Foinaven

[NC 383 527]–[NC 327 460]

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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 5.16)a. 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 (Figure 5.16), (Figure 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.* (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 ultracataclasites 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 northwest 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 Arlde. Reconnaissance work there suggests that these imbricate slices also involve the False-bedded Quartzite Member together with Pipe Rock.

Relationships between thrusts at Creag Shombairle [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 'piggyback' 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 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 unnamed 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 foot-wall. 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.

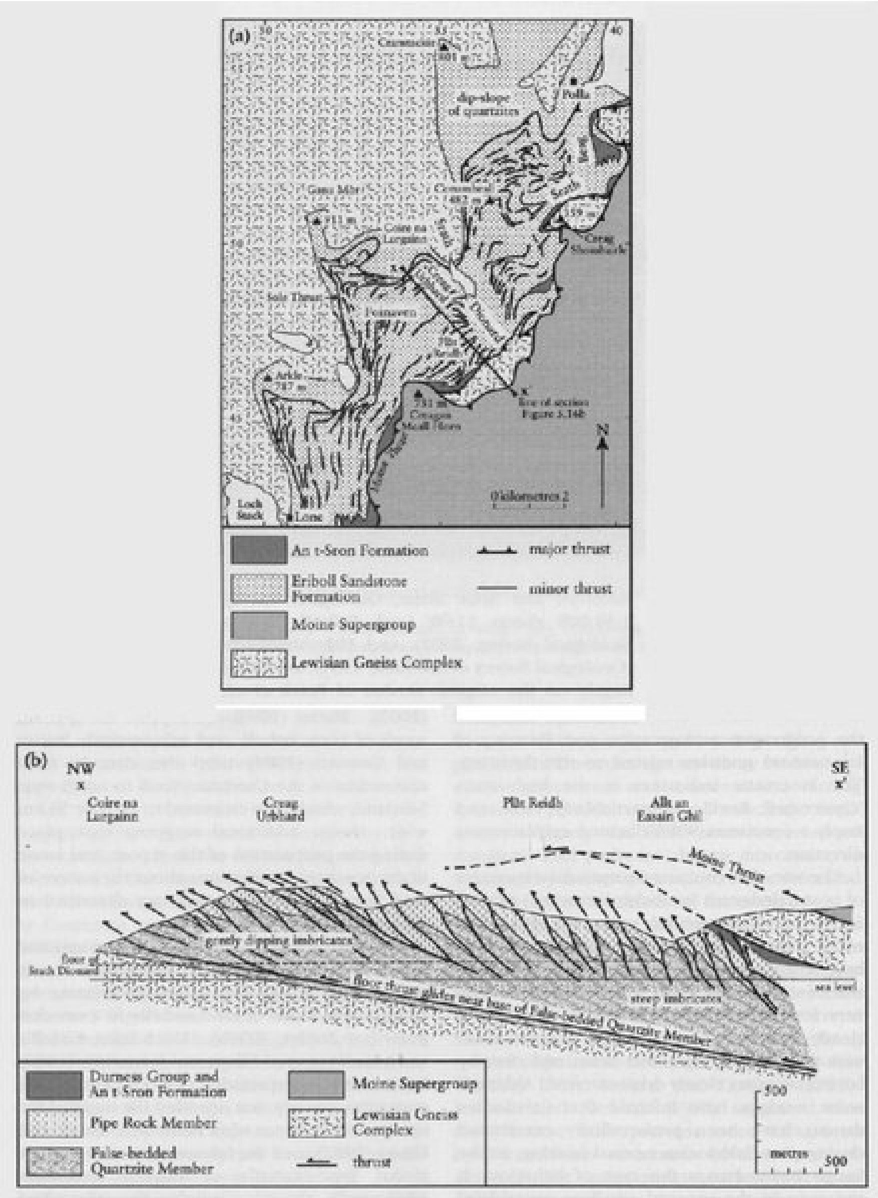
Conclusions

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 dearly 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.

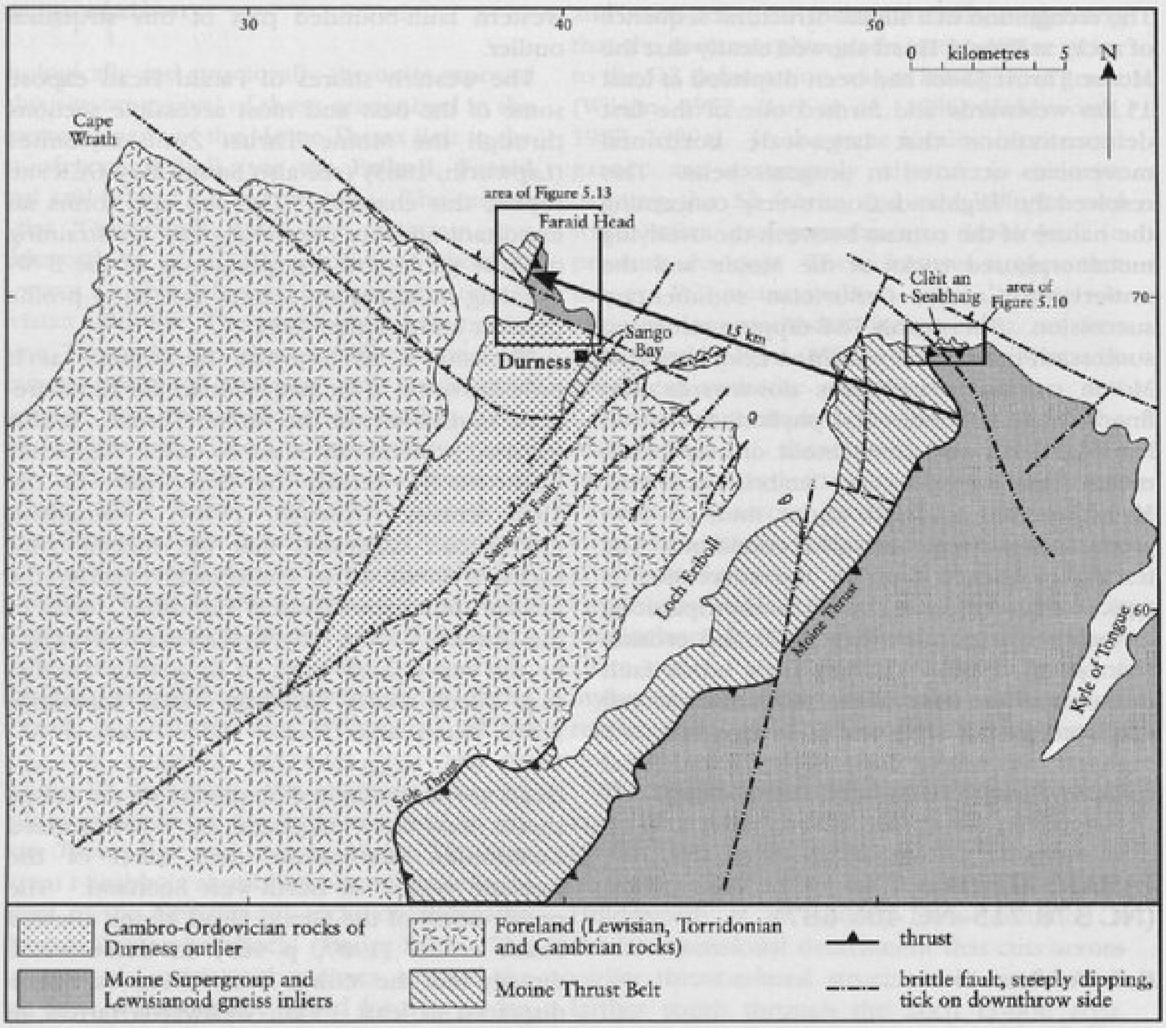
The area is superb for tracking the detailed lateral variation in imbricate structures and for examining the transition in fault-rock type across a broad swathe of the Moine Thrust Belt. Yet it remains to be established how far the late motions at the base of the Moine Thrust Sheet can be traced. The 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.

[References](#)

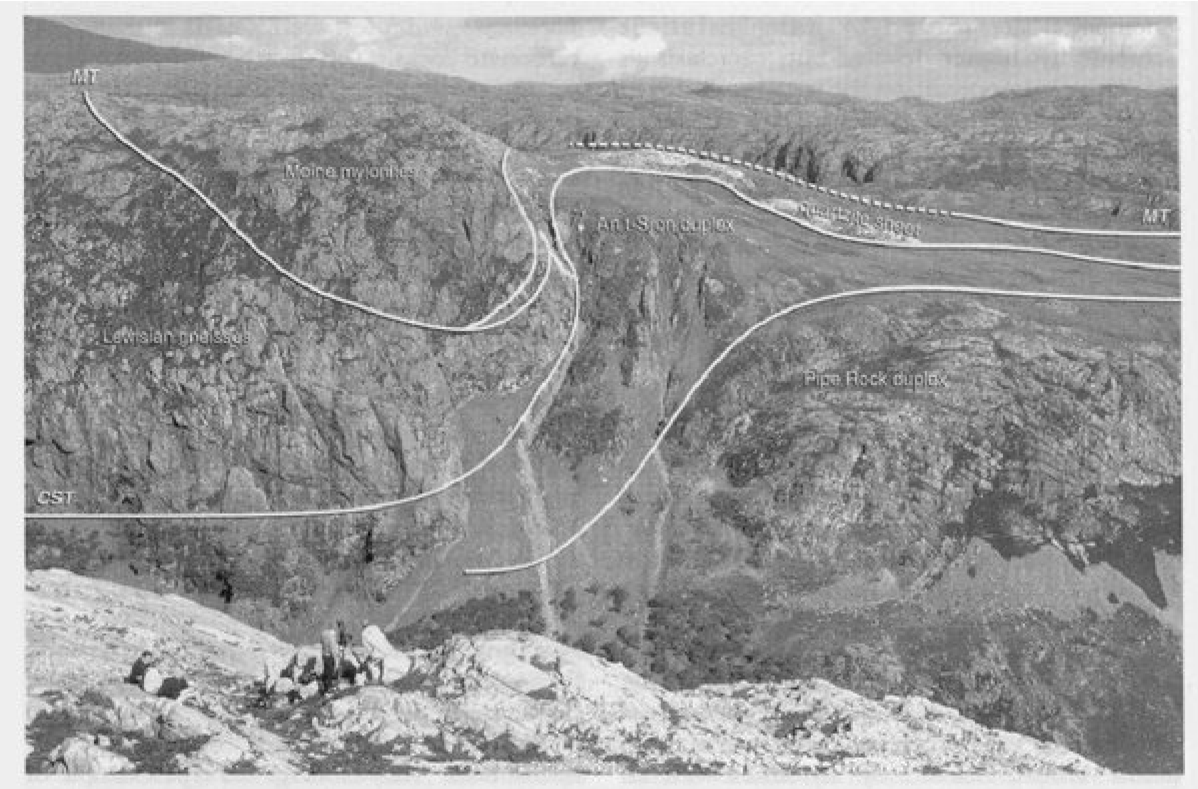


(Figure 5.16) (a) Map of the Foinaven Arkle area. (b) Cross-section through Foinaven; position of section (x—x') is indicated on (a). After Butler (2004a).

(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.)



(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.*



(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.)