Lewisian, Torridonian and Moine Rocks of Scotland

J.R. Mendum,

A.J. Barber,

R.W.H. Butler,

D. Flinn,

K.M. Goodenough,

M. Krabbendam,

R.G. Park

and

A.D. Stewart

GCR Editor: **P.H. Banham**

JOINT NATURE CONSERVATION COMMITTEE

British Geological Survey

NATURAL ENVIRONMENT RESEARCH COUNCIL

Chapter 5

Moine Thrust Belt

INTRODUCTION

R.W.H. Butler

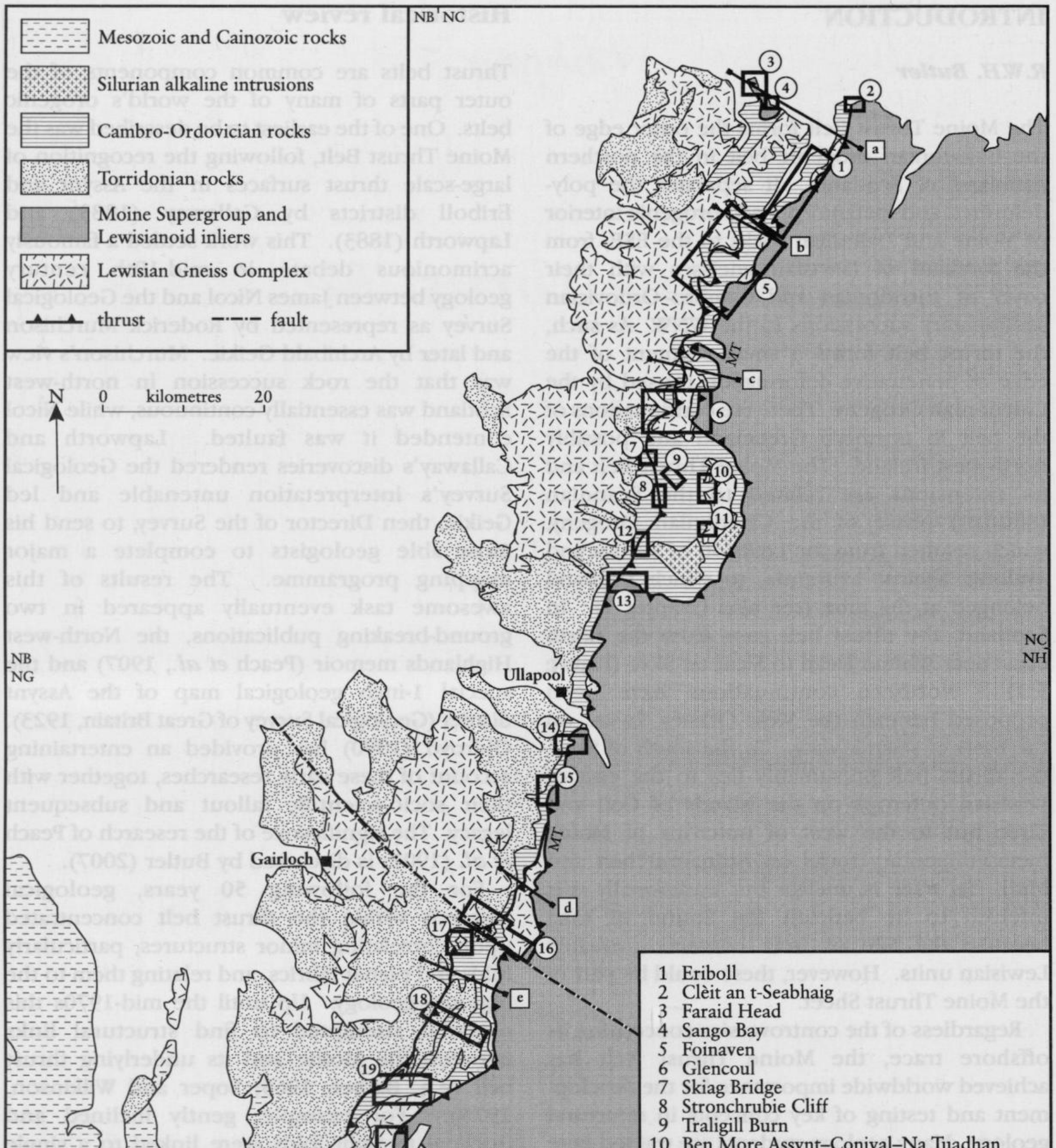
The Moine Thrust Belt forms the outer edge of the Caledonian orogenic belt in the northern mainland of Scotland. It separates the poly-deformed and metamorphosed orogenic interior of Moine and Dalradian rocks to the ESE, from the foreland of Lewisian gneisses with their cover of Torridonian and Cambro–Ordovician sedimentary successions to the WNW. As such, the thrust belt forms a small segment of the edge of penetrative deformation caused by the Caledonian Orogeny. There are continuations of the belt in northern Greenland and possibly north-west Ireland. The Moine Thrust Belt and its extensions are related to the Scandian (Silurian) phase of the Caledonian Orogeny, which resulted from the collision of Baltica and Avalonia against Laurentia, to which Scotland belonged at the time (see also Chapter 1). In Scotland, the thrust belt runs from the north coast near Whiten Head to Sleat on Skye (Figure 5.1). Northern continuations have been proposed beneath the West Orkney Basin, on the basis of seismic data. To the south of Skye, the thrust belt presumably lies to the east of Lewisian outcrops on the islands of Coll and Tiree but to the west of outcrops of Moine metasedimentary rocks on Ardnamurchan and Mull. Its trace is unclear but traditionally it is inferred to lie beneath the Sound of Iona because the Isle of Iona contains probable Lewisian units. However, these could be part of the Moine Thrust Sheet.

Regardless of the controversies concerning its offshore trace, the Moine Thrust Belt has achieved worldwide importance for the development and testing of key concepts in structural geology. Many geology students are trained here in structural analysis and mapping techniques every year. The landscape is of great beauty as highlighted in guides and booklets (e.g. Mendum *et al.*, 2001; British Geological Survey, 2004d). This introductory section highlights the historical importance of the thrust belt, outlines its broad structural elements and provides a regional framework for the GCR sites. It also emphasizes the variations in the types of structures and their relative importance along the belt.

Historical review

Thrust belts are common components of the outer parts of many of the world's orogenic belts. One of the earliest to be described was the Moine Thrust Belt, following the recognition of large-scale thrust surfaces in the Assynt and Eriboll districts by Callaway (1883) and Lapworth (1883). This work settled a famously acrimonious debate in mid-19th century geology between James Nicol and the Geological Survey as represented by Roderick Murchison and later by Archibald Geikie. Murchison's view was that the rock succession in north-west Scotland was essentially continuous, while Nicol contended it was faulted. Lapworth and Callaway's discoveries rendered the Geological Survey's interpretation untenable and led Geikie, then Director of the Survey, to send his most able geologists to complete a major mapping programme. The results of this awesome task eventually appeared in two ground-breaking publications, the North-west Highlands memoir (Peach *et al.*, 1907) and the special 1-inch geological map of the Assynt district (Geological Survey of Great Britain, 1923). Oldroyd (1990) has provided an entertaining account of these early researches, together with their socio-scientific fallout and subsequent legacy. The significance of the research of Peach *et al.* (1907) is discussed by Butler (2007).

For the following 50 years, geological research within the thrust belt concentrated upon correlating minor structures, particularly folds and planar fabrics, and relating them to the regional geology. Up until the mid-1970s this research attempted to find structural links between the Moine and its underlying thrust belt (e.g. Barber, 1965; Soper and Wilkinson, 1975). For example, gently inclined and isoclinal to tight folds were linked to a single mylonite-forming event (termed 'D1'). This type of structural analysis received added impetus with the application of radiometric dating techniques to igneous intrusions within the Northern Highlands; these age dates apparently calibrating the relative structural histories built up from field studies (e.g. Woolley, 1970; van Breemen *et al.*, 1979a). A review of the evidence from the igneous rocks in Assynt appears in GCR Volume 17, *Caledonian Igneous Rocks of Great Britain* (Parsons, 1999).



Mesozoic and Cainozoic rocks
Silurian alkaline intrusions
Cambro-Ordovician rocks
Torridonian rocks
Moine Supergroup and Lewisianoid inliers
Lewisian Gneiss Complex
thrust
fault
N
0 kilometres 20
NB NC
NB NG
NC NH
NG NM
NH NN
NM NN
Ullapool
Gairloch
MT
a
b
c
d
e
f
1 Eriboll
2 Clèit an t-Seabhaig
3 Faraid Head
4 Sango Bay
5 Foinaven
6 Glencoul
7 Skiag Bridge
8 Stronchrubie Cliff
9 Traligill Burn
10 Ben More Assynt–Conival–Na Tuadhan
11 Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel
12 Cam Loch
13 Knockan Crag
14 Dundonnell
15 Càrn na Canaich
16 Slioch–Heights of Kinlochewe
17 Meall a' Ghiubhais
18 Beinn Liath Mhor
19 Cnoc nam Broc
20 Slumbay Island
21 Carn a' Bhealaich Mhòir
22 Hangman's Bridge
23 Ard Hill
24 Ord
25 Tarskavaig
26 Ard Thurinish–Port na Long

◂**Figure 5.1** Map of the Moine Thrust Belt with locations of GCR sites indicated. Lines of sections of Figure 5.2 are also indicated. The Moine Thrust Belt lies between the Moine Supergroup and the foreland rocks, and its eastern boundary is the Moine Thrust itself.

In the late 1970s, renewed interest in the structural evolution of the Moine Thrust Belt was propelled by the application of analytical techniques developed in the foothills of the Rocky Mountains (e.g. Bally *et al.*, 1966; Dahlstrom, 1970) and the Appalachians of North America (Rich, 1934; Milici, 1975). Elliott and Johnson (1980) pioneered this approach in the North-west Highlands. The critical conceptual leap was that thrust belts evolve by individual thrusts growing, linking, moving and then dying. They form in a general foreland-propagating sequence so that higher nappes are carried 'piggy-back' upon lower ones. In the Appalachians, Mitra and Elliott (1980) showed that folds and deformation fabrics could be explained by local thrusting processes rather than by regional tectonic events, prompting a similar re-assessment of minor structures within the North-west Highlands. These new approaches led to a major programme of remapping within the thrust belt, in many cases re-examining, for the first time in a hundred years, the geometrical relationships between thrusts and the sheets that they carry. Much of this work confirmed the ideas of Elliott and Johnson (1980), recognizing in particular that many of the structural complexities and bewildering networks of faults originated from the repetition of individually rather simple geometric elements. However, some parts of the thrust belt show fault geometries that are not predicted by Elliott and Johnson's ideas, particularly extensional structures that cut down the stratigraphical section in the direction of transport (Coward, 1982). Controversy remains as to the larger-scale tectonic significance of these features, in particular whether they accommodated crustal extension, gravitational collapse or even the locally complex effects of purely compressional tectonics (Coward, 1983; Butler, 2004a; Butler *et al.*, 2006, 2007; Holdsworth *et al.*, 2007).

The renewed interest in thrust belt structure, particularly in north-west Scotland, came when structural geologists began to relate the deformation recorded by mountain belts to plate-tectonic processes through integrating surface geology with deep seismic reflection profiles (Soper and Barber, 1982; Brewer and Smythe, 1984). Central to this were attempts to quantify the magnitude of horizontal displacements responsible for stacking up piles of thrust sheets, primarily using so-called 'balanced cross-sections' (Dahlstrom, 1969). These constructions are geological profiles drawn parallel to the inferred direction of displacement in such a way that the stratigraphy may be restored graphically to a predicted undeformed state. Although simple palinspastic reconstructions have been made of parts of mountain belts for almost a century, balanced sections are a significant improvement because they attempt to quantify the displacements experienced by all layers, an important part of testing models of structural geometry and evolution for internal consistency. By representing three-dimensional tectonic structure in two-dimensional profiles, balanced cross-sections have a general assumption of plane strain, in that there is no movement of material out of the profile. Notwithstanding this limitation, balanced sections were crucial for providing estimates of almost 60 km for the original width of that part of the Cambro–Ordovician shelf succession now stacked up within the Moine Thrust Belt (Butler and Coward, 1984; Coward, 1985). Estimates for the whole belt suggest some 100 km of sub-horizontal displacement (Elliott and Johnson, 1980). These movements have carried the Moine rocks and the orthotectonic part of the Caledonide Orogen, apparently as a relatively thin sheet, by this amount across the foreland Lewisian gneisses.

The map-scale structural geometry, along with the application of material science methods, provided a springboard for detailed micro-structural studies of fault rocks (e.g. White, 1977; Knipe, 1989). The purpose of these studies was to define better the conditions under which the thrust faults and shear zones developed, and thereby understand how the very large tectonic displacements were accumulated on such relatively narrow features.

A prime reason for the successful mapping of the Moine Thrust Belt, together with its continued popularity as a training ground for students, lies in the well-differentiated litho-stratigraphy. The stratigraphy of the Torridonian

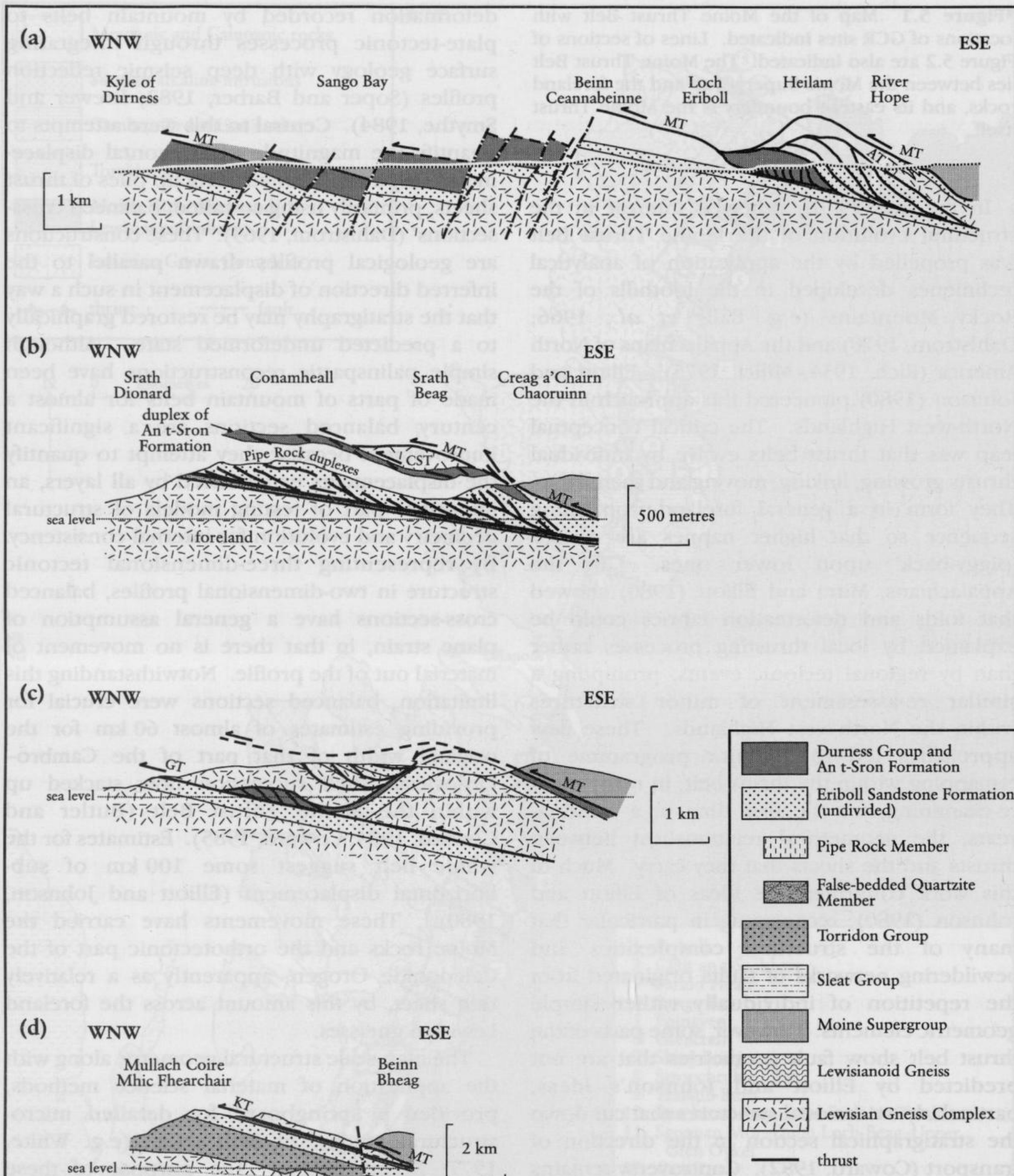


Figure 5.2 Selected simplified cross-sections across the Moine Thrust Belt, showing variations along strike. MT – Moine Thrust; AT – Arnaboll Thrust; CST: – Creag Shomhairle Thrust; GT – Glencoul Thrust; KT – Kinlochewe Thrust. (a) Arnabol–Durness; (b) Foinaven; (c) north Assynt; (d) An Teallach–Càrn na Canaich. Sections (a)–(d) by R.W.H. Butler. *Continued opposite.*

sedimentary rocks and the nature of the different blocks of Lewisian basement are outlined elsewhere in this volume. The unconformity at the base of the Torridonian is spectacularly exposed in the GCR site at **Slioch–Heights of Kinlochewe** where it rests upon an

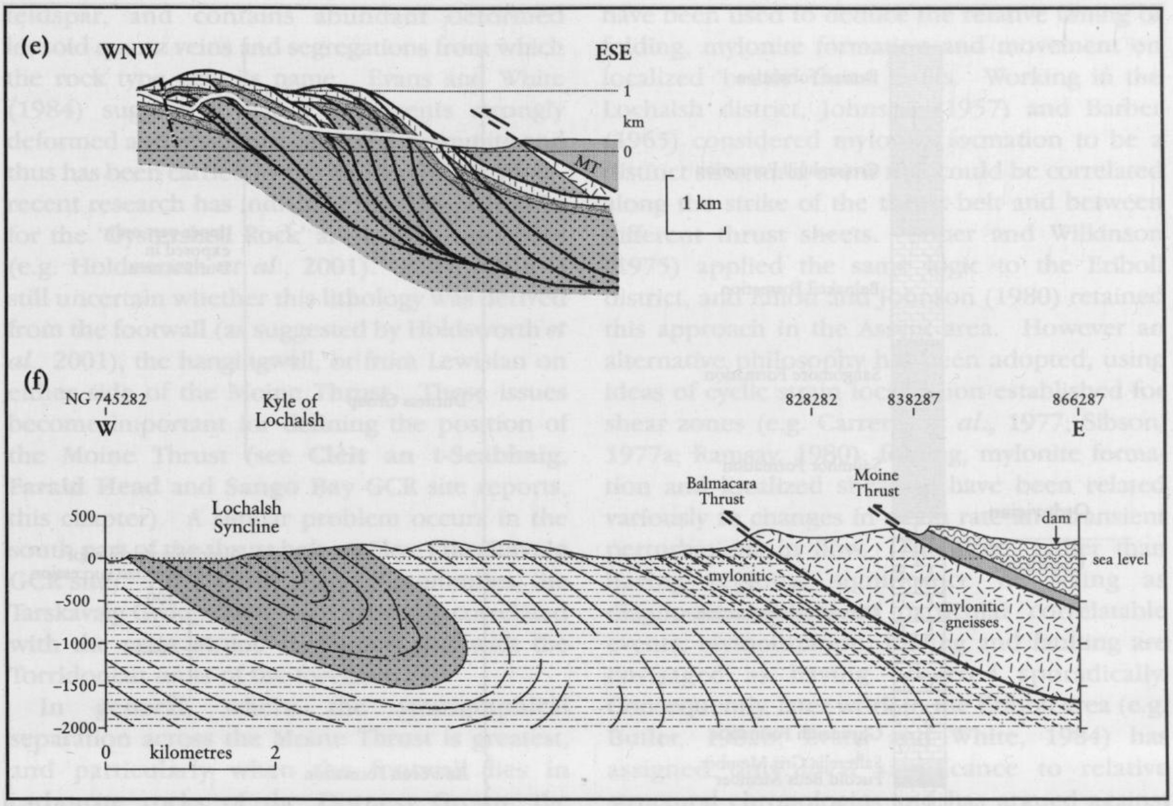


Figure 5.2 – ***continued.*** **Selected simplified cross-sections across the Moine Thrust Belt, showing variations along strike: (e) Torridon; (f) Lochalsh. Section (e) by S.J. Matthews (in Butler *et al.*, 2007), section (f) by A.J. Barber.**

irregular land surface with almost 500 m of relief. Regionally the Precambrian rocks are capped by a remarkably planar unconformity which underlies a surprisingly layer-cake succession of Cambro–Ordovician sedimentary rocks (Figure 5.3). The geometry of this unconformity can be appreciated in the Arkle–Foinaven area and at An Teallach. The Cambro–Ordovician succession comprises three distinctive units. The oldest is represented by about 150 m of quartzites (the Eriboll Sandstone Formation), the middle one is a highly differentiated collection of sands, silts and muds capped by clean quartzites (the An t-Sron Formation), and the upper one is a thick (over 1500 m) succession of carbonate rocks (the Durness Group). These units are readily identified, commonly from a great distance, allowing exceptionally complex tectonic interleavings to be unravelled by field geologists. They also provide exposures of thrust and fold structures of unrivalled clarity, well illustrated by the GCR sites in this volume. The *Skolithos* trace fossils in the Eriboll Sandstone Formation are ideal strain markers and have played a key role in the understanding of strain patterns, both in the **Eriboll** GCR site (e.g. Coward and Kim, 1981), and in thrust belts generally. GCR sites representing the stratigraphy and palaeontology of the Cambro–Ordovician succession are described in the *British Cambrian to Ordovician Stratigraphy* GCR Volume (Rushton *et al.*, 2000).

The Moine Thrust and its mylonites

The Moine Thrust is defined as the tectonic contact along which the Moine metasedimentary rocks, together with the Lewisian basement upon which they were deposited, were carried to the WNW. These units now rest tectonically upon Cambro–Ordovician and Torridonian sedimentary rocks, which in turn overlie Lewisian basement of the foreland (Figures 5.1, 5.2). The Moine Thrust is characterized by extensive mylonite development in both its footwall and hangingwall; indeed the term 'mylonite' was first coined by Lapworth (1883) for strongly sheared rocks within the **Eriboll** GCR site. The resultant mylonite zone varies in

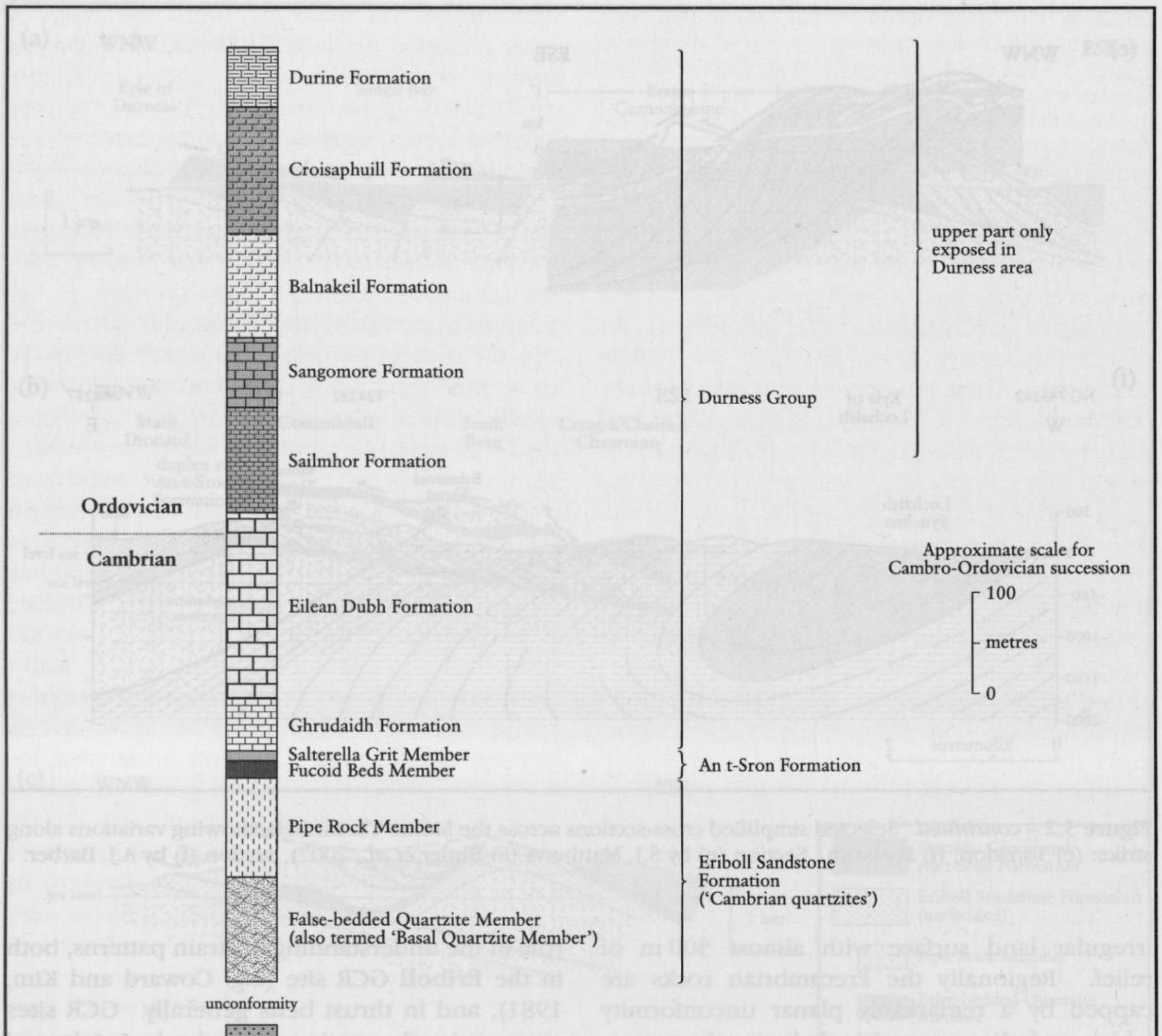


Figure 5.3 Stratigraphical column of Cambro–Ordovician sequence in north-west Scotland. Based on Swett (1969), Prigmore and Rushton (1999)and British Geological Survey (2002).

thickness from a few metres to several hundred metres. This zone can contain thin mylonite units derived from the different protoliths. The Pipe Rock generates near-monomineralic quartz mylonites and as such it is straightforward to relate the deformed rocks to the protolith type. In contrast, the protoliths of the common chloritic mylonites and phyllonites can be difficult to correlate, for example, the so-called 'Oystershell Rock' of the Geological Survey (Peach *et al.*, 1907). This crenulated phyllonite is composed chiefly of chlorite, white mica, quartz and feldspar, and contains abundant deformed lensoid quartz veins and segregations from which the rock type gets its name. Evans and White (1984) suggested that it represents strongly deformed and retrogressed Moine psammite and thus has been carried by the Moine Thrust. More-recent research has indicated that the protoliths for the 'Oystershell Rock' are Lewisian gneisses (e.g. Holdsworth *et al.*, 2001). However, it is still uncertain whether this lithology was derived from the footwall (as suggested by Holdsworth *et al.*, 2001), the hangingwall, or from Lewisian on either side of the Moine Thrust. These issues become important for defining the position of the Moine Thrust (see **Clèit an t-Seabhaig**, **Faraid Head** and **Sango Bay** GCR site reports, this chapter). A similar problem occurs in the south part of the thrust belt on Skye (**Tarskavaig** GCR site). Here highly sheared psammites, the Tarskavaig Group, have been variously correlated with the main Moine succession and with the Torridonian units of the foreland.

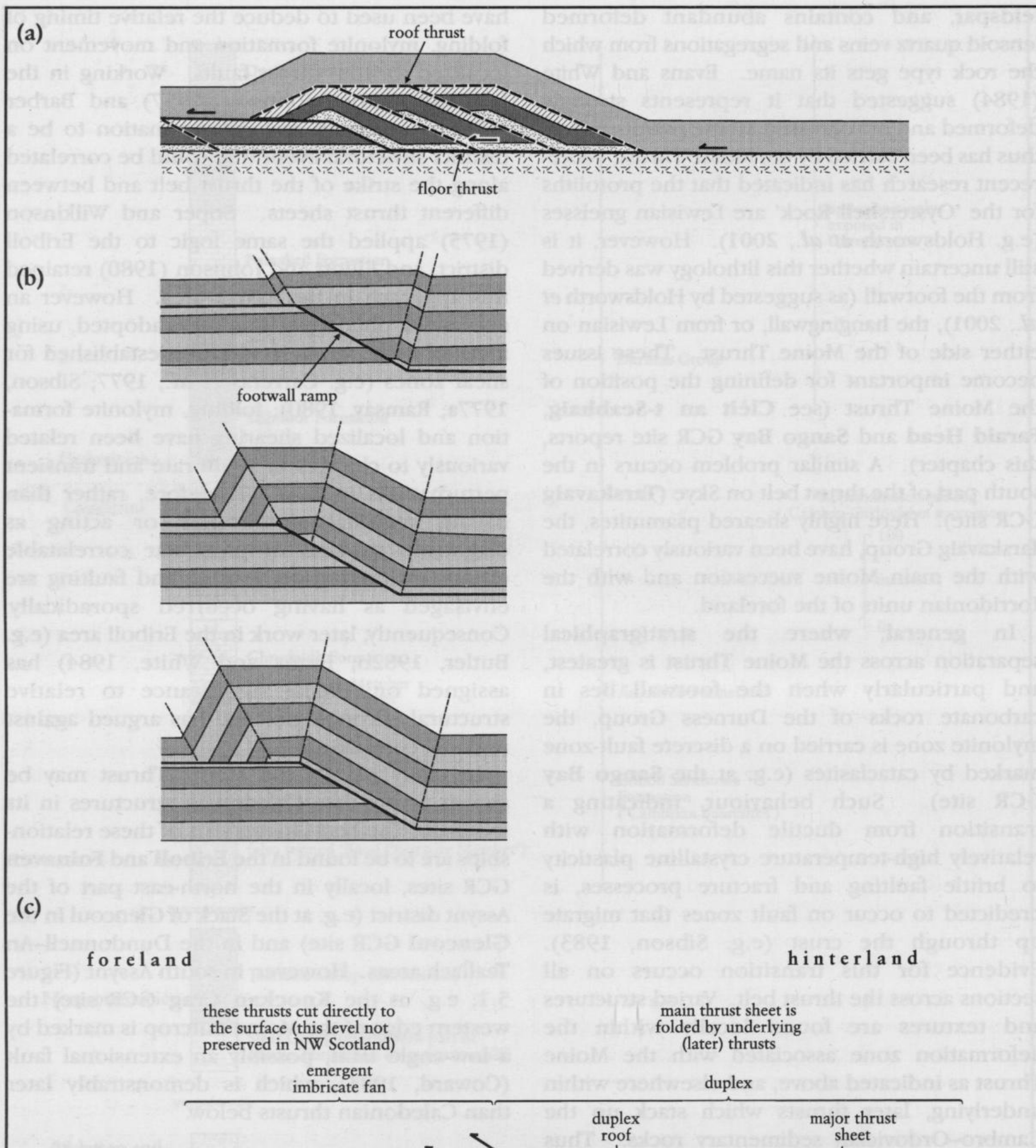
In general, where the stratigraphical separation across the Moine Thrust is greatest, and particularly when the footwall lies in carbonate rocks of the Durness Group, the mylonite zone is carried on a discrete fault-zone marked by cataclasites (e.g. at the **Sango Bay** GCR site). Such behaviour, indicating a transition from ductile deformation with relatively high-temperature crystalline plasticity to brittle faulting and fracture processes, is predicted to occur on fault zones that migrate up through the crust (e.g. Sibson, 1983). Evidence for this transition occurs on all sections across the thrust belt. Varied structures and textures are found locally within the deformation zone associated with the Moine Thrust as indicated above, and elsewhere within underlying, later thrusts which stack up the Cambro–Ordovician sedimentary rocks. Thus the Moine Thrust changes its character from place to place. Indeed, the western edge of the Moine outcrop is not everywhere defined by the Moine Thrust; later thrusts and faults, some associated with later basin formation, characterize the boundary of Moine rocks in places. In the Lochalsh area (Figure 5.1), it is commonly difficult to establish whether the western boundary of the Moine outcrop is the Moine Thrust or a late fault contact (e.g. at the **Hangman's Bridge** and **Ard Hill** GCR sites).

Classic investigations using the overprinting relationships of structures on an outcrop scale have been used to deduce the relative timing of folding, mylonite formation and movement on localized 'brittle' thrust faults. Working in the Lochalsh district, Johnson (1957) and Barber (1965) considered mylonite formation to be a distinct structural event that could be correlated along the strike of the thrust belt and between different thrust sheets. Soper and Wilkinson (1975) applied the same logic to the Eriboll district, and Elliott and Johnson (1980) retained this approach in the Assynt area. However an alternative philosophy has been adopted, using ideas of cyclic strain localization established for shear zones (e.g. Carreras *et al.*, 1977; Sibson, 1977a; Ramsay, 1980); folding, mylonite formation and localized shearing have been related variously to changes in strain rate and transient perturbations in flow. Therefore, rather than having regional significance or acting as diagnostic markers of particular correlatable events, mylonitization, folding and faulting are envisaged as having occurred sporadically. Consequently, later work in the Eriboll area (e.g. Butler, 1982b; Evans and White, 1984) has assigned only local significance to relative structural chronologies and has argued against regional correlations.

In many places, the Moine Thrust may be shown to pre-date Caledonian structures in its footwall. The best illustrations of these relationships are to be found in the **Eriboll** and **Foinaven** GCR sites, locally in the north-east part of the Assynt district (e.g. at the Stack of Glencoul in the **Glencoul** GCR site) and in the Dundonnell–An Teallach areas. However, in south Assynt (Figure 5.1; e.g. at the **Knockan Crag** GCR site) the western edge of the Moine outcrop is marked by a low-angle fault, possibly an extensional fault (Coward, 1983), which is demonstrably later than Caledonian thrusts below.

Structural styles within the thrust belt

Cross-sections through thrust belts, including the Moine Thrust Belt, can appear to be frustratingly complex (Figure 5.2). However, careful studies have established that a few simple geometries recur (Figure 5.4), and it is the combination of these 'building blocks' that produces elaborate three-dimensional thrust belt geometries. Individual thrusts can be shown to have complex geometries with layer-parallel segments (termed 'flats') and steeper


(a)
roof thrust
floor thrust
(b)
footwall ramp
(c)
foreland
hinterland
these thrusts cut directly to the surface (this level not preserved in NW Scotland)
emergent imbricate fan
main thrust sheet is folded by underlying (later) thrusts
duplex
duplex roof
major thrust sheet
thrust tip
'blind' thrust
floor to imbricates
imbricate thrusts
duplex floor
imbricate thrusts branch onto the master (roof) thrust before they reach the surface

◂**Figure 5.4** Idealized thrust geometries. (a) Idealized duplex (Boyer and Elliott, 1982): three imbricate thrust slices between a roof and a floor thrust. (b) Suppe's model for the development of fault-bend fold in the hangingwall, formed as a thrust sheet climbs up a footwall ramp (after Suppe, 1983). (c) Diagram showing imbricate thrusts, duplex, duplex floor and roof and other thrust geometries.

linking segments (called 'ramps') that cut across layering. Movement up ramp–flat profiles generates folds in the hangingwall strata. Thrusts rarely occur in isolation but rather occur in complex arrays, called 'imbricate zones', in which individual thrusts (ramps) splay upwards from an underlying floor thrust. If these ramps re-combine up-dip onto another major flat (the roof thrust) the entire structure is termed a 'duplex' (Figure 5.4). The essence of these structures was described by Peach *et al.* (1907) and was formalized for the Moine Thrust Belt by Elliott and Johnson (1980). They are generally representative of the fundamental structural geometries that stack up segments of continental crust, particularly during collision orogeny.

Understanding the evolution of thrust systems has always involved deduction of the relative timing of formation of the various thrust faults. Peach *et al.* (1907) decided on balance that structurally higher thrusts (including the Moine Thrust) moved later, truncating imbricate thrusts in their footwall. This 'overstep' model was challenged first by Dallstrom (1970), based on studies in the Canadian Rockies, and in the Moine Thrust Belt by Elliott and Johnson (1980), who argued that thrusts developed strictly from top to bottom. Such has been the influence of this work that this 'piggy-back' thrust model is embedded in the general literature. However, Coward and Butler (Coward, 1983; Butler and Coward, 1984; Butler, 1987) demonstrated that piggy-back thrusting was not universally applicable in the Moine Thrust Belt. Recent studies have shown that within individual duplex systems, the relative order of thrusting is variable with certain limits, leading to a more-general model of synchronous, rather than strictly sequential, thrusting (Butler, 2004a; Butler *et al.*, 2007). Many of the critical locations for these debates lie within the GCR sites described here.

There are several different types of thrust-related structure developed beneath the Moine Thrust. The GCR sites provide an excellent introduction to these variations, which are illustrated on Figure 5.4. The terms 'thrust sheet' and 'nappe' are virtually synonymous; 'thrust sheet' is herein used for structures that are dominated by brittle thrusting, whereas the term 'nappe' is used for more ductily deformed sheets that are dominant in the southern part of the belt.

Lewisian thrust sheets

Amongst the most striking structures within north-west Scotland are the large thrust sheets that contain Lewisian basement, generally with remnants of the original Cambrian or Torridonian cover. The three most famous of these are prime constituents of GCR sites; the Arnaboll Thrust Sheet at **Eriboll** and the Glencoul and Ben More thrust sheets of Assynt (**Ben More Assynt–Conival–Na Tuadhan** GCR site). Other examples are found in the southern part of the thrust belt; the Kinlochewe and Kishorn thrust sheets, which are parts of the **Slioch–Heights of Kinlochewe** and **Cnoc nam Broc** GCR sites respectively. The thrusts are remarkable in that they appear to have cut through massive, apparently competent gneisses as discrete planes with only a metre or two of associated tectonite (Butler *et al.*, 2006). The Kinlochewe Thrust in the **Meall a' Ghiubhais** GCR site has similar characteristics but also cuts across irregularities in the Lewisian–Torridonian unconformity.

Imbricate zones

The distinctive and planar-bedded Cambro–Ordovician sedimentary rocks were particularly prone to imbrication by thrusts so that individual units can be repeated many times. In the northern part of the thrust belt (Figure 5.1), the Cambrian quartzites, particularly the Pipe Rock Member, appear to have accommodated many tens of kilometres of shortening (Figure 5.2b) through the formation of duplexes on scales from centimetres to tens of metres (Figure 5.5). This is most clearly demonstrated at the **Foinaven** GCR site (e.g. Elliott and Johnson, 1980; Butler, 1982b, 2004a), but the **Eriboll**, **Skiag Bridge** and **Stronchrubie Cliff** GCR sites also contain spectacular repetitions of Cambro–Ordovician units. Farther south, for example

Figure 5.5 Example of a single-bed duplex structure developed within the Pipe Rock. This is the Beyond Hope duplex of Bowler (1987), exposed in coastal outcrops south of Whiten Head. (Photo: R.W.H. Butler.)

between Loch Broom and Kinlochewe (including the **Càrn na Canaich** GCR site), the thrust belt contains very little imbrication. Indeed in many places it consists entirely of the Moine Thrust. However, imbricate zones are present in the Torridon area (Butler *et al.*, 2007) with thick slices containing Torridonian and Cambrian strata, for example at Sgorr Ruadh, as described in the **Beinn Liath Mhor** GCR site report (this chapter).

Lateral variations in the geometry of thrusts are responsible for major culminations along the thrust belt. The presence of ramps can generate radical variations in the content of individual thrust sheets. Where many imbricate slices are stacked, complex folds and culminations may have been generated within the thrust belt. The Assynt Culmination furnishes the largest example (Figure 5.1). This bulge in the Moine Thrust is formed by laterally restricted thrust sheets of Lewisian basement (the Ben More and Glencoul sheets) together with vast piles of imbricate structures within the Cambro–Ordovician succession. The culmination also includes major intrusions (e.g. the Loch Ailsh Syenitic Pluton; Parsons, 1999) that Elliott and Johnson (1980) suggested were a major cause of the abundant imbrication. The process of culmination formation may be best appreciated on an outcrop scale at Creag Shomhairle in the **Foinaven** GCR site.

Fold–thrust complexes

Folds may be associated with thrusts simply as a geometric consequence of movement along ramp–flat profiles. These antiformal, so-called 'fault-bend folds' (e.g. Rich, 1934; Suppe, 1983) only develop in the hangingwall (e.g. at Heilam, **Eriboll** GCR site, see Figure 5.6). Examples are also exposed on cliff sections on Foinaven and in the Sgorr Ruadh area (Figure 5.1). However, in many natural examples, folds are interpreted to have initiated as buckles, subsequently being cut through by a thrust (e.g. Fischer and Coward, 1982; Williams and Chapman, 1983). This composite behaviour may be distinguished from simple fault-bend folding by identifying deformation in the footwall to thrusts, particularly large-scale synforms, which form the complementary fold pair to the hangingwall antiforms. Large-scale buckle folds have evolved into thrust sheets as some limbs shear out, generating tight folds carried on thrust-sense shear-zones. In ideal cases, these folds face in the direction of tectonic transport (e.g. Coward and Potts, 1983). This type of behaviour appears to characterize deformation in the southern part of the Moine Thrust Belt. The Kishorn Nappe (Figure 5.1) contains areas of overturned Torridonian sedimentary rocks, which pick out large-scale footwall synclines beneath higher-level thrusts, for example the Lochalsh Syncline

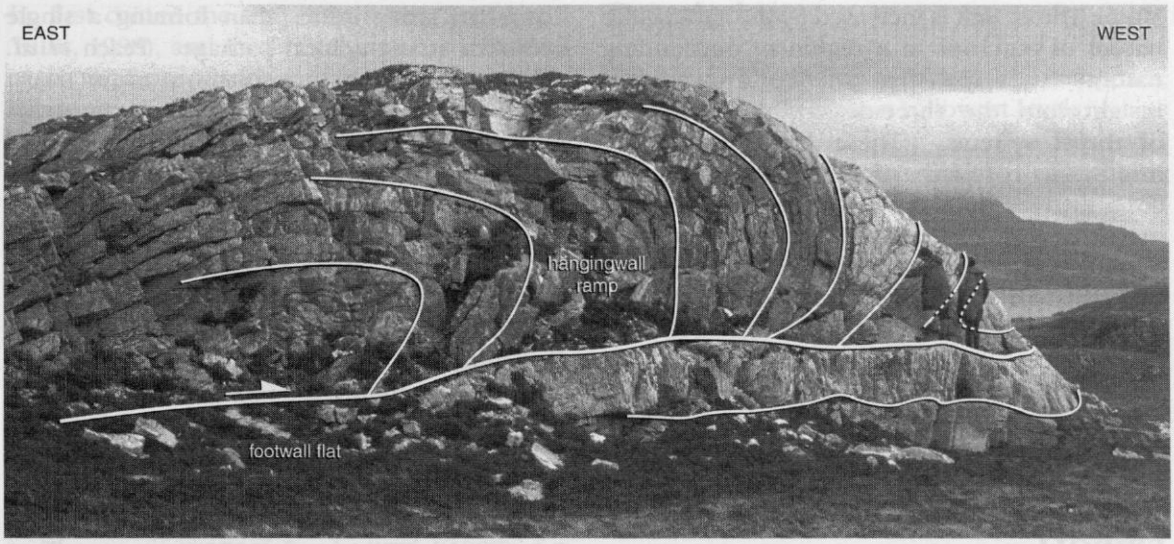


Figure 5.6 Small-scale fold–thrust complex in quartzite, Heilam, **Eriboll** GCR site. (Photo: R.W.H. Butler.)

that dominates the geology of Sleat and forms one of the largest folds in the thrust belt. Associated with these large folds are widespread schistosities and minor folds, well displayed in the **Ard Hill** and **Carn a' Bhealaich Mhòir** GCR sites. This style of broadly distributed deformation is in marked contrast to the Lewisian-cored thrust sheets of central and northern Assynt (Butler *et al.*, 2006). The change in structural style coincides with the presence of a thick Torridonian sedimentary sequence in the southern part of the thrust belt. It apparently indicates that the interface between Torridonian and Lewisian rocks was prone to buckling, perhaps nucleating on pre-existing normal faults, whereas the Cambrian–Lewisian unconformity favoured thrust ramps.

Timing

It is generally accepted that thrust tectonics had ended in north-west Scotland by earliest Devonian times (*c.* 400 Ma), but the evidence for this paradigm is rather sparse. Estimating the timing of displacements within the Moine Thrust Belt relies on radiometric ages from various alkaline igneous intrusions. The Loch Borralan Syenitic Pluton of Assynt, which appears to cut the Ben More Thrust (e.g. Parsons, 1979, 1999), has been dated at 430 ± 4 Ma (van Breemen *et al.*, 1979a). The Loch Ailsh Pluton, which is apparently cut by Caledonian structures (see **Ben More Assynt–Conival–Na Tuadhan** GCR site report, this chapter), has yielded an age of 439 ± 4 Ma (Halliday *et al.*, 1987). In addition, the Canisp Porphyry sills, which lie in the foreland immediately west of the thrust belt but are absent from the belt itself, have a U-Pb TIMS zircon intrusion age of 437 ± 4.8 Ma (Goodenough *et al.*, 2006). However, direct dating of mylonite formation in the hangingwall to the Moine Thrust implies that ductile movements associated with recrystallization continued until about 410 Ma (Freeman *et al.*, 1998). There are no clear indications from geological relationships of the time of final cessation of movement in north-west Scotland. Although minor intrusions spatially associated with the Loch Borralan Pluton (e.g. the 'nordmarkite' dykes) are found on both sides of the Moine Thrust, no individual intrusions have been found that definitively suture the thrust belt. Neither are there any sedimentary rocks earlier than Triassic age that unconformably overlie the structures.

Summary

The Moine Thrust Belt forms the outer, north-west margin to the Scottish Caledonides. As such it provides spectacular examples of the range of structures found with the marginal zone of an orogenic belt. Over 150 years of geological investigation have seen a number of revolutions in the analytical philosophy behind different types of tectonic analysis and interpretation. The international importance of the

Moine Thrust Belt is increased by the spectacular nature of outcrops in a region of outstanding natural landscape that provide unparalleled insight into the three-dimensional structure of thrust systems. These locations provide important resources for teaching and for continued research; the region remains a heavily used natural laboratory for testing tectonic models. The GCR sites reflect this history and the range of structures that can be found in thrust belts, both in style and scale. They are described broadly from north to south, starting at Loch Eriboll, the historical site where the 19th century 'Highlands Controversy' was resolved (Lapworth, 1883; Peach *et al.*, 1888).

ERIBOLL (NC 485 622–NC 380 501)

R.W.H. Butler

Introduction

The Eriboll GCR site, on the south-east side of Loch Eriboll, is of international historical importance for its role in the development of concepts in structural geology and mountain building, particularly thrust tectonics. It is well exposed and readily accessible by road, and formerly by sea, so that it has attracted geological investigations for almost two centuries (see Oldroyd, 1990 for a review of the early studies). The north-west flank of the sea loch is a spectacular dip-slope formed of Cambrian quartzites (Eriboll Sandstone Formation), one of the largest of such surfaces exposed in the British Isles. To the south-east and above the loch lies the Moine Supergroup (hereafter referred to as the 'Moine'), separated from Cambrian strata by the Moine Thrust Belt (British Geological Survey, 2002). The region was critical in Lapworth's resolution of the relationship between the Moine and the foreland Cambro–Ordovician successions to the west (Lapworth, 1883, 1883–1884). He applied a three-dimensional approach to the understanding of structural relationships, through geological mapping and profile construction, rather than relying on reconnaisance transects alone, as in previous investigations. Lapworth demonstrated repetition of Lewisian and Cambrian strata and showed that the Moine metasedimentary rocks had been emplaced tectonically upon the Cambrian strata rather than forming a single coherent stratigraphical package. Peach *et al.* (1888, 1907) went on to map out major thrust sheets of Lewisian basement and intricate arrays of imbricate thrusts. Indeed the term 'thrust' was first coined for these structures at Eriboll (Geikie, 1884).

The studies of Peach *et al.* (1907) were thorough and meticulous, such that little significant tectonic research was undertaken in the Eriboll area until the 1970s. There followed three distinct approaches to understanding structural evolution, the first based on deformation correlations, the second on microstructural evolution and the third on a re-examination of cross-section-scale structural relationships.

Soper (1971), Soper and Barber (1973) and Soper and Wilkinson (1975) attempted to correlate deformation histories between the Moine rocks of the Caledonian Orogen and their highly sheared equivalents in the mylonite zones along the Moine Thrust, particularly along the Creagan Road section of the Eriboll GCR site. Evans and White (1984) outlined a brief history of these researches. The basic assumption was that there was a distinct mylonite-formation event, a correlatable time-marker that could be linked to deformation histories in both the southern part of the Moine Thrust Belt, and the amphibolite-facies metamorphic Moine rocks of the orogen. As the mylonites at Eriboll contain deformed Cambrian strata, Soper and others concluded that all shearing events in the Northern Highlands were of post-Cambrian age, precluding intense Precambrian deformation of these rocks.

The regional correlation of deformation-based chronologies within folded and sheared rocks, such as applied by Soper and others at Eriboll, has underpinned many attempts to understand orogenic processes in examples throughout the world. However, through the 1970s it became increasingly clear that folding and strain localization features can occur cyclically in shear zones (e.g. Carreras *et al.*, 1977). This eventually led Evans and White (1984) to re-interpret the deformation histories at Eriboll in terms of local transient processes, removing the basis for correlation into the Moine. Dayan (1981) reached similar conclusions, and more recently Williams (1997) and Casey and Williams (2000) have modelled such processes.

Microstructural investigations have built upon the seminal work of Lapworth (1883), in which he first coined the term 'mylonite' (Snoke and Tullis, 1998), and the Eriboll area has remained at the forefront of such studies (e.g. White, 1979; White *et al.*, 1982). Evans and White (1984) studied the quartzite mylonites in particular, to show complex histories of recrystallization and shearing on a grain scale. This formed the springboard for more-detailed petrophysical modelling of the deformation paths recorded by the quartz mylonites (e.g. Law *et al.*, 1984, 1986). On a larger scale, the ideal strain markers provided by the trace fossils in the Pipe Rock Member (Eriboll Sandstone Formation) permitted studies of distributed deformation within thrust sheets to elucidate emplacement mechanisms (McLeish, 1971; Coward and Kim, 1981; Fischer and Coward, 1982; Coward and Potts, 1983).

The perceptions of Peach *et al.* (1907) that thrusts can form in linked arrays were re-assessed using concepts developed in North America (Elliott and Johnson, 1980). Ideally, in duplexes (linked thrust arrays), there is a strict sequence of faulting that migrates from top to bottom. Thus older thrusts are carried 'piggy-back' upon the lower later ones. Elliott and Johnson (1980) proposed that the northern part of the Moine Thrust Belt formed in such a sequence. Although their examples came largely from the Assynt district (see the relevant GCR site reports), the Eriboll area became critical for demonstrating relative timing of displacements within thrust arrays (Coward, 1982). Although Elliott and Johnson's (1980) 'piggy-back' model has been confirmed in places, there are important deviations.

The Eriboll area contains the closest onshore outcrops to the regional deep seismic reflection profiles that have been acquired off the north Scottish coast (e.g. Snyder, 1990). It was the acquisition of these data that prompted the first attempts at balancing cross-sections on a crustal scale (Soper and Barber, 1982; Butler and Coward, 1984).

The Eriboll site is arguably the most important part of the Moine Thrust Belt GCR network, not only for its historical significance but also for the range and accessibility of its structural geology. The area is regularly used for training by student parties and continues to attract research interest. Nevertheless, the structure is exceptionally complex and there remain unresolved issues on the relative timing of structures and the nature of the Moine Thrust itself (e.g. Butler *et al.*, 2006; Holdsworth *et al.*, 2006).

Description

The Moine Thrust Belt at Loch Eriboll comprises, from structurally highest to lowest levels:

- the Moine Thrust Sheet, comprising mylonitized Moine metasedimentary rocks and their Lewisianoid basement;
- penetratively deformed Lewisian slices and mylonites derived from Lewisian gneisses together with Cambrian quartzites that formed their cover;
- the Arnaboll Thrust Sheet, containing Lewisian basement little affected by penetrative Caledonian strain;
- variably imbricated Cambrian sedimentary rocks.

The structure of this region is illustrated simply on Figure 5.7a and representative cross-sections are shown in Figure 5.8.

Imbricated Cambrian strata form the lowest structural level to the Moine Thrust Belt at Eriboll. These are best represented in the north, around Ben Heilam (Coward, 1984a). Pipe Rock dominates the imbricate slices in the east with the younger An t-Sron Formation and Durness Group carbonate rocks forming the closely imbricated, structurally lower, western areas adjacent to the loch. The Heilam imbricate zones are structurally overlain by the Arnaboll Thrust Sheet, formed mainly of Lewisian gneisses. The gneisses form the prominent crags of Creag Ruadh (NC 485 622) and those on the western flanks of Ben Arnaboll (NC 455 590). However, the Arnaboll Thrust has climbed up-section in its hangingwall so that farther west Cambrian quartzites and younger units have been emplaced onto Durness Group carbonates (Figure 5.9). The thrust runs offshore in Kempie Bay, and carbonates, which are generally poorly exposed, form much of the eastern side of Loch Eriboll around Eriboll Farm.

The Lewisian gneisses of the Arnaboll Thrust Sheet, which show little penetrative post-Cambrian strain (Butler *et al.*, 2006; cf. Ramsay, 1997), are separated from the Moine mylonites by a tract of highly deformed Cambrian quartzites and phyllonites derived from a Lewisian protolith (Rathbone *et al.*, 1983). The mylonites have received considerable attention, initially in attempts to correlate deformation episodes and fold generations throughout the Northern Highlands (e.g. Soper and Wilkinson,

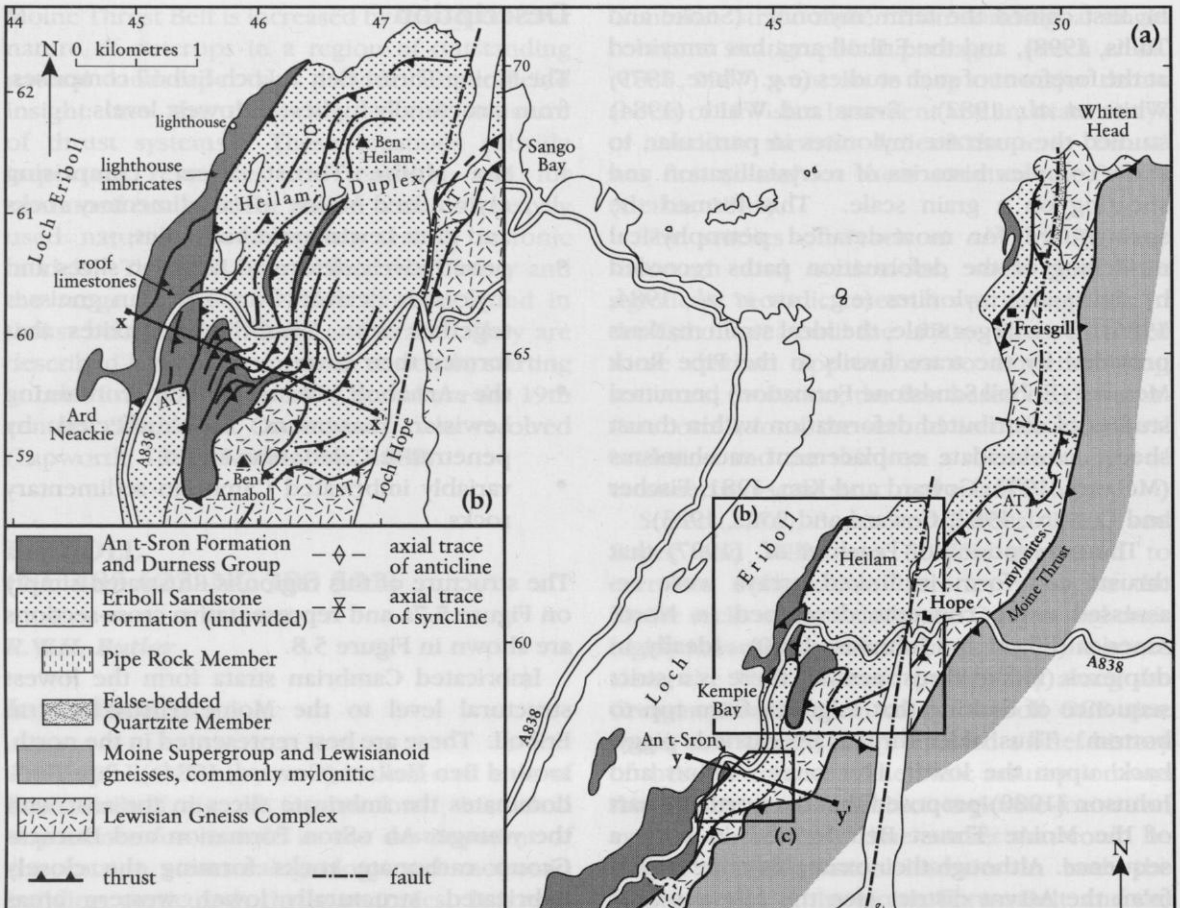


Figure 5.7 Simplified structure of the Moine Thrust Belt at Loch Eriboll. (a) Map of the area around Loch Eriboll. (b) Map of the area around Ben Arnaboll. (c) Map of the area between Bealach Mhari and Church Crag. AT – Arnaboll Thrust. After Butler *et al.* (2006).

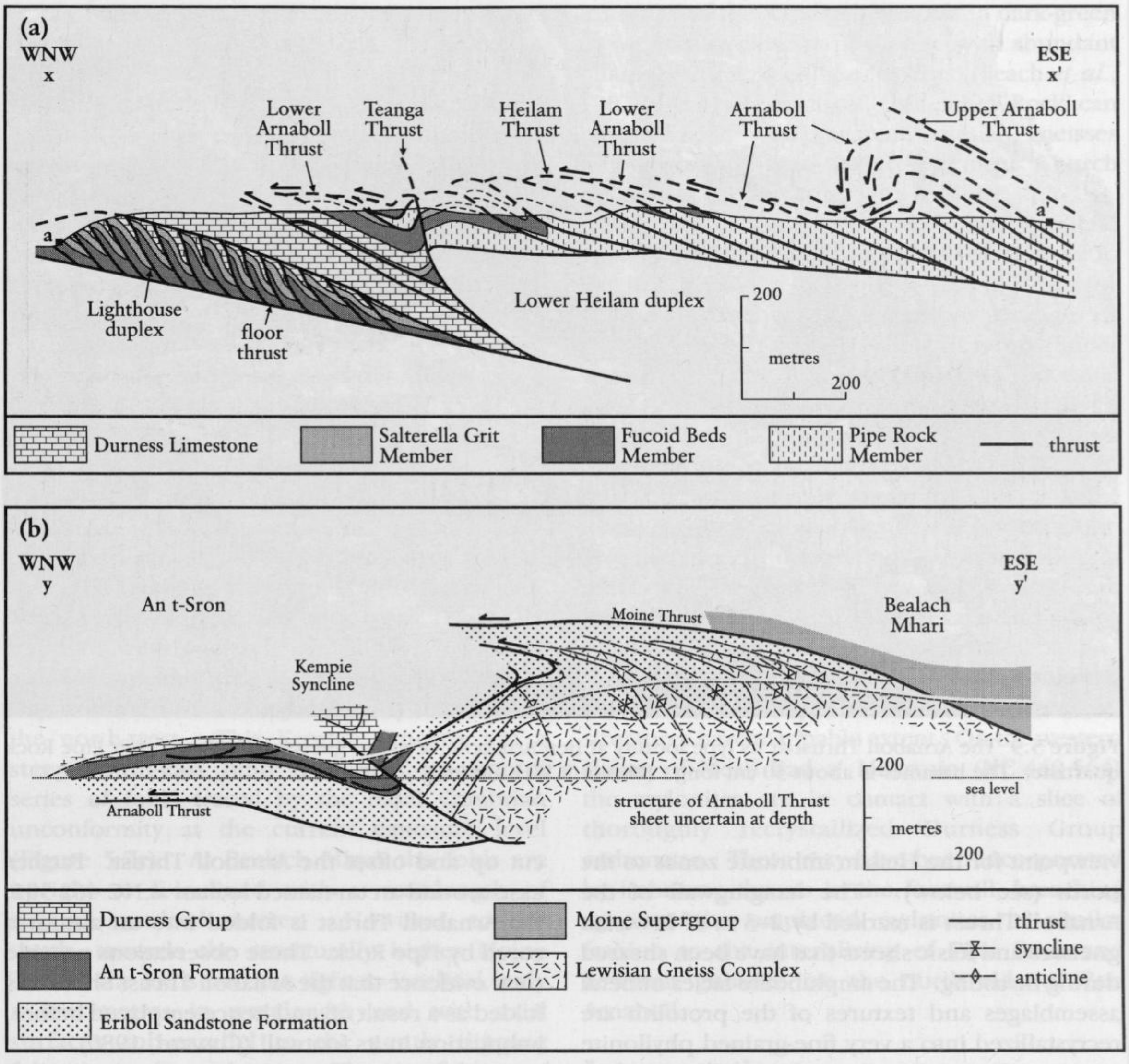


Figure 5.8 Sketch sections through the Moine Thrust Belt at Loch Eriboll, see Figure 5.7 for locations. (a) Ben Heilam (x–x'), after Coward (1984a); (b) Kempie–Bealach Mhari (y–y'), after Butler *et al.* (2006).

1975). Although this approach has since been refuted, the relationships between folds, mylonites, distributed shearing and thrusting remain controversial.

As will be clear from the above description, the site is one of the most structurally complex areas in Scotland. This account concentrates on describing the detailed geology of four key localities.

Ben Arnaboll (NC 462 597)

The northern and western slopes of Ben Arnaboll offer a microcosm of Moine Thrust Belt geology (Figure 5.7b). The top of the hill is a plateau of Lewisian gneiss that has been emplaced onto the Pipe Rock Member along the Arnaboll Thrust. The thrust plane is well exposed in several places. Sparse *Monocraterion* ('Trumpet Pipes') clearly show the Pipe Rock to be stratigraphically right-way-up. On the western scarp (Am Breac-leathad), the Pipe Rock in the footwall has a lensoid structure with prominent bedding cut-offs superficially similar to sedimentary channels. These structures are small thrust-bound slices (horses), visible here in across-transport section.

The Arnaboll Thrust is famously exposed in a 10 m-high cliff at the north-west end of the plateau (Figure 5.9), which is also a spectacular

Figure 5.9 The Arnaboll Thrust at its type locality at Ben Arnaboll: Lewisian gneisses are thrust over Pipe Rock quartzite. The hammer is about 30 cm long. (Photo: R.W.H. Butler.)

viewpoint for the Heilam imbricate zones to the north (see below). The hangingwall of the Arnaboll Thrust is marked by 2–3 m of Lewisian gneisses and felsic sheets that have been sheared during thrusting. The amphibolite-facies mineral assemblages and textures of the protolith are recrystallized into a very fine-grained phyllonite composed mainly of epidote, chlorite and quartz. These are Lapworth's (1883–1884) type mylonites (White, 1998). Thin pegmatitic veins within the host gneisses become increasingly deformed downwards, towards the thrust plane. Deflection of these pre-thrust markers indicates top-to-the-WNW shearing, as do minor shear bands and asymmetrical fabric boudinage. The footwall is in the upper part of the Pipe Rock. Here the pipe structure defined by *Skolithos* and rare *Monocraterion* show systematic deflections indicating a top-to-the-WNW shear sense. Shear strains are variable, being especially high along phyllosilicate-rich bedding surfaces, but generally attain γ values between 1 and 2 (Fischer and Coward, 1982).

Imbricate thrusts within the Pipe Rock of the footwall, which can be mapped onto Ben Arnaboll from the adjacent Ben Heilam area (see below), cut up and offset the Arnaboll Thrust. Farther east, around an un-named lochan at NC 462 591, the Arnaboll Thrust is folded into an antiform cored by Pipe Rock. These observations provide clear evidence that the Arnaboll Thrust Sheet was folded as a result of, and hence emplaced before, imbrication in its footwall (Coward, 1980).

The imbricate structures west of Ben Heilam (NC 458 517)

The ground to the north of the A838 road shows abundant evidence of imbrication, clearly visible from the northern crags of Ben Arnaboll. Leading down to the River Hope, the eastern slopes of Ben Heilam comprise imbricated Pipe Rock, which is exposed as prominent ridges, and Fucoid Beds that form hollows. *Skolithos* within the Pipe Rock Member is generally deformed with elliptical bedding-plane sections and inclined profiles relative to bedding. Fischer and Coward (1982) showed these strains to be primarily due to folding associated with thrust ramps. The thrusts are exposed locally and are marked by a few centimetres of fault gouge and ultramylonite (White, 1979).

The Heilam district is noted for the imbricated Middle to Upper Cambrian strata, the An t-Sron Formation and Durness Group limestones and dolostones, that crop out along the coast (Figure 5.7b). These are especially well seen near the lighthouse, particularly from the sea. Despite their narrow width, the imbricate slices show remarkable lateral persistence, although the imbricate thrusts climb up- and down-section to incorporate slight stratigraphical variations along strike.

The mylonite belt from Bealach Mhari (NC 455 577) to the Creagan Road (NC 438 555)

The ground above Kempie Bay provides an excellent place to examine major folds developed adjacent to the Moine Thrust and the ductile reworking of the folds into metre-scale alternations of mylonitic rock-types (Butler *et al.*, 2006; Holdsworth *et al.*, 2006). The axis of a major syncline runs south-west from Kempie Bay, and there is a complementary anticline to the north-west. This Kempie Syncline has a steep south-east limb that runs up into a series of folds traced by the basal Cambrian unconformity at the current exposure level (Figure 5.7c). At Bealach Mhari the folds are upright to E-inclined with a wavelength of several hundred metres. However, to the south, towards the structurally higher Moine Thrust, the folds become tight to isoclinal, only a few metres in wavelength and with axial surfaces sub-parallel to the gently dipping foliation in the mylonites. The interfolding of Lewisian gneisses and Cambrian quartzites is accompanied by intense deformation. The Lewisian gneisses are recrystallized into fine-grained chloritic phyllonites. The quartzites show intense L-S fabrics with a prominent, ESE-plunging mineral lineation and locally developed shear bands.

Farther south, displacements at the base of the interleaved quartzite and Lewisian-derived mylonite zone are localized along a distinct tectonic contact. Thus, at Church Crag (Figure 5.7c), a locality cited by Lapworth (1883), the mylonites lie upon Pipe Rock. The greatest development of varied mylonite and phyllonite units lies along the Creagan Road (Soper and Wilkinson, 1975; Evans and White, 1984; NC 438 555 and environs), where the mylonites are multiply folded. These outcrops include examples of the 'Oystershell Rock', a dark-green to white mica-chlorite phyllonite with abundant quartz blebs, shaped like 'oysters' (Peach *et al.*, 1907). In places tracts of 'Oystershell Rock' can be correlated with sheared Lewisian gneisses (Holdsworth *et al.*, 2001; e.g. near Church Crag).

All the mylonites show an intense mineral elongation lineation that generally plunges to the ESE, within a generally gently ESE-dipping foliation. They contain extensive packages of minor folds that show a variety of forms (Soper and Wilkinson, 1975). These include intrafolial folds with axial surfaces parallel to and over-printed by the regional mylonitic foliation. There are other, inclined folds of the mylonitic foliation with variable vergence. All of these structures have hinge lines that show considerable variation in orientation, dispersed about a mean ESE-directed plunge. There are rare examples of curvilinear folds (Evans and White, 1984; Williams, 1997; Holdsworth *et al.*, 2006).

The mylonites contain local, late kink-folds and small, localized faults. Some of these late structures have mappable extent. On the western slopes of Meall Bad a' Mhartuin (NC 440 564) the mylonites are in contact with a slice of thoroughly recrystallized Durness Group carbonates. These may have been incorporated by imbricate thrusts in the footwall, breaching up into the emplaced mylonites in similar fashion to the inter-slicing of Pipe Rock and Lewisian gneisses on the north side of Ben Arnaboll.

Interpretation

The imbricate systems of the Eriboll GCR site have varied stratigraphical contents. This implies that the glide horizons for the bounding roof and floor thrusts for these arrays are variable. In general there are important detachments developed within the basal Fucoid Beds and a few metres up into the Durness Group carbonates. Further detachments occur at levels within the Pipe Rock. The complexity of thrust systems on a map scale can be explained by thrusts climbing up-section laterally, the resulting culminations generating plunge variations in the overlying structures (Coward, 1984a). This behaviour is typified by the folding of the Arnabol Thrust to the west of its type area. Re-imbrication, with the breaching of duplex roof thrusts, is common throughout the Moine

Thrust Belt (Butler, 1987) and is typified by field relationships at Ben Arnaboll. It represents an important deviation from the strict piggy-back geometries of Elliott and Johnson (1980). The process may also explain the presence of small slices of non-mylonitized Cambrian strata within the mylonite belt. In general all the features are consistent with foreland propagation of thrusting, as proposed regionally by Elliott and Johnson (1980), and for the Eriboll district by Coward (1980) and Rathbone *et al.* (1983).

The relationship between folding, thrusting and mylonite formation may be established in the ground above Kempie Bay. The interleaved quartzites and Lewisian rocks beneath the Moine Thrust at Eriboll are locally mylonitic. In thin section the quartzites show abundant evidence for crystalline plasticity with ribbon grains (Evans and White, 1984). Petrofabric studies of these rocks (Law *et al.*, 1984) indicate a combination of overthrust shear and layer extension. These observations suggest that some of the folding within the Arnaboll Thrust Sheet was synchronous with at least the later part of mylonite development. This deformation history is a significant departure from models of systematic thrust sequences (e.g. Elliott and Johnson, 1980). Overall the geometry suggests that this zone acted as a ductile roof thrust with fold axial surfaces replacing the thrusts of the conventional duplex (Butler *et al.*, 2006). However, Holdsworth *et al.* (2006) contend that the mylonite zone has been carried by a late, possibly extensional, fault, which they term the 'Lochan Raibhach Thrust' (see **Clèit an t-Seabhaig** GCR site report, this chapter).

Structural evolution in the mylonites is complex and controversial. Evans and White (1984) interpreted the variations in fold orientation to progressive growth and modification during shearing. Williams (1997) and Casey and Williams (2000) showed that folding in the mylonites was controlled by the mechanical anisotropy of the strongly developed foliation produced during mylonitization. Therefore folding and other deformation chronologies at Eriboll are only of local significance, relating to local processes. These conclusions argue against traditional approaches to the understanding of tectonic evolution in mountain belts that use relative deformation chronologies derived from individual outcrops to build correlations between different sites (cf. Soper and Wilkinson, 1975). Although these larger-scale approaches are no longer viewed as appropriate to the mylonites at Eriboll, local relative chronologies are useful in some areas (see **Faraid Head** and **Slumbay Island** GCR site reports, this chapter).

The location of the Moine Thrust within the mylonites at Eriboll has long been a source of controversy (see review in Law *et al.*, 1984). Part of the confusion seems to arise from the notion that a single mappable surface must exist that carries a distinct sheet of Moine and Lewisian rocks across a substrate derived exclusively from rocks of the orogenic foreland. Various authors have attempted to trace such a structure (Peach *et al.*, 1907; Soper and Wilkinson, 1975; Holdsworth *et al.*, 2006). However, the expectation that there is a single surface may be false, although all workers accept that there was once such a structure. For it to have a long, continuous map-trace the Moine Thrust must not have been modified by slightly later thrusts breaching through from the footwall. In addition, shearing associated with the early thrusting may have caused interfolding of footwall and hangingwall units. Both of these processes can be demonstrated in the Eriboll GCR site and other parts of the thrust belt. Breaching is well illustrated along the Arnaboll Thrust. Alternations of psammitic and quartzitic mylonites (Soper and Wilkinson, 1975) argue for the interleaving of Moine and Cambrian rocks during at least the later stages of the emplacement of the Moine Thrust Sheet.

Conclusions

The Eriboll region has become one of the most important international localities for the development of structural geology and for the understanding of continental compressional tectonics. The readily accessible and compact outcrop areas of the GCR site provide excellent near-three-dimensional exposures of thrust architectures and related folds. These structures include sheets of Lewisian gneisses together with fine-scale imbrication of the Cambrian stratigraphy. Imbricate thrusting has caused repeated alternations of the main sedimentary units and resulted in the internal thickening of individual formations. The geometry of individual thrust surfaces and the constituent ramps and flats are clearly displayed in many locations. The relative order of thrusts and folds generally follows the top-to-bottom sequence of Elliott and Johnson's (1980) piggy-back model, but locally shows significant departures. These arise from breaching re-imbrication contemporaneous with continued shearing along the Moine Thrust, thus reworking the underlying structures (Butler *et al.*, 2006).

The range of structural levels allows study of the variations in fold geometry and deformation modes at an outcrop scale. Many of the structures have been developed in the Pipe Rock, which contains fossilized pipe-like burrows that act as deformation markers to quantify bed-parallel shortening and shear strains associated with thrusting and folding. As the Pipe Rock Member is almost exclusively composed of quartz grains, it has provided a link between laboratory experiments in rock deformation carried out on monomineralic aggregates and on natural materials. With the acquisition of marine deep-seismic reflection data close by, the Eriboll area is crucial in linking field structural geology and microstructural investigations to geophysical studies of the structure of continental crust. The site is internationally important for understanding thrust tectonics and associated deformations from kilometric- to grain-scales. Its historical significance is matched by its continuing importance in the study of structural geology and tectonics.

CLÈIT AN T-SEABHAIG (NC 507 682–NC 524 685)

R.E. Holdsworth

Introduction

The sea cliffs to the east of Whiten Head preserve some of the most northerly exposures in mainland Scotland of Moine and Lewisianoid rocks within the Moine Thrust Sheet, together with mylonites of the uppermost Moine Thrust Belt (Figure 5.10). Several distinct lithotectonic units are exposed, dipping mainly ESE at shallow angles. Moine psammites overlie a 15 m-thick unit of Lewisianoid orthogneiss followed by 200 m of white mica-chlorite phyllonite (the 'Oystershell Rock' of Peach *et al.*, 1907) that includes interleaved units of mylonitic Lewisian gneiss. The phyllonites overlie a thin, discontinuous unit of mylonitic Cambrian quartzites and Lewisian-derived mylonites interleaved with further units of mylonitic quartzite. The intensity of shearing decreases downwards and the lowest parts of the section consist of relatively undeformed Lewisian gneisses. The dominant deformation fabrics in the rocks are associated with mid- to low-greenschist-facies mineral assemblages.

The site is of historical importance, since it was in these steep coastal cliffs in 1884 that B.N.

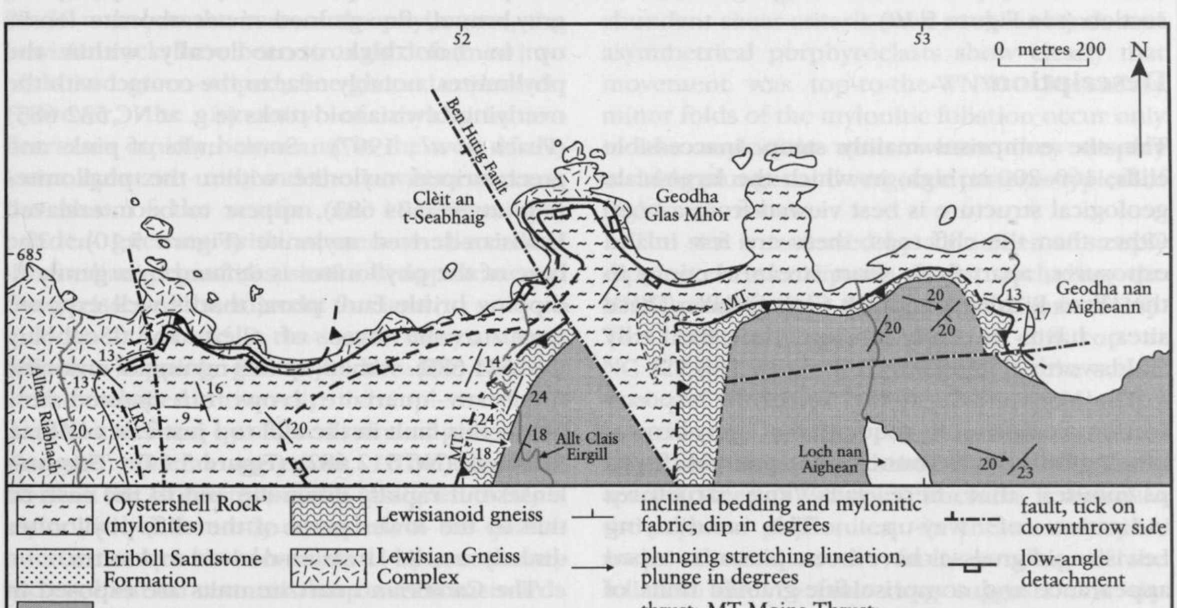


Figure 5.10 Map of the area around Clèit an t-Seabhaig. See Figure 5.12 (**Faraid Head** GCR site report) for location.

Peach and J. Horne of the Geological Survey first observed directly the structure that they considered to be the Moine Thrust (Peach and Horne, 1884; Peach *et al.*, 1907). The recognition of this major low-angle fault and of the down-faulted klippe, which exposes a similar structural sequence of rocks in the Durness area (see **Faraid Head** and **Sango Bay** GCR site reports, this chapter), showed clearly that the Moine Thrust Sheet had been displaced westwards by at least 15 km. This resolved the 'Highlands Controversy' concerning the nature of the contact between the overlying metamorphosed rocks of the Moine and the underlying Cambro–Ordovician sedimentary succession (see Oldroyd, 1990). It was also one of the first demonstrations that large-scale horizontal movements have occurred in an orogenic belt. Following remapping of the area (British Geological Survey, 1997b), Holdsworth *et al.* (2001) suggested that the structure identified by the Geological Survey as the Moine Thrust at Clèit an t-Seabhaig is a late-formed brittle extensional detachment, named the 'Lochan Riabhach Thrust', which lies at the base of the mylonites ('Oystershell Rock'). Holdsworth *et al.* (2006) suggested that this structure truncates earlier thrusts in its footwall, and formed during a hiatus in thrust stacking. The earlier, ductile Moine Thrust, across which the main shortening has occurred, lies some 200 m higher in the section (see Figure 5.10).

Description

The site comprises mainly steep, inaccessible cliffs, 160–200 m high, in which the large-scale geological structure is best viewed from a boat. Other than the cliff tops, there are few inland exposures, apart from short stream sections in the Alltan Riabhach and Allt Clais Eirgill. These sites have recently been described by Holdsworth *et al.* (2007).

The Moine rocks at the top of the exposed section comprise a sequence of grey-brown, lithologically monotonous, fine-grained flaggy psammites that here lack any structures indicative of way-up. The underlying Lewisianoid gneisses have a conspicuous striped appearance and comprise fine-grained units of pink and dark grey-green, strongly mylonitized felsic and mafic gneiss, interbanded on a millimetre- to centimetre-scale. Lenticular pods of concordant dark-green amphibolites and hornblendite up to 10 cm thick are also present locally. The concordant contact between Moine and Lewisianoid rocks is exposed in the steep cliff on the west side of Geodha nan Aigheann (NC 531 682), in the cliff between NC 525 683 and NC 530 684, and in the Allt Clais Eirgill stream section around NC 522 683, immediately south-west of the Ben Hutig Fault (Figure 5.10). The rocks are all highly sheared and although the psammites adjacent to the Lewisianoid gneisses contain some pebbles, there is no trace of a basal conglomerate or discordance. The sharp, concordant contact between the Lewisianoid-derived mylonitic rocks and the underlying 'Oystershell Rock' is exposed in the cliffs between Geodha nan Aigheann (NC 531 682) and Allt Clais Eirgill (NC 520 682).

Most of the 'Oystershell Rock', so termed by the early surveyors because of numerous lunate quartz segregations and veins (resembling 'oysters'), is a fine-grained, dark grey-green white mica-chlorite-rich phyllonite. In thin section it consists of muscovite, chlorite, quartz, plagioclase (albite) and calcite with accessory magnetite, pyrite, apatite, biotite and potash feldspar. Relict garnet porphyroclasts up to 2 mm across are preserved in this phyllonite unit 2–3 km inland and to the south of the coastal section (Holdsworth, 1987; Holdsworth *et al.*, 2001). Subordinate layers of grey quartzo-feldspathic rock up to several metres thick, and grey-brown, fine-grained metacarbonate lenses up to 1 m thick occur locally within the phyllonites, notably near to the contact with the overlying Lewisianoid rocks (e.g. at NC 532 683) (Peach *et al.*, 1907). Some units of pink- and green-striped mylonite within the phyllonites (e.g. at NC 524 683), appear to be interleaved Lewisian-derived mylonite (Figure 5.10). The base of the phyllonites is defined by a gently E-dipping brittle fault plane that is well exposed near to the base of Clèit an t-Seabhaig (NC 521 685). A thin (up to 8 m) unit of mylonitic Cambrian quartzite crops out immediately below this fault in the cliff top just east of Alltan Riabhach (NC 512 682) (Figure 5.11). This unit lenses-out rapidly down-dip and to the east, so that in the lower parts of the cliff, phyllonites directly overlie Lewisian-derived mylonites.

The Cambrian quartzite units are exposed in cliff-top outcrops and 20 m lower down in the section at NC 515 682, where at least one further unit is interleaved with Lewisian mylonites. They are fine- to medium-grained,

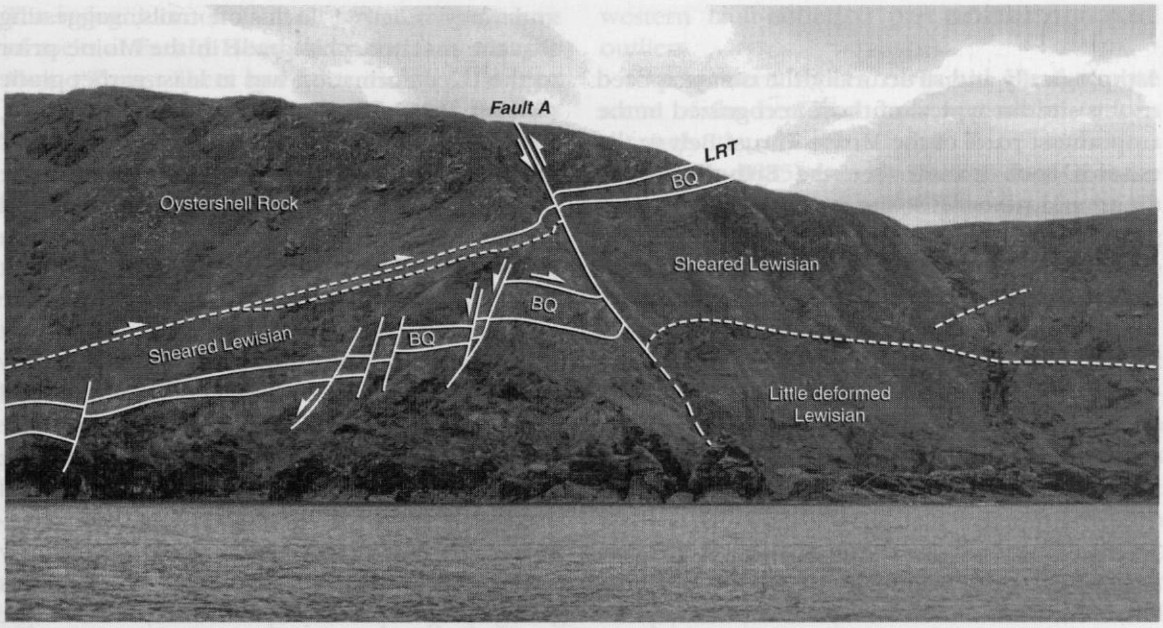


Figure 5.11 Southward view of the cliff section near Alltan Rhiabhach (stream with waterfalls to right) in the western part of the Clèit an t-Seabhaig GCR site. Lewisian mylonites ('Oystershell Rock') have been thrust westward over Basal Quartzite (BQ), which overlies Lewisian gneisses, which are less pervasively sheared than the 'Oystershell Rock'. LRT – Lochan Riabhach Thrust, mapped as the Moine Thrust by the original surveyors. In the eastern part of the cliff, sheared Lewisian below the LRT is thrust over a unit of Basal Quartzite that in turn unconformably overlies almost undeformed Lewisian gneisses at the base of the cliff. The westward continuation of the quartzite and associated thrust is uncertain to the right of the subvertical Fault A, but the thrust may follow the indicated boundary between sheared and less-deformed Lewisian gneisses. Note that the lower quartzite is offset by several steep late normal faults. (Photo: R.E. Holdsworth.)

pale grey-pink recrystallized mylonitic rocks. For 20–30 m below the base of the phyllonites, the Lewisian rocks have been strongly deformed into pink- and green-striped, fine-grained mylonites. However, the intensity of mylonitization decreases rapidly below and to the west of the lower quartzite unit, and the Lewisian rocks at the base of the section are coarse-grained, banded gneisses with numerous discordant 'Laxfordian' pegmatites, similar in appearance to the gneisses of the adjacent foreland.

Most of the rocks in the section carry a strong foliation dipping gently to the ESE with a well-developed down-dip mineral-stretching lineation defined by aligned mineral grains and elongate mineral aggregates. The dominant fabric in the Moine psammites (assigned to S2) is mylonitic but is mostly annealed, as the quartz-microstructure is dominated by secondary recrystallization textures that coarsen eastwards (Holdsworth, 1987; Holdsworth and Grant, 1990). The mylonitic fabric can be traced downwards into finer-grained, sub-parallel, mylonitic L-S fabrics that affect the underlying mylonitic units, including the Cambrian quartzite. Here, abundant shear criteria such as shear bands and asymmetrical porphyroclasts show clearly that movement was top-to-the-WNW. Secondary minor folds of the mylonitic foliation occur only in the mylonitic units where they display variable plunges and vergence patterns typical of high-strain zones.

The site is traversed by a number of steeply dipping, brittle dip-slip faults, including the NNW-trending Ben Hutig Fault (Figure 5.10). This fault is exposed at the cliff top at NC 522 683 where it dips steeply to the south-west and is marked by 10 cm of incohesive red breccia and gouge. A 3 m-wide zone of irregularly orientated brittle folds and closely spaced, steep, SW-dipping fractures is found in the adjacent phyllonites. In the metamorphic rocks adjacent to the fault, bending of the foliation due to fault drag suggests that the south-west side has been dropped down and that the movement sense is normal. Offsets of the major boundaries indicate between 50 m and 100 m of vertical offset.

Interpretation

Lithologically and structurally, the units exposed at this site are typical of those recognized in the uppermost parts of the Moine Thrust Belt to the east of Loch Eriboll (see the **Eriboll**, **Faraid Head** and other GCR site reports). The origins of the 'Oystershell Rock' are uncertain, but Holdsworth *et al.* (2001) considered them to represent a highly deformed metamorphic unit of Lewisian affinities. The problem of defining the Moine Thrust in this area is difficult, because gneissose rocks of Lewisian and Lewisianoid parentage are juxtaposed and possibly inter-leaved in this area. The Geological Survey (e.g. Peach and Horne, 1884; Geological Survey of Scotland, 1889; Peach *et al.*, 1907) placed the Moine Thrust at the base of the 'Oystershell Rock' phyllonites, hence including them within the Moine Thrust Sheet. However, subsequent mapping in the region east of Loch Eriboll has shown that this unit is overlain by quartzite mylonites derived from Cambrian rocks of the foreland (e.g. Soper and Wilkinson, 1975). Unless the quartzite mylonites represent an example of breaching, this suggests that the phyllonites are more correctly assigned to the Moine Thrust Belt and that the Moine Thrust at Clèit an t-Seabhaig should be placed at the basal contact of the Lewisianoid rocks overlying the mylonitic 'Oystershell Rock' (Figure 5.10). The same unit of Lewisianoid gneisses, termed the 'Loch Fada inlier', can be traced for over 20 km to the south on to the west side of An Lean Charn (Geological Survey of Scotland, 1889; Peach *et al.*, 1907; Soper and Wilkinson, 1975; Holdsworth, 1987; Holdsworth *et al.*, 2001). The contact between the Lewisianoid and overlying Moine rocks is interpreted as a highly sheared unconformity (cf. Holdsworth, 1989a).

The observed continuity between D2 fabrics in the Moine and the mylonitic fabrics in the underlying units is consistent with these structures having a common origin and being of *broadly* the same age. Shear-sense criteria throughout are consistent with top-to-the-WNW thrust displacements and are presumed to be of Caledonian age based on their similarity with other parts of the Moine Thrust Belt. The grade of metamorphism in the lower part of the Moine Thrust Sheet is difficult to assess due to the dominantly psammitic lithologies. Garnet porphyroblasts in coarse-grained pelites on nearby Ben Hutig are strongly wrapped by S2 and carry relict S1 inclusion trails, suggesting that the metamorphic grade in the Moine prior to the D2 deformation was at least garnet grade (Wilson, 1953; Barr *et al.*, 1986; Holdsworth, 1987, 1989a). In the same locality, biotite and garnet are extensively altered to chlorite defining the S2 fabric, and new chlorite and white mica overgrowths are developed in pressure shadows. These features suggest that the syn-D2 metamorphism was a retrograde mid- to low-greenschist-facies event, as first recognized by Read (1931, 1934). This is broadly consistent with the mineral assemblages and deformation textures developed during the main phase of shearing in the underlying mylonites derived from Lewisian gneiss and Cambrian quartzite protoliths. Greenschist-facies retrogression is ubiquitous in the originally gneissose Lewisian rocks, with amphiboles extensively replaced by chlorite, and calcic plagioclase by fine-grained aggregates of albite, sericite and epidote. As the intensity of mylonitization increases, the effects of retrogression are more widespread, suggesting that these processes are inter-related.

The age and sense of movement on the low-angle detachment at the base of the phyllonites in this area is uncertain, as this structure is nowhere exposed in an accessible location. Holdsworth *et al.* (2006) have identified a similar extensional detachment that cuts across earlier thrust-related structures in its footwall farther south through the Loch Eriboll area. They term this structure the 'Lochan Riabhach Thrust' and contend that it is a regional structure that formed by collapse of an evolving thrust wedge during a hiatus in thrust stacking. They correlate the detachment with a similar low-angle thrust fault at the base of the 'Oystershell Rock' at Sango Bay some 11 km to the west, where it is preserved in a down-faulted klippe (Hippler and Knipe, 1990; see **Sango Bay** GCR site report, this chapter, for alternative interpretation).

Conclusions

The Clèit an t-Seabhaig site contains some of the most northerly exposures of the Moine Thrust Sheet and upper Moine Thrust Belt in mainland Scotland. Historically, the site is of international importance, as it was here in 1884 that the structure considered to be the Moine Thrust was first observed directly in the steep coastal cliffs.

The recognition of a similar structural sequence of rocks at **Faraid Head** showed clearly that the Moine Thrust Sheet had been displaced at least 15 km westwards and formed one of the first demonstrations that large-scale horizontal movements occurred in orogenic belts. This resolved the 'Highlands Controversy' concerning the nature of the contact between the overlying metamorphosed rocks of the Moine and the underlying Cambro–Ordovician sedimentary succession. The mainly ESE-dipping structural succession preserves a transition from annealed Moine psammitic mylonites downwards into finer-grained mylonites and phyllonites derived from Lewisian and Lewisianoid orthogneisses, metasedimentary rocks and Cambrian quartzite. Mylonitization occurred under mid- to low-greenschist-facies metamorphic conditions. The textural sequence seen in the succession is typical of fabrics formed by foreland-propagating thrusting synchronous with uplift and erosion (Barr *et al.*, 1986). The low-angle brittle fault that defines the base of the phyllonites is well displayed in the cliffs and is interpreted as a regional structure, formed by extensional collapse during a period of thrust stacking.

FARAID HEAD (NC 378 715–NC 406 687)

R.E. Holdsworth

Introduction

Faraid Head, to the north of the village of Durness, preserves an important klippe of Moine and Lewisianoid rocks belonging to the Moine Thrust Sheet, together with mylonites in the upper part of the Moine Thrust Belt. These rocks form part of the larger fault-bounded Durness outlier that stretches from Leirinmore (NC 425 670) in the east, to Balnakeil Bay and the Kyle of Durness in the west (Figure 5.12). The Sangobeg Fault, the major south-eastern bounding fault to the inlier, drops down the Durness carbonate rocks against the Lewisian gneisses. The Durness outlier is important in that it provides the most complete section through the Cambro–Ordovician sequence of the foreland (see the Durness and Balnakeil GCR site report in the ***British Cambrian to Ordovician Stratigraphy*** GCR Volume; Rushton *et al.*, 2000). Faraid Head forms the north-western fault-bounded part of this structural outlier.

The western shores of Faraid Head expose some of the best and most accessible sections through the Moine Thrust Zone mylonites (Lapworth, 1885) (see also **Sango Bay** GCR site report, this chapter). The site also forms an important onshore reference point constraining offshore geological interpretations of the E–W-trending MOIST deep seismic reflection profile (Brewer and Smythe, 1984).

The site is of historical importance as it provided some of the first evidence for kilometre-scale translation on the Moine Thrust. It also featured prominently in the so-called 'Highlands Controversy' during the latter part of the 19th century (Oldroyd, 1990). Murchison (1859) had suggested that the metamorphic rocks of Faraid Head conformably overlay the nearby unmetamorphosed carbonate rocks of the Durness Group. This hypothesis was refuted by the subsequent work of numerous authors (e.g. Nicol, 1861; Callaway, 1881; Lapworth, 1883; Peach and Horne, 1884; Peach *et al.*, 1907) who suggested that the units of Faraid Head are down-faulted remnants of the thrust sheets that were emplaced by WNW-directed Caledonian movements over most of the foreland region in north-west Scotland. The preservation of the Faraid Head klippe allowed Peach *et al.* (1907, p. 469) to demonstrate directly that the Moine Thrust Sheet had been displaced at least 15 km westwards (arrow in Figure 5.12). Together with early work in the Alps (e.g. Heim, 1878, 1919), this was one of the first examples of documented large-scale horizontal movements to be demonstrated in an orogenic belt. The detailed structure of the Faraid Head peninsula was described recently by Holdsworth *et al.* (2007).

Description

Faraid Head forms a narrow 3 km-long peninsula that rises to 100 m above OD at its north-west edge, but whose low-lying, central and southern parts are mainly covered by sand dunes (Figures 5.12, 5.13). Most of the coastline comprises cliffs and rocky shore, except in the west where beaches (Balnakeil Bay) separate isolated outcrops of rock. Much of the coastal outcrop is accessible at low tide, apart from the 20–80 m-high steep cliffs in the northern part of the peninsula. The site exposes three distinct lithotectonic

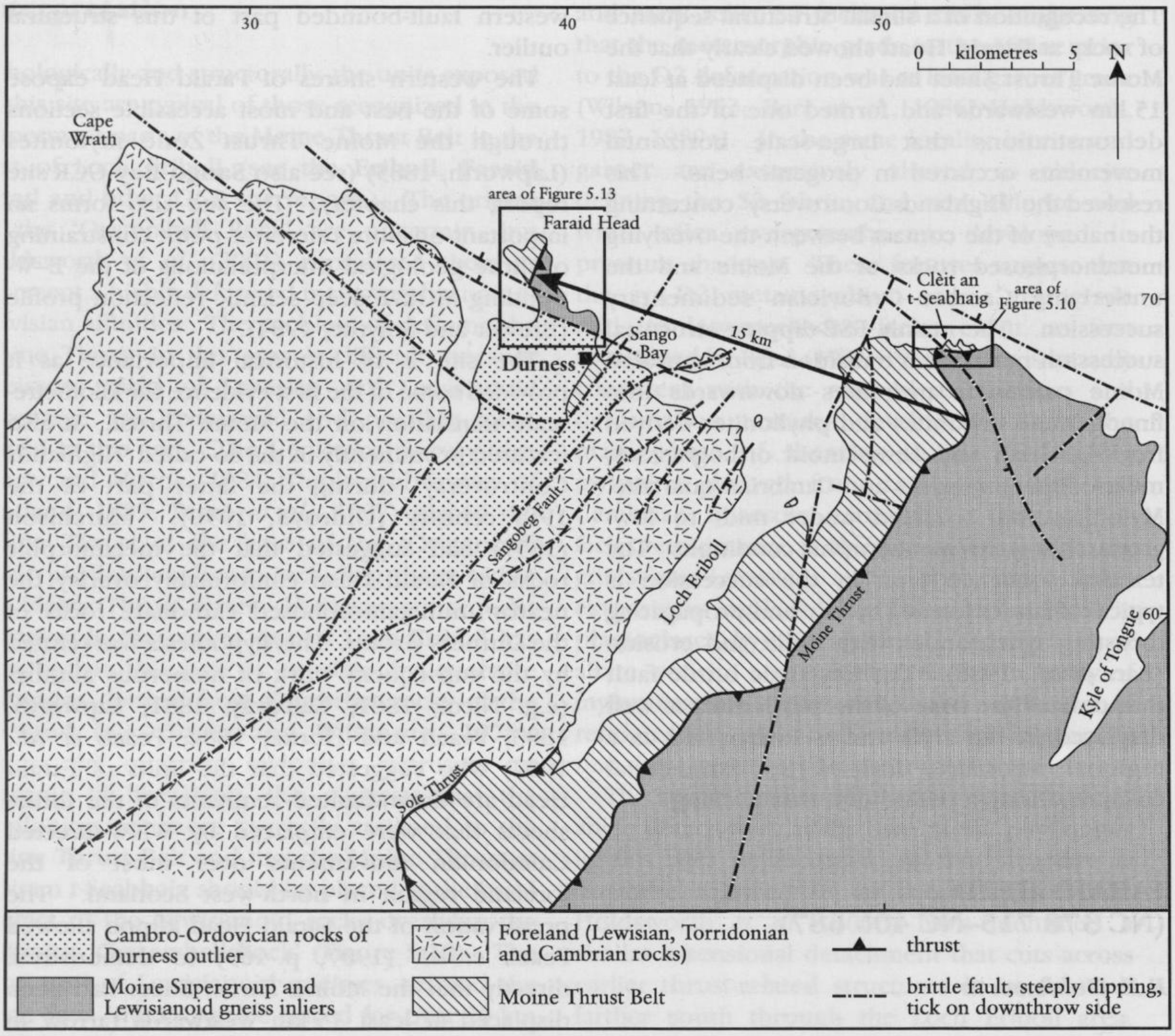


Figure 5.12 Map showing the relationship between the Moine Thrust Sheet and the Durness Klippe. Arrow drawn parallel to regional thrust transport direction (290°) shows minimum displacement of 15 km required along Moine Thrust due to preservation of Faraid Head klippe. Areas of Figures 5.10 and 5.13 are indicated.

units that dip mainly gently to the ESE (Figure 5.13). An upper unit of Moine psammites overlies a unit of variably mylonitized Lewisianoid orthogneisses with subordinate units of meta-carbonate rock and schistose metasedimentary rocks. The Lewisianoid rocks in turn overlie a white mica-chlorite-rich phyllonite unit – the 'Oystershell Rock' of Peach *et al.* (1907). The presumed faulted contact of the metamorphic rocks with the Durness Group carbonate rocks to the south – the 'Boundary Fault' (Figure 5.13) – is largely obscured by blown sand in the southern part of the peninsula.

The Moine rocks comprise at least 500 m of lithologically monotonous, fine- to medium-grained, grey-brown bedded psammites that crop out mainly on the craggy eastern shores of the peninsula between Gob nan Leac and Geodha Brat (Figure 5.13). Subordinate layers of sparsely garnetiferous semipelite and pelite, generally less that 10 mm thick, are preserved locally (e.g. at NC 390 698), as are narrow seams and diffuse pods of fine-grained, pale-green epidotic material that may represent poorly developed calc-silicate lithologies. The Lewisianoid units are lithologically more varied, comprising units of variably mylonitized, pink felsic to dark grey-green mafic gneisses, interbanded on both millimetre- and metre-scales. Minor lenticular intercalations of grey-brown

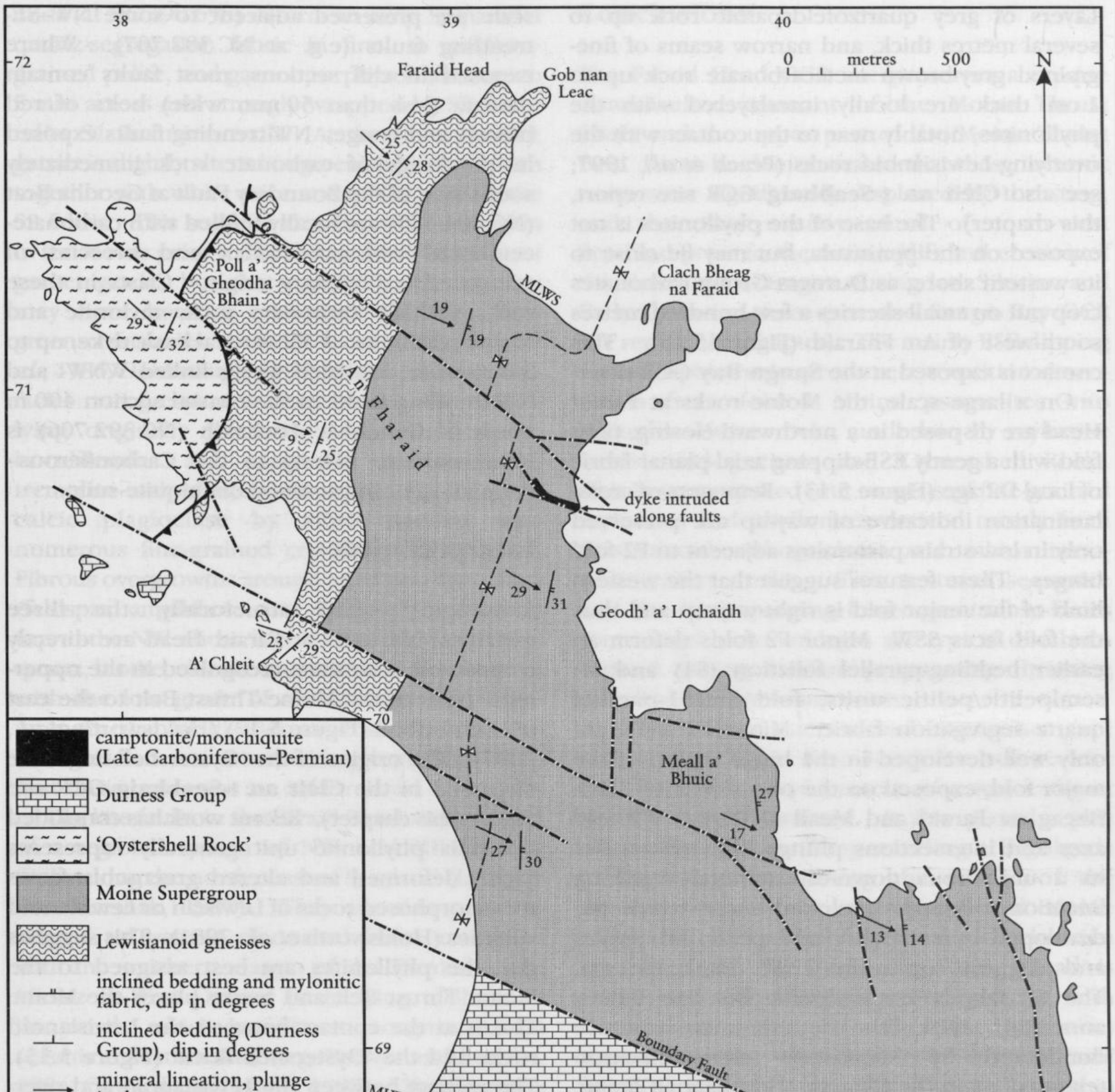


Figure 5.13 Map of the area around Faraid Head. After Holdsworth *et al.* (2007). See Figure 5.12 for location.

carbonate rock, dark-brown biotite schist and concordant bright-green actinolitic amphibolites, up to 1 m thick, are also present locally. The concordant contact between Moine and Lewisianoid rocks is exposed only in the steep cliffs 300 m SSW of Gob nan Leac at NC 391 715.

The concordant contact between the Lewisianoid-derived mylonitic rocks and the underlying 'Oystershell Rock' is exposed halfway up the steep cliffs west of Poll a' Gheodha Bhain (NC 382 713) and on the shore 0.5 km NNW of A' Chleit (NC 382 708), where it is offset by a late fault (Figure 5.13). The 'Oystershell Rock' comprises a mottled dark grey-green fine-grained, white mica-chlorite-rich phyllonite (see **Clèit an t-Seabhaig** GCR site report, this chapter).

Layers of grey quartzofeldspathic rock up to several metres thick, and narrow seams of fine-grained grey-brown metacarbonate rock up to 1 cm thick are locally interlayered with the phyllonites, notably near to the contact with the overlying Lewisianoid rocks (Peach *et al.*, 1907; see also **Clèit an t-Seabhaig** GCR site report, this chapter). The base of the phyllonites is not exposed on the peninsula, but may lie close to its western shore, as Durness Group carbonates crop out on small skerries a few hundred metres south-west of An Fharaid (Figure 5.13). This contact is exposed at the **Sango Bay** GCR site.

On a large scale, the Moine rocks at Faraid Head are disposed in a northward-closing, tight fold with a gently ESE-dipping axial-planar fabric of local D2 age (Figure 5.13). Remnants of cross-lamination indicative of way-up are preserved only in low-strain psammites adjacent to F2 fold hinges. These features suggest that the western limb of the major fold is right-way-up and thus the fold faces SSW. Minor F2 folds deform an earlier bedding-parallel foliation (S1) and, in semipelitic/pelitic units, fold an S1-parallel quartz segregation fabric. Minor F2 folds are only well developed in the hinge region of the major fold, exposed on the coasts west of Clach Bheag na Faraid and Meall a' Bhuic. F2 fold axes and intersections plunge ESE sub-parallel to a ubiquitous down-dip mineral-stretching lineation. Poorly developed shear bands are developed in semipelitic and pelitic lithologies and suggest top-to-the-WNW displacements. The S2 fabrics are mylonitic but are mostly annealed, with the quartz-microstructure dominated by secondary recrystallization textures. As in the Clèit an t-Seabhaig GCR site, the D2 fabrics pass downwards into the mylonitic Lewisianoid gneisses and into the finer-grained, sub-parallel, mylonitic L-S fabrics affecting the underlying 'Oystershell Rock' unit.

The rocks of the Faraid Head peninsula are cut by a dominant set of subvertical, NW-trending faults including the inferred Boundary Fault that separates the metamorphic rocks from the Durness Group (Figure 5.13). Where similarly orientated minor fault planes are exposed, they preserve predominantly dip-slip slickenslides and offset geological boundaries, implying that the downthrow is mainly to the north-east. Other brittle faults are also steeply dipping and display various trends between NNW and west. E- to SE-plunging, open, brittle-style folds of the ductile foliation on a metre-scale are preserved adjacent to some NW–SE-trending faults (e.g. at NC 382 707). Where exposed in cliff sections, most faults contain narrow (less than 50 mm wide) belts of red breccia and gouge. NW-trending faults exposed in the crags of carbonate rock immediately south-west of the Boundary Fault at Geodha Brat (NC 404 685) are locally infilled with carbonate-cemented red sandstones and breccias of presumed sedimentary origin. Clasts in these rocks include carbonate rock, mylonite and Moine psammite. A subvertical basic dyke, up to 2.0 m wide, intruded along linked WNW- and NW-trending faults in the coastal section 400 m north of Geodh' a' Lochaidh (NC 392 706) is interpreted to belong to the Carboniferous–Permian-age camptonite-monchiquite suite.

Interpretation

Lithologically and structurally, the three metamorphic units at Faraid Head are directly comparable with units recognized in the uppermost parts of the Moine Thrust Belt to the east of Loch Eriboll (Figure 5.12) (Holdsworth *et al.*, 2007). The origins of the 'Oystershell Rock' are discussed in the **Clèit an t-Seabhaig** GCR site report (this chapter). Recent work has concluded that this phyllonite unit generally represents highly deformed and altered greenschist-facies metamorphosed rocks of Lewisian or Lewisianoid affinities (Holdsworth *et al.*, 2001). This suggests that the phyllonites are best assigned to the Moine Thrust Belt and hence places the Moine Thrust at the contact between the Lewisianoid rocks and the 'Oystershell Rock' (Figure 5.13). The contact between the Lewisianoid and overlying, apparently right-way-up Moine rocks at Faraid Head is therefore again interpreted as a highly sheared unconformity (cf. Holdsworth, 1989a; Holdsworth *et al.*, 2001).

The observed continuity between D2 fabrics in the Moine and the mylonitic fabrics in the underlying units is consistent with these structures being broadly the same age. Shear-sense criteria (e.g. shear bands, asymmetrical porphyroclasts) are abundant throughout, and consistently imply top-to-the-WNW thrust displacement. The movements are presumed to be of Caledonian age based on their similarity with other parts of the Moine Thrust Belt. The grade of metamorphism in the lower part of the Moine Thrust Sheet is difficult to assess due to the dominantly psammitic lithologies. Minor F2 folds (at NC 390 698) deform an early, S1-parallel quartz-segregation fabric in fine- to medium-grained pelite, and garnet porphyroblasts, up to 5 mm across and strongly wrapped by S2, carry relict S1 inclusion trails. At the same locality, garnet is slightly altered to greenish biotite, which together with white mica and quartz, define the S2 fabric. This suggests that the metamorphism in the Moine prior to D2 deformation was at least garnet grade, but that syn-D2 metamorphism may have been a retrograde mid- to low-greenschist-facies event (Wilson, 1953; Barr *et al.*, 1986; Holdsworth, 1987, 1989a). Greenschist-facies retrogression is ubiquitous in the underlying originally gneissose Lewisianoid rocks; hornblendes are replaced extensively by tremolite–actinolite, biotite and chlorite, and calcic plagioclase by albite seeded with numerous fine-grained crystals of clinozoisite. Fibrous overgrowths around relict porphyroclasts (feldspar, amphibole and epidote), and along top-to-the-NW shear bands, typically consist of quartz, biotite, chlorite and white mica, consistent with the low grade of metamorphism. As the intensity of mylonitization increases, the effects of retrogression are more widespread, suggesting that these processes are inter-related.

The late faults in the Faraid Head area are part of a regional system of NW- and NE-trending faults along the north coast of Scotland (Laubach and Marshak, 1987). They are also probably related to systems of normal faults associated with the southern margin of the Devonian and Mesozoic West Orkney Basin lying offshore to the north, which have been recognized from seismic reflection data (e.g. Brewer and Smythe, 1984; Coward and Enfield, 1987). The kilometre-scale anticlockwise swing observed in the foliation of the Moine psammites as they are traced from Geodh' a' Lochaidh southwards to the Boundary Fault (Figure 5.13) is interpreted as a late warping associated with variations in displacement along the NW-trending fault-zones. These faults probably formed close to the land surface, as the upper parts of structures adjacent to the Boundary Fault preserve a sedimentary infill. The NW-trending faults were probably initiated during the late Silurian or Devonian, prior to final exhumation of the Moine Thrust Sheet and the later intrusion of a Permo–Carboniferous camptonite-monchiquite dyke along pre-existing faults. Subsequent reactivation of some faults may have occurred.

Conclusions

The Faraid Head GCR site preserves a unique down-faulted remnant of the Moine Thrust Sheet and the upper part of the Moine Thrust Belt. It can be demonstrated that these tectonic units were significantly displaced by thrusting, and that they overlay much of north-west Scotland prior to the main uplift and erosion of the Caledonian Orogen during late Silurian and Early Devonian times (see also **Sango Bay** GCR site report, this chapter). The mainly ESE-dipping metamorphic rocks preserve a transition downwards from folded Moine psammites into mylonitic Moine rocks, underlain by mylonitic Lewisianoid gneisses and 'Oystershell Rock'. This lowest exposed unit consists of fine-grained mylonites and phyllonites derived mostly from Lewisianoid orthogneisses and minor meta-sedimentary rocks. This textural sequence and the accompanying lower greenschist-facies metamorphic assemblages are typical of fabrics formed during foreland-propagating thrusting accompanied by exhumation.

The site is of international importance as it was one of the first localities where the kilometre-scale displacement of a major thrust sheet was demonstrated. It also played a part in resolving the long-standing 'Highlands Controversy' concerning the nature of the contact between the metamorphosed Moine rocks and the underlying Cambro–Ordovician succession of the foreland. Faraid Head is excellent for teaching structural geology, with the easily accessible and well-exposed mylonites exposed on the western side of the peninsula being particularly instructive. The site lies within the larger fault-bounded Durness structural outlier and also offers an opportunity to study late faulting spatially associated with the southern margin of the Devonian and Mesozoic West Orkney Basin that lies offshore to the north.

SANGO BAY (NC 406 681–NC 412 676)

R.W.H. Butler

Introduction

Peach *et al.* (1907) recognized the importance of the **Faraid Head** and Sango Bay outcrops of Moine metasedimentary rocks and mylonites in that they lay distant from their main outcrop east of Loch Eriboll. The basal contact of these allochthonous units with the underlying substrate of Cambro–Ordovician Durness Group carbonate rocks is exposed in the Sango Bay area (Figure 5.14), just east of Durness village. Small sea stacks and crags in the bay also provide spectacular outcrops of 'Oystershell Rock', together with a range of less-deformed correlative units.

Sango Bay lies in a small fault-bounded wedge-shaped structural outlier that itself lies within the larger down-faulted Durness outlier (Figure 5.12), which preserves the Cambrian foreland sequence (see **Faraid Head** GCR site report, this chapter). The Sangomore Fault, whose

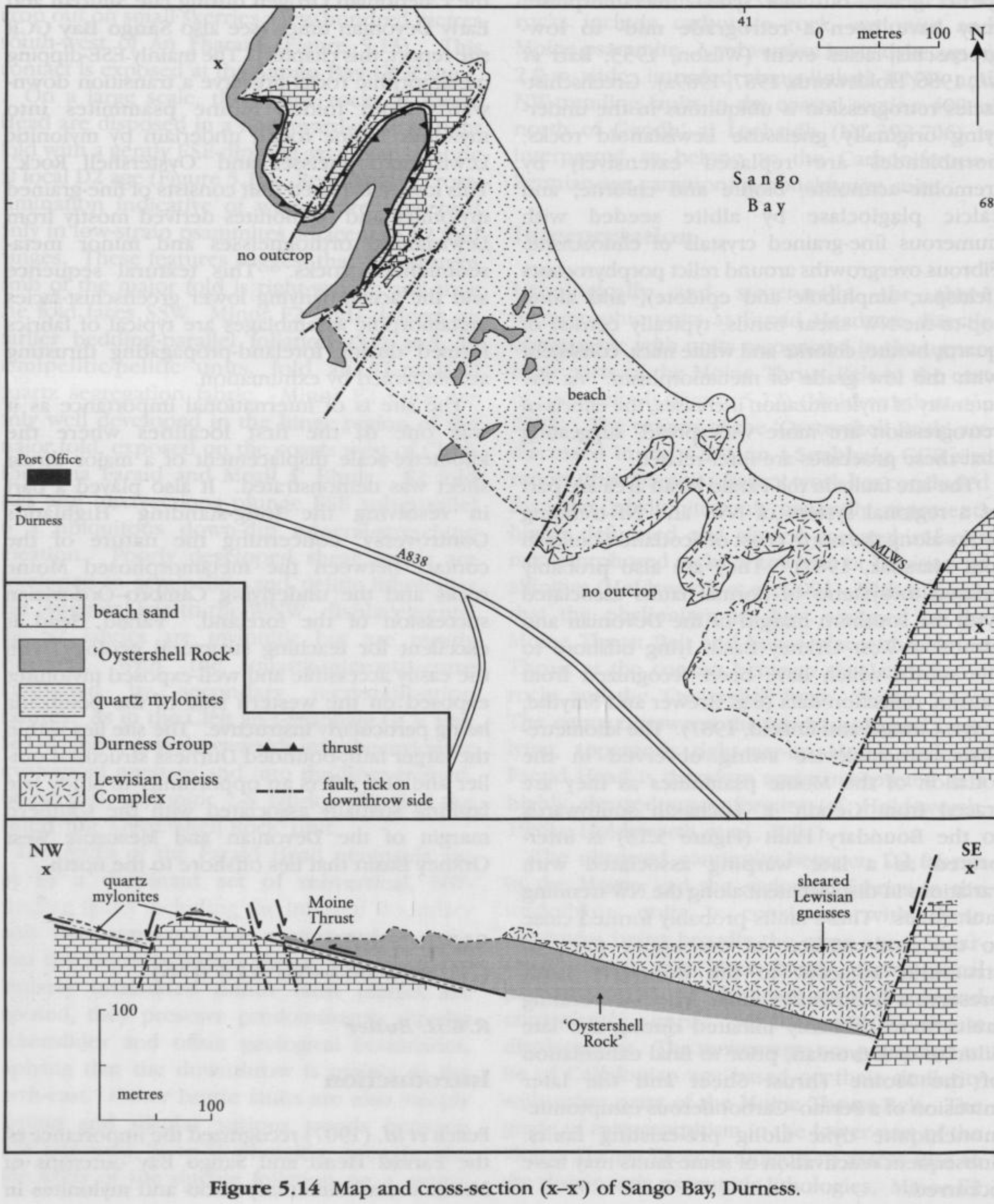


Figure 5.14 Map and cross-section (x–x') of Sango Bay, Durness.

fault scarp forms the south-east side of Sango Bay, drops down units of the allochthonous thrust sheet against these carbonate rocks. The site includes arrays of normal faults that relate to the main NNE- to NE-trending bounding faults of the Durness outlier. These faults form part of a complex set that probably relate to the formation of Devonian and Mesozoic offshore basins.

Since the work of the Geological Survey in the late 19th century, the Sango Bay area has been little studied, although the published patterns of the late normal faults have been used to link onshore with offshore basin tectonics (e.g. Enfield and Coward, 1987). Laubach and Marshak (1987) linked the coastal outcrops at Durness inland to explore how basement structures might have influenced the geometry of the fault system. Hippler (1989) investigated fault-rock evolution, particularly the structural overprinting of quartz mylonites by cataclasites associated with the faults (Hippler and Knipe, 1990). Her terminology of fault names is followed here. Most recently, Beacom (1999) has remapped the faults along the coast between Loch Eriboll and Cleit Dhubh as part of a regional study of brittle fracturing patterns in the Lewisian Gneiss Complex.

Description

The margins of the spectacular sandy Sango Bay site are defined by long, NNE-trending cliff-lines, developed along eroded fault scarps partially coated with cemented breccia largely derived from Durness Group carbonate rocks (Figure 5.14). The structurally highest rocks in the area now lie downthrown in the hangingwalls to these late normal faults.

Exposed on low skerries and stacks around NC 410 676 are banded quartzofeldspathic and amphibolitic gneisses. These show characteristics of Lewisian or Lewisianoid rocks but contain penetrative greenschist-facies (chlorite, actinolite and epidote-bearing) assemblages, indicative of significant retrogression. Small chlorite- and epidote-rich shear-zones cut the gneisses. Westwards, the degree of retrogression and deformation appears to increase so that outcrops immediately below the public house (NC 408 677) are unrecognizable in origin. At these localities, small sea stacks are composed of crenulated chloritic phyllonite with small lensoid blebs of quartz. This is the 'Oystershell Rock' of Peach *et al.* (1907). Locally the quartz blebs contain a strong ESE-plunging mineral lineation. The phyllonites generally preserve an intersection lineation defined by the axes of the crenulations. These are dispersed around the quartz lineation. The crenulations themselves are generally extensional with respect to the early foliation and imply a top-to-the-WNW shear sense.

The basal contact of the 'Oystershell Rock' is found on the small peninsula at NC 406 680. It is clearly a thrust contact that emplaced the sheared and retrogressed Lewisianoid mylonites onto the Durness Group carbonate rocks. A 1 m-thick band of mylonitic quartzite lies along this thrust contact (Figure 5.15). The thrust can be mapped, offset by small faults, into the western coves of Sango Bay. It can be shown to have a gentle ESE dip and is everywhere above the carbonate rocks. Along the thrust contact the phyllonites are generally platy and do not show the crenulated texture that typifies them away from this contact. However, they do contain a locally strong ESE-plunging mineral lineation.

The fault rocks associated with the normal faults in Sango Bay are very different to the mylonites and phyllonites along the low-angle thrust. The freshest outcrops are found on the north-west face of the little peninsula at NC 406 680, where a fault scarp in brecciated carbonate rocks is spectacularly exposed. This fault can be seen to have a throw of about 8 m. The carbonate fault-breccias show composite angular fragments (less than 0.5 mm to 5 cm) that are themselves composed of cataclasites. Micro-veining and carbonate cementation are ubiquitous, including patchy development of pink-stained iron-rich carbonate precipitates. The micro-veins show network textures on a millimetre- to centimetre-scale. The matrix to the breccias is a combination of carbonate rock flour and cement.

Cataclasis also affects the ductile shear fabrics of the thrust contact. Hippler (1989) and Hippler and Knipe (1990) described microfracturing and brecciation on all scales in the quartz mylonites at the late fault contacts. Optical and transmission electron microscopy show that fracture patterns on a grain scale can be influenced by the earlier microstructure of the mylonite.

Interpretation

Peach *et al.* (1907) interpreted the low-angle thrust contact that carries quartz mylonites, 'Oystershell Rock', and recognizable Lewisianoid

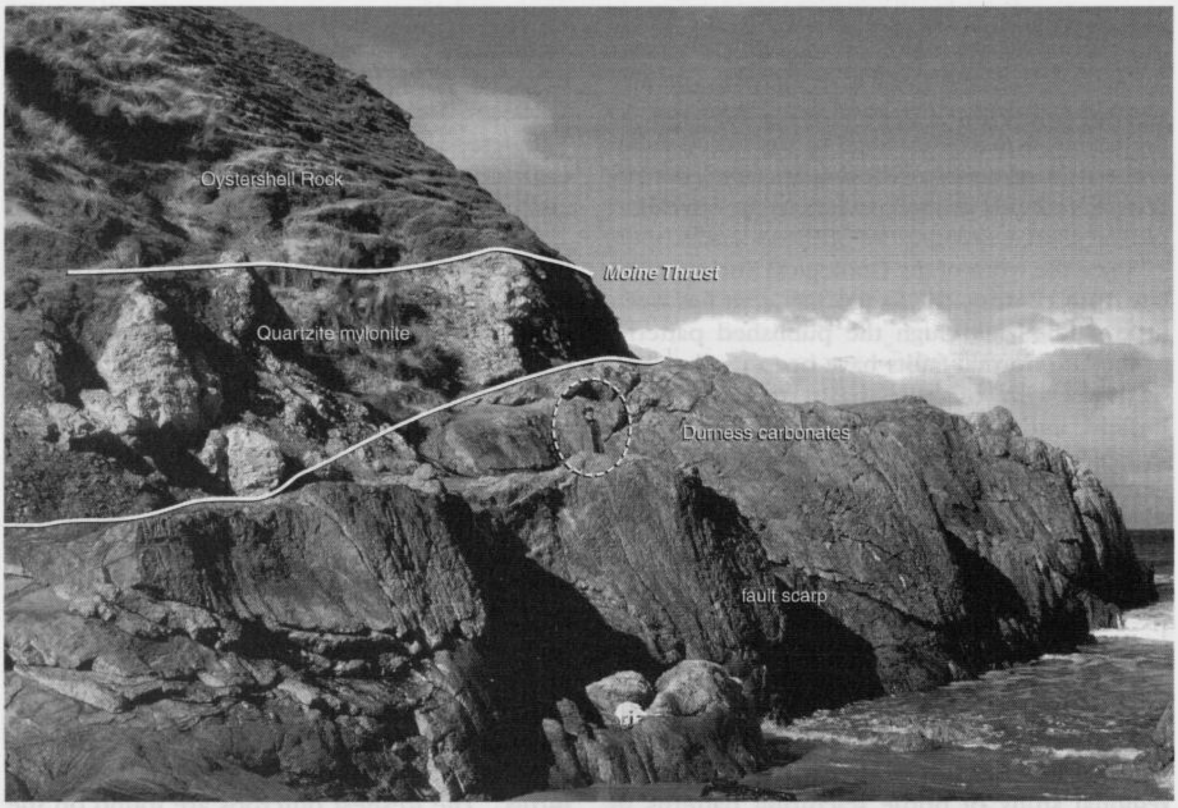


Figure 5.15 Thrust contact at Sango Bay, emplacing 'Oystershell Rock' over quartz mylonite and Durness carbonate. This thrust was interpreted by Peach *et al.* (1907) as the Moine Thrust. (Photo: R.W.H. Butler.)

gneisses in its hangingwall as the Moine Thrust. Kinematic indicators clearly show a WNW-directed sense of emplacement onto the upper part of the Durness Group. Holdsworth *et al.* (2001) contested this nomenclature, suggesting that the contact in Sango Bay is a lower structure than the Moine Thrust as they inferred that the 'Oystershell Rock' was derived from Lewisian gneisses that were once overlain by Cambrian rocks (see **Clèit an t-Seabhaig** GCR site report, this chapter). Regardless of these debates it is clear that the thrust contact carries allochthonous mylonites and their less-deformed equivalents from the east of Loch Eriboll out onto the foreland succession. Peach *et al.* (1907) and subsequent workers used this inference to deduce a minimum displacement on the base of the allochthon in excess of 15 km, the distance between exposures of the Moine Thrust Belt rocks on **Faraid Head** and Sango Bay and those east of Loch Eriboll.

The late faults that drop down the allochthonous sheets against their footwall of Durness carbonate rocks, show complex histories of brecciation and veining. They are probably of Devonian age and show evidence of cyclic movement and cementation during quiescent periods, typical of cataclastic fault-zones. Clearly the fault zones represented transient fluid pathways during movement, as indicated by the complex nature of the veins and the differing iron contents of the cements.

On a larger scale, the Sango Bay outcrops raise important issues concerning the relationship between the post-Caledonian normal faults and the Caledonian and earlier structures. Using offshore seismic data, several workers have proposed that the normal faulting utilized Caledonian structures (e.g. Brewer and Smythe, 1984; Enfield and Coward, 1987). Laubach and Marshak (1987) suggested that the Durness fault patterns were influenced by Precambrian structures of the foreland, although the subsequent work of Beacom (1999) suggested that this proposal is invalid. Although the latter controversy cannot be resolved at Sango Bay, the Caledonian influence can be assessed. Microstructural investigations have suggested a granular control on fracture processes exerted by the fabrics in the quartz mylonites (Hippler, 1989; Hippler and Knipe, 1990). However, it is highly unlikely that these controls operate on a larger scale through such a varied rock sequence (e.g. Beacom, 1999). Further, the normal fault array in Sango Bay clearly cross-cuts the Caledonian thrusts and shows no evidence of having re-activated the simple thrust contacts nor even of having been refracted along them. Thus, at this locality, there is no support for models involving the reactivation of Caledonian structures or their fabrics to influence later basin formation.

Conclusions

The Sango Bay outcrops are critical for establishing minimum displacements on the base of allochthonous, mylonite-bearing thrust sheets in northern Scotland. This was first recognized by the original surveyors in the late 19th century, and hence the GCR site is of considerable historical importance. The outcrops are clean and readily accessible, making them admirably suited for study, unlike some other parts of the Moine Thrust Belt. Further, there is an excellent array of outcrops that show the progressive retrogression and shearing of Lewisianoid gneisses related to the thrusting. The kinematic indicators in the high-strain 'Oystershell Rock' are particularly clear and imply a consistent WNW-directed emplacement direction.

The site also contains exceptional exposures of post-Caledonian (probably Devonian) normal faults with spectacular carbonate-rich fault rocks. These show complex cyclic histories of brecciation and cementation that are characteristic of seismogenic faults. This is also one of the very few places where Caledonian thrusts are clearly cut by post-Caledonian normal faults with the overprinting of the earlier mylonites by later cataclasites clearly demonstrated. Although some workers have inferred that Caledonian thrusts have been preferentially reactivated during post-Caledonian normal faulting, in the Sango Bay outcrops this type of behaviour is not seen in the exposed, shallow crustal-level faulting.

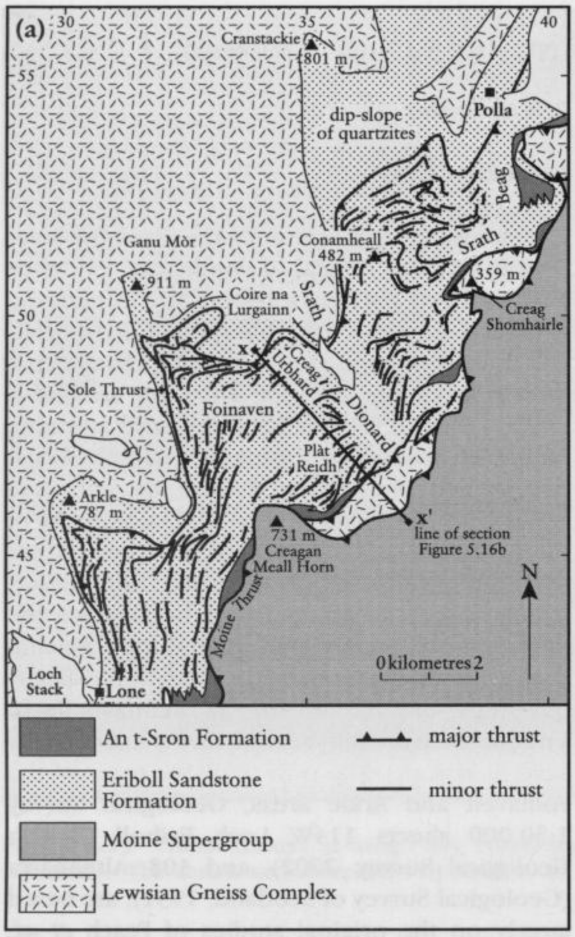
FOINAVEN (NC 383 527–NC 327 460)

R.W.H. Butler

Introduction

The mountain wilderness to the south of Loch Eriboll includes critical, if conflicting, evidence that has been important historically in building structural models. The massifs of Conamheall, Foinaven and Arkle are ridges of quartzite that form a designated SSSI for landscape and floral reasons (Figure 5.16a). They also offer stunning natural cross-sections through the Moine Thrust Belt, which is dominated here by imbricate zones within the Pipe Rock. The complexity of the thrust geometry within these transects has been underestimated (Peach *et al*., 1907; Elliott and Johnson, 1980), perhaps because of the uniformity of the original stratigraphy, making thrust repetitions less obvious than in the classic examples on Heilam or at Achnashellach. Undoubtedly the difficulty of access has discouraged fieldwork. The only available maps of the Foinaven and Arkle areas, Geological Survey 1:50 000 sheets 114W, Loch Eriboll (British Geological Survey, 2002), and 108, Altnaharra (Geological Survey of Scotland, 1931), are based largely on the original studies of Peach *et al*. (1907). Butler (1982b) remapped the ground south of Loch Eriboll, and subsequently Butler and Coward (1984) used this data in their restoration of the Cambrian shelf in north-west Scotland, which they estimated to be over 54 km wide. Some additional mapping took place during the preparation of this report, and some of the resultant conclusions about the nature of roof thrusts in thrust models are described in Butler (2004a).

The area around Foinaven was inspirational for Cadell (1888), who performed early experiments to model imbricate systems by compressing layers of sand and clay in a wooden press (see Butler, 2004b). Much later, Cadell's work itself inspired Elliott and Johnson's (1980) important re-interpretation of Moine Thrust Belt structures, a study that provided the impetus for much of the modern work in the belt. Boyer and Elliott (1982) used the Foinaven transect as their global type-example of duplex structure. Additionally, the site includes the telescoped transition in fault-rock type, from mylonites



along the Moine Thrust into cataclasites near the Sole Thrust (Butler, 1982b).

Description

The Foinaven GCR site is large, extending for over 15 km from the head of Loch Eriboll to Loch Stack. It encompasses several steep-sided mountain ridges up to 900 m in elevation, separated by remote deep valleys, the most notable of which is Srath Dionard (Figures 5.16, 5.17). Various contrasting structural geometries are exhibited within the Moine Thrust Belt, but the following description focuses on three keys aspects.

The imbricate system above the Sole Thrust

Lewisian gneisses of the foreland together with the sub-Cambrian unconformity are exposed on the sides of Srath Dionard, in Coire an Easain Uaine, around the shores of Loch Stack, and as an inlier above the cottage of Polla in lower Srath Beag. The unconformity is almost perfectly planar without offsets by faults. In contrast, the overlying Cambrian quartzites forming the ridges of Cranstackie (800 m)–Conamheall (482 m), Foinaven (908 m) and Arkle (787 m) contain numerous imbricate thrusts. These chiefly involve the Pipe Rock. Indeed Peach *et al.*

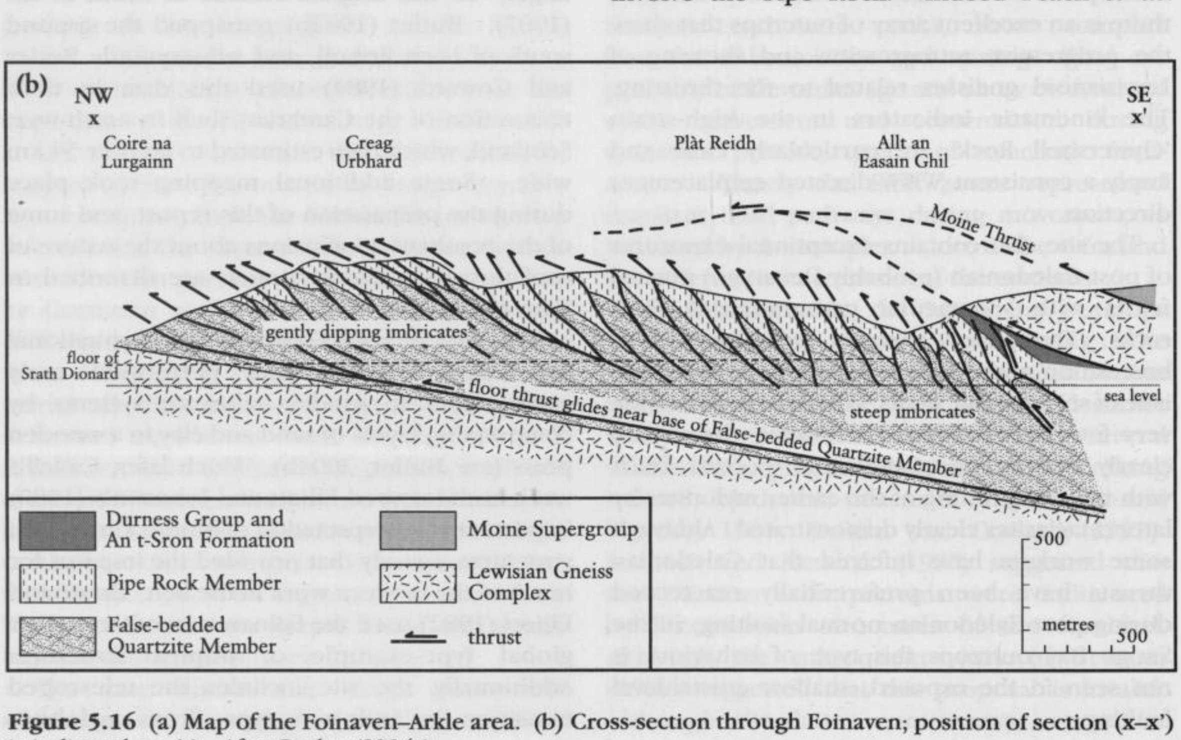


Figure 5.16 (a) Map of the Foinaven–Arkle area. (b) Cross-section through Foinaven; position of section (x–x') is indicated on (a). After Butler (2004a).

Figure 5.17 Thrust structures in the Foinaven duplex, in the N-facing cliff overlooking Srath Dionard. The Moine Thrust on the left overlies a thick stack of imbricates formed of Pipe Rock that dip towards the hinterland. (Photo: R.W.H. Butler.)

(1907) suggested that the lower part of the Eriboll Sandstone Formation, the False-bedded Quartzite Member, was not involved in thrusting. Elliott and Johnson (1980) perpetuated this view as they placed the regional Sole Thrust at the base of the Pipe Rock.

The best-known and most accessible transect through the imbricate zones of Cambrian quartzites lies on the western flank of Srath Beag. It is readily seen from the A838 at the southern end of Loch Eriboll. The quartzites of the foreland dip gently to the ESE and can be traced for 4 km down-dip from the summit of Cranstackie. However, the lower parts of the dip-slope contain large-scale folds, clearly recognized by Cadell (in Peach *et al.*, 1907) and subsequent workers. These folds appear to be simple structures, carried on thrusts. The upper parts of the structures locally contain slices of An t-Sron Formation rocks (e.g. in the stream section north-east of Conamheall summit; NC 371 518). Cadell considered that the thrusts in essence repeat the entire stratigraphical thickness of the Pipe Rock (about 75 m). However, the structure is far more complex (Butler, 1982b). The large antiforms are composite features within which multiple bedding cut-offs can be identified. These indicate imbricate thrusts. In some locations (e.g. NC 373 510) individual beds can be found repeated on thrusts that diverge up-dip off one bedding plane, only to re-combine into the next bedding plane up-section. Higher thrusts are folded around structures developed beneath them, so the fault surfaces are no longer planar. Structural complexity generally increases up-section. Furthermore, thrusts can be mapped along strike as they climb up and down the stratigraphical section and link and branch from each other (Butler, 1982b).

Despite the imbrication within the Conamheall section, the Pipe Rock itself displays very little distortional strain. *Skolithos* burrows retain near-circular sections on bedding planes and remain perpendicular to bedding in profile, except where adjacent to some thrust surfaces. *Monocraterion* ('trumpet pipe') burrows show some flattening, implying weak layer-parallel shortening in a WNW–ESE direction. The contrast between the two types of burrow probably reflects the more-porous nature of

Monocraterion-bearing quartzites, rendering them capable of exhibiting small amounts of strain.

Fault rocks in the Conamheall section are dominantly cataclasites. Faults are decorated by breccias in many localities. However, there are ubiquitous seams of ultra-cataclasites that have a characteristic mottled blue appearance in hand-specimen, akin to bruising. Optical studies show that these fault rocks are characterized by intense grain-size reduction by fracturing, although the fine-grained zones show some dynamic recrystallization.

The Foinaven transect is very similar to the neighbouring Conamheall section. The structure is spectacularly seen in the Creag Urbhard cliffs above Loch Dionard (NC 350 488; Elliott and Johnson, 1980), but is disappointingly poorly exposed on the plateau of Plàt Reidh. The plateau outcrops are almost exclusively made up of Pipe Rock with small tracts of An t-Sron Formation rocks (NC 347 482). On the north-west slopes of An t-Sail Mhòr (NC 342 489) the quartzite-carrying thrusts cut up-section as far as the Salterella Grit.

Peach *et al.* (1907) considered the entire structure of Creag Urbhard to be formed by stacked Pipe Rock. However, recent mapping has found that the lower parts of the imbricate slices contain significant thicknesses of cross-bedded, non-bioturbated quartzite (Butler, 2004a). Consequently it is probable that the floor thrust to this imbricate system, the regional Sole Thrust, moves down succession towards the base of the Cambrian quartzites within the False-bedded Quartzite rather than within the Pipe Rock. It remains to be established whether this conclusion is also appropriate for the neighbouring transect of Arkle. Reconnaissance work there suggests that these imbricate slices also involve the False-bedded Quartzite Member together with Pipe Rock.

Relationships between thrusts at Creag Shomhairle (NC 380 505)

The western flank of Creag Shomhairle offers a spectacular natural section, 350 m deep and normal to the regional thrusting direction (Figure 5.12). It is an ideal location to examine lateral variations in thrust structures and is critical for establishing the relative timing of various thrusts (Butler, 1982b, 2004a). Most of Creag Shomhairle consists of Lewisian gneisses similar to those within the analogous Arnaboll Thrust Sheet (see **Eriboll** GCR site report, this chapter). These gneisses are only weakly affected by deformation associated with thrusting. The base of the Lewisian sheet is the Creag Shomhairle Thrust of Butler (1982b). Its foot-wall lies in Cambrian strata but is only exposed in a few localities.

The Creag Shomhairle Thrust Sheet is structurally overlain by Moine-derived mylonites, preserved in a NW-trending synform that crops out on the summit of Creag Shomhairle (Figure 5.18). Farther south, Moine-derived mylonites lie directly on Cambrian rocks without an intervening Lewisian sheet. Consequently it may be deduced that the Creag Shomhairle and Moine thrusts join together, isolating the Lewisian gneisses of the Creag Shomhairle Thrust Sheet as a thrust-bounded horse. The synform that folds the tapered edge of the Creag Shomhairle Thrust Sheet and the Moine Thrust also folds the Creag Shomhairle Thrust and its local footwall, an imbricated package of An t-Sron Formation units. These imbricate slices wrap a 100 m-high dome formed of thin slices of Pipe Rock that have been stacked up by thrusts (Figure 5.19). The slices, individually less than 5 m thick, have progressively steeper dips towards the hinterland. This is the classic form of an antiformal-stack duplex (Boyer and Elliott, 1982; Butler, 1987), whose geometry is indicative of 'piggy-back' thrusting. Below lie more gently dipping Pipe Rock units that pass beneath the synform on Creag Shomhairle without being folded. Consequently there is an overall tendency for decreasing structural complexity with depth. The implication is that the highest structures formed early in the relative sequence of thrust sheet emplacement so that they were folded by subsequent, lower-level imbrication (Butler, 1982b). In detail the structural sequence is more complex, as quartzites are re-imbricated into the overlying Moine mylonites. However, these relationships add further support to the overall higher-first, lower-later (i.e. 'piggy-back') thrusting sequence.

As well as providing critical evidence for the sequence of thrusting, the Creag Shomhairle area is an excellent site to examine variations in fault-rock types across a thrust array. The transition from crystalline plasticity required for mylonite formation (White, 1982) to cataclasis indicates a decrease in temperature and/or an increase in strain rate. The thrusts on Creag

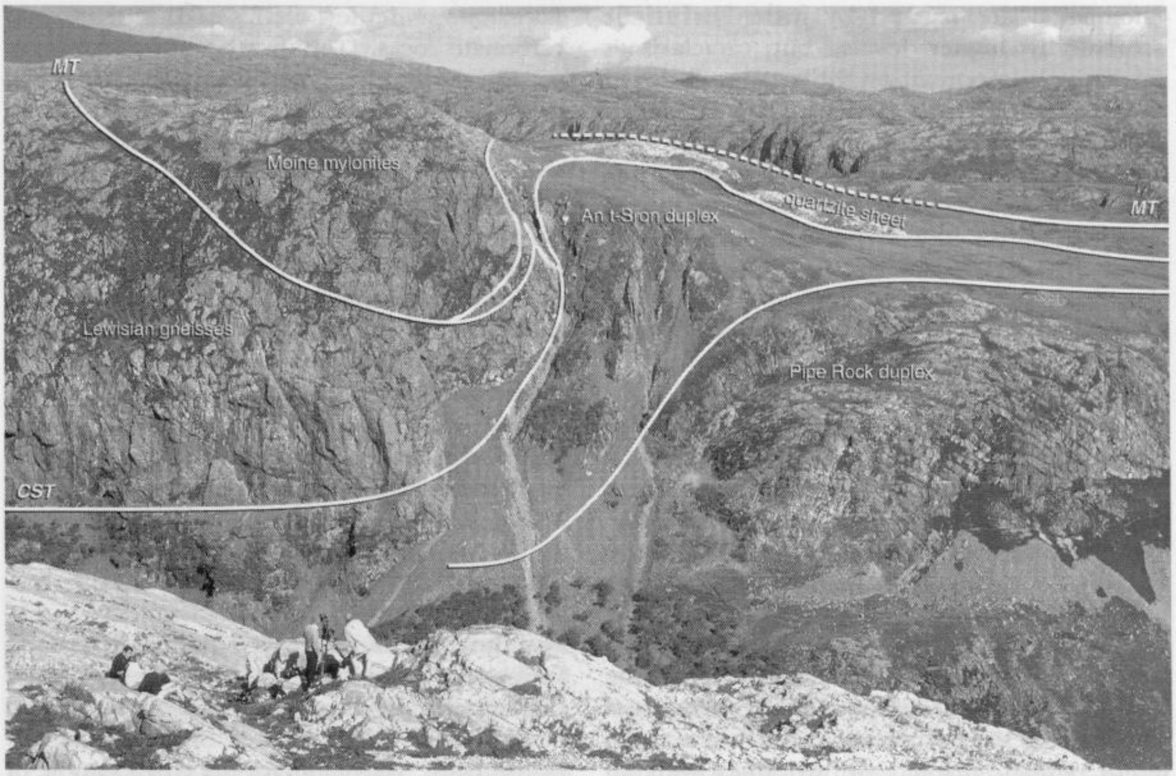


Figure 5.18 View onto the western flank of Creag Shomhairle. The Moine Thrust (MT) is folded by underlying duplexes of An t-Sron Formation and Pipe Rock. CST – Creag Shomhairle Thrust. (Photo: R.W.H. Butler.)

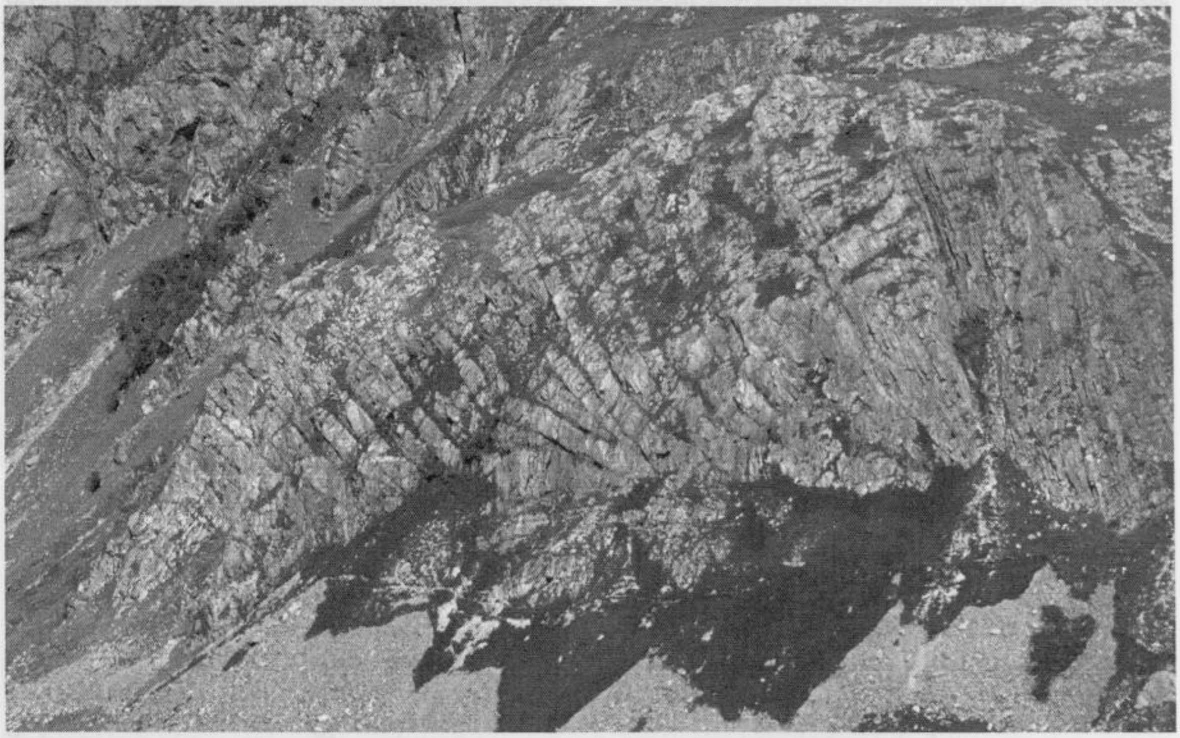


Figure 5.19 Imbricated Pipe Rock forming an antiformal stack on the western flank of Creag Shomhairle. (Photo: R.W.H. Butler.)

Shomhairle are marked by mylonites at the structurally higher levels, but cataclasis is increasingly important on the structurally lower thrusts (Butler, 1982b). Bowler (1987) provided descriptions of cataclasites from the Pipe Rock antiformal stack, which show multiple fracturing and grain-size reduction. The transition to cataclasis can be followed across Srath Beag to Conamheall.

Creagan Meall Horn and the An Dubh-loch area

Elliott and Johnson (1980) were unaware of the structural relationships at Creag Shomhairle when they re-interpreted the Foinaven transect in terms of simple duplex geometries. Consequently they considered the roof thrust to the duplex to be essentially flat. This architecture later came to be used as the classic example of a 'hinterland-dipping' duplex, so named because of the dips of bedding and imbricate thrusts (Boyer and Elliott, 1982). The roof thrust for these interpretations was taken as the Moine Thrust, marked by mylonites with an ubiquitous ESE-plunging mineral lineation. The thrust is exposed on the northern slopes of Creagan Meall Horn (NC 350 458) in a superb section that runs around the headwall of Coir' an Dubh-loch (Butler, 2004a). These outcrops also contain the southern limit of a sheet of Lewisian gneisses, analogous to the Creag Shomhairle Thrust Sheet. The sheet occupies the floor of Coire Lochan Ulbha and continues northwards as far as Bealach a' Chonnaidh (NC 369 491). As in the Creag Shomhairle Thrust Sheet, the Lewisian here generally shows little Caledonian deformation apart from directly beneath the overlying Moine Thrust and near its basal contact.

In general, the Moine Thrust to the east of Foinaven is relatively planar. It certainly does not show the complexity of the Creag Shomhairle area. The underlying thrust that carries the un-named Lewisian sheet of Coire Lochan Ulbha shows more complexity. Above Coir' an Dubh-loch, this structure shows warps that overlie small ramp-related culminations in the underlying imbricate slices of Cambrian strata. In this respect the un-named thrust behaves as predicted for a roof to the Foinaven duplex. However, in detail there are complexities.

The imbricate slices below the Lewisian-bearing thrust contain Pipe Rock, An t-Sron Formation and a few metres of Durness Group carbonate rocks. The thrusts cut up-section as seen in the Coir' an Dubh-loch cliffs. However, their apparent roof thrust truncates these structures, transgressing from Fucoid Beds, across Salterella Grit and into Durness carbonate rocks, then back across these units around the corrie walls (Butler, 2004a). Thin, detached slices of Durness carbonate rocks decorate the roof. These relationships clearly suggest that the roof thrust moved after the structures in its footwall. However, truncating segments of the roof thrust can be traced up onto shears that cut through the un-named Lewisian sheet. These shears do not cut into the Moine mylonites suggesting that they link upwards onto the Moine Thrust.

Interpretation

The outcrops of imbricated Eriboll Sandstone Formation quartzites that form the ridges of Conamheall, Foinaven and Arkle contain the most continuous exposures of thrusts in the British Isles. They embrace the type example of duplex structure (Boyer and Elliott, 1982). However, the imbricate structures are far more complex than envisaged by Boyer and Elliott (see also Elliott and Johnson, 1980). There is no simple basal detachment. Rather, various levels within the quartzites form major thrust flats, and individual beds can show substantial shortening through imbrication (Butler, 1982b). Balanced cross-sections provide an estimate of 54 km for the original width of the current 6 km-wide Pipe Rock section on Conamheall, a figure used for crustal balancing in north-west Scotland (Butler and Coward, 1984).

Thrust structures display a range of deformation mechanisms across the site. Mylonites generally typify the highest structural levels with cataclasites dominating the deeper levels near the Sole Thrust. This trend is best preserved in the Creag Shomhairle area. This apparent conundrum, typical of much of the Moine Thrust Belt, is explained by the higher thrusts forming first under greater tectonic overburden, with subsequent deeper thrusts forming at shallower levels in the crust. Erosion from the top of the accumulating thrust wedge presumably outpaced the overall rate of cumulative thickening at the base of the evolving Moine Thrust Sheet, although Holdsworth *et al.* (2006) concluded that extensional collapse was important in controlling the critical taper of the growing thrust wedge.

The relationships between the upper thrusts that carry the Moine and far-travelled Lewisian sheets and the underlying Cambrian-bearing imbricate slices are variable within the Foinaven site. The field relationships at Creag Shomhairle are best explained by progressive folding of higher thrust sheets by the later-formed, underlying structures (Butler, 1982b). The upper thrusts in a stack were the first to move, whereas deeper thrusts moved later, carrying the earlier structures on their backs. An additional complication here is that the Lewisian gneisses of the Creag Shomhairle Thrust Sheet are locally imbricated with the Moine mylonites. These imbricate thrusts generated their own minor folds and crenulation fabrics within the Moine mylonites, enabling correlation of the folding in the mylonites with local displacements and shear localization. Butler (1982b) cited these relationships when arguing against using local structural chronologies to correlate regionally in thrust belts.

In contrast to Creag Shomhairle, the outcrops just north of Creagan Meall Horn imply a different sequence of thrusting. Here the upper thrusts have clearly truncated the imbricate slices in their footwall. It appears that the thrust at the base of the Moine mylonites, ostensibly the Moine Thrust, moved late in the sequence. These late displacements cut across the Cambrian rocks, entraining the upper parts of the imbricate zone as a series of dismembered slices. The edge of the intervening Lewisian thrust sheet beneath the Moine is also cut and entrained into the underlying imbricate slices. Farther north-east, away from these late movements, the Lewisian-bearing thrust is folded and warped by the underlying imbricate slices suggesting that, originally, it was this structure that formed the roof to the Foinaven duplex. Nevertheless the overall flat-roof to the Foinaven duplex envisaged by Elliott and Johnson (1980) is largely a result of late motion on this upper thrust and perhaps should not be considered to be a general feature of duplexes (cf. Boyer and Elliott, 1982). As the original 'roof thrust' to the Foinaven duplex shows a complex geometry, Butler (2004a) proposed that movement may not be confined to a single thrust at any one time, and consequently the resultant duplexes may have much more-complex geometries.

Conclusions

The Foinaven wilderness contains some of the most dramatic exposures of thrust geometry in Europe. Near-three-dimensional exposures of thrusts and related folds make this GCR site area ideal for appreciating the range and complexity of structural geometries that can result from repeated imbrication and ramp–flat thrust surfaces. The individual fault surfaces are exposed in many localities.

The regional Sole Thrust to the imbricate zone on Foinaven and Conamheall is generally difficult to identify because of the complexity of small-scale thrust surfaces. On Foinaven itself, the sole must lie within the False-bedded Quartzite Member as this unit is found within the imbricate slices on Creag Urbhard. However, the imbricate zone in general climbs up into the An t-Sron Formation as these rocks are found preserved in some thrust slices. It is likely that the original roof to the imbricate zone lay for a few metres within the carbonate rocks of the Durness Group. The nature of the present roof to the imbricate zone is variable but thrust relationships are clearly displayed on Creagan Meall Horn. It is likely that the imbricate slices passed upwards into a thrust that carried isolated slices of Lewisian gneiss; presumably attached to the Moine Thrust Sheet. However, in places the imbricate slices are truncated by later thrusts and in others the upper thrusts are folded by the imbricates. Thus the simple sequential models of thrust development (e.g. Boyer and Elliott, 1982; Butler, 1982a) do not apply here and the geometries are better explained by synchronous thrusting (Butler, 2004a). These are new concepts for the Moine Thrust Belt, and for thrust systems in general, and it remains to be seen how widely they are applicable.

The area is superb for tracking the detailed lateral variation in imbricate structures and for examining the transition in fault-rock type across a broad swathe of the Moine Thrust Belt. Yet it remains to be established how far the late motions at the base of the Moine Thrust Sheet can be traced. The outcrop quality is ideal for investigating the distribution of cataclastic fault rocks, developed in the Pipe Rock, but to date there has been remarkably little work on these materials, in contrast to the ductile mylonites found elsewhere in the thrust belt. The area is of international importance for the study and understanding of linked thrust systems.

GLENCOUL (NC 236 304–NC 295 288)

R.W.H. Butler

Introduction

Loch Glencoul is a spectacular glacier-carved fjord with steep valley-sides that leads eastwards into the remote country north of the Ben More Assynt range. The dramatic scenery also provides one of the most important sections through the Moine Thrust Belt, in which the various rock units form well-marked features distinguishable from a great distance. The view across Loch Glencoul of the slopes of Beinn Aird da Loch and the Stack of Glencoul, from the A894 above Kylesku (Figure 5.20) has inspired generations of geologists since Callaway (1883) first recognized its significance. It is undoubtedly one of the most dramatic geological views in the British Isles and this, together with its historical association, has assured wide international recognition.

On Beinn Aird da Loch, Lewisian gneisses have been emplaced upon a thin tract of imbricated An t-Sron Formation, resting on intact Cambrian quartzites that in turn lie unconformably upon Lewisian of the foreland. Callaway described these field relationships and concluded that they are the result of lateral tectonic forces; the tectonic contact was subsequently termed the 'Glencoul Thrust' (Peach *et al.*, 1907). The displaced Lewisian above the Glencoul Thrust has its own cover of Cambrian quartzites that are overlain by Moine metasedimentary rocks. Here too, Callaway (1883) interpreted a tectonic contact; this is the Moine Thrust. Its dramatic exposure on the Stack of Glencoul includes several hundred metres of mylonites derived both from the Moine and the underlying Cambrian quartzites.

The foreland part of the Glencoul site has additional structural significance in that the famous 'double unconformity' between Lewisian, Torridonian and Cambrian units is exposed (Figure 5.21). The sub-Cambrian unconformity oversteps from Lewisian onto Torridonian in an up-dip direction. This feature is important for correlating thrust sheets in the Assynt district (Elliott and Johnson, 1980).

As with much of the Moine Thrust Belt, following the pioneering studies of the late 19th century (Peach *et al.*, 1907), subsequent

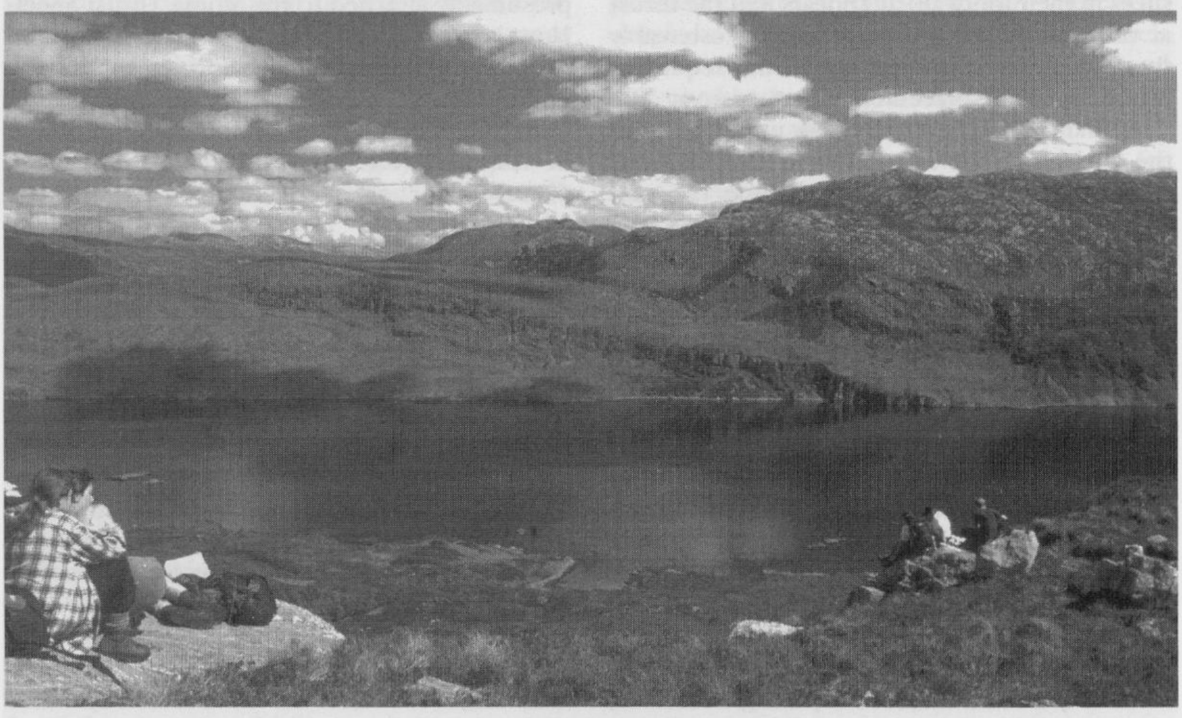


Figure 5.20 The Glencoul Thrust on Beinn Aird da Loch, from the south-west side of Loch Glencoul. Lewisian gneiss has been thrust over cliffs of Cambrian quartzite. Compare with cross-section shown in Figure 5.21b. (Photo: R.W.H. Butler.)

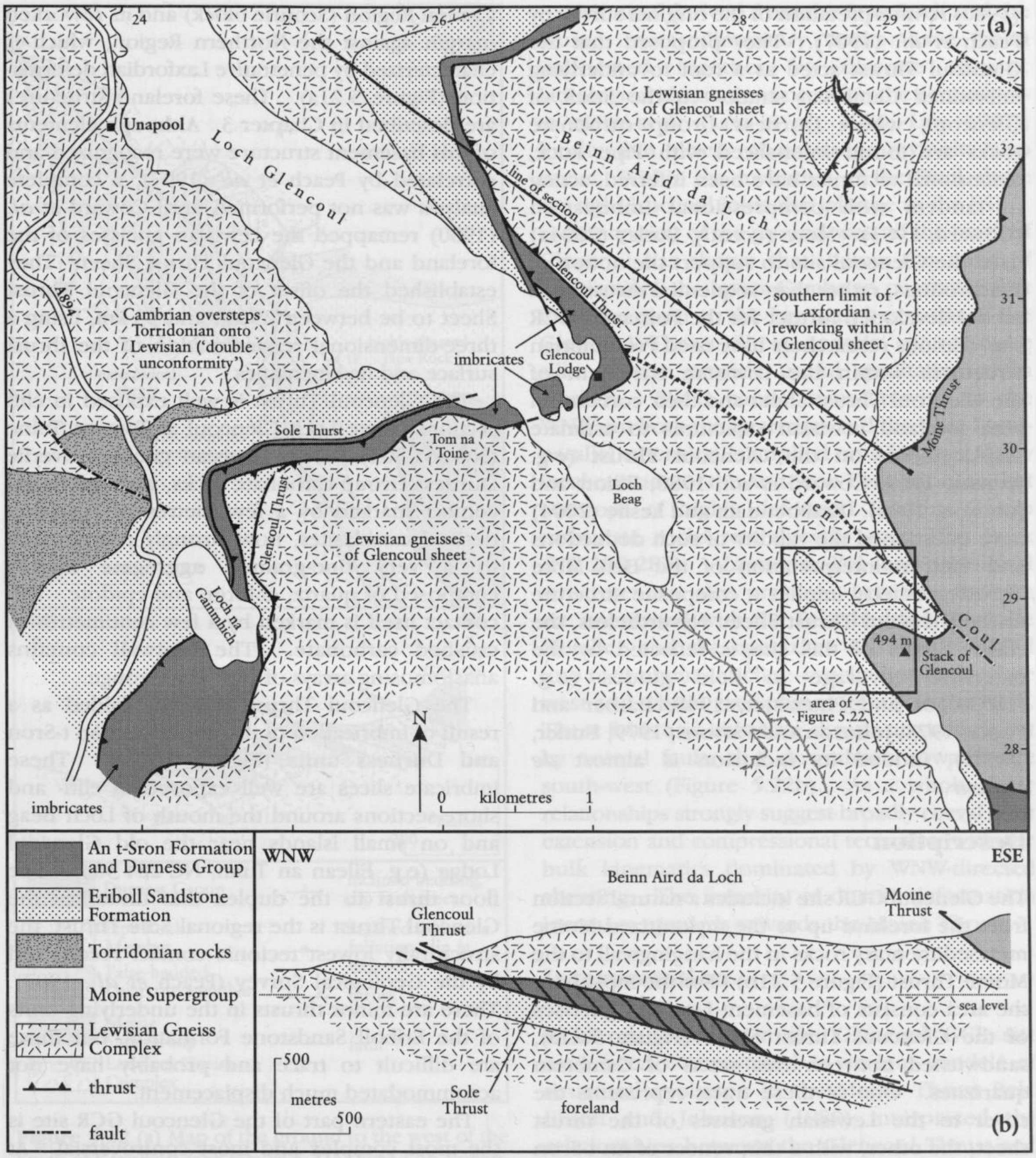


Figure 5.21 Geological relationships at the Glencoul GCR site. (a) Map of the area around Loch Glencoul (modified after Peach *et al*., 1907; Coward *et al*., 1980; British Geological Survey, 2007). (b) Schematic cross-section through the Moine Thrust Belt on Beinn Aird da Loch (vertical and horizontal scales equal and as (a)).

research in the Glencoul area concentrated on using minor structures to establish kinematic histories. Christie (1963, 1965) used minor folds to infer movement directions on the Moine Thrust and pioneered quantitative studies of mylonite formation using crystallographic methods. Christie's work on the mylonitized Pipe Rock has been greatly extended by Law and co-workers (Law *et al*., 1986; Law, 1987). These Pipe Rock outcrops were used for early attempts to quantify the strain associated with mylonite formation (McLeish, 1971; Wilkinson *et al*., 1975). Larger-scale studies of thrust geometry were given impetus by Elliott and Johnson's

(1980) re-interpretation of the original survey by Peach *et al.* (1907). They proposed that the Glencoul Thrust acted as a roof to underlying imbricated Cambrian strata. At the Stack of Glencoul, where Durness Group carbonate rocks are found inter-sliced with Pipe Rock, extensional tectonics have been inferred, acting in tandem with compressional imbrication (Coward, 1983). More recently, Butler (2004a) used the Glencoul site to support the notion of synchronous, rather than sequential thrusting, a model developed further for the **Foinaven** GCR site. Various researchers have used Precambrian structures within the Lewisian basement of the Glencoul Thrust Sheet and their correlation with foreland Lewisian structures to estimate displacements on the Glencoul Thrust (e.g. Ramsay, 1969; Coward *et al.*, 1980; Elliott and Johnson, 1980). Krabbendam and Leslie (2004) have questioned the validity of such deductions and their re-interpretation of the Ben More Thrust geometry implies a composite structure to the Glencoul Thrust Sheet. Nevertheless, the classic status of this site is reflected by the extensive coverage in field guides (e.g. MacGregor and Phemister, 1948; Barber and Soper, 1973; Johnson and Parsons, 1979; Butler, 1988a); indeed its inclusion is almost *de rigueur*.

Description

The Glencoul GCR site includes a natural section from the foreland up to the mylonitized Moine metasedimentary rocks in the hangingwall to the Moine Thrust (Figure 5.21b). For the most part, the area consists of basement Lewisian gneisses of the Glencoul Thrust Sheet (Figure 5.21a), sandwiched between two tracts of Cambrian quartzites. One of these tracts represents the cover to the Lewisian gneisses of the thrust sheet; the other, with a thin veneer of An t-Sron Formation and carbonate rocks of the Durness Group, is the cover of the foreland succession. The carbonate rocks form the immediate footwall to the Glencoul Thrust. The Lewisian gneisses in the hangingwall have remained virtually unaffected by Caledonian strain despite having being carried on the Glencoul Thrust (Wibberley, 1997). Fortuitously, they have preserved Proterozoic structures that can be correlated with those of the foreland. Most important of these is the structural and metamorphic transition between the Archaean Central Region (Scourie block) and its reworked margin against the Northern Region, which is characterized by penetrative Laxfordian deformation (Figure 5.21a). These foreland structures are described in Chapter 3. Although elements of this basement structure were recognized and correlated by Peach *et al.* (1907), a complete analysis was not performed until Coward *et al.* (1980) remapped the Lewisian gneisses of the foreland and the Glencoul Thrust Sheet. They established the offset of the Glencoul Thrust Sheet to be between 25 km and 33 km, using a three-dimensional reconstruction of the thrust surface and its kinematics.

The Glencoul Thrust is well exposed in cliff sections above Loch Glencoul at Tom na Toine (NC 261 302). Here Lewisian gneisses overlie Durness Group carbonate rocks, with the thrust contact marked by a few metres of Lewisian-derived cataclasites, now strongly retrogressed to a very fine-grained aggregate mainly composed of quartz, chlorite and epidote. The contact itself is marked by a few centimetres of crushed carbonate. The footwall contains anastomosing arrays of carbonate gouge.

The Glencoul Thrust is gently folded as a result of imbrication of the underlying An t-Sron and Durness units (Figure 5.21b). These imbricate slices are well exposed in cliff- and shore-sections around the mouth of Loch Beag and on small islands near the old Glencoul Lodge (e.g. Eilean an Tuim, NC 264 303). The floor thrust to the duplex that underlies the Glencoul Thrust is the regional Sole Thrust, the structurally lowest tectonic contact recognized by the Geological Survey (Peach *et al.*, 1907). There are minor thrusts in the underlying units of the Eriboll Sandstone Formation, but these are difficult to trace and probably have not accommodated much displacement.

The eastern part of the Glencoul GCR site is the most complex and most controversial. At the Stack of Glencoul (NC 290 286), the Moine Thrust marks the boundary between Moine metasedimentary rocks and Pipe Rock (Figure 5.22a). Both lithologies are strongly mylonitized. Intense ductile strain in the Pipe Rock is indicated by the deformed *Skolithos* pipes that have been extended and now lie at a low angle to the bedding/foliation. The pipes plunge gently to the ESE, parallel to the intense stretching lineation developed in both mylonite lithologies. Wilkinson *et al.* (1975) used the deformed pipes to infer bed-parallel simple-shear strains of 9 or

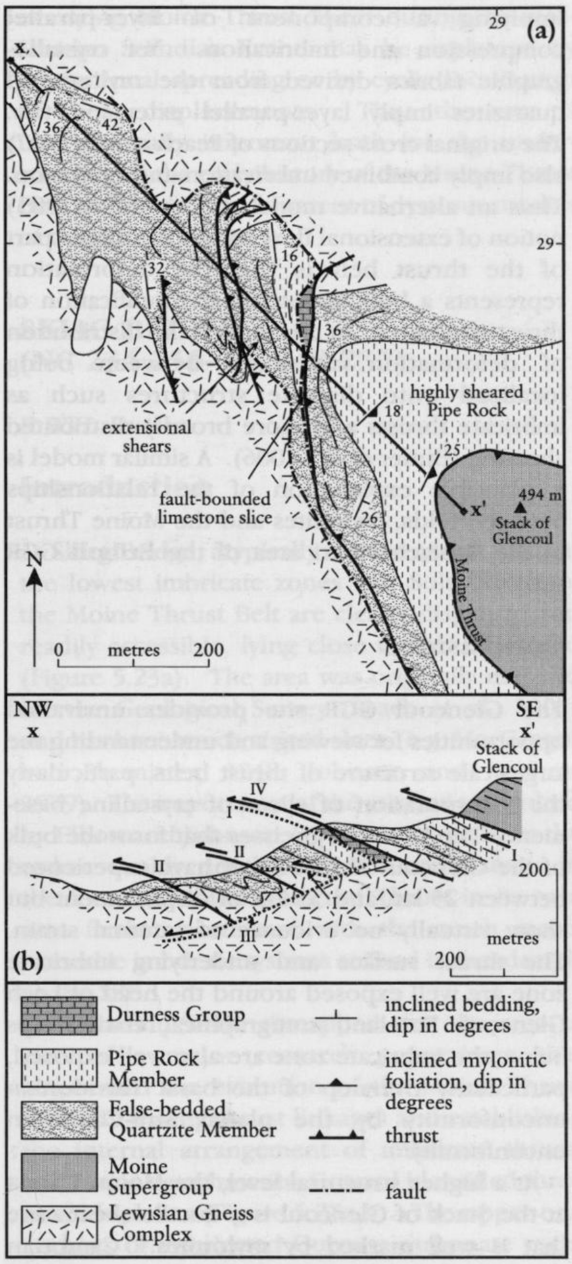


Figure 5.22 (a) Map of the ground to the west of the Stack of Glencoul (see Figure 5.21a) based on remapping by the author. (b) Schematic cross-section (x–x') through the map area of (a) showing the relationships between layer extensional (dotted) and contractional (solid) faults. These are grouped and numbered in the inferred order of displacement (I–IV in time). The relative timing of the Moine Thrust is uncertain but it probably moved broadly simultaneously with these other shearing deformations.

greater, but Coward (1983) proposed that the strains also involved significant (5:1) layer-parallel extension.

Mylonites derived from the Pipe Rock and the Moine metasedimentary rocks have been imbricated together by discrete thrusts. Lithological alternations occur on the centimetre- to metre-scale (Law *et al.*, 1986; Law, 1987); locally thin slivers of gneissose mylonite also occur. Within the mylonites at the Stack there are tight/isoclinal folds that plunge to the ESE.

Remapping of the ground west of the Stack of Glencoul has shown that, below this zone of imbrication, the lower Cambrian quartzites that form the cover to the Lewisian basement of the Glencoul Thrust Sheet contain microsyenite sills. These provide useful qualitative strain markers. Shear bands downthrowing to the WNW cut both the quartzites and the sills. Layer-parallel extension is implied on a larger scale by local excision of the An t-Sron Formation, so that outcrops of highly deformed Durness Group carbonate rocks rest directly upon Pipe Rock (NC 288 287). Layer-parallel compressional structures are also present. Lewisian gneisses are imbricated with the False-bedded Quartzite Member and the quartzites are tightly folded into recumbent anticline–syncline pairs that face west and whose axes plunge gently to the NNE. These folds and imbricate thrusts are in turn cut by normal faults that downthrow towards the south-west (Figure 5.22b). As a whole these relationships strongly suggest broadly coeval layer extension and compressional tectonics, with the bulk kinematics dominated by WNW-directed shearing. The intensity of ductile deformation increases upwards towards the Moine Thrust.

Interpretation

Field relationships in the Glencoul GCR site have been controversial in various models of structural evolution in the Moine Thrust Belt. Elliott and Johnson (1980) interpreted the relationships between the Glencoul Thrust and its underlying imbricate zone to imply that the Glencoul Thrust moved across an undeformed footwall of Cambrian strata, which later imbricated to form a duplex. The floor to this duplex was presumed to lie at the top of the Pipe Rock as this lithology is absent from the imbricate slices. However, although the broad structure of the duplex can be established at Glencoul, few of the exposures are easily accessible. Similar structures are well seen however, some 6 km farther south at the **Skiag Bridge** GCR site.

The simple duplex model proposed by Elliott and Johnson (1980) has been challenged by Butler (2004a) because not all imbricate slices contain Durness carbonate rocks. This could be explained if the Glencoul Thrust has not acted as a true roof thrust, but instead has decapitated the imbricate slices in its footwall (see Butler *et al.*, 2006). This overstep behaviour was favoured by Peach *et al.* (1907). However, the thrust does appear to be folded by the underlying structures, particularly in the ground to the north of the Glencoul GCR site (Elliott and Johnson, 1980). An alternative explanation is that the Glencoul Thrust cuts gently down stratigraphical section in its footwall and that it was this partially incised stratigraphy that formed the duplex (Butler, 2004a).

The Glencoul Thrust Sheet has been translated with almost no significant internal deformation (Wibberley, 1997). However, interpretation of its internal structure has recently become controversial. Krabbendam and Leslie (2004) suggest that the Ben More Thrust (see the eponymous GCR site below) branches onto the Glencoul Thrust at the mouth of Loch Beag. This model implies that the Lewisian gneisses that lie within the thrust belt on either side of Loch Glencoul belong to separate thrust sheets, making the correlation of Precambrian structures between the Glencoul Thrust Sheet (as originally mapped) and the Caledonian Foreland unwarranted (cf. Coward *et al.*, 1980; Elliott and Johnson, 1980). Undoubtedly, there are problems associated with correlation of structural and metamorphic features between the thrust belt and the foreland, but this revised model has yet to attain general acceptance, and existing syntheses still retain the original correlations and thrust linkages (e.g. Butler *et al.*, 2006).

Stratigraphical excision and the interplay between compressional and possibly extensional tectonics have been especially controversial in tectonic interpretations for the Stack of Glencoul. Extensional tectonics at high levels within the Moine Thrust Belt were proposed by Coward (1983) who envisaged a significant component of gravity spreading in driving thrust displacements. Detailed field and microstructural investigations by Law *et al.* (1986) and Law (1987) confirmed formerly held opinions that the Moine Thrust mylonites developed by predominantly WNW-directed simple-shear. However, they also showed that the Moine and Pipe Rock-derived mylonites are interleaved, implying a component of layer-parallel compression and imbrication. Yet crystallographic fabrics derived from the mylonitized quartzites imply layer-parallel extension too. The original cross-sections of Peach *et al.* (1907) also imply combined imbrication and extension. Thus an alternative model to Coward's (1983) notion of extensional flow within the upper part of the thrust belt is that the deformation represents a bulk simple-shear modification of thrust structures. In this model, the distribution of deformation alternates between being localized onto discrete structures such as imbricate thrusts and more broadly distributed shearing (Butler *et al.*, 2006). A similar model is a plausible explanation of the relationships between folds, mylonites and the Moine Thrust in the Bealach Mhari area of the **Eriboll** GCR site.

Conclusions

The Glencoul GCR site provides unrivalled opportunities for viewing and understanding the large-scale structure of thrust belts, particularly the incorporation of slices of crystalline basement. The Lewisian gneisses that form the bulk of the Glencoul Thrust Sheet have experienced between 25 km and 33 km of displacement but show virtually no evidence of internal strain. The thrust surface and underlying imbricate zone are well exposed around the head of Loch Glencoul. Foreland stratigraphical relationships below the imbricate zone are also well exposed, particularly overstep of the basal Torridonian unconformity by the planar sub-Cambrian unconformity.

At a higher structural level, the Moine Thrust at the Stack of Glencoul is a ductile shear-zone that is well marked by mylonites. Cambrian quartzites which dominate the lower part of the shear zone show spectacular deformed pipe-like burrows (*Skolithos*), which record combinations of WNW-directed overshear and layer-parallel extension. These quartzites have been important for qualitative and quantitative studies of mylonite formation through crystallographic analysis. The upper parts of the shear zone here contain imbricate thrusts and recumbent folds, together with ductile extensional structures and normal faults. WNW-directed overshear appears to have dominated all these structures, whether compressional or extensional. These relationships, formed during the emplacement of the overlying Moine Thrust Sheet during the mid-Silurian Scandian Event, may be explained by gravitational spreading or by cyclic localization of shear displacements. Thus the area is internationally important both for the understanding of the early history of the Moine Thrust Belt and for the development of dynamic models of thrust tectonics.

SKIAG BRIDGE (NC 234 256–NC 240 237)

R.W.H. Butler

Introduction

At Skiag Bridge, atypically for the Assynt district, the lowest imbricate zones and Sole Thrust of the Moine Thrust Belt are clearly displayed and readily accessible, lying close to the A894 road (Figure 5.23a). The area was originally mapped for the Geological Survey (Peach *et al.*, 1907) and has been much visited since (e.g. MacGregor and Phemister, 1948; Johnson and Parsons, 1979). The importance of the area, as recognized by Elliott and Johnson (1980), is that it links the rather weakly developed imbricate systems in the footwall to the Glencoul Thrust in its type area farther north-east with the much more-extensive imbricate systems around Inchnadamph to the SSE.

Coward (1984b) remapped the site area as part of a major research programme that re-assessed the evolution of the Moine Thrust Belt. By tracing thrust linkages and establishing the internal arrangement of imbricate thrusts and major detachments, Coward identified three main duplexes (Figure 5.23a,b). The upper one consists of imbricated Durness carbonate rocks and lamprophyre sills. The floor thrust to this system lies a few metres above the base of the carbonate rocks and it acts as a roof to the underlying middle duplex, formed in Fucoid Beds, Salterella Grit and involving a few metres of Durness carbonate rocks. The lowest duplex contains a few metres of Pipe Rock and Fucoid Beds and its floor is the regional Sole Thrust. A few minor thrusts occur beneath the Sole Thrust, within the underlying Pipe Rock, and some of these have been the focus of microstructural investigations aimed at studying processes of cataclastic faulting in quartzites (Lloyd and Knipe, 1992; Knipe and Lloyd, 1994). All thrust structures show substantial variations along strike; the site provides an excellent illustration of the lateral variations in thrust belts.

Coward (1984b) also mapped out thrust-related folds. These are particularly well developed within the carbonate rocks of the upper duplex where the fold axes trend NNW–SSE and the structures face SSW, highly oblique to the inferred thrusting direction. Coward interpreted these as forming within an important lateral ramp zone, which gave rise to a wrench-shear component of deformation during thrusting.

Description

Unlike the imbricate systems that are readily seen on the sparsely vegetated mountains of Arkle, Foinaven and Conamheall in northern Sutherland, those of western Assynt are not well appreciated from distant views. The Skiag Bridge GCR site lies astride a major strike swing in the thrust belt, from NNE–SSW and perpendicular to the inferred direction of thrusting on the southern side of the **Glencoul** GCR site, to NNW–SSE, parallel to the north-eastern shore of Loch Assynt. This swing coincides with a major variation in the content of imbricate slices that can be best appreciated by considering three transects along well-exposed stream sections (Johnson and Parsons, 1979).

The northern stream section (NC 234 256–NC 237 257) is dominated by Fucoid Beds. Coward (1984b) recognized ten repetitions of this member. Presumably the floor thrust to this system lies just within the Fucoid Beds and the section must intersect rather deep levels in the duplex. Only towards the upper, eastern reaches of the stream do carbonate rocks dominate the outcrop. Coward (1984b) suggested that this region contains the major detachment horizon that acted as a roof to the duplex (his 'system B') and a floor to an overlying duplex (his 'system A'). Overall there is a tendency within the imbricate slices of 'system B' to attain steeper bedding dips up-section. This implies that a process of back-steepening occurred during thrust stacking, as predicted by the 'piggy-back' thrusting model.

The central stream section (NC 235 249–NC 238 255) is the best transect in which to appreciate stratigraphical repetition through thrust imbrication in this segment of the thrust belt. Coward (1984b) recorded 15 such

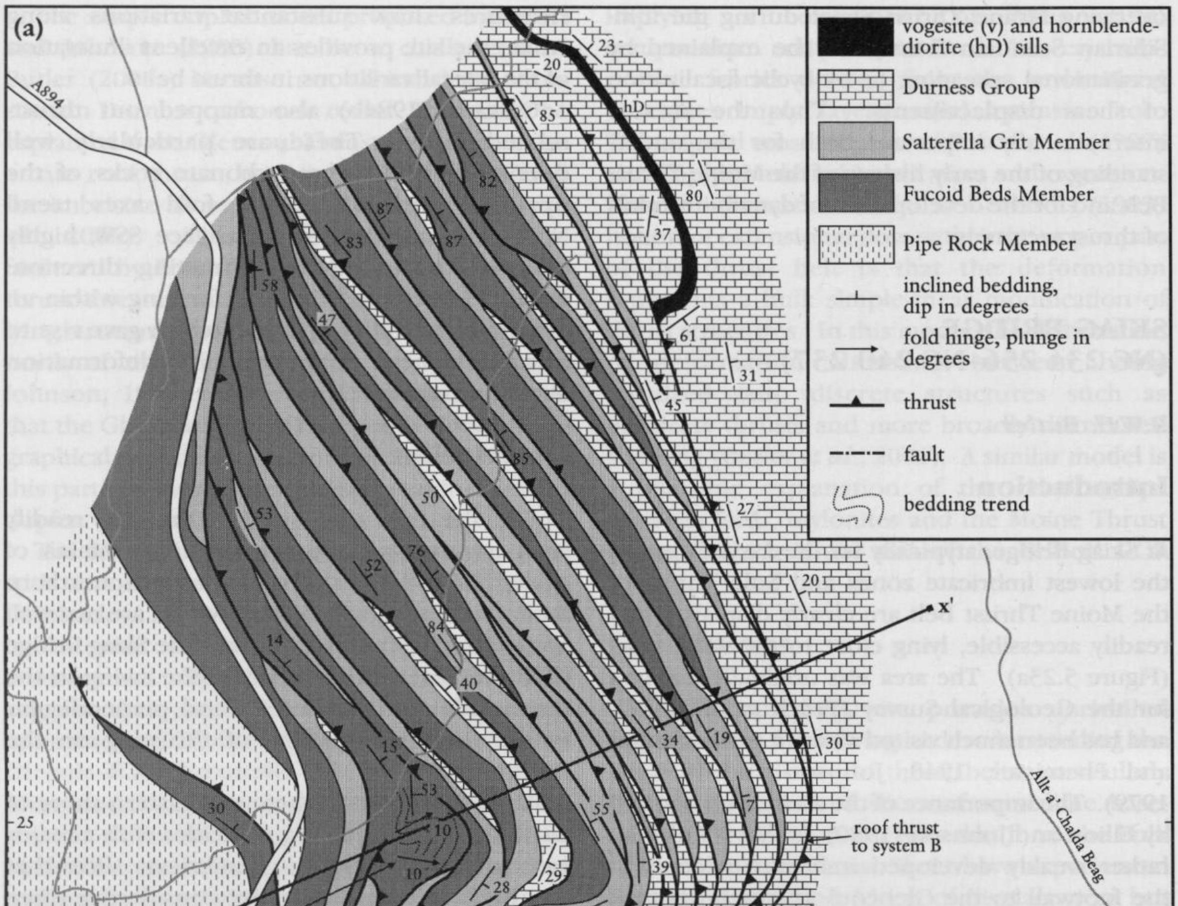


Figure 5.23 (a) Map of the imbricate thrust slices north of Skiag Bridge. After Coward (1984b). *Continued opposite.*

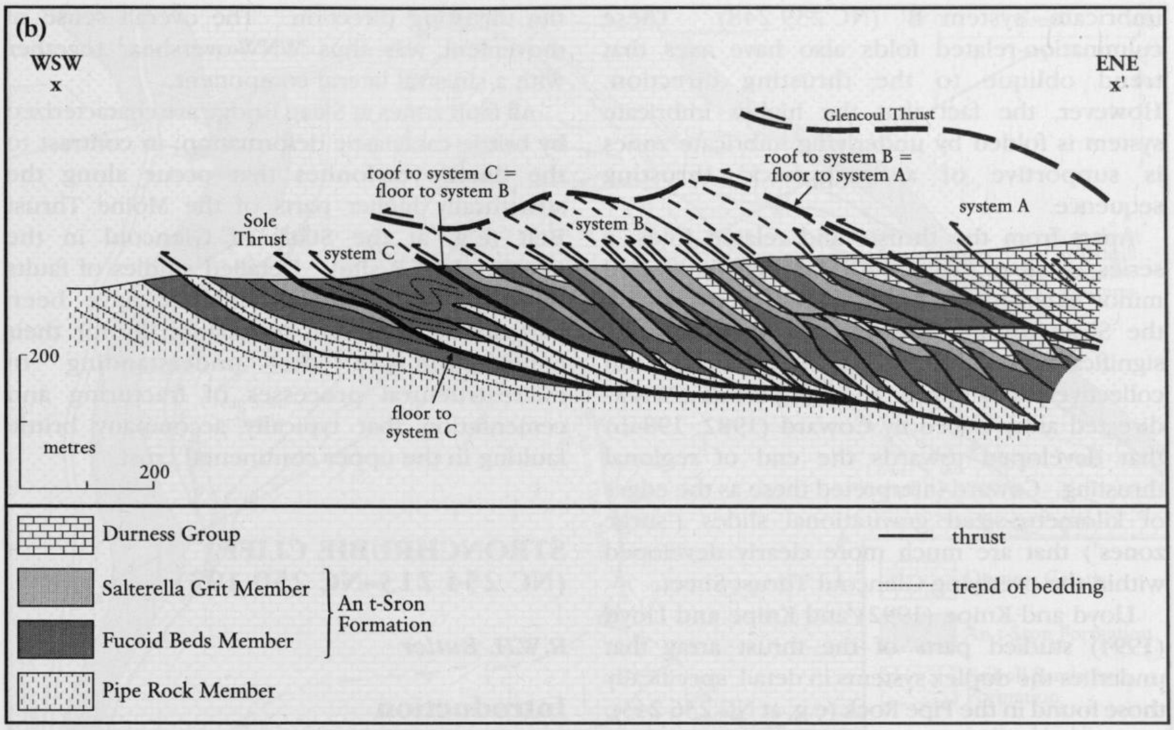


Figure 5.23 – *continued*. (b) Cross-section through the Skiag Bridge GCR site. Location x–x' on (a). Note that the line of secton is oblique to the direction of thrusting.

repetitions, in which the Salterella Grit (with a stratigraphical thickness of less than 8 m) is encountered 13 times in 1 km on the ground. This geometry (Middle Duplex or Coward's 'system B') underpins the generalized cross-section of Figure 5.23b.

The southern stream section (Allt a' Chalda Beag; NC 241 237–NC 243 243) contains only imbricated Durness Group carbonate rocks and lamprophyre sills of Coward's 'system A'. The strata and thrusts occur in folds that face south-west and have NNW-trending axes. Both the Ghrudaidh and Eilean Dubh formations are represented, the former dominating the lower outcrops while the latter is more prevalent at higher structural levels. These observations suggest that the duplex has a floor just a few metres up into the Ghrudaidh Formation and a roof within the Eilean Dubh Formation. The floor thrust level is maintained farther south in the ground around Inchnadamph (e.g. the **Stronchrubie Cliff** GCR site) suggesting that these lowest parts of the Durness Group carbonate succession acted preferentially as a weak detachment horizon during thrusting.

Interpretation

The stratigraphical content of the three duplex systems within and adjacent to the Skiag Bridge GCR site varies laterally along the thrust belt. Overall, the Sole Thrust climbs up the stratigraphical section to the south. At the **Stronchrubie Cliff** GCR site, 3 km to the SSE, the imbricate slices contain only carbonate rocks of the Eilean Dubh Formation. In contrast, for the areas north of the Skiag Bridge GCR site it is the base of the Fucoid Beds that is the principal basal detachment horizon. The major lateral ramp inferred from the stratigraphical content of duplexes at Skiag Bridge is mirrored in a zone of folds that are well displayed by Coward's 'system A'. The SW-facing folds appear to be rotated counterclockwise and their development may reflect a component of sinistral wrenching. These folds, presumably formed at the oblique tips of propagating thrusts, are especially well displayed just east of the Allt a' Chalda Beag (NC 243 239). Elsewhere, folds in the carbonate rocks may be related to underlying thrust stacks, for example the lateral culminations in Coward's imbricate 'system B' (NC 239 248). These culmination-related folds also have axes that trend oblique to the thrusting direction. However, the fact that the higher imbricate system is folded by underlying imbricate zones is supportive of a 'piggy-back' thrusting sequence.

Apart from the thrusts and related folds, a series of steep, apparently wrench faults and minor extensional structures also occur within the Skiag Bridge GCR site. The nature and significance of these structures is unclear, but collectively they appear to form part of a WNW-directed array traced by Coward (1982, 1984b) that developed towards the end of regional thrusting. Coward interpreted these as the edges of kilometre-sized gravitational slides ('surge zones') that are much more clearly developed within the overlying Glencoul Thrust Sheet.

Lloyd and Knipe (1992) and Knipe and Lloyd (1994) studied parts of the thrust array that underlies the duplex systems in detail, specifically those found in the Pipe Rock (e.g. at NC 236 243). These late thrusts developed by brittle processes but grain-fracturing processes were accompanied by crystal plasticity and pressure solution. These studies have underpinned subsequent microstructural analyses of upper crustal faults, particularly from oil-prone sedimentary basins.

Conclusions

The Skiag Bridge GCR site provides easily accessible exposures of thrust-related stratigraphical repetitions and related folds. There are over 12 repetitions of individual units exposed in stream sections, giving rise to complex thrust-belt geometries. The structurally higher imbricate systems are folded by the underlying ones, suggesting an overall foreland-directed ('piggy-back') thrusting sequence. Comparisons between different transects through the site imply that an important lateral ramp exists on the regional Sole Thrust, climbing up-section from north to south, from the base of the Fucoid Beds of the An t-Sron Formation to just within the Ghrudaidh Formation of the Durness Group. This ramp zone was long-lived during the formation of thrust structures hereabouts and has strongly influenced the geometry of thrust-related folds, inferred thrust ramps, and associated culminations, which are all aligned oblique to the thrusting direction. The overall sense of movement was thus WNW-overshear together with a sinistral lateral component.

All fault zones at Skiag Bridge are characterized by brittle cataclastic deformation, in contrast to the ductile mylonites that occur along the structurally higher parts of the Moine Thrust Belt (e.g. at the Stack of Glencoul in the **Glencoul** GCR site). Detailed studies of faults within the Pipe Rock Member have been particularly important internationally for their contribution to the understanding of microstructural processes of fracturing and cementation that typically accompany brittle faulting in the upper continental crust.

STRONCHRUBIE CLIFF (NC 254 213–NC 250 193)

R.W.H. Butler

Introduction

The Assynt district of the Moine Thrust Belt is justly famous for its large-scale thrust structures with three-dimensional geometries that can be inferred from the geological maps and cross-sections of the area (e.g. Peach *et al.*, 1907; British Geological Survey, 2007). The major thrust sheets that are represented in the more-mountainous parts of the district are generally well exposed. However, evidence for the internal structure of imbricate thrust systems is only rarely seen. Exceptions to this are the sections immediately south of Inchnadamph, represented by the Stronchrubie Cliff and **Traligill Burn** GCR sites (Figure 5.24). Together, these two sites provide a useful insight into thrust structures developed exclusively within Durness Group carbonate rocks. Both sites lie within the lower imbricate zone of the central Assynt area, and the basal thrust to this imbricate system, the Sole Thrust, lies just beneath the Stronchrubie Cliff.

Although examples of imbricate thrusts are probably best displayed in the **Foinaven** and **Beinn Liath Mhor** GCR sites, these Assynt localities have been visited frequently by geological field parties, not least because of their ready accessibility to the Inchnadamph Hotel (e.g. MacGregor and Phemister, 1948; Johnson and Parsons, 1979). The Stronchrubie Cliff is especially helpful because its geological structure is well appreciated from the A837 road

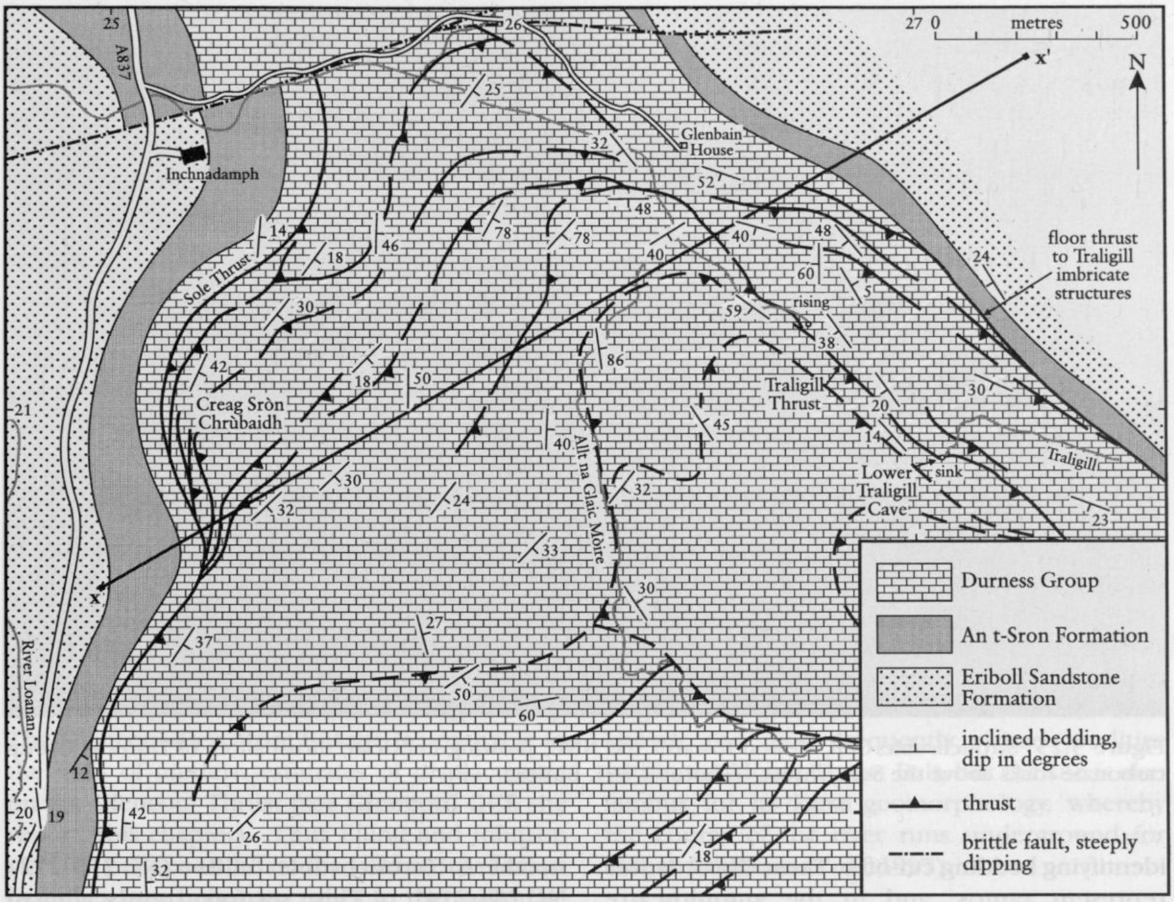


Figure 5.24 Map of the area south-east of Inchnadamph showing the relationship between the Stronchrubie Cliff and **Traligill Burn** GCR sites. Structure in Durness Group rocks modified from British Geological Survey (2007).

(Figure 5.25). The area is also of great importance for its caves and karst geomorphology (Waltham *et al.*, 1997), and for occurrences of sills of the North-west Highlands Minor Intrusion Suite that were intruded prior to thrusting (Parsons, 1999; Goodenough *et al.*, 2006).

Description

The A837 road just south of Inchnadamph runs along a bench of poorly exposed ground characteristic of the underlying Fucoid Beds. These strata, together with the overlying Salterella Grit, comprise the An t-Sron Formation and form the upper part of the undeformed foreland Cambro–Ordovician succession in this area. Above and east of the road is the 120 m-high escarpment of Stronchrubie Cliff that provides a continuous 2 km-long section (Figure 5.25). The structure of the southern part of the cliff as seen from the road seems deceptively simple, since it is evidently a near-strike section. The lower part of the escarpment contains rocks of the lowest formation of the Durness Group, the Ghrudaidh Formation. These dolostones, together with a laterally continuous sill of vogesite (hornblende-rich lamprophyre), dip gently to the ESE. The upper part of the cliff contains carbonate rocks of the Eilean Dubh Formation; although this formation succeeds the Ghrudaidh Formation stratigraphically, these strata dip more steeply at 50°–60° to the ESE, indicating a structural discontinuity between the two formations. This discontinuity is the Sole Thrust. The relationship between the two dip domains is most clear on the northern wall of a broad natural amphitheatre in the Stronchrubie cliff-line between NC 252 209 and NC 254 207 (Johnson and Parsons, 1979; Butler, 1988b) (Figures 5.24, 5.26).

Above the Sole Thrust, individual thrusts of the imbricate zone may be inferred by

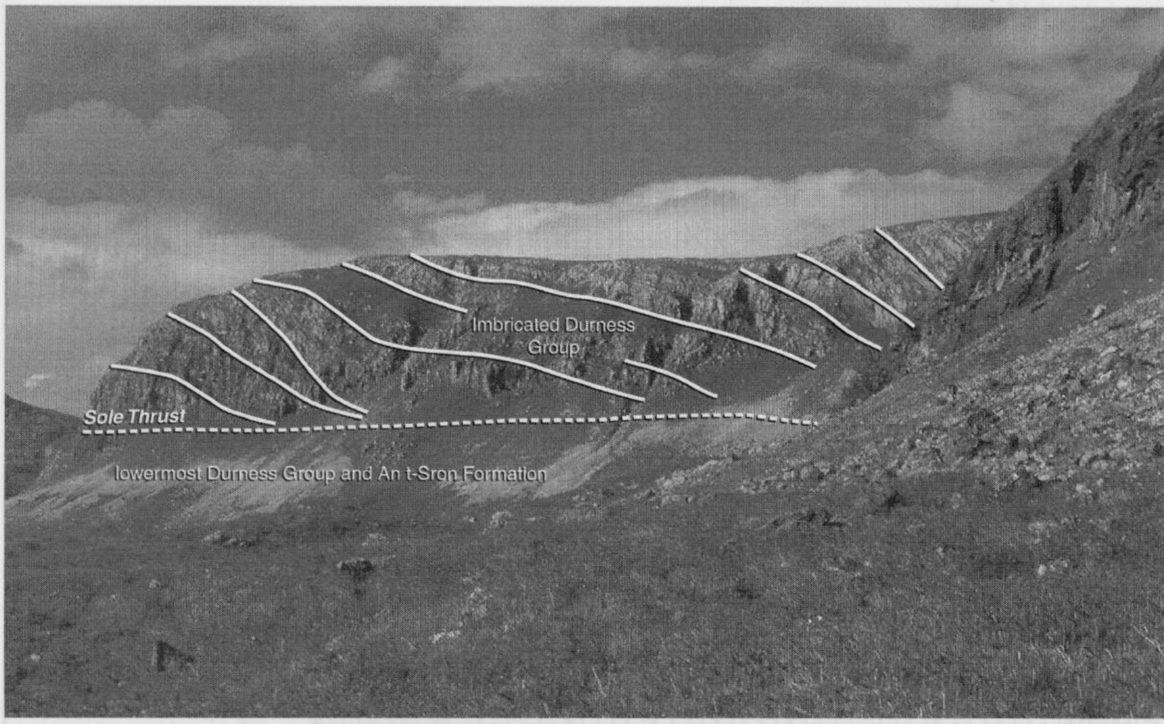


Figure 5.25 Stronchrubie Cliff, viewed towards the NNE, showing imbricate thrust slices of Durness Group carbonate rocks above the Sole Thrust. (Photo: R.W.H. Butler.)

identifying bedding cut-offs. These discordances represent ramps, and in the amphitheatre these ramps lie in the footwall to each inferred imbricate thrust. Seven such thrust slices can be identified (Figure 5.24), with bedding becoming increasingly steep in the more-internal and structurally higher slices. Imbricate thrusts may also be identified from bedding cut-offs in the northern Stronchrubie cliffs (NC 253 212–NC 254 214). This section trends almost perpendicular to the inferred direction of thrusting so that the ramps are presumably lateral or oblique (Figure 5.26). Higher thrust slices can be traced and are visibly folded by underlying imbricate structures, indicative of 'piggy-back' thrusting.

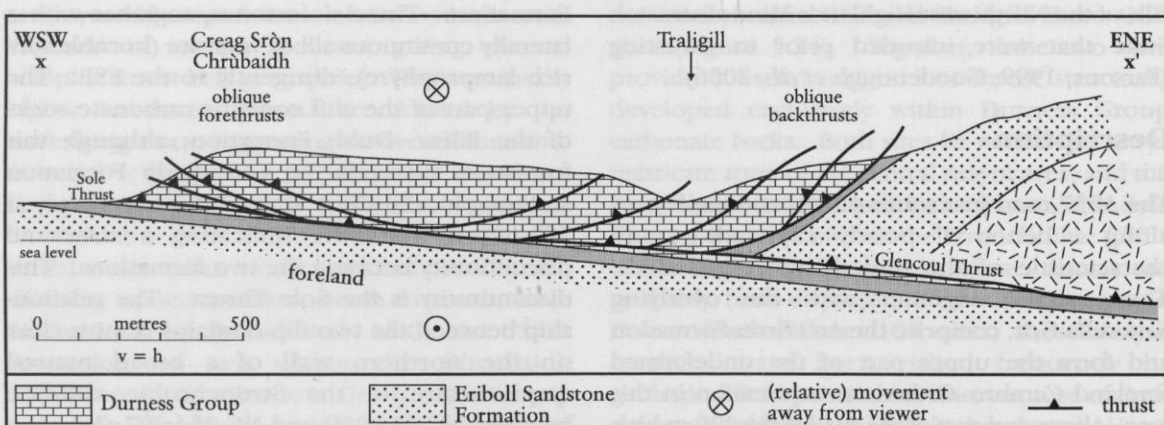


Figure 5.26 Cross-section (x–x' on Figure 5.24) drawn near-orthogonal to the inferred thrust transport direction, illustrating the thrust geometries at the Stronchrubie Cliff and **Traligill Burn** GCR sites.

Interpretation

The imbricate thrusts in the Stronchrubie cliffs are all interpreted as splays from the Sole Thrust that acted as the floor thrust. Although this basal thrust is not exposed, its presence is readily inferred because the underlying strata are clearly not involved in the imbrication. A more-complete three-dimensional picture of this imbricate system can be gained by considering outcrops in the Traligill Valley (Figures 5.24, 5.25) (see 'Interpretation', **Traligill Burn** GCR site report, this chapter).

The linkages between major thrusts and imbricate systems in the Inchnadamph district have long been controversial. Peach *et al.* (1907) joined the Glencoul Thrust to the Ben More Thrust by running it across the Allt Poll an Droighinn, an arrangement also followed essentially by Christie (1963). This view was contested by Bailey (1935), who considered the Glencoul Thrust to terminate roughly at the Allt Poll an Droighinn, well north of Traligill Valley. The Glencoul–Ben More linkage is untenable in the light of modern estimates of displacement on the Glencoul Thrust (see **Glencoul** GCR site report, this chapter). Thus Elliott and Johnson (1980) proposed that the Glencoul Thrust branches into imbricate zones in the carbonate rocks to the south of the Traligill Valley. A more-radical solution was proposed by Coward (1982, 1984b) who considered the base of the Glencoul Thrust Sheet and the fault exposed in the Traligill Burn GCR site to be extensional features that cut across the Glencoul Thrust and imbricate zones.

Conclusions

The thrust structures admirably exposed in the carbonate rocks of the Durness Group to the south and east of Inchnadamph represent duplexes that are detached along the Sole Thrust and accommodate displacements arising from the Glencoul Thrust. The Stronchrubie Cliff GCR site provides an important insight into the internal architecture of bedding and thrusts within the lower part of a duplex. Together with the nearby GCR sites at **Traligill Burn** and **Skiag Bridge**, the site is representative of the most westerly, structurally lowest, imbricate structures in Assynt. These areas are critically important for understanding the three-dimensional geometry of these imbricate structures and their relationship to the major Glencoul Thrust. They also have a more-general value for elucidating how displacements transfer across thrust systems. The Stronchrubie Cliff GCR site is nationally important and remains excellent for teaching purposes.

TRALIGILL BURN (NC 265 213–NC 271 209)

R.W.H. Butler

Introduction

Although the **Stronchrubie Cliff** GCR site provides an insight into the structural geometry of imbricate stacks, the individual thrust surfaces are not accessible. However, at the neighbouring Traligill Burn GCR site, 2 km ESE of Inchnadamph, the seasonally dry river-bed has excavated an actual thrust surface within the lower imbricate zone of the central Assynt area (Figures 5.24, 5.27). This is one of the best-known and most frequently visited localities within the Moine Thrust Belt, but the site is also famous for its karst geomorphology, whereby the course of the river runs underground for 400 m (Waltham *et al.*, 1997).

Description

On the northern side of the dry valley of the River Traligill is a bedding-plane surface of dolostones, which dips at 20°–25° to the south-west (Figure 5.27). These pale-grey dolostones belong to the Eilean Dubh Formation of the Durness Group and form the footwall to the Traligill Thrust. The thrust itself is marked by readily eroded carbonate gouge, and a few centimetres of breccia, and also dips at 20°–25° to the south-west. In contrast, the hangingwall to the thrust is marked by more gently inclined (10°–15°) dark-grey dolostones of the Ghrudaidh Formation, which is stratigraphically below the Eilean Dubh Formation. These relationships are indicative of a hangingwall-ramp upon footwall-flat fault geometry, and the older-upon-younger stratigraphical separation is diagnostic of thrusting.

Interpretation

Although the basic description of the imbricate thrust at Traligill is straightforward, there are

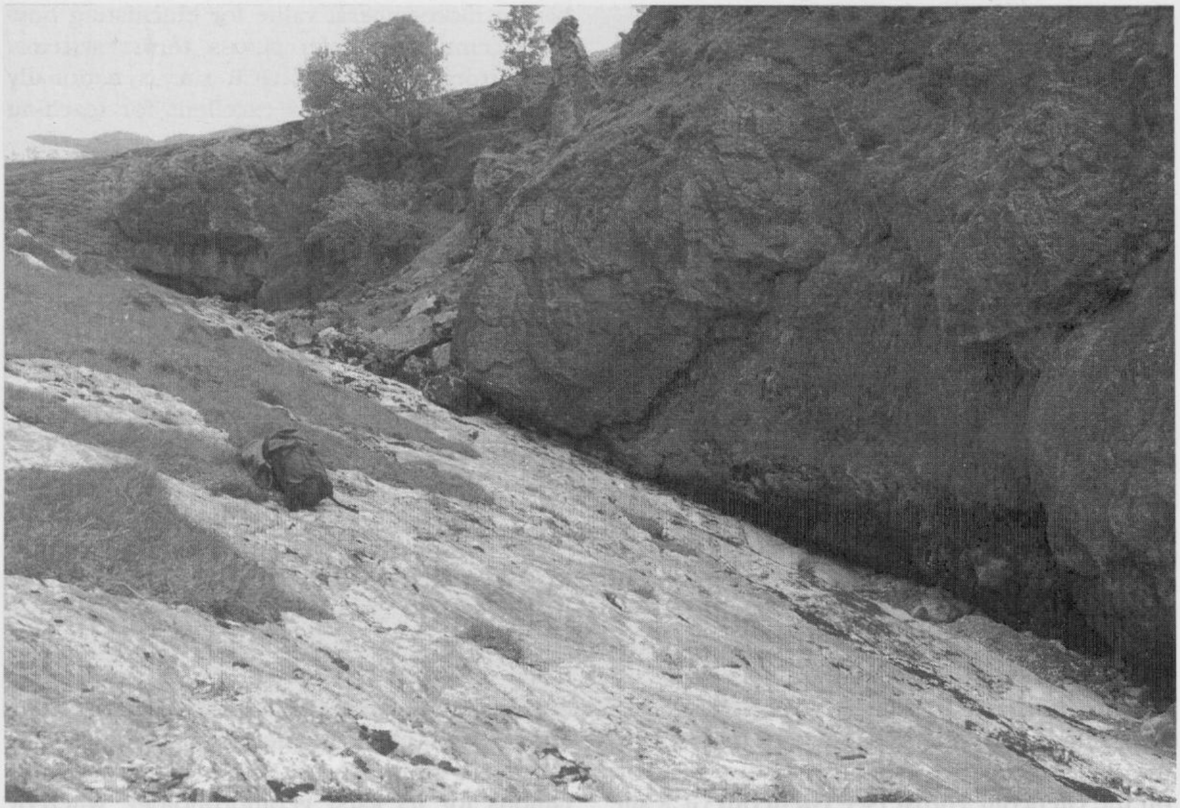


Figure 5.27 Thrust at Traligill Burn, carrying dark dolomites of the Ghrudaidh Formation onto pale carbonate rocks of the Eilean Dubh Formation. Viewed looking along strike towards the ESE. (Photo: R.W.H. Butler.)

complexities. The strike trend is north-west–south-east, and the area forms part of a WNW-trending zone of oblique structures traced by Coward (1984b) and interpreted as having formed by major sinistral wrench faulting. The zone can be traced though to the Sole Thrust at Loch Assynt (Figure 5.24), and links with the similar structural trend at the **Skiag Bridge** GCR site. The relationships of the strata at the imbricate thrust are more compatible with oblique back-thrusting than with simple WNW-directed thrusting. The south-west dips suggest that the structure overlies the cover to the Lewisian gneisses of the Glencoul Thrust Sheet. These features are indicated on the cross-section (Figure 5.25), which is constructed normal to the thrusting direction. It shows the Glencoul Thrust transferring displacement laterally into the imbricate zones of Durness Group carbonate rocks such as those exposed in the **Stronchrubie Cliff** GCR site. In essence, this is the model of Elliott and Johnson (1980), although Figure 5.25 also shows the back-thrust nature of the Traligill thrust systems. This arrangement has the advantage of being able to explain local field relationships more adequately and account for the large displacements across this part of the thrust belt, as implied by offset correlations in the Glencoul Thrust Sheet (Coward *et al.*, 1980).

Conclusions

The Traligill Burn GCR site, together with the nearby GCR site at **Stronchrubie Cliff**, is representative of the most westerly and structurally lowest imbricate structures in Assynt. It is nationally important in that it provides ready access to the surface of a thrust plane, which separates carbonate rocks belonging to different formations of the Durness Group. Clay-rich gouge material and breccia associated with the thrusting can be seen. The structures can be traced into those of the Stronchrubie Cliff GCR site, and together the two sites enable the three-dimensional geometry of these imbricate structures and their relationship to the major Glencoul Thrust to be determined.

BEN MORE ASSYNT–CONIVAL–NA TUADHAN (NC 300 220–NC 324 198)

R.W.H. Butler

Introduction to the Ben More Thrust

Of all the segments of the Moine Thrust Belt, it is the Assynt district that is the best known internationally. Two major thrust sheets occur in the Assynt district, the Glencoul Thrust Sheet and the overlying Ben More Thrust Sheet, both containing Lewisian gneiss in addition to Cambro–Ordovician rocks. The critical relationships of the Glencoul Thrust are described in the **Glencoul** GCR site report, this chapter (but see Krabbendam and Leslie, 2004; Butler *et al.*, 2006). The Ben More Thrust Sheet is represented in this GCR volume in two site reports that are closely linked; namely, the Ben More Assynt–Conival–Na Tuadhan GCR site and the **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site (Figure 5.28).

The Ben More Thrust Sheet contains Lewisian gneiss, Torridon Group strata and the lower part of the Cambro–Ordovician sequence. It also contains the 'double unconformity' between Lewisian basement and the two cover successions of Torridonian and Cambro–Ordovician sedimentary rocks. In the north, it overlies the Glencoul Thrust Sheet, whereas south of Ben More Assynt it overlies imbricate thrust slices dominated by quartzite and carbonate rocks that lie structurally underneath the Glencoul Thrust. In this area, a series of klippen occur, some of which are described in the **Cam Loch** GCR site report (this chapter). Some of these klippen probably form outlying parts of the Ben More Thrust Sheet, with the intervening ground since eroded.

The classic status of the Assynt district was promoted by the Geological Survey, initially through the preparation of a three-dimensional model exhibited in its offices and in museums, and then by the publication of the 1:63 360 geological map as an Assynt special sheet in 1923 (Geological Survey of Great Britain, 1923). It is only recently that selective remapping and integration of areas mapped during academic studies in the 20th century have resulted in a new 1:50 000-scale geological map (British Geological Survey, 2007). For much of the period following the original survey work of Peach *et al.* (1907) there was relatively little re-examination of thrust structures in the district. Interest was rekindled by attempts to use the igneous intrusions of south-central Assynt to date thrust activity (e.g. Woolley, 1970; van Breemen *et al.*, 1979a). Also, small areas were re-examined to elucidate the relationships between folds and thrusts, for example in the southern part of the Ben More Thrust Sheet (Milne, 1978). However, the work of the Geological Survey was finally re-interpreted on a larger scale by Elliott and Johnson (1980), and this, together with a general rise in interest in thrust tectonics, led to a spate of more-extensive studies in Assynt and throughout the thrust belt. However, the high ground of central Assynt (Figure 5.28) has remained unattractive for extensive modern structural investigations, presumably due to the combination of inaccessibility, poor weather and the perceived definitive status of the compilations by Peach *et al.* (1907). However, the area is frequently visited and is well covered by field guides (Johnson and Parsons, 1979; Allison *et al.*, 1988).

Introduction to the Ben More Assynt–Conival–Na Tuadhan GCR site

The Ben More Assynt–Conival–Na Tuadhan GCR site, in conjunction with the grouped sites at **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel**, provides a coherent picture of the thrust-dominated geology of central Assynt, particularly concerning the continuity of the Ben More Thrust and the evolution of structures in its hangingwall (Figures 5.28, 5.29). These structures have played a pivotal role in interlacing the tectonic and igneous events and hence in establishing a chronology of deformation in north-west Scotland (see Parsons, 1999). North of Loch Bealach a' Mhadaidh, the course of the Ben More Thrust is unclear, and Peach and Horne, Clough (in Peach *et al.* 1907), Bailey (1935), Elliott and Johnson (1980) and Krabbendam and Leslie (2004) propose different traces of the thrust in this complicated ground. However, on Na Tuadhan and farther south, the Ben More Thrust is a very clear and unambiguous thrust structure with spectacularly exposed fold structures in its hangingwall. It is also responsible for repetition of the Cambrian quartzite sequence, so that the western slope of Conival (as seen for instance from Inchnadamph) is a high wall of quartzite.

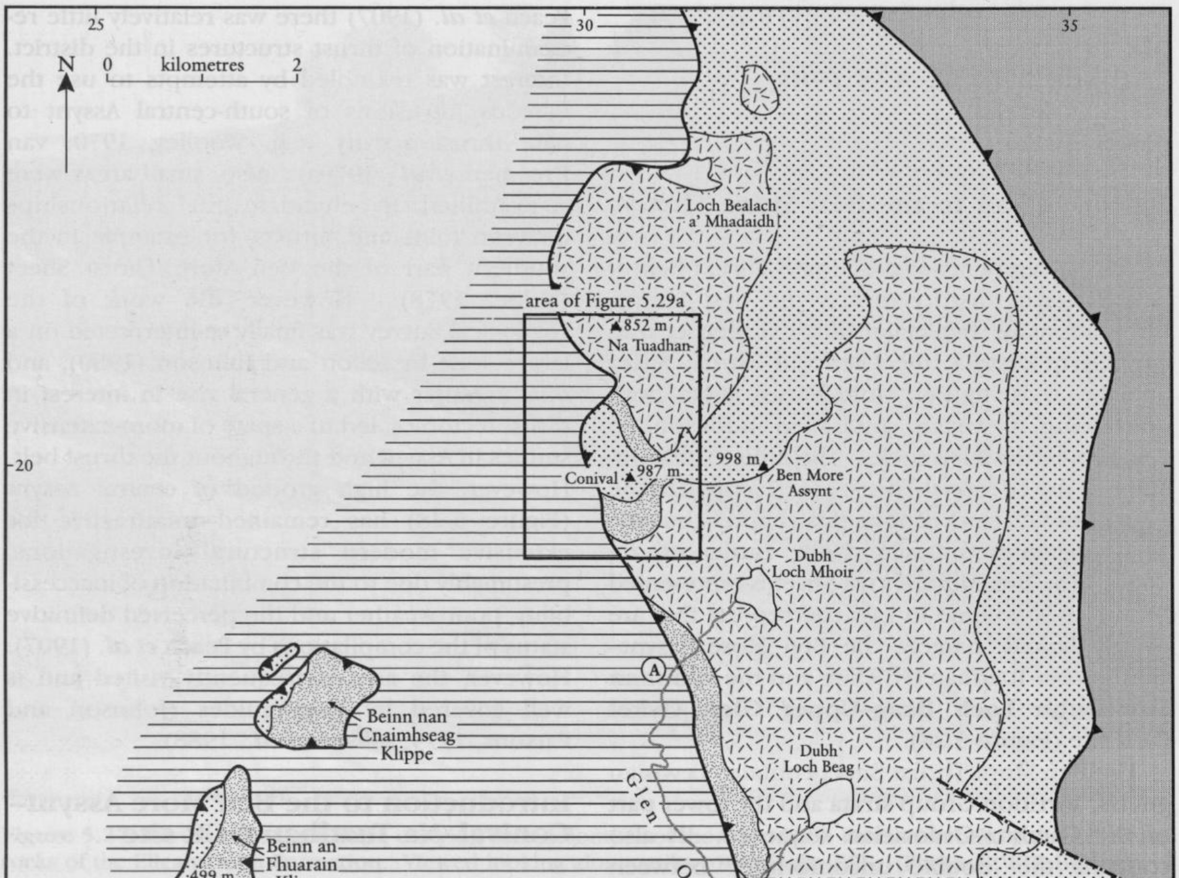


Figure 5.28 Map of the Ben More Thrust Sheet in the Assynt District of the Moine Thrust Belt. A = Allt an Dubh Loch Mhoir. The locations of Figures 5.29a and 5.31a are indicated. After British Geological Survey (2007).

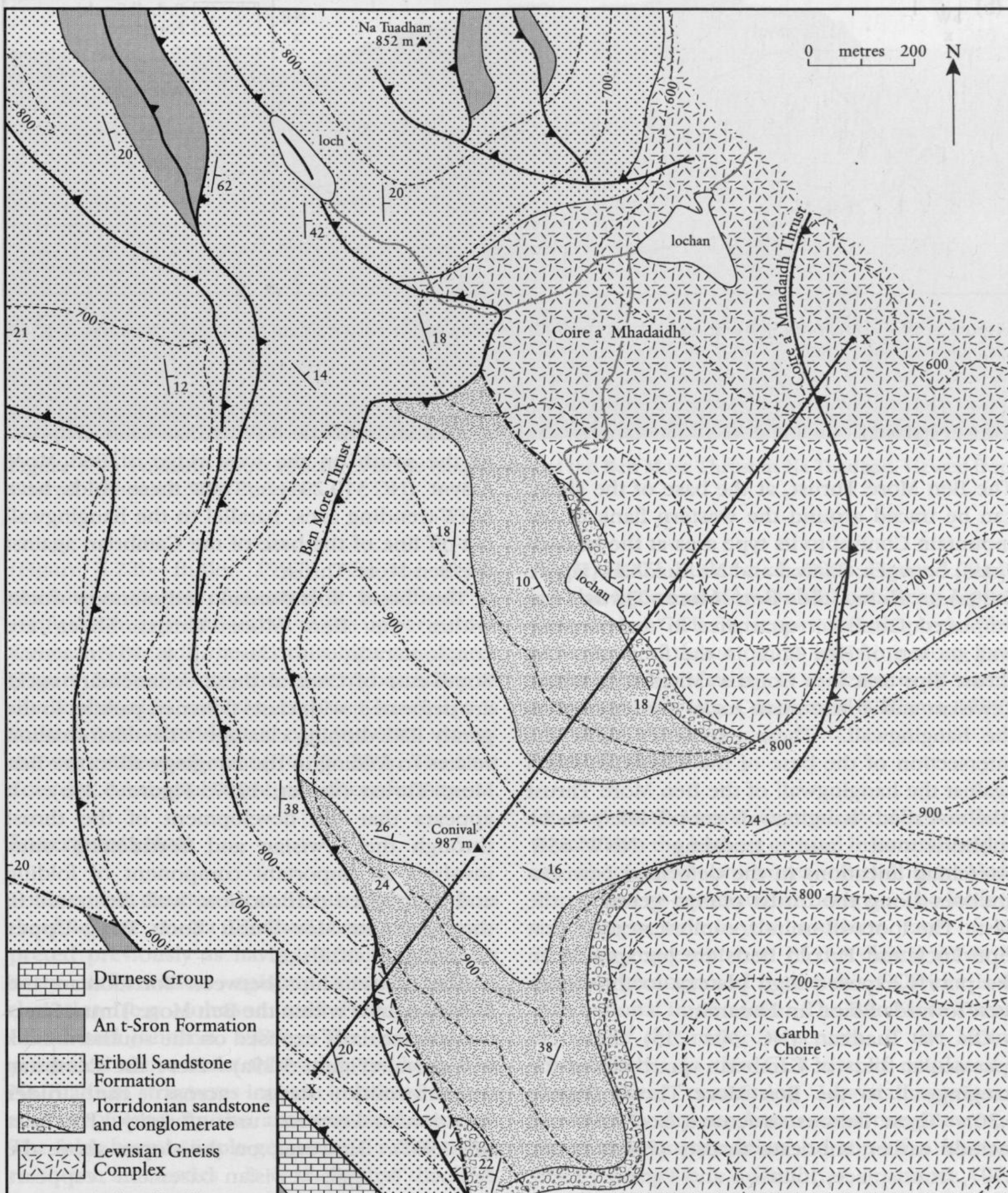


Figure 5.29 (a) Map of the Ben More Thrust Sheet at Conival. Location shown on Figure 5.28. Topographical contours in metres. After Butler (1997). *Continued overleaf.*

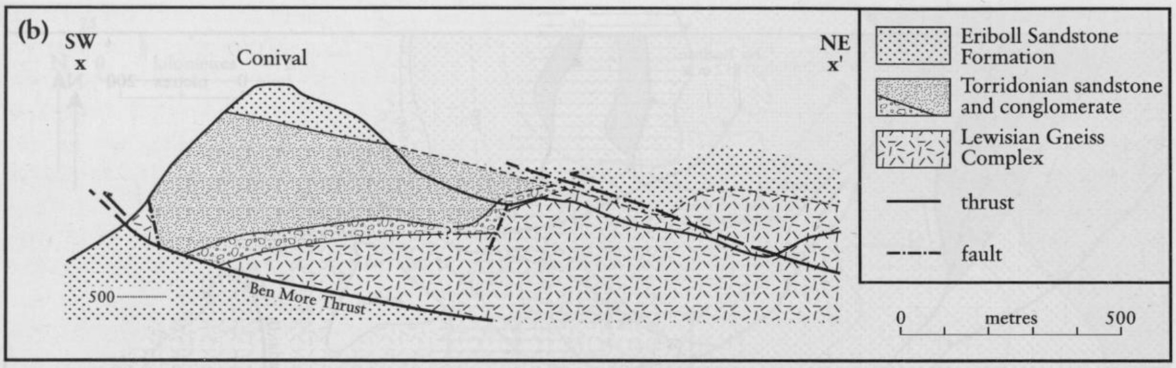


Figure 5.29 – *continued*. (b) Cross-section through the Ben More Thrust Sheet at Conival (location: x–x' on (a). After Butler (1997).

Description

The Ben More Thrust, at the base of the sheet, can be traced around the western flank of the mountain Conival to its type area at the bealach (pass) between Conival and Na Tuadhan (Figure 5.29a). Here, the Ben More Thrust has emplaced Cambrian quartzites in the hangingwall on top of Pipe Rock in the footwall. The thrust dips east into Coire a' Mhadaidh, where Lewisian and Torridonian rocks are exposed in the hangingwall. These exposures show the intersection of the base of the Cambrian strata against the hangingwall of the Ben More Thrust (the so-called 'hangingwall cut-off line') to be subhorizontal and trending NNW–SSE. Stretching lineations in the deformed Lewisian gneisses along the thrust plunge gently to the east. The footwall units are imbricated, so that Pipe Rock and Fucoid Beds are juxtaposed on the poorly exposed high plateau to the north-west towards Beinn an Fhuarain.

On Na Tuadhan (NC 304 215) there are spectacular folds of Cambrian quartzites in the hangingwall to the Ben More Thrust (Figure 5.30). These famous structures face WSW and include earlier imbricate thrusts (Peach *et al.*, 1907, frontispiece; Johnson and Parsons, 1979, fig. 7). The imbrication has carried the quartzites onto poorly exposed Fucoid Beds by a combination of fore- and back-thrusts. The imbricate thrusts splay from a floor thrust, named here the 'Coire a' Mhadaidh Thrust', that can be mapped across the corrie to where Lewisian gneisses have been carried over a thin slice of Cambrian quartzites (NC 310 205). Presumably the Coire a' Mhadaidh Thrust itself splays from the Ben More Thrust at depth. The continuation of the Na Tuadhan folds crop out to the south on the west ridge of Ben More Assynt (NC 310 201). Thus these folds have NNW-trending axes, parallel to the hangingwall cut-off line of the base of the Cambrian against the Ben More Thrust.

The basal Torridonian sedimentary rocks within the Ben More Thrust Sheet are conglomeratic, with clasts up to 10 cm across. South-east of Conival these sedimentary rocks are deformed, with clasts flattened parallel to the gently ENE-dipping cleavage. This deformation relates to folding in the hangingwall to the Ben More Thrust (Butler, 1997; Figure 5.29b). It appears that the development of the thrust through the Lewisian and Torridonian units involved an important component of folding and distributed deformation, well illustrated in the **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site.

The relationships between Torridonian and Lewisian units within the Ben More Thrust Sheet are spectacularly exposed on the southern flank of Conival (Figure 5.29a). Here the Cambrian unconformity steps across the older Torridonian–Lewisian unconformity (Peach *et al.*, 1907). However, on the slopes above the Bealach Traligill, Lewisian basement reappears at NC 302 195. The basal conglomeratic facies of the Torridonian abut this Lewisian slice, consistent with a faulted contact. Milne (1978) attributed these relationships to thrusting. However, the sub-Cambrian unconformity above, on Conival, shows no such deformation. Another explanation is that the Torridonian has been downthrown against the Lewisian by a normal fault that pre-dates both the Ben More Thrust and the sub-Cambrian unconformity

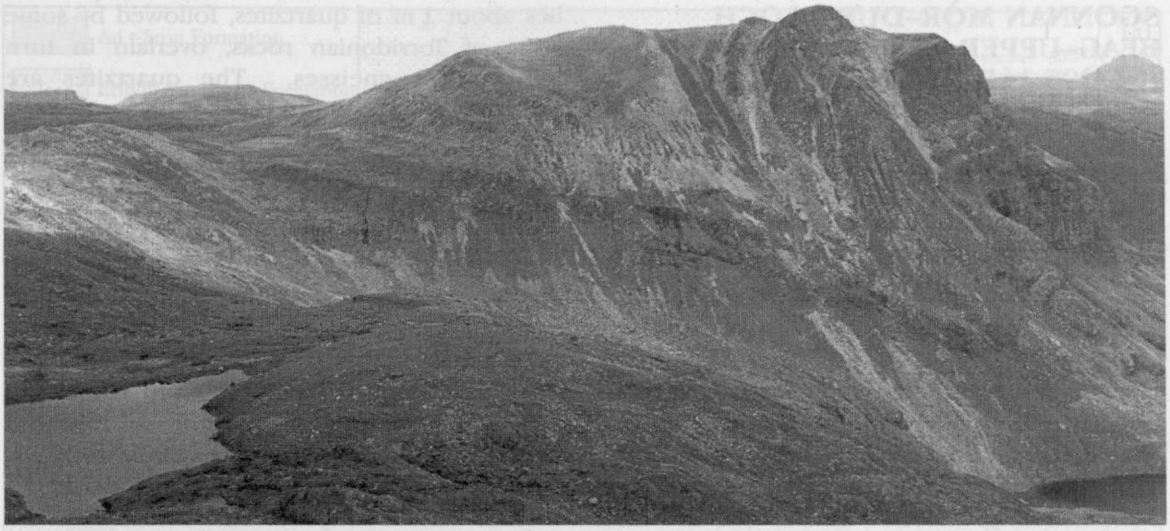


Figure 5.30 Fold and thrust structures in the hangingwall of the Ben More Thrust at Na Tuadhan, viewed from Conival. (Photo: R.W.H. Butler.)

(Figure 5.22b; Butler, 1997). On the steep, south-west slopes of Conival it is difficult to verify this interpretation but in the upper part of Coire a' Mhadaidh the relationships are clearer (Figure 5.29a). Here, the eastern boundary of the Torridonian with the Lewisian basement is faulted, with Torridonian conglomerate downthrown to the south-west (NC 303 209). The fault does not cut the sub-Cambrian unconformity.

Interpretation

Folds within the Ben More Thrust Sheet, such as the fold pair on Na Tuadhan, have been interpreted previously as having formed during an early deformation episode that pre-dated thrusting (e.g. Johnson and Parsons, 1979; Elliott and Johnson, 1980). The observations presented above make this rather unlikely. The Na Tuadhan structures include imbricate thrusts that are folded by the antiform–synform pair. The folds have a simple geometrical relationship to thrust kinematics. It is likely that the folds formed during the growth of the thrust ramp that formed as the Ben More Thrust climbed from basement into the Cambrian cover. Throughout the central Assynt area the Ben More Thrust is characterized by heavily deformed Torridonian sedimentary rocks and possibly by Precambrian faults in its hangingwall. It is tempting to speculate that the ramp climbing up out of the Precambrian rocks was controlled by pre-existing basin structures (Butler, 1997; Butler *et al.*, 2006; Figure 5.29a,b; see also **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site report, this chapter). This behaviour, of thrust ramps initiating along pre-existing basin faults, is a feature of many mountain belts (e.g. Cooper and Williams, 1989).

Conclusions

On Ben More Assynt, Conival and Na Tuadhan, which form the highest ground in central Assynt, are spectacular exposures of the Ben More Thrust and its associated structures. The folds in the hangingwall in the southern face of Na Tuadhan represent one of the classic views of Scottish geology, and hence this GCR site is of international importance. The Ben More Thrust is one of the major structures of the Moine Thrust Belt. In this GCR site, it emplaced a thrust sheet containing Lewisian gneisses, Torridon Group sandstones and conglomerates and Cambrian quartzites on top of a footwall mainly composed of Cambrian quartzites. The famous 'double unconformity' – between the Lewisian gneisses, Torridonian and Cambrian strata – also occurs in this GCR site. Exposures in its type area around the head of Coire a' Mhadaidh are critical in relating the geometry of the thrust to structures developed in the hangingwall of the Ben More Thrust. Folding was related to thrust stacking and to buckling, as thrust ramps climbed out of the Lewisian basement into the Cambrian cover.

SGONNAN MÒR–DUBH LOCH BEAG–UPPER GLEN OYKEL (NC 295 145–NC 298 132, NC 316 155–NC 320 160, NC 308 180–NC 312 185)

R.W.H. Butler

Introduction

The three separate areas that make up the Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel GCR site provide exposures of the Ben More Thrust and its associated structures (Figure 5.28). This site report should be read in conjunction with that on the adjacent **Ben More Assynt–Conival–Na Tuadhan** site and the 'Introduction to the Ben More Thrust'. The folds in the hangingwall of the thrust at this site (and at Na Tuadhan) have been important in defining the temporal relationship between individual major thrusts and the Loch Ailsh Pluton, and thus in determining the relative and absolute timing of thrust displacements. Elliott and Johnson (1980) correlated these so-called 'Sgonnan Mòr structures' as a single deformation episode, so that intrusion events could be linked to thrusting. However, the use of such structural correlations can be erroneous and hence yield unreliable results (see also **Foinaven** GCR site report, this chapter). Butler (1997) related these folds to the propagation of the Ben More Thrust, possibly nucleating on Precambrian normal faults that offset the Lewisian–Torridonian unconformity.

Description

In south-central Assynt, the Ben More Thrust crosses upper Glen Oykel, and structures associated with the thrust are exposed on either side of the glen. In its type area, just to the west of Ben More Assynt, the thrust sheet emplaces Lewisian and Torridonian rocks together with their cover of Cambrian quartzites over younger parts of the Cambrian quartzite sequence, which are intruded by pre-thrusting peralkaline rhyolite ('grorudite') sills. This thrust relationship is also clearly demonstrated in the stream section of the Allt an Dubh Loch Mhoir (NC 311 182, 'A' on Figure 5.28) in Upper Glen Oykel. Here the footwall lies in Durness Group carbonate rocks, which lie above a continuous, gently NE-dipping section of Pipe Rock, Fucoid Beds and Salterella Grit. Above the thrust lies about 1 m of quartzites, followed by some 30 m of Torridonian rocks, overlain in turn by Lewisian gneisses. The quartzites are presumed to be the lowest part of the Cambrian succession so that the hangingwall is an inverted stratigraphical sequence (cf. Milne, 1978). Uncertainty exists with this interpretation because of the intense deformation associated with the thrust, which has obscured sedimentary structures in the hangingwall strata. The footwall strata are metamorphosed, presumably not only by sills of vogesite (hornblende-rich lamprophyre), but also by the nearby Loch Borralan Pluton, so that the Durness carbonate rocks are now marbles. The thrust plane dips parallel to bedding in the footwall and to the mylonitic foliation in the overlying quartzites. It is marked by 10 cm of carbonate-rich gouge and brecciated marble. The quartzite mylonites contain an intense ESE-plunging mineral lineation. The mylonitic deformation, brecciation and presumably, all the displacement on the Ben More Thrust, post-date the igneous activity and metamorphism at this locality.

Folding and cleavage development in the hangingwall of the Ben More Thrust are well illustrated by outcrops around Bealach Choinnich (NC 296 146) on the west side of Glen Oykel (Figure 5.31). Here, a tight, W-facing fold, termed the 'Sgonnan Mòr Syncline' (Johnson, 1965), is cored by Torridonian sandstones and conglomerates (Butler, 1997). Its axial surface lies sub-parallel to the Ben More Thrust. The distinctive basal conglomerate unit of the Torridonian is missing from the inverted, upper limb on the northern slope of Sgonnan Mòr, suggesting a faulted contact. A similar faulted contact between Lewisian and Torridonian may be inferred on the normal limb of the syncline as exposed on the south side of Bealach Choinnich (Figure 5.31). Here the contact dips more steeply than bedding in the right-way-up Torridonian. The bedding is discordant and the facies is not conglomeratic. This inferred fault surface may be traced around the synclinal fold closure, implying that it originally had a southward downthrow (Butler, 1997).

Near the Allt Dubh Loch Beag, on the east side of Glen Oykel, the hinge zone of the Sgonnan Mòr Syncline is well exposed, partly in the stream section, partly in nearby roches moutonnées. On its western limb are flat-

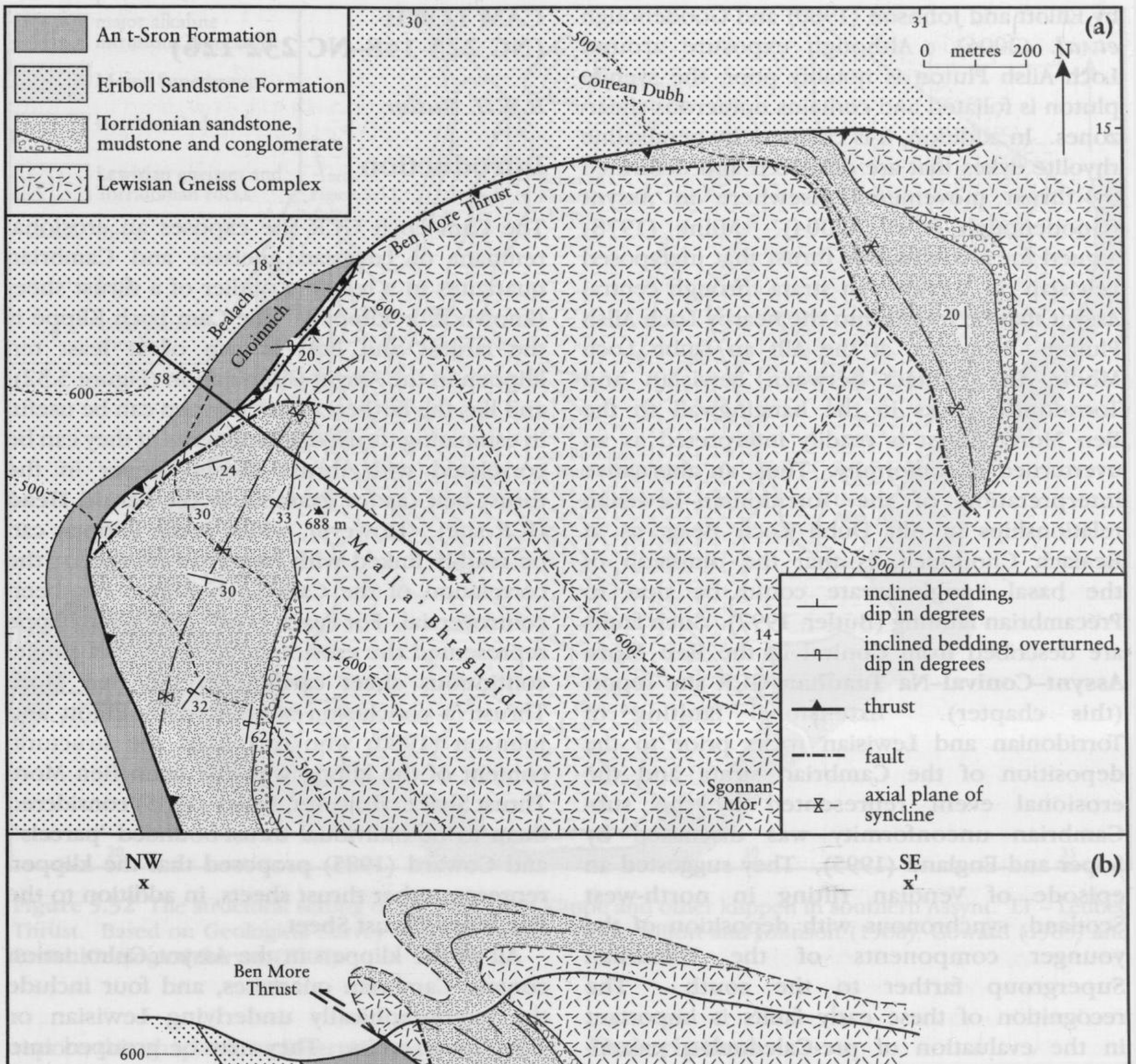


Figure 5.31 (a) Map of the Ben More Thrust Sheet at Bealach Choinnich, Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel GCR site (see Figure 5.28 for location). Topographical contours in metres. Two inliers of Torridonian strata are shown; the one south of the bealach was remapped by the author, whereas the map of the inlier near Coirean Dubh is modified after Milne (1978). (b) Sketch cross-section through the southern inlier (x–x' on (a)). The geometry of the sub-Cambrian unconformity (upper inferred boundary) is placed using adjacent outcrops farther to the south-east and at Bealach Choinnich. After Butler (1997).

lying Torridon Group basal conglomerates containing cobble-sized detritus; this limb is not strongly sheared. In contrast, the eastern limb is steep to overturned, with a narrow shear-zone.

Interpretation

The relationships between folds, thrusts and igneous intrusions within the Ben More Thrust Sheet are controversial and have been discussed by Elliott and Johnson (1980) and Goodenough *et al.* (2006). Although exposure around Loch Ailsh Pluton is notably poor, the syenite pluton is foliated and contains numerous shear-zones. In addition, it is cross-cut by peralkaline rhyolite dykes that are displaced and deformed by thrust movements elsewhere in Assynt (Goodenough *et al.*, 2004). Milne (1978) argued for a continuous thrust that juxtaposed Lewisian on Torridonian strata through central Assynt that he traced into the nearby Loch Ailsh Pluton. However, at the Allt an Dubh Loch Mhoir, the contact between Lewisian and Torridonian rocks in the hangingwall to the Ben More Thrust is readily interpreted as an overturned unconformity. Thus, an alternative interpretation of the Torridonian–Lewisian relationships at Allt Dubh Loch Beag, as at Bealach Choinnich, is that the omission of the basal conglomerate could be due to Precambrian faulting (Butler, 1997). Such faults are described from Conival in the **Ben More Assynt–Conival–Na Tuadhan** GCR site report (this chapter). Extensional faulting of Torridonian and Lewisian rocks prior to the deposition of the Cambrian strata and the erosional event represented by the sub-Cambrian unconformity was discussed by Soper and England (1995). They suggested an episode of Vendian rifting in north-west Scotland, synchronous with deposition of the younger components of the Dalradian Supergroup farther to the south. The recognition of these early faults is important in the evaluation of pre-Caledonian palaeogeography across northern Scotland and through the North Atlantic region.

Conclusions

The Ben More Thrust Sheet preserves critical relationships between Torridonian and Lewisian units that can best be explained in terms of Caledonian deformation acting upon pre-existing Precambrian extensional faults, probably formed during a period of Vendian rifting. Although the Loch Ailsh Pluton, which was intruded at *c.* 439 Ma, cross-cuts these early faults, it demonstrably pre-dates Caledonian folding and thrusting. These relationships, linked to radiometric age determinations, provide an important constraint on the timing of deformation within the Moine Thrust Belt.

CAM LOCH (NC 225 148–NC 232 126)

R.W.H. Butler

Introduction

The Cam Loch GCR site exposes an erosional remnant of Lewisian gneisses and Cambrian quartzites in a tectonic outlier of a thrust sheet (known as a 'klippe'). The Cam Loch Klippe is the largest and best known of at least ten klippen in the Assynt Culmination (Figure 5.32), and lies the farthest west. Klippen can be useful in estimating thrust displacements, if they can be correlated with thrust sheets deeper in the thrust belt (as for example in the **Faraid Head** GCR site). However, whilst some klippen can be readily linked with larger thrust sheets, the correlation of the Cam Loch Klippe has been controversial. For Peach *et al.* (1907), the klippe represented the erosional remnants of a single, continuous sheet carried on the Ben More Thrust, a conclusion supported by Elliott and Johnson (1980) who correlated the structural content of the klippe with the main Ben More Thrust Sheet. However, Bailey (1935) considered them to be individual thrust-bounded 'parcels', and Coward (1985) proposed that the klippen represent other thrust sheets, in addition to the Ben More Thrust Sheet.

All of the klippen in the Assynt Culmination contain Cambrian quartzites, and four include the stratigraphically underlying Lewisian or Torridonian units. They may be grouped into four sets. The klippen of Beinn nan Cnaimhseag (NC 274 178) and Beinn an Fhuarain (NC 262 159) both contain Torridon Group strata and constitute the Assynt klippen of Elliott and Johnson (1980) (Figure 5.32). They are likely to be parts of the Ben More Thrust Sheet. An array of small outliers of False-bedded Quartzite and Pipe Rock form the Ledbeg klippen, distinct in turn from the main Cam Loch Klippe. The fourth set, the Cromalt klippen lie adjacent to the Moine Thrust in southern Assynt, and are described in the **Knockan Crag** GCR site report (this chapter).

The Cam Loch GCR site also provides crucial constraints in relating folding to thrusting processes. For Elliott and Johnson (1980) the folds within the Cam Loch Klippe are part of their 'Sgonnan Mòr family' (see **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site

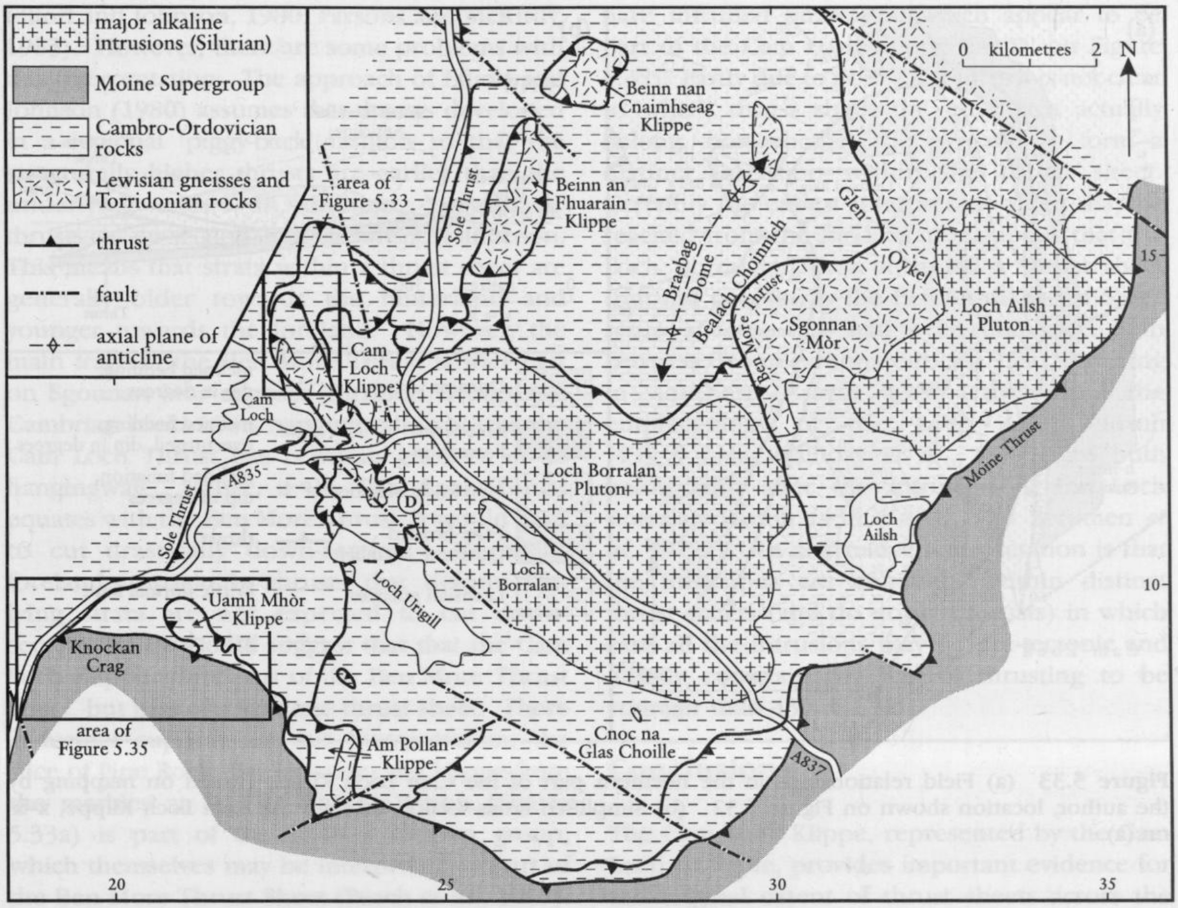


Figure 5.32 The structural setting of the Cam Loch Klippe and other klippen in southern Assynt. LT – Ledbeg Thrust. Based on Geological Survey of Great Britain (1923), Elliott and Johnson (1980), Coward (1985) and British Geological Survey (2007).

report, this chapter), an interpretation central to linking the klippe with the Ben More Thrust Sheet. They interpret the folds as entirely pre-dating the thrust upon which they have been carried and recognize no thrust-fold link. Alternatively, a thrust-fold causative relationship may be readily postulated.

The klippe is also important in establishing the relationship between thrusting and intrusion episodes associated with the Loch Borralan Pluton (Parsons and McKirdy, 1983). To the south-east of the designated GCR site, recently excavated exposures within the klippe show quartzites intruded by syenites and pyroxenites of the Loch Borralan Pluton (location 'D' on Figure 5.32). These relationships suggest that the Cam Loch Thrust has been cut by the intrusions, and therefore emplacement pre-dates their intrusion at *c.* 430 Ma (van Breemen *et al.*, 1979a).

Description

Within the Cam Loch GCR site, the eponymous klippe consists of Lewisian basement together with its Cambrian cover of False-bedded Quartzite and, locally, Pipe Rock (Figure 5.33a). These units are well exposed in a major fold, termed here the 'Innse-Ruaidhe Anticline', which faces north-west and has a strongly over-turned forelimb (Figure 5.33b). Cross-bedding in the quartzite gives younging directions away from the Lewisian in the fold core. Locally the quartzites contain minor rhyolitic dykes that have been sheared, presumably during folding; one such dyke at Creag na h-Innse Ruaidhe (NC 224 140) is described in the *Caledonian Igneous Rocks of Great Britain* GCR Volume (Parsons, 1999).

Although not shown on published maps (e.g. Geological Survey of Great Britain, 1923;

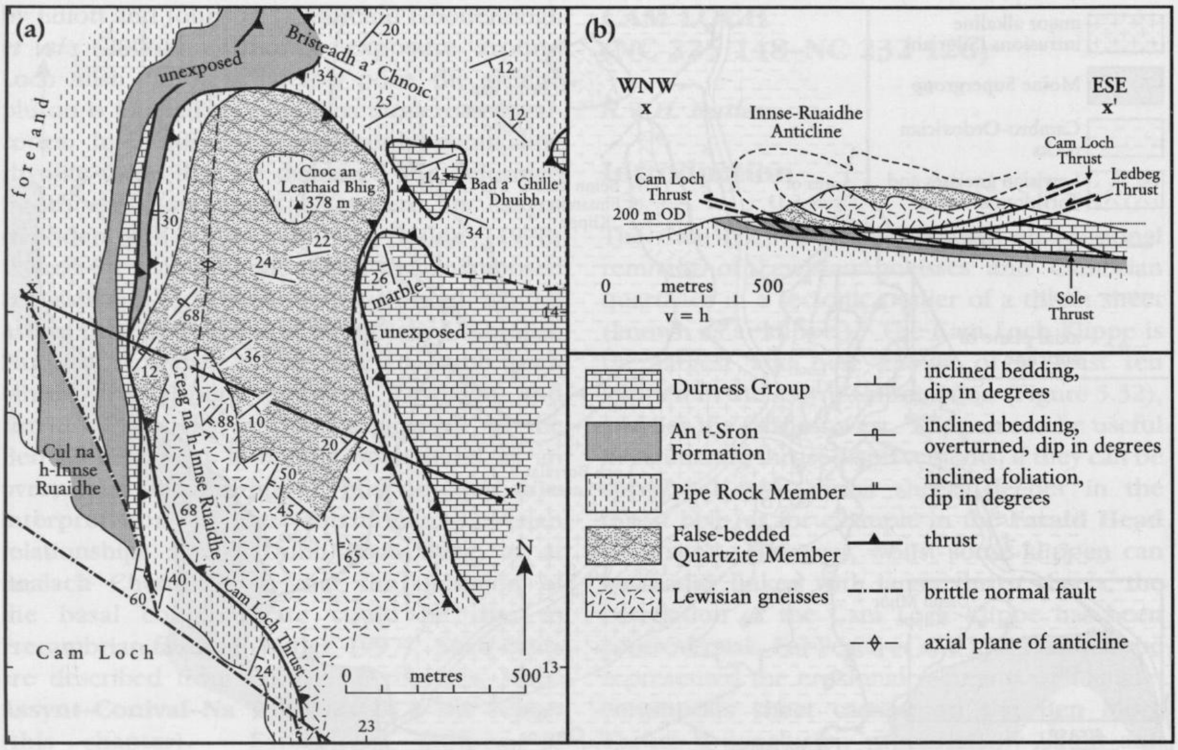


Figure 5.33 (a) Field relationships in the northern part of the Cam Loch Klippe (based on mapping by the author, location shown on Figure 5.32. (b) Simplified cross-section through the Cam Loch Klippe, x–x' on (a).

Johnson and Parsons, 1979), the summit region of Cnoc an Leathaid Bhig lies in the Pipe Rock on the normal limb of the Innse-Ruaidhe Anticline. These strata can be traced around the fold onto the forelimb where they are overturned. The Innse-Ruaidhe Anticline is related to the hangingwall ramp of Lewisian rocks against the thrust that carries the Cam Loch Klippe. As such it has the geometry of a so-called 'thrust-propagation fold' (Williams and Chapman, 1983) in which the formation of a thrust ramp is pre-conditioned by buckling.

The footwall to the Cam Loch Klippe is generally poorly exposed. Above Cam Loch itself, Lewisian gneisses overlie Pipe Rock (Johnson and Parsons, 1979). The thrust is not exposed, but nearby structurally higher Lewisian outcrops are mylonitic, with a SE-dipping foliation. The quartzites in the immediate footwall contain cataclasite seams. The continuity of this sheet of Pipe Rock in the footwall is obscure. There are no exposures in the region of Cul na h-Innse Ruaidhe (Figure 5.33a) save for isolated portions of the foreland succession. It is likely that the Pipe Rock forms a sheet carried with the Cam Loch Klippe onto Durness Group carbonate rocks (Johnson and Parsons, 1979).

On the east side of Cnoc an Leathaid Bhig, overturned Pipe Rock quartzites of the klippe overlie carbonate rocks of the Durness Group, at the top of the foreland succession. Thus here the thrust carrying the klippe has branched onto the regional Sole Thrust (NC 223 142; Figure 5.32). On the eastern side of the klippe, at Bad a' Ghille Dhuibh (NC 232 144 and NC 231 141), the deepest structural levels contain metamorphosed Durness Group carbonate rocks. These marbles have been folded so that the outcrops represent the crests of domal structures, and are structurally overlain by a thrust sheet of Pipe Rock. This thrust-bounded Pipe Rock unit underlies stratigraphically right-way-up False-bedded Quartzite of the klippe, but does not itself form part of the Cam Loch Klippe.

Interpretation

The importance of the Cam Loch GCR site stems chiefly from its status as a detached part of the Ben More Thrust Sheet (Peach *et al.*, 1907;

Elliott and Johnson, 1980; Parsons and McKirdy, 1983). However, there are some problems with this interpretation. The approach of Elliott and Johnson (1980) assumes that thrusts developed in a regional 'piggy-back' fashion so that the structurally higher thrusts are earlier than the underlying ones. In addition, 'piggy-back' thrusts cut up-section in their transport direction. This means that strata within a thrust sheet are generally older towards the hinterland and younger towards the foreland. However, the main trace of the Ben More Thrust farther east on Sgonnan Mòr exposes Torridon Group and Cambrian rocks in its hangingwall, whereas the Cam Loch Thrust has Lewisian gneisses in its hangingwall. Hence, if the Cam Loch Thrust equates with the Ben More Thrust, it would have to cut drastically down-section. Normally, foreland-propagating thrusts that deform flat-lying strata are not expected to cut down-section, which would suggest that that the Cam Loch Klippe is not part of the Ben More Thrust Sheet, but part of a separate thrust sheet. There is further support for this interpretation; the slice of Pipe Rock that separates the klippe from the marbles at Bad a' Ghille Dhuibh (Figure 5.33a) is part of the Ledbeg klippen group, which themselves may be interpreted as part of the Ben More Thrust Sheet (Peach *et al.*, 1907). Thus the Cam Loch Klippe overlies the Ben More Thrust Sheet and presumably roots back farther to the east.

An alternative interpretation is that the Ben More Thrust cut previously folded rocks; thrusts that cut previously folded rocks can cut both up-section and down-section. This has been a traditional view of fold–thrust relationships in the Assynt area (e.g. Peach *et al.*, 1907; Johnson and Parsons, 1979), largely arising from correlations of the Sgonnan Mòr structures. As discussed in the **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site report (this chapter), these correlations are probably unsound, with the folds better interpreted as related to local thrusting processes. Exceptions exist within the Cromalt klippen, and these are discussed in the **Knockan Crag** GCR site report (this chapter).

For thrust correlations in southern Assynt it is also important to establish the relative timing of emplacement of thrust sheets and major igneous intrusions. Most intrusions in Assynt appear to be earlier than the (local) Scandian structures. However, Parsons and McKirdy (1983) showed that pyroxenites of the Loch Borralan Pluton have intruded quartzites, which appear to be part of the Cam Loch Klippe (at 'D' on Figure 5.32). Partly due to poor exposure, it is not clear to which thrust sheet the quartzites actually belong, nor whether the pyroxenites form a distinct intrusion within the thrust sheet. Certainly the easiest interpretation that may be reached from the field relationships is that the Loch Borralan Pluton intruded a thrust sheet (but not necessarily the Ben More Thrust Sheet *sensu stricto*) that had been emplaced onto Durness Group carbonate rocks. If so, thrusting in southern Assynt was active after the emplacement of the Loch Ailsh Pluton (439 ± 4 Ma, Halliday *et al.*, 1987) and both before and after the intrusion of the Loch Borralan Pluton (430 ± 4 Ma, van Breemen *et al.* 1979a). An alternative interpretation is that the intrusions are contained within distinct thrust sheets (and do not cut thrusts) in which case all the intrusions may be pre-tectonic and merely constrain the age of thrusting to be younger than 430 ± 4 Ma.

Conclusions

The Cam Loch Klippe, represented by the Cam Loch GCR site, provides important evidence for the original extent of thrust sheets across the Assynt Culmination. One school suggests that the klippe forms part of the Ben More Thrust Sheet, which originally enveloped almost all of central and southern Assynt. However, the interpretation favoured here is that the Cam Loch Klippe forms part of a sheet distinct from – and structurally higher than – the Ben More Thrust Sheet. Regardless of the validity of these conclusions, the site is important in providing a testing ground for methods of three-dimensional analysis of thrust structures (e.g. Elliott and Johnson, 1980; Coward, 1985).

The klippe itself contains a major anticline that faces WNW and has a strongly overturned forelimb. It is a good example of a style of deformation termed 'thrust-propagation folding', whereby thrust ramping is accompanied by a buckling component reflecting a rate of thrust propagation that was slower than that of thrust displacement. Historically this deformation style underpinned classic ideas of thrust formation developed in the Alps. However, in the Moine Thrust Belt the original surveyors rejected this requirement for thrusting to be necessarily preceded by folding, since many thrusts show very little such deformation. The Cam Loch GCR site, together with other examples of 'Sgonnan Mòr structures' within the **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** GCR site, is important because it illustrates that both styles of thrusting, with or without preceding folding, may occur within the same thrust belt.

KNOCKAN CRAG (NC 186 083–NC 221 093)

R.W.H. Butler

Introduction

For much of its outcrop length from Loch Eriboll to Skye, the basal contact of the Moine Thrust Sheet is poorly exposed. A glorious exception to this is found in the Knockan area, at a GCR site that is particularly fortunate in being very easily accessible from the road between Inchnadamph and Ullapool. Here, mylonites derived from meta-sedimentary rocks of the Moine Supergroup overlie carbonate rocks of the Durness Group (Figure 5.34). The section at Knockan Crag is deceptive in that it displays an apparently simple upward progression through the foreland Cambro–Ordovician strata into the apparently conformable Moine (Figure 5.35). Indeed it was critical for the old Murchison doctrine of stratigraphical continuity between the Cambrian and the Moine (Murchison and Geikie, 1861). However, following work at Eriboll, the basal Moine contact at Knockan Crag was recognized as being a thrust (Callaway, 1883). For the Geological Survey (Peach *et al*., 1907) the Knockan area was important in defining the relationship between the major thrusts and the subsidiary imbricate zones. For them the over-stepping of the imbricate zones by the Moine Thrust was clear evidence that this structure was the last to form in this area, a conclusion they transferred to the whole Moine Thrust Belt.

Since the 19th century the Knockan Crag GCR site has become one of the most visited localities of the Moine Thrust Belt and has gained international recognition (MacGregor and Phemister, 1948; Johnson and Parsons, 1979; McClay and Coward, 1981). It is now one of few sites in Britain, or indeed in Europe, with a purpose-built visitor centre and waymarked trail dedicated almost exclusively to the geology. The structural interpretations described in the Geological Survey memoir (Peach *et al*., 1907) were largely unquestioned until the work of Elliott and Johnson (1980). They interpreted the overstep relationship as forming a roof to a duplex below the Moine mylonites, and inferred that the Moine Thrust moved first, with imbrication of the underlying Durness Group happening later. This prompted a programme of remapping by Coward (1985) and the definition of two types of Moine Thrust in southern Assynt. For the most part the Moine Thrust can be shown to be folded and to be cut by underlying thrusts, observations consistent with the hypothesis of Elliott and Johnson (1980). However, at Knockan the Moine Thrust clearly truncates the underlying structures, as described by Peach *et al*. (1907), so that here it is undoubtedly a late structure.

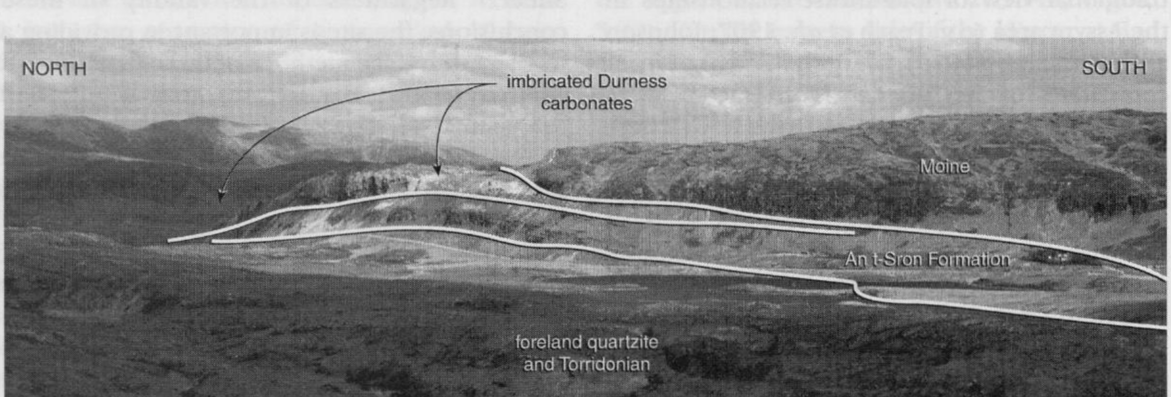


Figure 5.34 View eastwards towards the Knockan Crag from the slopes of Cul Mor. To the right (south), the Moine Thrust rests directly on the foreland succession; to the left (north) is the southern termination of the Assynt Culmination, with imbricated slices of Durness Group carbonate rocks separating the Moine Thrust from the foreland. (Photo: R.W.H. Butler.)

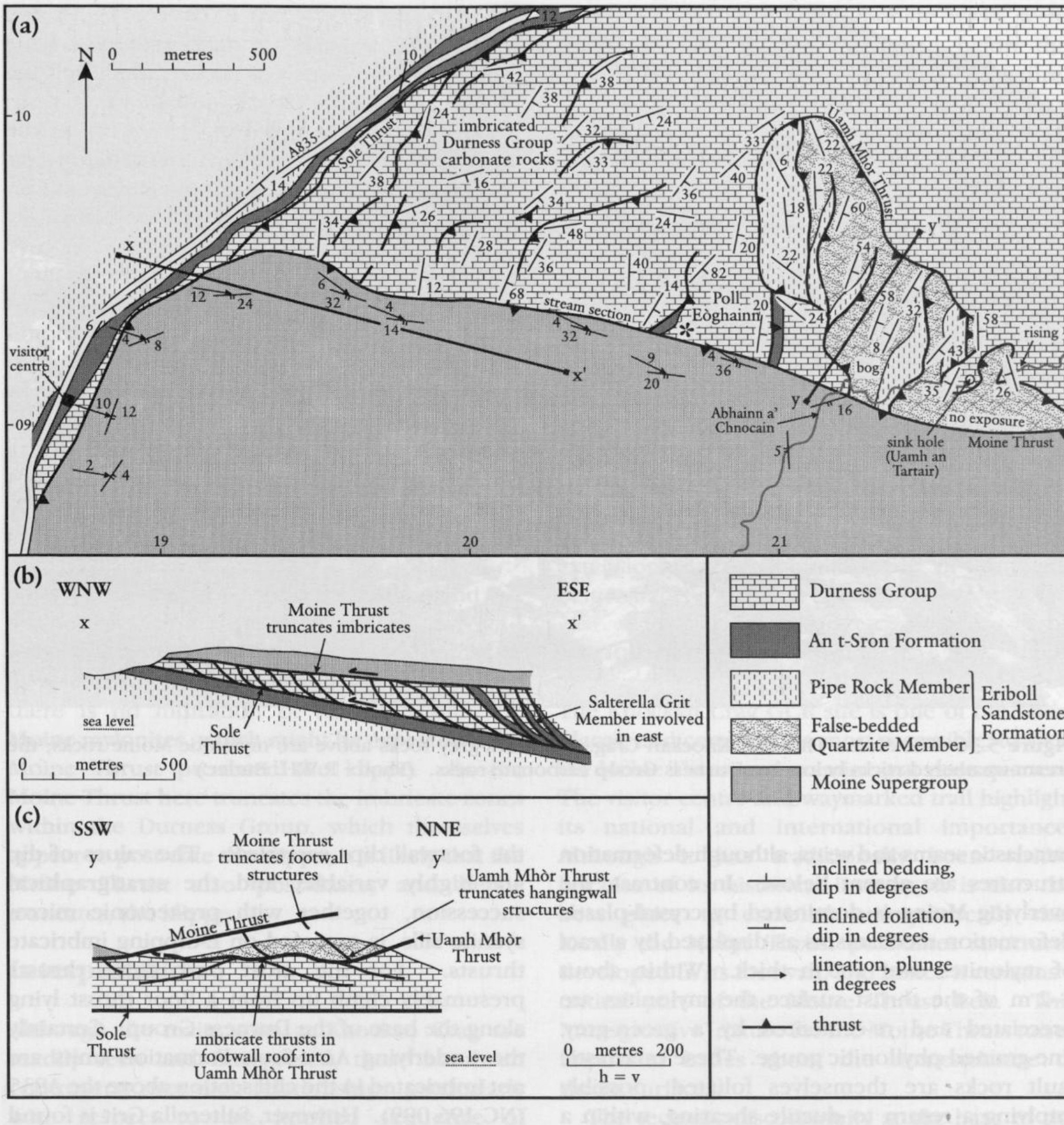


Figure 5.35 (a) Map and cross-sections through the Knockan Crag GCR site. (b) Section x–x' is constructed parallel to the inferred direction of thrusting. The nature of the Moine Thrust (MT) shown here, truncating imbricated thrust slices of Durness Group and An t-Sron Formation in its footwall, is based on the stream section shown on the map. (c) Section y–y' is perpendicular to the inferred direction of thrusting. It shows the Uamh Mhòr Thrust truncating thrusts in its hangingwall but being folded by imbricate thrust slices in its footwall. All structures are cut by the Moine Thrust which here dips gently towards the south.

Description

The Knockan Crag GCR site contains four different structural units: the foreland Cambrian strata (Pipe Rock, Fucoid Beds and Salterella Grit members); imbricated Durness Group carbonate rocks and pre-tectonic microsyenite sills; the Uamh Mhòr Klippe of Cambrian quartzites; and the Moine Thrust Sheet (Figure 5.35). At Knockan Crag the Moine lies directly upon Durness Group carbonate rocks that form the upper part of the foreland succession (Figure 5.36). Indeed, the Moine Thrust alone represents the entire thrust belt here. Within a few metres of the thrust, carbonate rocks of the Durness Group are sheared and cut by

Figure 5.36 The Moine Thrust at Knockan Crag. The dark-grey rocks above are mylonitic Moine rocks; the cream-weathered rocks below are Durness Group carbonate rocks. (Photo: R.W.H. Butler.)

cataclastic seams and veins, although deformation structures are absent below. In contrast, the overlying Moine is dominated by crystal-plastic deformation mechanisms as displayed by a tract of mylonites over 100 m thick. Within about 1–2 m of the thrust surface the mylonites are brecciated and re-cemented by a green-grey, fine-grained phyllonitic gouge. These cataclastic fault rocks are themselves foliated, possibly implying a return to ductile shearing, within a few centimetres of the thrust surface. The thrust surface is sharp, marked by a few centimetres of dominantly carbonate gouge. It is the ready weathering of the gouge that results in the sharply incut expression of the fault surface at Knockan Crag.

The Moine Thrust can be traced eastwards from Knockan Crag around to the stream section (Figure 5.35) that runs down to the swallow hole of Poll Eòghainn (NC 206 094). The mylonitic foliation in the Moine rocks is generally concordant with the thrust plane, dipping gently southwards but containing an intense ESE-plunging mineral lineation. Bedding in the carbonate rocks of the Eilean Dubh Formation in the footwall dips eastwards. The values of dip are highly variable, and the stratigraphical succession, together with pre-tectonic micro-syenite sills, is repeated on E-dipping imbricate thrusts. For the most part these thrusts presumably climb up from a floor thrust lying along the base of the Durness Group. Certainly the underlying An t-Sron Formation units are not imbricated in the cliff section above the A835 (NC 196 099). However, Salterella Grit is found within the imbricate slices farther east, at the sinkhole at Poll Eòghainn, implying that towards the hinterland the floor thrust lies within this unit (Figure 5.35). Bedding in the Eilean Dubh Formation seen in the stream section at NC 201 094 is highly discordant to the Moine Thrust, strongly suggesting that the Moine Thrust truncates the imbricate zones in its foot-wall.

The imbricated Durness Group carbonate rocks are overlain tectonically by Cambrian quartzites of the Uamh Mhòr Klippe. The contact is commonly correlated with the Ben More Thrust (e.g. Johnson and Parsons, 1979), although this is rather uncertain. Consequently it is termed here the 'Uamh Mhòr Thrust'. At the sinkhole which lends its name to the klippe (NC 217 092) and the adjacent cave (Uamh an Tartair), the carbonate rocks in the footwall to the Uamh Mhòr Thrust are exposed in the core of an antiform, wrapped by quartzites of the klippe. The ridge to the north-west (Cnoc a' Choilich Mor, NC 211 097) consists of imbricated Pipe Rock and False-bedded Quartzite members. Bedding within these imbricate slices is oblique to, and presumably truncated by, the Uamh Mhòr Thrust. In contrast, bedding within the carbonate rocks in its footwall here lie generally parallel to the thrust. These relationships are well exposed at the ESE margin of the klippe, at the rising of the Abhainn a' Chnocain (NC 217 091). The relationships (Figure 5.35) suggest that the thrust carrying the klippe post-dates the overlying imbricate zones but pre-dates those in its footwall.

The relationship between the klippe and the Moine Thrust is less clear, as the critical ground on the southern bank of the Abhainn a' Chnocain is very poorly exposed. However, there is no indication of folding within the Moine mylonites, which might be expected if the Moine Thrust pre-dated the klippe. As the Moine Thrust here truncates the imbricate zones within the Durness Group, which themselves appear to post-date the klippe, it is likely that the Moine Thrust also post-dates, and hence truncates, the klippe.

Interpretation

Although the main units at Knockan Crag are readily seen and interpreted, there has been controversy over their relationships, particularly with respect to the implied sequence of thrusting. Much of the controversy arises from attempts to reach a unified explanation of thrust sequences for the entire thrust belt. The field relationships at Knockan Crag seem clear. The Moine Thrust clearly truncates the imbricate zones in the Durness Group of its footwall, as seen in the stream section some 2 km east of Knockan Crag. The relationships of the Moine Thrust to the Uamh Mhòr Thrust and to the imbricate zones, both in its hangingwall and footwall, are less obvious. On balance it is likely that the Uamh Mhòr Thrust cut through a previously developed imbricate stack of Cambrian quartzites, carrying the upper portions of this stack onto undeformed carbonate rocks of the Durness Group. These carbonate rocks were then imbricated, folding the klippe, before the Moine Thrust truncated the composite structure.

The above structural history is rather more complex than that of Elliott and Johnson (1980). Coward (1985) interpreted the discordant relationship between bedding in the quartzites and the mapped margins of the Uamh Mhòr Klippe as due to a combination of thrusting and extensional faulting. As these inferred extensional faults do not offset the trace of the Moine Thrust but do offset some other thrust structures, he deduced that extensional and compressional tectonics operated broadly together. As such, the model is similar to the one he proposed for the Stack of Glencoul (see **Glencoul** GCR site report, this chapter). However, at Knockan Crag the field relationships are not as clear, and the widespread development of extensional faults within this part of the thrust belt remains somewhat speculative.

Conclusions

The Knockan Crag GCR site is one of the finest places, and certainly the most accessible, to view the Moine Thrust and examine it at close quarters. The visitor centre and waymarked trail highlight its national and international importance. Although it has traditionally been visited because of its historical interest, it is also the best place to establish unequivocally that locally the Moine Thrust post-dates structures developed in its footwall, and hence it remains a critical part of the Moine Thrust Belt. This 'transgressive' nature for the Moine Thrust raises important issues about the nomenclature of thrust surfaces.

The tectonic discontinuity at the base of the Moine Thrust Sheet at Knockan Crag has been termed the 'Moine Thrust' since the original geological survey. Yet, while it does clearly juxtapose the Moine succession against the Cambrian foreland sequence, the thrust structure exposed is clearly distinct from the Moine Thrust at **Eriboll** or **Dundonnell** for example. This distinction is reflected not only in the relationship between the discontinuity and the surrounding structures but also in its fault-rock characteristics. Where the Moine Thrust is early, both hangingwall and footwall are mylonitic. At Knockan Crag, where the thrust is late, there is a multi-stage evolution of fault rocks. Ductile mylonites are carried on a carpet of brittle cataclasite containing brecciated fragments of mylonites that are themselves locally re-sheared. So the exposures on Knockan Crag are important not only in illustrating the role of thrusting and thrust sequences in building complex structures, but also in linking grain-scale processes to the larger-scale tectonic features.

DUNDONNELL (NH 114 880–NH 137 880)

R.W.H. Butler and S.J. Matthews

Introduction

The Dundonnell GCR site (Figure 5.37), at the head of Little Loch Broom *c.* 2–4 km east of Dundonnell, demonstrates that the Moine Thrust is tightly folded, yet the intensity of folding decreases downwards in the underlying thrust sheets and may be absent altogether from lower structural levels. The structure, now interpreted as an antiformal-stack duplex, has been crucial in arguments concerning the sequence of thrust development in the Moine Thrust Belt.

During the original mapping by the Geological Survey (Peach *et al.*, 1907), considerable debate built up between different surveyors as to the relative timing of movements on the Moine Thrust and the underlying structures of the thrust belt. For the principal authors of the 1907 memoir, the field relationships in southern Assynt were critical and led them to finally deduce an overall sequence whereby the Moine Thrust was the last to develop (see **Knockan Crag** GCR site report, this chapter). However, Cadell (in Peach *et al.*, 1907, pp. 471–2) dissented from this model, partly based on experimental modelling (Cadell, 1888), suggesting instead that the thrusts developed with the highest (i.e. the Moine Thrust) being the earliest and the deeper ones being younger. The structural relationships at Dundonnell, illustrated in figure 45 of Peach *et al.* (1907), were cited to support his notion. Field mapping at Dundonnell (by W. Gunn) showed that the Moine Thrust is tightly folded whilst structurally lower thrusts are unfolded or only gently folded; in essence a microcosm of the Assynt Culmination. These field relationships were largely ignored until re-examined by Elliott and Johnson (1980). They restored the stack of thrust slices within the Dundonnell culmination to their original disposition and related folds farther to the east, within the Moine outcrop, to the underlying thrust process. Matthews (1984) remapped the area as part of a re-appraisal of the thrust sheet geometry, but the Dundonnell locality is rarely visited despite its importance.

Description

The Dundonnell GCR site extends east for some 2 km from the top of the forestry in Srath Beag and includes the 150–200 m-high W-facing scarp and the oblong protruding Creag Chorcurach (374 m). Unfortunately, the site is not well exposed, with the flat wet peaty plateau of Fèithe Bhàite occupying its eastern part. There are a few critical exposures of the thrust sheets developed in the footwall to the Moine Thrust and there are reasonable exposures of Moine mylonites, together with less strongly deformed Moine metasedimentary rocks, around the flanks of the culmination (Figure 5.37). The crucial part of the Dundonnell GCR site lies on a broad plateau and is represented by a nearly complete window through the Moine mylonites within which lie intermediate thrust slices. It is an antiformal feature, about 1 km across, with a hinge line trending WSW–ESE.

The structure of the western part of the site is best appreciated from three stream sections (Figure 5.37). In the southern one (Allt na Creag Chorcurach), the Moine Thrust lies on a footwall of Pipe Rock quartzites. The thrust climbs up-section to the north to lie within the Salterella Grit. These An t-Sron Formation rocks, and locally the lowest beds of the Durness Group, are weakly imbricated so that the outcrop of Fucoid Beds is repeated tectonically when seen in the stream section of Allt a' Char in the northern part of the site. These imbricate slices form the lowest structures in this part of the Moine Thrust Belt, presumably flooring along the Sole Thrust, which runs at the base of the Fucoid Beds. The Sole and Moine thrusts join to the south.

In the Allt a' Char section, the imbricate slices of An t-Sron Formation are overlain tectonically by Torridonian sandstones of Elliott and Johnson's (1980) 'Sheet II'. This thrust sheet continues to the south, capping the imbricate slices of An t-Sron Formation, and eventually lensing out against the overlying Moine Thrust before reaching the Allt na Creag Chorcurach

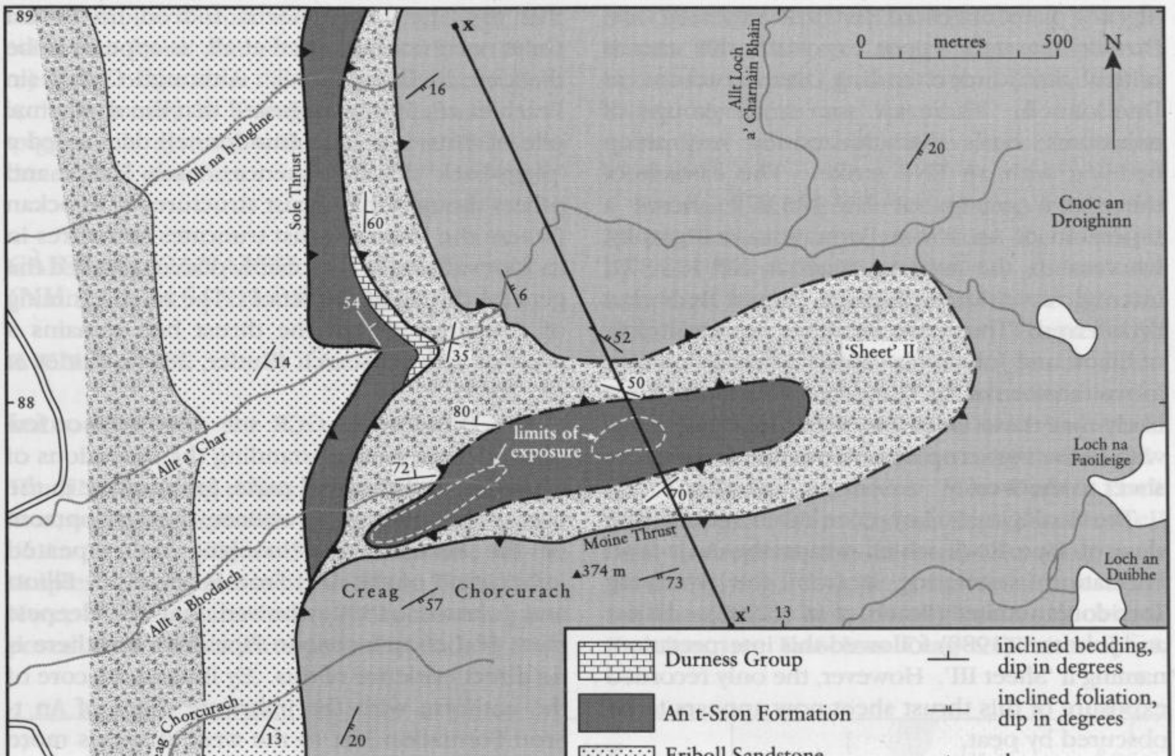


Figure 5.37 Map and cross-section through the antiformal-stack duplex structure of the Dundonnell GCR site. Based on Matthews (1984) and modified after Elliott and Johnson (1980). Note that the section line is highly oblique to the direction of movement.

section (Figure 5.37). Shattered and generally steeply dipping Torridonian sandstones dominate the few exposures in the boggy ground that drains into the Allt a' Bhodaich. This area also contains rare exposures of Lewisian gneisses (e.g. at NH 120 888), presumably basement to the Torridonian and indicative of internal thrust repetition within this thrust sheet.

The Torridonian sandstones of the composite 'Sheet II' appear to wrap around a steeply dipping panel of Fucoid Beds and Salterella Grit. Despite the rather poor exposure, this area is critical for understanding the structure at Dundonnell. There are two small groups of exposures, both characterized by very steep bedding with an ENE strike. The eastern of these two groups at NH 126 879 shows a repetition of An t-Sron Formation stratigraphy, whereas in the western one at NH 123 877, internal repetition within the Fucoid Beds may be inferred. These two localities represent part of Elliott and Johnson's (1980) 'Sheet IV', which forms the core of the Dundonnell Antiform. It is likely that these imbricate slices are continuous with those that crop out below the Torridonian sheet to the west.

The Geological Survey recorded an intermediate slice of Pipe Rock which wraps the An t-Sron Formation, separating it from the overlying Torridonian sheet (Peach *et al.*, 1907). Elliott and Johnson (1980) followed this interpretation, naming it 'Sheet III'. However, the only recorded exposure of this thrust sheet now appears to be obscured by peat.

The antiformal structure at Dundonnell, if rather difficult to reconstruct from available exposures in its core, is well displayed by the trend of mylonitic foliation and lithological banding within the Moine Thrust Sheet. The northern limb of the antiform may be traced eastwards as a belt of near-vertical foliation and otherwise anomalous folds (Figure 5.37). These are well displayed on glaciated pavements on Cnoc an Droighinn (NH 145 887).

Interpretation

Elliott and Johnson (1980) interpreted the Dundonnell structure as a thrust culmination, formed by the 'superposition of the sheets directly above one another'. Since then this structure has acquired international fame and become accepted as a type example of an 'antiformal-stack duplex' – a pile of imbricate thrust slices where the lower ones bulge up the higher ones into an antiformal shape (e.g. Boyer and Elliott, 1982). This type of geometry is widely thought to be diagnostic of a sequence of thrusting where the structurally highest thrust sheet was the earliest to be emplaced, followed systematically in turn by those underneath – a sequence described as 'piggy-back' (e.g. Elliott and Johnson, 1980). The earliest and structurally highest thrust sheet is folded more intensely than the later, lower sheets. Indeed, the lowest sheet need not be folded at all, as appears to be the case in Dundonnell. Although Cadell (in Peach *et al.*, 1907) suggested that the antiformal pile of thrust slices at Dundonnell demanded a 'piggy-back' thrust sequence, Peach, Horne and others thought that thrust structures at Knockan (where the Moine Thrust truncates structures in its footwall and is reasonably planar) typified the general thrusting sequence. The relative timing of structures within the thrust belt remains a topic of active research (Butler, 2004a; Butler *et al.*, 2007).

The Dundonnell GCR site does offer a few conundrums, notwithstanding the limitations of exposure in the critical parts, for example in the core of the antiform. In essence, the development of the thrust stack involves the repeated imbrication of the An t-Sron Formation. Elliott and Johnson (1980) showed that the deepest parts of the stack contain Pipe Rock but there is no direct evidence of this. By linking the core of the antiform with the imbricate slices of An t-Sron Formation just to the west, it seems more plausible that imbrication developed along a floor thrust, the regional Sole Thrust, located at the base of the Fucoid Beds (Figure 5.37). However, the trend of the antiform suggests that the imbricate zones developed along an oblique ramp, orientated about 30° away from the thrusting direction. It is by no means clear why such a ramp orientation occurred repeatedly.

Conclusions

The Dundonnell GCR site consists of a small but highly significant upwarp of the Moine Thrust, beneath which are tightly folded imbricate slices of Cambrian and Torridonian rocks. The various structural features, although poorly exposed, are of international importance as together they form the type example of a structure known as an 'antiformal-stack duplex' – a stack of imbricate slices where the lower ones bulge up the higher ones into an antiformal shape. These structures are important in explaining large-scale folds within thrust belts and orogens and also give clear evidence for the sequence of thrust development, from hinterland to foreland. This site provides a fine example of how such conclusions may be drawn from limited field data. In this respect, the Dundonnell GCR site has historical significance: the principal original surveyors were of the opinion that movement on the Moine Thrust was the latest event, but evidence from the site suggested to other members of the team that the Moine Thrust Belt, at least locally at Dundonnell, operated as a 'piggy-back' system, with the Moine Thrust as the earliest structure.

CÀRN NA CANAICH (NH 110 845–NH 086 820)

R.W.H. Butler

Introduction

The NNE-trending ridges of the Càrn na Canaich area, on the eastern side of the mountain massif of An Teallach (Figure 5.38) show one of the simplest developments of the Moine Thrust Belt. Here, Moine metasedimentary rocks are juxtaposed over Cambrian quartzites, Fucoid Beds and Salterella Grit, separated only by a single thrust. The Càrn na Canaich area is important because it contains various lateral transitions in thrust structure and provides an excellent example of 'smooth-slip' behaviour of the Moine Thrust.

For much of its preserved outcrop length, the Moine Thrust is separated from the foreland by subsidiary thrust structures, sheets and imbricate stacks. These testify to progressive abandonment of the Moine Thrust with displacements transferring onto lower structures. As a consequence, culminations in the thrust belt are developed such as in Assynt and at Dundonnell (see **Ben More Assynt–Conival–Na Tuadhan**, **Sgonnan Mòr–Dubh Loch Beag–Upper Glen Oykel** and **Dundonnell** GCR site reports, this chapter). In other areas the underlying imbricate zones and thrust sheets are truncated by new, low-angle faults, such as at Knockan (see **Knockan Crag** GCR site report,

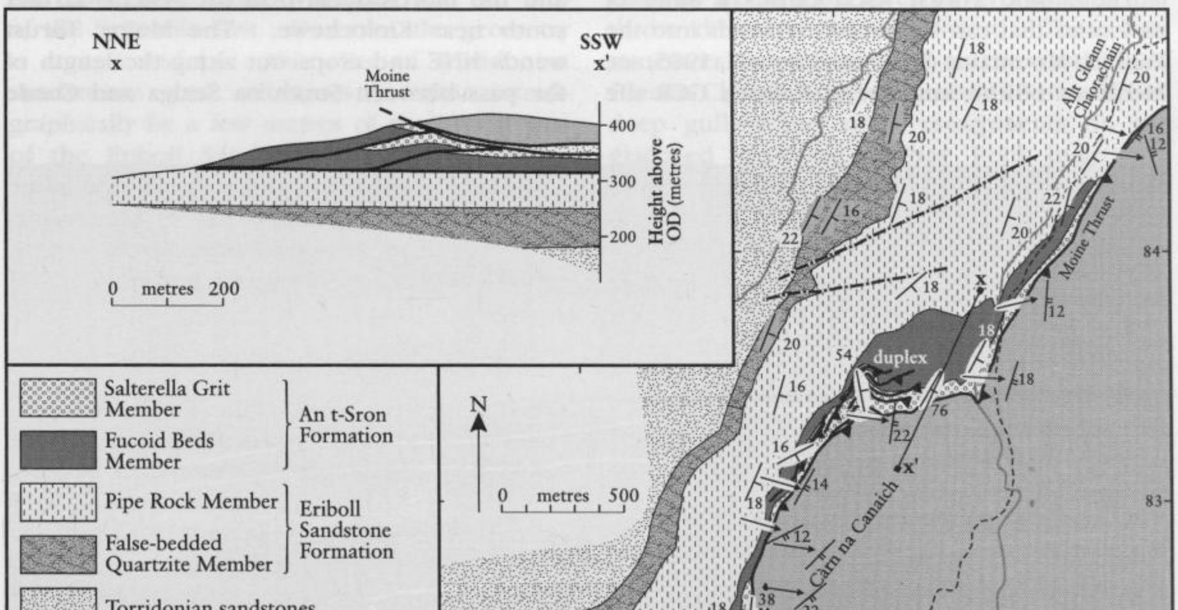


Figure 5.38 Map and cross-section of the area of Càrn na Canaich. Section x–x' is constructed at right angles to the thrusting direction.

this chapter). However, considerable portions of the central part of the Moine Thrust outcrop are characterized by no appreciable thrusting in its footwall. Elliott and Johnson (1980) coined the term 'smooth-slip' to describe this behaviour.

An Teallach is famous for its extensive exposures of Torridonian sandstones (Peach *et al.*, 1907) and its remnant cappings of Cambrian quartzite as erosional outliers. However, east of An Teallach, Moine metasedimentary rocks cap the main outcrops of Cambrian strata (Figure 5.39). The simplicity of these field relationships reinforced the earlier misconception that the Moine succeeded stratigraphically from the underlying Cambrian strata (see Oldroyd, 1990). The area was remapped by the Geological Survey, showing that the Moine Thrust lay between Moine metasedimentary rocks and the underlying strata (Peach *et al.*, 1907), but since these early studies the area has been seldom visited by research geologists (Butler, 2000).

The Moine Thrust itself carries a suite of mylonites that can be traced eastwards into the Fannich Mountains (Kelley and Powell, 1985; see **Meall an t-Sithe and Creag Rainich** GCR site report, Chapter 7). In general the thrust glides on a footwall situated at the top of the Salterella Grit. However, there is a local imbricate system developed in the Fucoid Beds and Salterella Grit that weakly bulges the Moine Thrust. Elsewhere there are thin slices of far-travelled Torridonian sedimentary rocks, which contain internal imbricate thrusts. However, these are local structures, and generally the Moine Thrust has slipped smoothly across a footwall that remained generally undeformed.

Description

This GCR site area lies just east of the An Teallach mountain group in the Dundonnell Forest, where the Moine Thrust and the underlying Cambrian quartzites form a prominent NNE-trending scarp and dip-slope topography. The upstanding ridges culminate in Càrn na Canaich (471 m above OD). Geologically the site lies between the Dundonnell culmination and the more-extensive thrust systems farther south near Kinlochewe. The Moine Thrust trends NNE and crops out along the length of the pass between Strath na Sealga and Corrie

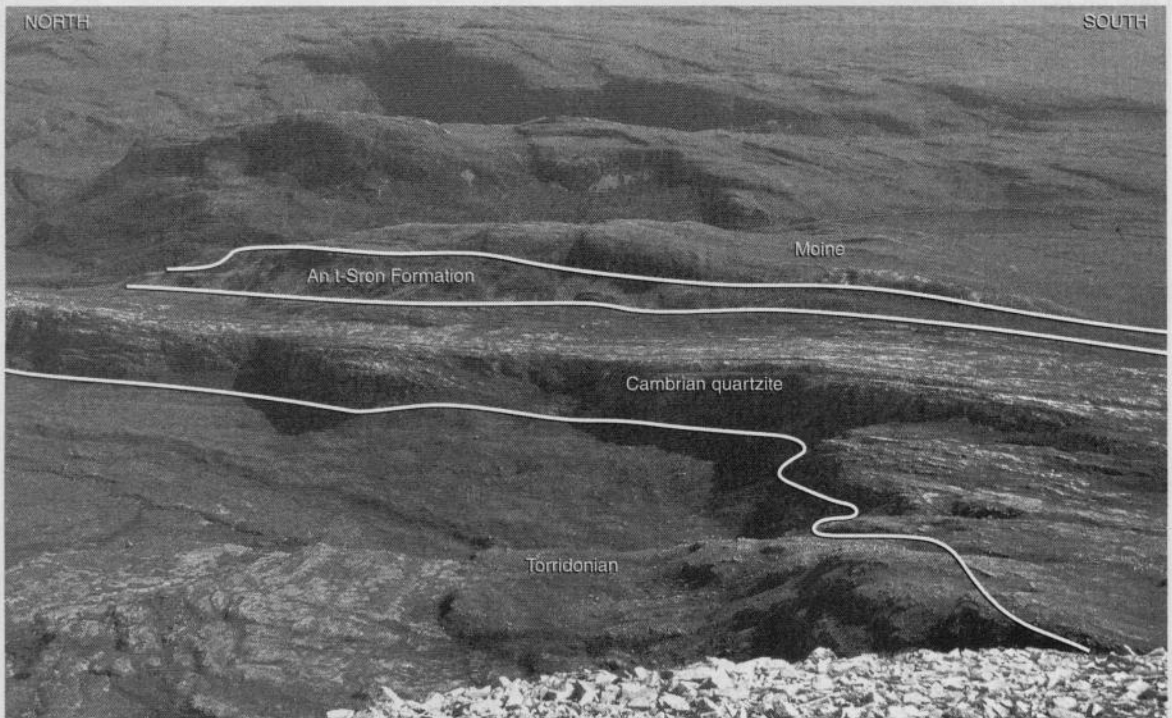


Figure 5.39 View looking east onto the Càrn na Cainich GCR site from the upper part of the Sail Liath ridge of An Teallach. Moine rocks have been thrust towards the viewer over a duplex formed in the An t-Sron Formation. (Photo: R.W.H. Butler.)

Hallie on the A832 (Figure 5.38). The mylonitic rocks in its hangingwall appear to be exclusively derived from Moine metasedimentary rocks and show an intense mineral-stretching lineation that plunges almost due east. In general, these mylonites lie directly on Cambrian strata of the foreland. In the north of this area, in Gleann Chaorachain, Salterella Grit is present in the footwall. However, on the slopes leading down to the south, mylonites lie on the Pipe Rock without the stratigraphically younger strata. Presumably in this sector the An t-Sron Formation, together with the Durness Group, which is absent through this site, has been carried off in the hangingwall of the Moine Thrust. Thus the thrust shows a low-angle lateral ramp in its footwall.

The transition in footwall to the Moine Thrust is exposed on Càrn na Canaich (NH 097 827). The west face of this hill displays a series of lateral ramps; movements on the Moine Thrust generally lie within the top of the Fucoid Beds, but movement locally climbs to the top of the Salterella Grit. However, the geometry is complicated by a thin slice of Torridonian sandstones and siltstones overlain stratigraphically by a few metres of the lowest part of the Eriboll Sandstone Formation. These rocks represent a small, far-travelled horse that is accreted to the base of the Moine Thrust Sheet. Bedding within the Torridonian and Cambrian strata is very difficult to recognize in the field, and both units are strongly deformed. Localized zones of especially strong deformation within the Torridonian slice climb up to involve the overlying Moine mylonities. This has resulted in local interleaving of Moine and Torridonian strata. Consequently the Moine Thrust must have transferred displacement locally onto the base of the horse in its footwall.

The northern slopes of Càrn na Canaich (Cul a' Chairn; NH 102 834) display a tectonically thickened section of Fucoid Beds beneath a thin veneer of Salterella Grit in the footwall to the Moine Thrust. The western part of this slope (NH 101 835) displays four repetitions of Salterella Grit, each separated by thin seams of Fucoid Beds. Thus the tectonic thickening of the Fucoid Beds represents a duplex, here termed the 'An t-Sron Formation duplex'. The underlying Pipe Rock remains gently dipping towards the ESE. Consequently the duplex may be inferred to have a floor thrust along the stratigraphical top of the Pipe Rock. The roof is the Moine Thrust that here is not breached by footwall structures. However, it is folded by the underlying duplex.

Notwithstanding the An t-Sron Formation duplex, in general the Cambrian strata beneath the Moine Thrust at Càrn na Canaich is not affected by deformation linked to the Scandian thrusting (Figure 5.39). Indeed, the Pipe Rock is wonderfully exposed on large ESE-inclined dip-slopes, where *skolithos* trace fossils (burrows) are patently undeformed, retaining circular sections on the bedding surfaces. Similarly there are excellent exposures of the False-bedded Quartzite below, together with the unconformable contact with the underlying Torridonian sandstones. This unconformity is well exposed around the headwall of Coire a' Ghiubhsachain and famously as an outlier on Sail Liath (NH 072 825), the south-eastern summit of the An Teallach massif.

The Moine Thrust and underlying strata are offset by NE-trending steep to vertical faults that throw down to the north-west. These late structures are well exposed on the west side of Gleann Chaorachain, where they are masked by deep gullies and small escarpments on the glaciated dip-slope of Pipe Rock quartzites. Displacement on the faults appears to decrease towards the north-east.

Interpretation

The Moine Thrust Belt in the Càrn na Canaich area is remarkably simple, in essence represented by the Moine Thrust alone with only local development of imbrication in its footwall. At first sight these relationships are similar to those in south Assynt (see **Knockan Crag** GCR site report, this chapter), where the Moine Thrust Sheet is brought into juxtaposition with the foreland because of late displacements at the base of the sheet. At Càrn na Canaich, the Moine Thrust acted as a roof to the local duplex of An-t Sron Formation in its footwall and the Moine Thrust Sheet is folded by these lower structures. The Moine Thrust was presumably the first structure to develop in this sector, possibly pre-dated by the mylonites in its hangingwall. These mylonites are interleaved with Torridonian strata from the footwall. Consequently the last displacements across the system certainly occurred after shearing within the mylonites. This supports the contention from several other areas in the Moine Thrust Belt that the Moine Thrust formed early in the overall thrust sequence.

Conclusions

The Càrn na Canaich outcrops are nationally important because they display examples of the Moine Thrust in its simplest form, having moved without developing significant imbricate zones in its footwall. A minor duplex is developed locally that bulges up the Moine Thrust. However, for the most part the foliation in the Moine mylonites is parallel to bedding in the adjacent foreland successions of Cambrian quartzites. The relationships reflect simple 'smooth-slip' on the Moine Thrust. This behaviour is unusual compared with the Eriboll, Assynt and Achnashellach districts, and shows that large displacements on thrusts are possible without necessarily developing imbricate zones in their footwalls. The geology is strongly reflected in the scarp and dip-slope topography.

SLIOCH–HEIGHTS OF KINLOCHEWE (NG 989 707–NH 089 649)

R.W.H. Butler and S.J. Matthews

Introduction

The ground north of Kinlochewe (Figure 5.40) provided critical evidence used by both Murchison and Nicol during their early skirmishes in the mid-19th century as part of the 'Highlands Controversy' (Oldroyd, 1990). The transect to the south-west of the mountain of Slioch, along the north shore of Loch Maree and the continuation south-eastwards to Incheril and the glen containing the Abhainn Bruachaig (formerly known as 'Glen Logan' but here termed 'Glen Bruachaig') offer spectacular large-scale views (e.g. Figure 5.41) of the geometrical relationships between the main rock units of the North-west Highlands (Peach *et al.*, 1907). Murchison and Geikie (1861) interpreted this transect as forming a simple, E-younging rock

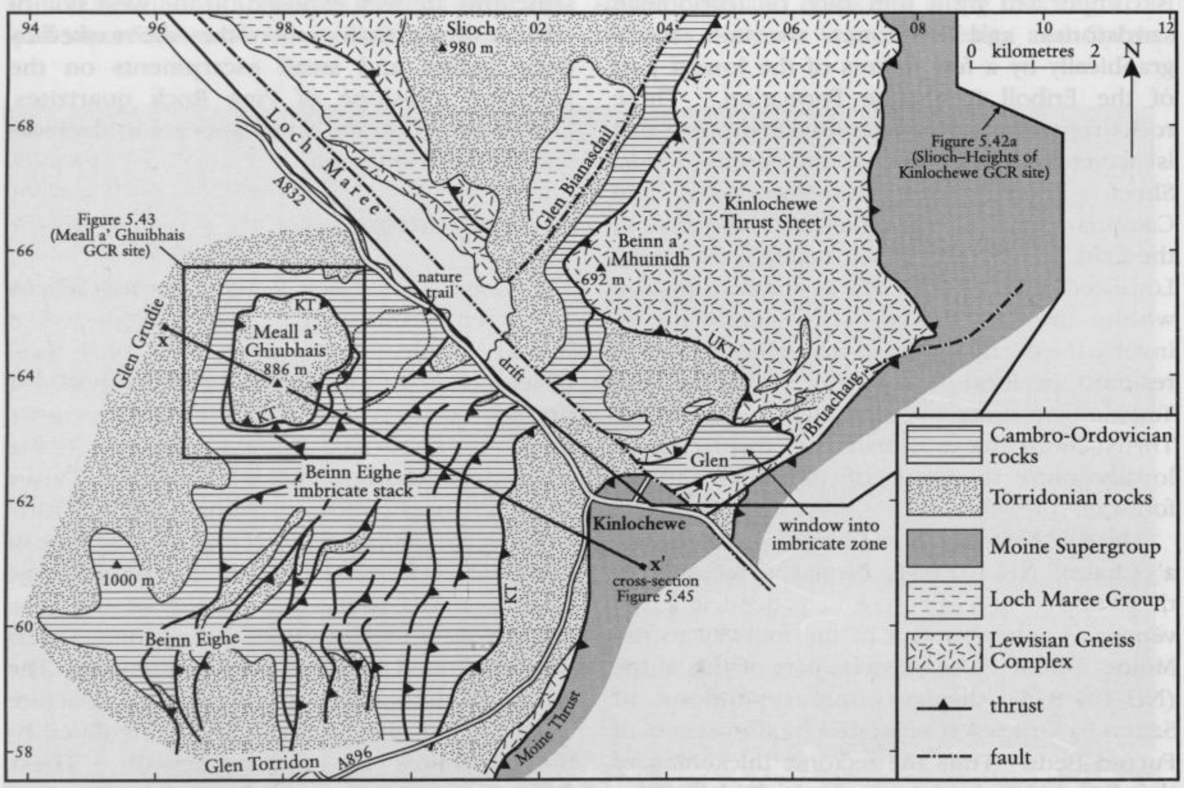


Figure 5.40 Map of the Slioch–Meall a' Ghuibhais–Beinn Eighe area, showing the regional geological setting of the Slioch–Heights of Kinlochewe GCR site (north-east of Loch Maree) and the **Meall a' Ghiubhais** GCR site. KT = Kinlochewe Thrust; UKT = Upper Kinlochewe Thrust. Locations of Figures 5.42a and 5.43 are indicated. Based on Geological Survey of Scotland (1913a) and Matthews (1984).

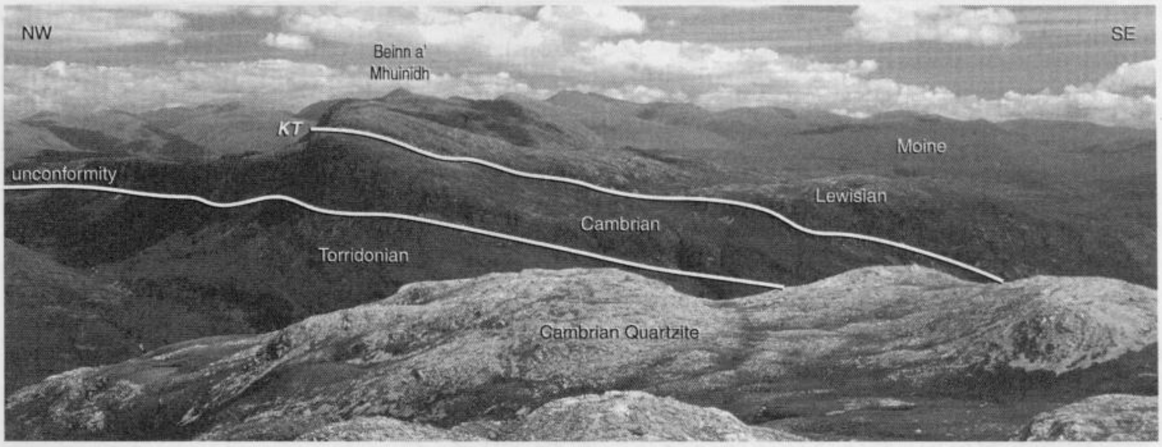


Figure 5.41 View north-east from the Beinn Eighe Nature Reserve to Beinn a' Mhùinidh showing the Kinlochewe Thrust Sheet. Lewisian gneisses are thrust WNW over the Cambrian rocks along the Kinlochewe Thrust (KT). Moine rocks form the hills to the north-east, including in the Fannich Mountains on the far skyline. The Moine Thrust is hidden from view. (Photo: R.W.H. Butler.)

sequence, while Nicol (1861) saw it as disrupted by faults. The edge of the Moine outcrop in Glen Bruachaig includes outcrops of crystalline rocks, termed the 'Logan Rock' by early workers and interpreted by both teams as being of igneous origin (e.g. syenite of Murchison and Geikie, 1861). Subsequent studies by Bonney (1880), in an early example of linked field and petrological descriptions (see Oldroyd, 1990), demonstrated the Lewisian origin of the 'Logan Rock', presaging the concluding act in the 'Highlands Controversy'. Work by Peach *et al.* (1907) established the 'Logan Rock' to be Lewisian gneiss and part of the far-travelled Kinlochewe Thrust Sheet.

This GCR site has more than historical significance. Offset Precambrian structures within the Lewisian of the Kinlochewe Thrust Sheet were used by Ramsay (1969) to deduce a slip in excess of 45 km on its basal thrust, one of few such estimates made in the southern Moine Thrust Belt. Furthermore, in the lower part of Glen Bruachaig, the footwall to the Kinlochewe Thrust Sheet is exposed in a window – one of very few such structures in the entire Moine Thrust Belt. Peach *et al.* (1907) described how the footwall is made of imbricated Cambrian strata. Based on these early studies, McClay and Coward (1981) initially interpreted the Kinlochewe Thrust as forming a simple roof to the imbricate zones. However, Coward (1982) later suggested that the Kinlochewe Thrust Sheet acted as a 'surge zone' which cuts gently down-section towards the west. Work by Matthews (1984; Butler *et al.*, 2007) suggested that the down-cutting of the Kinlochewe Thrust occurred before imbrication. The site is therefore important for establishing the geometrical relationships between the major thrust sheets and the underlying imbricated foreland strata.

The Caledonian Foreland to the west also includes spectacular geology. This includes arguably the most spectacular and famous demonstration of sub-Torridonian buried landscape, on the southern slopes of Slioch. The underlying Lewisian includes dramatic amphibolite-facies thrust zones that relate to Laxfordian crustal shortening (e.g. Droop *et al.*, 1998) and the thrust repetition of Archaean continental crust onto early Proterozoic supracrustal rocks of the Loch Maree Group. Although these field relationships have not received much attention in the specialist literature, they are important as the only places on the Scottish mainland where simple crustal thickening structures are exposed as part of the Lewisian Gneiss Complex (see Chapter 3 for an introduction to the Lewisian gneisses in north-west Scotland). This is one of only a few sites within this GCR volume that straddles two major geological elements of the North-west Highlands. It is therefore an excellent place for building up a geological history of the region, as recognized by the original workers in the mid-19th century.

Description

The site area stretches south-east from the craggy Torridonian sandstone Heights of Slioch (980 m) across Loch Maree Group mafic metavolcanic and subsidiary metasedimentary rocks, to the NE-trending Glen Bianasdail, developed along the Fhasaigh Fault. South-east of this fault Cambrian quartzites overlie Torridonian sandstones, above which lie imbricated An t-Sron Formation and the Kinlochewe Thrust Sheet. The bulk of the thrust sheet is composed of Lewisian grey and subsidiary mafic gneisses, which are well exposed on Beinn a' Mhùinidh (692 m) and the surrounding cliffs and plateau. Torridonian rocks and Cambrian quartzites occur in the lower part of the thrust sheet that occurs around Meallan Ghobhar (468 m; NH 029 645) and along the *c*. 250–400 m-high crags that overlook Kinlochewe to the north-east. The Moine Thrust lies farther south-east in Glen Bruachaig. The geology of this large GCR site is summarized on a simplified map and cross-section (Figure 5.42). The components of the site are described in order of their structural level, which broadly runs from west to east.

The Lewisian geology of the north-eastern side of Loch Maree forms part of a tract of supracrustal rocks that correlates with the metasedimentary and metavolcanic rocks of the Gairloch area (Park *et al*., 1987; Park, 2002). These rocks constitute the Loch Maree Group and are described in Chapter 3; here they lie within a late (D3) Laxfordian structure, the Letterewe Synform. The group comprises a varied suite of schistose amphibolites, quartzose psammites, semipelites and graphitic pelites, together with larger amphibolite sheets, all metamorphosed under amphibolite-facies conditions. Structurally overlying the supracrustal rocks and forming the core of the Letterewe Synform is a tract of quartzofeldspathic gneisses intruded by amphibolite sheets. These rocks, the Letterewe Gneisses, have been interpreted as belonging to the older Archaean part of the Lewisian Gneiss Complex which pre-dates the Loch Maree Group. They were thrust over the Loch Maree Group, and the contact is marked by strong mylonitization that overprints the peak metamorphic fabrics in both hangingwall and footwall (Droop *et al*., 1998). Stretching lineations plunge moderately to the south-east and asymmetrical structures imply a top-to-the-NW shear sense.

The Lewisian rocks are overlain unconformably by rocks of the Torridon Group. These form a 900 m-thick continuous section on the mountain of Slioch. The unconformity shows a remarkable palaeorelief of over 450 m, from a low at Smiorasair bothy (elevation 90 m; NH 003 670) to highs near Meall Riabhach (elevation 300 m; NH 012 670) and immediately beneath the western cliffs of Slioch (NG 997 693).

The western outcrops of the Torridonian, including small outliers of Diabaig Formation, contain breccias derived from the immediate substrate (chiefly amphibolite). However, most of the Slioch section is made up of the typical facies of the younger Applecross Formation, including dominantly well-rounded clasts of quartz and quartzofeldspathic aggregates. Across the palaeovalley, centred on Smiorasair bothy, the bedding in the Torridonian onlaps the gneissose basement.

The Fhasaigh Fault (Figure 5.42), a NNE-trending structure that throws down to the ESE, separates the Lewisian–Torridonian geology from the ground dominated by Caledonian thrust structures to the east (Peach *et al*., 1907). The Kinlochewe Thrust Sheet is made up of Lewisian gneisses overlain by small erosional remnants of Torridon Group sedimentary rocks. Scourie dykes within the sheet trend north-west–south-east, parallel to those in the foreland Lewisian. This implies that the thrust sheet was emplaced without significant rotation about a vertical axis. There is little internal deformation of Caledonian age within the sheet and Scourian-type field relationships are preserved intact through large areas. However, the ground above the hamlet of Incheril contains outcrops of Torridon Group (chiefly Applecross Formation). Peach *et al*. (1907) considered that these form the sedimentary cover to the main outcrop of Lewisian gneisses within the Kinlochewe Thrust Sheet, which crops out farther north. However, Matthews (1984) showed that the Lewisian basement overlies the Torridonian sandstones, separated by a thrust. Consequently he defined an Upper and a Lower Kinlochewe Thrust Sheet, the upper one carrying chiefly Lewisian gneisses, the lower one Torridonian sandstones with locally its own Lewisian basement (Butler *et al*., 2006). The upper sheet has small in-folded remnants of its cover of Diabaig Formation rocks (e.g. at NH 058 635), which lie in ENE-trending

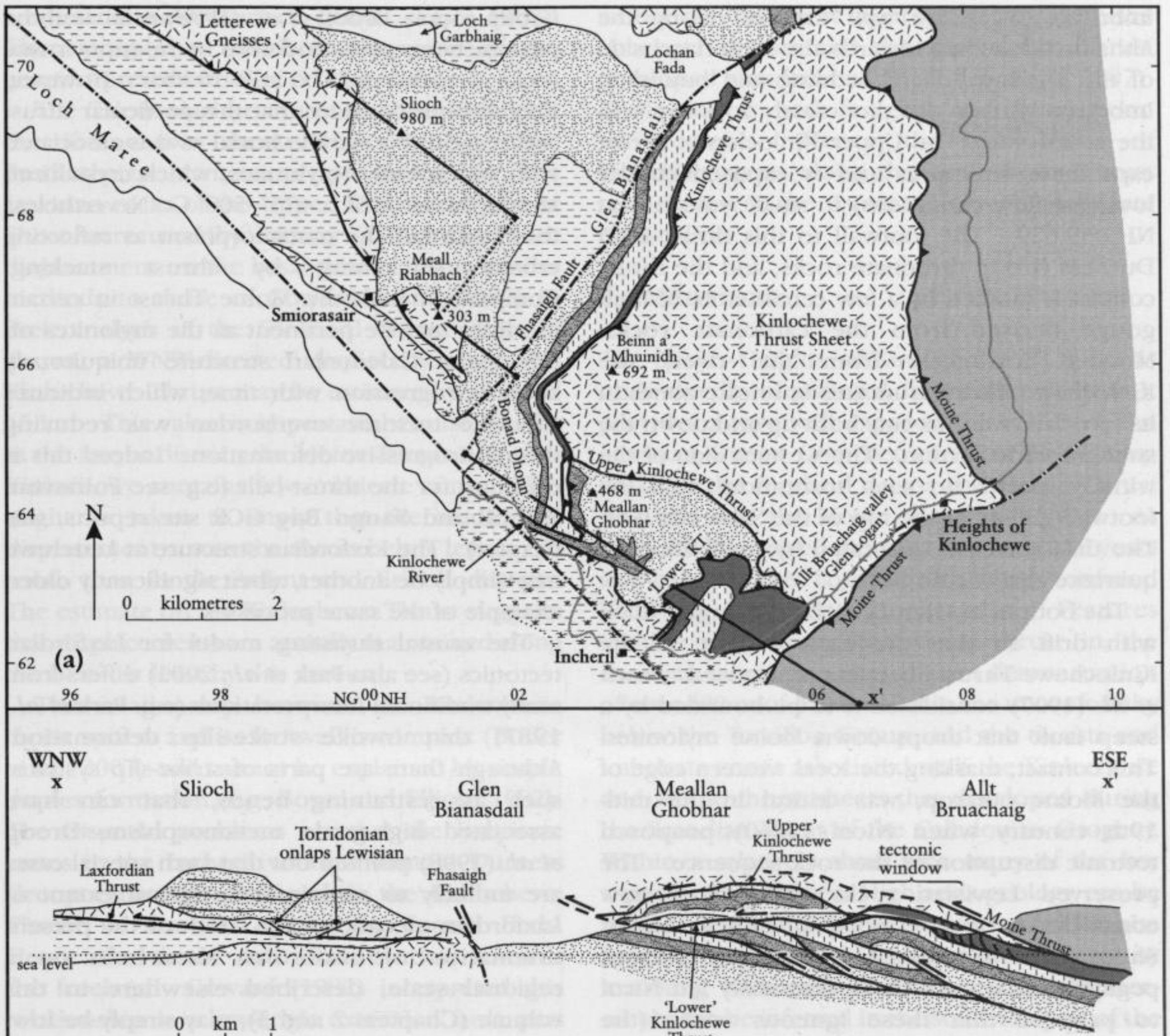


Figure 5.42 Map (a) and cross-section (b) of the Slioch–Heights of Kinlochewe GCR site. The part to the south-east of the Fhasaigh Fault is based on the work of Matthews (1984). Note that the section line is segmented and offset to the south-west at several points.

synclines. Similarly trending folds, containing small outliers of Cambrian quartzites are also found in the Lower Kinlochewe Thrust Sheet (e.g. at NH 045 636).

The Kinlochewe thrust sheets are bulged up and eroded to expose a small window into their footwall on the slopes 2 km north-east of Incheril in the lower part of Glen Bruachaig (Butler *et al.*, 2007). The window contains imbricated Cambrian strata, from the Pipe Rock, An t-Sron Formation and small amounts of the Durness Group carbonate rocks. These imbricate slices are well exposed along the Abhainn Bruachaig towards the hinterland side of the window. Here bedding and bounding imbricate thrusts dip moderately to steeply to the south-east. The Upper Kinlochewe Thrust caps these structures and is exposed (under low river-flow conditions) in small waterfalls at NH 059 629. The footwall to this thrust is in Durness Group carbonate rocks, and the thrust contact is marked by a few centimetres of fault gouge derived from the carbonate rocks. Moving north-west from the river, the Kinlochewe Thrust truncates imbricate zones in its footwall and thus cuts both up and down the stratigraphical section. The western side of the window shows no such truncation, with the footwall gliding at the top of the Salterella Grit. The thrust itself is decorated by small slices of quartzite and Fucoid Beds.

The bottom of Glen Bruachaig is largely filled with drift so that the eastern edge of the Kinlochewe Thrust Sheet is not exposed. Peach *et al.* (1907) considered it to be bounded by a steep fault that drops down Moine mylonites. This contact, marking the local western edge of the Moine outcrop, was critical in the mid-19th century when Nicol (1860) proposed tectonic disruption of the rock sequence. The preserved Lewisian rocks of what is now considered to be the (Upper) Kinlochewe Thrust Sheet are dominated by quartz-feldspar pegmatite, a feature that presumably led Nicol to propose that these igneous rocks (the mysterious 'Logan Rock' of the 19th century workers) were intruded up along the fault contact. However, there are outcrops of gneisses with clear banding, together with other attributes of Lewisian basement rocks, as recognized by Bonney (1879) and subsequently by Peach *et al.* (1907).

Interpretation

The GCR site contains geology that encompasses a long and varied history. The oldest rocks in the area are the Letterewe Gneisses that lie in the hangingwall to a thrust above the Loch Maree Group supracrustal rocks. Park *et al.* (1987) considered these rocks to be of Scourian affinity and therefore of late Archaean age. The thrust itself is interpreted as an early-Laxfordian structure. Park *et al.* (1987) considered that this thrust sheet represents the base of the slab that buried and metamorphosed the Loch Maree Group rocks. Droop *et al.* (1998) estimated the peak metamorphic conditions in the supracrustal rocks as *c.* 600 ± 25° C at 8–10 kbar. However, they did not consider that this particular thrust was responsible for the burial as it is associated with retrogressive mylonites, which crystallized at temperatures of *c.* 475°–500° C. Nevertheless they regarded the metamorphism as reflecting crustal thickening by thrust stacking. Comparison with the Moine Thrust in certain localities may be pertinent as the mylonites on this major Caledonian structure ubiquitously show retrogression with time, which indicates that the tectonic overburden was reducing during progressive deformation. Indeed this is common for the thrust belt (e.g. see **Foinaven**, **Eriboll** and **Sango Bay** GCR site reports, this chapter). The Laxfordian structure at Letterewe may simply be another, albeit significantly older, example of the same processes.

The crustal thrusting model for Laxfordian tectonics (see also Park *et al.*, 2001) differs from many traditional interpretations (e.g. Park *et al.*, 1987) that invoke strike-slip deformation. Although there are parts of strike-slip systems, such as restraining bends, that can have associated high-grade metamorphism, Droop *et al.* (1998) pointed out that such special cases are unlikely to explain the regional extent of Laxfordian metamorphism. Indeed the present orientation of Laxfordian shear-belts on a regional scale, described elsewhere in this volume (Chapters 2 and 3), may simply be low-angle structures that have been folded during a late stage of Laxfordian reworking (Park *et al.*, 2001). The Letterewe structure shows such late folding (F3), with the thrust now preserved in a NW-trending synform.

Laxfordian deformation on the north-eastern side of Loch Maree can be correlated with the main outcrop areas of Loch Maree Group supracrustal rocks in the Gairloch area. Park *et al.* (2001) dated peak metamorphism (Laxfordian D1) at *c.* 1900 Ma, with the later north-west–south-east folding (analogous to the F3 Letterewe Synform) occurring at *c.* 1700 Ma.

The Torridon Group sedimentary rocks of Slioch that overlie the Lewisian of Letterewe are part of the Applecross Formation (Peach *et al.*, 1907; Park *et al.*, 1994), with local patches of Diabaig Formation. The highly irregular unconformity at the base of these sedimentary rocks has long been recognized as representing a subaerial palaeosurface (Peach *et al.*, 1907). The example at Slioch charts some of the greatest preserved relief on this surface.

The Caledonian structures on the site include the Kinlochewe thrust sheets. The offset Precambrian structures preserved in the Lewisian rocks of the Upper Kinlochewe Thrust Sheet were used by Ramsay (1969) to deduce displacement on the basal thrust. Using similar methods to those of Coward *et al.* (1980) in their analysis of the Glencoul Thrust Sheet in Assynt, a WNW-directed displacement on the Kinlochewe Thrust may be estimated to exceed 45 km. This value is important because, unlike in the Assynt district, the Moine Thrust Belt near Kinlochewe contains few imbricate zones. This might be taken to imply that the amount of displacement across the thrust belt is less in the south than in the Assynt and Eriboll districts. The estimate on the Kinlochewe Thrust suggests that displacements are actually maintained along the belt – at least by this amount.

The relationship between the Kinlochewe thrust system and its footwall is complex (Butler *et al.*, 2007) and cannot be explained by simple duplex formation (e.g. Boyer and Elliott, 1982). The essential problems are that the imbricate zones in the Incheril window contain Durness Group carbonate rocks, while the Kinlochewe Thrust to the west glides on Fucoid Beds. Hence the thrust cuts down-section towards the foreland. Coward (1982) interpreted this relationship as a low-angle extension fault, part of a rotational gravity slide system – or 'surge zone'. Matthews (1984) pointed out that an alternative interpretation is that the thrust cut down-section because the foreland rocks dipped towards the east prior to thrusting. A derivation of this could include low-angle faulting running across a series of down-to-the-E normal faults so that the hinterland parts of the footwall contain younger rocks than those to the foreland.

The sequence of thrusting is problematic, particularly the relative timing between the Kinlochewe Thrust and the imbricate zones in its footwall. Peach *et al.* (1907) showed the Kinlochewe Thrust to be folded, suggesting that it pre-dated imbrication ('piggy-back' thrusting, Boyer and Elliott, 1982). However, both Peach *et al.* (1907) and Matthews (1984) also showed the imbricate zones to be truncated by the Kinlochewe Thrust, suggesting overstep thrusting (in the sense of Butler, 1987). A compromise model may be more appropriate whereby the imbricate thrusts and the Kinlochewe Thrust developed simultaneously (Butler *et al.*, 2007). The result is both bulging and decapitation of structures. Hence, the small lenses of Cambrian strata along the Kinlochewe Thrust may represent the truncated tops of imbricate thrust slices.

Conclusions

The Slioch–Heights of Kinlochewe GCR site is undoubtedly of national importance in that it provides a very well exposed transect from the Lewisian Gneiss Complex and Torridon Group rocks of the foreland across the Moine Thrust Belt and into the Moine rocks in the east. As such it has received attention for over 150 years and contains the 'Logan Rock', which confused Victorian geologists for decades. Features include a putative Proterozoic thrust in the Lewisian outcrops, a magnificent demonstration of over 400 m of palaeorelief in the unconformity below the Torridon Group, and the thrusts and imbricate zones associated with the Kinlochewe and Moine thrust sheets that developed during the Scandian Event of the Caledonian Orogeny. Within a relatively short area many of the key aspects of North-west Highlands geology can be placed in their relative sequence. The site includes one of very few locations where, by matching basement structures, large displacements can be inferred in the southern part of the Moine Thrust Belt. It also displays significant complexity in the relative sequence of movements on major and minor thrusts as displayed in the unique Incheril window.

MEALL A' GHIUBHAIS (NG 975 656–NH 022 619)

R.W.H. Butler and S.J. Matthews

Introduction

The Meall a' Ghiubhais GCR site lies at the eastern end of the Torridon hills, within the Beinn Eighe National Nature Reserve and overlooking Loch Maree (Figure 5.40), itself a GCR site for its well-preserved record of Holocene vegetation (Birks in Gordon and Sutherland, 1993). The Torridon district is renowned for its magnificent mountain scenery and exhibits some of the most dramatic thrust structures in the British Isles. Excellent exposure combined with the good fortune of being largely formed of the distinctive red-brown-weathering Torridonian sandstones and the white- to pale-grey-weathering Cambrian quartzites, makes the geological structure spectacularly visible in the landscape views. The site contains a klippe, largely composed of Torridonian sandstones and part of the regionally important Kinlochewe Thrust Sheet, together with well-exposed folds and thrusts in the underlying Cambrian sedimentary rocks. The site also offers spectacular views across Loch Maree onto the southern flanks of Slioch and Meallan Ghobhar, which display in cross-section the structural relationships between Lewisian, Torridonian and Cambrian strata of the foreland together with the far-travelled Lewisian and Torridonian of the Kinlochewe Thrust Sheet (Figure 5.40) (see **Slioch–Heights of Kinlochewe** GCR site report, this chapter).

The primary source of information on this GCR site lies within the memoir of the Geological Survey (Peach *et al.*, 1907), together with the 1:63 360 map (Sheet 92, Inverbroom) (Geological Survey of Scotland, 1913a). Peach *et al.* (1907) documented the units within the Kinlochewe Thrust Sheet and noted that it was folded by underlying imbricate structures. Since that work, there has been little published research. The Meall a' Ghiubhais Klippe is regularly an objective of student mapping projects and was remapped as part of a major analysis of thrust system geometry in the Torridon area by Matthews (1984; Butler *et al.*, 2006, 2007).

Description

Meall a' Ghiubhais (878 m, NG 977 637), the chief focus of the GCR site (Figure 5.43), is a conical rocky hill with a summit edifice consisting of 250 m of Torridonian sandstone. This represents a tectonic outlier (klippe) of the Kinlochewe Thrust Sheet and rests upon a plinth of Cambrian strata (Figure 5.44). The southern half of the klippe is separated from the coherent Cambrian succession of its plinth by a detached slice of Cambrian quartzite. In contrast, on its western side the footwall rocks form part of the foreland. On the east, the footwall contains a spectacular array of folds and thrusts, part of the

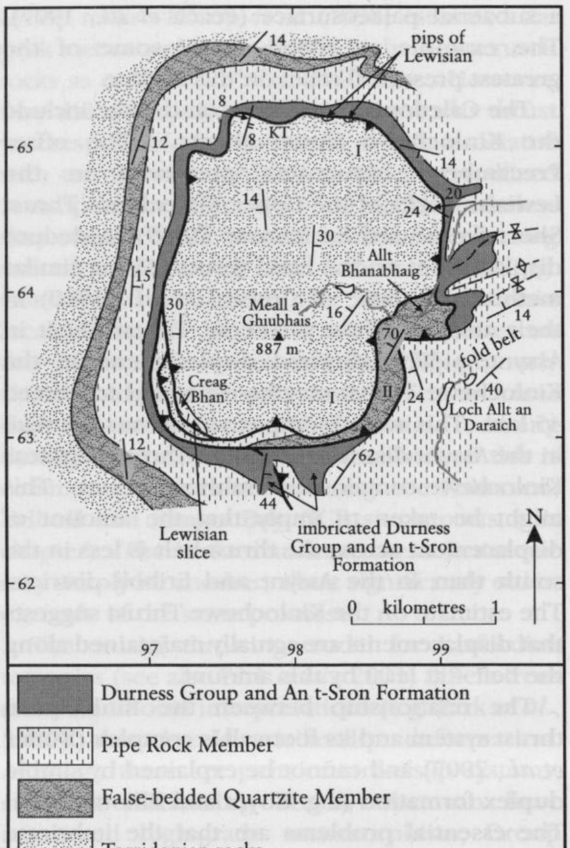


Figure 5.43 Map of the Meall a' Ghiubhais GCR site. KT – Kinlochewe Thrust. Based on Geological Survey of Scotland (1913a) and Matthews (1984).

extensive lower imbricate system that dominates the geology of neighbouring Beinn Eighe. Note that on the opposite side of Loch Maree and northwards to Dundonnell, these imbricate structures are not developed. The site thus contains important structural transitions: from the foreland into the Beinn Eighe imbricate stack and the lateral (northern) termination of this imbricate stack (Butler *et al.*, 2007).

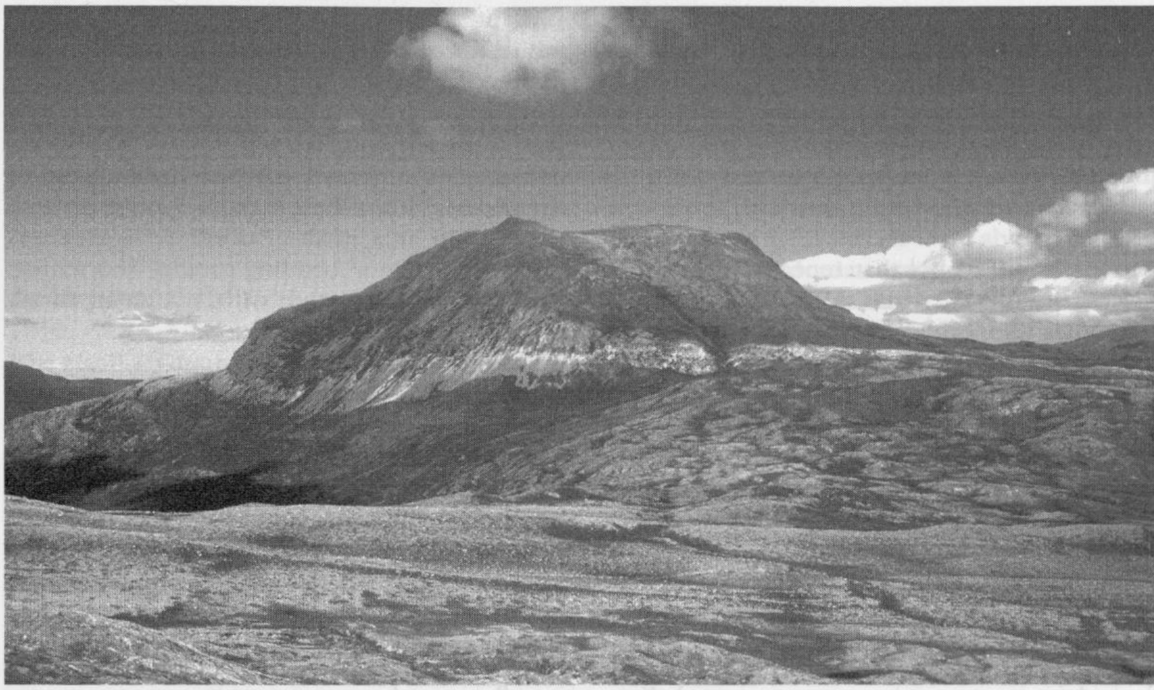


Figure 5.44 Looking north to the Meall a' Ghiubhais Klippe from Beinn Eighe. The darker, upper part of the hill is made up of Torridon Group rocks in the Kinlochewe Thrust Sheet. The Kinlochewe Thrust occurs just above the pale Cambrian quartzites, which lie in a separate thrust sheet. In the foreground are imbricated thrust slices of Torridonian sandstones and Cambrian quartzites. (Photo: R.W.H. Butler.)

Meall a' Ghiubhais Klippe

The klippe is composed mainly of a normal, right-way-up succession of Torridonian strata, comprising the older, Diabaig Formation and the younger, Applecross Formation. The succession is repeated by minor imbricate thrusts, well displayed on the northern slopes of the summit cone of Meall a' Ghiubhais. Small bodies of Lewisian gneisses decorate the base of the klippe, locally forming the basement to the overlying Torridonian (Butler *et al.*, 2006). The largest of these is exposed on the south-west corner of the klippe at NG 971 633, where a 200 m-long slice of Lewisian gneisses has been thrust over a thin slice of Torridonian sandstones (Figure 5.43). The gneisses are bounded above by the sub-Torridonian unconformity. More Lewisian rocks are found along the northern edge of the klippe (NG 982 653). These small pips, again bounded above by the sub-Torridonian unconformity and below by the Kinlochewe Thrust, are most plausibly interpreted as palaeohills in the Precambrian landscape, planed off by the Kinlochewe Thrust.

Detached thrust slice

The Kinlochewe Thrust carries the Meall a' Ghiubhais Klippe onto the foreland so that, above Glen Grudie, Torridonian strata overlie gently dipping Fucoid Beds that here underlie a broad shelf (Figure 5.44). However, at Creag Bhan (NG 971 633, Figure 5.43) the klippe is directly underlain by an un-named thrust slice of quartzites of the Pipe Rock Member. The overlying Kinlochewe Thrust has been folded during formation of the underlying thrust slice.

The detached slice of quartzites may be traced eastwards in the immediate footwall to the Kinlochewe Thrust around to the Allt Bhanabhaig (Butler *et al.*, 2007). Here it is composed of the False-bedded Quartzite Member and again clearly appears to have bulged up the higher thrust sheet. Cross-bedding within the quartzites shows that they young upwards towards the overlying Torridonian and thus have a tectonic contact with the klippe. However, the stratigraphy of the quartzite slice changes from east to west beneath the klippe so that the footwall to the Kinlochewe Thrust and the hangingwall to the un-named sub-slice thrust can be inferred to have climbed up the stratigraphical section in their transport direction (Figure 5.45).

The imbricate system

The folds and thrusts that repeat the Cambrian succession on the east side of the Meall a' Ghiubhais Klippe form the northern part of the Beinn Eighe imbricate stack (Butler *et al.*, 2007). This major thrust system differs from those found farther north in the Moine Thrust Belt (e.g. at the **Eriboll** and **Skiag Bridge** GCR sites) in that the individual imbricate slices are notably thick. Imbricate thrusts climb up, via single ramps, through the thick Torridonian succession that typifies this part of the Caledonian Foreland (Figure 5.45). Within the site, the deeper parts of the thrust system are exposed in profile on the slopes above the head of Loch Maree (Figure 5.40). However, at the current erosion level the Pipe Rock Member is dominant. The imbricate slices, ramps, and particularly the associated folds are very well exposed on the ground around Loch Allt an Daraich (Figure 5.43). Although consisting of frost-shattered blocks and pavements, this awkward terrain is rendered easily accessible by way of the nature trail. An array of anticlines and synclines with NE-trending axes provide spectacular bedding-plane outcrops, which display exemplary sections through the ubiquitous trace fossils of the Pipe Rock Member. Of the two common trace fossils present, *Monocraterion* shows very weak strain, while *Skolithos* is virtually undeformed. Originally circular pipe sections now show weakly elliptical shapes with axial ratios typically less than 1.2:1. These very low strains are characteristic of most of the lower parts of the Moine Thrust Belt here (but contrast with the Heilam area in the **Eriboll** GCR site) and imply only minor bedding-parallel shortening, presumably associated with incipient thrust growth.

Nature of the Kinlochewe Thrust

The Kinlochewe Thrust is marked by a few metres of mylonite with E–W-trending stretching lineations. The mylonitic foliation is generally sub-parallel to the thrust surface. The thrust is folded by the accreted, underlying quartzite slice on the southern and eastern sides of the klippe. These are both folded above the imbricate zones of Pipe Rock just to the west of Loch Allt an Daraich (Figure 5.43).

Outcrops around the north side of the Meall a' Ghiubhais Klippe show that the footwall to the Kinlochewe Thrust changes its stratigraphical horizon (Figure 5.43). In upper Allt Bhanabhaig (NG 989 640) the footwall lies in quartzites, but to the north, at Cnoc na Gaoithe (NG 990 647) it is in Fucoid Beds. The thrust continues to climb up-section to the north-west into the lower part of the Durness Group, but still farther west, it drops back down onto Salterella Grit. These relationships define a near-perfect lateral ramp in the footwall to the Kinlochewe Thrust. A

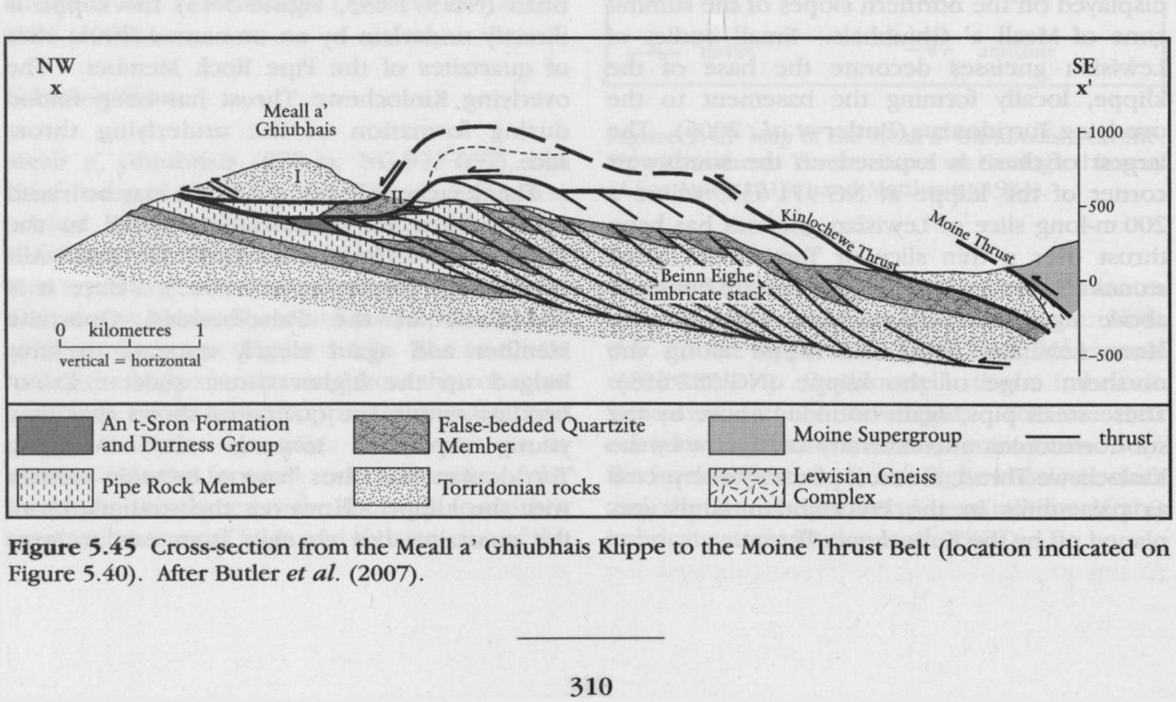


Figure 5.45 Cross-section from the Meall a' Ghiubhais Klippe to the Moine Thrust Belt (location indicated on Figure 5.40). After Butler *et al.* (2007).

similar ramp may be inferred to lie on the south side of the klippe (NG 977 630), where an imbricate system in the footwall contains Durness Group carbonate rocks together with units of the An t-Sron Formation. These imbricate slices probably represent the remnants of an otherwise eroded duplex at the base of the Beinn Eighe imbricate stack.

Interpretation

The Meall a' Ghiubhais Klippe is an outlier of the Kinlochewe Thrust Sheet, a major detached unit of Lewisian and Torridonian rocks which directly underlies the Moine Thrust. Using balanced cross-sections, Butler *et al.* (2007) estimated that this part of the thrust belt, including the Kinlochewe Thrust, contains a minimum of 15 km of shortening. This figure is probably a gross underestimate of the true amount of thrust displacement.

The Kinlochewe Thrust Sheet was emplaced prior to imbrication in its footwall, as its base is folded by the underlying imbricate zones. The Kinlochewe Thrust shows subtle variations in its geometry around the klippe, with the stratigraphical level of its footwall ranging from the top of the Pipe Rock to the lowest part of the Durness Group. Around the klippe these relationships may be explained by lateral and frontal ramps, with the thrust cutting up-section in its transport direction.

The outcrops of the Kinlochewe Thrust at Meall a' Ghiubhais raise significant mechanical issues for thrust localization and displacement (Butler *et al.*, 2006). Theoretical analyses of fault mechanics commonly assume that thrust trajectories are primarily controlled by the anisotropy of well-layered sedimentary rocks. Yet the Kinlochewe Thrust cuts back and forth across the irregular Torridonian–Lewisian unconformity rather than follow bedding in the cover sedimentary rocks, and it also appears to have cut gently down-section across the Cambrian stratigraphy.

The imbricate zones underlying the Kinlochewe Thrust Sheet, which form the Beinn Eighe system (Figure 5.45), are restricted to the southern side of Loch Maree. These structures involve considerable thicknesses of Torridonian sandstones and imply the presence of a Sole Thrust that is substantially deeper than elsewhere in the Moine Thrust Belt. The relatively abrupt termination of these structures to the north can be explained by consideration of the Precambrian geology across the area (Figure 5.40). The NW-trending Loch Maree Fault displays a component of south-westerly down-throw, thus preserving a much greater thickness of Torridonian sedimentary rocks on its south-west side. As a result, in the Meall a' Ghiubhais and Torridon areas thrusts were able to cut deep into the Torridonian sandstone succession, building up a thick thrust stack, as seen for example on Beinn Eighe (Butler *et al.*, 2007). To the north the Torridonian is virtually eliminated towards the east by the overstep of the sub-Cambrian unconformity, inhibiting thrust development.

Conclusions

The Meall a' Ghiubhais GCR site, within the Beinn Eighe National Nature Reserve, offers spectacular views of major thrust sheets, together with smaller more-detailed thrust structures, both within the site itself and across to the famous landscapes on the north side of Loch Maree (see **Slioch–Heights of Kinlochewe** GCR site report, this chapter). The fine exposures have attracted numerous geological visitors, largely to obtain views. The geology within the site is nationally important for understanding how major and minor thrusts link up with, and relate to one another, and also raises important issues concerning the mechanics of thrusting and faulting.

The Kinlochewe Thrust can be demonstrated to have formed early and to have been folded during the formation of underlying thrust structures. These types of observation are fundamental in the reconstruction of the timing and geometrical evolution of different parts of a thrust belt. The rocks in the hangingwall of the Kinlochewe Thrust alternate between Torridonian and Cambrian sedimentary rocks and Lewisian basement gneisses, all of which have radically different mechanical properties. Narrow zones of mylonitization associated with the thrust are undoubtedly localized in the more-massive rocks that lacked obvious bedding or a strong foliation. Hence studies of thrust geometry at this site, like those at the **Glencoul** GCR site, have much to contribute to the debate about differences in thrust mechanics between regions of deformed cover sedimentary rocks and those involving crystalline basement.

BEINN LIATH MHOR (NG 954 522–NG 988 515)

R.W.H. Butler

Introduction

Culminations that bulge up the Moine Thrust to expose underlying thrust sheets range from outcrop size up to tens of kilometres wide in north-west Scotland. Assynt provides by far the largest of the examples, but a particularly instructive example crops out in the hills between Glen Torridon and Achnashellach in the Beinn Liath Mhor GCR site area (Figure 5.46). Unlike Assynt, where an array of basement-cored thrust sheets and a complex series of imbricate systems are found, at Beinn Liath Mhor the enclosed imbricate structures are considerably less complex, making it ideal for developing an understanding of how such large-scale culminations can be generated by thrust imbrication.

The structure of the Achnashellach area was first reported by Nicol (1860), who described thrust repetitions of what are now known as Torridonian sandstones and Cambrian quartzites. His key section traversed the mountain of Beinn Liath Mhor, and this transect was also used in the Geological Survey memoir of Peach *et al.* (1907), whose authors considered it to be one of the most spectacular sections through imbricate thrusts anywhere in north-west Scotland. Thrust ramps and associated folds are well picked out by the colour contrast between the red-brown sandstones and white quartzites, and by the regular bedding in the quartzites. Therefore, it is arguably the best place in the entire thrust belt for demonstrating the importance of large-scale imbrication to non-specialists. The north-eastern part of the area was mapped by Matthews (1984) and the south-western part by Morgan (1985), both as part of PhD studies. This work is incorporated into a larger study of thrust system geometry through

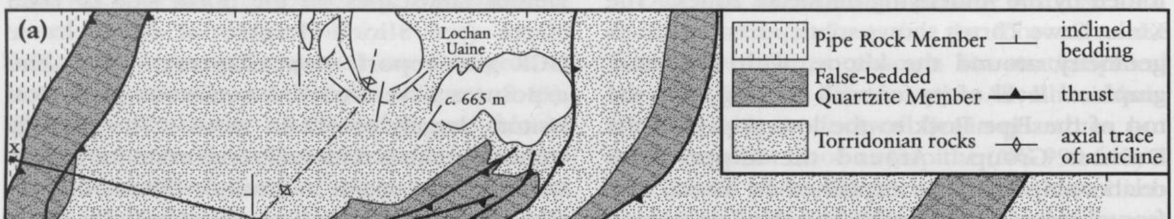


Figure 5.46 Map (a) and cross-section (b) of Beinn Liath Mhor. Inset box on section shows location of Figure 5.47. Based on Matthews (1984), Morgan (1985) and Butler *et al.* (2007).

the Achnashellach culmination that includes the classic central sector through Beinn Liath Mhor and the neighbouring ridge of Sgorr Ruadh (Butler *et al.*, 2007).

Description

Beinn Liath Mhor is a 3 km-long, E–W-trending ridge that has three distinct tops. The highest, at 926 m, lies at the western end of the ridge (Figure 5.46a). Its northern and southern slopes provide a near ideal section, 300–500 m deep (Figures 5.46b, 5.47). The structure can be well appreciated from the neighbouring summit of Sgorr Ruadh (962 m, NG 959 505), which itself displays fine thrust belt geology. Much of the crest of Beinn Liath Mhor is made up of cross-bedded quartzites of the Cambrian Eriboll Sandstone Formation. These form generally ESE-dipping panels, separated by narrower outcrops of Torridonian sandstones. However, Torridonian rocks dominate on the lower slopes of the mountain. These relationships are critical for understanding the structure of the mountain, for they imply that the two rock units are juxtaposed by thrust faults that dip more steeply ESE than the bedding in the sedimentary rocks (Butler *et al.*, 2007).

The most westerly thrust in the GCR site to show stratigraphical separation crops out to the west of Beinn Liath Mhor. It can be traced along a bench (e.g. at NG 954 530) where well-bedded gritty sandstones and conglomerates of the Torridonian Applecross Formation lie on cross-bedded quartzites of the False-bedded Quartzite Member. The quartzites are folded on a wave-length of *c.* 100–200 m and show truncations of bedding indicative of thrust repetition. Matthews (1984) and Butler *et al.* (2007) have mapped out similar structures on the neighbouring hill of Sgurr Dubh to the north-east. The Torridonian sandstones in the hangingwall to the main thrust define a large NE-trending anticline whose axial trace extends from the western part of Lochan Uaine (NG 965 525) and to the western end of the Beinn Liath Mhor ridge at Sail Gharbh (NG 958 520). Cambrian quartzites, lying unconformably on the Torridonian rocks, can be traced from the eastern Lochan Uaine onto the summit ridge of Beinn Liath Mhor. At this higher elevation, Pipe Rock is preserved above the lower False-bedded Quartzite Member. In the highest exposed rocks the two quartzite members are repeated by imbricate thrusts (Figure 5.46). This tract of quartzites can be mapped south to Sgorr Ruadh.

The quartzites beneath the main summit of Beinn Liath Mhor lie on Applecross Formation rocks that are folded into an anticline. The hinge line of this fold can be traced through the

Figure 5.47 The south side of the Beinn Liath Mhor ridge from Sgorr Ruadh. Steep thrusts separate imbricate thrust slices containing Torridon Group sandstones and Cambrian quartzites. A hangingwall anticline occurs left of centre. Compare with cross-section shown in Figure 5.46b. (Photo: R.W.H. Butler.)

mountain, plunging gently north-east and with an interlimb angle of *c*. 90°. Quartzites in the footwall to the thrust that carries the folded Torridonian rocks contain truncated synclines. These observations imply that buckling is an important precursor to thrusting.

The eastern top of the Beinn Liath Mhor ridge (876 m; NG 983 515) is capped by cross-bedded quartzites that are also folded into NW-facing structures and are cut by thrusts, equivalent to the structures on the western end of the ridge. The quartzites cannot be mapped out farther south, as deep erosion of the Coire Lair valley means that only Torridonian rocks are preserved. Where exposed on the eastern end of the Beinn Liath Mhor ridge, the Torridonian rocks dip gently in a broadly ESE direction. The same simplicity holds at deeper structural levels, as exposed in the river Lair valley. The Torridonian rocks are overlain stratigraphically by Cambrian quartzites on Carn Eite (NG 998 498), to the east of Coire Lair.

Interpretation

The thrusts in the area around Beinn Liath Mhor climb from the Torridonian up into Cambrian quartzites, and outwith of the GCR site they cut the An t-Sron Formation (Butler *et al*., 2007). Spectacular exposures on the ridge and flanks of the mountain show that the imbricate thrusts have a simple form, with ramps cutting across the stratigraphical contacts. Here, thrusting is associated with folds, particularly of the basal Cambrian unconformity. This suggests that buckling may have preceded displacements on thrust ramps. However, in general the imbricate slices show only minor internal distortional strain, as shown by the little distorted *Skolithos* burrows in the Pipe Rock. In the Torridonian rocks, cleavage is developed locally in siltstones of the Applecross Formation and the sandstones contain weakly developed, quartz-filled fracture arrays, but otherwise thrust stacking appears to have been accomplished with very little internal deformation. This is the most southerly part of the Moine Thrust Belt to show such simplicity.

Conclusions

The steep flanks of Beinn Liath Mhor are of national importance in that they show arguably the clearest large-scale examples of imbricate thrusts and associated folds anywhere in north-west Scotland. The spectacular structures are readily seen from distant viewpoints on account of extensive rock exposure and the marked colour contrast between the main rock-types involved, red-brown Torridonian sandstones and white Cambrian quartzites. Collectively the imbricate structures appear to have resulted in an updoming of the upper structures of the Moine Thrust Belt, including the Kishorn and Kinlochewe thrust sheets, consisting mainly of Lewisian gneisses, and the Moine Thrust, to form a structural inlier known as the 'Achnashellach culmination' (Butler *et al*., 2007). These relationships suggest that the imbricate structures of Beinn Liath Mhor formed after movements on the higher structures. The structures can be traced north-east to Beinn Eighe and the **Meall a' Ghuibhais** GCR site, and south-west to the **Cnoc nam Broc** GCR site.

CNOC NAM BROC, KISHORN (NG 838 420–NG 892 450)

R.W.H. Butler

Introduction

The southern part of the Moine Thrust Belt is radically different in structure to that in the north in that the broad systems of imbricate thrusts that stack up the Cambrian stratigraphy in the Assynt and Eriboll districts are absent. On Skye and in Lochalsh the thrust belt is characterized by a major fold–thrust complex, termed the 'Kishorn Nappe'. The best place to study the relationships between the Kishorn Nappe and underlying structures is centred on Cnoc nam Broc on the eastern side of the Kishorn Valley, between the head of Loch Kishorn and Bealach a' Ghlas-chnoic (Figure 5.48).

Despite the importance of the area, there has been little published material on the geology in and around the Cnoc nam Broc GCR site since the Geological Survey's North-west Highlands memoir (Peach *et al*., 1907) until Butler *et al*. (2007). The origin of the Kishorn Thrust Sheet is discussed by Butler *et al*. (2006). The area is frequently visited and studied by student groups, no doubt drawn by the generally excellent exposure of imbricate thrusts and the Kishorn Nappe. It offers excellent opportunities to examine many aspects of thrust tectonics: large nappes and major thrust surfaces;

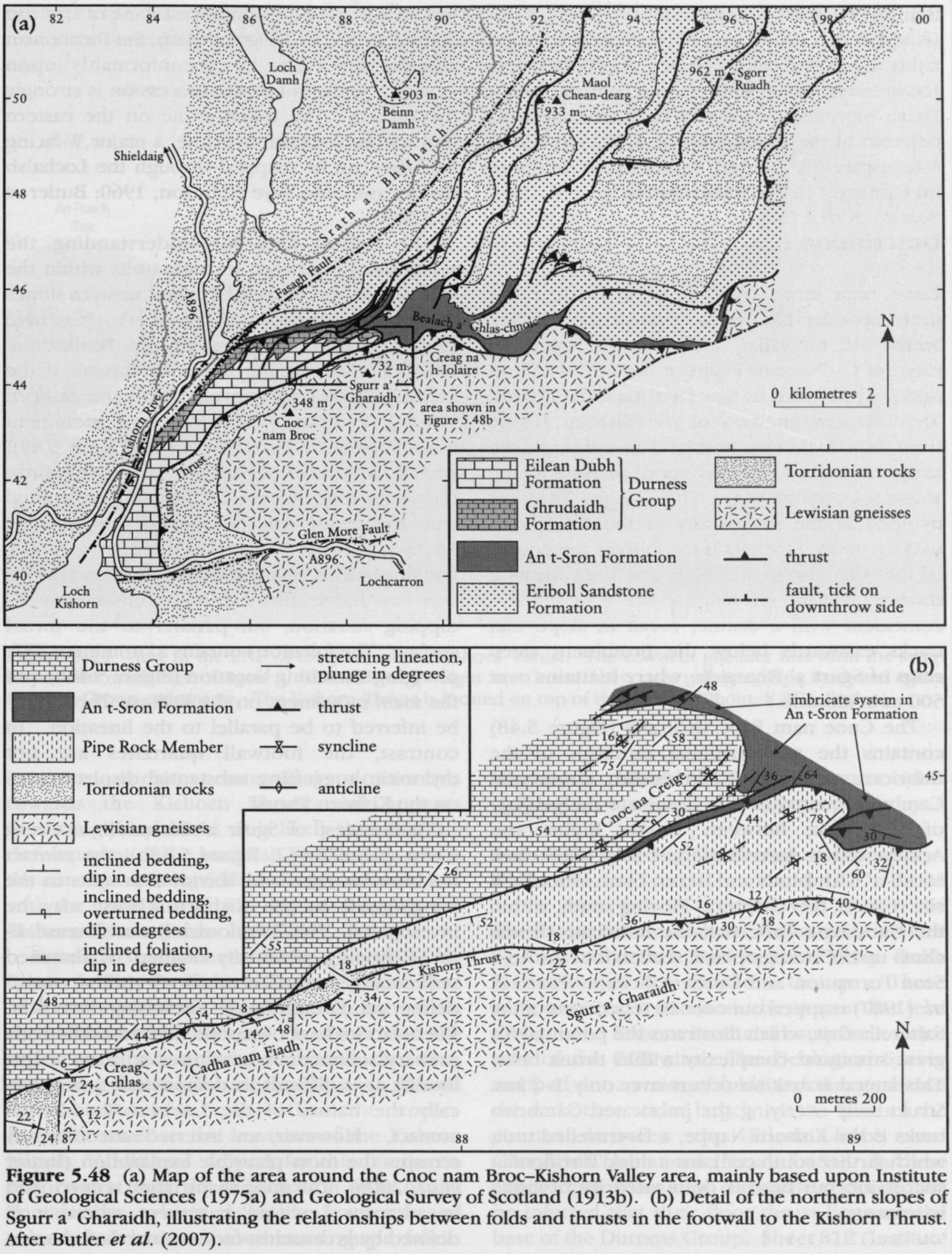


Figure 5.48 (a) Map of the area around the Cnoc nam Broc–Kishorn Valley area, mainly based upon Institute of Geological Sciences (1975a) and Geological Survey of Scotland (1913b). (b) Detail of the northern slopes of Sgurr a' Gharaidh, illustrating the relationships between folds and thrusts in the footwall to the Kishorn Thrust. After Butler *et al.* (2007).

deformation fabrics associated with these features; lateral variations in nappe content and in branching imbricate thrusts; evidence for the sequence of thrust stack development. In addition to these examples of contractional structures associated with the Moine Thrust

Belt, the GCR site also includes the Fasagh Fault (Peach *et al.*, 1907), one of the major Mesozoic faults associated with the Sea of the Hebrides sedimentary basin (Butler and Hutton, 1994). These 'morphotectonic' structures are commonly reflected in the topography (e.g. Watson, 1984) and apparently exerted considerable influence on Cainozoic landscape evolution.

Description

Cnoc nam Broc (348 m) is a small rocky protruberance that overlooks the Kishorn Valley. To the ENE the valley side rises up to the rocky ridge of Cadha nam Fiadh (*c.* 560 m), which in turn is overlooked by Sgurr a' Gharaidh (732 m). The Lewisian gneisses of the Kishorn Nappe form these higher summits and also underlie the extensive lochan-studded rocky plateau to the south at *c.* 550–700 m. The Kishorn Thrust is mapped in the lower part of the Alt Mòr at *c.* 70 m above OD. Its trace follows the course of the Allt Mòr to the ENE and then forms a distinct feature by Cnoc nam Broc and is coincident with a distinct break in slope that tracks eastwards below the prominent steep crags of Sgurr a' Gharaidh, where it attains over 500 m in altitude.

The Cnoc nam Broc GCR site (Figure 5.48) contains the southernmost outcrops of the imbricate thrusts of Torridonian strata and Cambrian quartzites that dominate the geology of the area between Beinn Eighe and Achnashellach (see Butler *et al.*, 2007; and **Meall a' Ghiubhais** and **Beinn Liath Mhor** GCR site reports, this chapter). Moving south, within the Cnoc nam Broc site, the imbricate thrusts climb up the stratigraphical section into the An t-Sron Formation and Durness Group. Peach *et al.* (1907) mapped out over 20 repetitions of the Salterella Grit, which illustrates the potential for great structural complexity within thrust belts. This lateral transition occurs over only 1–2 km. Structurally overlying the imbricated Cambrian rocks is the Kishorn Nappe, a far-travelled unit, which farther south contains a thick Torridonian succession but here is dominated by Lewisian basement.

The Kishorn Thrust and Nappe

The Kishorn Nappe is composed of Lewisian gneisses together with its cover of Torridonian Sleat Group grey sandstones and minor mudstones. On the south-west flank of Cearcall Dubh (NG 855 412, Figure 5.48a), the Torridonian sedimentary rocks lie unconformably upon Lewisian gneisses but the succession is strongly overturned. The outcrops lie on the eastern limb of the Lochalsh Syncline, a major W-facing fold that can be mapped through the Lochalsh district and onto Skye (Johnson, 1960; Butler *et al.*, 2006).

The critical area for understanding the relationships between tectonic units within the GCR site lies on the northern and western slopes of Sgurr a' Gharaidh (NG 884 444). It is here (Figure 5.48b), and around the Beallach a' Ghlas-chnoic, that the imbricate thrusts of the Achnashellach area converge with the Kishorn Thrust. The thrust crops out on a prominent bench below Creag na h-Iolaire (Figure 5.49), where it carries Lewisian basement onto Cambrian Pipe Rock. Deformation associated with the thrust may be studied north-east of Sgurr a' Gharaidh at NG 890 447 where the hangingwall is marked by a few metres of Lewisian-derived mylonite with a moderately SE-dipping foliation, sub-parallel to the thrust surface. The foliation contains a prominent ESE-plunging stretching lineation (Figure 5.48b) and the main movement on the Kishorn Thrust may be inferred to be parallel to the lineation. In contrast, the footwall quartzites are not mylonitic, suggesting substantial displacements on the Kishorn Thrust.

To the west of Sgurr a' Gharaidh, at Creag Ghlas (NG 870 442; Figure 5.48b), the contact between Lewisian and Torridonian units in the hangingwall to the Kishorn Thrust may be investigated. The Torridonian has an intense, E- to SE-dipping schistosity defined by flattened sedimentary grains and micas. Grain shapes also define an ESE-plunging stretching lineation. These fabrics have overprinted and modified any primary sedimentary structures so that, at this locality, it is difficult to demonstrate unequivocally the nature of the Lewisian–Torridonian contact. However, an inverted unconformity remains the most plausible explanation (Butler *et al.*, 2006). The same shape fabric is developed in adjacent Lewisian basement where it is defined by greenschist-facies minerals that overprint the original gneissose banding. However, pre-Caledonian agmatitic textures within the Lewisian basement may still be recognized in some exposures (e.g. NG 870 441). The greenschist-facies shape fabric developed in the

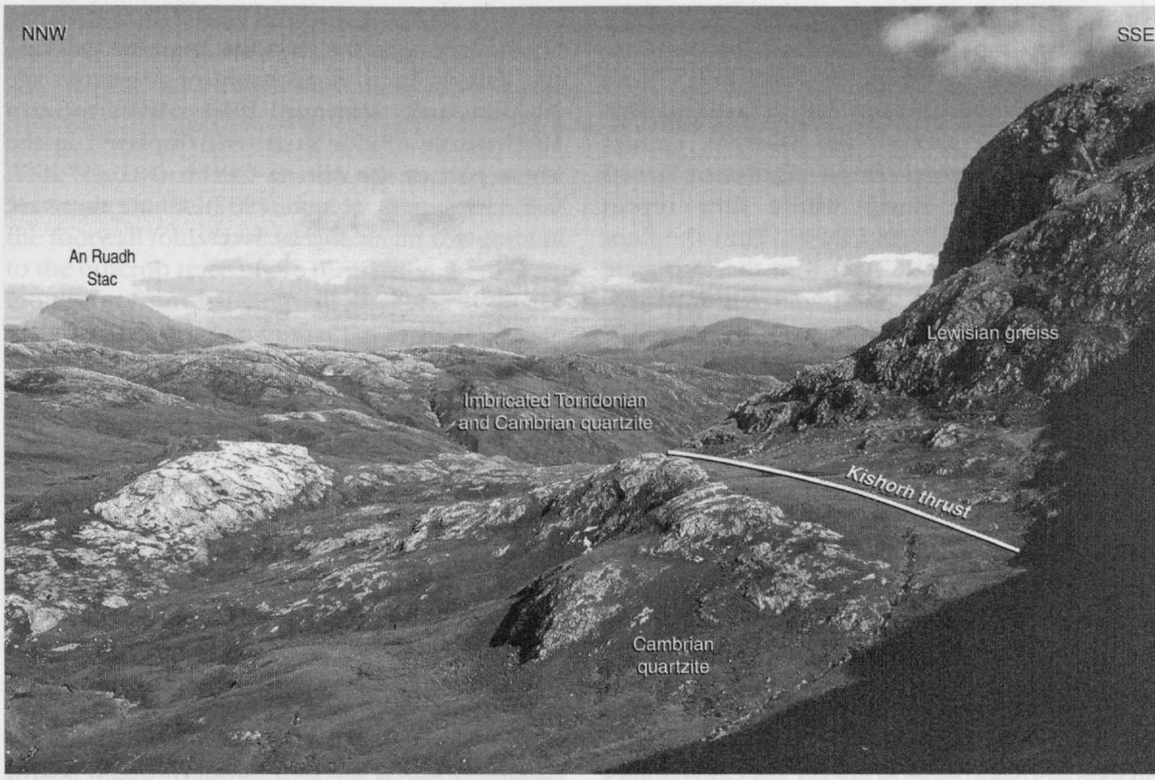


Figure 5.49 View to the ENE of the trace of the Kishorn Thrust. The Lewisian gneisses that form the steep slopes and north face of Sgurr a' Gharaidh to the right have been thrust over pale-grey Pipe Rock and white Durness Group carbonates. The Kishorn Thrust is located on top of the bench. (Photo: R.W.H. Butler.)

Lewisian gneisses intensifies downwards towards the Kishorn Thrust and appears increasingly mylonitic. It is likely then that the development of the Lochalsh Syncline, to which the outcrops at Creag Ghlas belong, was associated with the formation of, and displacement on, the Kishorn Thrust (Johnson, 1960).

Beneath Cadha nam Fiadh (NG 877 445; Figure 5.48b), the Kishorn Thrust carries a slice of Torridonian strata. The upper contact of the slice is marked by mylonitic Lewisian, and the mylonitic fabric is bulged around the slice, suggesting that the Torridonian slice is a distinct thrust-bound unit, rather than the unconformable cover to the Lewisian of the Kishorn Nappe. Additional support for this interpretation comes from the deformation style of the Torridonian, which is highly fractured and veined, but has no pronounced shape fabric. This is in contrast to the Torridonian sandstones at Creag Ghlas that are interpreted to be unconformable upon Lewisian gneiss within the Kishorn Nappe. These issues are dealt with further in the **Slumbay Island** and **Carn a' Bhealaich Mhòir** GCR site reports (this chapter).

Imbricate zones of Cambrian sedimentary rocks

The footwall to the Kishorn Thrust to the west of Sgurr a' Gharaidh lies in the Eilean Dubh Formation of the Durness Group. These carbonate rocks dominate the slopes that lead down to the Kishorn River and comprise a major part of the GCR site. The Geological Survey mapped out a series of folds and thrusts within the carbonate rocks, largely on the basis of the contact between the Eilean Dubh and Ghrudaidh formations (Figure 5.48a). As these structures involve only carbonate rocks, it may be inferred that their floor thrust lies near the base of the Durness Group. Sheet 81E (Institute of Geological Sciences, 1975a) shows this floor thrust folded around imbricate slices of An t-Sron Formation rocks on the southern side of Bealach a' Ghlas-chnoic (Figure 5.48a). The relationships between these two thrust systems (one in the Durness Group and one in the An t-Sron Formation) are exposed on the northern flanks of Cnoc na Creige (NG 885 452). Here imbricate thrusts carrying Salterella Grit climb into the basal part of the Durness Group, presumably via lateral ramps. The same thrusts continue to the north where they repeat Salterella Grit and Fucoid Beds. Thus the floor thrust to the imbricate system in the carbonate rocks acts as a roof to the underlying imbricate slices of An t-Sron Formation (Butler *et al.*, 2007).

A natural section through the imbricated Cambrian sedimentary rocks beneath the Kishorn Thrust is provided by hillsides running ESE from the north-east flank of Cnoc na Creige and forming the southern side of the Bealach a' Ghlas-chnoic (Butler *et al.*, 2007). In this area the Kishorn Thrust is separated from the Durness Group by a thrust-bounded slice of Pipe Rock, one of the upper parts of the imbricate thrust system of the Achnashellach area (Figure 5.48a). The slice tapers out against the Kishorn Thrust near Cadha nam Fiadh (Figure 5.48b). In the eastern part of the Bealach a' Ghlas-chnoic section the Pipe Rock is thrust over imbricated An t-Sron Formation rocks. This thrust is folded with its footwall and breached by the imbricate thrusts so that Salterella Grit and, locally, Fucoid Beds now lie upon the Pipe Rock. This style of folding and thrusting continues to the west where the imbricate thrusts and folds cored by An t-Sron Formation rocks incorporate slices of the overlying Durness carbonate rocks. Imbricate thrusts within the carbonate rocks are folded and truncated by the structurally lower thrusts.

Late faults

The east side of the Kishorn Valley contains a segment of the Caledonian deformation front on the Scottish mainland. In contrast, the western side consists of undeformed red-brown Applecross Formation (Torridon Group) sandstones, pebbly beds and local conglomerates, capped on Beinn Damh (NG 893 502; Figure 5.48a) by Cambrian quartzites. This abrupt change is due to a major fault that throws down the thrust belt to the south-east. This structure, the Fasagh Fault (Peach *et al.*, 1907), forms part of an array of extensional structures, which affect the neighbouring Applecross peninsula and the islands of Raasay and Scalpay. Although there are no sedimentary rocks younger than the Durness Group preserved in the Kishorn area, by analogy with the adjacent regional geology, the Fasagh Fault is probably of Mesozoic age (Butler and Hutton, 1994; Roberts and Holdsworth, 1999). It is well displayed in the lower part of the Allt na Criche (NG 857 447; G.E. Lloyd, pers. comm., 1997), where there are at least two major slip surfaces.

Interpretation

The Kishorn Nappe is a far-travelled unit of Torridonian and Lewisian rocks. Near the thrust plane both units are deformed by an intense greenschist-facies schistosity, which is mylonitic within a few metres of the thrust. The internal structure of the thrust sheet includes a NW-facing syncline with a preserved overturned limb of Torridonian strata. This is the northern preservation limit of the Lochalsh Syncline and marks the transition into the major recumbent fold system on Skye (Johnson, 1960). Butler *et al.* (2006) suggested that the folding initiated at Precambrian normal faults, as proposed for the structures along the Ben More Thrust in Assynt (Butler, 1997; see **Ben More Assynt–Conival–Na Tuadhan** GCR report, this chapter).

The movement direction on the Kishorn Thrust may be inferred to have been top-to-the-WNW. It is folded around underlying thrust slices and thus apparently moved at an early stage in the development of the thrust belt. On a regional scale (e.g. Figure 5.48a), the Kishorn Thrust appears to be bulged up by the large-scale imbrication of Torridonian and Cambrian units that crop out in the Achnashellach area (Butler *et al.*, 2007; see **Beinn Liath Mhor** GCR site report, this chapter). However, the sequence of thrust development in the units in the immediate footwall to the Kishorn Thrust is less clear.

The relative timing of thrust development in the Durness Group and An t-Sron Formation, together with other structures, may be inferred from the section beneath Sgurr a' Gharaidh (Figure 5.49). There, emplacement of the thrust slice of Pipe Rock that lies immediately beneath the Kishorn Thrust and at least partial imbrication of the Durness Group apparently occurred prior to thrusting in the underlying units. However, the relative timing of the Kishorn Thrust itself in this area is less easy to determine. It is not folded by underlying structures and is generally sub-planar, except where folded by the attached slice of fractured Torridonian rocks. These observations might suggest that the Kishorn Thrust, with its minor slice attached, moved later to truncate the folds in the Pipe Rock and Durness Group in its footwall. However, the field relationships are ambiguous: the footwall folds have axes that run sub-parallel to the outcrop trace of the thrust; and there is no indication from hangingwall structures that the Kishorn Thrust is late in that the mylonitic fabric is sub-parallel to the thrust.

Conclusions

The Cnoc nam Broc GCR site offers excellent opportunities for examining the Kishorn Nappe, one of the major structures of the southern Moine Thrust Belt, together within its relationship to surrounding thrust structures (Butler *et al.*, 2006). Inverted Torridonian sedimentary rocks within the thrust sheet are recognizably unconformable upon their overlying Lewisian basement, but Torridonian rocks also occur as small, highly fractured, thrust-bounded slices. The rocks show a variety of deformation states and are highly sheared locally.

The footwall to the Kishorn Nappe consists of folded and thrust Cambrian strata that show remarkable variations in structure along strike. Detachment horizons within the stratigraphical pile, notably at the base of the Fucoid Beds Member and just within the Durness Group, have allowed the development of two imbricate thrust systems. The structurally lower of these systems imbricated the An t-Sron Formation. It was the last to form and thereby folded and breached the structurally higher imbricate system within the Durness Group together with an overlying far-travelled thrust sheet of Pipe Rock (Butler *et al.*, 2007).

The site is therefore an excellent place to study not only lateral variations in thrust geometry, but also the evidence necessary to deduce the relative timing of thrust structures. It has the additional advantage of exposing an example of the post-Caledonian faults that formed during Mesozoic crustal extension, and control many topographical features in north-west Scotland. The Cnoc nam Broc GCR site is undoubtedly of national importance and the area remains suitable for further studies.

SLUMBAY ISLAND, LOCH CARRON (NG 896 385)

A.J. Barber

Introduction

Easily accessible examples of mylonites at the Slumbay Island GCR site provide a key to understanding the structural development of the Moine Thrust Belt, as a clear sequence of small-scale structures can be established. The mylonites of Slumbay Island are formed from Lewisian gneiss and amphibolite protoliths, which have been intensely cataclastically deformed and complexly folded. The mylonites form a thrust slice that lies between a lower thrust plane ('un-named thrust' in Figure 5.50) and the Moine Thrust plane to the east, in turn overlain by Moine psammites. The mylonites form a 2 km-wide band along the shore of Loch Carron that narrows northwards until transected by a major fault in Glen More (Figure 5.50). Inland, both the mylonite and the overlying Moine rocks are generally very poorly exposed.

Farther west below the un-named thrust lies the Kishorn Nappe in which sandstones of the Torridon and Sleat groups are folded into a large-scale overturned syncline, the northward continuation of the Lochalsh Syncline, which rests on the Kishorn Thrust (Figure 5.53 – see **Carn a' Bhealaich Mhòir** GCR site report, this chapter). In the Lochcarron area, only the inverted, upper limb of the syncline is represented. Within this upper limb, the bedding of the Torridonian and the foliation within the overlying Lewisian gneisses and the Moine psammites are sub-parallel and dip eastwards at *c.* 20°.

The area around Lochcarron was mapped during the primary geological survey by B.N. Peach and J. Horne (Peach *et al.*, 1907), and the 1:63 360 geological map (Sheet 82) was published in 1913 (Geological Survey of Scotland, 1913b). The area was later remapped by M.R.W. Johnson as part of a PhD study, in which particular attention was paid to the structural features of the rocks and the structural development of the thrust belt (Johnson, 1955, 1956, 1960). The formation of the mylonite was considered by Johnson to be the earliest event to affect the rocks of the Moine Thrust Belt. Although the mylonitization has destroyed or

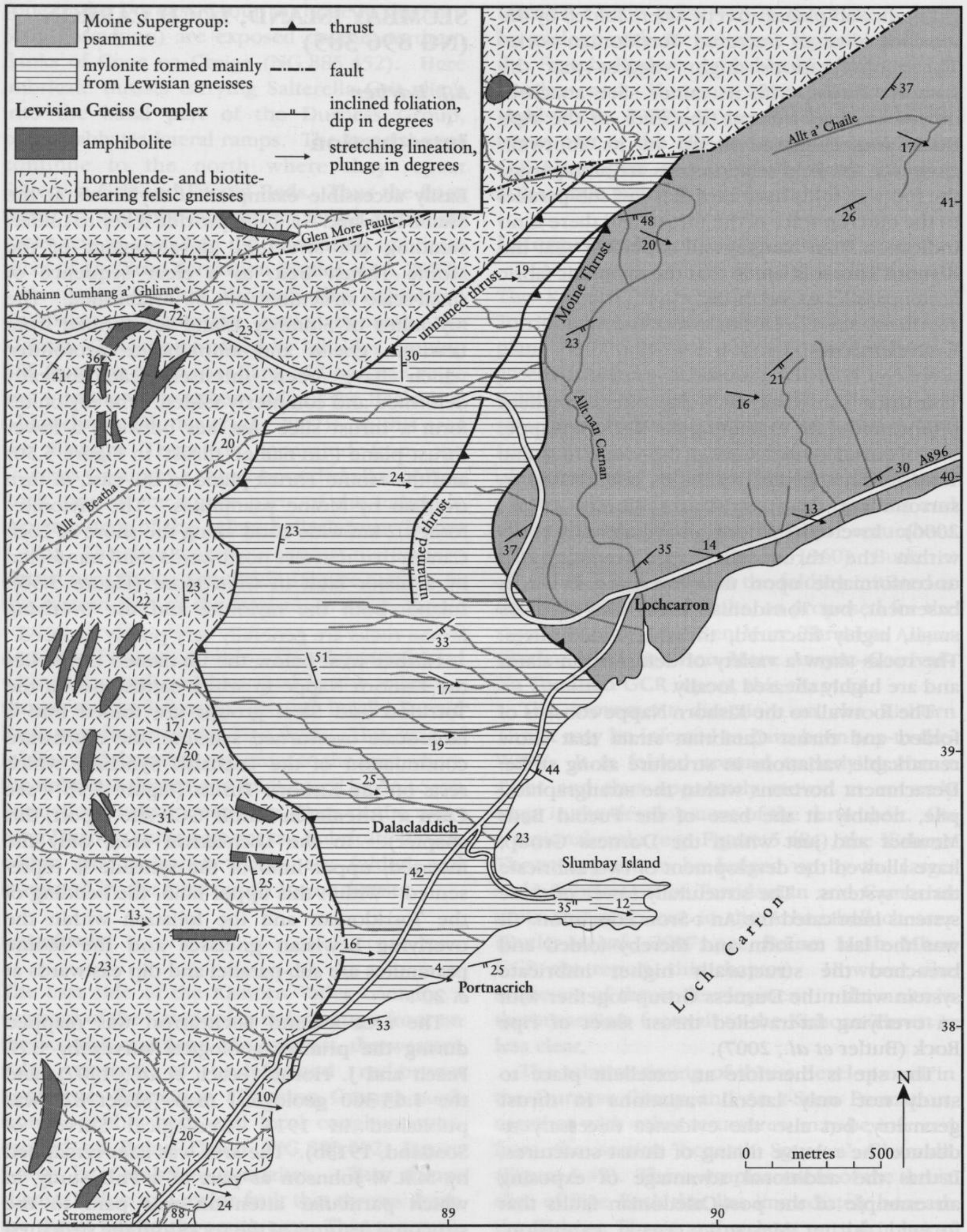


Figure 5.50 Map of the area around the Slumbay Island GCR site (based on mapping by M.R.W. Johnson).

at least masked the earlier structures in the rocks, the mylonitic foliation provides a datum upon which later tectonic events have been superimposed, enabling Caledonian structures to be separated from pre-Caledonian structures.

Description

Mylonite is well exposed over a distance of 250 m on the raised rock platform and in the backing cliffs along the southern and eastern sides of Slumbay Island, a small peninsula that projects eastwards into Loch Carron and is linked to the shore by a tombolo (Figure 5.50). At the eastern end of the peninsula, rocky exposures form roches moutonnées with ice-smoothed N-facing slopes.

The mylonites on Slumbay Island are finely laminated and foliated with pink quartzo-feldspathic material, in places coarser grained and recognizable as deformed quartz-feldspar pegmatites, alternating with darker laminae rich in chlorite and epidote. Mafic bands and lenses, up to 15 cm thick, are also present and a 1 × 3 m pod of amphibolite occurs in the cliff at the eastern end of the peninsula. On the southern side of the peninsula the foliation dips steeply to the north, but the dip is variable and flattens in the central part of the shore section to expose extensive foliation surfaces.

Three sets of fold structures post-date the mylonite foliation. Similar fold structures are also found in the deformed Torridonian, Lewisian and Moine rocks of Lochcarron. The earliest formed set consists of small-scale long-limbed tight to isoclinal folds with ESE-plunging axes. The isoclines fold the mylonite layering, with the dominant foliation axial planar to these structures (Johnson, 1960, fig. 7). Macroscopic folds of this generation are not abundant in the main mylonite belt but occur in other rock units. An ESE-trending mineral lineation, orientated parallel to the fold axes, is commonly developed (Johnson, 1960). The second folds are asymmetrical and overturned to the west with subhorizontal ENE-trending axes. Locally they have an associated E-dipping, axial-planar spaced cleavage. These folds deform the foliation and the associated ESE-trending lineation and more rarely are seen to refold the early isoclines (Johnson, 1960, figs 10a and 10b). The latest folds are kink folds, commonly occurring as conjugate sets and with no obvious preferred axial trend (Figure 5.51). No related cleavage is developed, but the fold axial planes may be marked by fractures. They affect structures related to both earlier fold sets (Johnson, 1956, 1960). Both large- and small-scale kink-folds are developed abundantly in the platy mylonites of Slumbay Island.

Johnson (1960) found that the mylonites and all the earlier structures are disrupted and brecciated in the neighbourhood of the thrust planes. An example occurs in the cliff at the south-west corner of Slumbay Island where the mylonite is cut by such a subhorizontal thrust surface, marked by a 1 m-wide brecciated zone. The development of brittle thrust planes is the last structural event related to thrusting.

In the upper part of the Kishorn Nappe the Lewisian gneisses show localized shear-zones, transitional upwards into mylonite gneiss and laminated augen mylonite. This development culminated in the formation of the fine-grained platy mylonites that form the main mylonite belt, as exposed at Slumbay Island.

Interpretation

Lewisian basement gneisses incorporated in the Moine Thrust Belt show a range of pre-Caledonian structures and metamorphic fabrics, as well as structures imposed during the Scandian Event. In parts it can be difficult distinguishing between Caledonian and pre-Caledonian structures. The value of the mylonites in the thrust zone is that the slate is effectively wiped clean; the mylonites can be treated as a relative time datum in the development of the Caledonian Orogeny.

The mylonites in the Moine Thrust Belt at Lochcarron show a clear sequence of structures. Mylonite formation occurred at an early stage in the development of this part of the thrust belt. Johnson (1960) related the mylonitization to formation of the Lochalsh Syncline and the inversion of the Torridonian and Lewisian rocks. This phase of deformation also brought bedding and foliation in the Torridonian and Lewisian rocks into parallelism at the unconformity.

Johnson (1960, fig. 2) mapped several dyke-like amphibolite bodies in the Lewisian rocks structurally above the overturned Torridonian unconformity. The dykes trend E–W or WNW–ESE, effectively parallel to the majority of Scourie dykes in the Lewisian gneisses of the foreland to the west. However, it seems unlikely that the Lewisian gneisses of the Kishorn Nappe are regionally inverted, although it would partly explain the concentration of strain along the unconformity (see **Carn a' Bhealaich Mhòir** GCR site report, this chapter, for further discussion).

The main mylonite belt in Lochcarron now occurs in a thrust slice that has been moved a

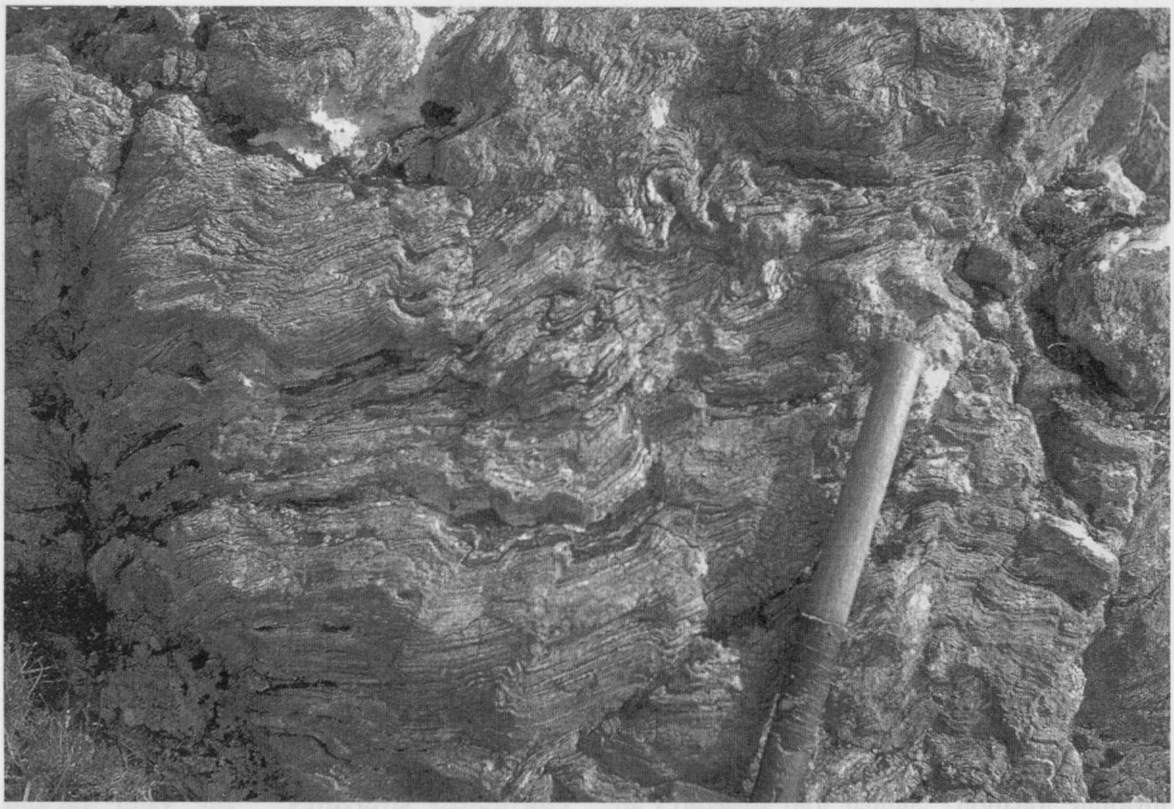


Figure 5.51 Close-up view of laminated mylonite below the Moine Thrust, with abundant late kink-folds, some of which form conjugate sets (e.g. left of centre). Western shore of Slumbay Island. (Photo: A.J. Barber.)

significant distance to the WNW. It presumably links to a more-widespread high-strain mylonite zone, now concealed beneath the overthrust Moine succession. The mylonites were formed under elevated temperatures and pressures aided by the availability of hydrous fluids. Lewisian gneisses became ductile, with the development of shear surfaces and grain-size reduction while undergoing continuous dynamic recrystallization. Quartz-rich gneisses were intensely deformed, whereas amphibolites proved more resistant to deformation and thus tend to be preserved. The earliest folding, which resulted in the long-limbed isoclines, is viewed as an intrinsic part of the mylonitization. Inhomogeneities in the layering would generate asymmetrical folds that would rapidly become overturned and tighter before being sheared out (Talbot, 1979). With increasing strain fold axes, initially formed at a high angle to the direction of movement, would rotate until they were near-parallel to the movement direction as represented by the ESE-plunging mineral lineation (e.g. see Cobbold and Quinquis, 1980).

The later fold phases that affect the mylonite layering and early-formed structures represent renewed compressional episodes during the exhumation and cooling of the mylonites and associated rocks. The secondary W-verging, asymmetrical folds represent continued westward movement of the rock units in the thrust belt at a stage in uplift and unloading, whereas the kink folds are semi-brittle structures formed under conditions in which vertical relief of stress was possible beneath a shallow overburden.

The final event in this part of the thrust belt was the movement of the rock units along thrust planes in a phase of brittle thrusting, which brecciated the mylonites and later fold structures, and disrupted the earlier structural pattern. This sequence of events in the mylonites of Slumbay Island records the continual westward movement of the rock units forming the thrust belt, under declining pressures and temperatures, during uplift and removal of the overburden.

Conclusions

The clear and easily accessible exposures of Slumbay Island in Loch Carron are of national importance in that they show the characteristic features of mylonite development in the Moine Thrust Belt. Three distinct fold phases can be distinguished in the mylonites. Fold styles range from early-formed, tight to isoclinal minor structures through asymmetrical minor folds, to kink folds. A late phase of localized brittle thrusting and brecciation post-dates the folding events. The early-formed folds and related ESE-plunging lineation and axial-plane foliation are interpreted as an integral part of the mylonitization event. The overall structural sequence demonstrates that the rocks in this part of the Moine Thrust Belt were initially deformed at depth farther east under greenschist-facies metamorphic conditions, resulting in the formation of the mylonites. The mylonites were subsequently uplifted, folded and thrust westwards towards the foreland. In the final phase of deformation, the mylonites, together with the associated rock units, were broken and disrupted during late-stage westward movements over the foreland along discrete thrust planes. The well-exposed structures at Slumbay Island show a structural sequence that can be matched in other places along the Moine Thrust Belt.

CARN A' BHEALAICH MHÒIR (NG 826 324)

A.J. Barber

Introduction

The escarpments of Carn a' Bhealaich Mhòir and Creag an Duilisg, overlooking Plockton on the south side of Loch Carron, expose the inverted unconformity between the Lewisian gneiss basement and its cover of Torridonian sandstones and conglomerates of the Sleat Group. This is the clearest locality in the Moine Thrust Belt where the original unconformity between these units may be traced, undisrupted by thrusting, over a distance of 1.5 km (Figures 5.52, 5.53).

The exposures on Carn a' Bhealaich Mhòir form part of the inverted limb of the Lochalsh Syncline which lies within the Kishorn Nappe, the lowest structural unit in the southern part of the Moine Thrust Belt (Figure 5.54). Highly deformed and metamorphosed Torridonian sandstone and conglomerate are overlain, without structural discontinuity, by highly deformed Lewisian gneisses, with clear affinities to the Lewisian Gneiss Complex of the foreland to the west. Eastwards, away from the contact, Caledonian deformation in the Lewisian gneisses diminishes, so that earlier structural features, such as cross-cutting amphibolite dykes, may be recognized.

The Torridonian conglomerate contains deformed pebbles of similar lithologies to those of the Lewisian, and the contact is an inverted unconformity (Figure 5.55). During Caledonian deformation a zone of high strain was localized along this unconformity. To the south of Carn an Reidh Bhric, the unconformity is truncated by the Letter Hill Thrust which carries another slice of deformed Torridonian and Lewisian rocks (Figure 5.53). The outcrop of the Letter Hill Thrust can be traced into the Balmacara Thrust and southwards as far as the **Ard Hill** GCR site (Figure 5.52).

The area around Carn a' Bhealaich Mhòir was originally mapped by B.N. Peach and J. Horne in 1892–1893 and their results were incorporated in the 1:63 360 map (Sheet 71, Glenelg) (Geological Survey of Scotland, 1909). In the accompanying memoir, Peach *et al.* (1910) defined the Torridonian stratigraphy, noted the deformation of the basal conglomerate, and recognized the inverted nature of the Torridonian and the unconformity. They assumed that the Lewisian gneisses are also overturned. However, Kanungo (1956) asserted that the Lewisian is not inverted, and that a substantial amount of displacement has occurred along the unconformity. Further accounts of the structure and structural development of the Moine Thrust Belt of Lochalsh, including the significance of the Lochalsh Syncline and the inverted unconformity, have been published by Bailey (1939, 1955), Barber (1965) and Coward and Whalley (1979).

Description

The site forms part of a NW-facing escarpment that rises from the wooded coastal areas up to 350 m and extends some 2.5 km from Fernaig (NG 847 338) to Gleannan Dorch. It includes

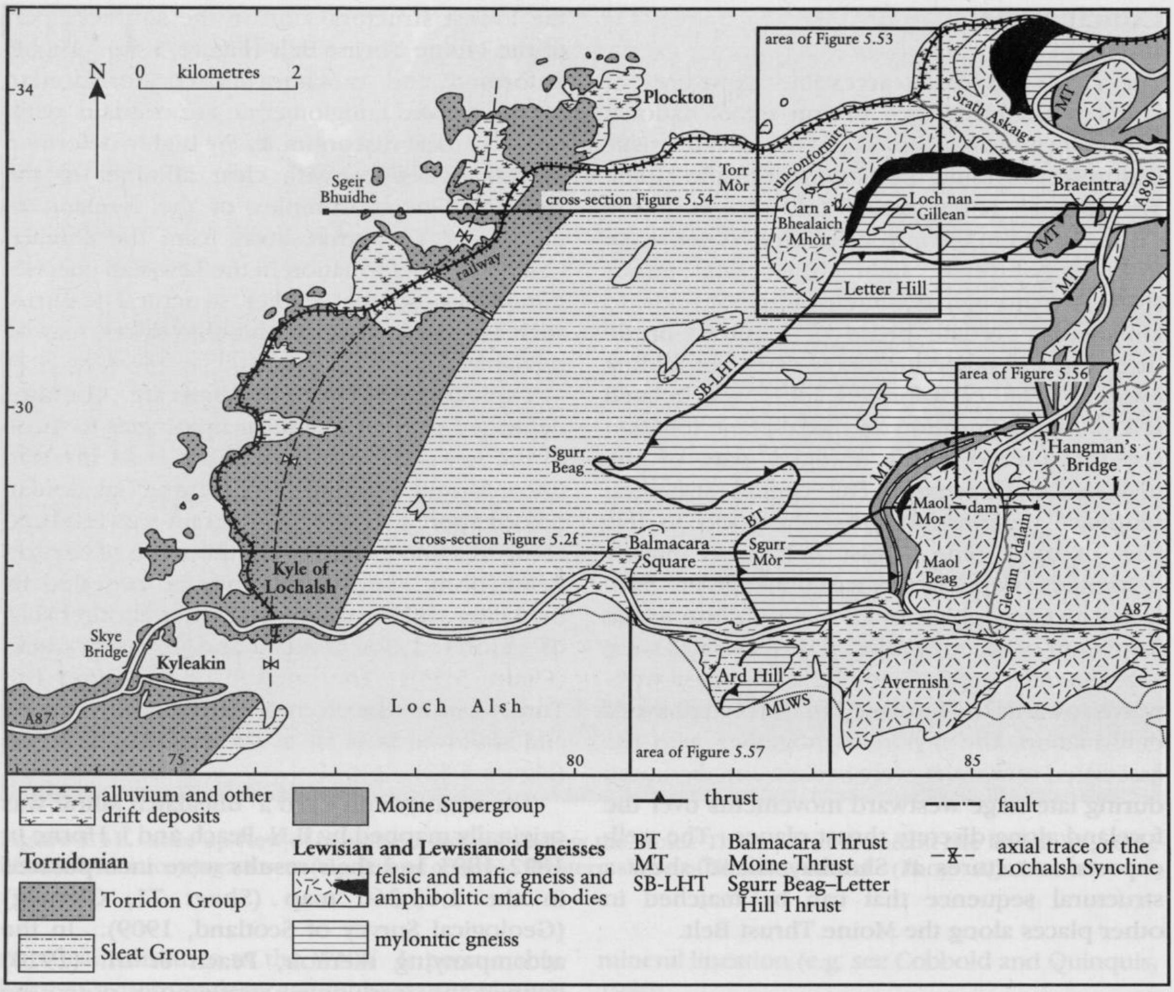


Figure 5.52 Map of the Lochalsh peninsula, showing the overall geology. Positions of Figures 5.53, 5.54, 5.56 and 5.57 are indicated. Based on Barber and May (1976) and Institute of Geological Sciences (1976a). Trace of Lochalsh Syncline after Coward and Potts (1985).

the summits of Creag an Duilisg, Carn a' Bhealaich Mhòir (343 m) and Carn an Reidh Bhric (Figure 5.53). Only scattered exposures occur on the lower slopes, but the cliffs show near-continuous exposure along the steep north-western edge of the escarpment. Rounded crags with heather-covered slopes, peat bogs and small lochans form the crest of the escarpment. A plateau at about 260–300 m with several large lochs extends eastwards to the slopes overlooking Srath Askaig to the north.

On the low hills west of the escarpment, for example Torr Mòr (NG 819 327), grey-green coarse sandstones of the Beinn na Seamraig Formation (Sleat Group) are exposed. The sandstones are composed of quartz, microcline, oligoclase and some clastic mica, in a fine-grained microgranoblastic quartz-sericite matrix. Heavy-mineral layers occur locally. Clastic mineral grains and quartz-feldspar veins show a strong ESE elongation.

Structurally overlying, but stratigraphically beneath, is the Loch na Dal Formation, which is exposed by the roadside at Fernaig and intermittently on the lower slopes of the escarpment as far as Gleannan Dorch. This consists of blue-grey, striped fissile and flaggy siltstones with calcareous bands, alternating with green and grey, pebbly sandstones (Peach *et al.*, 1910). These rocks contain a strong foliation dipping eastwards at *c.* 20°, which locally is crossed by a second cleavage that dips at *c.* 40° to the east. The Loch na Dal Formation is structurally overlain by epidotic gritty sandstones and

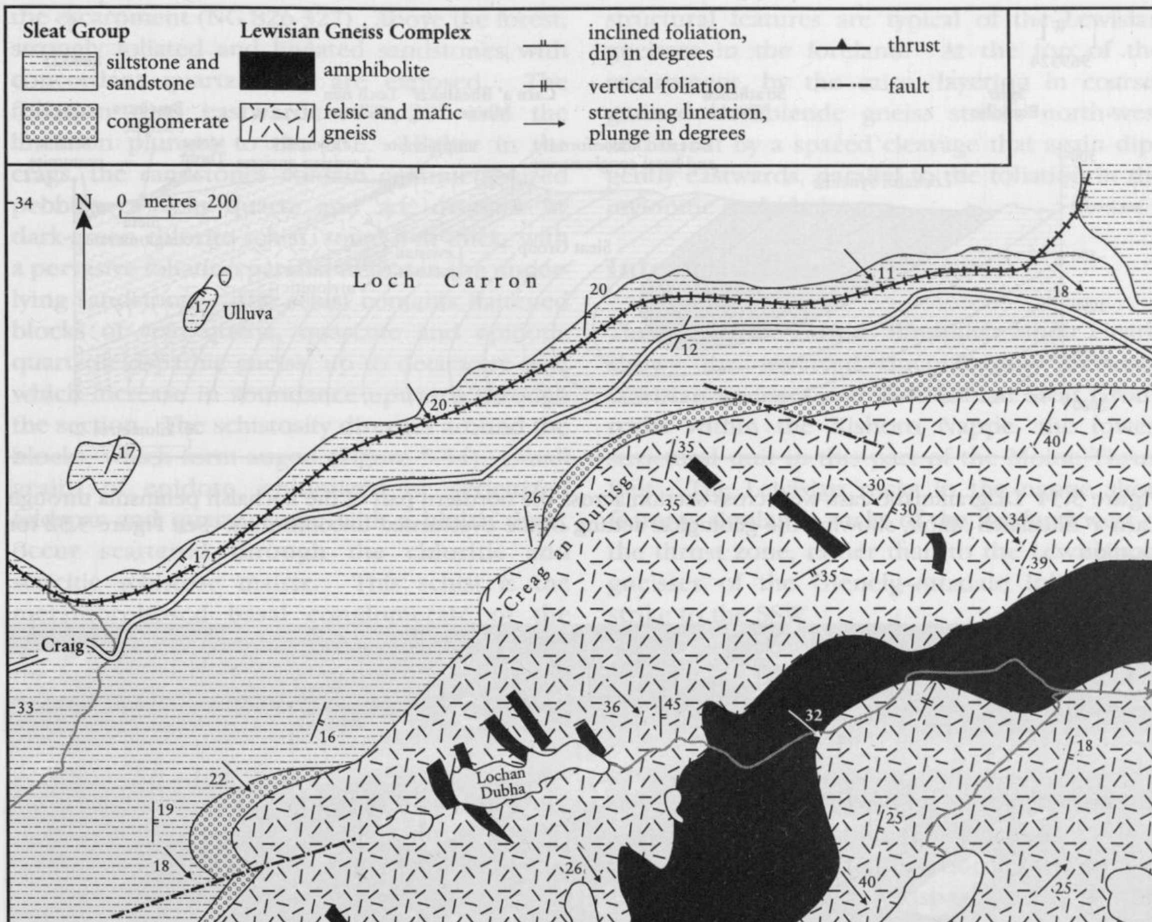


Figure 5.53 Map of the area around the Carn a' Bhealaich Mhòir GCR site. After Kanungo (1956).

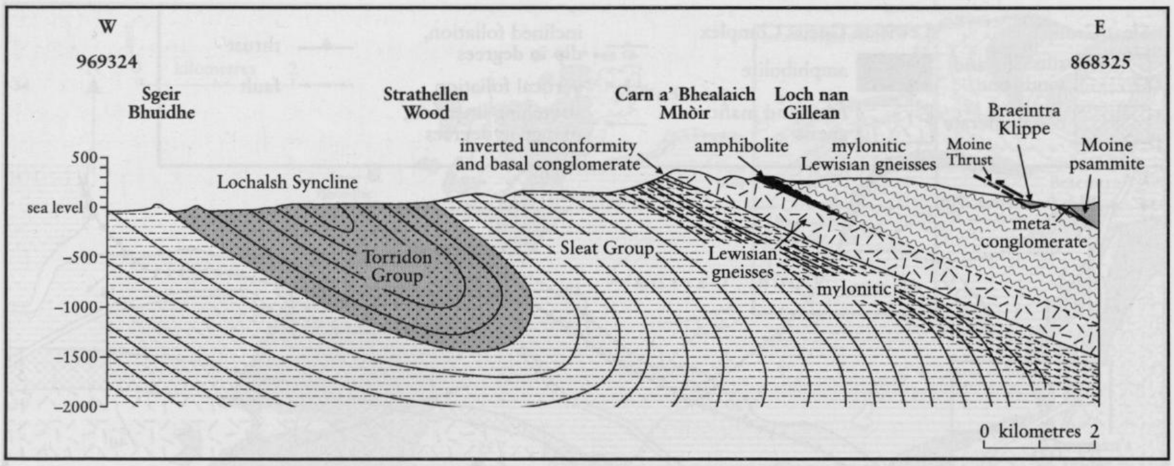


Figure 5.54 Diagrammatic east–west cross-section across the northern part of the Lochalsh peninsula through Carn a' Bhealaich Mhòir, showing the geological setting of the overturned unconformity. See Figure 5.52 for location.

Figure 5.55 Sheared and disrupted quartzofeldspathic clasts in schistose chloritic matrix, basal conglomerate of the Torridonian sequence, Carn a' Bhealaich Mhòir, Lochalsh. (Photo: A.J. Barber.)

conglomerates, exposed in the upper part of the crags, immediately below the unconformity with the Lewisian. These formations form part of the Sleat Group (see Chapter 4).

The Lewisian–Torridonian unconformity is best exposed in the gully between Carn a' Bhealaich Mhòir and Creag an Duilisg, which carries the stream from Lochan Dubha through the escarpment (NG 826 327). Above the forest, strongly foliated and lineated sandstones with concordant quartz veins are exposed. The foliation dips eastwards at *c.* 20° and the lineation plunges to the ESE. Higher in the crags, the sandstones contain centimetre-sized pebbles of vein quartz and are overlain by dark-green chlorite schist, some 6 m thick, with a pervasive foliation parallel to that in the underlying sandstones. The schist contains flattened blocks of vein quartz, quartzite and epidotic quartzofeldspathic gneiss, up to decimetre-size, which increase in abundance upwards through the section. The schistosity diverges around the blocks, which form augen (Figure 5.54). Small grains of epidote, epidotized or sericitized feldspar and quartz, some with a bluish tinge, occur scattered through the chloritic and sericitic schistose matrix. This schist is the metamorphosed basal conglomerate of the Torridonian, containing pebbles derived from the now overlying Lewisian gneisses.

The pebbles in the conglomerate are flattened in the foliation and are mainly elongated parallel to the ESE-plunging mineral lineation, although Soper (in Barber and Soper, 1973) pointed out that pebble elongation is commonly at a slight angle to the mineral lineation, suggesting that more than one phase of deformation was involved. Kanungo (1956) analysed the shape and orientation of the pebbles and obtained axial ratios (x:y:z) of 2.1:1:0.6. The pebbles are commonly broken into fragments by cross joints, orientated normal to the extension direction. However, a few pebbles, with axial ratios of 1.9:1:0.7, are elongated at right angles to the mineral lineation. The ESE and NNE directions of elongation in the pebbles may reflect deformation of undeformed pebble populations that at least locally had distinct sedimentary preferred orientations (see Ramsay, 1967, pp. 204–5).

The upper part of the crag is composed of grey hornblende-biotite quartzofeldspathic gneisses and amphibolite. Immediately above the conglomerate the gneisses are strongly foliated, with the mylonitic foliation and ESE-plunging mineral lineation orientated parallel to those in the underlying schist. In exposures towards the top of the crag, the gneisses are coarser grained and layered with lenses of amphibolite and quartz-feldspar pegmatites. They are folded and coarsely rodded, but the structural features are typical of the Lewisian gneisses in the foreland. At the top of the escarpment, by the cairn, layering in coarse-grained hornblende gneiss strikes north-west and is cut by a spaced cleavage that again dips gently eastwards, parallel to the foliation in the mylonitic rocks below.

Interpretation

The section at Carn a' Bhealaich Mhòir clearly shows the inverted unconformity between Lewisian gneisses and Torridonian Sleat Group rocks within the Kishorn Nappe, the lowest structural unit in this part of the Moine Thrust Belt. The Lewisian rocks in the nappe show features similar to rocks of the foreland west of the thrust zone, rather than to the Lewisianoid gneisses of the Glenelg–Attadale Inlier along strike to the SSW.

The absence of granulite-facies rocks, the presence of potash feldspar (microcline) in the gneisses, and the occurrence of NW-trending amphibolite-facies mafic dykes with relict ophitic textures (Kanungo, 1956), identifies this as a segment of the Lewisian Gneiss Complex that has undergone amphibolite-facies metamorphism, but shows few effects of Laxfordian reworking. In contrast, potash feldspar is rare in the Lewisianoid gneisses of the Western Unit of the Glenelg–Attadale Inlier.

In the foreland the contact between the Torridonian and the Lewisian is highly irregular, representing an eroded early Neoproterozoic land surface. Any evidence of an irregular contact at Carn a' Bhealaich Mhòir has been effectively erased by subsequent deformation. The Torridonian succession consists of a basal conglomerate, overlain by sandstones and siltstones, some calcareous, and then by coarse pebbly sandstones, representing deposition in terrestrial fluviatile and lacustrine environments. Although these Sleat Group rocks are confined to the Moine Thrust Belt, the overlying Torridon Group and general sequence in the thrust belt can be correlated with that of the nearby foreland (see Chapter 4).

At a late stage in the Caledonian Orogeny, during the Silurian-age Scandian Event, the Lewisian basement and its Torridonian cover were thrust westwards and folded into the large-scale Lochalsh Syncline, a large recumbent fold with a westerly vergence. During and possibly after folding, shearing and mylonitization of the Lewisian and Torridonian rocks was concentrated along the unconformity, reflecting differential movement of crystalline basement and sedimentary cover (Barber, 1965). Inversion of the Torridonian can be demonstrated in the western part of Lochalsh by abundant inverted sedimentary structures, for example cross-beds, in the less-deformed sandstones. Peach and Horne (in Peach *et al.*, 1910) presumed that the Lewisian basement was also overturned such that the overall succession was regionally inverted. However, Kanungo (1956) argued that the similar north-west trend of the amphibolite dykes in the Lewisian gneisses of the Kishorn Nappe and the Scourie dykes in the foreland implied that the basement was not inverted. He argued that if the Lewisian gneisses were inverted the dykes should now have a north-east trend. If correct, this deduction implies that substantial differential movements must have occurred along the Lewisian–Torridonian contact, giving rise to the zone of mylonitization, which is notably concentrated in the lowermost Torridonian rocks.

Minor asymmetrical folds with an associated axial-plane cleavage are developed in the Torridonian rocks, especially in the siltstone units within the Loch na Dal and Kinloch formations. Kanungo (1956) also reported kink folds in some flaggy units in the northern part of Lochalsh. These structures are equivalent to those described in the **Ard Hill** and **Slumbay Island** GCR site reports (this chapter). The sequence of thrusting and folding in the thrust belt is unclear in the Lochalsh area. The Letter Hill and Balmacara thrusts, which overlap the Lewisian–Torridonian contact to the south, truncate underlying structures, suggesting that they post-date the formation of the Lochalsh Syncline. It is unclear as to the nature and amount of ductile and brittle movements and their timing in this southern part of the Moine Thrust Belt. Certainly, late brittle movements to the west have occurred, but their magnitude is not known. Thus the stacking order of ductile displacements remains to be solved.

Recrystallization of the mylonites and the chlorite-sericite matrix of the deformed Torridonian conglomerate under greenschist-facies conditions implies that during mylonitization the rocks in the region of unconformity were buried to a depth of some 10–15 km. The deformational events took place at successively lower temperatures and pressures implying the progressive uplift and unloading of this part of the thrust belt until, in the final stage, the rocks were broken and transported along brittle thrust planes formed at a depth of only a few kilometres.

Conclusions

The Carn a' Bhealaich Mhòir GCR site lies within the Kishorn Nappe and shows a remarkable example of an overturned unconformity with fragments of Lewisian gneiss basement incorporated in the now underlying Torridonian basal conglomerate. Both Lewisian and Torridonian rocks in the immediate vicinity of the unconformity have been strongly mylonitized. The mylonitization is interpreted as the earliest Scandian tectonic event in the southern part of the Moine Thrust Belt, associated with the development of the Lochalsh Syncline, a large-scale recumbent fold developed largely in the Torridonian rocks of the Lochalsh and Sleat area. Only after a further minor phase of asymmetrical folding and the formation of brittle kink-folds, were the rocks disrupted by the formation of the thrust planes. Movement along brittle thrusts was the last event within the thrust belt. The unconformity is truncated to the east by the Letter Hill and Balmacara thrusts. The Lewisian and Torridonian rocks were transported on the Kishorn Thrust, and thrust westwards across the foreland to the Caledonian Orogen. The site is of national importance in that it is the best locality to study the Lewisian–Torridonian contact and the effects of thrusting and folding in the Kishorn Nappe.

HANGMAN'S BRIDGE (NG 856 298)

A.J. Barber

Introduction

Although the Moine Thrust can be traced over a distance of nearly 200 km from Eriboll in the north to the Sleat peninsula of Skye in the south, the actual thrust plane is exposed at relatively few localities along its whole length. The stream section at Hangman's Bridge, on a remnant of the old road from Auchtertyre to Stromeferry in Gleann Udalain, is one of two such localities in Lochalsh.

In the Lochalsh area, the Moine Thrust can be traced along the eastern slopes of Auchtertyre Hill, north of Auchtertyre village, and northwards into Coire Buidhe, but is unexposed in this segment (Figure 5.52). In addition to the exposure at Hangman's Bridge, the Moine Thrust plane is seen in a stream section near Braeintra (NG 864 323) to the north, at the base of a small klippe (Peach *et al.*, 1910).

At Hangman's Bridge (Figure 5.56), the footwall to the Moine Thrust is formed by mylonitized Lewisian gneisses of the Balmacara Nappe (see **Ard Hill** GCR site report, this chapter). The immediate hangingwall to the thrust across the Lochalsh area is formed by a narrow strip of mylonitized Moine rocks, in total about 200 m thick, which can be traced northwards to Stromeferry and southwards through Coire Buidhe and into the scarp faces of Maol Mor and Maol Beag, near Auchtertyre (Figure 5.52). The Moine rocks are overlain by Lewisianoid gneisses of the Glenelg–Attadale Inlier. This inlier experienced a very different geological history from the Lewisian gneisses of the foreland in that it was reworked during the Grenvillian Orogeny at *c.* 1000 Ma (see Chapter 7). The relict eclogite-facies metamorphic assemblages testify to its burial to a crustal depth of at least 60 km (Sanders *et al.*, 1984).

The area around Hangman's Bridge was mapped by B.N. Peach and J. Horne during 1892–1893 as part of the primary mapping of Lochalsh (Sheet 71; Geological Survey of

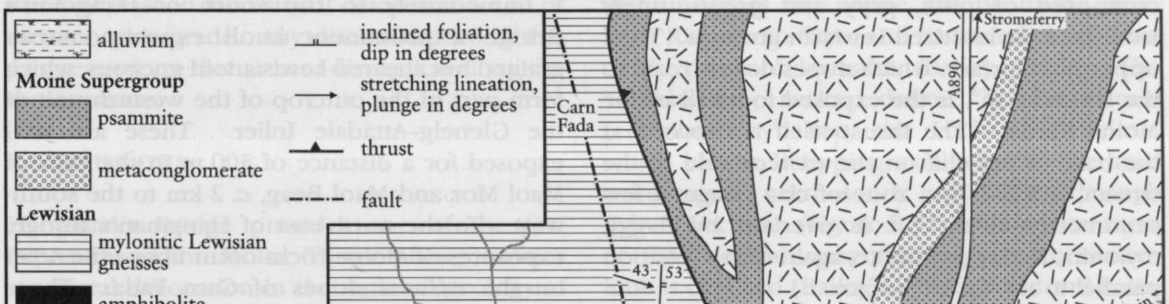


Figure 5.56 Map of the area around the Hangman's Bridge GCR site. The location of this figure is shown on Figure 5.52.

Scotland, 1909) and was described in the accompanying memoir (Peach *et al.*, 1910). Barber (1965, 1968) remapped the southern part of Lochalsh, including the Moine Thrust Belt, and this account is based on this later work.

Description

The section occurs in a tributary burn of the Allt Loch na Smeòraich that extends north from Hangman's Bridge on the old Auchtertytre–Stromeferry road. To the north of Hangman's Bridge, the Moine Thrust plane is exposed, together with its immediate footwall and hangingwall (Figure 5.56). About 100 m upstream from the bridge, the stream is incised into the southern slope of Carn Fada in a small gorge. The bed of the stream, about 2 m wide, is composed of pink, grey and green, finely laminated, mylonitized Lewisian gneisses. Their uppermost surface, which slopes downstream to the south at 14°, is the exposed footwall of the Moine Thrust. The thrust itself is exposed at the base of the cliff on the eastern side of the stream, marked by a zone of clay gouge, a few centimetres thick. It is overlain by flaggy, mylonitic Moine psammite, again with a foliation parallel to the thrust surface.

The Lewisian-derived mylonites below the thrust show few, if any, structural complexities at this locality. The lamination corresponds to a pervasive mylonitic foliation, which dips at *c.* 20° to the south-east and contains a strong ESE-trending mineral lineation. The mylonites form part of the extensive outcrop at Carn Fada and Auchtertyre Hill. Their petrographical features and minor asymmetrical- and kink-folds are similar to those documented at the **Ard Hill** GCR site.

The flaggy mylonitized Moine psammite above the thrust plane is well exposed on the western side of the stream. The Moine rocks break easily into flat slabs 2–3 cm thick, due to spaced foliation surfaces covered by lustrous flakes of white mica and pale-green chlorite. Compositional layering is not conspicuous, but some lithological striping is clear in polished slabs where locally it outlines tight to isoclinal fold hinges (Barber, 1968, fig. 14). A strong ESE-plunging mineral lineation is developed on the foliation surfaces parallel to the fold hinges. The flags are folded by large numbers of later small-scale kink-folds. A later gentle synclinal flexure of the Moine Thrust plane and the overlying Moine rocks is reflected in their arcuate outcrop and the inward dips of the foliation surfaces (Figure 5.52a).

In thin section the Moine-derived mylonites show small (< 0.1 mm) sutured quartz crystals with scattered large (1–3 mm) pink feldspar porphyroclasts, white mica flakes, and more rarely biotite and epidote. Feldspar grains include microcline, several types of microperthite, and plagioclase ranging from albite to andesine. Feldspar and white mica flakes are enclosed in augen, often surrounded by sheaths of sericite. Relict feldspar crystals may be broken, and the fragments pulled apart in the foliation and partially or completely replaced by aggregates of sericite (Barber, 1968). These are features typical of mylonitization under greenschist-facies conditions.

Immediately to the south of Hangman's Bridge a prominent knoll exposes coarse-grained but sheared Lewisianoid gneisses, which form part of the outcrop of the western unit of the Glenelg–Attadale Inlier. These are well exposed for a distance of 300 m in the cliffs of Maol Mor and Maol Beag, *c.* 2 km to the south-west. To the north-east of Hangman's Bridge, exposures of Moine rocks occur above the A890 on the eastern slopes of Carn Fada. These exposures include the basal Gleann Udalain Conglomerate, which lies directly on the Lewisianoid gneisses (Peach *et al.*, 1910; Bailey and Tilley, 1952). The conglomerate has been the subject of discussion as to its tectonic or sedimentary origin (see **Avernish** and **Attadale** GCR site reports, Chapter 7).

Interpretation

The Lewisian-derived mylonites below the Moine Thrust plane at Hangman's Bridge show a mylonitic foliation, an ESE-plunging stretching lineation, and a range of features similar to those seen at the **Ard Hill** GCR site, implying an extended history of deformation. The Moine rocks above the thrust are interleaved with deformed, but not mylonitic, Lewisianoid gneisses and amphibolites, which here form a tectonic slice within the Moine outcrop. As elsewhere in the Glenelg–Attadale Inlier, the earliest phase of Caledonian deformation appears to have been the interleaving of Moine and Lewisian rocks either by isoclinal folding or by thrusting. This phase of deformation is represented in the Moine-derived mylonites by the isoclinal folds of the compositional layering. There is evidence of early ductile thrusting followed by later brittle movements.

The mylonitic Moine psammites contain a variety of feldspar clasts, indicating that these rocks were originally feldspathic sandstones. The presence of the feldspar clasts and the greenschist-facies assemblages link these mylonites to those developed in the Torridonian sandstones of the Kishorn Nappe or possibly to (?Moine) psammites of the Tarskavaig Group rocks on Sleat (Skye). They contrast with the high-grade amphibolite-facies psammites of the main outcrop of the Moine to the east. Thus, the mylonitic Moine psammites at Hangman's Bridge are transitional in character between the Torridonian sandstones to the west and Moine psammites to the east, reflecting a gradual eastward increase in intensity of deformation and of metamorphic grade. Any discontinuities in this progression are due to later disruption along the thrust planes.

Conclusions

Hangman's Bridge provides one of the few exposures of the Moine Thrust plane, a major structural dislocation in the regional geology of north-west Scotland. In the Lochalsh area, Moine rocks in a thin structural slice immediately above the thrust plane show structural and metamorphic features that link the mylonitic low-grade metamorphic rocks of the Moine Thrust Belt with the overlying higher-grade but less-deformed Lewisian gneisses of the Glenelg–Attadale Inlier. Observations near Hangman's Bridge support the interpretation from the **Ard Hill** and **Knockan Crag** GCR sites that movement along the Moine Thrust plane in this area was a late event, preceded by a long sequence of deformational events, at progressively shallower crustal levels. In particular, they confirm the conclusions from the **Avernish** GCR site that mylonitization in the thrust belt was later than the phases of folding and metamorphism that interleaved the Moine psammites and the Glenelg–Attadale gneisses. These observations all contribute to a model in which Caledonian orogenic events commenced in the central part of the orogenic belt and spread westwards towards the foreland, resulting in progressively more-brittle deformation with time.

ARD HILL (NG 818 265)

A.J. Barber

Introduction

A 2 km-long coastal section along the northern shore of Loch Alsh at Ard Hill, Balmacara, exposes Torridonian sandstones of the Kishorn Nappe and overlying Lewisian gneisses of the Balmacara Nappe, juxtaposed along the Balmacara Thrust (Figure 5.57).

Feldspathic sandstones of the Torridon and Sleat groups are found in the west of the Lochalsh area. These rocks lie within the Kishorn Nappe, the lowest and most westerly of the thrust slices that make up the southern part of the Moine Thrust Belt. The Kishorn Thrust that underlies the nappe can be traced from Loch Kishorn to Skye, and its trace lies offshore to the west of Lochalsh (Bailey, 1955). The Torridonian rocks define a large-scale recumbent syncline, the Lochalsh Syncline, which has an E-dipping axial plane. The axial trace trends north–south and passes through Kyle of Lochalsh (Figure 5.52), so that over most of the Lochalsh area the overturned, eastern limb is exposed (Bailey, 1939; Coward and Potts, 1983). The core of the fold is occupied by sandstones of the Applecross Formation, which contain a spaced cleavage. These are structurally overlain by a gently dipping inverted succession of cleaved siltstones and sandstones of the Sleat Group, which become increasingly deformed towards the east.

East of Balmacara the deformed and locally mylonitic sandstones of the Kishorn Nappe are overlain by mylonitized Lewisian gneisses of the Balmacara Nappe. The intervening Balmacara Thrust is exposed in the shore section on the western side of Ard Hill (Figure 5.56) and is the focus of the GCR site. The Balmacara Nappe is much smaller than the Kishorn Nappe and consists mainly of Lewisian gneisses, with only minor amounts of Torridonian strata (Figure 5.52). Near Ard Hill the nappe has an outcrop width of about 2 km, but it pinches out both to the north-east near Strath Ascaig, and to the south beneath Loch Alsh. The 'roof thrust' to the Balmacara Nappe, the Moine Thrust, is not exposed along the coast, but crops out farther north at **Hangman's Bridge** (see GCR site report, this chapter).

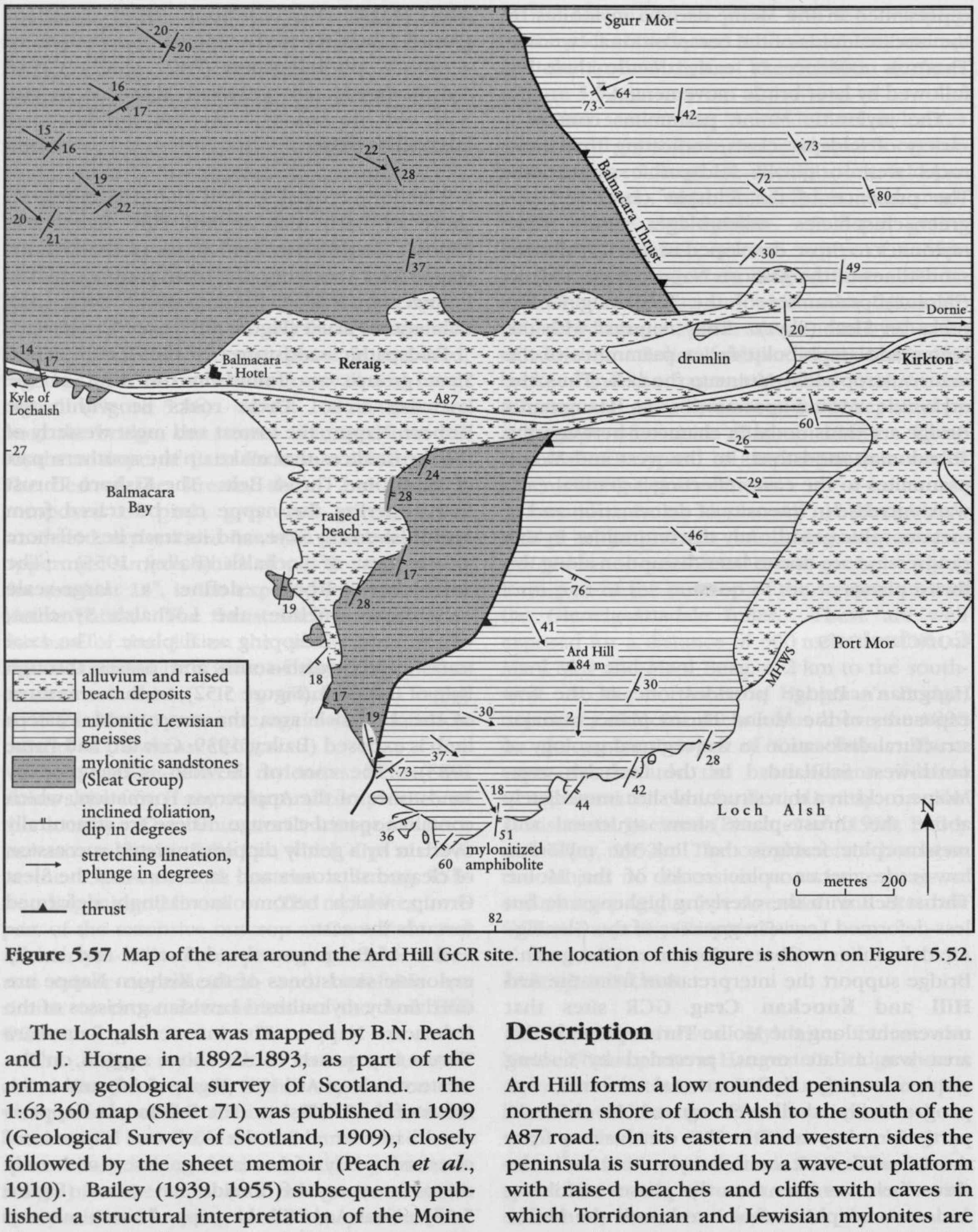


Figure 5.57 Map of the area around the Ard Hill GCR site. The location of this figure is shown on Figure 5.52.

The Lochalsh area was mapped by B.N. Peach and J. Horne in 1892–1893, as part of the primary geological survey of Scotland. The 1:63 360 map (Sheet 71) was published in 1909 (Geological Survey of Scotland, 1909), closely followed by the sheet memoir (Peach *et al.*, 1910). Bailey (1939, 1955) subsequently published a structural interpretation of the Moine Thrust Belt in Skye and Lochalsh based on the Geological Survey mapping. The Ard Hill area was remapped by A.J. Barber (1965, 1968) as part of a wider PhD study. Subsequently Coward and Whalley (1979) and Potts (1982, 1983) studied the microstructural development of the deformed Torridonian sandstones.

Description

Ard Hill forms a low rounded peninsula on the northern shore of Loch Alsh to the south of the A87 road. On its eastern and western sides the peninsula is surrounded by a wave-cut platform with raised beaches and cliffs with caves in which Torridonian and Lewisian mylonites are very well exposed. Mylonitic Torridonian sandstones are exposed on the western side of Ard Hill; mylonitic Lewisian gneisses on the east side. The mylonites are brecciated and brought together along the Balmacara Thrust, which is exposed in a raised cliff near the point of the headland (Figure 5.57).

In the Torridonian sandstones, a new foliation that dips uniformly east at c. 20° has been strongly overprinted on the bedding, giving the rocks a pervasive flaggy parting. Freshly broken foliation surfaces are covered by a thin film of glossy white mica and green chlorite, suggesting the foliation formed under greenschist-facies metamorphic conditions. A strong ESE-plunging penetrative mineral lineation defined by the elongation of small crystals and aggregates of quartz, feldspar, chlorite and white mica is developed. On some foliation surfaces the lineation has a similar appearance to slickensides. Few obvious folds relate to the lineation, although the axes of a few small vague folds within the foliation and some folded en echelon tension gashes plunge in the same direction.

Immediately below the Balmacara Thrust, asymmetrical folds with horizontal N–S-trending axes and a westerly vergence fold the mylonitic foliation and the associated lineation. The folds are tight with attenuated limbs and thickened, rounded hinges and amplitudes of between 2 m and 6 m. An associated axial-planar fracture/spaced cleavage, which in parts is outlined by quartz veins, dips eastward more steeply than the mylonitic foliation. Fold limbs are commonly sheared along the cleavage and may be attenuated to the point where antiforms are juxtaposed and the intervening synform excised. A N-trending intersection lineation is also developed, and relict feldspars may be elongated parallel to this secondary lineation.

Where tight folds of the mylonitic Torridonian sandstones are absent, small-scale kink-folds are notably abundant. The folds range in amplitude from 1 cm to several metres and have interlimb angles of 90° or more. The hinges are sharp and angular with no limb attenuation or hinge thickening, and the folds are commonly fractured along their axial planes. Locally, conjugate kink-folds are present.

Mylonitic Lewisian gneisses in the hanging-wall of the Balmacara Thrust are well exposed in the shore section at the southern point of the headland and all along the east coast. The mylonites are typically pink, green and grey, finely laminated, extremely fine-grained rocks. The laminae range in thickness from millimetres to centimetres and represent attenuation of the original gneissic compositional layering. Alternating grey, white and pink layers represent quartzofeldspathic gneiss protoliths with thicker layers or lenses present where the mylonites were derived from coarse-grained pegmatites (Figure 5.58). The contrasting thin dark-green to black layers are rich in chlorite, epidote and iron oxides and represent hornblendic or biotite-rich gneiss protoliths. Large relict crystals of feldspar, hornblende and epidote commonly form augen structures. Mafic bodies are generally retrograded to chlorite schist, but larger bodies may preserve cores of the original amphibolite, with hornblende crystals showing cataclastic textures (NG 820 263).

The mylonitic layering in the gneisses dips generally eastwards, but minor later folding results in variations in dip and strike. A pervasive foliation defined by white micas, chlorite and quartz is developed generally parallel to the banding. In parts the layering is folded by millimetre- to metre-scale, tight to isoclinal minor folds with gentle ESE-plunging axes and accompanied by a pervasive mineral lineation.

As in the Torridonian mylonitic rocks, the early-formed structures are folded by asymmetrical, W-vergent folds, examples of which are well exposed on the shore platform on the eastern side of Ard Hill. In places refolded isoclines can be seen. The secondary folds are open in style, with fold axes that generally plunge to the south or south-east. Sharp angular 'ripples' in the foliation define a linear structure, and, more rarely, a quartz-feldspar rodding is developed parallel to the fold axes. Axial planes generally dip eastwards at a steeper angle than the foliation. A fracture cleavage is developed parallel to the axial planes and may contain quartz veins.

Large numbers of small-scale kink-folds, from metres to millimetres in size, are found throughout the Lewisian-derived mylonite outcrop. The abrupt changes in the dip of the foliation, for example the steep dips in the mylonite immediately above the Balmacara Thrust plane, may reflect large-scale folds of this type. The structures are similar to those described from the Torridonian-derived mylonites, but are much more abundant and range down in size to small ripples, reflecting the more finely laminated nature of the Lewisian-derived mylonites. Fold-axis orientations are extremely variable; individual fold hinges may curve some 40° on foliation surfaces and may diverge or converge, with interference effects where hinges cross each other. Conjugate kink sets are common. Kink folds occur less commonly where mylonites are affected by

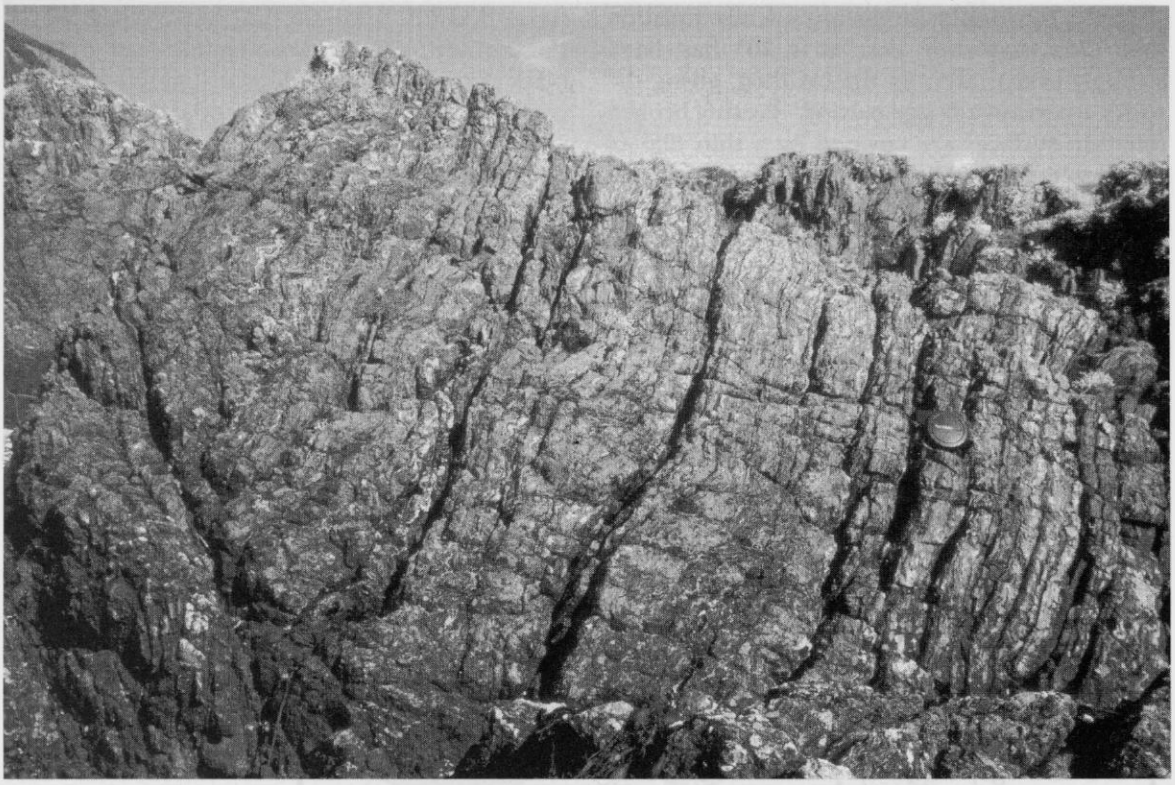


Figure 5.58 Laminated mylonite with alternating quartzofeldspathic and chloritic (dark) laminae, derived from layered Lewisian gneiss, Moine Thrust Zone, southern point of Ard Hill, Lochalsh. (Photo: A.J. Barber.)

asymmetrical folds, but in places the kink folds affect the well-developed axial-plane cleavage in these folds, confirming that the kink folds were formed later.

The Balmacara Thrust that separates the Torridonian- and Lewisian-derived mylonites is exposed on the western side of Ard Hill, in the raised cliff close to the southern point of the headland (NG 818 263). The thrust plane can be followed northwards from Ard Hill to the scarp face of Sgurr Mòr (NG 821 282) (Figures 5.52, 5.57). The thrust plane dips eastwards at *c.* 30°, but below the thrust the mylonitic foliation in the Torridonian dips uniformly eastwards at *c.* 20°, so that the thrust transects the foliation. The mylonitic foliation in the Lewisian-derived mylonites above the thrust is highly folded and vertical in places, so that the thrust cuts across the foliation in the Lewisian at a high angle and transects large-scale folds. In the cliff face, the thrust is marked by a 3–5 m-wide zone of yellow-weathered gouge and breccia, containing fragments of mylonite up to 30 cm in size, mainly of Lewisian origin but also with minor Torridonian input.

Interpretation

The earliest Caledonian structure recognized in the Moine Thrust Belt in Lochalsh is the Lochalsh Syncline, a kilometre-scale fold, overturned towards the west. Kanungo (1956) related the generation of quartz-filled tension-gash sets, commonly found in the Torridonian sandstones near the hinge, to fold formation. A coherent axial-planar pressure-solution cleavage is developed in the core of the fold, but farther east in the inverted limb the bedding is transposed into a mylonitic foliation. The foliation is axial planar to folds that affect the quartz tension-gashes, suggesting that mylonitization occurred at a late stage in the development of the Lochalsh Syncline.

The structural features of the Lewisian-derived mylonites, namely compositional lamination, foliation, tight to isoclinal folding and ESE-plunging extension lineation, all suggest that the mylonites were developed during significant WNW translation in the thrust belt. The fabrics and mineralogy of the Torridonian-derived mylonites suggest that this predominantly ductile deformation occurred under greenschist-facies conditions at temperatures of 300°–400° C and depths of *c.* 15 km.

Continued east–west compression resulted in the formation of a secondary cleavage in the siltstones of the Kinloch Formation and asymmetrical folds in the Torridonian- and Lewisian-derived mylonites of Ard Hill. This secondary cleavage dips more steeply than bedding and the sub-parallel mylonitic foliation on the inverted limb of the Lochalsh Syncline. The asymmetrical folds have a westerly vergence (S-profile looking north), incompatible with their position on the inverted limb of the syncline. Hence, the cleavage and asymmetrical folds were superimposed on the already inverted limb of the Lochalsh Syncline and on the mylonites. The limited degree of associated recrystallization and strain-slip and fracture cleavages indicate that deformation occurred under lower metamorphic temperatures and pressures, signifying progressive uplift and exhumation during thrusting. The presence of kink folds testifies to a later and yet more-brittle phase of deformation.

The final stage of deformation in this area generated the Balmacara Thrust, which in its present form cross-cuts the mylonite zone but juxtaposes Lewisian-derived mylonites onto uniformly dipping Torridonian-derived mylonites. The thick zone of breccia along the thrust plane indicates that movement occurred under very shallow conditions, possibly at depths of only 1 km or so. The predominance of Lewisian blocks in the breccia zone reflects the considerable angular discordance between the thrust plane and the foliation in the Lewisian-derived mylonites.

Conclusions

The Ard Hill GCR site provides excellent exposures of the Balmacara Thrust and both footwall and hangingwall mylonites derived from Torridonian sandstones and Lewisian gneisses respectively, clearly demonstrating the complex nature of the structural history of the southern Moine Thrust Belt. Mylonite formation is related to the generation of the Lochalsh Syncline, which dominates the geological structure of Lochalsh and southern Skye. Two subsequent fold phases can be recognized in the mylonites, and their geometry and related fabrics show that renewed westward movements occurred under progressively lower temperatures and pressures during exhumation of the Moine Thrust Belt. The Balmacara Thrust, which carries the Balmacara Nappe over the inverted limb of the Lochalsh Syncline, represents a more-brittle phase of deformation that terminated movements in this part of the thrust belt. The site is of national importance and remains suitable for teaching and for further work.

ORD
(NG 605 126–NG 691 125)

R.F. Cheeney and M. Krabbendam

Introduction

The Ord Window on the Sleat peninsula of southern Skye is a structural inlier of Cambro–Ordovician and Torridonian rocks of the foreland sequence (Figure 5.59). The inlier is surrounded by structurally overlying Torridonian rocks that lie on the lower limb of the recumbent Lochalsh Syncline in the Kishorn Nappe, the lowest and most westerly part of the Moine Thrust Belt on Skye. The window is one of the best examples of a tectonic inlier in the British Isles, but is characterized by complicated outcrops of folded, steeply dipping, fault-bounded slivers. The detailed structure is difficult to elucidate and, despite several published studies and countless student exercises, there is still no overall satisfactory solution.

Clough was part of the Geological Survey team that mapped the Moine Thrust Belt in the 1890s, and reached Skye in 1896. He envisaged the Ord structure as a tectonic window with two thrusts that were both folded into relatively open antiforms (see Peach *et al.*, 1907). Both thrusts were interpreted as lying structurally beneath the Kishorn Nappe. Bailey (1939, 1955) re-interpreted Clough's work, and suggested that the two thrusts were lower and upper branches of the Kishorn Thrust, and effectively regarded the core of the Ord Window as part of the foreland. In contrast, Potts (1983) re-interpreted the Ord Window as a recumbent fold, analogous to, but at a lower position than, the Lochalsh Syncline. He suggested that thrust faults at the western, leading edge of the window, in combination with normal faults at the eastern, trailing edge, had brought the

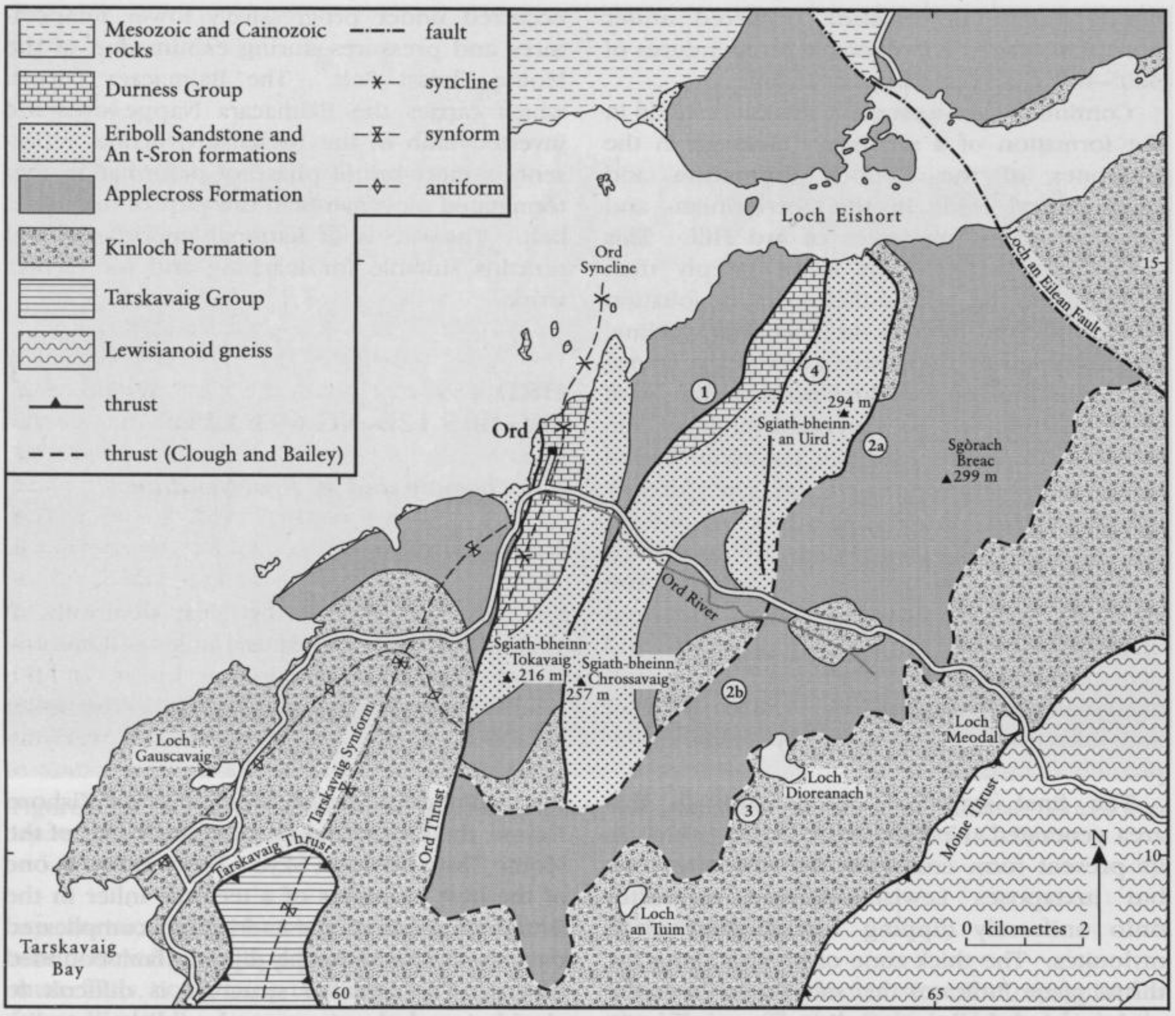


Figure 5.59 Geological map of the Ord Window, after the work of Clough (see Institute of Geological Sciences, 1976b; and Potts, 1983). Note that different authors refer to many of the lithological contacts by different names. On the map, disputed contacts are numbered as follows: (1) – Sgiath-bheinn an Uird Thrust, eastern limb (Clough in Peach *et al*., 1907); Kishorn Thrust (Bailey, 1939); Western Fault, normal fault (Potts, 1983). (2) a+b – Sgiath-bheinn an Uird Thrust, eastern limb (Clough in Peach *et al*., 1907); lower branch of Kishorn Thrust (Bailey, 1939); (2a) Allt a' Chinn Mhoir Fault, normal fault; (2b) normal stratigraphical contact (Potts, 1983). (3) – Sgiath-bheinn Tokavaig Thrust, eastern limb (Clough in Peach *et al*., 1907); upper branch of Kishorn Thrust (Bailey, 1939); normal stratigraphical contact (Potts, 1983). (4) Eastern Fault (Potts, 1983).

recumbent fold to higher structural levels. In this interpretation, the Ord Window is not a classic thrust window, and the structure is perhaps best referred to as the 'Ord Inlier'.

The Ord Window contains the southernmost outcrops of the Cambro–Ordovician succession of the Moine Thrust Belt. The immediate surroundings of Ord are also a GCR site for Cambro–Ordovician stratigraphy (Rushton *et al*., 2000), which demonstrates the remarkable north–south uniformity of shallow-water sedimentation on the margin of Laurentia.

Description

The Ord GCR site encompasses a large but irregular area (*c*. 23 km^2) in the central part of the Sleat peninsula extending south and east from Loch Eishort for several kilometres. The minor road to the small village of Ord traverses the undulating terrain but the area is devoid of paths. The upper slopes are heather-clad with grass areas, but deciduous woods occur on the lower north-western slopes and in the narrow valleys. The area contains several prominent rocky ridges; Sgiath-bheinn an Uird (294 m), Sgiath-bheinn Tokavaig (216 m) and Sgiath-bheinn Chrossavaig (255 m) are formed of Cambrian quartzites, but Torridonian sandstones form more-subdued topography around Sgòrach Breac (299 m).

The Cambro–Ordovician rocks of the Ord Window include the Eriboll Sandstone Formation, the An t-Sron Formation and the lower part of the Durness Group; in essence the same sequence as that on the mainland of north-west Scotland (see also Ord GCR site report in Rushton *et al.*, 2000). However, the carbonate rocks are typically highly altered so that division into formations is not easy.

The structures of the Ord Window are best described from west to east, starting outside the window itself.

West of the Ord Inlier, Torridonian rocks are folded into the open Tarskavaig Synform (Figure 5.59) that also folds the Tarskavaig nappes (see **Tarskavaig** GCR site report, this chapter). Within the Tarskavaig Synform, close to Ord, the sequence is inverted as the Kinloch Formation (Sleat Group) overlies the Applecross Formation (Torridon Group), which in turn overlies the basal Cambrian False-bedded Quartzite Member. The inverted unconformity of the basal Cambrian quartzite, locally marked by pebbly layers, can be seen clearly close to the low-water mark in Ord Bay and farther along the coast to the south-west. Clough (in Peach *et al.*, 1907) noted the inversion and attributed it to an early phase of recumbent folding. The axial trace of an early recumbent anticline was later located by means of sedimentary structures in the Torridon Group sandstones and siltstones (Bailey, 1939; Karcz, 1963; Potts, 1983). Potts (1983) named this structure the 'Eishort Anticline' (Figure 5.59) and followed the axial trace from Tarskavaig Bay north-eastwards around the Tarskavaig Synform to where it is truncated by the Ord Thrust (see below).

The eastern limb of the Tarskavaig Synform is truncated by the steep, roughly N-trending reverse fault that Bailey (1939, 1955) and Potts (1983) termed the 'Ord Thrust'. Clough (in Peach *et al.*, 1907) termed this structure the 'Sgiath-bheinn Tokavaig Thrust' and envisaged it as bounding the Ord Window. Later work showed that the 'thrust' does not continue around the window, certainly on its eastern and north-eastern side. Hence, the terminology of Bailey and Potts is adopted here (Figure 5.60). Immediately east of the Ord Thrust, which forms the western boundary of the Ord Window, the Cambro–Ordovician succession is folded into a tight syncline, the Ord Syncline. Its western limb and axial trace are truncated by the thrust, which is manifest as a complex fault-zone on the foreshore at Ord (NG 616 133). However, detailed relationships are difficult to unravel and a single discrete surface of displacement cannot be recognized.

Within the Ord Window are two outcrops of Cambro–Ordovician rocks separated by Torridonian rocks. On the western side of the window in the Ord Syncline the overall sequence youngs and dips steeply to the west, although in parts the bedding is locally vertical and even overturned to dip steeply east. The sequence ranges from Applecross Formation to Durness Group carbonate rocks, which on the coastal section north-east of Ord contain abundant black and grey chert nodules and lenses. Small-scale imbrication can be seen locally (e.g. west of Cnoc na Fuarachad, NG 621 131) and in coastal outcrops north-east of Ord (at NG 621 139) (Bell and Harris, 1986). As the axial trace of the Ord Syncline lies close to the Ord Thrust, the plunge of the fold is difficult to define, but it appears to be moderately steep.

To the east is the Western Fault (Potts, 1983), a steep NNE-trending structure that juxtaposes the eastern outcrop of Torridonian and Cambro–Ordovician rocks against those of the Ord Syncline (Figures 5.59, 5.60). Clough (in Peach *et al.*, 1907) termed this structure the 'Sgiath-bheinn an Uird Thrust'. This eastern sequence again youngs towards the west. Near to Loch Eishort, the beds dip gently west and are right-way-up, but towards the south-east dips increase, and south-east of the Allt a' Coile Moire the beds are steeply east dipping and overturned. Potts (1983) interpreted these bedding orientations as defining a recumbent, W-facing, gently SSW-plunging syncline (analogous to the Lochalsh Syncline), with the northern exposures in the lower, right-way-up limb, and the southern exposures in the upper, inverted limb. Near the southern end of Sgiath-bheinn an Uird the syncline is offset by a N–S-trending fault, termed the 'Eastern Fault' (Potts, 1983), which appears to have a normal downthrow towards the east.

The eastern outcrop of Cambro–Ordovician rocks is bounded to the east by a further fault

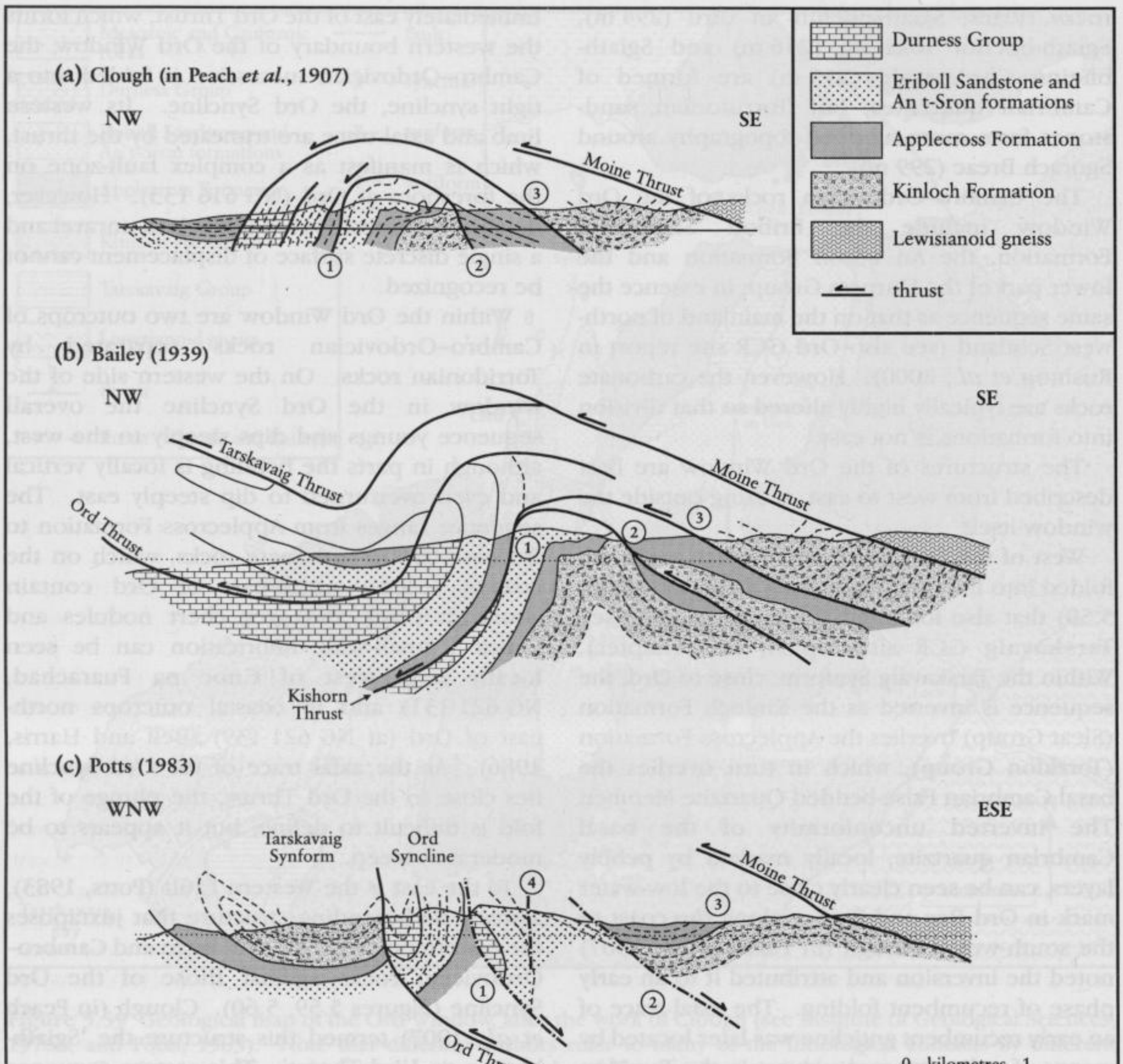


Figure 5.60 Cross-sections through the Ord Window. (a) After Clough (in Peach *et al.*, 1907). (b) After Bailey (1939). (c) After Potts (1983). Sections (a) and (b) follow the same line, but section (c) lies farther south-west. Several contacts, interpreted as thrusts by both Clough and Bailey, have been re-interpreted as normal stratigraphical contacts or as extensional faults by Potts. The Ord Syncline has been interpreted as an antiform by Bailey, but a synform by Potts. For explanation of numbered contacts, see Figure 5.59.

(see Figure 5.60). This structure is variously termed the 'Sgiath-bheinn an Uird Thrust' (Clough in Peach *et al.*, 1907), the 'lower branch of the Kishorn Thrust' (Bailey, 1939), or the 'Allt a' Chinn Mhoir Fault' by Potts (1983) who regarded it as a normal fault. The fault can be traced along the Allt Dearg, across the south-east slopes of Sgiath-bheinn an Uird, and along the valley of the Allt a' Chinn Mhoir. In the steep northern section of the Allt a' Chinn Mhoir, the dip of the fault increases northwards over a horizontal distance of *c.* 150 m from 28° to 70° to the ESE, suggesting that it has a listric geometry. Cambrian quartzites form the footwall of the fault, whereas the hangingwall comprises Applecross Formation rocks and, in the northerly reaches of Allt a' Chinn Mhoir, includes rocks of the underlying Kinloch Formation. Bedding in the Applecross and Kinloch formations is commonly highly oblique to the fault surface, whereas in the Cambrian quartzites bedding is generally sub-parallel to the fault surface. Breccias and vein systems are developed widely along this section, not only close to the fault plane, but also in the adjacent rocks.

To the south of the Ord River the boundary between the Eriboll Sandstone Formation and the Applecross Formation appears to be unmodified and to represent the original unconformity. East of the Allt a' Chinn Mhoir Fault lies a 2 km-wide outcrop of Torridonian rocks that is dominated by red-brown-weathering, convolute stratified sandstones of the Applecross Formation, but contains some Kinloch Formation. The strata dip gently to the south-east or north-west. The contact with the main outcrop of grey-weathering sandstones and minor siltstones of the Kinloch Formation stretches from Sgùrr na h-Iolaire (NG 617 091) in the south-west to the Loch an Eilean Fault to the north-east. It was taken as the south-eastern limit of the Ord Window by Clough and Bailey, but the interpretation of this contact is controversial. Exposure is poor along the major part of the eastern trace; it is best constrained between the Loch an Eilean Fault and An Cruachan (NG 656 122), but even there the formations are rarely exposed within 10 m of each other. Brecciated zones up to 75 m in strike length that dip at about 30° to the ESE are developed locally in exposures of the Applecross Formation. They contain arrays of quartz-filled veinlets, although this does not necessarily indicate faulting, as rocks distant from the contact are comparably veined. South-west of An Cruachan, the degree of exposure is very poor, and delineation of this south-eastern contact of the window is largely conjectural.

Some features of the Ord Window can be recognized on the north side of Loch Eishort. On Torr Mòr (NG 629 164), a small outcrop of basal Cambrian quartzite rests with an angular unconformity of about 10° on Applecross Formation sandstones. The basal quartzite and the unconformity are in turn unconformably overlain to the west by Jurassic limestone. This outcrop appears to be a continuation of the Cambrian quartzites of the western outcrop of the Ord Window; the nature of the termination of the eastern outcrop is unclear.

Interpretation

The structure of the Ord Window is complex, and the generally poor quality of inland exposure has hampered detailed mapping. The area remains controversial and three very different interpretations have been published (Figure 5.60).

Clough (in Peach *et al.*, 1907) considered that the window was composed of two thrust sheets that were envisaged to have been folded after thrusting, resulting in a dome-shaped antiformal culmination (Figure 5.60a). The lowest thrust (the Sgiath-bheinn an Uird Thrust) was thought to form a roof thrust to the eastern outcrop of Cambro–Ordovician and Torridonian rocks in the window. The upper thrust, named the 'Sgiath-bheinn Tokavaig Thrust', was thought to envelop the western package of Cambro–Ordovician rocks and a large swathe of mainly Applecross Formation strata on the east side of the window. A corollary of this interpretation is that the hangingwalls of both the Sgiath-bheinn Tokavaig and the Sgiath-bheinn an Uird thrusts would show down-dip displacements on their steeply dipping western limbs. Clough also concluded that the inversion of Cambrian and Torridonian strata west of the Ord Window was probably caused by a large-scale recumbent, isoclinal fold, but did not delineate the hinge zone of this fold (the Eishort Anticline).

Bailey (1939, 1955) retained the basic model of the Ord Window as an antiformal culmination exposing lower thrust sheets in its central part, but he incorporated various ideas on fold nappe formation into his interpretation. He renamed the westernmost thrust the 'Ord Thrust' and envisaged it as the sheared upper limb of the Ord Syncline (Figure 5.60b), hence defining this structure as an antiform. The W-dipping Ord Thrust was considered to be structurally higher than the thrusts that crop out farther to the east. Bailey equated the eastern thrusts with the Kishorn Thrust, splitting it into a lower and upper branch on the eastern side of the window. The point of divergence of the two branches would be located at the southernmost outcrop of Cambrian quartzite, just east of Creagan Dubh (NG 610 102). Bailey suggested that the Ord Thrust cuts the lower branch of the Kishorn Thrust just north of Creagan Dubh (Figure 5.59). In this interpretation, the eastern package of Cambro–Ordovician rocks would be part of the foreland, whereas all other rocks would be part of an internally complicated Kishorn Nappe. It is interesting that Bailey (1939) suggested that the 'Ord Inversion', i.e. the inverted Cambrian and Torridonian strata west of the Ord Window itself, became right-way-up near Tarskavaig, but that this inversion 'probably does not correspond with the Loch Alsh Inversion'.

Potts (1983) suggested a more-radical re-interpretation of the geology. He postulated that the window is effectively the result of large-scale recumbent folds that were subsequently faulted by both reverse and normal faults to produce the current outcrop (Figure 5.60c). In ascending structural order the three folds in the area are the Ord Syncline, the Eishort Anticline and the Lochalsh Syncline. The later E-dipping Ord Thrust thus juxtaposes the hinge zone of the Ord Syncline in its hangingwall virtually against the hinge zone of the Eishort Anticline in its footwall. In contrast to the previous interpretations, the Cambro–Ordovician sequence in the western part of the Ord Window was thought to be in the hangingwall, rather than in the footwall of the Ord Thrust. All the faults east of the Ord Thrust were regarded as extensional. Potts (1983) also regarded the outcrops of the Kinloch and Applecross formations east of the Allt a' Chinn Mhoir Fault as part of the right-way-up, lower limb of the Lochalsh Syncline. Thus, the eastern boundary of the Ord Window (inlier) is taken along the Allt a' Chinn Mhoir Fault, rather than along the Kinloch Formation–Applecross Formation boundary, some 2–3 km farther to the south-east. Potts (1983) argued that this latter contact dips to the north-west and hence is more-or-less a normal stratigraphical contact, albeit modified locally by folding and minor thrusting. It follows from this interpretation that the axial trace of the Eishort Anticline, which would be duplicated by thrusting along the Ord Thrust, must have been excised by extension, supposedly along the Allt a' Chinn Mhoir Fault. This fault brings the right-way-up, lower limb of the Lochalsh Syncline in its hangingwall, down onto the inverted upper limb of the Ord Syncline.

The contact between the Applecross and Kinloch formations is a major point of difference between Potts and Clough and Bailey, in that it radically changes the size of the Ord Window dependent on which interpretation is favoured. Clough named this contact the 'Sgiath-bheinn Tokavaig Thrust' and envisaged it as a coherent regional structure underlying the Kishorn Thrust. Bailey saw it as an upper branch of the Kishorn Thrust. Coward and Potts (1985) showed it as a normal fault, whereas Potts (1983, and pers. comm., 1997) regarded it as a normal stratigraphical contact. The solution to this conundrum depends partially on whether the Kinloch Formation dips underneath the Applecross Formation (required for a stratigraphical contact) or whether the Kinloch Formation lies at a structurally higher level than the Applecross Formation, as shown on the cross-sections of Clough and Bailey. The poor exposure and generally shallow dips make the nature of this boundary unclear, but further fieldwork may clarify relationships.

Conclusions

The Ord Window comprises Cambro–Ordovician and Torridonian strata of the foreland succession that form a structural inlier within the Kishorn Nappe in the southern Moine Thrust Belt. The window itself has been interpreted as an antiformal culmination exposing lower thrust sheets beneath the lower parts of the Kishorn Nappe. However, it contains steep faults and tight folds that show complex and contentious relationships, geometries quite different from the low-angle imbricate thrust systems that dominate the Moine Thrust Belt on most of the mainland.

Three very different structural interpretations of the structure have been proposed. The original explanation by C.T. Clough (in Peach *et al.*, 1907) portrays it as a tectonic window through two thrust sheets, whereby all the rocks remained essentially right-way-up. The second interpretation by E.B. Bailey (1939, 1955) involved a large pair of recumbent folds with associated inversion of strata, dissected by thrusts, with the overall edifice then refolded in a regional antiform and synform. The most recent model of Potts (1983) envisages the interplay between thrusts and extensional faults to drop down an originally higher package of folded strata.

There is no consensus as to which of the above models is (most) correct; indeed, none is wholly satisfactory. The Ord Window is clearly a structural inlier and contains distinctly different structures to other parts of the Moine Thrust Belt. However, it remains one of the few places where the actual geometry of the various structures remains enigmatic, and until the basic geometry is known, the mechanics of the thrust system cannot be assessed. The Ord GCR site is undoubtedly of national importance, but remains eminently suitable for further detailed work.

TARSKAVAIG (NG 583 097–NG 572 064)

R.F. Cheeney and M. Krabbendam

Introduction

The large GCR site that extends south from Tarskavaig Bay, in the south-western part of the Sleat peninsula on the Isle of Skye, contains three distinctive Tarskavaig nappes that lie between the Kishorn Nappe and the Moine Thrust. The nappes provide the only exposures of the Tarskavaig Group, a distinctive clastic metasedimentary sequence that has features in common with both the Torridonian and the Moine sequences but cannot be directly correlated with either. It is the only part of the possible 'Moine' sequence that occurs below and to the west of the Moine Thrust itself, and its origin and history remain something of an enigma. In addition, it appears that the thrusts exposed here do not conform to the foreland-propagating thrust sequence model, which dominates in the Moine Thrust Belt on the mainland (Figure 5.61).

The Kishorn Nappe is the dominant structure of Lochalsh and eastern Skye, and its included Torridonian sequence is folded into a large W-facing syncline, the Lochalsh Syncline. However, south of Ord the apparent structural simplicity within the Kishorn Nappe breaks down and the area contains an array of thrusts, large folds and listric normal faults, whose complex geometry, origin and timing are more obscure. The geology of south-east Skye, between Loch Eishort and the Sound of Sleat, consists of four structural units. The highest unit is the Moine Thrust Sheet, mainly composed of Lewisianoid gneisses with minor Moine metasedimentary rocks. Below the Moine Thrust are the Tarskavaig nappes, which in turn overlie the southern continuation of the Kishorn Nappe, composed mainly of sandstones of the Sleat and Torridon groups. The Kishorn Nappe overlies the complex 'Ord Window', described in the **Ord** GCR site report (this chapter).

The three Tarskavaig nappes are, from the top down, the Loch Lamascaig Nappe, the Caradal Nappe, and the Tarskavaig Nappe itself (Figure 5.61). The Tarskavaig Thrust juxtaposes the Tarskavaig Nappe onto Sleat Group rocks of the Kishorn Nappe; both nappes are folded by the tight, locally recumbent Tarskavaig–Caradal Synform whose axis plunges gently southwards and trace trends NNE (Karcz, 1963; Coward and Potts, 1985). The trend of this fold is perpendicular to the WNW transport direction of the Moine and Tarskavaig thrusts (Law and Potts, 1987). All three Tarskavaig nappes are characterized by basal thrusts immediately overlain by mylonites of Lewisian or Lewisianoid affinity, which are succeeded by tightly folded sequences of dominantly quartzofeldspathic metasedimentary rocks of the Tarskavaig Group. Similar folding occurs in the Sleat Group rocks of the Kishorn Nappe, which are folded by the earlier Gillean–Eishort Anticline some 2 km north of Tarskavaig. This tight, recumbent structure is probably complementary to the underlying Lochalsh Syncline (see also **Ord** GCR site report, this chapter, and Figure 5.59).

Rocks of the Tarskavaig Group occupy an intermediate lithological, stratigraphical, tectonic and metamorphic position between rocks of the Moine Supergroup *sensu stricto* (lying east of the Moine Thrust), and Torridon and Sleat groups in the Kishorn Nappe and the foreland farther north. This problem is exacerbated by the definition of the Moine Thrust as the western limit of the Moine Supergroup: if the Tarskavaig rocks are truly Moine, then the Moine Thrust is a different structure on Skye to that on the mainland.

Charles Thomas Clough undertook the first systematic mapping of the Moine Thrust Belt in Skye for the Geological Survey. Working southwards along the belt, Clough reached Skye in 1892 and in the next five years he recognized and documented all of the main lithologies and structures, although questions regarding the structural interpretations remained. Clough's fieldwork in Skye was completed in 1897 and was formally described in both the North-west Highlands memoir (Peach *et al.*, 1907) and the Glenelg (Sheet 71) memoir (Peach *et al.*, 1910). Considerably later, Cheeney and Mathews (1965) divided the Tarskavaig metasedimentary rocks into three lithostratigraphical 'groups', now formally defined as formations: (from the top) the Aruisg Psammite Formation (feldspathic

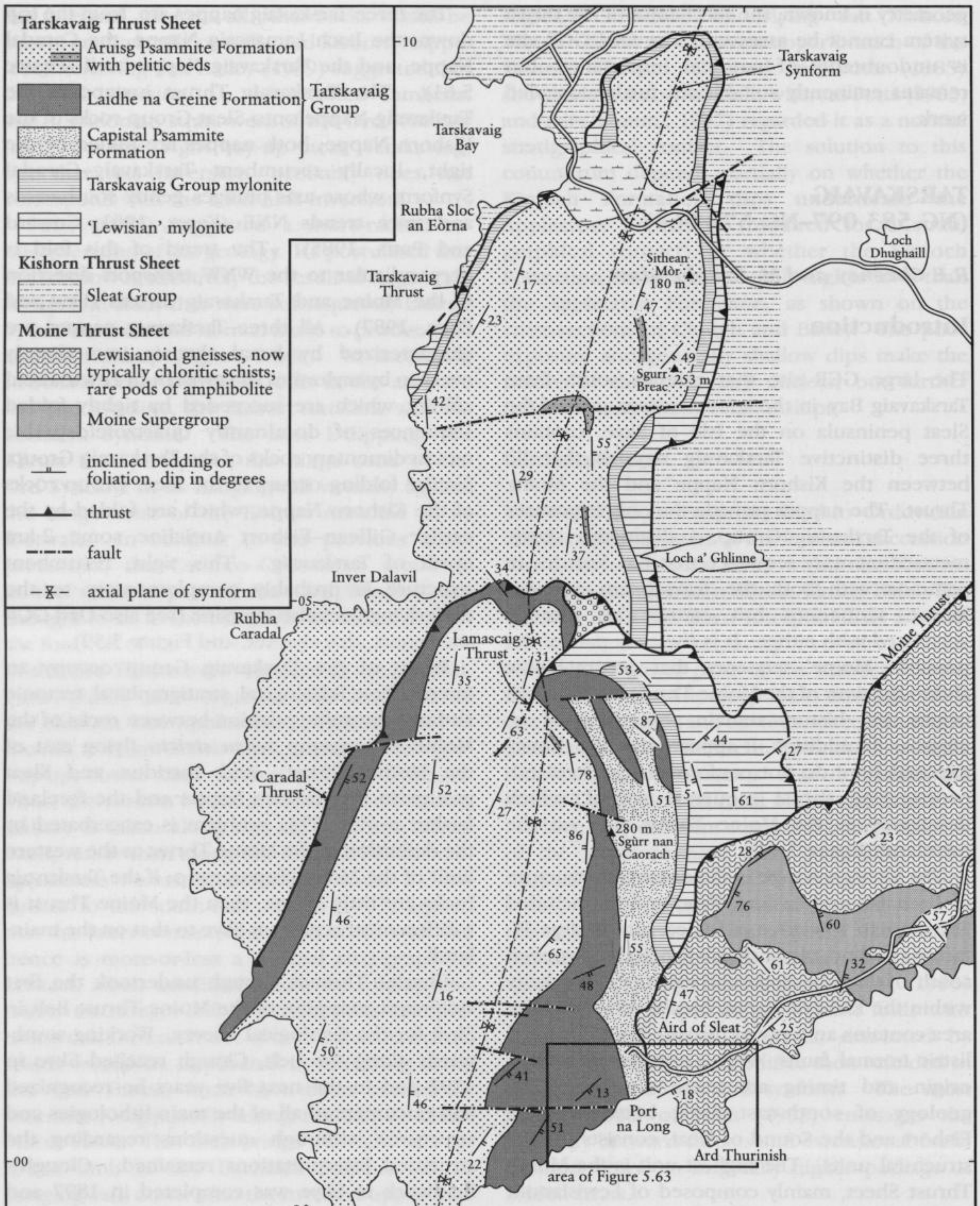


Figure 5.61 Geological map of the Tarskavaig nappes in south-east Skye. After Cheeney and Mathews (1965).

psammites), the Laidhe na Greine Formation (mixed pelites and psammites), and the Capistal Psammite Formation (psammites with locally quartzitic pebble beds, subsidiary semepelites). In the vicinity of Tarskavaig Bay, nearly all of the Tarskavaig Group rocks belong to the uppermost formation; the two lower formations possibly occur within the mylonitized rocks close to the Tarskavaig Thrust. The rocks lie in the greenschist facies, mostly at biotite grade, but with some garnet-grade rocks present in the most south-easterly exposures, near the **Ard Thurinish–Port na Long**) GCR site (Bailey, 1939, 1955).

Description

The GCR site extends south from Tarskavaig Bay to An Garbh-allt and eastwards to Loch Ic Iain (NG 602 067). The topography of the south-west part of the Sleat peninsula is one of low rounded hills, mainly between 150 m and 200 m above sea level and only rarely exceeding 250 m. West of the Moine Thrust, rock exposure is locally good, as glaciation has left an ice-moulded and plucked landscape with a NNW grain, irregularly covered with drift deposits and scattered with peaty hollows and numerous lochans. The coastline is rocky throughout, with near-continuous bedrock exposure that offers few difficulties of physical access. The area has no roads and only a few tracks.

The Tarskavaig Thrust, the Sleat Group in the footwall and the mylonitic Lewisian or Lewisianoid gneisses and Tarskavaig Group rocks in the hangingwall are all exposed at Tarskavaig Bay.

On the north side of Tarskavaig Bay, the Kinloch Formation (Sleat Group) shows abundant folds, mostly with angular hinges, which are especially clear in the argillaceous units. Sedimentary way-up structures show that the rocks here are right-way-up. On the south side of the bay (around NG 583 085), strongly folded Sleat Group sandstones crop out in cliffs just below the well-exposed Tarskavaig Thrust (Figure 5.62). The thrust plane itself can be traced southwards in cliff sections around Rubha Sloc an Eòrna for over 1 km, where it dips gently to the ESE. About 1 km south of Rubha Sloc an

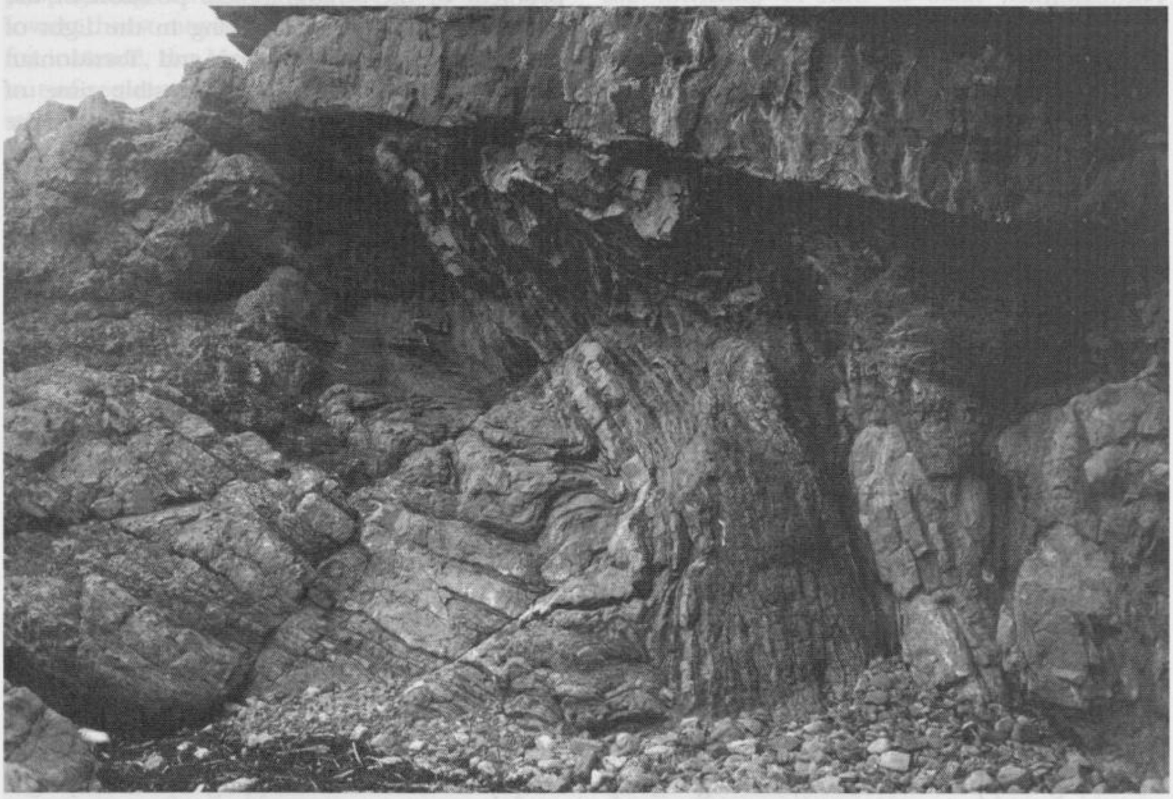


Figure 5.62 The Tarskavaig Thrust at the south side of Tarskavaig Bay. Tarskavaig Moine rocks lie above the thrust with folded Torridonian Sleat Group rocks below. (Photo: K.M. Goodenough.)

Eòrna (at NG 576 077), spectacular recumbent folding occurs in Sleat Group rocks just below the thrust plane. In contrast, the foliation of the overlying mylonites and Tarskavaig Group rocks is generally parallel to the thrust surface. This relationship – near-conformable above, but markedly discordant beneath – appears common to thrusts throughout Sleat and is reproduced at all scales. Above the thrust, there is a thin (1–30 m-thick) layer of greenish-grey, chlorite- and epidote-bearing mylonite with abundant red quartzofeldspathic streaks that is derived from 'Lewisian' gneisses (Clough in Peach *et al*., 1907; Bailey, 1955). Locally, tight to isoclinal folds occur within these mylonites. This locality is a good example of a thrust that has not developed along the obvious rheological contrast of cover and basement. Above the mylonitic 'Lewisian' gneisses there follows about 30 m of mixed semi-pelitic, pelitic and psammitic rocks, all highly sheared. These mylonitic rocks pass up gradually into feldspathic psammites that are less deformed and locally contain cross-bedding, but which are still lineated, foliated, and cross-cut by numerous quartz veins. These last rocks probably belong to the Aruisg Psammite Formation.

At a small bay just south of Rubha Sloc an Eòrna at NG 578 081, a vertical lamprophyre dyke of probable Caledonian affinity cuts across the Tarskavaig Thrust. The dyke in the hanging-wall is recorded as having moved 'a few feet *southward*' with respect to the footwall (Bailey, 1955), opposite to the general WNW-directed thrust movement.

Although the Tarskavaig Thrust plane itself is not exposed south-east of Tarskavaig Bay, the same mylonites and transition to less-deformed Tarskavaig Group psammites can be found on the eastern slopes of Sithean Mòr around NG 598 081 (Bell and Harris, 1986). From here, the mylonites can be followed to Sgurr Breac and further to Loch a' Ghlinne (Figure 5.61), where, the mylonitic foliation has an easterly dip of 35° with Sleat Group rocks structurally *above* it. Assuming that the mylonitic foliation lies parallel to the thrust, the Tarskavaig Thrust here must be overturned on the eastern limb of the Tarskavaig Synform.

Farther south, the Caradal Nappe and the Loch Lamascaig Nappe structurally overlie the Tarskavaig Nappe. In the Tarskavaig Group rocks of the Loch Lamascaig Nappe an early NNE-trending isoclinal fold pair occurs, named the 'Capistal Anticline' and 'Capistal Syncline' by Cheeney and Matthews (1965). Apart from these internal folds, the structure of the nappes appears relatively simple, each exhibiting a synformal shape, defined by the Tarskavaig and Caradal synforms. Whilst the synform is relatively open in the case of the higher Loch Lamascaig Nappe, the rocks of the Tarskavaig Nappe, along with the Tarskavaig Thrust, have been deformed into a tight fold, with the eastern limb overturned.

Interpretation

Early geologists, notably Clough and Bailey, had already noticed the rather unusual lithological characteristics of the Tarskavaig rocks, with respect to the Torridonian on the one hand and the Moine on the other. Clough (in Peach *et al*., 1907) suggested that both the Moine and the Tarskavaig rocks once formed a single mass in which metamorphism increased towards the south-east, and hence that the Moine rocks had been transported a greater distance on the Moine Thrust than the Tarskavaig rocks had been transported on the Tarskavaig thrusts. The problem of the stratigraphical position of the Tarskavaig Group is interesting in the light of recent age dating of Moine and Torridonian rocks. Rb-Sr dating of the possible time of diagenesis (Turnbull *et al*., 1996), re-dating of the West Highland Granite Gneiss Suite that intrudes the Moine successions (Friend *et al*., 1997), and detrital zircon ages (Rainbird *et al*., 2001) all contribute to constrain the deposition of both the Torridonian and the Moine sequences to between *c*. 1000 Ma and 870 Ma. Hence, it is feasible that the Tarskavaig Group rocks could have been deposited in an intermediate position between the Torridonian and Moine basins or depocentres (Strachan and Holdsworth, 2000).

The age relationships of the thrusts around Tarskavaig are particularly interesting. Clough observed that, south of Loch a' Ghlinne, the Loch Lamascaig Thrust cuts across an already inverted Tarskavaig Thrust, as well as the Caradal Thrust. The order of thrusting appears to be constrained by such cross-cutting relationships (albeit in rather poorly exposed ground), and also from the observation that the rocks in the lowest nappe (the Tarskavaig Nappe) are the most steeply inclined and most tightly folded, with progressively less folding and gentler inclinations higher up in the structural pile, so that the

Moine Thrust is a rather planar, gently inclined structure. In the light of these observations, Bailey suggested that the sequence of emplacement of the thrust units was: Tarskavaig, Caradal, Loch Lamascaig and, lastly, Moine.

Cheeney and Matthews (1965) supported this sequence of structural emplacement. They suggested that the first deformation events produced the isoclinal Capistal folds and the mylonites of the Tarskavaig Nappe. Further movement along the Tarskavaig Thrust plane occurred in a brittle manner, followed by development of the Tarskavaig and Caradal synforms, which fold and locally overturn the Tarskavaig Thrust. Movement along the Caradal and the Lamascaig thrusts truncated the overturned Tarskavaig Thrust and folds. These late thrusts appear to lack mylonites above them, in contrast to the Tarskavaig and Moine thrusts. Last of all the Moine Thrust partially truncated earlier, lower structures.

It should be noted that all of these studies pre-dated the work of Dahlstrom (1970) in the Canadian Rockies, and of Elliott and Johnson (1980) in Assynt who both showed that many thrust belts are characterized by foreland-propagating thrust sequences, in which the lowest thrust moved last. Thus, at Knockan Crag for instance, the Moine Thrust plane itself is an out-of-sequence, late brittle thrust. If the structural sequence in the Tarskavaig area is really lowest first and uppermost last, as described by Clough and Bailey, then the area is doubly interesting in effectively representing a hinterland-propagating thrust sequence – an entire array of out-of-sequence thrusts.

Conclusions

Together with the GCR site at **Ord**, the Tarskavaig GCR site provides valuable insights into major features of the southernmost section of the Moine Thrust Belt. The site focuses on three separate nappes, the Tarskavaig, Caradal and Lamascaig nappes, which are sandwiched between the overlying Moine Thrust and the underlying Kishorn Nappe. Each nappe contains Tarskavaig Group rocks with minor thrust slices of Lewisian or Lewisianoid gneisses. The thrusts and nappes are folded, with the intensity of folding dying out upwards. The higher thrusts also appear to truncate the lower thrusts and folds. This thrust geometry suggests that the order of thrusting was from lowest to highest, in marked contrast to the 'foreland-propagating', 'piggy-back' thrust sequence that is dominant on the mainland. Some of the major features can be seen in excellent exposures in Tarskavaig Bay.

South-west Sleat is the only place where the Tarskavaig Group rocks occur. These rocks show lithological characteristics that are intermediate between the structurally lower Torridonian sequence and the structurally higher Moine Supergroup rocks and may yet prove to be some of the key lithologies for deciphering Neoproterozoic basin evolution in Scotland. These unique lithologies, together with the thrust geometries, make the Tarskavaig GCR site of national importance.

ARD THURINISH–PORT NA LONG (NG 587 001–NM 595 999)

R.F. Cheeney

Introduction

Senior members of long established families in the township of Aird of Sleat maintain that Ordnance Survey names are incorrectly assigned. According to local usage, 'Port na Long' (Bay of the Boat) refers to the haven to the *east* of Ard Thurinish; the bay to the *west* is known as Port a' Chuil (Bay of the Nook or Cranny). However, to avoid confusion with the published topographical and geological maps, the Ordnance Survey names are retained here. The situation is further complicated by the use of the term 'Port a' Chuil folds' by Cheeney and Matthews (1965) with reference to the westerly bay; here they are renamed the 'Port na Long folds'.

At Port na Long at the south-west end of the Sleat peninsula of Skye, the most southerly outcrop of the Moine Thrust is clearly exposed. The gentle ESE-dipping thrust plane separates the Moine Thrust Sheet above from the Caradal Nappe, the uppermost of the Tarskavaig nappes, beneath (Figure 5.63).

In this part of Sleat, the rocks of the Moine Thrust Sheet are dominantly schistose and partly mylonitic Lewisianoid felsic and mafic gneisses, interleaved with minor mylonitic Moine metasedimentary rocks. During the Caledonian Orogeny these rocks were metamorphosed to epidote-amphibolite facies followed by greenschist-facies retrogression. The underlying

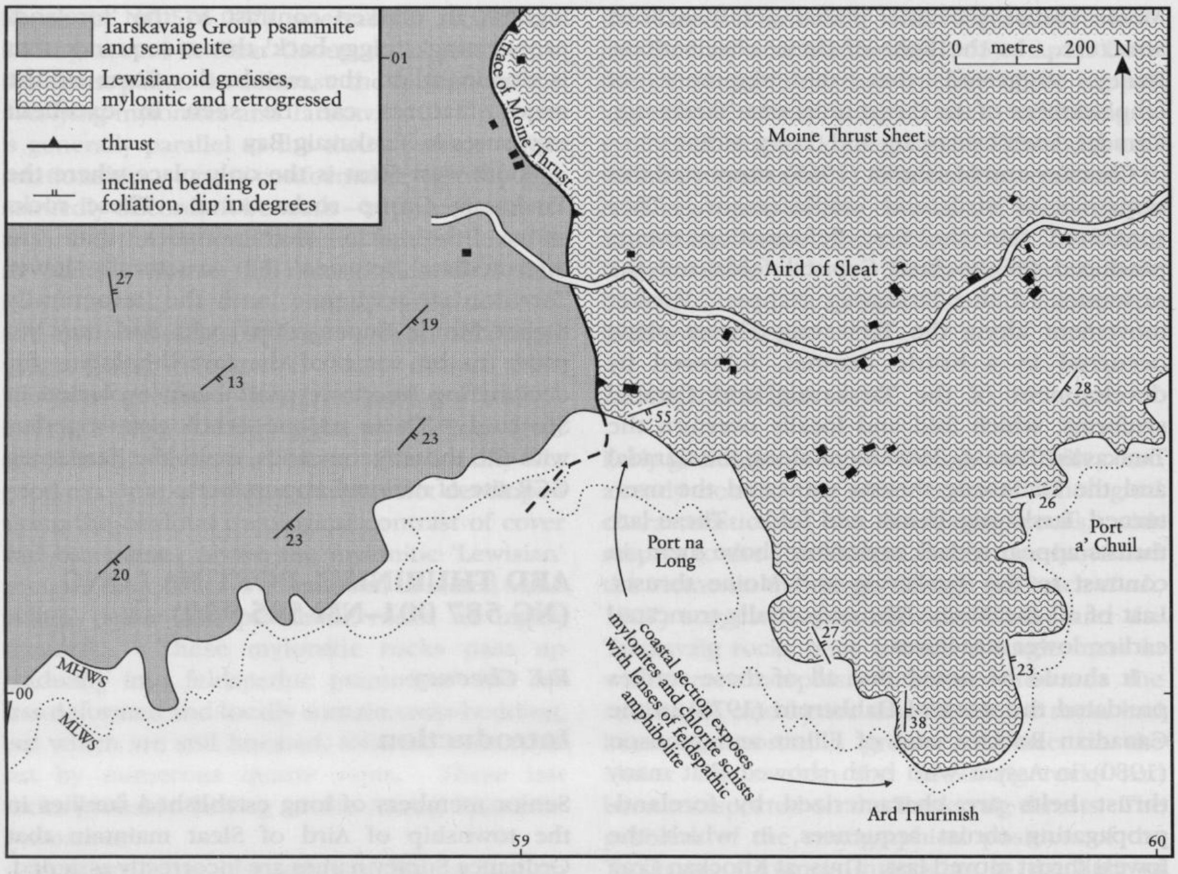


Figure 5.63 Map of area around the Ard Thurinish GCR site.

Caradal Nappe is composed mainly of semipelites, pelites and psammites of the Tarskavaig Group, metamorphosed to greenschist facies, but it also contains lenses of deformed Lewisian or Lewisianoid gneisses. Inland from Ard Thurinish, mylonitic Lewisianoid rocks of the Moine Thrust Sheet have been thrust over 'Lewisian' gneisses of the Caradal Nappe, and consequently the trace of the Moine Thrust is unclear in these areas. Several episodes of Caledonian minor folding are recognized within the area of the GCR site and these represent late-stage deformation and movements focused on the Moine Thrust. Numerous NNW-trending basalt dykes of the Palaeogene Skye swarm cross-cut the earlier Caledonian features.

C.T. Clough mapped the area for the Geological Survey in 1896 and recognized the main structural elements (Clough in Peach *et al.*, 1907). He noted that the Moine Thrust Sheet contains both Lewisianoid and Moine rocks, despite their strong Caledonian overprint. Bailey (1939, 1955) subsequently revised the structural interpretation of the area. This account is mainly based upon Cheeney and Matthews (1965) who remapped the area. Powell and MacQueen (1976) later studied the link between garnet growth and deformation in the Moine rocks to the east.

Description

Around Ard Thurinish, south of the hamlet of Aird of Sleat, a coherent cross-section is exposed along the coast, both in the intertidal zone and in low cliffs. Inland, exposure is generally poor in the low hilly terrain, especially in the Moine Thrust Sheet. The Moine Thrust itself is exposed on the coast section about 70 m south-west of the old schoolhouse (NG 5916 0048), close to some Palaeogene basaltic dykes. It is defined by the sharp contact between pink and green, mylonitized rocks above, and attenuated psammitic rocks beneath. It can be traced as an ill-defined topographical feature across the slopes to the north, above the hamlet (Figure 5.63).

Moine Thrust Sheet

The Lewisianoid rocks in this sheet now occur as alternating pink and dark-green, finely laminated mylonites and phyllonites. The quartzo-feldspathic and chloritic layers that range from less than 1 mm to over 50 mm thick, represent the original felsic and mafic gneiss protoliths (Clough in Peach *et al.*, 1907). The fine-grained rocks contain porphyroblasts of biotite, chlorite and green amphibole, all of which contain epidote trails. Larger lenses of coarser-grained schistose amphibolites are present within the mylonites (Matthews and Cheeney, 1968). The subsidiary Moine rocks are mylonitic and schistose, interlaminated psammites and semi-pelites, with rare garnets. The compositional layering and mylonitic foliation in the Lewisianoid and Moine rocks are parallel to each other and to the Moine Thrust plane.

Caradal Nappe

The Tarskavaig Group rocks in the Ard Thurnish–Port na Long GCR site consist of alternating beds of psammites and semipelites with local pelite. In the west, gritty psammites with well-developed cross-bedding are present. Close to the Moine Thrust, some coarser-grained psammite units also occur. Psammite–pelite contacts range from sharp to gradational. These rocks belong to the Capistal Psammite Formation and pass upwards to the west into the Laidhe na Greine Formation (Figure 5.61) As the Moine Thrust is approached, cross-bedding is modified by deformation such that younging direction can rarely be recognized. Within 300 m of the thrust plane, porphyroblasts of biotite become prominent; most notably in the psammitic layers. In associated pelitic layers Clough (in Peach *et al.*, 1907) reported small garnets.

Structure

Numerous minor folds occur within the Ard Thurinish–Port na Long GCR site. In the basal part of the Moine Thrust Sheet, the observed fold phases post-date the formation of mylonites. Powell and MacQueen (1976) attempted to correlate these fold episodes more widely, but correlations are uncertain (see also 'Introduction', this chapter). Consequently, the fold phases are referred to here in terms of type localities, following Cheeney and Matthews (1965).

On Ard Thurinish, a distinctive phase of minor folds is recognized in the schistose and mylonitic rocks of the Moine Thrust Sheet. The axial surfaces and congruent cleavages dip at 30°–50° towards the south-east or ESE. These 'Ard Thurinish phase' folds are generally tight with curvilinear hinges and widely dispersed axial orientations. They are typically asymmetrical, but do not show a consistent vergence. In quartzo-feldspathic layers, the folds deform an earlier lineation. Some quartz veins in the Lewisianoid rocks of the Moine Thrust Sheet cut across 'Ard Thurinish phase' folds; these veins also contain chlorite, biotite and amphibole.

Chlorite- and biotite-bearing quartz veins also occur in the south-east corner of the Caradal Nappe. These carry a persistent ENE-trending lineation that lies parallel to the hinges of the 'Port na Long' folds (note that Cheeney and Matthews, 1965 termed these folds the 'Port a' Chuil phase' – see 'Introduction'). The Port na Long folds are only found within about 300 m of the Moine Thrust. In the Moine Thrust Sheet, they are small-scale structures with tight to isoclinal profiles and a coaxial ENE- or WSW-plunging lineation. In the Tarskavaig Group rocks, the Port na Long folds have been recognized for some 200 m west of the Moine Thrust, where they are delimited by a subsidiary thrust surface. Strong lineations are developed coaxial with the folds, particularly in psammites, and in places constitute fold mullions.

A later phase of kink folds, commonly conjugate, is widely developed in the schists and mylonites of both the Moine Thrust Sheet and the Caradal Nappe. Near the Moine Thrust, these folds deform structures belonging to the 'Port na Long' fold phase. Within about 20 m of the Moine Thrust, the rocks are notably fissile and mylonitic and, as Clough noted (in Peach *et al.*, 1907), 'occasional lines of crush break up the earlier structures in the rock', including the late-stage conjugate folds.

Interpretation

The nature of the Moine Thrust and the overlying Moine Thrust Sheet at its southernmost outcrop at Ard Thurinish is different to their occurrences farther north. The Lewisianoid gneisses that form part of the Glenelg–Attadale Inlier (see 'Introduction', Chapter 7), are extensively mylonitized and retrograded, and possibly reflect several deformational events.

The interleaved Moine psammites in the mylonites above the thrust presumably belong to the Morar Group. In contrast, the rocks below the Moine Thrust belong to the distinctive but separate Tarskavaig Group. Their present juxtaposition is due to movements on the Moine Thrust and the associated mylonites. The trace of the thrust surface cuts discordantly across the folds, nappes and thrusts of Tarskavaig. This suggests that the Moine Thrust seen here is an out-of-sequence, possibly late-stage structure, or the thrust stacking sequence is different in Sleat with the youngest thrust at the structurally highest level (see **Tarskavaig** GCR site report, this chapter). The interleaving of mylonitic Moine rocks and Lewisianoid rocks within the Moine Thrust Sheet may relate to Knoydartian, Grampian (early Ordovician) or Scandian (late Silurian) tectonic and metamorphic events. Certainly, evidence for all these events occurs in the Glenelg–Kintail region a short distance along strike to the north-east.

The sequence of fold structures outlined above (the Ard Thurinish, Port na Long, and late-stage conjugate kink-fold phases) that post-date the mylonites, indicate clearly that the zone of active deformation became increasingly constrained with time, culminating in brecciation adjacent to the fault surface itself. Kinematic interpretation of the Ard Thurinish structures suggests that the eastward direction of net slip in this deformation zone was oblique to the general ESE dip of the Moine Thrust surface. Cheeney and Matthews (1965) showed that the Ard Thurinish and Port na Long fold phases and lineations were later than the fold phases developed more widely in the Skye–Glenelg region. In the rocks of the Caradal Nappe, a similar convergence of zones of deformation towards the Moine Thrust is seen. However, the distinctive biotite and garnet porphyroblasts in these rocks suggests prograde metamorphism, in contrast to the rocks in the Moine Thrust Sheet that show retrograde metamorphism.

Conclusions

The Ard Thurinish–Port na Long GCR site contains the southernmost exposure of the Moine Thrust. It separates dominantly Lewisianoid rocks of the Moine Thrust Sheet above, from the thrust and folded Tarskavaig Group metasedimentary rocks of the Caradal Nappe below.

The overlying Lewisianoid gneisses, together with some Moine rocks, are strongly mylonitic, and have been pervasively retrograded to greenschist metamorphic facies. The Tarskavaig Group rocks are mainly psammites and semipelites that show increased deformation as the thrust is approached. Localized deformation post-dates the mylonitization and three discrete phases of minor folding have been recognized. The first two phases, named the 'Ard Thurinish' and 'Port na Long' phases, result in close to tight and isoclinal folds with related cleavages and axial lineations. The last phase results in a more-brittle style of chevron folding.

The national importance of this GCR site stems from its location at the southern end of the outcrop of the Moine Thrust Belt. The site also provides evidence of periodic movement on the Moine Thrust itself. The marked differences between the structural and metamorphic features seen here and farther north provide a clear demonstration of the along-strike complexity and variability of the thrust belt.