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The nature and age of Mesoproterozoic strike-slip faulting based on Re-Os geochronology of syn-tectonic copper mineralization, Assynt Terrane, NW Scotland

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Abstract:

In ancient basement regions such as the Lewisian Complex, NW Scotland, the ages of brittle deformation events are commonly poorly constrained due to a lack of datable fills. An array of NW-SE sinistral and antithetic E-W dextral faults related to a regionally recognized episode of brittle shearing cut Neoarchaean gneisses and c. 2.25 Ga quartz-pyrite veins close to the trace of the unexposed, regional-scale NW-SE fault. Copper-iron mineralisation occurs at an intersection between an antithetic dextral fault and an older *c.* 2.25 Ga quartz vein. Optical microscopy, SEM and XRD analyses reveal an array of intergrown, co-genetic copper-iron sulphides, hematite and barite. Complex mm-thick zoned alteration rims rich in epidote occur at contacts between the sulphides and gneisses. Rhenium-Osmium copper-iron sulphide geochronology yields an age of *c*. 1.55 Ga for the hydrothermal mineralization event associated with faulting. Fault movements demonstrably overlap with mineralisation based on the asymmetric fibrous growth forms of these minerals within local dextral shears which acted as local channelways for mineralizing fluids during and after faulting. We tentatively propose that this regionally recognised strike slip faulting, previously termed the 'Late Laxfordian', should be referred to as the '*Assyntian'* in order to distinguish it from kinematically distinct Laxfordian events. **[end]**

The Neoarchaean gneisses of the Lewisian Complex in NW Scotland form a well exposed and relatively accessible area of Laurentian continental basement rocks that lie in the immediate foreland region of the Palaeozoic Caledonian Orogen (Wheeler *et al*. 2010). The metamorphic gneisses preserve evidence for several tectonic events each formed under different P-T conditions (MacDonald *et al*. 2015; Park 2005). The superimposition of multiple ductile and brittle deformation events, in addition to several episodes of metamorphism, mineralisation, hydrothermal alteration, and igneous intrusion have generated a complex deformational fabric. The Lewisian Complex therefore represents a good opportunity to study a wide array of geological processes that occur through deep geological time.

Cross-cutting and overprinting relationships observed in the field and thin section are traditionally used in basement complexes to allow relative age relationships to be established on both regional and local scales. Only radiometric ages, however, are able to give information concerning the absolute ages of events. Despite the emergence of an increasing number of geochronometers, the relative scarcity of material suitable for reliable radiometric dating remains a significant problem, particularly for the later brittle and brittle-ductile phases of deformation. Since such events can form over periods spanning many hundreds of million years, this means that a large part of the geological history is poorly constrained. More specifically, a lack of absolute age data has become somewhat problematic in Scotland ever since Kinny *et al*. (2005) and Friend & Kinny (2001) proposed that the Lewisian Complex may comprise a number of lithologically and geochronologically distinct tectonic units (fault/shear zone-bounded terranes) assembled progressively during a series of Precambrian amalgamation episodes perhaps spanning more than a billion years.

This paper describes a hitherto little studied set of epidote mineralized NW-SE sinistral and antithetic E-W dextral brittle faults which cut the Neoarchaean Lewisian gneisses, Palaeoproterozoic mafic dykes, and quartz-pyrite veins in part of the Assynt Terrane close to the NW-SE-trending regional scale

Loch Assynt Fault (Figs 1a-c). Rhenium-Osmium geochronology on associated syn-tectonic copper-iron sulphide mineralization is used to provide an absolute age for the brittle-ductile shearing deformation for the first time. This permits tentative correlation with other regional events in nearby regions of Baltica and Laurentia. In addition to advances in our understanding of deformation in continental cratons, the present paper also demonstrates the value of the Re-Os technique for dating Proterozoic-age sulphide mineralisation events.

Regional setting

The Precambrian rocks of the Lewisian Complex, NW Scotland form a fragment of the continental basement of Laurentia that lies to the west of the mid-Silurian Caledonian Moine Thrust (Fig. 1a). The rocks are largely unaffected by Caledonian deformation and have experienced a number of much older crustal-scale geological events during the Neoarchaean and Palaeoproterozoic. The Lewisian Complex is divided into a number of tectonic regions or terranes which are predominantly separated by steeply-dipping shear zones or faults (Fig. 1a; e.g. Park 2002, 2005).

The Assynt Terrane (Fig. 1b) forms the central part of the Lewisian Complex in mainland NW Scotland. It comprises grey, banded, tonalite–trondjemite–granodioritic (TTG) gneisses which are locally highly heterogeneous lithologically, and also include distinct units of mafic-ultramafic composition (e.g. Sheraton *et al.* 1973; Guice *et al.* 2018). The TTG gneisses are thought to be derived from igneous plutons intruded at *c.* 3.03–2.96 Ga (high precision U-Pb and Sm-Nd geochronology; Hamilton *et al.* 1979; Friend & Kinny 1995; Kinny & Friend 1997). These rocks then underwent deformation and granulite facies metamorphism during the so-called Badcallian event(s) the timing of which is incompletely resolved with current age constraints suggesting either a more widely favoured age of *c*. 2.76 Ga (e.g. Corfu *et al*. 1994; Zhu *et al.* 1997; MacDonald *et al.* 2015), and/or a younger age of *c*. 2.49–2.48 Ga (e.g. Friend & Kinny 1995; Kinny & Friend 1997).

The central part of the Assynt Terrane is cut by the *c.* 1.5 km wide, NW-SE-trending, steeply dipping dextral transpressional Canisp Shear Zone (CSZ; Attfield 1987; Fig. 1a). There are also many other smaller steeply-dipping, NW-SE to WNW-ESE trending minor shear zones cutting the surrounding Badcallian gneisses (Park & Tarney 1987) including the Stoer Shear Zone. Some of these shear zones are thought to have developed initially during Inverian deformation and amphibolites-facies retrogression which affected substantial parts of the Assynt Terrane (Attfield 1987). The absolute age of this event is also somewhat unclear, with a majority of studies considering it to be *c*. 2.4 Ga (e.g. Corfu *et al*. 1994; Love *et al.* 2004; Goodenough *et al.* 2013). The Badcallian and Inverian structures are cross-cut by a regionally extensive set of NW-SE trending mafic and ultramafic intrusions referred to as the Scourie Dyke Swarm (Fig. 1b). Individual intrusions range in thickness from a few millimetres to several tens of metres and were intruded as two suites of differing age: a dominant *c.* 2.42-2.38 Ga set and a more minor group at *c.* 2.0 Ga (Rb-Sr whole rock and U-Pb geochronology; Chapman 1979; Heaman & Tarney 1989; Davies & Heaman 2014). These dykes display evidence of having been emplaced under amphibolite facies pressures and temperatures, i.e. in the middle crust, possibly immediately following the Inverian event (O'Hara 1961; Tarney 1973; Wheeler *et al.* 2010).

In the Assynt and Gruinard terranes (Fig. 1a), the dykes and older structures in the host rock gneisses are cross cut by a regional set of quartz-pyrite veins emplacement of which has been dated using Re-Os geochronology at *c.* 2.26 Ga (Vernon *et al.* 2014). These veins, and the older structures, are all heterogeneously overprinted by younger Laxfordian deformation with widespread retrogression of the TTG gneisses under lower amphibolite to upper greenschist-facies metamorphic conditions (e.g. Sutton & Watson 1950; Attfield 1987; Beacom *et al.* 2001). The regionally recognised Laxfordian begins with a series of magmatic events *c*. 1.9–1.87 Ga – at least some of which are related to island arc development – followed by a protracted orogenic episode lasting from 1.79 to 1.66 Ga (see discussion in Goodenough *et al.* 2013). The effects of Laxfordian reworking in the Assynt Terrane are highly localised, being largely restricted to the central 1 km wide centre of the CSZ and other, narrower local shear zones, as well as along the margins of the Scourie dykes. This contrasts with the Rhiconich and Gruinard Terranes which lie respectively NE and SW of the Assynt Terrane (Fig. 1a), where the Laxfordian event reached amphibolite facies and was associated with more pervasive ductile shearing and reworking (Droop *et al.* 1989). This led to the suggestion that the Assynt Terrane represents a shallower depth crustal block during the Laxfordian (e.g. Dickinson & Watson 1976; Coward & Park 1987).

In both the Assynt and Gruinard terranes, a younger set of sinistral low greenschist-facies mylonitic shear zones, brittle faults and localised folds is recognised developed sub-parallel to the pre-existing high-strain fabrics in Laxfordian and Inverian shear zones, and the margins of some Scourie dykes (Beacom *et al.* 2001). These structures are informally referred to as the 'Late Laxfordian' and are thought to include the initial development of the regional scale Loch Assynt Fault (Fig. 1b; cf. Krabbendam & Leslie 2010). The precise age of the 'late-Laxfordian' faulting is poorly constrained, but in the Assynt Terrane these structures demonstrably pre-date deposition of the unmetamorphosed and little deformed *c*. 1.2 Ga Torridonian Stoer Group (Beacom *et al.* 2001). This suggests that the presently exposed parts of the Lewisian Complex had been exhumed to the surface by that time. Regionally, both the Stoer Group and the Lewisian Complex are in turn unconformably overlain by younger Torridonian sequences (Diabeg and Torridon groups) thought to have been deposited no earlier than 1.04 Ga (Park *et al.* 1994).

The present study focusses on a small region of copper sulphide mineralisation, which is found spatially associated with quartz veins and faults cutting Lewisian gneisses on a small island linked to the N shore of Loch Assynt when water levels are low (NC2127 2497, Figs 2a, b). The occurrence of copper mineralisation is rarely described in the Assynt Terrane and has only been briefly referred to at localities near to the Bay of Clachtoll (Boyd & Crichton 1960) and at Loch an Eisg-brachaidh (MacLeod in Boyd &

Crichton 1960). We were unable to locate the occurrence of such mineralization at those locations during the present study.

Field and laboratory methods

Fieldwork, sampling and petrography

Fieldwork studied faults and associated mineralization cutting Lewisian gneisses and Scourie dykes exposed along or close to the shores of Loch Assynt (Figs 2a, b) where the water level – and therefore ease of access to the outcrop - varies dependent on recent rainfall patterns. The relative ages of country rock fabrics, igneous intrusions, mineral veins and fault rocks were ascertained from observed cross cutting relationships. Structural geometries were recorded through collection of orientation data; brittle fault kinematics were determined based on offsets of markers in the host rocks, local preservation of slickenline lineations and preservation of asymmetric brittle shear criteria such as en-echelon veins and slickenline steps (Petit 1987). A representative sample set of orientated hand specimens were collected from country rocks, fault rocks and mineral veins and were used to study microstructures and the timing of mineralization relative to deformation. Both reflected and transmitted light optical microscopy, and scanning electron microscopy (BSEM) were used to study the composition and microstructural characteristics of the copper and associated mineralization. Having identified and removed appropriate material for dating, Re-Os geochronology was used to determine the age of copper-iron sulphide mineralisation and sulphur isotope composition to constrain the mineralizing fluid origin.

Rhenium-Osmium geochronology analytical methods

The copper mineralization comprises of co-genetic intergrown copper sulphides (55%, anilite, djurleite in roughly equal amounts), copper-iron sulphides (40%, bornite) and minor supergene alteration products (5%, malachite, covellite) (see below). Given the intimate micron-scale intergrowth textures, a pure monomineralic separate could not be achieved. A bulk copper sulphide mineral separate (0.5 g) was therefore taken from an area with only minor evidence of the supergene minerals covellite and malachite. Given that our petrographic observations suggest that all the sulphide phases are co-genetic, we suggest that an analysis of a single relatively unaltered bulk sample of copper mineralization is justified. Optical light microscope observation of the obtained 70-200 mesh fraction mineral indicates that the separate was 90% copper-iron sulphides with the remaining 10% comprising intergrown hematite > barite > malachite > covellite. The Re-Os analysis was performed at the Durham Geochemistry Centre in the Arthur Holmes and Source Rock and Sulphide Geochemistry and Geochronology laboratories using the protocols outlined in Selby *et al.* (2009) and Vernon *et al.* (2014). Briefly, the sulphide mineral separate (0.4 g) together with a known amount of mixed ^{190}Os + ^{185}Re tracer solution and a 1:2 mix of inverse *aqua-regia* (3 mL 11N HCl and 6 mL 15N HNO_3) were loaded and sealed into a Carius tube, and heated to 220˚C for 48 hours. Osmium was purified from acidic solution using solvent ($CHCl_3$) and micro-distillation methods. From the Os extracted acidic solution, Re was isolated using solvent extraction (NaOH-acetone) and anion chromatography. The purified Re and Os fractions were loaded onto Ni and Pt wire filaments respectively, with the isotope compositions determined using a Triton Thermo Scientific Mass Spectrometer. Rhenium isotopes were measured statically using Faraday Collectors, with the Os measured in peak hopping mode using the Secondary Electron Multiplier. All data are blank corrected using a total procedural blank run alongside the analysis (Re = 2.5 ± 1.1 pg and 0.10 ± 0.05 pg, respectively, with an $^{187}Os/^{188}Os$ of 0.25 ± 0.05. The Re and Os uncertainties presented in Table 1 are determined by the full propagation of uncertainties from the mass spectrometer measurements, blank abundances and isotopic compositions, spike calibrations, and the results from analyses of Re and Os standards (running averages; Restd = 0.59782 ± 0.0005; DROsS = 0.16083 ± 0.00005). The Re standard data together with the accepted $^{185}Re/^{187}Re$ ratio (0.59738; Gramlich *et al.* 1973) are used to correct for mass fractionation.

Sulphur isotope analytical methods

Sulphur isotope analysis was performed on several milligrams of sulphide using the analytical protocol of Robinson & Kusakabe (1975). Isotope ratios were measured on a VG SIRA II dual inlet mass spectrometer and the data are reported in the conventional delta per mil notation relative to standard V-CDT ($\delta^{34}S$ ‰ V-CDT). Analytical precision at one sigma is ±0.2‰ for isotopically homogeneous material; for standardisation NBS 123 gives -17.1‰ and IAEA S-3 gives -32.1‰.

Field and cross-cutting relationships, Loch Assynt shore

Early basement features

Low-lying outcrops of Lewisian gneisses occur on the NE coast of Loch Assynt and immediately SW of the A838 Inchnadamph-Lochinver road (Figs 2a, b; map reference NC 21 25). These easily accessible exposures have been visited by generations of UK geology students during university-run field trips and are widely referred to in published field guides (e.g. Johnson & Parsons 1979; Smith & Raine 2011). The amphibolite- to granulite-facies TTG gneisses of the Assynt Terrane here show foliation and compositional banding development (e.g. Fig. 3a) from millimetre to tens of metre scales (e.g. Sheraton *et al.* 1973). The foliation is best developed in intermediate composition gneisses, where it is defined by 0.5–5 cm thick layers of contrasting light (plagioclase and quartz) and dark (pyroxene, hornblende and biotite) layers, with individual layers rarely continuing laterally for more than a few metres (Jensen 1984). Ultramafic units typically occur as lensoid pods up to several tens of cm across, flattened in and wrapped by the foliation. Representative samples from the intermediate composition gneisses in the Loch Assynt area typically contain 30% quartz, 20% plagioclase, 10% microcline, 10% orthopyroxene and 30% heavily retrogressed clinopyroxene. The mafic minerals are typically partially to wholly replaced by fine grained intergrown aggregates of hornblende, actinolite, epidote and chlorite (Vernon *et al.* 2014). Foliations in the gneisses dip moderately to the WNW (Fig 2ci), with isolated, cm-scale open to tight minor folds preserved locally.

Mineral lineations defined by aligned mafic minerals and elongate quartz-feldspar aggregates plunge NW down the dip of the associated foliation and sub-parallel to minor fold hinges (Fig 2ci). Structures of this kind and orientation are typical of *c.* 2.7-2.8 Ga Badcallian structures in the Assynt Terrane (Sheraton *et al.* 1973), an inference confirmed by the fact that they are all cross cut by the Scourie dykes (see below). There is no evidence in the area shown in Figure 2a for the development of the NW-SE Inverian structures seen in other parts of the Assynt Terrane.

The fabrics in the gneisses are cross-cut at high angles by two steeply-dipping to sub-vertical NW-SE dykes assigned to the *c.* 2.0-2.4 Ga Scourie dyke suite (Fig. 2a; Johnson & Parsons 1979). A *c.* 9 m thick fine to medium grained ultramafic dyke, which lies to the SW, is only exposed in shoreline exposures at [NC2124 2504]. It displays a chilled northern contact with the gneisses (the southern contact is not seen) and has been described as a feldspathic picrite (Johnson & Parsons 1979). The *c.* 45 m wide sub-parallel dyke located a few metres to the N is much better exposed both along the shoreline and inland, with discordant igneous contacts exposed at a number of locations (e.g. Fig. 3b; NC 2105 2519, 2114 2519 and 2147 2503). This dyke too displays a well-developed chilled margin up to 0.5m thick and, where least deformed, preserves relict igneous textures. However, olivine, orthopyroxene and clinopyroxene are largely replaced by blue green hornblende which occurs in addition to calcic plagioclase and minor quartz and ore.

The dykes – and older foliations in the gneisses - are both cross-cut by clusters of mainly NE-SW-trending sub-vertical quartz-pyrite veins individually up to 0.5 m thick (Figs 2cii, 3c) and dated at *c.* 2.25 Ga by Vernon *et al.* (2014) using Re-Os geochronometry. Vein margins locally preserve evidence for syn-emplacement sinistral shearing based on the local preservation of sub-horizontal quartz slickenlines, en echelon offshoot veins and dilational jogs (Vernon *et al.* 2014).

Elsewhere in the Assynt Terrane, the quartz-pyrite veins and dykes are consistently overprinted and reworked by lower amphibolite to upper greenschist facies dextral shear fabrics related to the Laxfordian event, including the development of the central part of the Canisp Shear Zone (Fig. 1b; Attfield 1987). No field evidence for such ductile dextral fabrics is preserved in the Loch Assynt exposures and the *c.* 2.25 Ga quartz pyrite veins here are notably little deformed and show no significant grain-scale deformation textures at temperatures greater than 300°C (Vernon *et al.* 2014).

Brittle structures

All of the features described in the preceding section are cross-cut by brittle faults, associated cataclastic fault rocks and, locally, mineralization. These fall into two groups: one which pre-dates and a second which post-dates deposition of the Torridonian and Cambro-Ordovician cover sequences. The dominant set in the earlier group are NW-SE trending faults which are mostly sub-vertical to steeply NE dipping (Fig. 2ciii). These comprise either clean break faults lined with narrow (<5 mm wide) seams of epidote-mineralized cataclasite (Fig. 3d) or en-echelon arrays of ESE-WNW-trending tensile veins (<5 mm wide) filled with fine epidote and quartz (Figs 2cv, 3e, f). Slickenline and quartz-epidote slickenfibre lineations on exposed fault surfaces are moderately to shallowly dipping and associated brittle shear criteria everywhere indicate sinistral senses of shear; local offsets of up to 0.5m are observed locally (e.g. Fig. 3d). These structures are found in most exposures and lie sub-parallel to the sinistral Loch Assynt Fault which lies no more than a few hundred metres to the SW (Fig. 1c; Krabbendam & Leslie 2010).

Another set of very much subordinate, sub-vertical to steeply N dipping fractures trend E-W (Fig. 2civ) and is associated with the same quartz-epidote mineralization. Moderately plunging slickenlines are locally preserved in exposed fault surfaces, with offset markers and en-echelon arrays of quartz-epidote-filled, WNW-ESE tensile fractures (Fig. 2cv) indicating dextral senses of shear. In a few localities, these structures occur in conjugate arrays with NW-SE sinistral faults which share the same fills (Fig. 3f). They are thus thought to be contemporaneous with, and antithetic to the dominant NW-SE sinistral faults.

The later set of faults are high angle normal faults with generally dip-slip slickenline lineations (Fig. 2cvi) and local developments of incohesive fault gouge and calcite mineralization (Pless 2012). Map scale faults are NE-SW and NW-SE trending with displacements of up to several tens of metres based on offsets of cover sequence boundaries (Fig. 2a). These normal faults are thought to be Mesozoic based on the preservation of relatively incohesive gouges consistent with formation close to the surface, the development of associated calcite mineralization and their regional relationship to outliers of Permian and younger strata elsewhere in NW Scotland (Wilson *et al.* 2010; Krabbendam & Leslie 2010; Pless 2012).

A localised irregular region of copper mineralisation measuring ~3 x 3.5 cm occurs on one of the small islands close to the N shore of Loch Assynt (NC 2127 2497). Here bright-green and dark metallic grey minerals occur within a dilational jog located close to intersection between an E-W fault (089/83N) and slightly more NE trending quartz vein belonging to the *c.* 2.25 Ga set (Fig. 4a-c). En-echelon sets of WNW-ESE tensile fractures (118/68NNE) associated with the fault suggest a dextral sense of shear consistent with the subordinate set of early pre-Torridonian antithetic structures described above.

In addition to samples taken for geochemical and geochronological purposes, an oriented polished thin section was made showing the local setting of the mineralization and how it cross-cuts both the gneisses and the quartz vein seen in the field; it also includes a marginal part of the dextral E-W fault (Fig. 4c). This thin section was then studied using optical (transmitted and reflected light) microscopy and an SEM, supplemented by an XRD analysis of a crushed sub-sample of the mineralization from the same specimen.

Petrography and mineralogy

Host rock and quartz vein

The Lewisian wall rocks comprise medium to coarse grained sericitized calcic plagioclase (80% of rock), biotite, chlorite and ore (after hornblende?), epidote and minor quartz with a weak foliation defined by compositional banding and alignment of mineral grains (Fig 4c). The quartz vein is very coarse grained (up to 15mm diameter grains) with local recrystallization and subgrain development consistent with a weak low temperature deformational overprint (see Vernon *et al.* 2014 for descriptions of similar textures in this region of Assynt). Brittle fractures and microcracks are widespread, but there is little evidence for significant cataclasis other than in shears close to the E-W dextral fault (see below).

Mineralized area

An XRD and thin section analysis of the mineralized material reveals a complex array of copper sulphides (anilite, djurleite; ca. 40% intergrown in roughly equal amounts), copper iron sulphide (bornite, ca. 30%), iron oxide (hematite, ca. 20%) and sulphate (barite, ca. 10%) (Fig. 5a). The latter mineral is found only in the mineralized area, most notably in its centre (Fig. 5b, c).

Reflected light optical microscopy of the main area of sulphide mineralization, most of which is opaque in transmitted light, reveals complex fine intergrowths of anilite, djurleite, bornite, barite and hematite (Figs 6a-c). Regions with hematite (some in discontinuous veinlets) and barite present are commonly poor in intergrown bornite (e.g. Fig. 6b) suggesting that all these minerals are co-genetic. Supergene alteration of <10% of copper sulphides to covellite and malachite is seen round many grain boundaries, along cleavage planes and in locally developed cracks (Fig. 6c). Contacts between the copper-iron mineralization and both the host quartz vein and the barite are characterized by bornite-poor rims +/- hematite intergrowths (Fig. 6d). Sulphide-quartz boundaries are sharp with local alteration to fibrous malachite (green), azurite (blue) and chlorite. Sulphide-gneiss contacts are more complex. Host rock feldspars are altered to epidote, which is intergrown with fine hematite, bornite and copper sulphide (Figs

6e, f). The mineralization develops rimmed textures which show cuspate-lobate forms consistent with the operation of diffusion mechanisms during mineral growth (Passchier & Trouw 2005).

Brittle-viscous shears

Zones of shearing are mostly located along the margins of the thin section close to the E-W dextral fault seen in the field (Fig. 4c), but poorly developed sub-parallel displacement zones occur as anastomosing arrays elsewhere in the gneisses. Away from the region of copper mineralization, the shears are associated with the deformation and new growth of iron oxides and chlorite which form asymmetric fibrous overgrowths consistent with the operation of low temperature diffusive mass transfer mechanisms synchronous with dextral shearing (Fig. 7a). The dextral shears also cut through the copper mineralization and appear to smear it along the fault planes when viewed with the naked eye (e.g. Fig. 4c). In reflected light and SEM images, the shears are seen to be associated with the new growth of fibrous copper sulphides (often partially altered to malachite), chlorite, barite, hematite and epidote with an asymmetric form consistent with the dextral shear sense (Figs 7b, c). This suggests that mineral growth and shearing overlap and are associated with the operation of diffusive mass transfer processes along fluid-rich fault zones. Shears closest to the mesoscale dextral fractures on the edge of the sample additionally host spectacular zoned colloform intergrowths of malachite, libethenite (copper phosphate) and brochantite (copper sulphate) (Fig. 7d), all formed by presumably somewhat later low temperature fluid flow along open fractures. These late phases cross-cut and therefore locally post-date the fibrous minerals seen in the shears, but are responsible for the bright green and blue colours seen in outcrop.

In summary, the XRD, petrological and microstructural observations suggest that the growth of the copper-iron sulphide and associated mineralization at least overlaps in time with dextral shearing along this E-W Late Laxfordian fault. This syn-tectonic relationship is based primarily on the observed growth of fibrous sulphides along dextral shears spatially associated with a mesoscale fault seen in the field (Figs 7b,c). The widespread growth of epidote co-genetically with sulphide mineralization (e.g. Figs 6e-f) also fits this interpretation as this mineral is very widely associated with so called 'Late Laxfordian' structures both locally (e.g. Figs 3e-f) and regionally (Beacom *et al.* 2001). Thus it is argued that geochronological dating of the sulphide mineralization also gives an age for the pre-Torridonian brittle faulting event in this part of the Assynt Terrane. Note that we believe that the analysis of a single bulk sample of copper mineralization is justified by the textural observations which show that all the sulphides are co-genetic (e.g. Figs 6a, b, d).

Rhenium-osmium geochronology

The analysed copper sulphide separate contains a total Re and Os abundance of 10 ppb and 179 ppt, respectively (Table I). The elevated $^{187}Re/^{188}Os$ (3700) and $^{187}Os/^{188}Os$ (97) values indicate that the bulk of the Os budget in the sample is radiogenic ^{187}Os ($^{187}Os^{r}$). To calculate a model Re-Os date the abundance of $^{187}Os^{r}$ must be obtained. Given that we only have one sample due to the fact copper mineralization is restricted to only a small area (3 x 3.5 cms), the $^{187}Os^{r}$ can only be determined using an assumed initial $^{187}Os/^{188}Os$ composition, rather than a composition determined from the regression of Re-Os data of several contemporaneous samples (e.g. Vernon *et al.* 2014). Using a moderately non-radiogenic $^{187}Os/^{188}Os$ value of 0.2 ± 0.1, 99.8 % of the ^{187}Os is radiogenic (Table I); coupled with the ^{187}Re data, a Re-Os model date of 1555.3 ± 17.1 Ma is obtained using the ^{187}Re decay constant of $1.666 \times 10^{-11}a^{-1}$ (Smoliar *et al.* 1996). However, given that fluid flow associated with the quartz veining and copper mineralization is through *c*. 2.7 and 2.4 Ga crustal units of the Assynt Terrane, the fluid $^{187}Os/^{188}Os$ value could have been significantly more radiogenic, although sulphur isotope analysis suggests that the sulphur associated with the copper mineralization and 2.2 Ga pyrite is isotopically indistinguishable from primitive mantle (this study – see below; Vernon *et al.* 2014). Although exhibiting large uncertainties, the initial $^{187}Os/^{188}Os$ for 2.2 Ga pyrite were shown to be 0.9 ± 9 and 3 ± 13 (Vernon *et al.* 2014). A more radiogenic initial $^{187}Os/^{188}Os$

results in the percentage of the ^{187}Os budget being slightly less radiogenic. For an initial ^{187}Os/^{188}Os of 0.9, 99.1 % of the ^{187}Os is radiogenic and 96.7 % for an initial ^{187}Os/^{188}Os of 3. Regardless of the value of the initial ^{187}Os/^{188}Os, the majority of the ^{187}Os budget (> 96 %) is radiogenic. As a result, the Re-Os model dates are very similar (1555.3 [initial ^{187}Os/^{188}Os of 0.2] vs 1544.2 [initial ^{187}Os/^{188}Os of 0.9] vs 1511 [initial ^{187}Os/^{188}Os of 3]; Table I). We therefore consider the copper mineralisation and by inference the precipitation of the associated quartz vein(s) and fracture formation to have occurred at *c*. 1.55 Ga (Fig. 8a).

Sulphur isotope analysis

In their analysis of the earlier suite of *c.* 2.25 Ga quartz-pyrite veins in the Assynt Terrane, Vernon *et al.* (2014) obtained one rather imprecise and significantly different age of *c*. 1.6 Ga from a pyrite sample at the Waterworks locality in the CSZ near Lochinver (Fig. 1b). The five sulphides showing 2.25 Ga ages had δ^{34}S (V-CDT) in the range 3.0 to 0.9 ‰ (averaging 1.7 ± 0.8 ‰, 1σ, n=5) whereas the sample from Waterworks giving the 1.6 Ga age had δ^{34}S of -2.2 ‰, leading Vernon *et al.* (2014) to speculate that it could represent a younger mineralization event. This age lies well within uncertainty of the Loch Assynt analysis obtained here for which sulphide δ^{34}S is 0.0 ‰. There are several points worthy of note here. Firstly, Lowry *et al.* (2005) in their compilation of sulphur isotope data and mineralogy of ore deposits in northern Britain note that data from Lewisianoid basement inliers interleaved with the Moine Supergroup cover sequences suggest "…a source of slightly ^{34}S-enriched sulphur in the range -3 ‰ to +5 ‰", consistent with the vein data discussed above and an original mantle source for the sulphur as concluded by Vernon *et al.* (2014). Secondly, the observation in this study of likely co-genetic ore sulphides and barite, and the accompanying stable isotope partitioning (perhaps assuming isotopic as well as textural equilibrium) between reduced and oxidised sulphur render further interpretation to the attribution of a definitive fluid $\delta^{34}S$ unwise without a much more detailed study of the distribution of sulphur isotopes amongst co-existing mineral phases (and an estimate of fluid pH and fO_2).

Discussion

The age and regional extent of the 'Late Laxfordian' event

The so-called 'Late Laxfordian' event is widely recognised in the Assynt Terrane and is associated with the development of steeply-dipping to sub-vertical, NW-SE sinistral fault zones which commonly, but not exclusively, reactivate similarly oriented Scourie dyke margins and Inverian-Laxfordian shear zone fabrics (Attfield 1987; Beacom *et al.* 2001, Wilson *et al.* 2011). Epidote mineralized cataclasites and local developments of pseudotachylyte are also associated with these structures (Beacom 1999; Hardman 2019). The regional-scale Loch Assynt Fault is thought to have initiated as one of these structures (Krabbendam & Leslie 2010) and is thought, at least in part, to reactivate the earlier Stoer Shear Zone seen at the NW end of Loch Assynt (Fig. 1b). The fault can be traced 15 km northwestwards to a coastal gully near Clashnessie (NC 0678 3169). Here it is associated with the development of a highly cemented hematite stained breccia zone ~10 m wide with sub-horizontal slickenlines on exposed slip surfaces and quartz-chlorite-epidote veins (Scott 2018). This fault does not cut – and therefore likely pre-dates – the basal unconformity of the ca 1200 Ma Stoer Group which lies along strike and to the northwest (Fig. 1b). In the region of Loch Assynt, the southeastern end of the fault has clearly experienced later reactivation as it offsets the foreland sedimentary sequences (Torridon Group, Cambro-Ordovician marine sequences) by 1300 m sinistrally and 120 m vertically (SW-side up) and also continues up into the lower parts of the overlying Moine Thrust Zone (see Krabbendam & Leslie 2010). A related fault with the same trend and smaller amounts of apparently sinistral and/or SW-side-up senses of offset is also seen displacing and locally folding the basal Cambrian sequence north of the A837 Inchnadamph-Lochinver road (Fig. 2a; folds seen 250 m NW of Lochan Feoir at NC 226 254).

We have shown that the *c*. 1.55 Ga copper-iron sulphide mineralization seen on the shore of Loch Assynt is related to dextral E-W faulting that is antithetic to the more widespread NW-SE sinistral faults seen in the area. We propose that these are typical 'Late Laxfordian' structures based on geometric and kinematic similarity with other structures assigned to this group elsewhere in the Assynt Terrane (Fig. 8a; e.g. Beacom 1999, Beacom *et al.* 2001; Wilson *et al.* 2011) and the widespread development of associated epidote mineralization along these faults. Additional support for relating the brittle structures seen on the north shore of Loch Assynt with regional brittle strike-slip faults comes from the local preservation of low temperature ultramylonites and pseudotachylytes along the reactivated NW-SE margins of the larger Scourie dyke in both gneiss (NC 21045 25192) and dyke (NC 21489 25025) (e.g. Figs 8b – d; Scott 2018). The ultramylonites here are characterised by pervasive sub-grain rotation recrystallization with sinistral S-C fabrics, minor folds and sigma porphyroclasts of both plagioclase and epidote (Fig. 8b). Quartz epidote veins run sub-parallel and at high angles to the foliation, with the former being frequently partially mylonitized or fibrous in form suggesting that mineralization occurred prior to, during and after local crystal plasticity. Discrete microscale faults also offset marker layers sinistrally, with associated dextral antithetic faults, and both root upwards and downwards into foliation-parallel detachments, some of which follow the deformed quartz-epidote layers (Figs 8b-d). These detachment faults are lined by dark brown pseudotachylytes, which locally show 'paired generation zone' (Grocott, 1981) geometries (Fig. 8d). Pseudotachylytes also form small (50 µm wide, ≤1 mm long) en-echelon injection veins once again consistent with sinistral shear (e.g. Figs 8b-d). These fault rock assemblages are typical of 'Late Laxfordian' faults in other regions (Beacom 1999; Beacom *et al.* 2001; Shihe & Park 1993).

In their analysis of the *c.* 2.25 Ga quartz-pyrite veins of the Assynt Terrane, one sample from the Waterworks locality in the CSZ near Lochinver (Fig. 1b) yielded, although imprecise (± 1.3 Ga), a significantly different age of *c*. 1.6 Ga (Vernon et al. 2014). The uncertainty in the presented Re-Os model date of the sample is largely controlled by the uncertainty in the initial $^{187}Os/^{188}Os$ used to calculate $^{187}Os^{r}$

obtained from the regression of the Re-Os data (0.9 ± 9; Vernon et al. 2014). If a nominal uncertainty of 0.1 in the initial $^{187}Os/^{188}Os$ is used, the uncertainty in the Re-Os model date reduces significantly to 0.2 Ga. Additionally, the Waterworks pyrite sample also exhibits a lower sulphur isotope signature compared to the other *c.* 2.25 Ga pyrite samples, which led Vernon et al. (2014) to speculate that it could represent a younger mineralization event. Interestingly, the Re-Os model age of the Waterworks pyrite sample is similar within uncertainty to that of the copper mineralization of Loch Assynt obtained here. Although there are only two samples, regression of the $^{187}Re/^{188}Os$ vs $^{187}Os/^{188}Os$ data for the Waterworks sample and the copper mineralization of this study yield a Re-Os date of 1538 ± 34 Ma, with an initial $^{187}Os/^{188}Os$ of 1.3 ± 1.8. This potentially suggests a more regional deformation-hydrothermal event across the Assynt Terrane at *c*. 1.55 Ga (Fig. 8a).

Superficially similar NW-SE sinistral faults associated with so called 'Late Crush Belts' are also recognised in the Gairloch region which forms part of the Gruinard Terrane lying immediately to the SW of the Assynt Terrane (Fig. 1a; Campbell *et al.* 2019). These zones are associated with extensive developments of cataclasite and pseudotachylyte and were assigned to the same suite of 'Late Laxfordian' structures in the regional studies of Beacom (1999) and Beacom *et al.* (2001).

Sherlock *et al.* (2008) used infrared laserprobe $^{40}Ar/^{39}Ar$ dating to date pseudotachylyte and host-rock minerals at Gairloch. Complex results were attributed to the presence of refractory host-rock clasts and mineral fragments in the pseudotachylyte and, on removing these complexities, the authors proposed ages for the friction melts of between 0.98 and 1.12 Ga, i.e. Grenvillian. Interestingly, these authors also obtained $^{40}Ar/^{39}Ar$ ages of 1.69-1.56 Ga from hornblende grains in the immediate host rocks adjacent to pseudotachylyte-bearing crush zones, whereas biotites yielded ages of 1.30 - 1.03 Ga, suggestive of a later tectonic event that did not exceed the closure temperature of Ar within the amphiboles (~500^{o}C). They attributed the older country rock ages to Laxfordian regional metamorphism and cooling, but they also lie close to the *c.* 1.55 Ga age obtained during the present study. Host rock mineral ages can also be related to local frictional melting events (e.g. Kelley *et al.* 1994) and it is clear that the crush zones at Gairloch show widespread local evidence for multiple movement and melting episodes along individual slip zones (Shihe & Park 1993; Beacom 1999; Campbell *et al.* 2019). Hence, we tentatively suggest that the older ages at Gairloch are related to frictional heating during the *initiation* of the NW-SE crush belts in Gairloch and that these structures were then reactivated during the Grenvillian as proposed by Sherlock *et al.* (2008). Thus we suggest that the *c*. 1.55 Ga age obtained using Re-Os geochronology at Loch Assynt plausibly gives an age for the regional *initiation* of 'Late Laxfordian' structures across both the Assynt and Gairloch terranes in NW Scotland.

The 'Assyntian' event: a proposal

The foregoing discussion highlights the likelihood that the *c*. 1.55 Ga shearing event is of regional extent through a large proportion of the Lewisian Complex, as suggested by Beacom *et al.* (2001). A palaeostress inversion was undertaken using inferred opening directions from tensile veins and slip vectors taken from measured shear fracture slickenline lineations using the Right Dihedron Method of Angelier & Mechler (1977) (Figs 9ai-iii). These yield broadly E-W horizontal compression and N-S horizontal extension directions with principle stress axes consistent with a strike-slip tectonic environment (sigma 2 vertical, Fig. 9b). As bedding in the local *c.* 1040 Ma Torridon Group strata that unconformably overlie the Assynt Lewisian basement is subhorizontal, we see no reason to re-orient the structural data or analysis. An inversion analysis of the later cross-cutting normal fault sets (Fig. 9aiv) yields a very different E-W extension and a principle stress pattern consistent with normal faulting (sigma 1 vertical) of likely Mesozoic age (Pless 2012; cf. Roberts & Holdsworth 1999).

The *c.* 1.55 Ga shearing event is kinematically distinct from the preceding Laxfordian ductile deformation which is associated with *dextral* shear along regional and local NW-SE shear zones such as the CSZ and Scourie dyke margins (Fig. 8a; Attfield 1987). In this regard, we believe that continued use of the term 'Late Laxfordian' is misleading as it represents a kinematically distinct and later deformation episode, albeit one much influenced by the presence of pre-existing dyke contacts and shear zones. In terms of regionally recognised events seen in nearby continental regions, the *c.* 1.55 Ga age is broadly contemporaneous with the latter stages of the Gothian orogeny in southern Scandanavia (Baltica), associated with widespread crustal accretion and calc-alkaline volcanics (Gaál & Gorbatschev 1987, Starmer 1996). It also lies within uncertainty of the close of the Labradorian Orogeny in Canada (Laurentia; *c*. 1.71-1.62 Ga; Kamo *et al.* 1996, Rivers 1997) meaning that it is possible that the *c*. 1.55 Ga event represents an important missing link in Scotland between these two regional episodes. In the light of this, we tentatively propose here that the 'Late Laxfordian' event should be referred to in future as the *'Assyntian'* in order to: a) separate it from the earlier Laxfordian events; and b) recognize its possible regional development. Clearly much further work is needed to further constrain the age, extent and regional significance of this brittle episode throughout the Lewisian Complex.

Conclusions

A distinctive set of steeply dipping sinistral and dextral brittle-viscous shears postdating local Neoarchaean Badcallian fabrics, Palaeoproterozoic Scourie dykes and quartz-pyrite veins are recognized cutting Lewisian gneisses exposed on the northern shore of Loch Assynt, a well visited teaching locality in the NW Scotland. A dominant set of NW-SE sinistral faults are parallel to the adjacent Loch Assynt Fault and reactivate dyke margins leading to the local development of low temperature ultramylonites and pseudotachylytes, whilst an E-W dextral set are subordinate and antithetic structures (Fig. 9c). Both fault sets are closely associated with steeply dipping NW-SE tensile quartz-epidote filled tensile fractures/veins. The association of these fault rocks with epidote-quartz-chlorite mineralization is typical of so-called 'Late Laxfordian' events in the Assynt Terrane and beyond. One of the dextral E-W faults close to Loch Assynt is associated the co-genetic development of copper-iron sulphides, iron oxide, epidote and barite.

Texturally, the mineralization is, at least in part, syn-tectonic based on the fibrous growth form of the sulphide and oxide minerals grown along local dextral shears. A Re-Os age from the copper-iron sulphides of *c.* 1.55 Ga likely dates the age of brittle shearing event in this terrane. Given its potential regional extent we propose that this event should be referred to as the '*Assyntian*' in order to distinguish it from earlier, kinematically distinct Laxfordian events. The palaeocontinental significance of this strike-slip deformation episode remains unproven, but overlaps in age with the closing stages of the Gothian and Labradorian orogenies in Baltica and Laurentia, respectively, and may provide a structural link between these two contemporaneous tectonic episodes located either side of Scotland in the Mesoproterozoic (e.g. see Starmer 1996). The findings further illustrate the ability of the Re-Os geochronometer to date Proterozoic sulphide deposits and associated deformation events.

Acknowledgements

We thank Durham University for supporting undergraduate field trips to the Assynt region over many years and Chris Rix at Inchnadamph Lodge for accommodation, patience and space for our wonderful field dogs, Ava and Tagish. Chris Ottley and Geoff Nowell are thanks for laboratory support. DS acknowledges the Total Endowment Fund and the CUG Wuhan Dida Scholarship. George Guice, Graham Leslie and John MacDonald are warmly thanked for their detailed constructive comments.

References

Angelier, J. & Mechler, P. 1977. Sur une méthode graphique de recherche des contraintes principales également utilisable en tectonique et en séismologie: la méthode des dièdres droits. *Bulletin Societe géologique France,* **19**, 1309–1318.

Attfield, P., 1987. The structural history of the Canisp Shear Zone, In: Park, R.G. & Tarney, J. (eds), *Evolution of the Lewisian and comparable Precambrian High Grade Terrains.* Special Publication of the Geological Society, London, **27,** 165-174.

Beacom, L.E., 1999. *The Kinematic Evolution of Reactivated and Non-Reactivated Faults in Basement Rocks, NW Scotland*, Queens University, Belfast, Unpublished PhD thesis.

Beacom, L.E., Holdsworth, R.E., McCaffrey, K.J.W. & Anderson, T.B., 2001. A quantitative study of the influence of pre-existing compositional and fabric heterogeneities upon fracture-zone development during basement reaction, In; Holdsworth, R.E., Strachan. R.A., Magloughlin, J.F. & Knipe, R.J, (eds). *The Nature and Tectonic Significance of Fault Zone Weakening,* Special Publication of the Geological Society, London, **186**, 195-211. https://doi.org/10.1144/GSL.SP.2001.186.01.12

Boyd, A.J. & Crichton, J.M. 1960. Discovery of Copper Minerals in Lewisian Gneiss. *Geological Magazine*, **98,** 88. https://doi.org/10.1017/S001675680000013

Campbell, L.R., Phillips, R.J., Walcott, R.C. & Lloyd, G.E. 2019. Rupture geometries in anisotropic amphibolite recorded by pseudotachylytes in the Gairloch Shear Zone, NW Scotland. *Scottish Journal of Geology*. https://doi.org/10.1144/sjg2019-003

Chapman, H.J. 1979. 2390 Myr Rb-Sr whole rock age for the Scourie dykes of north-west Scotland. *Nature* 277, 642-3.

Corfu, F., Heaman, L. & Rogers, G. 1994. Polymetamorphic evolution of the Lewisian Complex, NW Scotland, as recorded by U-Pb isotopic compositions of zircon, titanite and rutile, *Contributions to Mineralogy and Petrology,* 117, 215–228. https://doi.org/10.1007/bf00310864

Coward, M.P. & Park, R.G., 1987. The role of mid-crustal shear zones in the Early Proterozoic evolution of the Lewisian, In; Park, R.G. & Tarney, J. (eds), *Evolution of the Lewisian and Comparable Precambrian High Grade Terrains*, Special Publication of the Geological Society, London, **27**, 127-138.

Davies, J.H.F.L. & Heaman, L.M., 2014. New U-Pb baddeleyite and zircon ages for the Scourie dyke swarm: A long-lived large igneous province with implications for the Paleoproterozoic evolution of NW Scotland. *Precambrian Research*, **249**, 180-198, https://doi.org/10.1016/j.precamres.2014.05.007

Dickinson, B.B. & Watson, J. 1976. Variations in crustal level and geothermal gradient during the evolution of the Lewisian Complex of northwest Scotland. *Precambrian Research*, **3,** 365-374.

Droop, G.T.R., Fernandes, L.A.D. & Shaw, S., 1989. Laxfordian metamorphic conditions of the Palaeoproterozoic Loch Maree Group, Lewisian Complex, NW Scotland, *Scottish Journal of Geology*, **35,** 31-50.

Friend, C.R.L. & Kinny, P.D., 2001. A reappraisal of the Lewisian Gneiss Complex: geochronological evidence for its tectonic assembly from disparate terranes in the Proterozoic, *Contribution to Mineralogy and Petrology*, **142**, 198-218.

Gaál, G. & Gorbatschev, R. 1987. An outline of the Precambrian evolution of the Baltic Shield, *Precambrian Research*, **35,** 15–52. https://doi.org/10.1016/0301-9268(87)90044-1

Gramlich, J.W., Murphy, T.J., Garner, E.L. & Shields, W.R., 1973. Absolute isotopic abundance ratio and atomic weight of a reference sample of rhenium, *Journal of Research of the National Bureau of Standards*, **77A**, 691–698.

Goodenough, K., Crowley, Q., Krabbendam, M. & Parry, S. 2013. New U-Pb age constraints for the Laxford Shear Zone, NW Scotland: Evidence for tectono-magmatic processes associated with the formation of a Paleoproterozoic supercontinent, *Precambrian Research*, **233,** 1–19. https://doi.org/10.1016/j.precamres.2013.04.010

Grocott, J. 1981 Fracture geometry of pseudotachylyte generation zones: a study of shear fractures formed during seismic events, *Journal of Structural Geology***, 3,** 169–178. https://doi.org/10.1016/0191-8141(81)90012-2

Guice, G.L., McDonald, I., Hughes, H.S.R., MacDonald, J.M., Blenkinsop, T.G., Goodenough, K.M., Faithfull, J.W. & Gooday, R.J. 2018. Re-evaluating ambiguous age relationships in Archean cratons: implications for the origin of ultramafic-mafic complexes in the Lewisian Gneiss Complex, *Precambrian Research*, doi: https://doi.org/10.1016/j.precamres.2018.04.020

Hamilton, P., Evensen, N., O'Nions, R. & Tarney, J. 1979. Sm—Nd systematics of Lewisian gneisses: implications for the origin of granulites, *Nature,* **277,** 25-28. https://doi.org/10.1038/277025a0

Hardman, K. 2019. Cracking Canisp: Deep void evolution during ancient earthquakes. Geoscientist, **29** (1), 10-15. https://doi.org/10.1144/geosci2019-003

Heaman, L.M. & Tarney, J., 1989. U-Pb baddeleyite ages for the Scourie dyke swarm, Scotland: evidence for two distinct intrusion events, *Nature*, **340**, 705-708.

Jensen, L.N., 1984. Quartz microfabric of the Laxfordian Canisp Shear Zone, NW Scotland, *Journal of Structural Geology*, **6**, 293-302.

Johnson, M. R.W. & Parsons, I. 1979. Assynt District of Sutherland - Geological Excursion Guide. Edinburgh Geological Society, 76pp.

Kamo, S.L., Wasteneys, H., Gower, C.F. & Krogh, T.E. 1996. U-Pb geochrono!ogy of Labradorian and later events in the Grenville Province, eastern Labrador, *Precambrian Research,* **80,** 239-260.

Kelley, S.P., Reddy, S.M. & Maddock, R. 1994. Laser-probe 40Ar/39Ar investigation of a pseudotachylyte and its host rock from the Outer Isles thrust, Scotland. *Geology,* **22,** 443–446.

Kinny, P.D. & Friend, C.R.L., 1997. U-Pb isotopic evidence for the accretion of different crustal blocks to form the Lewisian Complex of northwest Scotland. *Contributions to Mineralogy and Petrology*, **129,** 326–340.

Kinny, P.D., Friend, C.R.L. & Love, G.L., 2005. Proposal for a terrane-based nomenclature for the Lewisian Gneiss Complex of NW Scotland, *Journal of the Geological Society*, **162**, 175-186.

Krabbendam, M. & Leslie, A. (2010) 'Lateral variations and linkages in thrust geometry: the Traligill transverse zone, Assynt Culmination, Moine thrust belt, NW Scotland', In: Law, R. D., Butler, R. W. H., Holdsworth, R. E., Krabbendam, M. & Strachan, R. A. (eds) *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne.* Geological Society, London, Special Publications, **335,** 335–357. https://doi.org/10.1144/sp335.16

Love, G.J.L, Kinny, P.D. & Friend, C.R.L., 2004. Timing of magmatism and metamorphism in the Gruinard Bay area of the Lewisian Gneiss Complex: comparisons with the Assynt Terrane and implications for terrane accretion, *Contributions to Mineralogy and Petrology*, **146**, 620-636.

Lowry, D., Boyce, A.J., Fallick, A.E., Stephens,W.E & Grassineau, N.V. 2005. Terrane and basement discrimination in northern Britain using sulphur isotopes and mineralogy of ore deposits. In: I. McDonald, A.J. Boyce, I.B. Butler, R.J. Herrington and D.A. Polya (eds) *Mineral Deposits and Earth Evolution*, Geological Society, London, Special Publication **248,** 133-151.

MacDonald, J.M., Goodenough, K.M., Wheeler, J., Crowley, Q., Harley, S.L., Mariani, E. & Tatham, D. 2015. Temperature–time evolution of the Assynt Terrane of the Lewisian Gneiss Complex of Northwest Scotland from zircon U-Pb dating and Ti thermometry. *Precambrian Research*, **260,** 55–75. https://doi.org/10.1016/j.precamres.2015.01.009

Mason, A.J. 2016. The Palaeoproterozoic anatomy of the Lewisian Complex, NW Scotland: evidence for two 'Laxfordian' tectonothermal cycles, *Journal of the Geological Society*, **173,** 153-169. https://doi.org/10.1144/jgs2015-026

O'Hara, M.J. 1961 Petrology of the Scourie dyke, Sutherland (Plate XVIII) *Mineralogical Magazine and Journal of the Mineralogical Society*, **32,** 848-865. https://doi.org/10.1180/minmag.1961.032.254.02

Park, R.G. 1994. Early Proterozoic tectonic overview of the northern British Isles and neighbouring terranes in Laurentia and Baltica, *Precambrian Research*, **68**, 65-79.

Park, R.G. 2002. *The Lewisian Geology of Gairloch, NW Scotland,* Geological Society of London, Memoir, 26, pp 88.

Park, R.G. 2005. The Lewisian terrane model: a review. *Scottish Journal of Geology*, **41**, 105-118.

Park, R.G. & Tarney, J. 1987. The Lewisian Complex: a typical Precambrian high-grade terrane?, In: Park, R.G. & Tarney, J. (eds), *Evolution of the Lewisian and Comparable Precambrian High Grade Terranes*, Special Publication of the Geological Society, London, **27,** 13-26.

Park, R.G., Cliff, R.A., Fettes, D.J. & Stewart, A.D. 1994. Precambrian rocks in northwest Scotland west of the Moine Thrust: the Lewisian Complex and Torridonian, In: Gibbons, W. & Harris, A.L. (eds), *A Revised Correlation of Precambrian Rocks in the British Isles*, Geological Society, London, Special Report, **22**, 6-22.

Passchier, C.W. & Trouw, R.A.J., 2005. *Micro-Tectonics*, Springer Berlin Heidelberg, New York.

Petit, J.P. 1987. Criteria for the sense of movement on fault surfaces in brittle rocks. *Journal of Structural Geology,* 9, 597-608, https://doi.org/10.1016/0191-8141(87)90145-3

Pless, J. 2012. *Characterising fractured basement using the Lewisian Gneiss Complex, NW Scotland: Implications for fracture systems in the Clair Field basement.* Unpublished PhD thesis, Durham University.

Rivers, T. 1997. Lithotectonic elements of the Grenville Province: review and tectonic implications. *Precambrian Research*, **86,** 117-154, doi.org/10.1016/S0301-9268(97)00038-7

Roberts, A.M. & Holdsworth, R.E. 1999. Linking onshore and offshore structures: Mesozoic extension in the Scottish Highlands. *Journal of the Geological Society, London,* **156,** 1061-1064. https://doi.org/10.1144/gsjgs.156.6.1061

Robinson, B.W. & Kusakabe, M. 1975. Quantitative preparation of sulfur dioxide for 34S/32S analyses from sulfides by combustion with cuprous oxide. *Analytical Chemistry*, **47,** 1179-1181.

Scott, L.J. 2018. *Dyke reactivation across the frictional-viscous transition: Precambrian deformation of Scourie dyke margins in NW Scotland.* Unpublished MSc thesis, Durham University.

Selby, D., Kelley, K.D., Hitzman, M.W. & Zieg, J. 2009. Re-Os sulphide (Bornite, Chalcopyrite, and Pyrite) systematic of the Carbonate-hosted copper deposits at Ruby Creek, Southern Brooks Range, Alaska, *Economic Geology*, **104**, 437-444.

Sheraton, J.W., Tarney, J., Wheatley, T.J. & Wright, *A.E. 1973*. The structural history of the Assynt district, In: Park, R.G. & Tarney, J. (eds), *The early Precambrian rocks of Scotland and related rocks of Greenland*, Department of Geology, Keele, 31-44.

Sherlock, S.C., Jones, K.A. & Park, R.G. 2008. Grenville-age pseudotachylite in the Lewisian: laserprobe 40Ar/39Ar ages from the Gairloch region of Scotland (UK), *Journal of the Geological Society*, **165,** 73-83, https://doi.org/10.1144/0016-76492006-134

Shihe, L. & Park, R.G. 1993. Reversals of movement sense in Lewisian brittle–ductile shear zones at Gairloch, NW Scotland, in the context of Laxfordian kinematic history, *Scottish Journal of Geology*, **29,** 9–19. https://doi.org/10.1144/sjg29010009

Smith, M.P. & Raine, R. 2011. Excursion 1 – Loch Assynt and the Achmore duplex. In: Goodenough, K.M. & Krabbendam, M. (eds): *A Geological Excursion Guide to the North West Highlands of Scotland*. Edinburgh Geological Society, 37-52.

Smoliar, M.I., Walker, R.J., & Morgan, J.W. 1996. Re-Os isotope constraints on the age of Group IIA, IIIA, IVA, and IVB iron meteorites, *Science*, **271,** 1099–1102.

Starmer, I.C. 1996. Accretion, rifting, rotation, and collision in the North Atlantic Supercontinent, 1700-950 Ma. In: Brewer, T., and Atkin, B. P. (eds.), *Precambrian crustal evolution in the North Atlantic regions*: Special Publication of the Geological Society, London, **112,** 226-252.

Sutton, J. & Watson, J., 1950. The pre-Torridonian metamorphic history of the Loch Torridon and Scourie areas in the north-west Highlands, and its bearing on the chronological classification of the Lewisian, *Quarterly Journal of the Geological Society*, **106**, 241-307.

Tarney, J. 1973. The Scourie dyke suite and the nature of the Inverian event in Assynt, In: Park, R.G. & Tarney, J. (eds), *The early Precambrian rocks of Scotland and related rocks of Greenland*, Department of Geology, Keele, 105-118.

Vernon, R., Holdsworth, R.E., Selby, D., Dempsey, E., Finlay, A.J. & Fallick, A.E. 2014. Structural characteristics and Re-Os dating of quartz-pyrite veins in the Lewisian Gneiss Complex, NW Scotland: evidence of an early Palaeoproterozoic hydrothermal regime during terrane amalgamation. *Precambrian Research,* **246,** 256–267, https://doi.org/10.1016/j.precamres.2014.03.007

Wheeler, J., Park, R.G., Rollinson, H.R. & Beach, A. 2010. The Lewisian Complex: insights into deep crustal evolution, In: Law, R.D., Butler, R.W., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds), *Continental Tectonics and Mountain Buildings: The Legacy of Peach and Horne*, Geological Society, London, Special Publications, **335**, 51-79**.** https://doi.org/10.1144/SP335.4

Wilson, R.W., Holdsworth, R.E., Wild, L.E., McCaffrey, K.J.W., England, R.W., Imber, J. & Strachan, R.A. 2010. Basement-influenced rifting and basin development: a reappraisal of post-Caledonian faulting patterns in the North Coast Transfer Zone, Scotland. In: Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M. & Strachan, R.A. (eds) *Continental Tectonics and Mountain Building: The Legacy of Peach and Horne,* Geological Society, London, Special Publication, **335**, 795-826. https://doi.org/10.1144/SP335.32

Wilson, R.W., Holdsworth, R.E. & Wightman, R. 2011. Excursion 2 - Transect through the Canisp Shear Zone, Achmelvich, North-west Highlands. In: Goodenough, K.M. & Krabbendam, M. (eds): *A Geological Excursion Guide to the North West Highlands of Scotland*. Edinburgh Geological Society, 53-73.

Zhu, X. K., O'Nions, R. K., Belshaw, N. S. & Gibb, A. J., 1997. Lewisian crustal history from in situ SIMS mineral chronometry and related metamorphic textures. *Chemical Geology*, **136,** 205-218.

Figure Captions

Figure 1) a) Regional location map with Lewisian Complex terranes in mainland of NW Scotland. Box shows location of maps in b) and c). b) Simplified geological map of the Assynt Terrane with Inverian-Laxfordian shear zones (in green) and trace of sub-vertical Loch Assynt Fault. Box shows location of Fig 2a. c) Simplified regional map showing locations and NW-SE trend of Scourie dykes in the Assynt Terrane.

Figure 2) a) Simplified geological map of the N shore of central Loch Assynt (pink = Lewisian gneiss; green = Scourie dykes; brown = Torridonian sandstones; orange = Cambrian Basal Quartzite; yellow = Cambrian Pipe Rock Quartzite; heavy black lines are late normal faults). Contours in metres. Box shows location of Fig 2b. b) GoogleEarth air photo of N shore showing location of mineralization (Fig. 4a). c) Equal area lower hemisphere stereonets (i-vi) of structural data from the Lewisian Complex from the region shown in Fig 2a and b.

Figure 3) Field outcrop relationships in Loch Assynt area. a) Typical banded dioritic-granodioritic gneisses with WNW-dipping Badcallian foliation (NC 2110 2503). b) Plan view of NW-SE-trending northern contact of thick Scourie dyke (dark rock, bottom) cross cutting foliation in Badcallian gneisses (top). Note interfingering of dyke and gneiss (above and to the left of the compass clino) and local later brittle reactivation adjacent to the original intrusive contact. (NC 2515 2518). c) Oblique view of undeformed NE-SW quartz-pyrite veins (*c.* 2.25 Ga) cross-cutting Badcallian foliation in gneisses (NC 2117 2508). d) Oblique view of quartz-pyrite veins offset by NW-SE subvertical sinistral fault; note pale green epidote mineralization to right of whistle (NC 2110 2517). e) Plan view of NW-SE trending en-echelon array of tensile quartz-epidote veins cutting gneisses (NC2124 2504). f) Plan view of conjugate sinistral and dextral en-echelon quartz-epidote tension gashes – note sinistral offset of older quartz-pyrite vein (NC 2124 2504).

Figure 4) a) Drone-based plan view air photo of island where copper-iron mineralization occurs (yellow box) with arrows showing NE-SW quartz-pyrite vein running across rock platform. b) Plan view of outcrop at NC2127 2497 showing NE-SW quartz-pyrite vein (blue) cross-cut by copper iron mineralization (yellow) and dextral faults (red). Location of thin section shown in Figure c also shown. c) Low power PPL view of thin section showing contact relationships between gneisses, quartz-pyrite vein, copper-iron mineralization and dextral faults.

Figure 5) a) XRD data of copper-iron mineralization sample from NC 2127 2497. b) low power and c) higher power PPL thin section images of typical barite-ore intergrowth textures consistent with co-genetic mineral growth.

Figure 6) Textural relationships consistent with cogenetic copper-iron-barite ore mineralization in thin section. a) Reflected light image of fine intergrowths of anilite (pale yellow-green), djurleite (pale-medium blue), bornite (pink), barite (grey) and hematite (yellow). Note that areas with intergrown hematite generally lack intergrown bornite and vice versa. b) Reflected light image of discontinuous veinlet of intergrown barite and hematite with bornite-free rim of anilite-djurleite. c) BSEM image of supergene alteration of copper sulphides to covellite and malachite. Note dendritic growth forms and localization along microcracks and cleavage planes. d) Reflected light image of intergrown copper sulphides and bornite (bottom) adjacent to region of intergrown copper sulphides, hematite and barite which forms a contact zone with larger region of barite (top). e) PPL transmitted and f) reflected light images of typical contact zone between copper-iron mineralization (bottom) and feldspathic Lewisian gneiss (top). The feldspar is altered to epidote and intergrown with fine hematite, bornite & Cu sulphide. The alteration rims show cuspate-lobate forms consistent with the operation of diffusion mechanisms during mineral growth.

Figure 7) Fibrous mineral growth textures associated with brittle-ductile dextral microshears. a) PPL transmitted light image of dextral asymmetric fibrous overgrowths of green chlorite and black hematite on hematite porphyroclasts and along shear surfaces. b) BSEM and c) reflected light images of dextral asymmetric fibrous growth of Cu sulphides (partly altered to malachite and sparse spots of bornite), epidote, chlorite, barite & hematite. The fibrous zone cross cuts a more massive region of intergrown cooper-iron sulphides, hematite, barite and epidote. d) BSEM image of zoned colloform intergrowths of malachite, libethenite (copper phosphate) and brochantite (copper sulphate) cross cutting fibrous copper sulphide and chlorite seen in dextral shear.

Figure 8) a) Revised chronology of events and relation to regional assembly of the Lewisian Complex. b-d) PPL transmitted light images of ultramylonite-pseudotachylyte and epidote-quartz mineralization in highly deformed gneisses along Scourie dyke margin at NC 2104 2519. Note the widespread development of sinistral shear criteria associated with both ultramylonite and pseudotachylyte development. Note also the fibrous form of the epidote adjacent to some foliation-parallel shears.

Figure 9) a) Stress inversion data for i) sinistral faults; ii) dextral faults; iii) tensile fractures/veins; iv) later (Mesozoic) normal faults. b) Stress inversion analysis for i) - iii) combined, with the Assynt Fault trend (red dashed line) shown together with a summary of mean planes, shear senses and opening directions. c) 3D summary diagram of fracture orientations and kinematics; not to scale.

Table

Table I) Re-Os and S isotope data for Copper mineral separate from vein in the Lewisian Complex, Loch Assynt, NW Scotland.

Table 1: Re-Os and S isotope data for Copper mineral separate from a quartz vein in the Lewisian Complex, NW Scotland.

Batch/Sample	Location (Lat/Long)/OS	Re (ppb)	±	Os[1] (ppt)	±	^{187}Re (ppb)	±	$^{187}Os^{r}$ (ppt)[2]	±	% $^{187}Os^{r}$	$^{187}Re/^{188}Os$	±	$^{187}Os/^{188}Os$	±	rho[3]	Model age[4]	±	Model age[5]	±	Model age[6]	±	δ^{34}S (per mil)[7]
RO628-7_Cu sample		10.04	0.04	178.8	5.3	6.31	0.02	165.6	2.4	99.8	3699.7	80.8	97.3	2.3	0.889	1555.3	17.1	1544.2	17.1 [145.2]	1511	17.1 [209]	0.0

Notes (see text for details): All uncertainites are reported at the 2□ level, $^{187}Os/^{188}Os$ uncertainties reported at 2SE; all data are blank corrected, blanks for Re and Os were 2.4 ± 0.5 and 0.10 ± 0.05 pg, respectively, with an average $^{187}Os/^{188}Os$ value of 0.25 ± 0.05 (1SD, n = 1);

All uncertainities are determined through the full propagation of uncertainties of the Re and Os mass spectrometer measurements, blank abundances and isotopic compositions, spike calibrations, and reproducibiity of standard Re and Os isotopic values;

[1] Total Os abundance

[2] $^{187}Os^{r}$ presented are calculated using an initial $^{187}Os/^{188}Os$ of 0.2 ± 0.1, 99.1 % using an $^{187}Os/^{188}Os$ of 0.9, 96.7 % using an $^{187}Os/^{188}Os$ of 3

[3] rho is the error correlation

A model age can be directly calculated using $^{187}Os^{r}/^{187}Re = e^{□t}-1$

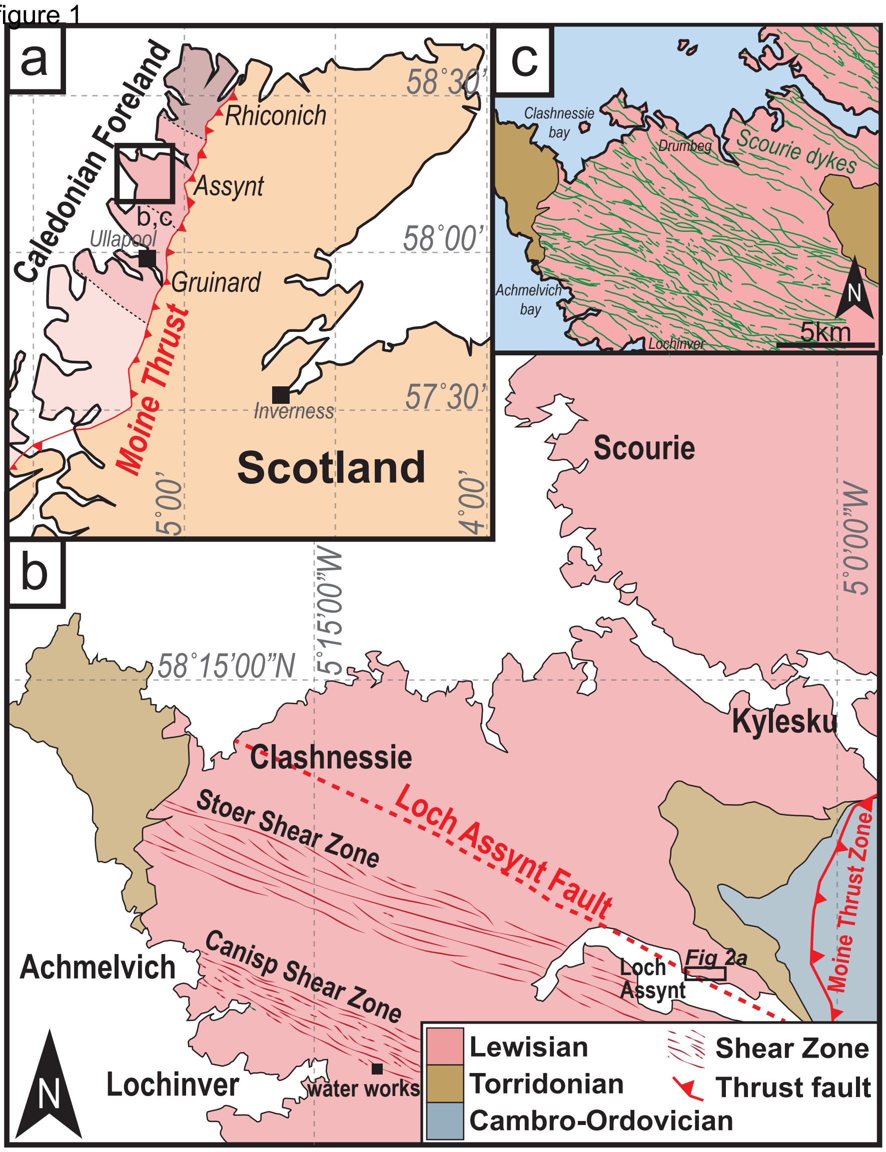
[4] model age determined using an initial $^{187}Os/^{188}Os$ value of 0.2 ± 0.1

[5] model age determined using an initial $^{187}Os/^{188}Os$ value of 0.9 ± 0.1[9]. Bracketed value is the uncertainty from regression of the Re-Os data from Vernon et al. (2014).

[6] model age determined using an initial $^{187}Os/^{188}Os$ value of 3 ± 0.1[13]. Bracketed value is the uncertainty from regression of the Re-Os data from Vernon et al. (2014).

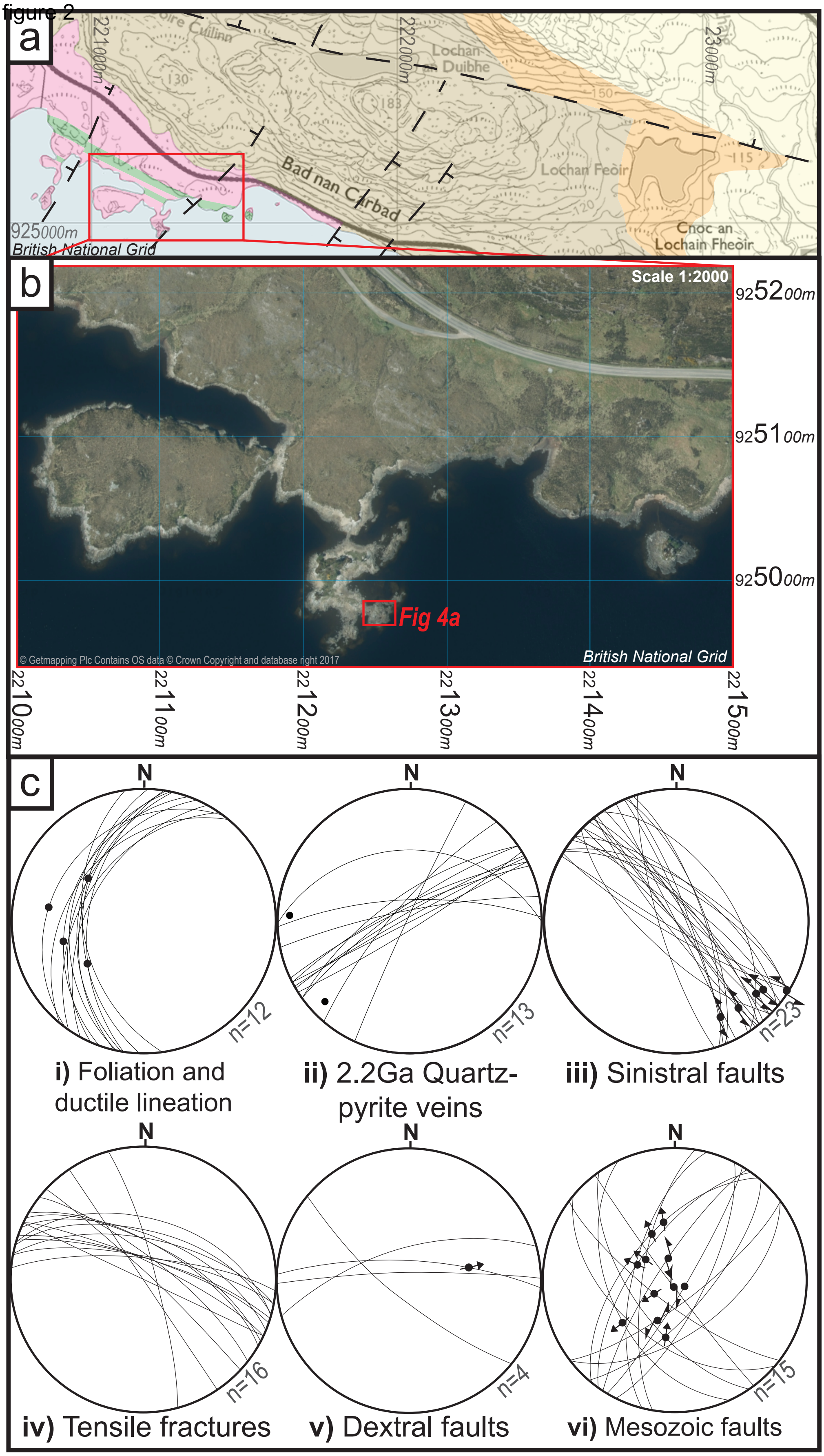
[7] The reproducibility based on full replicate analyses of internal laboratory standards was ±0.2 per mil (1σ) VCDT

figure 1



a
Caledonian Foreland
Rhiconich
Assynt
b,c
Ullapool
Gruinard
Moine Thrust
Inverness
Scotland
58°30'
58°00'
57°30'
5°00'
4°00'
c
Clashnessie bay
Drumbeg
Scourie dykes
Achmelvich bay
Lochinver
5km
N
b
Scourie
58°15'00"N
5°15'00"W
5°0'00"W
Kylesku
Clashnessie
Stoer Shear Zone
Loch Assynt Fault
Fig 2a
Loch Assynt
Moine Thrust Zone
Achmelvich
Canisp Shear Zone
Lochinver
water works
N
Lewisian
Torridonian
Cambro-Ordovician
Shear Zone
Thrust fault

figure 2



a
221000m
222000m
23000m
Lochan Duibhe
Bad nan Carbad
Lochan Feoir
Cnoc an Lochain Fheoir
925000m
British National Grid
b
Scale 1:2000
925200m
925100m
925000m
Fig 4a
© Getmapping Plc Contains OS data © Crown Copyright and database right 2017
British National Grid
221000m
221100m
221200m
221300m
221400m
221500m
c
N
n=12
i) Foliation and ductile lineation
N
n=13
ii) 2.2Ga Quartz-pyrite veins
N
n=23
iii) Sinistral faults
N
n=16
iv) Tensile fractures
N
n=4
v) Dextral faults
N
n=15
vi) Mesozoic faults

figure 3

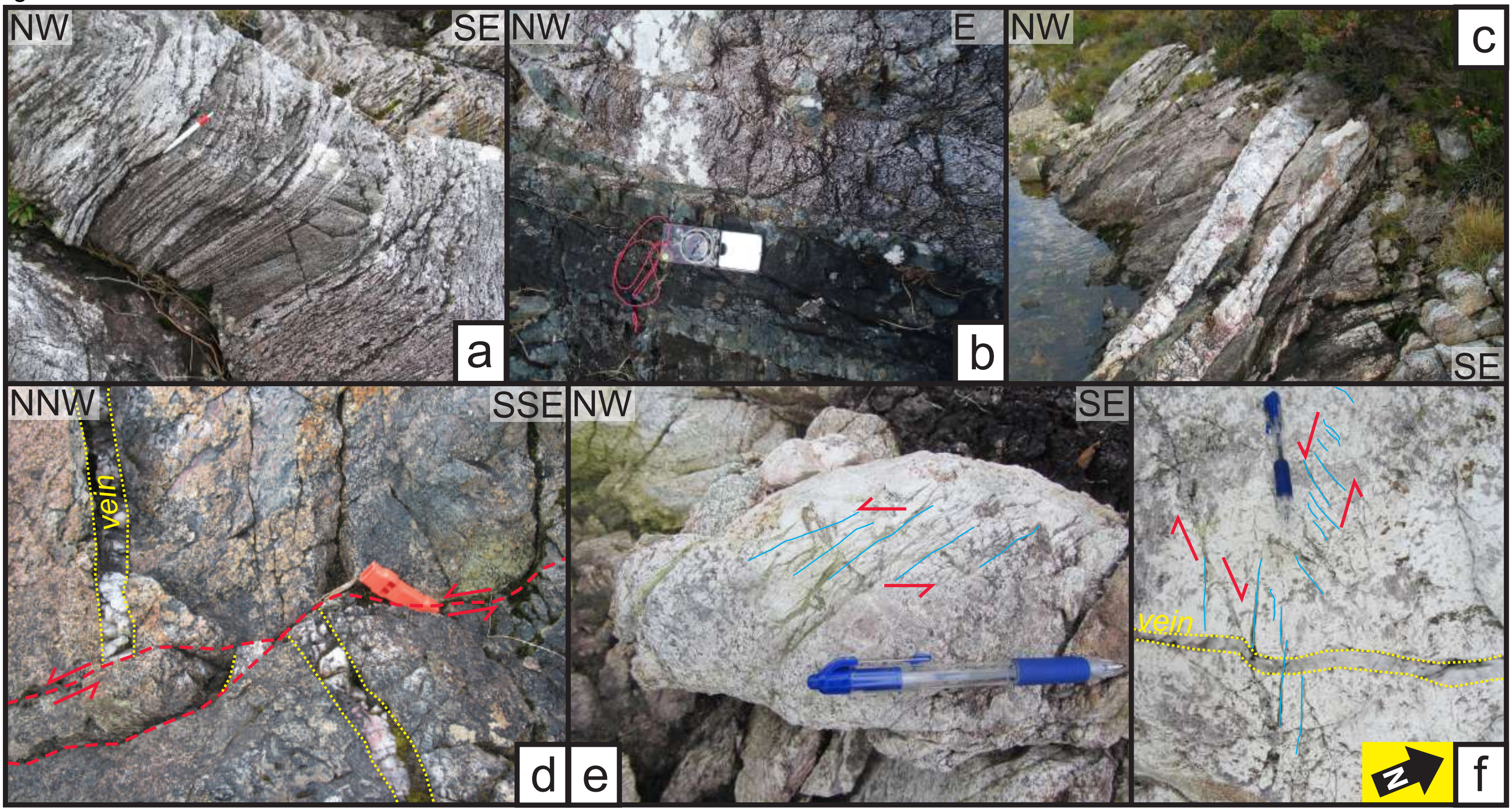


figure 4

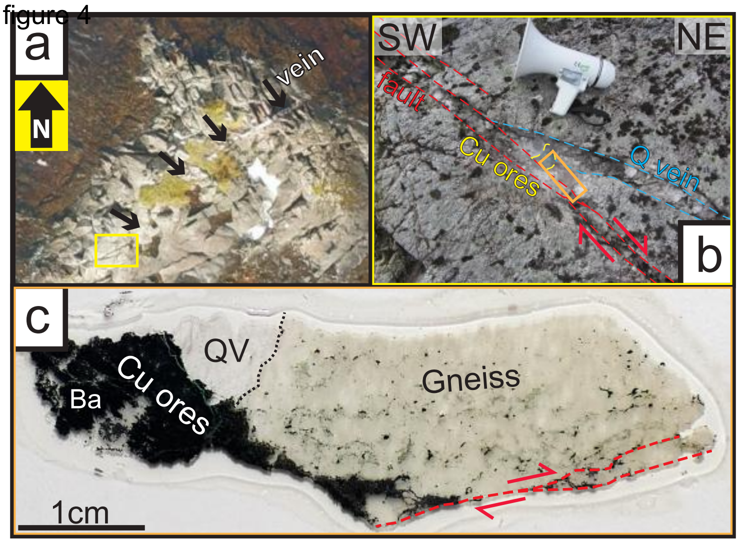


figure 5

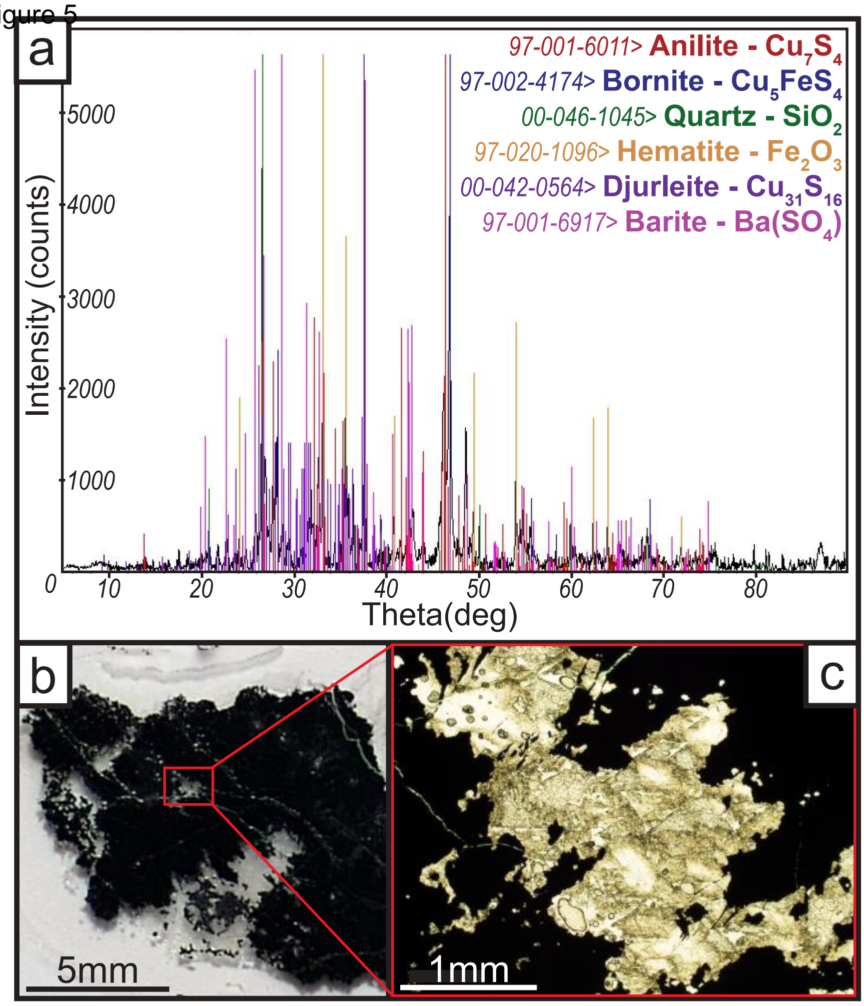
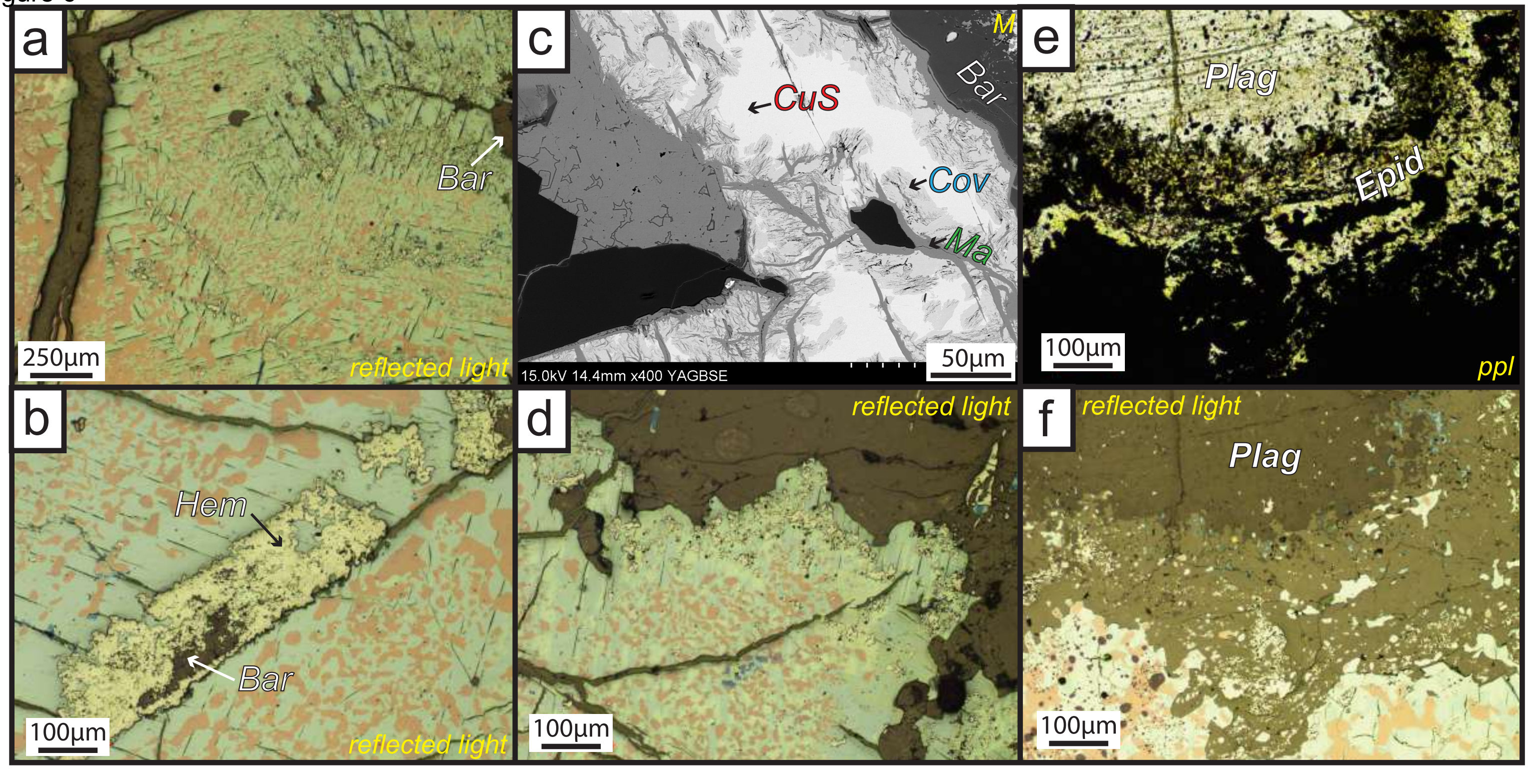
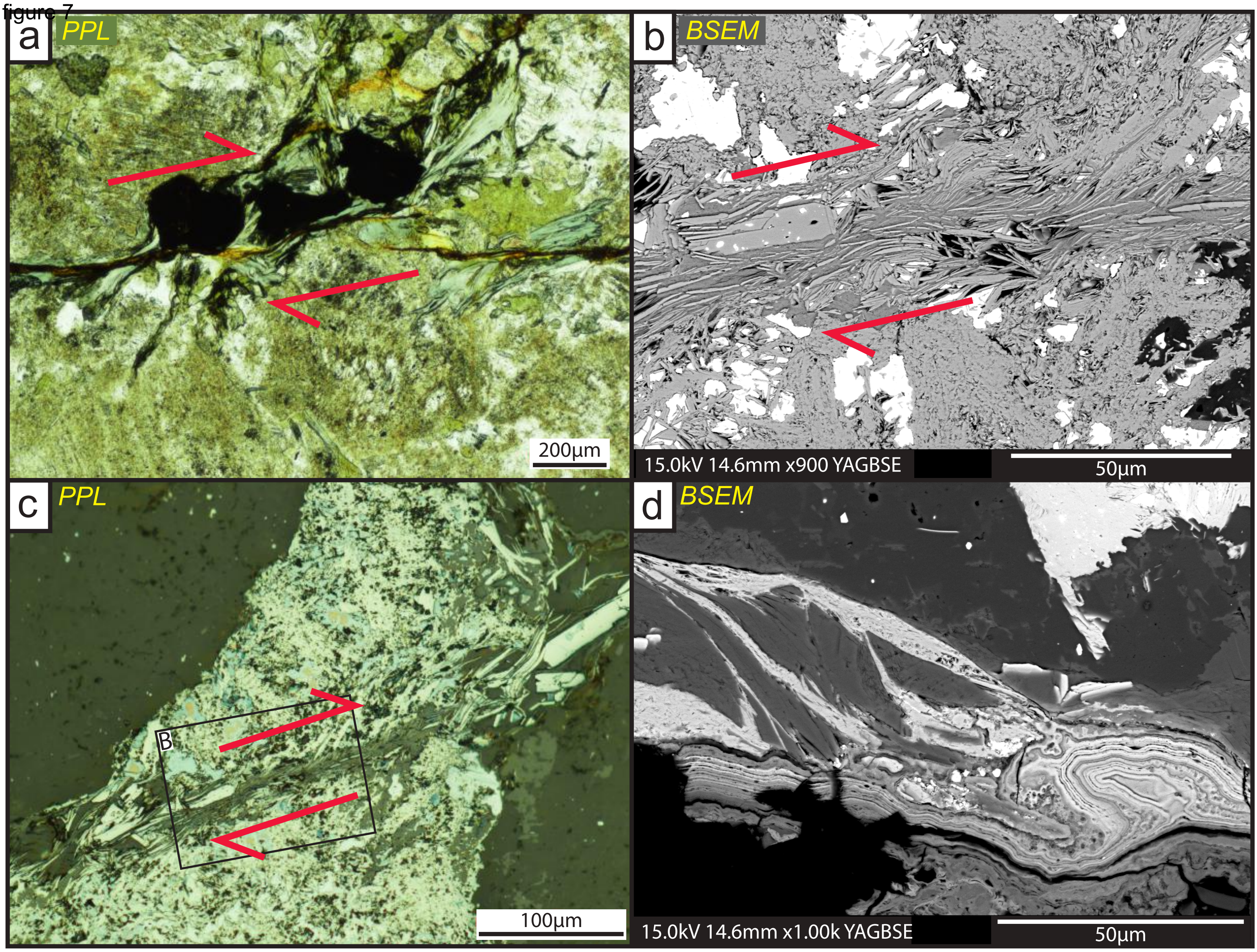

a
97-001-6011> Anilite - Cu7S4
97-002-4174> Bornite - Cu5FeS4
00-046-1045> Quartz - SiO2
97-020-1096> Hematite - Fe2O3
00-042-0564> Djurleite - Cu31S16
97-001-6917> Barite - Ba(SO4)
Intensity (counts)
5000
4000
3000
2000
1000
0
10
20
30
40
50
60
70
80
Theta(deg)
b
5mm
c
1mm

figure 6



a
Bar
250µm
reflected light
c
CuS
Cov
Ma
Bar
50µm
15.0kV 14.4mm x400 YAGBSE
e
Plag
Epid
100µm
ppl
b
Hem
Bar
100µm
reflected light
d
reflected light
100µm
f
reflected light
Plag
100µm

figure 7



a
PPL
200µm
b
BSEM
15.0kV 14.6mm x900 YAGBSE
50µm
c
PPL
B
100µm
d
BSEM
15.0kV 14.6mm x1.00k YAGBSE
50µm

figure 8

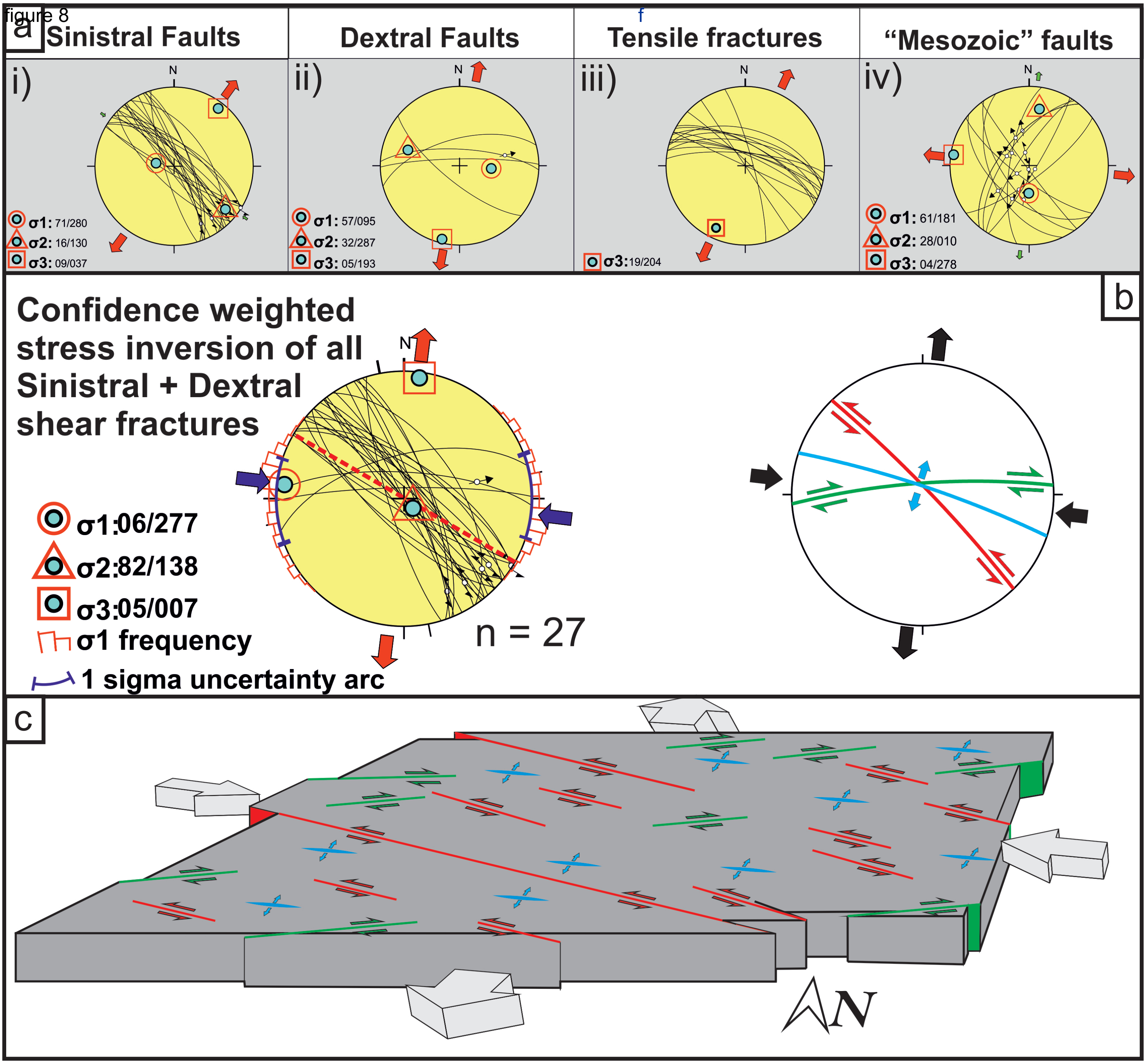
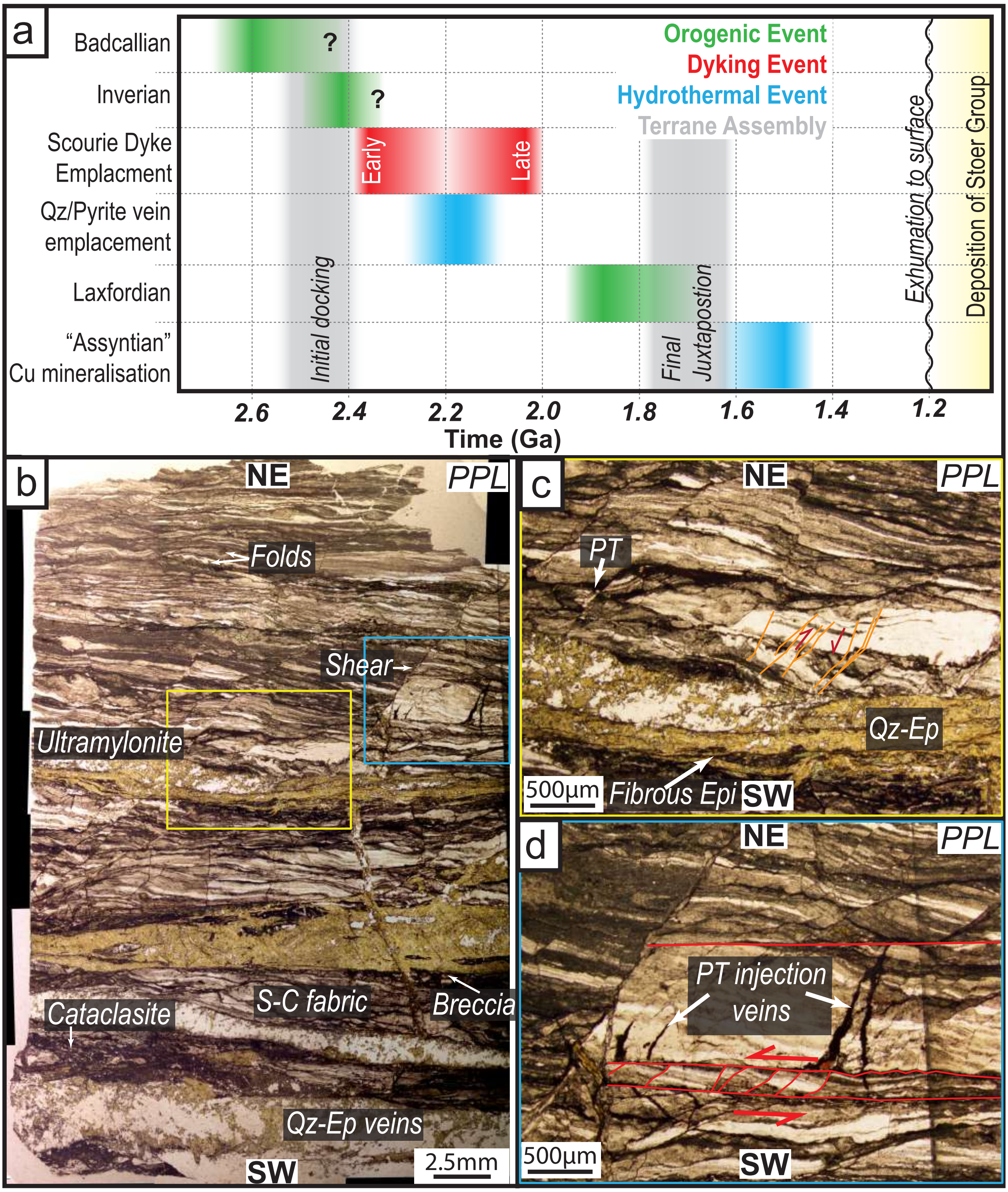

a
Sinistral Faults
Dextral Faults
Tensile fractures
“Mesozoic” faults
i)
ii)
iii)
iv)
N
σ1: 71/280
σ2: 16/130
σ3: 09/037
σ1: 57/095
σ2: 32/287
σ3: 05/193
σ3:19/204
σ1: 61/181
σ2: 28/010
σ3: 04/278
b
Confidence weighted stress inversion of all Sinistral + Dextral shear fractures
σ1:06/277
σ2:82/138
σ3:05/007
σ1 frequency
1 sigma uncertainty arc
n = 27
c
N

figure 9



a
Badcallian
Inverian
Scourie Dyke Emplacment
Qz/Pyrite vein emplacement
Laxfordian
"Assyntian" Cu mineralisation
Orogenic Event
Dyking Event
Hydrothermal Event
Terrane Assembly
?
?
Early
Late
Initial docking
Final Juxtapostion
Exhumation to surface
Deposition of Stoer Group
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
Time (Ga)
b
NE
PPL
Folds
Shear
Ultramylonite
Cataclasite
S-C fabric
Breccia
Qz-Ep veins
SW
2.5mm
c
NE
PPL
PT
Qz-Ep
500µm
Fibrous Epi
SW
d
NE
PPL
PT injection veins
500µm
SW