

The structural evolution of the Devonian rocks and associated basement in Foula and Shetland: An analogue for the Clair Basin

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**Support from the Clair Joint Venture
Group**



The Clair Field

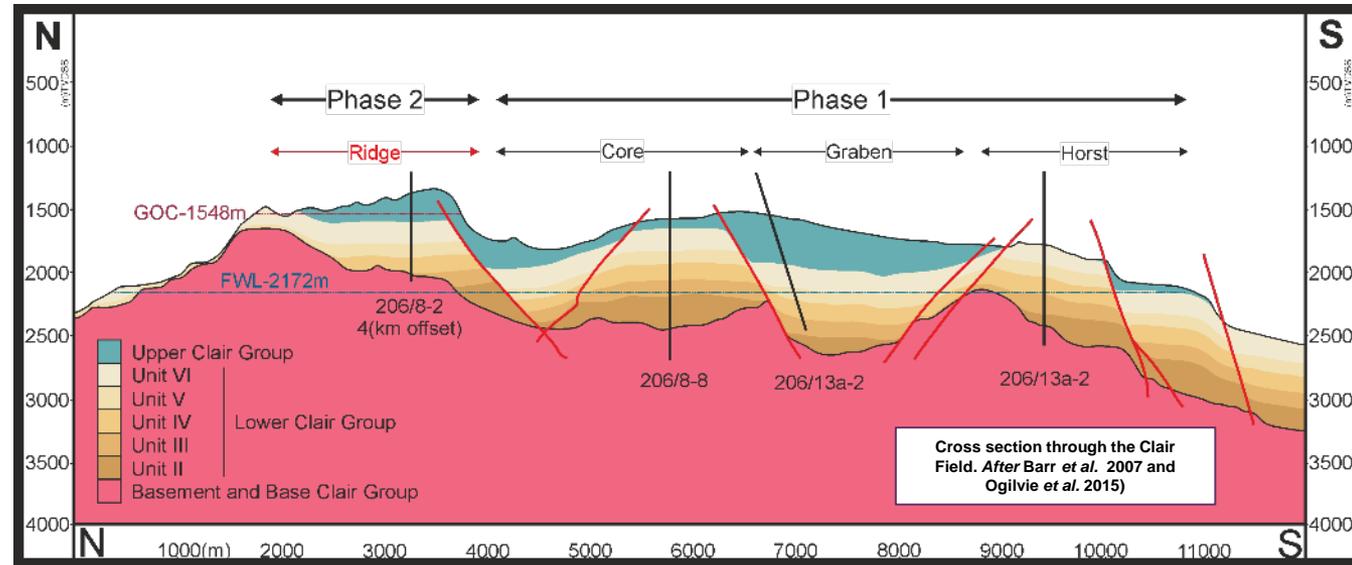
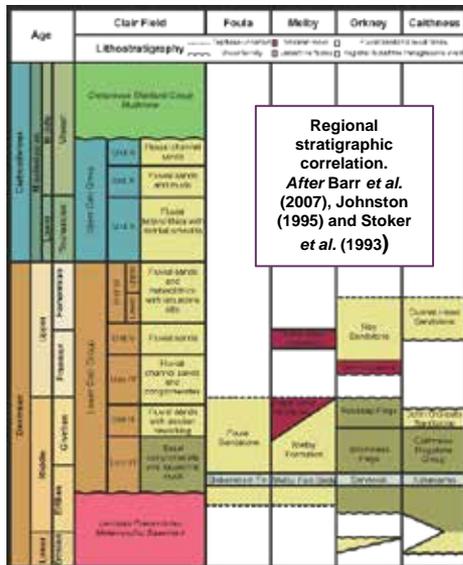
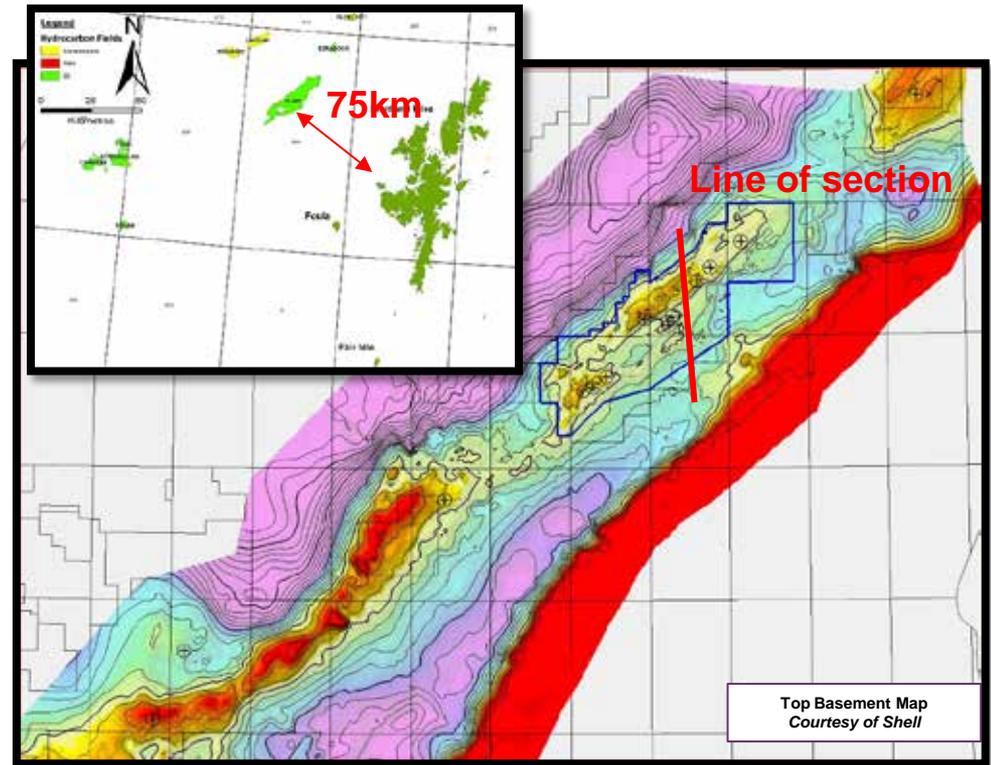
Largest known resource in the UKCS, with an estimated 7-8 Billion BOE in place

Fractured Devonian-Carboniferous sandstones (Clair Group) that overlie an up-faulted ridge of fractured Precambrian metamorphic basement

Significant proportion of hydrocarbons are stored within fractures

A greater understanding of fracture systems is required

Also need to better understand Devonian-Basement unconformity



Regional Context

Clair Basin developed during the Mid-Devonian to Early Carboniferous in NE/SW trending half graben

The extensional Orcadian Basin has long been used as the classic analogue for the Clair Field..BUT...

...alternatives exist in Shetland – these are thought to be **transtensional** (e.g. Serrane 1992, Dewey & Strachan, 2003)

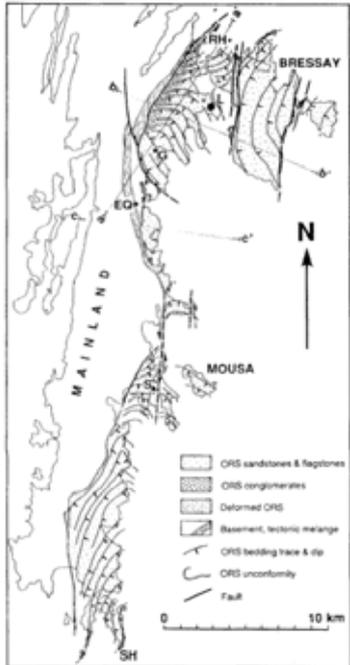


Fig. 3. Simplified map of Southeast Shetland basin. Location on Fig. 1. EQ, Easter Quarrf; G, Gulberwick; L, Lerwick; RH, Rona Head; S, Sandwick; SH, Sumburgh Head.

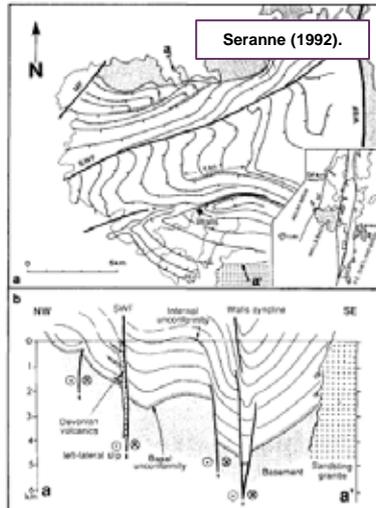
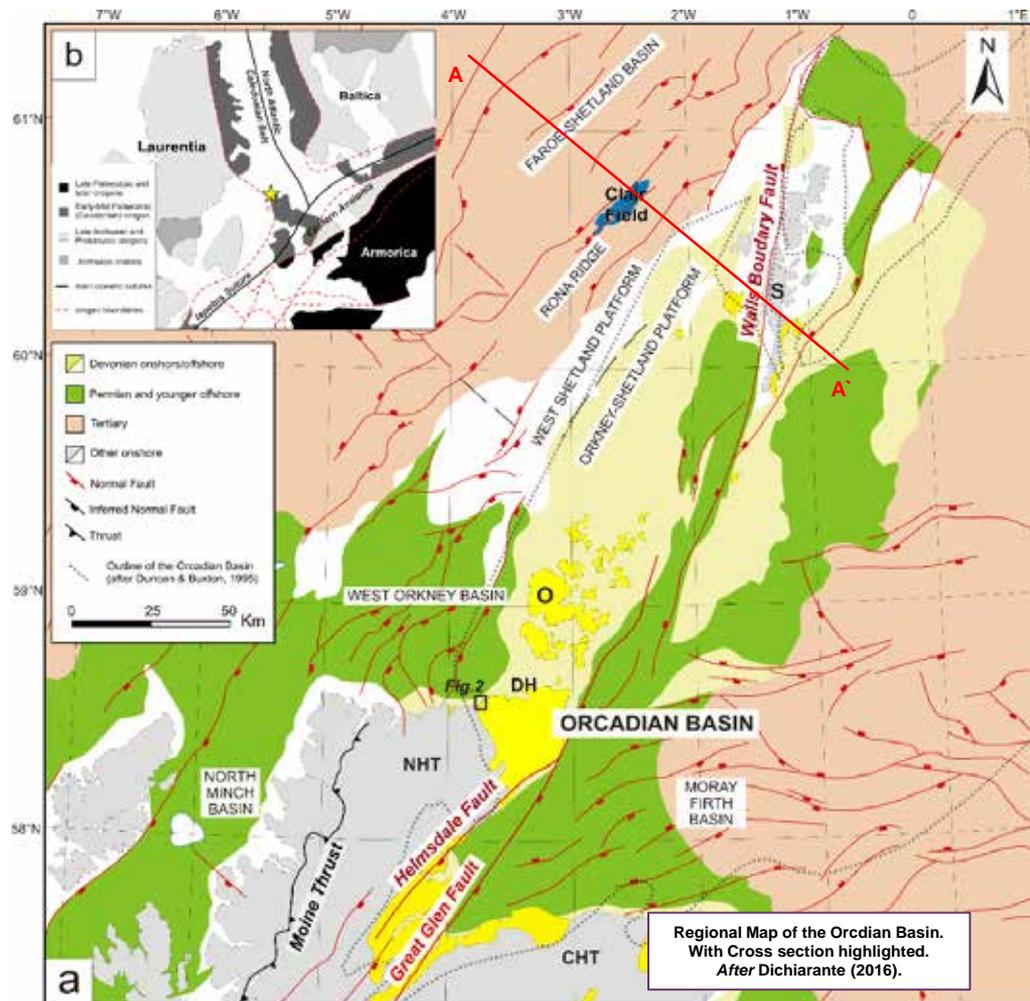
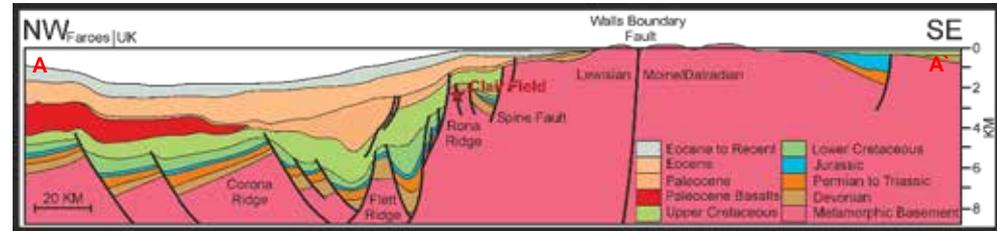


Fig. 2. (a). Simplified map of Devonian bedding in the Walls basin (west Shetland, location on Fig. 1), modified from Mykura (1976) and from personal observation on the northern margin. The effects of north trending folding have been removed. Sandstone granite and interbedded volcanic rocks are not represented. Old Red Sandstone series display internal unconformities and progressive syn-tectonic unconformities that demonstrate syn-depositional folding. Inset map shows the position of Devonian rocks (stippled) in Shetland. MF, Melby fault; SW, Sulma Water fault; WBF, Walls Boundary fault. (b) Section across Walls basin showing the relationship between basement faulting (left-lateral strike-slip) and folding of the sedimentary cover. Vertical and horizontal scales are the same.

Regional cross section through FSB and Shetland. After Ogilvie (2015).



Regional Map of the Orcadian Basin. With Cross section highlighted. After Dichiarante (2016).

Regional Context

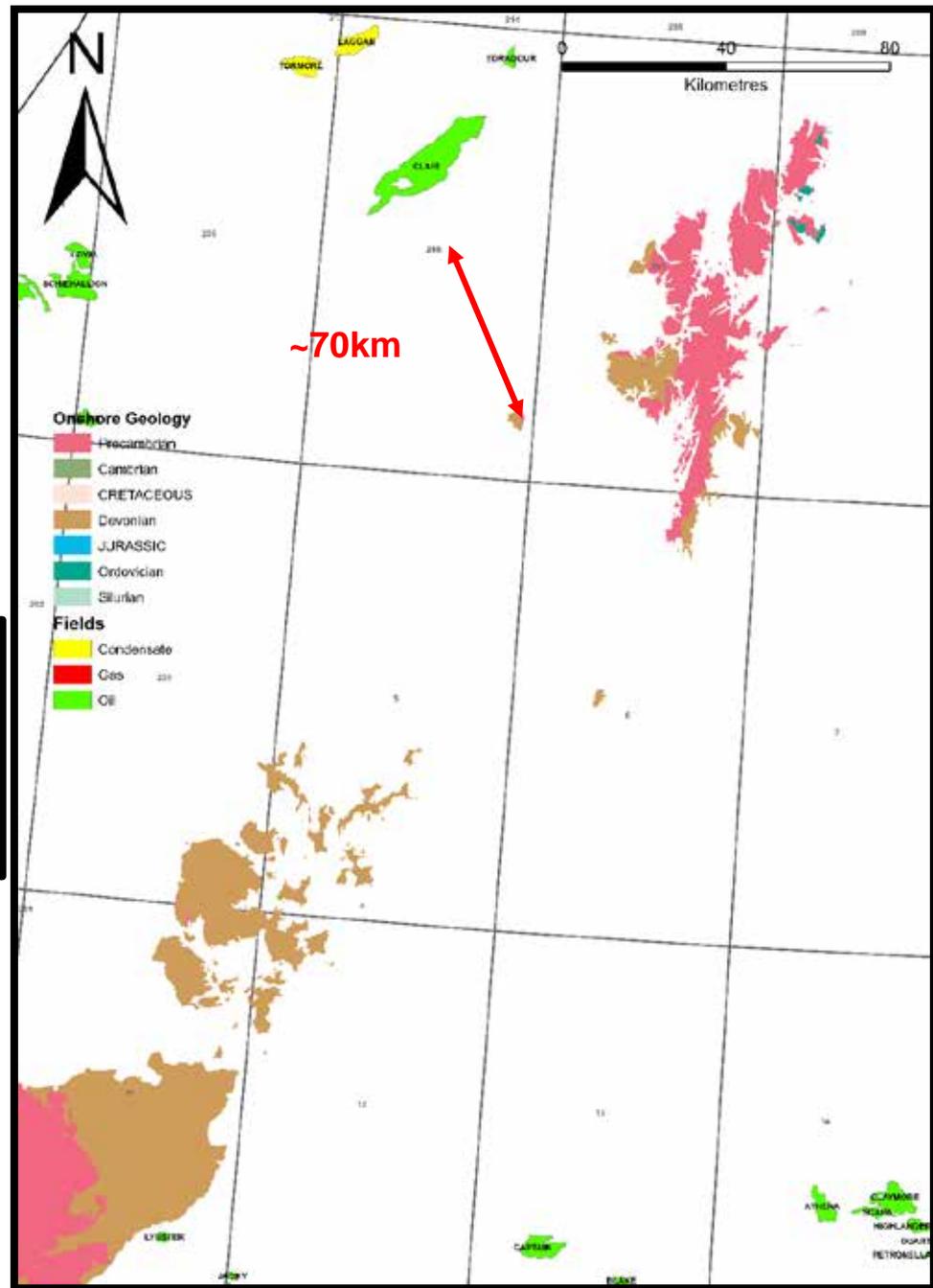
Foula is closest onshore analogue ~70km

Relatively poorly studied, despite its proximity

Comprises Middle (?) Devonian Sediments and Precambrian basement

Correlated regionally both onshore and offshore based on lacustrine facies and palynology

Age	Lithostratigraphy							
	Clair Field	Foula	Melby	Orkney	Caithness			
Devonian	Middle	Givetian	and conglomerates					
		Eifelian	Unit III	Fluvial sands with aeolian reworking	Foula Sandstone	Papa Stour Volcanics	Roussay Flags	John O'Groats Sandstone
	Unit I/II		Basal conglomerate and lacustrine muds	Blobersburn Fm	Melby Formation	Stromness Flags	Caithness Flagstone Group	
	Lower							
Silurian	Upper	Frasnian	Unit VI	Fluvial sands and heteroliths with lacustrine silt				
		Frasnian	Unit V	Fluvial sands		Hoy Sandstone	Cunnet Head Sandstone	
			Unit IV	Fluvial channel sands and conglomerates				
		Givetian	Unit III	Fluvial sands with aeolian reworking	Foula Sandstone		Roussay Flags	John O'Groats Sandstone
			Unit II	Basal conglomerate and lacustrine muds	Richardburn Fm	Melby Fish Beds	Sandwick	Caithness Flagstone Group
	Lower	Eifelian						
		Eifelian						



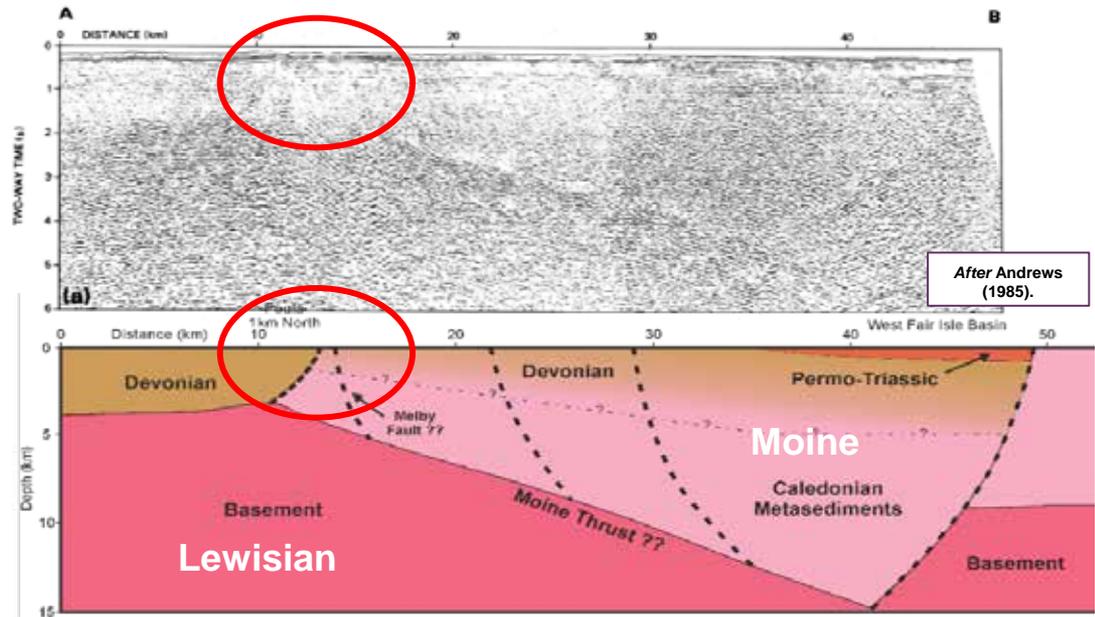
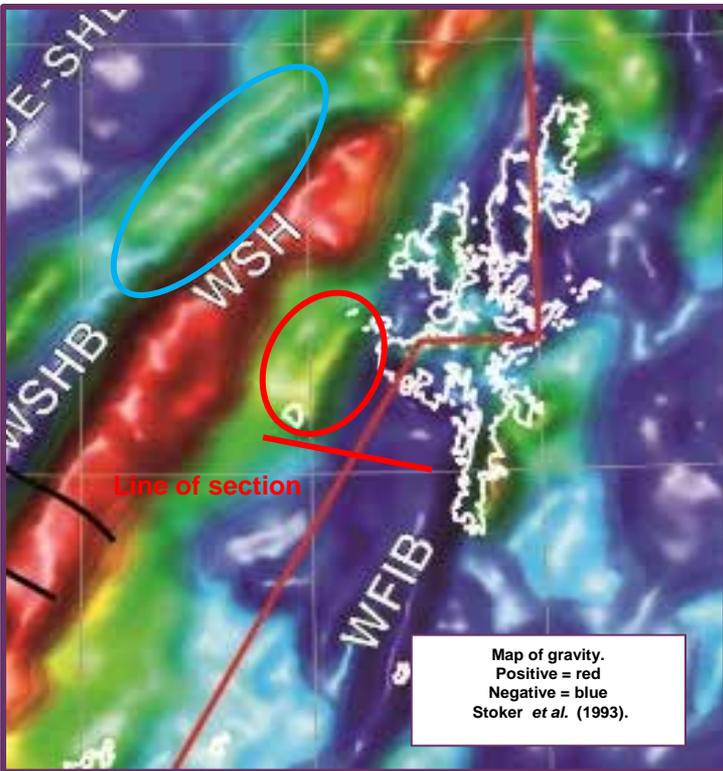
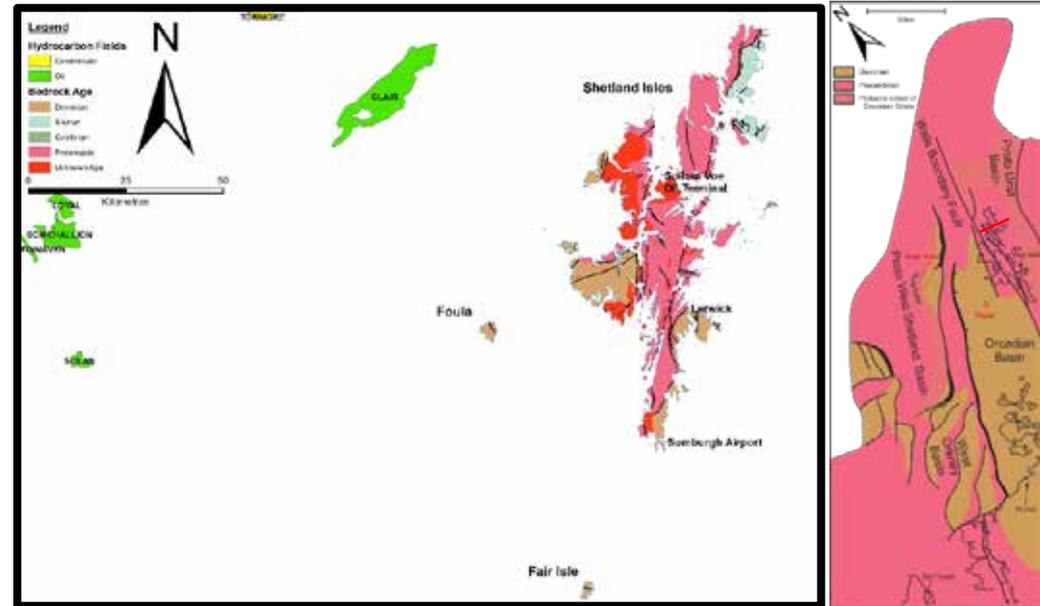
General Geology of Foula

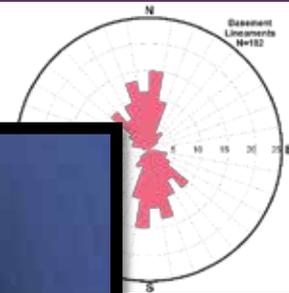
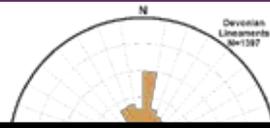
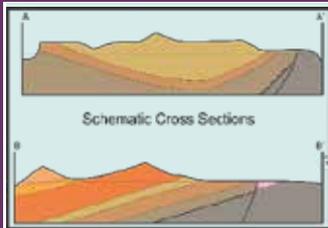
Foula part of a long lived NE/SW trending basement structural high: **Foula Ridge**

1600m of Middle Devonian clastics, unconformable & faulted against a ~1km wide strip of Precambrian basement

Asymmetric NNE-SSW half graben

Basement and Devonian highly fractured





Approach:
 Petrogeology and lineament analysis
 Fieldwork
 Fracture network characterisation
 Photogrammetric reconstruction and building of Virtual Outcrop Models (VOMs)



Geology	Depositional Environment
exposed sandstones but mostly TXB sandstones. Siltstones and muds.	Syn-sedimentary basin subsidence and development of wide sandy alluvial fan.
planar sandstones. Dolomitic. Little thickness range.	Wide submerged alluvial plan with poorly confined migrating fluvial channels.
exposed sandstones but mostly TXB sandstones. Mudstone with desiccation cracks.	Syn-sedimentary basin subsidence and development of wide sandy alluvial fan. Better developed fluvial systems with floodplains preserved.
sands/siltstones.	Shallow freshwater lake.
in the SE. M to F beds with pebbles. Laminated, 1-2cm in size. Quartz, quartzite, pink granite gneiss. Convolute bedding and mudstones.	Syn-sedimentary basin subsidence and development of wide sandy alluvial fan. Tributary fluvial system joining a much larger river system along axis of the basin.
coarse, VF/F grained sandstones with calcareous and silt/mudstones.	Largely sandy fluvial system with floodplain deposits.
orthogneisses and mafic mica schists. Amphibolite and epidote-altered ultrabasic sills.	

Updated geological map of Foula. After Blackbourn (1985).

- Pink microgranite intrusion of sills and dykes.
- Amphibolite facies. Multiple phases of deformation.
- Might correlate to the Neaneas Group of the Walls Peninsula/Moine in N Scotland/Yell, Shetland. Geochronology will confirm.

After Blackbourn (1985).

Basement Geology

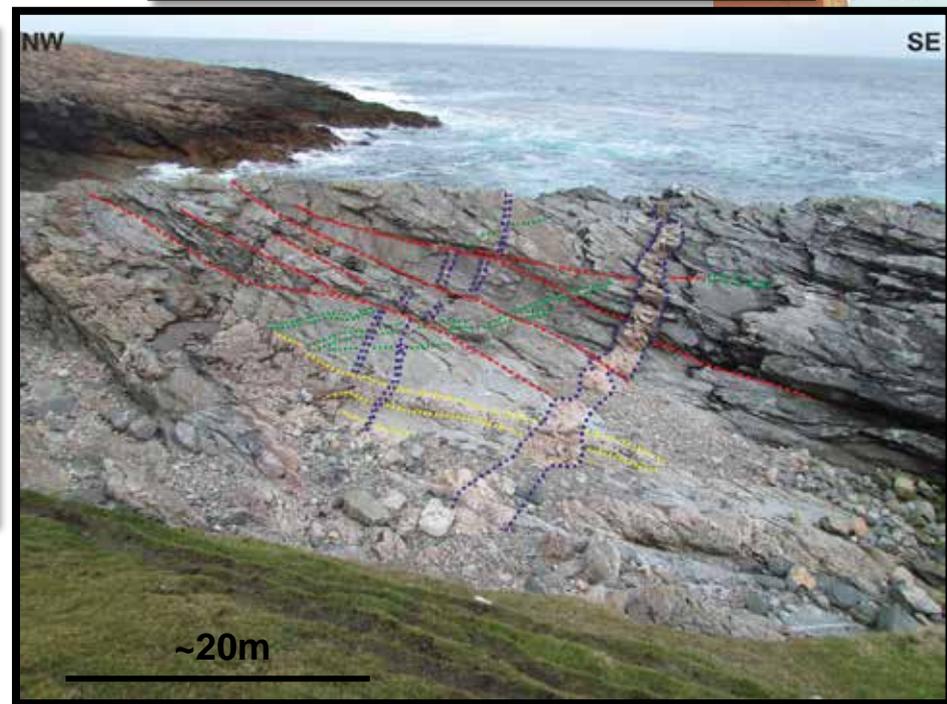
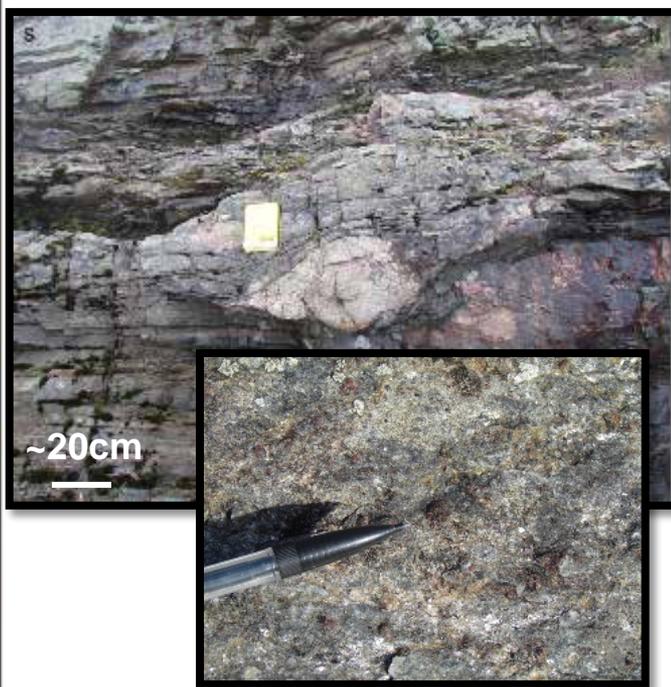
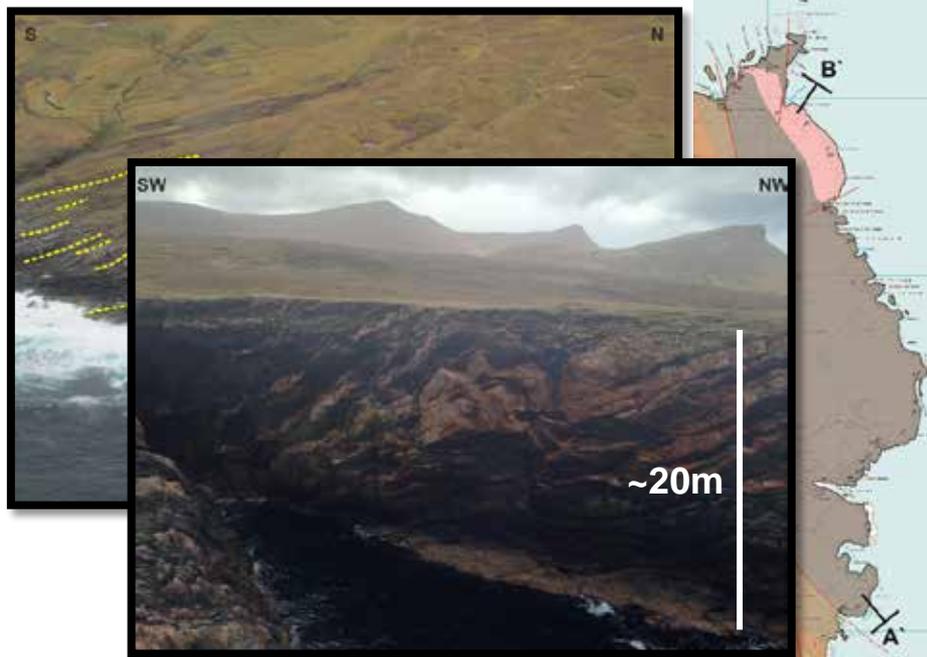
Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
	Da Ness Brough Member
Precambrian	Ruscar Head Microgranite

Basement may correlate with either Moine or Dalradian of Shetland

Amphibolite facies pelites, psammites, mafics and microgranite sills and dykes

Pervasive pegmatitic/granitic veining and Ruscar Head Microgranite

Pre-Middle Devonian as granite clasts in sedimentary breccias



Basement Structures

Foliation subtly folded, W through to SW

N/S to NNW/SSE, E dipping normal faults

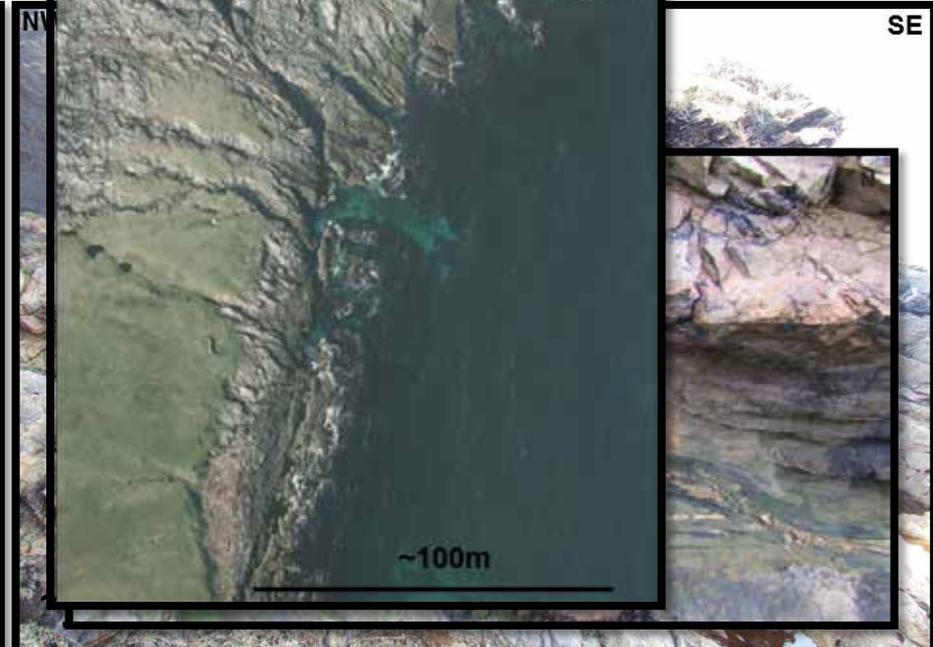
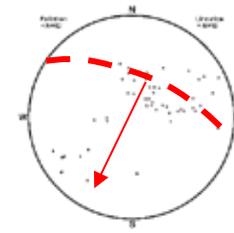
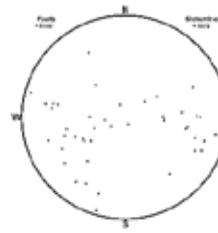
- With associated epidote alteration, iron staining and quartz mineralisation

Low angle detachments and thrusts

- N/S to NNW/SSE with dextral shear sense

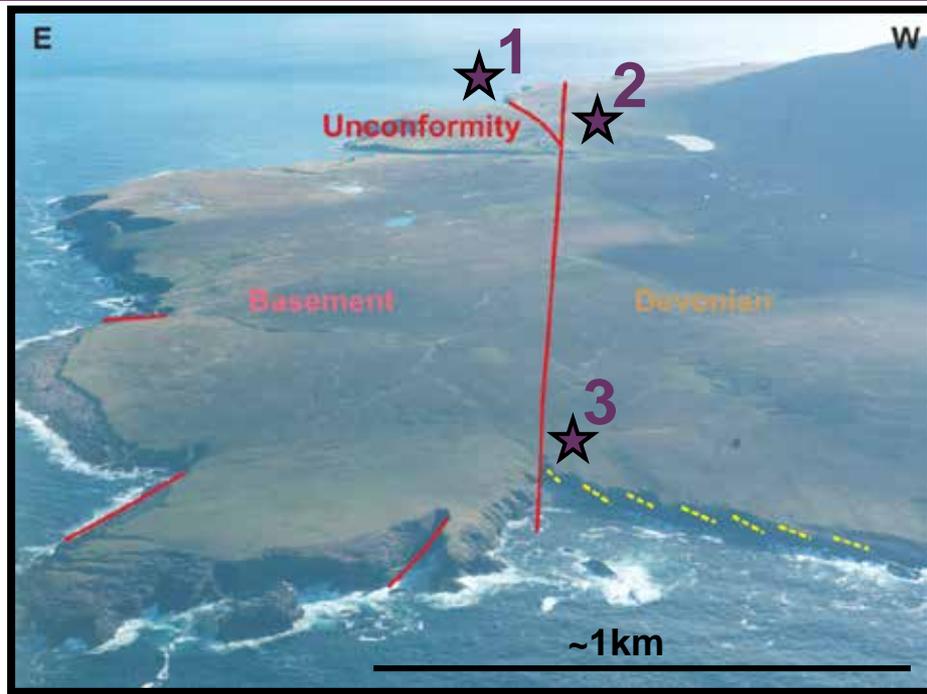
Discrete N/S fracture zones/corridors and shear zones

- Vertical/sub vertical, rare dextral strike slip indicators



Basement/Cover

Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
	Da Ness Brough Member
Precambrian	Ruscar Head Microgranite



Basement/Cover 1

Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
	Da Ness Brough Member
Precambrian	Ruscar Head Microgranite

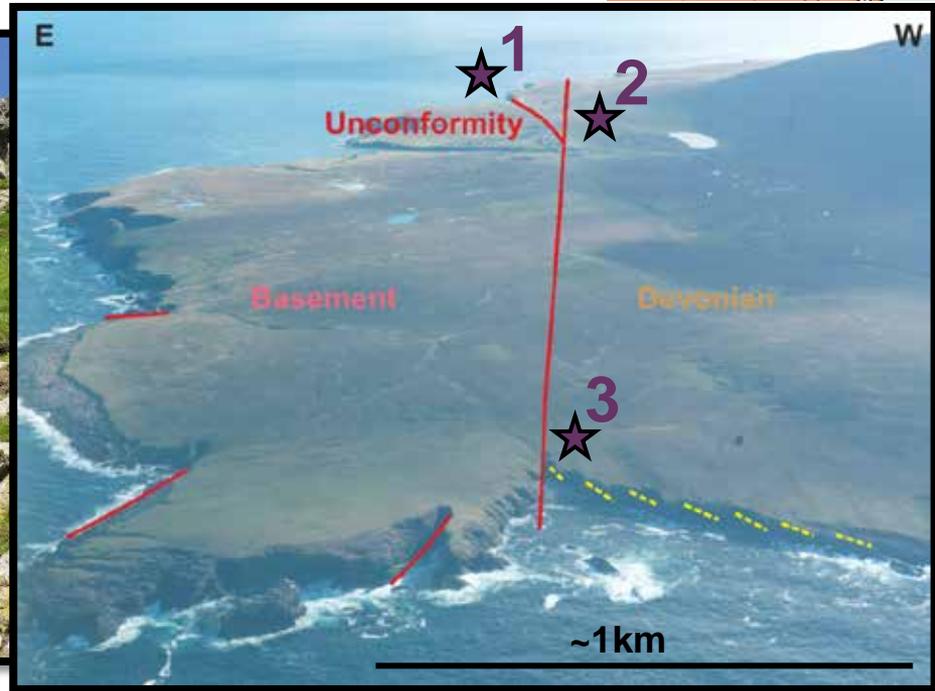
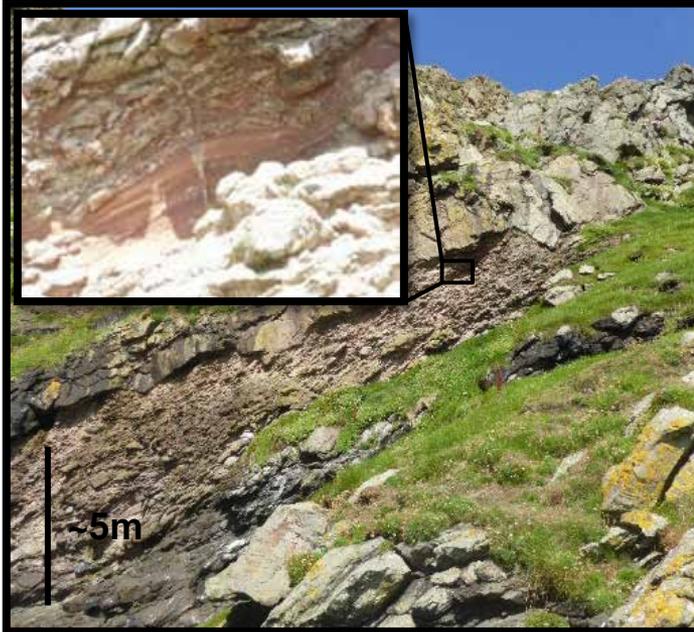
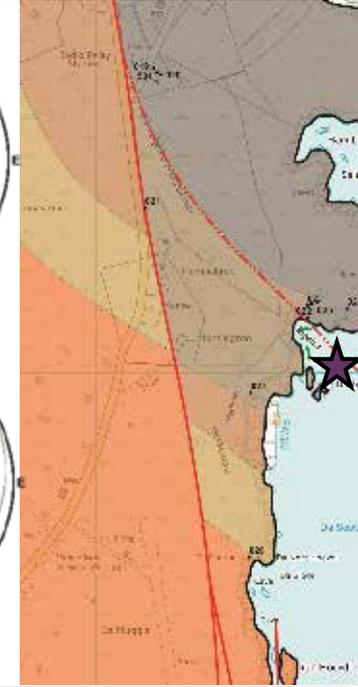
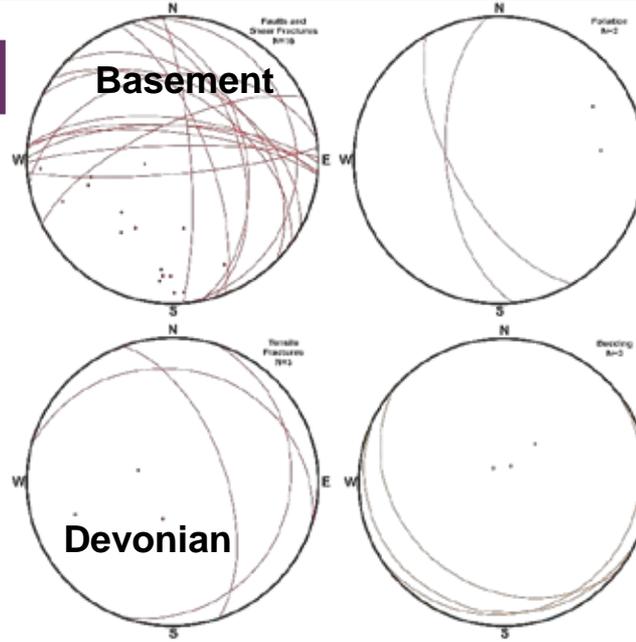
In south 3-5m zone of sheared basal conglomerate

Bedding sub parallel to SW dipping unconformity surface

Unconformity -// faults. Long axis of clasts parallel to fabric.

Asymmetric boudinage of clasts

Small syn-sedimentary NE dipping normal faults



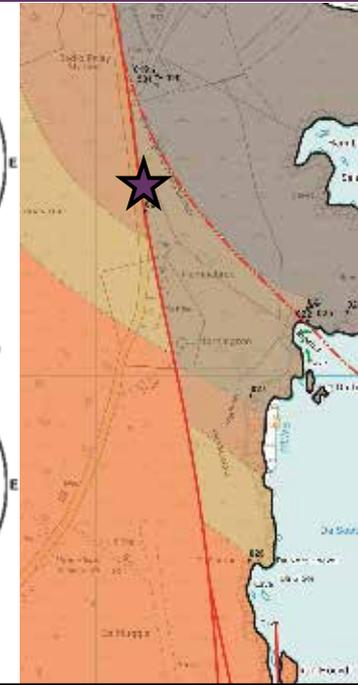
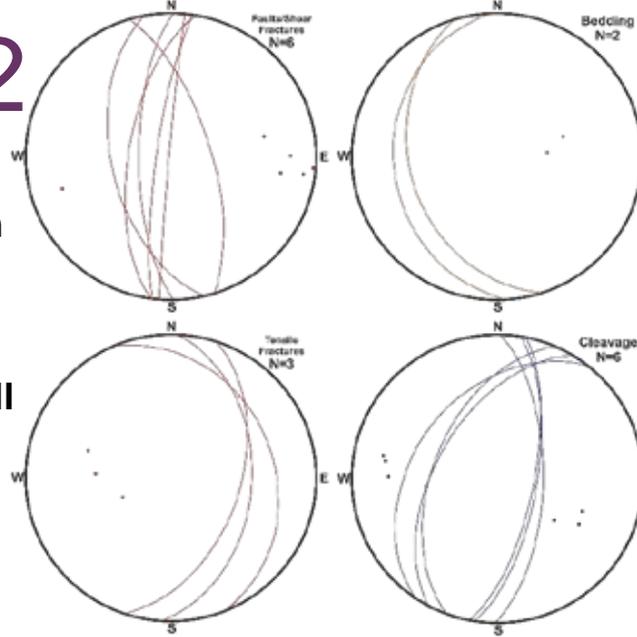
Basement/Cover 2

Small quarry where 15m wide fault zone juxtaposes sst of Da Ness Fm with sst/sltst of Soberlie Fm

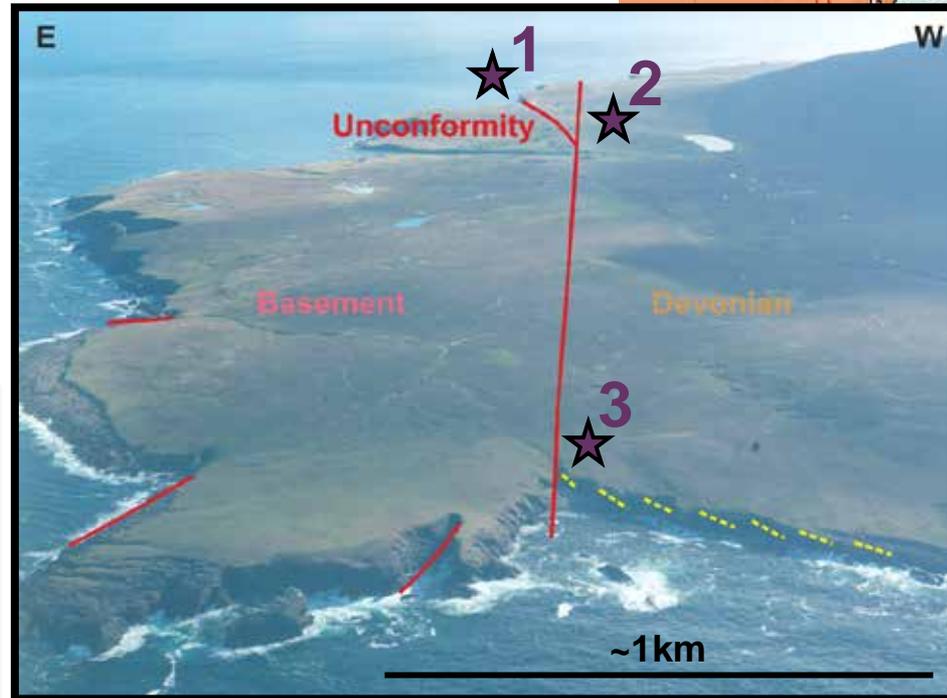
Steep N/S normal faults + tensile fractures, tension gashes and small open fractures - rare Qtz fills

Shale-rich units foliated close to faults

Development of 1-2cm thick clay rich fault gouge and crackle/crush breccia in HW of main fault, with clasts of ~0.5mm



Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
	Da Ness Brough Member
Precambrian	Ruscar Head Microgranite



Basement/Cover 3

Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
Precambrian	Da Ness Brough Member
	Ruscar Head Microgranite

In North, W dipping normal fault

- FW-foliated basement with abundant granite sheets
- HW-Interbedded sand and siltstones of Da Ness Fm
- ~100m throw

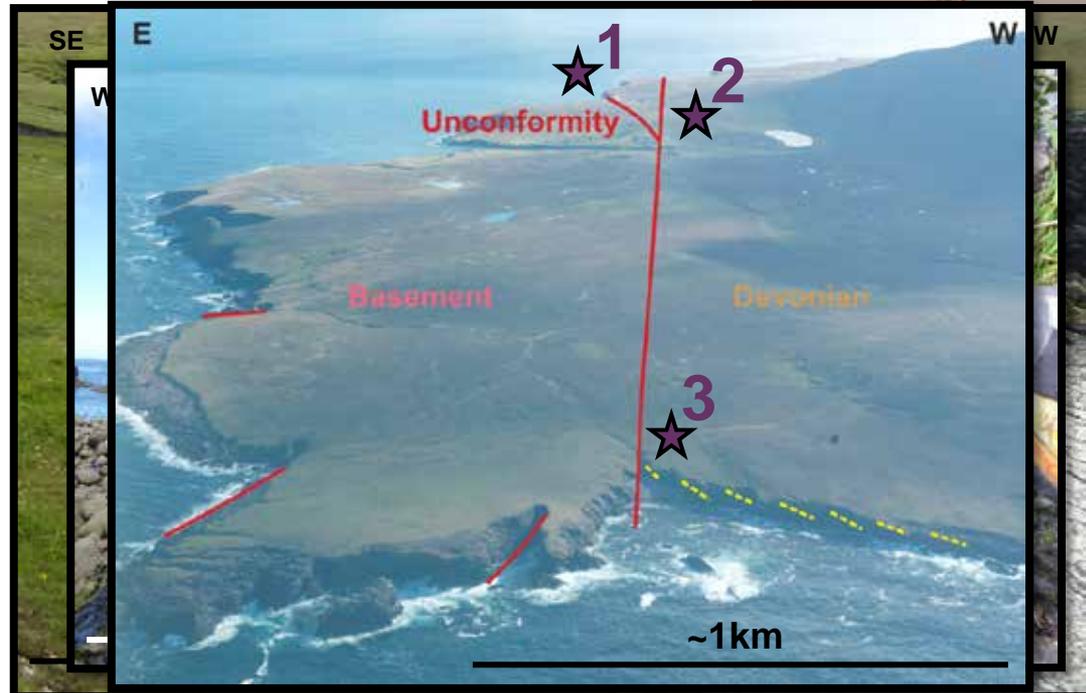
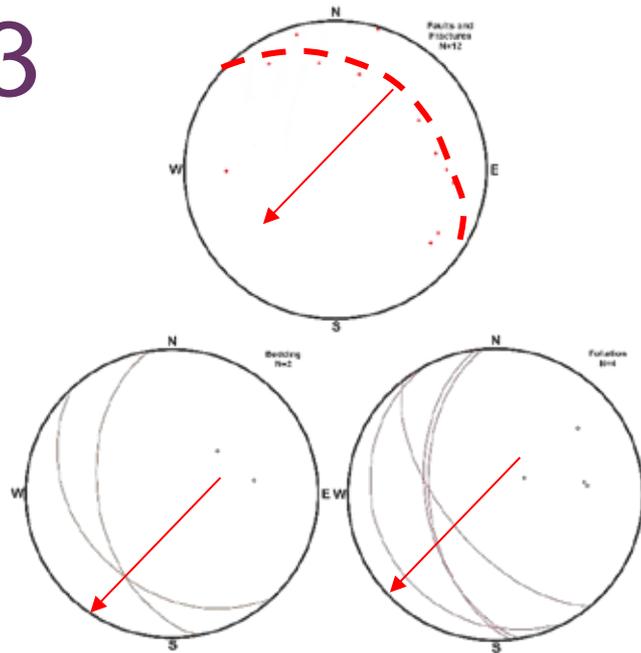
20-30cm folded /mullioned microbreccia below fault

Localised folding of both basement foliation and devonian bedding

- Local cleavage development
- Curvilinear minor folds generally plunging S to SSW

Curviplanar N/S to NNW/SSE faults and fracture corridors: 'folded geometry'

Beta axes of folded bedding, foliation and curviplanar faults all sub-parallel



Devonian Stratigraphy

Age	Formation
Devonian	Noup
	Daal
	Sneug
	Blobersburn
	Soberlie
	Da Ness Brough Member
Precambrian	Ruscar Head Microgranite

Basal conglomerate/breccia derived from NE

Fluvial/alluvial environment with frequent flooding and development of lacustrine facies

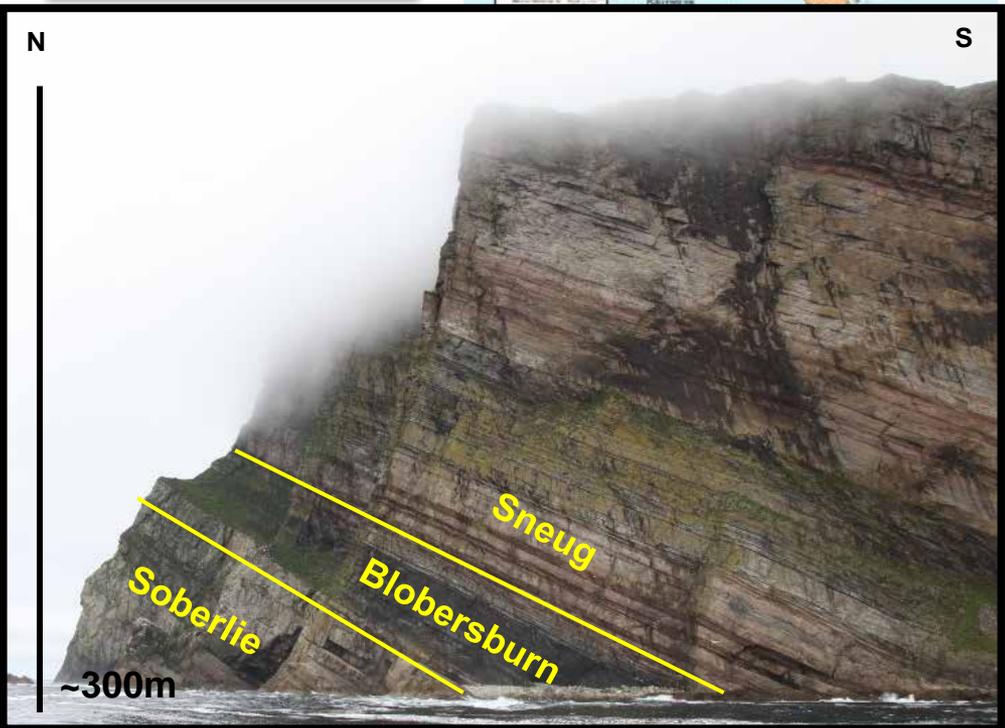
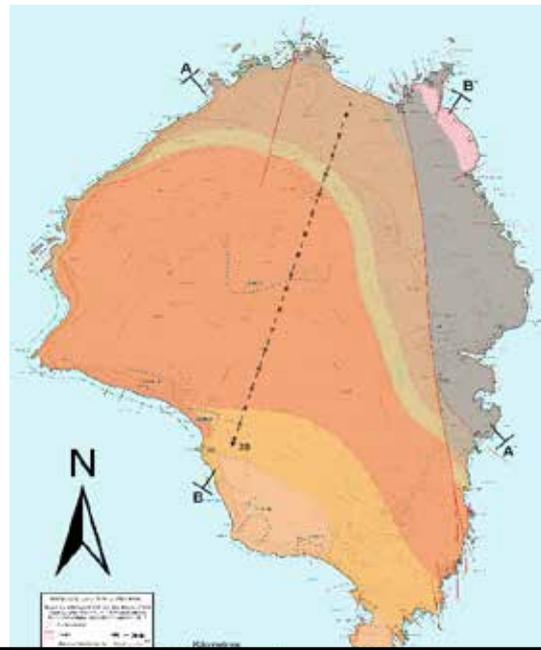
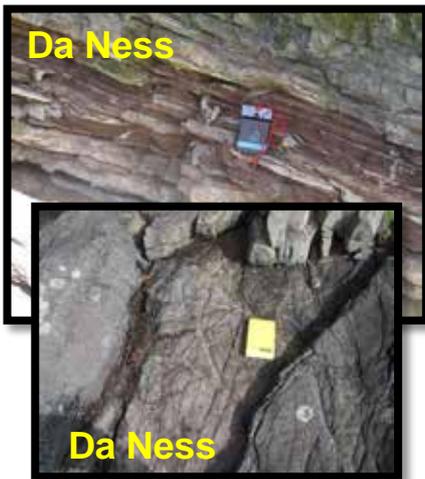
Thinning of Soberlie Fm. from 400m in HW in the NW to 35m in FW to the SE and 650m to 220m in the Sneug Fm

Soft-sediment deformation widespread in lower sequence

Bloberburn Fm lacustrine facies is regional marker

Palynology: L. Eifilian to Givetian

Changing temporal palaeocurrents



Devonian Structures

NE/SW deformation bands and fractures

N/S trending normal faults

- Conjugate sets of def. bands/ fractures, increase in frequency with proximity to meso scale faults
- No. of faults increases with proximity to the East.

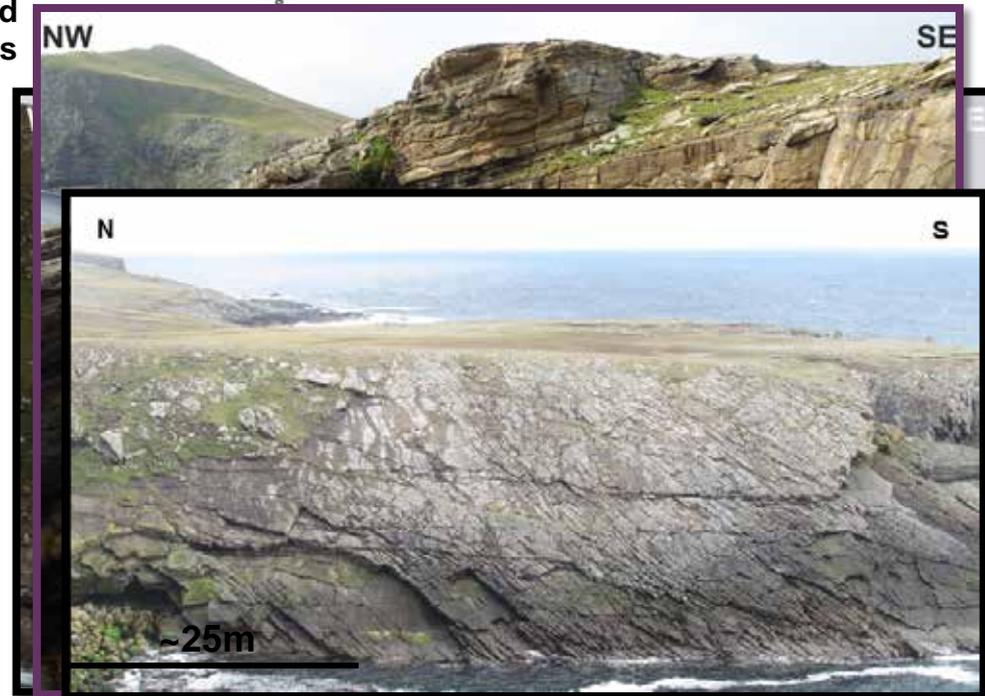
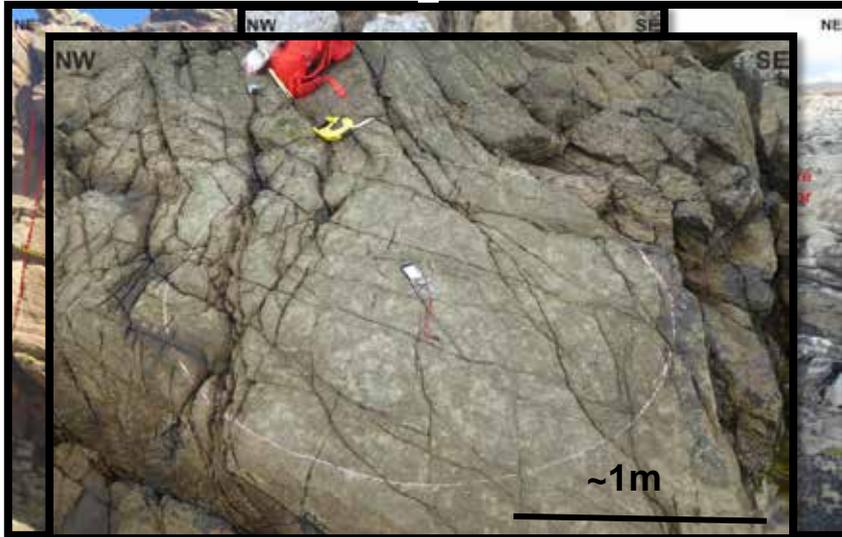
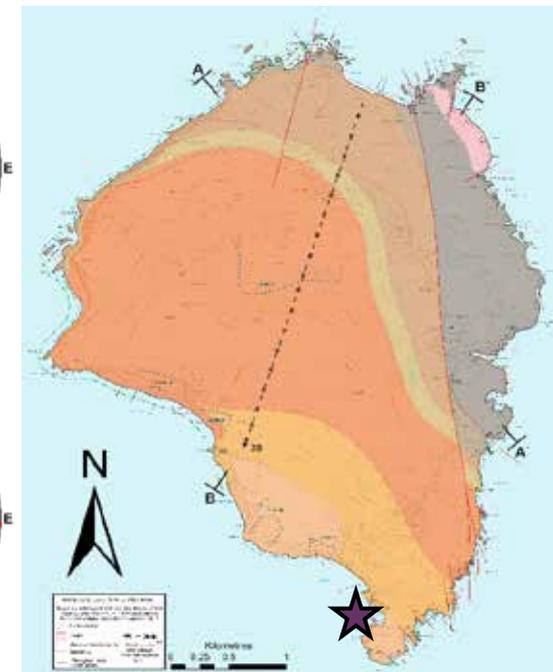
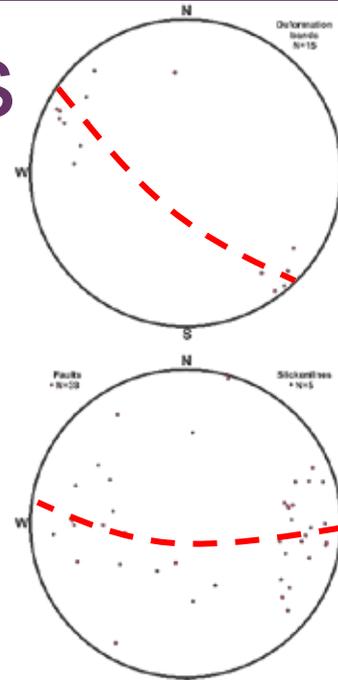
N/S and E/W discrete fracture corridors

- Sub-vertical, limited normal offsets. En-echelon.

Overall polymodal fracturing

- no clear cross cutting/abutting relationships.
- Distributed small offsets
- Spectacular pavements of fractures will be used for topology analysis of polymodal fracture sets

No mineralisation and rare slickenlines

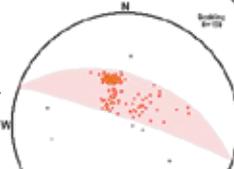
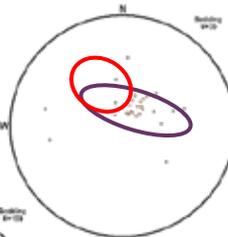


Devonian Structures

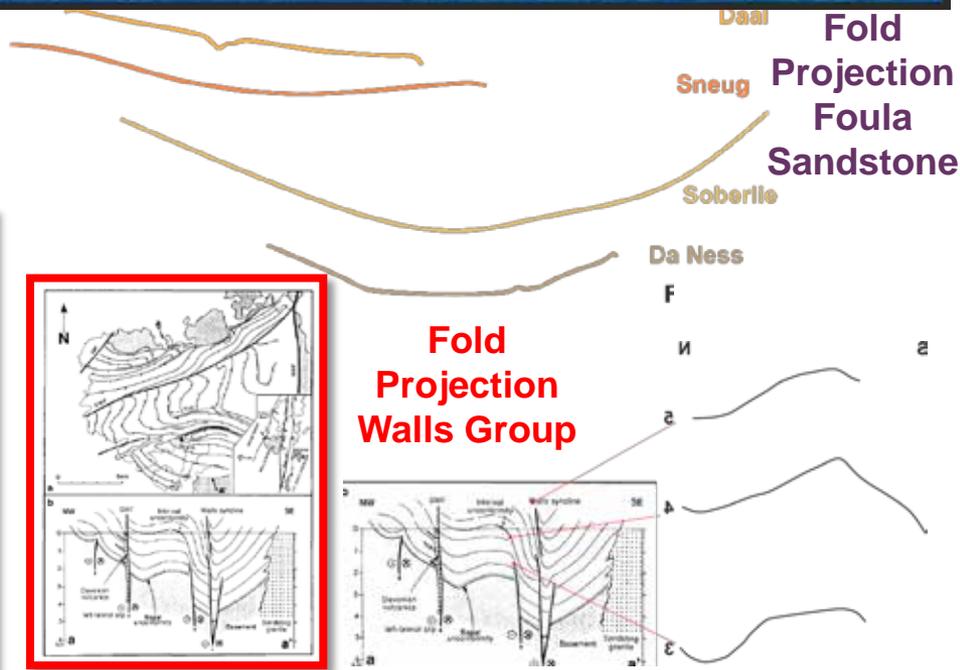
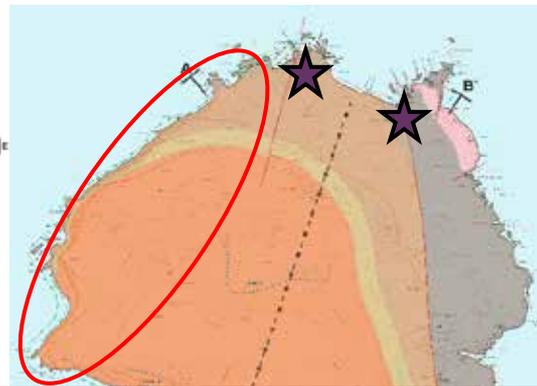
Broad open folds

- Gently open S to SSW plunging syncline
- Smaller scale broadly open folds
- Data missing from **W limb** due to inaccessibility

Field data



VOM and field data



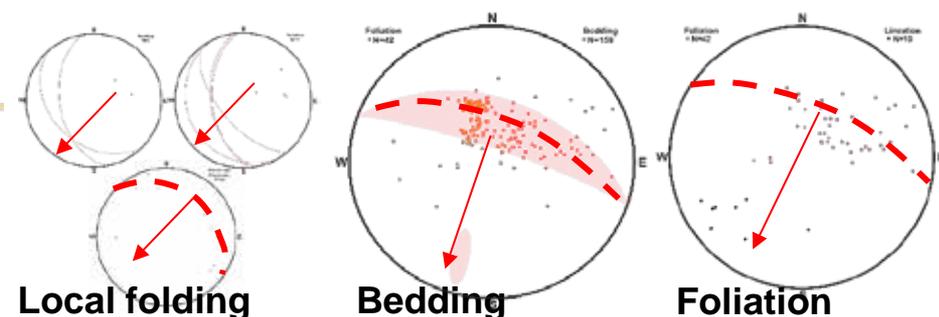
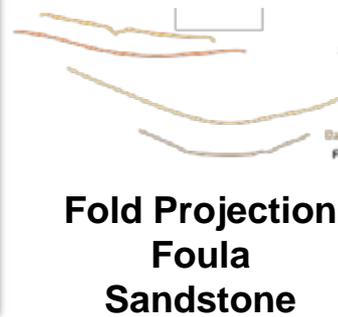
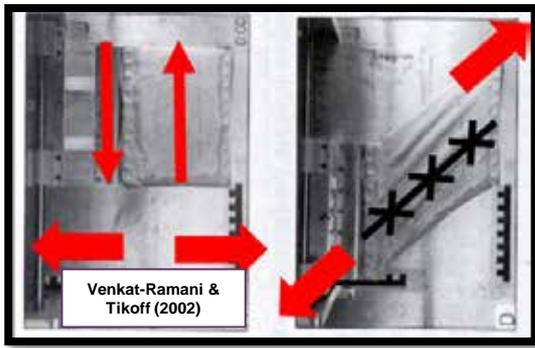
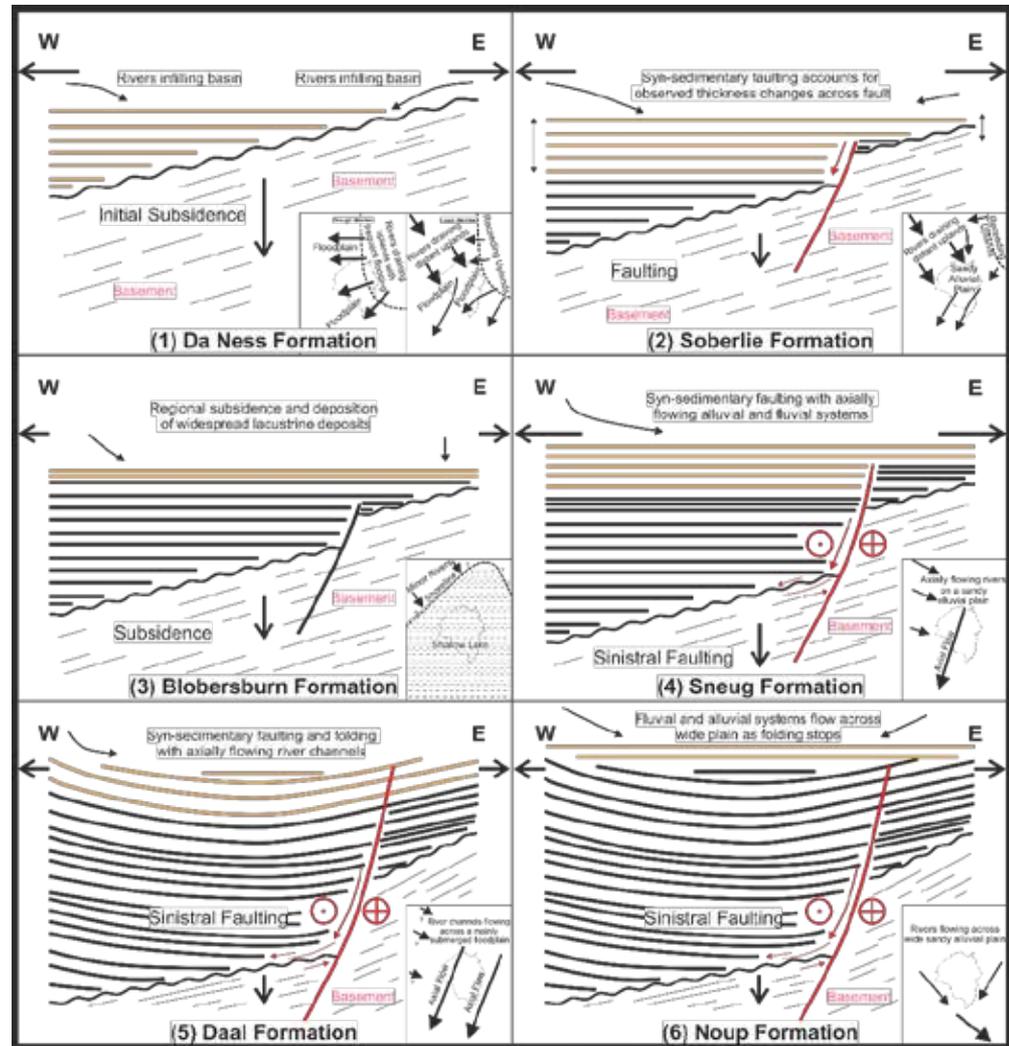
Summary

Main structures:

- NE/SW faults + deformation bands
- N/S dip slip to oblique slip normal faults and fracture corridors in basement and cover
- NE/SW to E/W mostly strike slip faults and discrete fracture corridors with limited offset
- Little mineralisation or fracture fills
- SSW to SW plunging folds in basement and cover, which open upwards
- Faulting and folding synchronous

Syn-sedimentary faulting/folding related to constrictional strain during transtension

- Fold hinges consistent with sinistral transtension along WBF in Mid. Devonian
- Related examples in Norway and Shetland (Dewey and Strachan, 2003)
- Laboratory examples (Venkat-Ramani & Tikoff, 2002)



Conclusions

1600m of gently folded Middle Devonian clastic sediments, unconformable and faulted against Precambrian basement high

Accumulated in ~NNE-SSW asymmetric half graben undergoing constrictional extension due to sinistral transtension along the WBF.

Similar to structures observed in Shetland as per Seranne (1992). *Scooped/Spoon* shaped Devonian basins.

Limited later dextral reactivation of structures during the Permo-Carboniferous as seen in Shetland and Orkney.

Long lived Caledonian structures related to closure of Iapetus controlling later reactivation

Some similarities to structures reported in the Clair Field (Barr et al., 2007 and Coney et al., 1993)

Alternative onshore analogue for the early development of the Clair Basin?

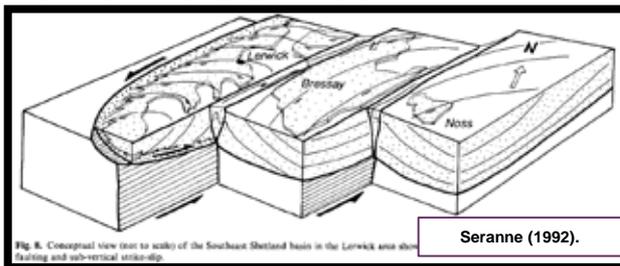
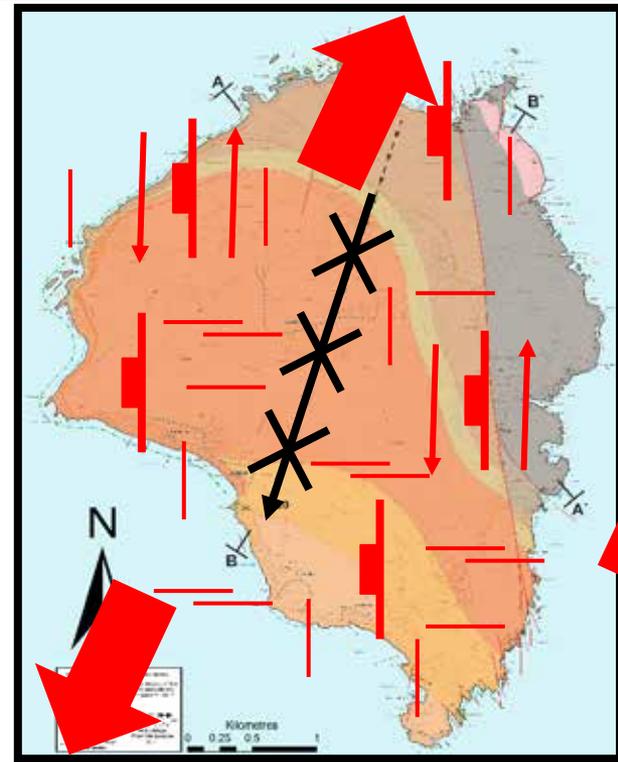
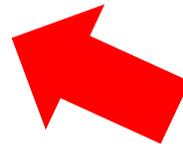
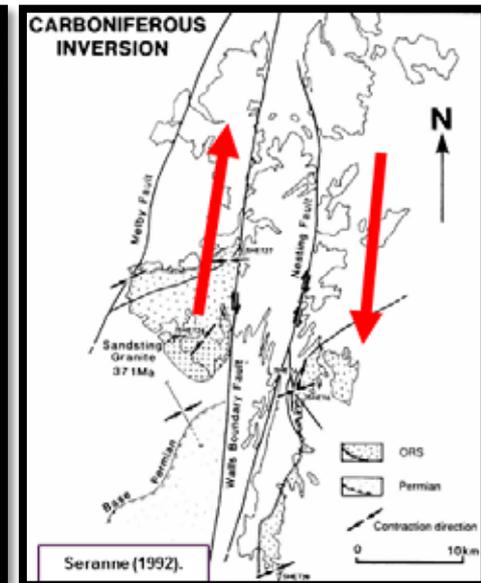
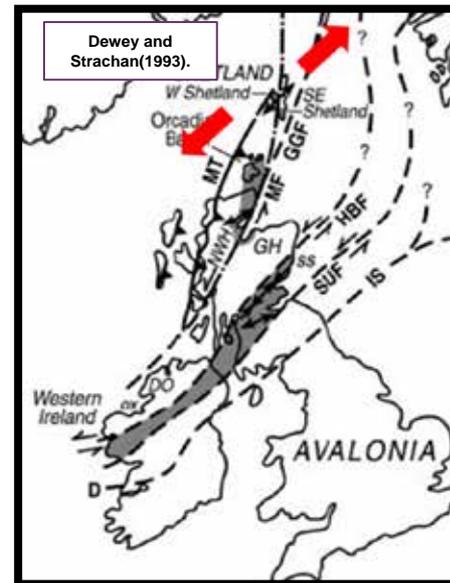


Fig. 8. Conceptual view (east to south) of the South-east Shetland basin in the Lerwick area showing faulting and sub-vertical strike-slip.



Future Work

Further Fieldwork:

- **Foula and Shetland (Walls Peninsula, Lerwick, Bressay and Noss, SE Shetland) Summer 2017**
- **Fair Isle/Orkney ~ 2017/2018 ??**
- **Return visits if required for further data acquisition using Lidar/Photogrammetry/Drone.**

Analyse data collected from the rest of Shetland:

- **Dating of mineralisation associated with 'Steep Belt' deformation on Bressay and in SE Shetland**
- **Analysis of structures and development of the Walls Basin/West Fair Isle Basin**
- **Examination of bathymetric surveys**

Reprocessing and reinterpretation of nearby seismic from the West Fair Isle Basin to link outcrop to seismic scale features and tie structures south through Orkney and into the Moray Firth..

Heavy mineral analysis and provenance work on the Foula and Melby Sandstones..

Microstructural analysis of fault rocks

Topology analysis of outcrops, outcrop models and lineament analyses to assess connectivity and permeability of fracture networks at multiple scales

Examination of related offshore cores and characterisation of fracture networks.



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Graham Blackbourn for permission to use information from his unpublished report on the geology of Foula.

Photogrammetric point clouds generated using Agisoft Photoscan and interpreted using the Virtual Reality Geological Studio, courtesy of David Hodgetts, Manchester University.

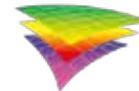
BP for providing imagery and the Clair JVG for continued interest into research at Durham.

Aerial Images courtesy of Canmore. Foula photo reproduced from John Pedley. panphotos.co.uk

Offshore shapefiles from Oil and Gas Authority, Open Data (OGA), 2016.



**Centre for Doctoral Training (CDT)
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**Geospatial
Research
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