Eriboll

[NC 485 622]–[NC 380 501]

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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 reassessed 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 'piggyback' 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 5.7)a 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, 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 5.7)b. 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 viewpoint for the Heilam imbricate zones to the north (see below). The hangingwall of the Arnaboll Thrust is marked by 2–3m 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 y 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 5.7)b. 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 5.7)c. 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 5.7)c, 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 overprinted 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).

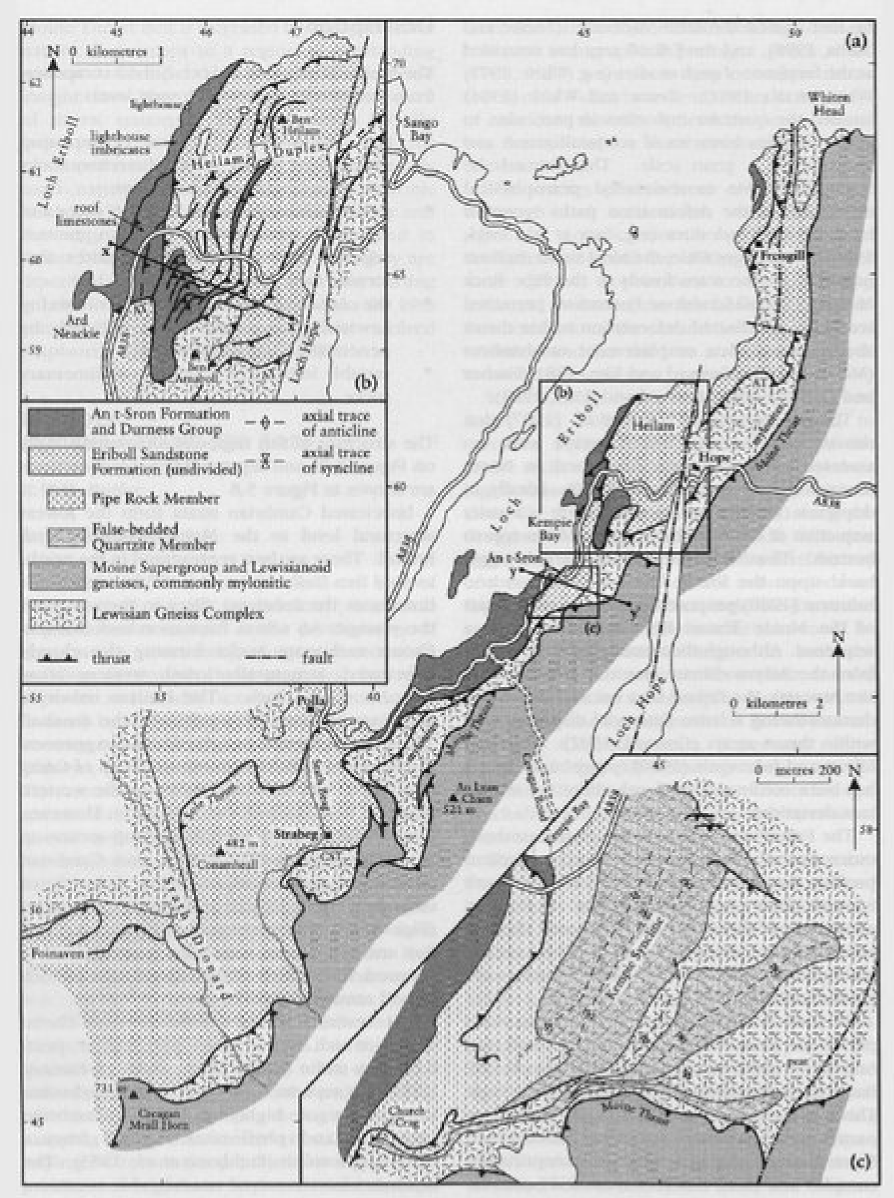
The location of the Moine Thrust within the mylonites at Eriboll has long been a source of controversy (see review in Law *et al.,* 1984). Part of the confusion seems to arise from the notion that a single mappable surface must exist that carries a distinct sheet of Moine and Lewisian rocks across a 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 foot-wall. 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

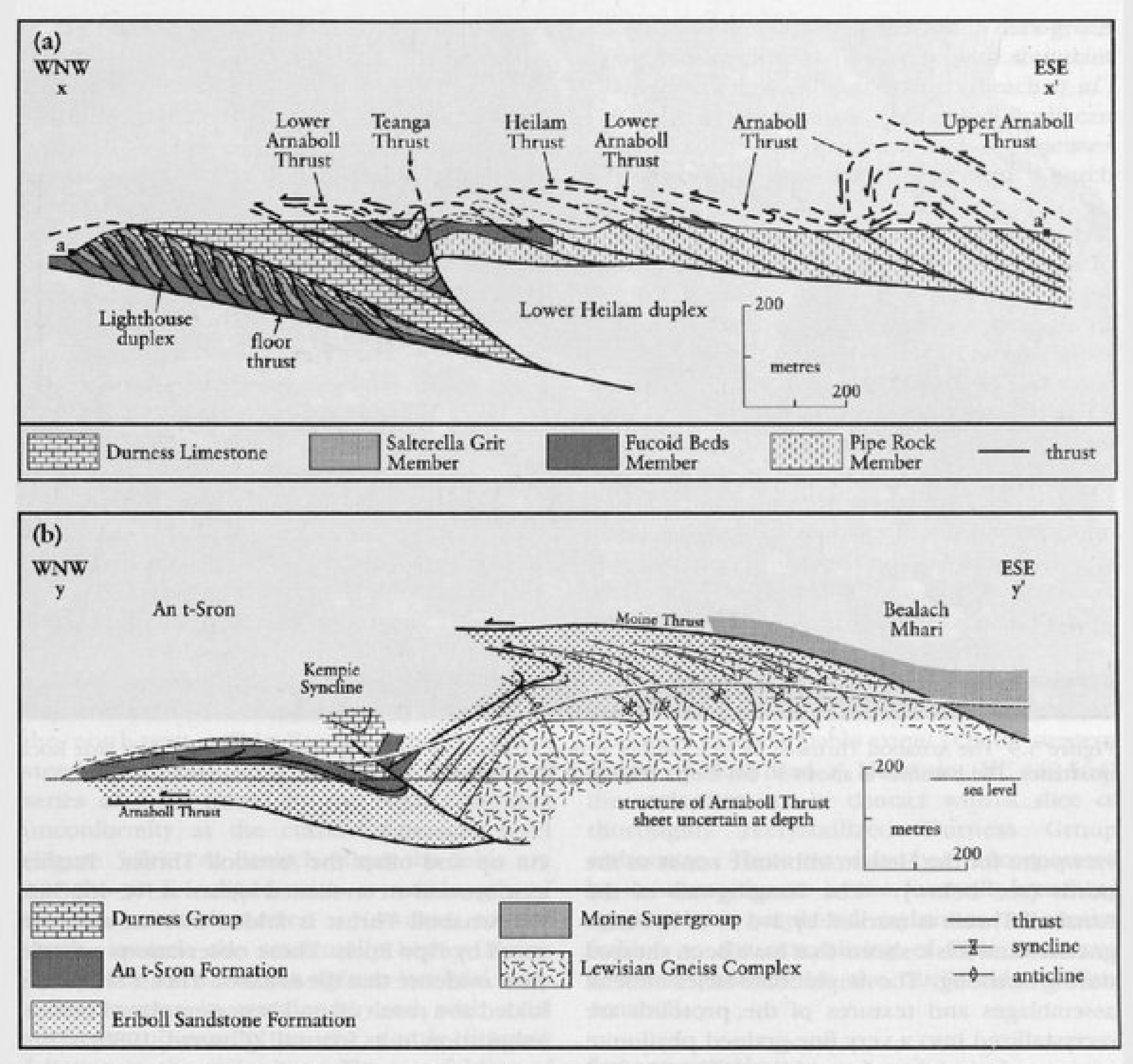
The Eriboll region has become one of the most important international localities for the development of structural geology and for the understanding of continental compressional tectonics. The readily accessible and compact outcrop areas of the GCR site provide excellent near-three-dimensional exposures 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.

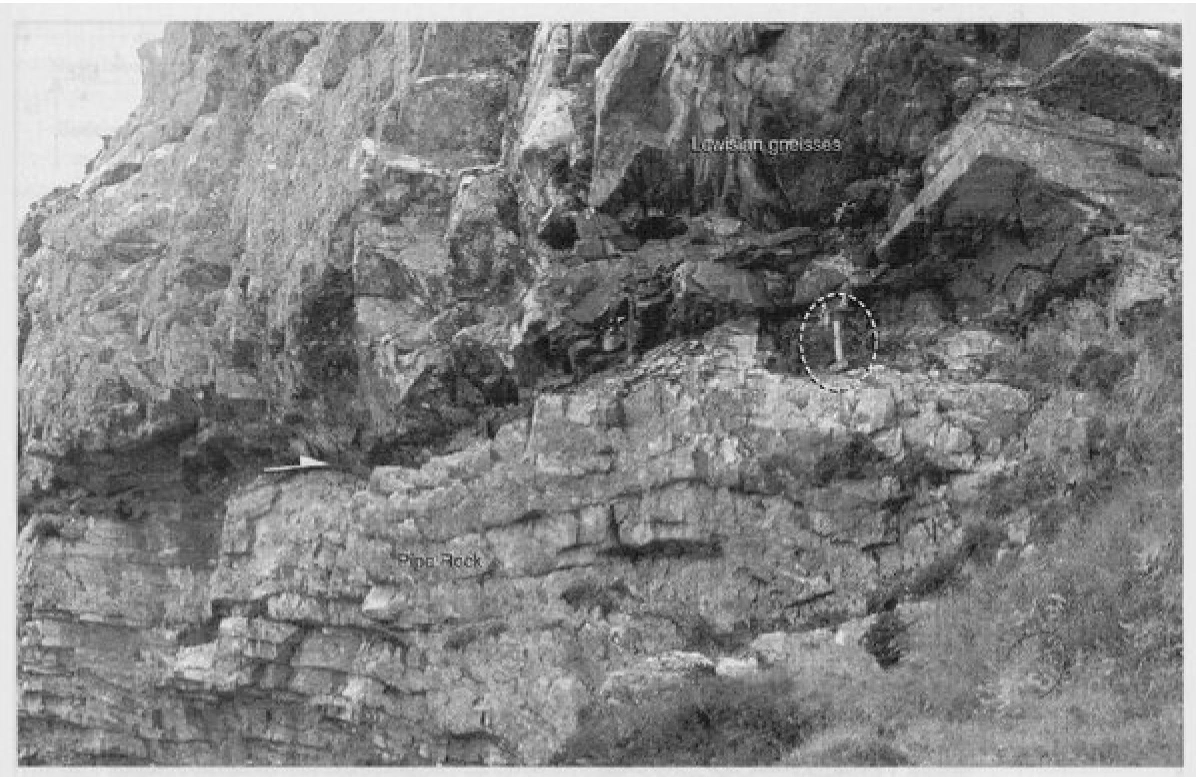
References



(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).



(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.)