassic sequence on Skye. The Cretaceous is not seen onshore in the Hebrides but is present occasionally in the Minch basins.

The Minch fault divides these sediments from the Lewisian gneiss, forming the westerly bounding normal fault to the North Minch and Sea of Hebrides half-grabens between the Western Isles and the mainland. Although steeper at the surface than the OHFZ, the Minch fault closely tracks the strike of the older structure and is inferred to form a hangingwall shortcut, partially reactivating the OHFZ. The oldest sediments in the Minch basin are probably the Permo-Triassic Stornoway Formation, but there have been arguments for the identification of the Neoproterozoic Torridon group in the base of wellcores and seismic sections (Stein 1988, Williams and Foden 2011), which requires extensional activity on the OHFZ as early as ~1Ga.

The Minch basin is part of a wider period of Mesozoic extension which may have a signature onshore through the mainland as well as offshore through the Hebrides and West Shetland shelves (Roberts and Holdsworth 1999). The offshore region to the north and west of the Outer Hebrides consists of a series of small basins separated by basement highs. While the extension accommodated by basin opening initiated in the Permo-Triassic, there is a strong argument for Caledonian structural inheritance (Stein and Blundell 1990), with former thrusts reactivating to basin bounding normal faults as for the Minch fault (Stoker et al. 1993).

Quaternary

Surviving glacial evidence suggests ice cover over the Hebrides during the last glacial maximum (Devensian, ~ 22ma) with a later, more restricted onset of valley glaciation around 11-13 Ka, equivalent to the Loch Lomond (Younger Dryas) Stadial on the mainland (Ballatyne 2007). The Last Glacial Maximum (~22Ka) saw the Outer Hebrides buried under a locally 600m thick ice cap. It is argued that this cap formed independently to the ice sheet on mainland Britain, but merged with it during the late Devensian (Selby 1989), with mainland lithologies found as erratics on the isles. The highest hills of Harris were left as emergent nunataks and were subject to widespread periglacial frost shattering (Stone and Ballatyne 2006). Trimlines marking the upper ice limits can still be traced (e.g. Uisgneabhal Mor, North Harris).

Glacial erosion is most easily seen in the hummocky, rounded cnoc-and-lochan topography characteristic of the gneiss, and in the distinctive U-shaped valleys such as Gleann Crabhadail (Cravedale), NW Harris. Glacial deposits are fairly localised onshore, mostly restricted to Lewis. However, offshore glacial and glaciomarine deposits record the expansion, limit and retreat of ice across the Hebridean Shelf (Stoker et al. 1993).

After the retreat of glaciation, pollen evidence shows the Hebrides became grassed and wooded, before a shift to a wetter climate favoured the production of peat bogs. Initial sea level rise caused by glacial melting trangressed into the shallowly sloping western coastal platform, drowning early peat beds (Ritchie 1985). The movement of marine sands towards the west coast, active by 5700 BP (Richie 1979), began the creation of the machair – the flat, sandy coastal plain found extensively on the west coast of the islands, particularly the Uists. The sand is up to 80% $CaCO_3$ and is probably sourced from a mix of glacial and biogenic marine deposits (Ritchie and Whittington 1994). Significant movement of sand bodies has been dated almost up to the present day (Dawson et al. 2004), with mobility linked to changes in storm activity throughout the last 5000 years.

Outer Hebrides Fault Zone (OHFZ)

Structure of the fault zone

The fault zone is exposed almost continuously up the eastern coast of the Outer Hebrides, skirting just seaward of Harris and continuing north from Lewis for perhaps another 100km offshore (Figs. 2, 23). It dips predominantly to the southeast at an angle of around 20°-30° and is seismically imaged to cut through the entire crust (e.g. Smythe et al. 1982). Additional, subparallel faults may occur further west of the main fault zone, for example in Barra and north Uist. The present segmented nature of the fault, with changes in strike and combinations of slip directions, is thought to reflect true compartmentalisation during fault activity (MacInnes et al. 2000, Imber et al. 2002).

Fault zone conditions

The OHFZ has long been considered a thrust, partly due to the similarities in strike with the mainland Moine Thrust and partly because granulite facies gneisses are juxtaposed above those of amphibolite facies in South Uist and Barra. However, kinematic indicators within the fault zone tend to reflect strike-slip or normal fault movement, and point to the complex reactivation history of the OHFZ. Initiation of faulting is argued to be pre-Caledonian, probably around 1Ga and therefore possibly part of the Grenvillian assembly of the Rondinian supercontinent.

This early phase is considered to be ductile thrusting and may only have been prevalent in the 'northern section' of the OHFZ (Imber et al. 2002). The northern and southern sections correspond roughly to Lewis with North Harris, and the Uists with Barra respectively. The division of these sections coincides roughly with the shear zones of South Harris, which has led some to suggest that ductile thrusting pre- 1100 Ma was offset by late reactivation of the South Harris shear zones (Imber et al. 2001). There is, however, evidence in Barra and South Uist for mylonites developed locally within fault planes.

Fluid inclusion studies have been used to calculate fault temperatures during active periods. In Harris, early ductile thrusting records 500 ± 30°C, phyllonitisation during left-lateral strike slip at 230 ± 20° and the late-Caledonian extension at 150 ± 20°C (Szulc et al. 2008). Variation along the fault strike is shown by Osinski et al. (2001) who record 370 ± 20°C for extensional phyllonitisation in South Uist. These temperatures are local to the fault zone; the wider gneiss has remained below biotite closure temperatures (250-300°C) since ~1100 Ma with no subsequent resetting (Cliff and Rex 1989). Purely brittle events (i.e. Caledonian brittle thrusting) are harder to constrain but are associated with greenschist alteration and veining.

Fault Rocks of the OHFZ

- ***Mylonites*** - found most extensively in SE Lewis, particularly within the Pairc district. There, individual layers of continuous mylonite can be hundreds of metres thick around localities such as Loch Bhrolluim [NB 321 031]. Further south, mylonites are more sporadically developed. Mylonite bands tend to be anastomosing with variable relationships to the country rock – with mylonitic foliation at a small angle to the host foliation, mylonites in SE Lewis seem to indicate normal movement and elsewhere show variations consistant with several phases of generation [e.g. NB 318 118]. Generally the fabric dips shallowly to moderately SE, with minor folds present in places. At the 'Seaforth Head' (Ceann Shìphoirt) locality in SE Lewis, mylonites appear in thin section to have resheared pseudotachylytes (White 1996).

- ***'Mashed/crushed' gneiss*** – bands of fragmented, cataclased country rock, a kind of highly fractured breccia. Often densely veined with pseudotachylyte, these zones are interpreted to show repeated fracturing and fault movement. Sometimes occurring as black, aphanitic 'crush zones' (e.g. Butler 1995) which on the lower thrusts can be ~30m thick [South Uist, NF 808 205], the dark appearance of this rock is as much to do with the abundance of ultracataclasite and a mafic protolith, as pseudotachylyte content. Elsewhere, in North Uist and Harris, these zones are retrogressed with little pseudotachylyte – possibly reflecting heterogeneity in fault zone fluid presence.

- ***Cataclasites*** – may form along fault planes outwith the mashed gneiss.

- ***Phyllonites*** – generally found in the eastern parts of the exposed fault . Fine-grained, well foliated flaggy rocks with a greenish tinge reflecting their greenschist assemblages. Bands of phyllonite anastomose around lenses of host gneiss, with which they may show a gradual transition to. These rocks are associated with fluid-present focussing of late strike-slip and extensional faulting.

- ***Pseudotachylytes*** – evidence for seismic activity on the OHFZ.
    1. Occurrence: typically seen as fault veins (Fig.9.), injection veins, networks of connected veins and as a matrix to fault breccias. Injection veins and typical fracturing allow distinction from dark ultracataclasites and ultramylonites. Pseudotachylyte is seen in large volumes around some sections of the OHFZ, but is also well-exposed in some headlands on the west coast [NF 646 048, NF 710 296] and elsewhere, notably central Lewis (Fig.8.).

    2. Petrology: Whole rock analyses of pseudotachylytes are almost identical to the surrounding host rock, but the survival of quartz and plagioclase as clasts in the vein show melting was not complete. Some veins may preserve glassy amorphous regions with quench textures such as dendrites, microlathes and spherulites (see Maddock 1983), others are microcrystalline and/or devitrified. Vein phases tend to be dominated by plagioclase (often as microlathes) and hornblende ± biotite. The overall melt composition is regarded as andesitic (Sibson 1975).

    3. Faulting environment: pseudotachylyte veins are usually linked to thrusting episodes, but fault veins but are not always parallel to the main faults and extensional pseudotachylytes have been recognised within the fault zone by Imber (1998) who regarded them as local extensional accommodation of thrust block movement. The depth of pseudotachylyte production in a Caledonian brittle thrusting phase is thought to be 5-10KM, the mylonite-hosted veins in the northern section from 15+km (Sibson and Toy 2006). The OHFZ is treated as fluid-absent during pseudotachylyte production.

    4. Dating: In older literature, the pseudotachylytes are almost always assumed to be formed during Caledonian thrusting. The first $^{40}Ar/^{39}Ar$ study confirmed this with a date of 430 ± 4 Ma (Kelley et al. 1994) on one OHFZ sample, while an earlier palaeomagnetic investigation suggested both a Caledonian and an earlier, ‘post-Laxfordian’ age ~1400 Ma (Piper and Poppleton 1989). A more recent $^{40}Ar/^{39}Ar$ study on multiple samples from across the islands produced dates of ~1900 Ma, 1200 Ma and 700 Ma (Sherlock et al. 2009).

Fig.7. View northwards of Malasgair, SE Lewis. A mylonitised zone of the OHFZ passes through here, and the ridges on hill flanks typically pick out fault planes dipping to the SE.

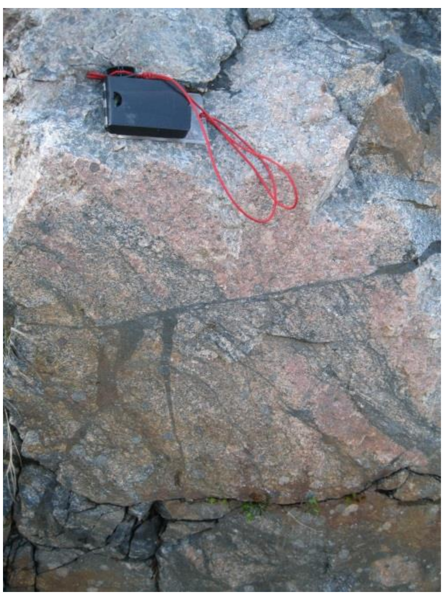


Fig.9. Pseudotachylyte fault vein with offset and injections, North Uist.

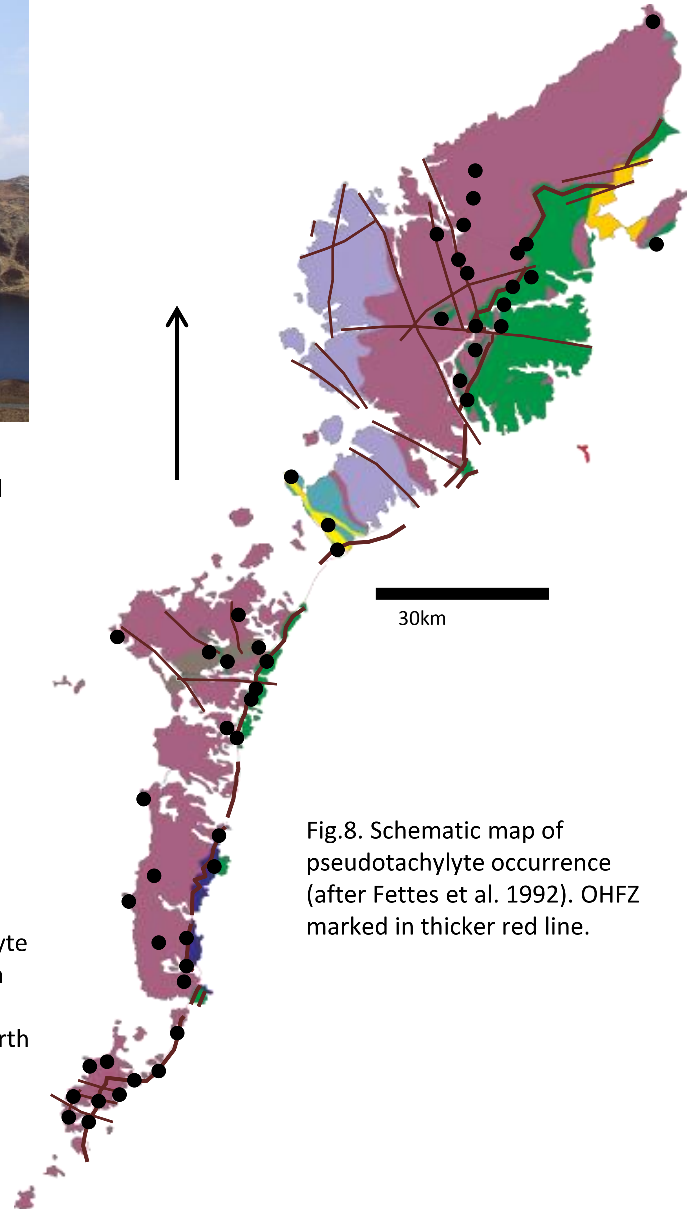
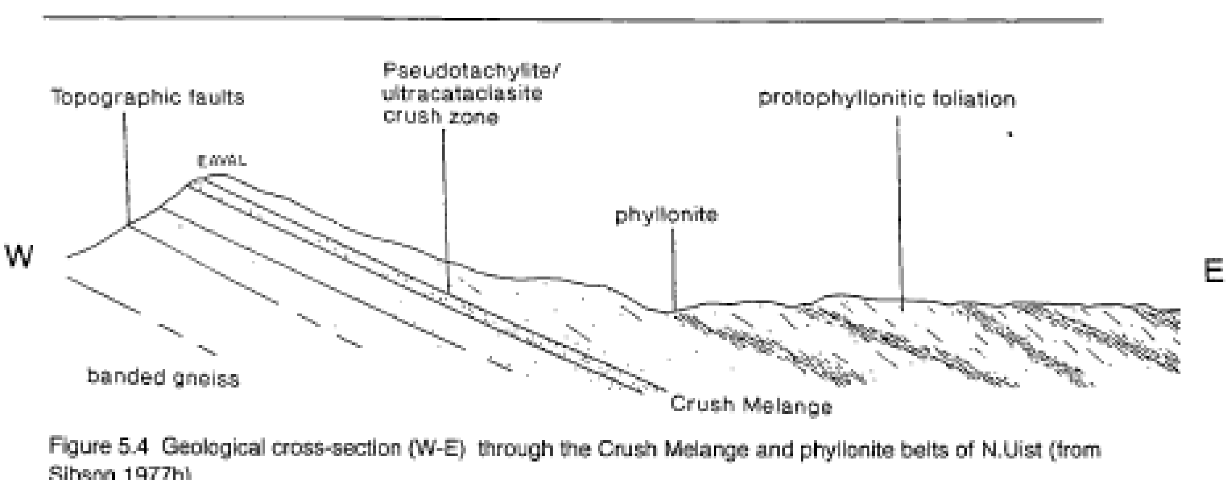


Fig.8. Schematic map of pseudotachylyte occurrence (after Fettes et al. 1992). OHFZ marked in thicker red line.

Fig.10. Typical structure across OHFZ in the Uists (Butler 1995)



Wednesday 17th June: Barra

Stop 1: Castlebay ferry terminal [NL 664 981]

A short walk from the hostel brings us to our first encounter with pseudotachylyte, nicely exposed by the ferry slipway. The OHFZ runs through here, and although the faulting is not really exposed at sea level here, the indented topography of the hill above Castlebay (Heabhal) picks out individual fault planes.

Stop 2: Vantage point

Stop 3: Vatersay causeway quarry [NL 638 977]

Stone from this quarry was used to construct the causeway across to Vatersay (Bhatarsaigh) from 1989-1991, in an effort to halt Vatersay's depopulation. The hill that the quarry is cut into, Beinn Tangabhal, shows fault-plane ridges on its flanks and may be an easterly branch of the OHFZ. Pseudotachylytes are also found exposed on its northern side. In the quarry, however, we see evidence for earlier deformation. Here, the quartzofeldspathic 'grey gneisses' which comprise the majority of the Outer Hebrides display Laxfordian structures, and mafic intrusions (now metamorphosed to amphibolite) can be seen folded and migmitized. Both major phases of mafic intrusion, the Older Basics and Younger Basics are present but are here rather difficult to tell apart. Small shear zones can also be seen.

Stop 4: Bàgh Halaman [NF 644 006]

At low tide, rocky outcrops in this beach expose pseudotachylyte faults and injection veins, and blocks of breccia can also be seen (though not always in situ). Veins can also be seen forming along the boundaries of mafic intrusions within the quartzofeldspathic gneiss. The gneiss itself displays a folded foliation/banding, probably from early-mid Laxfordian deformation.

Stop 5: Àird Ghrèin [NF 658 045]

First, we will take a look at some of the exposures on the beach to the south of Àird Ghrèin. [NF 657 039]. Here, the exposure steps along foliation planes, allowing the top surfaces of concordant veins to be seen. Some of these are pseudotachylyte-hosted 'breccias' although the clasts are notably rounded here. Between these lies an extensive network of pseudotachylyte veins, and cross-cutting relationships can occasionally be seen . Continuing westwards, a generation surface relating to pseudotachylyte veining can be seen at the foot of the beach [NF 65682 0402]. From here we head up onto the headland of Àird Ghrèin where further breccias and veins are well exposed in the bench-like topography of the hill

Fig.11. Pseudotachylyte associated with margins of basic intrusion, Bàgh Halaman , Barra. [NF 645 003]

Fig.12. Texture produced by weathering of clasts out of pseudotachylyte-breccia, Àird Ghrein, Barra [NF 657 039]

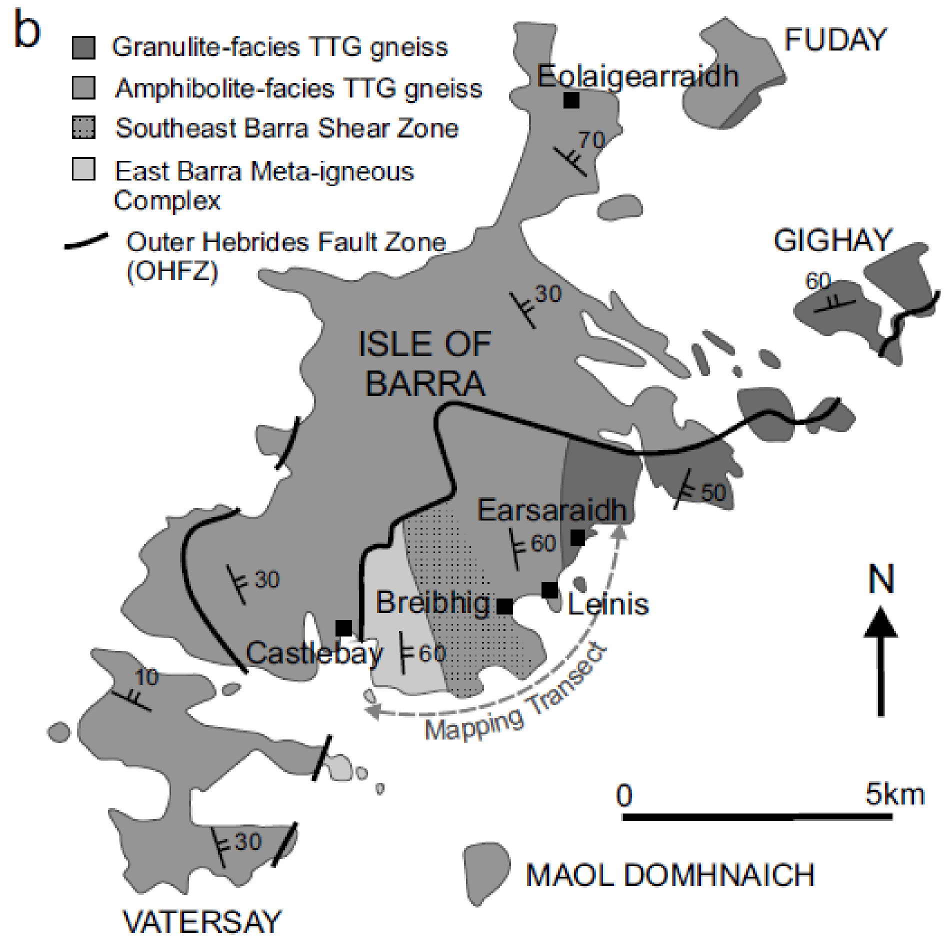


Fig.13. Map of main faults and lineations in Barra (MacDonald and Goodenough 2013)

Thursday 18th June: Uists

Stop 1: Beinn na Tobha [NF 816 285] and Rubha Bholuim [NF 830 284]

A traverse through the OHFZ (Fig.14.) showing Corodale Gneiss faulted over the quartzofeldspatic gneiss, and pseudotachylytes + other fault rocks.

1. Starting in Toabh a Tuath Loch Aineort (North Loch Eynort) and heading east to the head of Sloc Dubh, we should see banded garnet-bearing mafic intrusions in the crags. These display granite veining and an agmatitic texture – blocks of mafic/restite material surrounded by leucosomal melt – these are from the Older Basic suite. Later basic intrusions which cut these textures are also reported.
2. Onwards – the obvious feature in the slopes above is regarded as the basal thrust of the OHFZ – above this lies the rest of the fault zone along with most of the pseudotachylyte veining and cataclasis, and it separates the felsic, amphibolite facies grey gneiss from the mafic, granulite facies Corodale Gneiss above. Walking through the basal thrust and into the Corodale gneiss, down to the coast, we can observe the changing structures of fault deformation.
3. At Bàgh Bholuim the Corodale Gneiss shows retrogression and also interbanding with gneisses of different compositions.
4. To the north, at the headland of Rubha Bholuim [NF 830 282], a mylonitised fabric becomes increasingly apparent. This is part of the 'Usinish Phyllonite' of Butler (1995) which, elsewhere at least, is associated with late-Caledonian strike slip and extensional events. It also marks the upper observed limit of the Corodale gneiss.

Stop 2 (if time): Rubha Àird a' Mhuile [NF 712 299]

This headland forms one of the more westerly exposures of pseudotachylytes, far into the footwall of the OHFZ. The controlling faults for these pseudotachylytes are not obvious – it is possible that they lie just offshore further west, or that it lies on some NW-SE lineament which has produced melt as well. Several breccias and vein systems are apparent, sometimes with unusual geometries.

Fig. 14. Map of main Rubha Bholuim traverse stops as listed on pg20

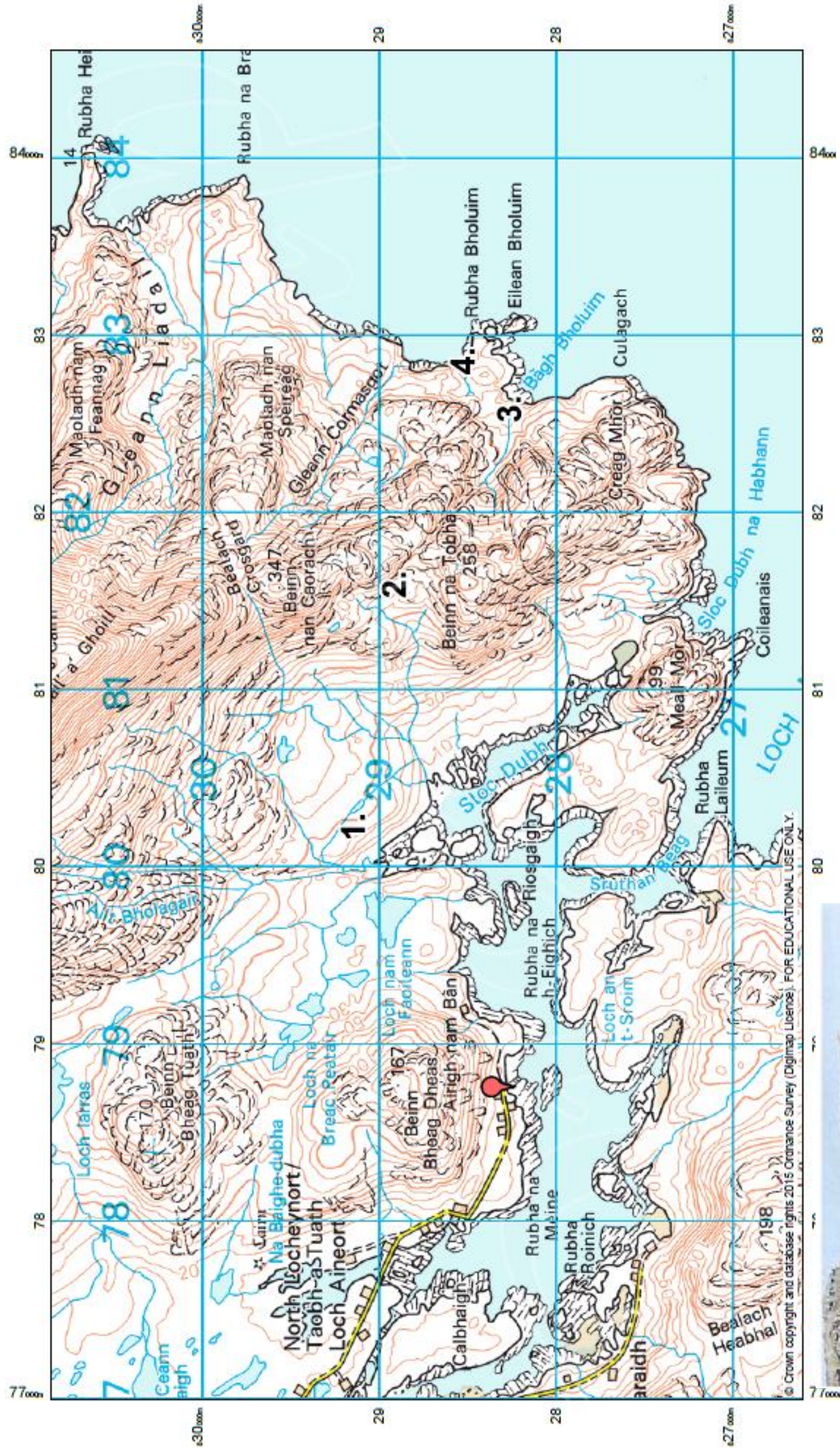


Fig.15. Structural data for Phyllonites (Butler 1995)

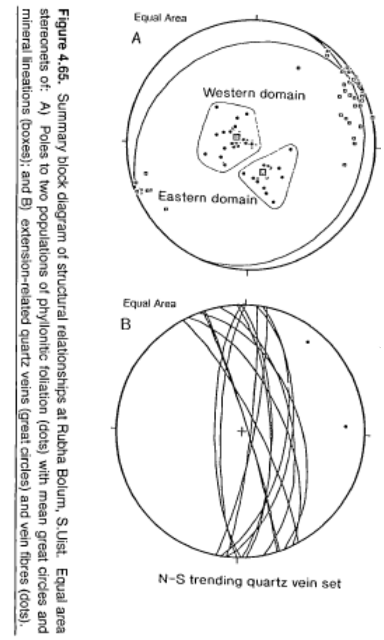


Fig.16. Converging detachemet faults at Rubha Bolum (NF 829 2840. Foliation varies above and below the lower fault (Butler 1995)

Stop 3: Gearraidh Siar, Benbecula [NF 757 533]

Gearraidh Siar is recognized as an area of low Laxfordian strain. However, within this low-lying headland the Laxfordian deformation is highly variable over short distances. The 4 phases of the Laxfordian in the Outer Hebrides, as defined by Coward (1973) were worked out here and at a similar locality in South Uist (see Structural History page for brief outline). At Gearraidh Siar, a swarm of Younger Basic dykes records the strain variations so that mostly undeformed dykes are almost adjacent to strongly deformed ones.

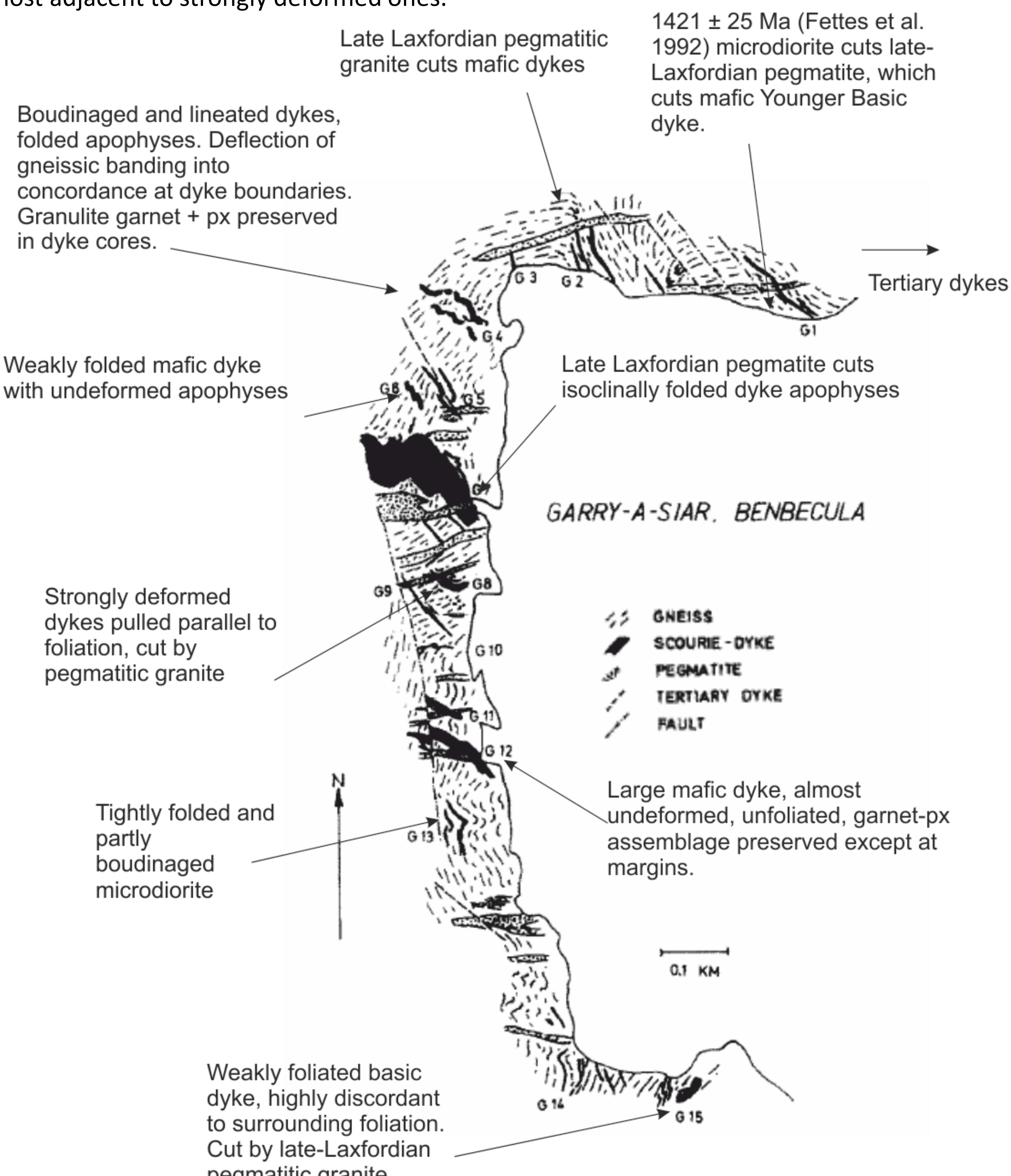


Fig.17.Gearraidh Siar, Coward (1973)

Friday 19th June: Harris

Stop 1: Sgalpaigh (Scalpay)

Sgalpaigh offers another opportunity to dissect the OHFZ. We will visit a handful of localities to illustrate this, travelling from west to east.

1. First, a roadside outcrop showing folded banded gneiss. Pseudotachylyte veins cut across a Laxfordian pegmatitic granite vein which in turn cuts across the banding [NG 2131 9655]. These pseudotachylyte veins at the top of the outcrop dip NE at a low angle to the banding, whereas towards the base they dip NW. A mafic intrusion is bordered by pseudotachylyte veins – these may be related to the offset seen in the mafic body. A matching offset down towards NW is also signified by sigmoidal foliation in the intrusion. If the pseudotachylyte and brittle offset occurred at the same time as the ductile deformation, the pseudotachylyte can be inferred to have formed during the 'early ductile thrusting' phase of the OHFZ at ~500ºC (Szulc et al. 2008), potentially around 1Ga.

2. Crag above road at [NG 2240 9562]. Phyllonites – termed the 'Cnoc na Croich phyllonite zone' (e.g. Sibson 1977), strong mylonitisation and cataclasis has occurred along a shear zone dipping moderately SE. Both felsic and mafic gneiss bands have been deformed here, and the greenschist conditions of shearing should be apparent in the mineral assemblages,

3. Road cutting [NG 2259 9510]. NOTE – overhanging parts of crags, take care! Here we find an apparently well preserved instance of Laxfordian deformation features, in an area where most of the rock has undergone OHFZ-related shearing and cataclasis. Younger Basic dykes cut discordantly through the banded gneiss and late-Laxfordian pegmatite veins are also present. These display signs of cataclastic fabric and occasional shear planes, but the ductile phase of OHFZ movement seen previously is not displayed here.

4. Lag na Laire, Scalpaigh [NG 2338 9436]. A short <1km walk from the roadend brings us into what is mapped as a phyllonite zone. However, the outcrops we see seem again to preserve the older Laxfordian/Scourian structures without much overprint from the OHFZ. It could be, as thought by Imber et al. (2001), that these outcrops represent patches of low OHFZ related strain . There is a SE dipping fabric superimposed, but note how the mafic bodies do not pick this up well – this apparent 'cross-cutting' led to the idea that movement on the OHFZ pre-dated the Younger Basics (Lailey et al. 1989). However, later workers have shown that the fabric does exist, if weakly, within the basic intrusions. On the return, a scarp feature picks out a fault plane containing mylonites and cataclasites. These gently dipping planes with localised fault rocks, and a superimposed fabric elsewhere, seem to be the typical OHFZ deformation in this area.

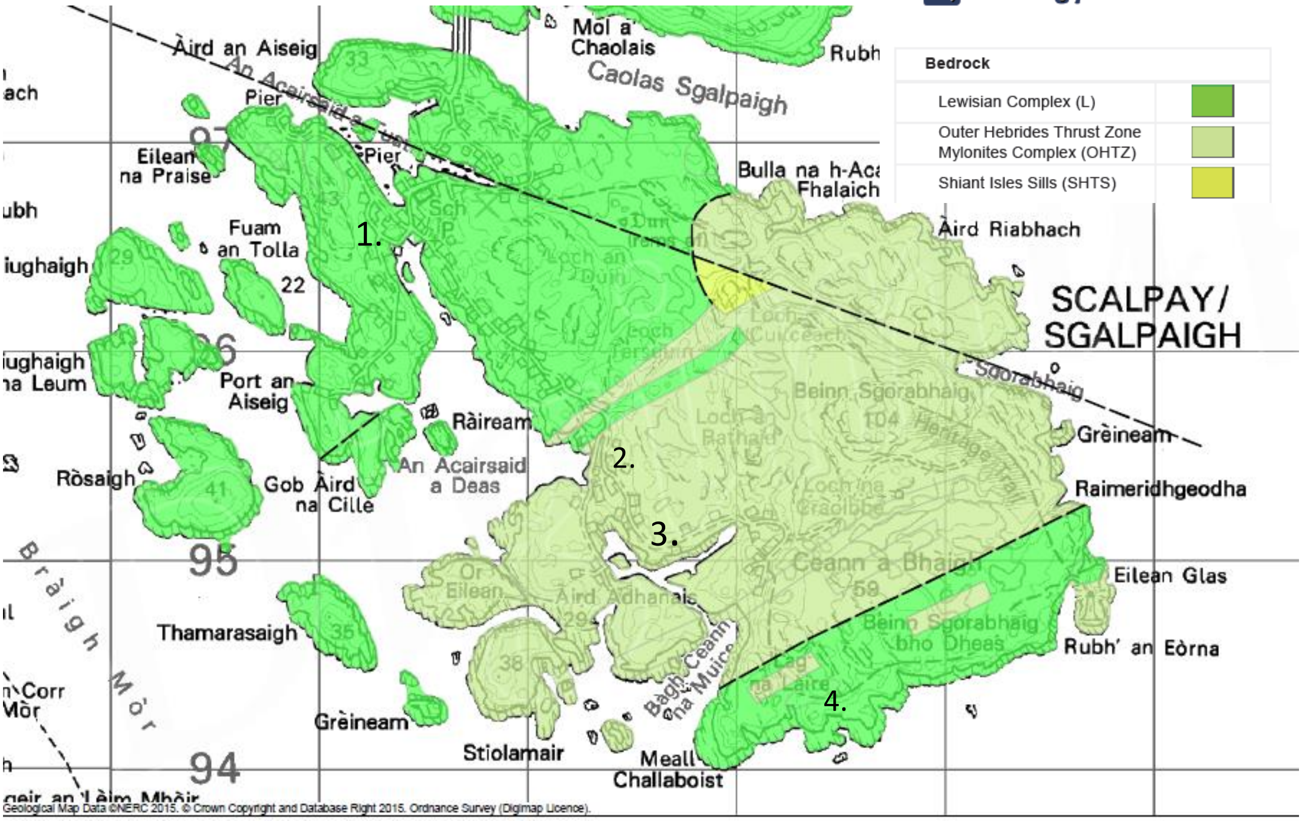


Fig.18. Geological map of Sgalpaigh with localities marked
Geological Map Data © NERC 2015

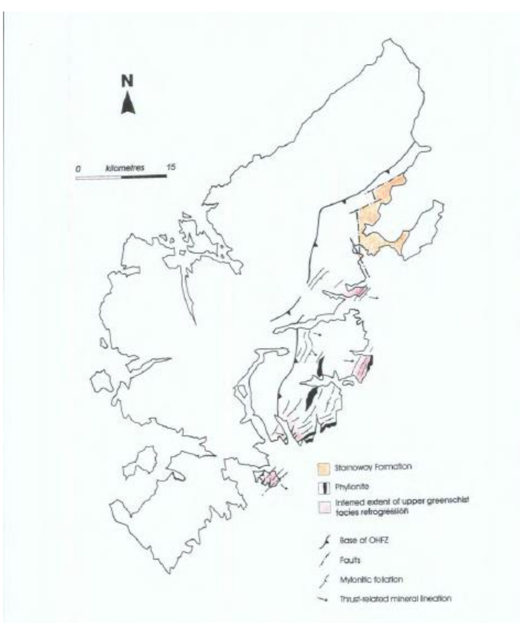


Figure 3.12 Map showing the orientation of planar and linear fabric elements and the extent of upper greenschist facies retrogression in the pervasive mylonite belt.

Fig.19. Scalpay in context of OHFZ northern section (Imber 1998)

Fig.20. Top down to NE extension seen in phyllonites, Sgalpaigh [NG 2420 9450] (Szulc et al. 2008)

Stop 2: South Harris

Moving south, our second region shows us the Langabhat metasediments and shear zones adjacent to, and including, the South Harris Igneous Complex.

1. Granite sheets and pegmatite veins of the Uig Hills granite complex are seen cutting basic gneisses and amphibolitised basic intrusions (Younger Basics). This is the unit lying to the north of the SHIC and the Langabhat belt [NG 033 954].
2. Moving southwards, note the strengthening of finer banding in the gneiss and the increasing number of amphibolite bands. On the SW side of the bay, strain in the gneiss is higher and granitic features almost absent. Structurally, two lineations can locally be seen – one extension (stretching) and one intersection lineation. The headland SW of the next bay contains several mafic amphibolite sheets alternating with felsic gneiss.
3. Heading overland to Sta Bay [NG 029 950], the Sta Series is exposed (no hammering please) – this is the lowest metasedimentary unit in the Langabhat belt whose origin remains undisputed. Garnet biotite schists, graphite schists, calc-silicates and dirty metalimestones make up the unit. Staurolite has been found in the semipelite members, as an index mineral. Look SW of the Allt Sta burn for examples of calcareous units – these are overlain by an amphibolite. For garnet- bearing rocks, look in the intertidal beach zone NW of the burn.
4. Between Sta Bay and the Allt Borgh Beag river lie a controversial set of rocks – these have been interpreted as part of the Langabhat Belt (Dearnley 1959), as mylonites (Friend and Kinny 2001) and as highly strained Lewisian gneiss, equivalent to those lying north of the Langabhat Belt (Mason et al. 2004). Only north of Allt Borgh Bheag, where we started, are migmatitic Lewisian grey gneisses indisputable.

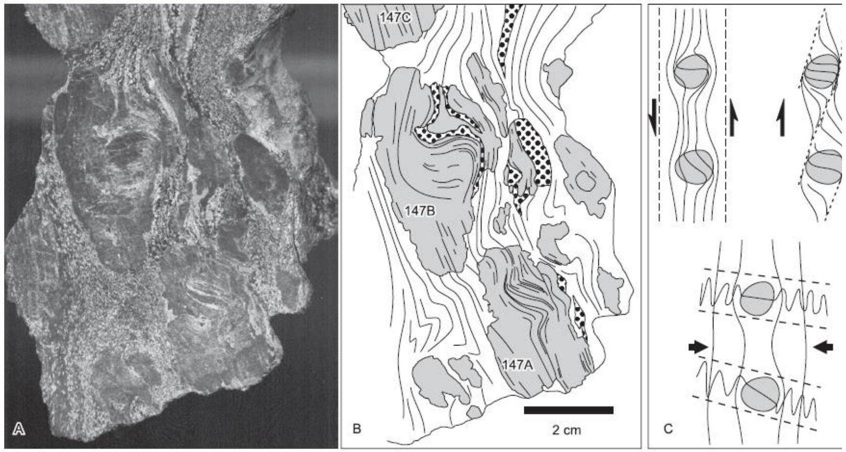


Fig.21. (A, B) Garnets showing quartz inclusion trails from Sta Series metapelites [NG 0559 8877] in Langabhat Belt, South Harris. C) Theoretical relationships of inclusion trails to foliation, with implied shear sense. The top left is considered a good match for this sample, although the overall shear sense implied is dextral as sample is upside-down (Mason 2012)

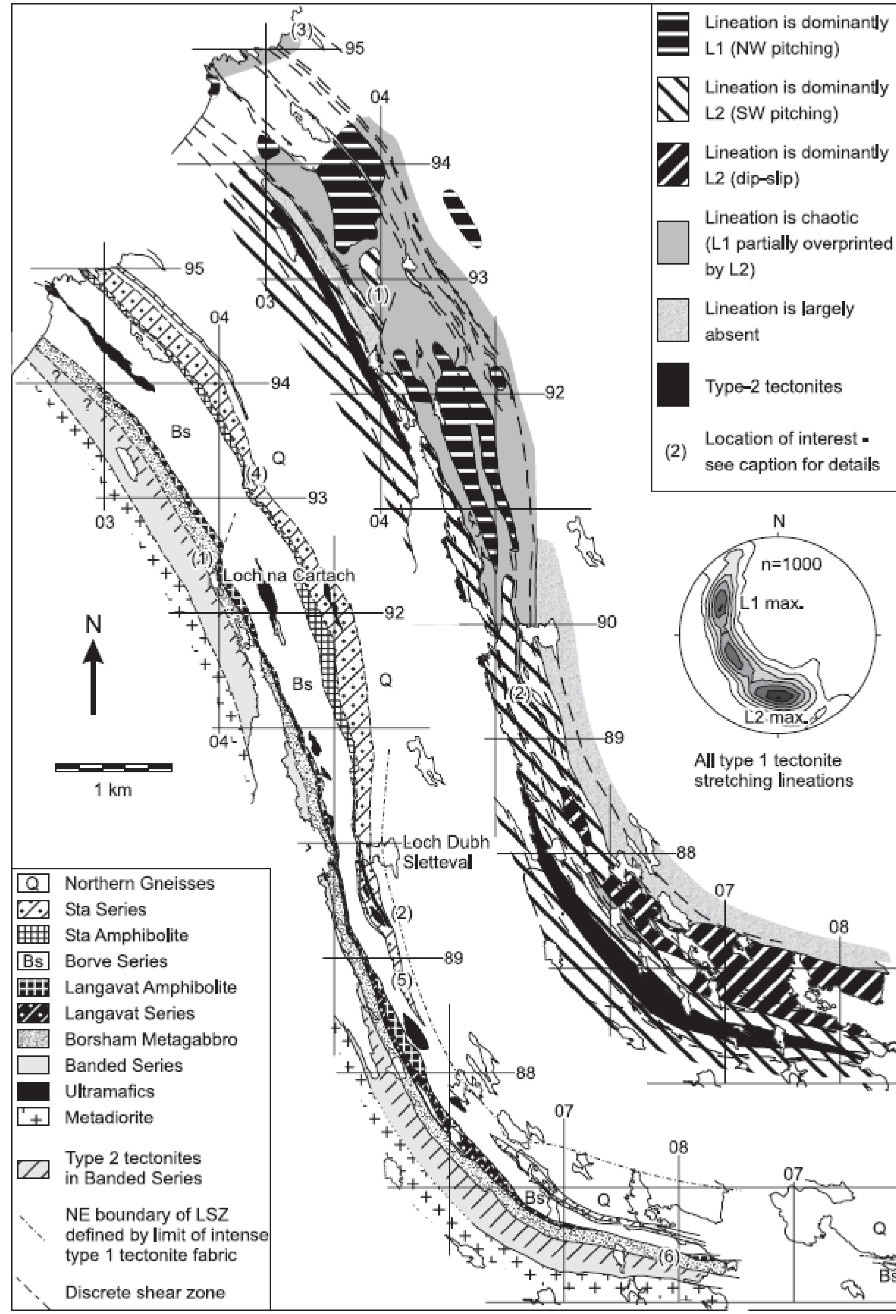


Fig.22. Maps of Langabhat Belt deformation (upper) and lithology (lower) (Mason 2012)

Saturday 20th: Lewis

Stop 1: Baile Allein, SE Lewis

The Seaforth Head area [NB 299 168] is a well-studied locality where pseudotachylytes cut through extensive mylonites. The OHFZ here displays its 'diffuse' form typical of the northern zone and especially Lewis, with the mylonitic zone spreading both westwards across the main Stornoway-Tarbet road, and eastwards to the coast. The significance of this area is that resheared, mylonitised pseudotachylytes have been seen in thin section, often cut by later undeformed pseudotachylyte veins (Butler 1995, White 1996). These relationships may record the early ductile thrusting phase of the OHFZ overprinted by the early-Caledonian brittle reactivation. We will stop slightly to the north at Baile Allein (Balallen), [NB 308 216] where small thrusts form low scarps at the side of a track. Cataclasite and pseudotachylyte veining is present at [NB 308 222], and at [NB 308 218] it is possible to see evidence for ductile mylonitisation overprinting pseudotachylytes and fragmented gneiss. Further up the track [NB 3085 2287], undeformed pseudotachylyte veins and brittle brecciation break up mylonite fabrics. A dyke in the small quarry by the track is Tertiary (Palaeogene).

Stop 2: Mangarstadh, W Lewis

The following localities lie in the Uig Hills granite complex and cross-cutting late- Laxfordian granite sheets can often be seen spectacularly in the sea cliffs. In the cliffs below the Mangarstadh (Mangersta) radio station, a prominent edge exposes a clear set of low angle fault planes dipping SE [NB 003 332]. Looking southwards, the same features can be tracked in the cliffs on the opposite side of the small inlet. Several fault rocks can be observed, both cataclasites, mylonites/protomylonites and cohesive rock units with superimposed sigmoidal foliations, and between and within the fault planes. Slickensides can be seen on some planes. Sense of shear indicators in the mylonites are generally thrust-sense, but occasionally extensional/strike slip markers also are found. These relationships can be studied both north and south of the small bay.

Stop 3: Àird Feinish, W Lewis

Walking to the headland of Àird Feinis from the road, the granite sheeting in the sea cliffs is easily seen. On the southern side [NA 992 292], a shear zone containing Younger Basic dykes is seen – the fabric in the intrusions is faint but present. Inland, the shear localises to the margins of the dykes and to select internal shear zones. Whether the dykes intruded into a pre-existing shear zone which reactivated during the Laxfordian, or that Laxfordian shear localised around the dykes for other reasons is not really clear. Foliation in the core of a granitic sheet points to syn-tectonic intrusion of these late-Laxfordian granites, though structural control on their orientation is never very clear.

Fig. 24. Pseudotachylytes cutting mylonites in SE Lewis, [NB 300 171]

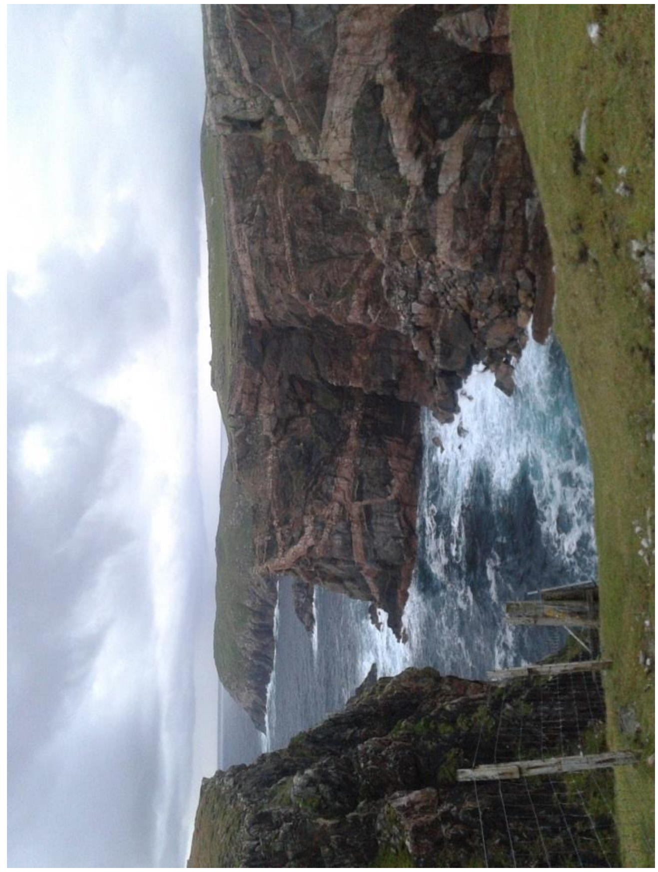


Fig.25. Granite sheets of late-Laxfordian Uig Hills Complex exposed in cliffs near Mangarstadh

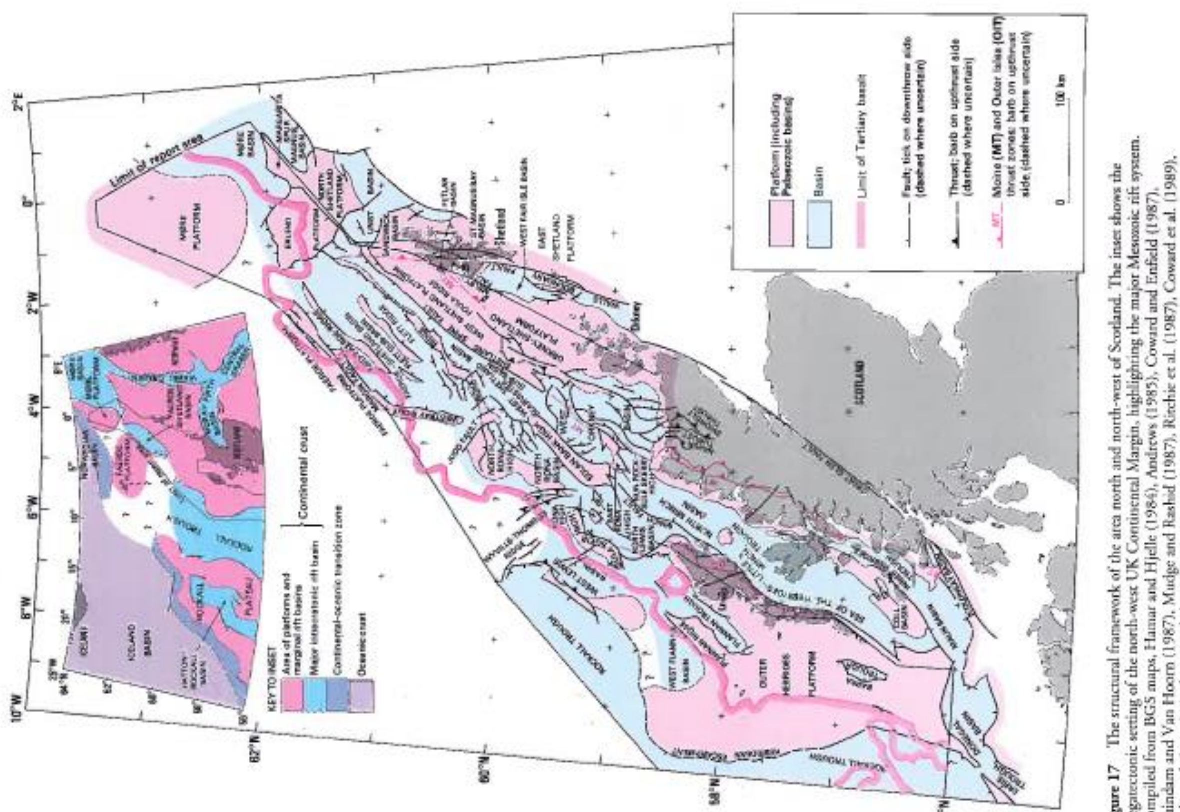


Fig.23. The Outer Hebrides in context of the Hebrides and West Shetland shelves (from Stoker et al. 1993).

Sunday 21st: Lewis

Stop 1: Rubha Àirinis, E Lewis

1. Roadcutting [NB 423 303] - The road section here shows once more the deformation of the Lewisian Gneisss related to the OHFZ. Both ductile structures and brittle faults are present, and a variety of fault rocks including pseudotachylytes, phyllonites and breccias.
2. Cliffs in industrial site [~NB 426 303] – conglomerates of the Stornoway formation with clasts of fractured Lewisian.
3. Coastal cliffs – [NB 427 302] – low angle normal faults with carbonate mineralisation can be seen within the Stornoway formation.
4. Small bay [NB 425 98] – A group of normal faults dip steeply east, with syntethic minor faults linking the larger structures. These faults form part of the set that bound the western margin of the Stornoway formation and later Mesozoic rocks in the Minch basin, although here we see them in the Lewisian basement. The faults display brecciated and mineralised damage zones.

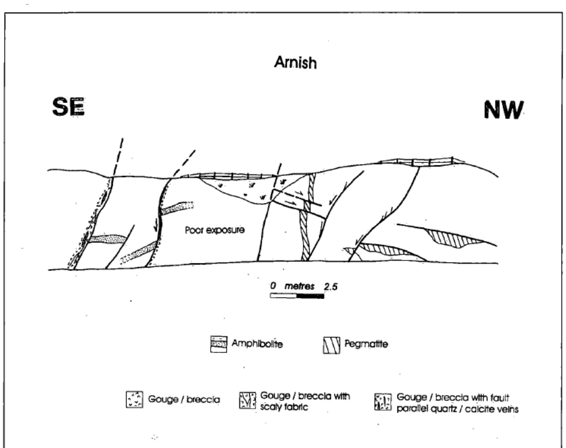


Figure 3.24 Vertical road cutting exposing faulted gneisses, Arnish point, northeast Lewis.

Fig. 26.(Left): Faulting in Lewisian at Àirinis (Imber 1998)

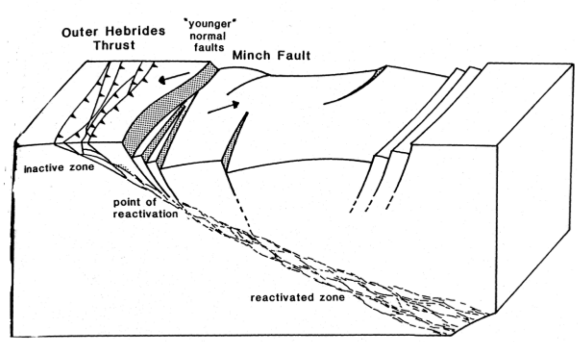


Fig.27. (Above): Probable relationships between OHFZ and Minch basin faults (Stein 1988)

Stop 2: Geodh' a' Chuibhrig, Eye Peninsula (An Rubha). [NB 494 300]

The unconformable contact between the Lewisian basement and the overlying Stornoway Formation is seen here. Low angle detachment faults are found near the unconformity, and later, steeper extensional faults can also be seen.

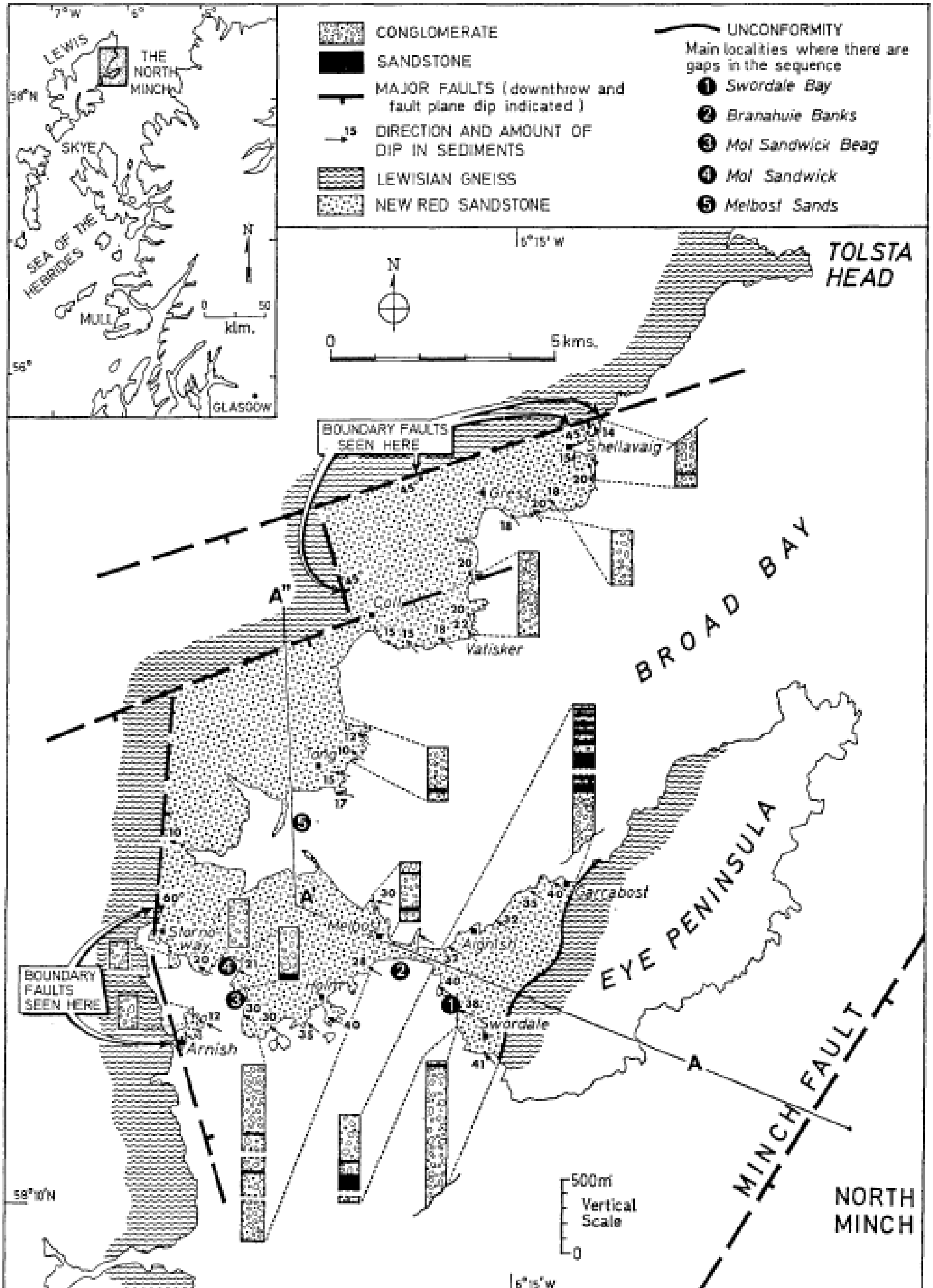
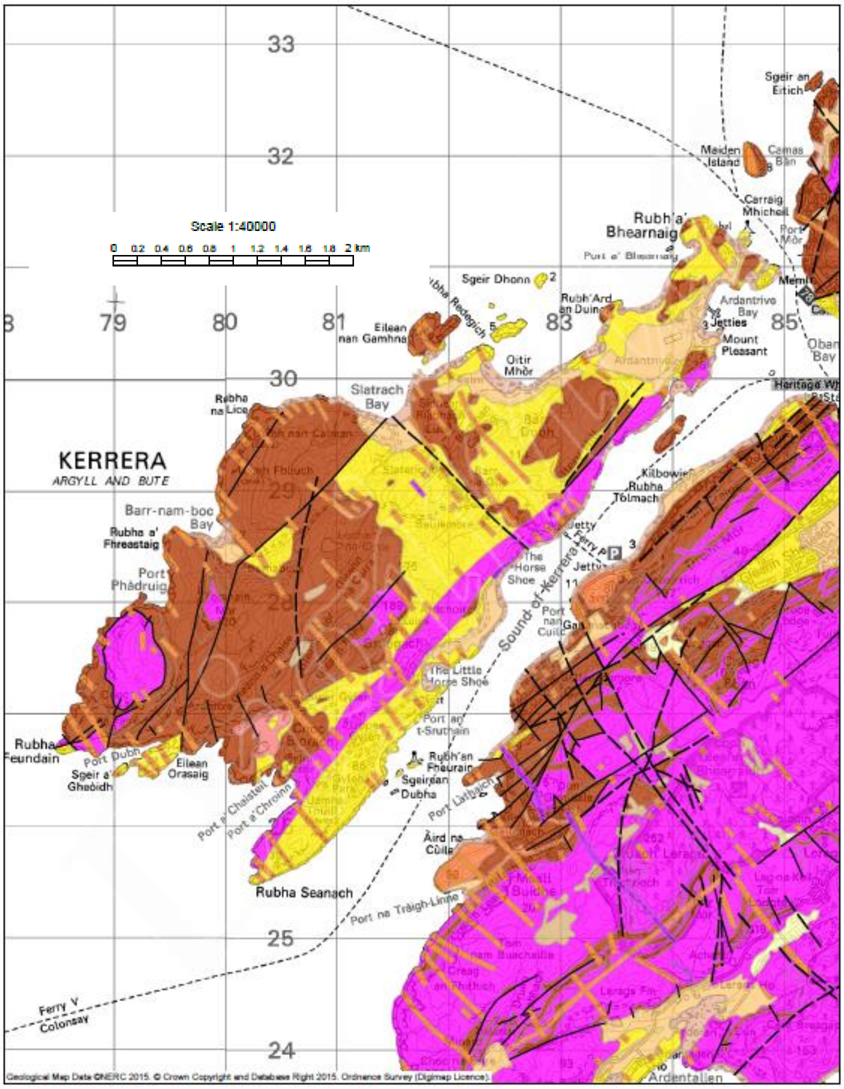
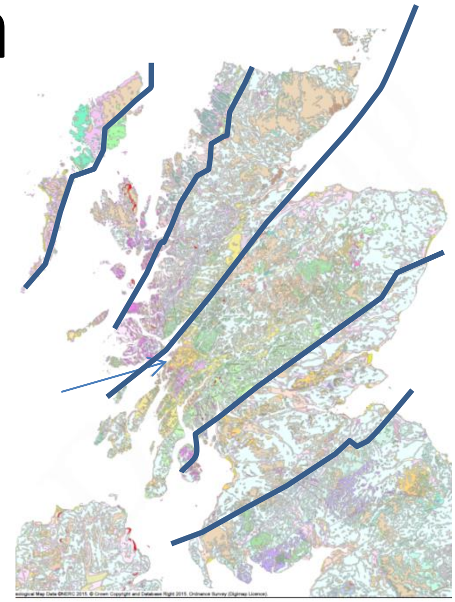


Fig.28. Map of Stornoway formation and bounding faults to the west (Steel and Wilson 1975). Arnish = Àirinis.

Monday 22nd: Kerrera

Much of southern Kerrera is a geological SSSI – **No hammering please!**





Bedrock	
Easdale Slate Formation (DBES)	
Glen More (Centre 1) Suite (GLMO)	
Kerrera Sandstone Formation (KESA)	
Lower Old Red Sandstone (LORS)	
Lorn Plateau Volcanic Formation (LPVO)	
Mull Central Complex (MUCC)	
North Britain Palaeogene Dyke Suite (PDNB)	
North Britain Siluro-Devonian Plug And Vent Suite (SDPV)	
Strontian Pluton (STRON)	
Superficial Deposits	
Alluvium (ALV)	
Marine Beach Deposits (MBD)	
Peat (PEAT)	
Raised Beach Deposits, 3 (RBD3)	
Raised Marine Beach Deposits Of Flandrian Age (RMBDF)	
Linear Features	
Faults	
Fault, Inferred, Displacement Unknown	-----
Fault, Observed, Displacement Unknown	——

The succession on Kerrera records metamorphism, deformation, erosion and volcanism during the Caledonian Orogen, recording the collision of an Iapetus oceanic arc with the continent of Laurentia – a precursor to the continent-continent collisions of Laurentia with Baltica and Avalonia. Lying in the Firth of Lorne, the Great Glen Fault runs just offshore to the north, truncating structures and lithologies from that of Mull and the Northern Highlands.

Monday 22nd: Kerrera

Dalradian metasediments

Fine-grained, penetratively foliated pelites interbedded with psammites, muddy pelites and metalimestones of the Easdale subgroup, Argyll group, Dalradian. Well exposed on the eastern and southern coasts. The top surface is highly erosive, with palaeo-relief of >10m visible [e.g. NM 805 265]. Relict sedimentary structures such as cross-laminations and dewatering structures [NM 814 267] show the unit to be upright and support the regional interpretation of the Easdale subgroup as a turbidite sequence in a rifting basin, with sediment contributions from footwall-high carbonate platforms. The subgroup has a depositional age of ~615 Ma based on dating constraints from the overlying Tayvallich volcanics (Halliday et al. 1989, Thomas et al. 2004).

Metamorphism of the Dalradian is connected with the Grampian phase of the Caledonian orogeny around 475 ± 15 Ma (Giletti et al. 1961). In Kerrera it was relatively low grade, within the greenschist facies. Folding and other associated deformation occurred at the same time, with two fold phases widespread and a third apparent locally across the island.

Old Red Sandstones

Unconformabley above the Dalradian lies a suite of sediments comprising massive conglomerate beds, sandstones and flaggy silt and mudstones. These belong to the lowest Stonehaven group of the Devonian Old Red Sandstones. The basal unconformity is sometimes filled by rip-up breccia consisting of angular Dalradian clasts [e.g. NM 795 813], more often by conglomerate, and on higher palaeo-hills by sandstone units. The sequence can be logged, at least in the south, to show two fining upwards sequences and is interpreted to show alluvial fans followed by floodplain deposits (Morton 1979). Overall the sediments here in Kerrera are thought to have been deposited as debris flow fans with associated sheet floods and shallow ephemeral lakes in an arid intermontane basin. Detrital provenance studies record exhumation of the uplifting metamorphosed highlands and fluxes of volcanism, consistent with the arc-continent collision of the Grampian orogenic phase. Fish fossils have been found in the flagstones date that unit to late Silurian - early Devonian, ~420 Ma (Trewin et al. 2012).

Old Red Sandstone volcanics

The uppermost unit is a sequence of basic and intermediate calc-alkaline lavas. These sit conformably, and sometimes interfingering with, the top of the sedimentary succession, although the underlying unit may be conglomerate or sandstone. Columnar jointing [NM 788 275] and pillow lavas [NM 788 266] occur in some flows. These are known as the Lorn lavas and are dated on the mainland at 425.0 ± 0.7 Ma (Neilson et al. 2009).

Intrusions

Some calc-alkaline dykes and sills are present, probably relating to the lavas. The most abundant intrusive suite is however the NW-SE tholeiitic fine-grained basaltic dykes of the Tertiary, related to the opening of the North Atlantic.

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