The internal structure of the Moine Nappe Complex and the stratigraphy of the Morar Group in the Fannichs – Beinn Dearg area, NW Highlands.

***M Krabbendam* [*],**

***R A Strachan* [1],**

A G Leslie,

K M Goodenough,

H C Bonsor

British Geological Survey, Murchison House, West Mains Road, Edinburgh, EH9 4LA, Scotland, UK

[1] University of Portsmouth

[*] Corresponding author: mkrab@bgs.ac.uk

Abstract

The Morar Group, the lowest group of the early Neoproterozoic Moine Supergroup in the Scottish Highlands, forms a >5 km thick metamorphosed siliclastic sequence, recently interpreted to form part of a Grenvillian (*c*. 1000 Ma) foreland basin. New mapping has elucidated the structure and stratigraphy of the Morar Group in the Fannich – Beinn Dearg area, where the Morar Group occurs in a single coherent thrust sheet (Achness Thrust Sheet), over 70 km long, 20 km wide, and up to 10 km thick. Within this thrust sheet, the strata are folded by two very large, west-vergent and west-facing cylindroidal anticline-syncline pairs that deform the overlying Sgurr Beag Thrust. The lowest long limb is parallel with and grades into the ductile Moine Thrust and Achness Thrust at its base. Low strain zones in steep limbs contain well preserved sedimentary structures. Reconstruction of the stratigraphical architecture shows five formations of metasandstone (psammite), alternating with meta-siltstone (semipelite). Large-scale lateral variations in the lowest metasandstone package are capped by a possible flooding surface of semipelite, followed by more metasandstone. The deformation history shows foreland-propagation of both deformation and metamorphism, from NNW-directed transport on the Sgurr Beag Thrust to WNW-directed transport on the Achness Thrust and Moine Thrust.

Introduction

The Morar Group is the lowermost group of the early Neoproterozoic siliclastic Moine Supergroup, and occurs in the hanging wall of the Moine Thrust in the Scottish Caledonides. It consists of a >5 km thick sequence of metamorphosed sandstone (psammite) with minor meta-mudstone (pelite and semipelite), and covers a 20-40 km wide and *c.* 250 km long swathe of terrain in the western and northern Highlands (e.g. Holdsworth *et al.* 1994; British Geological Survey 2007, see Fig. 1). In the last few years, the British Geological Survey has, with the aid of R.A. Strachan, D. Cheer and I. Alsop, revised and partially resurveyed a tract of Morar Group rocks stretching from Altnaharra in the north to Kinlochewe in the south (Krabbendam *et al.* 2008; Alsop *et al.* 2010; Leslie *et al.* 2010; Strachan *et al.* 2010). No studies carried out in this area since the 1950s dealt specifically with the Morar Group, and a thorough study was timely. It has recently been shown that the Morar Group can be correlated with the unmetamorphosed, sandstone-dominated Neoproterozoic Torridon Group, structurally below and to the west of the Moine Thrust (Krabbendam *et al.* 2008). Both groups are envisaged to have formed part of a large, orogen-parallel foreland basin to the earliest Neoproterozoic (*c.*1000 Ma) Grenville Orogen, remnants of which occur in eastern North America, SW Scandinavia and at Glenelg in Scotland. However, this particular correlation and interpretation was based exclusively on the Altnaharra Formation in Sutherland, the stratigraphically lowest locally formation of the Morar Group in the area. In the course of the continuing revision of the geological maps farther south into the Fannich – Beinn Dearg area, a much thicker and higher part of the Morar Group stratigraphy was encountered. In this paper, we report on new results from that area (Fig. 1, 2) and link these to the structures in Sutherland. We will focus here on the structure and stratigraphy of this region: the detailed sedimentology will be presented elsewhere (Bonsor *et al.* **in review**). This paper covers in part the same ground as described by Sutton & Watson (1954) and Kelley & Powell (1985). Sutton & Watson (1954) noted the abundance of sedimentary structures in what is now termed the Morar Group. They used these, and an early appreciation of vergence (without using this term as such, see Bell 1981), to describe a series of large-scale west-facing folds, and also erected a distinct stratigraphy. We confirm many of their inferences and expand upon them.

It has been recognised for some time that a simple D1-D3 structural analysis approach is not appropriate in a complex structural area such as this, in part because 'D2' in one place may not correlate with 'D2' in another (e.g. Tobish & Patterson 1988; Holdsworth 1989; 1990; Alsop & Holdsworth 1993, 2007; Alsop *et al.* 1996; Leslie *et al.* 2010; Strachan *et al.* 2010; see also Forster & Lister 2008). To fully understand the tectonic evolution of a large area it is necessary to analyse how a D1-Dn sequence in one place correlates with a D1-Dn sequence in another. Here, we therefore describe different D1-Dn deformation sequences separately within each individual thrust sheet, so that for instance D2 $_{Ac}$ and D2 $_{SB}$ are the second deformation phase within the Achness and Sgurr Beag thrust sheets respectively – a similar approach as Moorhouse & Moorhouse (1988). A second step is then to analyse how a D1-Dn sequence in one thrust sheet relates to that in another, and it may thus prove to be the case that D2 $_{SB}$ is in fact contemporaneous with – for instance – D1 $_{Ac}$. It should be noted that in places where all fabrics and thrusts are sub-parallel, as is the case in northern Sutherland, such analysis is difficult and for instance 'D2' structures in two different thrust sheets may look very similar (eg. Strachan & Holdsworth 1988; Moorhouse & Moorhouse 1988; Holdsworth 1989), yet may not be coeval. We use the terms vergence and facing in the sense of Bell (1981) and Holdsworth (1988) respectively.

Geological Setting

The Moine Supergroup comprises three groups: the Morar, Glenfinnan and Loch Eil groups (Holdsworth *et al.* 1994). They were deposited during the early Neoproterozoic on the eastern sector of Laurentia, which was at that time linked with Baltica and Amazonia to form part of the Rodinia supercontinent (Friend *et al.* 2003; Krabbendam *et al.* 2008; Cawood *et al.* 2004, 2007). Thrust slices or para-autochthonous fold cores of Archaean Lewisianoid gneiss within the outcrop of the Morar and Glenfinnan groups are interpreted as the Laurentian basement upon which the group was deposited (e.g. Ramsay 1957; Strachan & Holdsworth 1988, Holdsworth 1989; Holdsworth *et al.* 2001; Friend *et al.* 2008).

The Morar Group is structurally underlain by the Moine Thrust which forms the western margin of the Caledonian orogen in Scotland (Fig. 1). It is structurally overlain by the regionally important ductile Sgurr Beag Thrust (Tanner 1971; Rathbone & Harris 1979; Barr *et al.* 1986). Above the Sgurr Beag Thrust occurs the gneissose, pelitic Glenfinnan Group with slices of Lewisianoid gneiss presumably at its stratigraphic base. The Loch Eil Group, dominated by psammitic rocks, stratigraphically overlies the Glenfinnan Group. North of Dornoch, at least three large-scale ductile thrusts have been identified (Naver, Swordly, Skinsdale thrusts, Fig. 1; Barr *et al.* 1986; Moorhouse & Moorhouse 1988; Kocks *et al.* 2006). Which of these thrusts links with the Sgurr Beag Thrust remains uncertain, in part because the distinction between the Morar, Glenfinnan and Loch Eil groups in this area is obfuscated by structural complexity and high-grade metamorphism (Strachan & Holdsworth 1988; Kocks *et al.* 2006; Mendum 2009). A number of ductile thrusts (e.g. Achininver, Ben Hope and Dherue/Meadie thrusts) occur in northern Sutherland in between the Naver and Moine thrusts, within the Morar group, but involving Lewisianoid basement. These thrusts are considered to have formed in an overall foreland-propagating sequence (Butler 1986; Barr *et al.* 1986; Holdsworth 1989; Holdsworth *et al.* 2001).

There is evidence for three orogenic events affecting the Moine Supergroup (e.g. Strachan *et al.* 2002; 2010 for overview): the *c.* 440-410 Ma Scandian event (Silurian) related to Baltica-Laurentia collision; the *c.* 470-460 Ma Grampian event (Ordovician) , related to arc-continent collision; and the enigmatic Knoydartian event (Neoproterozoic: *c.* 820-780 and *c.* 740 Ma). The Scandian event probably affected the entire outcrop of the Moine Supergroup (Kinny *et al.* 2003a). Grampian deformation and metamorphism has been documented in the eastern Moine Supergroup above the Naver thrust (Kinny *et al.* 1999), near Fort Augustus (Rogers *et al.* 2001) and Glen Urquhart (Cutts *et al.* 2010), whilst Knoydartian mineral ages have been reported from Morar, Knoydart and Glen Urqhuart (e.g. Vance *et al.* 1998; Rogers *et al.* 1998; Tanner & Evans 2003; Cutts *et al.* 2010). However, it remains unclear how the different mineral ages relate to the regional tectonic evolution because the extent and limits of Grampian and Knoydartian deformation and metamorphism remain uncertain (e.g. Strachan *et al.* 2010). A number of augen granites, including the Inchbae / Carn Chuinneag intrusion (Fig. 1) date around 600 Ma and have been linked to late Neoproterozoic rifting of Rodinia (Kinny *et al.* 2003b; Oliver *et al.* 2008). Metamorphic grade in the Morar Group reached middle amphibolite-facies grade (Fettes *et al.* 1985; Thigpen *et al.* 2010): kyanite has overgrown andalusite in the thermal aureole of the Carn Chuinneag granite (Tilley 1935, Wilson & Shepherd 1979), attesting to at least medium-high pressures during Caledonian orogenesis.

Regional Structure

The overall structure of the Morar rocks, in the Moine Nappe *sensu lato* in the Sutherland – Central Ross-shire region, is described in this section and shown on Fig. 1. In the far north, along the coast, there are a number of ductile thrusts within the Morar Group, commonly carrying Archaean Lewisianoid gneisses in their immediate hanging wall. The thickness of the individual thrust sheets rarely exceeds 1 km, and only Altnaharra Formation rocks occur here, together with numerous slices and infolds of Lewisianoid gneisses (Holdsworth 1989; Holdsworth *et al.* 2001). Deformation is intense, with numerous high strain zones and tight to isoclinal folds, including many sheath folds (Holdsworth 1989; Alsop & Holdsworth 2004). Only limited stratigraphical or sedimentological information has been obtained in this area due to the high strain.

In central Sutherland, a number of thrusts either lose displacement or merge, so that individual thrust sheets become thicker, up to 5 - 7 km (Fig. 1; Krabbendam *et al.* 2008; Alsop *et al.* 2010). The two main thrusts here are the Ben Hope and Achness thrusts, forming the Cassley Culmination (Leslie *et al.* 2010), which lies in the hanging wall (and east of) the well studied Assynt Culmination of the Moine Thrust Zone (e.g. Elliott & Johnson 1980; Coward 1985; Krabbendam *et al.* 2010). The Cassley Culmination contains large-scale, west-facing folds. Their steep limbs are many kilometres thick, commonly exposing up to 5 km of little-deformed stratigraphy with very well preserved sedimentary structures (Krabbendam *et al.* 2008; Leslie *et al.* 2010; Alsop *et al.* 2010).

The Achness Thrust, exposed at Achness Falls, duplicates the Altnaharra Formation (Fig. 2; Leslie *et al.* 2010). The Achness Thrust merges with the Moine Thrust in the SE corner of the Assynt Culmination (Figs. 1, 2). The southern Moine Thrust and the Achness Thrust are thus one single thrust (referred to in the text as the Achness-Southern Moine Thrust, but shown separately on Fig. 2) with a single coherent thrust sheet in its hangingwall, termed here the Achness Thrust Sheet. The Moine Thrust north of the junction must have had a different deformational history from the southern part (it lacks the component of displacement along the Achness Thrust, see discussion). Thus, the Moine Thrust as a whole did not have a uniform displacement along its length and the different sectors are here referred to as the Southern and Northern Moine thrusts (Fig.s. 1, 2). The WNW-ESE trending part of the Achness Thrust SE of Assynt forms the Oykel Transverse Zone (Fig. 2), with its ubiquitous mullions (Leslie *et al.* 2010).

South of the Assynt Culmination, there is no significant thrust or shear zone between the Southern Moine Thrust and the Sgurr Beag Thrust, and all Morar Group rocks occur in one single coherent thrust sheet, the Achness Thrust Sheet. This thrust sheet extends from at least Loch Shin in the north to at least Kinlochewe in the SE, a minimum strike length of 70 km, and a width 15 – 45 km (Fig.s. 2, 3). Its *structural* thickness, constrained between the Achness-Southern Moine Thrust and the Sgurr Beag Thrust, varies between 1 and 12 km. The internal structure of this Achness Thrust Sheet, characterised by a series of km-scale folds (Figs.3, 4, 5, 6a), and its relation to the thrust sheets and their evolution farther north, is the focus of this paper.

Regional Stratigraphy

Within the Morar Group in the Achness Thrust Sheet there are five formations in ascending order: the Altnaharra Psammite Formation, the Glascarnoch Psammite Formation, the Vaich Pelite Formation, the Crom Psammite Formation and the Diebidale Pelite Formation.

Lewisianoid Gneiss: basement to Morar Group

Slices of Lewisianoid gneiss, comprising strongly sheared felsic and intermediate gneiss and amphibolite and locally marble, have been described at Achness Falls and Loch Shin (Read *et al.* 1926; Winchester & Lambert 1970). At Achness Falls, the gneiss sliver occurs in the immediate hanging wall of the Achness Thrust. Both occurrences have been interpreted as para-autochthonous basement to the Morar Group (Strachan & Holdsworth 1988; Leslie *et al.* 2010). Newly discovered slices of gneiss occur farther southeast, just above the Southern Moine Thrust in Dundonnell River [NH 115 847] and on the southern side of the Dundonnell Culmination [NH 125 877] (Fig. 2). The slices are highly sheared, mylonitic and isoclinally folded. Overall, it appears that the stratigraphical base of the Morar Group occurs approximately at the level of the Achness-Southern Moine Thrust.

Altnaharra Psammite Formation below the Achness Thrust

Below the Achness Thrust, within the Cassley Culmination, the Altnaharra Psammite Formation contains numerous low strain domains in the steep limbs of large-scale folds, in which the original sedimentary character of the psammite is commonly well preserved. A virtually undeformed stratigraphical thickness of at least 3 km, but possibly as much as 5 km, occurs in the steep limb of the Beinn Sgeireach Anticline (Krabbendam *et al.* 2008). The Altnaharra Psammite Formation comprises thick-bedded (50 – 500 cm) psammite. Gritty beds occur especially low down in the stratigraphy and locally semipelite beds occur higher up in the stratigraphy. Sedimentary structures include channels with pebble lags, planar and trough cross-bedding, slump-like folds, dewatering pipes and oversteepened cross-beds (Krabbendam *et al.* 2008). These authors interpreted the formation as high-energy braided fluvial deposits. Neither the top, nor the base of the formation occur below the Achness Thrust, so that the Cassley Culmination is composed entirely of Altnaharra Psammite rocks.

Altnaharra Psammite Formation in the Achness Thrust Sheet

The Altnaharra Psammite Formation within the Achness Thrust Sheet occupies a swathe of ground stretching from Loch Shin in the north, via Strath Oykel and Loch Broom to Kinlochewe. Over most of this area, the strata are moderately to intensely deformed. The psammites typically show thin, flaggy beds (5 to 30 cm thick), interbedded with thin micaceous layers, and rare semipelite layers. Sedimentary structures are generally obliterated or strongly modified by deformation, and (deformed) planar to trough cross-bedding and channelled bases have only been locally observed (e.g. [NH229 948]). Where preserved, younging evidence suggests that the unit is grossly right-way-up, although isoclinal folds result in local inversions.

The base of the Altnaharra Psammite Formation in this area is formed by the Achness-Southern Moine Thrust, close to its original stratigraphical base (see above). Therefore, the entire thickness of the Altnaharra Formation, albeit in deformed state, occurs in the Achness Thrust Sheet.

Glen Achall Psammite and Semipelite Member

The uppermost Altnaharra Psammite Formation is marked by a more mixed unit of psammite and semipelite, the Glen Achall Psammite and Semipelite Member. The base of this member is locally marked by a garnetiferous semipelite unit (10 – 20 m thick), followed by tabular cross-bedded psammites, with beds on a 5 – 20 cm scale. Garnetiferous semipelitic beds (0.2 to 10 m thick) comprise 10 – 20% of the sequence. The top of the member is commonly marked by a ~ 10 m thick, garnetiferous semipelite, which is locally overlain by a bed of quartzite. Around the head of Loch Broom, these thick semipelite units have not been seen, but the Glen Achall Member can be identified by its higher content of semipelitic beds relative to the overlying Glascarnoch Psammite Formation. In its most easterly occurrence, in an anticlinal fold closure near Loch Droma (Fig. 4), the member shows its greatest thickness at. *c.* 500 m and contains stacked trough cross-bedding. Here, the upwards transition to the overlying Glascarnoch Psammite Formation is well exposed, but can only be identified by subtle lithological changes (Bonsor *et al. in review*).

Glascarnoch Psammite Formation

The Glascarnoch Psammite Formation occupies a large swathe of ground, with excellent sections exposed in low strain zones on the shores of Loch Fannich and Loch Glascarnoch (when water levels are low), and on various slopes south of Beinn Dearg (Bonsor *et al. in review*). The lower part of the Glascarnoch Formation is characterized by moderately thick, stacked trough- and planar-cross psammite beds, 30 – 200 cm thick, showing decametre-scale coarsening-upwards cycles. The uppermost part of the formation comprises more complex and marked coarsening upwards units of rhythmically interbedded psammitic and pelitic beds, 5 – 30 cm thick. Water escape forms and slump folding are abundant, especially towards the top of the formation. Bonsor *et al.* (*in review*) interpret these changes in terms of a transition from a distal fluvial braidplain to tidally-influenced shallow marine-depositional setting. The Glascarnoch Formation is up to 5 km thick east of Loch Fannich, but thins and wedges out to the west (see Discussion).

Vaich Pelite Formation

The most extensive exposure of the Vaich Pelite Formation is north and east of Seana Bhraigh, but the formation also appears on the hills NE of Braemore Junction and surrounds the Fannich Outlier (Figs. 2, 4). A progressive reduction in bed thickness down to *c.* 10 cm in the uppermost part of the underlying Glascarnoch Psammite Formation is typical. The base of the Vaich Pelite is generally abrupt, but locally marked by a10–20 m section of thinly inter-bedded dark grey semipelite and micaceous psammite. Moving upwards into the formation, thicker-bedded semipelite becomes dominant, with abundant garnets up to 2 mm across and a ‘striped’ appearance due to the presence of mm-scale alternations of quartzo-feldspathic and micaceous material. Pale brown layers of siliceous psammite (up to 5-20 cm thick) are sporadically developed in the massive semipelite. The unit is generally strongly deformed. A well-developed mica fabric is ubiquitous, and minor folds and crenulations are abundant. Sedimentary structures have not been observed and have presumably been obliterated. Thickness estimates are therefore unreliable, although the unit appears to thicken northeastwards from the western Fannichs towards Seanna Bhraigh (up to several 100 m thick?) and then thin again farther to the NE. The unit overlies the junction between the Glascarnoch, Glen Achall and Altnaharra formations (near point **A** on Fig. 4).

Crom Psammite Formation

The Crom Psammite Formation overlies the Vaich Pelite Formation. South of Croick (Fig. 2), an almost continuously exposed section youngs consistently from the upper part of the Glascarnoch Psammite, through the Vaich Pelite, into the basal part of the Crom Psammite. This basal part of the Crom Psammite comprises pale buff, siliceous to quartzitic psammite, with beds 20 – 40 cm thick. Cross-bedding and water escape structures are common. In the Allt Crom Loch section [NH 37 83], NE of Loch Vaich, the unit youngs consistently to the east in a section >1 km thick, without large-scale tectonic folds. Siliceous psammite contains planar bedded and upward-fining beds (40 – 80 cm thick), but also relatively abundant trough cross-bedding, suggesting channeling. Slump structures are common. Mud drapes occur on foresets and locally units preserve ripple drift lamination and planar lamination. One *c.* 40 cm thick distinctive unit of dark massive, garnetiferous pelite [NH 374 832] contains matrix supported quartzite clasts up to 3 cm across, possibly representing some kind of mudflow. Gritty and pebbly beds were reported by Peach *et al.* (1912). The area around Loch Vaich has not been resurveyed in detail, but the dips of strata as shown on fieldslips of the original survey (in the BGS archive) are locally steep and highly variable, suggesting the presence of steep folds that complicate the boundary with the Glascarnoch Psammite Formation between Loch Vaich and Loch Glascarnoch (Fig. 2).

Diebidale Pelite Formation

The Diebidale Pelite Formation stratigraphically overlies the Crom Psammite Formation and occurs mainly in the thermal aureole of the Carn Chuinneag granite gneiss pluton (Fig. 2). Both the pluton and the surrounding Diebidale Formation occur in a large-scale, west-facing synclinal closure (Wilson & Shepherd 1979), probably similar to the large-scale folds described below. It comprises massive schistose garnetiferous pelite, locally with calc-silicate and psammite layers, and is more semipelitic towards its base (British Geological Survey 2004). Where the pelite is hornfelsed it locally preserves laminations, ripple marks, cross-bedding and possible mud cracks (Peach *et al.* 1912; Wilson & Shepherd 1979).

Detailed Structure

Three successive sets of tectonic structures occur within the Morar Group in the Achness Thrust Sheet (see also Shepherd 1973, Kelley & Powell 1985). $S2_{Ac}$ is the dominant fabric, characterised by preferred orientation of biotite, muscovite and quartz ribbons. In psammite subjected to moderate to high strain, this fabric is generally penetrative, but it is virtually absent in low strain zones. In semipelitic rocks, $S2_{Ac}$ is commonly an intense sub-mm spaced crenulation foliation, with finely spaced microlithons. $S2_{Ac}$ fabrics are axial planar to the folded bedding and major fold axial surfaces can be located accurately based on consistent vergence changes. The $S2_{Ac}$ grades westward into a sub-parallel mylonitic fabric as the Southern Moine Thrust is approached (see below). $D2_{Ac}$ is therefore seen as the main deformational event in the area, which occurred close to peak-metamorphic conditions within the Morar Group (Fig. 8). A somewhat elusive and earlier, generally bedding-parallel quartz/mica fabric ($S1_{Ac}$) is discernible where crenulated by $S2_{Ac}$ in semipelitic rocks. On the limbs of some megascopic $F2_{Ac}$ folds, $S1_{Ac}$ was seen to make a small angle with both bedding and $S2_{Ac}$. $S1_{Ac}$ is absent or poorly developed in psammite. In some folds, a mm-scale $S3_{Ac}$ crenulation cleavage which folds the micas of $S2_{Ac}$ is well developed. $F3_{Ac}$ folds generally have angular, kink-like geometries, whilst $F2_{Ac}$ folds have more rounded and/or similar (*sensu* Ramsay 1967) geometries.

Basal part of Achness Thrust Sheet

The Southern Moine Thrust is a brittle thrust, overlain by a *c.* 100 m thick zone of intense mylonite. Eastwards and upwards, the mylonite grades into a wide, thick zone of flaggy psammite. Beds dip generally gently to the east (Fig. 5), but swing towards south to SSW dips into the Oykel Transverse Zone (Fig. 2), as a result of later development of the Cassley and Assynt culminations (Leslie *et al.* 2010).

The flaggy psammite contains a well-developed, penetrative $S2_{Ac}$ quartz/mica fabric at small angles (5 – 10°) to bedding. Bed thickness is on a mm- to cm-scale in the mylonitic psammite, but ranges between 5 and 50 cm throughout the flaggy zone, with an overall increase in bed thickness upwards and to the east. A simple shear of $\gamma \sim 5\text{-}10$ is consistent with the angle between bedding/$S2_{Ac}$ and also with a reduction of bed thickness down to 10-20%. Compared to the thick beds (50 – 200 cm) in lower strain Altnaharra Formation below the Achness Thrust, this suggests that strain in the flaggy zone above the Achness-Southern Moine Thrust was generally high, and that the thin flaggy bedding is largely caused by deformation rather than being an original sedimentary feature. This zone of high strain affects most of the Altnaharra Formation and the westernmost parts of the Glascarnoch Formation.

Bedding/fabric relations show a fairly consistent westerly vergence; other shear sense indicators such as shear bands also show westward shear sense. This, together with occasional occurrences of (variably deformed) cross-bedding, indicates that the Altnaharra Formation in this zone is broadly right-way-up. Mineral lineations are common in the mylonitic rocks above the Southern Moine Thrust (Figs. 3, 7a): these plunge fairly uniformly towards 100-110° (ESE), suggesting transport to *c.* 280-290° (WNW). Tight-to-isoclinal folds range in scale from 0.1 m to km-scale folds south of Oykel Bridge; their fold axes trend sub-parallel to the mineral lineation. Farther away from the Southern Moine thrust ('Braemore sector, Fig. 3) intersection lineations and fold axes gradually swing towards southeasterly plunges: in this area, mineral lineations become rare and strain gradually decreases. Thus, given the moderately high strains, the folds in this sector were probably rotated into broad parallelism to the transport direction. Similar fold rotations occur in northern Sutherland (Holdsworth 1989, 1990; Alsop & Holdsworth 2007), but in the Fannichs-Beinn Dearg area the rotation occurred more gradually and at a larger scale.

Braemore / Beinn Dearg and Fannich folds

A large-scale anticline-syncline pair, the Braemore Syncline and the Beinn Dearg Anticline, dominates the mountain massifs of Beinn Dearg and NE Fannichs (Figs.2, 3, 4, 5, 6). The hinge of the Braemore Syncline is well exposed in a small quarry at [NH 228 769] (point **B** on Fig. 4), whilst the hinge of the Beinn Dearg Anticline is well exposed in the north face of Beinn Dearg and Meall nan Ceaprachean (Fig. 6a). The folds trend approximately north-south, and verge and face to the west. They are approximately cylindrical folds, with little curvature of the fold axes. The intersection lineations and minor fold axes plunge gently south or north (Fig. 3, 7), whilst the axial planes dip 20-30° to the east (Figs. 5, 7c). The common limb between these two folds comprises steep, subvertical to overturned beds, over a zone up to 4 km wide, between point **B** and Loch Droma (Fig. 4, 5). Over large parts of this steep limb, the presence of thick bedding (up to 2 m), cross-bedding and slump folds and the absence of minor folds and absence or poor development of any fabric attest to low strain. Nevertheless, open parasitic folds on 10-200 m scale occur up to a kilometre either side of the main closures; a particularly impressive set occurs on the southern slopes of Beinn Dearg (Fig. 6c).

The Beinn Dearg Anticline is an open fold (interlimb angle *c.* 90°) and associated parasitic folds are also open folds which have the main $S2_{Ac}$ foliation as an axial planar fabric. Within these folds, bedding typically remains thick (>1m). In contrast, the Braemore syncline is a close-to-tight fold and contains abundant parasitic folds of both $F2_{Ac}$ and $F3_{Ac}$ generations in both Vaich pelite and Glascarnoch psammite lithologies. $F2_{Ac}$ folds are generally tight, similar folds with biotite axial planar fabrics (Fig. 6d). In contrast, $F3_{Ac}$ folds are generally open to close, angular, kink-like folds (Fig. 6e) that deform the $S2_{Ac}$ fabric with no change of $S0/S2_{Ac}$ vergence across their hinges. Biotite is crenulated in hinges of $F3_{Ac}$ folds. The $F2_{Ac}$ and $F3_{Ac}$ folds are coaxial and coplanar and typically alternate in stacks 10 – 50 m thick. It thus appears that the main folds developed primarily during $D2_{Ac}$ under peak-metamorphic conditions, coeval with biotite growth. Progressive tightening continued during $D3_{Ac}$ - possibly under cooler conditions – but mainly affected the syncline, without modifying the anticline and its associated minor structures.

To the north, the folding dies out remarkably quickly: near Beinn Dearg the common steep limb is only *c.* 1 km wide and consists of a series of decametre-scale, west-vergent parasitic folds (Section A-A' on Fig. 5). About 3 km north of Beinn Dearg, virtually all folding has died out, so that between Ullapool and Seana Bhraigh (and further north, Fig. 2) the strata are arranged in a simple, gently east-dipping sequence.

Towards the south, the Beinn Dearg Anticline forms a more or less continuous structure, crossing Loch Fannich and probably extending all the way along the eastern edge of the Fannich Outlier. Some complications occur between Sgurr Mòr and Loch Fannich, where a more westerly major fold structure, the Fannich Antiform, becomes the main closure over a strike length of *c.* 4 km (Fig. 4 and section D-D' on Fig. 5). Nevertheless, the Beinn Dearg Anticline can be regarded as a continuous structure over a strike length of at least 25 km. In contrast, the Braemore Syncline dies out NW of Sgurr Mòr, but its role is taken over by the Fannich Synform farther to the southwest (Fig. 4 and Fig. 5, section D-D' & E-E'). A number of intermediate folds, arranged in *en echelon* fashion, transfer the deformation from the Braemore Syncline to the Fannich Synform east of Sgurr Mor. In the NW of the Fannich Outlier, the Fannich Synform is an open structure, but south of Loch Fannich, both the Fannich Synform and the Beinn Dearg Anticline tighten up considerably, so that the common limb (which here contains the Sgurr Beag Thrust) is vertical at Loch Fannich, but becomes overturned farther south (Fig. 5, section D-D' & E-E').

An Eigin / Glascarnoch fold pair

The eastern limb of the Beinn Dearg Anticline consists of a 20 – 40° east-dipping panel of strata, some 4 km wide (Fig. 5, sections B-B', C-C', D-D'). The northern shore of Loch Glascarnoch provides an excellent section with abundant way-up and vergence structures. These provide evidence for another syncline/anticline pair, the An Eigin Syncline and the Glascarnoch Anticline. At Loch Glascarnoch, these folds are tight (*c.* 10-20° interlimb angle) and their common overturned limb is *c.* 2.5 km wide. The An Eigin Syncline can be reliably traced towards the SSW across Loch Fannich, and then probably swings to the SW (Sutton & Watson 1954). Parasitic folds with axial planar fabric ($F2_{Ac}$) are most common, but locally angular parasitic $F3_{Ac}$ folds have been found. The axial planes of the two folds diverge and they open up to an interlimb angle of *c.* 60° east of Loch Fannich (Fig. 5, section E-E'). As a result, a very wide (> 7 km) belt of subvertical strata is developed east of Loch Fannich (Figs. 3,4), albeit containing some 100 m scale east-vergent parasitic anticline-syncline pairs in the River Grudie. Exquisitely preserved sedimentary structures exposed at low water along the eastern edge of Loch Fannich show that layer-parallel shortening in the psammitic part of this section was strictly limited (see Bonsor *et al.* in review for sedimentary details of these extraordinary outcrops). The stratigraphical thickness of the Glascarnoch Psammite in this section is therefore estimated to be about 5 km.

Relation with the Sgurr Beag Thrust and Fannich Inlier

The Sgurr Beag Thrust emplaces a large thrust sheet of gneissose Glenfinnan Group metasedimentary rocks and associated Lewisianoid orthogneiss over a thin unit of siliceous, locally quartzitic, psammite of the Morar Group (e.g. Kelley & Powell 1985). This psammite stratigraphically overlies the Vaich Pelite Formation, and is probably equivalent to the Crom Psammite Formation farther east (Fig. 4), although sedimentary structures have been obliterated by high strain. Our observations largely confirm those of Kelley & Powell (1985): the Sgurr Beag Thrust is a ductile shear zone *c.* 50 m thick, with highly strained, platy and mylonitic siliceous psammites in its footwall and strongly sheared, locally phyllonitic, pelitic Glenfinnan Group in its hanging wall; the actual contact is fairly sharp. The Sgurr Beag Thrust shear zone commonly shows a well developed mineral lineation that plunges uniformly to the SSE (Figs. 3, 7; see also Kelley & Powell 1985).

The Glenfinnan Group pelites within the inlier are gneissose, commonly with stromatic migmatitic layers. This is the earliest structure that we have identified within the Sgurr Beag nappe, and is here assigned to $S1_{SB}$ (Fig. 8). The migmatitic leucosome layers have been deformed into asymmetric augen within the Sgurr Beag Thrust shear zone (see also Kelley & Powell 1985, their Fig. 2). This clearly shows that the thrusting postdates migmatisation, and the thrusting has been assigned here to $D2_{SB}$.

Within the Sgurr Beag Nappe, numerous tight to isoclinal folds deform the migmatitic layering and hence post-date migmatisation. Garnets, wrapped by a penetrative mica fabric that is axial-planar to these folds, commonly contain oblique inclusion trails that relate to the earlier ($D1_{SB}$) high-grade tectono-metamorphic event. The fold axes plunge gently to the SSE, parallel to a prominent mineral lineation. These folds probably formed during the development of the Sgurr Beag Thrust and are also assigned to $D2_{SB}$. On the eastern side of the Fannich Outlier is an elongate (100 by 5000 m) sliver of platy and mylonitic siliceous psammite, indistinguishable from the sheared siliceous Morar psammite (Crom Psammite Formation) that elsewhere underlies the Sgurr Beag Thrust. We interpret this sliver as a tight infold of Morar Group psammite, within the outcrop of the Glenfinnan Group (Fig. 5, section E-E'). This would imply that the Sgurr Beag Thrust was at least locally involved in tight folding, probably close to the time of thrusting. In the absence of other evidence, we also assign this folding to $D2_{SB.}$

Upright, tight to open, north-south trending folds crenulate the mica fabric and developed during the formation of the regional-scale Fannich Synform: these are assigned to $D3_{SB}$. It follows then that $D3_{SB}$ equates with $D2_{Ac}$ (see discussion).

Lineations

Lineations, separated into different geographical sectors, are plotted on Fig. 3 and shown in the stereograms of Fig. 7. The lineations have been separated into **a)** mineral lineations comprising mineral lineations of quartz, quartz aggregates (including quartz rodding), feldspar aggregates or amphiboles, depending on lithology; **b)** intersection lineations between bedding and the main foliation; **c)** mullions, mainly from Glen Oykel. Minor fold axes are also plotted on the stereograms. Mineral lineations ('stretching lineations') are abundant in the westernmost Moine Thrust and Fannich sectors (Fig. 7 a, b). In both sectors, mineral lineations, (most) fold axes and intersection lineations are sub-parallel, attesting to high strain (e.g. Escher & Watterson 1974). However, the lineations in the Moine Thrust sector plunge ESE, whilst in the Fannich sector they plunge to the SSE.

In the northeast of the area, the Oykel sector lies at the base of the Achness Thrust sheet, at a similar structural level to the Moine Thrust sector. In this sector, mineral lineations, fold axes and intersection lineations are all sub-parallel, with a consistent plunge of *c.* 30° towards 140° (Fig. 7f); they are thus at a *c.* 30° angle to the lineations in the Moine Thrust sector. This was probably caused by later folding and tilting of the early ($D2_{Ac}$) fabrics as the Oykel Transverse Zone developed during $D3_{Ac}$, coeval with mullion formation (Leslie *et al.* 2010).

In contrast, in the Beinn Dearg and Cassley sectors (Fig. 7 c, d), mineral lineations are rare and where found occur at high angles to intersection lineations and minor $D2_{Ac}$ and $D3_{Ac}$ fold axes; the latter trend broadly north-south. This, together with the widespread preservation of sedimentary structures in these areas, indicates that strain was relatively low, that folds developed mainly by buckling during broadly east-west oriented shortening and that little or no subsequent rotation during non-coaxial strain occurred. In terms of abundance of mineral lineations and the angle between mineral and intersection lineations, the Braemore sector is transitional between the Beinn Dearg / Cassley sectors and the Moine Thrust / Oykel sectors. This sector thus has been affected by strain of intermediate intensity.

Discussion

Tectonic evolution

The first tectono-metamorphic event recognized in the Moine rocks of the Fannich-Beinn Dearg area (Fig. 8 for overview) is the high-grade metamorphism associated with migmatisation of the Glenfinnan Group above the Sgurr Beag Thrust ($D1_{SB}$). Migmatitic schlieren have been deformed into augen close to the Sgurr Beag Thrust so that the main thrust movement ($D2_{SB}$) clearly post-dated migmatisation (Kelley & Powell, 1985). Thrusting along the Sgurr Beag Thrust was to the NNW.

Grant & Harris (2000) suggested multiple movements along the Sgurr Beag Thrust farther east, but this has not been confirmed in the Fannichs.

All subsequent deformation features in the Glenfinnan Group are shared with the Morar Group in the Achness Thrust Sheet below the Sgurr Beag Thrust. The early '$S1_{Ac}$' fabric in the Morar Group is not associated with large-scale structures and its age and origin is uncertain. It could be i) a result of loading by the Sgurr Beag Nappe, in which case $D1_{Ac}$ would be coeval with $D2_{SB}$; ii) the first part of a progressive $D1_{Ac}$ -$D3_{Ac}$ sequence, in which case it would postdate $D2_{SB}$.; iii) an entirely unrelated earlier event. Similar early, usually elusive D1fabrics and rare isoclinal folds have been recognized in northern Sutherland (Barr *et al.* 1986; Holdsworth 1989; Strachan *et al.* 2010).

The following main deformation in the Achness Thrust Sheet ($D2_{Ac}$) resulted in the formation of the large scale Beinn Dearg-type folds including the Fannich Synform. Deformation was accompanied by biotite recrystallisation, and included the formation of the flaggy panel in the hanging wall of the Achness-Southern Moine Thrust, signaling the start of the formation of this major thrust. Note that in this stage, the Northern Moine Thrust had not yet developed. Subsequently, folding developed in the Cassley area below the Achness Thrust, bulging up the latter, and resulting in the formation of the Ben Hope Thrust and the Cassley Culmination (Leslie *et al.* 2010, Fig. 11). These folds ($D2_{BH}$) demonstrably deform the Achness Thrust and the flaggy fabric ($S2_{Ac}$) above it, so that $S2_{BH}$ was coeval with $D3_{Ac}$ (Leslie *et al.* 2010). The $D2_{BH}$ phase represents the main folding and shearing event within the Cassley Culmination and was coeval with biotite growth/recrystallisation. This indicates that not only the deformation, but also the main phase of metamorphic mineral growth, propagated in time towards the foreland.

North of Strath Oykel, thrusting propagated forward again, from the Ben Hope Thrust onto – finally - the Northern Moine Thrust, approximately coeval with the development of large-scale folds near Ben Hee (Alsop *et al.* 2010). In the meantime, WNW-directed transport of the Achness Thrust Sheet south of Strath Oykel was taken up continuously along the Southern Moine Thrust (see also Leslie *et al.* 2010). As deformation progressed, and the nappe pile cooled, deformation in the Assynt sector propagated forward again, resulting in the classic semi-brittle thin-skin thrusting in the Assynt Culmination (e.g. Elliott & Johnson 1980; Coward 1985; Krabbendam & Leslie 2004, Krabbendam *et al.* 2010). This brittle movement was probably responsible for the brittle movement along the Southern Moine Thrust as seen at Knockan Crag. From this it follows that thrust displacement north of Glen Oykel was distributed over three ductile thrusts (Achness, Ben Hope and Northern Moine thrusts) and the brittle thrusts within the Assynt Culmination, whilst to the south *all* this displacement was taken up by the Southern Moine Thrust. Consequently, the Southern Moine Thrust developed earlier, had a longer deformational history and experienced further cumulative displacement than the Northern Moine Thrust.

Overall, a picture emerges of low strain zones with cylindroidal folds formed probably by buckling during east-west shortening in the Cassley and Beinn Dearg sectors. Non-coaxial strain increased towards the underlying thrusts (Achness Thrust and Southern and Northern Moine Thrusts) with fold axes progressively rotated towards a WNW-directed transport direction in the manner first described by Escher & Watterson (1974). Similar such rotation have been extensively documented in northern Sutherland (Holdsworth 1989, 1990; Alsop *et al.* 1996; Alsop & Holdsworth 2004), although in the Fannich Beinn-Deag area the rotation occurs on a wider, more gradual scale and few sheath folds have been found, suggesting that the internal strain within the Achness Thrust Sheet was generally lower than within the thrust sheets in northern Sutherland. This deformation was preceded by NNW-directed transport along the Sgurr Beag Thrust, at a high angle to the WNW-directed movement along the Moine Thrust (see also Kelley & Powell 1985).

In all thrust sheets, the local 'D2' is the main deformation event, coeval with the main phase of metamorphic mineral growth, but 'D2' in any particular thrust sheet is demonstrably older than 'D2' in the thrust sheet above it and demonstrably younger than in the thrust sheet below it. This implies that the concept of a regional, Moine-wide D2 or D3 deformation phases (e.g. Rogers *et al.* 1998; Tanner & Evans 2003; Kocks *et al.* 2006), is not valid. We have shown here that a D1-Dn sequence is only valid within a single thrust sheet and that it is necessary (and possible) to analyze the relationship between D1-Dn sequences in different thrust sheets.

Lineations and transport direction

In north Sutherland, Holdsworth (1989) and Holdsworth *et al.* (2001) documented a *gradual* change in the orientation of mineral lineations from *c.* 160° along the Torrisdale Thrust in the east, via *c.* 140-150° along the Naver Thrust, *c.* 130° in intermediate thrusts sheets (e.g. Dherue and Ben Blandy shear zones) to *c.* 100° along the Moine Thrust. Such a gradual swing is not obvious in the Fannich Beinn Dearg area (Figs. 3, 7), where instead there appears a more *abrupt* swing from 140-150° along and above the Sgurr Beag Thrust, to *c.* 100° along and above the Moine Thrust, with very few mineral lineations of intermediate orientation (see also Kelley & Powell 1985). (The gradual swing in *intersection* lineations –not related to transport direction - in the Fannich-Beinn Dearg area (Fig. 3) is most likely caused by progressive rotation of fold axes, see above). A similar abrupt change in mineral lineation orientation across the Sgurr Beag Thrust was noted by Grant & Harris (2000) near Dornoch. This lack of intermediate orientation of mineral lineations appears to be linked with the lack of intermediate thrusts, one of numerous lateral changes within the Moine Nappe Complex as a whole.

SSE to south plunging lineations (suggesting NNW to northerly directed transport) for high-level thrusts, such as the Sgurr Beag and Naver thrusts, as well as in nearby syn-tectonic intrusions, are widely reported along the length of the Northern Highlands (Rathbone & Harris 1979; Kelley & Powell 1985; Grant & Harris 2000; Kinny *et al.* 2003a). This would suggest that the early ductile Sgurr Beag-type thrusts did have a systematically different transport direction to the lower, Moine Thrust. If the NNW transport direction applies to the entire Sgurr Beag / Skinsdale thrust sheet (assuming correlation of these two structures as suggested by Kocks *et al.* 2006), its displacement must have exceeded 100 km, the distance along a *c.* 145° vector (SE) between the hanging wall of the Skinsdale Thrust near Dounreay and the footwall of the Sgurr Beag Thrust south of Loch Sunart (see also Winchester 1985, but see Butler 1986 and discussion thereof: Holdsworth *et al.* 1986). Such a large displacement, combined with the evidence of lateral facies changes within the Morar Group (see below). renders the critical correlation of the upper part of the Moine sequence on Mull (e.g. Scoor Pelitic Gneiss) with the Glenfinnan Group on the mainland (c.f. Holdsworth *et al.* 1987; Holdsworth *et al.* 1994) unlikely.

Timing of events

Thrusting within the Moine Thrust Zone has recently been well constrained at 431-429 Ma (Goodenough *et al.* in review), although it is possible that later brittle movement may have continued for several million years (Freeman *et al.* 1998; Dallmeyer *et al.* 2001). The main phase of ductile thrusting and associated folding and fabric development affecting the Morar Group probably occurred slightly earlier, in the interval 435 – 430 Ma (Kinny *et al.* 2003a; Goodenough *et al.* in review). This would imply that all deformation episodes from $D2_{Ac}$ onwards (Fig. 8) occurred during the Scandian orogenic event. Note that the large-scale $D2_{Ac}$ folds postdate the late Neoproterozoic (*c.* 600Ma) Carn Chuinneag intrusion. The Skinsdale Thrust in the north is also thought to be a Scandian structure (Kocks *et al.* 2006).

Syn-tectonic granites with SSE plunging lineations either side of the Naver Thrust have yielded Silurian (Scandian) U-Pb zircon crystallization ages of c. 430 – 425 Ma (Kinny *et al.* 2003a). This would suggest that Scandian thrusting did involve an early phase of NNW-directed transport, followed by a change to WNW-directed transport. A change in local transport direction (as opposed to changes in plate motion) could occur if orogenesis was transpressional (Holdsworth & Strachan 1991; Soper 1992) and if this transpression became increasingly partitioned as the orogen developed over time (Dewey & Strachan 2003). In the northernmost Highlands, it is thus permissible that the majority of the thrusts, including the Sgurr Beag Thrust and the ductile thrusts of northern Sutherland, are all Silurian (Scandian) in age.

In contrast, Tanner & Evans (2003) argued for Knoydartian movement along the Sgurr Beag Thrust in the SW Moine, an area that also has yielded Knoydartian mineral ages from Moine rocks and pegmatites above and below the Sgurr Beag Thrust (see overview in Strachan *et al.* 2002, 2010). Partial melting during both Knoydartian and Grampian orogenic events has been documented elsewhere within the Moine Supergroup (Kinny *et al.* 1999; Cutts *et al.* 2010) and either could have been responsible for the as yet undated migmatitic fabrics observed in the Fannich Outlier. It is possible that early components of displacement on the structure were Ordovician (Grampian), or mid-Neoproterozoic (Knoydartian) in age, or a combination of two or all three of these orogenic episodes (e.g. Tanner & Evans 2003). The 'D1' fabrics and rare isoclinal folds in northern Sutherland have been considered to have formed during the Knoydartian event (Barr *et al.* 1986; Holdsworth 1989; Strachan *et al.* 2010). It is possible that if the Sgurr Beag thrust is (in part) a Knoydartian structure, that the elusive 'D1' in its footwall is related to thrusting and then also Knoydartian in age. For the moment, the age and evolution of the Sgurr Beag Thrust as well as the 'D1' fabrics below it, remain unresolved, whilst the large structures below the Sgurr Beag Thrust described here are almost certainly Scandian in age.

Footwall stratigraphy of the Sgurr Beag Thrust – evidence for late Neoproterozoic tilting?

The footwall of the Sgurr Beag Thrust in the Fannich Outlier comprises a relatively thin unit of quartzitic psammite which probably represents the lower (and highly sheared) part of the Crom Psammite Formation. However, farther east the Crom Psammite Formation occurs with both base and top exposed and is, in parts, relatively undeformed. It is stratigraphically succeeded by the Diebidale Pelite Formation (British Geological Survey, 2004). The footwall of the Sgurr Beag Thrust farther east in the Garve / Ben Wyvis sector (e.g. Rathbone & Harris 1979; Grant & Harris 2000) therefore occurs at a stratigraphically higher level than the base of the Diebidale Pelite Formation. The Sgurr Beag Thrust thus apparently cuts down stratigraphy in its footwall from a level high up in the Diebidale Pelite Formation in the east, to low down in the Crom Psammite Formation in the west. This, however, should not be necessarily taken as evidence for out-of-sequence thrusting or an extensional geometry, because it should not be assumed that the Morar sequence was horizontal prior to thrusting. The Morar Group may have been affected by pre-Caledonian orogenesis (see above). An alternative scenario is a *c.* 10° tilting down to the east, analogous to the 5-10° westward tilting of the Torridon Group prior to the deposition of the Cambrian shallow marine shelf sequence of the Caledonian Foreland, possibly caused by rift-related faulting, associated with the *c.* 600 Ma opening of the Iapetus Ocean farther to the SE.

Pre-orogenic disposition of units: Morar Group stratigraphical architecture

With continuing discoveries of low-strain zones within the Morar outcrop that offer detailed sedimentological information (Glendinning 1988, Bonsor *et al.* 2008; Krabbendam *et al.* 2008, Bonsor *et al. in review*) there is an increasing need to place such information in a realistic stratigraphical framework. In doing so, the effects of later tectonic strain must be taken into account. In the west and north of the study area (Dundonnell, Achness, Loch Shin), the Altnaharra Psammite Formation rests upon basement. Unfortunately, the Altnaharra Psammite Formation above this is strongly deformed. The total *structural* thickness of the Altnaharra Psammite Formation in the strongly deformed basal part of the Achness Thrust Sheet is about 1.5 km, increasing to about 3-4 km in Strath Oykel. In a large-scale low strain domain below the Achness Thrust (in the Cassley Culmination), however, the *stratigraphical* thickness in the steep limb of the Beinn Sgeirach Anticline (Fig. 2) is at least 3 -5 km (Krabbendam *et al.* 2008). This would imply a considerable component of vertical thinning of the Altnaharra Formation above the Achness Thrust. A component of vertical tectonic thinning (accompanied by simple shear) has been documented both in Moine Thrust mylonites and farther above the Moine Thrust (Mendum 1976; Thigpen *et al.* 2010; Alsop *et al.* 2010) and, given the flaggy nature of the rocks, is also likely to have occurred in the Braemore sector (Fig. 3). We here suggest that the stratigraphic thickness of the Altnaharra Psammite Formation was at least 3, possibly as much as 5 km.

The westerly outcrops of the Glen Achall Member are modified by moderately high strain. However, in the anticlinal inlier near Loch Droma, some 300 m of stratigraphy is exposed in rocks that experienced little strain. The Glascarnoch Psammite Formation is well exposed in several sections. The widest steep sector is in the River Grudie, with a structural width of at least 6 km. The stratigraphical thickness of this section is in the order of 4-5 km, when the effect of parasitic folds is removed. NE of Loch Glascarnoch, the thickness of the Glascarnoch Psammite Formation in a little deformed section is about 4 km (Fig. 5 and Bonsor *et al. in review*). The Vaich Pelite Formation varies in structural thickness between 0 and 1-2 km near Seana Bhraigh. However, the Vaich Pelite Formation has taken up much shortening and folding, so its maximum stratigraphical thickness is probably less than 0.5 km. The Crom Psammite Formation is, in the Allt Crom Loch section, at least 1 km thick but the total thickness of this formation is probably much more, in the order of 2-3 km.

The total stratigraphical thickness of this sequence, when the thicknesses of different sections are added, would exceed 10-14 km. However, the outcrop of Glascarnoch Psammite Formation pinches out NW of the Fannich Outlier (point A on Fig. 4), as does the Glen Achall Member a short distance to the south. Whilst the rocks NW of the Fannich Outlier are sheared, the strain does not appear to be sufficient in this area to tectonically excise > 4 km of Glascarnoch Psammite Formation strata: tectonic excision would also require special pleading in an overall thrust setting. A more likely explanation would be that this pinching out is part of the original stratigraphical architecture.

We assume here that the disposition of units on the map and cross-sections is predominantly the result of an original stratigraphical geometry, depicted schematically in Fig. 9. The Altnaharra Psammite Formation forms the lowest unit of the Morar Group in the west, as shown by the occurrence of basement slivers above the Southern Moine Thrust. To the east, the Altnaharra Psammite Formation thins and is laterally replaced by the Glascarnoch Psammite Formation: this formation thickens to the east, but is not present in the west. The Glen Achall Member is probably a series of laterally restricted semipelite lenses that represent a diachronous, non-horizontal transition between the two psammite units. The base of the Vaich Pelite Formation overlies the Altnaharra to Glascarnoch transition and is marked by a sharp, sudden incoming of semipelite. This is likely to represent an onlapping flooding surface which would by inference represent a palaeo-horizontal surface. Whether the Altnaharra Formation disappears completely towards the east and the Glascarnoch Psammite Formation rests ultimately on basement is currently not known. Altogether, this implies that the thickness of the Glascarnoch Formation, for instance as exposed in the Grudie Steep Belt, should not be added to the thickness of the Altnaharra Psammite Formation (Fig. 9). Instead, the total stratigraphical thickness from the base of the Altnaharra Formation to the top of the Crom Psammite Formation is in the order of 6-9 km.

Conclusions and implications

The Morar Group from Achness to Kinlochewe and Achnasheen occurs in one single coherent Achness Thrust Sheet, at least 70 km long, up to 10 km thick. Within the Achness Thrust Sheet, the Morar Group is deformed into two very large, west-facing cylindroidal anticline-syncline pairs, with a north-south trending strike length in excess of 25 km. The lower limb of the westernmost syncline grades into a very wide shear zone, which in turn grades into the underlying ductile mylonites of the Southern Moine Thrust below. These folds have an axial planar biotite fabric, developed during peak-metamorphic conditions. However, some large-scale folds kept tightening during post-peak metamorphic conditions, developing new parasitic folds that crenulated the biotite fabric. This resulted locally in coaxial and co-planar refolding of folds.

The ductile Sgurr Beag Thrust is deformed by these folds, and must therefore precede them, whilst it post-dates migmatisation in its hanging wall. Folding and thrusting structurally below the Achness Thrust, in the Cassley Culmination, post-dated the folding in the Fannich area, and was followed in turn by thrusting within the Assynt Culmination of the Moine Thrust Zone, all in a foreland-propagating sequence. In each thrust sheet, the main deformation coincided with the main growth event of metamorphic minerals: the locus of deformation and metamorphic mineral growth propagated towards the foreland. Therefore, the concept of single D1-Dn sequence applicable to the entire Moine Supergroup is not valid: a D1-Dn sequence is only valid within a clearly defined structural unit, such as an individual thrust sheet, and temporal links to D1-Dn sequences in adjacent structural units should not be assumed but need careful analysis.

All folding and shearing below the Sgurr Beag Thrust can be linked to WNW-directed transport, culminating in the formation of the Moine Thrust, and is consequently related to the Scandian event. The age of the Sgurr Beag Thrust, and the age of migmatisation that preceded thrusting, is currently unknown, except that both must precede Scandian deformation of the Morar Group. Knoydartian, Grampian or early Scandian deformation are all possibilities. The Sgurr Beag Thrust shows large-scale (>100km) NNW directed transport, markedly oblique to the WNW-directed Moine Thrust-related movement. Mineral lineations intermediate in orientation are rare and not associated with large-scale structures, suggesting at least in the Fannich-Beinn Dearg area, a jump in orientation of thrust direction.

The Sgurr Beag Thrust cuts stratigraphically down-section in its footwall lying above the Crom Psammite Formation in the east, and the basal Crom Psammite Formation in the west. Late Neoproterozoic tilting, analogous to the pre-Cambro-Ordovician tilting experienced by Torridon Group in the Caledonian Foreland, could explain this feature.

Large low strain zones occur in steep limbs of large folds and sedimentary structures are locally well preserved. A reconstruction of the stratigraphic geometry indicates large-scale lateral variations in stratigraphy: the Altnaharra Formation thins towards the east, whilst the Glascarnoch Formation thickens to the east and forms its lateral equivalent; both units are 3-5 km thick. The Vaich Pelite Formation overlies both of these formations and its base may represent an onlapping flooding surface. The Crom Psammite Formation follows and possibly represents a return to high-energy sedimentation. The total stratigraphical thickness of the Morar Group is therefore in the order of 6-9 km.

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Figures

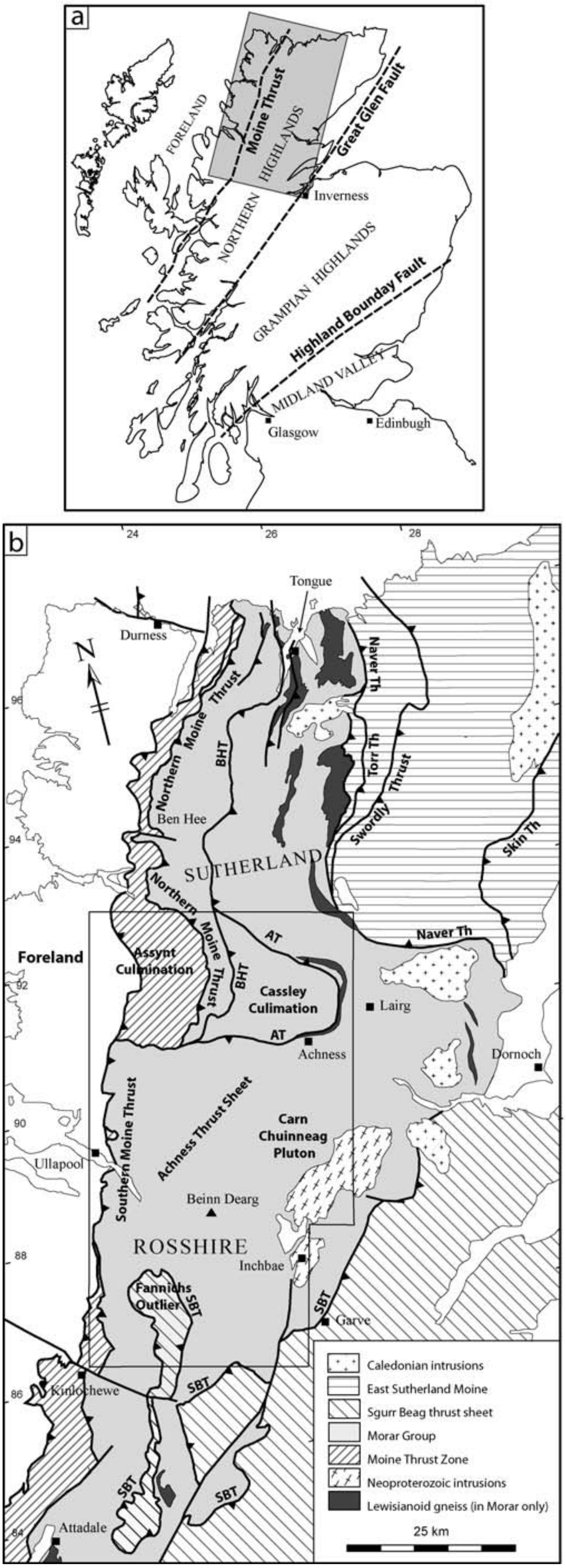

Fig. 1. (**a**) Location map of Scotland, with large-scale structures and location of Fig. 1b shown. (**b**) Overview map of the main thrusts in the Northern Highlands, with the thrust sheet nomenclature used in this paper. After British Geological Survey (2007) and Mendum (2009). AT = Achness Thrust, BHT = Ben Hope Thrust, Torr Th = Torrisdale Thrust; Skin Th = Skinsdale Thrust; SBT = Sgurr Beag Thrust. Lewisianoid Inliers are only shown within outcrop of Morar Group. Inset box shows position of Figs. 2 and 3.

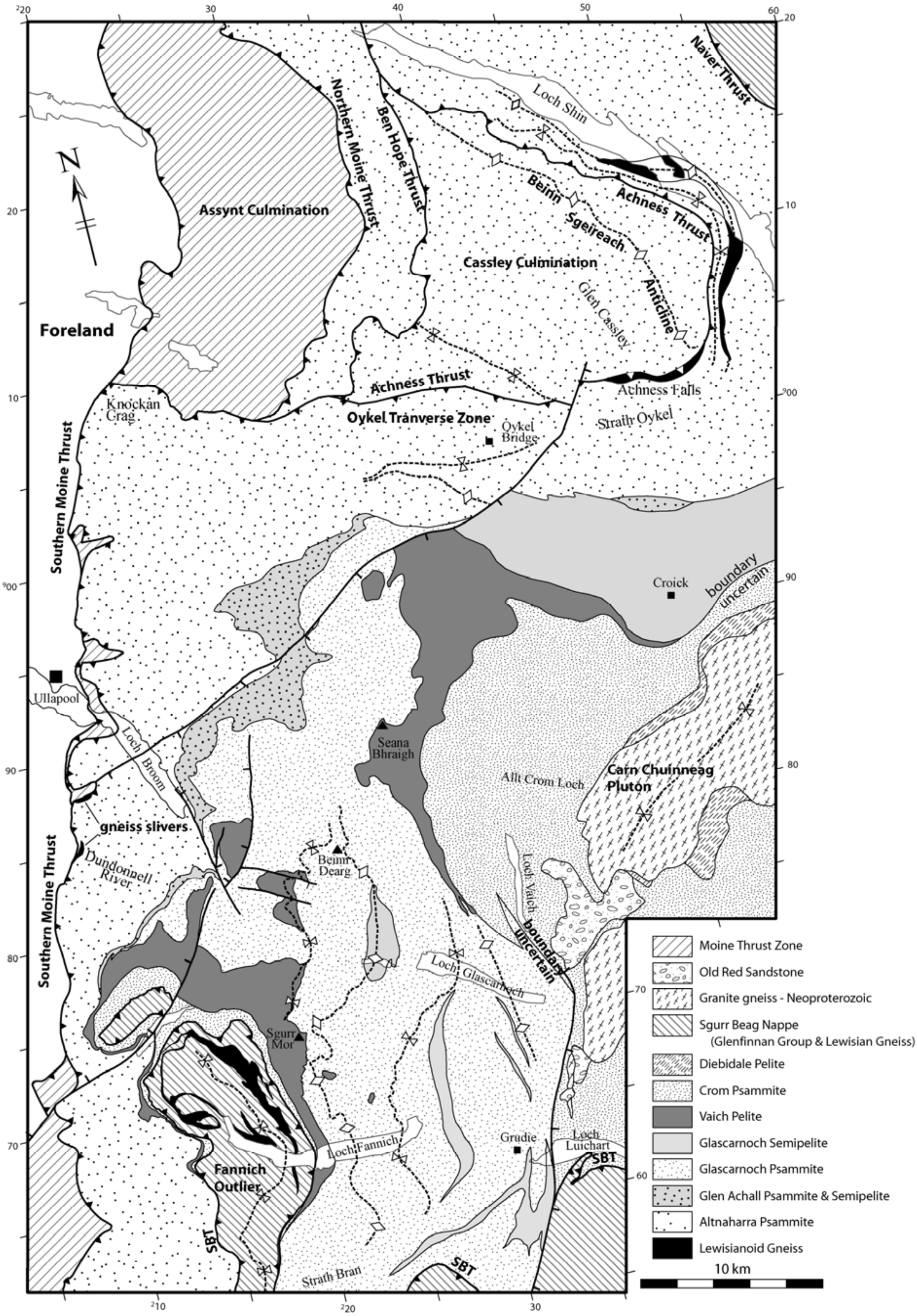

Fig. 2. Geological map of the Fannich-Loch Shin area. For location see Fig. 1.

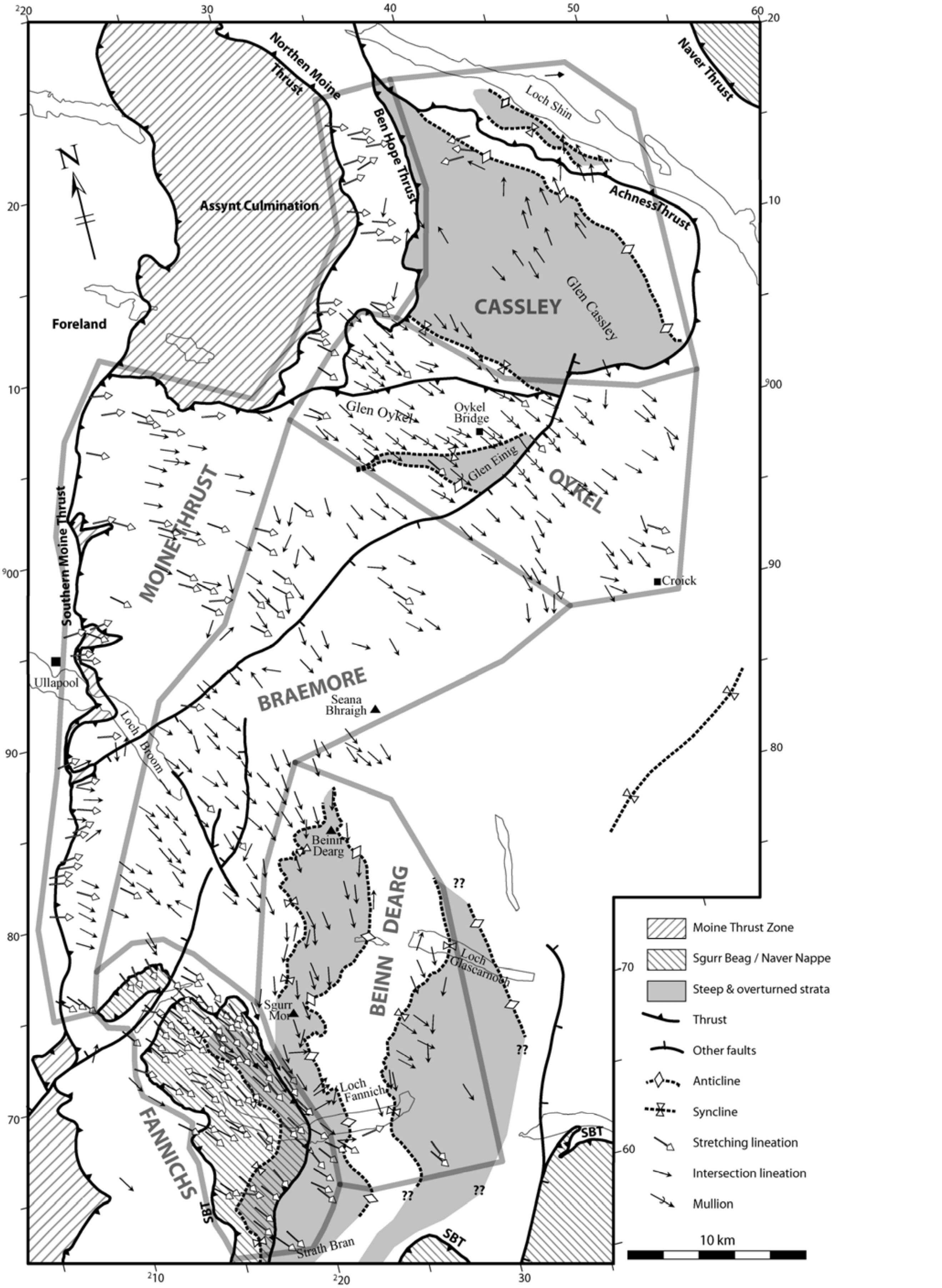

Fig. 3. Map showing main structures and lineation data from the Fannich-Loch Shin area. For location see Fig. 1. Sector boundaries for stereograms (Fig. 7) are indicated.

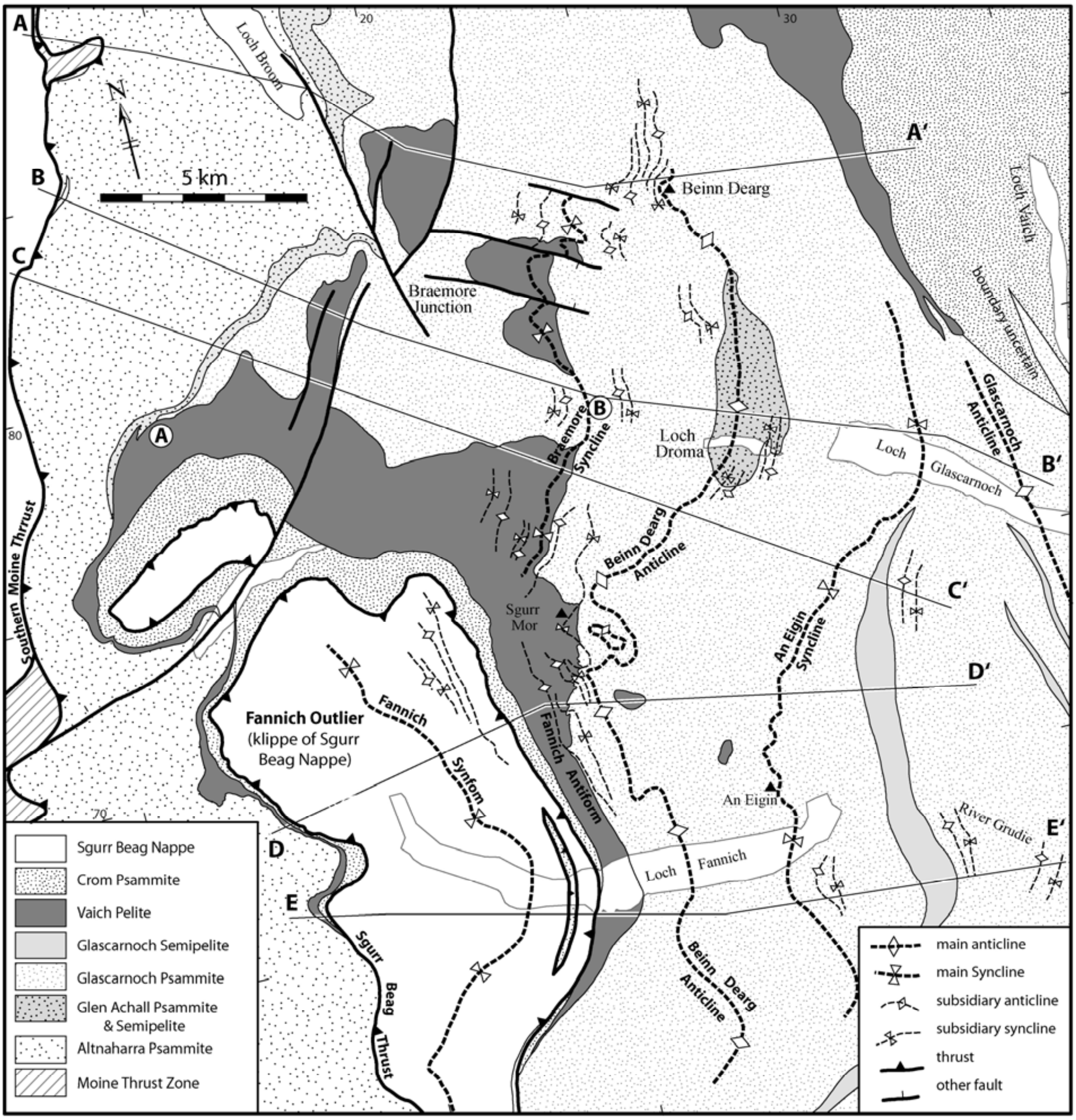

Fig. 4. Geological map of the Fannich-Beinn Dearg area. Lines of section shown in Fig. 5 are indicated

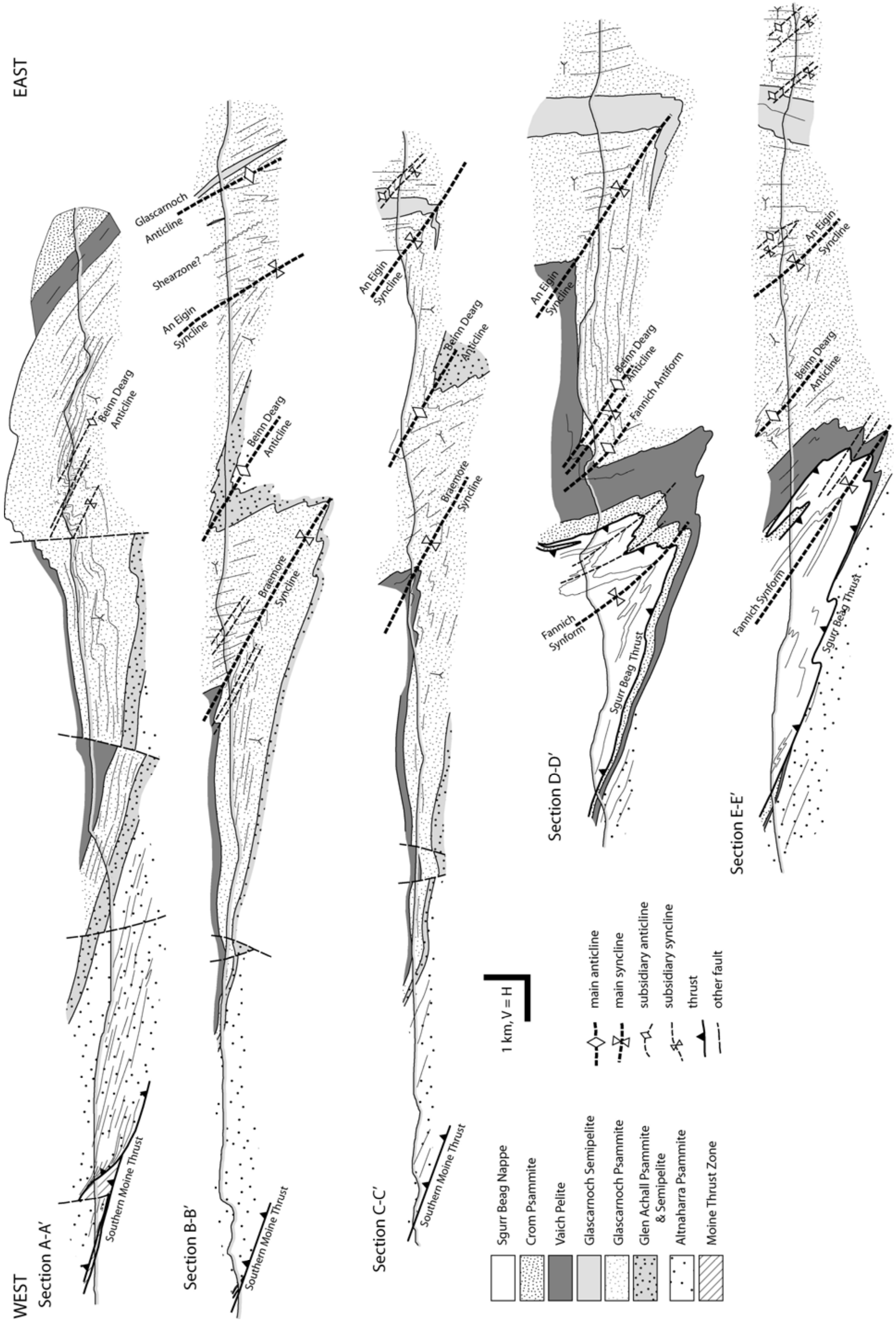

Fig. 5. Cross-sections across the Fannich-Beinn Dearg area. Lines of section shown in Fig. 4.

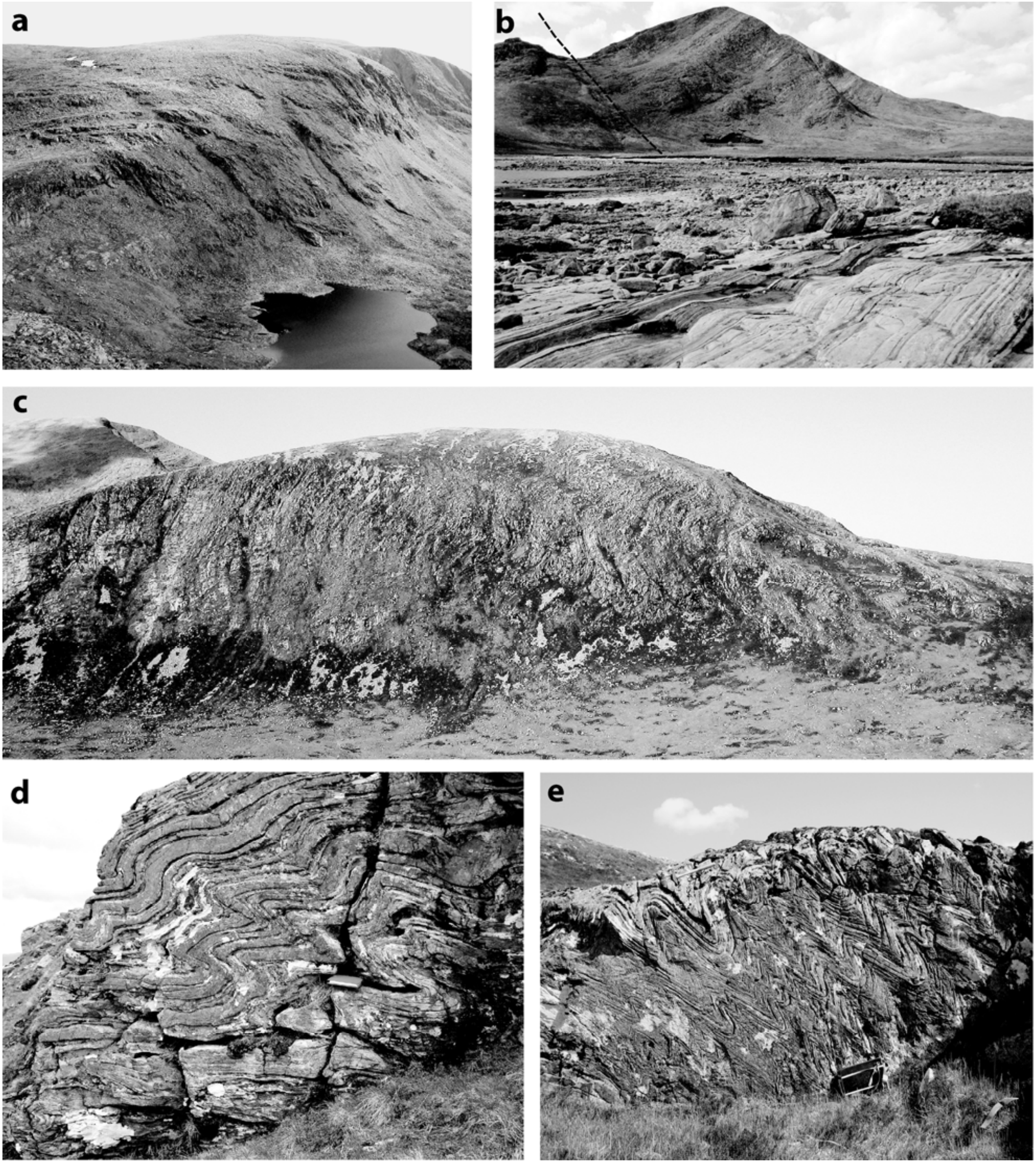

Fig. 6. Photos of structures

(**a**) Example of large-scale folding: the hinge zone of Beinn Dearg Anticline. View to the south on Meall nan Ceaprachean, 2 km north of Beinn Dearg [NH 25 83]. Height of slope *c.* 250 m. BGS photo P669319, © NERC.

(**b**) Example of large-scale folding: the hinge zone of the An Eigin Syncline (axial trace indicated), seen from the eastern end of Loch Fannich. In the foreground are subvertical, but little deformated strata of the Glascarnoch Psammite Fomation. Height of hill above loch level *c.* 550 m, [NH26 65].

(**c**) Example of large-scale folding: Steep limb, with medium-scale east-vergent parasitic folds between Beinn Dearg Anticline and Braemore Syncline, 2 km south of Beinn Dearg. Height of hill *c.* 350 m; width of view *c.* 1500 m, view to the north. Strata young to the west (left). BGS photo P668520, © NERC

(**d**) Example of parasitic $D2_{Ac}$ folds, biotite is axial planar. Note book is 10 cm wide. View to the north. Meall nan Ceapraichean [NH 2563 8243], BGS photo P668363, © NERC.

(**e**) Example of parasitic $D3_{Ac}$ kink folds, biotite is folded. Map case is 30 cm wide. View to the north. North of Loch Droma [NH 2738 7545], BGS photo P668386, © NERC.

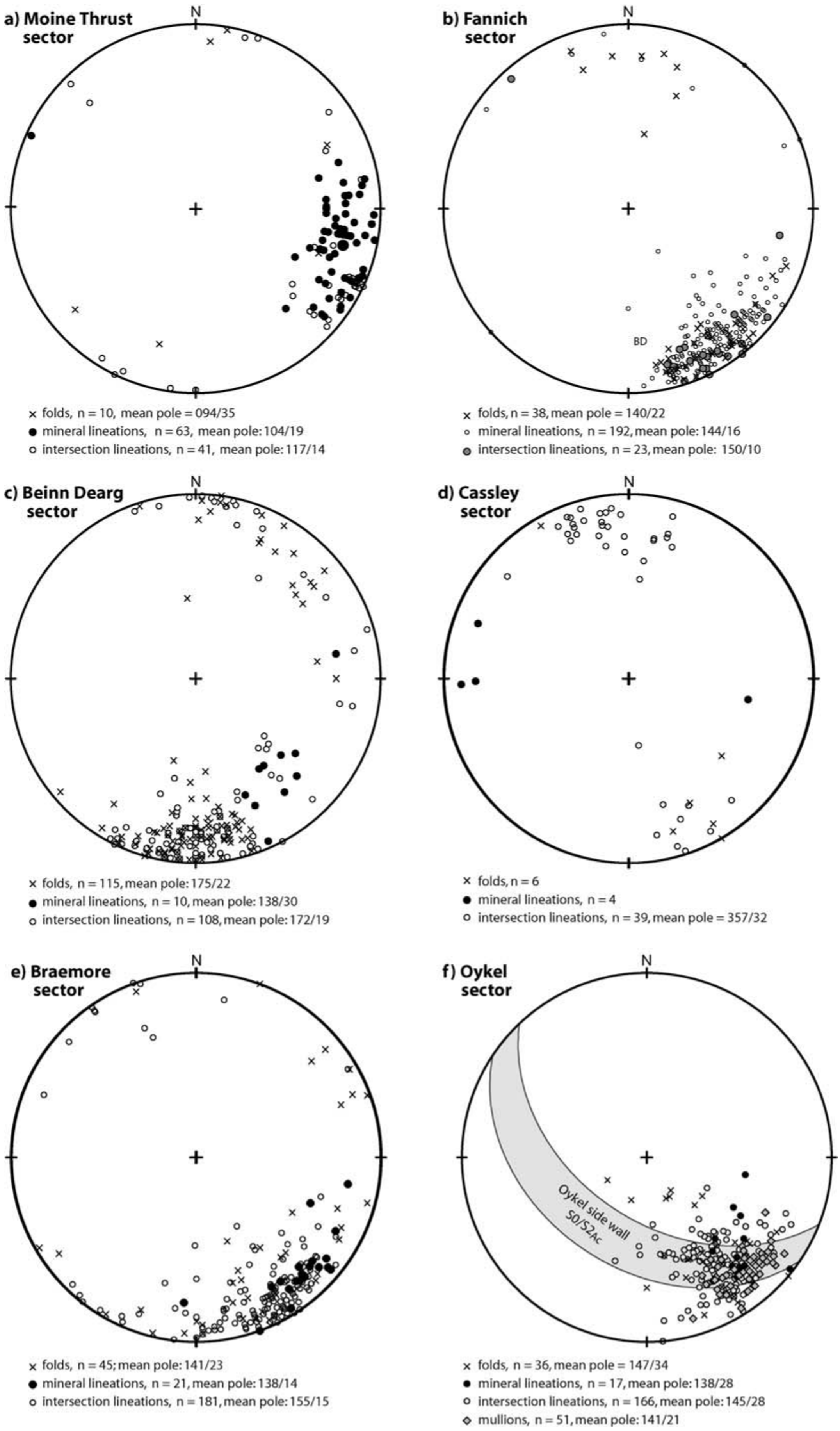

Fig. 7. Stereograms of structural data, in six different sectors: see Fig. 3 for sector boundaries. Equal area lower hemisphere projection.

west ⟵ east

Moine Thrust Zone	Ben Hope Thrust Sheet (BH) (Cassley Culmination)	Achness Thrust Sheet (Ac)	Sgurr Beag Thrust Sheet (SB)	time
Brittle reactivation of Moine Thrust	Brittle reactivation of Moine Thrust	Brittle reactivation of Moine Thrust		~ 415 Ma? (1)
WNW thrusting within Moine Thrust Zone (Ben More Thrust, Glencoul Thrust, etc)				431 - 419 Ma (2)
	Development of ductile Northern Moine Thrust Glen Oykel; Folds near Ben Hee; Ben Hope Thrust Folded	Continuing ductile thrusting of Southern Moine Thrust Limited movement along Achness Thrust;		
	Folds in Glen Cassley; WNW ductile thrusting along Ben Hope Thrust; Peak metamorphism (**$D2_{BH}$**)	Achness Thrust folded by underlying Cassley folds Oykel Transverse Zone with mullions develops Folding of main fabic (**$D3_{Ac} = D2_{BH}$**)		~ 435 - 430 Ma (3)
		Folds of Beinn Dearg; Development of flaggy fabric; WNW ductile thrusting along Achness - Southern Moine Thrust Peak metamorphism (**$D2_{Ac}$**)	Sgurr Beag Thrust folded by underlying Beinn Dearg folds, (**$D3_{SB} = D2_{Ac}$**)	
	Early S1 fabric by loading by Sgurr Beag Nappe?	Early **$D1_{Ac}$** fabric by loading by Sgurr Beag Nappe?	NNW thrusting along Sgurr Beag Thrust (**$D2_{SB}$**) Migmatisation and layering; Peak metamorphism (**$D1_{SB}$**)	pre-435

Fig. 8. Diagram showing the different deformation phases in different sectors, implying an overall foreland propagating deformation sequence. References to geochronological constraints: 1) Freeman *et al.* (1998); 2) Goodenough *et al.* (in review); 3) Kinny *et al.* (2003a).

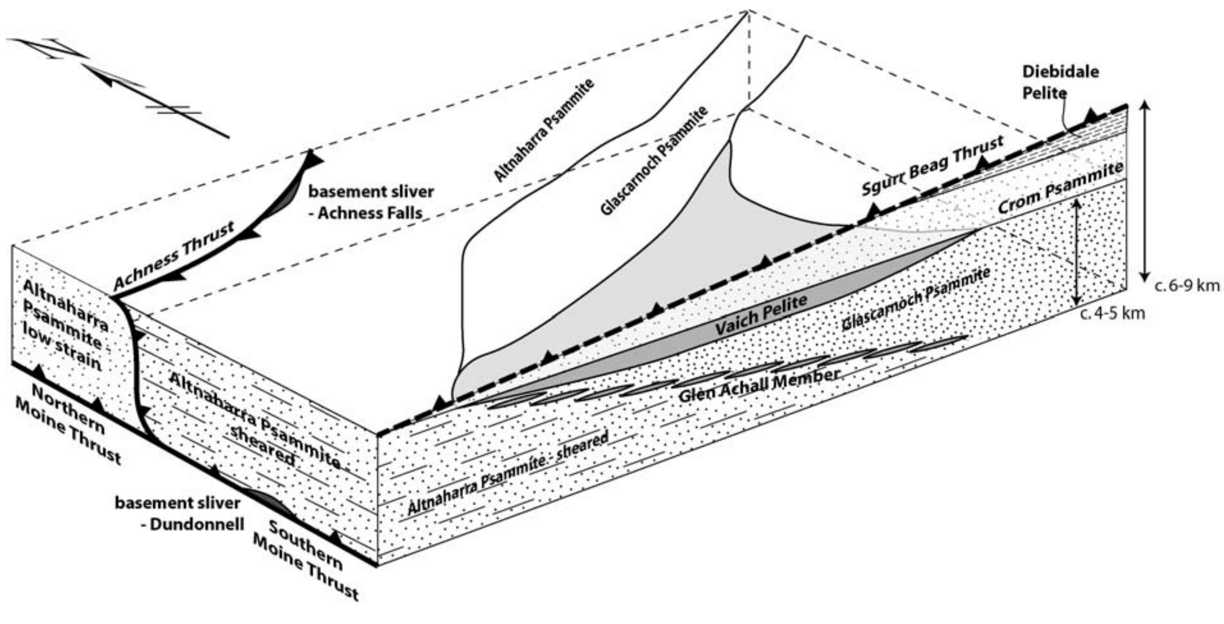

Fig. 9. Schematic interpretation of the stratigraphical relationships within the Morar Group. Not to scale, see text for explanation.