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Dykes as buffers to metamorphic overprinting: an example from the Archaean-Palaeoproterozoic Lewisian Gneiss Complex of Northwest Scotland

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ABSTRACT

The early history of polymetamorphic basement gneiss complexes is often difficult to decipher due to overprinting by later deformation and metamorphic events. In this paper, we integrate field, petrographic and mineral chemistry data from an Archaean tonalitic gneiss xenolith hosted within a Palaeoproterozoic mafic dyke in the Lewisian Gneiss Complex of NW Scotland to show how xenoliths in dykes may preserve signatures of early tectonothermal histories. The Archaean tonalite-trondhjemite-granodiorite (TTG) gneisses of the Lewisian Gneiss Complex are cut by a suite of Palaeoproterozoic (~2400 Ma) mafic dykes, the Scourie Dyke Swarm, and both are deformed by later shear zones developed during the amphibolite-facies Laxfordian event (1740-1670 Ma). Detailed field mapping, petrographic analysis and mineral chemistry reveal that the xenolith of TTG gneiss entrained within a Scourie Dyke has been protected from amphibolite-facies recrystallization in a Laxfordian shear zone. Whilst surrounding TTG gneiss displays pervasive amphibolite-facies retrogression, the xenolith retains a pre-Scourie Dyke, granulite-facies metamorphic assemblage and gneissic layering. We suggest that retrogressive reaction softening and pre-existing planes of weakness, such as the ~2490 Ma Inverian fabric and gneiss-dyke contacts, localised strain around but not within the xenolith. Such strain localisation could generate preferential flow pathways for fluids, principally along the shear zone, bypassing the xenolith and protecting it from amphibolite-facies retrogression. In basement gneiss complexes where early metamorphic assemblages and fabrics have been fully overprinted by tectonothermal events, our results suggest that country rock xenoliths in mafic dykes could preserve windows into the early evolution of these complex polymetamorphic areas.

Key words: metamorphic overprinting; mafic dyke; buffer; TTG gneiss; xenolith

INTRODUCTION

Unravelling the geological history of polymetamorphic basement gneiss complexes is often difficult because older tectonothermal events are commonly overprinted by younger metamorphism and deformation. In particular, recrystallisation of the rock to form new mineral fabrics and metamorphic assemblages can obliterate older fabrics and mineral assemblages related to early tectonothermal events. Thermal resetting can also overprint isotopic and trace element signatures in petrogenetic indicator minerals such as zircon (e.g. Hoskin & Schaltegger, 2003). These processes may therefore obscure our understanding of early tectonothermal events. However, complete overprinting does not always occur. For example, phenomena such as reaction softening and strain localisation can result in spatially heterogeneous tectonothermal overprinting (e.g. White, 2004; Oliot*, et al.*, 2010). This is because structures generated by reaction softening and strain localisation (e.g. shear zones) may channel fluid flow, which is required for metamorphic reactions occurring in the amphibolite-facies, promoting heterogeneous tectonothermal overprinting (e.g. White & Knipe, 1978).

To investigate potential controls on heterogeneous overprinting, we present field, petrographic and geochemical evidence from the polymetamorphic tonalite-trondhjemite-granodiorite (TTG) Archaean gneisses of the Lewisian Gneiss Complex of Northwest Scotland (Fig. 1a). This work suggests that igneous intrusions may impede post-entrainment metamorphism and deformation of gneissic country rock xenoliths. In the Assynt Terrane (Kinny*, et al.*, 2005) of the Lewisian Gneiss Complex (Fig. 1a), the location of this study, field evidence shows that the TTG gneisses have undergone three tectonothermal events: (i) an initial granulite-facies metamorphism with formation of gneissic layering (the Badcallian event); (ii) an amphibolite-facies metamorphism with formation of shear zones several kilometres wide (the Inverian event) followed by mafic dyke intrusion; and (iii) a final amphibolite-facies metamorphism with formation of shear zones tens of metres wide (the Laxfordian event) (e.g. Sutton & Watson, 1951; Evans, 1965; Park, 1970; Wynn, 1995). We examine a TTG xenolith, within a Scourie Dyke, that is characterised by an early gneissic layering and granulite-facies mineral assemblage, despite being entrained within a dyke that is deformed and metamorphosed by a shear zone formed during the Laxfordian event.

GEOLOGICAL SETTING

The Archaean-Palaeoproterozoic Lewisian Gneiss Complex, located in Northwest Scotland (Fig. 1a), is predominantly composed of tonalite-trondhjemite-granodiorite (TTG) gneiss, with abundant small bodies of mafic gneiss and sparse larger mafic bodies metasedimentary gneisses (e.g. Peach*, et al.*, 1907; Tarney & Weaver, 1987). Early mapping of structures and metamorphic mineral assemblages by Sutton and Watson (1951) led to the recognition of two tectonothermal events, temporally separated by the emplacement at ~2400 Ma (Davies & Heaman, 2014) of a suite of mafic dykes known as the Scourie Dyke Swarm. Subsequent work has shown that the pre-dyke tectonothermal event can be subdivided into a gneiss-forming, granulite-facies event (the Badcallian; Park, 1970) and a younger amphibolite-facies event (the Inverian; Evans, 1965). The Badcallian is characterised by a generally flat-lying gneissic layering and a granulite-facies assemblage of plagioclase, clinopyroxene, orthopyroxene and quartz in the TTG gneisses. There has been much debate over the age of the Badcallian tectonothermal event (Friend & Kinny, 1995; Park, 2005; Crowley*, et al.*, 2014) but is now generally accepted to have occurred at ~2700 Ma (Crowley, et al., 2014). A major fluid influx in the ~2490 Ma (Crowley, et al., 2014) Inverian tectonothermal event resulted in widespread hydrous retrogression of Badcallian pyroxenes to hornblende. Major shear zones up to ten kilometres wide were formed, such as the Laxford Shear Zone (Goodenough*, et al.*, 2010) (Fig. 1b), while the areas between these major shear zones underwent partial static retrogression (e.g. Beach, 1974).

Both the Badcallian and Inverian are heterogeneously overprinted by a post-dyke tectonothermal event, the Laxfordian, and are only preserved in certain areas of the complex, most notably the Assynt Terrane (Fig. 1b) (Kinny, et al., 2005). Throughout much of the Lewisian Gneiss Complex, the Laxfordian is characterised by pervasive deformation at lower amphibolite facies (e.g.

Sutton & Watson, 1951; Park*, et al.*, 1987). In contrast, the Laxfordian event in the Assynt Terrane is represented by numerous discrete tens-of-metres-wide shear zones (e.g. Wynn, 1995; MacDonald*, et al.*, 2013; MacDonald*, et al.*, 2015b) dated at c. 1740 Ma and 1670 Ma (Kinny, et al., 2005), as well as extension-related alkaline granite sheets at c. 1880 Ma and compression/partial melting granite sheets at c. 1770 Ma (Goodenough*, et al.*, 2013). Because of the localised nature of Laxfordian deformation, metamorphic assemblages and deformation fabrics of the earlier Badcallian and Inverian tectonothermal events are locally preserved between these Laxfordian shear zones.

RESULTS

FIELD RELATIONSHIPS

The field area for this study is located to the north of Loch a' Phreasain Challtuinne (NC 188 467; British National Grid) (Fig. 1c). This locality is within the Laxford Shear Zone, a ~5 km-wide shear zone formed during the Inverian tectonothermal event and reactivated during the Laxfordian tectonothermal event as multiple smaller shear zones that are tens of metres wide (Goodenough, et al., 2010). The margin of the Laxford Shear Zone is marked by a change from shallow-lying, moderately-developed Badcallian gneissic layering of the country rock to more steeply dipping, planar Inverian layering. The nearest pristine pyroxene-bearing granulite-facies Badcallian gneisses are located several kilometres to the southwest of the study area, e.g. around Scourie (e.g. Sutton & Watson, 1951; Johnson & White, 2011; MacDonald*, et al.*, 2015a). We conducted detailed mapping of a small part of the Laxford Shear Zone encompassing the polyphase deformation history of the area.

At the studied locality, a north-south oriented relatively planar Scourie Dyke, ~50 m wide, cross-cuts layering in the TTG gneiss at angles of up to 90° (e.g., NC18919 46689 and NC 18906 46735; Fig. 2). This TTG layering is characterised by fine (~5-10 mm thick), alternating layers of felsic and mafic minerals dipping at *c.* 70° to the SW. Weak mineral aggregate lineations of hornblende or quartz are also sparsely developed in the TTG gneiss. Both the planar and linear fabrics here are considered to be Inverian in age as they are associated with pyroxene-absent amphibolite-facies mineralogy, but are cross-cut by the Scourie Dyke and are located within the Inverian section of the Laxford Shear Zone mapped by Goodenough et al., (2010). The dyke is coarse-grained and composed of equant hornblende crystals with interstitial plagioclase.

Around NC 1889 4675, the dyke is deflected to a WNW-ESE orientation and deformed by a narrow Laxfordian shear zone (Figure 2). A strong fabric of plagioclase aggregates is developed within the dyke, parallel to the planar fabric in the TTG gneisses. Within this narrow Laxfordian shear zone, layering in the gneisses is flaggy with quartz and plagioclase aggregate lineations dipping at *c.* 5° WNW. The dyke contains discrete zones of a well-developed L-S tectonite fabric (e.g., NC 18838 46814; Fig. 3a), defined by aggregates of amphibole and/or plagioclase, clearly distinguishable from the tectonically undeformed dyke outside the Laxfordian shear zone. The dip and strike of the planar fabric is subparallel to the dyke-contact and dips >40° to the southwest. The transition in fabric style within the dyke is gradational over approximately 5 m and is characterised by the progressive elongation of anhedral, interstitial plagioclase into a zone where both hornblende and plagioclase form a strong L-S tectonite fabric (Fig. 3b). The offset of the dyke across the shear zone is sinistral and this is in accord with the observation of Wynn (1995) and published mapping (BritishGeologicalSurvey, 2007). In the TTG gneisses, both the Inverian and Laxfordian planar fabrics dip at *c.* 60-70° to the southwest, suggesting Laxfordian deformation reactivated the earlier Inverian fabric.

Where the dyke is displaced by the Laxfordian shear zone, it contains four xenolithic masses of TTG gneiss (Fig. 2). These bodies are referred to as xenoliths because they do not have the same Inverian amphibolite-facies metamorphic assemblage as the country rock surrounding the dyke. The largest and southernmost of these xenoliths has an elliptical plan-view morphology and is *c.* 60 × 15 m in size with its long axis parallel to the dyke margins. Around this xenolith the Scourie Dyke displays a Laxfordian L-S tectonite fabric. However, only the outermost *c*. 1 m of the TTG gneiss xenolith has a dyke-contact parallel flaggy fabric (Fig. 3c), interpreted to be Laxfordian. The majority of the xenolith contains moderately well-developed gneissic layering which is defined by 5-20 mm wide layers of mafic and felsic minerals, consistent with Badcallian gneissic layering (Fig. 3c); clinopyroxene is abundant and is indicative of a Badcallian assemblage as it is not found in Inverian assemblages in the Lewisian Gneiss Complex. This TTG gneiss xenolith enclosed within the Scourie Dyke therefore appears to have been transported to its current location and largely escaped overprinting, despite its position in a Laxfordian shear zone. In order to investigate this further, samples for petrographic and mineral chemistry analysis were collected from the: (i) xenolith; (ii) deformed and (iii) undeformed Scourie Dyke; (iv) TTG gneiss in the Laxfordian shear zone; and (v) TTG gneiss away from the shear zone with the Inverian planar fabric.

PETROGRAPHY

Sample JM08/32 (NC 18904 46681) – TTG gneiss with Inverian fabric

Sample JM08/32 is composed of *c*. 50% quartz, *c*. 30% plagioclase, *c*. 10% hornblende, and *c*. 10% biotite. Accessory opaque minerals are commonly spatially associated with biotite. The plagioclase crystals are subhedral, up to 2 mm long, with occasional lamellar twinning and zoned extinction. The quartz crystals are up to 0.5 mm in diameter and locally aggregate to form a linear fabric (Fig. 4a). Hornblende occurs together with quartz in a sieve-texture, suggesting it has replaced pyroxene. In places these pseudomorphs are elongate parallel to the quartz aggregate linear fabric (Fig. 4b). Biotite laths are commonly clumped together but only very weakly align with the quartz fabric (Fig. 4c). The quartz aggregate lineation and elongated hornblende and quartz pseudomorphs were formed during the Inverian event (Coward & Park, 1987; Goodenough, et al., 2010).

Sample JM08/28 (NC 18919 46696) – Undeformed Scourie Dyke

Sample JM08/28 is composed of *c*. 65% hornblende, *c*. 30% plagioclase and *c*. 5% quartz with accessory opaque minerals. The hornblende occurs dominantly in a sieve texture with quartz, indicating replacement of igneous pyroxene. These pseudomorphs are generally *c.* 2 mm in diameter and have rims of hornblende aggregates with hornblende 'sieving' sub-millimetre rounded quartz crystals in the centre (Fig. 4d). Clinopyroxene cores are locally preserved within the pseudomorphs. Plagioclase forms 1-2 mm subhedral-to-anhedral crystals with well-preserved albite-pericline lamellar twinning and zoned extinction (Fig. 4e). As well as occurring in a sieve texture with hornblende, minor sub-millimetre anhedral quartz crystals are also found in the matrix. The lack of any planar or linear fabrics show that this sample of Scourie Dyke has not been deformed but the sieve-textured hornblende and quartz replacing igneous pyroxene demonstrates that it has been statically retrogressed in the Laxfordian.

Sample JM09/DC01 (NC 18959 46752) – TTG gneiss in the Laxfordian shear zone along strike from the Scourie Dyke

Sample JM09/DC01 is composed of *c*. 55% plagioclase, *c*. 25% quartz, *c*. 15% hornblende and *c*. 5% biotite. Plagioclase crystals are subhedral, equant and 0.5-1 mm in diameter. They are thoroughly sericitised and lamellar twinning and zoning are only rarely preserved. Quartz crystals are subhedral, equant and 0.1-0.5 mm in diameter. They commonly aggregate to form a strong linear shape fabric (Fig. 4f). Hornblende and biotite are also moderately aligned and parallel to this linear fabric.

Sample JM08/29 (NC 18919 46758) – Deformed Scourie Dyke

Sample JM08/29 is composed of *c*. 80% hornblende, *c*. 15% plagioclase and *c*. 5% clinopyroxene with accessory opaques. Hornblende crystals range from subhedral elongate to anhedral rounded shapes, 0.2-1 mm in diameter, which aggregate together to define a strong linear fabric (Fig. 4g). The pleochroic colour change happens at the same angle in most crystals indicating that they grew during deformation. Plagioclase crystals are sub-millimetre in diameter and have an anhedral rounded shape. The clinopyroxene occurs in elongate lenses aligned with the hornblende fabric. The pyroxenes have a speckly altered appearance, occasionally pale-green in colour (Fig. 4h) with pink or blue birefringence. They have a reaction rim of equant plagioclase crystals which generally have well-defined concentric extinction (Fig. 4i). The clinopyroxenes are interpreted to be relict igneous crystals which have been partially buffered from retrogression and deformation by their rims of plagioclase.

Sample JM08/30 (NC 18905 46760) – TTG gneiss from xenolith in Scourie Dyke

Sample JM08/30 is composed of *c*. 40% plagioclase, *c*. 25% clinopyroxene, *c*. 20% quartz and *c*. 15% hornblende. There is a compositional layering of mafic and felsic minerals at the thin section scale as well as at the hand specimen scale but no linear fabrics. The plagioclase crystals are subhedral and generally squarish, 0.5-2 mm in diameter; lamellar twinning and zoned extinction are commonly preserved. Quartz crystals have anhedral irregular shapes and are 0.1-1 mm in size. Clinopyroxene crystals are typically aggregated together in mafic bands and are pale green in colour with one prominent cleavage (Fig. 4j). They are squarish and 1-2 mm in diameter with reaction rims of aggregated equant sub-millimetre hornblende crystals. These rims are less than 1 mm wide and the hornblende is locally associated with very small quartz blebs (Fig. 4k); some clinopyroxenes have virtually no reaction rim and are in textural equilibrium with adjacent plagioclase (Fig. 4l). The reaction rims record minor retrogression to amphibolite-facies. Retrogression in this sample has been of a much lesser degree than in the four other samples.

MINERAL CHEMISTRY

In order to quantify the chemical changes that occurred with chemical reactions during the different tectonothermal events indicated by petrographic observations, major element mineral chemistry was conducted. Si, Ti, Fe, Al, Mn, Mg, Ca, Na, K and Ti oxides were measured using a Cameca SX100 electron microprobe at the Natural History Museum, London. Operating conditions were 15 kV accelerating voltage, a specimen current of 20 nA and a spot size of 1 micron. Silicate or oxide standards were used, apart from for K for which a potassium bromide standard was used. Detection limits were ~0.02-0.05 oxide weight percent. Full data are given in the Supplementary Data; negligible core to rim zoning was observed and hence average values for each crystal are given in Table 1.

Hornblende and plagioclase in the Scourie dyke samples JM08/28 and JM08/29 both recrystallised during the Laxfordian tectonothermal event, although they are texturally different. The abundance of Na_2O and CaO in plagioclase is almost identical in the two samples and major element oxides in hornblende are also similar (Fig. 5, Table 1). Plagioclase in the TTG gneiss samples is much more sodic and less calcic than in the Scourie Dyke samples, X_{An} of ~0.3 compared to 0.44. Plagioclase in the xenolith (sample JM08/30) is slightly more calcic and less sodic than those in the Inverian or Laxfordian assemblages X_{An} of 0.31-0.33 compared to 0.29 (Fig. 5, Table 1). Clinopyroxenes in the xenolith have low K_2O (<0.1 wt.%) but the narrow hornblende trims around them have higher K_2O (~1.3-1.5 wt.%) than the Laxfordian shear zone hornblendes and significantly higher K_2O than Inverian shear zone hornblendes (~0.8 wt.%). TiO_2 shows a similar pattern between samples than K_2O (Fig. 5, Table 1). Sieve-textured hornblende from the Inverian TTG gneiss is more silicic (~43.5 wt.%) than narrow hornblende rims around clinopyroxene in the xenolith (~41-43 wt.%) and hornblende laths recrystallized in the Laxfordian shear zone (42 wt.%).

DISCUSSION

The TTG gneiss xenolith contains a weak gneissic layering and equant clinopyroxenes with small retrogression rims of hornblende. Whilst no orthopyroxene was found in thin section in this sample, the presence of clinopyroxene clearly distinguishes it from the Inverian and Laxfordian metamorphic assemblages observed in the surrounding TTG gneiss; the xenolith is therefore most likely a relatively pristine Badcallian assemblage. The presence of narrow hornblende rims suggests that very minor amphibolite-facies retrogression driven by fluid interaction has occurred within the xenolith. Overall, the xenolith mineral assemblage contrasts with the TTG gneiss host rock adjacent to the Scourie Dyke, which displays evidence of overprinting by tectonothermal events. This is demonstrated by: (i) a planar fabric and the absence of pyroxene in the Inverian shear zone (sample JM08/32), whereby original pyroxene has been completely retrogressed to sieve-textured hornblende and quartz (e.g. Beach, 1974); (ii) the depletion of K and Ti in hornblende within sample JM08/32, relative to the minor hornblende rims in the xenolith (Fig. 5c & f; and (iii) sericitised feldspars and the development of planar and linear fabrics in sample JM09/DC01 consistent with its position within the Laxfordian shear zone (e.g. Sheraton*, et al.*, 1973). The enrichment of Ti and K in hornblende in the Laxfordian shear zone sample is attributed to an influx of K-rich fluids in the Laxfordian, consistent with granite formation around the Laxford Shear Zone associated with partial melting of local crust (Goodenough, et al., 2010; Goodenough, et al., 2013). It is important to note that only the outer *c*. 1 m of the TTG xenolith displays a contact-parallel flaggy fabric.

Xenolith source and transportation

How did the Badcallian xenolith attain its current position in the Scourie Dyke in the Inverian- and Laxfordian- age Laxford Shear Zone? One hypothesis is that it is in fact in-situ and is a low-strain lacuna within the Inverian-age Laxford Shear Zone, which has been enveloped by the Scourie Dyke. However, the proximity of its current location to Inverian deformation would suggest that even if the xenolith had not been deformed during the Inverian, fluids circulating through the rocks would likely have completely retrogressed its Badcallian assemblage. Badcallian gneisses that have been statically retrogressed by Inverian fluids have very distinctive sieve-textured hornblende and quartz pseudmorphs after pyroxene (e.g. MacDonald, et al., 2015a), something not seen in the xenolith. As a result, we favour the interpretation that the xenolith was entrained and transported by the NE-SW oriented Scourie dyke from a position within the Badcallian TTG gneiss in the Assynt Terrane to the southwest of its current location (Fig. 1b). We favour this source position because: (i) no TTG gneisses with Badcallian granulite-facies assemblages are found to the northeast of the xenolith locality (Fig. 1b) (e.g. Beach, 1974; Cohen*, et al.*, 1991; Whitehouse & Kemp, 2010); and (ii) the TTG gneisses below the outcrop are still expected to lie within the steeply southwest-dipping Inverian-age Laxford Shear Zone. This model therefore implies that dyke emplacement involved a significant proportion of lateral, northwards-directed flow. Given that the xenolith is longer than the thickness (~50 m) of the dyke, it is probable that: (i) they were transported with their long axes oriented NE-SW, parallel to the dyke contact; and (ii) were subsequently rotated to a WNW-ESE orientation during the development of the Laxfordian shear zone. The absence of stretching fabrics within the xenolith implies that this potential reorientation occurred due to rotation rather than shearing.

Post-emplacement dyke and xenolith evolution

Our observations indicate that the Scourie Dyke and the TTG gneiss host rocks in and around the Laxfordian shear zone were retrogressed to amphibolite-facies during the Laxfordian tectonothermal event. This is supported by: (i) the hornblende aggregate lineation in the Scourie Dyke, which unequivocally shows that it was deformed and retrogressed in the Laxfordian shear zone; (ii) static retrogression of igneous pyroxene to hornblende and quartz, which demonstrates that the dyke was also affected by the Laxfordian thermal regime and fluids beyond the shear zone; (iii) the complete recrystallisation at amphibolite-facies of the TTG gneiss outside the dyke in the Inverian and Laxfordian parts of the shear zone; and (iv) narrow hornblende rims around the xenolith clinopyroxenes are closer in their chemistry, particularly Ti and K, to Laxfordian shear zone hornblende than Inverian shear zone hornblende. The variation in plunge and plunge direction of the lineation in the L-S tectonite fabric reflect the complication of having the xenolith in the Scourie dyke. These chemical, mineralogical and textural modifications observed in both the Scourie dyke and the TTG gneiss host rock indicate that H_2O-rich fluids circulated through these rocks during the Laxfordian shear zone formation.

In contrast to those samples obtained from the Scourie dyke or the TTG gneiss host rock, our results imply that the TTG gneiss xenolith was largely protected from retrogression and recrystallization during the Laxfordian. This is supported by: (i) the preservation of a granulite-facies assemblage in the TTG gneiss xenolith; (ii) the limited development of hornblende rims around pyroxenes in the xenolith; and (iii) the restriction of deformation fabrics to the outer margin of the xenolith. To explain this localized heterogeneity in the distribution of amphibolite-facies retrogression during the Laxfordian, we invoke a model whereby preferential metamorphism, reaction softening and strain localisation in the dyke restricted xenolith-fluid interactions.

We suggest that during the initial influx of fluid in the Laxfordian, likely coincident with the formation of the Laxfordian shear zone (e.g. Beach, 1976), pyroxenes in both the Scourie Dyke and the TTG gneiss xenolith started to undergo retrogression. This could explain the formation of small hornblende rims on pyroxenes in the xenolith and the development of a contact-parallel fabric in the outer margin of the xenolith generated by the onset of shear zone deformation. The fact that the narrow hornblende rims around clinopyroxenes in the xenolith have similar concentrations of Ti and K to the Laxfordian shear zone hornblende, and both are higher than the Inverian shear zone hornblendes, supports this hypothesis. Because of the relatively large proportion of quartz, and plagioclase to a lesser extent, in the TTG gneiss xenolith compared to the Scourie Dyke, we suggest that the contemporaneous retrogression of both rock types progressed at a faster rate within the dyke; i.e. there was a greater amount of pyroxene available that could retrogress to hornblende. Importantly, these mineralogical and chemical changes from pyroxene to hornblende could change the physical properties of the rock. In particular, this transformation can be considered a form of reaction softening (e.g. White & Knipe, 1978; Wibberley, 1999; Stünitz & Tullis, 2001; Holyoke & Tullis, 2006a; Holyoke & Tullis, 2006b). Similarly, the formation of hornblende aggregates in sample JM09/DC01 (the Laxfordian shear zone) can instigate a mineral preferred orientation and thereby 'weaken' the rock. Plagioclase alteration to sericite (e.g., sample JM09/DC01), a much weaker phyllosilicate, also induces reaction softening. Additionally, many studies have documented that the occurrence of reaction softening processes in metamorphic rocks can focus strain, promoting the formation of shear zones (e.g. Keller, *et al.*, 2004; Whitmeyer & Wintsch, 2005; Oliot, et al., 2010). We suggest that the greater propensity for reaction softening retrogression of pyroxene to amphibole in the Scourie Dyke, compared to the more felsic TTG gneiss xenolith, would have resulted in strain localisation in the dyke. In conjunction with field and microstructural work demonstrating that the Scourie dykes deform preferentially to the TTG gneisses (Pearce, *et al.*, 2011), this strain localisation may explain why strong planar and linear fabrics are developed in the dyke but only at the outer margin of the TTG gneiss xenolith.

The increase in shear fabric intensity at the dyke margins suggests strain may also have preferentially accrued along the dyke margins. This supports the observations of Wheeler *et al.*, (1987) who showed that Laxfordian deformation was concentrated along dyke margins at Diabaig in the southern part of the mainland Lewisian Gneiss Complex outcrop. Park *et al.*, (1987) suggested that as deformation progressed, strain initially localised at the dyke margins would start to affect the whole of the dyke. Strain localisation can control fluid flow and is here interpreted to have been an important process in directing fluids around, but not through, the xenolith. This is consistent with previous studies, which have shown that the Laxfordian shear zones throughout the Lewisian Gneiss Complex acted as preferential fluid flow pathways during the Laxfordian tectonothermal event (Beach, 1973; Beach, 1976). Strain localisation leading to directed fluid flow is a common phenomenon and many examples are discussed in the literature (e.g. Goldblum & Hill, 1992; Ring, 1999; Babiker & Gudmundsson, 2004; Clark, *et al.*, 2005; Blenkinsop & Kadzviti, 2006; Tartese, *et al.*, 2012). Whilst we acknowledge that these are a near-surface analogue for our mid-crustal study in the Lewisian Gneiss Complex, the general principal of dyke-fluid interaction geometry is the same. Several studies have similarly demonstrated that crystallised igneous intrusions may deflect migrating fluids along their margins (Rateau, *et al.*, 2013; Grove, 2014; Jacquemyn, *et al.*, 2014).The proposed model (Fig. 6) implies that the interplay between the processes of reaction softening, strain localisation (e.g., shear zone development) and directed fluid flow resulted in the xenolith escaping amphibolite-facies retrogression. This combination of factors clearly has the potential to allow preservation of early metamorphic assemblages and fabrics in polymetamorphic terranes, specifically in dyke-hosted country rock xenoliths.

CONCLUSIONS

This study illustrates an example of a mafic dyke acting as a barrier to metamorphic overprinting of entrained country rock xenoliths from the Archaean-Palaeoproterozoic Lewisian Gneiss Complex of Northwest Scotland. Field mapping and petrographic analysis show that a tonalite-trondhjemite-granodiorite (TTG) gneiss xenolith entrained in a member of the Scourie Dyke Swarm retains a Badcallian granulite-facies pyroxene-bearing mineral assemblage and coarse gneissic layering with no lineation, whereas the dyke and surrounding country rock display evidence of Inverian and Laxfordian amphibolite-facies overprinting. We suggest that the xenolith was entrained by the dyke from an area, likely to the SW of the current exposure from an area unaffected by the Inverian tectonothermal event. Mineral chemistry highlights some of the chemical changes that have occurred within the major minerals due to the influx of fluid that resulted in retrogressive metamorphic reactions. We interpret that the xenolith escaped Laxfordian retrogression through an interplay of factors: reaction softening, strain localisation and directed fluid flow. Retrogressive reaction softening, along with planes of weakness such as the pre-existing Inverian fabric and gneiss-dyke contacts, localised strain around but not within the xenolith. Strain localisation generated preferential flow pathways for fluids, principally along the shear zone. In the Lewisian Gneiss Complex, areas with early metamorphic assemblages and fabrics survive but in many polymetamorphic terranes this is not the case. This study shows that gneissic country rock xenoliths in mafic dykes could help to unravel polymetamorphic histories of basement gneiss complexes where the majority of the country rock has been overprinted, obscuring early tectonothermal events.

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Figure Captions

Fig. 1. Location maps. (a) Outcrop of the Lewisian Gneiss Complex in Northwest Scotland, inset map shows location in the wider British & Irish Isles. (b) Location of the locality investigated in this study relative to the major geological structure in the area, the Laxford Shear Zone.

Fig. 2. Detailed field map of lithology and structure at the locality with sample locations marked.

Fig. 3. (a) Photograph of deformed Scourie dyke with inset sketch showing L-S tectonite nature of fabric. (b) Field sketch showing onset of deformation in the Scourie dyke at the margin of the Laxfordian shear zone with photographs of fabric styles. (c) Detail map of TTG gneiss xenolith within the dyke, sample location marked.

Fig. 4. Photomicrographs of the samples analysed petrographically. (a) Quartz mineral aggregate lineation in sample JM08/32, TTG gneiss with Inverian fabric. (b) Elongate sieve-textured hornblende and quartz pseudomorphs after pyroxene in sample JM08/32. (c) Clumps of weakly aligned biotite laths, roughly aligned with the quartz aggregate lineation. (d) Pseudomorphs after pyroxene of sieve-textured hornblende and quartz in sample JM08/28, undeformed Scourie dyke; the edges of the pseudomorphs are dominated by hornblende with more quartz in the cores. (e) Plagioclase

showing well-preserved lamellar twinning and zoned extinction in sample JM08/28. (f) Quartz mineral aggregate lineation in sample JM09/DC01, TTG gneiss in the Laxfordian shear zone along strike from the Scourie dyke. (g) Hornblende crystals aggregated to form a strong lineation in sample JM08/29, the deformed Scourie dyke. (h) Elongate lenses of relict clinopyroxene in sample JM08/29. (i) A reaction rim of equant plagioclase crystals around the clinopyroxene in (h). (j) Clinopyroxene crystals aggregated together in sample JM08/30, TTG gneiss from xenolith in Scourie dyke. (k) Clinopyroxene with rim of aggregated hornblende crystals in sample JM08/30. (l) Clinopyroxene with no hornblende rim in textural equilibrium with plagioclase in sample JM08/30.

Fig. 5. Plots of mineral chemistry data (in weight percentage cation oxide) from the samples analysed in this study. (a) Na vs CaO in plagioclase. (b) Mg vs Si in hornblende. (c) Ti vs Si in hornblende. (d) Na vs Si in hornblende. (e) Mn vs Si in hornblende. (f) K vs Si in hornblende.

Fig. 6. Schematic maps illustrating the tectonothermal evolution of the xenolith and surrounding rocks.

Table Captions

Table 1. Mineral chemistry data. Cation oxide values in weight percent. Cation values in number of ions per formula unit; number of oxygens used in this calculation: hornblende = 23, clinpyroxene = 6, plagioclase = 8, biotite = 11. “plag” denotes plagioclase, “cpx” clinopyroxene, “bt” biotite and “hbl” hornblende.

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Table 1

Sample	JM08/28			JM08/29	JM08/30		JM08/32	JM09/DC01	JM08/30				JM08/32
Mineral	plag	plag	plag	plag	plag	plag	plag	plag	cpx	cpx	cpx	cpx	bt
SiO_2	57.14	57.41	58.22	57.17	59.26	61.50	61.72	62.63	50.31	51.39	51.77	50.48	34.98
TiO_2	0.00	0.02	0.02	0.01	0.03	0.00	0.00	0.00	0.14	0.07	0.10	0.11	2.46
Al_2O_3	27.62	27.51	27.68	26.65	25.14	25.08	25.02	24.62	2.02	1.27	1.46	1.59	16.85
FeO	0.24	0.09	0.08	0.18	0.09	0.04	0.02	0.05	11.10	9.87	10.52	10.59	20.78
MnO	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.56	0.57	0.59	0.58	0.13
MgO	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00	11.36	12.09	11.63	11.64	11.63
CaO	9.31	9.33	9.43	9.12	7.10	6.62	6.36	6.10	23.17	24.17	24.02	23.88	0.11
Na_2O	6.45	6.61	6.57	6.57	7.92	8.13	8.43	8.33	0.71	0.62	0.67	0.68	0.16
K_2O	0.24	0.07	0.07	0.07	0.23	0.24	0.06	0.10	0.10	0.00	0.01	0.02	6.93
Cr_2O_3	0.01	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.05	0.04	0.04	0.06	0.05
Total	101.09	101.08	102.07	99.77	99.77	101.62	101.64	101.85	99.56	100.14	100.87	99.68	94.32
Si	2.54	2.55	2.56	2.57	2.66	2.70	2.70	2.73	1.93	1.95	1.95	1.93	2.68
Ti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.14
Al	1.45	1.44	1.43	1.41	1.33	1.30	1.29	1.26	0.09	0.06	0.06	0.07	1.52
Fe	0.01	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.36	0.31	0.33	0.34	1.33
Mn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.02	0.02	0.02	0.01
Mg	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.68	0.65	0.66	1.33
Ca	0.44	0.44	0.44	0.44	0.34	0.31	0.30	0.28	0.95	0.98	0.97	0.98	0.01
Na	0.56	0.57	0.56	0.57	0.69	0.69	0.72	0.70	0.05	0.05	0.05	0.05	0.02
K	0.01	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.68
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
X_{Mg}									0.65	0.69	0.66	0.66	0.50
X_{An}	0.44	0.44	0.44	0.43	0.33	0.31	0.29	0.29					
Total Cations	5.01	5.01	5.00	5.00	5.03	5.01	5.01	4.99	4.05	4.04	4.03	4.05	7.73

Sample		JM08/28		JM08/29		JM08/30			JM08/32		JM09/DC01
Mineral	hbl	hbl	hbl	hbl	hbl	hbl	hbl	hbl	hbl	hbl	hbl
Texture	sieve-texture	sieve-texture	sieve-texture	rim around remnant cpx?	rim round cpx	rim round cpx	rim round cpx	rim round cpx	sieve-texture	sieve-texture	lath
SiO_2	42.75	41.64	45.31	42.39	40.85	42.90	41.55	40.77	43.68	43.52	41.97
TiO_2	0.89	0.77	0.48	0.77	0.78	0.64	0.77	0.79	0.29	0.54	0.94
Al_2O_3	11.05	12.42	9.46	12.63	11.49	9.84	12.11	11.38	11.23	11.12	11.63
FeO	18.85	20.44	18.30	18.53	19.73	18.30	18.29	19.82	17.51	17.70	18.33
MnO	0.33	0.32	0.31	0.29	0.44	0.45	0.45	0.46	0.34	0.31	0.30
MgO	9.15	7.86	10.19	8.77	8.72	9.31	9.07	8.66	10.27	9.94	9.56
CaO	11.94	11.74	12.18	11.33	12.10	13.02	12.16	12.14	11.91	11.89	11.94
Na_2O	1.54	1.57	1.19	1.61	1.34	1.19	1.38	1.30	1.27	1.32	1.47
K2O	0.45	0.61	0.37	0.57	1.44	1.32	1.53	1.47	0.78	0.81	1.22
Cr_2O_3	0.04	0.04	0.13	0.03	0.07	0.05	0.11	0.06	0.03	0.04	0.05
Total	97.22	97.64	98.12	97.23	97.07	97.10	97.51	96.96	97.45	97.33	97.69
Si	6.52	6.37	6.78	6.43	6.33	6.58	6.35	6.33	6.58	6.58	6.39
Ti	0.10	0.09	0.05	0.09	0.09	0.07	0.09	0.09	0.03	0.06	0.11
Al	1.98	2.24	1.67	2.26	2.10	1.78	2.18	2.08	2.00	1.98	2.09
Fe	2.40	2.62	2.29	2.35	2.56	2.35	2.34	2.57	2.21	2.24	2.33
Mn	0.04	0.04	0.04	0.04	0.06	0.06	0.06	0.06	0.04	0.04	0.04
Mg	2.08	1.79	2.28	1.98	2.01	2.13	2.07	2.00	2.31	2.24	2.17
Ca	1.95	1.92	1.95	1.84	2.01	2.14	1.99	2.02	1.92	1.93	1.95
Na	0.46	0.47	0.35	0.47	0.40	0.35	0.41	0.39	0.37	0.39	0.43
K	0.09	0.12	0.07	0.11	0.29	0.26	0.30	0.29	0.15	0.16	0.24
Cr	0.00	0.00	0.02	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.01
X_{Mg}	0.46	0.41	0.50	0.46	0.44	0.48	0.47	0.44	0.51	0.50	0.48
Total Cations	15.62	15.67	15.50	15.59	15.85	15.73	15.79	15.85	15.62	15.61	15.74

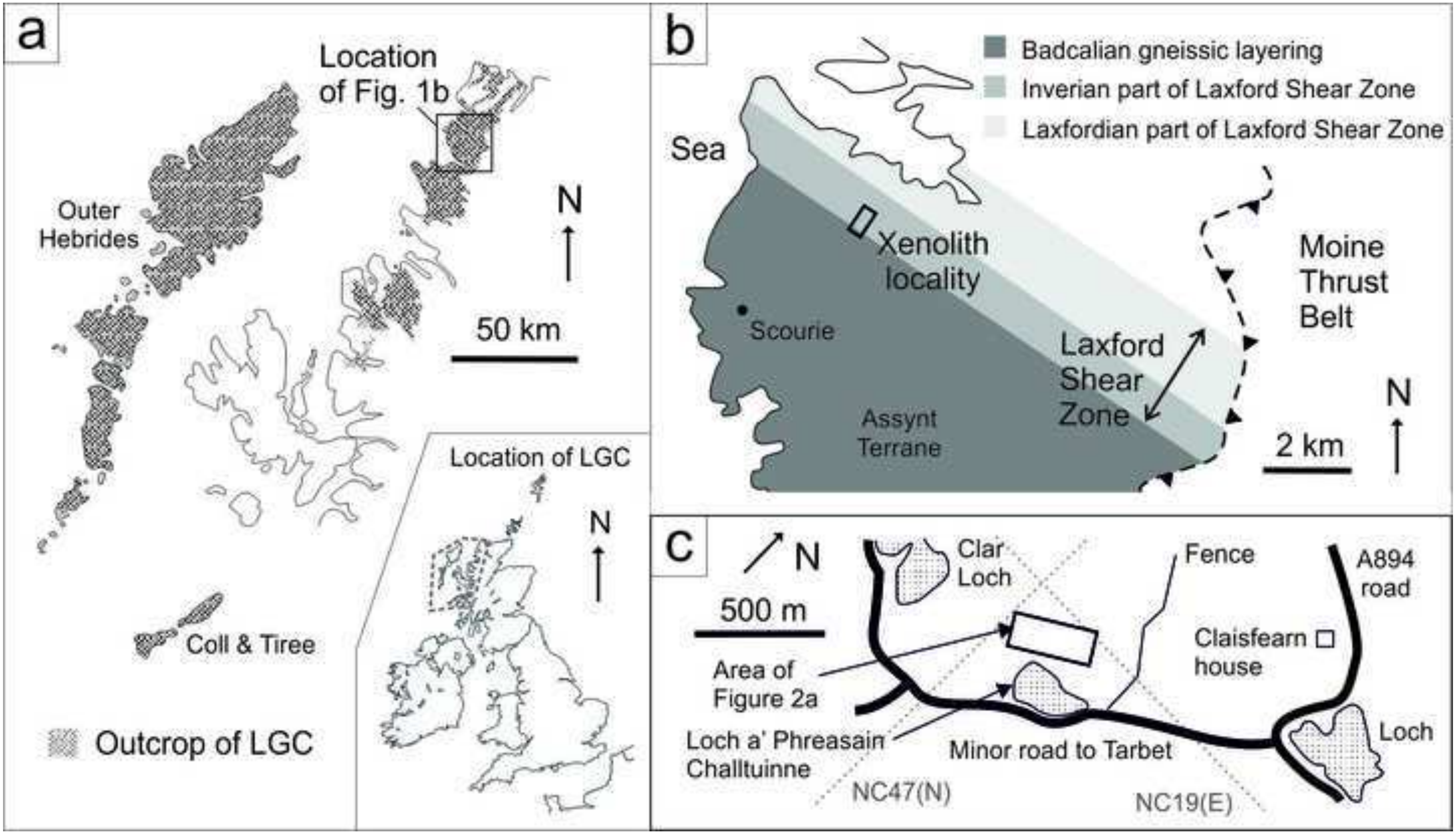
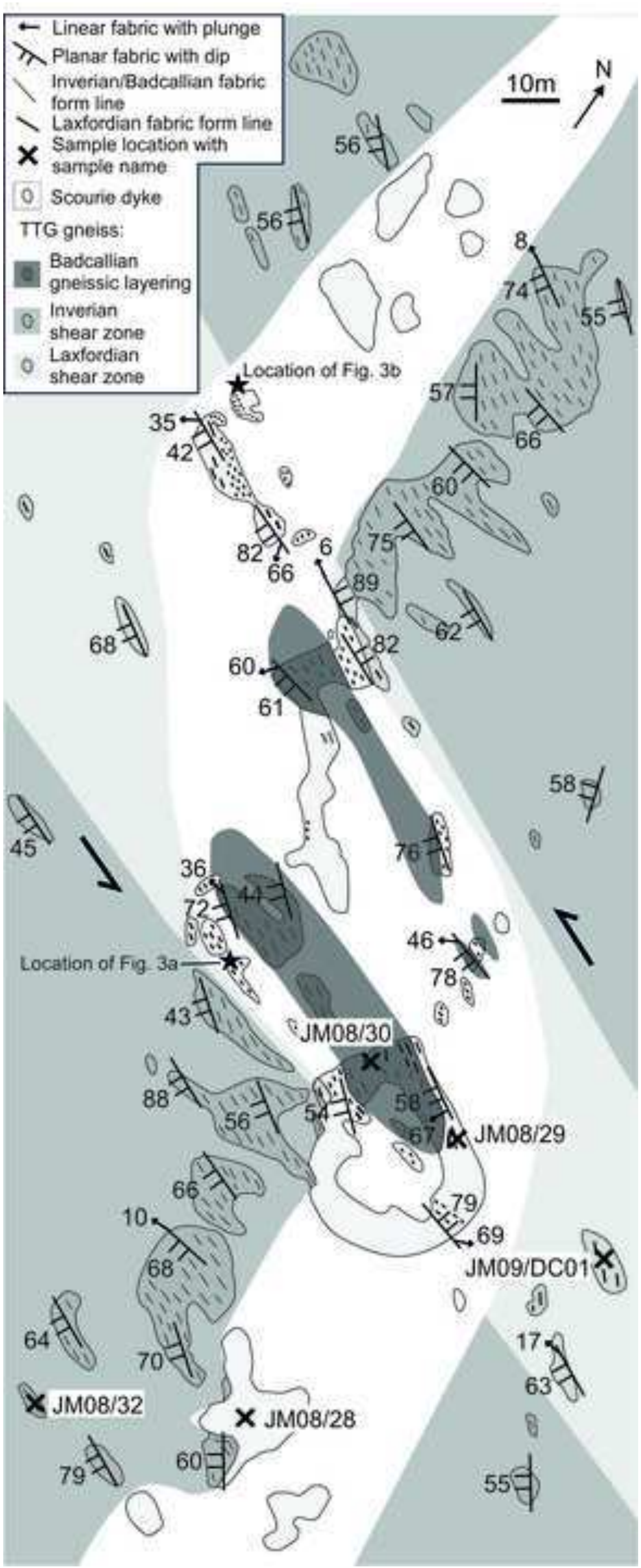
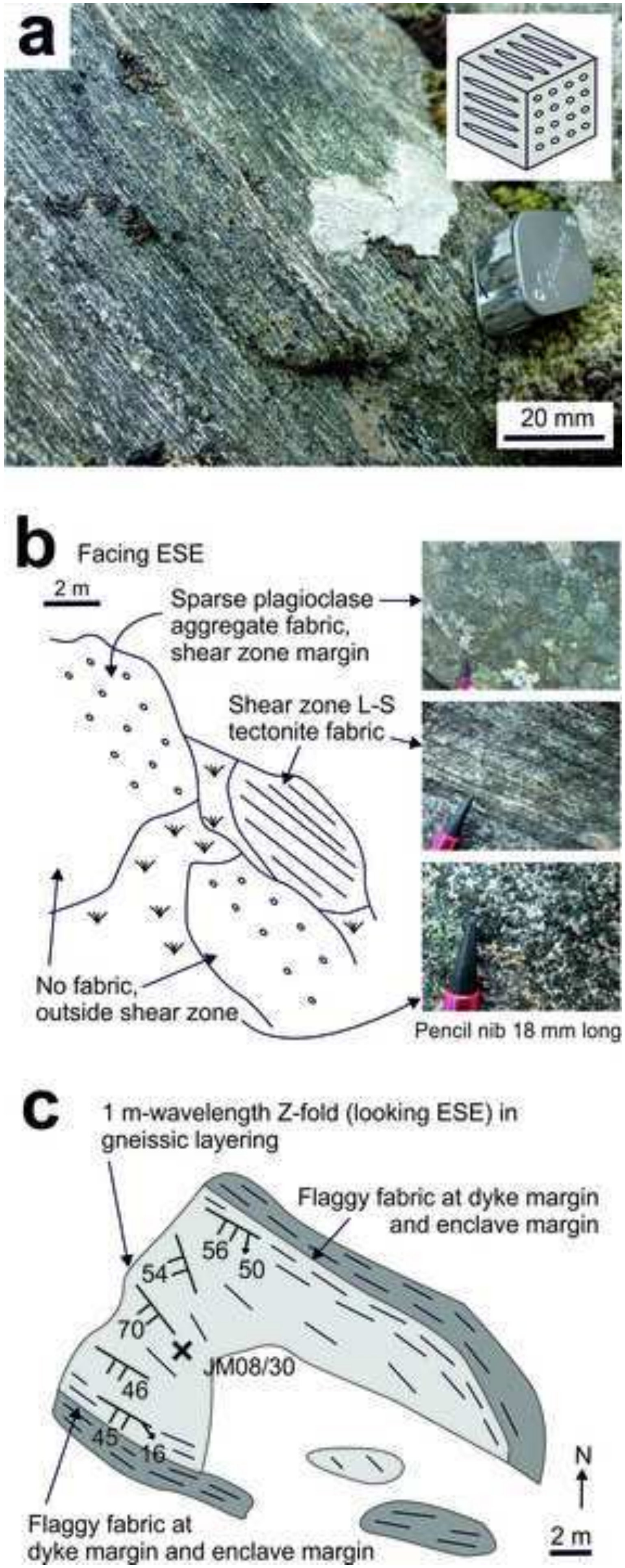

a
Location
of Fig. 1b
Outer
Hebrides
N
50 km
Location of LGC
N
Coll & Tiree
Outcrop of LGC
b
Badcalian gneissic layering
Inverian part of Laxford Shear Zone
Laxfordian part of Laxford Shear Zone
Sea
Xenolith
locality
Moine
Thrust
Belt
Scourie
Laxford
Shear
Zone
N
Assynt
Terrane
2 km
c
N
500 m
Clar
Loch
Fence
A894
road
Claisfearn
house
Area of
Figure 2a
Loch a' Phreasain
Challtuinne
Minor road to Tarbet
Loch
NC47(N)
NC19(E)

Figure Click here to download Figure Fig. 2 v2.jpg




a
20 mm
b
Facing ESE
2 m
Sparse plagioclase aggregate fabric, shear zone margin
Shear zone L-S tectonite fabric
No fabric, outside shear zone
Pencil nib 18 mm long
c
1 m-wavelength Z-fold (looking ESE) in gneissic layering
Flaggy fabric at dyke margin and enclave margin
56
50
54
70
JM08/30
46
45
16
N
2 m
Flaggy fabric at dyke margin and enclave margin

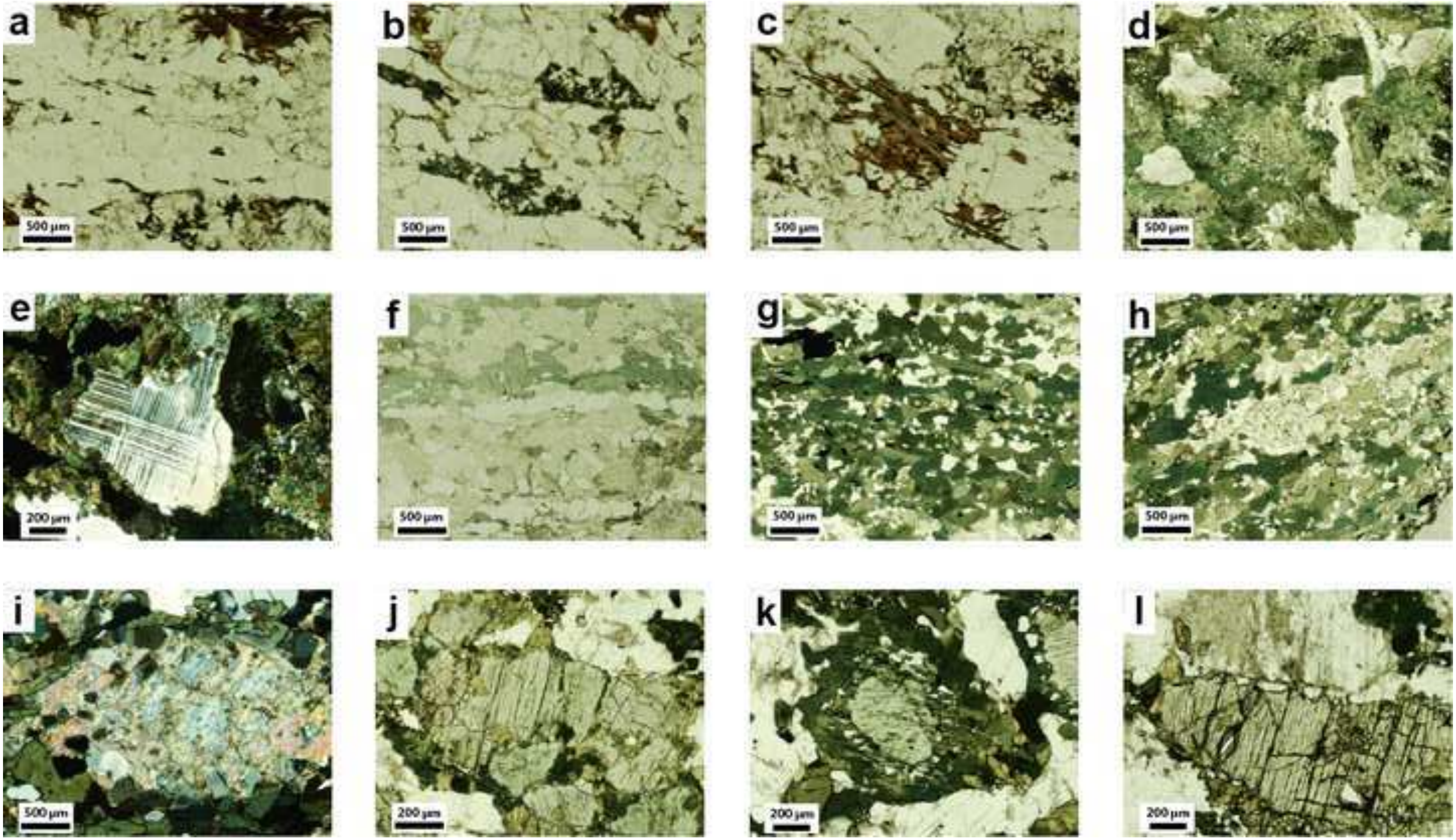

a
500 μm
b
500 μm
c
500 μm
d
500 μm
e
200 μm
f
500 μm
g
500 μm
h
500 μm
i
500 μm
j
200 μm
k
200 μm
l
200 μm

Figure Click here to download Figure Fig. 5.png

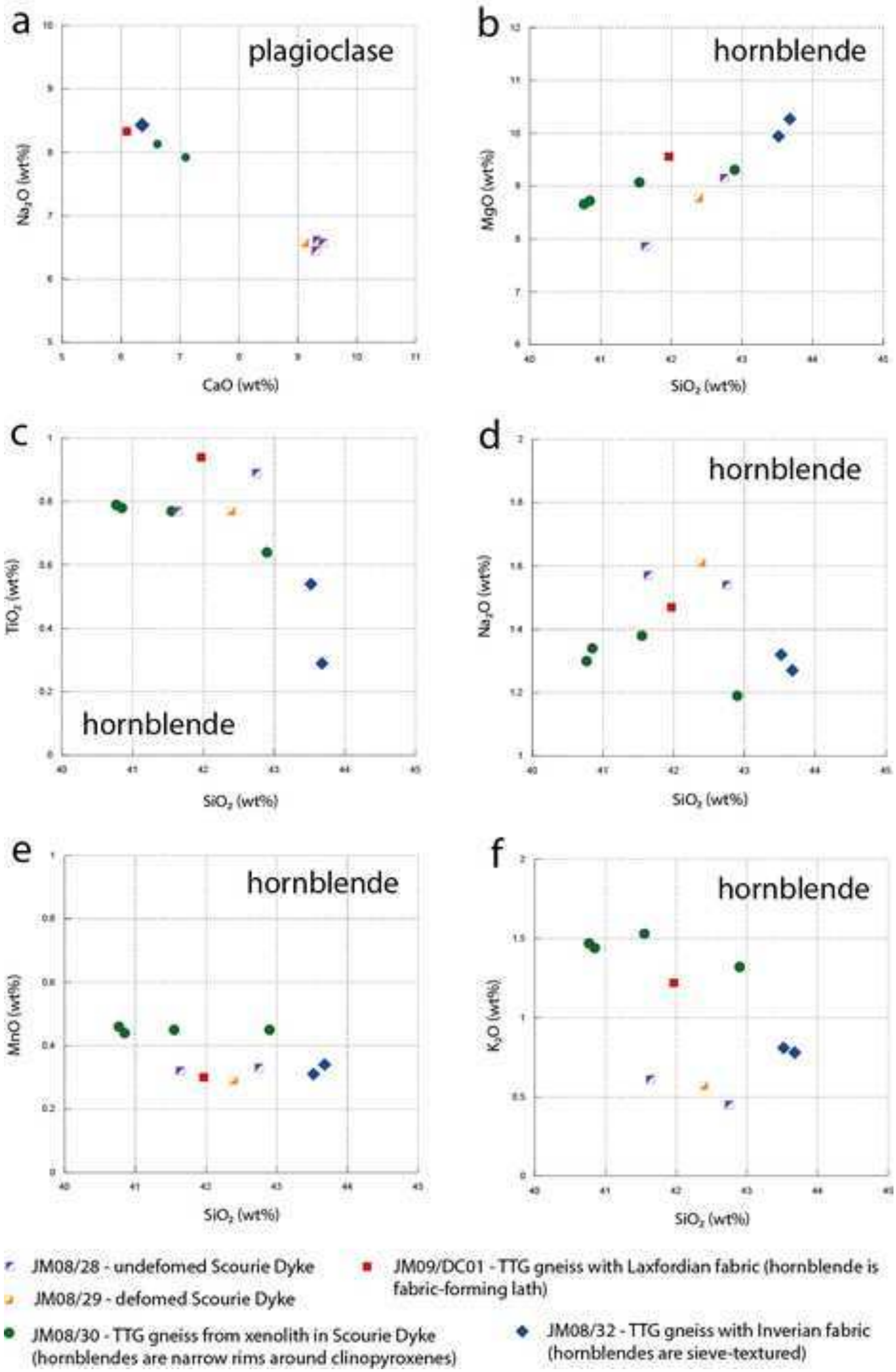
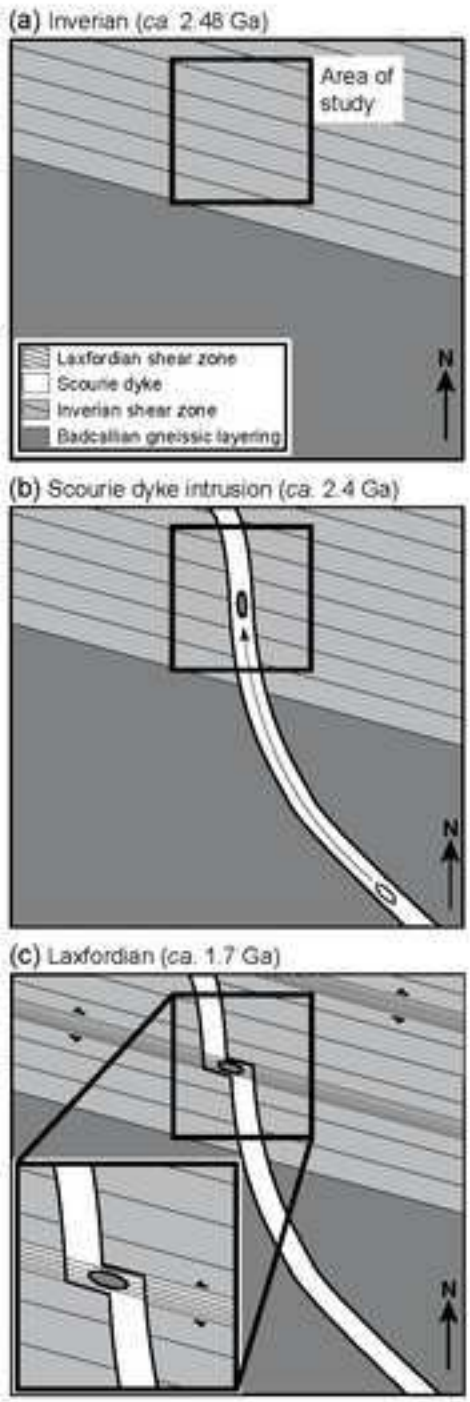


Figure Click here to download Figure Figure 6 - evolution cartoon.png



Dataset

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