T. ARMITAGE AND K. SMITH

UK Structure Site Report: Walls Boundary Fault, Shetland

British Geological Survey

Abstract

Understanding the architecture and structural history of ancient lithospheric faults is important for building wider regional geological models and helps us understand present-day analogies. The Walls Boundary Fault at Ollaberry, Shetland, is an ideal location for fault zone mapping and descriptions due to its almost unique location, excellent preservation of fault-deformation structures and relative ease of accessibility. Previous studies have characterised the wider fault zone on Shetland and the specific field locality (Watts et al. 2007; Armitage 2021; Armitage et al., 2021; 2024), however, none combined field descriptions with drone imagery to build integrated remote sensing and fieldwork workflows. Therefore, the following report is a characterisation for the Walls Boundary Fault at Ollaberry using a combination of unpublished and published material from Armitage et al. (2021) in addition to a detailed photogrammetric 3D model.

Statement of Intent

This work was undertaken as part of the British Geological Survey's National Geoscience UK Structure programme.

The data pack is intended as a resource that provides an overview of fault structure and fault network architecture through a mechanically layered metasedimentary sequence, using an example from Ollaberry, Shetland. The work highlights the complexity of major faults that is not resolvable on 1:50 000 and 1:10 000 scale geological maps, where faults are expressed as a single line. The data pack can be used as an analogue for understanding potential fault networks in the subsurface in similar stratigraphic packages. The data pack focusses on vertical coastal cliff sections.

Bibliographical reference

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BGS Report No. OR/25/026

BGS Project Code: NEE7165S

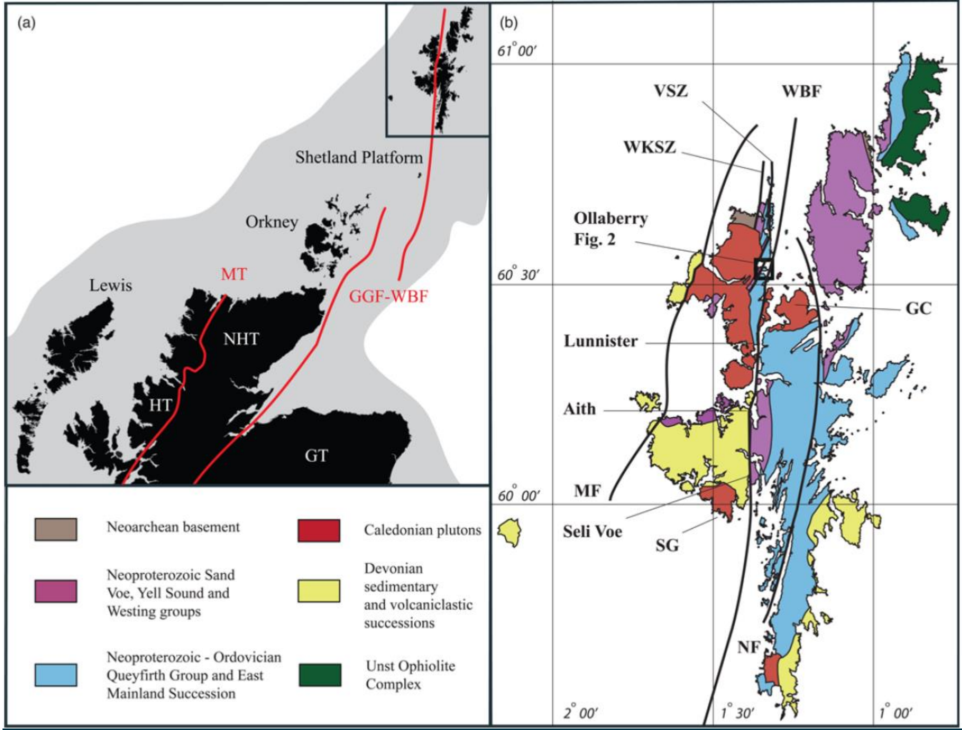
Front cover photo: Photogrammetric model of the Walls Boundary Fault escarpment at Ollaberry North Beach.

Shetland Regional Setting

Shetland occupies the centre of the Shetland Platform, a Mesozoic to Present-day basement high located equidistant from mainland Scotland and Norway. Shetland forms a key link between distal geological provinces of the Scottish, Norwegian and Greenland Caledonian orogeny and subsequent opening of the North Sea and North Atlantic.

The Shetland Platform is transected by a series of N-S striking transcurrent faults, the most significant of which is the Walls Boundary Fault (WBF). The WBF divides Shetland's Mainland along a N-S axis and acts as a major control for the island's geological and geomorphological development. It is widely believed that the WBF is the northern continuation of the Great Glen Fault of mainland Scotland (McGeary 1989; Flinn 1992) as both were active during the sinistrally transpressional collision of Laurentia and Baltica during the Caledonian orogeny, and the subsequent sinistrally transtensional collapse during the Devonian. Since the Devonian, both structures have been reactivated a number of times, including a major dextral reversal during the Carboniferous (Watts et al. 2007; Armitage et al., 2021).

On Mainland Shetland, the WBF separates two regions of Precambrian–Palaeozoic rocks with distinctive geologies that have been correlated with equivalent regions in mainland Scotland. To the west, Neoarchaean Uyea Gneiss and Neoproterozoic Sand Voe and Queyfirth metasediments form the North Roe Nappe and have been respectively linked to the Lewisian, Moine and Dalradian supergroups (Armitage et al. 2024). To the east are the Yell Sound and Westing groups, which are again equivalent to the Moine and Dalradian (Flinn 1988). A range of mainly granitic plutons was intruded either side of the WBF between the Late Ordovician (c. 465 Ma) and the Late Devonian (c. 360Ma) (Lancaster et al. 2017).



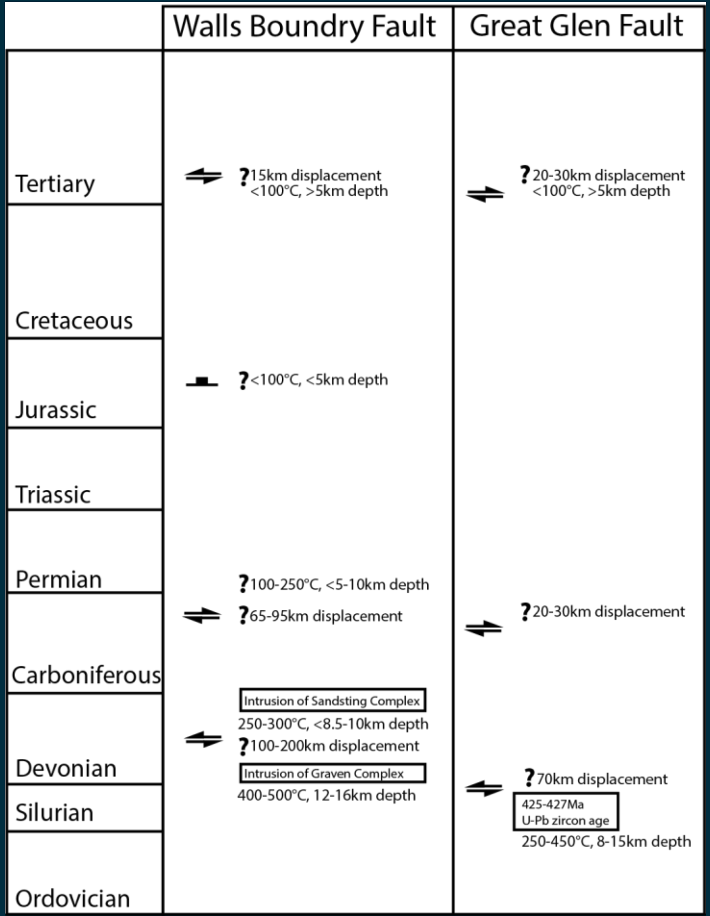
(a) Map of geological terranes of mainland Scotland, (b) map of Shetland showing notable outcrops for Walls Boundary Fault. From Armitage et al. (2021).

Walls Boundary Fault

The WBF is the most geologically significant structural discontinuity transecting Shetland (Flinn 1977, 1992). Seismic surveys of the adjacent Shetland Platform show a lithosphere-scale structure that offsets the Moho and juxtaposes crusts of different thicknesses (McGeary 1989). Onshore, the fault is primarily defined by a zone up to 2 km wide composed of braided, subvertical faults associated with broad zones of cataclasites, phyllosilicate-rich fault gouge and local pseudotachylytes, interpreted to have formed during dextral strike-slip movements (Watts et al. 2007; Armitage et al. 2021).

Fragments of prior sinistral movement are preserved at Sali Voe and Aith within blastomylonitic and mylonitic fault rocks, indicating an earlier phase of sinistral strike-slip movement (Watts et al. 2007). These mylonites are derived from, and interleaved with, banded orthogneisses of similar protolith composition to either the North Roe Nappe Uyea Gneiss (Watts et al. 2007). Because the igneous Graven Complex (Fig. 2) only preserves evidence of dextral deformation, Watts et al. (2007) suggested that older sinistral movement along the WBF initiated prior to its intrusion, which is constrained by U–Pb zircon emplacement age at c. 440 Ma (Lancaster et al. 2017). More recent Jurassic and Cenozoic movements are also recorded, showing exhumation and uplift of the fault (Watts et al. 2007).

Xenoliths of mylonites within the Sandsting Granite are crosscut by brittle dextral shears. The emplacement of the Sandsting Granite then provides a lower limit on the initiation of dextral reactivation on the WBF, dated as 370 Ma. Meanwhile, offshore the Permian unconformity (*c.* 330-300 Ma) is continuous across the WBF, suggesting dextral movement had ceased before this time. This implies that dextral reactivation occurred between these dates.



Deformation – depth – time diagram summarising the main kinematic and fault rock evolution of the Walls Boundary and Great Glen faults (Redrawn after Watts et al. 2007).

Ollaberry Site Description

The most complete section through the fault core is located at Ollaberry, which divides the Queyfirth Group to the west from the Graven Granodiorite to the east. The village of Ollaberry is located on the Yell Sound, NW Mainland Shetland. Adjacent to the village are two beaches, Back Sands and Moo Wick, which expose an almost continuous section through the fault core and adjacent damage zone.

Queyfirth Group

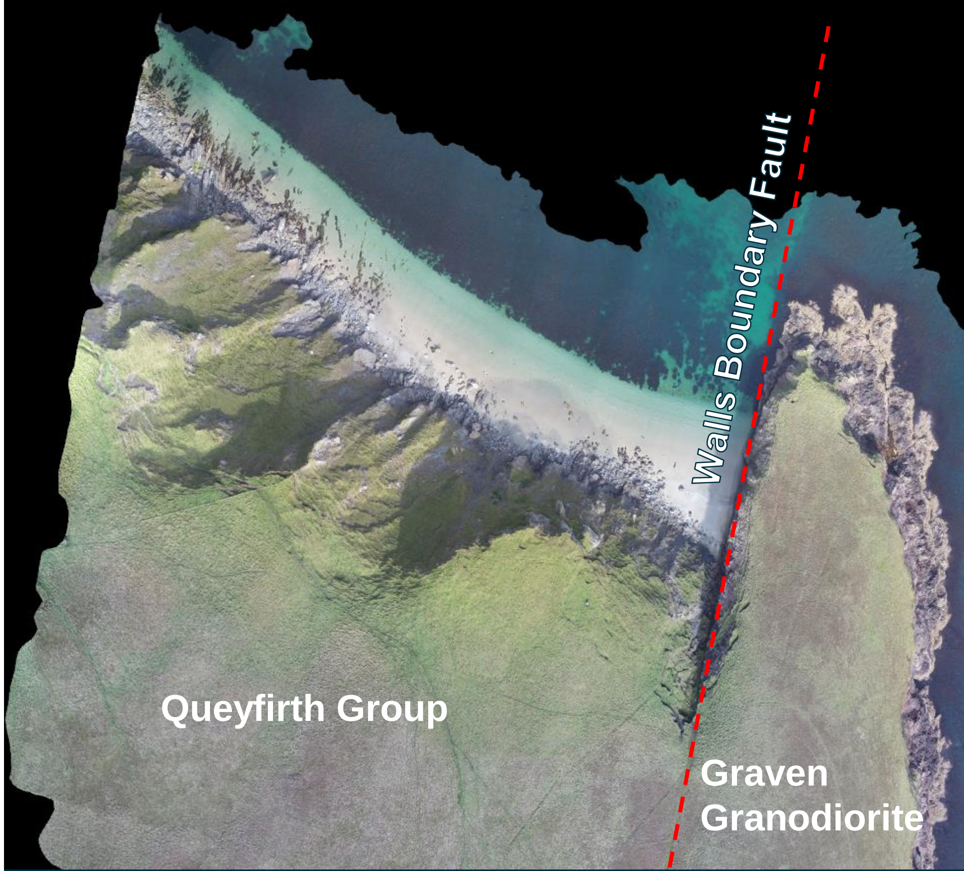
The Queyfirth Group is composed of a series of quartzites, pelites, limestones and basaltic tuffs metamorphosed under upper greenschist to lower amphibolite facies conditions (Armitage et al. 2024). No formal stratigraphic succession has been determined for the Queyfirth Group.

Graven Granodiorite

The Graven Complex is formed of equigranular- to coarse-grained granodiorite, composed of quartz, K-feldspar, epidote, chlorite and minor biotite. No magmatic or ductile fabric is present.

Field Observations

Detailed mapping show a heterogeneous pattern of deformation. To help model the WBF, deformation has been grouped into NNE–SSW-trending fault-bound domains (termed A-C) within the Queyfirth Group that characterise unique deformation styles. Two main phases of deformation are recognised at field- and micro-scale: ‘Early’ and ‘Late’.

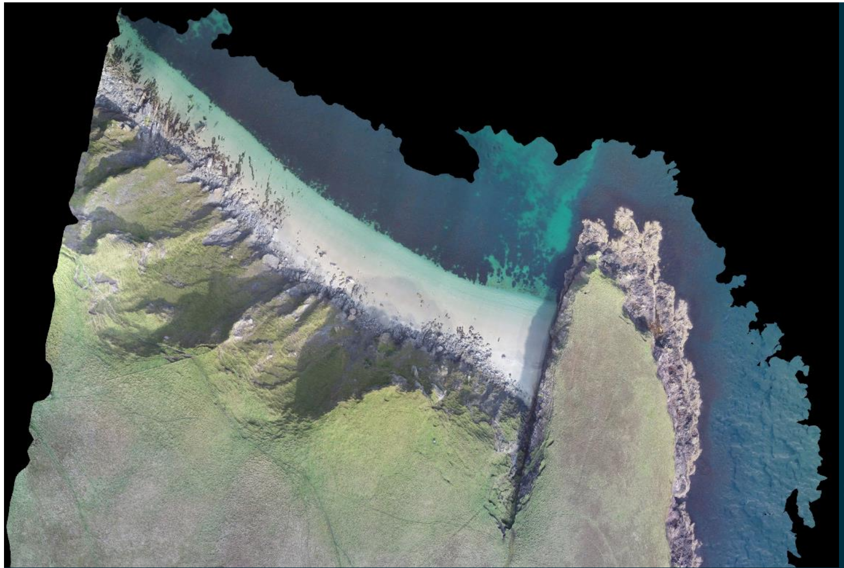


Ollaberry North Beach area showing the prominent peninsular of the Graven Granodiorite, juxtaposed to Queyfirth Group metasediments. Dividing the two are the Walls Boundary Fault, marked by a prominent *c.* 20 m escarpment.

Project methodology

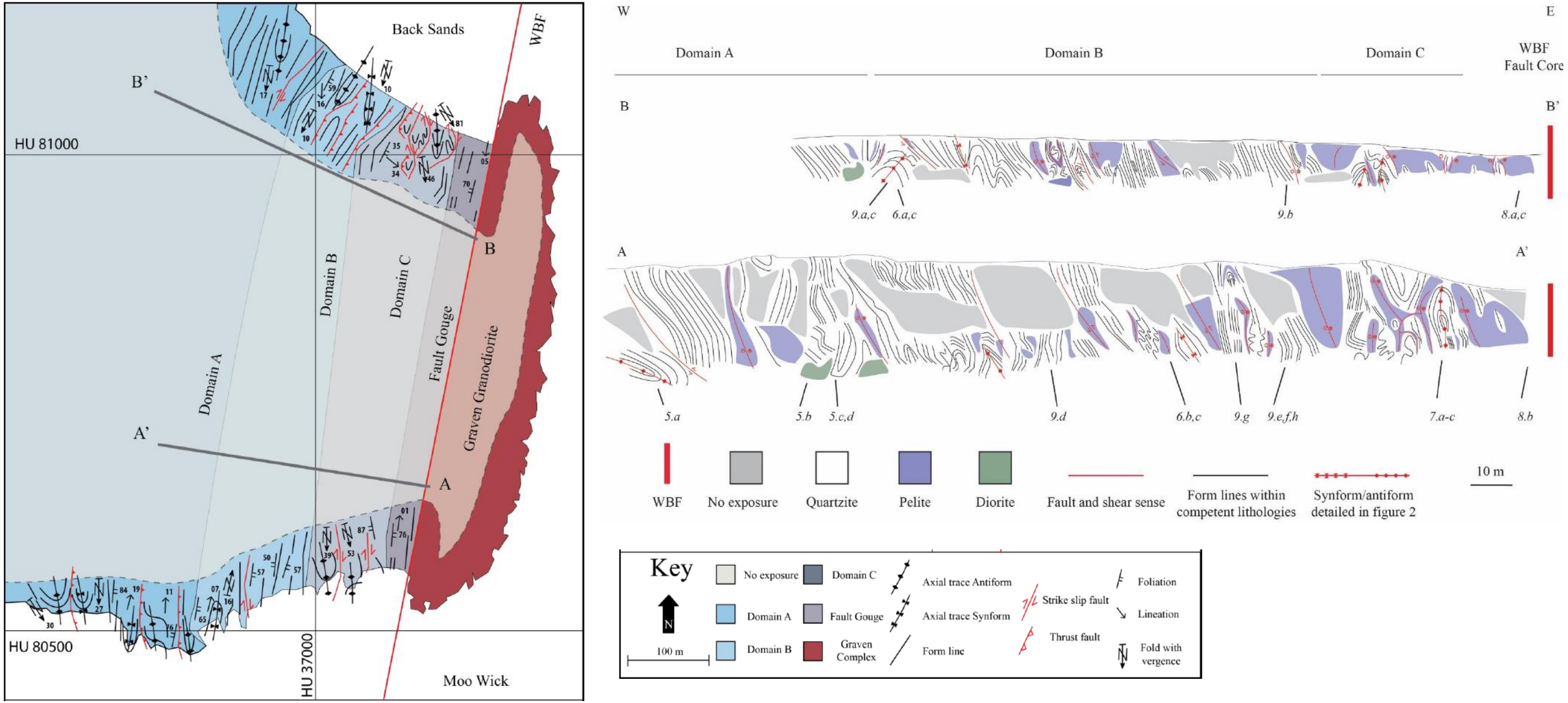
Previous studies have characterised the wider fault zone on Shetland and the specific field locality (Watts et al. 2007; Armitage 2021; Armitage et al., 2021; 2024). This project planned to undertake fieldwork to conduct geological and structural mapping (Tim Armitage) combined with drone imagery (Kay Smith) during the summer of 2024. However, due to unforeseen circumstances, only drone imagery was able to be completed. Therefore, the following report is a characterisation for the Walls Boundary Fault at Ollaberry using a combination of unpublished and published material from Armitage et al. (2021) in addition to a detailed photogrammetric 3D model from Kay Smith.

Drone imagery was acquired using a Zenmuse XT2 sensor (simultaneous RGB and Thermal) mounted on a DJI Matrice 210 platform. This was flown using a DJI Pilot software at 60m altitude (above ground level), with 75% forward image overlap and 75% overlap between adjacent flightlines. PIX4Dmapper software was then used to generate a photogrammetric 3D model from the RGB imagery as a point cloud (shown) and a 0.05m DSM. Caveat: DSM is offset in Z by 140 m and a correction needs to be applied.



WALLS BOUNDARY FAULT

WBF was subdivided into 4 domains to the east of the principal fault plane, to better characterise fault deformation. Increasing fault control deformation is observed as you approach to the fault plane.



(a) Geological map for Ollaberry and cross sections showing the principle structural features of the Walls Boundary Fault at Back Sands and Moo Wick exposures. Adapted after Armitage et al. 2021.

Domain A Field Observations

Located 300-175 m west of the WBF core, Domain A is mostly ‘Early’ ductile regional deformation overprinted by localised ‘Late’ brittle deformation.

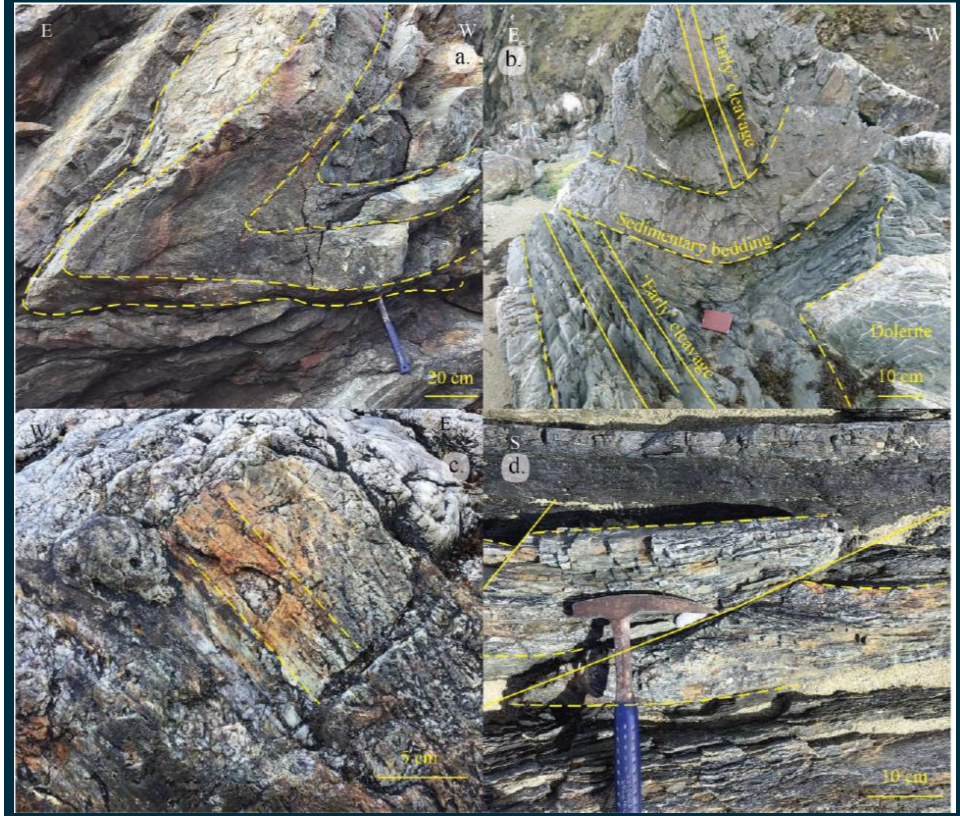
‘Early’ deformation

Mesoscale, tight to isoclinal, curvilinear ‘Early’ folds plunge shallowly to moderately N-S, with upright to inclined axial planes verging west. A cleavage is well developed parallel to fold axial planes, with cleavage-foliation intersection lineations sub-parallel to fold hinges.

‘Late’ deformation

Within relatively weaker pelitic horizons, minor ‘Late’ structures include tight mm- to cm-scale microfolds and kink bands that plunge vertically to steeply north or south, with axial planes striking NW–SE and a Z-verging dextral shear sense.

Some faults, including domain-bounding faults, are confined to pelite horizons and show predominantly steeply dipping, anastomosing geometries. S-C fabrics and slickenlines suggest two main fault sets that are identified with reverse and dextral strike-slip shear senses, respectively. Both are associated with the development of blue, incohesive, foliated clay fault gouges up to 5 cm thick with breccia development is limited. Due to lack of cross cutting and similar gouge formation, they are interpreted as ‘Late’ structures.

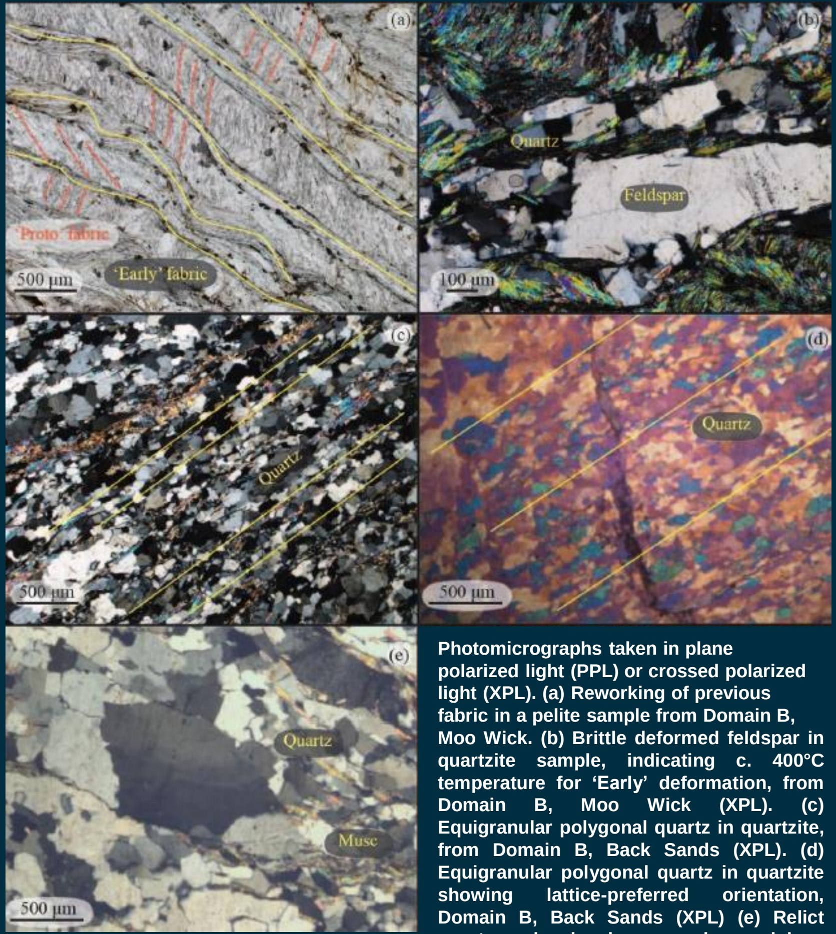


Summary of the features observed in Domain A at Ollaberry. (a) A tight ‘Early’ fold with an inclined axial plane and moderately plunging hinge. (b) ‘Early’ west-vergent fold in Domain B of Moo Wick. (c) Fault plane showing top-to-the-west slickenlines associated with contractional ‘Late’ deformation. (d) Dextrally offset quartzite layer. Adapted from Armitage et al (2021).

‘Early’ Microstructures

‘Early’ structures that were observed in field-scale were also replicated within thin section. In thin section, quartz microstructures were used to ascertain the deformation conditions of the fabric, where quartz was recrystallised via either bulging, subgrain rotation or grain boundary migration. This method is cross-referenced with mineral assemblages and feldspar deformation microstructures.

Medium- to fine grained (0.1–0.5 mm), equigranular and polygonal quartz grains show a shape and lattice preferred orientation. Subgrains of quartz and relict clasts of undulosed quartz show a range of recrystallised and original grains with varying strain accommodation. The dominant recrystallisation method was interpreted to have been subgrain rotation, indicating deformation under upper greenschist to lower amphibolite conditions, c. 400 °C.



Photomicrographs taken in plane polarized light (PPL) or crossed polarized light (XPL). (a) Reworking of previous fabric in a pelite sample from Domain B, Moo Wick. (b) Brittle deformed feldspar in quartzite sample, indicating c. 400°C temperature for ‘Early’ deformation, from Domain B, Moo Wick (XPL). (c) Equigranular polygonal quartz in quartzite, from Domain B, Back Sands (XPL). (d) Equigranular polygonal quartz in quartzite showing lattice-preferred orientation, Domain B, Back Sands (XPL) (e) Relict quartz grain showing sweeping undulose extinction and lattice preferred orientation oblique to the samples ‘Early’ fabric, from Domain B (XPL). Adapted from Armitage et al (2021).

Domain B Field Observations

Located 175-60 m west of the WBF core. Much of the deformation is expressed in the same terms as Domain A, however, Domain B has a higher component of 'Late' brittle local deformation.

'Early' deformation

Tight to isoclinal folds are developed within quartzitic horizons showing boudinaged limbs, indicating a substantial component of ductile shearing. Fold hinges are curvilinear and variably plunge shallowly NNE or SSW, and are west-vergent with axial planes striking NNE–SSW. Fold pairs are commonly discontinuous, with some hinges being truncated by faults and phyllosilicate-rich gouge, indicating 'Late' reworking.

'Late' deformation

Centimetre-scale kink bands that show Z-shaped dextral vergence in map view. Associated with the kink bands is a weak crenulation cleavage and microscale to mesoscale folds that are well developed within pelite and interbedded pelite–quartzite horizons. Hinge orientations are highly curvilinear, plunging shallowly to steeply along a NW–SE girdle and become increasingly variable towards the fault core. The axial planes and axial planar cleavage strike NNE/NNW–SSW/SSE.

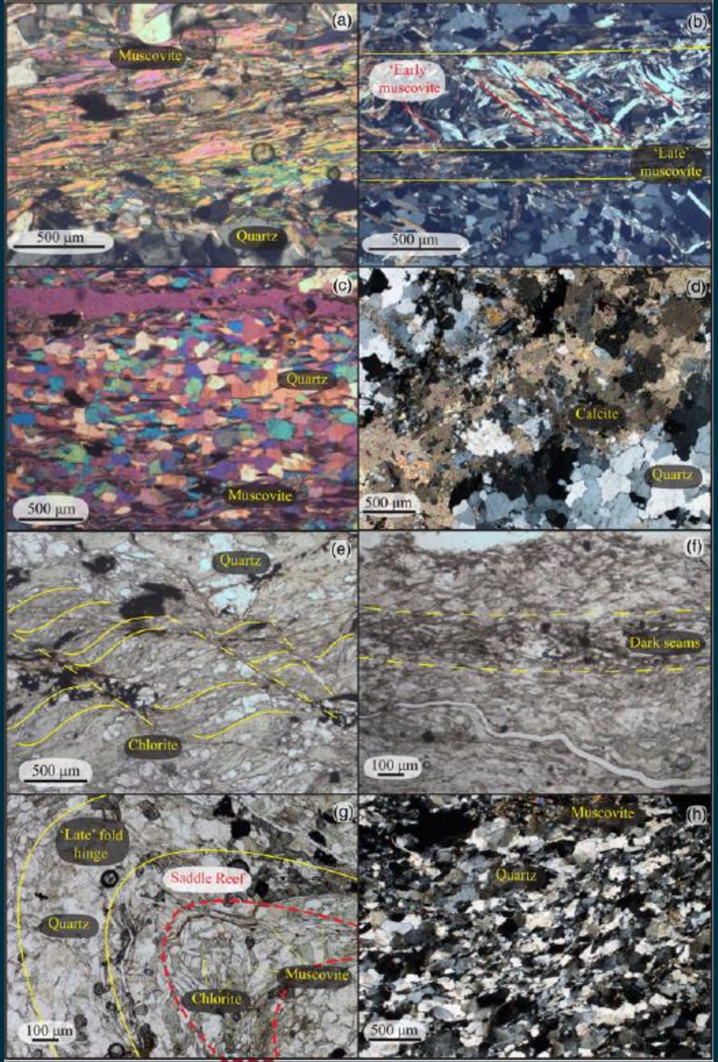
Reverse dip-slip and dextral strike slip faults are widely developed and preferentially formed in peleitic horizons, composed of foliated gouge. Dip-slip faults mostly dip east and display top-to-the-west shear bands and stepping slickenlines.

Summary of the features found in Domain B at Ollaberry. (a) 'Early' west verging fold hinge. (b) Dextrally verging 'Late' folds in pelite. (c) 'Proto' cleavage preserved in an 'Early' fold hinge. 'Proto' fabric is oblique to original sedimentary bedding in multiple outcrops, indicating a poorly preserved 'Proto' deformation phase. (d) Dextrally offset quartzite layer. Adapted from Armitage et al. (2021).

‘Late’ Microstructures

‘Late’ aged microstructures were best observed in Domains B and C pelitic samples. Overall, the grain size is fine (0.1-0.4 mm) displaying a penetrative foliation with a shape and lattice preferred orientation (a, c). Two generations of muscovite orientations are observed, those oblique or parallel to the ‘Late’ foliation (b). Some quartz ribbons are observed showing interstitial muscovite, with both sheared into SC’ fabrics showing a dextral sense of shear (e).

Voluminous amounts of sericite, chlorite and tabular twinned calcite in places overgrown quartz and muscovite rims, forming saddle reef structures in ‘Late’ fold hinges (g). These minerals are interpreted as indicator minerals due to their syn-tectonic ‘Late’ presence. Overalls, the sweeping undulose extinction for quartz, indicator minerals and calcite twins suggest an a lower-greenschist/zeolite facies (150-300 °C) temperature for ‘Late’ deformation.



Photomicrographs taken in plane polarized light (PPL) or crossed polarized light (XPL). (a) Muscovite showing strong shape-preferred orientation and lattice-preferred orientation (XPL, Domain B). (b) ‘Early’ muscovite grains truncated and overgrown by ‘Late’ muscovite in a pelite (XPL, Domain B). (c) Quartzite with interstitial muscovite showing moderate shape-preferred orientation and no lattice-preferred orientation (XPL with tint plate inserted, Domain B). (d) Quartz overgrown by calcite during ‘Late’ deformation in quartzite sample, Domain B, Back Sands (XPL). (e) Dextrally sheared S-C′ fabric in pelite. Muscovite has been extensively replaced with chlorite and minor calcite. (PPL, Domain C). (f) Dark seams of opaque material in surrounding mica-rich horizon (PPL, Domain B). (g) ‘Late’ fold hinge, defined with yellow form lines, with chlorite and muscovite forming in a ‘Late’ saddle reef structure, defined with red lines. Pelite sample, Domain C, Back Sands (PPL). (h) Quartz grains overgrown by ‘Late’ muscovite. Quartz grains display sweeping undulose extinction closer to the Walls Boundary Fault, quartzite sample, Domain C, Back Sands (XPL). Adapted from Armitage et al (2021).

Domain C Field Observations

Located between 60 m west of the WBF core. Domain C is composed of phyllosilicate-rich sheared locally derived material. Amongst this, lenses of quartzite blocks float within fault gouge acting as sheared markers. Deformation is predominantly ‘Late’, with windows of ‘Early’ deformation exhibited within quartzite blocks.

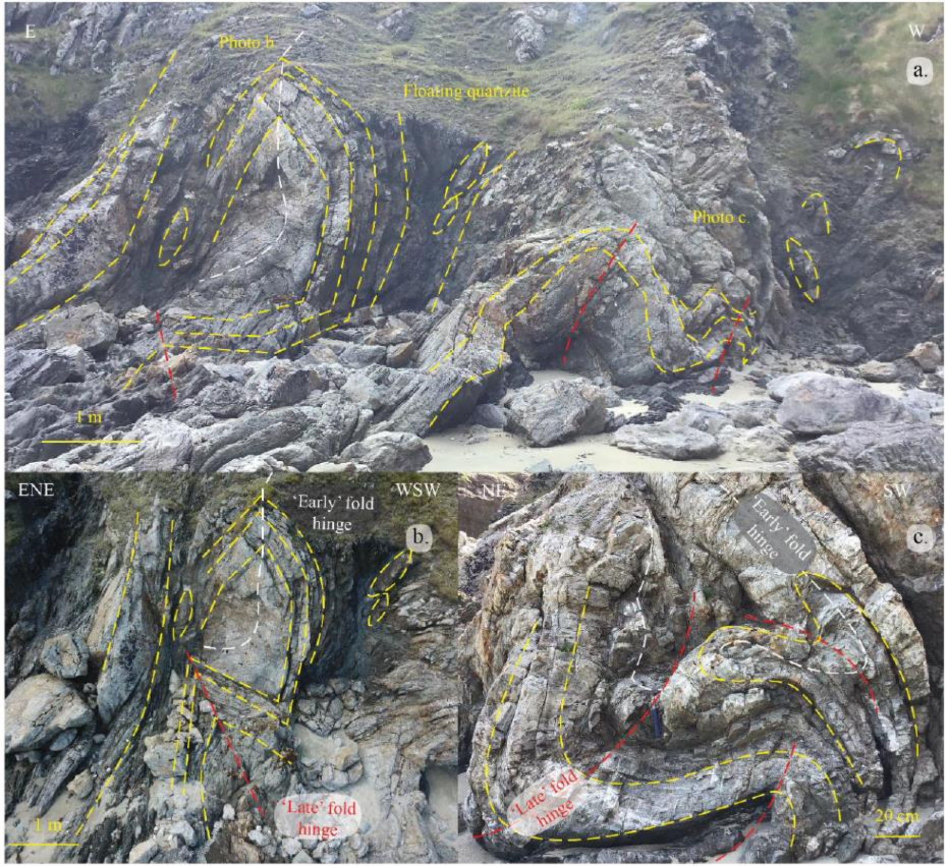
Refolded quartzite

Within quartzites, discontinuous hinges of mesoscale, tight to isoclinal ‘Early’ folds are preserved with limbs sheared out or faulted. Folds are reworked by open to tight, highly curvilinear ‘Late’ folds with an overall Z dextral 7).

Centimetre-scale kink bands are developed in sheared pelites between quartzite lenses and display parallel hinge and axial plane geometries to the ‘Late’ folds. The ‘Late’ folds display variable shallowly south–SE to subvertical plunges spread out along a girdle parallel to their mean axial plane. Axial planes are steeply ENE-inclined to vertical and strike NNW–SSE. Refolding of ‘Early’ folds during ‘Later’ deformation results predominantly in ‘Type-2’ and, in places, ‘Type-3’ interference patterns (sensu Ramsay 1967).

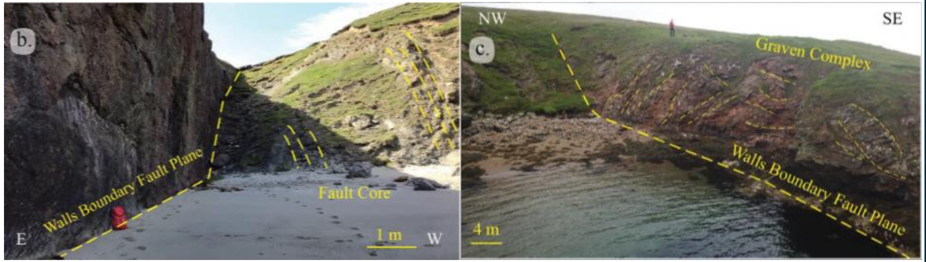
Faulting patterns

Subvertical fault planes are infilled by 10–15 cm thick horizons of highly sheared gouge containing brecciated quartz clasts. Fault planes are along lithological boundaries and border ‘floating’, highly deformed quartzite lenses in an anastomosing array of interconnected fault planes. Faults strike typically NNE– SSW, sub-parallel to the WBF plane, and display sub-horizontal slickenlines associated with dextral S-C’ fabrics.



Examples of interference patterns between ‘Early’ and ‘Late’ folds in Domain C at Back Sands. (a) Highly deformed quartzite lenses ‘float’ between phyllosilicate-rich sheared pelites. Quartzite lenses show decimetre-scale, upright, west-vergent ‘Early’ fold hinges. (b) Close-up of part (a). Limbs of favourably aligned ‘Early’ folds are sheared and replaced with phyllosilicate-rich fault gouge. (c) Closeup of part (a). Type 2 fold interference pattern between ‘Early’ and ‘Late’ folds. Yellow lines, foliation trace; white lines, ‘Early’ fold trace; red lines, ‘Late’ fold trace. Taken from Armitage et al. (2021).

Walls Boundary Fault Core



Ollaberry provides a relatively poorly exposed fault core due to landslip and erosion of weaker fault gouge. However, good examples of the core's architecture are found interspersed. The core is c. 10 m thick, comprising cataclasites and gouge derived locally from the Queyfirth Group and Graven Granodiorite, exhibited as blue- and red- clays, respectively. These are interleaved as c. 1 m thick sub vertically parallel to the NNE-SSW fault plane. Exposed on the fault escarpment on the Graven Granodiorite are sub-horizontal slickenlines indicating strike-slip movement, although no shear sense may be determined.

Adapted from Armitage et al (2021).

Graven Granodiorite Deformation

East of the WBF, 100 m of granodiorite forms the eastern end of the Ollaberry Peninsula. The Graven Granodiorite here is cut by numerous mutually cross-cutting structures.

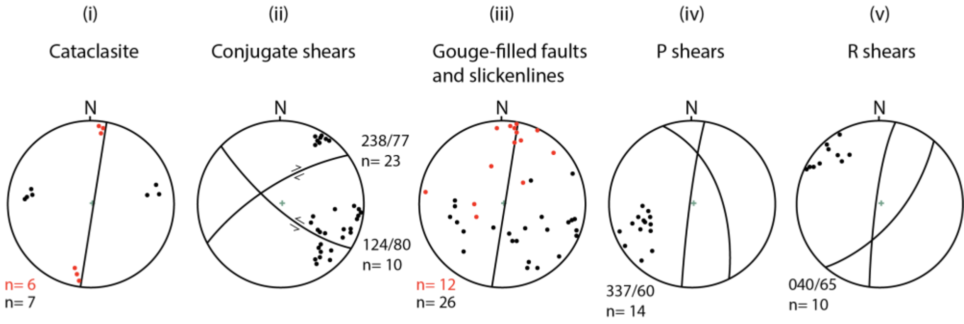
Fault parallel structures

Cataclasite to ultracataclasite seams several centimetres thick form a series of anastomosing north–south-striking faults orientated sub-parallel to the fault core and are infilled with dextrally-stepping quartz fibres. Cataclasites and ultracataclasites often envelope fractured granitic clasts on a micro- to mesoscale and clasts are irregularly orientated north–south.

Conjugate structures

Seams of fractured granodiorite and ultracataclasite are mutually cross-cut by conjugate sinistral and dextral faults, which typically show offsets of up to several centimetres. These fractures trend subvertically SW–NE and NW–SE, respectively. The cataclasites, ultracataclasites and conjugate shear fractures mutually cross-cut earlier gouge-filled faults locally. These faults contain red and blue clay gouge and bound slices of relatively undeformed pegmatitic granite. Two subsets of subvertical faults are orientated NNW–SSE anticlockwise and NNE–SSW clockwise of the WBF, respectively. Both contain slickenlines and offset markers indicating dextral movements. These are interpreted, respectively, as P and R shears in an overall dextral shear regime.

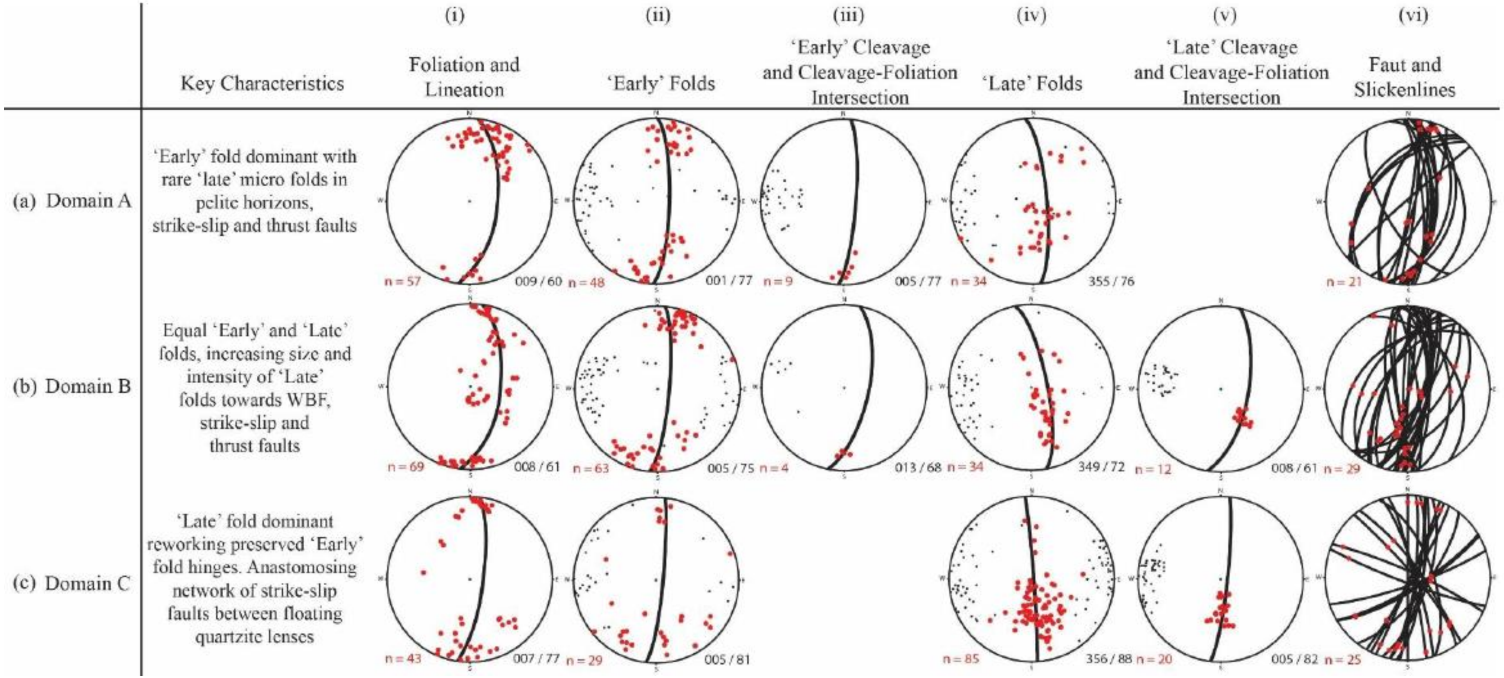
Planes are black pole-to-plane dots and the average plane is drawn as great circle and noted for ii and iv-v. The mean value for the Walls Boundary Fault is drawn as a great circle for i, iii-v, orientated 198/89. **Linear** measurements are red dots.



Stereonets for structures observed east of the WBF showing cataclasite, conjugate shears, faults and slickenlines, P shears and R shears. Adapted and redrwarn after Armitage et al. (2021).

Walls Boundary Fault Stereonet Data

Overall, the damage zone shows an increase of highly variable orientations for folding due to fold interference closer to the fault plane, with increasing prominence of 'Late' deformation.



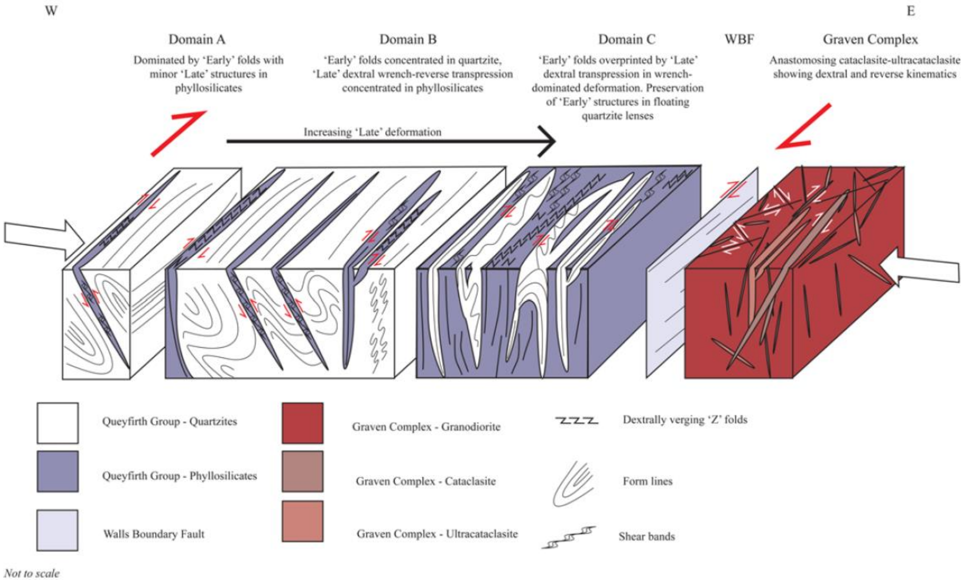
Planes are black pole-to-plane dots and have a mean plane drawn as great circles and noted. **Linear** measurements are red dots.

Adapted from Armitage et al (2021).

Conceptual model

The Walls Boundary Fault at Ollaberry shows a complex interaction of two phases of deformation, ‘Early’ and ‘Late’ deformation. The ‘Early’ phase of deformation is only preserved in the Queyfirth Group and is therefore thought to have been developed as a regional fabric within the metasedimentary units, showing meso-scale W-vergent folding and sinistral shear throughout the field location pre-juxtaposition of the Graven Granodiorite.

Closer to the Walls Boundary Fault, ‘Late’ deformation becomes more prominent, with the intensity of ‘Late’ deformation increasing to the east. Vertical dextral Z micro- and meso-scale folds are well developed in phyllosilicate interbeds and fault-gouges. Close to the Walls Boundary Fault, in Domain C, ‘Early’ deformation windows are preserved within harder-quartzite layers, showing re-shearing and fold interference between multiple deformation phases.



Block diagram summarising the structures observed at Ollaberry and the kinematic model proposed for the Walls Boundary Fault. Adapted from Armitage et al (2021).

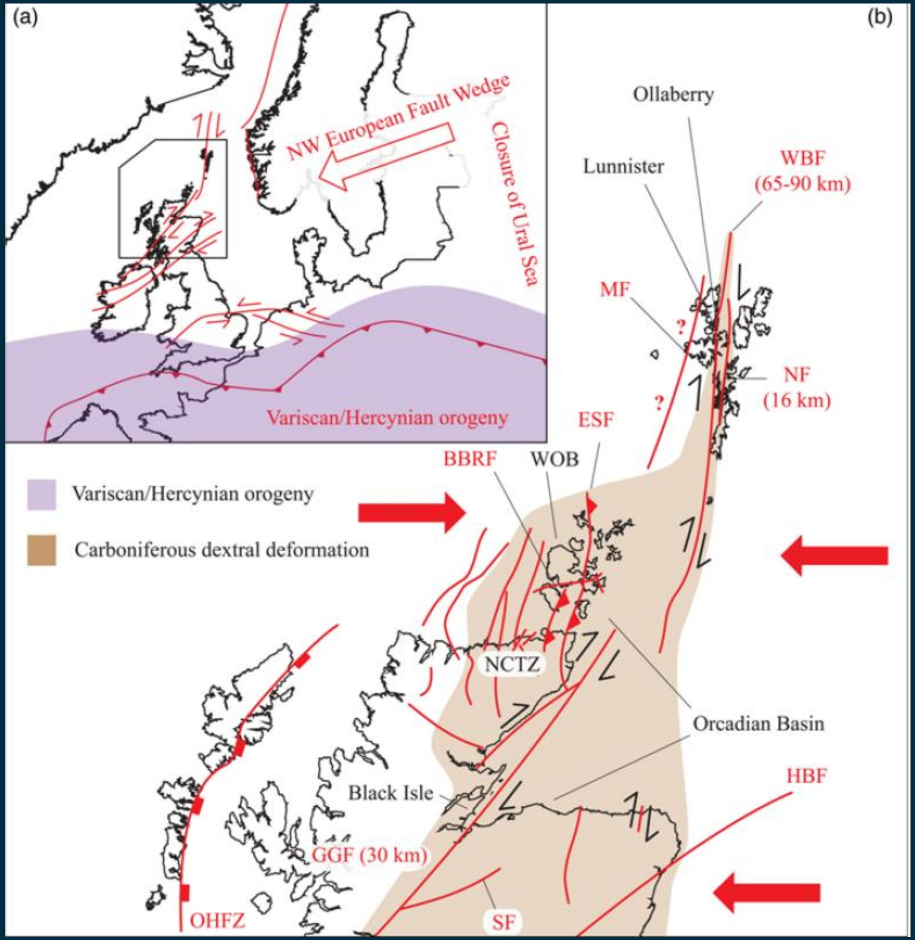
Regional Context

The Walls Boundary Fault has a long history of reactivation, sometimes in parallel with other regional Caledonide fault zones (Watts et al. 2007; Armitage et al. 2021). Sinistral shear and regional N-S folding may be observed throughout the Queyfirth Group and has been linked to the Caledonian orogeny (c. 480-440 Ma; Walker et al. 2016; Armitage 2021). Similarly, initial sinistral movement on the Walls Boundary Fault has been dated as >440 Ma (Watts et al. 2007; Lancaster et al. 2017). The ‘Early’ deformation observed at Ollaberry is therefore likely the preservation of this Caledonian event.

The major phase of dextral strike-slip reactivation of the Walls Boundary Fault Zone is constrained only to be younger than the Sandsting Granite and therefore must be late or post-Devonian; although the absolute age and magnitude of offset are uncertain.

During the Carboniferous, the Devonian Orcadian Basin was widely affected by local inversion folding, while the Orkney East Scarpa, Brough Brims Risa, Sronglairig and Great Glen faults were reactivated as dextral. Similarly, N-S orientated structures along the North Coast of Caithness were reactivated reverse dip-slip as part of a wider dextral transpressional event. The characteristics of these deformation are dispersed and diffuse, which is in contrast with Shetland where the only dominant deformation observed during this phase is located along the Walls Boundary Fault. An explanation for this observation could be that the Walls Boundary Fault on Shetland was such a lithospheric weakness that all strain was accommodated along the fault, with no strain dispersed into the surrounding country rock (Armitage et al., 2021).

The dextral movement during the Carboniferous has been ascribed to the far field affects of the Variscan orogeny in southern Britain and the closure of the Ural Sea, casing the NW European fault wedge to be pushed westwards.



Adapted from Armitage et al (2021).

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