Major early thrusting as a control on the Palaeoproterozoic evolution of the Lewisian Complex: evidence from the Outer Hebrides, NW Scotland

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Abstract: New structural, metamorphic and geochronological data suggest that the Lewisian Complex of the Outer Hebrides can be interpreted as a Proterozoic orogen in which a thrust sheet of juvenile arc material was driven over Archaean gneisses at an early stage. Incubation and loading of the underlying Archaean gneisses triggered prograde metamorphism and extensive ductile deformation with a strong gravitational flattening component combined with top-to-the-WNW transport. Large shear zones developed at this time are of local importance, but are not fundamental structural boundaries. The recognition of early orogenic thrusting followed by extensive ductile deformation shows a close resemblance to the sequence of events recognized within the Nagssugtoqidian orogen, with which the Lewisian Complex is correlated. As in the Nagssugtoqidian orogen, younger penetrative ductile deformation often masks the major structural boundaries formed by older thrusts.

Supplementary material: Detailed structural and lithological maps of the Langavat Belt, and geochronological data and analytical methods description are available at www.geolsoc.org.uk/SUP18515.
The Southern Gneisses are largely 2.8 Ga TTG orthogneiss, but contain abundant minor metasedimentary–metabasite belts of uncertain age and affinity (Coward et al. 1969; Fettes et al. 1992; Whitehouse & Bridgwater 2001; Mason et al. 2004a). The gneisses are predominantly amphibolite facies, but small areas of granulate-facies gneisses occur in the south (Francis 1973).

The Harris Granulite Belt is a group of metasedimentary and meta-igneous (meta-anorthosite, metabasite, metadiorite) rocks derived largely from c. 1.9 Ga protoliths, metamorphosed relatively shortly after formation, under high-P granulite-facies conditions (Cliff et al. 1983, 1998; Schenk & Timmermann 1997; Baba 1998; Friend & Kinny 2001; Timmerman et al. 2001; Whitehouse & Bridgwater 2001; Mason et al. 2004a). Detrital zircons in the metasedimentary rocks are derived largely from a c. 1.9 Ga source (Friend & Kinny 2001; Whitehouse & Bridgwater 2001).

The Langavat Belt comprises amphibolite-facies metabasite, ultramafic rocks and metasedimentary material interleaved with highly deformed Archaean gneiss (Mason 2003; Mason et al. 2004a; Kelly et al. 2008). The main metasedimentary gneisses have never attained granulite-facies conditions and contain detrital zircons derived from a source comparable with the adjacent Archaean gneisses (Mason et al. 2004a).

The Northern Gneisses are predominantly 2.8 Ga amphibolite-facies TTG gneiss, locally with components as old as 3.125 Ga (Friend & Kinny 2001; Mason et al. 2004a; Kelly et al. 2008). The western portion of the Northern Gneisses hosts a large area of migmatization and c. 1.675 Ga granite and granite pegmatite intrusions (Fettes et al. 1992; Friend & Kinny 2001), the Injection Complex (Fig. 1).

The Ness Assemblage (Watson 1969) comprises quartzofeldspathic gneisses of largely unknown age, but including some Archaean material (Whitehouse & Bridgwater 2001), along with subordinate anorthosites, metadiorites and metasedimentary rocks. Whitehouse (1990) demonstrated a probably early Proterozoic age for the anorthosites.

OH dyke remnants are present within the Northern Gneisses, Southern Gneisses and Langavat Belt, but appear absent from the Harris Granulite Belt (Mason & Brewer 2004). Watson (1969) has also documented possible dyke remnants from the northern part of the Ness Assemblage.

Severe shears are present on the Outer Hebrides (Fettes et al. 1992). The Langavat Shear Zone has already been mentioned and is NW–SE striking and steeply SW dipping. Parallel to the Langavat Shear Zone and 10 km to the SW is the Berneray Shear Zone (Fig. 1). Perpendicular to the Langavat Shear Zone is the near-vertical Coastal Shear Zone (Fig. 1). Much of the Ness Assemblage also appears to fall within a flat-lying shear zone.

Various studies of the post-dyke deformation history of the Outer Hebrides (e.g. Watson 1968; Coward et al. 1970; Myers 1971; Francis 1973; Graham & Coward 1973; Fettes et al. 1992) have recognized the main deformation (D3) as a phase of widespread and often intense vertical shortening. This phase recumbently folded and fragmented the dykes and transposed older structures producing a flat-lying regional gneissic fabric (F3 of Coward et al. 1970; Davies et al. 1975; Lisle 1977; and dL2 of Fettes et al. 1992). A phase of more upright NW–SE folding (D4) followed. Superimposition of D3 on the D2 grain has been considered to have produced the currently observable large-scale structure, considered to be a series of broad antiforms separated by tight, high-strain synforms. D3 deformation is poorly understood. In this structural framework, the Harris Granulite Belt sits in a major D3 synform, whereas Berneray straddles the corresponding antiform and another synform.

The Ness Assemblage

The main outcrop of the Ness Assemblage (Figs 1 and 2) occurs north of a line running WNW from near Cellar Head on the east coast to Dell Sands on the NW coast (Watson 1969; Fettes et al. 1981). A second smaller outcrop occurs near Melabost on the NW coast (Fig. 2b).

Within the main outcrop, two lithological areas can be recognized. The first comprises the area east and north of Eoropie, and contains mainly flaggy high-strain hornblende gneisses, possibly...
amphibolite pods (OH dyke remnants) that are absent from the
(Fig. 2b and c). The adjacent Northern Gneisses contain numerous
garnet porphyroblasts that forms large rafts within sparsely por-
ymphlitic metadiorite, and calc-silicates, although similar high-strain felsic gneisses still form much of the assem-
blage, and locally this can be seen to be intruded by the anorthosites.
Most lithologies are strongly foliated (the main exception being the anorthosites) and have foliation-parallel contacts.

The east coast is poorly accessible and inland exposure is scarce. On the west coast at Dell Sands (Fig. 2c), the Ness Assemblage
overlies the Northern Gneisses; the contact is moderately NE dip-
ing. This dip persists through a c. 1 km wide border zone that to the NE gives way to a larger zone with an overall gentle east to ESE dip. The transition occurs in a synformal zone, the hinge of which is marked by a belt of tight, upright, gently plunging, and NW–SE-trending folds flanked by more open folds. This area appears to represent a ‘crumple zone’ accommodating the steepening of the SW border zone with respect to the flatter area to the NE.

Around Eoropie (Fig. 2a), NNE–SSW-trending subhorizontal, WNW-facing (s-folds looking north), disharmonic folds are develop-
ed, which towards the Butt of Lewis become increasingly promi-
inent, and modify the overall gentle eastwards dip. Comparable folds appear to be developed along at least part of the eastern coast section (e.g. at Caiashader Shore, Fig. 2d). The axes of these folds appear to be approximately perpendicular to the regional lineation, which typically plunges gently to the ESE. θ-type feldspar fish, and δ-type rotated calc-silicate pods observed at Caiashader Shore (Fig. 2d) suggest top-to-the NW transport associated with the lineation, con-
sistent with the sense of asymmetry of the folds described above.

SW from Dell Sands, the strike rotates anticlockwise bringing the Ness Assemblage back onto land at Melabost (Fig. 2b), where the rocks are NE–SW striking, and steeply NW dipping. The Ness Assemblage overlies the Northern Gneisses; the contact is highly sheared. The rocks at Melabost are irregularly banded, somewhat migmatisitic amphibolite with minor clinopyroxene and sporadic garnet porphyroblasts that forms large rafts within sparsely por-
ymphlitic foliated metadiorite; similar rocks occur at Dell Sands (Fig. 2b and c). The adjacent Northern Gneisses contain numerous amphibolite pods (OH dyke remnants) that are absent from the
metadiorite, and are texturally unlike its enclosed amphibolite rafts. The main foliation is NE–SW striking, steeply inclined, and parallel to the general trend of the lithological boundaries. Unlike OH dykes in other high-strain zones, such as the Langavat Belt (see below), those within the highly sheared Archaean gneisses at Melabost are anomalously strongly podded. The pod cores retain remnants of a steeply inclined foliation highly oblique to the main NE–SW foliation; remnants of an oblique foliation are likewise seen within the adjacent Ness Assemblage rocks.

The Melabost outcrop falls within the Coastal Shear Zone (Fig. 1). The rotation of the foliation and the displacement of the Ness Assemblage indicate apparent sinistral movement along this zone. The complex foliation relationships at Melabost are absent in the equivalent rocks at Dell Sands. The earlier oblique foliation at Melabost may well represent the traces of the NW–SE structural grain present at Dell Sands, which at Melabost has been overprinted by the Coastal Shear Zone.

The Langavat Belt

The Langavat Belt is sigmoidal with an overall moderate to steep SW dip (Fig. 3), and is above the Northern Gneisses and beneath the Harris Granulite Belt (Mason et al. 2004b). Seven main litho-
logical units have been described by Mason et al. (2004b), which from structurally lowest to highest are: (1) Sta Series; (2) Sta Amphibolite; (3) Borve Series; (4) Langavat Amphibolite; (5) Langavat Series; (6) Borsham Metagabbro; (7) Banded Series.

The Sta Series is largely of metasedimentary origin, and includes marble, calc-silicates, and semi-pelitic and rare pelitic gneisses. The Sta Series is not migmatized. The overlying Sta Amphibolite is a generally fine-grained discordant metabasite.

The Borve Series comprises strongly foliated Archaean tonalites (Mason et al. 2004b) with a c. 2.8 Ga protolith age comparable with that of the Northern Gneisses (Kelly et al. 2008). There are also subordinate, sparsely garnetiferous semi-pelites, at [NG 0255 9450] to [NG 0410 9280] (UK national grid reference), which have a striped and migmatisitic appearance unlike those of the Sta Series; their relationship to the tonalites is unknown. The tonalites, the semi-pelites, and the migmatisitic veining within the semi-pelites are cut by probable OH dykes, at [NG 0255 9450]. The Borve Series semi-pelites thus record pre-OH dyke metamorphism. The Borve Series contains at least two horizons of ultramafic pods (Fig. 3).
The Langavat Amphibolite comprises heterogeneous, generally coarse-grained amphibolite with numerous ultramafic pods. The Langavat Series comprises finer grained, pinkish-weathering amphibolite with subordinate sparsely garnetiferous, non-migmatized semi-pelites, comparable with those in the Sta Series.

The Borsham Metagabbro is a coarse-grained, concordant, foliated amphibolite with relict igneous textures occasionally preserved; it is intruded by thin tonalitic sheets.

The Banded Series is a group of strongly deformed striped or banded rocks derived from a range of protoliths, which at outcrop scale are stretched out into near perfect parallelism.

The OH dykes within the Langavat Belt are concordant or very nearly concordant bodies of strongly foliated amphibolite. Relict igneous textures are occasionally preserved.

The main lithological units are tabular to slightly boudinaged, but laterally maintain a fairly consistent sequence, apparently without repetition by folding.

The Langavat Belt is parallel to, and within the Langavat Shear Zone. Almost all of the rocks within the Langavat Belt (and the adjacent margins of the Harris Granulite Belt and Northern Gneisses) are tectonites related to the Langavat Shear Zone. These can be divided into an older amphibolite-facies group, now highly annealed (Type-1), and a younger little-annealed greenschist-facies group (Type-2) (Mason et al., 2004b). These are largely separated by the intrusion of 1675–1657 Ma granite pegmatites, from which the Type-2 tectonites are commonly derived (Mason et al., 2004b; Mason & Brewer 2005). Mason et al. (2004b) considered the Langavat Belt to be a pre-Type-1 tectonite imbricate zone.
Deformation associated with the Type-2 tectonites is significant only within the lower part of the Banded Series, and has been described fully elsewhere (Mason & Brewer 2005). Within the remainder of the belt, a Type-2 tectonite overprint is limited to superficial foliation-parallel dextral-normal shear zones, and trains of open to moderately tight z-geometry drag folds.

This study focuses on the Type-1 tectonites and their protoliths, and follows on from the work of Mason et al. (2004b).

**Fabrics and deformation history**

The Type-1 tectonites contain three main fabric elements (Fig. 3): (1) an almost ubiquitous moderately to steeply SW-dipping composite foliation, which parallels the major lithological boundaries, and is continuous with the gneissic foliation in the Northern Gneisses; (2) a NW-pitching (WNW-plunging) stretching lineation (L1) developed on the above foliation; (3) a SE-pitching (south-plunging) stretching lineation (L2) developed on the above foliation. It is the intensity of development of these fabrics that delimits the Langavat Shear Zone.

The relationship between L1 and L2 is best seen around Loch Dubh Sletteval (Fig. 3), where several of the lithological divisions thin dramatically southwards, and define kilometre-scale boudins. Within the cores of these, L1 is relatively well preserved. The boudins are mantled by domains of chaotic lineation, which pass southward into stable L2 domains as the belt is further attenuated; that is, the boudin cores represent L2 low-strain zones, and hence L2 is younger than L1.

L1 plunge/trend measurements cluster around 36°/295° with a secondary maximum around 45°/250° (Fig. 3). L1 measurements cluster around 35°/180° and bisect the obtuse angle between the two L1 clusters; the secondary L1 cluster presumably results from L1 being deflected and partially reoriented about the L1 orientation.

Domains with an incomplete L1 overprint are characterized by a chaotic lineation orientation. L1 and L2 sometimes coexist with L1 preserved as a penetrative rodding defined by stretched mineral aggregates, and L2 defined by an incipiently developed mineral elongation lineation. L1 becomes dominant to the SE, and is particularly pervasive for around 1.5 km south of Loch Dubh Sletteval (Fig. 3). Further SE, within the lower part of the belt and the adjacent Northern Gneisses, as the strike swings to east–west, a domain of anomalous dip-slip lineation is developed (Fig. 3); this will be regarded as the Northern Gneisses, as the strike swings to east–west, a domain of anomalous dip-slip lineation is developed (Fig. 3); this will be regarded as the

Two further crystals (both are exposed on the surface and contain pervasive, but it is not known whether these represent traces of bedding, an earlier tectonic fabric, or a locally rotated early component of the main foliation.

Rare pelites within the Sta Series (at [NG 0431 9331], Fig. 3) contain the assemblage quartz–K-feldspar–cordierite–sillimanite–garnet–biotite.

Cordierite does not coexist with garnet and sillimanite in the assemblage, whereas staurolite occurs sometimes as inclusions within garnet. The following prograde reaction (Xu et al. 1994) can explain the assemblage:

\[
\text{cordierite} + \text{sillimanite} + \text{quartz} \rightarrow \text{garnet} + \text{sillimanite}.
\]

The inclusions of staurolite in garnet indicates the reaction was proceeding from left to right (prograde), but did not go to completion, hence the surviving cordierite + staurolite. The lack of muscovite suggests that the slightly higher temperature reaction (Xu et al. 1994) was not crossed:

\[
\text{biotite} + \text{sillimanite} + \text{quartz} \rightarrow \text{muscovite} + \text{garnet} + \text{sillimanite}.
\]

According to Xu et al. (1994), the former reaction occurs between 590°C at 3.7 kbar and 641°C at 6.1 kbar and semi-quantitatively constrains peak metamorphic conditions in the Sta Series.

Sample SH01-70, from the same location, contains a SW-dipping foliation and L1, lineation defined by centimetre-scale elongate mineral aggregates, most conspicuously of garnet. Sillimanite occurs as fibrous mats and slender prisms; the latter form radial splays that cut across the foliation (largely defined by biotite) and are clearly post-tectonic with respect to the foliation and L1. The fibrous sillimanite forms foliation-parallel mats, but the single needles are not aligned. The same gneiss also contains well-developed S–C fabrics, defined by aggregates of the same minerals that define L1. The S–C fabrics indicate a dextral component of motion: dextral-normal with the SW dip of the foliation and NW pitch of the L1 stretching lineation.

Garnet semi-pelites developed at [NG 0559 8877] (Fig. 3) contain 3–4 cm anhedral garnet porphyroblasts with prominent inclusion trails. At this location, much of the matrix has been weathered away, allowing the porphyroblasts, and their inclusion trails, to be seen in three dimensions. A sample from these gneisses (SH00-147, Fig. 4) contains tabular garnets with planar inclusion trails defining a foliation, which is frequently parallel to, and continuous with the SW-dipping foliation in the matrix, and perpendicular to the short axis of the enclosing crystal (i.e. these garnets appear to have grown along the foliation) (Fig. 4). The foliation surfaces within the garnets carry a fine NW-pitching L1 lineation. The matrix is dominated by L2, but where the tabular garnets still lie in the plane of the main foliation, the L1 remnants are consistently oriented between adjacent porphyroblasts. Another crystal is markedly elongated parallel to, and boudinaged perpendicular to L1. Two further crystals (both are exposed on the surface and contain L1, and a SW-dipping foliation) have 6-type geometry rotated cores (Fig. 4). Combined with the other evidence, syn-L1 garnet growth is indicated, and the sense of rotation of the garnet cores, along with the SW dip of the foliation and the NW pitch of L1, implies a dextral-normal movement (it should be noted that the sample is viewed from below in Fig. 4, and thus appears sinistral).

The relationship of L1 to the garnets in SH00-147, and to the garnet–sillimanite assemblage in SH01-70, implies syn-L1 prograde amphibolite-facies metamorphism that peaked post-L1. Furthermore, because the main foliation passes through the cores of the large garnets in SH00-147, its oldest component appears to have been formed under low-grade (i.e. sub-garnet-grade) conditions, prior to amphibolite-facies metamorphism.

Deformation and metamorphism of the Sta Series

The Sta Series contains L1, L2, and the NW–SE-striking composite foliation. Crenulated relics of an older oblique ‘fabric’ are locally
A general feature of many garnets within the Sta Series is the presence of distinct overgrowths. The cores are typically very rich in both quartz and opaque inclusions, whereas the overgrowths typically contain only opaque inclusion trails. In some cases, the overgrowths passively enclose opaque grains paralleling the matrix foliation, and appear post-tectonic. Some crystals comprise only the post-tectonic component.

Deformation fabrics in other lithological units

All units contain the main composite foliation. The Sta Amphibolite and Borve Series both contain well-preserved L₁ domains (Fig. 3); L₁ is traceable into the Northern Gneisses. L₂ is less well preserved in the Langavat Series and Langavat Amphibolite, which are dominated by L₂. A NW-pitching hornblende-defined mineral lineation is present in the Banded Series, but only rarely, suggesting that L₁ was developed but has now largely been replaced by L₁ (Fig. 3).

The Borsham Metagabbro is somewhat anomalous in that most units display well-developed L₁ where L₂ is absent, but this is not the case for the Borsham Metagabbro; where L₂ is absent, this unit is weakly deformed and L₁ is only feebly developed (Fig. 3). L₁ is strongly developed in the felsic sheets cutting the Borsham Metagabbro.

L₂ is traceable into the margin of the Harris Granulite Belt and is associated with total retrogression to amphibolite facies; L₁ is not apparent, but may have been obliterated by the L₂ overprint.

Intense L₁ and L₂ fabrics are developed within the OH dykes, indicating that they predate both fabrics. As the OH dykes are followed out of the Langavat Shear Zone the deformation style changes, and although they become less deformed, the dykes are boudinaged and disrupted into blocks and trains of pods.

Relationship of the Langavat Shear Zone to the Injection Complex

Injection Complex granites become increasingly abundant as the Langavat Belt is approached until c. 200–300 m below the Sta Series where they almost entirely disappear. The granites typically are only slightly deformed and can be seen to intrude highly tectonized gneisses with a probably L₁ lineation (e.g. at [NG 034 962]); their near-total disappearance 200–300 m below the Langavat Belt is not associated with intense deformation of the granites themselves.

Conversely, granite pegmatites continue throughout the Langavat Belt and Harris Granulite Belt. They cross-cut the fabrics in the...
The banding shows σ-type geometry deflection within the Sta Series is oblique to the strain shadow created by the asymmetric boudinage (Fig. 3). The intensity of deformation of the Borsham Metagabbro correspondingly sits deformed portion of the Borsham Metagabbro. Deformation, dextral-thrust movement is indicated, and the less undeformed. Lineations are not well developed or well preserved in this area, making correlation with L1 or L2 uncertain.

Figure 5. L2 shear-sense criteria in the Langavat Belt. (a) Asymmetric boudins separated by shear band in the Banded Series [NG 069 863]. Vertical surface, SSW to the left. The boudin neck can be seen to be perpendicular to L2 on the left side of the outcrop. The similarity of geometry to the kilometre-scale boudinage developed in the north of the belt (Fig. 3) should be noted. Horizontal field of view c. 10 cm. (b) Low-angle shear bands dissecting felsic sheets in the Borsham Metagabbro [NG 0595 8744]. Horizontal surface, SW towards left. Pen c. 15 cm long. Type-1 tectonites, and usually show little deformation (except in the zone of Type-2 tectonites). The only significant exception is seen within the Archaean gneisses c. 150 m below the Sta Series along the NW coast around Borvebeg Burn (Fig. 3), where the rocks comprise interbanded amphibolite, Archaean gneiss and strongly deformed granite pegmatite; only a few of the largest pegmatites are undeformed. Lineations are not well developed or well preserved in this area, making correlation with L1 or L2 uncertain.

Kinematic criteria and apparent transport directions

Kinematic criteria associated with L1 have already been described and indicate oblique-slip dextral extension. Given the orientation of L1, this translates approximately to top-to-the-WNW movement. The gross orientation of L2 implies either top-to-the-north (dextral-thrust) or top-to-the-south (sinistral-normal) movement. Macroscopic kinematic criteria are present in several areas. Around Loch na Cartach the Langavat Belt displays an asymmetric boudin neck associated with an enhanced L2 overprint (Fig. 3). Within this neck is a NNE–SSW-striking oblique shear, which, based on the displacement of the Langavat Amphibolite, has a dextral component of movement. The intensity of deformation of the Borsham Metagabbro drops significantly across this structure to the NW. If we make the assumption that the oblique shear zone is synthetic to the main L2 deformation, dextral-thrust movement is indicated, and the less deformed portion of the Borsham Metagabbro correspondingly sits in the strain shadow created by the asymmetric boudinage (Fig. 3).

South of Loch Dubh Sletteval, L2 is strongly developed, and the lithological banding within the Sta Series is oblique to the series boundaries. The banding shows σ-type geometry deflection (Fig. 3), suggesting a dextral component of movement. Moreover, the curvature of the Langavat Belt implies that the SE portion of the belt has moved southward (dextrally) relative to the NW portion across this L2 domain. In this regime, the east–west-striking, SE part of the Belt would form a frontal ramp, explaining the domain of anomalous dip-slip lineation in this area.

Mesoscopic L2 shear-sense criteria are best demonstrated in L2–dominated hornblende-rich lithologies where greenschist-facies Type-2 tectonite overprints are most easily avoided. Mesoscopic analogues of the large-scale asymmetric boudinage (Fig. 5a), and deflected oblique banding have been observed, along with low-angle shear bands (Fig. 5b), and have a consistent sense of shear (i.e. dextral-thrust). Millimetre-scale and microscopic structures such as σ-type feldspar fish and S–C fabrics, show an inconsistent shear sense, and the unusually fine-grained fold-associated L2 domains appear to be dominated by either z-geometry drag folds or s-geometry drag folds, again suggesting inconsistent shear sense. Based on the two different styles of deformation associated with L2, and the inconsistent small-scale kinematic criteria, it is suggested that at least one minor, younger deformation event is superimposed on the main dextral-thrust event that formed the bulk of L2. Localized zones of slightly younger reworking provide an explanation for the area around Borvebeg Burn where the Injection Complex pegmatites are anomalously incorporated into the Type-1 tectonites, contrary to their usual post-L2 relationship.

Berneray

Berneray (Fig. 1) has an overall SW-facing monoclinal structure, with the steep middle limb formed by a c. 2.5 km wide high-strain zone with a steep SW dip, and a generally subhorizontal to moderately NW-pitching lineation (L1). The rocks comprise mainly tonalitic gneisses and early granite, both cut by highly deformed, but little disrupted OH dykes. A thin strip of pelitic gneiss is present (at [NF 9295 8170]) with large garnet porphyroblasts with curved, presumably synkinematic inclusion trails, and sillimanite oriented parallel to the lineation. Definitive shear-sense criteria have not been observed, but the monoclinal structure suggests a component of downthrow to the SW (i.e. dextral-normal, when considered with the NW-pitching lineation and SW dip). Granite pegmatites are present and are mainly strongly deformed. Towards the edges of the shear zone (particularly on the NE coast) NW–SE-trending, metre-scale recumbent folds are abundant, but they are less frequent within the core of the shear zone. On the northern coast ([NF 925 838]) there is an anomalous zone in which the recumbent folds have been attenuated, and the granite pegmatites have been strongly deformed and a new SE-pitching lineation (L3) is developed.

The Berneray and Langavat Shear Zones show a comparable deformation style where the OH dykes are strongly stretched and flattened, but with little disruption. This contrasts with the more moderately deformed areas that dominate the Archaean gneisses where the dykes are usually disrupted into blocks or trains of pods.

Geochronology

Timing of metamorphism in the Ness Assemblage

To constrain the timing of metamorphism of the Ness Assemblage, monazite has been dated from pelitic gneiss (OH04-3) from Caishader Shore ([NB 5585 6108], Fig. 2d). The sample originates from a c. 2 m thick layer of garnet–biotite–sillimanite gneiss within locally gneissic quartzofeldspathic gneiss. The nature of the contacts could not be determined, but both the pelite and the adjacent rocks contain a gently inclined foliation and gently SE-plunging
amphibolite-facies stretching lineation. Nearby, a c. 3 m thick deformed anorthosite dyke cuts the quartzofeldspathic gneisses. The sample contains scattered felsic blebs, which may record incipient migmatization, and as far as possible these were removed.

The four monazite analyses fall to the right of concordia between c. 1820 and c. 1904 Ma (Fig. 6a). The array shows some scatter in excess of analytical uncertainty (MSWD=3.8), but there is an inverse correlation between $^{206}\text{Pb}/^{204}\text{Pb}$ and the degree of discordance, implicating Pb diffusion or radiogenic Pb loss. Regression of the three least discordant analyses yields an (upper intercept) age of 1911 ± 7 Ma (95% confidence, MSWD = 1.1) considered to represent the timing of monazite growth, and hence the timing of metamorphism. It should be noted that these data are plotted in $^{207}\text{Pb}/^{206}\text{Pb}$–$^{238}\text{U}/^{206}\text{Pb}$ space because of the lower precision of the measured $^{207}\text{Pb}/^{235}\text{U}$ ratios.

Age of deformation in the Langavat Belt

Sample SH01-64 from near Borsham ([NG 0792 8639] Fig. 3) is a tonalitic sheet cutting the Borsham Metagabbro, and containing an intense $L_2$ lineation.

The zircons comprise two populations: small (<150 µm long) slender euhedral prisms and anhedral, irregular, rounded grains. Backscatter SEM imaging reveals prominent dark oscillatory-zoned cores embayed and overgrown by much brighter zircon with weaker oscillatory zoning. Some grains comprise only the darker zircon. Both components are considered to be of magmatic origin.

The results are shown in Figure 6b. Two single-grain analyses, a euhedral prism (Z110) and an irregular grain (Z113), yield concordant ages of 1746 ± 6 Ma and 1873 ± 4 Ma (2σ), respectively. Given the difference in these ages, the zircon population is complex, consistent with the grain morphologies and imaging. The $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1880 ± 3 Ma (2σ) from analysis Z111 (a euhedral prism) indicates the presence of a component slightly older than the apparent age of Z113. The remainder of the analyses are considered to represent mixing between a c. 1880 Ma inherited component and a ≤1746 Ma indigenous component, with superimposed Pb loss in some analyses. The mixing line is extremely close to concordia, and hence the 1746 Ma analysis could be significantly biased by an inherited component and still overlap concordia. The 1746 Ma age should thus be taken as the maximum intrusion age, and the maximum age for $L_2$. The inheritance is similar in age to the metadiorite in the overlying Harris Granulite Belt (Mason et al. 2004a).

Discussion

Regional ductile deformation

The $L_2$ deformation in the Berneray Shear Zone and the $L_1$ event in the Langavat Shear Zone are comparable in terms of style, orientation of fabrics, and apparent top-to-the-NW or -WNW transport direction and shear sense (oblique dextral-extension). Both zones appear to have been coeval with prograde amphibolite-facies metamorphism, and to be unaffected by the events responsible for dismembering the OH dykes in areas of more moderate deformation. The Ness Assemblage main outcrop, although not steeply inclined, also records top-to-the-NW transport, suggesting all three high-strain zones were initiated, or at least active, during a common event. The lack of dyke fragmentation in the Langavat and Berneray Shear Zones compared with the more moderate areas of deformation in the Archaean gneisses indicates they must have been initiated at an early stage during ductile deformation, before the dykes became fragmented.

In terms of the regional structural framework (Watson 1968; Coward et al. 1970; Myers 1971; Francis 1973; Graham & Coward 1973; Davies et al. 1975; Lisle 1977; Pettiet et al. 1992), the $D_2$ shear zones thus represent the onset of regional $D_2$ in terms of the development of the shear zones. The apparent extensional component of movement in the Langavat and Berneray Shear Zones during $L_1$ is consistent with the vertical flattening ascribed to $D_2$ (e.g. Graham & Coward 1973).

The Harris Granulite Belt supposedly sits in a major $D_3$ synform (e.g. Coward et al. 1970) and the Berneray Shear Zone forms the steep common limb between the corresponding antiform and another synform. However, in the interpretation presented here, the Harris Granulite Belt can also be considered to sit in a $D_2$ ductile half-graben controlled by the Langavat Shear Zone (Fig. 1). Likewise, the large folds flanking the Berneray Shear Zone can be interpreted as drag features related to the shear zone. This is more self-consistent than $D_3$ controlling the major structure, because on Berneray the supposedly steep limb of a major $D_2$ fold pair (i.e. the Berneray Shear Zone) is folded by recumbent $F_2$ folds. Neither interpretation...
accounts for the Harris Granulite Belt sitting above lower-grade rocks, or provides a loading mechanism to produce D₂ flattening; both appear to require some sort of additional pre-D₂ event.

Both the Berneray and Langavat shear zones show evidence of reaction of reactivation associated with the formation of a new lineation (local L₂ events), which in the former zone distorts (regional) D₁ folds. The top-to-the-north transport direction associated with (local) L₂ in the Langavat Shear Zone suggests north–south compression; the sinistral Coastal Shear Zone could then be a conjugate zone (Fig. 1). The complex foliation relationships at Melabost suggest that the Coastal Shear Zone cuts the presumably D₁ L-S fabric system in the main Ness Assemblage outcrop, further supporting correlation with the (local) L₂ event in the Langavat Shear Zone. Age constraints from the Langavat Belt indicate that this reactivation occurred after c. 1.746 Ma, but mostly prior to the 1675–1657 Ma granite pegmatites associated with the Injection Complex. This reworking is of post-D₂ age, but it is not at present clear how this relates to D₂ folding.

The Type-2 tectonites in the Langavat Shear Zone post-date the Injection Complex, which itself partially post-dates D₁ (Fettes et al. 1992).

Evidence for major thrusting in the Langavat Belt

The Borve Series tonalites and Northern Gneisses are indistinguishable (Mason & Brewer 2004; Mason et al. 2004b; Kelly et al. 2008), and on metamorphic and geochronological grounds are demonstrably older than the interleaved Sta Series.

Folding capable of accounting for this interleaving is not observed, implying imbrication by thrusting.

The Sta Series records amphibolite-facies metamorphism peaking around 590–641 °C at 3.7–6.1 kbar, contrasting sharply with c. 800 °C at 13–14 kbar recorded in the overlying Harris Granulite Belt (Baba 1998). Assuming a normal lithostatic pressure gradient, vertical displacement of the order of 25 km is indicated, further implying thrusting, and on a massive scale. Inherited c. 1880 Ma zircons in the felsic sheet cutting the Borsham Metagabbro indicate the possible presence of rocks derived from the overlying Harris Granulite Belt; hence the major structural break may fall within the Langavat Belt rather than at the contact with the Harris Granulite Belt. The semi-pelites in the Langavat Series are notigmatized, and therefore are unlikely to have undergone granulite-facies metamorphism, and thus are below the major structural break.

The Sta Series had been buried and was undergoing amphibolite-facies metamorphism during L₁ deformation. L₁ is common across the Langavat Belt. Therefore L₁ dextral thrusting cannot have initially buried the Sta Series. However, L₂ deformation reaches its maximum intensity above the Sta Series, and thus may have resulted in further burial, accounting for a second pulse of garnet growth marked by the commonly observed rims. The L₁ deformation has an apparent extensional component, and thus cannot easily account for either the Harris Granulite Belt being placed over the Langavat Belt, or the imbrication and burial of the Sta Series. Moreover, neither L₁ nor L₂ deformation formed discrete shear zones bounding the Sta Series that could have accommodated the interleaving.

The Langavat Shear Zone is defined by L₁- and L₂-related deformation. As neither event seems capable of explaining the assembly of the belt, pre-Langavat Shear Zone thrusting must be considered (see Mason et al. 2004b). The earliest components of the main foliation in the Sta Series predate garnet growth, and therefore must relate to initial burial or events shortly after (i.e. pre-amphibolite-facies metamorphism). The main foliation forms the continuation of the regional D₂ fabric in the Northern Gneisses, suggesting that regional D₂ began around the time the Sta Series was initially buried, and hence around the time of thrusting.

Comparison of the Ness Assemblage and Harris Granulite Belt

The Harris Granulite Belt and Ness Assemblage both contain relatively rare lithologies, notably anorthosite and metadiorite. Presumed OH dyke remnants, abundant in the Archaean gneisses, are absent in the metadiorites of Ness; likewise, they are absent from the c. 1.9 Ga rocks of the Harris Granulite Belt (Mason & Brewer 2004). In both areas, the metadiorites intrude or contain rafts of irregularly banded metabasite (see above, and Deanley 1963). Timmerman et al. (2001) have obtained a c. 1.910 Ma monazite age from the metasemides of the Harris Granulite Belt, comparable with the 1911 ± 7 Ma age obtained here. Whitehouse & Bridgwater (2001) also obtained a c. 1.860 Ma U–Pb date from a probable Archaean (but geochronologically complex) orthogneiss within the Ness Assemblage and comparable with Sm–Nd mineral isochron ages obtained from the Harris Granulite Belt (Cliff et al. 1983). This is significant because several geochronological studies have failed to find evidence of comparable metamorphism in the Northern and Southern Gneisses (Cliff et al. 1998; Friend & Kinny 2001; Whitehouse & Bridgwater 2001; Mason et al. 2004b; Kelly et al. 2008).

Comparison of the Northern and Southern Gneisses

Protolith ages of the Northern and Southern Gneisses are comparable, with 2800–2850 Ma ages dominating (Friend & Kinny 2001; Whitehouse & Bridgwater 2001; Mason et al. 2004a; Kinny et al. 2005; Kelly et al. 2008). Kelly et al. (2008) reported evidence for a 2.730 Ma high-grade metamorphism in the Northern Gneisses. A c. 2.730 Ma age for granulite-facies metamorphism has also been reported in the south for gneisses on Barra (Fig. 1) above the Outer Hebrides Fault Zone (Kinny et al. 2005). Francis (1973) correlated these granulite-facies gneisses with similar gneisses beneath the Outer Hebrides Fault Zone, suggesting a relatively modest displacement, and hence the 2.730 Ma metamorphic age is also probably representative of the Southern Gneisses. Mafic dyke remnants (i.e. the OH dykes) within both the Northern and Southern Gneisses areas are comparable (Mason & Brewer 2004), and the deformation histories appear identical.

Regional architecture

It is envisioned that there are only two main terranes on the Outer Hebrides, one below the other, and separated by a major thrust zone (Fig. 1): (1) the lower comprises c. 2.8–2.85 Ga orthogneisses metamorphosed around 2.73 Ga and supracrustal cover imbricated with the orthogneisses during thrusting, plus the OH dykes; locally migmatized c. 1675 Ma; (2) the upper includes abundant Proterozoic juvenile rocks, distinctive meta-igneous rocks including anorthosite and metadiorite, and some highly reworked Archaean orthogneisses, all metamorphosed c. 1.91–1.86 Ga prior to thrusting.

The Harris Granulite Belt and Ness Assemblage represent fragments of the latter, isolated by a combination of younger deformation and erosion, whereas the Northern and Southern Gneisses represent windows through the overlying thrust sheet exposing the same lower terrane (Fig. 1). This explains why 1910–1860 Ma high-grade metamorphism is absent from the underlying Archaean gneisses or Langavat Belt, but is present in areas now separated by c. 80 km, and why the Northern and Southern Gneisses are indistinguishable from each other.
Regional early thrusting (regional D₁) interleaved the Archaean gneisses with their supracrustal rocks and buried them beneath the upper terrane. Subsequently, the Langavat Shear Zone was initiated with a dextral-normal shear sense (L₁ event) as part of regional D₂, deflecting the major thrust downward to the SW, and leaving what is now the Harris Granulite Belt as a klippe preserved in the hanging wall. The view of the Harris Granulite Belt as an outlier is consistent with geophysical evidence that it extends only to around 7 km depth (Westbrook 1974).

The loading of the lower terrane by the upper terrane provides a mechanism for producing vertical shortening associated with regional D₂ (i.e., F₂ of Coward et al. 1970; Davies et al. 1975, etc.), and accounts for the extensional component of the Langavat and Berneray Shear Zones. Incubation of the lower terrane by the thrust sheet additionally provides a driving mechanism for the metamorphism of the lower terrane (and newly buried Sta Series) that culminated in the c. 1675 Ma Injection Complex. Moreover, the extensional movement of the Langavat Shear Zone could have assisted the unroofing or uplift of the deeper, hotter parts of the Northern Gneisses in the Langavat Shear Zone footwall, making it a particularly favourable site for subsequent migmatization, hence the location of the Injection Complex.

There is around 195 Ma between the exhumation of the Harris Granulite Belt c. 1870 Ma (Cliff et al. 1983) and the formation of the Injection Complex c. 1675 Ma (Friend & Kinny 2001) making it unlikely that D₁ thrusting was both associated with exhumation of the Harris Granulite Belt and the driving mechanism for c. 1675 Ma metamorphism. The estimated peak metamorphic pressure in the Sta Series is substantially lower than that in the Harris Granulite Belt, indicating that much of the overburden on the Harris Granulite Belt must have been removed prior to its emplacement over the Langavat Belt, favouring the latter possibility. Also, given that prograde metamorphism was occurring in the Langavat Belt during L₁ (regional D₁) and peaked sometime after, and that the Langavat Belt appears to still have been relatively cold during c. 1675 Ma migmatization of the Northern Gneisses (the Langavat Belt not being significantly migmatized), argues for early thrusting, the initiation of the Langavat Shear Zone, and the formation of the Injection Complex all happening in fairly rapid succession. It is possible that D₁ and D₂ are stages of the same top-to-the-WNW event, the event progressing from low-grade thrusting towards pervasive ductile deformation with local extensional components or gravitational flattening, as an inevitable consequence of the weakening of the lower terrane by the prograde metamorphism initiated by the event itself.

The Harris Granulite Belt constitutes part of a 1.9 Ga continental volcanic arc (Baba 1998; Mason et al. 2004a), with a high proportion of juvenile igneous material and only relatively minor older components (Cliff et al. 1983; Friend & Kinny 2001; Whitehouse & Bridgewater 2001; Mason et al. 2004a). Based on the current examination, and the geochronology of Whitehouse & Bridgewater (2001), the Ness Assemblage is compositionally intermediate between the lower terrane and the Harris Granulite Belt, inasmuch as it probably contains a high proportion of Archaean rocks, but only a small proportion of anorthosites and metadiorites comparable with those in the Harris Granulite Belt. It is suggested that the Ness Assemblage represents the original interface between the lower terrane (or another Archaean block) and the arc rocks of the Harris Granulite Belt.

**Comparison with the mainland Lewisian**

The model outlined here has some parallels with that proposed for the Loch Maree Group (Fig. 1) by Park et al. (2001). They regarded this unit as a subduction–accretion complex marking the suture between blocks of Archaean gneiss, and separated from them by thrusts. They also recognized c. 1.9 Ga juvenile felsic rocks (Ard Gneiss), and a phase of early ductile deformation related to top-to-the-NW transport (their D₂/D₃ event). Park (2010) correlated D₂ in the Loch Maree Group with the Type-1 tectonites in the Langavat Shear Zone. This correlation is complicated by the presence of two events in the Type-1 tectonites; however, correlation with the L₁ event is permissible based on the common transport direction. Younger deformation associated with folding and dextral shearing of the Loch Maree Group (D₃ of Park 2010) was correlated with D₁ on the Outer Hebrides, and more specifically with the Type-2 tectonites of the Langavat Shear Zone. However, the Type-2 tectonites post-date the Injection Complex, which is itself of syn- to post-D₃ age (Fettes et al. 1992); a better correlation may be with the L₂ event. However, this is a minor point, as the D₁ deformation of Park (2010) merely modified the relationships of units already juxtaposed prior to or during D₃, and therefore is of secondary importance.

Other work has identified c. 1.9 Ga granulite-facies metamorphism in c. 2 Ga gneisses (Ialltaig gneisses) associated with the amphibolite-facies Loch Maree Group (Love et al. 2010). Love et al. (2010) regarded the Ialltaig gneisses and Loch Maree Group as separate terranes. However, the Ialltaig gneisses would provide a local source for c. 2 Ga detrital zircons in the Loch Maree Group metasediments (Whitehouse et al. 1997). The Loch Maree Group–Ialltaig gneiss association thus bears parallels to the Langavat Belt–Harris Granulite Belt association of the Outer Hebrides.

It is suggested that the upper terrane on the Outer Hebrides marks the same suture zone as the Loch Maree Group; a similar idea was proposed by Park (2005). Park et al. (2001) regarded the Loch Maree Group as dipping beneath the well-preserved granulite-facies Archaean gneisses to the NE (Gruinard and Assynt Terranes of Love et al. 2010). On the Outer Hebrides, the upper boundary of this zone is above the current level of exposure (Fig. 1), which may explain the historical difficulty in correlating with the mainland; in particular, the lack of gneisses equivalent to the Assynt Terrane (Corfu et al. 1994; Friend & Kinny 1995, 2001; Whitehouse & Bridgewater 2001; Mason et al. 2004a). If such rocks did occur on the Outer Hebrides, they lay on the opposite side of the suture, and above the current level of exposure. Moreover, this interpretation places the well-preserved Assynt and Gruinard terranes (Fig. 1) at a structurally high level within the orogen (see Coward & Park 1987; Park 2005), which may account for their escape from Proterozoic reworking, and also for the generally higher metamorphic grade observed in the mafic dykes on the Outer Hebrides relative to the mainland (Fettes et al. 1992).

**Comparisons with the Nagssugtoqidian orogen**

In pre-Atlantic reconstruction the Lewisian is usually correlated with the c. 1.8–1.9 Ga Nagssugtoqidian orogen (e.g. Buchan et al. 2000). The large-scale thrusting associated with the Harris Granulite Belt, Langavat Belt and the Ness Assemblage that drove and probably graded into regional ductile deformation is similar to Nagssugtoqidian D₁–D₂ deformation in west Greenland (van Gool et al. 1999, 2002). In the Nord Stømfjord area supracrustal rocks associated with juvenile arc material are interleaved on early thrusts with the Archaean gneisses (van Gool et al. 1999). As in the present view of the Outer Hebrides, it is the early thrusts that are regarded as the fundamental structural boundaries, not the more conspicuous steep ductile lineaments and shear zones (Connelly et al. 2000).

In the Ammassalik area of east Greenland too there are general similarities. Nutman et al. (2008) invoked thrusting of arc rocks...
(Ammassalik intrusive complex) over Archaean TTG gneisses as a mechanism to explain high-P metamorphism in the Archaean gneisses, and the overthrust arc material has a pre-thrust metamorphic signature. Subsequently, the relationships have been modified by later deformation and retrograde metamorphism, masking the position of the major boundaries, as in the Lewisian.

Park (2005) regarded c. 1740 Ma events (including D2 folding) in the mainland Lewisian to be peripheral effects related to post-Nagssugtoqidian arc accretion associated with the Labrador–Gothen orogen further to the SW. In the model presented here, D2 (at least in its latter stages) probably represents the onset of orogenetic collapse, but post-D3 (L.) reactivation of the Langavat Shear Zone appears to represent inferred (north–south) compression. Given the 1746–1675 Ma time constraint for this reactivation, it fits well with the ideas of Park (2005).

Conclusions

The Lewisian Complex of the Outer Hebrides can be explained in terms of Proterozoic orogenesis in which volcanic arc material was thrust over Archaean gneisses and associated supracrustal cover. This loaded and incuated the Archaean block, leading to prograde amphibolite-facies metamorphism in the supracrustal cover and extensive ductile deformation with a vertical flattening component. Large-scale shear zones in a range of orientations but with a top-to-the-NW or -WNW component of movement were initiated. Although locally significant features, many of these zones are secondary structures that are not related to the assembly of the complex, but merely modified the already existing relationships.

The slab of arc material on the Outer Hebrides, along with the Loch Maree Group on the mainland, may mark the orogenic suture zone cutting obliquely through the complex. This places the bulk of the mainland Lewisian on the opposite side of the suture zone, and structurally above the Outer Hebrides, which may explain much of the long-standing difficulty in correlating between these two areas.

The recognition of early orogenic thrusting predating and perhaps grading into regional ductile deformation brings the deformation history of the Lewisian Complex into line with the general sequence of events known in the Nagssugtoqidian orogen, with which the Lewisian is correlated. Thrusting is an important mechanism for incorporating juvenile components and driving metamorphism, but its presence is often masked by subsequent polyphase ductile deformation.

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