Journal of Structural Geology 66 (2014) 1–10

Contents lists available at ScienceDirect

Journal of Structural Geology

journal homepage: www.elsevier.com/locate/jsg

Identifying multiple detachment horizons and an evolving thrust history through cross-section restoration and appraisal in the Moine Thrust Belt, NW Scotland

Hannah Watkins*, Clare E. Bond, Robert W.H. Butler

Geology and Petroleum Geology, School of Geosciences, University of Aberdeen, Kings College, Aberdeen AB24 3UE, UK

ARTICLE INFO

Article history:
Received 14 February 2014
Received in revised form
24 April 2014
Accepted 3 May 2014
Available online 20 May 2014

Keywords:
Cross-section restoration
Moine Thrust Belt
Multiple detachments
Out-of-sequence thrust

ABSTRACT

Many thrust systems, including parts of the Moine Thrust Belt, are commonly interpreted as rather simple imbricate fans, splaying from a master detachment (floor thrust) at depth. We use field observations and geological map data to construct cross-sections through the Achnashellach Culmination, southern Moine Thrust Belt, Northwest Scotland, to test this interpretation. Initially cross-sections are constructed by assuming a single lower detachment; line length imbalances and thrust trajectory mismatches between deformed and restored-state sections indicate an invalid model. Significant differences in horizon lengths between two rock units are seen, indicating the position of a second detachment which, when incorporated into the deformed-state cross-section creates a valid structural model. The presence of this second detachment accounts for complex geometries seen at outcrop, and indicates that the Achnashellach Culmination is likely to have formed by the sequential activation of two detachment horizons. This new structural model has been derived using an iterative workflow involving cross-section construction, section balancing and integration of field observations from across the study area, ensuring model validity in three dimensions. This workflow is applicable to other systems in general.

1. Introduction

Simple duplex geometries have traditionally been considered to be formed by a foreland-propagating sequence, where younger thrusts are developed in the footwall of the previously active thrust (e.g. Dahlstrom, 1970; Cooper, 1981; Boyer and Elliott, 1982; Butler, 1987). In this description, thrust faults collectively form imbricate fans that splay from a common master detachment (floor thrust) at depth. In simple duplex interpretations, these imbricate thrusts recombine up-dip onto a single upper detachment (roof thrust). However, it is increasingly realised that structural geometries of thrusts and their surrounding stratigraphies as expressed in field outcrops and some subsurface datasets cannot be explained by these simple models alone (Morley, 1986; Butler, 1987, 2004).

Pavlis (2013) suggests structural complexities seen at outcrop can be caused by synchronous movement on two thrusts, and notes that so-called out-of-sequence thrusting (in the sense that strict foreland-directed step-wise evolution of thrusts in an imbricate fan is invalid) is common. This synchronous movement can result in complex geometries such as isolated horses formed by movement on a lower thrust being entrained into the hangingwall of an upper thrust. These complex geometries do not prove synchronous movement; they can be formed in other scenarios involving break-back thrusting (where younger thrusts develop in the hangingwalls of older thrusts (McClay, 1991)) such as sequential movement of two separate detachments, thrust reactivation or breaching of the roof thrust. This is shown by McClay and Coward (1981) who illustrate structural complexities caused by changes in detachment levels during the evolution of the Moine Thrust Belt at Loch Eriboll. Pavlis (2013), citing examples described by Holdsworth et al. (2006), Butler (2004) and Butler et al. (2007), suggests that the Moine Thrust Belt of NW Scotland is an ideal field laboratory within which to develop and test thrust sequence models and their implications for structural geometry. The purpose of this paper is to explore this suggestion, with specific reference to the Moine Thrust Belt's Achnashellach Culmination, as described by Butler et al. (2007).

In our paper, we examine the role of detachments, specifically establishing a workflow for their identification and significance. In many thrust belts, extensive detachments are commonly

* Corresponding author. Tel.: +44 (0)1224 273519.
E-mail addresses: h.watkins@abdn.ac.uk (H. Watkins), clare.bond@abdn.ac.uk (C.E. Bond), rob.butler@abdn.ac.uk (R.W.H. Butler).

http://dx.doi.org/10.1016/j.jsg.2014.05.001
0191-8141/

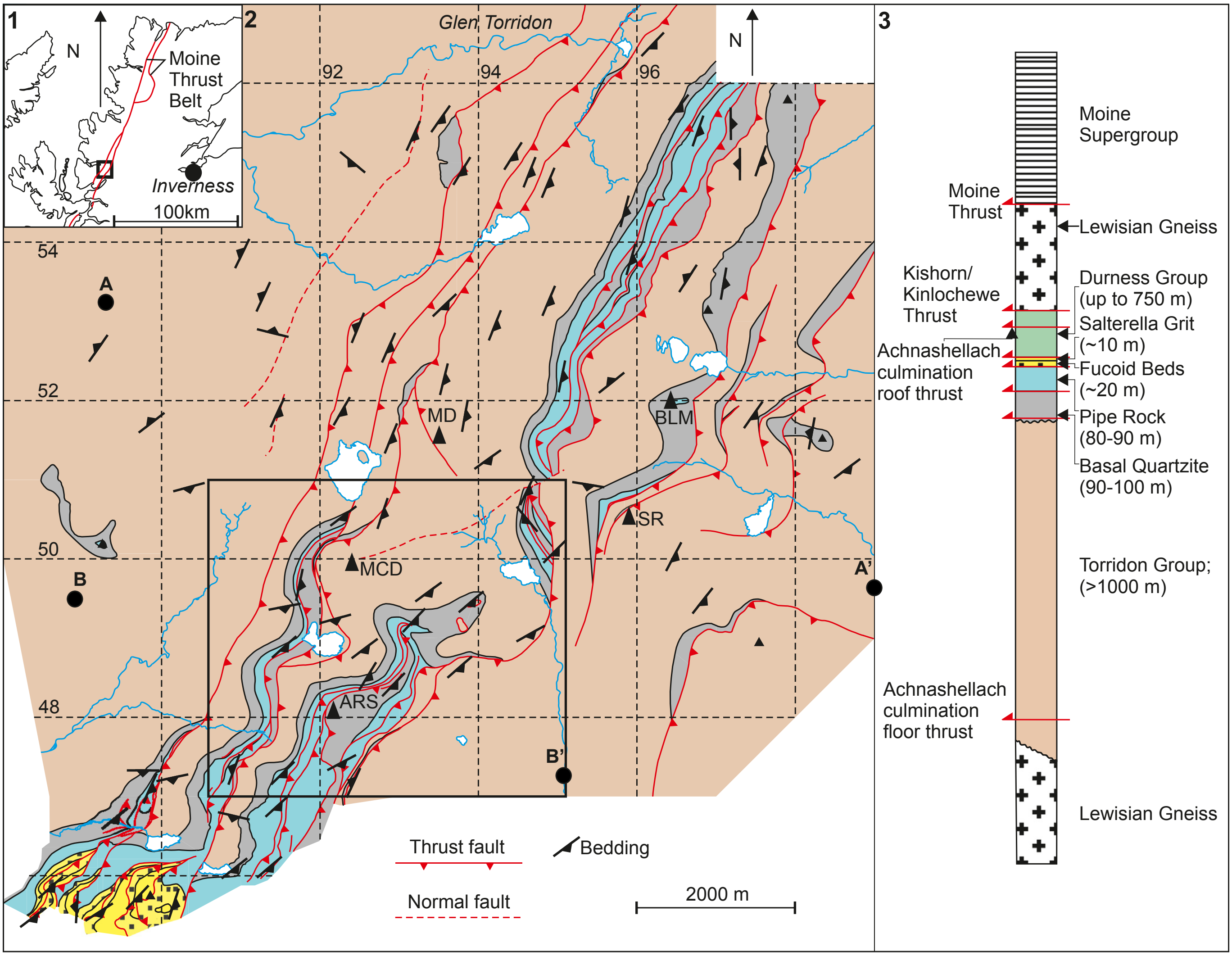


Fig. 1. 1) map of north-west Scotland showing the location of the study area in the box and the trace of the Moine Thrust Belt (bold line). 2) detailed geological map of the Achnashellach Culmination study area showing lithological units involved in thrusting, major thrust traces and the Sgorr Ruadh, A–A′ (Fig. 3 and 6) and An Ruadh-Stac, B–B′ (Fig. 5) section traces. The box indicates the area shown in the detailed geological map (Fig. 4). Abbreviated mountain names are as follows: An Ruadh-Stac (ARS), Beinn Liath Mhor (BLM), Maol Chean-dearg (MCD), Meall Dearg (MD) & Sgorr Ruadh (SR). Gridlines on the map and coordinates referred to in the text are UK National Grid numbers. 3) stratigraphic column showing the lithological units involved in Moine thrusting in the Achnashellach area and the locations of detachment levels. Stratigraphic column acts as the key to Figs. 1–6. In this paper we focus on deformation between the floor thrust and Achnashellach Culmination roof thrust. Unit thickness estimates are taken from Butler et al., 2007, McClay and Coward, 1981 and Stewart, 2002. Terminology follows that of the British Geological Survey, 2007.

considered to form along regionally continuous weak stratigraphic horizons such as mudrocks and shales (e.g. de Vera et al., 2010; Morley et al., 2011). In prospective thrust belts such as the Zagros Mountains (e.g. McQuarrie, 2004; Farzipour-Saein et al., 2009), these inferred detachments are invoked to explain disharmonic faulting and folding in thick multilayers, which can greatly increase uncertainty in predicting hydrocarbon reservoir distribution and trap structure (Cooper, 2007). In poorly imaged examples, it may be necessary to carry forward multiple interpretations of structural geometry. The challenge then is to develop tools and workflows for discriminating between, and validating these, interpretations. As Bond et al. (2008), Pavlis (2013) and others have noted, section balancing and restoration can provide some of these tests. It is an approach we develop here.

2. Moine Thrust Belt

The Moine Thrust Belt, the outer part of the Caledonian Orogenic Belt on mainland Scotland, is well-studied and accessible (Peach et al., 1907; Elliott and Johnson, 1980; Mendum et al., 2009; Butler, 2010). Structures are principally developed within a characteristic layer-cake stratigraphy of Cambrian rocks (see Fig. 1.3 for stratigraphy) with readily identified rock units. For our study we have chosen the Achnashellach area of the southern Moine Thrust Belt where distributed strains within Cambrian strata are very low (undetectable from analysis of widespread strain markers in the Pipe Rock, Butler et al., 2007, Mendum et al., 2009), unlike other parts of the thrust belt (e.g. Coward and Kim, 1981; Fischer and Coward, 1982). A combination of layer cake stratigraphy and undetectable distributed strain reduces uncertainty in cross-section construction and restoration as variations in cross-sectional area of units can be related to thrust cut-offs. Since unit thicknesses remain constant throughout the study area and there is little evidence for internal deformation we will test the validity of cross-sections through Achnashellach Culmination using line length restoration (e.g. Dahlstrom, 1969; Geiser, 1988).

Within the southern part of the Moine Thrust Belt, including the Achnashellach Culmination, the Cambrian strata rest unconformably upon a Proterozoic clastic sequence, the Torridon Group. Thicknesses of the Torridon Group are highly variable due to the irregular basal unconformity above the underlying Lewisian Gneiss, which has relief of up to 600 m (Stewart, 2002). Thicknesses of the Torridon Group in this region are unknown, but visible exposure of horizontally bedded strata on the southern slopes of the mountain Liathach, to the north of Glen Torridon (see Fig. 1.2 for location of the latter), exceeds 950 m. The regional sole thrust (basal detachment to the thrust structures we describe here) is likely to be within the Torridon Group as no older strata are found within the thrust structures. The regional roof thrust is located within mid-Cambrian strata; to the south of the Fucoid Beds and Salterella Grit of the Achnashellach Culmination (see Fig. 1.2 and 1.3) thrusting terminates within imbricated limestones of the lower Durness Group (see Fig. 1.3).

Various horizons have acted as detachments within the thrust belt, forming important floor thrusts and roof thrusts to duplex systems (Elliott and Johnson, 1980; Butler, 2010). On the north coast of Scotland, the detachment climbs up sequence from the quartzites into the Fucoid Beds (McClay and Coward, 1981), whereas in the southern Moine Thrust Belt (including the Achnashellach Culmination) the Torridon Group hosts the main detachment horizon (Butler et al., 2007).

3. Achnashellach Culmination

The Achnashellach Culmination lies to the south of Glen Torridon and displays imbricated and folded Torridon Group and Cambrian strata. The imbricates are capped by the Kinlochewe and Kishorn thrust sheets, which are overlain by the Moine Thrust sheet (see Fig. 1.3, and Butler et al., 2007). The Culmination displays the greatest range of relief (c. 1000 m) in the entire thrust belt, which allows thrust ramps to be mapped (Butler et al., 2007). Thrusts cut up section to the WNW (Butler et al., 2007) which is consistent with a WNW-vergent regional transport direction determined from fault plane slickenlines and mylonite lineations (McClay and Coward, 1981; Barr et al., 1986). Regional mapping of the study area (location shown in Fig. 1.1), enhanced by the PhD studies of one of us (HW), is shown in Fig. 1.2.

We now describe field relationships throughout the culmination, which have aided in cross-section construction; the following descriptions refer to locations indicated on Fig. 1.2. Locations are reported using standard mountain names on UK Ordnance Survey (OS) topographic maps and OS grid references; we use six figure references, accurate to 100 m.

3.1. Beinn Liath Mhor (Grid reference NG 954523 to NG 990512)

Up to 500 m of relief on the southern slopes of Beinn Liath Mhor (Fig. 2.1) allows constraint of the dips of thrust faults, and allows for fault-fold relationships to be determined. The Beinn Liath Mhor ridge runs sub-parallel to the section traces examined here and also to the estimated transport direction for the Moine Thrust Belt. Torridon Group, Basal Quartzite and Pipe Rock are preserved on Beinn Liath Mhor, with no disruption in the stratigraphic sequence. Asymmetric folds (Fig. 2.1) have axial surfaces inclined moderately to the south east; therefore folds face towards the foreland. These folds are dissected by widely spaced thrust faults.

The relatively simple relationship between folds and thrusts on Beinn Liath Mhor are consistent with being formed on a single detachment at depth, where back-steepening of thrusts is due to a foreland propagating sequence. Since Torridon Group rocks are the oldest involved in thrusting we infer the sole thrust (lower detachment) is within this unit. Fault spacing on Beinn Liath Mhor is too wide to allow complex interactions between different thrust blocks; in other parts of the study area, such as on An Ruadh-Stac (see Fig. 1.2 for location), fault spacing is much tighter and there are more complex thrust geometries. We describe these geometries in the following sections.

3.2. An Ruadh-Stac (Grid reference NG 925484)

An Ruadh-Stac (see Fig. 1.2 for location) exposes repetitions of Basal Quartzite and Pipe Rock on top of a single layer of Torridon Group sandstones. A thrust below the Torridon Group is poorly exposed but this location does allow structures in the quartzites to be observed, unlike on Beinn Liath Mhor (Fig. 2.1). Quartzite bedding dips gently to the south east (Fig. 2.2); cross bedding in the Basal Quartzite indicates the units are the correct way up.

The quartzite package (Basal Quartzite & Pipe Rock) on An Ruadh-Stac is 300 m thick (Fig. 2.2), compared to a 200 m thickness for foreland successions. No evidence of stratigraphic change is seen between the foreland and this location indicating the same facies is observed, and no evidence of internal strain can be detected. From this we infer over thickening is due to the presence of bedding-parallel thrusts within the quartzites, at this location. As on Beinn Liath Mhor (Fig. 2.1), we see no evidence for out-of-sequence thrusting or interactions between multiple imbricate fans. This suggests the structures could fan from a single detachment (floor thrust).

3.3. Sgorr Ruadh (Grid reference NG 958507)

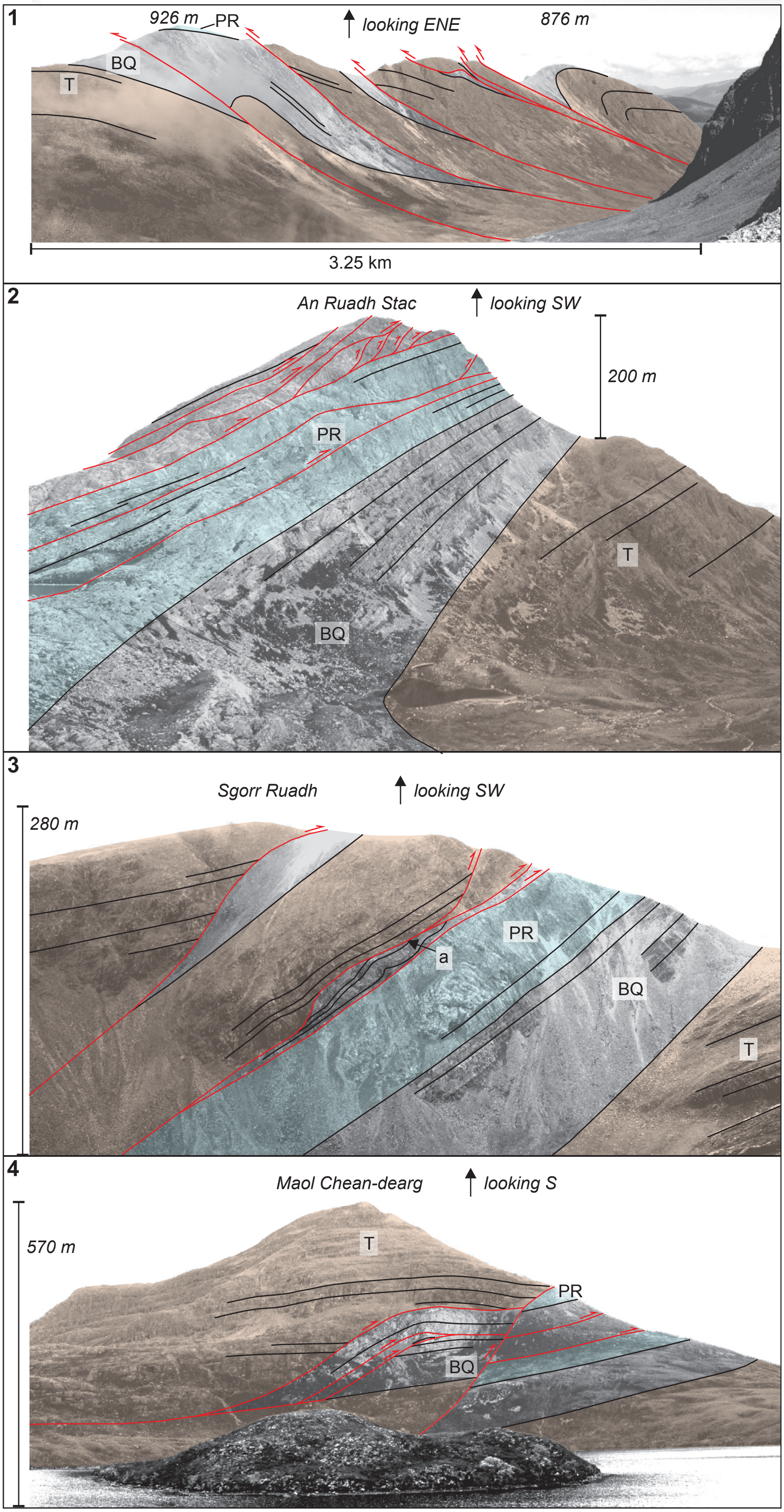
Further internal complications within the quartzites can be seen in other locations throughout the study area. The north eastern face of Sgorr Ruadh (Fig. 2.3) exposes repeated slices of Torridon Group, Basal Quartzite and Pipe Rock. The occurrence of Torridon Group and Basal Quartzite on younger rocks indicates the presence of three thrusts. The thrust at position "a" on Fig. 2.3 is decorated by an isolated horse of Basal Quartzite that has been incorporated into its hangingwall. Basal Quartzite bedding terminating downwards against Torridon Group rocks indicate the fault has cut down stratigraphic section, in its transport direction.

Cross-cutting relationships on Sgorr Ruadh suggest the thrust carrying Torridon Group above point a may have been activated or reactivated later than the thrust below. This thrust sequence suggests either later breaching through the original roof thrust or two separate thrust systems with multiple detachment levels. Multiple structural evolution models are implied from the geometries on Sgorr Ruadh (Fig. 2.3). These models include hinterland propagating thrusting, thrust reactivation, synchronous thrust movement, a multistage thrust history involving more than one detachment or the presence of late-stage low angle normal faults, as suggested by Holdsworth et al. (2006).

3.4. Maol Chean-dearg (Grid reference NG 924503)

Other evidence for complex thrusting in the quartzites can be found on Maol Chean-dearg (Fig. 2.4). The upper 300 m of the mountain contains Torridon Group dipping gently to the ESE, showing very little internal deformation. This Torridon Group is separated from the Basal Quartzites immediately below by a thrust running parallel to quartzite bedding. The Basal Quartzite in the footwall of this thrust is folded and contains internal bedding-parallel thrusting which appears not to involve the Torridon Group below.

Had the Torridon Group rocks been in their current position prior to quartzite folding, internal deformation and steeper dips would be expected within this unit. In this scenario the Torridon Group would be passively folded by movement on the quartzite


1
926 m
PR
looking ENE
876 m
BQ
T
3.25 km
2
An Ruadh Stac
looking SW
200 m
PR
T
BQ
3
Sgorr Ruadh
looking SW
280 m
PR
a
BQ
T
4
Maol Chean-dearg
looking S
570 m
T
PR
BQ

thrusts below. The geometries of Torridon Group and Basal Quartzite on Maol Chean-dearg cannot have formed from a single detachment surface involving a foreland propagating deformation front. As on Sgorr Ruadh (Fig. 2.3) the thrust carrying Torridon Group was activated or reactivated later than the thrusts in its footwall.

4. Two cross-sections through the Achnashellach Culmination

The geometries described in preceding sections from Beinn Liath Mhor, An Ruadh-Stac, Sgorr Ruadh and Maol Chean-dearg, are not unique within the study area; examples can be found throughout the culmination. We will now explore how these structural geometries relate to regional deformation by up scaling observations at outcrop (Fig. 2) to cross-section scale, spanning several kilometres through the fold-and-thrust belt. Cross-section traces run through the study area at an orientation of 110–290°, which is parallel to the thrust belt transport direction (WNW) and average dip direction of bedding in the Torridon Group and overlying quartzites. A total of seven regional cross-sections spaced at 1500–1800 m intervals were constructed; we will present two representative sections here.

Cross-section construction in the Cambrian units was simple as bedding is parallel to the base-quartzite unconformity so unit thicknesses remain constant. Difficulties arise when constructing the Torridon Group bedding as significant differences in dip between the Torridon Group and Cambrian units occur, reflecting a period of Precambrian normal faulting (Stewart, 2002) preceding deposition of the Cambrian strata. The Torridon Group also contains irregular bedding surfaces due to the nature of its deposition in fluvial systems (Stewart, 2002), as well as many intraformational unconformities. This means Torridon Group bedding planes are not parallel to the Cambrian units above. For the purpose of section construction we denote a reference horizon parallel to Cambrian bedding, within the Torridon Group at an arbitrary depth of 500 m below the top Torridon unconformity; it is the length of this unconformity-parallel horizon that is conserved during deformation.

Another uncertainty in section construction is the total thickness of the Torridon Group involved in thrusting, which is used to infer the depth to detachment. Since we don't see the detachment at outcrop its exact position is model-dependent. Fold geometries on the regional cross-section (Fig. 3) indicate the depth to this surface is at least 1000 m below the base quartzite unconformity.

Cross-section construction was completed using section construction tools in Move software by assuming parallel-type folds (Ramsay, 1967) across the extent of the section traces. Cross-sections were restored using a bed-by-bed restoration whereby a pin was fixed at the WNW end of each cross-section (see Figs. 3, 5 and 6) and bed lengths for each horizon were measured. Thrust locations and geometries were determined by the positions of bed terminations.

The two cross-sections presented here have been constructed (section end points shown on Fig. 1.2) using data on the geological map (Fig. 1.2) as well as field observations (Fig. 2). The Sgorr Ruadh section (line A–A′, Fig. 1.2) was constructed to depict the cross-culmination regional geology, with the An Ruadh-Stac section (line B–B′, Fig. 1.2) constructed to test the validity of the initial structural model on the regional section (Fig. 3).

4.1. Sgorr Ruadh cross-section

Both the Sgorr Ruadh section and the An Ruadh-Stac section were constructed by projecting bedding dips and fault/unit boundaries onto a topographic profile running between cross-section end points (see Fig. 3.1). Fault lines were then projected both into the subsurface and above ground level, and unit boundaries were constructed to honour geometries seen at outcrop (Fig. 2). The result is a cross-section best representing the structures seen (Fig. 3.2.1-Sgorr Ruadh section (A–A′)).

The regional section (Fig. 3.2.1, see Fig. 1.2 for section end points) was initially constructed using a single detachment horizon in the Torridon Group rocks. The cross-section uses structural geometries seen on the slopes of Beinn Liath Mhor, 750 m adjacent to the section trace (Fig. 2.1). Thrusts cut smoothly up section from the Torridon Group to the Durness Group along a single trajectory creating ramp geometries which account for the back-steepening of thrusts seen towards the hinterland (ESE) (see Fig. 2.1). Thrust-related anticlines are accompanied by folding in the thrust footwalls indicating some degree of buckling also occurred during shortening.

Line length restoration of the Sgorr Ruadh cross-section (Fig. 3.2.2) shows a very small length imbalance exists whereby the Torridon Group is longer than the overlying units by 555 m. This value is less than 3% of the total section length. Small errors such as this may be caused by uncertainties in décollement depth, poorly known stratigraphy and deformation at a smaller scale than the resolution of the section (Judge and Allmendinger, 2011), so may be considered acceptable. The cross-section can easily be adjusted to balance by altering the geometries of thrusts or folds (Fig. 3.3.1), providing the new cross section still adheres to surface data. Fig. 3.3.1 shows an example of this adjustment, where dashed lines are thrust and fold geometries before alteration and solid lines are the geometries after alteration. Minor length reductions of the top Torridon Group horizons and Torridon Group marker horizon for each thrust and fold add up to eliminate the length imbalance on Fig. 3.2.2. A new cross section (Fig. 3.3.2) displays equal line lengths for each horizon when restored (Fig. 3.3.3).

Careful consideration of the thrust trajectories on the restored section, do however indicate a problem. The cross-section must be resolved on a ramp-by-ramp basis to ensure the restored state section honours bedding cut-offs for the final state section. Looking closely at the bedding cut-off angles a mismatch is seen between the regional section (Fig. 3.4.1) and the restored section (Fig. 3.4.2). On the final state section (Fig. 3.4.1) cut off angles for F2 and F3 are steep, reflecting the hangingwall and footwall ramp geometries. Looking at the same region on the restored state section (Fig. 3.4.2) bedding cut-off angles are less steep in the Basal Quartzite and Pipe Rock indicating a decrease in fault gradient through these units.

The outlined workflow of bed length restoration and thrust trajectory analysis provides an additional tool for validation. The geometrical mismatch in thrust trajectories shows the current structural interpretation represented on Fig. 3.3.2 is invalid;

Fig. 2. 1) the southern slopes of Beinn Liath Mhor exhibits a series of widely spaced (100's metres) thrusts (red lines) causing the repetition and folding of Torridon Group (T), Basal Quartzite (BQ) and Pipe Rock (PR). Black lines depict bedding. 2) the northern face of An Ruadh-Stac shows multiple repetitions of Basal Quartzite (BQ) and Pipe Rock (PR) in a 200 m cliff face with Torridon Group (T) below. Repetition of quartzites (BQ & PR) is caused by multiple closely spaced thrusts (red lines) parallel to bedding (black lines), causing small scale thrusting. 3) the north eastern slopes of Sgorr Ruadh; an isolated horse of Basal Quartzite (BQ) thrust onto a block of Pipe Rock (PR) is overridden by Torridon Group (T) that cuts down section creating footwall cut-offs in the horse (a). Thrusts are shown as red lines and bedding as black lines. 4) the northern slopes of Maol Chean-dearg; folding and thrusting in Basal Quartzite (BQ) is overridden by Torridon Group (T) which shows little internal deformation indicating out of sequence thrusting. Thrusts are shown as red lines, bedding as black lines and Pipe Rock as PR. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

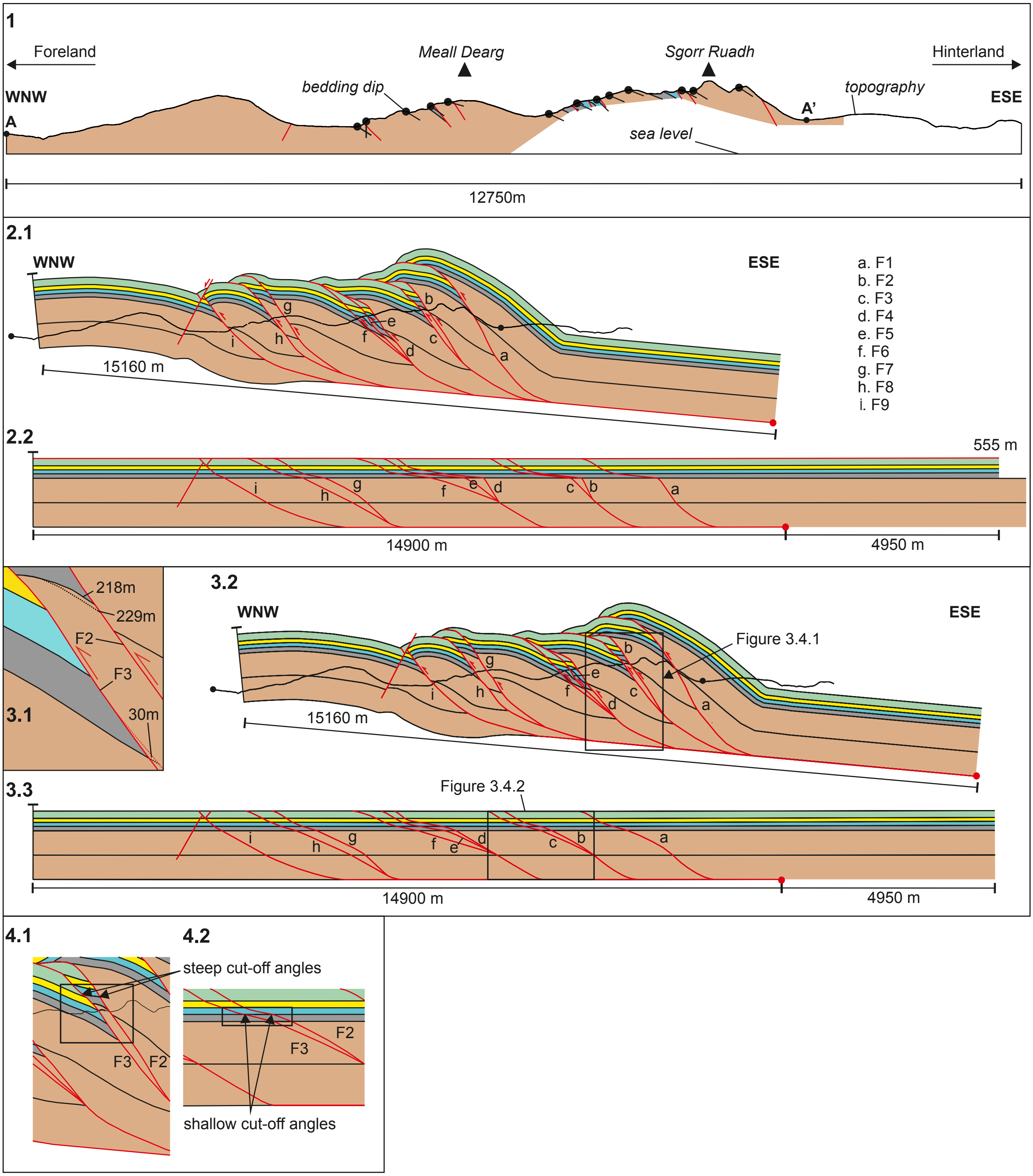


Fig. 3. (key to units shown in Fig. 1.3). 1) outcrop data for the regional cross-section (Sgorr Ruadh section trace) from A to A′ on Fig. 1.2 2.1) Sgorr Ruadh cross-section (see Fig. 1.2 for section trace) constructed using the assumption of simple thrusting with a single detachment. 2.2) line length restoration of the cross-section indicates a minor length imbalance between the Torridon Group and Basal Quartzite units. 3.1) Minor changes in fold and thrust geometries shorten the length of Torridon Group horizons meaning the news section (Fig. 3.3.2) now balances when restored (Fig. 3.3.3). Dashed lines are the original fold and thrust geometries from Fig. 3.2.1 and solid lines are the new geometries of Fig. 3.3.2. 3.2) Sgorr Ruadh cross-section following minor adjustment of Fig. 3.2.1. The box shows the extent of Fig. 3.4.1. 3.3) Line length restoration of Fig. 3.3.1 shows horizon lengths are now equal. The box shows the extent of Fig. 3.4.2. 4.1) zoomed in area of Fig. 3.3.2 showing steep hangingwall and footwall cutoffs to Faults 2 and 3. 4.2) Zoomed in area of Fig. 3.3.3 showing shallower cut off angles in the quartzites than the equivalent region in the deformed state (Fig. 3.4.1).

structures did not evolve from a single detachment at depth. In order to resolve this we must look for evidence of geometries, elsewhere in the culmination where the quartzites are better exposed.

4.2. An Ruadh-Stac cross-section

A detailed map of the southern part of the field area (Fig. 4) shows quartzites here are well preserved, as are thrusts. A cross-section (Fig. 5.1) through a short section of the field area (see Fig. 1.2 for location of the section line B–B′) has been constructed. This section shows two clusters of imbricates, constrained within the quartzites, detaching off a base-quartzite detachment. Thick packages of Torridon Group are not involved in quartzite imbrication above, consistent with the field observations (Fig. 2.2). Exposure on An Ruadh-Stac enables the deduction that the overlying Fucoid Beds, Salterella Grit and Durness Group are not involved in this imbrication; bedding parallel thrusts on An Ruadh-Stac (Fig. 2.2) emplace Basal Quartzite directly onto Pipe Rock meaning that the roof thrust of this system is at the top of the Pipe Rock, at this location.

Restoration of the An Ruadh-Stac cross-section (Fig. 5.2) shows a major length imbalance between the quartzites and other units; the Basal Quartzite and Pipe Rock are 1745 m longer than other units. This length imbalance is too large to be an error in section construction or line balancing, as could be argued for the Sgorr Ruadh section (Fig. 3.2.1). Analysis of thrust trajectories in quartzites and Torridon Group for Fig. 5.1 and 5.2 shows that the thrust geometries are consistent between final and restored state sections, indicating the structural model represented on this cross-section is geometrically valid.

The length imbalance between the Torridon Group and the quartzites, shown on Fig. 5.2, is likely to be caused by differential shortening. A detachment is present at the base of the Basal Quartzite which allows significantly more shortening in the Cambrian sediments than in the Torridon Group. The length imbalance between the Pipe Rock and overlying Cambrian sediments (Fig. 5.2) suggests a significant length of Fucoid Beds, Salterella Grit and Durness Group is missing on the cross-section (Fig. 5.1) to the WNW of the quartzite imbricate clusters. This extra length could be accounted for by imbrication of these units in the eroded material above the present day topography, and is illustrated at the WNW end of Fig. 6.1.

Line length balancing of the An Ruadh-Stac section invokes a new model for structural evolution, involving two lower detachment horizons, one in the Torridon Group and one at the base of the Basal Quartzite. We have tested this model on the rest of the field area, focussing firstly on the north eastern corner of Fig. 4 (x). Here, bedding-parallel thrusts equivalent to F5 and F6 (see Fig. 3.2.1) are cut off, suggesting that F4, despite being closer to the hinterland, was active in the later stages of deformation. These thrusts that have been cross-cut by F4 are structurally equivalent to the quartzite imbricate clusters seen at the top of An Ruadh-Stac, indicating the detachment surface at the base of the Basal Quartzite was active prior to the deeper detachment within the Torridon Group. From the map patterns we suggest a two-stage thrust evolution involving the two detachment surfaces.

5. Implications of structural evolution in the Achnashellach Culmination

We now apply findings from the An Ruadh-Stac cross section and restoration (Fig. 5) to the regional cross-section (Sgorr Ruadh Section) in order to refine the interpretation and correctly show thrust geometries. The new Sgorr Ruadh cross-section (Fig. 6.1) has been constructed with the addition of imbricates in the Fucoid

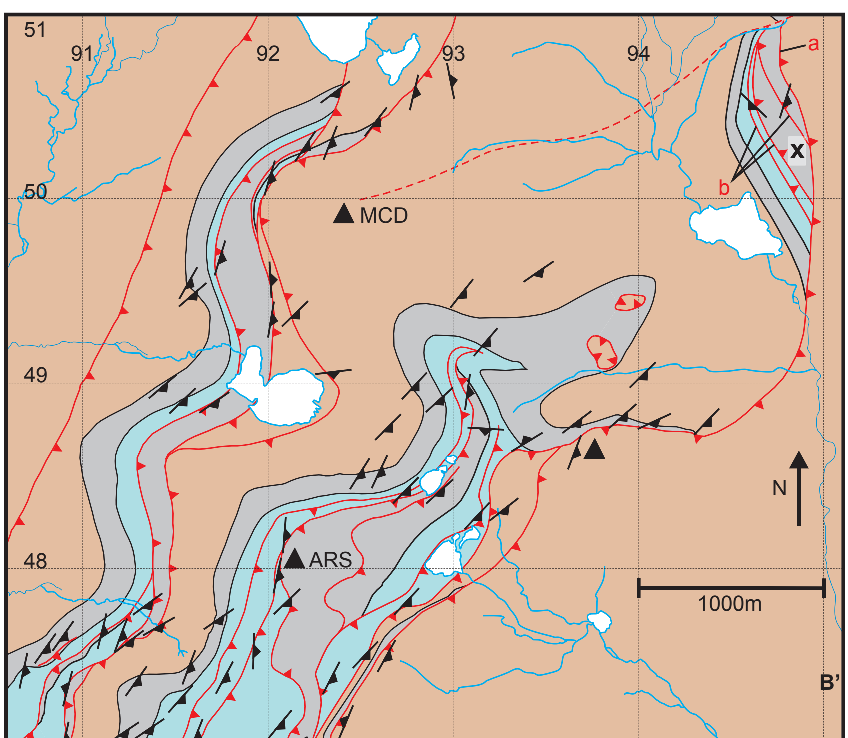


Fig. 4. (key to units shown in Fig. 1.3) zoomed in geological map of the southern Achnashellach Culmination (box on Fig. 1.2) showing multiple thrusts within Basal Quartzite and Pipe Rock on An Ruadh-Stac and fault cut-offs (×). F4 is denoted by "a" and F5 and F6 equivalents are denoted by "b". Mountain name abbreviations are as follows: An Ruadh-Stac (ARS) & Maol Chean-dearg (MCD). Gridlines on the map are UK Ordnance Survey National Grid.

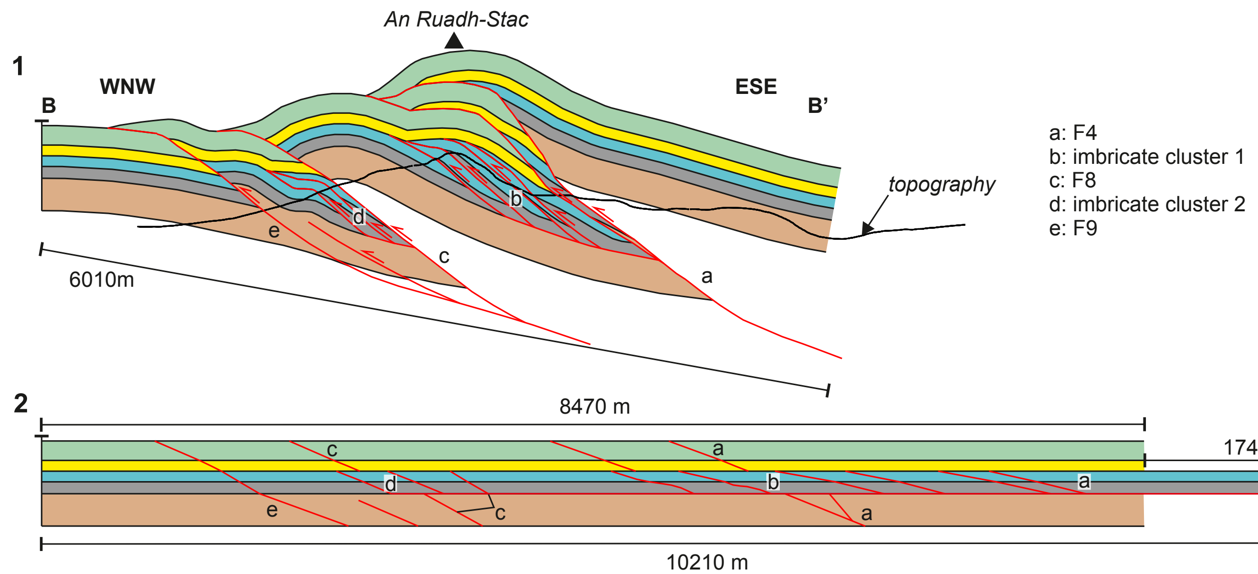


Fig. 5. (key to units shown on Fig. 1.3). 1) cross-section through An Ruadh-Stac (see Fig. 1.2 for section trace). First imbricate cluster (b) represents thrusting seen in Fig. 2.2. 2) Line length restoration of the An Ruadh-Stac cross-section shows a significant length imbalance between the Basal Quartzite and Pipe Rock to all other units. A detachment occurs beneath the Basal Quartzite and lengths are missing from the Fucoid Beds, Salterella Grit and Durness Group.

Beds, Salterella Grit and Durness Group (l-o) to the foreland (WNW) end in order to account for the missing lengths on Fig. 5. The lower detachment horizon for the quartzite imbricate cluster (j & k) has been re-located at the base of the Basal Quartzite unit so the Torridon Group is not deformed by these thrusts. An intermediate step in the fold-and-thrust belt evolution, showing deformation within Cambrian sediments, prior to movement on the Torridon Group detachment, is shown in Fig. 6.2.

Restoration of the cross-section (Fig. 6.3) shows the addition of imbricates in the upper units (l-o) results in the Fucoid Beds, Salterella Grit and Durness Group units having the same lengths as the Basal Quartzite and Pipe Rock below. Fig. 6.3 also reflects the

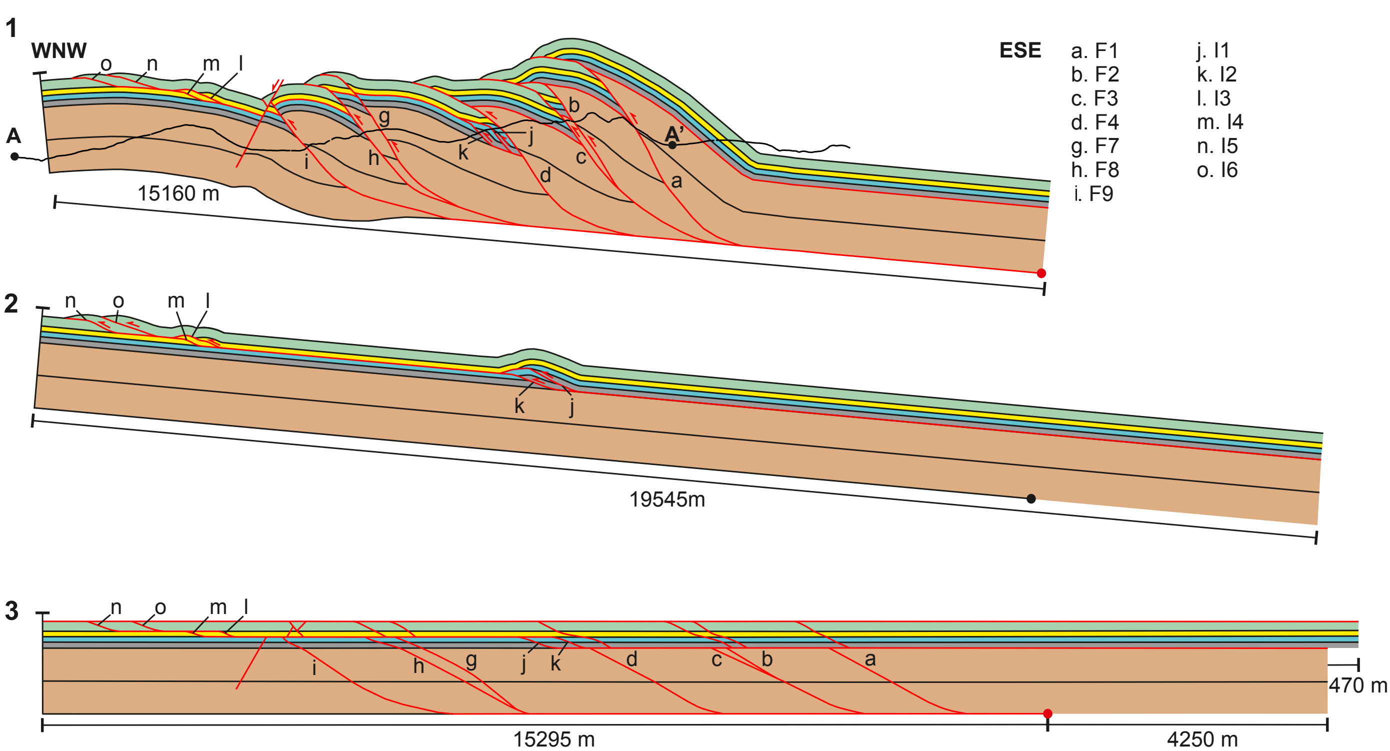


Fig. 6. (key to units shown on Fig. 1.3). 1) Cross-section through Sgorr Ruadh following a two-stage thrust sequence model with slip on both the base-Quartzite and Torridon Group detachments. 2) Geometry of the Achnashellach Culmination following thrusting on the base-Quartzite detachment. At this stage thrusting in the Torridon Group had not yet commenced. 3) line length restoration of the new Sgorr Ruadh cross-section (Fig. 6.1) shows a detachment between the Torridon Group and Basal Quartzite, imbricates in the upper units (l–o) have been added to make the section balance.

two-stage thrusting history of the Achnashellach Culmination due to the segmentation of thrusts branching off the lower detachment within the Torridon Group. The imbalance between the Torridon Group and overlying Cambrian sediments must be resolved by further deformation to the hinterland (ESE), beyond the extent of the cross-section. The Torridon Group and overlying Cambrian strata are not preserved in the hinterland so we can only speculate as to the style of deformation which has caused this imbalance.

By using observations from across the entire study area rather than from a single, two dimensional section line we have been able to derive an alternative structural model for the evolution of the Achnashellach Culmination, that honours all available data. Line length restoration and thrust trajectory analysis have shown that length imbalances can identify the location of detachments. From this we can infer the presence of an extensional regime beyond the limits of the cross-section line. We now know that a two-stage thrust evolution with two major lower detachments (sole thrusts) is more likely to have formed the Achnashellach Culmination, rather than a simple foreland propagating thrust sequence with a single detachment surface; this new model is consistent with field observations (detailed in Fig. 2.3 and 2.4).

We infer a structural evolution as follows; activation of the base quartzite detachment caused quartzite imbrication (j & k Fig. 6.2); displacement was transferred laterally along the top Pipe Rock horizon towards the foreland where further imbricate thrusts formed in the upper units (l-o Fig. 6.2). Slip on the base quartzite detachment ceased; the lower detachment surface within the Torridon Group activated forming much larger scale thrusts throughout a wider thrust belt (a-d & g-i Fig. 6.1).

6. Discussion

This example from the Achnashellach Culmination has shown that a cross-section may appear plausible, however when it is restored by line length restoration we see a length imbalance indicating a missed detachment horizon. This indicates the current structural model represented on the original cross-section is invalid, and the extent of the cross-section trace is too short to show the entire deformation régime. The cross-section must be reconstructed in order for it to balance.

The workflow used can be applied to other areas to determine valid structural evolutions, such as elsewhere in the Moine Thrust Belt. Earlier work on the Moine Thrust Belt has evoked various forms of complex thrust sequencing and normal faulting (Holdsworth et al., 2006); and the occurrence of roof thrusts cutting up and down sequence, potentially as a result of synchronous displacement on thrust arrays (Butler, 2004). In the Achnashellach area, Butler et al. (2007) described how upper-level thrust sheets were bulged above by underlying imbricate structures but that these thrusts also truncated the thrusts in their footwalls. This was explained by synchronous displacement on thrust arrays. It would seem from our work and that of previous authors that the Moine Thrust Belt is a complex structural region which does not always follow a simple foreland propagating thrust sequence. Line length restoration and thrust trajectory analysis may help to resolve some of these complexities and validate, or otherwise, existing models.

Although a two-stage thrust history is a geometrically valid model for the structural evolution of the Achnashellach Culmination, it is not necessarily the only valid interpretation. Fig. 7 shows two restored state models involving the sequential activation of two foreland propagating thrust systems. Fig. 7.1 represents the current model where early stage imbrication is confined to unit a. This is followed by later thrusting involving the entire sequence where thrusts detaching off the base of unit b utilise some of the pre-existing fault planes in unit a. Fig. 7.2 is an alternative model

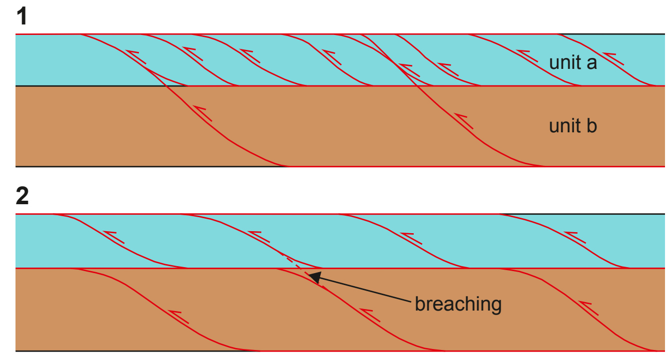


Fig. 7. 1) stage 1 imbrication confined to unit a, stage 2 imbrication involves a lower detachment at the base of unit b and an upper detachment at the top of unit a. Pre-existing fault planes in unit a are reactivated by stage 2 thrusting. 2) two independent imbricate systems develop in units a and b. Reactivation of unit b thrusts causes breaching of the upper detachment (top unit b).

where two imbricate systems have developed independently of each other. Later reactivation of thrusts in unit b has led to breaching of the roof thrust (top unit b). Both examples could result in the geometries seen in the Achnashellach Culmination if only a single fault was active at any given time. Alternative valid models might be identified that result from even more complex thrusting sequences.

As mentioned previously, simultaneous movement on a pair of ramp-flat faults could result in complex geometries seen throughout the Moine Thrust Belt (Pavlis, 2013), including isolated horses. This simultaneous movement therefore could be an alternative model to out of sequence thrusting such as that proposed by Holdsworth et al. (2006) for complex regions of the Moine Thrust Belt, and the sequential detachment activation model we propose here. Indeed the geometry of the isolated horse of Basal Quartzite seen on Sgorr Ruadh (Fig. 2.3) is very similar to the model results described by Pavlis (2013). This, however, cannot prove simultaneous fault activity, only that some form of break-back thrusting has occurred. Cross-section restoration is a powerful tool in validating and, in this case, deriving structural models, however it can only distinguish between valid and invalid interpretations, it cannot resolve unique solutions (Elliott, 1983).

7. Conclusions

In order to determine a valid structural evolution of a region it is necessary to use all data available. Creation of a single cross-section may provide a solution that appears to balance in two dimensions but this needs to be tested in the rest of the study area to check it is valid along strike. Length imbalances determined from detailed cross-section restoration in our study area indicate the location of multiple detachment horizons. This suggests a more complex structural evolution model than originally derived in our initial cross-section. Other observations such as map cut-off patterns can help to reinforce the new structural model. The original cross-section must be adjusted to comply with the new model, and field observations. Through an iterative modelling process, combining cross-section construction, with section balancing and detailed observations of field geometries we propose a new structural model for the Achnashellach Culmination.

The structural model we propose involves the sequential activation of two foreland propagating thrust systems, each splaying off detachments (floor thrusts) at different stratigraphic levels. The workflow we outline should be applicable to other situations. We suggest that even small mismatches in bed-lengths should be confronted when restoring cross-sections, rather than accepting these as unavoidable errors. In examples where pre-existing stratigraphic variations and distributed strains are more strongly developed than in our case, complex thrust sequences might have gone unrecognised.

Acknowledgements

The research presented here is funded by a NERC CASE studentship (NERC code GL041 RGA1511) in partnership with Midland Valley. The authors would like to thank Midland Valley for the use of their Move and FieldMove software, Maarten Krabbendam of the BGS for providing DTM data, Graham Leslie & Rick Groshong for helpful reviews, and Dave Healy for constructive comments.

References

Barr, D., Holdsworth, R.E., Roberts, A.M., 1986. Caledonian ductile thrusting in a Precambrian metamorphic complex: the Moine of northwestern Scotland. Geol. Soc. Am. Bull. 6, 754–764.

Bond, C.E., Shipton, Z.K., Gibbs, A.D., Jones, S., 2008. Structural models: optimizing risk analysis by understanding conceptual uncertainty. First Break 26 (6), 65–71.

Boyer, S.E., Elliott, D., 1982. Thrust systems. Am. Assoc. Petrol. Geol. Bull. 66 (9), 1196–1230.

British Geological Survey, 2007. Assynt. Scotland Special Sheet. British Geological Survey. Bedrock. 1:50 000, Keyworth.

Butler, R.W.H., 1987. Thrust sequences. J. Geological Soc. Lond. 144, 619–634.

Butler, R.W.H., 2004. The nature of 'roof thrusts' in the Moine Thrust Belt, NW Scotland: implications for the structural evolution of thrust belts. J. Geol. Soc. Lond. 5, 849–859.

Butler, R.W.H., Matthews, S.J., Morgan, R.K., 2007. Structural Evolution of the Achnashellach Culmination, Southern Moine Thrust Belt; testing the duplex model. In: Ries, A.C., Butler, R.W.H., Graham, R.H. (Eds.), Deformation of the Continental Crust: the Legacy of Mike Coward, 272. Geological Society, London, pp. 103–120. Special Publications.

Butler, R.W.H., 2010. The role of thrust tectonic models in understanding structural evolution in NW Scotland. In: Law, R.D., Butler, R.W.H., Holdsworth, R.E., Krabbendam, M., Strachan, R.A. (Eds.), Continental Tectonics and Mountain Building: the Legacy of Peach and Horne, 335. Geological Society, London, pp. 293–320. Special Publications.

Cooper, M.A., 1981. The internal geometry of nappes: criteria for models of emplacement. In: McClay, K.R., Price, N.J. (Eds.), Thrust and Nappe Tectonics, 9. Special Publications of the Geological Society, London, pp. 225–234.

Cooper, M., 2007. Structural style and hydrocarbon prospectivity in fold and thrust belts: a global review. In: Ries, A.C., Butler, R.W.H., Graham, R.H. (Eds.), Deformation of the Continental Crust: the Legacy of Mike Coward, 272. Geological Society, London, pp. 447–472. Special Publications.

Coward, M.P., Kim, J.H., 1981. Strain within thrust sheets. In: McClay, K.R., Price, N.J. (Eds.), Thrust and Nappe Tectonics, 9. Geological Society, London, pp. 275–292. Special Publications.

Dahlstrom, C.D.A., 1969. Balanced cross sections. Can. J. Earth Sci. 6, 743–757.

Dahlstrom, C.D.A., 1970. Structural geology in the eastern margin of the Canadian Rocky Mountains. Bull. Can. Petrol. Geol. 18, 332–406.

de Vera, J., Granado, P., McClay, K., 2010. Structural evolution of the Orange Basin gravity-driven system, offshore Namibia. Mar. Petrol. Geol. 27, 223–237.

Elliott, D., 1983. The construction of balanced cross-sections. J. Struct. Geol. 5, 101.

Elliott, D., Johnson, M.R.W., 1980. Structural evolution in the northern part of the Moine Thrust Zone. Trans. Royal Soc. Edinb. Earth Sci. 71, 69–96.

Farzipour-Saein, A., Yassaghi, A., Sherkati, S., Koyi, H., 2009. Mechanical stratigraphy and folding style of the Lurestan region in the Zagros Fold-Thrust Belt, Iran. J. Geol. Soc. 166, 1101–1115.

Fischer, M.W., Coward, M.P., 1982. Strains and folds within thrust sheets: an analysis of the Heilam Sheet, Northwest Scotland. Tectonophysics 88, 291–312.

Geiser, P.A., 1988. The role of kinematics in the construction and analysis of geological cross sections in deformed terranes. In: Mitra, G., Wojtal, S. (Eds.), Geometries and Mechanisms of Thrusting, with special reference to the Appalachians, 222. Geological Society of America Special Paper, pp. 47–76.

Holdsworth, R.E., Strachan, R.A., Alsop, G.I., Grant, C.J., Wilson, R.W., 2006. Thrust sequences and the significance of low-angle, out-of-sequence faults in the northernmost Moine Nappe and Moine Thrust Zone, NW Scotland. J. Geological Soc. Lond. 163, 801–814.

Judge, P.A., Allmendinger, R.W., 2011. Assessing uncertainties in balanced cross sections. J. Struct. Geol. 33, 458–467.

McClay, 1991. Glossary of thrust tectonics. In: McClay, K.R., Price, N.J. (Eds.), Thrust and Nappe Tectonics, 9. Geological Society, London, pp. 419–433. Special Publications.

McClay, K.R., Coward, M.P., 1981. The Moine Thrust Zone: an overview. In: McClay, K.R., Price, N.J. (Eds.), Thrust and Nappe Tectonics, 9. Geological Society, London, pp. 241–260. Special Publications.

McQuarrie, N., 2004. Crustal scale geometry of the Zagros fold-thrust belt, Iran. J. Struct. Geol. 26, 519–535.

Mendum, J.R., Barber, A.J., Butler, R.W.H., Flinn, D., Goodenough, K.M., Krabbendam, M., Park, R.G., Stewart, A.D., 2009. Lewisian, Torridonian and Moine Rocks of Scotland. In: Geological Conservation Review Series, 34. Joint Nature Conservation Committee, Peterborough.

Morley, C.K., 1986. A classification of thrust fronts. Am. Assoc. Petrol. Geol. Bull. 70 (1), 12–25.

Morley, C.K., King, R., Hillis, R., Tingay, M., Backe, G., 2011. Deepwater fold and thrust belt classification, tectonics, structure and hydrocarbon prospectivity: a review. Earth Sci. Rev. 104, 41–91.

Pavlis, T.L., 2013. Kinematic model for out-of-sequence thrusting: motion of two ramp-flat faults and the production of upper plate duplex systems. J. Struct. Geol. 51, 132–143.

Peach, B.N., Horne, J., Gunn, W., Clough, C.T., Hinxman, L.W., Teall, J.J.H., 1907. The Geological Structure of the N.W. Highlands of Scotland. Memoirs of the Geological Survey U.K.

Ramsay, J.G., 1967. Chapter 7: Folds and folding. In: Folding and Fracturing of Rocks. McGraw-Hill Book Company.

Stewart, A.D., 2002. The Later Proterozoic Torridonian Rocks of Scotland: their Sedimentology. Geochemistry and Origin. Geological Society, London, Memoirs, p. 24.