Fault architecture of reactivated faults in Carboniferous sediments, Northumberland, Great Britain

Magnus Vestheim Kjemperud
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Acknowledgement

In the preparation of this thesis, I am especially thankful to my supervisor Professor Roy H. Gabrielsen for excellent guidance and support.

I will also like to acknowledge Professor Roald B. Færseth for guidance during the field work, and Senior Researcher Simon Buckley for providing the LiDAR dataset utilized in this work.

Further I would like to thank my fellow student Lovise Valdresbråten for fruitful discussions and assistance in field.

In addition, a special thanks to my beloved Lise for her consideration and motivation, and my family for their support throughout the process of this thesis.
Abstract

The study comprises two extensional fault systems affecting coal-bearing sediments of Carboniferous age, located at the coastal section of Northumberland, East England. The two studied localities of Hartley Steps and Howick Bay are situated northeast of Newcastle where faults are well displayed in three dimensions including cliff sections and strandflats. The affected lithologies are, alternating shale, siltstone, sandstone and coal-beds, with some limestone stringers. The data sets include aerial photographs, field observations, and fault architecture data analyzed by the use of traditional statistical methods (fracture frequency diagrams, orientation data) and LiDAR scan data.

The study aims at analyzing the fault history, determine the fault architecture and finally to evaluate the effect of the actual faults on fluid flow in the subsurface. To achieve this, following was done:

1) The outcrops were studied by the use of aerial photography to determine the traces of the most important faults,
2) The master faults were studied in the outcrops and the general pattern of displacement and the fault architecture were established
3) Fracture frequency diagrams covering the footwall, hanging wall and fault cores were generated together with
4) the relation between fault core lenses and high strain zones (fault rocks and smear products)
5) Finally rock samples were collected

The total fault zone width of the Hartley Steps fault is estimated to 60 meters and its maximum fault core width is approximately 1 meter. It displays a vertical cumulative displacement of approximately 15 meters, of which the master fault accommodates about 10 meters. The master fault included fault lenses derived from sandstone, siltstone and shale. The fracture frequency diagrams indicate more intense deformation on the hanging wall side than on the footwall side. However, most deformation was accommodated by the fault core. Fault related folds and drag structures are evident and illustrate oversteepning towards the hangingwall in some cases. Various contractional structures are observed, especially in fine-grained rocks and coal. The Howick Bay master fault has a normal offset of about 200 meters and it strikes in an east west direction. The bulk fault zone is about 100 meters wide. A more developed damage zone as seen at Howick implies that the complexity of the fault zone increases with throw, and that most of the fracture damage is in the hangingwall. Accommodation structures include antithetic and synthetic faults with irregular fault geometries, most likely due to stepping along varying weak and strong layers. Particularly complex fault geometries are seen in the zones of fault intersections. Lenses originated from the limestone and form duplexes separated by slip surfaces and mineralized fractures. Sandstone and limestone produce drag structures and confined lenses, whereas shale contribute to smear along the fault plane.

The complex fault geometries may indicate several stages of deformation, which point towards a syn-sedimentary to/soft-sediment extension, post-consolidation extension, and a phase of tectonic inversion. The complex geometry associated with the multistage structuring are likely to influence fluid flow across and along the Hartley Steps and Howick Bay fault zones.
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1. Introduction

The Study is part of the Fault Facies II project at Center of Integrated Petroleum Research (CiPR) at The University of Bergen (UiB). The current work is performed at University of Oslo (UiO).

The field work was carried out over a period of three weeks in July, 2010. Four days of extensive introduction was given by Professor Roy H. Gabrielsen and Professor Roald B. Færseth. Support and communication with the supervisors was provided by e-mail during the fieldwork.

Two separate locations within the Northumberland basin, Hartley Steps in the south and Howick Bay in the north (Figure 1) were studied; both coastal cliff locations where the structural elements are excellently exposed. The tectonic history in the area is well established, and both localities are within a 40 km wide extensional basin located in the northern part of England north of Newcastle (Figure 6).

The objectives of this study is to describe fault history and fault architecture by analyzing two reactivated extensional faults of two distinct fault zones outcropping at the coast in the Northumberland Basin in North England, and to evaluate the effects of fault zone properties on fluid flow.
Figure 1. a) Satellite image of Great Britain. b) Enlarged area showing Northumberland. c) The Hartley Steps locality, blue square indicate the position of the study area. d) The Howick Bay locality, blue square indicate the position of the study area. (GoogleMaps™ 2011).
1.1 Methods and Dataset

Two fault zones (Howick Bay and Hartley Steps) were studied in the outcrops and the
genereal pattern of displacement and the fault architecture were established, by the means of
traditional techniques including strike/dip measurements, sketches and visual observations.

Fracture frequency diagrams covering the footwall, hangingwall and fault cores were
generated together with the relation between fault core lenses (horses) and high strain zones
(fault rocks and smear products). In addition rock samples were collected for further
analysis.

Furthermore a LiDAR scan of the Howick Bay locality was performed. The data acquisition
was carried out by Simon Buckley during a three days period. Two scans were performed,
one at the Howick Bay locality and the other at Craig Point. The latter is described in
(Valdresbraaten 2011). The data was processed and finalized by Simon Buckley and given as
a virtual outcrop incorporated in a software (LIME) also developed by Simon Buckley. The
detection points in the dataset are spaced with an increment of 7.5 cm.

Both field localities are coastal cliffs with limited vegetation so the structural elements are
excellent exposed. Some of the faults are also exposed on the tidal flat, but the quality of the
exposures is varying due to recent beach deposits.
1.1.1 Equipment

<table>
<thead>
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<th>Equipment</th>
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<tr>
<td>Compass</td>
<td>Brunton Pocket Transit International Method: Right hand rule</td>
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<tr>
<td>LiDAR</td>
<td>LiDAR (Light Detection And Ranging) is an optical remote sensing equipment. The LiDAR apparatus can measure the distance to target with laser and produce a 3D model of the outcrop.</td>
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**Software and web**

<table>
<thead>
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<th>Software</th>
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<tr>
<td>LIME\textsuperscript{©}</td>
<td>LIME (Lidar Interpretation and Manipulation Environment) is a software developed by Simon Buckley at CIPR. It handles the LiDAR data and visualizes the data as a virtual outcrop in 3D. The program enables strike, dip and distance measurements (Buckley 2010)</td>
</tr>
<tr>
<td>Google</td>
<td>Maps, satellite images and position taken from (GoogleMaps\textsuperscript{SM} 2011)</td>
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<td>GEOrient\textsuperscript{©}</td>
<td>Software used to plot field measurement, and calculate statistics (Holcombe 2010)</td>
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<tr>
<td>Getmapping\textsuperscript{©}</td>
<td>Ordered Aerial photography used for the Howick Bay locality (Getmapping\textsuperscript{©} 2010)</td>
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1.1.2 Terminology

The nomenclature given by Nystuen (1989) will be used in the subsequent description (Figure 2). A fracture may or may not display displacement. A fault has clearly been displaced, opposed to a joint which have no displacement. Fissures are joints or cracks which can be open or filled with mineral growth (Nystuen 1989). In this work the term vein is used as a synonym to fissure.

Figure 2. Relationship between fracture, fault, joint and fissure (Nystuen 1989).

Faults zones are described as a zone consisting of 1) fault core, 2) damage zone and 3) undeformed host rock (protolith) which again can be subdivided into subunits (Figure 3). These three components differ structurally, mechanically and petrophysically (Caine et al. 1996, Berg and Skar 2005, Lindanger et al. 2007, Braathen et al. 2009, Gabrielsen 2010). The fault core, damage zone and host rock components does not all have to be present in order to be defined as a fault zone (Caine et al. 1996). The fault core will be defined as the: “structural, lithologic, and morphologic portion of a fault zone where most of the displacement is accommodated” after Caine et al. (1996) p. 1025.
Fault cores may consist of slip surfaces, gouge, breccias, cataclasites, clay smears, horses and geochemically altered zones (Chester and Logan 1987, Caine et al. 1996, Berg and Skar 2005). The damage zone is the volume of rock consisting of subsidiary structures on either side of the fault core. These structures comprise small faults, veins, joints, stylolites, fractures, cleavage, folds and deformation bands (Chester and Logan 1987, Bruhn et al. 1994, Heynekamp et al. 1999). The protolith is the volume of rock that has not been influenced by the fault, but it is typical to find a background fracture network in the protolith which is not related to the actual fault zone (Caine et al. 1996, Berg and Skar 2005).
The Howick Bay and Hartley Steps localities will both be regarded as a fault zone, including the preceding elements. Individual faults in the damage zones will be regarded as fault members, which will also constitute a fault core and damage zone.

Lenses have been measured and documented according to Lindanger et al. (2007). A lens is defined by three axes, where a-axis represents the maximum thickness, b-axis is the length along the dip direction, and c-axis is the length along the strike direction (Figure 4, 1a). The ratio between a:b:c defines the geometry of the lens (Lindanger et al. 2007).

Lenses are considered to be symmetrical, therefore the a:b:c ratios will not be affected by where the lens is cut (Lindanger et al. 2007) (Figure 4, 1b). This enables measurements of half lengths of the b and c-axes in field where the lenses are not completely exposed. The initial lens that is formed is regarded as the first order lens, and when subjected to progressive strain the lenses tend to break down and from lower order lenses (Lindanger et al. 2007) (Figure 4, 1c).
Lens initiation and corresponding segment development will be termed after Gabrielsen and Clausen (2001). They have defined six principal configurations for lens development. a) Tip-line coalescence, b) segment linkage, c) tip-line biforcation, d) asperity biforcation, e) hangingwall segment splaying, f) hangingwall segment amalgamation (Figure 4, 2).

The continuity of fault rocks is described using the terminology proposed by Braathen et al. (2009) as shown in Figure 5. Breccias have been classified according to Mort and Woodcock (2008).

<table>
<thead>
<tr>
<th>Continuity</th>
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<tr>
<td>Continuous</td>
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<td>Semicontinuous</td>
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<td>Pocket</td>
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Figure 5. Classification of continuity of fault rock appearance (Braathen et al. 2009).

Fracture frequency is the number of fractures per unit distance. The two scales used are fractures/meters and fractures/decimeters.
1.2 Structural and stratigraphic framework

Northumberland Basin is a 50 km wide half graben (Figure 6), where the principal orientation of the Basin is ENE (Leeder 1974, Soper et al. 1987, Chadwick et al. 1993). The Basin is thought to be formed by an extensional reactivation of the Iapetus suture during the early Carboniferous, where the upper and middle parts of the crust controlled the development of the Basin (Johnson 1984, Chadwick and Holliday 1991). The Basin is filled in with Carboniferous sediments resting on Lower Paleozoic and early Devonian rocks (Chadwick et al. 1993).

The southern margin of the Northumberland Basin is defined by the Ninety Fathom fault, and The Stublick fault system, which separates the Basin with the structural higher Alston Block. The faults on the southern margin have taken up most of the throw, and Carboniferous and younger sediments display a maximum sediment thickness of about 5 km (Kimbell et al. 1989, Chadwick et al. 1993) (Figure 7). The sediments are thinning toward the north, and the Cheviot Block represents the northern margin of the Basin. The structural highs on either side consist of granite stabilized blocks (Leeder 1974, Chadwick and Holliday 1991, Chadwick et al. 1993). The western Basin margin is defined by a basement high representing the boundary and beginning of the Solway Basin (Figure 6). The Solway Basin share the same structural trend as the Northumberland Basin, and show maximum sediment thickness of more than 6 km (Chadwick et al. 1993).
Figure 6. Upper) Surface geology and lower) The main structural elements of the Northumberland Basin (Trough) (Chadwick et al. 1993).
Figure 7. Interpreted seismic cross-section across the Northumberland Basin (Trough). NFF: Ninety Fathom Fault, SF: Stublick Fault System (Chadwick et al. 1993).

Figure 8. Stratigraphy of the Northumberland Basin and adjacent areas (Chadwick et al. 1995). The stratigraphic position of the study areas are indicated in red.
1.2.1 Tectonic setting

The early Devonian convergence of Laurentia (Scottish) and Eastern Avalonia (England) formed the Iapetus suture during the Caledonian Orogeny, termed the Iapetus Convergence Zone (Soper et al. 1987). The thrust sheet direction was determined to be ENE-trending and northerly dipping (Soper et al. 1987). Geophysical data discussed by Chadwick and Holliday (1991) indicates a low angle (25 degree) shear zone which is dipping north separating Laurentia and Avalonia, where the Avalonian crust in south is subducted beneath the Laurentian crust (Figure 9). The throw of the thrust is likely to be in the scale of kilometers (Chadwick and Holliday 1991).

![Figure 9. Conceptual illustration of the development of the Iapetus Convergence Zone. a) Collision between the northern Laurentian crust and the southern Avalonian crust b) Continued compression and formation of a fold and thrust belt c) Extension and reactivation of the Iapetus Convergence Zone, and the development of Northumberland-Solway Basin. (Chadwick and Holliday 1991).](image)

The extension and reactivation of the Iapetus Convergence Zone is thought to have occurred in early Carboniferous which initiated the development of The Northumberland Basin. Rifting
was probably most significant during the Dinantian, but locally may have been initiated in late Devonian times (Collier 1989, Kimbell et al. 1989, Chadwick et al. 1995).

The majority of faulting occurred during the Courceyan to Holkarian in the early Dinantian (Johnson 1984, Chadwick et al. 1993), but minor normal faulting continued into Namurian and Westphalian times most likely due to thermal subsidence (Kimbell et al. 1989). Syn-depositional normal planar faults define the southern margin of the Basin. These include the Ninety fathom fault and Stublick fault system, which are the main structures (Kimbell et al. 1989). The faults in Northumberland Basin are generally dipping 60 degrees, and syn-depositional offsets are up to 300 meters, which is mainly confined to the Lower Border Group (Chadwick et al. 1993). The syn-rift sediments include the Lower and Middle Border Group (Chadwick et al. 1993). An increased component of thermal subsidence is recorded in younger Dinantian formations. Chadwick et al. (1993) suggest the Holkerian to Absian being the end of the syn-rift phase, although fault controlled subsidence continues into the Westphalian, but to a lesser degree. From the early Absian to Namurian fault controlled subsidence became less significant (Chadwick et al. 1993). Upper crustal extension factor of 1.15-1.19 and crustal and lithospheric extension factor of 1.3 are suggested by Kimbell et al. (1989).

The closing of the Rheic Ocean in northern France and southern England culminated in the Variscan Orogeny (Fraser and Gawthorpe 1990). This event started in Bolsovian (Late Wesphalian) and ended in the early Permian. The deformation inferred by the Variscan Orogeny on the Carboniferous rocks in the Northumberland Basin is thought to be initiated in late Westphalian C (Fraser and Gawthorpe 1990), where the second and strongest pulse is dated to Westphalian D. The influence of the Variscan Orogeny ceased in early Permian (Chadwick et al. 1993). Evidence for inversion is expressed by NE-SW to NNW-SSE trending folds and faults in the northern and western parts of the Basin (Collier 1989). Seismic study by Chadwick et al. (1993) also shows ENE trending hangingwall anticlines close to the margin faults in the southern part of the Basin. De Paola et al. (2005) point out two main problems with the existing inversion model. Firstly the suggested shortening direction (E-W) is not parallel with the NNW trending Variscan convergence. Secondly the
emplacement of eruptives is not consistent with a shorting, but rather with an extension. An alternative view is proposed by De Paola et al. (2005) suggesting the folds and faults interpreted as inversion structures related to the Variscan Orogeny to be related to strain partitioning. De Paola et al. (2005) proposed that one phase of 15 ma basin controlled dextral oblique extension is responsible for inversion structures formed in the late Carboniferous to early Permian.

A quartz-dolorite sill named the Whin Sill intruded in the late Variscan Orogeny, and is thought to post date the main inversion event (Collier 1989). The timing of the Whin Sill complex is uncertain, some author relate the intrusions to the Variscan inversion, other to later extensional event (De Paola et al. 2005).

The Carboniferous is separated from the Permian rocks by an angular unconformity, suggesting an uplift and subsequent erosion (Collier 1989). The rifting and opening of the early Northern North Sea in early Permian is thought to have affected the Northumberland Basin as an E–W extension. This caused a transtensional stress field on former NE-SW Caledonian lineaments, and caused dextral reactivation of faults (Collier 1989, Fraser and Gawthorpe 1990). The separation of Greenland and Scotland in early Tertiary, led to easterly tilt of the eastern part of England, and Alpine Orogeny caused inversion of faults in northern England (Fraser and Gawthorpe 1990).
1.2.2 Stratigraphy

The sediment fill of the Northumberland Basin is divided into syn-rift and post-rift sediments. The syn-rift sediments are thickest close to the southern margin where the maximum thickness is between 2500-4000 meter (Chadwick et al. 1995).

Syn-rift

The first phase started with the deposition of the Upper Old Red Sandstone (Johnson 1984, Chadwick et al. 1993). The Upper Old Red Sandstone are fluvial deposits and are up to 200 meter thick and display an north eastern paleo current flow, and are probably of Courceyan age (Chadwick et al. 1993).

The Upper Old Red Sandstone is overlain by the Lower Border Group. Marine transgression took place, and progressively the Lower Border Group was deposited during Courceyan-Chadian in a time of rapid subsidence (Johnson 1984, Chadwick et al. 1995). The sediments show a cyclic nature indicating repeated sea level fluctuations, and are interpreted to be fluvio-deltaic systems that build out from the east (Chadwick et al. 1993). The Lower Border Group comprises the major fraction of the syn-rift sedimentary fill, and is close to the southern Basin margin more than 4000 meter tick (Chadwick et al. 1995).

The Middle Border Group displays maximum thickness in the range of 600-800 meters, and was deposited during the Arundian to Holkerian (Chadwick et al. 1993, Chadwick et al. 1995) The sedimentary infill was dominated by more marine clastic deposition, where the sediment were supplied from the north east (Johnson 1984), and the sediment thicknesses became gradually more laterally uniform and thickening toward the Basin center, suggesting an increased component of the post-rift thermal relaxation effect (Chadwick et al. 1993).
Post-rift

As the basin filled in the structural reliefs became less significant, generating more uniform sedimentation across the region, compaction and thermal subsidence now became the important factor creating accommodation space (Johnson 1984, Chadwick et al. 1995).

The Upper Border Group of early Absian age is about 800 meter thick, and is characterized by sedimentary cycles of fluvio-deltaic deposits with a current direction from east and north (Johnson 1984, Chadwick et al. 1995). It was occasionally interrupted by marine carbonates from the west and southwest (Chadwick et al. 1993).

Howick Bay Locality

The northern part of Howick Bay comprises Dinantian (Brigantian) rocks from the Middle Limestone Group. The Howick fault zone juxtapose the Upper Limestone Group in the north by the Middle Limestone Group in the south, with a stratigraphic throw of about 200 meters (Farmer and Jones 1969).

The Limestone Group is sub-divided into the Lower, Middle and Upper Limestone Group. The Limestone Group is about 1000 m thick comprising 20-100 m thick cycles referred to as the Yordale cyclothems (Scarboro and Tucker 1995). These cycles typically start with a limestone deposited during a marine transgression flooding the delta plain. The limestone is overlain by a succession of prograding delta deposits forming an upward shallowing and coarsening successions. The uppermost part of the cycles consist of cross-stratified, channelized or non-channelized sandstones overlain by marsh deposits comprising palaeosoils and coals. The uppermost succession is interpreted as delta plain deposits (Elliott 1976).

One cycle of the Yordale cyclothems in the Middle Limestone Group is exposed at the Howick Bay (Reynolds 1992). The cycle begins with a marine shale which is overlain by a marine bioclastic limestone (Acre Limestone) (Reynolds 1992). The Acre Limestone gradually grades into a black shale. From the limestone the cycle shows a gradual increase in clastic deposits interpreted as a consequence of an advancing shoreline. The uppermost part
of the cycle is characterized by wave ripple-laminated and hummocky cross-stratified sediments interpreted as embayment fill and prograding storm-dominated shorelines, respectively (Reynolds 1992). The documented transgression and following progradation may have been formed by change in sea-level, subsidence, sediment input or delta lobe switching (Johnson 1984).

The Upper Limestone Group is a 228 meter thick succession of Namurain age comprising coal bearing-clastic rocks with some marine limestone stringers (Farmer and Jones 1969, Elliott 1976). The central part of the Upper Limestone Group is exposed at Howick Bay displaying an approximate 20 meter sedimentary succession (Figure 11).
Figure 11. Stratigraphic section of the Upper Limestone Group and a sedimentary sequence from the Howick Bay (Elliott 1976).

The exposed sediments are interpreted as minor river deltas comprising mouth bar, crevasse channel and prograding beach spit deposits (Elliott 1976). The succession is interrupted by a marine carbonate (Howick (Lickar) limestone) deposited during a transgressive event drowning the river delta (Elliott 1976) (Figure 11).

**Hartley Steps Locality**

The Hartley Steps locality comprises Duckmantian (Westphalian B) rocks from the Middle Coal Measures. The Hartley Steps fault zone self juxtapose the Middle Coal Measures by 15 meters.

The Coal Measures are sub-divided into the Lower, Middle and Upper Coal Measures. The Coal Measures in the Northumberland is Basin 830 meter thick at its maximum, and display repeated succession of upper and lower delta plain deposits with interrupted peat beds(Collier 1989), with a sediment input from the north (Fraser and Gawthorpe 1990).
deposition of the coal bearing strata was controlled by increased rate in thermal, and compaction assisted subsidence from late Namurian into the Westphalian (Johnson 1984, Chadwick et al. 1995).

The sediments at Hartley Steps are interpreted to be deposited in shallow lakes extending several kilometers across (Haszeldine 1984). Deltas build into the lakes and deposited distal muds coarsening up to silty mouth bars, and sandy channel fills (Haszeldine 1984).

Figure 12. Stratigraphic sections of the Westphalian C (Duckmantian) Coal Measures in the local region. Red square indicate the studied sediments (O’Mara and Turner 1999).

The deposition ceased in late Carboniferous, and late Westphalian deposits are mostly restricted to the Western part of Solway Basin, which are of fluvial and lacustrine origin. These sediments are thought to be deposited under differential subsidence (Johnson 1984).
2. **Structural description**

The complete sections showed in Figure 14 and Figure 43, Hartley Steps and Howick Bay respectively each display a master fault and associated structures. The faults will be divided into architectural elements (core and damage zones). This will be regarded as the first order fault zone.

The damage zones on either side of the first order fault zone include faults and fractures. These faults and fractures will be described as individual structures; consequently the architectural terms will be applied. These will be regarded as the second order fault zones.

The description will be presented in accordance with the first order fault envelope in the subsequent order for both localities, 1) Fault core, 2) Footwall damage zone, 3) Hangingwall damage zone.

2.1 **Locality 1 - Howick Bay**

The Howick Bay Locality is situated in the northern part of the Northumberland Basin approximately 10 km northeast of Alnwick, between Longhoughton in the south and Craster in the north. It can easily be accessed from the beach; however the strandflat section of locality is inaccessible during high tide, whereas the cliff section is partly accessible.

The locality is found in a coastal cliff (Lat/long 55.455024,-1.591408 (WGS84)) where the faults and affiliated structures are excellently exposed. The strandflat is excellently exposed on either side of the fault zone, although the fault traces are commonly covered by kelp, barnacle, sand and boulders.

The Howick Bay locality and the Howick fault was discussed by Westoll et al. (1955). They reported a 200 meter (700 ft) stratigraphic throw of the main Howick fault and North-south trending dip-slip faults throwing to the south, with an average fault plane angle of 45 degree. It was also recorded steeper fault planes in sandstones compared to shales, and the faults were occasionally transferred to bedding parallel slip. Detailed work on the stratigraphy
carried out by Farmer and Jones (1969) supports a 200 meters throw and they also suggest that the fault may have a horizontal component. Pointing out a difference in the strike of the bedding on either side of the fault, folds at high angle to the fault and shattered calcite veining to support this assumption.

A more recent study by De Paola et al. (2005) describes the locality in greater detail. They term the hangingwall subsidiary faults as dip-slip Andersonian conjugate normal faults. The faults are suggested to be syn-sedimentary due to listric geometries and soft sediment deformation, and interpreted as active in Dinantian-Namurian times. Further east on the strandflat De Paola et al. (2005) report more steeply dipping fault planes with sub-horizontal slickenlines. The principal E-W faults show dextral movement, and is linked by NE-SW trending dextral faults. This is interpreted as a dextral restraining bend. Furthermore the Whin Sill dolorite is bounded by two faults, but is not brecciated. From this De Paola et al. (2005) suggest that the Howick fault zone is composed of syn-sedimentary normal faults formed in the Dinantian, and later reactivated at the same time as the emplacement of the Whin-Sill at the Carboniferous-Permian boundary.

The Howick Bay locality encompasses a fault zone which includes some ten recognized normal faults (Figure 13) with a throw greater than one meter. The master fault which is clearly identified on the cross section (Figure 14) has a normal throw and separates the footwall damage zone in north, and the hangingwall damage zone in south.

The fault members in the hangingwall damage zone have a cumulative normal offset of 10 meters. The faults display irregular geometries, with abrupt fault dip changes. Particularly complex fault geometries are seen in the zones of fault intersections. The faults are orientated EW, and show normal down to the south displacement.

The footwall damage zone accommodation structures from south to north starts with a synthetic nearly vertical fault with a normal offset of about 3 meters. The fault (FW1) juxtaposes the Acre Limestone with a calcareous shale, and display shale smear in the cliff section (Figure 14). The fault trace can be followed along the foreshore, and is studied in areas FW1b-FW1d (Figure 13). The subsequent fault (FW2) is antithetic and shows a normal
down to the north throw. The fault displays a fault core that is studied in greater detail in area FW2. The two northernmost faults throws down to the north, they were not studied in detail but are covered by the fracture frequency profile. All faults show normal throw of a few meters. The fault traces show fault branches that splay and intersect.

Figure 13. a) Aerial photo showing the escarpment and the strandflat at the Howick Bay (Getmapping© 2010). b) Colored interpretation displaying the fault branches related to the master fault. The black squares indicate the areas that are examined in greater detail. Green line indicates the position of profile (Figure 14). Red lines are bedding plane measurements, blue are fracture frequency measurements. The hangingwall side is colored yellow and represents the fluvio-deltaic sediments (Namurian). The footwall is colored blue and represents limestone and calcareous shale (Brigantian).
Figure 14. Top: LiDAR image of the Howick Bay section showing the hangingwall damage zone, the master fault is positioned in the northernmost part. Bottom: Profile of the entire investigated section, including the location of the examined faults. Right: Stratigraphic column of the exposed sediments covering the hangingwall side. The column is based on measurements from the LiDAR, and field observations. The image show the hangingwall faults the master fault which juxtapose Namurian rocks in south by Brigantian rocks in north.

Figure 15. Fracture frequency diagrams displaying the number of fractures/meter. a) Collected on the cliff section b) collected on the strandflat. Calcite mineralization is restricted to the footwall. There is generally a higher frequency recorded in the footwall opposed to the
hanging wall. Grey areas indicate areas that are covered. The master fault, FW1 and FW2 is given by approximate position.

Figure 16. The complete lens dataset of the Howick Bay locality, showing the a:c and a:b ratios of 47 defined lenses.

2.1.1 Master fault

The master fault of the Howick Bay is an E-W striking normal fault with a normal displacement of approximately 200 meters (Westoll et al. 1955). A complete section through the fault is exposed at the locality. The fault is accessible to an elevation of 10 meters. The fault is characterized by a thin fault core. Lithologies on the hanging wall side include sandstone, siltstone, shale and coal and belong to the Upper Limestone Group, and the footwall side includes calcareous shale and limestone and belongs to the Middle Limestone Group. The fault was measured to have an average strike and dip of 093/52 (Figure 18).
Figure 17. a) Showing the master fault in south, where the red stippled lines indicates the footwall and hangingwall master branchline. The red stippled line in north indicate footwall fault member (FW1). The yellow stippled lines indicate the approximate bedding b) Displays the hangingwall accommodation structure related to the master fault. Lens A consisting of sandstone has been displaced about 3 meters and Siltstone B has been displaced about 2 meters. Red lines indicate slip surface.

Figure 18. a) Stereoplot showing the orientation of the master fault plane b) Slip surfaces within the hangingwall accommodation structure.

Fault core

The fault plane is planar, and the fault core is in the range of a few cm to 20 cm wide and consists of clay or fault gouge.

Hangingwall

Figure 17a clearly illustrates how the hangingwall sedimentary layers are “bent” to form normal drag fold. The strata which consist of sandstone, siltstone shale and coal show a complex accommodation structure, expressed by antithetic and synthetic faults and non-rigid deformation (Figure 18, Figure 17). Lenses were observed along the hangingwall master
branchline, where several of them constitute the accommodation structure (Figure 17b). Within the accommodation structure one should note the coal layer, which at one place seem to have been stacked to twice the thickness. The observed lenses are derived from the hangingwall strata and display displacements of 0.5 to 3 meters. The eight rock lenses that were measured gave an a:c ratio of 1:3.8. The fracture frequency is more than 40 fractures/meter close to the hangingwall master branchline, but drops down to about 10 fractures/meter after 5 meter south (Figure 15).

**Footwall**

The footwall side encompasses a high strain zone bounded by the master fault and FW1 fault member (Figure 17b). The bedding is increasingly becoming more inclined towards the FW1 fault plane, and eventually parallel to the fault plane. Normal drag fold and associated shale smear to the fault denoted FW1. The shale smear consists of calcareous shale, which includes small (10 cm) lenses/pockets of shattered limestone mineralized by calcite (Sample_HB_15). The master fault and FW1 is linked by a fault striking NNE with a normal throw down to the ESE referred to as Mfα (Figure 19).

**Mfε**

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**Figure 19. Cross section of the master fault showing:** a) Sketch displaying ramp-flat-ramp geometry, where the fault sole out in shale. b) Picture showing the increase in deformation approaching the branchline. Position of the profile is given in Figure 13.
The outcrop is about 10 meters east of the cliff on the foreshore and represents the eastwards continuation of the master fault. It was not possible to determine the position of the master branchlines, but the fault colored in red is a likely candidate (Figure 19). The hangingwall damage zone consists of a base of shale overlain by silt coarsening up to a two meters massive sandstone. The entire footwall side is covered by beach and boulders. The average strike and dip of the branchline and associated slip surfaces is 095/49 (Figure 20). The master branchline shows a ramp-flat-ramp geometry where it is bedding plane parallel for about 1 meter at the lithologically boundary between sandstone and shale. Pockets of breccia is seen along the fault plane at the base of the sandstone, and subsidiary synthetic, antithetic bedding plane slip of few cm is observed in the sandstone (Figure 20). The ramp to flat turning point area also shows a higher deformation frequency. Fault rock lenses of sandstone and siltstone are present in the hangingwall and show normal displacement of 10 cm to 1 meter. Adjacent to the lenses there is in addition three defined segments that are splaying in an up-dip direction with a segment alcamation configuration. This may represent the initiation of lens development.

Figure 20. Stereoplots showing the orientation of: a) Hangingwall master branchline and associated slip surfaces b) Fractures and slip surfaces denoted b.
Figure 21. a) Lenses formed in calcareous shale in the footwall block of the master fault. Hangingwall master branchline defined by normal throw and slightly oblique striated slickenside lineations on a calcite surface. Mosaic breccias also are recorded, and mosaic-chaotic breccias are seen along the lens boundaries. Fault core lenses display an average a:b ratio of 1:2.9. b) Calcite mineralization along the hangingwall master branchline, position of picture is given in a).

Figure 22. Stereoplot showing the orientation of a) Lens boundaries and fractures, b) Trend and plunge of slickenlineations.

The fault with associated lenses positioned between the master fault and FW1 fault (Figure 23). The fault self juxtapose calcareous limestone of unknown displacement, but probably no
more than a few meters (The sedimentary unit is about 4-5 meter thick). The fault shows an average strike and dip of 040/60. The footwall master branchline is exposed and display slickenside lineations in calcite with a trend and plunge of 162/52 and 087/65. Breccias are positioned along the branchline and an along lens boundaries, and is characterized by high matrix (calcite) content with small limestone fragments (Sample HB_4). The core includes lenses that show a dense to open network of fractures, where the majority is filled with calcite. Three lenses were measured and display an average a:b ratio of 1:2.9.

2.1.2 Footwall damage zone

FW1

The FW1 (Figure 17) can be described as a sub vertical fault. It displays a normal offset of approximately 3 meters derived from sketch given in Westoll (1955). The fault juxtapose calcareous shale on the hangingwall side with the Acre Limestone, both within the Middle Border Group see (1.2.2). The fault can be traced on the strandflat for approximately 100 meters eastwards, and the subsequent description will be along this trace, which include the described areas FW1b-d (Figure 13).

The FW1 fault is exposed in the cliff section. The fault is also mentioned previously with regards to the master fault (Figure 17). The fault is characterized as sub-vertical and displays a strike and dip of 100/85. A gradual increase in bedding plane dip can be seen towards the FW1 fault core. From nearly horizontal to 33 degrees, and the fold axis is oriented 320/82. Normal drag is seen in the hangingwall, where the more competent layers are ruptured, and the softer shale is continuous passing through the fault core.

Footwall

Display slight normal drag, the footwall also occupy a fault oblique to FW1, this fault is denoted FW1a (Figure 14).

FW1a

The fault normal offset calcareous shale of unknown displacement. It is at the same stratigraphic level as the MFa fault, so a more than 4 meter displacement is unlikely. The
fault plane is exposed and display slickenside lineations in calcite. The mean orientation of the fault is 030/57 and display close to dip-slip movement (Figure 23). Two lenses are positioned on the FW1a fault plane, and appear to be cross cut by the FW1 fault. The mean a:c ratio of the two lenses was calculated to 1:2.5.

Figure 23. Stereoplot showing the footwall master branchline. Red dots represent trend and plunge of slickenside lineations. Key map to the right shows FW1a and MFa position.

FW1b

Figure 24. a) Close up sketch of the FW1 fault seen from above. For position see Figure 13. The fault has an estimated displacement of 3-5 meters. Profile A and B represents the position of
the fracture frequency measurements. The green line represents the cross section (b) Cross section, master branchlines in red. Stereoplot showing the bedding plane orientation. Blue arrows indicate the position of samples.

![Figure 25. Stereoplot showing a) Footwall master branchline b) Hangingwall master branchline c) Antithetic faults on the hangingwall side. b) Slickenside lineation on footwall master branchline.](image)

**Fault core**

The fault core varies in thickness from west to east from a few cm to 40 cm at its maximum. The fault rock lens denoted A (Figure 24) constitute of approximately 15 percent calcite veins, where the widest are up to 0.5 cm. It was also recorded a fracture frequency of 11 fractures/decimeter. The fault rock lens denoted B consists of approximately 30 percent calcite veins (Figure 24). The two measured lenses has a mean a:b ratio of 1:6.

**Footwall**

Along strike the footwall master branchline is slightly undulating, and the fault plane is steeply inclined. The mean orientation is calculated to 095/85 (Figure 25). Patches of breccia is evident on the entire fault surface, and a semi-continuous 1-5 cm lamina of clay is
positioned along the footwall master branchline. The distribution of breccias varies along strike, and several types were recognized: 1). clast supported 20 percent matrix and clast size of 1-2 cm. 2). matrix supported, and clast size of 0,5-1 cm. 3). clast supported, 15 percent matrix, and angular clast of 2-4 cm. Slickenlines measured on the fault surface displayed a trend and plunge of 100/55 (Figure 25), indicating a strike-slip component, making it a sinistral fault.

On the footwall side a 10-20 cm wide zone seems to be more resistant to erosion (Figure 24a colored grey). This zone has a higher density of mineralized fractures (5 fractures/decimeter) compared to the adjacent rock in the north which show 0-1 fractures/decimeter.

**Hangingwall**

The hangingwall master branchline separates the fault core from by steeply inclined calcareous shale beds seen in the hangingwall damage zone. The branchline displays a more irregular surface in three dimensions. It shows a slightly more gentle dip than the footwall master branchline. The mean orientation was calculated to 104/79 (Figure 25).

The hangingwall side is not completely exposed; however antithetic faults were seen 0.5 meters south of the hangingwall master branchline (Figure 24). The calcareous shale show a fracture frequency of approximately 1-2 fracture/decimeter (Figure 26), and two antithetic faults with a mean orientation of 264/55 (Figure 25). As seen in Figure 25, bedding planes A, B and C is going from nearly horizontal to steeply inclined, and in several places fault plane parallel. The calcareous shale beds are dragged along the fault surface, and show a higher deformation close to lens A (6.5 fractures/decimeter). The western part shows 3 fractures/decimeter (Figure 26).
Figure 26. Fractures/decimeter of profiles A and B, position given in Figure 24. The diagrams display measurements from north (right) to south (left).

FW1c

No. of Data = 4
Mean Principal Orientation = 98/66
Mean Resultant dir’n = 66-188
Mean Resultant length = 0.99
(Variance = 0.01)
Calculated girdle: 200/66
Calculated beta axis: 24-110

No. of Data = 5
Mean Principal Orientation = 103/68
Mean Resultant dir’n = 52-181
Mean Resultant length = 0.61
(Variance = 0.39)
Calculated girdle: 199/76
Calculated beta axis: 14-109

No. of Data = 2
Trend/Plunge
174/56
134/55
Figure 27. Map sketch FW1c to the left. Located approximately 10 m east of FW1b (Figure 13). a) Stereoplot showing the orientation of the footwall master branchline b) Stereoplot showing the orientation of slip surfaces in the core c) Slickenside lineations measured on the footwall master branchline surface.

Along strike the footwall master branchline is slightly undulating. The mean orientation is calculated to 098/66 (Figure 27a). The fault plane consists of breccias. The breccias are clast supported and have a calcite matrix content of about 30 percent. Elongated clasts in the size of 1-5 cm are found. Slickensides on the fault surface display a trend and plunge of 174/66 and 135/55 (Figure 27c). This indicates an oblique shear sense. Also a low angle bedding parallel fault is seen in Figure 27.

FW1d

Figure 28. Top: Map view sketch of traced slips surfaces and fractures. Blue arrows indicate the position of the samples collected. Black arrows indicate the position of the pictures. The black lines represent what is considered principal fractures, while grey lines represent less distinct fractures. Areas outside the stippled line are poorly exposed. Details shown in photos a), b) and c).

Figure 28. Top: Map view sketch of traced slips surfaces and fractures. Blue arrows indicate the position of the samples collected. Black arrows indicate the position of the pictures. The black lines represent what is considered principal fractures, while grey lines represent less distinct fractures. Areas outside the stippled line are poorly exposed. Details shown in photos a), b) and c).
Sub-areas a, b and c can be seen in Figure 28. Sub-area a display the continuation of the fault trace FW1. The footwall master branchline can be traced for about 5 meters eastwards and displays a 10-30 cm wide zone of calcite (Figure 28a). The continuation of FW1 fault trace is uncertain, however it is likely that is follows the northern EW trending lineament, which is mapped from aerial photo. The mean orientation of the fractures is 090/73.

The area is characterized by a complex pattern of fractures and fault rock lenses. All fractures show calcite mineralization, and the average calcite content in the studied area was determined to occupy about 10% of the host rock.

The mean a:b ratio of the measured lenses was calculated to 1:7. Figure 28c shows a higher order lens in area c that is split into two lower order lenses. The initial a:b ratio of the higher order lens is 1:4.2, and the two lower order lenses have ratios of 1:3.4 and 1:3.5, see also Figure 16.
Figure 30. Map view sketch of fault trace FW2, position is found in Figure 13. The green lines indicate the position of the fracture frequency profiles. Blue arrows indicate the position of the collected samples. Areas illustrated as breccias indicate more than 15% calcite.

The fault is antithetic to the master fault and is positioned about 20 meters north. It self-juxtapose the Acre Limestone by 2-5 meters, and strikes EW and has a throw close to dip slip (Figure 31d) down to the north (Figure 13 and Figure 14).

The fault core width varies from 10-20 cm to 2 meters at its widest. The core is heavily fractured, and all fractures are mineralized by calcite. The calcite veins are generally oriented in the strike direction, and are in some places several cm wide and display a number of generations (Figure 30b). The core comprises 10 defined lenses with average fracture frequency of 5 fractures/decimeter and an average a:b ratio of 1:6.3. Breccias are typically seen along the master branchlines and along lens boundaries. The breccias are dilation breccias and are mostly characterized as mosaic to chaotic (Mort and Woodcock 2008) (Figure 30e).

The lenses seen in Figure 30 (numbered 1-10) are bounded by high strain zones colored blue. The two first lenses (1-2) are barely separated and consist of calcite veins in the size of 1 cm which are dominantly EW trending (Figure 31c). Close to the master branchlines the fracture frequency increases from 4-5 fractures/decimeter to about 10 fractures/decimeter (Figure 32a). Close to the footwall master branchline mosaic breccia is observed (Figure 30e). Lenses 3, 4 and 5 are 2nd order lenses that construct one 1st order lens. The 1st order lens display an a:b ratio of 1:7.5, while the 2nd order lenses show a:b ratios of 4.9, 4.5 and 5.4 respectively. The lenses are characterized by a swarm of calcite veins, where some are arranged as low angle en echelon (Figure 30c). Breccias along the boundaries are mosaic to chaotic. Lens 6 is separated from lens 5 by a 20 cm thick zone of chaotic breccia with more than 50 percent calcite matrix. Lens 6 show a conjugate set of fractures (Figure 30a) with a preferred orientation of 265/80. The lens shows a total of 8 percent of calcite. Lens 8 and 9 are completely perforated with calcite which makes up more than 60 percent of the lenses (Figure 32c). Lens 10 is highly fractured and displays 5 fractures/decimeter (Figure 32d).
Footwall

The footwall master branchline shows a mean orientation of 281/79 (Figure 31), and a sharp boundary separate the fault core from the footwall damage zone (Figure 30d). The trace of the branchline is generally displaying a straight line, but shows a northern shift of about 5 meters. The damage zone in this area has a higher deformation, than in the adjacent areas. The footwall damage zone displays an irregular decrease in fracture frequency. Close to the footwall master branchline there is about 3 fractures/decimeter, and a few meters south it is averagely decreasing to about 2 fractures/decimeter (Figure 32d). The calcite percentage in the host rock shows an average of 8% in the first 60 cm south of the fault core (Figure 32c).

Hangingwall

The hangingwall master branchline dips more gently than the footwall master branchline and is more irregular and displays an average orientation of 281/61 (Figure 31a,b). The hangingwall damage zone displays thin calcite veins positioned parallel to the master branchline. The average fracture frequency is about 2-3 fractures/decimeter, and the frequency is regularly decreasing towards the fault core (Figure 32b and d).

Figure 31. Stereoplot showing, a) Footwall master branchline, b) Hangingwall master branchline c) Fractures and slip in the fault core d) Slickenside lineation from the footwall master branchline.
Figure 32. Diagrams displaying number of fractures/decimeter in a, b and d across the FW2 fault. Average fracture frequencies in the core is about 5, while the hangingwall and footwall damage zone display fracture frequencies in the range of 2-3 fractures/decimeter. Diagram c. displays the percentage of calcite vs. host rock. This illustrates that the deformation intensity is much higher in the core compared to the adjacent damage zones. In relations to the fractures frequency profiles it demonstrate that the thickness of the calcite veins are much thinner in the damage zones compared to the fault core.
2.1.3 Hangingwall damage zone

This section is covered by the LiDAR dataset.

*HW1, HW2 and HWa*

Figure 33. a) Snapshot from the LIME software displaying the complex faulting, b) Ramp-flat-ramp geometry and folding and c) Complex faulting at the intersection points. Inset in figure a show the position.
Figure 34. Stereoplot showing: a) Orientation of fault denoted HW1 b) Orientation of fault denoted HW2 c) Orientation of accommodation structures denoted HWa. Black indicates field measurements and red represents LiDAR measurements.

The HW1 fault a) displays listric geometry and has an average strike and dip of 110/52 (Figure 34a). The fault plane is steeper when cutting through sandstones, and seems to sole out on weaker shale beds. The fault is generally absent of a core, and the fault plane is characterized by a sharp boundary between the footwall and hangingwall (Figure 33b). However at the upper footwall part of the fault a 1.5 meter thick shale together with a 15 cm thick coal seam is incorporated in the fault core, and smear is recorded. The core is thinning to nil obliquely over 3.5 meters. The coal is ruptured to semi-continuous for 3 meters, and defines one lens shaped coal body positioned along the footwall master branchline. The a:c ratio of the coal lens was measured to 1:2.8 (Figure 16). The fault has a normal throw of 1.8 meters and an oblique displacement of almost 9 meters.

Accommodation structures in the footwall denoted HWa (Figure 33a), show faults that generally trend in the same orientation as the HW1 fault. The faults are slightly steeper dipping, and die out up-section. Measurements from field also reveal some more gently dipping ENE-WSW trending faults that were not detected from the LiDAR dataset (Figure 34c). The normal throw of the faults are in the scale of 0.5-0.8 meters.
The hangingwall is characterized by a complex pattern of minor faulting in the scale of millimeters to centimeters. The ramp-flat-ramp geometries also seem to accommodate fault-bend anticlines (Figure 33b).

The fault denoted HW2 is antithetic, and cross cut the HW1 fault. The intersection is distinguished by complex faulting and folding (Figure 33c). The fault has a 1 meter normal offset and a mean orientation of 268/37, also confirmed by LiDAR data (Figure 34c). Moreover, thickening in the hangingwall strata, opposed to the conformable layering of the footwall strata of HW2 can be observed.

**HW3, 4 and 5**

![Figure 35. Snapshot from the LIME software displaying LiDAR data. Showing the faults HW3, HW4 and HW5. Inset indicate the position.](image_url)
Figure 36. Stereoplot displaying: a) The mean orientation of FW3 reverse fault b) The mean orientation of faults HW4 and HW5.

HW3 display a thrust fault with a vertical reverse displacement of approximately 15 cm (Figure 35). The fault is shallowly dipping toward the north, and shows a mean orientation of 270/07 (Figure 36a). The fault is slightly steeper dipping passing through sandstone beds, and appears to sole out in shaly beds. There is no defined fault core, but several splays and sub-parallel fractures are seen in the shale. Minor indication of reverse drag is observed on both the footwall and hangingwall side.

The HW4 fault has a normal vertical offset of 1 meter, and a mean strike and dip of 106/52 (Figure 36b).

The HW5 is a low angle fault with a mean orientation of 111/30 (Figure 34b). The normal throw of the fault was estimated to about 7 meters, whilst the oblique displacement was calculated to 10 meters.

HW6

Figure 37. Snapshot from the LIME software handling the LiDAR data. Displaying the fault plane in light blue. Red square represents the sketch showing ramp-flat-ramp geometry and associated drag/rollover structure.
Figure 38. Stereoplot of a) Strike and dip measurements from field and b) results from the LiDAR dataset. Measurements in field are only from the lower section of the cliff, LiDAR dataset also present data from the upper part of the cliff.

The southernmost fault is a low angle normal fault, which constitute dip-slip slickensides and show an average orientation of 98/28 (Figure 38a and b). The vertical displacement is not gradual, but change abruptly closer to the Lickar (Howick) Limestone. The coal seam was measured to have a normal vertical throw of 0.5 meter, while the Lickar (Howick) Limestone displays a 10 cm vertical normal offset. The fault completely terminates in the uppermost massive sandstone (Figure 37). The LiDAR data show a 10 degree difference in strike orientation from the field measurements. This may be due to changes in the fault plane orientation up-section which is inaccessible for field measurements.

The fault has no clear core, and the footwall side is only separated by a millimeter thin lamina of clay and occasionally small lenses in the size of few cm is seen. At one place along the fault plane a ramp-flat-ramp geometry is recorded (Figure 37 inset), where the flat is bedding parallel at the base of the coal seam, and the top of a one meter thick silty sandstone. The fault plane is bedding parallel from about 20 cm. The hangingwall side display ruptured coal smear, which is positioned along the fault plane and displaced for about 15 cm. Layers of shale is folded on top of the ramp break.

Up-section the fault segment splays, and can be characterized by tip-line biforcation configuration. This demonstrate the early development of a first order fault lens, and show
an a:c ratio of 1:7.7. Along the footwall branchline splay, a defined lens is mapped out and display an a:c ratio of 1:6.6 (Figure 16).

Figure 39. LiDAR scan of the northern section of the Howick Bay locality showing one way to utilize the data set. Apparent syn-wedge can be ruled out by accurate measurements of inaccessible strata.

Based on visual observations of inaccessible strata, a presumably clear syn-sedimentary growth in one distinct layer can be seen from a foreshore view (in field). However, when measuring the thickness in the LiDAR profile the thickness variations is not obvious and the small variations are 1-2 percent and are well within the accuracy of the method (Figure 39). The observed growth is a geometric/optical illusion and this is an example how LiDAR profiles, which are fixed in a known spatial coordinate system, can be used to do reliable measurements in inaccessible areas.
2.1.4 Summary – Howick Bay

The Howick Bay locality comprises a master fault which displays a mean orientation of 094/51 (Figure 40b). The fault core is semicontinuous consisting of gouge, and generally no more than 20 cm thick.

The hangingwall damage zone includes six defined faults of which one is a thrust fault. The faults frequently show a ramp-flat-ramp geometry which is accommodated small folds, and display a mean strike of 105, while the dips are ranging from a few degrees to about 60 degrees (Figure 40a). The HW1 fault is clearly listric in geometry and display a ruptured shale smear. The faults are generally absent of fault cores, accordingly the transition from the hangingwall to the footwall side is marked by a sharp boundary in addition to this hangingwall thickening is recorded. A second set of fractures trending ENE-WSW are documented and are restricted to the nearby 10 meters of the master fault. A third set of sub vertical fractures are oriented NS, and are likely to be the background fractures.

The footwall damage zone displays a mean orientation of 093/86. The faults are generally steep and a network of sets of fractures is recorded in the fault cores of the fault members (Figure 40c). Lenses have an average thickness to length (a:b and a:c) ratio of 1:5.5 and the initiation of a 1st order lenses show tip line biforcation in one case and Riedel sharing at the footwall fault members in all other cases. A considerable part of the footwall volume consisted of calcite particularly in the footwall fault cores and several places display mosaic to chaotic breccias.

The fracture frequency show more than 40 fractures/meter close to the master fault and the frequencies irregularly decreases away from the core. Highest intensity is in the footwall, but the hangingwall has the widest zone of deformation. It is a marked difference between the orientations of the bedding planes on either sides of the master fault (Figure 41).
Figure 40. Contoured plot showing a) Fractures and faults in the hangingwall damage zone, b) the orientation of the master fault and c) fractures and faults of the footwall damage zone.

Figure 41. Contoured plot showing a) bedding plane orientation in the hangingwall damage zone and b) bedding plane orientation in the footwall damage zone.
2.2 Locality 2, Hartley Steps

This locality was first brought to attention by Jones (1968). He reported three EW trending faults with a normal cumulative offset of about 15 meters (49 ft). It was also observed horizontal striations indicating a strike-slip component. De Paola et al. (2005) termed the faults as classical Andersonian, indicating normal offset and 60 degree dip-slip movements. Faerseth et al. (2007) observed fault gouge and steeply inclined rock lenses incorporated in the fault of the largest throw (master fault), and it was also reported a normal cumulative offset of 17 meters.

The Hartley Steps locality is situated in the southern part of the Northumberland Basin approximately, five kilometers north of the Ninety Fathom fault, or the town center of Whitley Bay. The study area is located between St. Mary’s Lighthouse to its south and Crag Point to its north (Figure 42). It can easily be accessed from the beach, but one should be aware of the tide. The high tide extends all the way to the cliff, and low tide is roughly marked on the map in light brown.

The locality is found in a coastal cliff (Lat/long 55.07362,-1.460689 (WGS84)) where the fault trace and its affiliated structures are excellently exposed. The strandflat is mostly covered by sand, but isolated exposures can be seen on the tidal flat.
Figure 42. a) Location of the exposure of the master fault at Hartley Steps. b) Exposed fault traces at Hartley Steps indicating the strike of the observed faults along the section. The red line shows the position of the profile in Figure 43. The figure is based on aerial photos (Google, 2010), and field observations. c) Aerial photography showing the scarp and the strandflat, position of faults as mapped and position of profile shown in Figure 43 (Google 2010).

The section at Hartley Steps displays a section well exposed sedimentary layers of sandstone, siltstone, shale and coal of Carboniferous age (Jones 1968). The height of the cliff is about 15 meters and the fault zone consists of a number of subsidiary faults related to the master fault. The faults are generally irregular and steeply inclined. The width of the fault envelope is estimated to 50 meters and it displays a normal cumulative displacement of 15 meter, of which the master fault accommodates 10 meters (Figure 43). The master fault includes approximately one meter wide fault zone of imbricated fault lenses that are separated from the hangingwall by a continuous fault gouge.
Good reference points are the coal seams named The Low Main Seam and 5 inch coal seam after Jones (1968). These provide useful markers to determine the magnitude and sense of displacement. The Low Main Seam can be followed on the footwall side, while the 5 inch coal seam can be followed on the hangingwall side. The general strike of the major faults at Hartley Steps is ENE-WSW. All major faults show normal down-to-SEE displacement (Figure 44).

Figure 43. NW-SE-oriented section displaying the structural elements and the lithostratigraphy at Hartley Steps. The areas that are not colored are not exposed. The stippled line represents the lower delineation of the exposure, so that everything below is an interpretation. The lithological column is modified from Jones (1968) according to own field observations. Sub areas are marked in with red lines pointing to specific faults and areas.

Fracture frequency measurements were collected across the faults zone (Figure 45). The two dataset was collected from sandstone and siltstone.
Figure 45. Fracture frequency diagram showing the number of fractures per meter. Most fractures are located close to the master fault where the frequencies exceed 60 fractures/meter. The background fracture frequency is 1-2 fractures/meter.

Figure 46. The complete lens dataset of the Hartley Steps locality, showing the a:c and a:b ratios of 12 defined lenses.

2.2.1 Master fault

The master fault of the Hartley Steps locality is an ENE-WSW striking normal fault with a normal displacement of 10 meters. A complete section through the fault is exposed at the locality. The fault core is accessible to an elevation of 10 meters. The fault is characterized by a 1 meter wide fault core which can be investigated in a 6 meter high section. The fault core includes several lenses separated by high-strain zones. Lithologies of the lenses include...
sandstone, siltstone, shale and coal. The master fault and related fault core will further be described by profile FC1 and FC2 seen in Figure 47.

Figure 47. Map view covering the area of the master fault and FW1. The fault core is separated by the hangingwall and footwall master branchlines, where two detailed profiles are made (FC1 and FC2). Profile A represents the position of Figure 48. FD1 is a profile of a fold in the footwall damage zone. FD2 is a profile showing an increase in bedding plane dip towards the hangingwall master branchline. Close up B covering the master fault to the FW1 fault displaying lithology, fractures and fault rocks The position of the fracture frequency profiles 1-4 are colored blue.
Figure 48. Showing the master fault to the SE, and the incipient secondary fault core to the NW (FW1). The fault core is about 1 meter wide. The fault core is separated by the hangingwall master branch line and the footwall master branchline. The central core include six defined lenses. Green squares indicate areas that are closer examined.

Figure 49. a) Stereoplots showing, a) the mean orientation of the hangingwall master, b) the mean orientation of the footwall master branch line, c) and the mean orientation of the FW1 fault.
Five lenses are well exposed in the lower part of the cliff, and Figure 50 shows the architectural elements. The core show imbricated lenses that make up a duplex. The lenses are lozenge shaped and show a width to length ratio ($a:c$) of 1:6 (Figure 46). The fault lenses are derived from sandstone, shale and coal. The lenses have been positioned accordingly to the sequence in which they were cut from the footwall and hangingwall, respectively. The lenses are separated by high strain zones which coincide with the bedding planes in some cases.

The shale lens shows anatomizing network of shears with some competent patchy rock bodies. Zones of platy shale are often oblique to bedding planes. The lens is surrounded by a high strain zone winch include remnants of the laminated shale. The $a:c$ ratio was calculated to 1:5.8. The coal lens is less deformed, and displays an open network of fractures. The $a:c$ ratio was calculated to 1:9.1. The bedding planes in the lens are partly oblique to the adjacent coal (mother rock) in the distal core. Along the footwall master branchline one can see small coal lenses in the scale of 5 cm. The Silt lens display bedding planes semi parallel to the c-axis, and it shows an open network of fractures. The fractures density however, is increasing towards the tips of the lens. The sand lens has five distinct zones within the lens that have been subjected to higher strain. The high strain zones are parallel or semi parallel to the bedding planes. Patches of 10-20 cm are nearly undeformed The sand lens has an $a:c$ ratio of 1:4.5. The sand lens up section indicated on (Figure 48) demonstrates more steeply inclined bedding planes. It can be seen as an anatomizing network of shears, where minor more competent lens shaped rock bodies are in the size of 10-20 cm. No distinct fracture system was recorded in this lens. FR1 is a semi-continuous silty protobreccia positioned along the tip of the sand lens. FR2 is a small shale lens that is about to be formed, through the process of asperity biforcation, and show an $a:c$ ratio of 1:6.7. The bedding planes are intact and do not deviate from the hangingwall strata. FR3 is a ruptured shale smear that is heavily sheared but is more competent than the gouge. The faults gouge is derived from shale coal and siltstone. It is a 10-15 cm wide continuous zone that separates the fault core from the hangingwall by the hangingwall master branchline. It comprises shale fragments, pockets of coal and silty clasts in the size of 1-3 cm.
The lenses also display different displacement patterns. The coal lens has been displaced approximately 1-2 meters, whilst the shale, silt and sand lenses which are in their correct lithostratigraphic sequence have been transported 3-5 meters from its mother rock.

Figure 50. A close up interpretation of the fault core (FC1) showing an extensional duplex, where the individual lenses are isolated by high strain zones coinciding with bedding planes, and separated from the hangingwall by a 10-15 cm thick fault gouge. Lens initiation is evident by asperity biforcation (FR2), derived from hangingwall strata (Note that horse is used as a synonym for lens in this figure).
Figure 51. Stereoplots of the orientation of lens boundaries in green, the bedding planes in red, and the fractures in pink. The shale, silt and sand lenses show that lens boundaries coincide with bedding planes.

**FC2**

Cross section of the master fault further out on the strandflat. The fault trace could be followed about 20 meter NW of the cliff, and the normal displacement was estimated to 10 meters. The footwall side encompasses 2 meters thick sandstone and siltstone beds at the base. The hangingwall consist of a shale at the base, continuing up-section a 1.5 meters thick sandstone which is gradually becoming more silty at the top, and subsequently the siltstone is becoming more shaly up-section (Figure 52a).

The fault core was not exposed, probably due to erosion and it was also covered by the beach sand. The footwall master branchline can be observed in three dimensions, and show a clear fault surface. Several places on the surface pockets of breccia can be seen. The footwall master branchline is oriented 062/44.
The hangingwall master branchline is not exposed but a subsidiary fault normal offsets a rock lens by 50 cm. The fault is oriented 070/61. Deformation is increasing up-section within the lens, the lens is apparently undeformed, but it is observed that the displacement at the base of the lens is 20 cm, while the center is offset 50 cm. Drag folding is seen on the hangingwall side along the fault plane, and a close up of the fault showing a core width of about 5 cm (Figure 52b). The core is characterized by a few cm wide zone of anatomizing network of fractures and shears which is positioned in the hangingwall. Along the fault plane a semiconsicious shale smear is recorded over a distance of 2 meters. The fault plane consists of a 0.5-2 mm thick striated fault gouge (Figure 52b).

Shale smear is seen along the fault plane. At the top of the lens the fault plane steps left approximately 10 cm. The zone between comprise folded shale and silt particularly from two layers which accumulate at the top of the lens, as seen in Figure 52a and c.
Figure 52. Cross section of the master fault (FC2). a) Showing the footwall master branchline in the NW and accommodation along the hangingwall master branchline. b) Close up of the fault showing thin gouge and bedding that is parallel to fault plane, and drag folding in the footwall. c) Shale smear culminates at the top of the lens as folds. d) Polished surface of gouge with oblique striations. The position of the profile is displayed in Figure 47 (FC2).
2.2.2 Footwall damage zone

FD1

Folded sandstone and shale in the hangingwall of a fault plane is seen 2 meters NW of the master fault in the upper part of the cliff (Figure 47 and Figure 48). The fault plane show a strike and dip of 048/70, but the exact displacement was not possible to determine, however the author suggests a minimum normal offset of 1 meter, which is the displacement needed to rotate the folded beds to a horizontal position (Figure 54).

The fault plane is irregular and steps about 80 cm to the NW and continues along the bedding planes. This occurs at the lithological transition between sandstone and shale. Fault segment B (Figure 54) displays an orientation of 065/60. It is uncertain whether the bedding parallel fault continues along the bedding, or if it is simply connecting segment A and B.

The hangingwall side of the fault (segment A and B) show a fold denoted Fold 1 where the fold axis is calculated to strike 132/71 (Figure 55). The fold is composed of sandstone and
shale. Breccia is observed in sandstone especially at the places of maximum curvature and partly along the fault plane. On the footwall side Fold 2 shows drag folding, and the bedding is parallel to the fault plane along segment B. Up-section the sediments are upward coarsening from shale to sandstone.

Figure 54. a) Sandstone and shale beds are folded (Fold 1) along fault planes A and B. Footwall drag fold (Fold 2).

Figure 54. b) Sandstone and shale beds are folded (Fold 1) along fault planes A and B. Footwall drag fold (Fold 2).

<table>
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<th>Mean Resultant dir'n</th>
<th>Mean Resultant length</th>
<th>Variance</th>
<th>Calculated girdle</th>
<th>Calculated beta axis</th>
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Figure 55. Stereoplots of a) Fold axis or fold 1 A b) fold axis for Fold 2 c) and orientation of segment A. (FD1).

**FD2**

The cross section show a gradual increase in dip towards the footwall master branchline, which is documented in Figure 57. Two fracture frequency dataset have been collected in two different sandstone beds covering the same distance (Figure 57). Profile 2 show an average fracture frequency of 6.5 fractures/decimeter. Nearly all fractures are mineralized by calcite and some are arranged in an en echelon geometry (Figure 56b) Several places the fractures are cut by a younger generation of mineralized fractures. Profile 1 shows an average fracture frequency of 2.55 meter. The sandstone layer is thinner and no fractures are mineralized. The fracture frequencies can be seen in Figure 64.

The footwall master branchline (Figure 56) show a fault surface (which is also seen in Figure 52a) which contain breccia and some calcite. The breccia is clast supported with 20 percent matrix, the matrix content increased towards the fault plane. The clast varied in size between 0.5-3 cm.

Figure 56. a) The bedding plane dip is increasing towards the footwall master branchline in the SE. The position of profiles 1 and 2 is given by the blue lines. b) Two generations of mineralized fractures. Blue arrow indicates the position of the sample. The position of the profile can be seen in Figure 47 (FD2).
Figure 57. Bedding plane measurements demonstrate an increased dip angle towards the fault. Fold axis is oriented ENE.

**FW1**

No. of Data = 4  
Mean Principal Orientation = 215/9  
Mean Resultant dir/n = 9-305  
Mean Resultant length = 0.99  
(Variance = 0.01)  
Calculated girdle: 329/86  
Calculated beta axis: 4-239

Figure 58. a) Sketch showing the FW1 fault plane and associated lenses A-F. Blue markers indicate the position of the collected samples. The sketch is not to scale.
Figure 59. Stereoplot showing the relationship between the lens boundaries and the measured bedding plane orientation within the lenses A-F (FW1).

The fault plane of FW1 is steep and planar and breccias are positioned along the plane at several places. Striations are also evident, indicating a horizontal component 227/50. Along the fault plane a few mm fault gouge/clay lamina is present.

**Incipient core**

The incipient core comprises six defined lenses denoted A-F (Figure 58) Lens A is mainly siltstone and show an approximate displacement of 50 cm. The rock is deformed and most of the lens can be characterized as a protobrecchia with a fracture frequency of about 10 fractures/decimeter. The bedding shows only minor drag close to the FW1 fault. Antithetic slip is seen inside the lens with few cm normal offset. Bedding orientation and the lens boundary measurements can be seen in Figure 58, and the a:c ratio is measured to 1:4. Lens B (Sample HS_9) show a normal offset of about 2 meters. It is composed of sandstone and along the boundaries of the lens breccia is present. The lens denoted C can be matched with its origin on the hangingwall side, and the N-E part has an offset of approximately 1.5 meters, while the S-W part is show a normal offset of about 2.5 meters. The bedding plane measured in the lens showed a mean orientation 341/20, which indicate that the bedding planes have been rotated about 20 degrees to the west. The lens is composed of sandstone and show drag along the FW1 fault. The a:b ratio is 1:2, and striations where documented along the boundary of lens C and D, the trend and plunge is measured to 219/11. Lens D also show rotated beds, and the NE part shows an offset of approximately 2.5 meters, while the
SW part shows an offset of about 4 meters. a:b ratio measured to 1:3.5. Lens E (Figure 47) display a deformed sand lens with a vertical displacement of 20-30 cm, the a:c ratio is calculated to 1:3.3. Lens F, is a second order lens. The boundaries of the first order lens were not exposed, and therefore not determined. The lens consists of coal from the Low Main Seam. The a:c ratio was measured to 1:2.5. A five cm wide high strain zone comprised of coal smear separates Lens E from F. Based on the striations the strike-slip component can be calculated. Fault FW1 has a strike-slip component of approximately 1.5 meters, while fault FW2b has a component of approximately 6 meters.

**Footwall**

Fault FW1a (Figure 58) terminates up-section in a shaly siltstone. The layer shows drag on the hangingwall side and breccia is gradually introduced. The breccia has a matrix content of 30 percent. The deformed siltstone below is also deformed and indicates 10 percent matrix. The deformed siltstone displays clasts with an average size of 1-2 cm, where the largest are 5 cm. The clasts are rounded and elongated and show a preferred orientation. The trend and plunge is measured to 236/18.

**FW2**
FW2a is a normal throw of 80 cm (Figure 60). The principal orientation is 061/60. Striations on the FW2a fault plane are close to dip-slip and show a trend and plunge of 142/59. Breccia is positioned along the fault plane and display matrix content between 20 to 50 percent and clasts are ranging between 0.5 to 3 cm. The fault show a normal offset of 80 cm. FW2b Display an average strike and dip of 093/64, and has a normal displacement of 40 cm. The two faults confine a fault block by tip-line bifurcation, which is characterized as an incipient core. The width is between 1-3 meters. The core comprises drag folds in shale, and a fracture set (A) with an average orientation of 258/78 (Figure 61).
FW3

The northernmost fault on the section has a normal offset of approximately 25 cm, and shows a listric geometry, with displacement that regularly goes to zero (Figure 62). Fault FW3b is measured to have a normal offset of 12 cm, and shows a listric geometry, with displacement that regularly goes to zero. The two fault branches are linked to a sole fault, and confine a rotated fault block. The faults display an average strike and dip of 091/65 (Figure 63). Fault branch FW3b consist of a thin discontinuous fault core of a few cm. Small lenses are positioned along the fault plane, and are in some cases brecciated. Drag is seen in shale on the footwall side. Fractures denoted F (Figure 62) has an average orientation of 103/83 (Figure 63), and are not linked up with the faults.

Figure 62. Close-up of the northernmost fault. The fault display a listric profile and dies out up-section.
Figure 63. Stereoplots showing mean orientation of a) fault a and b) The fractures (joints) F (FW3).

No. of Data = 7
Mean Principal Orientation = 91/65
Mean Resultant dir'n = 65-182
Mean Resultant length = 0.97
(Variance = 0.03)
Calculated. girdle: 325/38
Calculated beta axis: 52-235

No. of Data = 3
Mean Principal Orientation = 103/83
Mean Resultant dir'n = 83-193
Mean Resultant length = 1.00
(Variance = 0.00)
Calculated. girdle: 198/55
Calculated beta axis: 35-108
Fracture frequencies
The profiles (1, 2, 3 and 4) show number of fractures/decimeter (Figure 47 and Figure 56). Fracture measurements 1, 2 and 3 all had a starting point at the footwall master branchline, and measurement were collected to the northwest. 1 and 2 is collected in two different sandstone beds, while 3 collected in the equivalent as 2. 5 meters west. It display that there are significant differences in the values obtained. The measurements clearly show an increased frequency close to the master fault and FW1. It shows that there is a more intensely fractured zone in the first few meters from the faults (Figure 64).

Figure 64. Fracture frequency in the footwall damage zone. Measurements are collected from the master fault to FW1. Position is given in Figure 47.
2.2.3 Hangingwall damage zone

The following faults that will be described are on the hangingwall side of the master fault, and its location is marked on Figure 43. The southernmost fault on the Hartley Steps section displays the faults denoted HW1(a,b) and HW2 (a,b) (Figure 65). The faults planes are irregular and form complex fault geometries and fracture/slip patterns. The faults strike NE and dips 60-70 degrees towards the SW. Detailed observations was difficult to document due to organic overgrowth along the fault plane of HW1.

Figure 65. The southernmost fault on the Hartley Steps section, displaying a normal offset of 230 cm. b) The Low Main Seam reappears at the strandflat. c) Small thrust in the 5 inch coal seam (5 cm normal offset). d) Sketch of the fault system showing the slip surfaces and fractures and the fold.
The HW1 fault normal offsets the 5 inch coal seam (Figure 65) by 230 cm. The fault has a 10-20 cm semicontinuous fault core. The fault core is comprised of lenses of varying degree of deformation and display an anatomizing network of slip and fractures including fault plane parallel laminated shale. The lenses are in size of few cm to 50 cm. Lenses derived from shale show fault plane parallel bedding, whilst lenses derived from sandstone/siltstone often show protobreccia and breccia (Figure 65).

The fault splays out up section and form a new fault branch denoted HW1b. This branch is out of reach, and therefore not measured, but as seen in Figure 65 the fault has a more gentle dip than the HW1 fault plane, and the throw is estimated to 20 cm. Complex geometries is observed in the vicinity of intersection between HW1a and HW1b.

Hangingwall

Tracing HW1 along strike on the strandflat coal from the Low Main Seam is observed (Figure 65b). It appeared as a lens shaped feature. Whether it is continuous along the strike direction is not possible to determine due to sand and boulders. Nevertheless the coal is much higher stratigraphically than expected. The estimated displacement from its origin is calculated to 5 meter.

A low angle normal fault which offsets the 5 inch coal seam by 5 cm can be seen in Figure 65c). The fault however, also has a reverse component of similar magnitude. One meter to the NW a minor thrust fault of few cm offset which confine a small rock lens is recorded. The 5 inch coal seam displays normal drag at the HW1a.

Footwall

The fold (Figure 65d) seen on the footwall side is asymmetric. A steep SE facing limb along the fault plane is observed, indicating a nearly overturned geometry. The fold axis strikes and dips 305/ 89. Within the fold two minor faults are seen (A1), reverse offsetting a 30 cm thick sandstone by 10 cm and 3 cm, respectively going from SE to NW. Interbedded shale is not completely ruptured by these faults but draped/folded and only display minor slip.
The HW1 fault normal offsets the 5 inch coal seam by 2.3 m. From the 5 inch coal seam on the footwall side and down section the drag is increasing, and at the base the bedding is parallel to the fault plane. From the strandflat and 2.5 meters up section the fault has a planar geometry. Above a 20 cm wide core and minor drag on the hangingwall side is seen. At the base breccia and protobreccia is observed in siltstone mainly on the south side of the fault.

The coal seam is ruptured and reappears at the HW1b splay segment where it is semicontinuous for about 40 cm dipping towards the fault plane.

**HW2**

HW2 normal fault is situated approximately 2 meters NW of HW1 and has a normal throw of 15 cm. The fault plane is irregular and strikes NE and dips towards the SW. The fault splay HW2b dies out at the 5 inch coal seam. Minor drag is observed, and breccias are seen especially at the intersection point.

**Fault core**

The HW2 fault is characterized by a 10-15 cm semicontinuous fault core. The fault core consists of lenses and displays an anatomizing network of slip surfaces and fractures. The lenses are 10 to 20 cm in size. Some lenses are deformed and show breccias and protobreccias, while other seems to be undeformed.

![Figure 66. Stereoplots, a) average orientation of HW1 and HW2 fault planes b) Fold axis of the fold c) Orientation of A1 Fractures in black and orientation of A2 reverse faults in purple.](image)

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**HW3**

The HW3 fault (Figure 43) is a normal fault oriented ENE-WSW displaying a normal separation of 8 cm down to the NNW (Figure 67 and Figure 68), and is located approximately two meters NW of HW2. The fault is characterized by a discontinuous fault core and a steeply dipping planar fault plane. The fault displacement diminishes gradually up-section to zero. Minor normal drag structures are observed on the footwall side, and breccia is seen at the point of the observed maximum displacement.

![Figure 67. Minor fault with a normal offset of 8 cm. Zero displacement at the top (The end of the red stippled line).](image)

![Figure 68. Stereoplot projection of strike and dip measurements (n=3). Calculated mean strike and dip of 077/58 (HW3).](image)
HW4

The HW4 fault shows a minimum throw of 1 meter, indicated by the offset of the 5 inch coal seam (Figure 69). The fault has an average strike and dip of 125/55 (Figure 70).

Shale is dragged along the fault plane and is in some cases parallel. Breccia and protobreccia is seen several places but, mostly on the hangingwall side. Antithetic structures with an offset of few cm are also present on the footwall side.

A rock lens seen at the base show a gradual increase in deformation up dip. It starts off with zero offset and has an offset of 8 cm at the top. It displays initiation by asperity biforcatin, and an a:c ratio of 1:6.5. Drag is principally on the footwall side. Millimeter thin fault gouge separates the lenses from the master fault plane.

The fault plane runs parallel to the shale smear and associated drag structures are seen on the hangingwall side at the upper part where the fault splays and the throw of the splay segment is in the order of cm (Figure 69c).

![Figure 69](image)

*Figure 69. Sketch of a fault with a minimum throw of 1 meter. b) Rock lens that is gradually more deformed up-dip. Starts off with zero offset and has an offset of 8 cm at the top. c) Fault plane parallel shale smear with related drag structure is seen on the hangingwall side.*
2.2.4 Summary – Hartley Steps

The Hartley Steps fault zone consists of well defined architectural elements. The master fault is irregular and the orientation is ENE-WSW and down to the SEE displacement. The fault core is approximately 1 m wide and includes seven defined lenses, a continuous fault gouge and a semicontinous shale smear. The general characteristics the hangingwall damage zone are steep irregular normal faults of which one show an asymmetric fold and thrust faults are in some cases seen in relation to coal seams. The footwall damage zone displays an incipient core of which six lenses have been defined. The bounding faults show a strike slip component calculated to 7 meters, spread out on two slip surfaces within the incipient core. Lenses have an average thickness to length (a:b and a:c) ratio of 1:4.8 and the initiation of a 1st order lenses show asperity biforcation and and tip-line biforcation. The fracture frequency show a clear increase around the master fault and the incipient core, up to 60 fractures/meter is recorded.
3. Discussion

The dataset presented and described in the preceding chapters include spatial distribution of fault rocks, fault plane orientations, geometry of fault rock lenses and fracture frequency measurements covering the fault cores, damage zones and host rock, in addition to LiDAR data. The data will be discussed with the intention to understand the development of the two studied faults and the conditions that have caused the differences between them. The aim is to determine the fault history, in respect to the fault core and damage zone evolution, and comment on the effect of fluid flow. Finally put the faults into a regional setting, based on the given interpretations.

3.1 Geometry and structural style

The Northumberland Basin was formed by extension as the main driving force and the two studied faults display predominantly features reflecting this. The Howick Bay master fault displays a planar normal fault with a dip of 50 to 60 degrees as predicted by the Andersonian principle of fault orientation relative to the principle axes of stress. The highly fractured footwall is characterized by high calcite content. The Hartley Steps displays steep, irregular, normal faults. There are, however, a number of observations which cannot easily be explained by extension and it can be discussed whether these features are caused by a regional event or if they are small-scale local effects.

Faults in the hangingwall (HW1) at Howick Bay display irregular listric geometry and the fault core is characterized by a ruptured shale/coal smear. Fault cores are very thin or even absent, but small lenses and smear products occur occasionally. The faults are at a large scale clearly extensional. Some of the fault planes are very gentle and for instance the HW1 fault (Figure 33) has a normal horizontal separation of nearly 10 meters while the vertical throw is only two meters and at the base a thrust fault (HW3) can be seen (Figure 35). These observations indicate gravitational sliding in unconsolidated to semi-consolidated sediments which may have been triggered by a single stretching event. Gravity driven structures typically display listric profiles, and the extension created upslope must correspond to the
same amount of contraction or spreading at the toe (Roberts and Yielding 1994, Mourgues et al. 2009). These types of structures are generally formed in unconsolidated to partially consolidated sediments (Roberts and Yielding 1994).

Breccias are restricted to fault intersections and zones of fault dip changes. These areas are also folded in some cases. All observed slickensides are dip-slip or only with a slight deviation. One thrust fault is located at the base of the HW1 fault. A few places at the Howick Bay locality it was recorded that strain localized in coal seams (Figure 17). The hangingwall accommodation structure close to the master fault displays a coal seam that is stacked to double thickness. It was recognized several places that folding took place at the ramp-flat turning point, (HW1b, HW6) in fault intersections (HW1c) and reverse fault. The faults and associated folds displayed an average trend to the ENE. This is deviating from the principal stress documented from the far field effect of the Variscan inversion. It is possible that folds and reverse fault are formed by a transpressional event, but it is more likely that the observed structures are generated by extension and modified by local geometric irregularities. A sandbox experiment by McClay and Ellis (1987) illustrates an analogue to the examples in field. They demonstrated that fault-bent anticlines could form by extension on ramp-flat-ramp geometry (Figure 71).

At Hartley Steps several of the studied structures have a contractional component The HW1 fold (Figure 65d) seems to constitute different styles of deformation, one ductile expressed by folded shale and one brittle expressed by steeply inclined reverse faults. Moreover the coal seam in the hangingwall also displays a thrust fault (Figure 65c). The small scale
folding seen at FC2 (Figure 52c) is another indication of compression as is folding positioned along the incipient core at FD1 (Figure 54), and the reverse drag at FD2 (Figure 56). It is documented oblique slip at the FW1 fault and associated lenses. It is plausible that the FD1 fold is directly related to a horizontal component. The above mentioned folds and thrust can be assigned to a releasing and restraining bend model. Changes in the strike orientation create bends in the faults which will allocate strain during progressive displacement (Berg and Skar 2005).

It is difficult to construct this type of geometry by extension alone. It is likely that it has been influenced by a strike-slip component. This could be explained as a local effect such as rotation during a glide, or as a regional external compressional effect such as the Variscan inversion.

Faults in the footwall of Howick Bay display a complex fracture network. The fractures are mineralized primarily by calcite, and are many places several cm thick and in several cases occupy significant volumes particularly of the fault cores. In order to create accommodation space for the calcite several explanations are proposed and discussed below.

Figure 72. Fault dip changes as a result of differences in lithology (Ferrill and Morris 2003)

Ferrill and Morris (2003) suggest that the mechanical strength of a rock affects the fault angel in heterogeneous sediments. Competent rocks like limestone will produce a higher
fault angle than less competent rocks like shale. As a consequence dilation will occur in the competent rock, whilst restrain will take place in the shale. 2) The intrusion of eruptives may create the necessary space for calcite to precipitate/mineralize by hydrothermal circulation (De Paola et al. 2005). By this assumption the calcite veins are a direct consequence of the intrusion, hydrofracturing due to fluid pressure build-up creating crackle to chaotic brecciation (Mort and Woodcock 2008) which is later mineralized by hydrothermal circulation.

The Whin Sill is located in the hangingwall damage zone and has undoubtedly had effect on the surrounding rocks due to its buoyant nature at the time of emplacement and it is therefore probable that this has caused the dilation and consequently the precipitation of calcite in fractures. The succession of competent limestone (Acre) and less competent calcareous shale present at the hangingwall side may also have contributed. Also hydraulic fracturing is very common for faults transecting mechanically strong limestone e.g. Kilve fault (Brenner and Gudmundsson 2004). A combination of these factors is probable, but a conclusion on the relative importance cannot be drawn due to insufficient data.

### 3.2 Fault architecture

The Howick Bay and Hartley Steps faults are well exposed and easily accessible and would be good candidates to compare published fault architectural models with field observations. It is widely recognized in the literature that a fault encompasses a fault core, a damage zone and undeformed host rock (Chester and Logan 1986, Caine et al. 1996, Berg and Skar 2005, Braathen et al. 2009) (Figure 3). The architectural elements are by several authors further subdivided. For instance Heynekamp et al. (1999) proposed the damage zone to include also a mixed zone, Berg and Skar (2005) subdivided the damage zone into inner, outer and transitional, while Micarelli et al. (2003) separated between an intensely and weakly deformed damage zone.

The fault core is the portion of the fault zone that accommodates most of the strain and displacement, and may consist of slip surfaces, gouge, breccias, cataclasites, clay smears, lenses and geochemically altered zones (Chester and Logan 1986, Bruhn et al. 1994, Caine
et al. 1996, Berg and Skar 2005). The damage zone is the volume of rock consisting of subsidiary structures on either side of the fault core. These structures may comprise faults, veins, joints, stylolites, fractures, cleavage, folds and deformation bands (Caine et al. 1996, Heynekamp et al. 1999, Shipton and Cowie 2003, Berg and Skar 2005). The host rock is the volume of rock that has not been influenced by the fault; however, it is typical to find a background fracture network in the host rock which is not related to the actual fault zone (Caine et al. 1996).

Both the Howick Bay and the Hartley Steps locality can be divided into three parts that differs in structural style, the master fault, the hangingwall damage zone and the footwall damage zone. Quantitative measurements of fracture frequencies make it possible to define the architectural elements of the fault zone. The Howick Bay fault zone was estimated to be 100 meters wide, where the master fault display andersonian geometry and comprises a fault gouge varying from a few cm to 30 cm thick. The adjacent hangingwall and the footwall damage zones display a cumulative normal offset of about 20 meters, while the entire fault zone has a total normal displacement of 200 meters. This means that approximately 90 percent of the displacement is accommodated by the fault core. The Hartley Steps fault zone was estimated to be 60 meters wide. The core is 1 meter thick consisting of gouge/cataclasis and fault rock lenses and accommodates more than 60 percent of the cumulative displacement across the fault zone.

Shipton and Cowie (2003) introduce a slip-patch model for how the damage zones develop. They suggest that there is a strong correlation between the throw of the fault and the damage zone width.

In the slip-patch model proposed by the authors it is assumed that the fault slips repeatedly in small patches. After a slip event the fault instantaneously heals, which means the stress can be supported by the adjacent rocks. The widening of the damage zone is explained by this kind of repeated slip mechanism. Each slip event causes additional deformation to be formed in the damage zone, and these areas experiences strain hardening. When the deformation density reaches a critical level a slip surface will develop at a given distance from the master fault. This new slip surface can in turn accumulate damage and form other
ruptures. Consequently this will widen the damage zone and form a hierarchy of subsidiary fractures.

The proportional relationship between throw and damage zone width is given by Shipton and Cowie (2001) as a linear equation $w = 2.6t + 7.2$, where $w$ is damage zone width and $t$ is fault throw. The authors state that calculated damage zone width may vary 10-20 percent for any given value of throw. Applying this to the Hartley Steps fault gives a calculated damage zone width of 45 meters, opposed to a measured 60 meters (-25%). At Howick Bay the value is calculated to 530 meters opposed to the 100 meters that was measured in field. An explanation for this large discrepancy at Howick Bay could be a result of syn-depositional faulting or gravitational sliding. The 200 meters throw may not have full effect in creating the large damage zone due to a constant supply of sediments. This would, however, not explain the observations of gravitational sliding which occupy the hanging wall damage zone (Figure 34). The gravitational slide is thought to have occurred as an abrupt event at the time of deposition which does not fit with the gradually growing damage zone as described by the slip patch model.

The damage zone width is not only controlled by the throw of the master fault, but also the grain size and the distribution of beds with various lithology. The damage zone width in a rock of alternating beds of sandstone and claystone will be governed by strain hardening in sandstone, resulting in widening. Strain softening in claystone will localize the deformation into a narrower zone (Heynekamp et al. 1999).

At Howick Bay the fracture frequency measurements in the hangingwall show an increased frequency approaching the fault core, and close to the core more than 40 fractures/m were recorded. Fracture frequency measurements on the footwall side show generally a higher frequency than those on the hangingwall side (Figure 15), this bring concerns about the mechanical properties affecting the deformation in different lithologies. Heynekamp et al. (1999) noted that damage zone development was clearly affected by grain size, and Berg and Skar (2005) imply that the fracture distribution is controlled by lithology, layering and bed thickness. Much of the data on the footwall side is collected in a calcareous shale, opposed to sandstone beds on the hangingwall block. The anomaly can be assigned to the above
mentioned factors, but it might also be related to the emplacement of the sill. Despite this, it is clear that fracture frequencies are higher close to faults.

Moreover the measurements display a damage zone asymmetry where the higher percentage of the damage zone is localized in the hangingwall (60%) than in the footwall damage zone (40%). This is also recorded at Hartley Steps, where the majority of deformation is confined to the hangingwall damage zone.

3.2.1 Lenses

Previous studies have shown that the development of lenses is controlled by a number of factors like, the orientation of the fault plane, displacement and magnitude of the fault and host rock lithology (Lindanger et al. 2007, Bastesen et al. 2009). Initiation of lenses most commonly start by a principal configuration, such as segment linkage and asperity biforcation, which is found to be the most frequent development (Gabrielsen and Clausen 2001) (Figure 4). Progressive development of the lenses is thought to be governed by linkage of Riedel shears (Bastesen et al. 2009, Braathen et al. 2009), but also the mechanical strength, lithology and magnitude of the fault is influential (Lindanger et al. 2007, Bastesen et al. 2009).

The development of lenses at the Hartley Steps master fault seems to be primarily influenced by the principal fault plane. However bedding planes appear to act as slip surfaces that control the development of lower order lenses. Although no isolated 2nd order lenses were documented, it was clear that strain intensity was higher along bedding planes. The lenses were positioned in a duplex configuration (Figure 50), and are likely to be derived from the hangingwall block. One lens displayed clearly asperity biforcation (FR2) (Figure 50).

The average a:c ratio of the lenses were 1:5.4. This result deviated from the 1:12.5 ratio found by Lindanger et al.(2007). It is likely that the lenses have been broken down by splitting into lower order lenses, which is a possible explanation for the lower ratios. Lindanger et al.(2007) showed that lenses split down to lower order tend to form lower ratios. However, abrasion of the fault core lenses caused by progressive shearing by the
master branchlines are prone to thin the a-axis (Bastesen et al. 2009). The derived fault gouge, breccias and highly deformed rocks along the master branchlines are more likely to be partly cut off from lenses, than the more stable sidewalls. It is expected that these lenses are primarily controlled by the heterogeneous layering. The weak bedding planes and alternating mechanical strengths makes it preferable to shearing. The initiation of 1\textsuperscript{st} order lens is illustrated in Hartley Steps (HW4) (Figure 69), which demonstrates that it is derived from the hangingwall, and the 2\textsuperscript{nd} order lenses are still intact as beds.

The FW1 fault (incipient core) at Hartley Steps show lenses with a different geometry (Figure 58). Some of the lenses are “diamond” shaped, and oblique striations, indicating that they have been subjected to a strike slip movement. Three sandstone lenses were measured and showed a:b ratios of 1:2 and 3.5, and a:c ratio of 1:4 (Figure 46). The thick nature of the lenses does not seem to be primarily controlled by the lithological variations, but rather along Riedel shears formed by a strike slip component.

At Howick Bay limestone and shale lenses show a mean a:b ratio of 1:5.5, and fits with several of the plaster experiments by Lindanger et al.(2007), although they show a:c measurements (implying symmetric lenses, see Figure 4 ). Lenses positioned in the FW2
fault core show that a 1st order lens is split up to three lower order lenses, this is also documented in FW1. The lenses seem to be broken down by initiation of Riedel shears, probably due to a dextral slip. The decay of lenses was studied by Lindanger et al. (2007), which demonstrated that higher order lenses broke down to lower order lenses by cross cutting Riedel shears, which in turn created a lower ratio. The lowered ratio was recognized in two higher order lenses (Figure 74).

![Figure 74](image)

**Figure 74.** Top: 1st order lenses broken down to 2nd order lenses, where Riedel shears define the boundaries. Bottom: Higher order lenses that form lower thickness to length ratios when broken down.

### 3.3 Fluid flow

Faulting in granular material may influence porosity and permeability in the fault zone, and this may cause compartmentalization and fault sealing (Antonellini and Aydin 1995). The challenge is to define quantitative criteria to determine whether the fault zones will enhance or hamper fluid flow.
The main factors affecting the permeability of a fault zone are the composition of the host rock, fault displacement, the width of the fault and the pressure and temperature conditions at the time of movement (Odling et al. 2004).

Fracture systems are generally thought to increase the permeability within a fault zone (Caine et al. 1996), but Odling et al. (2004) showed that the damage zone ability to act as a flow barrier seem to be significant. A fault zone absent of a damage zone is entirely dependent on a lateral sealing (impermeable) core to act as a barrier where the core is thin high pressure gradients could build up and fluid flow occur. The damage zone will in these zones act as a barrier and prevent flow. The damage zone to act as a barrier was found to be more efficient perpendicular to the fault zone than parallel, due to the sub-parallel orientation of the fractures (Odling et al. 2004). This is also in concordance with Berg and Skar (2005) which showed that the majority of fractures were oriented sub-parallel to the master fault, which is also well documented in this study (e.g. Figure 40)

A standard method used, particularly when working with seismic data is plotting the lithological boundaries seen on the footwall block on the same diagram as the boundaries on the hangingwall block. These so-called Allen (Seal) diagrams (Allan 1989, Knipe 1997) will reveal the probability of any juxtaposition of permeable and impermeable rocks and are used in the assessment of sealing capacity of faults. As the current study has shown a fault zone is much more complex than the imaging capability of any seismic data and additional methods have to be used to get a more precise and versatile prognosis of fault behavior. In an attempt to systematize the observation of faults Yielding et al. (1997) introduced the SGR (shale gouge ratio). SGR is calculated as the sum of shale bed thickness divided by fault throw expressed as percentages. They also describe four important factors determining the permeability of fault planes i.e. 1) juxtaposition of permeable or impermeable sediments, 2) clay smear into the fault plane, 3) cataclasis and 4) diagenesis. Juxtaposition sand to sand will increase the cross fault permeability, while clay smear, gouge and diagenesis will decrease permeability. Another method was introduced by Lindsay et al. (1993) i.e. the SSF (shale smear factor) which is calculated as fault throw divided by the shale layer thickness. Calculation of SGR and SSF has also become standards in evaluation of seal capacity in
hydrocarbon reservoirs where the database consists of seismic and well logs/cores (Faerseth et al. 2007).

The sections at Howick Bay and Hartley Steps are studied to see if juxtaposition on the scale observed in the field is applicable for evaluating fault seal probability. In this study the faults are only fully exposed in two dimensions opposed to in seismic data where three dimensional analyses can be performed. At Howick Bay the two main units juxtapositioned against each other are a mixed clastic sequence (clay, silt and sand) against a limestone grading up to a shale. This setting is likely to be sealing due to the low permeable limestone and shale (Faerseth et al. 2007). However, on a smaller scale an intensely deformed hangingwall damage zone including several fault members have been recorded e.g. Figure 15 and Figure 28. Minor faults within the sandy units on this scale display sand to sand juxtaposition (Figure 14). The faults are characterized by sharp boundaries and are generally absent of a core. Fluid communication is likely, both perpendicular, due to the sand-sand contact (Faerseth et al. 2007), and parallel close to fault segments where the fracture frequencies are higher (Odling et al. 2004) (Figure 15). The limestone of the footwall side is highly affected by fractures sub parallel to the master fault; this could have resulted in excellent permeability along the fault core, but poor permeability perpendicular and across the core (Figure 15, Figure 26 and Figure 32). However, precipitation of calcite (Figure 28 and Figure 30) is likely to reduce permeability significantly make the footwall side a barrier (Berg and Skar 2005).

At Hartley Steps sand to sand juxtaposition is recorded at one level (Figure 43), but the sand units are separated by a one meter wide fault core (Figure 50). In the two dimensional exposure of the fault core it seems to be sealing, at least the 10-15 cm gouge, however, sand lenses not exposed might transport fluids across the fault core (Faerseth et al. 2007, Bastesen et al. 2009). The lateral continuity of the smear products is critical for the fault to act as a barrier, but an irregular fault geometry that is generally observed suggests countless pathways for fluid communication. The faults of the size described would have been recognizable on seismic data, but any prognoses of sealing capability would have been
dubious based on the standard industry methods without extensive core data to characterize the lithologies.

Another method of calculating the permeability potential of fault zones is presented by Caine et al. (1996). They state that there is a relation between the damage zone and the width of the total fault. The equation proposed is the ratio of the damage zone width to the total fault zone width, which is the fault zone architectural index (Fa). The index range from 0 to 1, when Fa is 0, the fault zone will ideally be impermeable, due to the underdeveloped damage zone and act as a barrier. If Fa is 1, the relative wide damage zone will enhance fluid flow and act as a conduit.

The values derived from Howick Bay and Hartley Steps fault zones give Fa ratios of 0.99 and 0.98 respectively, which characterize both fault zones as distributed conduits (Caine et al. 1996). This approach seems to be too simple and from a qualitative perspective the Hartley Steps fault core display a well developed continuous gouge, which should classify the fault zone as a combined conduit barrier according to (Caine et al. 1996).

3.4 Timing and regional implications

The Howick Bay fault is of the same age (syn-sedimentary) as the faulted sediments or younger. This suggests that the first potential movement may have occurred during the late Visean. It is widely agreed that the exposed strata at the Howick Bay locality are deposited during the post-rift stage of the basin, and are only subjected to minor faulting which are mainly accommodated by thermal subsidence (Johnson 1984, Collier 1989, Chadwick et al. 1993, Chadwick et al. 1995). In the preceding description it has been shown that all major faults show a NE-SW trend which is in agreement with the regional stretching associated with the opening of the basin. The magnitude of the master fault (200 meters) and the NE-SW orientation suggest that the fault may be linked up with older basement faults formed during the active rifting.

The faults at Hartley Steps are affecting sediments of Duckmantian age, which is thought to be deposited during a late stage of the basin infill (Chadwick et al. 1993). The major faults
are generally trending ENE-WSW and several are steeply dipping. The faults may have been initiated in Duckmantian, most likely caused by thermal subsidence. Syn sedimentary faulting or faulting close after deposition is supported by listric geometry as seen in Hartley FW3 which is commonly associated with gravitational sliding (Roberts and Yielding 1994, Mourgues et al. 2009). Furthermore, sandstone layers are folded and continuous in Hartley HW1 indicating that the sediments were unconsolidated when deformation took place.

The Northumberland Basin was situated in the foreland of the Variscan Orogeny. This is thought to have caused compressional structures with a NE-SW to NNW-SSE trend (Collier 1989, Chadwick et al. 1995). Faults acted as zones of weakness and may have been reactivated. Structures that imply contraction are associated with thrusts, reverse faults and folds. Such structures are documented at both localities.
4. Conclusions/summary

- The two faults examined in the Northumberland Basin display all elements in published and widely accepted fault architectural models, i.e. fault core, damage zone. The quantities and magnitudes of the different elements are differently expressed in the two faults and the study illustrates that the variability is large and generalization is challenging.

- The Howick Bay fault was initiated in the post rift stage and seems to be linked to E-W striking basement faulting. The fault has experienced numerous episodes of reactivation reflected by several generations of fault and fractures in the core and damage zone. Syn-depositional faulting is evident by hangingwall thickening, and the hangingwall sediments displays a fault with listric profile and associated thrust in the hangingwall which implies gravitational sliding in unconsolidated sediments.

- The Hartley Steps fault was probably initiated later than the Howick Bay fault, but still in the post rift phase. The fault is steep striking ENE-WSW and the throw is 15 meter. Small folds and thrusts have been recorded indicating either compressional influence or strike-slip component. The most likely is a transtensional reactivation causing the faults to in a strike-slip sense, hence generating steep irregular faults, accommodated by small folds and thrusts.

- Lenses are initiated by asperity biforcation, tip line biforcation and segment alcamation. The lenses show average length to thickness ratio of 1:6. Breakdown of high order lenses to lower order lenses reduces the ratio. The main controls for lens decay are bedding plane weaknesses and Riedel shear effects.

- Fracture frequency profiles show a clear correlation to the distance from the fault core in both studied localities. The profiles show that the hanging wall damage zone is wider than the footwall damage zone. This might be ascribed to irregularities in the
fault plane e.g. releasing and restraining bend model or the mechanical properties of the affected lithology.

- The two studied faults show a magnitude difference in throw (15 and 200 m), but no distinct relationship in average core thickness or damage zone evolution have been found.

- At Howick Bay the master fault juxtapose siliclastic strata against limestone. This is likely to be sealing due to the low permeable limestone and shale. Fractures in carbonated rocks are often mineralized by calcite, which commonly decrease permeability, but fluids can be transported parallel to in fractures networks both in the footwall and hangingwall. At Hartley Steps 10-15 cm fault gouge is observed, which is likely to obstruct fluid flow across the fault zone. However, permeable lenses and fractures in the core might serve as fluid pathways along and across to the fault zone. At Hartley Steps fluid flow is likely to be obstructed by gouge and smear in the two dimensional section. Lateral sealing is less likely due to irregular fault geometry.
References


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