**Evidence for pre-Caledonian discontinuities in the Achnashellach Culmination, Moine Thrust Zone: the importance of a pre-thrust template in influencing fold and thrust belt development**

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**Abstract**

South of the Loch Maree Fault in the Northwest Highlands of Scotland, an unexplained step-wise thickening of Torridon Group strata, from approximately 200 m to 1000 m, occurs towards the Loch Maree Fault, within the trailing edges of the stacked thrust sheets of Achnashellach Culmination in the Caledonian Moine Thrust Zone.

This thickening cannot be explained readily by Caledonian thrust tectonics alone, and suggests that thrusting was superimposed upon a Pre-Caledonian non-layer-cake template giving rise to a thrust parallel thickness change of Torridon Group strata in the thrust belt. Cross-section constructions within the culmination constrain discrete abrupt thickness changes of the Torridonian succession preserved within the Coire nan Clach and Toll Ban thrust sheets. We infer the existence of a pre-existing discontinuity in the form of either a set of Pre-Caledonian faults striking parallel or sub-parallel to the long-lived Loch Maree Fault in its south-western wall, or palaeovalleys creating locally greater thicknesses of Torridon Group sediments in the pre-thrust template. Such palaeovalleys may have been eroded along pre-existing discontinuities. In either case, these discontinuities will have contributed to generating step-wise thickness changes in preserved Torridonian Group strata prior to Cambro-Ordovician overstep and then contributed to controls on the observed (lateral) variations in thrust architecture and the northwards step-wise thinning of the Achnashellach Culmination towards the Loch Maree Fault. This northern termination of the Achnashellach Culmination demonstrates the importance of the pre-thrust template in constraining the three-dimensional architecture of lateral changes within fold-and-thrust belts.

**Background**

The classic study of fold-and-thrust belts assumes simple layer-cake sequences and geometries prior to compression and thrusting. More recently, studies have revealed many examples where this is not the case, and pre-existing faulting, basin architectures, or a combination of same have influenced the structural development of the later thrust belt. (e.g. Mitra 1988; Paulson & Marshak 1997, 1998; Thomas 1990; Alsop *et al*. 1996; Fermor 1999; Bégin & Spratt 2002; Soto *et al*. 2002; Thomas & Bayona 2002; Krabbendam & Leslie 2010). Pre-thrust geometries that strike oblique, or normal to the later thrust transport direction can contribute to the formation of a transverse zone in the later belt. Such zones are recognised in both brittle and ductile fold and thrust belts and several transverse zones have been identified and studied within the Moine Thrust Zone (e.g. Alsop *et al*. 1996; the *Oykel Transverse Zone,* Leslie *et al*. (2010); the *Traligill* *Transverse Zone,* Krabbendam & Leslie (2010)).

Features that have been used to identify structures such as transverse zones, lateral ramps or lateral culmination walls in map view in fold and thrust belts include plunging ends of ramp anticlines, bends of longitudinal thrust faults and associated folds, transverse faults, changes in stratigraphical level of detachment, displacement transfer between frontal ramps and changes in structural style (Calassou *et al*. 1993; Paulson & Marshak 1997; Thomas 1990; Thomas & Bayona 2002). Experimental sand-box studies examining the effects of basement faults that trend parallel to the thrust direction have also revealed identifying geometries that include: (i) lateral inter-fingering of thrust sheets in map and cross-section, producing a bend in the thrust front, and (ii) contrasting thrust geometries in the compartments on either side of the transverse zone with fewer but thicker thrust sheets on the downthrown faulted side (Calassou *et al*. 1993).

Both experimental and field based studies have produced a number of theories about conditions required for the formation of transverse zones. So-called zones of weakness can be caused by lateral facies changes within stratigraphy (Kwon & Mitra, 2012), or palaeo-topographic surfaces which could conceivably provide ‘easy glide’ horizons perpendicular to the thrust transport direction. Alternatively, pre-existing ‘parental’ basement faults that are active during or after the deposition of cover strata can juxtapose comparatively thin and thick packages of stratigraphy, causing the distortion of the regional thrust-related strain field and the subsequent formation of a transverse zone when incorporated into thrust belts (Krabbendam & Leslie 2010).

Recent structural mapping of parts of the Moine Thrust Zone in the Northwest Highlands of Scotland (Fig. 1) suggests that a distinct structural change takes place within the region of the Beinn Eighe Massif some ten kilometres to the southwest of the Loch Maree Fault. Here, units of Precambrian Torridon Group sandstone, with a total stratigraphical thickness of 1000 m form thick imbricate packages in the thrust zone (Butler *et al*. 2007). Just five kilometres northeastwards however, towards the Loch Maree Fault, Cambro-Ordovician quartzites are present only 200 m above the floor thrust, indicating significant thinning of the Precambrian sediments. This change suggests structural compartmentalisation within the Beinn Eighe region that here is interpreted as reflecting significant differences in the pre-thrust template from southwest to northeast.

This work presents a detailed reappraisal of the structural styles and thrust geometries observed on Beinn Eighe, the kinematic behaviour observed in the units exposed, and observations on the interactions between different stratigraphical units. This has enabled construction of detailed transport-parallel and transport-lateral cross-sections through and across the Beinn Eighe Massif. Detachment levels are identified in a model of the pre-thrust template so derived that explains the thickness changes of the Precambrian sediments that are observed across the Beinn Eighe Massif.

The thrust imbricate structure observed on the Beinn Eighe Massif is developed in a relatively simple stratigraphy, comprising Neoproterozoic and Cambro-Ordovician sediments that unconformably overlie the basement gneisses of the Lewisian Gneiss Complex (Fig. 1). The basal unit of the sequence is characterised by lenticular heterolithic units of conglomerate, breccia sandstone and mudstone (Diabaig Formation) overlain by several kilometres of coarse, red, arkosic, cross-bedded sandstones (Applecross Formation) and that together comprise the Torridon Group (Stewart 2002). A major unconformity separates the Torridon Group from the overlying Cambrian marine sediments, that consist of the cross-bedded Basal Quartzite member, and the intensely bioturbated (*Skolithos*) Pipe Rock member of the Eriboll Formation (Wilkinson *et al*. 1975; Coward & Kim 1981; Park *et al*. 2002).

**Geological Setting**

The structural geometries exposed across the Beinn Eighe Massif form part of the Moine Thrust Zone (MTZ) a fold and thrust belt that defines the northwestern limit of the penetrative Scandian (Silurian) phase of Caledonian orogenic deformation in the region (e.g. van Breemen *et al.* 1979; Freeman *et al*. 1998; Dallmeyer *et al*. 2001; Strachan *et al*. 2002; Cocks and Torsvik 2011). During this phase of the Caledonian Orogeny, Proterozoic to Ordovician sediments deposited on the continental margin of Laurentia were transported several tens of kilometres to the west-northwest (e.g. Strachan *et al*. 2002). Evidence for these ductile and brittle movements is presented by deformed *Skolithos* (worm tubes) and stretching lineations in mylonites (Wilkinson *et al*. 1975; Coward & Kim 1981; Butler *et al*. 2007). The MTZ dips gently towards the east-southeast, with an onshore strike length of approximately two-hundred kilometres between Loch Eriboll on the north coast of the Northwest Highlands, and the Isle of Skye to the southwest. Offshore from Loch Eriboll, the MTZ can be traced northeastward with some offsets towards Shetland, and southwestward from Skye to towards Mull, a distance of around five-hundred kilometres in total (Ritchie *et al*. 1987; Strachan *et al*. 2002).

*The Achnashellach Culmination*

The Beinn Eighe Massif is situated in the northern part of the Achnashellach Culmination, which forms a bulge in the Moine Thrust Zone. The culmination is located between the villages of Kinlochewe and Kishorn (Fig. 1). The culmination comprises imbricate stacks of Torridon Group rocks with a maximum stratigraphical thickness of c. 1000 m) along with approximately stratigraphical thickness 200 m of Cambro-Ordovician strata (Fig. 2), with ramp-on-ramp structural geometries forming a stack of alternating Torridonian and Cambro-Ordovician strata (Butler *et al*. 2007). The Moine Thrust *s.s.* does not directly overlie the Achnashellach Culmination; instead allochthonous Lewisian Gneiss rocks and Torridonian strata contained within the Kinlochewe Thrust Sheet (Fig. 1) form the roof in the north of the culmination, whilst younger, Durness Group strata are contained within the thrust sheet on the Meall a’Ghubhais Klippe farther west in the northern part of the culmination (Butler *et al*. 2007). Southwards, the structural position of the Kinlochewe Thrust Sheet is replaced by the Kishorn Thrust Sheet (Fig. 1), (Coward & Whalley 1979; Butler 2009).

The northern termination of the culmination is defined by the Loch Maree Fault (LMF, Fig. 1), (Butler *et al.* 2007). This structure marks a distinct lateral change in thrust architecture, effectively compartmentalising the Moine Thrust Zone. North of the Loch Maree Fault, both right-way-up and over-turned Torridonian and Lewisian rocks are structurally emplaced above Cambro-Ordovician sediments, and Torridon Group strata are devoid of any syn-sedimentary thickness changes. The maximum thickness of these strata present is c. 100 m thick to the north of the LMF, whereas to the south it is up to 1000 m. A sharp change occurs to the south of the LMF, where the more classically imbricated system is developed within Neoproterozoic and Cambro-Ordovician sediments.

**Thrust architecture of the Beinn Eighe Massif**

The Beinn Eighe Massif preserves a thrust architecture that can be divided into six discrete thrust sheets. These sheets are separated by large, map-scale thrusts termed here as the Coire Domhain Thrust, the Sgurr na Conghair Thrust, the Toll Ban Thrust, the Coire an Laoigh Thrust and the Sole Thrust. These structures act as major controls on the observed geometries as clearly seen in Figure 3. The dramatic mountainous terrain across the Beinn Eighe Massif provides up to 900 m of vertical relief and some excellent bedrock exposure (Fig. 3), thus allowing for a detailed examination of the preserved three-dimensional geometries.

The eastern-most major thrust sheet has been transported on the Coire Domhain Thrust. The sheet contains a number of subsidiary thrusts which together constitute an imbricate fan (**A** on Fig. 2), generated from a branch point in the extreme north-east part of the mapped area (**1** on Fig. 4). In three-dimensions, the Sgurr na Conghair Thrust functions as an undisturbed roof thrust to the thrust system exposed across Beinn Eighe (**B** on Fig. 4). The rocks in the footwall of the Sgurr na Conghair Thrust were transported by movement along the Creag Dhubh Thrust, and subsequently form constituent parst of the Creag Dhubh Thrust Sheet. This thrust sheet contains a second imbricate fan, with a branch point just north of the Beinn Eighe ridge (**2** on Fig. 2; **C** on Fig. 4). Many of the splays cannot be followed southward within the mapped area, and instead tip out within the Torridon block.

In the centre of the mapped area, the Toll Ban Thrust transports the Toll Ban Thrust Sheet, which shows a large and consistent stratigraphical separation, emplacing Torridon Group sandstones onto Pipe Rock in the both the north and south (**D** on Fig. 4). West of the Toll Ban Thrust, the geometry of the system changes and the frequency of subsidiary thrusts decreases and the thickness of the imbricates increases (**E** on Fig. 4). The Coire an Laoigh Thrust Sheet underlies the Toll Ban Thrust and contains a much greater volume of Torridon Group sediments, particularly towards the south of the sheet where much thicker imbricates are accommodated by a much deeper detachment (**3** on Fig. 2). Northwards along strike, the volume of Torridon Group rocks in the Coire an Laoigh Thrust Sheet decreases in a similar manner as it does in the structurally higher thrust sheets. The decrease of Torridon Group rocks marks a significant thinning of the Coire an Laoigh thrust sheet along strike from south to north, clearly cpoincident with the deflection in the Coire an Laoigh Thrust shown on the transverse cross-section (**F** on Fig. 4). The thinning of this sheet is accompanied by a strike-parallel and northward loss of stratigraphical separation, with Basal Quartzite replacing the Torridon Group sandstones in the immediate hanging-wall at the same topographical level, marking a significant climb to a higher stratigraphical level of the Coire an Laoigh Thrust (**4** on Fig. 4).

The youngest thrusts are contained within the Sole Thrust Sheet (Fig. 2), which contains a network of individual thrust faults alongside a large hanging wall anticline and mimics the Coire an Laoigh thrust in both geometry and stratigraphical separation trend (**5** on Fig. 2), losing stratigraphical separation northwards along strike.

Overall, as the thrust stack developed by west-northwest translation, the number of individual thrusts formed in the various thrust sheets decreased. The structural style and thickening developed by imbricate fans in the structurally higher parts of the massif did not develop in the structurally lower thrust sheets. These lower sheets are characterised by a reduced number of sinuous thrusts, alongside a greatly increased volume of Torridon Group sediments, particularly in the southern part of the mapped area, thus requiring a considerably deeper level of detachment (Fig. 4 – C-C’).

**Interpretation**

The mapped thrusts and cross-sections demonstrate that there is a discrete and significant increase in the preserved volume of Torridon Group strata southward. The step in thickness of stratigraphy contained within the Sole Thrust Sheet is demonstrated on the transverse cross section (Fig. 4 - B’ - B), where the level of the Soul Thrust decreases from c.-200m to c. -1100m southwards. A similar, mimicked trend can be seen within the Coire an Laoigh thrust sheet, which also contains a significantly increased volume of Torridon Group sandstones southward as the thrust decreases in elevation from c.300mto –c.100m southwards.

We propose that this increase in thickness is not easily explained by a layer-cake pre-thrust template, and instead is the result of compression superimposed on a pre-existing variable thickness geometry with an already increased volume of Torridon Group sediments preserved south of what has become the modern day exposed Beinn Eighe ridge. We propose that this northward thinning is a result of either a pre-existing structural template related to thickness changes across Precambrian faults, or the perhaps to the existence of a large palaeovalley infilled by Torridon Group Sediments. The latter may of course have been preferentially eroded along a pre-existing fault-related linear discontinuity of Precambrian age.

**Discussion**

Unlike many other studies (Butler et al. 2007; Krabbendam & Leslie 2010 and references therein) which examine transverse zones, the proposed potential causes of thrust parallel discontinuities across the Beinn Eighe Massif are cryptic in nature, and not openly represented by the present-day exposure. However, the interpretations are based on a well constrained map and a series of cross-sections and we below present the most pragmatic explanations for the distinct thickness change of the Torridon Group northward towards the LMF.

The proximity of the Beinn Eighe Massif to the long-lived, Loch Maree Fault, which is a significant northwest-southeast, structure that downthrows to the southwest with well evidenced pre- and post-Torridonian movement as well as post-Caledonian movement (Stewart 2002; Butler *et al*., 2007) may provide potential clues to a pre-thrust structural template that could have accommodated northward thickening of the Torridon Group strata prior to Cambrian overstep. We propose, as a first hypothesis, that a set of synthetic faults parallel to the Loch Maree fault produced fault blocks containing varying thicknesses of Torridon Group strata prior to Caledonian thrusting (Fig. 5). As the subsequent thrust front advanced, lateral ramps and geometrical anomalies were created by pre-existing structure, which may have compartmentalised the later compressional structure into the different zones of structural styles that are mapped (Fig. 2). Similar fault models have been observed in the Tralligil transverse zone, which overlies the pre-existing Loch Assynt fault, giving rise to (Krabbendam & Leslie 2010).

Whilst a pre-thrust template created by LMF-related structures could create the contrasting thicknesses of Torridon Group strata required to generate the present day thrust architectures there is a distinct lack of outcrop evidence for the Pre-Cambrian post-Torridon Group deposition faulting, so it is important to investigate other potential causes of thrust-parallel discontinuity. Attention must be given to the impact of paleovalleys and other paleo-erosional surfaces preserved within the Lewisian basement. Palaeorelief of at least 300 m occurred near Slioch, just NE of the Loch Maree Fault (Peach et al. 1907). Palaeovalleys are partially filled by the Diabaig Formation (Stewart 2002; Kinnaird et al. 2007) and can create undulating and non-linear thrust surfaces in the later thrust sheets.

Across the mapped area of the Beinn Eighe Massif no explicit evidence can be gathered from the distribution of the Diabaig formation as it not mappable. The preserved strata may provide some evidence however, as south of the Beinn Eighe ridge, within the largest volume of Torridon Group sediments multiple soft-sediment deformation and de-watering structures can be observed. The lack of any such sedimentary structure in the north of the mapped ground may suggest that sediment was being deposited much more quickly in the south, in a relatively deeper depocentre such as a large valley. It is possible, that such palaeotopography may have been controlled by late by the development of pre-Torridonian, Late Laxfordian (1400 – 1200Ma) northwest – southeast trending structures (Beacom *et al*. 2001).

Kwon and Mitra (2012) suggest another alternative theory, proposing changes in along strike stratigraphical level of thrusts may be attributed to primary sedimentary basin shape or lateral facies variations. Such explanations may allow for the shallowing of the Achnashellach floor thrust, but run into problems when the general thickness and continuity of the Torridon Group are considered.

**Conclusion**

The detailed re-mapping of the Beinn Eighe Massif, along with the construction of several transport-parallel and transport-lateral cross sections has identified a lateral step of the Sole Thrust zone, causing Torridon Group strata to undergo stepwise thinning northeast-wards towards the Loch Maree Fault. The interactions between an advancing thrust fronts, combined with a pre-existing basement anomaly has produced an interesting series of discontinuities within the Torridon Group strata across the Beinn Eighe Massif. We propose a pre-thrust template that relies on the existence of either pre-existing, Precambrian extensional faults related to the long lived Loch Maree Fault, perhaps combined with the effects of palaeotopography controlled by late by the development of pre-Torridonian, Late Laxfordian (1400 – 1200Ma) northwest – southeast trending structures.

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**Figure Captions**

**Fig. 1:** A simplified geological map of the Moine Thrust Zone at the Achnaschellach Culmination alongside the simplified stratigraphy with thicknesses appropriate for the Achnaschellach area. Study area is highlighted by box. KTS, Kinlochewe Thrust Sheet; LMF, Loch Maree Fault; SCF, Strathcarron Fault; MTS Moine Thrust Sheet; KL, Kinlochewe; KH, Kishorn; BE, Beinn Eighe; MAG, Meall a’ Ghuibhais Klippe (modified after Butler *et al*. 2007; Park *et al*. 2002).

**Fig. 2:** A new structural geological interpretation of the Beinn Eighe massif, with areas of interest marked and key thrusts named. Grid ticks refer to NG square of the British National Grid. Contours are derived from OSGB projection and are spaced at 100 m. For location see figure 1.

**Fig. 3:** A field photograph taken looking north at the Beinn Eighe Massif. The foreland is on the left hand side of the image, with example thrust architectures marked in white. The distance between the two highest peaks is c.1000m

**Fig. 4:** Cross-sections drawn through the Beinn Eighe Massif (shown on Fig. 2). (A) The north-most section, with a relatively shallow detachment. (B). A NNE to SSW transverse section, showing thickness changes of Torridon contained within thrust sheets. (C) The southern-most section, with a much deeper detachment and a greater volume of Torridon Sandstone.

**Fig. 5:** A schematic ‘pre-thrust tamplate’ block diagram demonstrating the interpreted pre-thrust template for the Beinn Eighe Massif, showing a set of syn-depositional, extensional faults parallel to the Loch Maree fault, and associated conjugate syn-depositional extensional faults. The main Loch Maree-parallel fault (A) provides the down to the southwest step observed in the Corie an Laoigh Thrust, whilst a conjugate extensional fault (B) may be responsible for the change of structural style across the Toll Ban thrust.