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Cross-Strike Discontinuities (Transverse Zones): Lateral Variations within the Moine Thrust Zone, NW Scotland; the Cantabrian Arc, Northern Spain and Comparisons with Appalachian Transverse Structures*

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Abstract

Numerous authors have reported on geometry, kinematics, mechanics and hydrocarbon potential within fold-and-thrust belts. Whilst many works have dealt with palinspastic reconstructions and transport-direction-parallel balanced cross-sections, far fewer have focused on three-dimensional architecture of fold-and-thrust belts, or examined how lateral variations in thrust architecture in different segments of thrust belts are linked via so-called ‘transverse zones’. Systematic alignments of these lateral structures are suggested to include; sub-décollement basement faults, pre-thrusting cover strata deformation above basement faults, development of duplex structures/antiformal stacks, and/or along-strike variations in mechanical stratigraphy.

In this work, detailed three-dimensional topologies, geometries and kinematics of selected thrust systems are studied to fully analyse the evolution and cause/effects of lateral changes in thrust belts, in each case integrating the field and three-dimensional model interpretations. Project methodologies incorporate new studies of two well-understood and comprehensively mapped thrust belts; the Achnashellach Culmination/Loch Maree Fault, Moine Thrust Zone, NW Scotland and the Somiedo-Correcillas Unit, Cantabrian Arc, northern Spain. These are compared with structures situated within the Anniston, Bessemer and Harpersville transverse zones, Alabama, Appalachian Thrust Belt.

Findings achieved using branch-line/displacement vector analysis methodologies, stratigraphic separation diagrams, and full, sequential restorations of three-dimensional thrust models using new digital mapping/modelling methodologies, characterise the pre-thrusting template and asses that template's capacity to control subsequent lateral thrust geometries. Transverse zone structures are greatly dependent upon pre-thrust inheritance structures of the orogenic province. Within the study areas, frontal and/or lateral inheritance structures determine structural styles through the development of lateral ramps, displacement transfer faults and transverse faults, which in turn compartmentalise and segment fold-and-thrust belts creating stratigraphic separations and tectonic structures. Greater understanding of pre-thrust orogenic architecture within fold-and-thrust belts will greatly develop the understanding of global orogenic developments and provide important information for hydrocarbon exploration within potential complex orogenic exploration settings.

Achnashellach Culmination/Loch Maree Fault, Kinlochewe region, Moine Thrust Zone, NW Scotland

The Moine Thrust Zone represents the westernmost and youngest of the system of Scandian (395-425 Ma) thrusts on the mainland of Northern Scotland, defining the northwest edge of the Caledonian orogenic belt. The Moine Thrust Zone dips gently towards the ESE having an on-land strike length of c. 200 km between Loch Eriboll, northwest Highlands and the Isle of Skye, extending north-eastwards towards Shetland and south-westwards beyond Mull, totalling a distance of c. 500 km (Strachan et al., 2002) (Figure 1). Lithologies within this area comprise felsic to intermediate Archaean orthogneisses (Lewisian Scourian Gneisses); intruded by Early Palaeoproterozoic mafic and ultramafic Scourie dykes (Park et al., 2002). The complex is unconformably overlain by the early-Neoproterozoic Torridon Group (up to 1,000 m) comprising the Diabaig Formation, (breccias tabular sandstones, grey shales and sandstones) and the Applecross Formation, (red sandstones with trough and planar cross bedding). Another major unconformity separates the Torridon Group from the overlying Cambro-Ordovician succession, comprising up to 150 m of arenitic quartzites/coarse quartz arenite (Eriboll and An-t-Sron Formations). Structurally above the Moine Thrust, the Morar Group comprises a thick 5 km sequence of arkosic to sub-arkosic psammites with subsidiary pelite and semipelite of fluvial origin; all are of broadly similar age and origin to the Torridon Group of the foreland (Figure 2) (Johnstone et al., 1969; Brown et al., 1970; Butler et al., 2007; Krabbendam et al., 2008).

Previous work within the northern sections of the Achnashellach Culmination, towards the Loch Maree Fault (LMF) defines a structure developed in Cambrian quartzites and Torridonian sandstones. Distinct structural changes from north to south were recognised across the LMF at the northern termination of the culmination (Figure 3). New (2009 to 2011) detailed fieldwork along the north and south walls of the LMF at Kinlochewe allowed the generation of new transport-direction-parallel (Figure 3)/transport-lateral (Figure 4) cross sections and supported branch-line/displacement vector analysis across the northern termination of the culmination. A thrust dominated region of overturned Torridonian/Lewisian, overlying a right-way-up Cambrian succession can be clearly identified on the northern wall of the LMF (Figure 4), compared to a fold-and-thrust dominated section on the southern wall of the LMF. That section identifies a 'thin flap' of pipe rock/basal quartzite imbricates to the southeast of the Meall a' Ghuibhais Klippe comprising only 200 m of Eriboll quartzites and no Torridon within the thrust imbricates. This develops towards the hinterland into much thicker imbricate slices of pipe rock and Torridonian that can be traced farther south within the culmination into the Beinn Eighe region (Figure 3). Branch line/displacement vector analysis work within the region supports this conclusion and further illustrates locations of potential lateral structures, most notably the Beinn Eighe lateral ramp sequence in which a drastic imbricate style change can be seen from layer-parallel shear imbricates to thicker imbricate slices. Distinct compartmentalisation of the Moine Thrust Belt architecture is thus apparent across the LMF. The compartmentalisation is suggested to be a response to a step in basement that generated a transport-parallel lateral ramp or sidewall during thrusting. This transverse zone marks a change to the fold-and-thrust architecture of the southern sector of the Moine Thrust Belt.

Somiedo-Correcillas Unit, Cantabrian Arc, Northern Spain

The Iberian part of the Variscan Belt shows a prominent bend in the west, called the Ibero-Armorican or Asturian Arc (Matte 1991, Pérez-Estaún et al., 1994, Ábalos et al., 2002; Veselovský 2004). The Cantabrian Zone resides within the core of this arc, characterised by foreland-directed concavity with inward-facing structures (Veselovský 2004). Its western boundary is marked by the Narcea Antiform while its structural trend varies by about 180° around the Arc. Within the study area, Precambrian to Silurian sedimentary successions are dominated by siliciclastic sediments (Herrería, Oville, Barrios, Formigoso, San Pedro formations) and several long-term hiati. The only exemptions are lower Cambrian carbonates of the Láncara Formation. During the Devonian, alternating deposition of carbonates (Abelgas, Santa Lucía, and Portilla Formations) and siliciclastics (Esla, Huergas, Nocedo, and Fueyo Formations) evolved. The whole Cantabrian Zone was covered by siliciclastics (Ermita Formation) and condensed carbonates of the Alba Formation until the Early Namurian (Veselovský 2004). Thick syn-orogenic turbidites (Olleros Formation), initiated in the Serpukhovian Period, mark the onset of the Variscan orogenic phase in the Cantabrian Zone (Veselovský 2004). Large carbonate platforms developed (Barcaliente, Valdeteja formations), which were subsequently covered by terrigenous sediments from the approaching Variscan Orogen (San Emiliano Formation). Thicknesses of the mainly shallow marine Palaeozoic succession range between 3,800 to 5,000 m. Permian and Mesozoic/Cenozoic successions in the Cantabrian Zone were mostly eroded (if present at all).

New (2009 to 2011) detailed fieldwork along the trace of the Cantabrian Arc, has allowed the generation of new transport-direction-parallel/transport-lateral cross-sections and supportive branch-line/displacement vector analyses across this oroclinal system within key locations on a variety of scales. A regionally distinct structural style change to the southwest of the town of San Emiliano along the Villablino Hinge within the southwestern corner of the Cantabrian Arc can be clearly identified. This major structure separates the basin architecture of the southern arm of the Cantabria-Asturias Arc, (characterised by dominant thin-skinned tectonics with main detachment horizons located at the base of the Herrería and Láncara Formations (early Cambrian Period) and some minor décollements within higher stratigraphical horizons) from a major fold-and-thrust domain within the central and northern realms of the Cantabrian Arc. Thrust transport within the region taken from key kinematic indicator data across the Cantabrian Zone including; penetrative cleavages and deformation indicators such as quartz views, indicate a change from northwards (010) to north-eastern (030) transport regimes across this major hinge zone once the 30° rotation of Iberia is removed from the data. This possibly indicates an original slightly curved orogenic belt which has subsequently undergone rotation within individual thrust sheets, thus tightening structures within the region.

Within the Southern Cantabrian Zone, a “piggy-back thrust” mechanism shows a forward breaking sequence of individual thrust sheets as well as basal accretion within the Herrería Formation. Geometries are characterised by overlapping ramp anticlines, curved ramps, imbricated systems, duplexes and anticlinal stacks. The resulting thrust-sheet geometry is that of a series of individual ramp anticlines (according to the terminology of McClay 1992), although individual localised complexities also occur. Several out-of-sequence faults with unknown displacement factors and characteristics are present within the region. The most prominent of these is the León Line Fault System extending east-west for about 150 km. This fault system creates an important frontal inheritance structure, the Cueto Negra/Branillan Window along a potential basement derived lateral structure, which acts as a lateral sidewall orthogonal to the León Line. This major structure is interpreted as a half-graben, which has undergone inversion to its current position. Within the San Emiliano region, lateral inheritance structures can also be viewed within this hinge sequence. These include the Genestosa Fault system to the northwest of San Emiliano, which depicts abrupt changes in stratigraphic and structural architectures across this structure, possibly as the result of a basement fault. This structure compartmentalises the northern sectors of the Villablino Hinge, thus separating the fold-thrust domain from the dominant thrust domain.

Distinct localised structural style changes were also analysed and recorded to determine the role of inheritance structures within this complex structural setting through detailed remapping of key sites and detailed cross-sectional analysis. Localised detailed development of the different structural domains were also achieved using detailed collage montages of different structural styles including the original extension faults and subsequent inversion structures, fold/thrust structures, as well as localised back-thrust complexities in order to determine the chronology of deformation within the Cantabrian Zone. Results show the key interplay of extension, thrusting and wrench tectonics and the key role that these play in the evolution of the Cantabrian Zone, with regard to energy transfer due to thrust sheet rotations and reactivation of original extension structures. The data also adds weight to the interpretation that the dominant structures present within the Cantabria Zone are an overprint of later Hercynian orogenic progresses.

The Anniston, Bessemer and Harpersville Transverse Zones, Appalachian Thrust Belt, Alabama, U.S.A.

The southern Appalachian foreland thrust belt in Alabama and Georgia consists of late Palaeozoic (Alleghian), large-scale, northeast-striking thrust faults and associated folds bound by undeformed strata in the Black Warrior Foreland Basin on the northwest and by metamorphic thrust sheets of the Talladega Slate Belt and Appalachian Piedmont on the southeast. The southern Appalachian thrust belt consists of Palaeozoic sedimentary rocks that have been deformed by predominantly northeast striking, northwest-translated thrust faults and thrust-related folds during the late Palaeozoic Alleghanian orogeny (Thomas and Neathery 1980; Hatcher et al., 1989). Surface traces of the generally persistent strike-parallel structures are interrupted by three distinct transverse zones, the Bessemer Transverse Zone (TZ), Harpersville TZ, and the Anniston TZ (Groshong 1988; Cook and Thomas 2009). Palaeozoic rocks exposed within the study areas range in age from Late Cambrian to Early Pennsylvanian. Formal stratigraphic units include the Conasauga Formation; Ketona Dolomite; Knox Group undifferentiated; Chickamauga Limestone; Red Mountain Formation; Tuscumbia Limestone, Fort Payne Chert, and Maury Formation undifferentiated; Pride Mountain Formation; Hartselle Sandstone; Floyd Shale and Bangor Limestone undifferentiated; Parkwood Formation; and the Pottsville Formation, including the Boyles Sandstone Member.

The study areas of the Anniston, Bessemer and Harpersville transverse zone study areas were used as a comparative study against the two main locations to determine links between various geological settings and regimes. Fieldwork undertaken builds on the original interpretations and expands them through the creation of transverse cross-sections through key sites such as ‘The Knot’ (a horse block in the footwall of the Opossum Valley thrust sheet), within the Bessemer transverse zone. It has also allowed the generation of new transport-direction-parallel/transport-lateral cross-sections and supportive branchline/displacement vector analyses for this classic setting. Preliminary findings suggest an interaction between basement structures of the Birmingham basement fault system within the Bessemer transverse zone, where localised rotations of thrust sheets can be viewed. Key sites such as ‘The Knot’ clearly demonstrate the interaction of different structural styles, lithofacies and localised complexities. Two emergent frontal thrust ramps, the Jones Valley fault and the Opossum Valley fault are structurally jointed at this location and are the clearest expression of the Bessemer transverse zone within this region of the study area. Within ‘The Knot’, relationships can be seen between thrusting and extension with key data indicating the classic northwest-translated thrust transport direction. Detailed montages within this structure indicate the key stratigraphical relationships between competent Knox Group units and the less competent units of the Fort Payne Chert/Tuscumbia Limestone/Maury Formation undifferentiated beneath. These findings are also displayed in the analysis of the branchline/displacement vector analysis where alternations between hanging-wall ramps and hanging-wall flats display the structural relationships within the Bessemer transverse zone around ‘The Knot’ region.

Interactions within the Anniston and Harpersville transverse zones are much harder to interpret (based mainly on lack of decent exposure within the limited field season). Key locations analysed through detailed collage montages within these transverse zones do however, demonstrate the overall transport within this fold-thrust-belt setting with northeast striking, northwest-translated thrust faults and thrust-related folds present. Regional expressions of structures such as the Fort McClellan window (an eyelid window between the up-turned, northwest-dipping Pell City fault and the southeast-dipping Jacksonville fault) and adjacent windows also demonstrate similar findings, as well as the detailed interactions of thrusting and extension. It is therefore evident that on the scale of the Appalachian Thrust Belt, Alabama, a regional map approach is crucial for identifying key lateral structures, where localised sections will not give the overall structure.

Discussion

The identification of transverse zones must contend with several key questions; (1) What types of transverse structures are important; (2) the significance of the thrust transport relative to transverse structures and; (3) the significance of the pre-thrust template in the creation of such structures. It is clear that transverse zone research has to be implemented on a variety of scales. Firstly, a regional overview must be taken to overview the structural and lithological style changes before a detailed locality based study can be undertaken.

Within the Moine Thrust Belt at the Loch Maree Fault and within the Somiedo-Correcillas unit in the Cantabrian Arc, a distinct structural change from a fold-thrust dominant region to a thrust dominant region can be clearly seen. In this way, the two sites share a common heritage of potential basement faults or basement steps in the form of the Loch Maree Fault sidewall and Genestosa fault respectively. However, within the Moine Thrust Belt, this lateral variation is also clearly a response to stratigraphical controls. Clastic sediments on the southern side of the LMF are bulged up during the development of the Achnashellach Culmination and contrast with crystalline Lewisian gneisses on the northern side, which restrict the bulging of the culmination to the southeastern sections of the northern sidewall, thus resulting in the creation of a deformed lateral sidewall.

Within the Cantabrian Arc, a homogeneous stratigraphy is evident on both sides of the Genestosa fault. Therefore, a structural control is more likely to be important within this setting. This could be a result of the polyphase deformation history of Cantabria, in which Variscan east-west orientated structures were reactivated into a north-south orientation during the Hercynian orogeny creating buttressing effects and regional thrust sheet rotations. This also further complicates the identification of transverse zones within this region as structures will have been far travelled, and therefore not over their creative origins. This is in comparison to the LMF which has a polyphase deformation history, but one in which thrust translated has been in a uniform manner, therefore removing any rotational complexity.

Within the Appalachian thrust belt in Alabama, it is clear that within certain sections, such as the Anniston transverse zone, a basement fault control could be present creating structures such as the thrust terminations around the Angel region and the localisation of structures such as the Fort McClellan Window. However, within the Bessemer and Harpersville transverse zones, no basement faults have been interpreted. This could therefore indicate a more stratigraphical influence concerning the location of the transverse zones.

It is therefore also clearly important to understand the pre-thrust template and the orientation of thrust translation in response to that template. Within the LMF region a clear basement step structure along a Palaeoproterozoic shear zone has acted as a focus for lateral variations to occur, creating compartmentalisations along the Moine Thrust Belt because of structural and lithological changes either side of this basement structure. In Cantabria however, the reactivation of Variscan structures through the processes of inversion and thrust sheet rotations can be clearly seen. This is a result of buttressing due to polyphase orthogonal orogenic events within the Cantabrian Arc. Within the Appalachian belt in Alabama, it is clear that basement faults have played a part in the localisation of transverse zones. However, it is clear that a stratigraphical interpretation is key to the localisation of thrusting and as a result of this, localised complexities, culminating in structures such as ‘The Knot’, within the Bessemer transverse zone have been produced.

Within the study areas, it can be clearly seen that transverse zone structures are greatly dependent upon their pre-thrust inheritance template. Frontal and/or lateral inheritance structures determine structural styles through the development of lateral ramps, displacement transfer faults and transverse faults, which in turn compartmentalise and segment fold-and thrust belts creating sharply varying stratigraphic separations and anomalous tectonic structures. Greater understanding of pre-thrust orogenic architecture within fold-and-thrust belts is therefore essential for understanding of global orogenic developments. The identification of these structures and their linkages provides crucial information for hydrocarbon exploration within potential complex orogenic exploration settings with regards to potential migration pathways.

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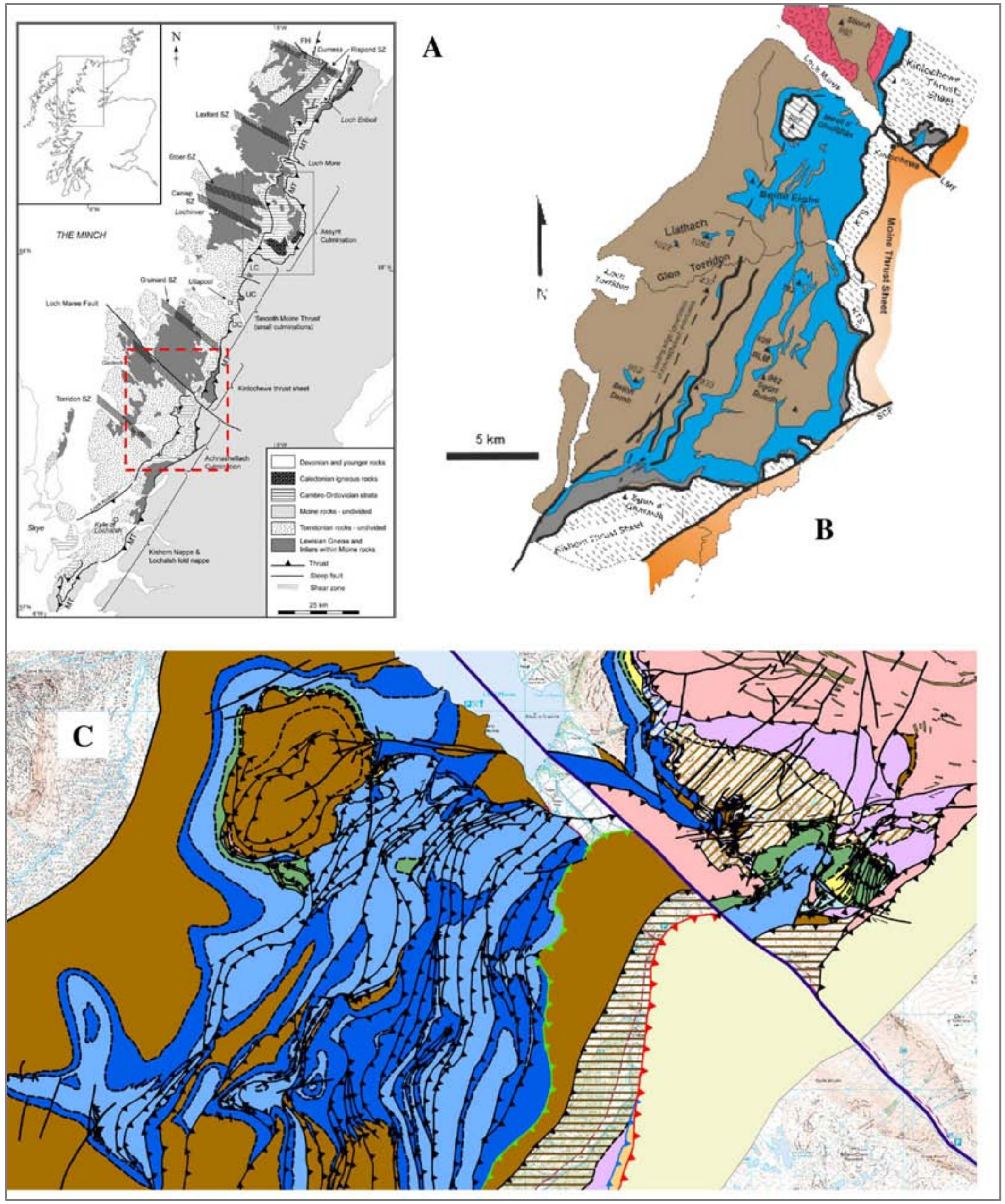

Figure 1. (A) Location of the Achnashellach Culmination/Loch Maree Fault within the Moine Thrust Belt (Modified from Krabbendam and Leslie 2010). (B) The Achnashellach Culmination in detail (Modified from Butler et al., 2007). (C) The Loch Maree Fault and the northeastern sections of the Achnashellach Culmination following the detailed remapping (2009 to 2011).

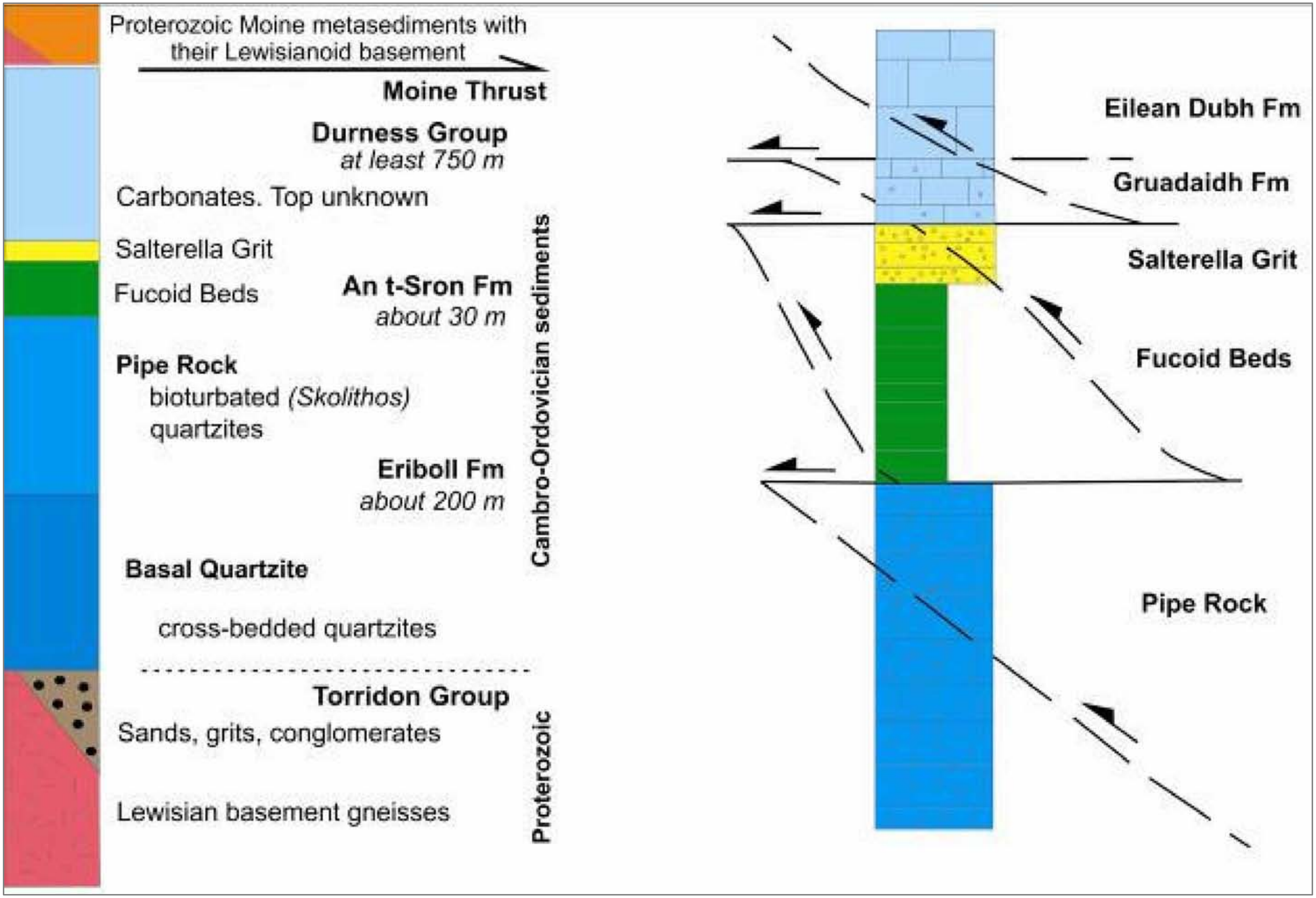

Figure 2. Stratigraphy and structural detachments present within the study area of the Loch Maree Fault (LMF) / Achnashellach Culmination within the northwest Highlands of Scotland (Modified from Butler et al., 2007)

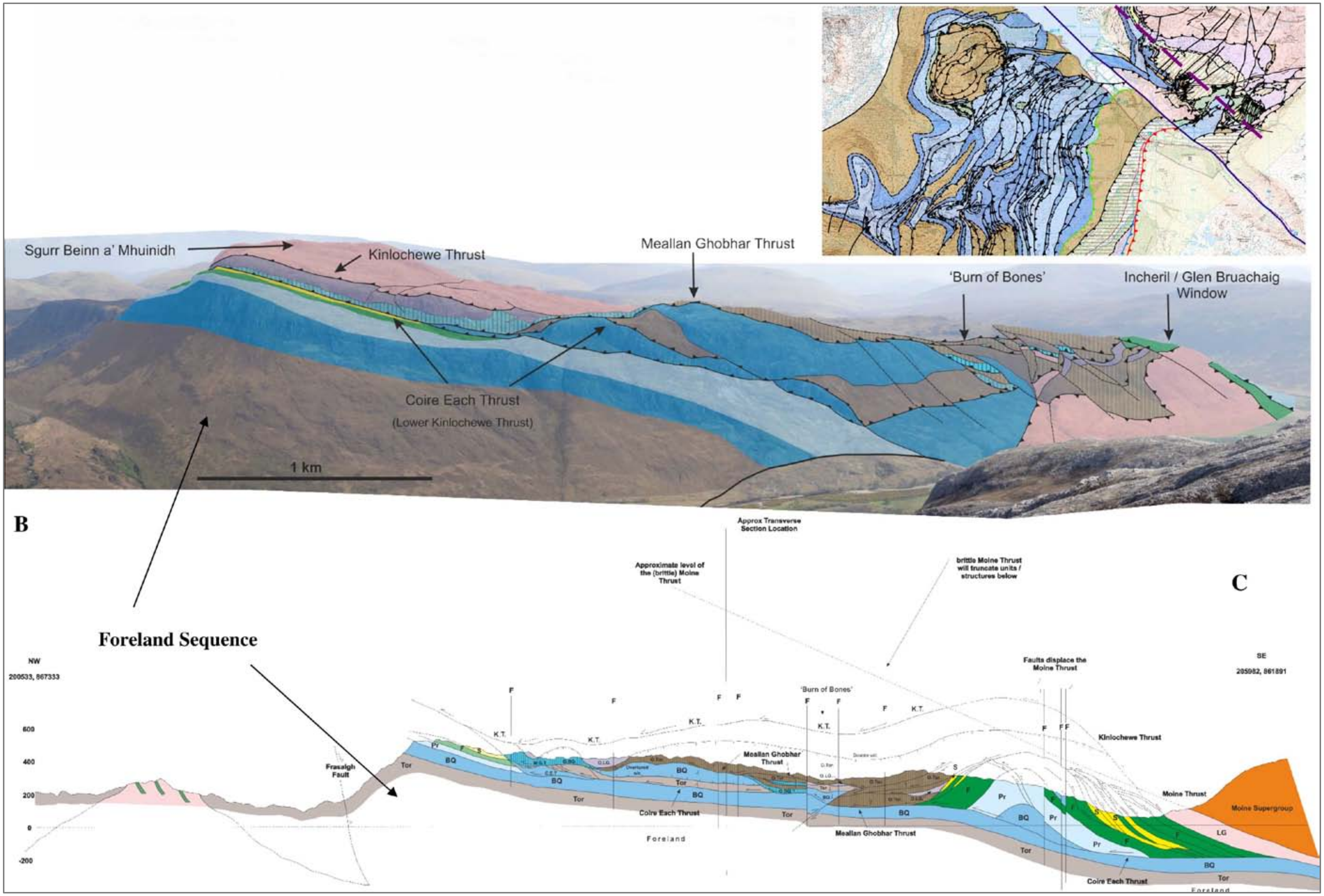

Figure 3. (A) Location of the Loch Maree Fault (LMF) parallel cross-section on the northern side of the LMF where a drastic contrast in thrust sheet architecture occurs (B and C) between right-way-up stratigraphy (solid colours) and overturned thrust sheets (hatched colours). In these images, it can be clearly seen the interaction and development of the thrust sheets on the northern side of the LMF. This major interaction on the northern side of the LMF, where the contrast is most clearly seen, is due to an earlier phase of folding which were then subsequently tightened and thrusted placing overturned units over a right way up Cambro-Ordovician succession.

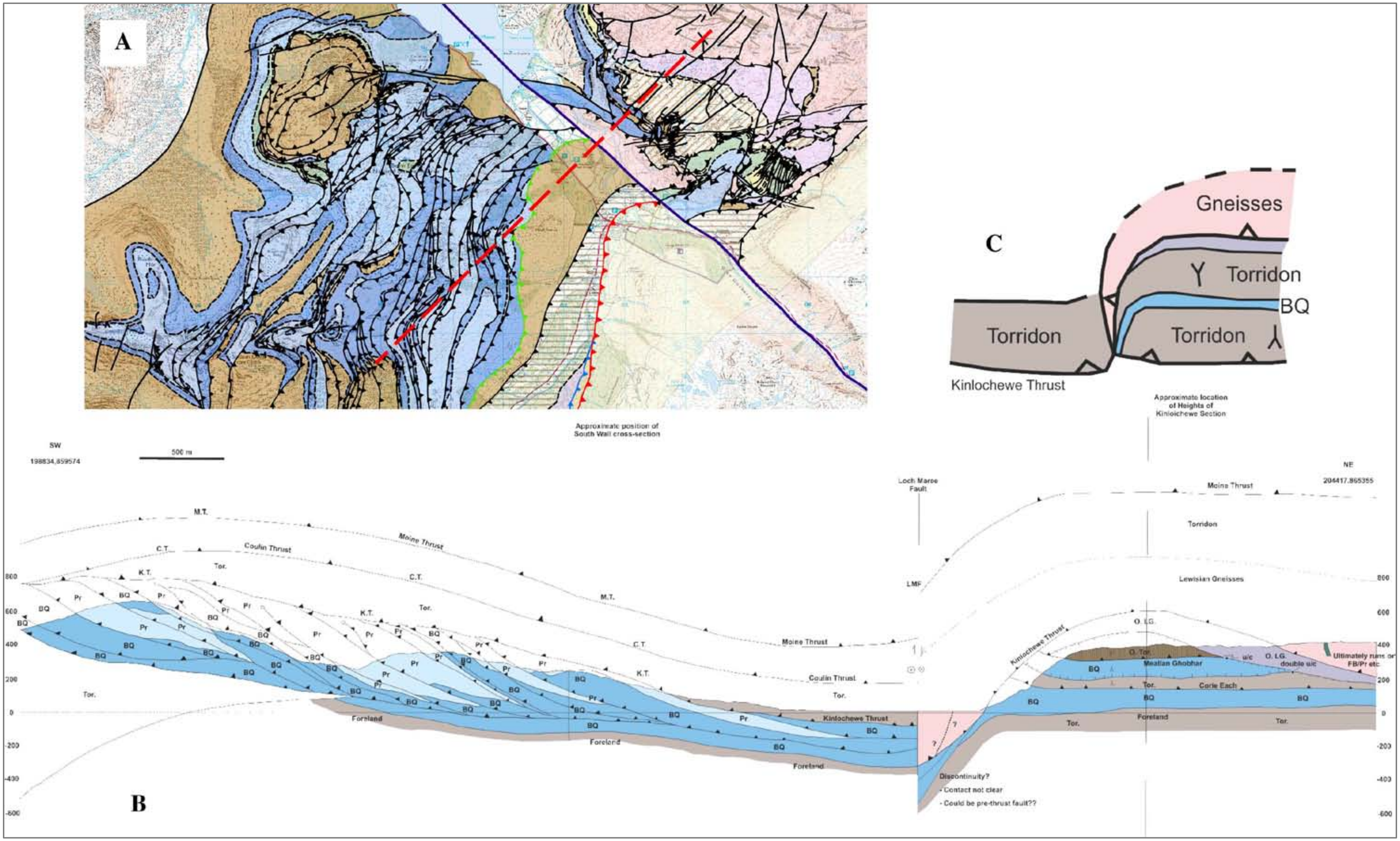

Figure 4. (A) Overview of the study area after the detailed 2009 to 2011 remapping depicting the abrupt lateral changes across the Loch Maree Fault (LMF) with the location of the transverse section present (red dotted line) demonstrating the transverse structural view across the LMF (B). The interpreted LMF sidewall present at the interaction with this cross-strike discontinuity is also shown for greater clarity (C).