Patterns of Silurian deformation and magmatism during sinistral oblique convergence, northern Scottish Caledonides.

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Abstract

Regional ductile thrusting and syn-kinematic granitic magmatism within the Caledonides of northern Scotland occurred within a sinistrally-oblique convergent tectonic setting during the Silurian closure of the Iapetus Ocean. The highest thrust nappes are dominated by structures of probable Grampian (Ordovician) age, and Scandian (Silurian) deformation dominates the underlying thrust nappes. Deformation was overall foreland-propagating but the nappe stack was modified by out-of-sequence thrusting and probable synchronous development of thrusts at different structural levels. Localised dextrally-transpressive deformation is related to an inferred lateral ramp located offshore. New U-Pb (CA-IDTIMS) zircon ages from syn-tectonic granites indicate that the internal Naver Thrust was active between c. 432 Ma and c. 426 Ma. This is consistent with other data sets that indicate that contractional deformation and high-grade metamorphism, and by implication displacements in the Moine Thrust Zone, may have lasted until c. 420-415 Ma.

The synchroneity of thrusting and strike-slip movements along the Great Glen Fault implies that partitioning of transpressional strain occurred above a regional basal decollement. The short duration of the Scandian orogen in Scotland (c. 437-415 Ma?) is consistent with only moderate crustal thickening and a location on the periphery of the main Laurentia-Baltica collision further north.

[End of abstract]

The Caledonian-Appalachian orogen in the North Atlantic region resulted from the closure of the early Palaeozoic Iapetus Ocean and the Silurian collision of Laurentia, Baltica and peri-Gondwanan microcontinents including Ganderia and Avalonia (Fig. 1; Soper & Hutton 1984; Soper et al. 1992; van Staal et al. 1998). The style and intensity of Silurian tectono-magmatic activity varies along the length of the orogen. In the northern Appalachians, Gander-Laurentia collision resulted in the Salinic orogenic event that was characterised by major crustal thickening and kyanite grade metamorphism (e.g. Cawood et al, 1994). In contrast, the coeval but 'soft' collision across the Iapetus Suture in the British Caledonides was not associated with significant crustal thickening or metamorphism (Soper & Woodcock 1990). Further north, the Scandian collision of East Greenland and NW Scotland (Laurentia) with Norway (Baltica) resulted in substantial crustal thickening, eclogite-facies metamorphism and a complex history of syn-convergent exhumation that lasted into the early Devonian (e.g. Andersen & Jamtveit 1990; Andresen et al. 2007; Gilotti & McLelland 2007). The Northern Highland Terrane (NHT) of Scotland (Fig. 1) represents a fragment of the Laurentian retro-wedge of the orogen and the southernmost part of the Scandian collision zone. However, in contrast to the main Laurentia-Baltica collision zone to the north, the NHT appears to only record moderate crustal thickening that occurred over a relatively restricted period in the mid- to late Silurian (Kinny et al. 2003a; Johnson & Strachan, 2006; Goodenough et al. 2011).

The easterly-dipping Moine Thrust Zone forms the northwestern limit of the exposed Scandian orogen in Scotland (Fig. 2). To the west, the Hebridean Foreland comprises Archaean-Palaeoproterozoic basement of the Lewisian Gneiss Complex, overlain unconformably by Meso- to Neoproterozoic Torridonian and Cambrian-Ordovician sedimentary rocks (Park et al. 2002). To the east and structurally above the Moine Thrust, the NHT is dominated by the early Neoproterozoic Moine Supergroup which is disposed in a stack of east-dipping Scandian thrust nappes (Fig. 2; Holdsworth et al. 1994; Strachan et al. 2002, 2010). In north Sutherland these are, from structurally lowest to highest, the Moine, Naver, Swordly and Skinsdale thrust nappes (Fig. 2; Barr et al. 1986; Moorhouse & Moorhouse 1988; Strachan & Holdsworth 1988; Kocks et al. 2006). We note that Thigpen et al. (2013) and Ashley et al. (2015) recognise an additional Ben Hope nappe on the basis that the eponymous thrust (Fig. 2) appears to represent an important thermal break. However, because it does not define a significant lithological difference, we incorporate the rocks in its hangingwall within the Moine nappe as defined here. Further south in Ross-shire and Inverness-shire, the main structural break is the Sgurr Beag Thrust (Fig. 2 inset; Tanner et al. 1970; Rathbone & Harris 1979). Syn-thrusting metamorphic grade increases progressively eastwards and up-section from greenschist to amphibolite facies (Soper & Brown 1971; Johnson & Strachan 2006; Thigpen et al. 2013; Ashley et al. 2015; Mazza et al. 2018; Mako et al. 2019). Syn- to late-tectonic granitic intrusions were emplaced during ductile thrusting and have yielded Silurian crystallisation ages (U-Pb zircon or monazite; Kinny et al. 2003a; Kocks et al. 2006, 2014; Alsop et al. 2010; Holdsworth et al. 2015). However, the inconsistency of some of the employed radioisotopic techniques and insufficient age resolution means that the precise timing and duration of Scandian thrusting and associated Barrovian metamorphism in the NHT remains somewhat uncertain.

The structural evolution of the lower to middle levels of the Scandian nappe stack in Sutherland has been well documented (e.g. Holdsworth 1989; Strachan & Holdsworth 1988; Alsop & Holdsworth 1993; Alsop et al. 1996; Holdsworth et al. 2001, 2006, 2007; Thigpen et al. 2010a & b, 2013). In this paper, we synthesise the detailed structure of the less well-known middle to upper structural levels to provide a complete section across this part of the NHT. We distinguish between Scandian and older structures and mineral assemblages, assess the kinematic significance of orogen-parallel lineations developed at the highest structural levels, and investigate the emplacement history of associated felsic melts. We also present the results of new high-precision U-Pb zircon geochronology obtained from syn-kinematic granitic intrusions using the chemical abrasion isotope dilution thermal ionization mass spectrometry (CA-ID-TIMS) method. This provides new constraints on the timing of thrusting in the central part of the nappe stack and enables us to draw conclusions concerning the kinematic significance of the regional variation in Scandian transport directions as well as the duration and wider tectonic context of Silurian orogenesis in the NHT.

Geological framework and synthesis of the Scandian thrust nappes in Sutherland

The Moine rocks of Sutherland comprise mainly psammites with subordinate pelites. Psammites within the Moine and Skinsdale nappes locally preserve sedimentary features such as cross-bedding, slump folds and gritty to conglomeratic layers (Holdsworth 1989; Holdsworth et al. 2001; Kocks et al. 2006; Alsop et al. 2010). In contrast, the intervening Naver and Swordly nappes are dominated by migmatitic gneisses where all sedimentary features have been obliterated by high strain and intense metamorphic recrystallisation (Moorhouse & Moorhouse 1988; Kinny et al. 1999). The lower Naver Nappe is largely psammitic, whereas the upper Swordly Nappe is dominated by pelitic lithologies. Concordant sheets and pods of garnet amphibolite up to 10 m thick are present in all nappes and are interpreted to be metamorphosed mafic intrusions which have undergone most of the tectonic history of their host rocks. The Moine rocks are additionally interfolded and inter-thrust with Archaean orthogneisses which represent their depositional basement marked by locally preserved unconformities (Fig. 2; Peach et al. 1907; Holdsworth 1989; Holdsworth et al. 2001; Friend et al. 2008).

The Moine rocks were affected by Neoproterozoic and Ordovician orogenic events prior to Scandian nappe stacking (e.g. Kinny et al. 1999; Friend et al. 2000; Cutts et al. 2010; Cawood et al. 2015; Bird et al. 2013, 2018). Neoproterozoic tectonothermal activity is thought to be related to development of the accretionary Valhalla orogen when the Moine rocks were located on the margin of Laurentia and close to the edge of Rodinia

(Cawood et al. 2010). Late Neoproterozoic supercontinent breakup was followed by opening of the Iapetus Ocean during the Cambrian (Cocks & Torsvik 2002). Ocean closure then followed the development of intra-oceanic subduction zones and collision of island arcs with Laurentia. This resulted in 'Grampian I' orogenesis at c. 480-470 Ma and metamorphism and deformation of the Moine rocks and the younger Dalradian Supergroup of the Grampian Terrane located SE of the Great Glen Fault (Dewey & Shackleton 1984; Dewey & Ryan 1990). U-Pb zircon ages of c. 470-460 Ma date migmatisation within the Naver and Swordly nappes (Kinny et al. 1999). The magmatic arc that collided with Laurentia lies south of the Highland Boundary Fault (Fig. 1), although in Scotland is largely covered by Devonian-Carboniferous successions (Dewey & Ryan 1990). A switch in subduction polarity to northwest-directed resulted in the development of the Southern Uplands accretionary prism between Caradoc times and the final closure of Iapetus (e.g. Leggett et al. 1979; Stone & Merriman 2004). A younger 'Grampian II' metamorphic event at c. 450-445 Ma resulted in substantial garnet growth (some syn-tectonic) in the Moine Nappe, although the tectonic driver of this episode is uncertain (Bird et al. 2013).

A more complex Grampian tectonic model has been proposed recently by Dunk et al. (2019) arising from a new U-Pb zircon protolith age of c. 503 Ma determined for the calc-alkaline Strathy Complex in Sutherland (Fig. 2). Isotopic and geochemical evidence (Burns et al. 2004; Dunk et al. 2019) indicate that this developed as a juvenile magmatic arc in a distal setting from the Laurentian margin. The complex is interpreted as allochthonous and located along a buried suture that formed during the 'Grampian I' orogeny. Dunk et al. (2019) propose that a microcontinental ribbon was detached from Laurentia during Iapetan rifting; the intervening oceanic tract closed by subduction during the late Cambrian and formed a juvenile arc, the protolith of the Strathy Complex. The microcontinental ribbon was then re-attached to Laurentia during 'Grampian I' orogenesis which transported the Strathy Complex as an allochthonous slice within a nappe stack. In this model, at least the initiation of the Naver and Swordly thrusts (or their precursor structures) would be Ordovician (Grampian I) in age.

Structural domains and relative intensities of Scandian deformation

The approach taken here in the analysis of the regional structure is to firstly summarise those structural features that are well constrained as having formed during the Scandian orogeny, and then to trace these eastwards into the structurally higher levels which are less well understood. The metasedimentary rocks of the Moine and Naver nappes record a similar Scandian deformational history involving two sets of overprinting and broadly foreland-propagating structures (described in detail below). These structures have also been traced structurally downwards into the belt of foreland-derived mylonites that forms the uppermost part of the Moine Thrust Zone (Holdsworth et al. 2006, 2007). Although they are referred to locally as 'D_2', and 'D_3', they developed diachronously and so D_3 at a high level in the thrust stack might be temporally equivalent to D_2 at a lower structural level (see also Butler 2010; Leslie et al. 2010). In addition, D_2 and D_3 in a single thrust sheet may have formed during a single progressive ductile thrusting episode (e.g. Alsop & Holdsworth 1993). Prior to ductile thrusting, the Moine rocks contained older composite structures and fabrics of probable Neoproterozoic and Ordovician age (Kinny et al. 1999; Bird et al. 2013, 2018). These are grouped as 'D_1' with an 'M', 'N' or 'S' suffix depending on their location in the Moine, Naver or Swordly nappes to emphasise the potential lack of correlation.

Scandian structures and deformation sequences in low to middle parts of the nappe stack

Structures that are widely described as 'D_2' and 'D_3' have been well documented from the Moine Nappe and the upper part of the Moine Thrust Zone (Fig. 2; Strachan & Holdsworth 1988; Holdsworth 1989, 1990; Holdsworth & Grant 1990; Alsop & Holdsworth 1993, 1999, 2002, 2004; Alsop et al. 1996, 2010; Holdsworth et al. 2001, 2006, 2007, 2015). Reclined, tight to isoclinal D_2 folds with southeasterly-dipping axial planes are ubiquitous between the Moine and Naver thrusts and developed on all scales. The largest basement inliers occupy the cores of west-vergent D_2 folds commonly modified by ductile thrusting. Regional D_2 ductile thrusting and folding resulted in development of an east- to southeast-dipping S_0-$S_{1M/N}$-S_2 (=S_n) foliation which intensifies into mylonitic rocks associated with the D_2 Moine, Ben Hope and Naver ductile thrusts. S_2 carries a mineral extension and rodding lineation (L_2) which is sub-parallel to the axes of local F_2 folds. L_2 gradually changes in orientation from a SSE azimuth (~170°) in the vicinity of the Naver Thrust to an ENE trend (~110°) close to, and within, the Moine Thrust Zone (Fig. 3; Phillips 1937; Kinny et al. 2003a; Law & Johnson 2010). Sections viewed normal to S_2 and parallel to L_2 contain minor structures (e.g. rotated porphyroclasts, S-C fabrics) that demonstrate a top-to-the-NNW to W sense of shear (Holdsworth & Grant 1990; Holdsworth et al. 2001). Sheath-fold geometries are locally common on all scales. Within the Moine Nappe, the widespread parallelism of hornblende with L_2 in mafic rocks implies that D_2 was accompanied by at least low amphibolite facies metamorphism, consistent with local occurrences of syn- to post-D_2 staurolite, kyanite and sillimanite (Burns 1994; Holdsworth et al. 2001; Ashley et al. 2015). D_{1M} structures are restricted to a strong S_{1M} foliation which is only confidently recognised where it is folded by F_2 folds, and a narrow belt of north-south trending L_{1M} lineations developed either side of the Kyle of Tongue (Fig. 2). No convincing examples of F_{1M} folds have been identified and facing analyses of D_2 structures in the Moine rocks within the Moine Nappe show that they were right way-up after D_{1M} (Holdsworth 1988, 1989).

The D_2 structures described above are deformed by local F_3 buckle folds developed on all scales (Alsop & Holdsworth 1993, 2007; Alsop et al. 1996; Holdsworth et al. 2006, 2007). F_3 fold axes and associated axial surfaces are variably oriented with respect to L_2 and have been related to the development of flow perturbations during differential displacements along underlying D_2 ductile thrusts (Holdsworth 1990; Alsop & Holdsworth 1993; Alsop et al. 1996). F_3 folds typically crenulate S_2 and fold L_2 and are not associated with a new elongation lineation.

Structural evidence indicates that deformation was broadly foreland-propagating. This is shown by the way in which major F_2 folds and D_2 ductile thrusts (Naver, Ben Hope, Achininver and Moine) are folded by underlying F_3 structures, which root downwards into D_2 ductile thrusts at lower structural levels. (Holdsworth et al. 2001, 2006, 2007; Alsop & Holdsworth 2007; Alsop et al. 2010; Leslie et al. 2010). However, out-of-sequence deformation can be demonstrated at two structural levels. Firstly, within the central Moine Nappe, the Ben Blandy Shear Zone (Fig. 2) comprises a belt of platy blastomylonites (Holdsworth et al. 2001). These are similar to those developed along ductile thrusts elsewhere, but: a) it does not follow thrust ‘rules’ as it juxtaposes younger Moine rocks over older basement; b) it coincides with a sharp 10-15° switch in L_2 direction; c) a major F_3 fold pair roots downwards into the shear zone (Alsop et al. 1996). These are all features consistent with out-of-sequence thrusting. Secondly, within the Moine Thrust Zone, the base of the mylonite belt is defined by the out-of-sequence Lochan Rhiabach Thrust (Fig. 2) which truncates Scandian structures in its footwall (Holdsworth et al., 2006) and is associated with a metamorphic break (Thigpen et al. 2010a, 2013).

Evidence for a Scandian age for the Swordly Thrust

Detailed mapping in central Sutherland has shown that F_2 and F_3 folds and associated structures dominate the lower parts of the Naver Nappe and extend east of the hitherto poorly-documented Swordly Thrust (Fig. 4). The Swordly Thrust is a sharp contact within a c. 50m thick high-strain zone, separating interbanded psammitic and semi-pelitic gneiss in the footwall from semi-pelitic gneiss in the hanging-wall (Fig. 4). In contrast to the Naver Thrust, there is little to distinguish the Moine rocks either side of the structure as all lithologies are migmatitic. The case that this contact represents a significant tectonic break rests on the presence of two thin sheets of strongly reworked Archaean basement (Fig. 4). The lithological asymmetry either side of these inliers requires that a tectonic break must lie along either their upper or lower boundaries. In central Sutherland, we interpret the lower boundary as a tectonic break (the Swordly Thrust) and the upper contact as a tectonically modified unconformity. In contrast, the Farr basement inlier on the north coast section (Fig. 5) lies well below the Swordly Thrust within uniform sequences of psammitic gneisses and most likely occupies the core of a large-scale isoclinal fold of uncertain structural age.

The orientations of S_n and L_2 are essentially the same on both sides of the Swordly Thrust (Fig. 4). S_n dips moderately to the southeast and L_2 plunges to the south-southeast

(Fig. 4; stereonets from sub-areas 1 and 2). F_2 fold hinges are rare, but where present, plunge parallel to L_2. Importantly, L_2 can be traced continuously from the dated Strathnaver Granite (U-Pb zircon, 429 ± 11 Ma; Kinny et al. 2003a) structurally upwards across the Swordly Thrust and into its hanging-wall (Fig. 4). D_2 structures are deformed by tight to open F_3 folds which are broadly co-planar and co-linear with the D_2 folds. The F_3 folds are developed on all scales, forming a large-scale, composite reclined SSW-vergent structure that folds the Swordly Thrust (Fig. 4). Adjacent to the Swordly Thrust, F_3 folds plunge gently towards the southeast and display moderately-dipping east to southeast-dipping axial surfaces (Fig. 4, stereonets from sub-areas 1 and 2). Associated minor structures include a tight crenulation of S_2 and an L_3 intersection lineation that plunges sub-parallel to L_2. The manner in which F_3 folds deform the Swordly Thrust replicates the structural pattern observed at lower levels within the nappe pile, whereby F_3 folds also deform the Naver, Ben Hope, Achininver and Moine thrusts (Fig. 2; Alsop & Holdsworth, 1993; Alsop et al. 1996; Holdsworth et al. 2006, 2007). The structural framework established previously for the Moine Nappe can therefore now be extended to structurally higher levels within the Naver Nappe, and the Swordly Thrust is interpreted as a D_2 structure.

Age and nature of orogen-parallel lineations above the Swordly Thrust

Regionally, the dominant mineral and stretching lineation within the NHT rotates anticlockwise down-structural section from north-south in the Swordly and Sgurr Beag nappes to east-southeast near the Moine Thrust (Fig. 3; Phillips 1937; Kinny et al. 2003a; Law & Johnson 2010). Whether this regional variation results from one or more orogenic events has not been clear. In east Sutherland, the north-south trending lineation and associated folds are best developed in the Moine rocks above the Swordly Thrust and in the Strathy Complex (Figs. 4 & 5). The Moine rocks here were migmatised during the Grampian I orogenic event (Kinny et al. 1999; Bird et al. 2013). The gneissic foliation is designated S_{1S}, although older (Neoproterozoic?) structures and mineral assemblages may be present.

The S_{1S} fabric and its associated structures are best preserved above the Swordly Thrust between Loch Strathy and Loch Crocach (Fig. 4, stereonet for sub-area 3). In this area, the regional foliation dips gently to the east-southeast and is associated with tight to isoclinal, commonly intrafolial, F_{1S} minor folds which have an axial-planar mica fabric. These folds commonly deform the migmatitic layering, but are themselves cut on all scales by gently discordant metre-decametre scale sheets of weakly-foliated leucogranite which are inferred to represent large accumulations of late-tectonic partial melt (Fig. 4). The folds are therefore viewed as having formed synchronous with regional migmatization. Associated with the foliation is a north-south-trending mineral extension and rodding lineation (L_{1S}) (Fig. 4, stereonet from sub-area 3). The lineation is defined by aligned amphiboles in mafic lithologies and by elongate quartz-feldspar aggregates in siliceous rocks. The lineation is also well developed within the grey gneisses of the Strathy Complex (Fig. 5, stereonet k). The lineation is commonly parallel with the axes of the F_{1S} folds which may display 'eye structures' indicative of sheath fold geometries when viewed on surfaces perpendicular to L_{1S} [e.g. NC 7503 6534]. Although the lineation is inferred to lie parallel to the direction of tectonic transport during regional deformation, there are no consistently developed kinematic indicators present that might establish the sense of shear.

Three lines of evidence are consistent with a Grampian (Ordovician) age for L_{1S} and associated F_{1S} folds. Firstly, the observation (above) that L_{1S} is cut by sheets of leucogranite that do not carry the lineation. Secondly, L_{1S} is most strongly developed in mafic and siliceous lithologies. These are typically less migmatised than pelitic lithologies within which L_{1S} is often absent. It is suggested that L_{1S} was largely obliterated in pelitic rocks as a result of grain-size coarsening associated with the migmatisation and which outlasted deformation. Thirdly, Lu-Hf dating of garnets within an amphibolite in the Strathy Complex yielded an age of 447 ± 15 Ma (Bird et al. 2013). Although the error is large, a late Ordovician age seems most likely. Importantly, the garnets (locally up to 7-8 cm size) appear to have statically overgrown an older S_{1S} gneissic fabric (Fig. 6a). In summary, field and isotopic evidence suggests that the dominant structures and metamorphic assemblages within the Swordly Nappe formed during Grampian I orogenesis. The regional lineation pattern within Sutherland is therefore likely to be a composite of Grampian and Scandian orogenic events.

The Skinsdale Thrust – an out-of-sequence Scandian thrust?

The Skinsdale Thrust (Fig. 2) corresponds to a 300 m thick, southeast-dipping high-strain zone that forms a sharp eastern limit to the migmatitic rocks of the Swordly Nappe (Kocks et al. 2006). The overlying Moine rocks of the Skinsdale Nappe are generally unmigmatised psammitic and quartzitic lithologies that locally preserve sedimentary structures (Strachan 1988). Blastomylonites associated with the thrust carry a SE-plunging L_2 mineral and stretching lineation and asymmetric feldspar porphyroclasts indicate a top-to-the-NW sense of shear parallel to the lineation (Kocks et al. 2006). At structurally higher levels further east, the dominant L_1 lineation trends approximately north-south where unaffected by later cross-folds, but kinematic indicators are rare and do not provide a consistent sense of tectonic transport (Strachan 1988; Kocks et al. 2006). L_1 here must have formed during the Caledonian orogeny because it deforms c. 590 Ma augen granites (Kinny et al. 2003b). The Naver and Swordly nappes appear to be progressively excised towards the south and are presumed to be cut out completely underneath Devonian cover by the Skinsdale Thrust (Fig. 2) which would therefore be an out-of-sequence structure. Whether or not the Skinsdale Thrust correlates with the Sgurr Beag Thrust south of the Dornoch Firth (Fig 2) as proposed by Kocks et al. (2006) remains to be demonstrated.

Transpressional reworking of Scandian thrusts within the Torrisdale Steep Belt

Along the north coast of Sutherland, all ductile structures in the Moine and Naver nappes are reworked in a large zone of transpressional deformation, the Torrisdale Steep Belt (TSB, Fig. 5; Holdsworth et al. 2001). The TSB has a broadly triangular map pattern and increases in width northwards to c. 9 km (Fig. 5). West and south of the TSB, in both Moine and Naver nappes, S_n and L_2 have broadly the same orientation as in central Sutherland

(Fig. 5, stereonets a & d). F_2 and F_3 folds are relatively common within the Moine nappe, axial surfaces and axes are coplanar and colinear with, respectively, S_n and L_2 (Fig. 5, stereonets b & c). A northeastward traverse into the TSB reveals that the north-south-trending composite regional foliation, the Naver and Swordly thrusts, and F_2 and F_3 fold axial planes all steepen and become rotated anticlockwise into a NNW-trend (Fig. 5, stereonets e & f). L_2 is progressively overprinted by a strong mineral and rodding lineation (local L_4) which plunges gently to the south-southeast, colinear with F_2 and F_3 fold axes (Fig. 5, stereonets e & f). A steep foliation is generally pervasive, although local zones of low strain preserve relic F_2-F_3 folds and lineations. Metamorphic temperatures during development of L_4 were at least c. 500°C because it is defined by aligned hornblende and recrystallized aggregates of garnet (Burns 1994; Holdsworth et al. 2001). It therefore seems unlikely that there was any significant temporal break between the development of the TSB and the main phase of regional ductile thrusting. Ubiquitous shear band and S-C fabrics within the Moine and basement rocks consistently indicate a dextral sense of shear parallel to L_4 (Figs. 6b and 6c).

Traversing eastwards and out of the TSB, the steep orientation of S_n is preserved, due to the tight, upright Kirtomy synform, but the characteristic L_4 is only rarely present (Fig. 5, stereonet g). The dominant folds within the Moine rocks on both limbs of the synform are tight-to-isoclinal D_{1S} structures, with steep to sub-vertical, NW-trending axial surfaces and steeply-plunging axes (Fig. 5, stereonet h). In contrast, further east within the Strathy Complex, poles to the S_n foliation define a broad east-west girdle (Fig. 5, stereonet i). The dominant lineation on S_n surfaces is assigned to L_{1S} and plunges gently to the south. D_{1S} axial surfaces and axes are, respectively, coplanar and colinear with S_n and L_{1S} (Fig. 5, stereonet j). Large-scale open-to-close folds have broadly upright axial surfaces and gently NNW-plunging axes (Fig. 5, stereonet k). Within the context of north Sutherland, the spatial coincidence of the TSB with the upright folds that are prominent east of Kirtomy Point, but die out a few kilometres to the south, suggests that these structures are probably of similar (D_4) age.

The overall kinematic significance of the TSB and associated late folds to the east is uncertain because the northern limit of this deformation zone lies offshore. However, it is suggested here that it resulted from the development to the north of an east-west trending lateral ramp or transfer zone within the Caledonian nappes (Fig. 7). Two other lines of evidence also point to the presence of offshore structures trending at a high angle to regional strike. Firstly, the prominent aeromagnetic anomaly coincident with the Strathy Complex terminates against an east-west trending lineament assumed to be a normal fault (Moorhouse & Moorhouse, 1983), Secondly, the analysis of on- and offshore structures is consistent with later development of a large-scale transfer zone (North Coast Transfer Zone) that was active during post-Caledonian basin formation in the Devonian and Permian (Wilson et al. 2010). It is suggested here that these brittle faults were localised along, and reactivated, an older ductile lateral ramp or transfer zone. Within the Torrisdale Steep Belt, the large-scale anticlockwise rotation and steepening of the regional foliation and pre-existing structures is consistent with a sinistral sense of shear across such a structure, although the former may have been partly inherited from earlier large-scale bending of S_2 around the northern termination of the major basement infold (Borgie inlier) lying immediately to the west of the TSB (Fig. 7). Distributed ‘domino-style’ foliation-parallel displacements within that zone of rotation can account for the dextral sense of shear shown by kinematic indicators. The focusing of the TSB within the Nappe may reflect the strong planar anisotropy of its constituent lithologies (mainly banded psammitic gneisses) in contrast to the more homogeneous migmatites of the Swordly Nappe and grey gneisses and amphibolites of the Strathy Complex.

Magma emplacement during Scandian thrusting and deformation in the Torrisdale Steep Belt

In central and southeast Sutherland, the Naver Nappe and structurally high levels of the Moine Nappe contain numerous concordant igneous intrusions (Read 1931; Brown 1967, 1971; Holdsworth & Strachan 1988; Holdsworth et al. 2001; Kinny et al. 2003a; Kocks et al. 2014). These are mostly felsic, including leucogranites, granites *s.s.* and granodiorites, but are locally dioritic. The leucogranites are likely crustally-derived (Brown 1967), whereas some of the more mafic bodies are comparable in their chemistry to the end-Caledonian Northern Highland high Ba-Sr granitoids which were in part mantle-derived (Fowler et al. 2008). They generally range from c. 10 cm to c. 30 m in thickness, although the Strathnaver Granite and Creag Mhor Quartz Monzodiorite (Fig. 2) are much larger. Some intrusions contain xenoliths and contacts with host rocks are invariably sharp, so it is clear that the sheets have migrated and have been emplaced into their present locations and were not generated *in situ*. Many intrusions cut D_2 folds but carry the S_2 schistosity and the L_2 linear fabric and show evidence for high-temperature (>450-500°C) solid-state recrystallisation (Holdsworth & Strachan 1988; Kinny et al. 2003a; Kocks et al. 2014). These observations are consistent with emplacement during D_2, broadly synchronously with displacements along the Naver Thrust. U-Pb zircon geochronology by secondary ion mass spectrometry (SIMS) performed on four syn-D_2 intrusions (Creag nan Suibheag, Strathnaver and Vagastie granites and the Klibreck Sill; Fig. 2) produced ages of c. 429-415 Ma, which form the basis for assigning D_2 (and younger) structures to the Scandian event (Kinny et al. 2003a; Alsop et al. 2010).

The proportion of intrusions increases towards the north coast section where the Naver Nappe and uppermost c. 200 m of the Moine Nappe contain voluminous amounts of variably deformed granite and felsic pegmatite (Burns 1994; Holdsworth et al. 2001). The foliated Clerkhill Intrusion (Fig. 5) is more variable, comprising diorite and granodiorite augen-gneisses with subordinate appinitic amphibolites. [e.g. NC 7145 6365] (Burns 1994). Around Torrisdale Bay and on Neave Island (Figs. 5 and 6d), granite and pegmatite intrusions locally form up to 50% of the outcrop, varying from veins a few cm thick to large sheet-like, anastomosing bodies up to 100 m thick and traceable laterally for up to 600 m [e.g. NC 694 608]. Most have broadly concordant, sharp contacts with host Moine/basement lithologies. There is a complete spectrum from relatively rare pre- to syn-D_2 intrusions that are foliated and carry L_2, to more common, generally unfoliated, sheets that cross-cut F_3 folds and L_4 (Holdsworth et al. 2001). Within the Torrisdale Steep Belt, various intrusions are tightly to isoclinally folded but show little evidence for internal deformation, which implies that they had not fully crystallised at the time of deformation, and so were injected syn-tectonically (see also Butler & Torvela 2018).

The proportion of granitoid sheets reduces structurally upwards within the regional nappe pile and the Swordly Thrust is not associated with any spatial density or focusing of these intrusions. This suggests that it was not as significant as the Naver Thrust in providing an ascent pathway for melts during Scandian thrusting. In contrast, at higher structural levels, the Strath Halladale Granite cuts discordantly at a low angle across the Skinsdale Thrust (Fig. 2). The pluton is an east-dipping sheeted complex dominated by granite and granodiorite with minor diorite and ultramafic components and associated with the Reay Diorite to the north (Fig. 2; Read 1931; McCourt 1980). Various lines of evidence support a late-D_2 structural age for intrusion, specifically: a) a magmatic foliation was reworked by solid-state deformation at high to moderate temperatures, b) shear zones within the pluton display top-to-the-NW sense of shear similar to that deduced for the Skinsdale Thrust, and c) granite sheets were deformed by curvilinear D_3 folds (Kocks et al. 2006). The U-Pb monazite age of 426 ± 2 Ma obtained from the pluton thus approximately dates late-D_2 in this eastern part of the Scandian nappe stack (Kocks et al. 2006).

In summary, the structural and field evidence indicates that the central Sutherland and Strath Halladale granites were emplaced during D_2. The parallelism of the intrusions to the regional easterly-dipping foliation suggests that they were emplaced as sills. The spatial coincidence of the intrusions with the Naver and Skinsdale thrusts further suggests that these thrusts acted as gently-inclined channel ways that focused the migration of the melts (Holdsworth & Strachan 1988; Kocks et al. 2006). In contrast, the syn- to post-D_4 age of granite and pegmatite intrusions within the steeply-inclined TSB suggests that these were instead channelled upwards as dykes within the developing transpressional shear zone. The increase in density of these pegmatites towards the north coast section further suggests that the proposed lateral ramp that controlled the development of the TSB was also acting as a focus for melt transport.

Precise U-Pb zircon dating of syn- to late-tectonic granitic intrusions

We conducted high-precision U-Pb geochronology by the CA-ID-TIMS method on zircons separated from three syn-D_2 intrusions that had previously been dated by the U-Pb SIMS technique (Vagastie Bridge Granite, the Klibreck Sill, the Creag nan Suibheag Granite) and one previously undated late-D_2 intrusion (Creag Mhor Quartz Monzodiorite) (Fig. 2). Details of analytical procedures, complete U-Pb isotopic data and methods of U-Pb age calculation and error reporting are given in the Supplementary Materials. Figure 8 summarizes the geochronological results.

Sample descriptions

A sample of the syn-D_2 Vagastie Bridge Granite (RS-14-19) was collected at [NC 5350 2825]. It occurs as a series of anastomosing concordant sheets, up to 500 m long and 50 m thick, that intrude Moine Nappe psammites (Holdsworth & Strachan 1988; Kinny et al. 2003a). The intrusion cuts F_2 folds but carries the S_2 foliation and L_2 lineation; the latter plunges on a bearing of 140° (Kinny et al. 2003a). It is a coarse-grained, pink gneissic granite with abundant augen (up to 1.25 cm size) of perthitic orthoclase. The augen are wrapped by fine- to medium-grained matrix of dynamically recrystallised plagioclase, K-feldspar, quartz, hornblende, biotite, with secondary chlorite and accessory titanite, zircon and magnetite.

A sample of the syn-D_2 Klibreck Sill (RS-14-18) was collected from [NC 5815 3110] where it intrudes psammitic gneisses of the Naver Nappe (Fig 2; Kinny et al. 2003a). It is traceable for c. 2 km as a concordant sheet no more than c. 30 m thick. The intrusion cuts F_2 folds but carries the S_2 foliation and L_2 lineation; the latter plunges on a bearing of 170° (Kinny et al. 2003a). It is a pink, equigranular, medium-grained meta-granite, comprised of plagioclase, K-feldspar, quartz and biotite, with accessory titanite, magnetite and zircon.

The syn-D_2 Creag nan Suibheag Granite (RS-14-20) was collected at [NC 3881 2926] where it intrudes psammites of the Moine Nappe (Fig 2; Alsop et al. 2010). It is c. 4 m thick and can be traced laterally for c. 25 m. The intrusion is concordant and carries the S_2 foliation and L_2 lineation; the latter plunges on a bearing of 125°. It is a fine- to medium-grained, pink, equigranular meta-granite comprised of quartz, plagioclase (albitic), K-feldpsar, muscovite and biotite, with accessory titanite, zircon and magnetite.

The late-D_2 Creag Mhor Quartz Monzodiorite (RS-14-26) was collected at [NC 7315 0869]. The intrusion occurs as a concordant sheet, c. 6 km long and up to c. 150 m thick, emplaced into Moine Nappe psammites and leucogranites in the immediate footwall of the Naver Thrust (Fig. 2; Kocks et al. 2014). It comprises a medium- to coarse-grained assemblage of plagioclase, quartz, biotite and hornblende, with minor K-feldspar and accessory titanite, magnetite and zircon. Aligned euhedral plagioclase and hornblende define a magmatic fabric, the planar component of which is parallel to S_2 in the country rocks, and the linear component to L_2. Tiling of hornblende grains shows that magmatic flow was directed towards the west (Kocks et al. 2014).

Age results and interpretations

Vagastie Bridge Granite (sample RS-14-19) Four analysed zircons from this sample form a statistically coherent cluster without any outliers and produce a weighed mean $^{206}Pb/^{238}U$ date of 432.35 ± 0.10/0.21/0.51 Ma and a mean square weighted deviation (MSWD) of 2.0 (Fig. 8). The latter best represents the emplacement age of the intrusion coeval with D_2 deformation within the Moine Nappe.

Klibreck Sill (sample RS-14-18) Analysed zircons from this sample yielded a range of Silurian $^{206}Pb/^{238}U$ dates from ~437 Ma to 426.18 ± 0.26 Ma. The presence of a discordant Precambrian analysis (z4) suggests that some of the observed age scatter in this sample might be due to xenocrystic zircon cores. However, the bulk of Scandian age analyses are concordant (Fig. 8) and are best interpreted as protracted zircon crystallization (c. 430-426 Ma) during D_2 deformation.

Creag nan Suibheag Granite (sample RS-14-20) Analysed zircons from this sample range in their $^{206}Pb/^{238}U$ dates from 432.93 ± 0.75 Ma to 428.34 ± 0.29 Ma. The older analyses (z5 and z6) are relatively imprecise (low U and radiogenic Pb) and discordant and may reflect an inherited component, whereas the younger two (z2 and z3) are concordant, but do not overlap with uncertainty (Fig. 8). These suggest a protracted, syn-D_2, zircon crystallization history for the intrusion.

Creag Mhor Quartz Monzodiorite (sample RS-14-26) Similar to that in the Klibreck Sill sample, the zircon analyses here produced a range of $^{206}Pb/^{238}U$ dates that, with the exception of one distinctly older analysis (z6), cannot be explained by zircon inheritance (Fig. 8). The 426.76 ± 0.25 Ma to 425.72 ± 0.21 Ma range of dates from this sample represent protracted zircon crystallization during late stages of D_2 deformation.

Discussion

New U-Pb geochronology

Previously published radioisotopic geochronology from the northern Scottish Caledonides includes age data of different vintages, produced by a variety of techniques and calculated using different chronometers, which often makes age comparisons problematic. Much of the existing U-Pb ID-TIMS geochronology from the region was based on analyses of multi-grain (µg size) aliquots of zircon, with or without any pre-treatment (e.g., van Breemen et al. 1979; Halliday et al. 1987; Strachan & Evans 2008; Kocks et al. 2014). These age data are in general of questionable accuracy by modern standards due to the possibility of open system behaviour (inheritance and/or Pb loss) in zircon and the manners in which the dates were calculated (e.g., mean $^{207}Pb/^{206}Pb$ or concordia intercept dates). Caution should therefore be exercised in constructing geologic histories based on compilations of inherently incompatible age results. Only U-Pb ages derived from $^{206}Pb/^{238}U$ dates of chemically abraded, single-zircon analyses (e.g., Goodenough et al. 2011) and especially those produced using the EARTHTIME tracers and analytical protocols have the precision and reproducibility to be directly compared to the U-Pb results of this study.

The enhanced precision of modern U-Pb analyses by the CA-ID-TIMS method helps unravel the complexities of zircon age populations in magmatic rocks that often go undetected by the lower precision in-situ dating techniques. The set of $^{206}Pb/^{238}U$ dates presented here have analytical uncertainties as low as ± 0.20 m.y. (0.09%), which can easily resolve the observed age scatters of 1 m.y. (RS14-26) to 4.6 m.y. (RS14-20) of this study. In comparison, even the most precise zircon SIMS analyses from the area have had 2σ analytical uncertainties of at least ± 10 m.y. (Alsop et al. 2010).

A limitation of the in-situ U-Pb dating techniques in terms of accuracy is their inability to perform chemical abrasion on zircon and thus mitigate the effects of Pb loss (e.g. Wu et al., 2016), especially when analysing zircon rims. Both the Vagastie Bridge Granite and Klibreck Sill have produced CA-ID-TIMS weighted mean dates that overlap only with the upper margin of their respective published SIMS dates (424 ± 8 Ma and 420 ± 6 Ma, respectively; Kinny et al. 2003a). None of our CA-ID-TIMS analyses from the Creag nan Suibheag Granite are as young as the reported U-Pb SIMS date of this intrusion. This suggests that the distinctly younger published age of the Creag nan Suibheag granite (415 ± 6 Ma: Alsop et al. 2010) should be viewed with caution.

Our new geochronology indicates a minimum c. 6 myr period of syn-tectonic zircon crystallization between c. 432 Ma (Vagastie Bridge Granite) and c. 426 Ma (Klibreck Sill and Creag Mhor Quartz Monzodiorite) associated with peak- to late-D2 deformation along the Naver Thrust. This period should be regarded as a minimum, as additional data from these and other intrusions may expand the age spectrum of zircons and thus the duration of deformation. Taken at face value, the data suggest that the deformation was older in the footwall of the Naver Thrust (Vagastie Bridge Granite), whereas it continued for another c. 6 myr above the thrust (Klibreck Sill). At present, our results do not seem to support a simple model of foreland-propagating, westerly younging, Scandian deformation. Additional high-precision geochronology, particularly from the western Sutherland, is necessary to resolve the timing of Scandian ductile deformation across this sector of the orogen.

Ductile thrust evolution of the Scandian thrust nappes

The Scandian nappe stack in northern Scotland developed from the ductile reworking of Moine rocks and their associated basement that had already been deformed and metamorphosed during the Neoproterozoic and the Ordovician. A critical question relates to the extent to which the major ductile thrusts and folds are composite structures that were initially formed during pre-Scandian orogenic events. Bird et al. (2013) noted curved (i.e. syn-tectonic) inclusion trails within 450-445 Ma (= Grampian II) garnets and suggested that some of the major folds within the Moine Nappe may have been initiated at this time, but only attained their present highly curvilinear sheath-fold geometry as a result of Scandian reworking. Dunk et al. (2019) invoked a Grampian I age for the Port Mor Thrust (Fig. 4) and 'proto' Naver and Swordly thrusts. However, the systematic eastward increase in deformational temperatures that is apparent from integrated microstructural and geothermometry studies related to proven Silurian fabrics (the L_2 lineation) demonstrates the reality of a Scandian orogenic wedge that resulted from crustal-scale ductile thrusting (Thigpen et al. 2013; Ashley et al. 2015; Mazza et al. 2018; Mako et al. 2019).

Curvilinear regional lineation trends of the type preserved in northern Scotland (Fig. 3) could result from one or more of three possible scenarios: 1) different generations of lineations associated with separate deformation events, 2) heterogeneity in the magnitude and direction of shear combined with strain partitioning during regional transpression, and 3) reorientation of a linear fabric due to a later deformation event. The findings reported here indicate that the first two of these are most relevant. On the regional scale the lineation pattern is probably a composite of Grampian and Scandian orogenic events. Scandian reworking was pervasive in the Naver and Moine nappes and associated with broadly northwest-directed transport. In contrast, Grampian structures may predominate in the structurally higher Swordly and Skinsdale nappes, characterised by north-south trending lineations, although the tectonic transport direction is unknown. The dominance of potentially older structures in the highest nappes in northern Scotland compares with the peri-Laurentian-derived thrust sheets of western Norway. These acquired their main deformational and metamorphic characteristics during the

Ordovician to early Silurian and were then emplaced southeastwards onto the Baltica margin as composite entities during the Scandian orogeny (Andersen & Andresen 1994; Corfu et al. 2014).

Within this regional framework, there is, however, still a considerable variation in the azimuth of the Scandian L_2 lineation that requires explanation (Fig. 3). This has been interpreted previously in different ways: either a gradual rotation in the strain field due to changes in the direction of plate convergence (e.g. Soper et al. 1992) or a progressive change in kinematic partitioning of deformation into coeval thrusting and strike-slip across the Scottish Caledonides (e.g. Dewey & Strachan 2003). Additional insights are provided by the isotopic dating of syenite intrusions thought to have been emplaced during thrusting within the Assynt culmination of the Moine Thrust Zone (Fig. 2; Goodenough et al. 2011). U-Pb CA-ID-TIMS zircon ages bracket their emplacement between 430.7 ± 0.5 Ma and 429.2 ± 0.5 Ma (Fig. 9; Goodenough et al. 2011) and are readily comparable with data in the present paper as they were obtained using essentially the same analytical procedures. The two data sets taken together therefore indicate that NW- to NNW-directed ductile thrusting along the Naver Thrust in the central part of the nappe stack overlapped WNW-directed thrusting within the Moine Thrust Zone. The regional lineation swing defined by L_2 therefore appears to reflect essentially *contemporaneous* deformation at different crustal levels, and is consistent with sinistrally oblique convergence.

Early interpretations of structural sequences in the external thrust belts of orogens suggested that thrusts tended to develop in a foreland-propagating manner (e.g. Bally 1966; Elliott & Johnson 1980) and this model was applied to the ductile thrust sheets of northern Scotland (Barr et al. 1986). While this model may well still apply in many cases, a more nuanced approach may be necessary to understand examples where thrusts appear to have moved simultaneously (e.g. Butler 2004) as well as out-of-sequence (e.g. Morley 1988). In northern Scotland, we envisage that the early widely-distributed shear at mid- to upper crustal levels indicated by the geochronological data was followed by the localisation of strain along discrete thrusts that broadly propagated towards the foreland.

This is consistent with folding of the Naver and Ben Hope thrusts by F_3 folds that developed in their footwalls (Holdsworth 1989; Alsop et al. 1996), and the passive folding of both thrusts above the Assynt culmination in the Moine Thrust Zone (Fig. 2). However, recognition that the Skinsdale Thrust is probably out-of-sequence (this study) as well as the Ben Blandy Shear Zone (Alsop et al. 1996) and the Lochan Rhiabach Thrust and its likely continuation in Assynt (Holdsworth et al. 2006; Thigpen et al. 2010a) suggests more widespread modification of the nappe stack by such structures than understood previously.

Magma emplacement during Scandian deformation

The focusing of intrusions that are partly mantle-derived along the Naver and Skinsdale thrusts demonstrates the crustal scale of these structures. In contrast, there is a marked lack of thrust-related Caledonian intrusions further south, in Ross-shire and Inverness-shire along the trace of the Sgurr Beag Thrust. One reason for this might be that Sutherland represents a deeper crustal level, which is consistent with the considerably greater amount of Archaean basement exposed within the Moine Nappe (Fig. 2). The association of the 'early' Moine Thrust north of central Assynt with a belt of greenschist-facies mylonites in its footwall and hangingwall (Thigpen et al. 2010a & b; 2013) might also be indicative of deformation at a deeper crustal level than further south where the Moine Thrust is a 'late' brittle structure (Law & Johnson 2010 and references therein).

Given apparently continuous subduction of Iapetan oceanic lithosphere beneath the Laurentian margin from c. 455 Ma to c. 420 Ma, it would be reasonable to invoke melting of mantle wedge sources during subduction to produce these magmas, as well as the c. 430 Ma syenite plutons of the Assynt Culmination in the Moine Thrust Zone and the Loch Loyal Syenite Complex (Fig. 2; Goodenough et al. 2011). Various arguments have been employed to explain the general lack of magmatism within the Northern Highland and Grampian terranes between 455 Ma and 430 Ma. This might be due either to low-angle subduction or erosional removal of a volcanic arc (Oliver et al. 2008; Miles et al. 2016). Alternatively, subduction at a high-angle to a continental margin could also suppress magma emplacement if active deformation was not producing the crustal-scale channel ways necessary to facilitate melt transport (Glazner 1991). The onset of magmatism at c. 430 Ma could therefore be directly linked to the Scandian collision and generation of the crustal-scale thrusts that are best developed in Sutherland. Caledonian plutons dated at between c. 465 Ma and c. 438 Ma have been recently recognised along-strike in the Shetland Islands c. 200 km north-northeast of mainland Scotland, perhaps suggesting an intervening change in subduction angle and/or distance between the subduction zone and the Laurentian margin (Lancaster et al. 2017).

Timing and duration of the Scandian event in northern Scotland

The results of the present study indicate that the Naver Thrust was active (at amphibolite-facies) between c. 432 Ma and c. 426 Ma (Fig. 9) and have implications for regional tectonic models. This is because it has generally been believed that the Scandian event in northern Scotland was terminated by c. 430 Ma given that: a) ductile thrusts within the hinterland are folded passively above culminations within the underlying, and therefore younger, thin-skinned Moine Thrust Zone, and b) dated syenite intrusions in the Assynt area (see above) apparently truncate thrusts in the central part of the Moine Thrust Zone (Woolley 1970; Goodenough et al. 2011; but see Searle et al. 2010). However, no field relationships preclude the continuation of thrusting post-430 Ma along the Sole Thrust and associated structures, and the Moine Thrust clearly truncates the 430.6 ± 0.3 Ma Loch Ailsh syenite (Fig 2; Goodenough et al. 2011).

A c. 430 Ma termination to the orogeny is difficult to reconcile with the results of other isotopic studies which also suggest a more protracted evolution. These include: a) Rb-Sr white mica ages (closure T = ~550°C) from Moine Thrust Zone mylonites which indicate that although the main cessation of deformation occurred at c. 430 Ma, there was evidence for strain localisation until c. 410 Ma (Freeman et al. 1998); b) Rb-Sr muscovite ages of c. 428, 423 and 421 Ma from the lower Moine Nappe (Dallmeyer et al. 2001); c) U-Pb titanite ID-TIMS ages (closure T = ~550-600°C) of 413 ± 3 Ma and 416 ± 3 Ma obtained from the Vagastie Bridge and Kilbreck Sill respectively (Fig. 9; Kinny et al.

2003a), d) monazite-xenotime thermometry and U-Pb geochronology that demonstrate that the Naver Nappe experienced peak temperatures of 700°C at c. 425 Ma (Mako et al. 2019), e) a U-Pb monazite age of 426 ± 2 Ma for the late-D_2 emplacement of the Strath Halladale Granite (see above) (Kocks et al. 2006), and f) a U-Pb concordia age of 426 ± 3 Ma obtained from multi-grain fractions of air-abraded zircon from the Glen Scaddle metagabbro in Inverness-shire to the south (Fig. 2), which predated regional scale upright folding at amphibolite-facies grade (Strachan & Evans 2008). In summary, isotopic studies suggest that high-grade metamorphism and contractional deformation within the Scandian nappes persisted until c. 420-415 Ma which necessarily implies a more protracted evolution of the Moine Thrust Zone than considered previously. The Moine Thrust is conventionally assumed to predate the Ross of Mull Granite, (Fig. 2; 418 ± 5 Ma, U-Pb SIMS zircon age, Oliver et al. 2008) which on its eastern boundary intrudes Moine rocks, and on its western boundary thermally metamorphoses rocks on Iona that are assigned to the Caledonian foreland (Potts et al. 1995). However, a para-autochthonous setting for Iona within the Moine Thrust Zone cannot be excluded, and hence the duration of upper crustal thrusting along the margin of the orogen is poorly constrained.

A previous estimate for the duration of the Scandian event in northern Scotland suggested that it occurred between 443 Ma and 425 Ma, and lasted <18 myr (Johnson & Strachan 2006). Conservatively, this can be amended to between 437 Ma, the oldest of the white mica $^{40}Ar/^{39}Ar$ ages recorded from Moine Thrust Zone mylonites (Freeman et al. 1998), and a lower limit possibly as young as 415 Ma (see also Mako et al. 2019), suggesting a duration of potentially up to 22 myr.

Partitioned thrusting and strike-slip displacements within the Scandian orogenic wedge

The late Silurian to mid-Devonian interval in the Caledonides has been interpreted in terms of a transition from sinistral transpression to strike-slip and then transtension, reflecting relative plate motions between Laurentia and Baltica-Avalonia (Dewey & Strachan 2003). If the Moine Thrust Zone was active until c. 420-415 Ma (see above), then brittle, upper crustal thrusting along the margin of the orogen must have overlapped early strike-slip displacements along the Great Glen Fault and related structures. The timing of the latter has been constrained to c. 430-420 Ma by the isotopic dating of syn-kinematic plutons emplaced along major faults (Rogers & Dunning 1991; Stewart et al. 2001; Kirkland et al. 2008; Kocks et al. 2014; Holdsworth et al. 2015). Many of these plutons have a mantle-derived component to the melts, indicating that the strike-slip faults along which they were emplaced must have been crustal-scale structures (Hutton & Reavy 1992; Reavy & Jacques 1994).

Synchronous movement of the Moine Thrust Zone and the Great Glen and related faults implies a large-scale partitioning of transpressional strain above a basal decollement (Stewart et al. 1999). Similar partitioned structural regimes have been demonstrated from other orogenic tracts such as the Qilan Shan (northeast Tibet Plateau) (Allen et al. 2017), the Canadian Cordilleras (Oldow et al. 1990), and the Caledonides of NE Greenland (Holdsworth & Strachan 1991; Smith et al. 2007). In Scotland, the overall tectonic regime was likely dominated by strike-slip displacements from 420-415 Ma onwards because the Great Glen Fault appears to truncate mantle reflectors that have been interpreted as Caledonian thrusts (Snyder & Flack 1990). Dating of syn-kinematic granites within the exhumed high-grade core of the Great Glen Fault demonstrated that sinistral movements continued until at least 399 Ma (Mendum & Noble 2010).

Regional Appalachian-Caledonian linkages

Silurian deformation and metamorphism along the Appalachian-Caledonian orogen between Newfoundland and northern Greenland and Norway resulted from the sinistrally-oblique collision of Laurentia, Baltica and peri-Gondwanan terranes (e.g. Avalonia and Ganderia) and consequent closure of the Iapetus Ocean (Fig. 1; Soper et al. 1992; Dewey & Strachan 2003). However, there are considerable differences in the intensities of this event (Fig. 10). In Newfoundland, ‘Salinic’ (c. 435-420 Ma) crustal thickening and metamorphism up to kyanite grade resulted from the collision of peri-Laurentian and peri-Gondwanan arcs across the Red Indian Line (Fig. 10; Cawood et al. 1994). Along strike in western Ireland, the slightly younger ‘Erian’ event (c. 424-416 Ma) was associated with sinistrally transpressive cleavage development and folding of the South Mayo Trough sedimentary succession at sub-greenschist facies (Fig. 10; Dewey et al. 2015). The easterly-younging and diachronous nature of the Silurian collision across the Solway Line between western Ireland and south Scotland has been well-documented (Soper & Woodcock 1990). Sinistrally-oblique collision at c. 420 Ma in south Scotland was not associated with significant crustal thickening or metamorphism. The main structures are low-grade NW-directed thrusts, possibly developed as the Southern Uplands accretionary prism was thrust onto the southern margin of the Midland Valley (Bluck 2002). There is no evidence of Silurian deformation in the Midland Valley itself where there is continuity of sedimentation across the Silurian-Devonian boundary (Phillips et al. 2004), nor within the Grampian Terrane to the north of the Highland Boundary Fault. The differences in the intensity and timing of Silurian orogenic events between Newfoundland and south Scotland can be attributed partly to irregularities in the shapes of colliding continental margins, and also to a gradual slowing of Avalonia-Laurentia convergence rates following initial 'Salinic' collision in Newfoundland (Soper & Woodcock 1990).

The relatively short-lived nature of the Silurian events in Newfoundland, Ireland and south Scotland contrasts with a much longer duration in East Greenland (Laurentia) and Norway (Baltica). Continental collision here was underway by c. 435 Ma, which corresponds in East Greenland to the oldest S-type granites (Kalsbeek et al. 2001), and in Norway to the oldest mineral ages that relate to development of a regional-scale extrusion wedge (Grimmer et al. 2015). Crustal thickening culminated in Devonian ultrahigh-pressure metamorphism at c. 415-390 Ma in East Greenland (e.g. McClelland & Gilotti 2003; Gilotti et al. 2004; Corfu & Hartz 2011) and c. 405-400 Ma in Norway (Carswell et al. 2003; Tucker et al. 2004). Unroofing of the Greenland-Norway orogenic wedge was at least in part achieved by sinistrally-oblique transtensional displacements along low-angle shear zones through the early to middle Devonian (Osmundsen & Andersen 2001; Osmundsen et al. 2003). The long history of convergence and 'hard' collision through the Silurian and the early Devonian contrasts markedly with the 'soft' Avalonia-Laurentia collision in south Scotland, and this was presumably accommodated by decoupling of Avalonia and Baltica along the Tornquist Line (Fig. 10; Dewey & Strachan, 2003).

The much shorter duration of the Scandian event in northern Scotland (<22 myr) relative to East Greenland and Norway (c. 45 myr) is consistent with a likely location on the periphery of the Laurentia-Baltica collision. This is thought to have been followed by sinistral strike-slip displacement of c. 500-700 km along the Great Glen Fault that juxtaposed the northern Scotland crustal fragment against the Grampian Terrane to the southeast which shows no record of Silurian ductile deformation and metamorphism (Fig. 10; Coward 1990; Dallmeyer et al. 2001; Dewey & Strachan 2003; Kinny et al. 2003a). It is envisaged that during the initial phase of collision at c. 435 Ma, northern Scotland was located opposite the southernmost part of the Baltica plate and that this drove regional ductile thrusting and development of the Moine Thrust Zone (Dewey & Strachan 2003). Continued sinistrally-oblique movement of Baltica relative to Laurentia moved the main locus of plate collision away from Scotland further north to East Greenland. The Caledonian thrust front in East Greenland is Devonian (c. 400-390 Ma; Dallmeyer et al. 1994) in contrast to the end Silurian age of the Moine Thrust Zone, which may account for the bend necessary to link the two structures (Fig. 10).

The lateral continuations of the Moine Thrust and the Great Glen Fault to the southwest and into Newfoundland are uncertain and it may be that there are no direct linkages. Given the magnitude of the sinistral displacement that has been proposed for the Great Glen Fault, it would be surprising if a correlative structure were not present in Newfoundland, even if its magnitude had diminished along strike. The steep Baie Verte Line-Cabot Fault (Fig. 10) is a potential candidate which has a long-lived and complex history and along which significant orogen-parallel displacements may have occurred (Lin et al. 2013). However, the main documented ductile displacements are dextral (Brem et al. 2007). The Appalachian Deformation Front (Fig. 10) is often shown as being continuous with the Moine Thrust on reconstructions but this is unlikely given the different tectonic drivers. In northern Newfoundland, White & Waldron (2019) have demonstrated that the frontal Appalachian thrusts formed during the mid-Devonian Acadian Orogeny. Although displacements are modest (<10 km), these or equivalent structures offshore may truncate or rework the lateral continuations of the Moine Thrust and the Great Glen Fault somewhere on the intervening continental shelves, adding to the difficulties in correlation.

Conclusions

1) The regional lineation pattern in the Caledonian thrust nappes of northern Scotland (Laurentia) is likely to be a composite of Grampian and Scandian orogenic events. The highest structural levels (eastern Swordly and Skinsdale nappes) are dominated by orogen-parallel lineations. Field and isotopic evidence suggests that these formed during the Grampian (Ordovician, c. 470-460 Ma) orogeny, but further geochronology is required to test this hypothesis. Pervasive ductile deformation during the Scandian (Silurian, c. 435-425 Ma) orogeny is characteristic of the underlying thrust nappes (Moine, Naver and western Swordly), associated with NNW- to WNW-directed thrusting. Localised dextrally-transpressive deformation within the Naver and Swordly nappes (the Torrisdale Steep Belt) is interpreted as the ductile expression of a lateral ramp structure located offshore.
2) Ductile thrusts at all structural levels are mostly deformed by folds developed in their footwalls and which root downwards into structurally lower ductile thrusts, suggesting an overall foreland-propagating sequence of deformation. However, evidence for out-of-sequence thrusting at three different structural levels suggests a more complex sequence of thrust stacking than previously supposed and that thrusts may have developed synchronously at different levels within the nappe stack.
3) Two of the structurally higher thrusts (Naver and Skinsdale) as well as the dextral transpression zone associated with the inferred lateral ramp acted as conduits for syn-tectonic granitic intrusions that have a mantle-derived component. Given the paucity of magmatism prior to 430 Ma in this part of Scotland, its onset at that time could therefore be directly linked to the Scandian collision and development of crustal-scale thrusts synchronously with slab-break-off.

4) New high-precision U-Pb zircon ages from syn-tectonic granitic intrusions indicate that the NNW- to NW-directed Naver Thrust was active (at amphibolite facies grade) between c. 432 Ma and c. 426 Ma. This overlaps the emplacement of previously dated syn- to late-tectonic syenite plutons within the WNW-directed Moine Thrust Zone. The regional arcuate anticlockwise swing in the L_2 lineation therefore appears to reflect contemporaneous deformation at different crustal levels and is consistent with sinistrally oblique convergence. We envisage that early distributed shear was followed by localisation of strain along discrete foreland-directed thrusts.
5) The results of the present and previous isotopic studies suggest that high-grade metamorphism and contractional deformation within the Scandian nappes persisted until possibly c. 420-415 Ma which implies a more protracted evolution of the Moine Thrust Zone than previously considered.
6) If the Moine Thrust Zone was active until the latest Silurian to earliest Devonian, brittle, thrusting at relatively shallow crustal levels along the margin of the orogen overlapped sinistral strike-slip displacements along the Great Glen Fault and related structures which are known to have been initiated at c. 425 Ma. The synchroneity of thrusting and strike-slip movements implies a large-scale partitioning of transpressional strain above a regional-scale basal decollement.
7) The relatively short duration of the Scandian orogen in Scotland (c. 437-415 Ma?) is consistent with the only moderate amount of crustal thickening recorded and a location on the periphery of the main Laurentia-Baltica collision further north which continued until c. 390 Ma. During initial collision, Scotland was located opposite the southernmost part of the Baltica plate. The loci of crustal thickening then moved progressively along strike to the north during the sinistrally-oblique convergence of Baltica and Laurentia, partly accommodated by sinistral shear along the Tornquist Line.

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Figure captions

Figure 1. Map of the Caledonide-Appalachian orogen in the North Atlantic region prior to Mesozoic rifting (modified from Waldron et al. 2014). NHT, Northern Highland Terrane; GGF, Great Glen Fault; HBF, Highland Boundary Fault.

Figure 2. Regional geology of north Sutherland (modified from British Geological Survey 1997, 2002, 2003, 2004a & b). Inset map shows location in northern Scotland. Abbreviations of structures: AT, Achininver Thrust; ACT, Achness Thrust; BBSZ, Ben Blandy Shear Zone; BHT, Ben Hope Thrust; LRT, Lochan Riabach Thrust; MT, Moine Thrust; NT, Naver Thrust; PMT, Port Mor Thrust; ST, Swordly Thrust; SKT, Skinsdale Thrust; SoT, Sole Thrust; TT, Torrisdale Thrust. Abbreviations of intrusions: CM, Creag Mhor Quartz Monzodiorite; CSG, Creag Suilbheag Granite; G, Grudie Granite; GSM, Glen Scaddle Metagabbro; HG, Helmsdale Granite; KG, Klibreck Granite; LA, Loch Ailsh Syenite; LB, Loch Borrolan Syenite; LL, Loch Loyal Syenite Complex; LS, Loch Shin Granite; RIC, Rogart Igneous Complex; ROM, Ross of Mull Granite; SHG, Strath Halladale Granite; SNG, Strathnaver Granite; VBG, Vagastie Bridge Granite.

Figure 3. Regional trends of the dominant mineral and extension lineations within the Caledonian thrust sheets of northern Scotland (modified from Law & Johnson 2010).

Figure 4. Detailed geological map of the Swordly Thrust in central Sutherland (see Fig 2 for location) together with structural data presented as lower hemisphere, equal area stereographic projections (see text for discussion). Data for sub-areas 1 and 2 taken from above and below the Swordly Thrust. AB, Archaean basement.

Figure 5. Map, cross section and structural data from North Sutherland (see Fig. 2 for location) together with structural data presented as lower hemisphere, equal area stereographic projections (see text for discussion). Abbreviations: FBI, Farr basement inlier; NT, Naver Thrust; PMT, Port Mor Thrust; ST, Swordly Thrust; TT Torrisdale Thrust; TSB, Torrisdale Steep Belt. Subsurface structure from British Geological Survey (1997) (western section) and Dunk et al. (2019) (eastern section).

Figure 6. a) post-D_1 garnets within the Strathy Complex (Lu-Hf age is 447 ± 15 Ma) are statically overgrowing an S_{1S} fabric that is folded (NC 7982 6590); remaining images are all from the Torrisdale Steep Belt: b) view of a horizontal surface showing L_2 folded around an F_3 hinge, and D_4 dextral shear bands at Swordly Bay (NC 7354 6355); c) view of a horizontal surface at Swordly Bay showing dextrally-sheared lozenges of granitic gneiss (NC 7354 6355); d) view northwestwards to Aird Torrisdale from NC 6885 6285, showing steeply-dipping and foliation-parallel granite and pegmatite sheets.

Figure 7. Simplified map showing the location and main components of the D_4 Torrisdale Steep Belt and the inferred lateral ramp/transfer zone located offshore. The inset shows how foliation-parallel displacements within a zone of overall sinistral transpression would result in the widespread dextral shear sense indicators observed at outcrop. Abbreviations are as in Fig 5 with addition of: BI, Borgie inlier; SC, Strathy Complex.

Figure 8. Conventional concordia plots of the analysed zircons. Error ellipses are plotted at 2 sigma. Dashed lines represent uncertainties in U decay constants displayed as the concordia error envelope.

Figure 9. Summary of U-Pb (CA-IDTIMS) zircon ages (dark arrows; Goodenough et al. 2011 and this study) and U-Pb (TIMS) titanite ages (grey arrows; Kinny et al. 2003a). CNSG, Creag nan Suibheag Granite; CMQM, Creag Mor Quartz Monzodiorite; KS, Klibreck Sill; MT, Moine Thrust; NT, Naver Thrust; ST, Swordly Thrust; VBG, Vagastie Bridge Granite. See Fig. 2 for locations.

Figure 10. Summary map showing the distribution, timing and varying intensities of Silurian (Scandian) deformation and metamorphism (stippled areas) in the North Atlantic Caledonides and northern Appalachians (see text for discussion)

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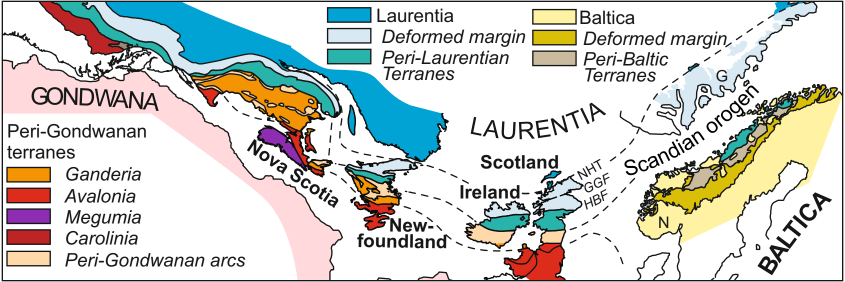
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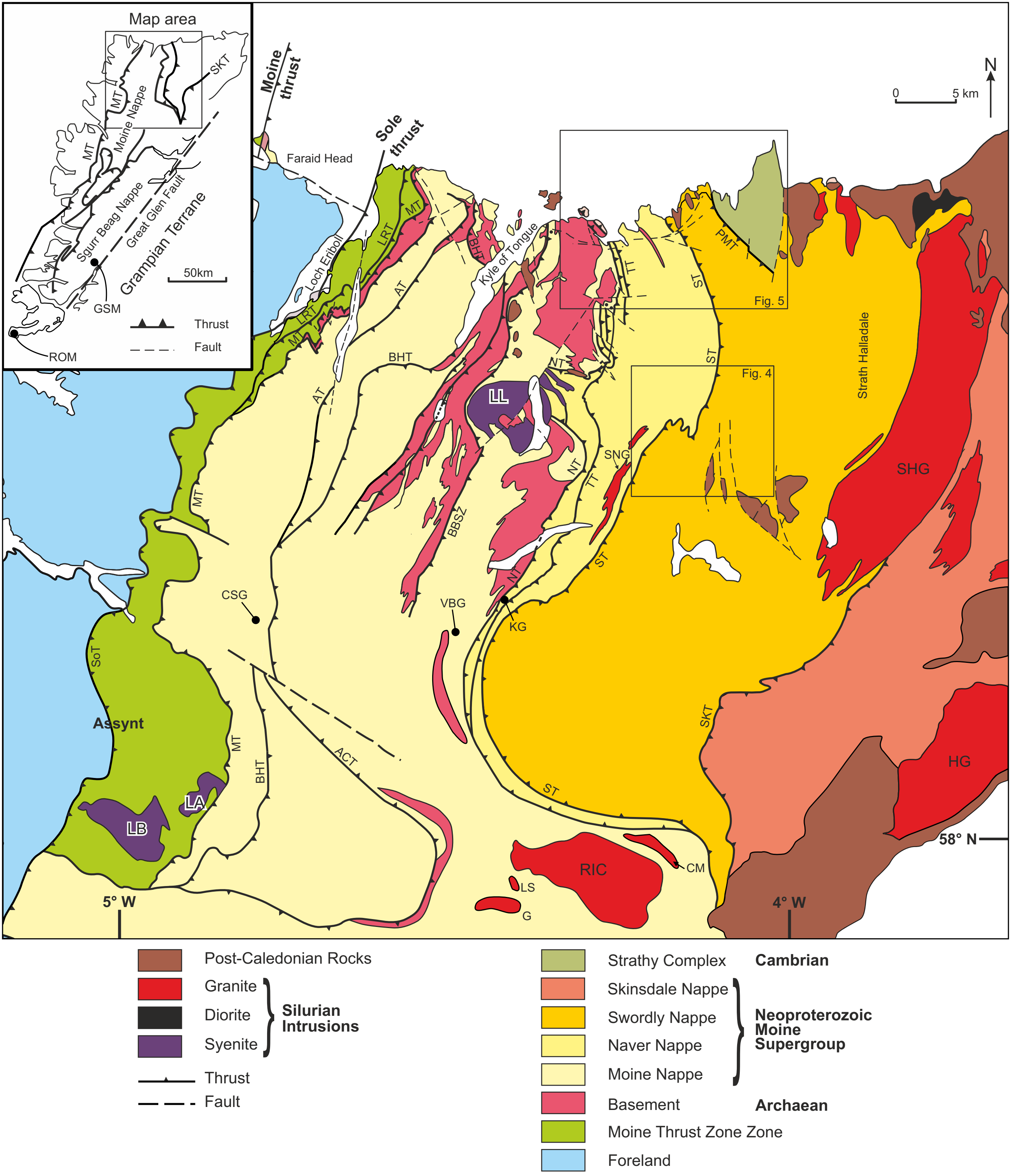
Map area
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Moine Nappe
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Moine thrust
Sole thrust
Faraid Head
Loch Eriboll
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Fig. 5
Fig. 4
SNG
Strath Halladale
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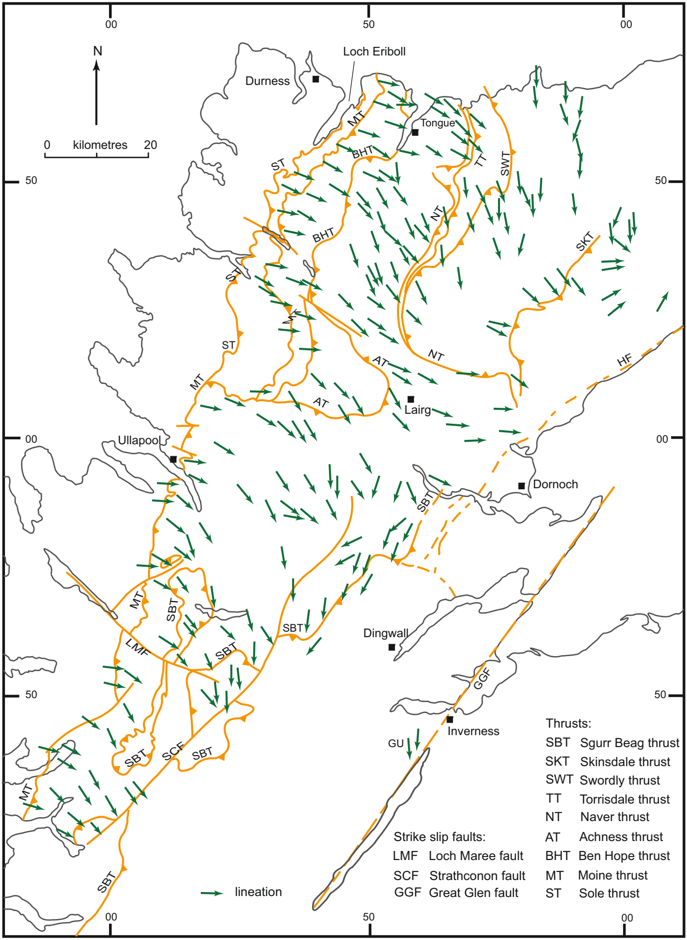
Post-Caledonian Rocks
Granite
Diorite
Syenite
Silurian Intrusions
Thrust
Fault
Strathy Complex
Cambrian
Skinsdale Nappe
Swordly Nappe
Naver Nappe
Moine Nappe
Neoproterozoic Moine Supergroup
Basement
Archaean
Moine Thrust Zone Zone
Foreland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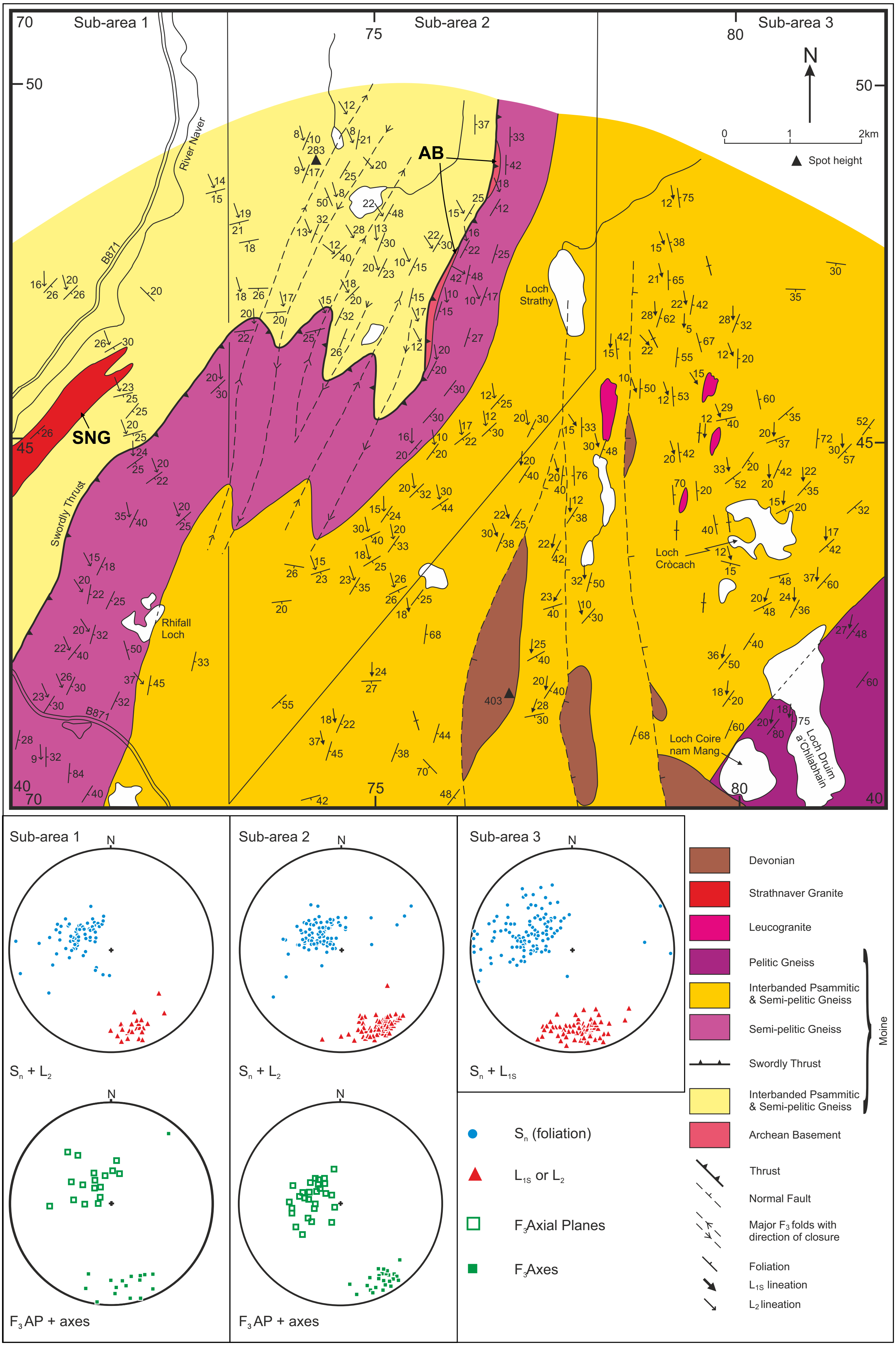
Thrusts:
SBT Sgurr Beag thrust
SKT Skinsdale thrust
SWT Swordly thrust
TT Torrisdale thrust
NT Naver thrust
AT Achness thrust
BHT Ben Hope thrust
MT Moine thrust
ST Sole thrust
Strike slip faults:
LMF Loch Maree fault
SCF Strathconon fault
GGF Great Glen fault
lineation


70
Sub-area 1
75
Sub-area 2
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Sub-area 3
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40
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Spot height
River Naver
B871
SNG
Swordly Thrust
AB
283
Loch Strathy
Rhifall Loch
403
Loch Cròcach
Loch Coire nam Mang
Loch Druim a Chliabhain
Sub-area 1
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Sub-area 3
$S_n + L_2$
$S_n + L_2$
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F_3AP + axes
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F_3Axial Planes
F_3Axes
Devonian
Strathnaver Granite
Leucogranite
Pelitic Gneiss
Interbanded Psammitic & Semi-pelitic Gneiss
Semi-pelitic Gneiss
Swordly Thrust
Interbanded Psammitic & Semi-pelitic Gneiss
Archean Basement
Moine
Thrust
Normal Fault
Major F_3 folds with direction of closure
Foliation
L_{1S} lineation
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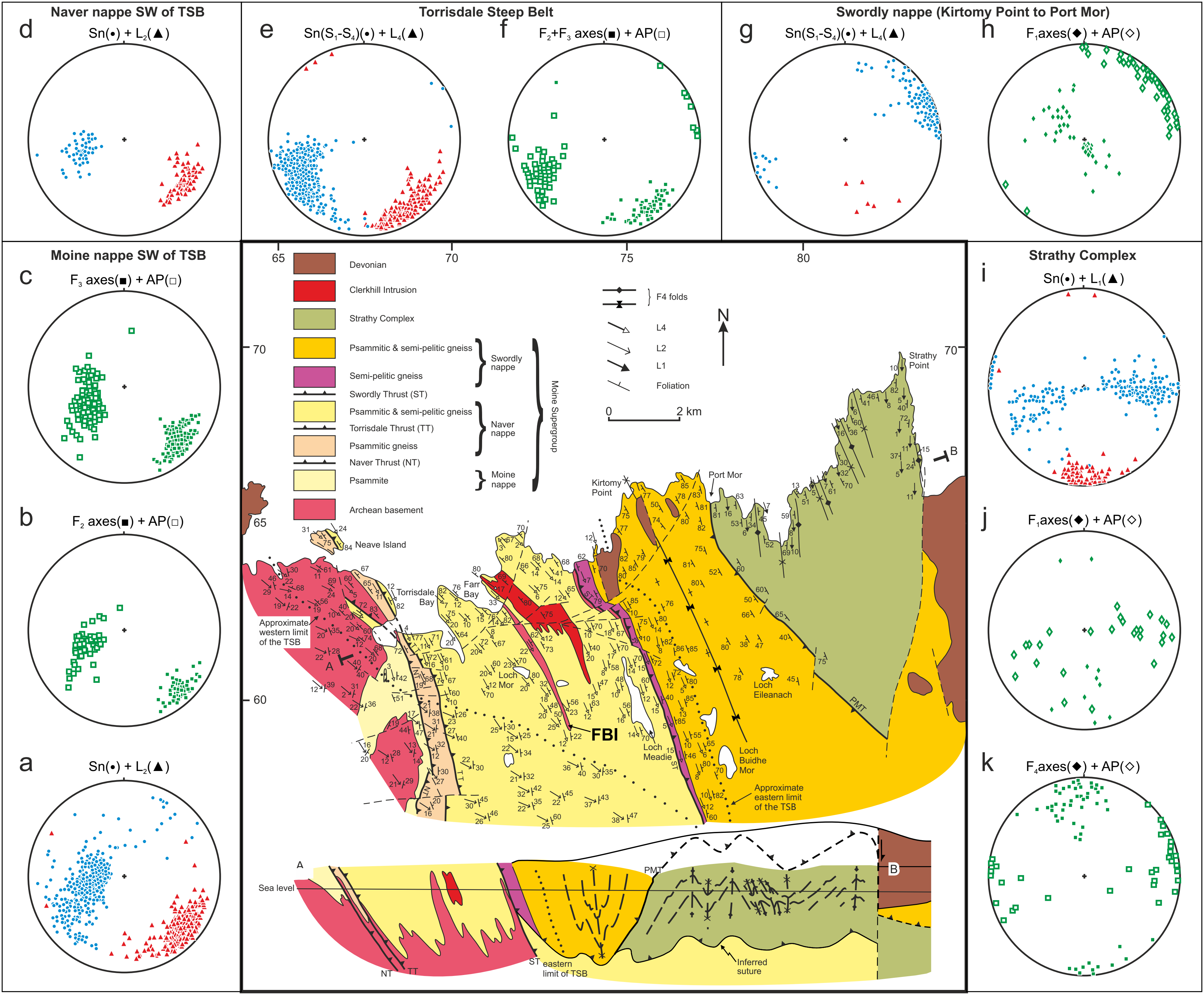
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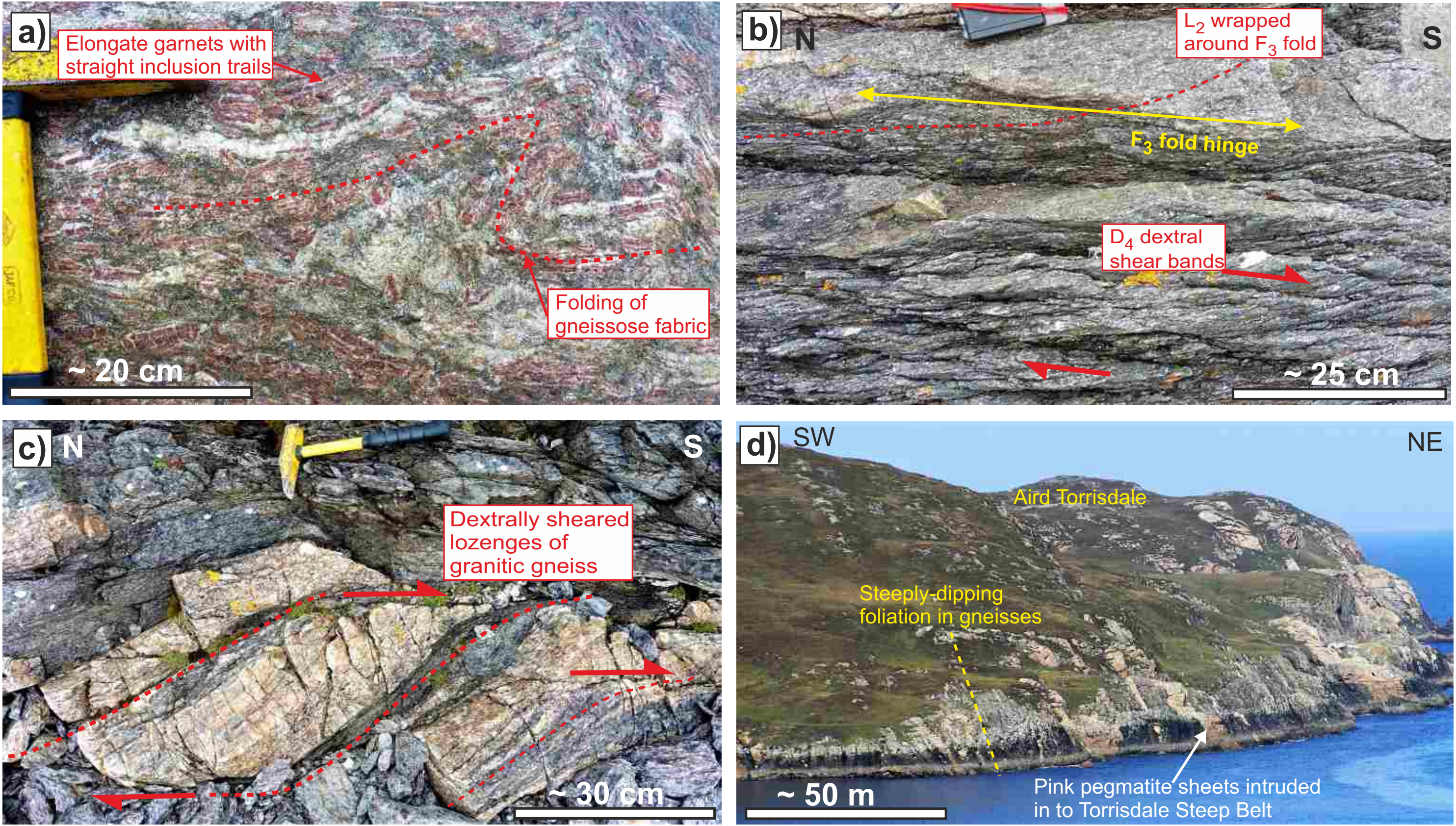
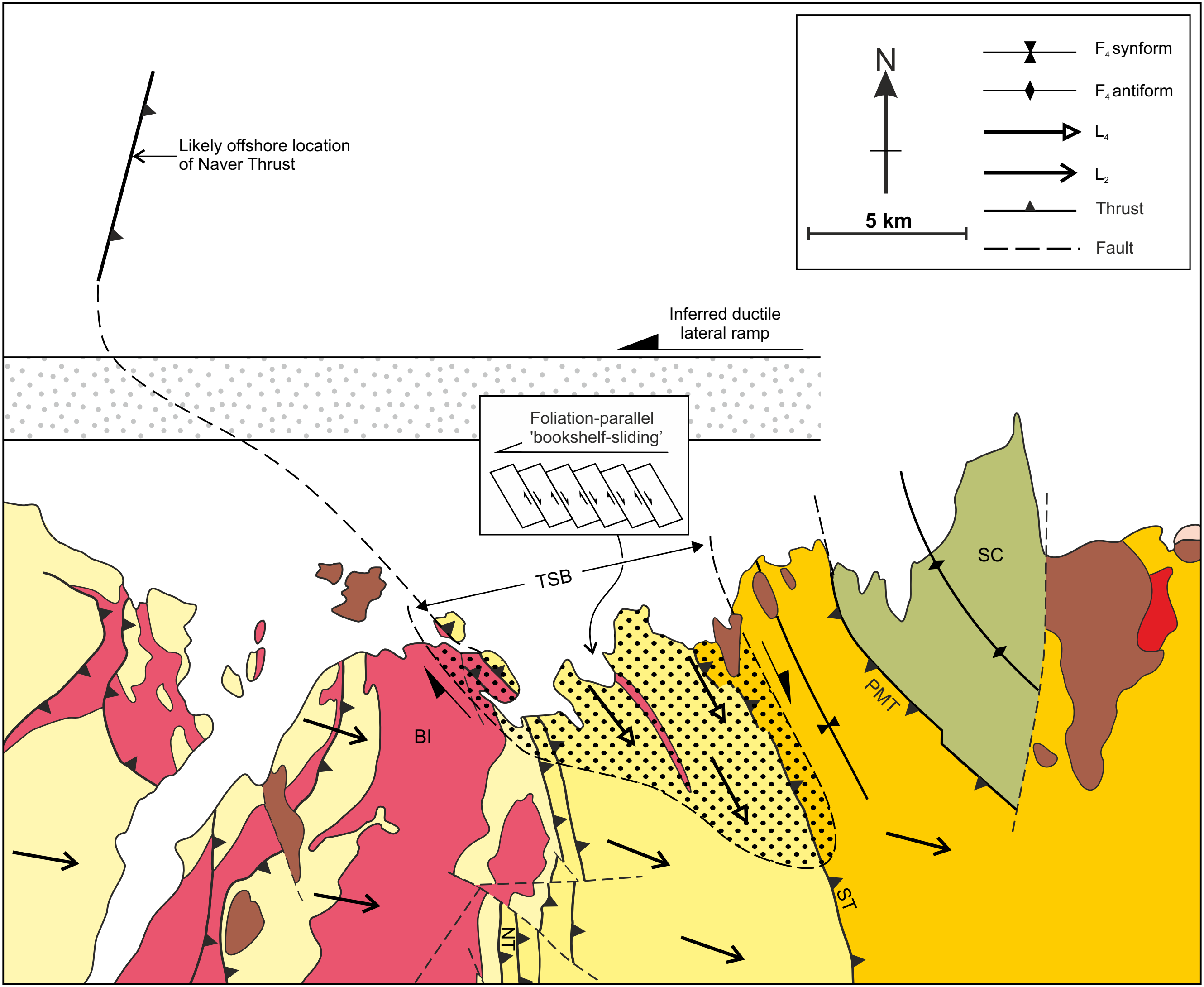
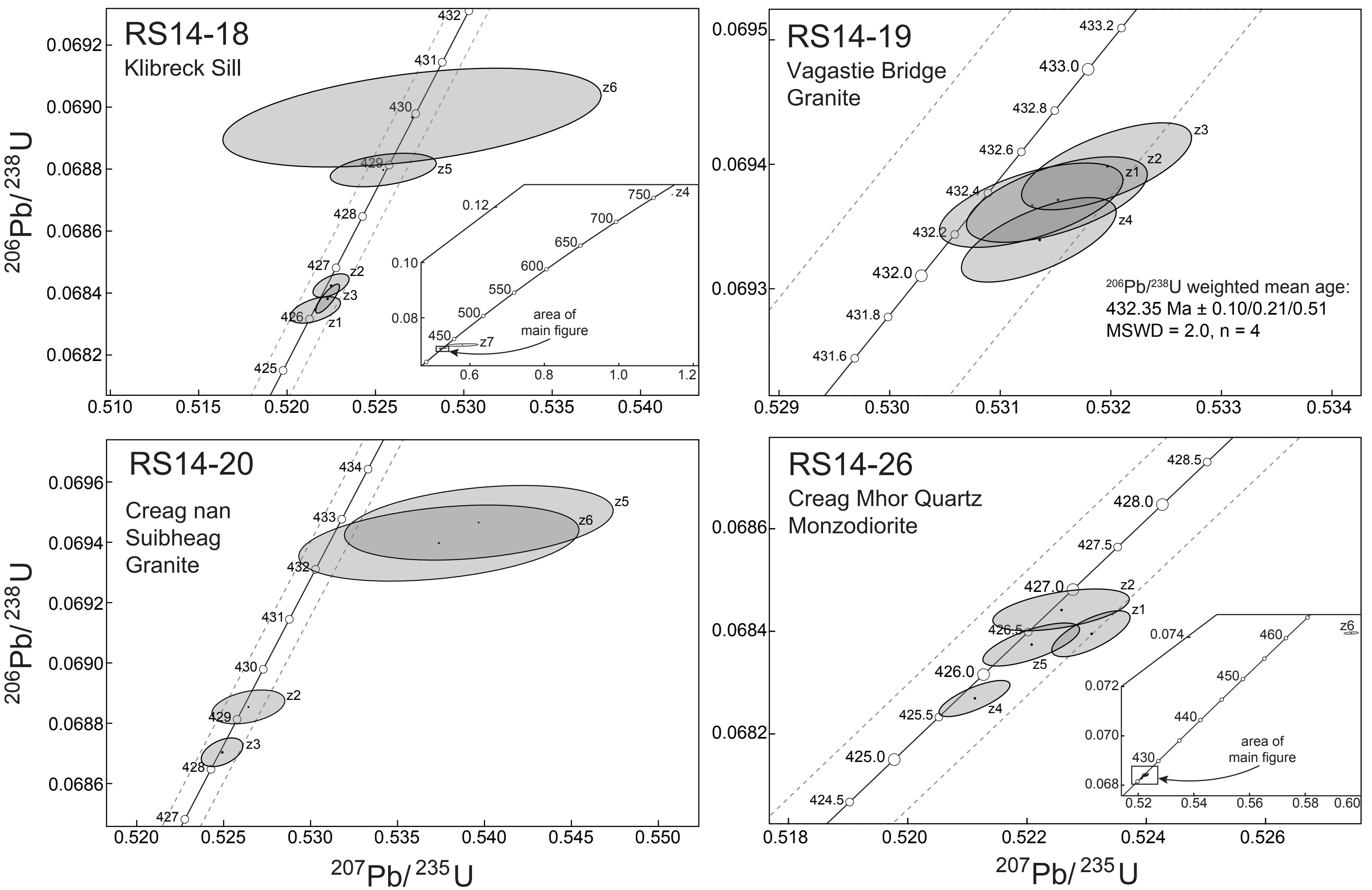
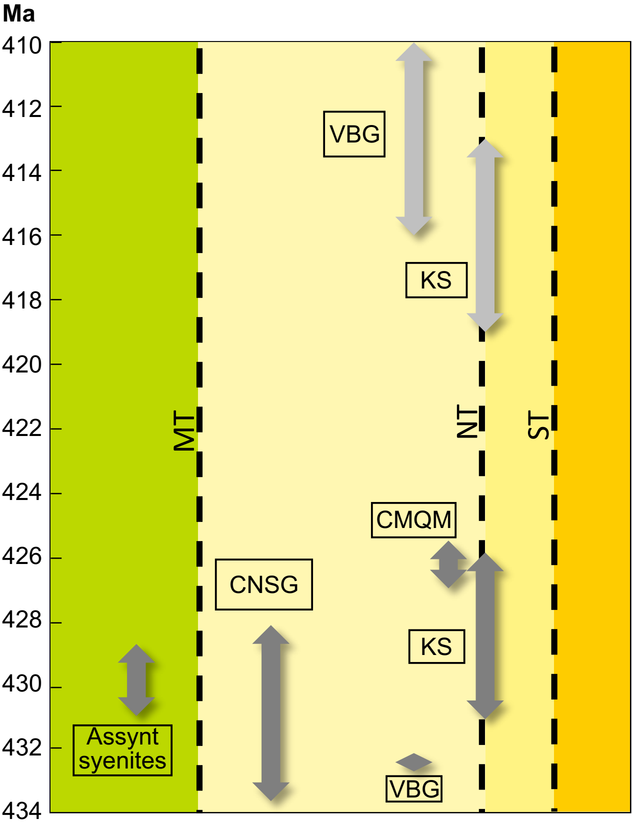
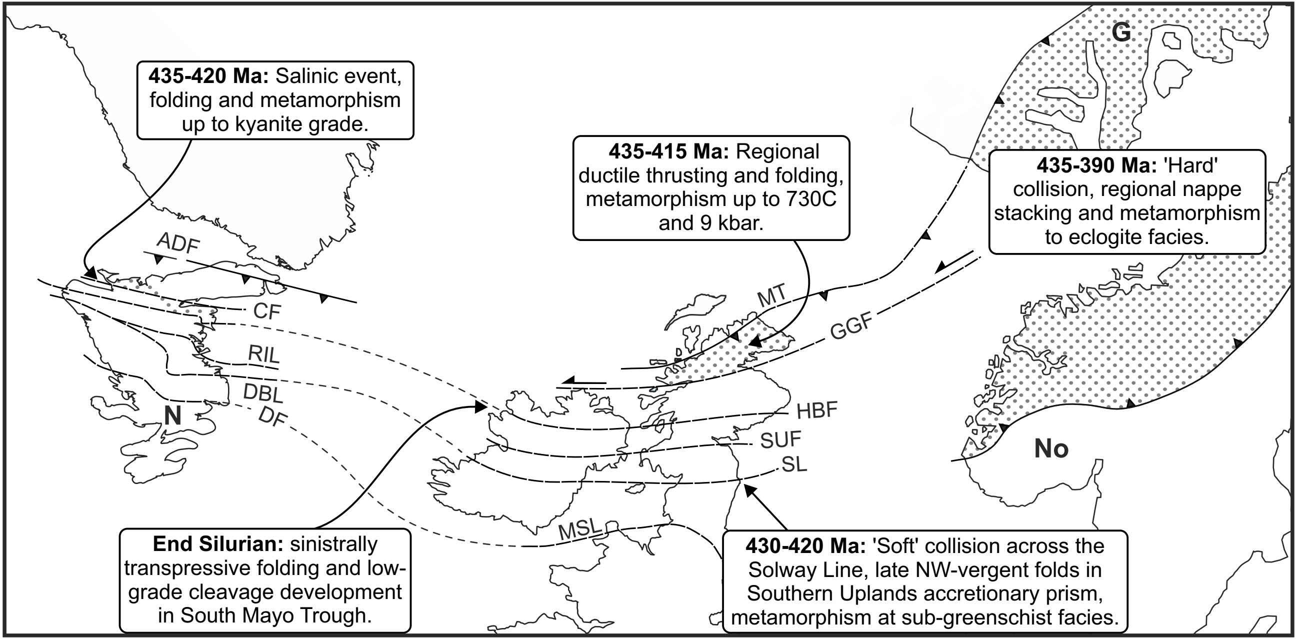
Sn(S$_1$-S$_4$)(•) + L$_4$(▲)
f
F$_2$+F$_3$ axes(■) + AP(□)
Swordly nappe (Kirtomy Point to Port Mor)
g
Sn(S$_1$-S$_4$)(•) + L$_4$(▲)
h
F$_1$axes(◆) + AP(◇)
Moine nappe SW of TSB
c
F$_3$ axes(■) + AP(□)
b
F$_2$ axes(■) + AP(□)
a
Sn(•) + L$_2$(▲)
Strathy Complex
i
Sn(•) + L$_1$(▲)
j
F$_1$axes(◆) + AP(◇)
k
F$_4$axes(◆) + AP(◇)
65
70
75
80
70
65
60
Devonian
Clerkhill Intrusion
Strathy Complex
Psammitic & semi-pelitic gneiss
Semi-pelitic gneiss
Swordly nappe
Swordly Thrust (ST)
Psammitic & semi-pelitic gneiss
Torrisdale Thrust (TT)
Naver nappe
Psammitic gneiss
Naver Thrust (NT)
Psammite
Moine nappe
Moine Supergroup
Archean basement
F4 folds
L4
L2
L1
Foliation
N
0
2 km
Strathy Point
Port Mor
Kirtomy Point
Neave Island
Torrisdale Bay
Farr Bay
Approximate western limit of the TSB
A
B
Loch Mor
FBI
Loch Meadie
Loch Eileanach
Loch Buidhe Mor
Approximate eastern limit of the TSB
PMT
ST
TT
NT
Sea level
eastern limit of TSB
Inferred suture


a)
Elongate garnets with straight inclusion trails
Folding of gneissose fabric
~ 20 cm
b)
N
S
L_2 wrapped around F_3 fold
F_3 fold hinge
D_4 dextral shear bands
~ 25 cm
c)
N
S
Dextrally sheared lozenges of granitic gneiss
~ 30 cm
d)
SW
NE
Aird Torrisdale
Steeply-dipping foliation in gneisses
Pink pegmatite sheets intruded in to Torrisdale Steep Belt
~ 50 m


Likely offshore location of Naver Thrust
Inferred ductile lateral ramp
Foliation-parallel 'bookshelf-sliding'
TSB
BI
NT
ST
PMT
SC
N
5 km
F₄ synform
F₄ antiform
L₄
L₂
Thrust
Fault


RS14-18
Klibreck Sill
z1
z2
z3
z5
z6
z4
z7
area of main figure
425
426
427
428
429
430
431
432
450
500
550
600
650
700
750
0.12
0.10
0.08
0.6
0.8
1.0
1.2
0.0692
0.0690
0.0688
0.0686
0.0684
0.0682
0.510
0.515
0.520
0.525
0.530
0.535
0.540
RS14-19
Vagastie Bridge Granite
z1
z2
z3
z4
431.6
431.8
432.0
432.2
432.4
432.6
432.8
433.0
433.2
$^{206}Pb/^{238}U$ weighted mean age:
432.35 Ma ± 0.10/0.21/0.51
MSWD = 2.0, n = 4
0.0695
0.0694
0.0693
0.529
0.530
0.531
0.532
0.533
0.534
RS14-20
Creag nan Suibheag Granite
z2
z3
z5
z6
427
428
429
430
431
432
433
434
0.0696
0.0694
0.0692
0.0690
0.0688
0.0686
0.520
0.525
0.530
0.535
0.540
0.545
0.550
RS14-26
Creag Mhor Quartz Monzodiorite
z1
z2
z4
z5
z6
424.5
425.0
425.5
426.0
426.5
427.0
427.5
428.0
428.5
430
440
450
460
0.074
0.072
0.070
0.068
0.52
0.54
0.56
0.58
0.60
area of main figure
0.0686
0.0684
0.0682
0.518
0.520
0.522
0.524
0.526
$^{206}Pb/^{238}U$
$^{206}Pb/^{238}U$
$^{207}Pb/^{235}U$
$^{207}Pb/^{235}U$


Ma
410
412
414
416
418
420
422
424
426
428
430
432
434
MT
NT
ST
VBG
KS
CMQM
CNSG
KS
Assynt syenites
VBG



435-420 Ma: Salinic event, folding and metamorphism up to kyanite grade.

435-415 Ma: Regional ductile thrusting and folding, metamorphism up to 730C and 9 kbar.

435-390 Ma: 'Hard' collision, regional nappe stacking and metamorphism to eclogite facies.

End Silurian: sinistrally transpressive folding and low-grade cleavage development in South Mayo Trough.

430-420 Ma: 'Soft' collision across the Solway Line, late NW-vergent folds in Southern Uplands accretionary prism, metamorphism at sub-greenschist facies.