Weakening mechanisms and the role of easy slip horizons in thrust belt development: a microstructural approach

Moine Thrust Zone, NW Scotland

The Late Silurian Moine Thrust Zone (MTZ) formed during final stages of Caledonian orogeny that culminated on the Iapetus closure. The thrust faults in the MTZ typically show ramp-flat geometries, with bedding-parallel flats often following specific stratigraphic horizons over long distances (regionally accommodating over 100 km WNW dip slip motion; Elliott and Johnson, 1980). The Cambro-Ordovician sedimentary sequence is intrinsically involved in this complex imbrication zone, suggesting these units may have acted as easy-slip horizons. In this work, we focus on the structurally lower thrust sheets of the MTZ, where the effects of mylonitization are limited or absent.

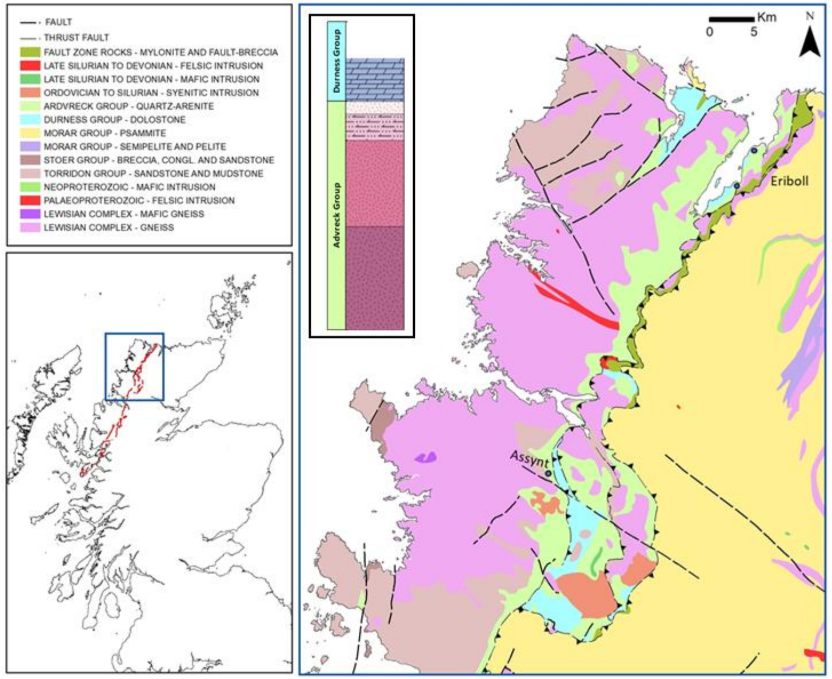


Figure 1- Geological map of Northern Moine Thrust Zone, Scale 1:625.000. modified from Geological Survey of Great Britain; DigMapGB-625, 2010.

Cambro-Ordovician sedimentary sequence and deformation localization

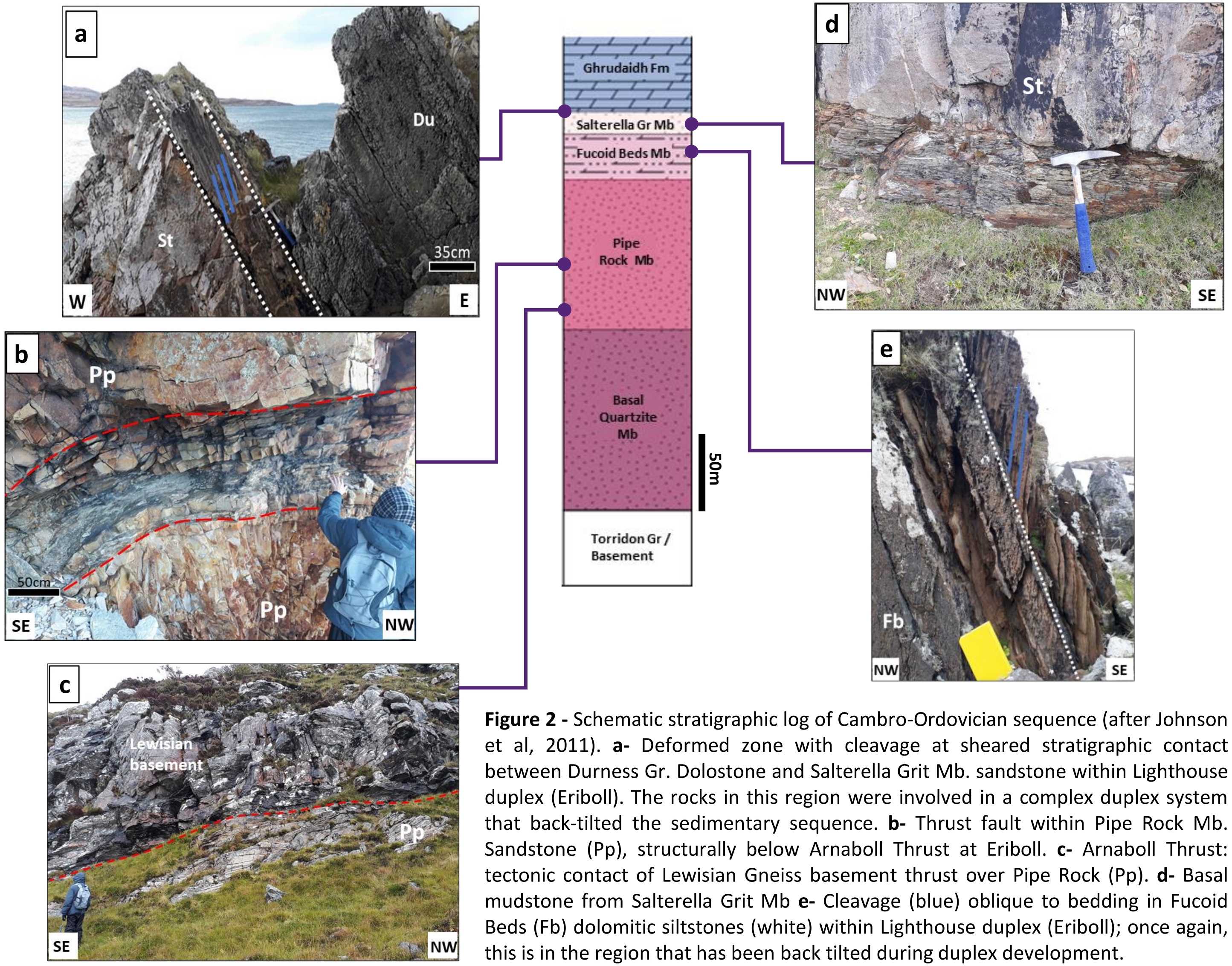


Figure 2 - Schematic stratigraphic log of Cambro-Ordovician sequence (after Johnson et al, 2011). **a-** Deformed zone with cleavage at sheared stratigraphic contact between Durness Gr. Dolostone and Salterella Grit Mb. sandstone within Lighthouse duplex (Eriboll). The rocks in this region were involved in a complex duplex system that back-tilted the sedimentary sequence. **b-** Thrust fault within Pipe Rock Mb. Sandstone (Pp), structurally below Arnaboll Thrust at Eriboll. **c-** Arnaboll Thrust: tectonic contact of Lewisian Gneiss basement thrust over Pipe Rock (Pp). **d-** Basal mudstone from Salterella Grit Mb **e-** Cleavage (blue) oblique to bedding in Fucoid Beds (Fb) dolomitic siltstones (white) within Lighthouse duplex (Eriboll); once again, this is in the region that has been back tilted during duplex development.

Deformation versus lithology - a microstructural approach

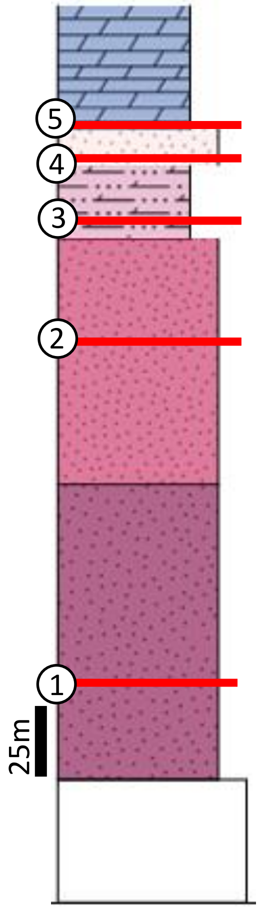
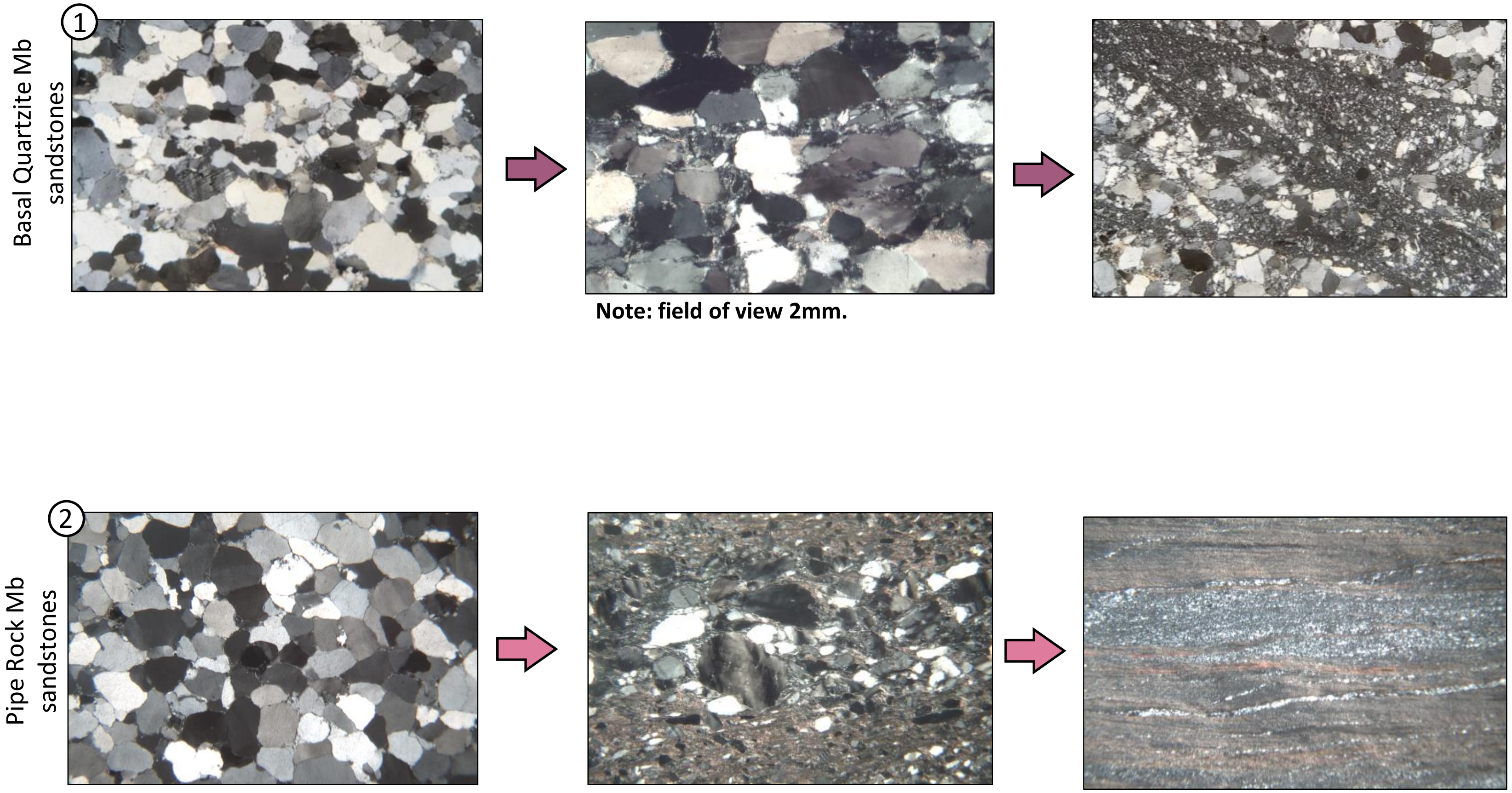


Figure 3- Simplified Cambro-Ordovician log. In red, schematic stratigraphic position of faults rocks addressed in this study.

Underformed

Deformed



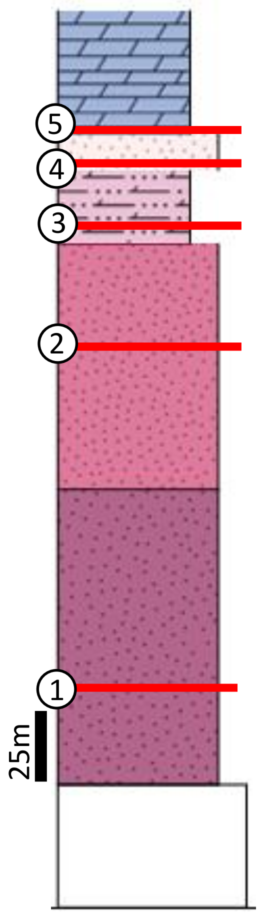
Photomicrographs (cross polarized light) of microstructures comparing undeformed and deformed rocks. Field of view 4mm.

Basal Quartzite member coarse sandstones have higher content of feldspars, including sub-arkose levels. The profuse presence of this group of minerals, that behave essentially in a brittle manner in the shallow crust, explains the dominant deformation mechanism taking place be the brittle fracturing of framework grains, leading to the onset of cataclastic flow, in the final stages of thrusting. Dissolution and chemical enhanced alteration of feldspar, locally forming clay matrix, lead to limited development of interconnecting weak layers with load-bearing framework maintained.

Quartz-rich load-bearing framework of Pipe Rock member, during deformation, is progressively cut by clay matrix interconnected layers. Remaining quartz-rich bands undergo grain size reduction through dynamic recrystallization (bulging and sub-grain rotation), forming elongate mantled quartz grains. Clay matrix layers increasingly interconnect, and quartz-rich bands displays very fine-grained quartz neoblasts in heavily deformed phyllonite.

Deformation versus lithology - a microstructural approach

Underformed | Deformed



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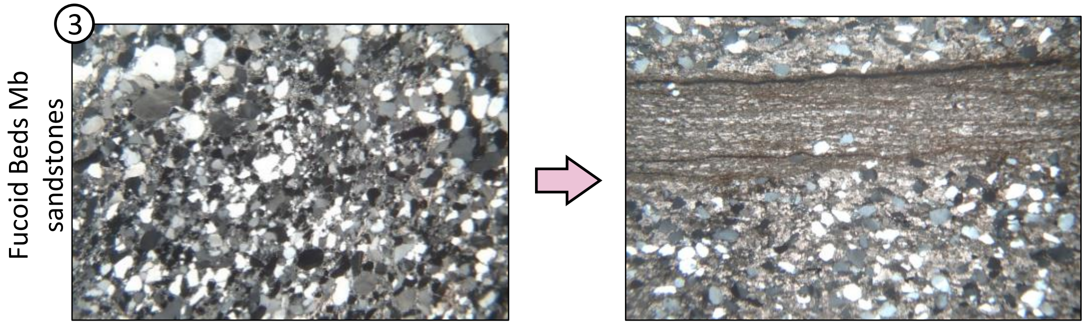
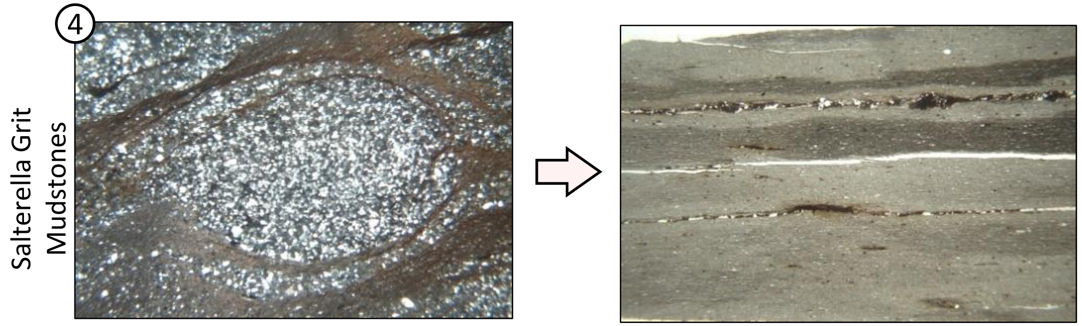
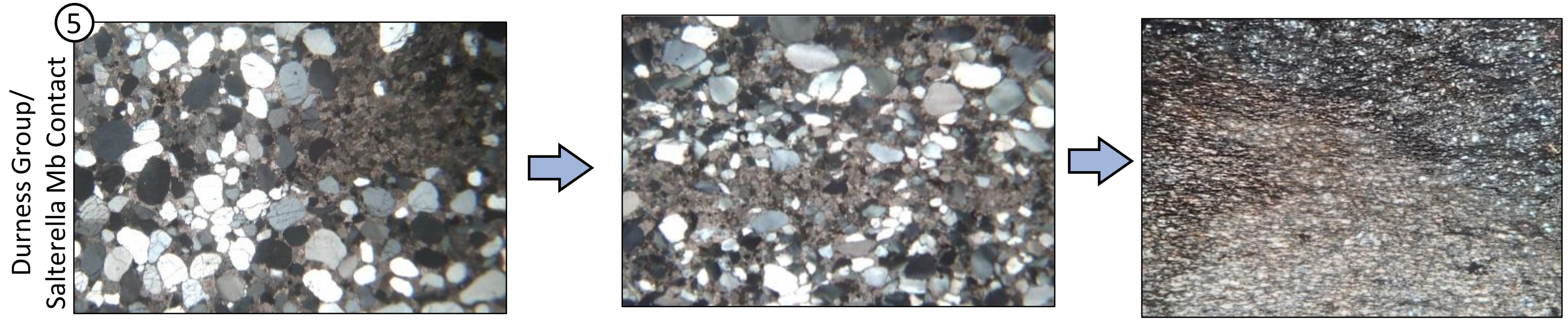


Sandy units of dolomitic Fucoid beds are cut by deformation bands, leading to grain size reduction. Pressure solution processes flatten matrix dolomite grains along deformation bands (parallel to cleavage) and dissolve quartz grains.
Note: Fucoid Beds member is a naturally heterogeneous sedimentary unit, with lithologies varying from laminated muds to dolomitic siltstones and sandstones, and dolomitic grainstone beds.



"Undeformed" Salterella mudstones comprise siltstone fragments enclosed in interconnecting clay matrix layers. Grain size reduction, during deformation, occurs driven in part by dissolution-precipitation processes, resulting in very fine detrital quartz grains enclosed in an ultra-fine matrix, that have a preferred orientation along cleavage. Quartz veinlets occur aligned to cleavage and display asymmetric fabric consistent with shearing.



Deformation process in the arenaceous carbonate involves segregation of carbonate and siliciclastic material, forming parallel-to-cleavage carbonate-rich zones. Progressive diffusive mass transfer associated with grain-scale fracturing leads to grain size reduction while dissolution seams define cleavage planes.

Photomicrographs (cross polarized light) of microstructures comparing undeformed and deformed rocks. Field of view 4mm.

Results: Weakening mechanisms and deformation microfabric

Table 1 - Summary of deformation processes and potential weakening mechanisms in each lithology

Sedimentary Sequence	Lithology	Structure	Domintant weakening mechanisms	Deformation fabric
Ghrudaidh Fm	Dolostone	LBF	DP + GW + TW + minor CT	Flattened dolomite grains along cleavage, Pressure solution seams
Salterella Grit Mb	Quartz-arenite	LBF	IWL + BF + BLG (qtz)	Interconnecting clay matrix, fracturing in quartz and fragments
	Mudstone	IWL	IWL+ DP + GW	Grain size reduction, DP quartz in veins (dynamic)
Fucoid Beds Mb	Clastic-carbonate seq	IWL	IWL + DP+ PS (dolomite and quartz) + TW (dolomite) + GW	Compositional segregation (carbonate/clastic), GS reduction, aligned flat dolomite, PS seams
Pipe Rock Mb	Quartz-arenite	LBF	IWL + Quartz: BF + BLG + SGR, Feldspar: RE+ BF + KK	Interconnecting clay matrix, Grain size reduction through dynamic recrystalization in quartz-rich bands.
Basal Quartzite Mb	Quartz-arenite	LBF	CT + BF + RE	Cataclasite, reaction enhanced softening in feldspar, minor IWL

IWL: Interconnected weak layers; LBF: Load-bearing framework; PS: Pressure Solution; GW: Geometric wekeaning; CT: cataclasis; BF: Brittle fracture; BLG: Bulging; SGR: Subgrains rotation; KK: Kinking; TW: twinning; DP: Dissolution-Precipitation.

Field observations coupled with microstructural analyses highlight a strong lithological control on slip localization in Northern Moine Thrust zone. Evidence suggests that rheological contrasts are playing an important role in deformation localization. Pressure solution, evidenced by changes in the shape of minerals along cleavage surfaces and the presence of dissolution seams and caps, is ubiquitous, making the hypothesis of that syn-deformational fluid-influx has substantially enabled breakdown of the load-bearing framework very likely.

Conclusions and considerations

The work presented here is research in progress and further investigation is necessary to better constrain what aspects inherited from protoliths within specific layers potentially favour the deformation localization and their influence on the evolution of the MTZ. However, some preliminary conclusions can be drawn:

- Progressive development of fine-grained interconnecting weak layers, resulting from incongruent diffusive mass transfer combined with mechanical grain size reduction, is enhanced in the more mineralogically heterogeneous units of the Cambro-Ordovician sedimentary sequence, particularly **Fucoid beds member** and basal parts of the **Ghrudaidh Fm** (Durness Group).

- Within quartz-rich members, such as the **Pipe Rock** and **Salterella Grit members**, impure levels (e.g. clay-rich interbeds and mudstone layers) lead to the progressive replacement of the load-bearing framework by phyllosilicate-rich ultra-fine-grained interconnecting layers, seemingly facilitating weakening and localization of deformation.

- Feldspars seem to control the weakening behavior occurring within the **Basal Quartzite Mb** through brittle deformation. The rheology of this member would explain why Basal Quartzite sandstones are rarely concentrating thrusting deformation within the MTZ.

❖ **Future work will include** X Ray Diffraction, to allow mineralogical characterization of the fine-grained matrix compositions. The outcome of this analysis will better constrain weakening mechanisms, for instance, highlighting the presence of anomalously weak phyllosilicates and will aid the validation of syn-deformation fluid influx hypothesis. Electron Back Scattered Diffraction analysis, to investigate whether intrinsic factors, such as grain size distribution, grain shape preferred orientation and crystallographic fabric favours (or not) deformation localization and fieldwork to further constrain the behaviour of Cambro-Ordovician sediments and to characterise southern region of MTZ in this respect, including the Lewisian basement inliers and Neoproterozoic Torridonian sedimentary sequence involved in the thrusting zone in that region.

References

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