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The nature of 'roof thrusts' in the Moine Thrust Belt, NW Scotland: implications for the structural evolution of thrust belts

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Abstract: Buried thrust systems, commonly analysed in terms of duplex structures, are often interpreted as forming in a particular sequence. This model considers that only one thrust is active at a time and the resulting structural geometry is well ordered. However, a reappraisal of structural geometries from the Moine Thrust Belt in NW Scotland has shown that many apparent duplex structures are more complex. Although the upper (roof) thrust of some duplexes may be folded and bulged by underlying imbricate slices (in accordance with simple duplex models), the footwall to these roof thrusts cut up and down stratigraphic section (in conflict with the simple duplex models). Examples include the Glencoul Thrust with its underlying imbricate system, and the Foinaven 'duplex'. Simultaneous slip on an array of imbricate thrusts can bulge duplex roofs (relationships classically used to infer piggy-back sequences of thrust 'propagation'). However, activity on more hinterland-ward imbricate thrusts can cause the roof onto which they branch to truncate more foreland-ward structures. In this fashion, the 'duplex roof' can cut up and down stratigraphic section, mimicking an extensional fault. By varying thrust activity in three dimensions within an imbricate system, local parts of 'roof thrusts' can generate domains of overstep behaviour that have only local significance. Existing interpretations of overstep relationships in the Moine Thrust Belt as representing late-orogenic low-angle extensional faults may need revision. The new interpretations of deformation activity, where displacements in thrust arrays happen synchronously rather than sequentially, are consistent with emergent thrust and fold belts, with analogue experiments and with mechanical models of orogenic wedges.

Keywords: thrust faults, duplexes, Moine Thrust Belt.

In thrust belts that commonly characterize the outer edges of orogens, it is well established that the relative timing of structures can be determined on geometric grounds. Thrust systems are commonly described as forming step-wise, with each thrust forming progressively later towards the foreland (a 'foreland-propagating' or 'piggy-back' sequence). Less commonly, thrusts are interpreted as forming in a less ordered, so-called 'out-of-sequence' way (e.g. McClay 1992, and references therein). A spectrum of geometic criteria has been developed for assessing these sequences (e.g. Butler 1987; Morley 1988). The most commonly used starting point for understanding thrust array evolution is the duplex model of Boyer & Elliott (1982). These structures consist of low-angle bounding roof (upper) and floor (lower) thrusts linked by steeper imbricate thrusts that delineate fault-bounded slices. Provided the strata were horizontal and layer-cake prior to thrusting, each imbricate thrust cuts up-section in its transport direction. The 'older-on-younger' stratigraphic relationships are preserved so that the overall stratigraphic architecture within the duplex is systematic and predictable. Higher thrusts are folded by those below (Fig. 1a). However, this simple model has failed to account for all structural geometries in thrust belts. In some cases, 'overstep' relationships have been recognized where high-levels thrusts have less geometric complexity than the underlying ones and they truncate strata in their footwall (Fig. 1b). Nevertheless, even these types of geometry are considered to form in a sequential fashion, with only one thrust active at a time. Boyer (1992) seriously questioned this view, using examples from the Canadian Rockies, and argued that thrust splays may have operated simultaneously, but his examples did not include roof-type thrust structures.

The view of sequential thrusting that generally arises from studies of finite structural geometries is in marked contrast to those provided by emergent thrust systems that preserve growth strata (Fig. 1a). Synorogenic sediments can record the timing and duration of deformation around thrust structures. The approach has been widely used in young systems such as the NW Himalayas (e.g. Burbank 1983; Burbank *et al*. 1996), Pyrenees (e.g. Vergés & Muñoz 1990; Meigs 1997), Moroccan Rif (Morley 1992) and Sicily (Butler & Lickorish 1997). These studies all show that individual structures can be active over protracted periods and that thrusts within arrays can develop synchronously. These results are in accord with some analogue experiments (e.g. Cadell, 1888; Dixon & Liu 1992), which show that, although thrusts might step forward through a model, they remain active in parallel for much of the deformation history. Some mechanical models of thrust systems also predict that thrusts within orogenic wedges have been active together (e.g. Platt 1988).

The paradox between supposedly sequential structural evolutions in once-buried thrust systems and the more variable development of emergent structures forms the theme of this paper. Here structural geometries in selected parts of the northern Moine Thrust Belt of NW Scotland (Fig. 2a) are reassessed for their implications for the relative timing of structures. This thrust belt has been a testing ground for models of thrust array development (e.g. Elliott & Johnson 1980; Butler 1987); indeed, the type example of duplex structures is from this system (Boyer & Elliott 1982). The question arises as to how well do existing models of sequential, chiefly 'piggy-back', thrusting explain the structural evolution in the thrust belt.

Structural evolution in the Moine Thrust Belt: previous work

The Moine Thrust Belt (Fig. 2a) forms the NW margin of the Caledonian (430–400 Ma) orogenic belt on mainland Scotland

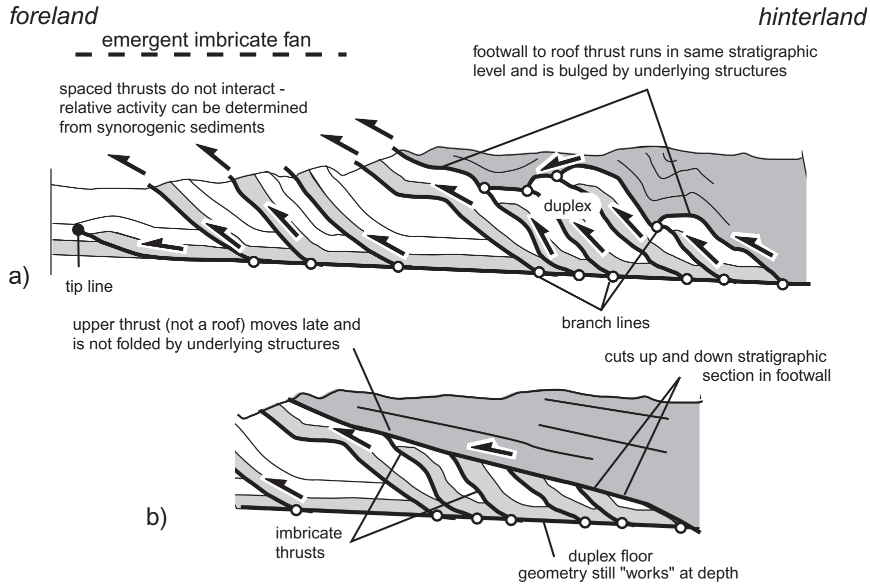

Fig. 1. Models for the geometry of thrust systems developed by different patterns of thrust activity. (**a**) Emergent and buried parts of a thrust belt formed largely by foreland-propagation. It should be noted that, as the individual thrusts are spaced and do not interact geometrically, synorogenic sediments are needed to establish the timing of thrust activity within the imbricate fan. Most modern systems show synchronous thrust activity in this part of orogens (see text for discussion). In the buried part, foreland-directed thrusting generates duplex geometries with folded roof thrusts and roof footwalls gliding in the same stratigraphic unit (or gently climbing section. (**b**) Overstep geometries are indicative of thrust activity stepping back into the orogen. They are recognized by the stratal relationships in the footwall to large-displacement, low-angle thrusts.

(e.g. Coward 1983). The orogenic 'foreland' comprises the Lewisian basement (of mid-early Proterozoic to Archaean age), the Torridon Group (late Proterozoic in age but not found in the examples presented here) and a cover of Cambro-Ordovician sediments. The Moine Thrust carries the Moine metasediments (of late Proterozoic age), their Lewisianoid basement and mylonites derived from these protoliths. The thrust is generally considered to have moved for over 100 km towards the WNW (e.g. Elliott & Johnson 1980; Coward 1988). It caps the underying Moine Thrust Belt, a tract of variably thrust and folded slices of the 'foreland' units. Fortunately, the highly differentiated and layer-cake nature of the Cambro-Ordovician sediments that existed prior to thrusting greatly facilitates structural studies. Here the stratigraphic terminology of current geological maps (e.g.British Geological Survey 2002) is used throughout (summarized in Fig. 2b).

The Moine Thrust Belt contains several major low-angle thrusts together with numerous steeper imbricate thrusts, generally developed in the Cambrian strata, that have much smaller displacements. Peach *et al*. (1907) discussed the relationship of the various major thrusts to each other and to adjacent imbricate thrust systems. Although they recognized that in some locations (e.g. Dundonnel, Fig. 2a) the Moine and other higher-level thrusts are folded above underlying structures, Peach *et al*. concluded that the general sequence of thrusting was that the structurally higher thrusts moved after, and truncated, the imbricates in their footwalls. This view held sway through later investigations where the Moine Thrust came to be defined as a continuous, late, brittle fault that truncated mylonites in its hanging wall and a range of folds and imbricate structures in its footwall (e.g. Soper & Wilkinson 1975). This type of geometric relationship has been termed 'overstep' (Elliott & Johnson 1980).

The overstep model was seriously questioned by Elliott & Johnson (1980), who reappraised many of the geometries of Peach *et al*. (1907) and introduced the duplex model to the northern part of Moine Thrust Belt. For them the relationships at Dundonnel (Fig. 2a) were critical, requiring foreland-propagation of thrusts. They went on to reinterpret the cross-sections of Peach *et al*. (1907) to show that particular arrays of steep imbricate thrusts were not truncated by the overlying, low-angle thrust but rather they joined on to it. Independent studies by Coward (1980) and McClay & Coward (1981) suggested that the Arnaboll Thrust in the Loch Eriboll area (Fig. 2a) truncated footwall structures but this was not typical of the thrust array as a whole: the general deformation style was one of foreland-propagation. Coward later reappraised the overstep geometry on the Arnabol Thrust (Coward 1984), using cut-off line maps to demonstrate that even this structure conformed to a foreland-propagation model.

This heralded a renewed programme of mapping in NW Scotland. In the ground south of Loch Eriboll, Butler (1982) showed the Moine Thrust and other high-level structures to be folded by underlying thrust culminations; relationships that demanded strict foreland-propagation of thrusts. However, this and other studies of the time (Butler 1982; Coward 1984) also indicated that, in certain localities, imbricate thrusts breach through overlying, low-angle thrusts. Therefore at certain structural levels the sequence of thrusting can be reversed and local overstep geometries produced.

The dogma of simple foreland-propagation, albeit with local breaching geometries, did not explain all fault geometries in the Moine Thrust Belt. Coward (1985) confirmed the interpretation by Peach *et al*. (1907) (see Elliott & Johnson 1980), in southern Assynt (Fig. 2a), showing that the Moine Thrust truncates and oversteps imbricate thrusts in its footwall. There is therefore no single model for thrust sequences that satisfies all parts of the Moine Thrust Belt.

The structural relationships used to define geometric criteria for determining local sequences in thrust arrays (Butler 1987) may be summarized. If a low-angle upper thrust is bulged up over culminations in underlying imbricates it is conventionally interpreted as forming a roof thrust and the overall thrusting sequence was foreland-propagating (Elliott & Johnson 1980). The expectation is that the roof thrust should glide in the same stratigraphic horizon or climb gradually in its transport direction (e.g. Coward 1985). In contrast, if the upper thrust is not bulged over culminations in the underlying imbricates it is inferred to have moved later and truncated them (overstep). Strictly, such low-angle structures should not be termed 'roof' thrusts (Boyer & Elliott 1982; Butler 1987). The expectation here is that the

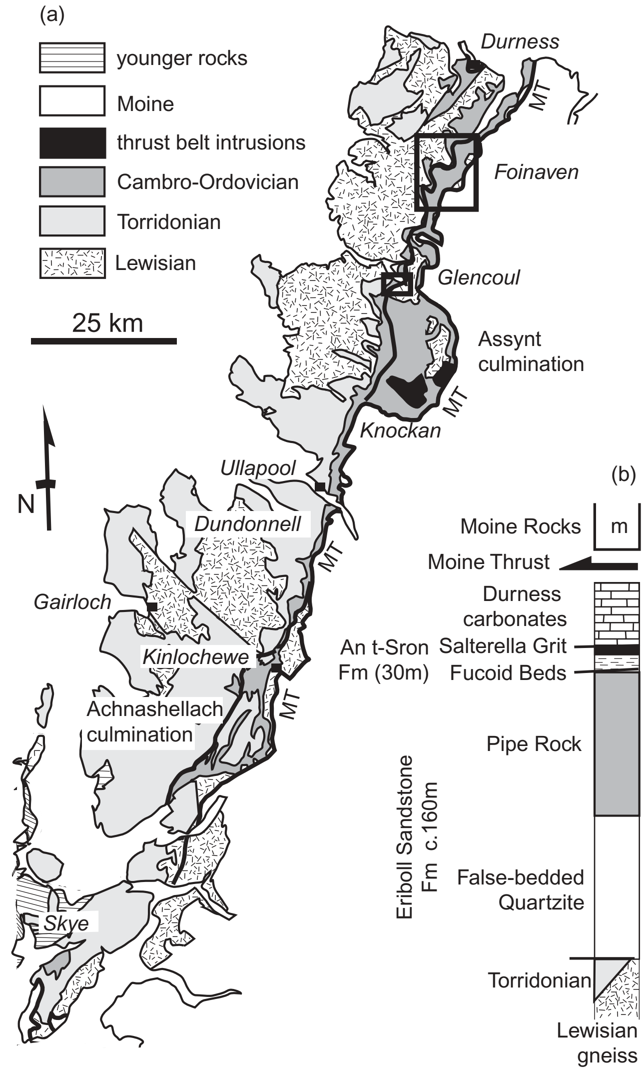

Fig. 2. (**a**) The Moine Thrust Belt. Localities mentioned in the text are labelled. (**b**) Stratigraphy of rocks involved in the Moine Thrust Belt (terminology follows that of theBritish Geological Survey 2002).

overstepping low-angle thrust cuts up and down stratigraphic section as it has sliced through the previously stacked strata beneath.

The above discussion illustrates that, in many respects, the debate on the relative development of thrusts within the Moine Thrust Belt is as unresolved as it was at the start of the twentieth century (Peach *et al*. 1907). Part of the problem lies in making comparisons between different parts of the thrust belt without also trying to trace the structural interpretations into adjacent areas with different structural geometries. In general terms, for a kinematic model to be valid, structures must be compatible with their neighbours. Further, models of thrust array evolution should satisfy all aspects of the structural geometry, not merely conform to a few well-chosen criteria. The opportunity to reappraise key parts of the thrust belt arose during remapping of selected parts of the thrust belt by the author as part of the Geological Conservation Review (Campbell *et al*. 1996). These sites are now discussed in turn. The numbers used in the text in square brackets are Ordnance Survey national grid references.

The Glencoul Thrust and underlying structures

The Glencoul Thrust is one of the major structures in the Moine Thrust Belt and it dominates the northern part of the Assynt half-window (Fig. 2). Its type area at Loch Glencoul is historically important as one of the sites where low-angle thrusts were first recognized (Callaway 1883). The area was mapped by Clough in 1883–1884 (Peach *et al*. 1888) and this pioneering work underpinned all future studies up to and including the reinterpretations of Elliott & Johnson (1980), a century later. These and subsequent studies show that the Glencoul Thrust carries a sheet of Lewisian basement with its cover of Cambrian sediments (the Glencoul Thrust Sheet). The correlation of Precambrian structures between the thrust sheet and the adjacent foreland has been used to estimate the offset on the Glencoul Thrust as 25–33 km (Coward *et al*. 1980; Elliott & Johnson 1980). This displacement has been achieved with virtually no internal deformation within the Lewisian rocks of the thrust sheet, save a few spaced fractures, now marked by epidote–chlorite seams (Wibberley 1997).

On the Aird da Loch peninsula (Fig. 3) the Cambrian strata in the footwall to the Glencoul Thrust are not involved in thrusting and therefore represent the foreland. However, on the down-dip, deeper levels exposed on the flanks of the peninsula (NE shore of Loch Glencoul), the sediments are imbricated [NC271306 to NC267311]. There are many repetitions of steeply dipping Fucoid Beds and Salterella Grit. These lie on a thrust slice of Pipe Rock [NC267310]. The overlying Glencoul Thrust is gently folded and, as described by Elliott & Johnson (1980), these broad

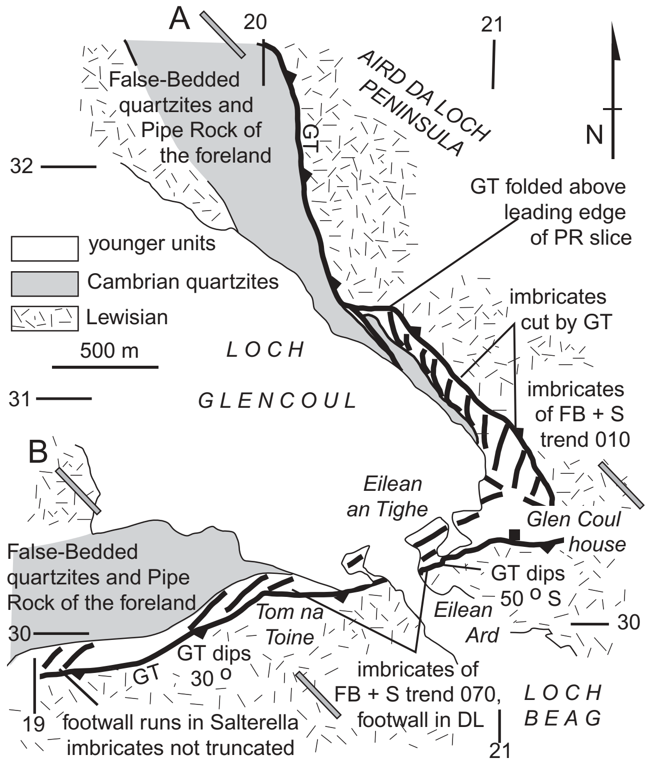

Fig. 3. Map showing the distribution of key structural relationships at the head of Loch Glencoul (location shown in Fig. 2a). GT, Glencoul Thrust; PR, Pipe Rock; FB, Fucoid Beds; S, Salterella Grit; DL, Durness carbonates. A and B are section lines of Fig. 4a and b, respectively.

folds are cored by culminations in the imbricated Cambrian strata. This geometry was taken to be diagnostic of a foreland-directed sequence of thrusting where the Glencoul sheet was emplaced first and imbrication of its footwall happened later.

The deepest exposed level of the Glencoul Thrust lies at the head of Loch Glencoul, where it is exposed on a series of small islands (Fig. 3). On Eilean Ard [NC267303] the thrust surface dips at 50°, subparallel to bedding in the underlying Durness carbonates. These carbonates are only a few metres thick and lie on top of a steeply dipping package of An t-Sron rocks, marked by alternations of Fucoid Beds and Salterella Grit. Stratigraphic way-up indicators are generally consistent (younging SE), indicating that the stratigraphic repetition within the An t-Sron Formation is caused by imbrication. The imbricates form a tract some 300 m across (between Eilean Ard to Eilean an Tighe; Fig. 3), although the stratigraphic thickness involved is only some 30 m. The dips decrease down structural section, as seen on the southern coast of Loch Glencoul (Tom na Toine, Fig. 3) until they become conformable with the underlying Cambrian quartzites of the foreland (Fig. 4).

The general form of bedding and imbricates in the footwall to the Glencoul Thrust is essentially as envisaged by the duplex model of Boyer & Elliott (1982). The geometry (Fig. 4) shows back-steepening by underlying imbricates yet preserves the ‘footwall flat’ architecture (beds in the Durness carbonate beneath the thrust lying parallel to the thrust itself), as predicted for simple duplexes. Furthermore, the thrust is tilted to be foreland-dipping above the leading edge of the Pipe Rock slice in its footwall (Fig. 4) along the NE shore of the loch. Therefore, using these criteria, the development of thrust structures at Glencoul appears to conform with the foreland-propagating model.

This picture becomes compromised when the relationship between the Glencoul Thrust and strata in its footwall is considered. The duplex model (Boyer & Elliott 1982) predicts that the footwall to the roof should cut up-section or glide on a constant stratigraphic horizon. At Glencoul, however, this is not the case. At Eilean Ard and on the mainland at Tom na Toine [NC260302] (Fig. 4) the Glencoul Thrust lies on 2–3 m of Durness carbonates. However, to the west of Tom na Toine the thrust runs along the Salterella Grit. It cuts down stratigraphic section in its transport direction (Fig. 4). There are local thin (<1 m) strips of strongly sheared and fractured Durness carbonates at a few sites along the thrust. On the NE side of Loch Glencoul, the Glencoul Thrust cuts across repeatedly from Salterella Grit to Fucoid Beds (Fig. 4). These behaviours are characteristic of overstep thrust geometries and indicate that the Glencoul Thrust has moved after the Cambrian strata in its footwall were stacked on imbricate thrusts. These imbricates have been decapitated (Fig. 4).

The structural relationships at Glencoul therefore present a conundrum. Not only is the Glencoul Thrust bulged up by the imbricates in its footwall, but it also truncates them. This suggests that at least some displacement on the Glencoul Thrust post-dates some of the imbrication beneath it; yet part of the thickening (by imbrication) of the footwall of the Glencoul Thrust post-dates movement on this thrust. This is not a unique problem for the Moine Thrust Belt.

The Foinaven ‘duplex’

The Moine Thrust Belt at Foinaven (Figs 5 and 6) was first mapped by H. M. Cadell in 1883–1884 (reported by Peach *et al*. 1888), becoming the inspiration for early analogue experiments of thrust development (Cadell, 1888). This pioneering work, after compilation byPeach *et al*. (1891, 1907), was eventually reinterpreted byElliott & Johnson (1980; Fig. 7a) and then used to build the type description of duplex structure by Boyer & Elliott (1982). All these studies show essentially the same structural interpretation. On the transect across Foinaven, some 5 km across and over 800 m thick, the geology is represented by imbricated Cambrian quartzites of the Eriboll Sandstone Formation with an undeformed stratigraphic thickness of *c*. 160 nm. The imbricate thrusts are spectacularly exposed on cliff sections above Strath Dionard (Fig. 6; Elliott & Johnson 1980). They cut up-section in the thrusting direction from the

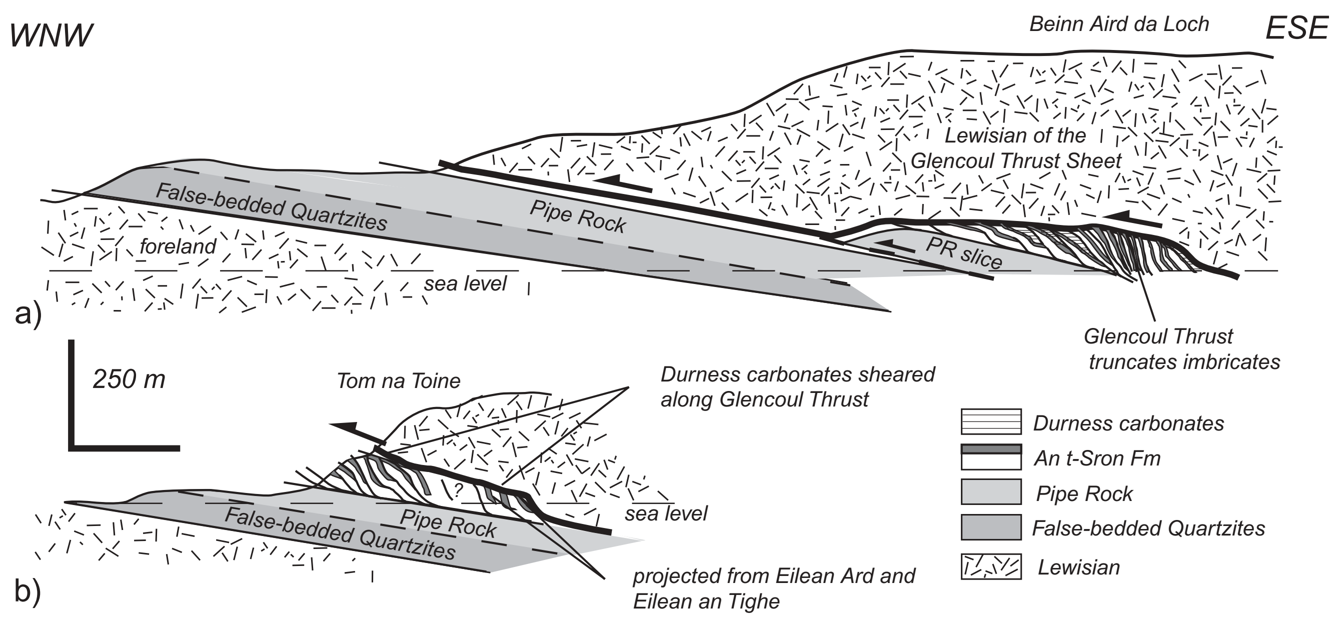

Fig. 4. Cross-sections through the Loch Glencoul area (locations, A and B respectively, in Fig. 3): (**a**) is based on structural relationships on the NE side of the fjord; (**b**) interprets the field relationships on the SW side of the fjord, including the type locality for the Glencoul Thrust on Tom na Toine.

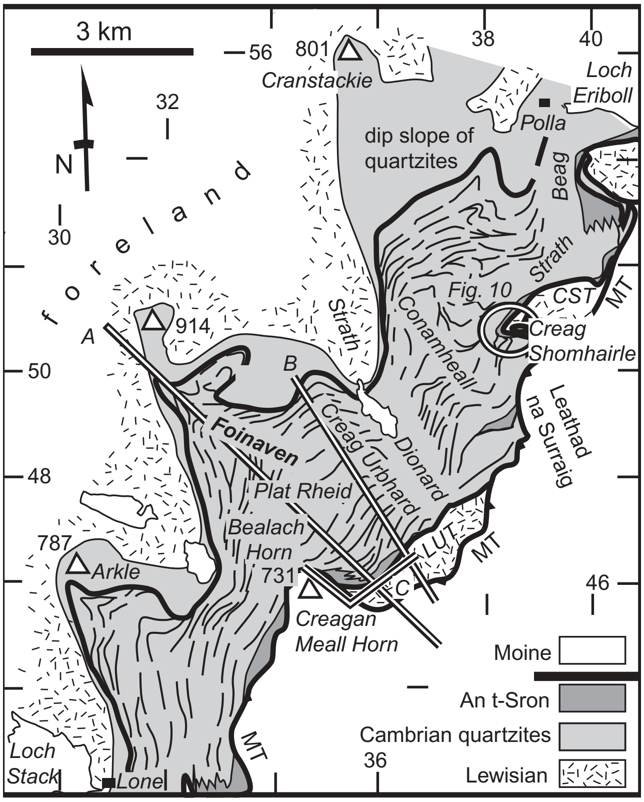

Fig. 5. Sketch geological map of the thrust systems in the Foinaven 'duplex' (location shown in Fig. 2a). CST, Creag Shomhairle Thrust; LUT, Lochan Ulbha Thrust.

lower part of the Cambrian quartzites into mid-Cambrian An t-Sron Formation rocks (Fig. 5). For Elliott & Johnson (1980), the duplex floor thrust runs in the Pipe Rock, leaving the underlying older strata and Lewisian basement undeformed below (Fig. 7a). The roof thrust is considered to be uniformly inclined and to glide on a footwall a few metres into the Durness carbonates.

Remapping in Strath Dionard (Fig. 5) shows that the False-Bedded Quartzite that stratigraphically underlies the Pipe Rock is involved in the imbricate structure of Foinaven (Fig. 6; seeBritish Geological Survey 2002). On Creag Urbhard over 19 separate stratigraphic repetitions can be found. Up dip these pass onto the plateau of Plat Rheid where the Pipe Rock is repeated. In this area it is difficult to detect individual repetitions on stratigraphic grounds, although Cadell was able to recognize repeated bioturbation styles in the Pipe Rock. Locally, however, the thrusts involve the Fucoid Beds and Salterella Grit. Collectively, these relationships indicate that the floor thrust must glide within the lower part of the Cambrian quartzites and involve more stratigraphy than interpreted by Elliott & Johnson (1980). Further, the scale of stratigraphic repetitions requires far more imbricate thrusts than proposed by Peach *et al*. (1888, 1907) and Elliott & Johnson (1980). The revised geometry is shown in Figure 7b. A critical difference from the Butler (1987); Fig. 7a) section is that the full imbricate stack of Foinaven is significantly thicker, implying that, if the system behaved as a duplex, the roof (Moine Thrust) should have been extensively bulged up.

The eastern part of the Foinaven duplex, exposed around the western slopes of the hill Creagan Meall Horn (Fig. 5), contains thin slices of Durness carbonate. Consequently, Elliott & Johnson (1980) suggested that the roof to the Foinaven duplex (i.e. the Moine Thrust) glided on a footwall of Durness carbonates. The Moine Thrust should everywhere in this part of the thrust belt have carbonates in its footwall if the ideal duplex model of Boyer & Elliott (1982) is appropriate for this structure. To examine geometries along the Moine Thrust the author remapped the eastern part of the Foinaven area. These new observations are here integrated with previous work in adjacent ground (Butler 1982). Two key sites are now discussed in turn.

Creagan Meall Horn

The critical ground for examining the relationship between the Moine Thrust and its footwall lies on the northern slopes of the hill, Creagan Meall Horn (Fig. 5). Field relationships are shown in Figure 7. Many of the features reported here were also recognized by Cadell (as recorded in his field notebooks, archived at the British Geological Survey).

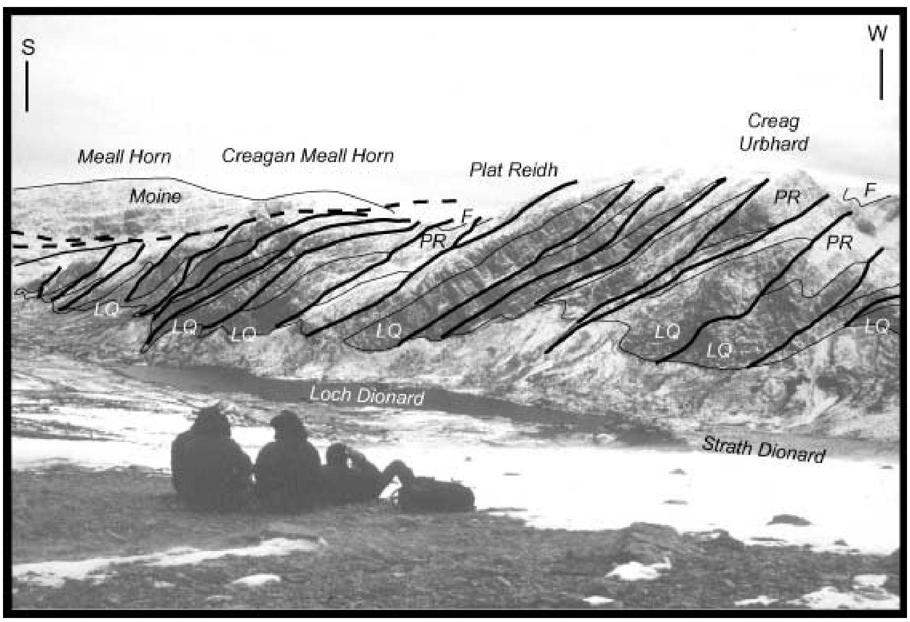

Fig. 6. Thrust geometries and the repetition of Cambrian quartzite stratigraphy seen on Creag Urbhard, SW side of Strath Dionard. Photograph taken from Conamheall (locations shown in Fig. 5). Loch Doinard (elevation *c*. 100 m above sea level) is about 1300 m long. The top of Creag Urbhard lies about 500 m above the loch. LQ, False-bedded Quartzites; PR, Pipe Rock; F, Fucoid Beds.

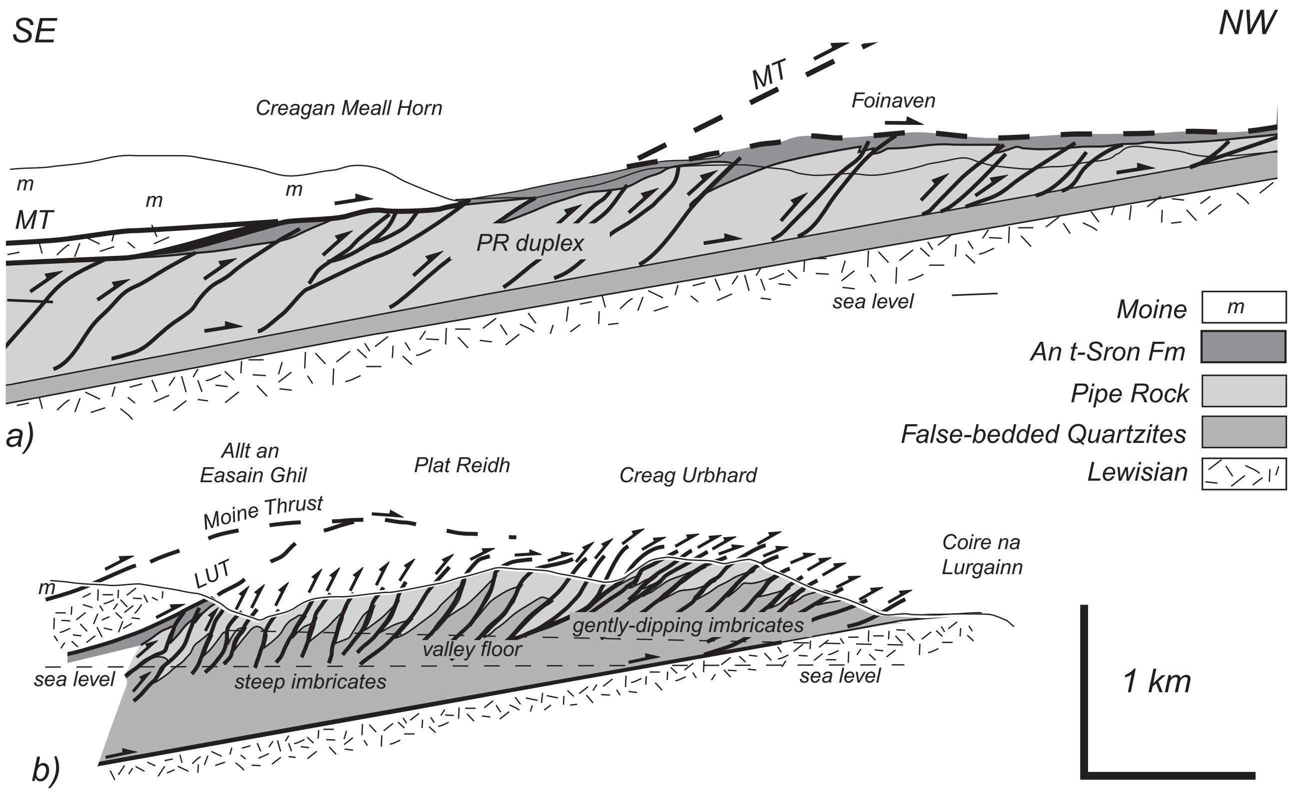

Fig. 7. (**a**) TheElliott & Johnson (1980; see also Boyer & Elliott 1982) interpretation of thrust structures in the Foinaven duplex (section line shown, A in Fig. 5). It should be noted that this section shows the floor thrust running at the base of the Pipe Rock, as the source maps (e.g.Peach *et al*. 1891) wrongly show that only Pipe Rock crops out on Creag Urbhard. (**b**) Cross-section through the Foinaven 'duplex' based on mapping by the author (section line B as in Fig. 5). This interpretation incorporates the repetitions of False-Bedded Quartzites and Pipe Rock as seen on Creag Urbhard (Fig. 6).

The upper slopes of the Creagan Meall Horn contain at least 300 m of mylonites, in the hanging wall to the Moine Thrust. Stretching lineations within the mylonites, derived from both the Moine and the Lewisian rocks below, trend WNW–ESE (Fig. 8). Shear indicators within these mylonites imply WNW-directed thrusting. Immediately below these mylonites, forming the floor to Coire Lochan Ulbha, lies a sheet of Lewisian basement (pegmatites and intermediate gneisses) that shows very little internal deformation associated with Caledonian thrusting. The thrust carrying this Lewisian sheet (termed here the 'Lochan Ulbha Thrust') is exposed in the broken cliffs between Lochan Ulbha and An Dubh-loch. Below is a package of inter-sliced Cambrian strata, chiefly from the An t-Sron Formation. These imbricates can be traced down into the underlying quartzites that dominate the Foinaven duplex. Similarly, the upper part of the imbricates contains slices of Durness carbonates. In the NE end of the section the Lewisian sheet lies directly on folded and imbricated Pipe Rock [NC364469]. Foliation within the Lewisian-derived mylonites, and presumably the Lochan Ulbha Thrust itself, dips gently ESE. Along the strike of the thrust, 300 SE [NC363466], the footwall is in Fucoid Beds. These units pass down structural level between two slices of Pipe Rock. The footwall to the Lochan Ulbha Thrust continues to climb stratigraphic section along strike, passing through the Salterella Grit [NC362465] and up a few metres into the Durness carbonates [NC361463]. As with the Fucoid Beds–Pipe Rock relationship, all these Cambrian strata in the footwall to the Lochan Ulbha Thrust are imbricated. Therefore in this section the Lochan Ulbha Thrust appears to act as a simple roof thrust to the imbricate stack below. It is gently warped over weak culminations in the underlying imbricates (Fig. 8). These folds attain amplitudes of about 40 m (e.g. at [NC358460]).

Durness carbonates continue to decorate the footwall to the Lochan Ulbha Thrust around the SE wall of Coir' an Dubh-loch, although they vary in thickness from a few metres to a few tens of centimetres. Beneath there are repetitions of Fucoid Beds and Salterella Grit. However, the carbonates do not continue into these imbricates. The implication is that the imbricate thrusts merge upwards onto slip along the base of the limestones. At depth the imbricates detach from the top of the Pipe Rock. However, Pipe Rock also has been carried onto Fucoid Beds. This implies that displacements within the deeper parts of the Foinaven 'duplex' pass into the imbricated higher parts of the Cambrian stratigraphy. These imbricates can be traced around the headwall of Coir' an Dubh-loch, into cliffs that trend parallel to the inferred thrusting direction. Here the rocks above the imbricated Cambrian strata are Moine mylonites. Mylonitic foliation is subparallel to the Moine Thrust. The leading edge of the Lochan Ulbha sheet of Lewisian crops out where the Moine and Lochan Ulbha thrusts merge [NC352457].

Geometries critical for testing the duplex model lie towards the WNW end of the escarpment [NC348460]. Here the Moine Thrust glides on its footwall of *c*. 1 m of Durness carbonates (Fig. 9). The mylonitic foliation in the hanging wall is subparallel to the thrust plane. The thrust itself is subplanar, dipping gently ESE. The carbonates in the footwall are strongly foliated

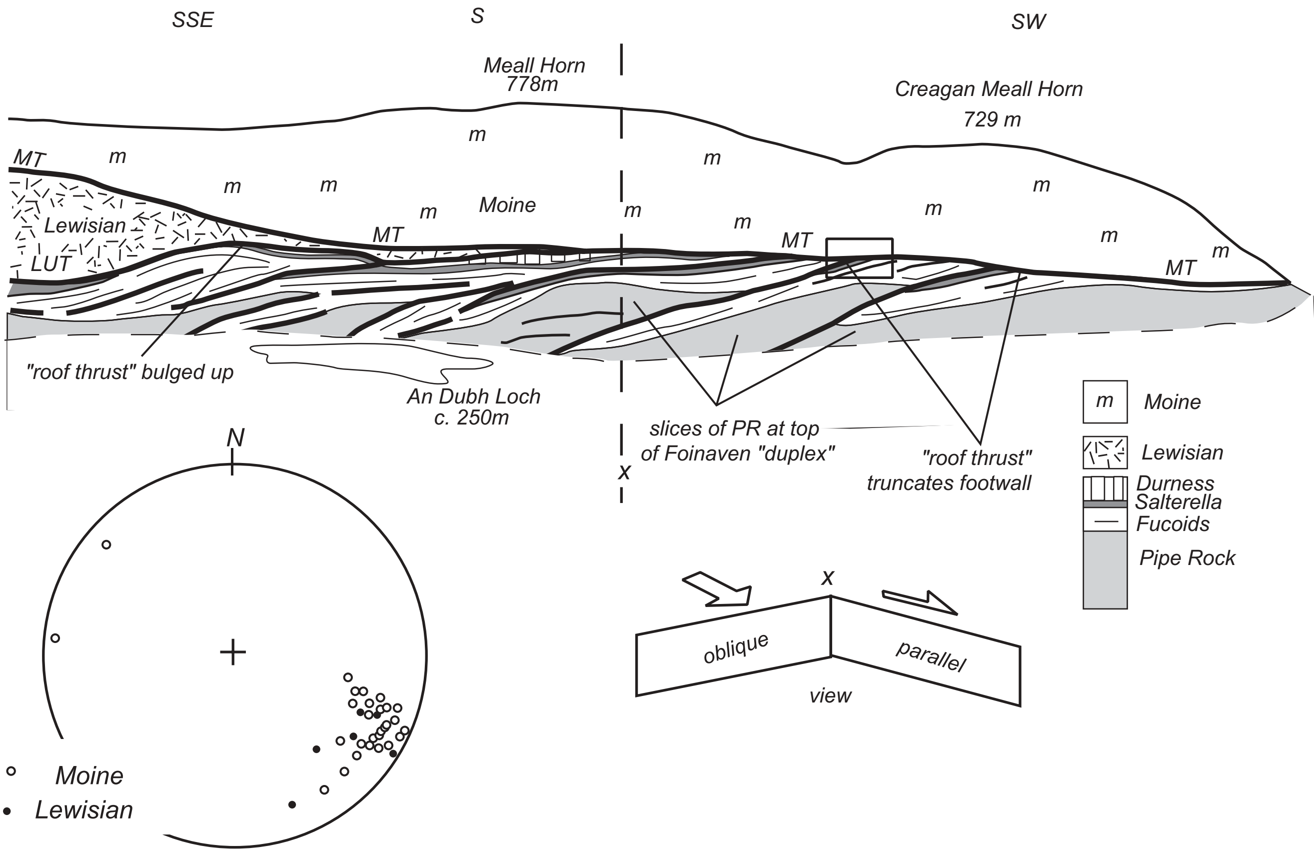

Fig. 8. Structural relationships on the NW flanks of Creagan Meall Horn (location C in Fig. 5). This panorama is based on field sketches made by the author. There is no single scale appropriate to this view. The distance along the ridge between Meall Horn and Creagan Meall Horn is *c*. 1 km and the length of An Dubh Loch is about 300 m. Labelled elevations give the vertical scale. The inset is a lower hemisphere stereoplot of stretching lineations in the Moine and sheared Lewisian units. These data indicate that thrust transport was on a WNW–ESE axis.

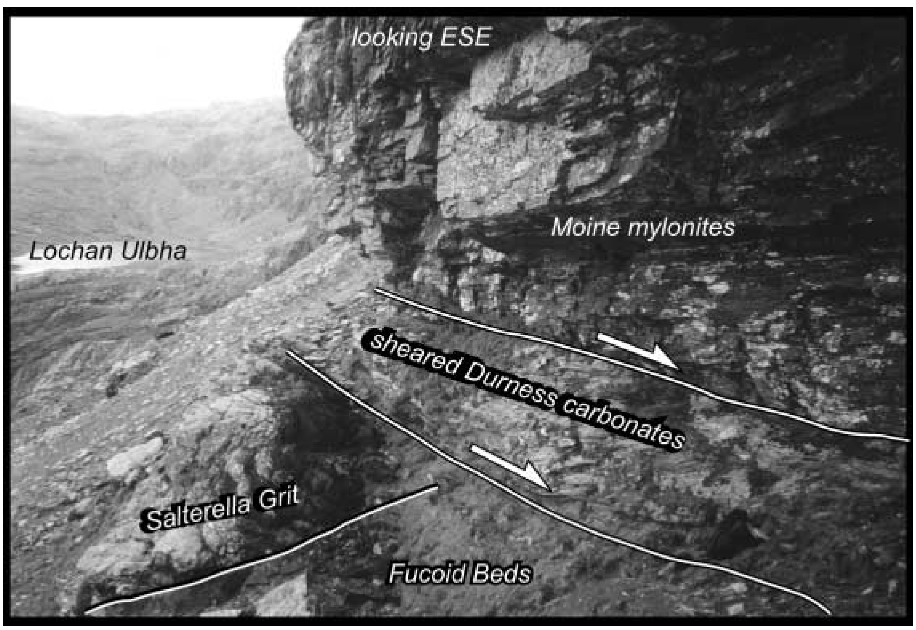

Fig. 9. Photograph of the Moine Thrust and its footwall at Creagan Meall Horn (boxed area in Fig. 8). The shear sense shown on the photograph was determined using shear band structures in both the Moine mylonites and the sheared Durness carbonates. It should be noted that the carbonates are carried down onto the Fucoid Beds with the omission of Salterella Grit.

and sheared parallel to the thrust. Imbricated Salterella and Fucoid Beds below dip 30–40° ESE and abut the carbonates. In places the carbonates lie directly upon tilted Fucoid Beds; a contact that has an apparently extensional offset in that stratigraphy (Salterella Grit) has been omitted. Further to the WNW, around Bealach Horn, Moine mylonites appear to rest directly upon Pipe Rock imbricate slices. These relationships are inconsistent with the duplex model.

The geometry of the Moine Thrust and its relationship to the Lochan Ulbha and imbricate thrusts in its footwall strongly suggests that it has moved late. This displacement was achieved in part by shearing the Durness carbonates along with slip on the thrust plane. In this way the carbonates are smeared across truncated geometries in the composite footwall.

Creag Shomhairle

The structural geometry of thrusts to the north of Foinaven and Creagan Meall Horn has been described by Butler (1982). Outcrops of equivalent structural positions to those around Coir' an Dubh-loch are provided by the 320 m cliffs and summit slopes of Creag Shomhairle (Fig. 10).

The lower slopes of Creag Shomhairle [NC379504] show exposures of imbricated Pipe Rock piled into a spectacular antiformal stack (Butler 1987). This structure is enveloped by a complex tract of imbricated An t-Sron units. These in turn are overlain by a series of structures including the Moine Thrust together with intermediate thrust sheets of Lewisian (the Creag Shomhairle Thrust Sheet of Butler 1982) and Pipe Rock. These upper sheets are bulged up and folded around the culminations created by the deeper imbricated Cambrian strata. The upper thrust sheet of Pipe Rock contains imbricate thrusts that breach into the overlying Moine mylonites. At this outcrop area, therefore, it is the high thrust sheets that were emplaced first, to be deformed later by underlying thrusts and folds (Butler 1982). This deduction is supported by minor structures, in that the folded Moine mylonites contain minor kink band folds and vein arrays that might be produced by culmination development.

Lateral continuity

The Moine Thrust can be traced from Creag Shomhairle around the sides of upper Strath Beag, and across to Coire Lochan Ulbha (Fig. 5). In general, the mylonites dip gently ESE, subparallel to the thrust. South from Creag Shomhairle the complex intermediate thrust sheets are absent, with the main imbricate slices of the Foinaven 'duplex' lying directly against the Moine mylonites. These imbricates are, however, rather complex, showing patterns of lateral branching and varying stratigraphic content. There are several mappable slices of Fucoid Beds caught amongst the Pipe Rock. On Leathad na Surraig [NC383491] these imbricates form a culmination picked out by three Pipe Rock–Fucoid Beds repetitions. These terminate abruptly to the NE at a fault that offsets the Moine Thrust. This type of behaviour is found in many sites along the Moine Thrust Belt (e.g. Elliott & Johnson 1980) and is typical of conventional roof thrusts where internal thrust slices branch rapidly along strike. Thus the Moine Thrust appears to form a conventional roof thrust south from Creag Shomhairle.

In summary, the roof thrust system to the Foinaven 'duplex' shows variable geometry. On a regional scale and at specific sites the Moine Thrust and intermediate thrust sheets are folded by the underlying imbricates. At other sites the roof (Moine Thrust) truncates imbricates in its footwall. However, these truncating geometries are restricted to only the upper parts of the 'duplex', levels characterized by the ductile Fucoid Beds and Durness carbonates. Deeper parts of the 'duplex', chiefly composed of Pipe Rock quartzites, are not apparently truncated. Yet the 'roof thrust' forms a single coherent structure. There is no evidence for the local overstep geometries found at Creagan Meall Horn forming part of a distinct through-going low-angle fault structure. Indeed, the quality of outcrop in both footwall and hanging wall to the Moine Thrust effectively prohibits such interpretations. As for the Glencoul example, neither a simple duplex model (Boyer & Elliott 1982) nor overstep models (Butler 1987) provide adequate explanations of the structural relationships within the Foinaven 'duplex'.

General model

The structural geometries described above yield similar pictures. They have major low-angle thrusts with deformation developed in their footwalls. In this regard the low-angle structures may be considered as 'roof thrusts'. The footwall deformation has bulged these roofs up, which, applying the Boyer & Elliott (1982) model, is suggestive of simple forward propagation of deforma-

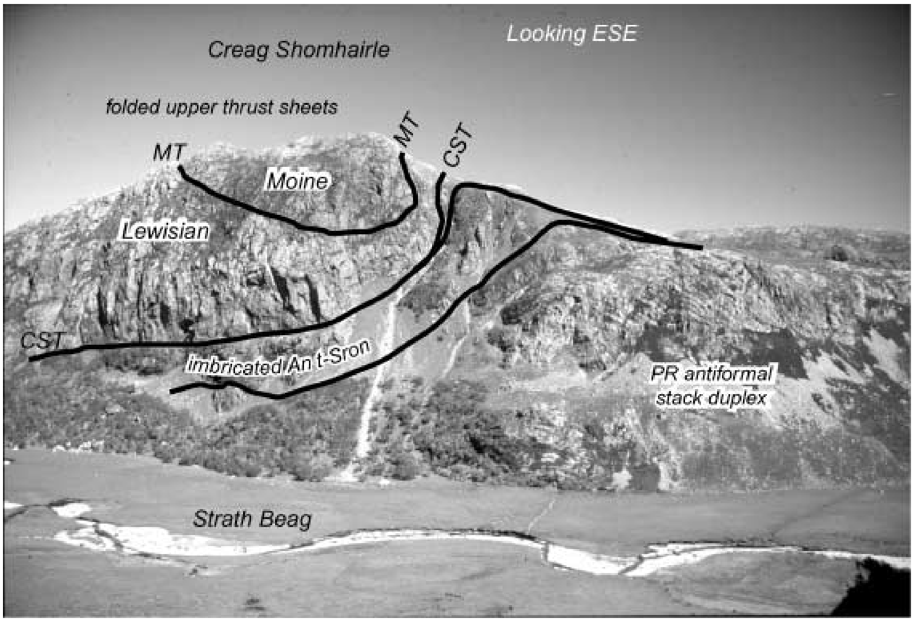

Fig. 10. Structural relationships on the NW face of Creag Shomhairle (after Butler 1982). It should be noted that the Moine Thrust (MT) and Creag Shomhairle Thrust (CST) are folded over the culmination of imbricated Cambrian strata. The thrusting direction is inferred to have been towards the WNW so this view is looking back down the transport (towards the ESE). About 300 m of topography is visible in this view. Location shown in Figure 5.

tion. However, examples presented here also show evidence for overstep, with structures in the footwall truncated and sheared out against the overriding thrust. These relationships are more suggestive of hindward propagation of deformation.

A solution to the conundrum is to propose that deformation through the parts of the Moine Thrust Belt did not occur in a strict sequence. Let us suppose that slip was partitioned, sometimes onto the low-angle roof thrust and at other times onto the imbricate thrusts below. In a duplex type of linked thrust system, displacement partitioning in this fashion is equivalent to slip alternating between the roof and floor thrusts, and, as these in turn are linked through imbricate thrusts, the system can be described as slip alternating between these imbricate thrusts. If these alternations of slip activity happen repeatedly the system as a whole can be considered to be moving simultaneously over extended periods. In effect, the behaviour is the same as for emergent thrust and fold belts, where structures are active not in a strict sequence but in parallel (e.g. Burbank *et al*. 1996; Butler & Lickorish 1997; Meigs 1997). It is also similar to the synchronous thrusting model of Boyer (1992). However, none of these previous studies considered the case where synchronously active thrusts attempt to recombine up-dip.

Let us consider an array of two linked imbricate faults (Fig. 11a). In the Boyer & Elliott (1982) duplex model it is the hindward thrust (y in Fig. 11a) that slips first. Slip on the more forward thrust (x in Fig. 11a) happens only after the earlier thrust stops completely. The fold created in the hanging wall to the new thrust bulges the old. However, if both structures are active simultaneously then part of the more hindward thrust surface must fold. This is likely to create mechanical problems. Intuitively, we might expect the hindward thrust to lock up and the whole imbricate system to become mechanically harder. This could lead to new thrust trajectories being carved, abandoning and truncating the folded part of the thrust surface. This creates local overstep geometries. If the two hypothetical thrusts were active synchronously then new thrust trajectories would be carved repeatedly.

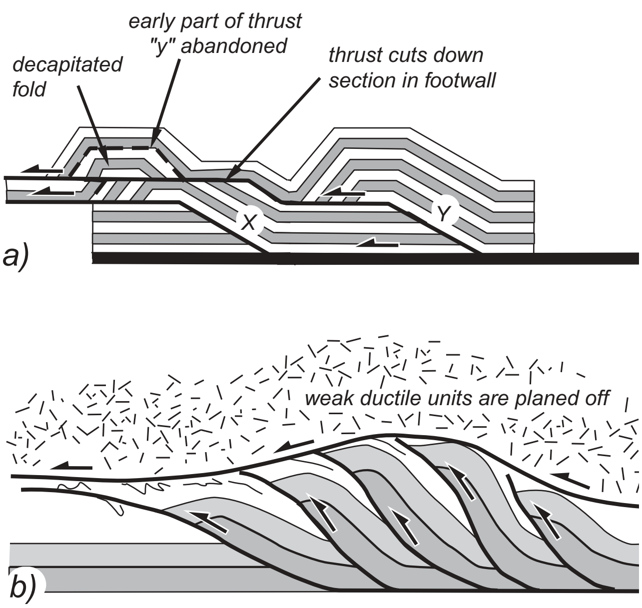

Fig. 11. (**a**) Inferred structural geometry resulting from alternating displacements on two thrusts (x and y). (**b**) Hypothetical model for a 'soft-top duplex'.

An alternative is that the slip in the roof of the imbricate system transfers into shear within the upper part of the imbricate system itself (Fig. 11b). In other situations, where the overriding thrust sheet is less competent than its imbricating footwall, the distributed shear could leave isolated tracts of roof material within the duplex. However, the upper thrust sheets in the Moine Thrust Belt appear to have behaved more competently than their footwalls so that the underlying 'duplex' acts with a soft top, shearing out bulges as imbricates amplify. In the context of the Foinaven 'duplex' discussed above, the soft top is provided by units above the Pipe Rock, so broadly synchronous imbrication at the level of the Pipe Rock is transferred up section onto the Moine Thrust. Slip from the more eastern (trailing edge) imbricates is then distributed into shear through the upper parts of the stratigraphy, chiefly the Durness carbonates. These more ductile rocks were then sheared across the imbricates below, a feature also seen at Glencoul. These more ductile rocks were then sheared across the imbricates below. The effect is to reduce the roughness in the trajectory of the roof thrust that would be produced by a simple, hard-linked transfer of displacement from imbricate thrusts to roof thrusts.

Missing hanging-wall geometries

The structural interpretations presented here have been concerned with 'roof thrusts' and their footwalls. However, if imbricate structures of folds are truncated by low-angle thrusts, the decapitated upper portions of the systems should be found, carried off towards the foreland. Regrettably, there are no preserved parts of the thrust belt found foreland-ward of either the Foinaven 'duplex' or the Glencoul section. However, in southern Assynt there is an array of tectonic outliers that preserve unusual structural geometries. The klippen are classically related to the Ben More Thrust Sheet (Peach *et al*. 1907), latterly using branch line and cut-off line maps (Elliott & Johnson 1980; Coward 1985). However, these analyses have not provided complete explanations for these structures. Peach *et al*. (1907) showed low-angle thrusts (e.g. their Ben More Thrust) carrying truncated folds and thrust structures. These are the types of structural relationships to be expected in the decapitated and translated upper portions of dismembered imbricate systems.

Towards a 3D solution

A feature of the Foinaven 'duplex' in particular and the Moine Thrust Belt in general is that the relationship between the various 'roof thrusts' and their footwalls varies along strike. A starting point for this discussion is where the locus of thrust activity generally migrates forward (Fig. 12a). Although thrusts can be active together, this end-member behaviour has thrusts progressively switching off behind the locus of activity and switching on ahead. The classical duplex model (Boyer & Elliott 1982) is merely an extreme version of this pattern. Such behaviour will generally not lead to 'roof thrusts' that truncate their footwalls. The roof thrust will be folded but only as parts of it cease to accommodate slip. An alternative to this model of thrust activity is for all thrusts within a duplex to be active together with the same slip rate (Fig. 12b). In this fashion, the roof thrust, although active along its entire section-length, can retain a simple form. Another end-member is for the thrusts at the trailing edge of the imbricate system to remain active after the cessation of displacement on those at the leading edge (or for the slip rate to be

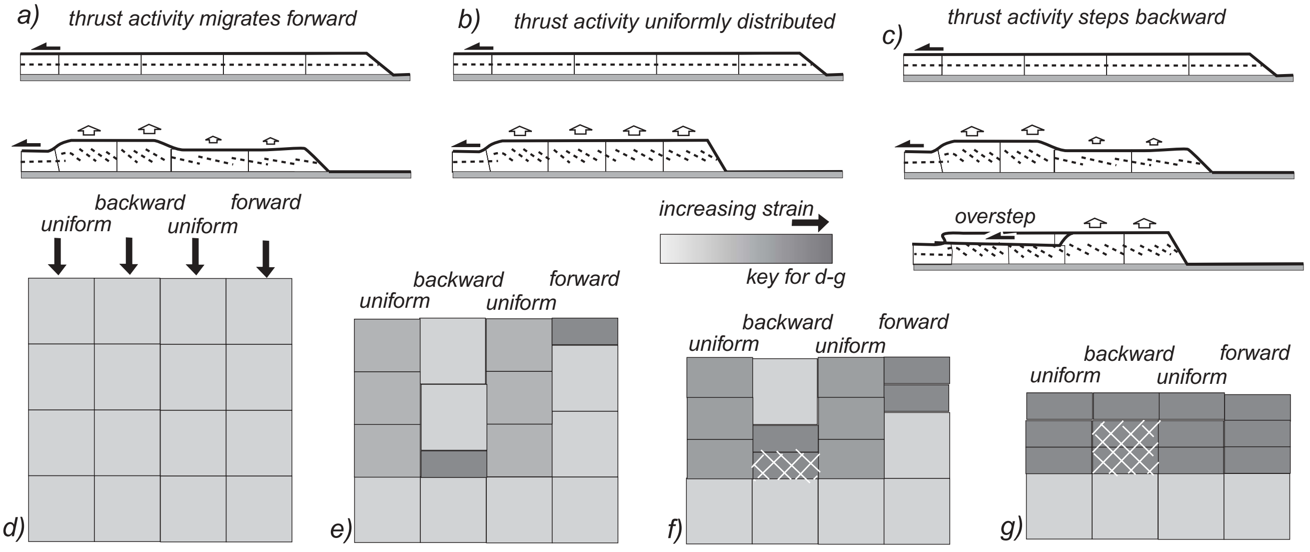

Fig. 12. Hypothetical model for the 3D evolution of duplex 'roof thrusts' for situations where the activity of displacement varies between adjacent parts of the structure. (**a**) Geometry of 'duplex' structure resulting from a progressive forward migration in thrust activity through an array of imbricate thrusts. (**b**) Pattern for a uniform distribution of thrust activity through an array. (**c**) Result of thrust activity migrating backwards (hinterland-wards) within an imbricate array. In this case there is increased likelihood for 'overstep' geometries towards the leading edge of the imbricate system. The remaining diagrams (**d**–**g**) in time show the evolution of a duplex roof in map form. Finite shortening within the imbricate system is indicated by the qualitative strain pattern. Probable sites of overstep geometry beneath the 'roof thrust' are indicated by hatching. It should be noted that the overstep patch is only locally developed.

greater towards the back; Fig. 12c). The result is for the roof thrust to have a greater chance of being folded. It is for this latter end-member behaviour that overstepping geometries are created.

Thrust activity within an imbricate system can vary along strike, linked via lateral ramps. There are many examples of such structures that have been mapped in the Foinaven 'duplex' (Butler 1982). We can explore this notion in map view (Fig. 12d–g in time). Let us consider a hypothetical case where the slip on imbricate thrusts varies in style along strike. In one section (far right side of Fig. 12d–g) the thrust activity migrates forward. In another the thrust activity steps back towards the hinterland. In adjoining sections the thrust activity is uniformly distributed through the imbricate array. The sections can be mutually compatible if they show the same net slip through the evolution of the structure and patches of thrust activity can link through lateral ramps. For the scenario as described, the section within which thrust activity steps back towards the hinterland will tend to generate overstep-type geometries (cross-hatching in Fig. 11f and g). However, these geometries will exist only in a patch in the roof thrust. They will not be laterally extensive. In this fashion, major thrust surfaces in the Moine Thrust Belt can show local overstep geometries that have only local significance.

Discussion

Major thrusts within the Moine Thrust Belt show structural relationships with their footwalls that locally imply forward-propagating thrust sequences, in which case they may be described as simple roof thrusts (in the sense of Boyer & Elliott 1982). However, there are other locations where major thrusts truncate their footwalls in overstep fashion (as originally described by Peach *et al*. 1907; see Elliott & Johnson 1980). These contrasting relationships can be shown at different localities on the same thrust. However, aspects of the two behaviours can be found at the same locality. At these sites (e.g. the footwall to the Glencoul Thrust and in the Foinaven 'duplex') the 'roof thrust' is weakly bulged but also truncates imbricate structures in its footwall. These structural relationships may be interpreted as resulting from broadly synchronous thrusting across an array of imbricate thrusts that transfer displacement upwards onto a low-angle 'roof' thrust.

Although thrusts may be active synchronously, they need not be active at the same rate. Further, partitioning of displacement onto thrust arrays need not be constant during the evolution of a 3D array. To maintain displacement compatibility within a 3D thrust array, zones of different thrust activity should be kinematically linked by lateral ramps or compartmental faults. Many such structures have been identified in the northern Moine Thrust Belt (e.g. Elliott & Johnson 1980; Butler 1982; Coward 1984), although their kinematic evolutions have not been assessed in terms of the synchronous thrusting model developed here. For ductile deformation styles, where thrust activities vary gradually, compatibility might be maintained through zones of oblique strain. Such zones have been described from the Moine Thrust Belt (e.g. Coward & Potts 1983) and elsewhere.

In buried systems such as the Moine Thrust Belt, imbricate thrusts merge upwards into low-angle tectonic contacts. In the simple duplex model (Boyer & Elliott 1982) these detachments are 'roof thrusts'. If there is a tendency for activity to increase on more hindward thrusts in an array, the forelandward parts of the upper detachment ('roof thrust') will have an increased propensity for truncating structures in its footwall. Therefore the pattern of slip evolution along 'roof thrusts' will be expected to be far more complex than that proposed by Boyer & Elliott (1982). Transient patches of active 'roof thrust' can generate overstep relationships that have only local significance.

The deduction that at least parts of the Moine Thrust Belt developed by synchronous thrusting across imbricate arrays raises other issues. The transfer of displacements onto 'roof thrusts' generating overstep relationships has been alternatively interpreted. Some late, low-angle tectonic contacts within the Moine Thrust Belt have been ascribed to top-to-WNW extensional faults (e.g. the 'surge zones' of Coward 1982) that were significant for the late-stage mechanical evolution of the mountain belt (e.g. Coward 1988). It is interesting that locations where low-angle extensional faults have been involved within the Moine Thrust Belt are all sites where the footwall to these faults lies in higher, generally imbricated parts of the Cambrian succession. Nowhere have such proposed faults been described to cut deeper into the foreland. Furthermore, all these inferred low-angle extensional faults have proved most difficult to map into adjacent areas. Consequently, these areas seem ripe for reappraisal.

This contribution is dedicated to the memory of Mike Coward (1945–2003); his work in the Moine Thrust Belt has inspired a generation of structural geologists. I thank J. Mendum for luring me, after an absence of 5 years, back to the Moine Thrust Belt to work on the Geological Conservation Review. I thank M. Krabbendam, J. Mendum and K. Goodenough of the British Geological Survey for facilitating access to archive material, particularly the spectacular notes of H. M. Cadell together with his and C. T. Clough's field maps. M. Krabbendam and G. Mitra are thanked for constructive reviews of an earlier version of this paper, together with A. Maltman for shepherding the paper through the editorial process.

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