The Laxford Shear Zone: an end-Archaean terrane boundary?

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Text 7,815 words; References 1,700 words; 7 figures; 1 table
Abbreviated title: The Laxford Shear Zone

Abstract

The Lewisian Gneiss Complex of north-western Scotland consists of Archaean gneisses, variably reworked during the Proterozoic. It can be divided into three districts – a central granulite-facies district between districts of amphibolite-facies gneiss to the north and south. Recent work has interpreted these districts in terms of separate terranes, initiating a controversy that has implications for how Precambrian rocks are understood worldwide. The northern district of the Lewisian Gneiss Complex (the Rhiconich terrane) is separated from the central district (the Assynt terrane) by a broad ductile shear zone known as the Laxford Shear Zone.

This paper reviews the geology of the Laxford Shear Zone, clarifying field relationships and discussing other evidence, to consider whether or not it does indeed represent a terrane boundary. A detailed review of field, geochemical and geochronological evidence supports the recognition of the separate Assynt and Rhiconich terranes. Mafic dykes (the Scourie Dyke Swarm) and granitoids, of Palaeoproterozoic age, occur on both sides of the Laxford Shear Zone and thus the terranes were most probably juxtaposed during the late Archaean to early Palaeoproterozoic Inverian event. Subsequently, the less-competent, more-hydrous amphibolite-facies gneisses of the Rhiconich terrane were affected by later Palaeoproterozoic (Laxfordian) deformation and partial melting, to a greater extent than the more-competent granulite-facies gneisses of the Assynt terrane. [end of abstract]

The Lewisian Gneiss Complex of north-western Scotland is one of the world's most intensively studied regions of high-grade Precambrian gneisses, yet it continues to provide fruitful ground for new research. It crops out on the islands of the Outer Hebrides and also in a 140 km-long strip along the north-west coast of the Scottish mainland, where it forms part of the foreland to the Caledonian orogen (Figure 1). The main outcrop is limited to the east by the Moine Thrust, although inliers of 'Lewisianoid' gneiss occur to the east of this major structure. The Lewisian gneisses form part of a now-disrupted Precambrian region in the North Atlantic, which also includes basement rocks in North America, Greenland and Scandinavia.

The essential elements of the Lewisian Gneiss Complex were identified a century ago by the authors of the classic Geological Survey Memoir on the Northwest Highlands (Peach *et al.*, 1907). They recognised that the complex consists largely of metamorphosed plutonic igneous rocks, with relatively minor metasedimentary and metavolcanic units, cut by a variety of less-deformed igneous intrusions. They also divided the mainland Lewisian into three districts, northern, central and southern; the central district consisted largely of pyroxene-bearing gneiss (now recognised as granulite facies), whereas more strongly deformed hornblende- and biotite-bearing gneisses (amphibolite facies) cropped out to the north and south.

The main events within the Lewisian Gneiss Complex were later identified by Sutton and Watson (1951), who recognised two major episodes of metamorphism and deformation, the 'Scourian' and 'Laxfordian' events, temporally separated by intrusion of an extensive dyke swarm known as the Scourie Dyke Swarm. A third, amphibolite-facies event, younger than the Scourian but pre-dating the Scourie Dykes, was recognised by Evans (1965) and termed the 'Inverian'. The 'Scourian' event was later renamed 'Badcallian' (Park, 1970) and more tightly defined as a period of early granulite-facies metamorphism, which has to date only been recognised in the central district of the Lewisian Gneiss Complex.

Over the last hundred years, the Lewisian Gneiss Complex has provided a natural laboratory for studies into many aspects of basement geology (Park *et al.* 2002; Wheeler *et al.* this volume). Major crustal-scale shear zones within the Lewisian gneisses have been studied in detail, and provide large-scale examples of the type of shear zones described and analysed by the classic work of Ramsay and Graham (1970). Isotopic dating techniques were first harnessed for research into the history of the complex by Giletti *et al.* (1961) and have continued to provide crucial information as techniques – and the application of these techniques to high-grade metamorphic terranes – have been refined (see summary in Kinny *et al.*, 2005).

Most recently, geochronological data have been used to identify crustal blocks with different histories within the Lewisian Gneiss Complex, and it has been proposed that these represent separate terranes that were assembled along major shear zones (Friend and Kinny, 2001; Kinny *et al.*, 2005). The details of this model remain rather controversial, and a simpler version – in which two main terranes collided but were then divided into blocks by strike-slip movement – has also been proposed (Park, 2005). Overall, though, the idea that the Lewisian Gneiss Complex does not represent a contiguous block of Archaean crust is becoming more widely accepted. It is clear that the terrane model can usefully be tested by detailed investigations of the 'terrane-bounding' shear zones (Mason and Brewer, 2005).

One of the strongest candidates for a terrane-bounding shear zone is the Laxford Shear Zone, which separates the amphibolite-facies gneisses of the 'northern district' from the granulite-facies gneisses of the 'central district'. Following Coward and Park (1987), the Laxford Shear Zone is here defined as the broad (~ 8 km) zone of Inverian and Laxfordian ductile shear that extends along the southern shore of Loch Laxford and continues along the northern side of Ben Stack (Figures 2a, b). During the 'Continental Tectonics and Mountain Building' conference in Ullapool in May 2007, the authors of this paper engaged in two days of vigorous scientific discussion about the age and type of movements along that shear zone. The conclusions and further questions from that debate are presented here. This paper concentrates on reviewing previous work, clarifying the field relationships, and describing a consensus that has been reached by all the authors on the nature of the Laxford Shear Zone. Many disparate views on other aspects of the Lewisian exist within the author team, and these cannot all be addressed here.

Previous work on the Laxford Shear Zone

The Lewisian gneisses of the Laxford area were first mapped by the Geological Survey towards the end of the nineteenth century (Peach *et al.*, 1892) and described in the North-west Highlands Memoir (Peach *et al.*, 1907). The surveyors recognised that Loch Laxford lay roughly along a zone that separated biotite- and hornblende-bearing gneisses of the 'northern district' from pyroxene-bearing gneisses of the 'central district' of the Lewisian Gneiss Complex. They described the rocks of the northern district as containing mafic layers that could be deformed dykes 'of the Scourie type', and abundant granites and pegmatites that cross-cut all the other rock-types. They also noted 'it is probable that all the granite dykes were not intruded at the same time'. In the Loch Laxford area, they identified three WNW-ESE-trending belts in the Lewisian gneisses:

1) A north-eastern belt in which hornblende- and biotite-bearing gneisses are cut by intrusions of granite and pegmatite that 'probably exceed in bulk' the gneisses themselves.
2) A middle belt of hornblende- and biotite-bearing gneisses cut by mafic dykes, with abundant folds and shear zones. This belt was essentially what we would now describe as the Laxford Shear Zone.
3) A south-western belt of pyroxene-bearing gneisses in which the gently dipping gneissosity is cross-cut by undeformed mafic dykes (the Scourie Dyke Swarm).

The next major study of the area was that of Sutton and Watson (1951). They considered that three major 'episodes' could be recognised in the history of the gneisses around Loch Laxford: an early, 'Scourian' metamorphic event during which granulite-facies pyroxene-bearing gneisses were formed; a period of intrusion of dolerite dykes (the Scourie Dykes); and a second, 'Laxfordian' metamorphic event in which the gneisses of the northern district were retrogressed to form hornblende- and biotite-bearing gneisses (amphibolite facies metamorphism). Sutton and Watson believed that the gneisses of the central and northern districts shared the same early history, and were only distinguished by the later effects of the Laxfordian event. They divided the Loch Laxford area into five zones (Figure 2b) and suggested that the variations across the zones were controlled by an episode of deformation, 'producing structures with a north-west to south-east trend' and a front of migmatisation. The five zones are (from SW to NE):

1) The Scourie zone, in which Laxfordian movement and metamorphism have only had a local effect on the 'Scourian complex'. This equates to the south-western belt of the 1907 Memoir. Sutton and Watson (1962) suggested that the north-eastern boundary of this zone should be taken as the 'local Laxfordian front', and thus that all the gneisses to the north had undergone retrogression and metasomatism during the Laxfordian event.

2) The Claisfearn zone, consisting of flaggy gneisses with a steep south-westward dip, and 'numerous shear-belts'.

3) The Foindle zone, also with steep south-westward dips, and incorporating a thick band of mafic rocks (Figure 2a). Units of brown-weathering, schistose biotite-bearing gneisses were recognised and were considered to have formed through metasomatism of the mafic rocks. Shear belts were described as being 'entirely confined to the basic bodies' over much of this zone, and granite and pegmatite veins were considered to 'dwindle' southwards across the zone. The Claisfearn and Foindle zones together represent the middle belt of the 1907 Memoir.

4) The Badnabay zone, in which a large number of 'concordant sheets of granite-gneiss' appear and 'there are no shear-belts'; the main foliation in this area was considered to equate to the second foliation formed in the shear belts to the south.

5) The Laxford zone, 'thickly veined with granites and pegmatites' and with no second foliation. The Badnabay and Laxford zones together equate to the north-eastern belt of the 1907 Memoir.

An alternative theory was proposed by Bowes (1962), who was the first to suggest that the rocks of the northern district had been tectonically juxtaposed with those of the central district during the Laxfordian event. Lambert and Holland (1972) defined the boundary between the two districts as the Ben Stack line, equivalent to the boundary between the Foindle and Badnabay zones of Sutton and Watson (1951) (Figure 2b). Following the identification of the pre-Scourie Dyke Inverian event in the central district (Evans, 1965), Holland (1966) noted that the area around Loch Laxford also showed the effect of two successive amphibolite-facies metamorphic events (the pre-Scourie Dyke Inverian and post-dyke Laxfordian). Rb-Sr and K-Ar dating of gneisses placed the age of the Laxfordian event at Laxford Bridge as between c. 1850 and 1750 Ma (Lambert and Holland, 1972).

Geochemical studies of the Lewisian gneisses (Holland and Lambert, 1973; Sheraton *et al.*, 1973) indicated that, on average, the gneisses to the north of the 'Ben Stack line' are rather richer in K_2O, Rb, Th, U and SiO_2 than those to the south. This evidence supported the theory of Bowes (1962) that the northern district gneisses did not represent retrogressed equivalents of the granulite facies gneisses of the central district, and that the Laxford Shear Zone represented a major structure along which two separate crustal blocks were juxtaposed.

Beach *et al.* (1974) formalised the term 'Laxford Front', which was defined as the southern limit of migmatites and Laxfordian granite sheets. This limit is approximately equivalent to the Ben Stack Line, but is difficult to place in the field, since scattered Laxfordian granite sheets do occur to the south of the area of migmatitic gneisses (Peach *et al.*, 1907). Beach *et al.* (1974) studied the structural evolution of the Loch Laxford area, and recognised three significant deformation phases in the Laxford area, one pre-Scourie Dyke intrusion and two post-dyke. They mapped and described pre-Scourie Dyke folds but did not directly correlate their structures with the Inverian event, as defined near Lochinver by Evans (1965). They stated that 'there was negligible vertical displacement' on the Laxford Shear Zone during this first phase of deformation, but described post-Scourie Dyke shear zones with an oblique sinistral and north-up sense of movement. Structures formed in the third deformation phase were only recognised north of Laxford Bridge.

Davies (1974) followed suggestions made by Beach *et al.* (1974) in interpreting the brown-weathering, schistose biotite-bearing gneisses ('brown schists') of the Foindle zone as metamorphosed supracrustal rocks. He presented a detailed map of this zone and suggested that the supracrustal rocks lay on top of, and were infolded with, a layered, mafic igneous sheet. Davies (1976) presented evidence that the folding of this supracrustal/mafic igneous complex occurred before the end of the early granulite-facies metamorphism in the central district, and thus proposed that the belt of supracrustal rocks originated as a distinctive structure during the Archaean. Okeke *et* *al.* (1983) studied the chemistry of the brown biotite-bearing gneisses, and confirmed that they represented a metasedimentary sequence of pelitic, semi-pelitic and psammitic gneisses. Recent detrital zircon dating indicates that the metasedimentary rocks were most probably derived from central district gneisses (Love, 2004). It has been suggested that this association of mafic and ultramafic rocks with metasedimentary rocks could represent a marginal ocean-floor assemblage, tectonically accreted to the continental margin (Park and Tarney, 1987).

Coward and Park (1987) and Coward (1990) re-investigated the structures of the Laxford area. Coward (1990) stated that 'the southern margin of Laxfordian deformation…. has the form of a large scale ductile shear zone, and is often termed the Laxford Front'. This shear zone was described as striking NW-SE, and ~ 8 km in width, with heterogeneous deformation throughout. Coward (1990) recognised that pervasive Laxfordian deformation had occurred in a zone to the south of Laxford Bridge (the Badnabay zone) whereas further to the south (in the Claisfearn and Foindle zones) discrete Laxfordian shears are superimposed on Inverian deformation. Coward and Park (1987) suggested that the granulite-facies gneisses of the central region had been thrust over the amphibolite-facies gneisses to the north during the Inverian. The granulite-facies gneisses were then displaced back down toward the south during early Laxfordian deformation. A later Laxfordian movement, following granite emplacement, was described as having a south-up, dextral shear sense.

In the late 1980s, a sea-change began to occur in the way in which the Lewisian gneisses were investigated. Whitehouse (1989) used Sm-Nd isotopic data to suggest that the crust of the different 'districts' within the Lewisian Gneiss Complex might have formed at different times. Following on from this, modern isotopic techniques – particularly U-Pb dating of zircons – were used to date events in the Lewisian Complex far more precisely than had hitherto been possible. Corfu *et al*. (1994) and Friend and Kinny (1995) presented U-Pb zircon and titanite data for gneisses in the central district immediately to the south of the Laxford Shear Zone. Differing techniques were utilised by these authors; Corfu *et al*. (1994) analysed whole grains or fragments of grains by conventional isotope dilution (ID-TIMS), whereas Friend and Kinny (1995) carried out *in situ* analysis using a high-resolution ion microprobe (SIMS). Both groups of authors recognised the complexity of the zircons in their samples, and different events affecting the zircons were recognised through the use of the differing techniques. The use of SIMS allowed Friend and Kinny (1995) to date the oldest zircon cores, giving an age for the tonalitic gneiss protoliths of c. 2960 Ma. The data in both studies were interpreted to show that the gneisses were metamorphosed to high grade at 2490-2480 Ma, with a later metamorphic phase at c.1750 Ma. However, an earlier high-grade metamorphic event at c. 2710 to 2760 Ma, which was recognised by Corfu *et al.* (1994) and Zhu *et al.* (1997), was not resolvable from the data of Friend and Kinny (1995). This has led to ongoing debate over the absolute ages of the Badcallian and Inverian events (Corfu, 2007; Friend *et al.*, 2007), which is largely focused upon the reconciliation of differences between data sets obtained by the different analytical techniques, and on the geological interpretation of complex internal zonation and age patterns among zircon samples.

Kinny and Friend (1997) presented further U-Pb (SIMS) zircon and titanite data which showed that the gneisses to the north of the Laxford Shear Zone had a markedly different history to those of the central district. Gneisses of the northern district were shown to have protolith ages of 2800-2840 Ma with evidence for later dioritic intrusions at c. 2680 Ma, but no evidence was found for early high-grade metamorphism. Isotopic evidence for Laxfordian reworking at c. 1750 Ma and c. 1670 Ma has been found in both districts (Kinny and Friend, 1997; Corfu *et al*., 1994).

This work thus led to the suggestion that the Laxford Shear Zone represented the boundary between two distinct crustal blocks, which were tectonically juxtaposed between 2480 Ma and 1750 Ma (Kinny and Friend, 1997). On the basis of these new dates, it has been proposed that the 'northern district' of Peach *et al*. (1907) should be re-named the Rhiconich terrane, and that the northern part of the 'central district' should be termed the Assynt terrane (Friend and Kinny, 2001; Kinny *et al.*, 2005). For ease of discussion, these names will be used henceforward in this paper – although this should not be taken to imply complete acceptance of the terrane model at this stage.

Subsequently, Friend and Kinny (2001) dated a granite sheet from the north side of Loch Laxford at c.1855 Ma. They believed that these granite sheets only occur in the Rhiconich terrane and thus stated that the two crustal blocks were juxtaposed between 1855 Ma and 1750 Ma. A sample of gneiss from the 'Badnabay zone' of Sutton and Watson produced a protolith age of c.2760 Ma, which was taken to indicate that this zone belonged to the Rhiconich terrane (Friend and Kinny, 2001). The boundary between the two terranes was described as 'the highly strained boundary between the Badnabay and Foindle zones' (Friend and Kinny, 2001) and this boundary was described as the Laxford shear zone (Kinny *et al.*, 2005). This is somewhat different from the Laxfordian front of Sutton and Watson (1962), which represented the southern limit of Laxfordian reworking and was taken at the southern margin of the Claisfearn zone. As discussed above, we follow Coward and Park (1987) in defining the Laxford Shear Zone as the broad, NW-SE zone of intense, ductile, Inverian and Laxfordian shear that runs along the southern side of Loch Laxford (Figure 2b), and encompasses the Badnabay, Foindle and Claisfearn zones of Sutton and Watson (1951). Within the Laxford Shear Zone, the true boundary between rocks of the Assynt and Rhiconich terranes is very difficult to place on the ground, as discussed in the next section.

Field relationships and structure

The Assynt terrane south of the Laxford Shear Zone

The typical gneisses of the Assynt terrane are chiefly TTG (tonalite – trondhjemite – granodiorite), granulite-facies gneisses, commonly grey in colour and well-banded on the scale of a few centimetres (Peach *et al.*, 1907). Enclosed within the grey gneisses are mafic to ultramafic enclaves, the largest of which approach a kilometre in size. Many of these enclaves represent low-strain zones and in some cases relict igneous textures such as cumulate layering can be identified (Davies, 1974), although the mineral assemblages are metamorphic (e.g. two pyroxenes + plagioclase + garnet in the mafic rocks). Gneisses of metasedimentary origin are also found at a few localities, notably on the north side of Scourie Bay (Okeke et al., 1983) and further south at Stoer (Cartwright et al., 1985). These are quartzofeldspathic gneisses with abundant garnet and biotite; kyanite, sillimanite, staurolite and corundum have been recorded. Granulite-facies assemblages are locally preserved within the grey gneisses, the mafic-ultramafic bodies, and the metasedimentary gneisses, although partial retrogression to amphibolite-facies assemblages is common throughout the Assynt terrane, and pervasive retrogression has occurred in discrete areas of later reworking.

The gneisses are cut by Scourie Dykes, which are relatively undeformed, except where they are cross-cut by Laxfordian shear zones.

The dominant early structure in the northern part of the Assynt terrane is a gently to moderately west- or north-west-dipping gneissose layering (Beach *et al.*, 1974), which encloses rare intrafolial folds of a pre-existing foliation (e.g. Sheraton *et al.*, 1973). This gneissose layering is the result of high to very high strain as evidenced by abundant pods, lenses and thin layers of mafic material that appear to have been extended and thinned parallel to it, and is generally considered to be associated with the Badcallian event (Park, 1970). A poorly-preserved weak grain-aggregate shape lineation generally plunges towards the west or north-west.

Within the Assynt terrane, the gneisses are cut by a number of discrete shear zones. The Canisp and Stoer shear zones are major, kilometre-wide steep zones of intense ductile deformation and amphibolite-facies retrogression. These major shear zones are considered to have formed in the Inverian and reactivated in the Laxfordian (Attfield, 1987; Coward and Park, 1987). Smaller-scale Laxfordian shear zones, a few metres to tens of metres in thickness, are common across the Assynt terrane. These Laxfordian shear zones increase in number northwards, into the Scourie zone of Sutton and Watson (1951). In this zone, the gneissose layering is affected by local open folds and by metre-scale monoclinal folds with thinned short limbs (shear zones) that are assigned to the Inverian (Evans 1965, Evans & Lambert 1974).

The Laxford Shear Zone

The Laxford Shear Zone (LSZ) can be divided into southern, central and northern sectors that essentially correspond to the Claisfearn, Foindle and Badnabay zones of Sutton and Watson (1951) (Figure 2b). The rocks within the LSZ are distinguished from those to the south both by the incoming of intense, pervasive ductile deformation, and by the ubiquitous presence of amphibolite-facies assemblages. The rock-types found in the southern and central parts of the LSZ (the Claisfearn and Foindle zones) include some evidence for relict granulite-facies assemblages (Davies, 1974) and so are considered to belong to the Assynt terrane, whereas the northern part (the Badnabay zone) largely belongs to the Rhiconich terrane (Kinny *et al.* 2005).

The southern and central parts of the Laxford Shear Zone

Within the southern part of the LSZ (the Claisfearn zone), the main foliation in the gneisses trends uniformly WNW–ESE, dips steeply (50-70^{0}) to the south-west, and is axial-planar to occasional folds of the earlier gneissose banding. The foliation is cut by several steep NW–SE-trending Scourie Dykes (Figure 3), and the discordant relationships can be seen at many localities (e.g, around Tarbet; Beach, 1978). This foliation is therefore considered to be Inverian, resulting from the thinning, steepening and transposition of the original Badcallian gneissose banding into a broad Inverian shear zone. In places, a weak to moderately strong mineral lineation plunges to the south-east. Together with the reported antiformal bending of the earlier foliation into the major Inverian shear zone, this suggests that the direction of movement on this shear zone was south-side-up and oblique dextral (Coward and Park, 1987). Larger-scale Inverian folds, also cross-cut by the dykes, were mapped and described by Beach *et al.* (1974) (Figure 3).

The central part of the LSZ (the Foindle zone) contains a major belt of metamorphosed mafic and ultramafic rocks, some garnetiferous, extending south-east from north of Tarbet as far as Ben Stack (Figure 2a; Davies 1974, 1976). These are commonly associated, and locally interfolded, with brown-weathering, garnet-biotite semipelitic gneisses. The mafic bodies range in size, from a few metres up to several hundred metres in thickness, and are laterally continuous for many kilometres. Significant variations in strain can be seen across the mafic-ultramafic belt: in low-strain areas, the rocks show relict igneous textures such as cumulate layering (e.g. north of Gorm Loch around NC 2150 4450; Davies, 1974) and granulite-facies assemblages may be preserved, with some spectacular large garnet aggregates (Davies, 1974); whilst in higher-strain areas amphibolite-facies mafic and metasedimentary gneisses are finer-grained, strongly foliated and lineated, with foliations dipping steeply south-west and mineral lineations plunging towards the south-east. Most of these fabrics can be shown to be Inverian, since relatively undeformed Scourie Dykes cut across the amphibolite/semipelite assemblage at a number of locations (e.g. south of Badnabay around NC 2335 4425). Davies (1976) showed that this assemblage had been folded prior to Scourie Dyke intrusion.

Within the southern and central parts of the LSZ described above, later Laxfordian deformation takes the form of discrete, narrow (1 – 100 m), steeply dipping shear zones, which have displaced the Scourie Dykes and led to the development of a localised foliation (Beach, 1974). A hornblende grain shape lineation within these zones plunges moderately south-east, approximately parallel to the earlier Inverian lineation, but the sense of movement is changed to oblique, sinistral and north side up (Beach *et al.* 1974). These Laxfordian shear zones only occupy a relatively small proportion (<10%) of the outcrop area, but the sum of movement associated with them may be of the order of tens of kilometres (Coward, 1990; Beach, 1974). Away from these narrow shear zones the overall Laxfordian strain in the southern and central parts of the LSZ appears to be very low, although Laxfordian strain within the gneisses is hard to distinguish from Inverian effects in areas where Scourie Dykes are absent. Minor folding of dyke margins appears to be restricted to the Laxfordian shear zones(Beach *et al.* 1974). There is no evidence throughout the south-central parts of the LSZ for any large-scale Laxfordian folds.

The Scourie Dykes maintain their NW–SE trend throughout the southern and central parts of the LSZ; although they are displaced by the discrete Laxfordian shear zones, they show no tendency to rotate overall into a more WNW–ESE orientation parallel to these shear zones. In the model suggested by Coward (1974) the Inverian shear zone acts as an antithetic south-down shear zone which rotates in an anticlockwise fashion, looking north-east, during the Laxfordian. Thus the south-down sinistral shear sense exhibited by the steeply dipping Laxfordian shear zones where they cut the Scourie Dykes is a response to horizontal north-directed shear (Figure 4).

In some places the Scourie Dykes deflect into and follow the zones of Inverian shear for a short distance, or send small veins parallel to them (e.g. south of Tarbet at NC1639 4854). These deviations from the normal trend of the dykes can often be shown to be intrusive features and not due to later Laxfordian deformation, as first deduced by Clough (in Peach *et al.* 1907; see also Park & Cresswell 1972).

Within the central part of the LSZ, scattered biotite granite and granitic pegmatite sheets up to 10 m thick cut across the mafic/ultramafic bodies, the semipelitic gneisses, and the quartzofeldspathic gneisses (e.g. south of Badnabay at NC 2168 4574). Some of the granitoid sheets carry a weak Laxfordian fabric, but they clearly cross-cut the dominant Inverian foliation (Figure 5). In some cases the granite sheets are axial-planar to small-scale upright Laxfordian folds. The relationship between these granite sheets and the discrete Laxfordian shear belts described above is unclear. However, it is important to note that these granitic sheets cut rocks (such as the mafic/ultramafic gneisses and metasedimentary gneisses) that are generally agreed to belong to the Assynt terrane, contrary to the suggestion of Friend and Kinny (2001) that the granitic sheets occur only in the Rhiconich terrane.

The northern part of the Laxford Shear Zone

The northern part of the LSZ is equivalent to the Badnabay zone of Sutton and Watson (1951) (Figure 2b). It is characterised by the presence of abundant sheets of granite and granitic pegmatite, varying in thickness from 1 to 100 m, which cut highly strained gneisses (Figure 6). The thicker granites are weakly foliated and are mostly concordant with the main foliation in the gneisses. This strong foliation dips steeply towards the south-west, and is essentially indistinguishable from the Inverian foliation in the southern and central parts of the LSZ. However, in the northern part of the LSZ this main fabric has been identified as Laxfordian in age (Coward, 1990). This conclusion is difficult to confirm due to the apparent absence of Scourie Dykes within the northern part of the LSZ, although the closest Scourie Dykes do seem to be strongly thinned (Peach *et al.*, 1892; Figure 2a) – this indicates that at least some of the deformation is Laxfordian, but it may have been superimposed upon significant Inverian deformation.

Sutton and Watson (1951) defined the southern boundary of their Badnabay zone by the incoming of abundant, weakly foliated granitic sheets (the Rubha Ruadh granites). It is of course very difficult to draw a boundary along the southern side of the ‘zone of abundant granitic sheets’ since the definition of ‘abundant’ is naturally subjective. The most likely candidate for such a boundary would be the margin of a ~ 50 m thick granitic sheet, which forms steep cliffs on the northern slopes of Ben Stack, and extends north-west as far as Badnabay, beyond which it divides into thinner sheets that die out along strike (Figure 2a). The margin of this thick granitic sheet (and its extensions to the west) is discordant with the trend of the main foliation (as noted by Beach *et al.*, 1974). Furthermore, as described above, a number of weakly foliated to undeformed granite sheets up to 10 m thick occur to the south of this main granite sheet.

The boundary between the Assynt and Rhiconich terranes, which is considered to lie within the northern part of the LSZ, should separate banded tonalitic gneisses with mafic, garnetiferous amphibolitic pods, from migmatitic granodioritic gneisses to the north. This boundary cannot be defined as a sharp line on the ground. Around Loch Stack, it is typically obscured by thick granite sheets, but to the west it can be traversed at a number of localities. There are some localities where the boundary can be placed to within around one hundred metres; for example, in the A894 road cuts close to Loch na Claise Fearna (NC 2044 4710), outcrops of mafic and ultramafic rocks with associated metasedimentary units rapidly give way northwards to migmatitic gneisses. However, in other places the boundary appears much more gradational on a scale of hundreds of metres, with the incoming of increasing amounts of granodioritic material to the north. On the south side of Loch Laxford, near Rubha Ruadh, abundant granitic sheets cut tonalitic gneisses with mafic to ultramafic lenses, which appear to belong to the Assynt terrane (Figure 6).

The Rhiconich terrane north of the Laxford Shear Zone

To the north of Loch Laxford and the Laxford River (Figure 2a), thick granitic sheets (> 10 m) are much less common, and the rocks are chiefly migmatitic amphibolite-facies gneisses with an extensive, anastomosing network of thinner sheets of granite and pegmatitic granite. The migmatitic gneisses of this area are grey to pink in colour and broadly granodioritic in composition. Small mafic enclaves occur locally, but rarely exceed 1 m in size; large garnet amphibolite bodies are not found. At the northern margin of the LSZ the main (Laxfordian) foliation dips steeply to the south-west in parallel with that within the LSZ (Figure 3). To the north, the foliation becomes less steep and gradually bends over to a sub-horizontal attitude at the crest of the Rhiconich antiform. The foliation is associated with a moderately south-east-plunging lineation similar to that in the LSZ.

In some places, the granitic sheets make up > 50% of the outcrop area. They are commonly irregular in shape, cross-cut the gneissose layering, and are themselves weakly foliated to undeformed. Locally, foliation-parallel migmatitic leucosomes can be traced into cross-cutting pegmatitic sheets (e.g. in road-cuts near Rhiconich at NC 2464 5191), indicating that these intrusive sheets are largely formed by partial melting of local crust. This was apparently confirmed by Rb-Sr and Pb isotopic data for granites north of the LSZ which indicated crustal sources (Taylor *et al.*, 1984). More recent experimental work (Watkins *et al*., 2007) has suggested that the composition of the granitic sheets could not be produced by the melting of local crustal sources in the Rhiconich terrane – although the parent gneisses used in their experiments had unusually low K_2O/Na_2O ratios when compared with the average compositions for gneisses north of the LSZ given by Holland and Lambert (1973). The origin of the granitic sheets in the Rhiconich terrane is therefore uncertain.

Amphibolite sheets that are interpreted as part of the Scourie Dyke Swarm are common in the region north of Loch Laxford. They are pervasively deformed, with a strong Laxfordian foliation, and are sub-parallel to the main gneissose layering, although local low-angle discordances indicate that the dykes post-date the gneissosity as in the Assynt terrane. The dykes, together with the gneissose layering, are affected by a set of north-east-verging asymmetric overfolds on a scale of metres (Beach *et al.*, 1974). The granite and pegmatite sheets cut both the Laxfordian foliation in the dykes and the overfolds, being in some cases parallel to the fold axial planes.

Correlation of structures across the Laxford Shear Zone depends on the identification of the dykes in the Rhiconich terrane as part of the Scourie Dyke Swarm. If this correlation is accepted, the pre-dyke foliation in the north could be correlated with the Inverian further south. There are however, significant differences in the post-dyke (Laxfordian) structure across the LSZ, the most obvious being the much greater intensity of Laxfordian deformation and folding in the north. These differences in deformation are most simply explained by the competence differences between the granulite-facies Assynt terrane and the more ductile gneisses of the Rhiconich terrane; experimental evidence shows that anhydrous granulite-facies rocks are significantly more competent than hydrous amphibolite-facies rocks (e.g. Wilks and Carter, 1990). The Inverian shear zone provided a convenient boundary along which the high Laxfordian strain was focused into the more ductile rocks of the Rhiconich terrane.

Geochemical characteristics of the Assynt and Rhiconich terranes

The Laxford Shear Zone separates two areas with very different geochemical characteristics; the gneisses of the Assynt terrane are conspicuously depleted in K, Rb, Th and U, and have very high K/Rb ratios, when compared to the gneisses of the Rhiconich terrane (Sheraton *et al.*, 1973; Holland and Lambert, 1973). The origin of these differences has been the subject of extensive debate, the conclusions of which have important implications for the terrane model.

The characteristic alkali element depletion in the Assynt terrane gneisses has been widely attributed to removal of these elements by CO_2-rich fluids during granulite-facies metamorphism (Sheraton *et al.*, 1973; Hamilton *et al.*, 1979; Weaver and Tarney, 1981a), although it has also been suggested that the gneisses represent the residuum left after the removal of partial melts (Pride and Muecke, 1980; Cartwright and Barnicoat, 1987). However, Tarney and Weaver (1987) raised the possibility that the element depletions seen in the Assynt terrane could be a primary feature of the original igneous intrusions, related to the subduction-zone processes through which the original magmas were formed. This idea was supported by the work of Cartwright and Valley (1992) who used oxygen isotope data to show that large volumes of fluid did not pass through the gneisses of the Assynt terrane during granulite-facies metamorphism, whilst Rollinson (1994) provided arguments against partial melting. More recently, Rollinson (1996) and Rollinson and Tarney (2005) have argued that the geochemical features of the Assynt terrane are indeed primary igneous features, with the original magmas being derived from a subducting slab that has undergone incremental melting and early removal of the fluid-mobile elements.

Recent work has revived the older idea that the gneisses of the Rhiconich terrane were originally also depleted, but were metasomatically enriched in K, Rb, Th and U, causing partial melting and migmatisation, during the Laxfordian (Sutton and Watson, 1951; Castro, 2004). Although the introduction of fluid may well have played some role in the Laxfordian migmatisation, it is likely that such metasomatism would have been localised along shear zones, and that it would be possible to find unmetasomatised regions that preserved a pre-Laxfordian composition. Examples of this process have been demonstrated in granulite facies gneisses in the Bergen Arcs (Austrheim, 1987). In the Rhiconich terrane, all the gneisses – even away from areas of intense deformation and migmatisation – have similar K, Rb, Th and U contents (Weaver and Tarney, 1981a).

It therefore appears most likely that the geochemical differences in the gneisses across the Laxford Shear Zone are a primary feature, due to distinctly different protolith geochemistries, rather than being related to metamorphic histories. The gneisses of the Assynt terrane were most probably formed from magmas derived by melting of a subducting slab (Rollinson and Tarney, 2005), whereas the chemistry of the Rhiconich gneisses is more like that of modern-day calc-alkaline igneous rocks, and the most likely origin for the magmas is in the mantle wedge above the subducting slab. The geochemistry thus does indicate that there were differences in the process of crust formation to the north and south of the Laxford Shear Zone (Rollinson, 1996).

As part of the recent BGS mapping of the area, Scourie Dykes from the Rhiconich terrane were sampled and analysed for major and trace elements (Table 1). These data can be compared with the geochemistry of the Scourie Dykes in the Assynt terrane, which has been studied by Weaver and Tarney (1981b). There is considerable geochemical variation within the Scourie Dykes of the Assynt terrane, and the samples from the Rhiconich terrane lie within the same range. On multi-element plots (Figure 7), all the dykes from both terranes are characterised by negative Nb anomalies, which have typically been considered to be a feature of the lithospheric mantle source of the Scourie Dykes (Weaver and Tarney, 1981b). The Scourie Dykes from within the Rhiconich terrane do typically have higher K and Rb contents than those within the Assynt terrane, but this can almost certainly be attributed to contamination of the magmas by the surrounding gneisses. Overall, the geochemical data indicate that Scourie Dykes from both the Rhiconich and Assynt terranes are likely to be part of the same dyke swarm.

Does the Laxford Shear Zone separate two distinct terranes?

The concept of separate terranes that have been accreted to form a now-contiguous tectonic belt was developed in the North American Cordillera. Terranes were described as blocks of crust that are 'characterised by internal homogeneity and continuity of stratigraphy, tectonic style and history' with the boundaries between terranes being 'fundamental discontinuities in stratigraphy' that separate 'totally distinct temporal or physical rock sequences' (Coney *et al.*, 1980). Boundaries between terranes were considered as 'faults that usually display complex structural history'.

Several lines of evidence support the recognition of different terranes to the north and south of the Laxford Shear Zone.

- Field and petrographical evidence clearly indicates different metamorphic histories across the Laxford Shear Zone – in particular the existence of a granulite-facies metamorphic event that affected the whole of the Assynt terrane but for which there is no evidence in the Rhiconich terrane.

- SIMS U-Pb zircon dating has showed that the protolith ages of gneisses in the Rhiconich terrane (2800 – 2840 Ma) are different from those in the Assynt terrane (2960 – 3030 Ma) (Kinny and Friend, 1997).
- A metamorphic event at c. 2490 Ma in the Assynt terrane (Corfu *et al*., 1994; Kinny and Friend, 1997) has not been identified in samples from the Rhiconich terrane.
- The gneisses of the Assynt terrane are strongly depleted in K, Rb, Th and U, and have very high K/Rb ratios, when compared to the gneisses of the Rhiconich terrane (Sheraton *et al*., 1973; Holland and Lambert, 1973). These geochemical differences are considered to be igneous rather than metamorphic (Rollinson and Tarney, 2005).
- The Laxford Shear Zone is a major structure with a complex structural history.

As pointed out by Park (2005), it is possible for rocks with different protolith ages and geochemistries to occur within the same terrane, simply representing plutons intruded at different ages but adjacent to each other. However, in the example under discussion here, it is clear that the plutonic rocks to the north and south of the Laxford Shear Zone have undergone different metamorphic histories, before being juxtaposed along a major ductile shear zone. When considered together, the variation in protolith ages, metamorphic histories, and protolith geochemistry provide evidence that the Laxford Shear Zone separates two blocks of crust that are both temporally and physically distinct. In this respect, the LSZ satisfies the criteria laid out by Coney *et al.* (1980) for a terrane boundary. However, it must be noted that the relative position of these terranes, prior to their juxtaposition, has not been quantified.

When were the two terranes juxtaposed?

There is little doubt that the two terranes were separated at the time that granulite-facies metamorphism (the Badcallian event) took place in the Assynt terrane, since there is no field, petrographical or geochronological evidence for this event in the Rhiconich terrane. The absolute age of this event is uncertain (Corfu, 2007; Friend *et al.*, 2007. However, a metamorphic event which occurred at c. 2490 Ma in the Assynt terrane (Corfu *et al.*, 1994; Kinny and Friend, 1997) has not been identified in zircons from the Rhiconich terrane, and this may indicate that the two terranes were separate up to this point (Friend and Kinny, 2001).

The first event that appears to be common to both terranes is the intrusion of the Scourie Dykes. The Scourie Dykes in the Assynt terrane have been dated as c. 2000 – 2400 Ma (Heaman and Tarney, 1989; Waters *et al.*, 1990); no examples have been dated from the Rhiconich terrane. As discussed above, the field relationships and geochemistry of the dykes in the Rhiconich terrane are compatible with their being part of the Scourie Dyke Swarm, and it is therefore possible that the two terranes were juxtaposed by the time of Scourie Dyke intrusion. Unfortunately, no Scourie Dykes can be traced that cut right across the Laxford Shear Zone; the early mapping indicated that they are strongly thinned into the area of intense Laxfordian deformation in the northern part of the LSZ (Peach *et al.*, 1892).

In their development of a terrane model, Friend and Kinny (2001) made the assumption that Laxfordian granite sheets (the 'Rubha Ruadh granites') only occur in the Rhiconich terrane. On this basis, having dated one of these granite sheets at 1854 ± 13 Ma, they suggested that the terranes must have been juxtaposed following the emplacement of the granites. However, as described above, further study of the field relationships shows that some granite sheets cut mafic-ultramafic bodies and metasedimentary gneisses that are generally agreed to be part of the Assynt terrane, as originally recognised by Sutton and Watson (1951), and the granites therefore 'stitch' the two terranes. No dates have yet been published for these granites within the Assynt terrane, but on the basis of field relationships they appear likely to be related to the Rubha Ruadh granites.

It has been shown that partial melting of Archaean granulite-facies tonalitic gneisses, like those of the Assynt terrane, only produces very small amounts of magma (Castro, 2004). In contrast, it is likely that the gneisses of the Rhiconich terrane, with higher amounts of the fusible, heat-producing elements and higher contents of hydrous mineral phases, could produce significantly larger volumes of partial melt. Thus, we suggest that partial melting and formation of granitic magmas occurred preferentially on the north side of the Laxford Shear Zone, with only limited intrusion of granites on the southern side. Similarly, later Laxfordian deformation was preferentially taken up by the more ductile gneisses to the north. The heat source that caused the partial melting is unknown, but it is possible that it may have been due to the introduction of more primitive, mantle-derived magma into the base of the crust. However, the only mafic magmatism known around that time is the South Harris Complex of the Outer

Hebrides Lewisian, which was intruded at c. 1880-1890 Ma (Whitehouse and Bridgwater, 2001; Mason *et al.*, 2004), some time prior to the formation of the Rubha Ruadh granites.

We have shown that the two terranes were certainly juxtaposed prior to c. 1854 Ma granite intrusion, and probably prior to 2000-2400 Ma Scourie Dyke intrusion, but clearly after the Badcallian granulite-facies metamorphism in Assynt. We therefore suggest that the two terranes were brought together during the first and most pervasive phase of deformation on the LSZ; the Inverian event. During this event, deformation was focused along the terrane boundary as the granulite-facies gneisses of the Assynt terrane were thrust over the gneisses of the Rhiconich terrane (Coward and Park, 1987). It should be noted that the terms 'Badcallian' and 'Inverian' are used here as they were originally defined; that is, as the granulite-facies and amphibolite-facies events, respectively, that occurred prior to the intrusion of the Scourie Dyke Swarm. The absolute age of these events continues to be the subject of a debate (Corfu, 2007; Friend *et al.*, 2007), which cannot be resolved by the evidence presented here.

Conclusions

This reappraisal of the Laxford Shear Zone highlights the importance of integrating field observations with geochronological and geochemical data in the development of any geological model for high-grade gneiss areas. There is significant evidence to show that the Assynt and Rhiconich terranes represent separate blocks of crust with very differing histories: the geochemical data illustrate differences in their petrogenesis, whilst geochronological, petrological and field data show that the Assynt terrane has experienced a granulite-facies tectonic event that did not affect the Rhiconich terrane.

These two separate terranes were juxtaposed along the major Laxford Shear Zone, which was a locus for both Inverian and Laxfordian deformation. Reappraisal of the field relations has indicated that Laxfordian granites occur across the Laxford Shear Zone and thus it is likely that the terranes were juxtaposed prior to the Laxfordian event. We therefore suggest that terrane juxtaposition occurred during the Inverian event, the exact age of which is as yet uncertain (although it is likely that it occurred relatively soon after the Archaean – Proterozoic boundary at c. 2500 Ma). The terrane-bounding shear zone was substantially reactivated during the Laxfordian, as a site of both deformation and magmatism.

Many questions remain to be answered with reference to the formation of the Laxford Shear Zone. How much movement was there along the LSZ in the Inverian, and what exactly were the kinematics of shearing? Do the mafic-ultramafic and metasedimentary rocks found within the LSZ represent a fragment of ocean floor that once separated the terranes and that was then accreted to the continental margin, as suggested by Park and Tarney (1987) – or were the two crustal blocks formed at a distance from each other within the same continental mass, and subsequently moved together? How can we harness the different available techniques to improve our interpretation of the complex zircons found in the Lewisian gneisses, and thus reach a consensus on the dates of the main events? What, indeed, is the absolute age of the Inverian, and was this a time of more regional terrane amalgamation? What were the tectonic processes that were operating at the end of the Archaean to bring these terranes together? As ever, the rocks of the Lewisian Gneiss Complex remain a fruitful subject for further research.

Acknowledgements

Rob Butler, Bob Holdsworth, Maarten Krabbendam, Rick Law and Rob Strachan organised the conference in Ullapool that stimulated our discussions on the Laxford Shear Zone. Randy Parrish, Martin Hand and John Mendum, as well as many other participants of the Ullapool conference, are thanked for discussions in the field. Editorial comments by Rob Strachan, constructive reviews by Hugh Rollinson and Martin Whitehouse, and comments on an earlier version by Roger Key and Martin Smith, were much appreciated. KMG, MK, QC and SCL publish with the permission of the Executive Director of the Geological Survey.

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Figure captions

Figure 1: Simplified geological map of the North-west Highlands, showing the outcrop of the Lewisian Gneiss Complex and the position of the Laxford Shear Zone.

Figure 2(a): Simplified geological map of the area around the Laxford Shear Zone, based on recent BGS mapping and the 19^{th} century BGS survey (Peach *et al.*, 1892). Ticks indicate British National Grid.

Figure 2(b): The zones identified by Sutton and Watson (1951), superimposed upon the map as in Figure 2a. 1 indicates the 'local Laxfordian Front' of Sutton and Watson (1951); 2 indicates the Ben Stack Line of Lambert and Holland (1972).

Figure 3: Sketch cross-section through the Laxford Shear Zone, modified after Beach *et al*. (1974). Not to scale.

Figure 4: Interpretation of the Laxfordian structures across the Laxford front in terms of a gently southward-inclined shear zone with a top to the north sense of shear (after Coward, 1974).

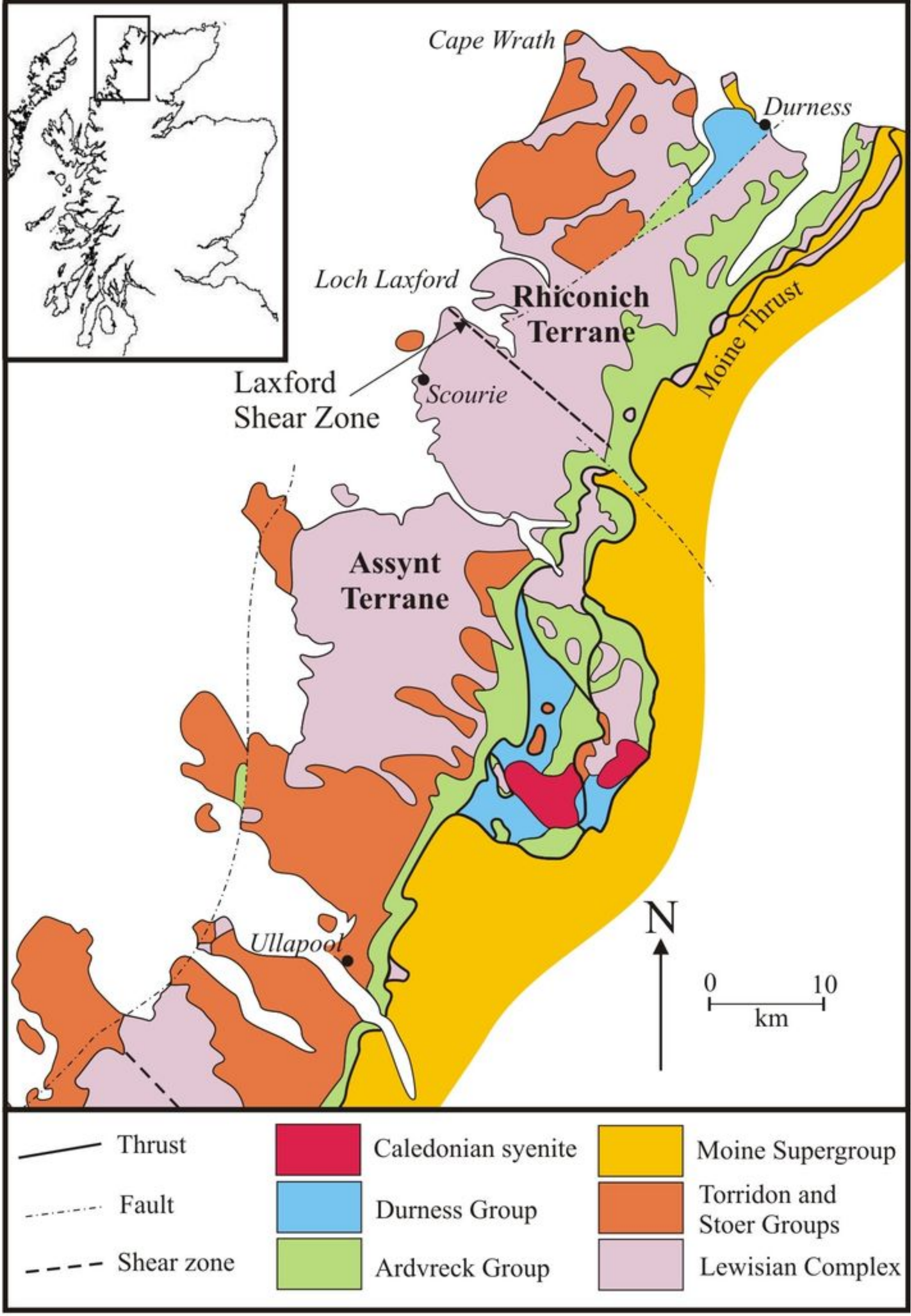
Figure 5: Photo of pink Laxfordian granite sheet cutting gneisses with a strong Inverian foliation in the central part of the Laxford Shear Zone [NC 1637 4941]. Field of view c. 5 m across. BGS photo P593114, © NERC.

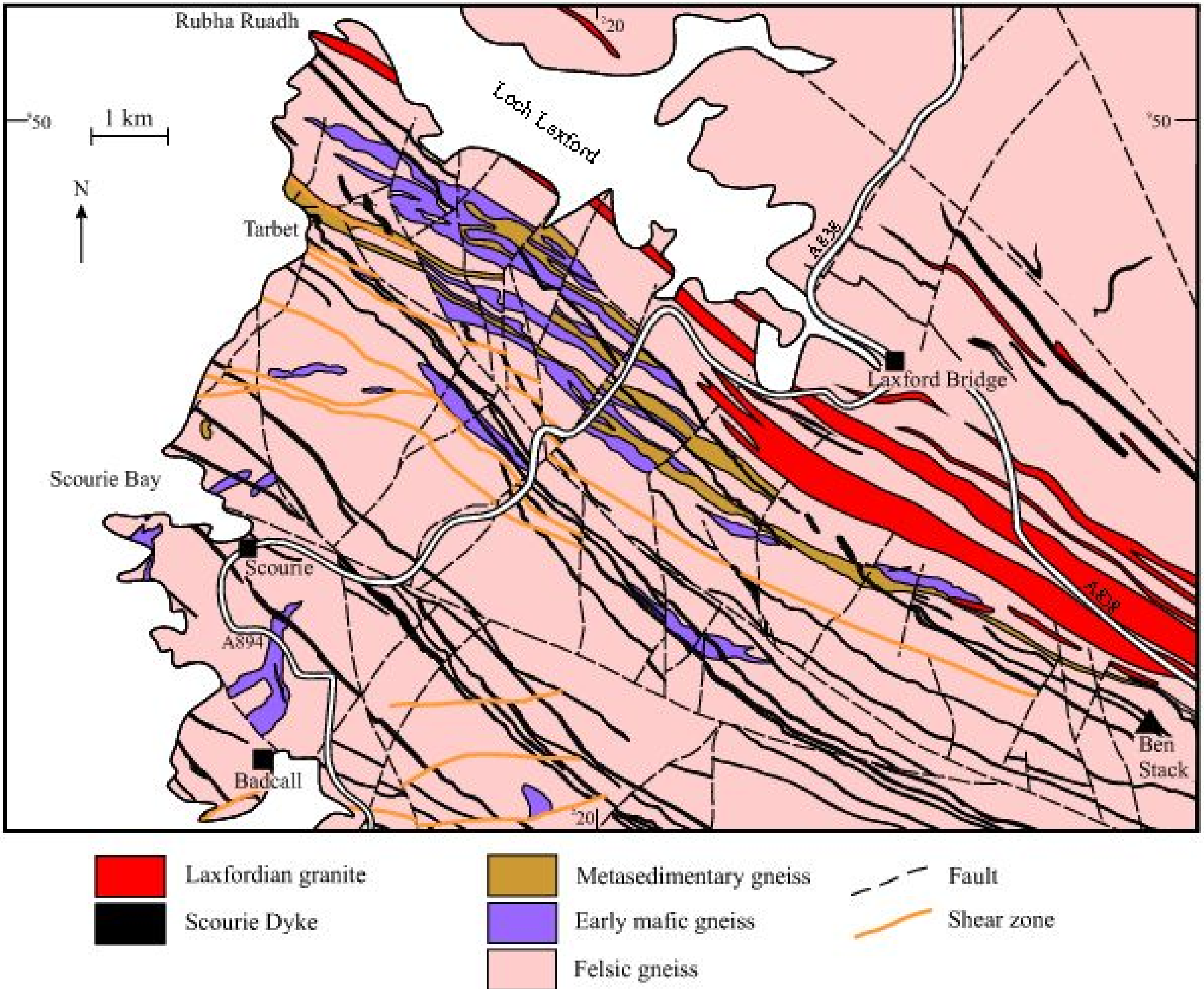
Figure 6: Photo of pink Laxfordian granite sheets cutting tonalitic gneisses with mafic and ultramafic lenses, in the northern part of the Laxford Shear Zone [NC 172 507]. Graham Park for scale. Photo © John Myers.

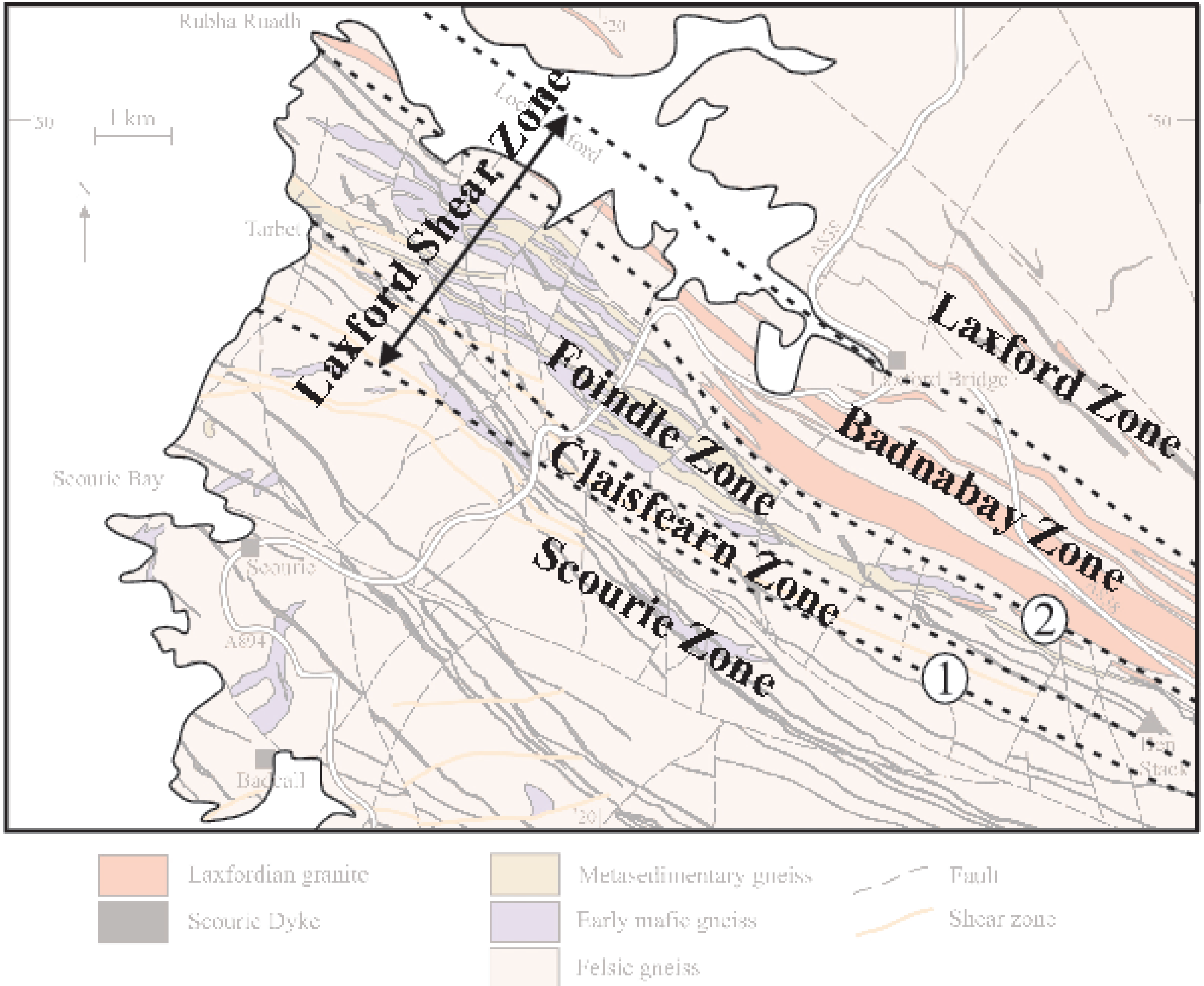
Figure 7: Primitive mantle-normalised trace-element plot for Scourie Dykes north and south of the Laxford Shear Zone. Data for all groups of Scourie Dykes from Assynt from Weaver and Tarney (1981b). Data for Rhiconich Scourie Dykes from Table 1.

Table 1: Major and trace element data for Scourie Dykes from the Rhiconich terrane. Analyses were carried out by XRF, using the PW2400 spectrometer and standard procedures employed by the UKAS-accredited analytical labs at BGS Keyworth.

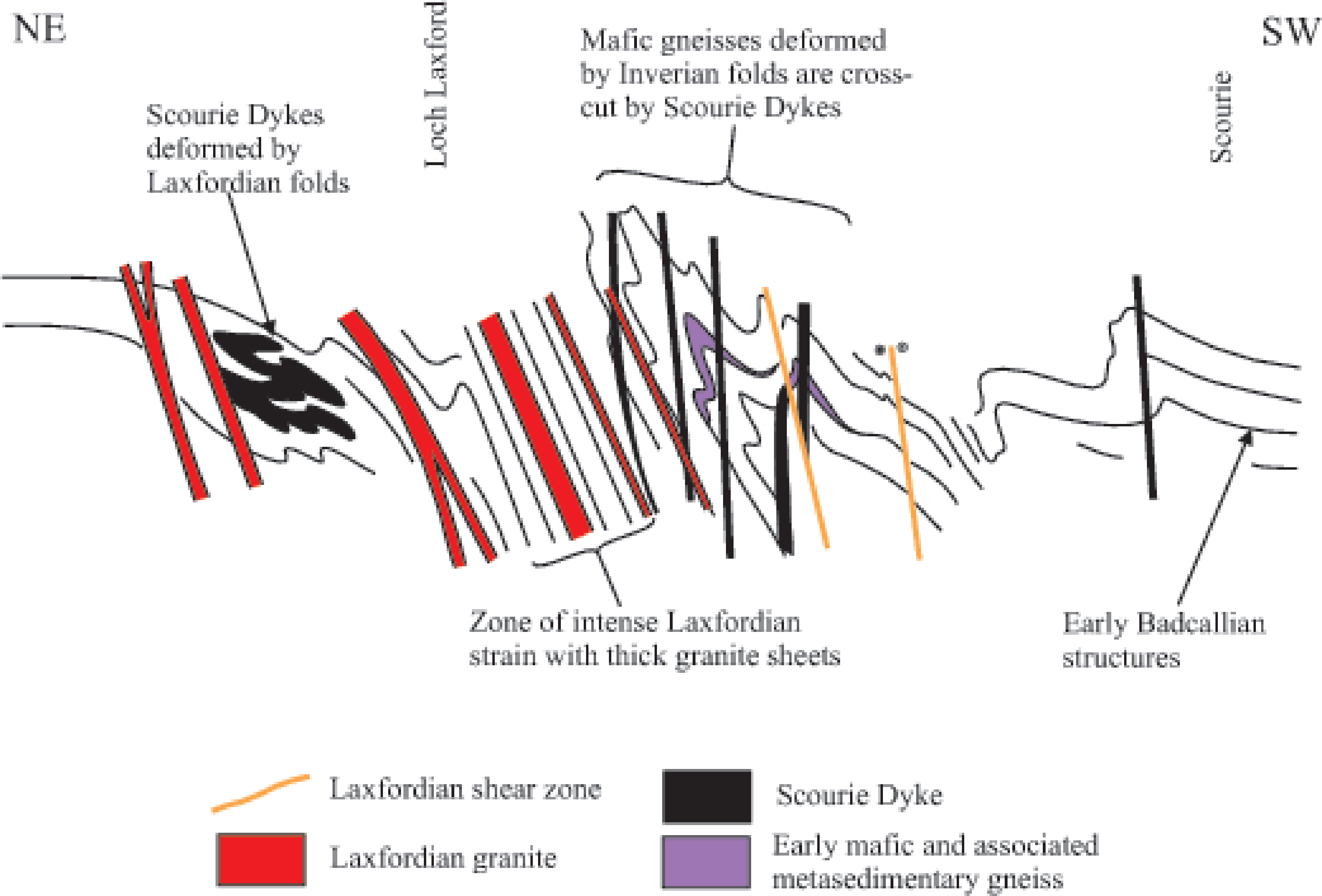
Sample		KG 099	KG 101	KG 103	KG 104	KG 105	KG 106	KG 107
Grid reference		NC 227 477	NC 230 482	NC 233 486	NC 269 529	NC 273 527	NC 273 527	NC 282 448
SiO2	wt%	56.80	46.72	45.95	50.47	50.22	49.30	51.04
TiO2	wt%	0.71	2.27	1.20	0.79	1.28	1.56	0.79
Al2O3	wt%	14.30	14.52	8.31	13.48	13.66	13.04	14.99
Fe2O3t	wt%	9.86	16.06	14.96	12.19	12.81	13.96	11.29
Mn3O4	wt%	0.16	0.24	0.24	0.21	0.20	0.24	0.20
MgO	wt%	5.27	5.40	15.30	7.10	7.06	6.34	7.24
CaO	wt%	8.06	8.74	8.14	10.29	10.28	9.69	9.03
Na2O	wt%	3.54	2.87	1.20	2.71	2.56	2.68	3.00
K2O	wt%	0.92	1.64	2.20	1.18	0.63	1.46	1.46
P2O5	wt%	0.12	0.34	0.11	0.07	0.09	0.11	0.09
LOI	wt%	0.71	0.80	1.72	1.09	0.87	0.96	1.27
Total	wt%	100.53	99.95	100.00	99.68	99.74	99.44	100.50
Sc	ppm	27	35	23	46	36	37	31
V	ppm	183	310	273	301	330	365	229
Cr	ppm	177	155	>1000	125	210	132	114
Co	ppm	36	44	89	45	47	45	38
Ni	ppm	49	66	919	77	124	105	121
Cu	ppm	6	76	116	103	74	36	9
Zn	ppm	69	149	137	92	104	160	102
Ga	ppm	17	22	18	15	18	20	21
Rb	ppm	9	59	110	35	13	20	37
Sr	ppm	409	263	49	201	200	213	256
Y	ppm	16	42	13	20	19	25	16
Zr	ppm	95	180	76	42	67	85	67
Nb	ppm	5	12	3	3	4	5	4
Ba	ppm	120	506	343	246	139	199	186
La	ppm	19	24	11	<6	10	9	12
Ce	ppm	40	57	20	9	13	21	23
Nd	ppm	19	30	15	5	8	11	11
Sm	ppm	2	4	6	<2	4	3	2
Yb	ppm	1	6	<1	3	3	2	3
Hf	ppm	1	3	2	<1	3	4	1

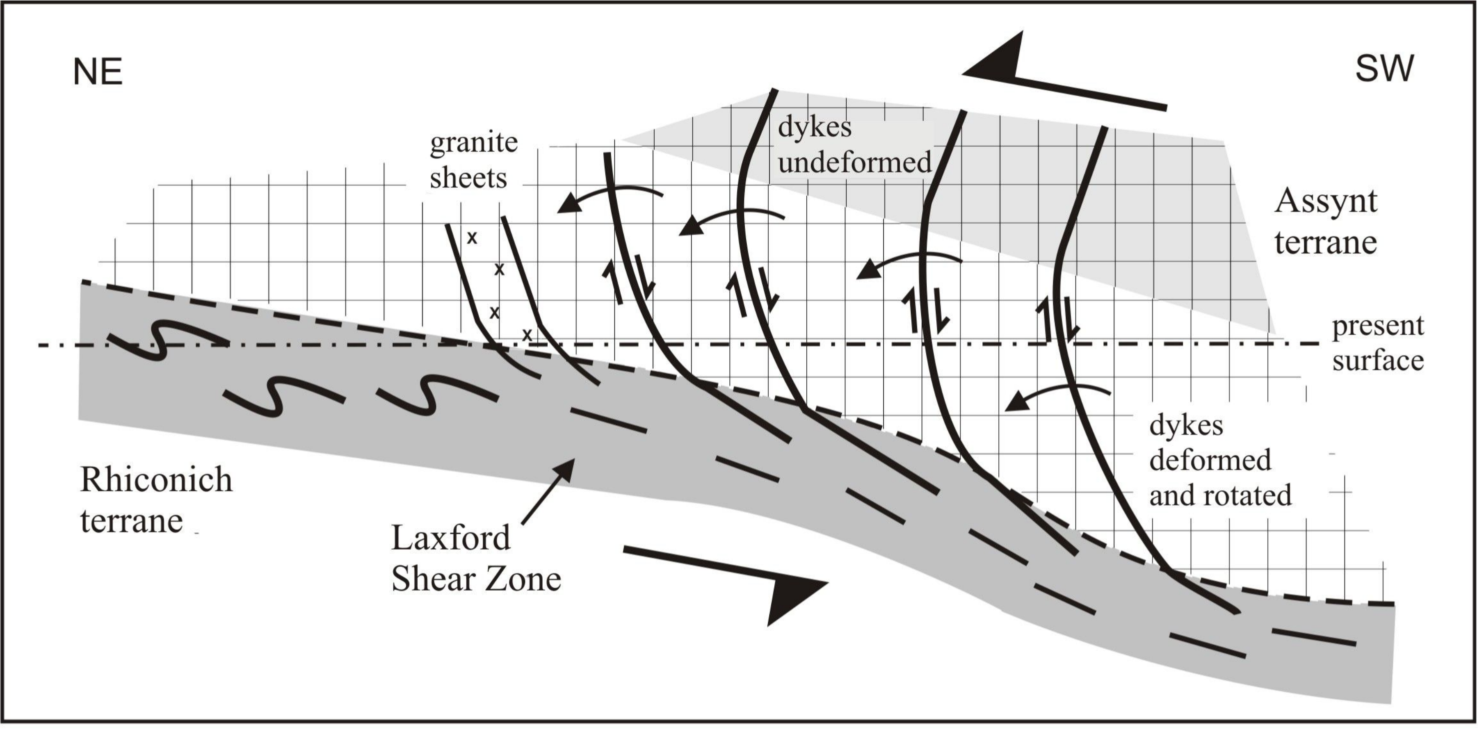

Cape Wrath
Durness
Loch Laxford
Rhiconich
Terrane
Laxford
Shear Zone
Scourie
Moine Thrust
Assynt
Terrane
Ullapool
N
0
10
km
Thrust
Fault
Shear zone
Caledonian syenite
Durness Group
Ardvreck Group
Moine Supergroup
Torridon and
Stoer Groups
Lewisian Complex

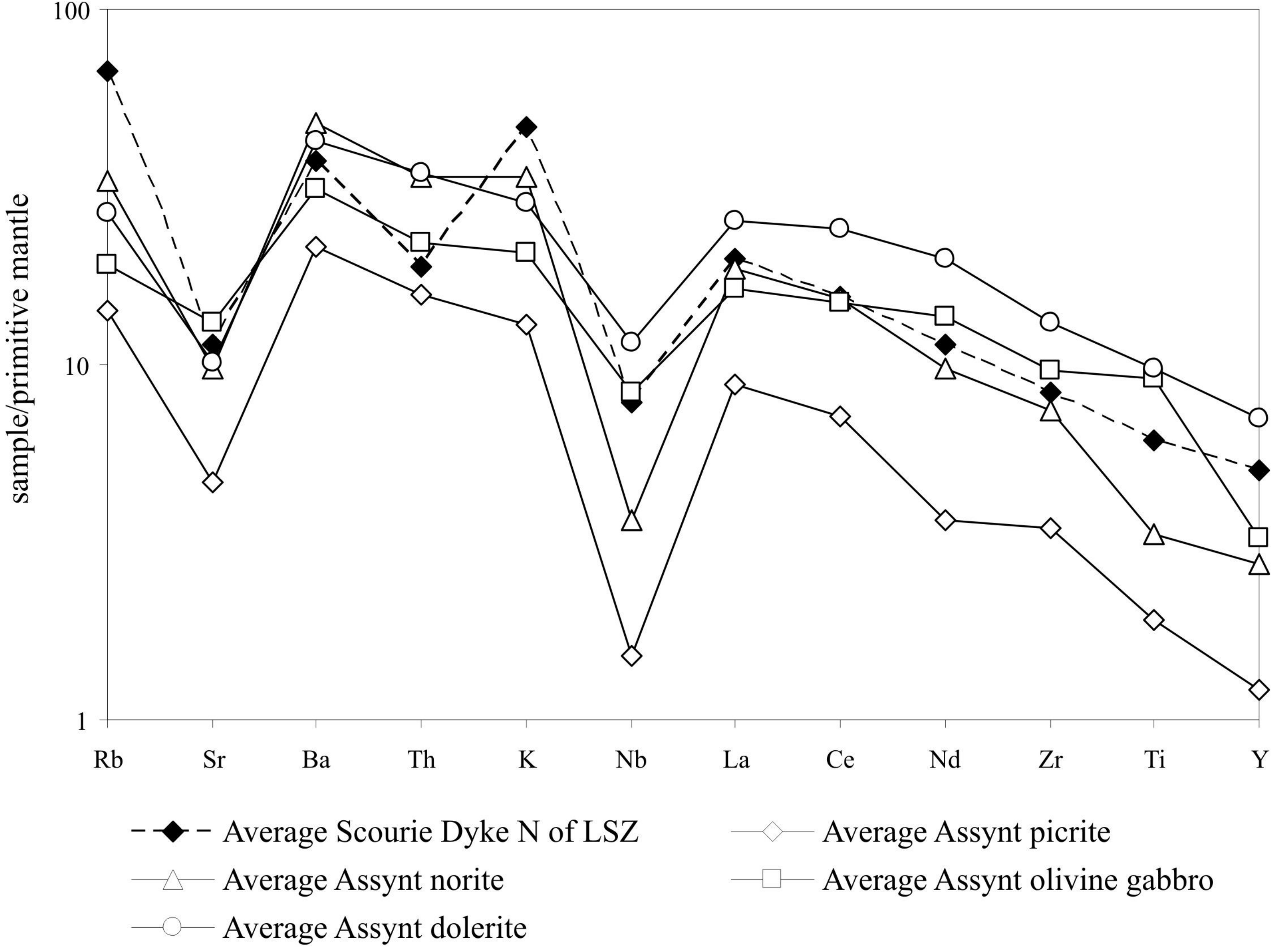

Rubha Ruadh
°20
Loch Laxford
°50
1 km
N
Tarbet
A838
Laxford Bridge
°50
Scourie Bay
Scourie
A894
A838
Badcall
°20
Ben Stack
Laxfordian granite
Scourie Dyke
Metasedimentary gneiss
Early mafic gneiss
Felsic gneiss
Fault
Shear zone



Rubha Ruadh
1 km
Tarbet
Scourie Bay
Scourie
A894
Badcall
Laxford Bridge
Ben Stack
Laxford Shear Zone
Laxford Zone
Badnabay Zone
Foindle Zone
Claisfearn Zone
Scourie Zone
1
2
Laxfordian granite
Scourie Dyke
Metasedimentary gneiss
Early mafic gneiss
Felsic gneiss
Fault
Shear zone


NE
SW
Loch Laxford
Scourie
Scourie Dykes deformed by Laxfordian folds
Mafic gneisses deformed by Inverian folds are cross-cut by Scourie Dykes
Zone of intense Laxfordian strain with thick granite sheets
Early Badcallian structures
Laxfordian shear zone
Scourie Dyke
Laxfordian granite
Early mafic and associated metasedimentary gneiss


NE
SW
granite sheets
dykes undeformed
Assynt terrane
present surface
dykes deformed and rotated
Rhiconich terrane
Laxford Shear Zone



100
10
1
sample/primitive mantle
Rb
Sr
Ba
Th
K
Nb
La
Ce
Nd
Zr
Ti
Y
Average Scourie Dyke N of LSZ
Average Assynt picrite
Average Assynt norite
Average Assynt olivine gabbro
Average Assynt dolerite