Regional-scale lateral variation and linkage in ductile thrust architecture: the Oykel Transverse Zone, and mullions, in the Moine Nappe, NW Scotland

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Abstract:

Sharp lateral changes in structural geometry of ductile thrust stacks are not widely reported. A regional-scale lateral culmination wall forms the southern boundary of the Cassley Culmination in Moine rocks in the Caledonides of Sutherland, Northern Scotland. This culmination wall is part of the Oykel Transverse Zone (OTZ), a kilometre-scale shear zone characterised by constrictional finite strain fabrics aligned sub-parallel to the regional WNW-directed thrust transport direction. Main phase folds and fabrics in the transverse zone hanging-wall are folded by main phase folds and fabrics in the footwall, thus recording foreland-propagating ductile deformation. South of the Cassley Culmination, shortening occurred uniformly, without development of discrete subsidiary thrusts; distributed deformation (fold development) alternated with localised thrusting within the culmination. The classic ESE-plunging mullions at Oykel Bridge are an integral part of the OTZ and were generated by constriction aligned sub-parallel to the transport direction. Constriction is attributed to differential, transtensional movement across the OTZ during culmination development. Subsequent formation of the underlying Assynt Culmination further accentuated upward-bulging of the Cassley Culmination, amplifying the lateral change across the transverse zone. The OTZ aligns with a pronounced gravity gradient on the south-western side of the Lairg gravity low. Interpretive modelling relates this gradient to a buried basement ramp that possibly controlled the location of the transverse zone.

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The structural geometries of fold-and-thrust belts commonly show significant lateral variation, often related to the development of duplexes and associated culmination structures (e.g. Elliott & Johnson 1980; Boyer & Elliott 1982; Butler 1987; Butler *et al.* 2007). Sharp lateral changes occur across transverse zones, which can comprise lateral culmination walls, strike-slip faults, and other structures that link thrusts laterally (Thomas 1990). Transverse zones in thrust systems are commonly understood to be coincident with, and caused by, deeper seated pre-existing structural features, such as faults that displace the basement-cover interface (Thomas 1990; Paulsen & Marshak 1999). Such lateral discontinuities, and their associated transverse zones, are mainly documented in the brittle, thin-skinned parts of fold-and-thrust belts (e.g. Paulsen & Marshak 1999; Krabbendam & Leslie this volume). In this paper, we describe a regional-scale ductile transverse zone developed in association with a ductile thrust stack in Moine rocks now arranged structurally above the more brittle or brittle-ductile structures of the classic Moine Thrust Belt in NW Scotland (Fig. 1). This Oykel Transverse Zone comprises a large-scale lateral culmination wall, marking the southern termination of a number of separate thrust sheets. The Cassley Culmination comprises a bulge at the southern limit of these thrust sheets and lies structurally above the brittle Assynt Culmination (Fig. 1, 2).

The Oykel Transverse Zone (OTZ) is marked by a *c.* 5 km wide and *c.* 20 km long panel of SW-dipping, highly deformed lithologies, striking broadly perpendicular to the overall trend of the thrust front, but approximately parallel to the overall transport direction (Fig. 2). The OTZ contains the classical Oykel Bridge mullion structures (Wilson 1953), and here we seek to link the development of these mullions to the kinematic evolution of the OTZ. Furthermore, the OTZ is coincident with the SW margin of the ‘Lairg low’ in the regional gravity field, one of the most conspicuous gravitational features in the Northern Highlands. In this paper we present new gravity modelling which implies that the location of the OTZ was strongly influenced by a prominent buried ramp, or series of steps, in the basement/cover interface. We propose a kinematic model for the OTZ that links development of the architecture of the OTZ, and of the Moine Nappe and the Cassley Culmination, with the compartmentalisation of structure in the underlying Moine Thrust Belt in Assynt (Krabbendam and Leslie this volume).

Geological setting

Baltica-Laurentia collision during the Scandian (Silurian) phase of the Caledonian Orogeny is expressed in the Northern Highlands of Scotland as a crustal-scale WNW-vergent fold-and-thrust belt. In northern Scotland, this Caledonian deformation culminated in development of the Moine Thrust Belt; this classic and well-studied belt defines the external part of the Caledonian Orogen. The Moine Thrust Belt records predominantly brittle, overall WNW-directed, thin-skinned thrust transport estimated of the order of 50–80 km (e.g. Lapworth 1885; Peach *et al.* 1907; Soper & Wilkinson 1975; Elliott & Johnson 1980; McClay & Coward 1981; Butler 1982; Butler *et al.* 2007; Krabbendam & Leslie this volume). The Moine Thrust defines the base of the Moine Nappe *sensu lato* (British Geological Survey 1997, 2002) and marks the boundary between the external and internal parts of the Caledonian Orogen in northern Scotland (Fig. 1). In Sutherland, in the more internal parts, the Naver Thrust defines the base of the overlying Naver Nappe; farther south the Sgurr Beag Thrust occupies a similar structural level at the base of the Sgurr Beag Nappe. Deformation within this internal part of the belt is thick-skinned and ductile, and generally occurred under greenschist- to amphibolite-facies metamorphic conditions (see Strachan *et al.* 2002 for overview).

The early Neoproterozoic metasedimentary rocks of the Moine Supergroup dominate the geology of the Northern Highlands. These Moine rocks are interfolded and intersliced with late Archaean ‘Lewisianoid’ orthogneisses regarded as fragments of the basement onto which the Moine sedimentary protoliths were deposited unconformably (Ramsay 1957; Holdsworth 1989; Holdsworth *et al.* 1994, 2001; Friend *et al*. 2008). Though disrupted by a number of ductile thrusts (Barr *et al.* 1986; Holdsworth 1989), the Moine Supergroup has been divided into three groups, the structurally and stratigraphically lowest of which is the Morar Group (Johnstone *et al.* 1969; Soper *et al.* 1998; Fig. 1). The younger Glenfinnan and Loch Eil groups mainly occur structurally above the ductile Sgurr Beag Thrust (Holdsworth *et al.* 1994; Strachan *et al.* 2002). Relevant here is that along its entire 200 km length, the hanging wall of the Moine Thrust (i.e. the Moine Nappe *sensu lato*) is composed only of Morar Group rocks or their associated basement gneisses.

The Morar Group was originally deposited as several kilometres thick package of siliciclastic strata and now occurs as dominantly psammitic rocks with subsidiary layers of pelite and semipelite. Sedimentary structures are commonly (but not ubiquitously) deformed, obscured or obliterated by regional metamorphism, especially in pelitic and semipelitic lithologies. North of Glen Oykel (Fig. 2), the Morar Group stratigraphy is dominated by the Altnaharra Formation and composed of rather uniform psammite with subsidiary layers of pelitic, semipelitic and pebbly rocks. Bed thickness typically varies from 20 cm to over 300 cm and sedimentary structures such as cross-bedding, nested cross-beds, and soft-sediment deformation are common and suggest deposition in a braid-plain fluvial setting. An original stratigraphical thickness in excess of 3 km can be demonstrated and a correlation with the Torridon Group in the Foreland has been suggested (Krabbendam *et al.* 2008).

Timing of events

The present-day disposition of rocks in the Northern Highlands is that of a foreland-propagating fold-and-thrust-belt system (Barr *et al.* 1986; Holdsworth *et al.* 2001, 2006, 2007), mainly the result of Caledonian (Scandian) orogenesis. However, the Moine rocks have experienced a number of much-debated tectonometamorphic events, namely an extensional event at *c.* 870 Ma followed by Knoydartian (820–740 Ma), Grampian (470–460 Ma) and finally by Scandian (430–400 Ma) orogenic events (see review in Strachan *et al.* 2002).

Movement along the Moine Thrust at the western boundary of the Caledonian Orogen is regarded as Silurian (Scandian) in age (van Breemen *et al.* 1979; Johnson *et al*. 1985; Kelley, 1988; Freeman *et al.* 1998; Dallmeyer *et al*. 2001). Isotopic dating of syn-tectonic granites suggests that Scandian deformation was also widespread within the Moine and Naver nappes in Sutherland (Kinny *et al.* 2003). Knoydartian tectonometamorphic ages have been recorded mainly in the south (van Breemen *et al.* 1974, 1978; Piasecki & van Breemen 1983; Rogers *et al.* 1998; Vance *et al.* 1998), where it is thought that the main movement along the Sgurr Beag Thrust is Knoydartian (Tanner & Evans 2003). Grampian effects are most evident in east Sutherland and eastern Inverness-shire (Kinny *et al.* 1999; Emery *et al.* in prep.). These regional variations in the intensity and spatial extent of orogenic events mean that correlation of structures is complex and problematical (Hobbs *et al.* 1976; Forster & Lister 2008). For example, 'regional S2' in the Morar Group of west Sutherland appears to be Silurian (Scandian) in age, whilst 'regional S2' in the Glenfinnan and Loch Eil groups appears to be Ordovician (Grampian) in age (Rogers et al. 2001; Kinny *et al.* 2003; Emery 2005). Further complexity is introduced because any individual deformation event may well be developed diachronously. In this paper we will show that there is no such thing as a 'regional S2 fabric' in the Cassley Culmination; we will demonstrate that in Glen Oykel the dominant 'S2' in one nappe is clearly overprinted by the dominant 'S2' in a structurally lower (i.e. younger formed) nappe in a foreland-propagating system.

The Cassley Culmination - overview

The structure of the central part of the Moine outcrop has received little or no attention since the rather cursory primary survey (Read *et al.* 1926). The exception to this has been the studies of the now classic mullion structures at Oykel Bridge (Figs. 3, 4a) described by Clough (in Peach *et al.* 1912), Read *et al.* (1926) and Wilson (1953).

New mapping in connection with a British Geological Survey (BGS) resurvey of the region has identified a structural culmination in the hanging wall of the Moine Thrust and SE of the classic Assynt Culmination; this structure is defined here as the Cassley Culmination (Figs. 1, 2). The Moine Thrust acts locally as the floor thrust to the culmination and the Achness Thrust is regarded as the roof thrust to the culmination; the Ben Hope Thrust lies within the culmination, between the Achness and Moine thrusts (Figs. 2, 3). The transport direction on each thrust is top-to-the-WNW, parallel to a locally well-developed quartz mineral and pebble elongation lineation. The Ben Hope and Achness thrusts have broadly arcuate outcrop traces and converge with the Moine Thrust at the SE corner of the Assynt Culmination (point A on Fig. 2), thus delineating the limit of the Cassley Culmination in the south and SW (Figs. 2, 3).

The southern lateral termination (culmination wall) of the Cassley Culmination is well-defined; the hanging wall of the Achness Thrust is marked by a km-scale thick, strongly deformed, planar zone of southward-dipping flaggy psammite (Figs. 2, 3). This zone contains a prominent belt of mullion structures which includes the classic Oykel Bridge locality (Wilson 1953, Fig. 4a). These mullions plunge SE, sub-parallel to the regional transport direction. Southwest of Loch Shin, the individual nappes comprise distinctive lithological packages and structural geometries; each are described in more detail below. The fabric overprinting relationships in the vicinity of the Achness Thrust demonstrate clearly that the age of the dominant schistosity ('S2') is different in each nappe. It is not appropriate therefore to simply refer to an 'S2' without reference to the structural domain in which that fabric has been recorded (Hobbs *et al.* 1976; Forster & Lister 2008); 'S2' has no single meaning across the culmination. Main phase fabric relations for the Cassley Culmination are summarised in Table 1 below, abbreviations in this table are used throughout. Stereographic projections of representative structural data for each thrust sheet are presented and summarised in Fig. 5.

Achness Nappe		**Ben Hope Nappe**		**Moine Nappe Northwest (below Ben Hope Nappe)**		**Regional event**
Early bedding parallel fabric	$S1_{AC}$	Early bedding parallel fabric (in semipelite only) Relationship to $S1_{AC}/S2_{AC}$ unclear	$S1_{BH}$	Early bedding parallel fabric??		??
<u>Main phase:</u> - flaggy fabric + biotite fabric - Einig Folds - Intersection lineation ($S0/S2_{AC}$)	$S2_{AC}$ $F2_{AC}$ $L2_{AC}$					Achness Phase
(steepening/ rotation of above structures) Mullions	$F3_{AC}$ L_M	<u>Main phase:</u> - biotite fabric - Cassley Folds - Crenulation in semipelite - Intersection lineation ($S0/S2_{BH}$) Mullions	$S2_{BH}$ $F2_{BH}$ $L2_{BH}$ L_M			Ben Hope Phase
Later phase - weak superimposed crenulation oblique to mullions ($S4_{AC}$)		Later phase - localised intense crenulation in semipelite, ($S3_{BH}$)		<u>Main phase</u>: - planar flaggy biotite fabric *(intensifies downward to)* Moine Mylonite fabric Quartz-stretching lineation	S_M S_{mylM} L_{qtzM}	Moine Thrust North Phase

Table 1. Summary of main phase structural fabric relationships in the Glen Oykel/Glen Cassley area of the Cassley Culmination. The arrow tracks the foreland-propagating deformation history.

Structure and lithologies of the Achness Nappe

The Achness Thrust forms the roof thrust to the Cassley Culmination (Fig. 2). The trace of the Achness Thrust is well constrained in the south, less so in the east and north. At its type section at the Achness Falls, the Achness Thrust dips *c.* 40° to 50° to the south (Fig. 6). North of the falls, and structurally below the thrust, thick-bedded psammitic rocks of the Ben Hope Nappe are folded by open to close, north-south trending $F2_{BH}$ folds (Cassley folds – see below); strata young overall to the west or south. Cross-bedding, younging towards the thrust, occurs as close as 50 m structurally beneath the trace of the Achness Thrust. Closer to the Achness Thrust, psammite becomes highly-deformed and sub-mylonitic. The Achness Thrust marks the contact between these psammites and a sheet of mylonitic Lewisianoid basement gneiss, *c.* 200 m thick (Fig. 6). The gneiss is bounded to the south by an intermittent layer of semipelitic schist up to 20 m thick, overlain by psammite which is locally gritty to pebbly. These units probably represent lowermost Morar Group strata occurring immediately above the inferred unconformity with the basement gneiss. Some 250 m south of this contact, cross-bedding youngs to the south, away from the Achness Thrust.

The Achness Thrust has not been studied in detail east and north of Achness Falls. Its location may be marked by a series of Lewisianoid slivers, associated with phyllonitic gneiss or psammite (Peacock 1975) that occur in the east. It is thought most likely that north of these inliers it trends northwestward across the poorly exposed ground south of Loch Shin, to link with the Ben Hope Thrust in the vicinity of Loch Merkland (Fig 2). According to this interpretation, the Airde of Shin basement inlier lies in the hanging wall of the Achness Thrust (Fig. 2). This inlier occurs in the core of a major tight anticline (the Loch Shin Anticline, LSA on Fig. 2). In contrast to the rather cylindrical $F2_{BH/AC}$ folds observed elsewhere across the Cassley Culmination, the Loch Shin Anticline is a curvilinear non-cylindrical fold, which, at Airde of Shin is locally sideways-closing and inferred to plunge to the ESE, parallel to the regional L2 stretching and mineral lineation (Strachan & Holdsworth 1988). The Loch Shin Anticline is tentatively correlated with the gently-plunging, cylindroidal Ben Hee Anticline farther north (Fig 2; and see Cheer *et al.* this volume). An alternative interpretation is that the Achness Thrust links with the Dherue Thrust ~30 km north of Loch Shin (Fig 2). This solution cannot be precluded completely given the sparse exposure around Loch Shin, but is thought less likely.

No Lewisianoid inliers occur in the hanging wall of the Achness Thrust towards the west, and within the lateral termination of the Cassley Culmination; psammite is emplaced on psammite (Figs. 3, 6). However, the character of the psammite on either side is quite different. The psammite structurally below the Achness Thrust (i.e. in the Ben Hope Nappe) is generally thick-bedded and massive. Fabric development is poor and related to the west-vergent km-scale ‘Cassley Folds’, ($F2_{BH}$); in many outcrops the fabric is at high angles to bedding (Fig. 5, and see Ben Hope Nappe section below). Only a small distance below the thrust (*c.* 100–200 m), the strike of the strata, and of the 'Cassley Folds', is at a high angle to the trace of the Achness Thrust (Figs. 6 & 7). In contrast, to the south and structurally above the Achness Thrust, psammite strata are thin-bedded (possibly caused by deformation, see below), with a well-developed bedding-parallel biotite-defined foliation $S2_{AC}$, (Table 1); both S0 and $S2_{AC}$ are sub-parallel to the Achness Thrust, i.e. ~E-W striking and south-dipping at 30–50° (Fig. 5). Using these criteria, the Achness Thrust can be traced from the Achness Falls, via the Tutim Burn to the Allt Rugaidh Bheag section (Fig. 7). Farther west, intermittent exposure suggests that the Achness Thrust joins the Moine Thrust at point A on Fig. 2.

Structure and lithologies of the Ben Hope Nappe

The Ben Hope Thrust is a strongly localised ductile tectonic break that separates grey flaggy psammite in its footwall from pale grey to white, commonly siliceous, psammite with minor grey semipelite in its hanging wall. Foliation is intense and subparallel to the thrust in its immediate vicinity. In limited exposure in Gleann na Muic (point C on Fig. 2) the thrust is associated with siliceous mylonite and in Glen Oykel with dark grey phyllonite *c.* 6 m thick (point D on Fig. 2). This thrust can be traced across the Cassley Culmination to connect with the trace of the Ben Hope Thrust farther north (Cheer *et al.* this volume) and south to its termination downwards against the Moine Thrust at the SE corner of the Assynt Culmination (near point A, on Fig. 2).

The Ben Hope Nappe is dominated by thick-bedded psammite with subsidiary layers of semipelite. In low strain zones (highlighted on Fig. 2), cross-bedding, channels, slump-folds and water escape structures are locally well preserved (e.g. Cheer 2006; Krabbendam *et al.* 2008, Fig. 4c); overall, the strata young towards the west and the succession is >3 km thick. The internal structure of the Ben Hope Nappe is dominated by a stack of kilometre-scale, west-facing and west-verging, open to close folds, termed here the 'Cassley Folds', ($F2_{BH}$, Table 1; see also Cheer *et al.* this volume). The low-strain zones referred to above typically occur in the steep to vertical short limbs of these large-scale folds (see sections b & c on Fig. 2). The folds trend roughly NNW-SSE (Fig. 5), have shallow plunging axes and are sub-cylindrical over many kilometres. The major Cassley Anticline marks a major change eastward to moderately E-dipping strata in the footwall of the Achness Thrust (CA on Fig 2); a well-developed planar schistosity is sub-parallel to bedding in the eastern long limb of this structure. In contrast, and in low strain areas on the steeply-dipping short limb of the fold, psammitic rocks typically show a complete lack of any tectonic fabric; a planar schistosity ($S2_{BH}$**)** and associated lineation ($L2_{BH}$**)** are locally present in gritty units. A well-developed fabric is typically only observed in semipelitic units (which become more prevalent higher up in the sequence towards the west); this is a variably intense crenulation fabric that deforms an earlier bedding-parallel schistosity ($S1_{BH}$).

The chronology of fabric development in the Ben Hope Nappe is readily determined in the Allt Rugaidh Mhor stream section (Figs. 3, 7). Strata young to the SW, decimetre-scale trough cross-bedding is well-preserved locally. The western 1.5 km of the section is a steep limb to a major anticline trace at point D on Fig. 7. East of this point the rocks are arranged in a ‘staircase’ of SW-vergent decametre-scale folds ($F2_{BH}$), with gently-dipping limbs and short, steep SW-dipping limbs. Axial surfaces are gently NE-dipping and axes plunge gently to the SE. These are typical Cassley folds.

The steeply dipping psammitic rocks in the western part of this section consistently show a well-developed sub-horizontal grain-shape fabric $S2_{BH}$ (quartz + feldspar + mica) at high angle to S0 in places and parallel to the axial surfaces of the $F2_{BH}$ folds. An intersection lineation ($L2_{BH}$) is well-developed on S0. Where mullions are developed close to the confluence with the Oykel River, and at An Stuc and Knock Craggie (Figs. 2, 3, 4b), they are seen to be always parallel to the $S0/S2_{BH}$ intersection lineation at outcrop (see also section on Mullions).

An $S1_{BH}$ (bedding sub-parallel) planar schistosity is observed locally in cm-thick semipelite layers; this is strongly crenulated by a mica-defined $S2_{BH}$, which is continuous with $S2_{BH}$ shape fabric in the adjacent psammite. In metre-scale layers of semipelite, an intense mica-defined crenulation fabric ($S3_{BH}$) locally overprints and transposes the earlier gently-inclined $S2_{BH}$ fabric into a new steeply-dipping, spaced anastomosing muscovite-biotite schistosity. Relicts of the older $S2_{BH}$ planar schistosity are preserved in $S3_{BH}$ microlithons. This superimposed fabric has only been observed in the short steeply-dipping limbs of the SW-vergent $F2_{BH}$ folds suggesting that orientation and scale of the incompetent layer is critical.

Structure and lithologies of the Moine Nappe (*s.s.*)

Moine rocks between the Moine and Ben Hope thrusts in Glen Oykel and Gleann na Muic (Fig. 2) comprise alternations of dark, to mid-grey micaceous psammite layers

(5–10 cm thick, only rarely as much as 20 cm thick) and subsidiary 2–5 cm thick layers of dark grey semipelite. Bedding locally appears to be right-way-up and the lack of any large-scale folding suggests that the succession is grossly right-way-up and *c.* 2 km thick in Gleann na Muic (Fig. 2), thinning south-westward to approximately 1 km in upper Glen Oykel. Farther to the south, the nappe terminates at the southeast corner of the Assynt culmination, (see Figs. 2, 3).

Local preservation of sedimentary grading suggests that this lithology may have originated as thinly-bedded layers of sandstone to siltstone. In the absence of reliable strain markers it is presently uncertain whether this layering is an original feature, or a result of subsequent strain – or a combination thereof. In sharp contrast, abundant large-scale cross-bedding in Morar Group rocks occurring at the same broad structural level north of Loch Shin (Fig. 2, Krabbendam *et al.* 2008) implies either rapid lateral facies changes or dramatic variations in ductile strain.

In the Moine Nappe in Glen Oykel, a penetrative planar to weakly anastomosing foliation (S_M, Table 1) is defined by alignment of biotite and muscovite sub-parallel to lithological layering. No earlier tectonic fabric has been definitely observed in these rocks. The geometry of the $S0/S_M$ relationship is consistently west-vergent; a faint quartz mineral lineation (L_M) plunges to the ESE on S_M surfaces (Figs. 3, 5). In upper Glen Oykel, a transition from the 'graded' metasandstones with well-developed planar S_M into splintery quartzofeldspathic mylonite (with S_{mylM}) occurs structurally downwards towards the Moine Thrust. A *c*. 100–200 m thick layer of psammitic mylonite occurs in the immediate hanging-wall of the Moine Thrust. Within these mylonites, stretching lineations, and the axes of tight to isoclinal minor folds (often doubly closing) of the mylonitic foliation, plunge ESE. The mylonites are underlain by the Moine Thrust.

Relationship between fabric development and folding in different nappes

In the Allt Rugaidh Bheag section (Fig. 7), the flaggy bedding and bedding–parallel foliation structurally *above* the Achness Thrust is folded by open to close NNW-SSE trending folds ($F3_{AC}$). These folds can be traced north and structurally *below* the Achness Thrust, into the Ben Hope Nappe as the 'Cassley Folds'. In other words, the dominant structures in the structurally lower Ben Hope Nappe ($F2_{BH}$ 'Cassley Folds') fold the Achness Thrust *and* the penetrative $S2_{AC}$ fabric in the structurally higher Achness Nappe (*c.f.* Table 1). This critical and consistent observation shows that the dominant deformation below the Achness Thrust *postdates and overprints* the penetrative fabric its hanging wall. The Cassley Anticline may also have this general relationship, folding the Achness Thrust in the SE corner of the Cassley Culmination (Fig. 2).

Termination of the Cassley Culmination

The trace of the Achness Thrust defines the southern limit to the Cassley Culmination. The hanging wall of the Achness Thrust in Glen Oykel comprises ESE-striking psammitic rocks which dip 30–60° to the SSW (Figs. 3, 5). This panel is some 5–7 km wide at outcrop and *c.* 20 km in length, traced from the Assynt Culmination to the Kyle of Sutherland (Fig. 1). It forms the southern lateral culmination wall of the Cassley Culmination. The strata in this panel are generally thin-bedded and flaggy (5–50 cm, Fig. 4d); massive thick-bedded (e.g. > 100 cm) strata, as seen in the Ben Hope Nappe, are never observed. Right-way-up cross-bedding has been observed locally and youngs south away from the Achness Thrust (e.g. Figs 3, 8). A fabric defined by biotite ($S2_{AC}$) is usually well-developed and is commonly (sub)parallel to bedding; where (small) angles exist between the biotite-defined $S2_{AC}$ and bedding, the intersection lineation ($L2_{AC}$) plunges 10–30° to the SE (Fig. 5). Whilst it is clear that the psammite in this domain has undergone significant strain, it is difficult to estimate to what extent the ‘flagginess’ is wholly or partially an effect of thinning of an original thick-bedded sequence, or whether the strata were originally thinner-bedded than those at Glen Cassley.

The km-scale $F2_{AC}$ Einig fold pair forms a prominent feature of this zone, aligned at a high angle to the Cassley folds in the Ben Hope Nappe structurally beneath (Figs. 7, 8). The major antiformal hinge is located at the confluence of the rivers Oykel and Einig (point E on Fig. 3), with the complimentary synformal closure located at point F (Fig. 3); the fold pair can be traced westwards to Allt Tarsuin (point G on Fig. 3). The fold pair is tight, asymmetrical, SSW-vergent and downward-facing; fold axes plunge uniformly to the SE (Fig. 8, *c.f.* Figs. 6, 7). The biotite-defined $S2_{AC}$ fabric is axial planar to the fold pair.

Mullions

The origin and tectonic significance of the mullion structures at Oykel Bridge were controversial for many years (Clough in Peach *et al.* 1912; Read 1931; Bailey 1935;

Phillips 1937; Wilson 1953). According to Clough, the mullions (or ‘rodding’) were formed by ‘pressures from four sides in opposite pairs, leaving constituents to squeeze out ...’ effectively describing a constrictional strain ellipsoid. In the Geological Survey Memoir, Read *et al*. (1926) thought that the mullions were formed by two *separate* deformation phases, the first being contraction in a NE–SW direction, the second extension along a NW–SE axis. The latter phase was clearly linked to movement along the Moine Thrust; “the stretching is in harmony with the dip of the Moine Thrust [….] and maybe regarded as an obvious accompaniment of the thrust-movement towards the northwest”.

Conspicuous columnar mullion structures are spectacularly displayed in a 400 m long section along the gorge of the River Oykel between the new road bridge [NC 3855 0090] and Oykel Falls [NC 3825 0115], (Figs. 4a, 8 and see Wilson 1953). Although the mullions are best developed and exposed near Oykel Bridge (on the northern long limb of the Einig fold pair), our mapping has shown that these features occur over a much wider area stretching from Knock Craggie and Salachy (Oykel River) in the NW to Langwell in the SE, in a zone several km wide (Figs. 2, 3). Mullions occur both in the Achness Nappe, and in the SW corner of the Ben Hope Nappe, so that the ‘mullion zone’ crosses the Achness Thrust near the confluence of Oykel River and the Allt Rugaidh Bheag (Figs. 3, 7). In the Achness Nappe, mullions are absent or only weakly developed on the inverted NE-SW trending common limb of the Einig fold pair. Mullions are also observed (albeit less well developed) on the southern long limb of the Einig fold pair. WNW-striking strata are clearly more sensitive to mullion development than the NE-SW striking strata. No mullions have been observed below the Ben Hope Thrust.

The mullions are best developed in relatively thick-bedded (2–50 cm) siliceous psammites. Of all the mullion types originally described by Wilson (1953), ‘fold mullions’ are best developed and are, as stated here, concavo-convex in section. The convex part is typically a decimetre-scale fold closure. The outer surface is often formed by a thin micaceous sheath and may be either concordant or sharply discordant with the internal layering (see Fig. 3 in Wilson 1953). However, (slightly deformed) cross bedding may often be seen when mullions are viewed down-plunge in profile, hence the observed discordance of internal lamination with the folded S0 surface. The mullions are strongly linear and consistently SE-plunging (130°N/40°) along the entire ‘mullion zone’ (Figs. 3, 5). The very consistent orientations and linearity of the mullions suggest a significant component of SE-oriented stretching; however, it appears that the complementary contraction was limited, possibly less than 10–20%, to judge by the geometry of preserved cross-bedding.

Relation of mullions and other structures

In terms of the relations between the mullions and other structures, the following observations are pertinent:

1) Within the Ben Hope Nappe, the mullions are only developed in its extreme SW corner, e.g. in the lower parts of the Allt Rugaidh Mhor section, along the Oykel River near Salachy. Here the mullions (L_M) are invariably exactly parallel to the intersection ($L2_{BH}$) of the main fabric ($S2_{BH}$) and S_0 at outcrop; this intersection lineation is related to the main phase of folding within the Ben Hope Nappe ($F2_{BH}$ 'Cassley Folds').
2) In the Achness Nappe, a well-developed $L2_{AC}$ mineral elongation alignment commonly lies sub-parallel to the mullions (L_M) and a weak axial planar schistosity is associated with an intersection lineation that likewise plunges sub-parallel to the mullions. Where a micaceous sheath is developed, it also commonly carries a weak superimposed $S4_{AC}$ crenulation fabric, oblique to the mullion axis. There are abundant examples of small and meso-scale reclined, tight to open, asymmetrical $F2_{AC}$ folds in the Oykel River gorge section, mullion lineations are aligned approximately parallel to these fold hinge lines and to the larger scale Einig Folds fold pair (Fig. 8).
3) Locally however, (e.g. west of Oykel Bridge, Fig. 8), a clear angle (30°) can be seen between the $L2_{AC}$ lineation and the mullions, with the mullions (L_M) folding the lineation.
4) The mullion zone crosses the Achness Thrust, suggesting that mullion development post-dated the formation of this thrust (Figs. 3, 7).
5) No mullions have been observed below the Ben Hope Thrust.

All of the above suggest that the mullions overprint and post-date the main deformation within the Achness Nappe and the formation of the Achness Thrust, but that mullion development was broadly coeval with the formation of the 'Cassley Folds' within the Ben Hope Nappe. The absence of mullions between the Moine Thrust and the Ben Hope Thrust may be a rheological response to lithology;

alternatively, it is possible that mullion development ceased after the development of the Ben Hope Thrust (see discussion below).

Geophysical data: the Lairg gravity low

Examination of the regional gravity field in Sutherland provides key insight into the sub-surface structure beneath the Cassley Culmination. The gravity field southeast of the Assynt culmination is dominated by the Lairg gravity low (Fig. 9). The centre of the low coincides approximately with the location of the Caledonian Grudie Granite Pluton (see Figs. 1, 9) and from there Bouguer gravity anomaly values increase linearly northwestwards to the outcrop of the Moine Thrust. The SW margin of the low is defined by a clear gravity lineament which extends southeastwards from the Oykel Bridge area towards the Kyle of Sutherland. North of Loch Shin the north-eastern side of the Lairg low crosses the area underlain by the Naver Thrust. In the NNW, the anomaly merges with a NW-trending gravity low centred over Laxfordian granitic rocks on the northern side of the Laxford Shear Zone (‘Ben Stack Line’, Bott *et al.* 1972, see Fig. 1).

Hipkin & Hussain (1983) ruled out the possibility that the Lairg gravity low is caused by a concealed Caledonian granite on the basis of its shape, which is quite distinct from that of the anomalies observed over other granites of this age, and the fact that a magnetic anomaly associated with the Grudie Granite has only a limited areal extent. Citing continuity with the gravity feature to the NNW, Hipkin & Hussain (1983) postulated that the Lairg gravity low may be explained by an extension of the low density Laxfordian rocks beneath the exposed Moine sequence. Butler & Coward (1984) preferred an interpretation involving thickening of the Moine rocks around Lairg linked to the transfer of sheets of Lewisian basement to the Assynt area. The modelling of Rollin (*in press*) also invokes a thickening of the Moine sequence. Further modelling described below investigates the source of the Lairg gravity low, and the implications of the relationship between its southern margin and the OTZ.

Rock densities

The estimated average density of the psammitic rocks of the Morar Group exposed within the study area is 2.65 Mg/m^3, based on laboratory measurements on 59 samples (BGS, unpublished data). There are no determinations of the density of the pelitic rocks in the study area and relatively few elsewhere in the Northern Highlands.

A clear correlation between local gravity highs and pelitic outcrops indicates that the latter have a higher density than the psammitic rocks (Hipkin & Hussain 1983); an average density of 2.75 Mg/m^3 has been assumed for the present modelling, based on the limited samples available. Bott *et al.* (1972) detected density variations within the exposed Lewisian basement in the vicinity of the Laxford Shear Zone but adopted a 'background' value of 2.78 Mg/m^3 in the Assynt area, a value which has also been assumed in the modelling described here.

Gravity modelling

Models have been constructed along two profiles across the Lairg gravity low (Figs. 9, 10). Profile 1 trends NW–SE and provides the clearest insights into the cause of the low while the NE–SW oriented profile 2 investigates the gravity gradient on its southwestern side and its relationship with the OTZ. The modelling employed 2.5-dimensional methods in which geological units are represented by bodies with constant polygonal cross-section and finite strike extent. A general northward and westward increase in the regional gravity field has been removed prior to modelling local structure. A background field was assumed which increases westwards from 4 mGal to 24 mGal along profile 1 and northwards from 11 mGal to 22 mGal on line 2. This field is not well-constrained and is a significant source of uncertainty in the modelling.

Along profile 1, the gravity field decreases linearly south-eastwards from the outcrop of the Moine Thrust (Fig. 10). The gradient is reproduced by the thickening of relatively low density Morar Group rocks above this thrust without the need to invoke density variations within the underlying basement. The Grudie Granite (see Fig. 1) makes a small contribution to the gravity low in its central part, as a slight steepening of the gravity gradients around the granite is more readily explained by the density contrast between it and its host rocks than by features at basement depth. Limited sampling does indicate such a contrast, at least with the monzogranite component of the intrusion (Rollin, *in press*). The Migdale Granite Pluton (see Fig. 1) has a very small gravity effect, implying a limited depth extent and/or a density similar to that of the surrounding Moine rocks. As there is no evidence for an increase in density of Morar Group rocks between the Grudie and Migdale granites, the southeastward rise in gravity field in this area is attributed to a relatively thick wedge (or wedges) of Lewisian basement above the Achness Thrust. The mapped Lewisian inliers are compatible with such an interpretation (Figs. 2 & 10). The steepening gravity gradient SE of the Migdale Granite Pluton is attributed to a combination of shallow basement and the presence of relatively dense pelitic rocks of the Glenfinnan Group above the Sgurr Beag Thrust.

The model for profile 1 suggests that 5–6 km of Moine rocks are present beneath the centre of the Lairg gravity low, and this was used as the starting point for modelling the depth to basement beneath profile 2 (Fig. 10). The northern end of this model is schematic; migmatitic Moine rocks with a relatively high density are present at surface, but the proportion of such rocks and the overall Moine thickness are poorly constrained. A distinct southward thickening of the Morar Group psammites has been modelled between kilometre 20 and 30 along this profile. This segment spans the Loch Shin Line (Watson 1984), which in turn lies on the projection of the Laxford Shear Zone (Fig. 1), so may reflect the influence of a pre-existing basement structure. There is, however, no obvious signature in the gravity profile to suggest a discrete zone of low-density Laxfordian granite in the basement.

The local gravity minimum associated with the Grudie Granite Pluton lies between about kilometre 27 and 37 on profile 2, but the steep gravity gradient that forms the SW margin of the more extensive Lairg gravity low is centred at kilometre 50 (Fig. 10). This linear feature appears to be enhanced by the near-surface density contrast between Moine psammite the north and a more heterolithic sequence to the south that includes the Vaich Pelite Formation (Fig. 1). Outcrops of the Vaich Pelite Formation can be correlated with residual gravity highs and the amplitude of the gradient is reduced where pelitic rocks are absent at surface south of the lineament. It is, however, difficult to explain all the gravity variation simply in terms of lithological contrast within the Moine. The profile 2 model (Fig. 10) includes about 40% of pelitic material at the southern end of the profile, which even if an overestimate when compared with the relative outcrop proportions, still requires an overall thinning of the Moine rocks. Sensitivity trials in which the proportion and density of pelitic rocks in this sequence are varied between reasonable bounds indicate that it is necessary for the model to retain a significant southward shallowing of the basement in this area. Comparison with the structural architecture of the geological model clearly shows that the southern termination of the Cassley Culmination is positioned over the buried basement ramp (or series of steps) indicated by the geophysical model (Fig. 10, profile 2).

Discussion

The Oykel Transverse Zone

The contrast between the numerous branching thrusts which make up the Cassley (ductile) and Assynt (brittle-ductile) culminations and the regions of folded, but not internally thrust, Moine rocks SW of Strath Oykel delineates a mid-crustal transfer zone, named here the Oykel Transverse Zone (OTZ). The pattern of thrusting observed here has been reproduced in analogue modelling of transverse zones in deforming thrust wedges (Liu Huiqi *et al.* 1991; Malaveille *et al.* 1991; Calassou *et al.* 1993), in particular the observation that where basement is vertically offset, lateral thrust ramps have their roots in the basal discontinuity. These ramps will then be steepened as thrusting continues to excavate new thrust packages during foreland-propagation (Thomas 1990; Calassou *et al.* 1993; Paulsen and Marschak 1999). Similarly, as the Cassley Culmination grew, the structurally higher, older nappes were deformed in response to the emergence, towards the west-northwest, of lower and younger nappes.

Thomas (1990) reviewed potential pre-thrust templates which might actively constrain the location and generation of transverse zones during thrusting. These include lateral facies and thickness variations in stratigraphy as well as dislocations across pre-, syn- and post-depositional fault displacements. There seems to be no reason that the location of the transverse zone would have been determined by lateral variations within the Moine rocks; no systematic change in lithological character, lithostratigraphy or gross thickness of these psammitic units occurs across the termination wall which might control rheology and therefore constrain the geometry and location of the developing culmination.

The geophysical modelling concludes that the south-western flank of the Lairg gravity low is generated largely as a response to an underlying basement ramp. Steps in the basement-cover interface generated across reactivated basement shear zones have also constrained the thrust architecture in the interior of the Assynt Culmination at a much smaller, more localised scale (Krabbendam and Leslie this volume). These re-activated sub-vertical basement shear zones have a long history of repeated movement prior to deposition of the Cambro-Ordovician succession on the Foreland (Beacom *et al.* 2001), and post-deposition kilometre-scale sinistral oblique displacements are known to have disrupted the Cambro-Ordovician ‘layer-cake’ prior to the onset of thrusting (Soper and England 1995; Krabbendam and Leslie this volume). The regional gravity data permits extrapolation of these important structures beneath the Moine outcrop; the OTZ aligns with the Strathan and Canisp Shear zones in the foreland (Fig. 1). We suggest that the basement ramp modelled at the SW margin of the Lairg gravity low exerted the major controlling influence over the development of the Oykel Transverse Zone (albeit at a larger scale).

Growth of the Cassley Culmination

The Cassley Culmination developed within an overall foreland-propagating deformation system. Critically, the main deformation phase above and associated with the Achness Thrust (Achness Phase) pre-dated the main phase of deformation below (Ben Hope Phase). These and other constraints are consistent with a structural evolution model described below (a-g) and illustrated in Fig. 11. Foreland-propagating thrusting is also documented within the Moine Nappe along strike to the north in the Ben Hee area (Cheer *et al.* this volume) and in north Sutherland (Holdsworth 1989; Alsop & Holdsworth 2007; Alsop *et al.* 1996; Holdsworth *et al.* 2001, 2006, 2007).

a) A pervasive LS fabric and associated tight-to-isoclinal folds formed first within the structurally highest Morar Group rocks in the incipient Achness Nappe. The Loch Shin anticline was associated with large-scale interfolding of Moine rocks and Lewisianoid basement gneisses. Some fold axes, including the Einig fold pair, were progressively rotated into sub-parallelism with the regional transport direction. This deformation episode constitutes the Achness Phase (Table 1, Fig. 11).

b) The earliest time slice in Fig. 11 represents focussed (easy) slip on the Achness Thrust plane which was associated with the interleaving of thin slices of Lewisianoid basement with the Moine cover.

c) As contraction continued, increased resistance to translation on the Achness thrust effected transfer of strain down into the footwall rocks. WNW-vergent fold systems (the $F2_{BH}$ ‘Cassley Folds’) developed in the incipient Ben Hope Nappe (Ben Hope Phase, Table 1). The Achness Thrust and structurally overlying folds were bulged up and folded in the developing Cassley Culmination. The Einig fold pair tilted towards the present downward-facing attitude and mullions begin to form in the OTZ (see also below)

d) The Ben Hope Thrust then developed, and strain became focussed along that structure. A branch line joining the Achness and Ben Hope thrusts was oriented (sub)parallel to transport; the Cassley Culmination and the OTZ became more sharply defined. Uplift of the Achness Nappe continued, but mullion development may have become much less significant in that panel.

e) In time, the above process repeated itself; translation stuck on the Ben Hope Thrust plane, strain transferred downwards once again, this time into the footwall of the Ben Hope Thrust, and (north of Loch Shin only) a series of west-vergent folds developed thus explaining the greater cross-strike width of the Moine Nappe *s.s.* in this region. Mullions formed in the Ben Hope Nappe and mullions overprinted earlier fabrics in the Achness Nappe/OTZ.

f) Major, smooth movement (up to 100 km?) on the Moine Thrust throughout the region occurred, but little localised uplift occurs with the Cassley Culmination or within its termination wall. Development of the Moine Thrust and the associated mylonitic rocks seems to be broadly similar north and south of the OTZ, in contrast to the earlier localisation of strain in the OTZ. Mullion development ceased in the OTZ.

g) Strain was transferred farther down into the footwall of the Moine Thrust and the Assynt Culmination began to develop below the Cassley Culmination, leading to further uplift of that structure and further steepening of the culmination wall. During this phase, uplift in the hanging wall of the Assynt Culmination also generated the swing in strike across Loch Shin (Figs. 1, 2).

The evolution of the Cassley Culmination is thus characterised by phases during which folding is dominant, alternating with phases during which thrusting is dominant, i.e. deformation alternates between distributed and localised modes. Strain localisation is generally associated with strain softening (e.g. Watts & Williams 1983, Bos and Spiers 2002), so this may also be seen as alternating phases of hardening and softening strain. Even assuming a constant overall convergence rate, it is likely that locally differential strain rates developed; a relatively fast strain rate when localisation occurred, a relatively slow strain rate when strain was more distributed. We postulate here that the Cassley Culmination did not, as a result, deform with constant strain rate, but in alternating 'slow' and 'fast' phases, associated with folding and thrusting respectively. In contrast, we suggest that the Achness Nappe to south of the OTZ experienced less strong strain rate changes and kept moving northwestward in a more continuous fashion, with smooth thrusting accommodated along the (proto-) Moine Thrust (i.e. along the segment between Knockan Crag and Ullapool, Fig. 1). This would have resulted in phases of differential movement along the OTZ – see below.

Origin of mullions and non-plane strain

The mullion fabric (L_M) has a clearly constrictional symmetry, characteristic of an overall prolate (cigar-shaped) finite strain ellipsoid. The precise mechanism by which the mullions developed into discrete, but interlocking, structures is not fully understood. Soper (in press) suggests that inner-arc space problems associated with the folding at Oykel Bridge, combined with flexural slip on non-parallel surfaces (bedding and cross-bedding) that were deforming within a constrictional flow field, led to the initiation of many small, roughly coaxial folds with variably oriented axial surfaces, and their eventual detachment to form the nested mullion columns.

How might growth of the Cassley Culmination have promoted the formation of mullions, and how was constriction achieved? In the scenario outlined above, there must have been periods of differential movement along the OTZ; in periods of distributed deformation when folds formed during ‘culmination building’, the Ben Hope Nappe moving north-westward at a slower rate than the Achness Nappe south of the transverse zone. This would have produced an effective dextral shear-couple across the culmination wall (Fig. 12). At times of localised thrusting on both sides of the transverse zone, the relative velocity of the separate nappes would be negligible, and so no differential movement would have occurred. Given development of a dextral shear couple, any angle between the strike of the culmination wall and the regional transport direction would result in either dextral transpression or transtension, and hence to strong non-plane strain development. From the gravity potential field data, the OTZ has a strike of *c.* 310°N, whilst the regional thrust transport direction was 290°N (McClay & Coward 1981). In this case, transtension with a high kinematic vorticity number (i.e. with a large component of strike slip) would result (Fig. 12). Transtension under such circumstances would result in a prolate finite strain ellipse (constriction) under most boundary conditions (Dewey *et al.* 1998 and references therein; Fossen & Tikoff 1998; see also Coward and Potts 1983), providing a plausible explanation for the formation of the mullions during culmination building.

Conclusions

We favour a model of punctuated movement during development of the Cassley Culmination. Thrust stacking in the Cassley Culmination built a ductile critical-taper wedge in the Moine rocks (Davis *et al.* 1983; Holdsworth 1989; Dahlen 1990; Williams *et al.* 1994). When that Moine wedge was sufficiently thickened to attain the critical taper angle, a large-scale basal detachment or décollement would be created (Williams *et al.* 1994), thus generating the thick welt of mylonitic rocks which are preserved in the hanging wall of the brittle Moine Thrust. In this model, the localisation and intensification of deformation represented by the mylonitic Moine rocks in the Moine Thrust Zone would 'switch off' any further deformation in the Cassley Culmination above the décollement. Any further uplift in the Cassley Culmination would be a response to the growth of the Assynt Culmination beneath and may have been limited to further steepening of the culmination wall and the strike-swing observed across Loch Shin. Finally:

- The Cassley Culmination is a regional-scale culmination in the hanging wall of the Moine Thrust, comprising a thick sequence of Morar Group psammitic rocks and associated slivers of basement gneiss. The Achness Thrust forms the roof thrust to the culmination, the Ben Hope Nappe lies within the culmination. The culmination is of similar scale to the classic Assynt Culmination, structurally below in the brittle Moine Thrust Belt.
- The OTZ defines the lateral southern termination of the culmination and strikes approximately parallel to the WNW-directed thrust transport direction. The culmination wall comprises a *c.* 5 km thick panel of sheared psammitic rock, extending for *c.* 20 km from Assynt almost to the Kyle of Sutherland. The classic mullions of Oykel Bridge occur within the OTZ.
- The OTZ is coincident with the southeast edge of the regional-scale Lairg gravity low. That feature is modelled as the signature of a pronounced NE-inclined ramp in the depth to basement.
- The dominant fabric and associated folds in the Ben Hope Nappe locally overprint the dominant fabric and folds in the Achness Nappe and the Achness Thrust itself; there is no single regional dominant 'S2' fabric in the Moine Nappe.

- The classic mullions of Oykel Bridge are more widely distributed than previously thought and occur in both the Achness and Ben Hope nappes. In the Ben Hope Thrust, the mullions are parallel to the main intersection lineation; in the Achness Nappe, the mullions overprint the main fabric and intersection lineation, although they commonly occur sub-parallel to the latter.
- A clear sequence of foreland-propagating thrust development can be ascertained. The Achness Nappe was the earliest to develop, with penetrative fabrics and tight folds in the hanging wall. This Achness phase was followed by development of folds below the Achness Nappe, but only north of the OTZ. These folds thickened the pile and uplifted the Achness Nappe north of Glen Oykel and the OTZ was formed. Mullion structures continued to develop at this time, perhaps predominantly in the Ben Hope Nappe. Subsequently, the Ben Hope Thrust formed.
- This process repeated itself. Fabrics developed in rocks lying in the footwall to the Ben Hope Thrust. As strain passed into the Moine Nappe below the Ben Hope Thrust, structural change in the Ben Hope and Achness nappes was limited to uplift and mullion development ceased. The ductile Moine Thrust now developed north of the OTZ forming the floor of the Cassley Culmination.
- Overall, thrust displacement was continually smooth south of the OTZ, whilst to the north intermittent thrust movement dominated, with periods of distributed deformation during fold development and thickening alternating with displacement along thrusts.
- This contrast of quasi-continuous versus intermittent fold-and-thrust movement resulted in periods of differential, dextral strike-slip movement along the OTZ. Given the observed small angle between transport direction and strike of the OTZ (*c.* 20°, Fig. 12), resultant transtension locally produced constriction, a plausible explanation for the development of the classic mullion structures observed at Oykel Bridge.

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Figure Captions

Figure 1: Geological map of the Northern Highlands, after British Geological Survey original. Abbreviations: AT = Achness Thrust; BHT = Ben Hope Thrust; MT = Moine Thrust; NT = Naver Thrust; SBT = Sgurr Beag Thrust. Inset shows location of Fig. 2.

Figure 2 : a) Geological map of the Cassley Culmination. **b**) Schematic cross section A-A’ through the Ben Hee area, NW-vergent structure; **c**) Schematic cross-section B-B’ through the Glen Cassley area, SW-vergent structure. BHA = Ben Hee Anticline; CA = Cassley Anticline; LSA = Loch Shin Anticline; LFS = Loch Fiag Syncline.

Figure 3: Detailed geological map of the Oykel Transverse Zone, after British Geological Survey original. Positions of Figs. 6, 7, & 8 are indicated. British National Grid in 100 km squares NC, NH.

Figure 4. a) Mullion structures in Altnaharra Formation psammitic rocks, Oykel Bridge, [NC 386 009]. (BGS Photograph P005824), rock outcrop is approximately 6 m high; **b**) mullion structures in Altnaharra Formation psammitic rocks, Knock Craggie, [NC 326 055], BGS Photograph P 616663), pencil is 14 cm long; **c)** well-preserved trough cross-bedding in low strain, massive, thick-bedded psammitic rocks, Altnaharra Formation, Ben Hope Nappe, Carn Mor, west of Glen Cassley [NC 408 045], (BGS Photograph P618129), map case is 32 cm wide; and **d**) highly strained, tabular bedded psammitic rocks, Altnaharra Formation, in the Achness Nappe/OTZ, River Conacher [NH 351 017], (BGS Photograph P616618), outcrop is approximately 2.5 m high.

Figure 5. Sterographic projections of representative structural data from the thrust sheets in the Cassley Culmination.

Figure 6. Geological map of the Achness Thrust at Achness Falls, after British Geological Survey original. Grid in NC square of British National Grid. For location see Fig. 3.

Figure 7. Geological map of the Allt Rugaidh area, after British Geological Survey original. Grid in NC square of British National Grid. For location see Fig. 3

Figure 8. Geological map of the Oykel Bridge/River Einig area, after British Geological Survey original. Grid in NC square of British National Grid. For location see Fig. 3.

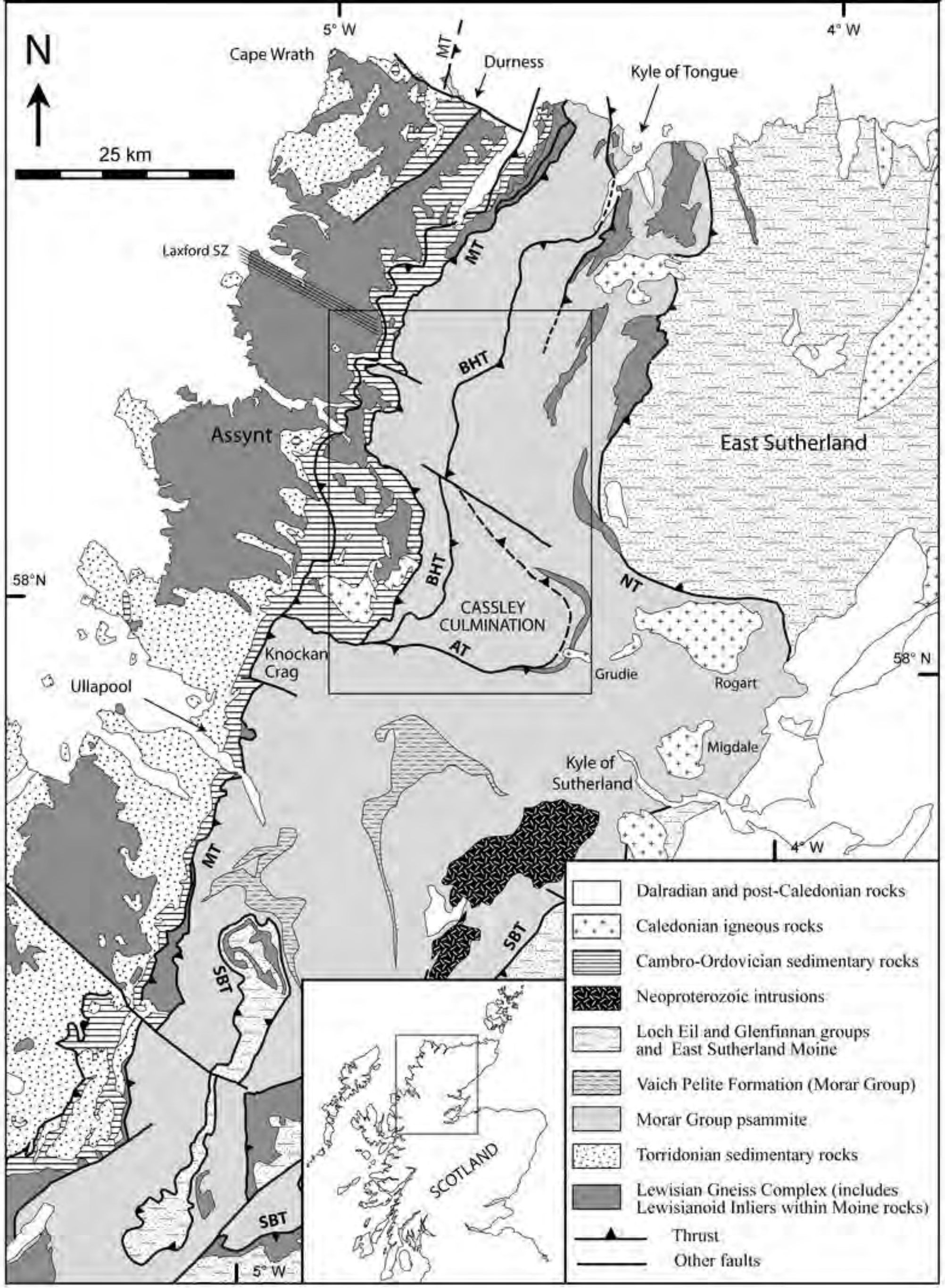
Figure 9. Bouguer gravity anomaly map of the Lairg area, based on gravity stations with an average distribution of 1 per 3 km^2. Contours at 2 mGal intervals are superimposed on a shaded image with vertical illumination and equal-area colour. Variable Bouguer reduction density according to surface geology. The large negative feature in the centre of the map is the Lairg gravity low. Heavy black lines are model profiles (1 and 2, see Fig. 10). Main thrusts (annotated in small map): AT = Achness Thrust; BHT = Ben Hope Thrust; MT = Moine Thrust; NT = Naver Thrust; SBT = Sgurr Beag Thrust.

Figure 10. Gravity models along profiles 1 and 2 (for locations see Fig. 9). Numbers in the legend are model densities in Mg/m^3. A simplified structural profile for the Cassley Culmination is superimposed upon the model for Profile 2, (*c.f.* Fig. 11). Abbreviations: AT = Achness Thrust; BHT = Ben Hope Thrust; MT = Moine Thrust; SBT = Sgurr Beag Thrust.

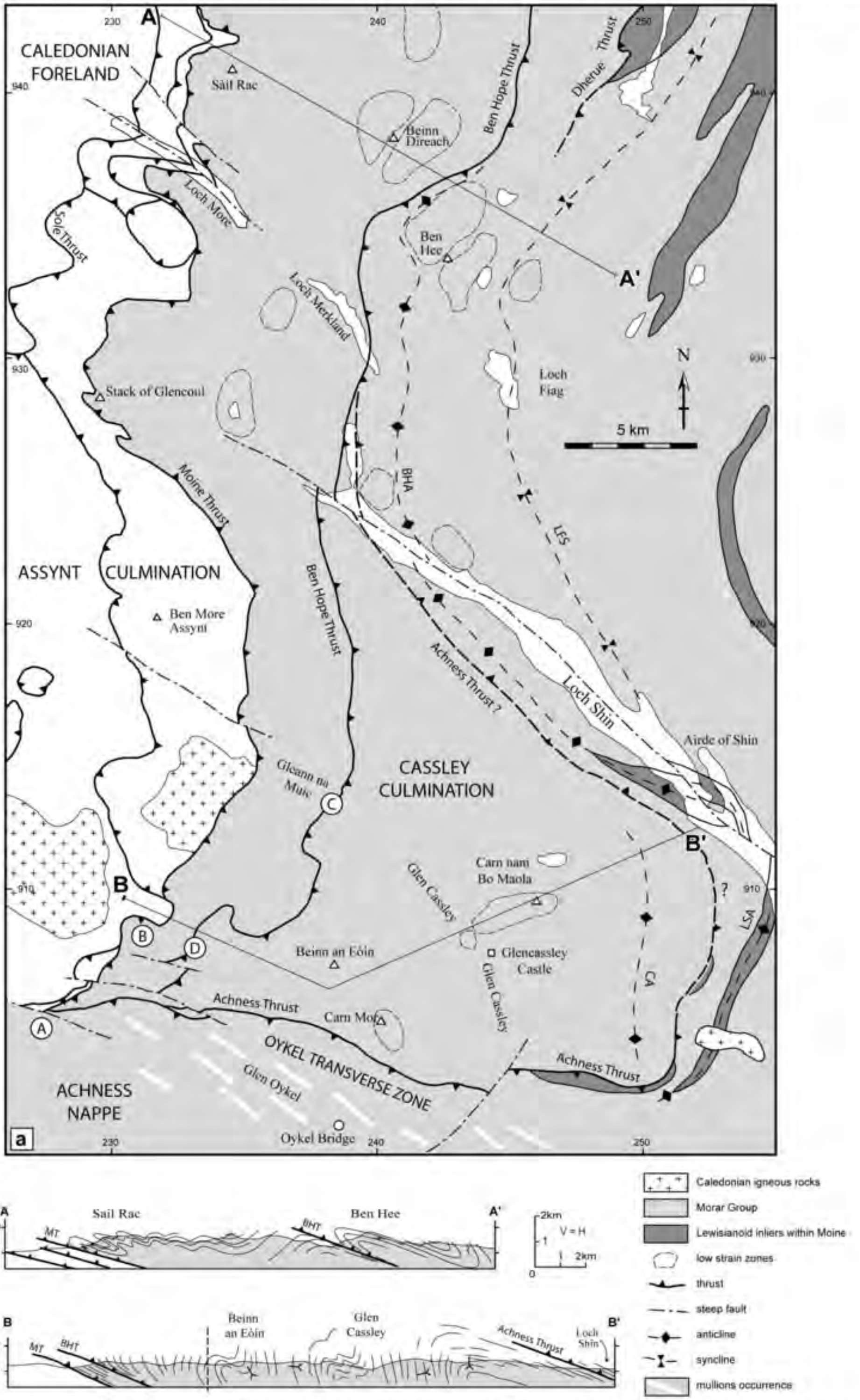
Figure 11. Structural evolution of Cassley Culmination. Sections in the left-hand column look down the regional transport direction to the SE, i.e. down-plunge on the mineral/stretching/mullion lineation. Sections in the right-hand column are constructed parallel to the transport direction.

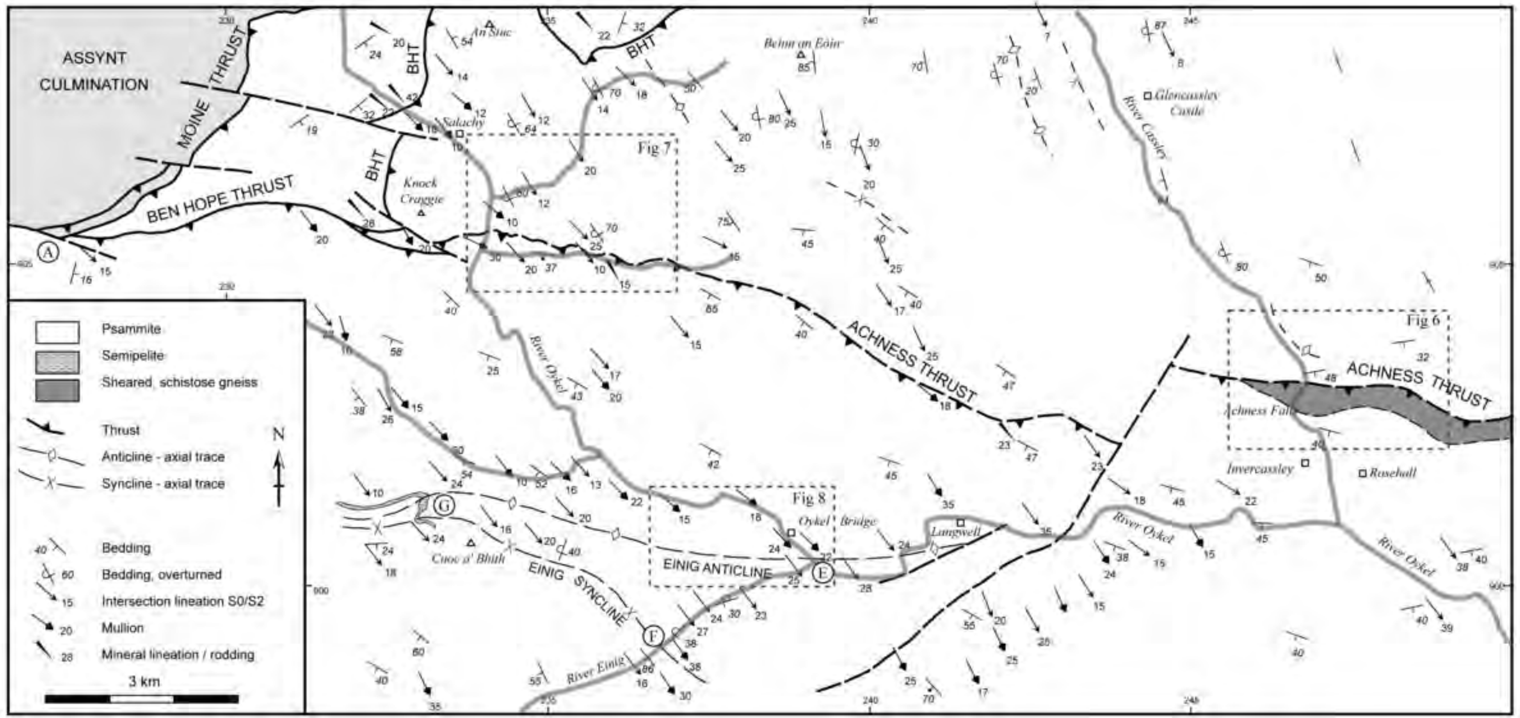
Figure 12. Block model with mullion detail in inset, illustrating how a small angle between the regional transport direction and the strike of the culmination wall can lead to local transtension. See text for further discussion.

11,096 words (including references and figure captions).

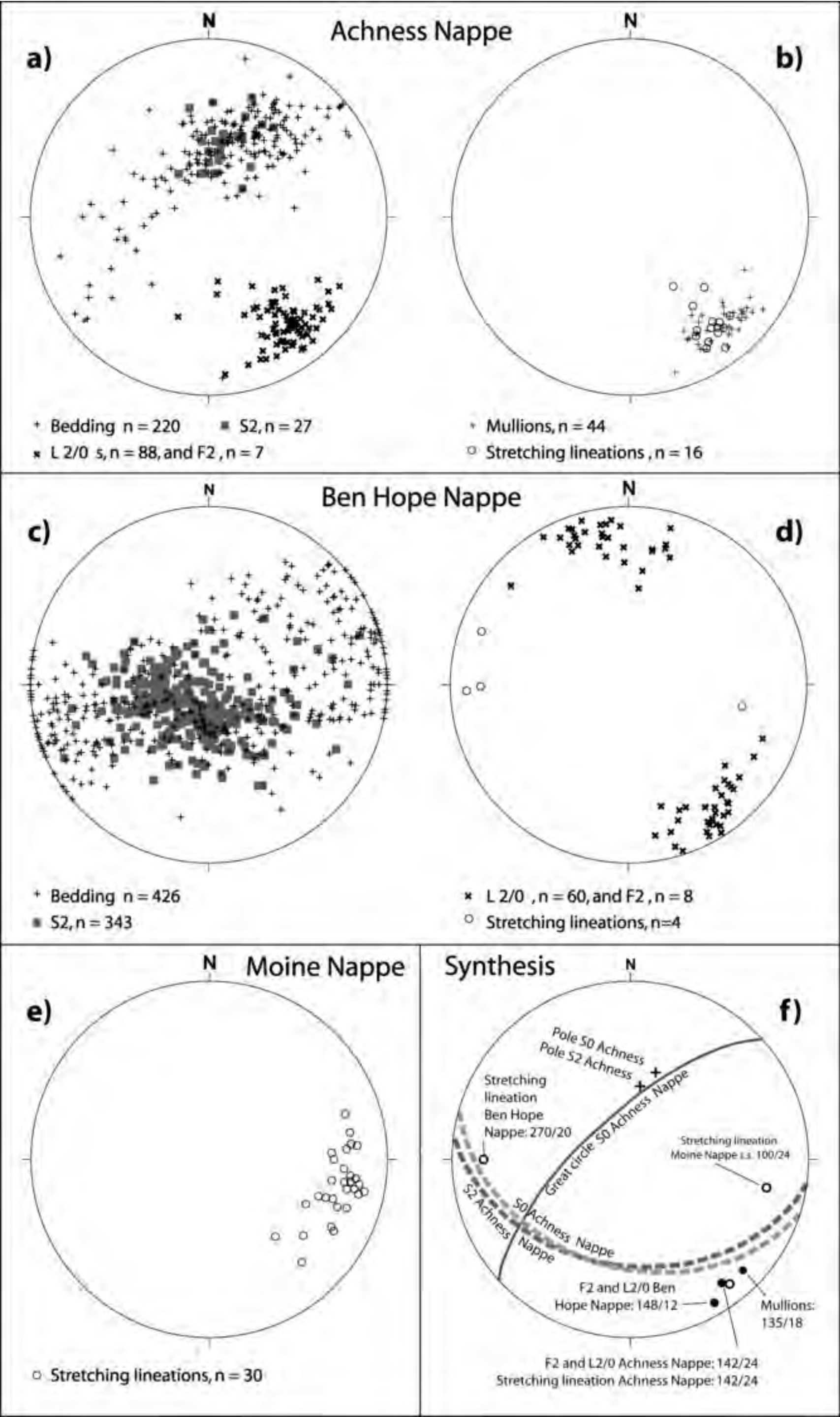


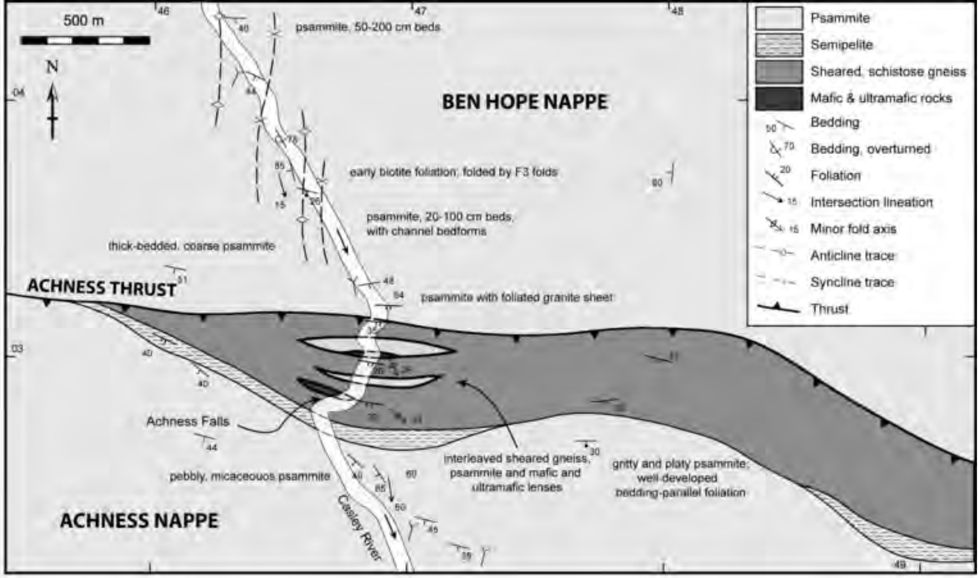
N
25 km
5° W
4° W
Cape Wrath
Durness
Kyle of Tongue
MT
Laxford SZ
BHT
Assynt
East Sutherland
58°N
58° N
NT
CASSLEY CULMINATION
AT
Knockan Crag
Ullapool
Grudie
Rogart
Migdale
Kyle of Sutherland
SBT
SCOTLAND
Dalradian and post-Caledonian rocks
Caledonian igneous rocks
Cambro-Ordovician sedimentary rocks
Neoproterozoic intrusions
Loch Eil and Glenfinnan groups and East Sutherland Moine
Vaich Pelite Formation (Morar Group)
Morar Group psammite
Torridonian sedimentary rocks
Lewisian Gneiss Complex (includes Lewisianoid Inliers within Moine rocks)
Thrust
Other faults


CALEDONIAN FORELAND
Sàil Rac
Beinn Direach
Ben Hope Thrust
Dherue Thrust
Loch More
Sole Thrust
Ben Hee
A'
Loch Merkland
Loch Fiag
5 km
Stack of Glencoul
Moine Thrust
BHA
LFS
ASSYNT CULMINATION
Ben More Assynt
Ben Hope Thrust
Achness Thrust ?
Loch Shin
Airde of Shin
Gleann na Muic
CASSLEY CULMINATION
Carn nam Bo Maola
Glen Cassley
Beinn an Eòin
Glencassley Castle
CA
LSA
Achness Thrust
Carn Mor
OYKEL TRANSVERSE ZONE
Glen Oykel
ACHNESS NAPPE
Oykel Bridge
a
Sail Rac
Ben Hee
MT
BHT
V = H
b
Beinn an Eòin
Glen Cassley
Achness Thrust
Loch Shin
c
Caledonian igneous rocks
Morar Group
Lewisianoid inliers within Moine
low strain zones
thrust
steep fault
anticline
syncline
mullions occurrence

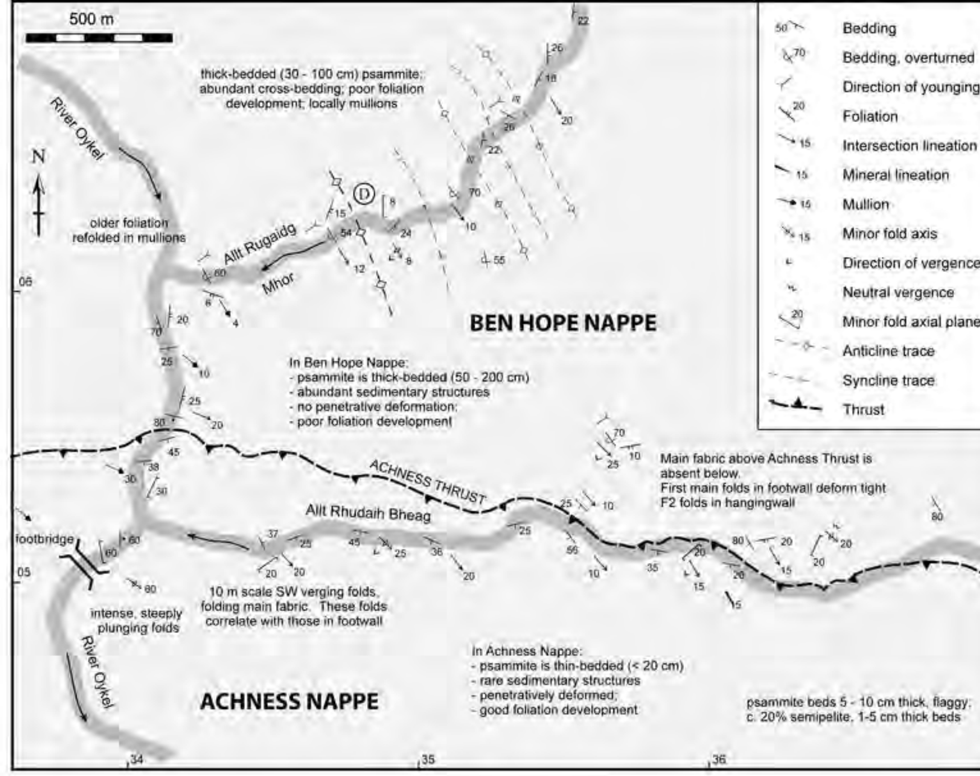

ASSYNT CULMINATION
MOINE THRUST
BEN HOPE THRUST
BHT
ACHNESS THRUST
EINIG ANTICLINE
EINIG SYNCLINE
An Stuc
Beinn an Eòin
Salachy
Knock Craggie
Glencassley Castle
River Cassley
River Oykel
River Einig
Oykel Bridge
Langwell
Achness Falls
Invercassley
Rosehall
Cnoc a' Bhith
Fig 6
Fig 7
Fig 8
A
E
F
G
Psammite
Semipelite
Sheared, schistose gneiss
Thrust
Anticline - axial trace
Syncline - axial trace
Bedding
Bedding, overturned
Intersection lineation S0/S2
Mullion
Mineral lineation / rodding
3 km
N


SE
NW
a)
P005824
NW
SE
b)
P616663
NW
SE
c)
P618129
SW
NE
d)
P616618

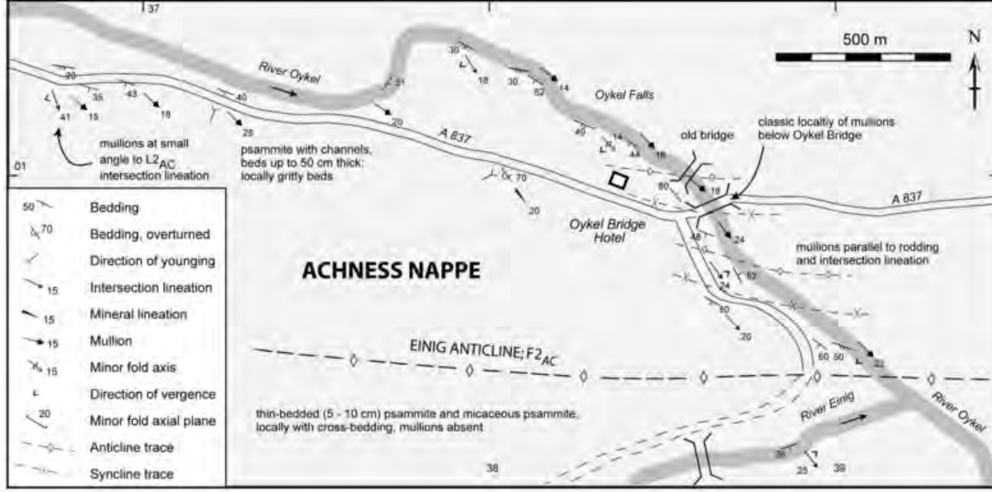

Achness Nappe
a)
b)
N
Bedding n = 220
S2, n = 27
L 2/0 s, n = 88, and F2, n = 7
Mullions, n = 44
Stretching lineations, n = 16
Ben Hope Nappe
c)
d)
Bedding n = 426
S2, n = 343
L 2/0, n = 60, and F2, n = 8
Stretching lineations, n=4
Moine Nappe
e)
Stretching lineations, n = 30
Synthesis
f)
Pole S0 Achness
Pole S2 Achness
Great circle S0 Achness Nappe
Stretching lineation Ben Hope Nappe: 270/20
Stretching lineation Moine Nappe s.s. 100/24
S2 Achness Nappe
S0 Achness Nappe
F2 and L2/0 Ben Hope Nappe: 148/12
Mullions: 135/18
F2 and L2/0 Achness Nappe: 142/24
Stretching lineation Achness Nappe: 142/24



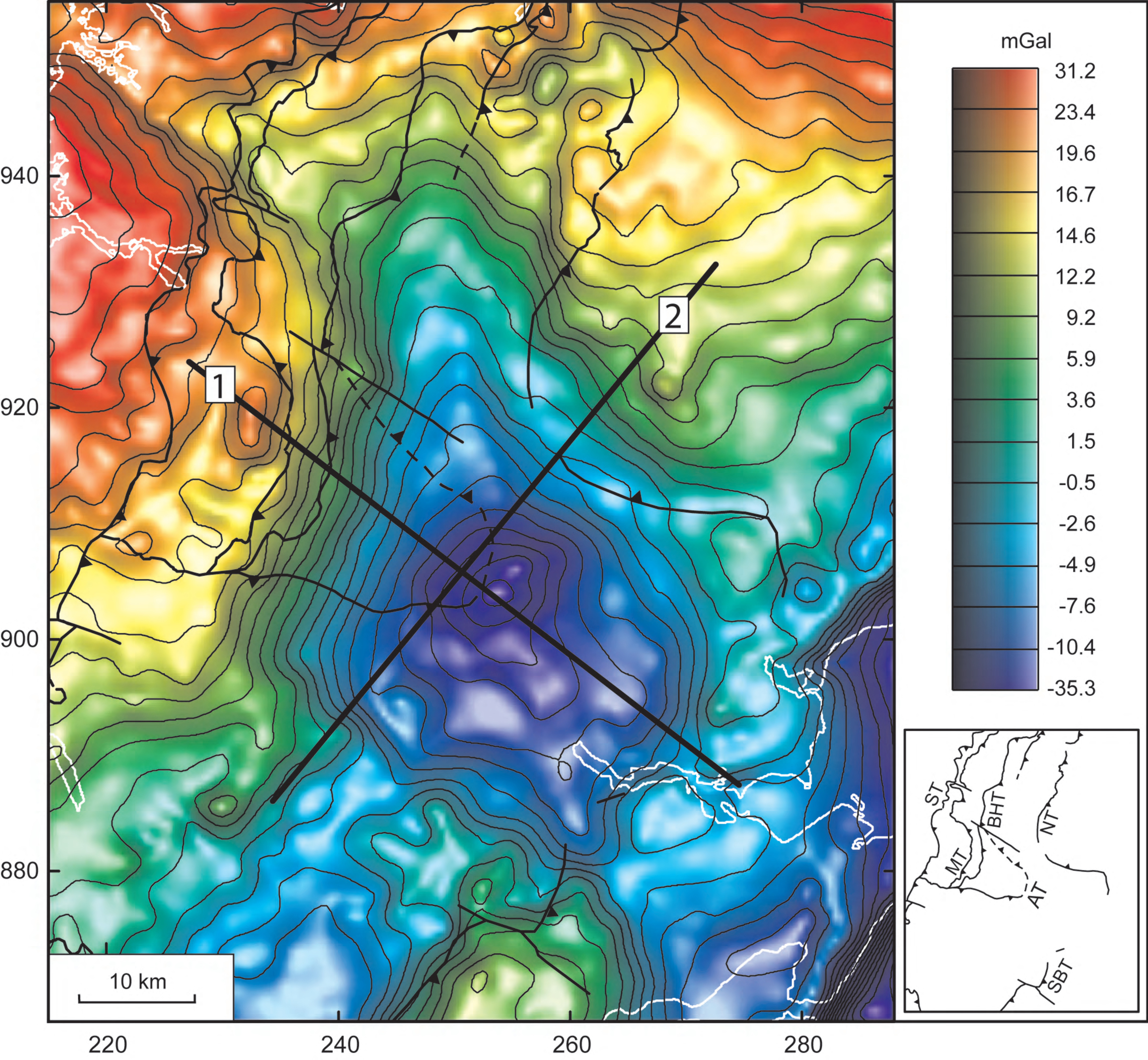
500 m
N
BEN HOPE NAPPE
ACHNESS THRUST
ACHNESS NAPPE
Achness Falls
Casley River
psammite, 50-200 cm beds
early biotite foliation, folded by F3 folds
psammite, 20-100 cm beds, with channel bedforms
thick-bedded, coarse psammite
psammite with foliated granite sheet
interleaved sheared gneiss, psammite and mafic and ultramafic lenses
gritty and platy psammite; well-developed bedding-parallel foliation
pebbly, micaceouos psammite
Psammite
Semipelite
Sheared, schistose gneiss
Mafic & ultramafic rocks
Bedding
Bedding, overturned
Foliation
Intersection lineation
Minor fold axis
Anticline trace
Syncline trace
Thrust

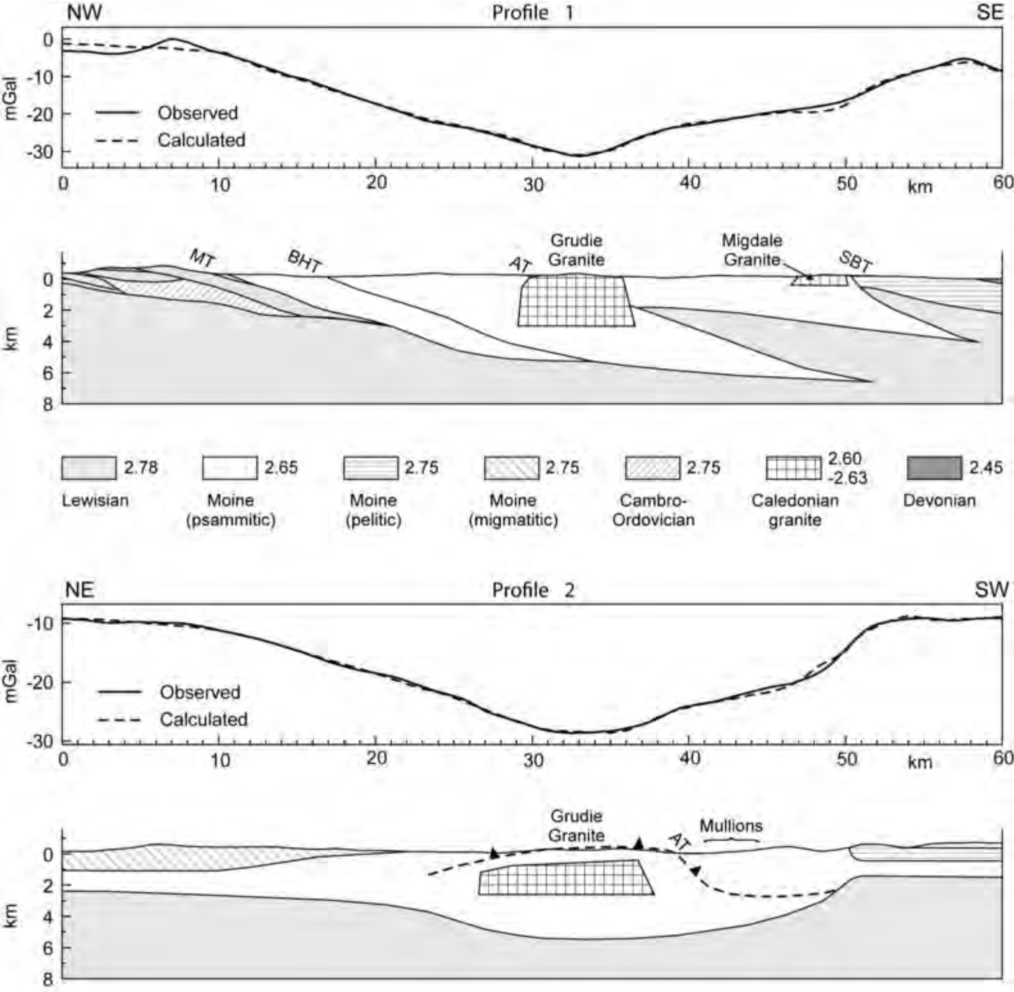


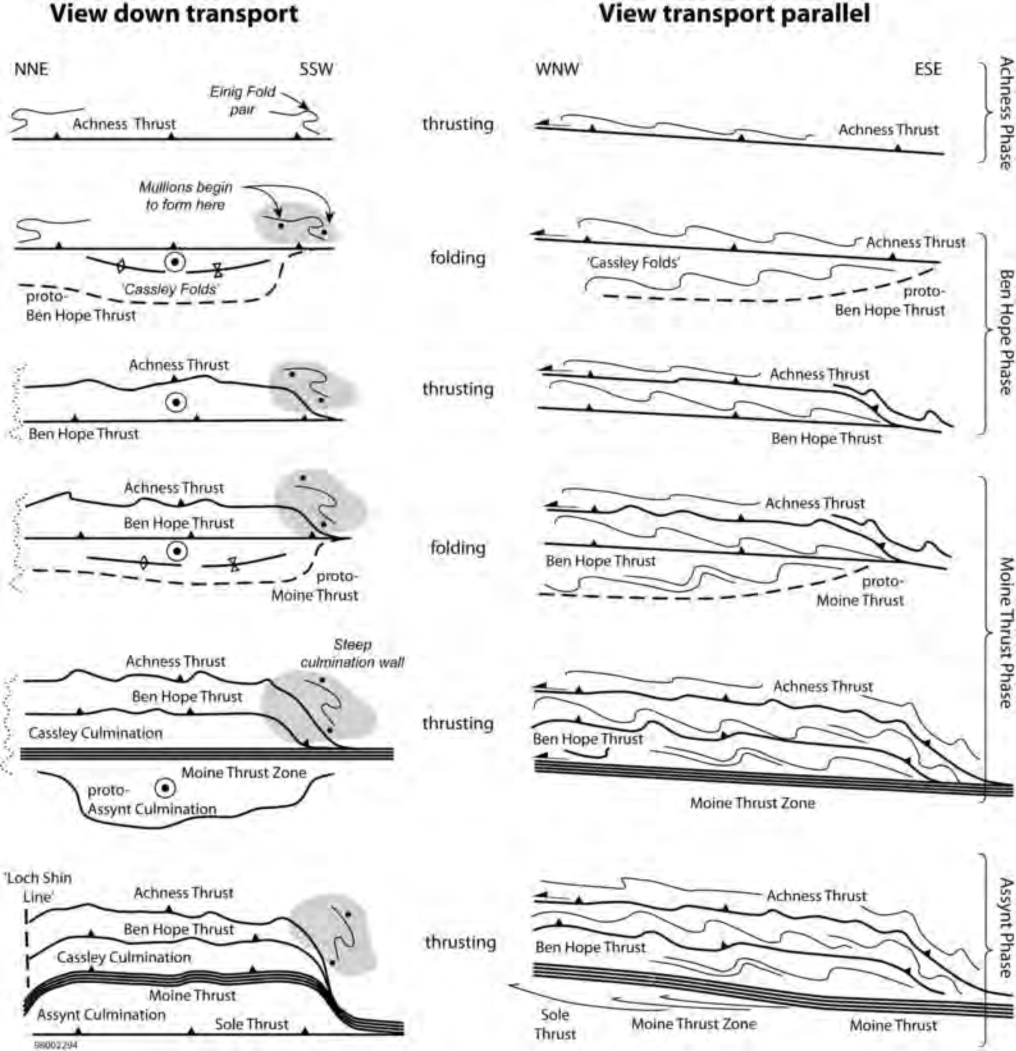
500 m
N
Bedding
Bedding, overturned
Direction of younging
Foliation
Intersection lineation
Mineral lineation
Mullion
Minor fold axis
Direction of vergence
Neutral vergence
Minor fold axial plane
Anticline trace
Syncline trace
Thrust
thick-bedded (30 - 100 cm) psammite; abundant cross-bedding; poor foliation development; locally mullions
River Oykel
older foliation refolded in mullions
Allt Rugaidg
Mhor
BEN HOPE NAPPE
In Ben Hope Nappe:
- psammite is thick-bedded (50 - 200 cm)
- abundant sedimentary structures
- no penetrative deformation;
- poor foliation development
ACHNESS THRUST
Main fabric above Achness Thrust is absent below.
First main folds in footwall deform tight F2 folds in hangingwall
Allt Rhudaih Bheag
footbridge
10 m scale SW verging folds, folding main fabric. These folds correlate with those in footwall
intense, steeply plunging folds
In Achness Nappe:
- psammite is thin-bedded (< 20 cm)
- rare sedimentary structures
- penetratively deformed;
- good foliation development
ACHNESS NAPPE
psammite beds 5 - 10 cm thick, flaggy; c. 20% semipelite, 1-5 cm thick beds
06
05
34
35
36

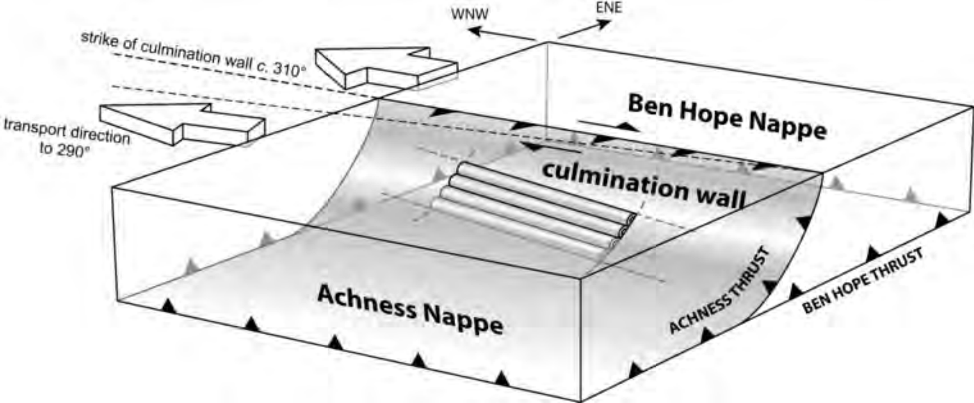


500 m
N
River Oykel
Oykel Falls
A 837
old bridge
classic localtiy of mullions below Oykel Bridge
mullions at small angle to L2AC intersection lineation
psammite with channels, beds up to 50 cm thick; locally gritty beds
Oykel Bridge Hotel
mullions parallel to rodding and intersection lineation
ACHNESS NAPPE
EINIG ANTICLINE; F2AC
thin-bedded (5 - 10 cm) psammite and micaceous psammite, locally with cross-bedding, mullions absent
River Einig
Bedding
Bedding, overturned
Direction of younging
Intersection lineation
Mineral lineation
Mullion
Minor fold axis
Direction of vergence
Minor fold axial plane
Anticline trace
Syncline trace


mGal
31.2
23.4
19.6
16.7
14.6
12.2
9.2
5.9
3.6
1.5
-0.5
-2.6
-4.9
-7.6
-10.4
-35.3
1
2
10 km
940
920
900
880
220
240
260
280
ST
BHT
NT
MT
AT
SBT


NW
Profile 1
SE
mGal
Observed
Calculated
km
Grudie Granite
Migdale Granite
MT
BHT
AT
SBT
2.78
Lewisian
2.65
Moine (psammitic)
2.75
Moine (pelitic)
2.75
Moine (migmatitic)
2.75
Cambro-Ordovician
2.60 -2.63
Caledonian granite
2.45
Devonian
NE
Profile 2
SW
mGal
Observed
Calculated
km
Grudie Granite
AT
Mullions


View down transport
View transport parallel
NNE
SSW
WNW
ESE
Eirig Fold pair
Achness Thrust
thrusting
Achness Phase
Mullions begin to form here
'Cassley Folds'
proto-Ben Hope Thrust
folding
Ben Hope Phase
Ben Hope Thrust
Moine Thrust Phase
proto-Moine Thrust
Steep culmination wall
Cassley Culmination
Moine Thrust Zone
proto-Assynt Culmination
'Loch Shin Line'
Moine Thrust
Assynt Culmination
Sole Thrust
Assynt Phase
98002294



WNW
ENE
strike of culmination wall c. 310°
transport direction
to 290°
Ben Hope Nappe
culmination wall
Achness Nappe
ACHNESS THRUST
BEN HOPE THRUST