The South Barra Shear Zone: A Composite Inverian-Laxfordian Shear Zone and Possible Terrane Boundary in the Lewisian Gneiss Complex of the Isle of Barra, Northwest Scotland

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Synopsis

The Lewisian Gneiss Complex (LGC) of Northwest Scotland largely comprises Archaean tonalite-trondhjemite-granodiorite (TTG) gneisses variably reworked in the Palaeoproterozoic. One form of this heterogeneous reworking is the formation of major shear zones in the earliest Palaeoproterozoic which are then reactivated in the late Palaeoproterozoic. Recent remapping of the LGC of southeast Barra, in the southern Outer Hebrides, has led to the interpretation of such a composite shear zone, the Southeast Barra Shear Zone (SBSZ). The SBSZ separates a block of heterogeneously overprinted pyroxene-bearing TTG gneisses from a dioritic meta-igneous complex to the west. Despite a lack of geochronological data, the juxtaposition of different protolith rocks along the SBSZ raises the possibility it may be a previously unrecognised terrane boundary.

Keywords: shear zone, Lewisian Gneiss Complex, Isle of Barra, TTG, terrane boundary

Introduction

The Archaean-Palaeoproterozoic Lewisian Gneiss Complex (LGC) outcrops on the Outer Hebrides island chain and the northwest coast of the Scottish mainland (Fig. 1a). The LGC is composed dominantly of felsic-to-intermediate gneisses with tonalite-trondhjemite-granodiorite (TTG) protoliths (e.g. Peach *et al.* 1907, Tarney and Weaver 1987). There are also small but frequent bodies of mafic gneiss and sparse metasedimentary gneisses and other granitoid intrusions. The LGC has a long and complex tectonothermal history (e.g. Wheeler *et al.* 2010). Detailed mapping of localities on the mainland enabled Sutton and Watson (1951) to distinguish two tectonothermal events, one before and one after the intrusion of the mafic to ultramafic Scourie Dyke Swarm. The later of the two events, termed the Laxfordian, comprised static and dynamic amphibolite-facies retrogression and heterogeneous deformation across the LGC. Sutton and Watson (1951) named the pre-Scourie dyke event the 'Scourian' but this was subdivided on the recognition that it comprised an earlier granulite-facies event (the Badcallian (Park 1970)) and a later amphibolite-facies event (the Inverian (Evans 1965)). Both Badcallian and Inverian metamorphic assemblages and structures are heterogeneously overprinted by Laxfordian reworking and are only preserved in certain areas of the complex, most notably the 'Central Region' of Sutton and Watson (1951), the area around Scourie (Fig. 1a). Corfu *et al*. (1994) attributed zircon U-Pb ages of ≥2710 Ma to the Badcallian and 2490-2480 Ma to the Inverian. U-Pb titanite and rutile ages of ~1670-1750 Ma were attributed to the Laxfordian tectonothermal event (Corfu *et al.* 1994, Kinny and Friend 1997, Kinny *et al.* 2005) while Heaman and Tarney (1989) dated baddeleyite from the Scourie Dyke Swarm at 1992 Ma and 2418 Ma. However, recent zircon geochronology has led to the LGC being reinterpreted as a group of amalgamated terranes generally separated by major shear zones (Kinny *et al.* 2005). At least some of the terranes shared a common history from the Inverian tectonothermal event onwards (Goodenough *et al.* 2010) but zircons record different Archaean age spectra from different regions before this time (Kinny *et al.* 2005).

On the Outer Hebrides, there is a similar relative chronology of structures and metamorphic assemblages as on the mainland. Dearnley (1962) named a suite of mafic dykes which occur throughout the Outer Hebrides the Younger Basic dykes and correlated them with the Scourie Dyke Swarm of the mainland. In most of the Outer Hebrides, the TTG gneisses have an amphibolite-facies metamorphic assemblage and have been reworked by a post-dyke tectonothermal event, correlated with the Laxfordian of the mainland (Coward 1972, Graham and Coward 1973, Lisle 1977). Pre-dyke fabrics and assemblages in the TTG gneisses which may correlate with the Badcallian and Inverian of the mainland are rare. Younger Basic dykes cross-cut fabrics in the TTG gneisses in areas of low Laxfordian strain, e.g. at Garry-a-Siar and Ardivachar (Fig. 1a). Granulite-facies metamorphic assemblages occur in south-east Barra (Francis 1973) and northern South Uist (Coward 1972) which are correlatable with the Badcallian of the mainland. Fettes *et al*. (1992) were cautious with respect to correlating pre-dyke structures between the Outer Hebrides and the mainland and applied the terms early-Scourian, late-Scourian and Laxfordian to the relative field chronology of the Outer Hebrides. This naming system will be used in this study and is summarised in Table 1. It should be noted that granulite-facies metamorphism also occurred in the South Harris Metaigneous Complex but at a much later date than early-Scourian, ~1870 Ma (Baba 1998, Cliff *et al.* 1998, Mason *et al.* 2004).

Geology of the island of Barra

Following early reconnaissance mapping (Jehu and Craig 1924), the geology and tectonic history of Barra were mapped in more detail by Hopgood (1971), Francis (1973) and Fettes *et al*. (1992), summarised in Fettes (2009). The island of Barra is bisected by the Outer Hebrides Fault Zone (OHFZ) (Fig. 1b), a major thrust running down the length of the Outer Hebrides island chain active during Proterozoic, Palaeozoic and Mesozoic times (e.g. Fettes *et al.* 1992, Imber *et al.* 2002). On Barra, the thrust zone is characterised by a gently east-dipping fault plane with cataclasite and pseudotachylite (Francis 1969, Sibson 1977). To the west of the OHFZ, structurally below it, are monotonous amphibolite-facies TTG gneisses with a Laxfordian foliation typical of the majority of the Outer Hebrides, termed the “Western Gneisses” by Francis (1973).

Structurally above the OHFZ in southeast Barra is the largest area of low Laxfordian strain and preserved Scourian fabrics and assemblages in the whole of the Outer Hebrides, termed the “Eastern Gneisses” by Francis (1973). Here it is possible to see in the TTG gneisses an early granulite-facies metamorphic assemblage, a pre-Younger Basic dyke amphibolite-facies assemblage and a post-Younger Basic dyke Laxfordian assemblage. There are also three suites of late-Scourian minor intrusions: microdiorites; monzonite granites; and pegmatitic granites. The microdiorites are the oldest and the pegmatitic granites are the youngest (Francis 1973, Fettes *et al.* 1992, Fettes 2009). Isolated examples of similar minor intrusions are found in other low Laxfordian strain areas of the Outer Hebrides (Fettes *et al.* 1992) while occasional late-Scourian (Inverian) granites and pegamtites are also found on the mainland LGC (e.g. Corfu *et al.* 1994, Goodenough *et al.* 2013). As well as minor late-Scourian intrusions, there is also a major late-Scourian intrusion, the East Barra Meta-igneous Complex (Francis 1973, Fettes *et al.* 1992) (Fig. 1b). This comprises massive sheets of homogeneous foliated pale-grey metadiorite, several hundred metres thick, which dip moderately eastwards and are interleaved with amphibolite-facies TTG gneisses and pink foliated granite (Francis 1973, Fettes *et al.* 1992).

Francis (1973) also recognised an area of low Laxfordian strain and granulite-facies metamorphic assemblages above the OHFZ which outcrops on the small islands to the northeast of Barra. The TTG gneisses have granulite-facies assemblages in places and undeformed pyroxene-bearing Younger Basic dykes cross-cut the TTG gneissic layering and occasional late-Scourian intrusions. Francis (1973) interpreted this area (termed the “Oitir Mhor” zone) to lie in the core of an antiform defined by the “Western Gneisses” and to be a direct correlative with the “Eastern Gneisses” above the OHFZ to the southeast. Francis (1973) interpreted the overall structure of Barra as an infrastructure-suprastructure relationship: the “Western Gneisses” being the suprastructure and the “Eastern Gneisses” the infrastructure. He interpreted that the part of the “Eastern Gneisses” with the most Laxfordian deformation and overprinting was actually part of the “Western Gneisses” which was folded down into the “Eastern Gneisses” in a pinched synform.

There is only very limited geochronological data from the island of Barra, and from anywhere in the southern Outer Hebrides for that matter. Kinny *et al.* (2005) included a metamorphic zircon U-Pb age of ~2730 Ma from southeast Barra in their terrane model. This correlates with the interpreted age of granulite-facies metamorphism from the Gruinard area of the mainland LGC (Love *et al.* 2004) and possibly also from Scourie (Corfu *et al.* 1994) although Friend and Kinny (1995) found no such age there. Francis *et al.* (1971) dated the late-Scourian pegmatites in southeast Barra by K-Ar and Rb-Sr but these gave a range of ages between ~2460 and ~2600 Ma.

Field Relationships and Petrography

A transect along the well-exposed coastal section between Earsaraidh and Castlebay (Fig. 1b) was mapped using an iXplore tablet computer with SigmaMobile software from the British Geological Survey (Jordan 2009). The transect is divided into six zones on the basis of this mapping. Five zones to the east of, and including, the major shear zone, represent varying degrees of tectonothermal overprinting in TTG gneiss (Fig. 2a). The sixth zone, to the west of the shear zone, is the East Barra Meta-igneous Complex (Fettes *et al.* 1992). The zones tend not to have sharp boundaries but changes in overprinting style can be recognised over metres to hundreds of metres. Samples were collected and thin sections made for further petrographic characterisation.

Zone 1

Zone 1 extends from the northeastern end of the transect around Meall nam Buth and ends just to the east of the Leinis peninsula (Fig. 2a). This zone is defined by granulite-facies metamorphic assemblages in the TTG gneisses and high-angle cross-cutting relationships between gneissic layering in the TTG gneisses, late-Scourian intrusion and Younger Basic dykes. On the south side of the Meall nam Buth peninsula, on a rocky platform opposite Eilean nan Gamhna at NF 70775 00027, the ENE-dipping compositional layering in the TTG gneiss is cut by an anastomosing but broadly northeast-trending late-Scourian pegmatitic granite body which is in turn cut by a north-trending subvertical member of the Younger Basic Dyke Swarm (Fig. 2b). The TTG gneiss here is composed of ~30% clinopyroxene (Fig. 3a), ~25% hornblende, ~20% quartz, ~15% plagioclase, ~5% orthopyroxene and ~5% biotite. The late-Scourian pegmatitic granite is dominated by potassium feldspar and quartz with crystals up to 2cm in diameter. The Younger Basic dyke is composed of ~50% hornblende, ~40% plagioclase and ~10% clinopyroxene.

To the southwest are several other bodies of late-Scourian pegmatitic granite and Younger Basic dykes. At the road corner at NL 70493 99867, these are cut by an undeformed vesicular basalt dyke, of Palaeogene age (Fettes 2009). At NL 70538 99720, a north-south-trending Younger Basic dyke cross-cuts a late-Scourian monzonite body. This pinkish-weathering rock clearly cuts the compositional layering in the TTG gneiss but is itself cut by a late-Scourian pegmatitic granite sheet.

At the corner in the road opposite the tidal island of Orasaigh, a ~1m-wide north-trending late-Scourian microdiorite dyke is cut by a ~1.5m-wide northeast-trending late-Scourian pegmatitic granite sheet. Both are cut by a Laxfordian pegmatitic granite sheet which also cuts a Younger Basic dyke (Fig. 2c). The microdiorite has a weak internal fabric defined by margin-parallel hornblende aggregates, and cuts the compositional layering in the TTG gneiss (Fig. 3b).

Zone 2

Zone 2 is characterised by high-angle cross-cutting relationships and an amphibolite-facies assemblage in the TTG gneisses. This zone covers the north-eastern half of the Leinis peninsula. On the northeast coast of the peninsula is a large body of amphibolite-facies mafic gneiss around NL 704

988 cut by an unfoliated hornblendite body. This is composed of ~50% 1-2cm diameter hornblende crystals in a 1-2mm diameter hornblende and plagioclase matrix. Continuing round the coast, a late-Scourian granite sheet is cut by several Younger Basic dykes, one of which is cut by a Laxfordian pegmatitic granite sheet and a Palaeogene basalt dyke.

At NL 70265 98647, 20cm-wide dykes of northwest-trending late-Scourian microdiorite cut the compositional layering in the TTG gneiss at a tight angle of <10° but are themselves cut at a high angle of ~45° by an east-trending late-Scourian pegmatitic granite sheet. This is in turn cut by a NNW-trending member of the Younger Basic Dyke Swarm (Fig. 2d). The Younger Basic dyke is composed of roughly even proportions of clinopyroxene, hornblende, plagioclase, with minor quartz and opaque minerals while the microdiorite is composed of ~30% plagioclase, ~30% hornblende, ~25% biotite, ~10% quartz and ~5% opaque minerals. The TTG gneiss here contains no pyroxene; the only mafic mineral is biotite (Fig. 3c). The most westerly late-Scourian minor intrusion is a NNE-trending pegmatitic granite which cross-cuts the NNW-trending compositional layering in the TTG gneisses but is cross-cut by a NNW-trending Younger Basic dyke. The Younger Basic dyke here cuts the compositional layering in the TTG gneiss at an angle of approximately 15° (Fig. 3d). Both the pegmatitic granite and the Younger Basic dyke are undeformed but the mafic mineral in the Younger Basic dyke is hornblende.

Zone 3

Approximately 100m along the coast from the last Younger Basic dyke in Zone 2, the margins of Younger Basic dykes are parallel to the ENE-dipping foliation in the TTG gneiss (Fig. 3e). At NL 69985 98650, a Younger Basic dyke is generally concordant with the ENE-dipping foliation in the TTG gneiss but occasional dyke apophyses cut this foliation. A weak margin-parallel mineral-aggregate lineation is developed in the dyke margins while the core is unfoliated. Hornblende has replaced pyroxene in the cores and margins of the Younger Basic dykes throughout Zone 3. Rare Laxfordian pegmatitic granites cross-cut the foliation in the TTG gneiss. There are occasional patches of partial melting in the TTG gneisses which indicate the onset of migmatisation at the transition into Zone 4.

Zone 4

This zone stretches from the western end of the dilapidated fence crossing the Leinis peninsula to near the jetty at the western end of Bagh Bhreibhig. It is characterised by a pervasive amphibolite-facies Laxfordian migmatitic foliation in the TTG gneisses. At NL 69883 98810, there is a flat rocky platform exposing migmatitic TTG gneiss. The white and dark grey colour contrast picks out the generally southeast-dipping fabric of stromatic leucosome and melanosome layers, ~1cm wide (Fig. 3f). The leucosomes have pushed through melanosome layers in some places, joining up to form cross-cutting bodies at right angles to the main stromatic migmatitic layering. There are also some much thicker layers of both leucosome and melanosome, up to 2m in width. A thick mafic restite layer is relatively coarse-grained with hornblende crystals up to 5mm in length which aggregate to form a south-plunging lineation. The thick white leucosome layer also has a coarse grain size with plagioclase crystals up to 5mm. Continuing north-westwards along the east coast of Bagh Bhreibhig, TTG gneisses dominate with a steeply ESE-dipping migmatitic foliation. At NL 69595 98979, an ellipsoidal ~1x5m undeformed mafic body is wrapped by the Laxfordian migmatitic foliation. This, and all other mafic bodies encountered in Zone 4, are homogeneous in appearance with a dark grey-black colour, sub-millimetre crystal size and are composed of hornblende and plagioclase.

On the foreshore below the minor road around NL 6942 9884, there is a range of fold geometries, including tight-to-isoclinal folding of the migmatitic foliation (Fig. 3g) as well as more chaotic close-to-isoclinal folding of single Younger Basic dyke remnants (Fig. 3h). The broad structure at this locality is a synform with a steeply east-dipping axial plane; a weak quartz aggregate mineral lineation on the western limb plunges gently to the south. A minor upright fold was noted on the eastern limb. There is also minor shearing where the migmatitic layering has been displaced along discrete planes which have been filled with partial melt (Fig. 3i). In addition, there is boudinage of more competent mafic Younger Basic dyke remnants (Fig. 3j) and SSE-plunging delta-type sigmoid feldspars indicating sinistral shearing. As at NL 69883 98810, coarse migmatitic leucosomes cross-cut the migmatitic layering on fold limbs and fold hinges. Late cataclasis and pseudotachylite has disrupted the migmatitic foliation. Patches of the rock have been broken into clasts of sub-millimetre to 3cm in diameter and the gaps have been filled with glassy black pseudotachylite veins to 3mm in width (Fig. 3k).

Zone 5

Between Breibhig and Rubha Charnain, the TTG gneisses are strongly foliated and widely migmatised (Fig. 3l), much like in Zone 4. These rather monotonous rocks have a strong ESE-dipping stromatic migmatitic foliation with a coarse granular texture and recrystallization appears to have destroyed any mineral lineations. As in Zones 3 and 4, there are no discernible late-Scourian minor intrusions. As well as being extensively folded, boudinaged and completely amphibolitised, Younger Basic dyke remnants are also internally deformed, revealed by a strong hornblende aggregate lineation plunging to the south.

Zone 6

To the west of Zone 5, between Rubha Charnain and the OHFZ, is the East Barra Metaigneous Complex (Fettes *et al.* 1992) (Fig. 1b). The dominant rock type here is a homogeneous weakly-foliated pale-grey metadiorite which forms massive sheets hundreds of metres thick that dip to the east at 50-60°. Plagioclase feldspars have a purplish colour which gives a purplish tinge to the overall pale-grey colour of the rock. There are good exposures around the mast at NL 668 973. The larger metadiorite sheets are tens of metres across and appear to have diffuse concordant contacts with the TTG gneisses which are unmigmatised here. Smaller bodies, however, cross-cut the gneissic layering in the TTG gneiss. The eastern end of Zone 6 is defined by the disappearance of the metadiorite sheets. They are only weakly deformed in Zone 6 and their relationship to the strong deformation, migmatisation, amphibolitisation and folding recorded in the TTG gneisses and Younger Basic dykes in Zone 5 is unclear.

In the western end of the zone, pink metagranite sheets are also present which locally cross-cut the metadiorite bodies and TTG gneissic layering. Biotite laths and 1-3cm feldspar augen define a margin-parallel planar fabric. Largely undisrupted and amphibolitised but undeformed Younger Basic dykes are found in the western part of Zone 6 where they occasionally cross-cut the metadiorites and augen metagranites. Towards the eastern end of the zone, they are concordant and may be have a hornblende aggregate mineral lineation, for example on the shore around NL 677 972, close to the intense Laxfordian deformation.

Discussion

Tectonothermal Overprinting in the Six Zones

The granulite-facies assemblage in the TTG gneisses in Zone 1 is attributed to the main early-Scourian gneissic layering-forming event (Francis 1973, Fettes *et al.* 1992). This may be tentatively correlated with the Badcallian event of Park (1970) of the Scourie area of the mainland. Kinny *et al.* (2005) published a metamorphic zircon age of ~2730 Ma from southeast Barra, the same age as metamorphic zircon from the Gruinard area of the mainland. There is some debate as to the date of the granulite-facies Badcallian metamorphism in the Scourie area (e.g. Corfu *et al.* 1994, Friend and Kinny 1995, Whitehouse and Kemp 2010) and the terrane model of Kinny *et al.* (2005) would suggest that granulite-facies metamorphism in these areas is unrelated. Fettes (2009) suggested that the very low Laxfordian strain and preservation of granulite-facies assemblages in southeast Barra is due to the competent anhydrous nature of the TTG gneisses.

Zones 1 and 2 are fairly similar in character apart from the complete overprinting of granulite-facies assemblages in Zone 2 by an amphibolite-facies event. This event must have been low strain as high-angle cross-cutting relationships are preserved and no lineations were found in the TTG gneisses. The margin-parallel clots in the microdiorites in Zone 2 could suggest some deformation although it is more likely to be related to magmatic flow during intrusion. The microdiorites cross-cut the TTG gneissic layering but are themselves cut by the Younger Basic dykes and are therefore late-Scourian in age. They are the oldest of the late-Scourian intrusions as they are cut by the monzonite granites which are in turn cut by the pegmatitic granites. K-Ar and Rb-Sr dating by Francis *et al*. (1971) determined ages of around 2600 Ma which supports interpretation from field relationships that they are late-Scourian. The deformation and metamorphic overprinting in Zone 2 occurred in late-Scourian times – the post-Scourian Younger Basic Dykes here are undeformed and there is none of the migmatisation characteristic of the Laxfordian tectonothermal event. Furthermore, Francis (1973) found fresh orthopyroxene-bearing Younger Basic dykes cutting retrogressed TTG gneisses in this area. Based on relative chronology, Fettes *et al*. (1992) correlated the late-Scourian tectonothermal event with the Inverian event of the mainland, as defined by Evans (1965) in the Scourie-Lochinver area and we agree with this correlation.

In Zone 2, Younger Basic dykes cross-cut the compositional layering in the TTG gneisses but in Zone 3, the dyke margins are parallel with the foliation in the TTG gneiss. If the deformation in Zone 3 was Laxfordian, one would expect to see a strong hornblende aggregate mineral lineation, as can be found in mainland Scourie dykes in Laxfordian shear zones (e.g. MacDonald *et al.* 2013) but the Younger Basic dykes show no such fabric. Furthermore, occasional dyke apophyses cut the margin-parallel fabric in the TTG gneisses indicating the fabric is pre-Younger Basic dyke intrusion. Cresswell (1972) and Park and Cresswell (1973) noted similar field relationships with the equivalent Scourie Dyke Swarm at some places on the mainland and suggested the dykes were emplaced along a pre-existing Inverian (late-Scourian) fabric. Although there is no clear change in TTG gneiss fabric orientation between Zones 2 & 3, the parallelism of the Younger Basic dykes to the fabric in Zone 3 but not in Zones 1 & 2 would suggest that the fabric in Zones 1 & 2 is early-Scourian while in Zone 3 it is late-Scourian. The amphibolite-facies assemblage of the Younger Basic dykes suggests Laxfordian static overprinting.

In Zones 4 and 5, there are many mafic bodies which are homogeneous in appearance with a hornblende-plagioclase mineralogy. These are interpreted to be fragments of Younger Basic dykes rather than older mafic bodies. The older mafics in the Outer Hebrides tend to have a characteristic compositional layering, for example at Rubh' Ard Mhicheil on South Uist (Fettes *et al.* 1992) or elsewhere on Barra (Francis 1969) but this is not seen in the mafic bodies in Zones 4 and 5 of this study. The migmatisation of TTG gneisses in Zone 4 is therefore clearly Laxfordian as it wraps and agmatises remnants of these amphibolite-facies Younger Basic dykes and there is widespread stromatic migmatisation of the post-Younger Basic dyke Laxfordian foliation. However, the migmatisation must have been in the earlier stages of the Laxfordian tectonothermal event as stromatic migmatitic layering can be seen to be folded in places. Fettes *et al*. (1992) did record some Scourian migmatisation on the island of Fuday, to the north of Barra, and Johnson *et al.* (2013) showed that gneisses in the Scourie area of the mainland underwent partial melting during the Badcallian tectonothermal, but the majority of migmatisation on Barra, and indeed throughout the Outer Hebrides, is Laxfordian. Although the migmatisation in Zone 4 can be rather chaotic, it is generally stromatic and follows the pre-existing north-south trend of the compositional layering in the TTG gneisses.

Similarly, the deformation, migmatisation and amphibolite-facies assemblage in Zone 5 are demonstrably Laxfordian as the Younger Basic dykes have been agmatised, retrogressed to amphibolite-facies and internally deformed. Francis (1973) interpreted what we map as Zone 5 to be an inclined isoclinal synform with a corresponding antiform to the east although both limbs dip steeply to the east and evidence for a major fold here is unconvincing.

In Zone 6, the Younger Basic dykes locally cross-cut the metagranite sheets which are therefore Scourian. As the metagranites cross-cut the TTG gneisses and metadiorites sheets, they must be late-Scourian in age. The presence of 1-3cm augen in these metagranite bodies led Fettes *et al*. (1992) to suggest that they were unrelated to the cross-cutting late-Scourian granite sheets present in Zones 1 and 2. The ambiguous field relationships of the metadiorite sheets – smaller sheets cross cut the TTG gneissic layering while larger sheets are concordant and have gradational contacts – means that their position in the relative chronology of the area is unclear. As they are cut by Younger Basic dykes, they must be at least late-Scourian, or earlier. The cross-cutting smaller sheets would indicate they are younger than the formation of the TTG gneisses although the diffuse concordant contacts of the larger sheets suggests they may even be coeval with the TTG gneisses. Whole-rock geochemical analysis by Fettes *et al*. (1992) shows that the metadiorite sheets are specifically diorites or quartz monzodiorites and are chemically distinct from the TTG gneisses. They were also found to be chemically similar to the small microdiorite dykes in Zones 1 and 2 (Fettes *et al.* 1992). However, the metadiorite sheets are somewhat different in appearance from the microdiorite dykes – the microdiorites are dark grey in colour with characteristic black margin-parallel clots while the metadiorites are pale grey with distinctive purplish plagioclase feldspars. The concordance and deformation of Younger Basic dykes at the eastern end of Zone 6 indicates moderate Laxfordian strain here.

The Overall Structure of Southeast Barra

Francis (1973) interpreted the whole of the island of Barra as an infrastructure-suprastructure. In southeast Barra, above the OHFZ, the majority of the rocks were part of the infrastructure but a small part of the suprastructure was folded down in a synform into the infrastructure. Compilation of previous work and remapping in this study has led to the interpretation that the synform of Francis (1973) may in fact be part of a large shear zone. The pattern of tectonothermal overprinting in Zones 1 to 5 suggests a composite late-Scourian and Laxfordian shear zone (Fig. 4) which we name the Southeast Barra Shear Zone (SBSZ). The intense Laxfordian deformation and metamorphic overprinting in Zone 5 indicates this is the core of the shear zone, with lower strain in Zone 4 indicating this is the margin of the Laxfordian shear zone. Zone 3 of this study has the characteristics of a late-Scourian shear zone, where the margins of internally undeformed Younger Basic Dykes are parallel to the foliation in strongly deformed TTG gneisses (Park and Cresswell 1973). Zones 1 & 2 are the country rock to the shear zone. From this overprinting pattern, it is interpreted that the overall structure of Southeast Barra comprises a discrete late-Scourian shear zone which cut through early-Scourian gneisses; the core of the late-Scourian shear zone was then reactivated in the Laxfordian. Zone 6 is outside the Laxfordian core of the shear zone but the variable deformation and lithologies here make it difficult to place it definitively in the same relative chronology as Zones 1-5. No shear sense indicators for the late-Scourian part of the shear zone were found but sigmoid feldspars and a south-plunging mineral lineation indicate sinistral transpression in the Laxfordian part.

Comparison of the tectonothermal overprinting relationships of major composite late-Scourian (Inverian) and Laxfordian shear zones elsewhere in the LGC with the SBSZ adds weight to the suggestion that it is indeed a composite late-Scourian/Laxfordian shear zone. In the Outer Hebrides, Fettes *et al*. (1992) noted several major shear zones. The Langavat belt (Fig. 1a) of South Harris is the most studied and detailed mapping (e.g. Graham 1980, Coward 1984, Mason *et al.* 2004, Mason *et al.* 2004, Mason and Brewer 2005, Mason 2012) has shown that none of the fabrics are older than the Younger Basic dykes. The Langavat belt is dominated by metasediments and mafic gneisses which deform in a different style to TTG gneisses which makes comparison with the SBSZ difficult. Shear zones are recorded on the islands of Berneray and Ensay (Fig. 1a) in the Sound of Harris but are not described in detail (Fettes *et al.* 1992, Friend and Kinny 2001, Mason 2012). On the mainland, Laxford, Diabaig, Shieldaig and Canisp (Fig. 1a) are well-characterised Inverian-Laxfordian shear zones. The SBSZ is compared to these to investigate if they are genetically related (Table 2).

The Canisp Shear Zone is a major shear zone which shares many aspects of tectonothermal overprinting style with the SBSZ. Granulite-facies TTG and mafic gneisses (equivalent to SBSZ Zone 1) are overprinted at amphibolite-facies by the Inverian Lochinver anticline which is cut by Scourie dykes (Attfield 1987). The Inverian shear zone is a steep belt formed by the northern limb of the anticline (similar to Zone 3). This is overprinted by a zone of strong Laxfordian deformation (similar to Zones 4 and 5) although there is no migmatisation. Minor cataclasis and pseudotachylite formation have been reported (Fettes 2009), similar to that found in Zone 4 of the SBSZ. Wheeler *et al*. (1987) recognised a major shear zone around Diabaig (Fig. 1a). This has a transitional zone of alternating Inverian and Laxfordian fabric at the edge of a zone of uniform Laxfordian strain, assumed to be the shear zone core. The zones of low Laxfordian strain reveal the earlier Inverian shear zone fabric (Cresswell 1972, Wheeler 2007). The shear zone at Diabaig is similar to the SBSZ in that the gneisses of the Laxfordian shear zone core are migmatitic and have a strong planar and linear fabric (Park *et al.* 1987). The Inverian fabric gives way to Badcallian banded gneisses to the northeast although no granulite-facies assemblages are recorded. Scourie dykes are often parallel to the Inverian fabric, as in Zone 3 of the SBSZ.

Although there are no granulite-facies assemblages present around the Shieldaig Shear Zone (Fig. 1a) (Park 2002, Kinny *et al.* 2005, Park 2010), there is a domain of Badcallian fabric which has undergone a later static overprint, cut by Scourie dykes, which is analogous to Zone 2 of the SBSZ. Adjacent to this is a domain of Inverian deformation where Scourie dykes are generally parallel to the foliation in the host TTG gneisses (equivalent to Zone 3) (Park 2002, Mendum *et al.* 2009). The zone of strong Laxfordian deformation of the Shieldaig Shear Zone is similar to Zones 4 and 5 of the SBSZ but is unmigmatised. The Laxford Shear Zone (LSZ) is the most northerly major shear zone in the mainland LGC outcrop (Fig. 1a). The LSZ has zones of Badcallian granulite-facies TTG gneiss, both preserved and statically overprinted, on its southwest side (Goodenough *et al.* 2010); this corresponds with Zones 1 and 2 of the SBSZ. The Scourie dykes in the LSZ, however, do not seem to follow the Inverian shear zone foliation as in the equivalent Zone 3 of the SBSZ. There is also a lack of

Laxfordian migmatisation in the LSZ, although there are numerous thick Palaeoproterozoic granite sheets in the shear zone core, some of which are locally sourced (Goodenough *et al.* 2010). Comparison of the overprinting relationships and relative chronology of these shear zones with the SBSZ indicates they are genetically related and the SBSZ was also affected by the Lewisian-wide late-Scourian/Inverian and Laxfordian tectonothermal events.

A recent development in the understanding of the formation and evolution of the Lewisian Gneiss Complex has been the suggestion that it is composed of distinct terranes with different early metamorphic histories (Kinny and Friend 1997, Friend and Kinny 2001, Kinny *et al.* 2005, Love *et al.* 2010) which amalgamated in the Inverian tectonothermal event (Goodenough *et al.* 2010). Some of these terranes are separated by major Inverian-Laxfordian shear zones such as the Laxford Shear Zone (LSZ) (Kinny *et al.* 2005, Goodenough *et al.* 2010). The rocks on both sides of the LSZ are dominated by TTG gneisses but whole-rock geochemistry indicated they have markedly different compositions (Sheraton *et al.* 1973, Tarney and Weaver 1987, Rollinson 1996, Watkins *et al.* 2007) while zircon geochronology indicates they have different Archaean protolith and metamorphic ages (Kinny and Friend 1997). While no geochronological data is available, the differences in lithology – dominant TTG gneisses with minor late-Scourian intrusions in Zones 1-5 but augen metagranites and large metadiorite sheets with the TTG gneisses in Zone 6 – sugest that the SBSZ could potentially be a terrane boundary.

Conclusions

Southeast Barra is one of few areas in the Outer Hebrides where high Laxfordian strain is not prevalent in the rocks of Lewisian Gneiss Complex (LGC). This enabled mapping of zones with variable degrees of late-Scourian and Laxfordian tectonothermal overprinting of early-Scourian pyroxene-bearing TTG gneisses. Parallelism between Younger Basic dyke margins and the TTG gneiss foliation but the undeformed nature of the dykes and cross-cutting apophyses indicate late-Scourian deformation in the TTG gneisses. Penetrative deformation and migmatisation of Younger Basic dykes and TTG gneisses fingerprints Laxfordian tectonothermal overprinting. The pattern of overprinting indicates the presence of a composite shear zone with late-Scourian (Inverian) and Laxfordian components, the Southeast Barra Shear Zone (SBSZ). Comparison with equivalent Inverian-Laxfordian shear zones in the mainland LGC supports the shear zone interpretation. The SBSZ juxtaposes TTG gneisses to the east with a mixture of TTG gneisses, large metadiorite sheets and augen-metagranites to the west. Although there is a lack of isotope geochronology from Barra, this difference in lithology across the SBSZ suggests it potentially may be a newly-recognised terrane boundary in the context of the LGC terrane model proposed by Kinny *et al*. (2005).

Acknowledgements

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Table Captions

Table 1: The tectonothermal event names used in the Outer Hebrides in this study and their mainland equivalents.

Table 2: A summary comparing the key features of the six zones of the Southeast Barra Shear Zone (SBSZ) to other major shear zones in the LGC.

Figure Captions

Fig. 1: a) Map showing the outcrop area of the Lewisian Gneiss Complex (LGC) and the location of major shear zones. The inset map shows the location of the LGC in the UK; **b**) Summary geology of the Isle of Barra, after IGS map sheet Uist and Barra (South) (1981).

Fig. 2: a) map of the transect from Zones 1 to 6, showing changes in structure and metamorphism; **b**) detail map showing high-angle cross-cutting relationships between TTG gneiss, a late-Scourian pegmatitic granite body and a member of the Younger Basic Dyke Swarm [NF 7078 0004]; **c**) detail map showing high-angle cross-cutting relationships between TTG gneiss, a late-Scourian microdiorite dyke, a late-Scourian pegmatitic granite sheet, a member of the Younger Basic Dyke Swarm and a Laxfordian pegmatitic granite sheet [NL 7043 9940]; **d**) detail map showing high-angle cross-cutting relationships between TTG gneiss, a late-Scourian microdiorite dyke, a late-Scourian pegmatitic granite sheet, and a member of the Younger Basic Dyke Swarm [NL 7028 9867].

Fig. 3: a) photomicrograph of pyroxene-bearing TTG gneiss [NF 70693 00290]; **b**) annotated field photograph showing cross-cutting relationships between TTG gneiss (TTG), a late-Scourian microdiorite dyke (mD) and a Laxfordian pegmatitic granite sheet (pG), 1.8m-long walking pole for scale [NL 70432 99403]; **c**) photomicrograph of amphibolite-facies biotite-bearing TTG gneiss [NL 70283 98666]; **d**) annotated field photograph showing a sub-parallel contact between a Younger Basic dyke margin and the foliation in TTG gneiss, the contact cuts the foliation at a tight angle, 3cm-long hand-lens for scale [NL 70118 98668]; **e**) annotated field photograph showing the margin of a Younger Basic dyke parallel to the foliation in TTG gneiss, 10cm-long compass clinometer for scale [NL 70056 98636]; **f**) field photograph showing migmatitic layering in TTG gneiss, 1.8m-long walking pole for scale [NL 69883 98808]; **g**) field photograph showing tight to isoclinally folded Laxfordian migmatitic TTG gneiss with boudinaged mafic layer, possibly a Younger Basic dyke remnant, on SE fold limb and sigmoid feldspar porphyroclast on NW fold limb indicating top-to-the-right dextral movement sense, 10cm-long compass clinometer for scale [NL 69412 98832]; **h**) field photograph showing Younger Basic dyke remnant in Laxfordian migmatitic TTG gneiss, closely to openly folded, 10cm-long compass clinometer for scale [NL 69412 98832]; **i**) field photograph showing Laxfordian

migmatitic TTG gneiss with small shear zones offsetting partial melt layers, 10cm-long compass clinometer for scale [NL 69412 98832]; **j**) field photograph showing boudinaged mafic layer, likely a Younger Basic dyke remnant, on fold limb surrounded by migmatitic partial melt, 1.8m-long walking pole for scale [NL 69412 98832]; **k**) field photograph showing cataclasis of migmatitic TTG gneiss with black pseudotachylite veins between gneiss fragments, 3cm-long hand-lens for scale [NL 69412 98832]; **l**) migmatised and deformed TTG gneisses and remnants of Younger Basic dykes, 1.8m-long walking pole for scale [NL 69914 97717].

Fig. 4: Cross-section through all 6 zones schematically illustrating the relationships of different lithologies and tectonothermal overprinting features; the position of the terrane-boundary shear zone in late-Scourian and Laxfordian times is shown.

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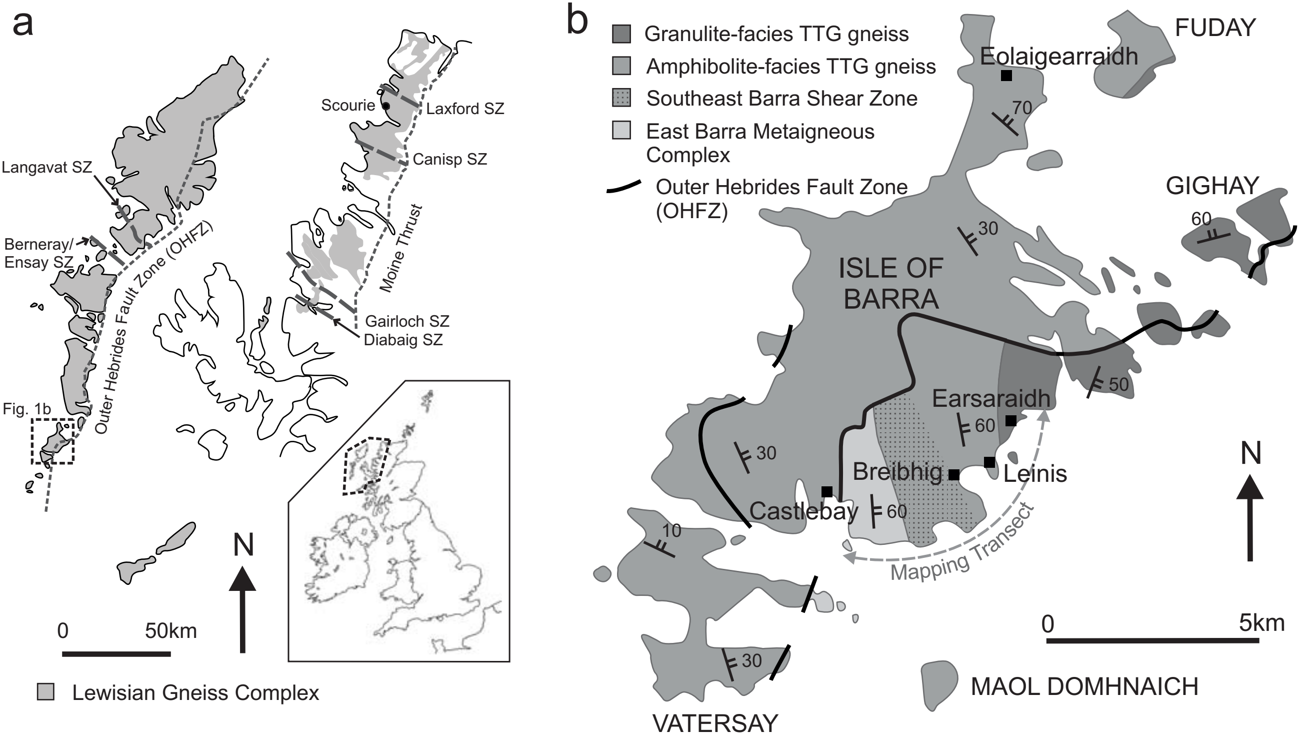
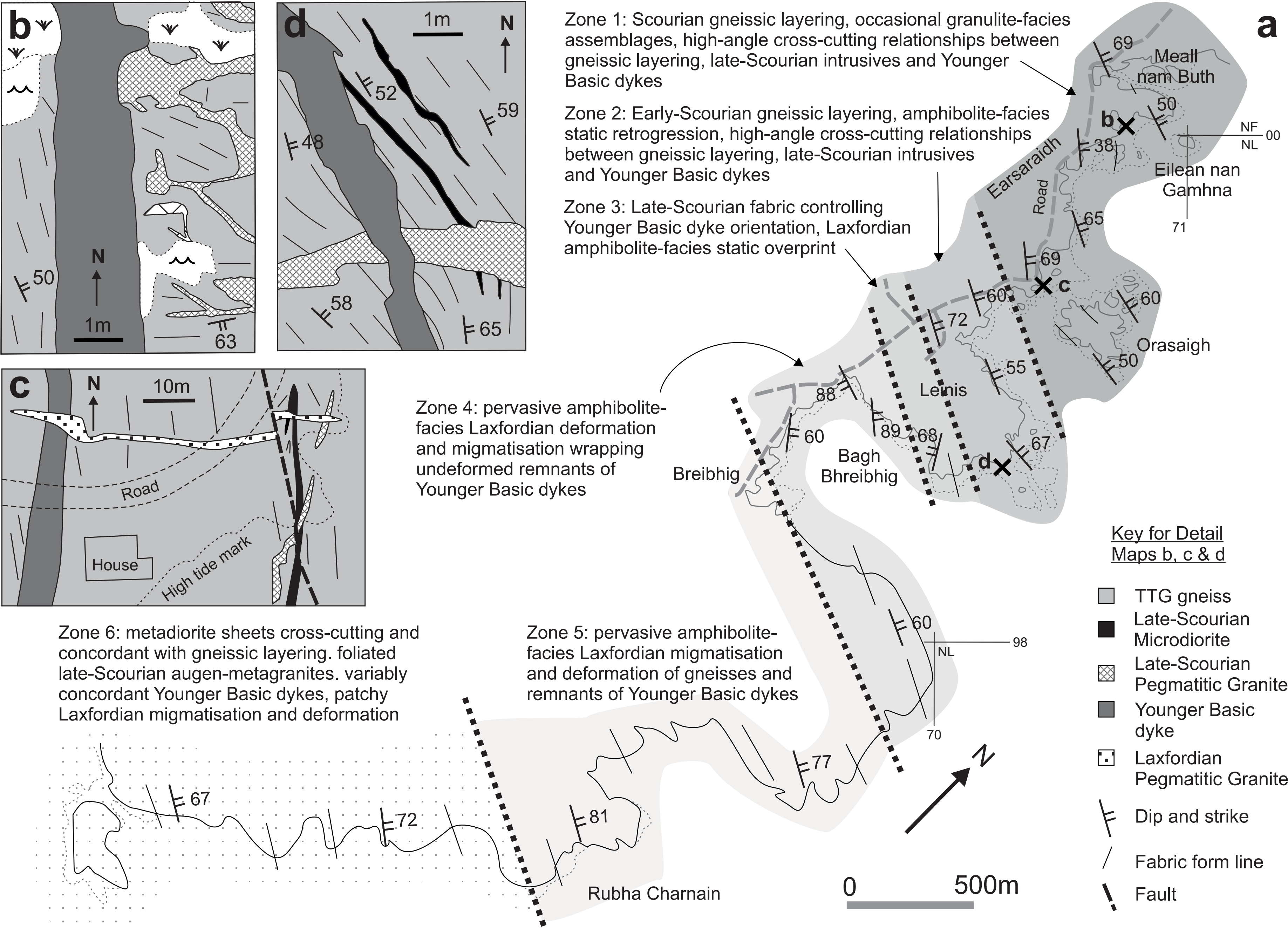
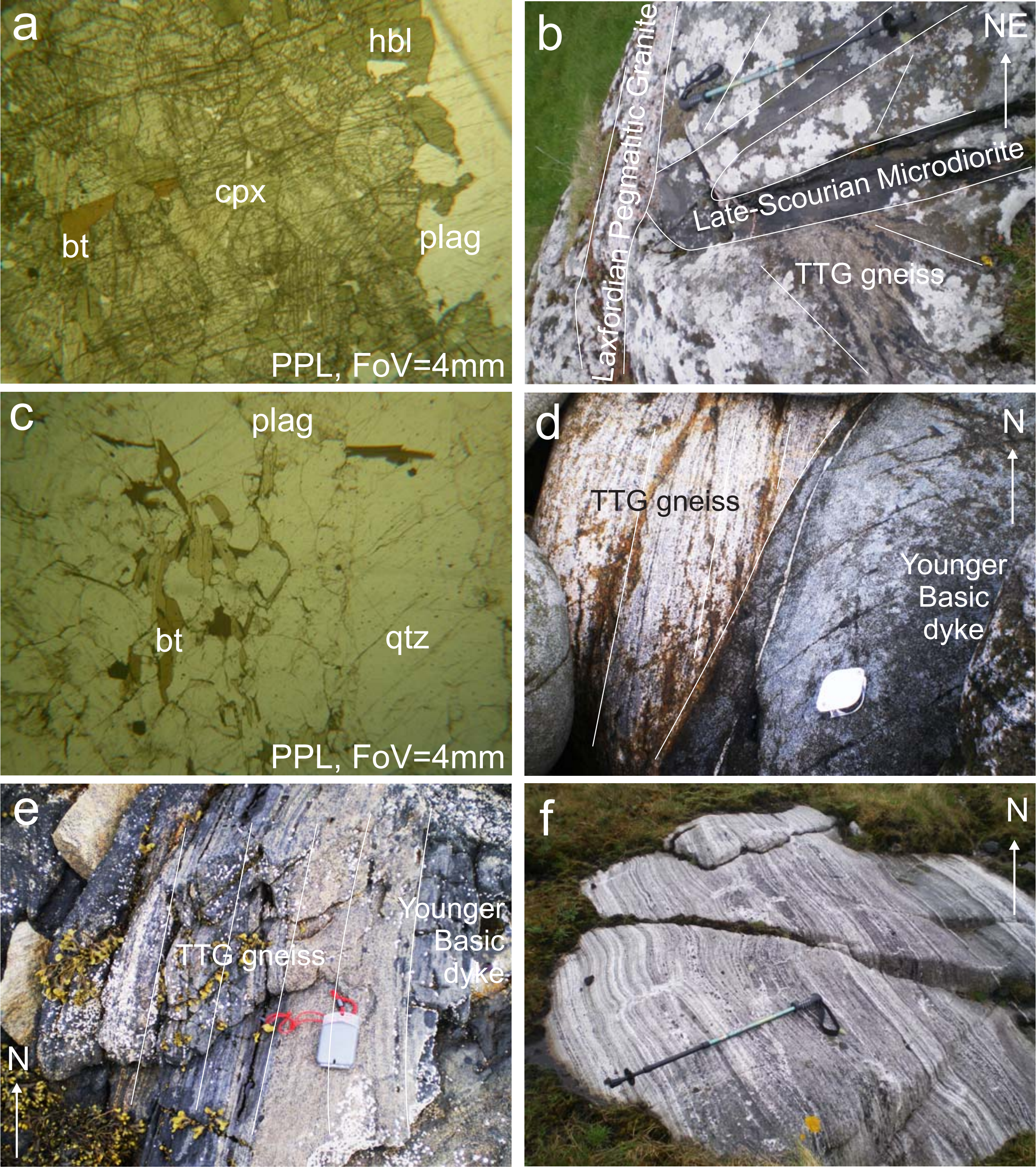
Name (Outer Hebrides)	**Characteristics**	**Mainland Equivalent**
Early-Scourian	Granulite-facies metamorphic assemblage	Badcallian
Late-Scourian	Amphibolite-facies metamorphic assemblage	Inverian
Younger Basic Dyke Swarm	Metadolerite dyke swarm	Scourie Dyke Swarm
Laxfordian	Amphibolite-facies metamorphic assemblage	Laxfordian

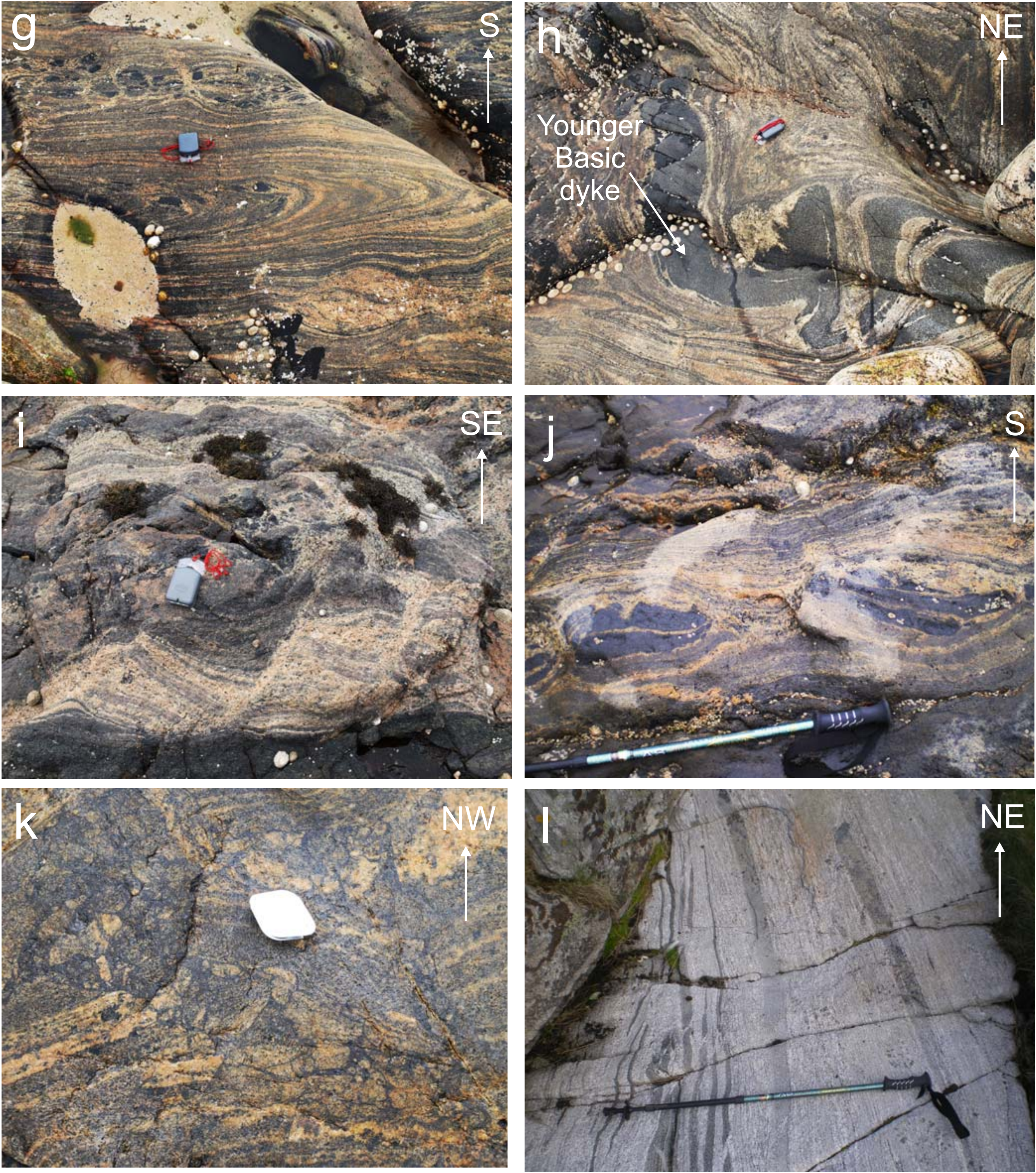
Shear Zone	Zone 1	Zone 2	Zone 3 (margin of Inverian/late-Scourian shear zone)	Zone 4 (margin of Laxfordian shear zone)	Zone 5 (core of Laxfordian shear zone)	Zone 6 (other side of shear zone)
Barra	Early-Scourian granulite-facies assemblage and compositional layering in TTG gneiss, high-angle cross-cutting relationships	Early-Scourian fabric and late-Scourian amphibolite-facies static overprint in TTG gneiss, high-angle cross-cutting relationships	Undeformed Younger Basic dykes, intrusion controlled by pre-existing fabric, static Laxfordian overprint	Moderate Laxfordian foliation and folding, Younger Basic dykes internally undeformed but wrapped and agmatised by migmatitic fabric	Younger Basic dykes deformed, strong Laxfordian foliation, widespread migmatisation	Castlebay Metadiorite Complex
Laxford	Badcallian granulite-facies assemblage in TTG gneiss, high-angle cross-cutting relationships	Badcallian gneissic layering cut by Scourie dykes, later amphibolite-facies static overprint	Inverian foliation cut by Scourie dykes, zone contains many narrow (tens of metres wide) discrete Laxfordian shear zones	None	Deformed Scourie dykes, strong planar and linear Laxfordian fabrics but no migmatisation	Rhiconich Terrane gneisses
Shieldaig	None	Badcallian gneissic layering cut by Scourie dykes, later amphibolite-facies static overprint	Inverian foliation generally sub-parallel to Scourie dyke margins	None	Deformed Scourie dykes, strong planar and linear Laxfordian fabrics but no migmatisation	Ard Gneiss and Loch Maree Group supracrustals of the Gairloch Terrane, Ialltaig Terrane gneisses
Diabaig	None	Scourie dykes sub-parallel to Inverian fabric, zone occurs as multiple lacunae bounded by zones of Laxfordian deformation	Heterogeneous distribution of Laxfordian strain as discrete zones bounding lacunae of preserved Inverian fabric	As Zone 3, the two zones are combined into one	Deformed Scourie dykes, strong planar and linear Laxfordian fabrics, widespread migmatisation	Not exposed
Canisp	Badcallian granulite-facies assemblage in TTG gneiss, high-angle cross-cutting relationships	Inverian amphibolite-facies foliation defining Lochinver anticline	Shear zone development on steep northern limb of Lochinver anticline	None	Deformed Scourie dykes, strong planar and linear Laxfordian fabrics but no migmatisation, some cataclasis and pseudotachylite	Same TTG gneisses with same tectonothermal overprinting style on both sides of the shear zone core


a
Scourie
Laxford SZ
Canisp SZ
Langavat SZ
Berneray/
Ensay SZ
Outer Hebrides Fault Zone (OHFZ)
Moine Thrust
Gairloch SZ
Diabaig SZ
Fig. 1b
N
0
50km
Lewisian Gneiss Complex
b
Granulite-facies TTG gneiss
Amphibolite-facies TTG gneiss
Southeast Barra Shear Zone
East Barra Metaigneous
Complex
Outer Hebrides Fault Zone
(OHFZ)
FUDAY
Eolaigearraidh
70
GIGHAY
60
30
ISLE OF
BARRA
50
Earsaraidh
60
30
Breibhig
Leinis
Castlebay
60
10
Mapping Transect
N
0
5km
30
MAOL DOMHNAICH
VATERSAY



a
b
c
d
Zone 1: Scourian gneissic layering, occasional granulite-facies assemblages, high-angle cross-cutting relationships between gneissic layering, late-Scourian intrusives and Younger Basic dykes
Zone 2: Early-Scourian gneissic layering, amphibolite-facies static retrogression, high-angle cross-cutting relationships between gneissic layering, late-Scourian intrusives and Younger Basic dykes
Zone 3: Late-Scourian fabric controlling Younger Basic dyke orientation, Laxfordian amphibolite-facies static overprint
Zone 4: pervasive amphibolite-facies Laxfordian deformation and migmatisation wrapping undeformed remnants of Younger Basic dykes
Zone 5: pervasive amphibolite-facies Laxfordian migmatisation and deformation of gneisses and remnants of Younger Basic dykes
Zone 6: metadiorite sheets cross-cutting and concordant with gneissic layering. foliated late-Scourian augen-metagranites. variably concordant Younger Basic dykes, patchy Laxfordian migmatisation and deformation
Meall nam Buth
Eilean nan Gamhna
Earsaraidh
Road
Orasaigh
Leinis
Bagh Bhreibhig
Breibhig
Rubha Charnain
NF
NL
00
71
98
70
House
High tide mark
1m
10m
0
500m
N
Key for Detail Maps b, c & d
TTG gneiss
Late-Scourian Microdiorite
Late-Scourian Pegmatitic Granite
Younger Basic dyke
Laxfordian Pegmatitic Granite
Dip and strike
Fabric form line
Fault


a
hbl
cpx
bt
plag
PPL, FoV=4mm
b
Laxfordian Pegmatitic Granite
NE
Late-Scourian Microdiorite
TTG gneiss
c
plag
bt
qtz
PPL, FoV=4mm
d
N
TTG gneiss
Younger
Basic
dyke
e
TTG gneiss
Younger
Basic
dyke
N
f
N


g
S
h
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Younger
Basic
dyke
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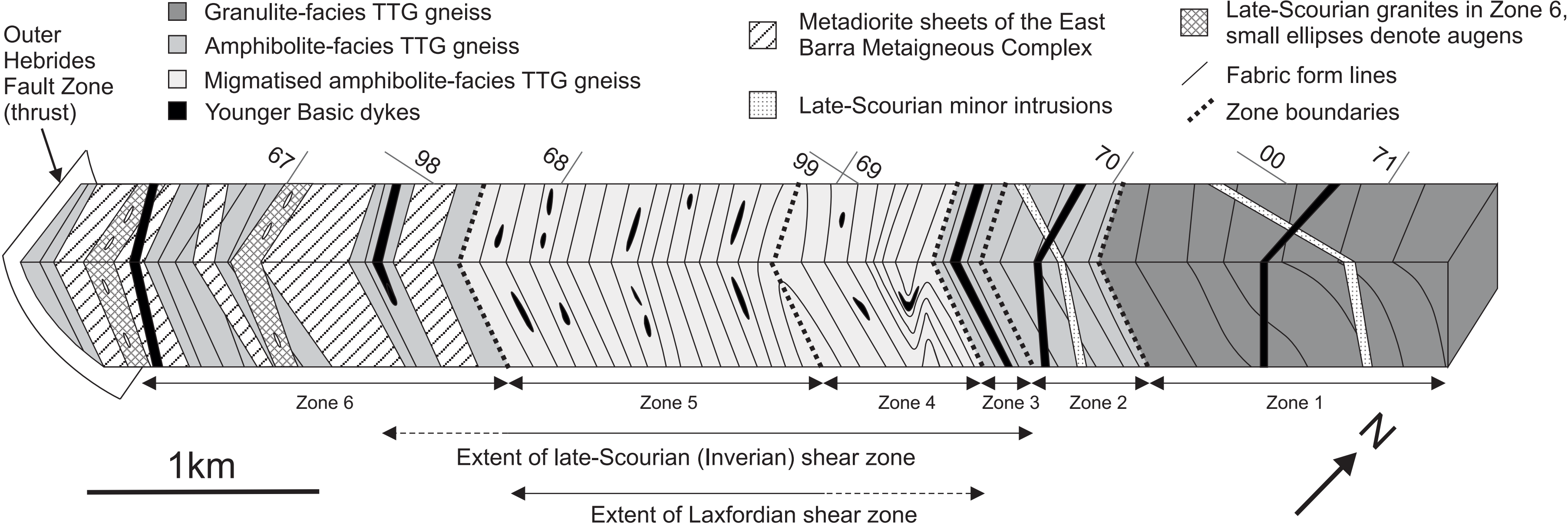
Outer Hebrides Fault Zone (thrust)
Granulite-facies TTG gneiss
Amphibolite-facies TTG gneiss
Migmatised amphibolite-facies TTG gneiss
Younger Basic dykes
Metadiorite sheets of the East Barra Metaigneous Complex
Late-Scourian minor intrusions
Late-Scourian granites in Zone 6, small ellipses denote augens
Fabric form lines
Zone boundaries
67
98
68
99
69
70
00
71
Zone 6
Zone 5
Zone 4
Zone 3
Zone 2
Zone 1
Extent of late-Scourian (Inverian) shear zone
Extent of Laxfordian shear zone
1km
N