New insights into the kinematics and timing of superimposed rifting events through integration of offshore data, onshore fieldwork and U-Pb geochronology: Inner Moray Firth Basin, Scotland

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UKRI Natural Environment Research Council

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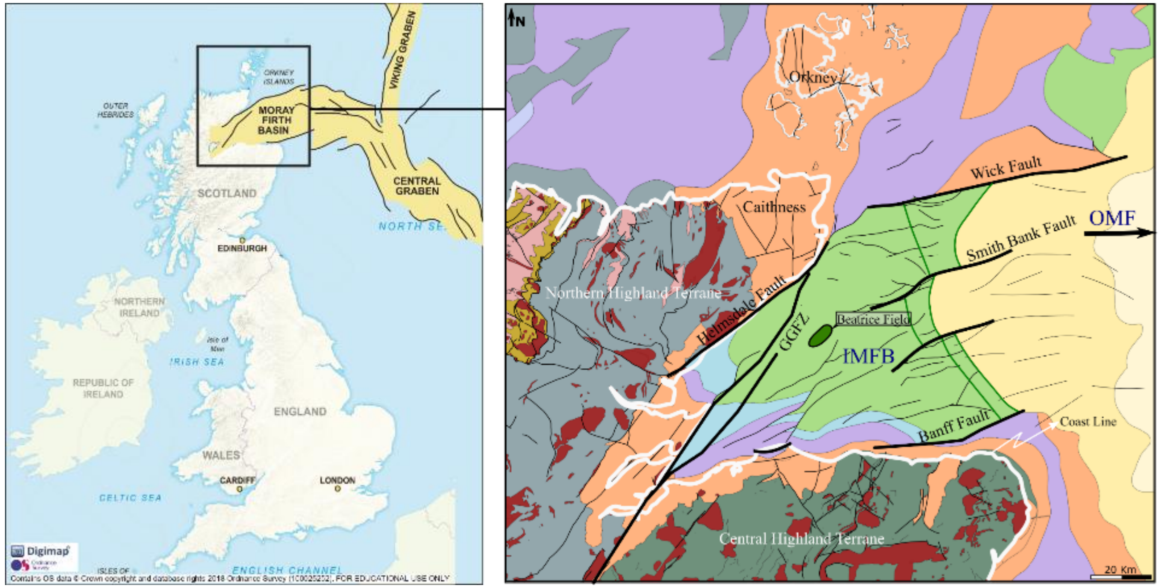
Inner Moray Firth Basin – superimposed rift system

Western part of the North Sea trilete rift system. Formed mainly in the Upper Jurassic

NE-SW dip-slip trending faults



Modified after Rojas and Underhill (2017), Zanella E. & Coward M.P. 2003, and British Geological Survey (BGS), UK. Using: EDINA Geology Digimap Service, <http://edina.ac.uk/digimap>
From Tamas et al., 2020 in prep.

Key To Geological Map

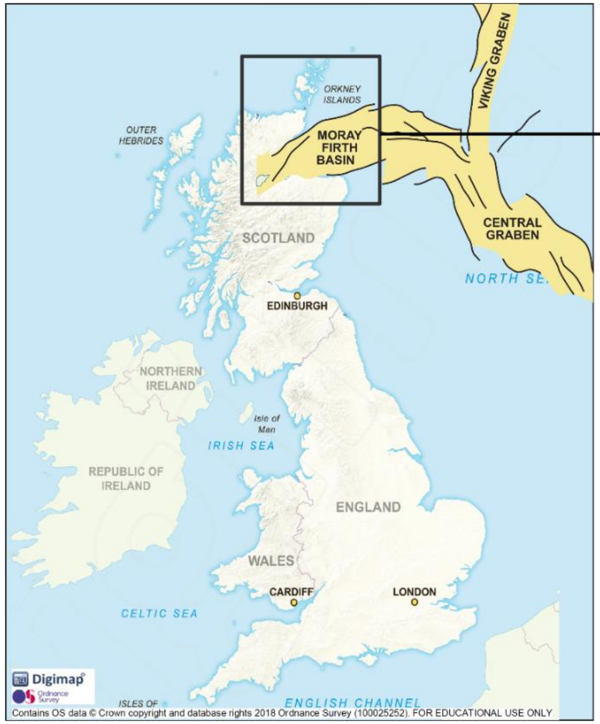
- Eocene Sedimentary Rocks
- Paleocene Sedimentary Rocks
- Cretaceous Sedimentary Rocks
- Jurassic Sedimentary Rocks
- Permo-Triassic Sedimentary Rocks
- Devonian Old Red Sandstone
- Neoproterozoic Sedimentary Rocks
- Neoproterozoic Moine Supergroup
- Neoproterozoic Dalradian Supergroup
- Archean Lewisin Gneiss
- Igneous Rocks
- Faults

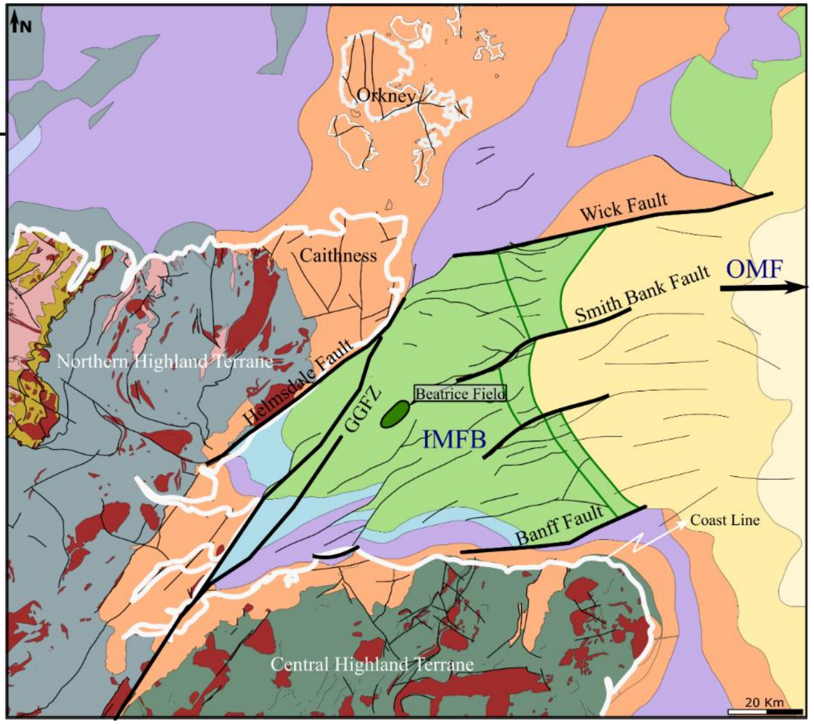
The IMFB forms the western part of the North Sea rift and opened mainly during Upper Jurassic (e.g. Underhill 1991). The IMFB is a petroleum province, although it is not very prolific compared to the other parts of the North Sea. This is mainly due to the perceived complex, superimposed deformation history in the area.

The basin is characterised mainly by regionally developed NE–SW trending faults formed during NW-SW extension (e.g. Underhill, 1991, Davies et al., 2001).
It is superimposed on Devonian sinistral transtensional rift system (Orcadian Basin) characterised mainly by north to-east trending dip-slip/oblique-sinistral faults formed during E–W to ENE-WSW extension (e.g. Wilson et al., 2010).
The IMFB is also superimposed on Permo-Triassic depocenters and experienced uplift and fault reactivation during the Cenozoic (e.g. Underhill, 1991).

This kind of complex evolution leads to significant uncertainties and can cause contradictory interpretations.

A few uncertainties regarding IMF basin development…





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- **Cenozoic reactivation – dextral reactivation of GGF** and sinistral reactivation of Helmsdale are thought to have occurred (e.g : Thomson and Underhill, 1993, . Le Breton et al., 2013)
  Relative timing, extent, impact?

Jurassic opening - many models suggested:

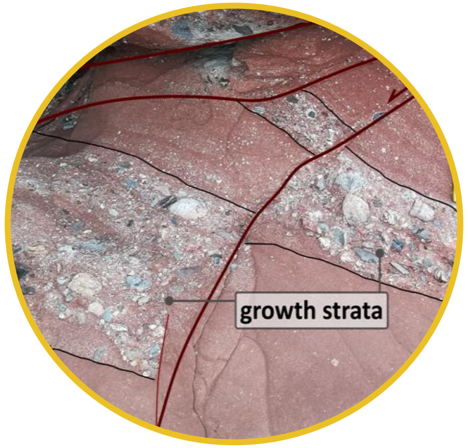
1. oblique /dextral-slip on GGF (e.g. McQuillin, et al., 1982)
2. dip-slip on GGF (Frostick et al., 1988)
3. strike-slip on GGF/Helmsdale (Roberts et al, 1990)
4. **dip-slip on Helmsdale** (Underhill, 1991)
5. **no evidence of oblique-slip faults** (Davies et al., 2001, Long & Imber 2010, Lapadat et al., 2018)

- **Permo-Triassic: rifting or no rifting?**
  rifting during Permian (Roberts et al, 1990) or Triassic (Frostick et al., 1988)
  no active rifting/**subsidence** (Andrews et al, 1990, Thomson and Underhill, 1993)

- **Role of Devonian pre-existing structures?**

The potential influence of older structures related to the Orcadian Basin on the kinematics of later basin opening has received little attention, partly due to the poor resolution of seismic reflection data at depth or sparse well data.

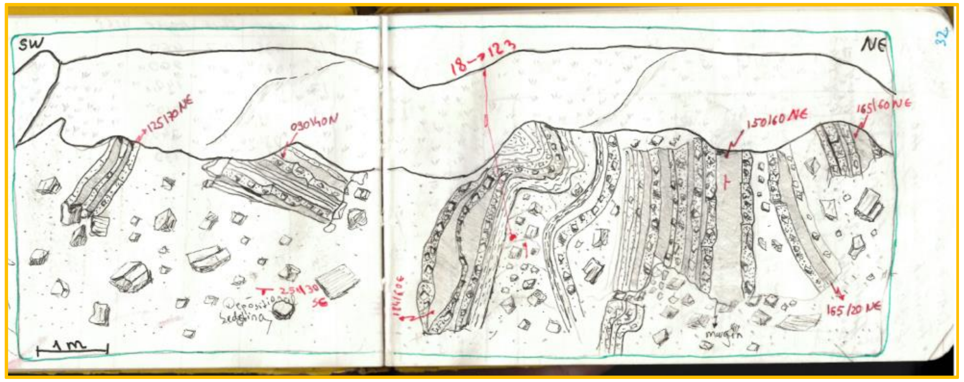
This research aims to bring new insights into...



- earlier kinematic history of the basin
- role of inherited Devonian faults
- sub-seismic structural styles
- fault reactivation

How?

Traditional detailed recording of field observations



Geochronology

UNIVERSITY OF HULL

U-Pb dating of syn-kinematic calcite veins
- critical to prove the age of faulting-

Digital field mapping and data processing

Fieldmove

sg2ps

Stereonet 10.0

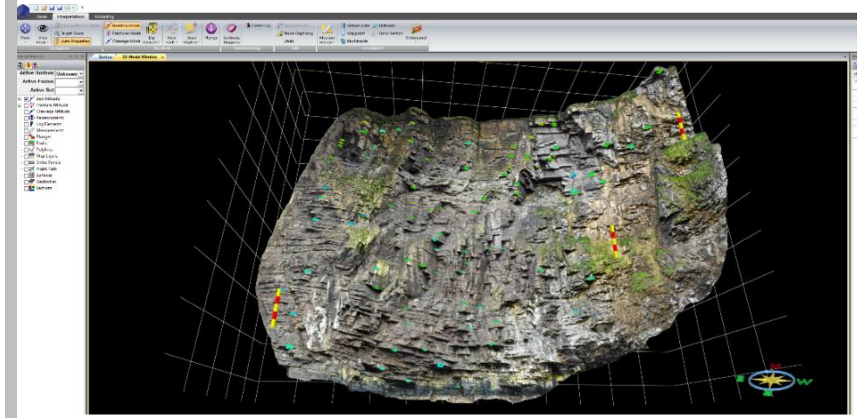
QGIS

Drone photogrammetry

Metashape

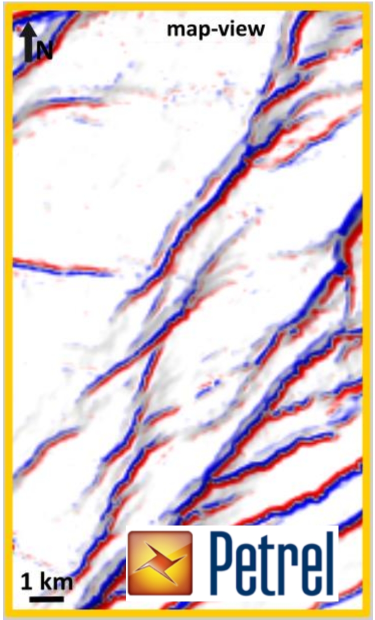
VIRTUAL REALITY GEOLOGICAL STUDIO
smarter geoscience software

- 3D digital outcrops
- DEM
- Orthomosaic
- + data extraction



Interpretation of the subsurface data

- 3D seismic
- 2D regional lines
- Wells + Well tops

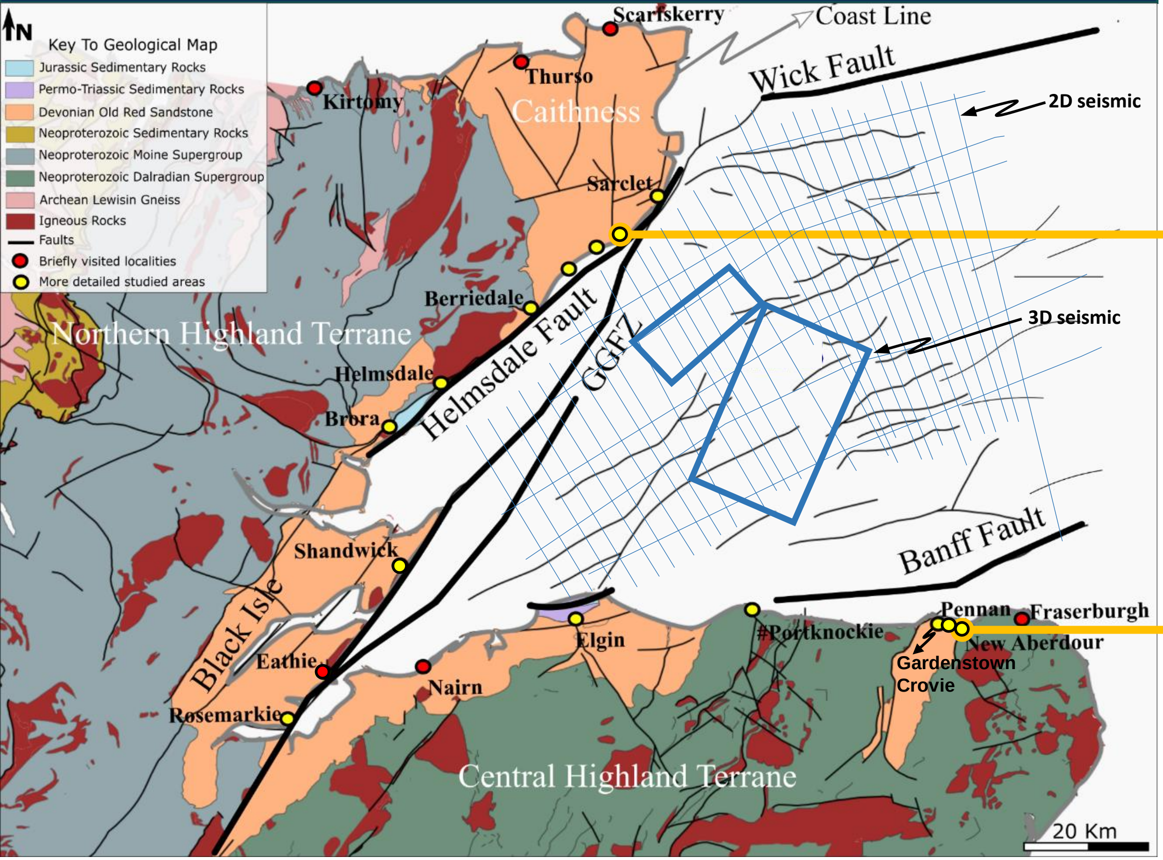


Spectrum

UK National Data Repository

Oil & Gas Authority

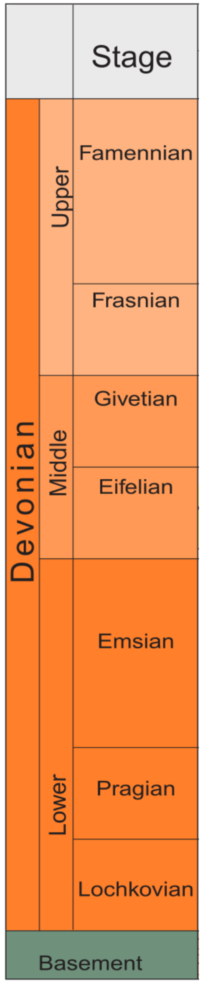
Where?



Modified after British Geological Survey (BGS), UK. Using: EDINA Geology Digimap Service, <http://edina.ac.uk/digimap>

mainly Middle Devonian lacustrine deposits, part of Caithness Flagstone group.

mainly Lower Devonian alluvial fans and alluvial plains.



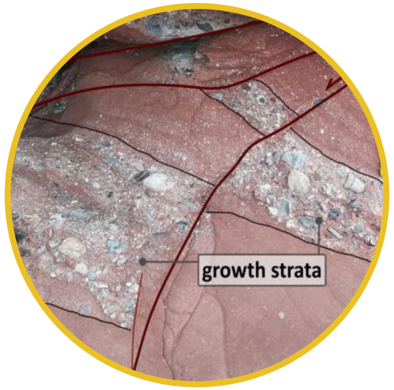
Several localities along the coast of Moray Firth have been investigated during three fieldwork campaigns, along with the interpretation of 2D and 3D profiles offshore (Note that these data are confidential and cannot be shared in this online forum).

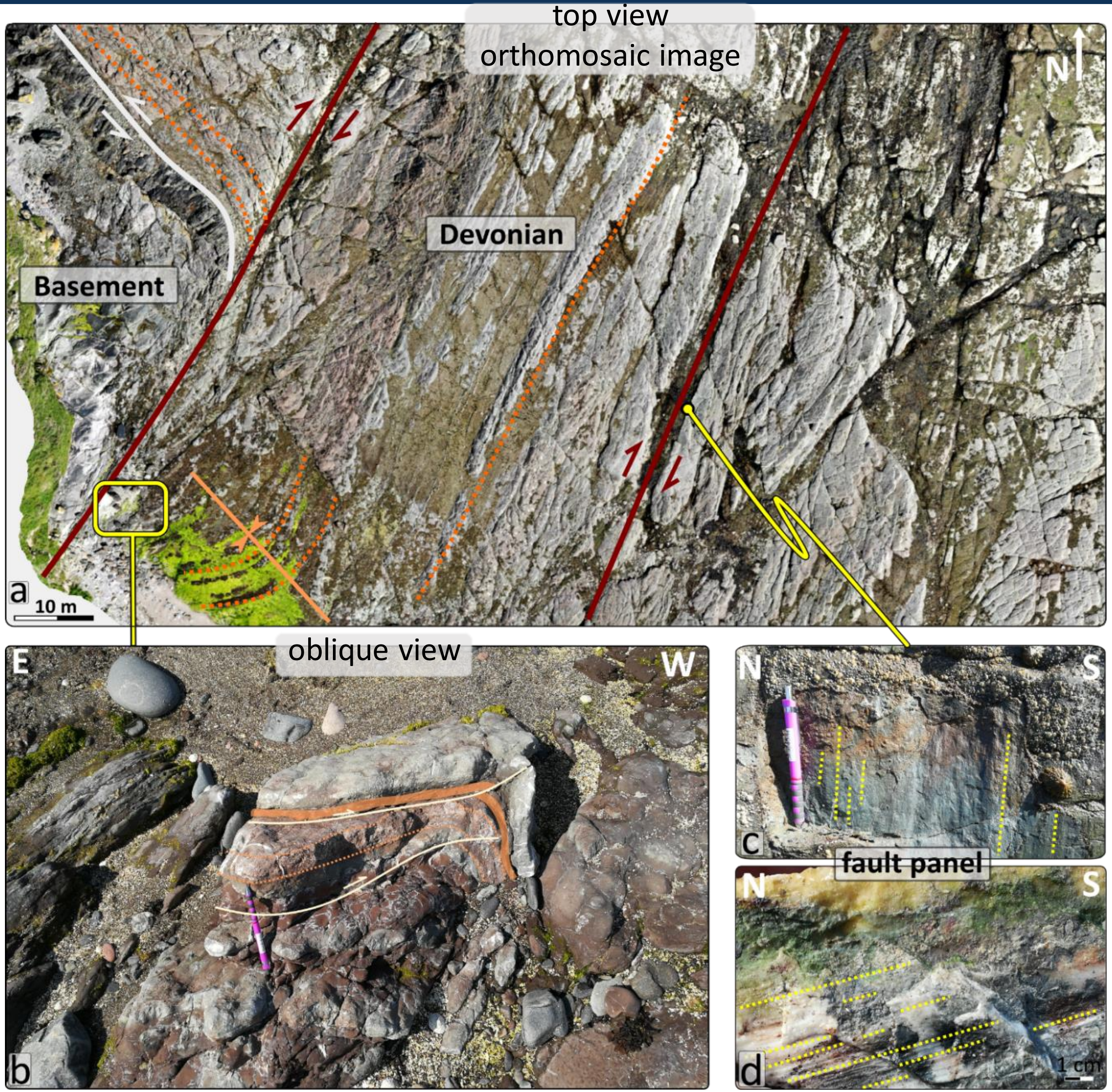
The results shown in the next slides are mainly presenting data from the representative area of the **south-eastern Caithness (e.g. Whaligoe Steps, N coast of IMFB)** and **Turriff Devonian basins (e.g. Pennan and New Aberdour, S coast of IMFB)**.

Turriff Basin – evidence of Upper Jurassic reactivation of Devonian structures

Mainly N-S to NNE-SSW striking faults and fractures (a). Fault panels show both dip-slip/slighty oblique-sinistral lineations (c) and normal-dextral slickenfibres (d).

The normal/oblique-sinistral N-S to NNE-SSW faults are syn-sedimentary based on the widespread preservation of growth strata.





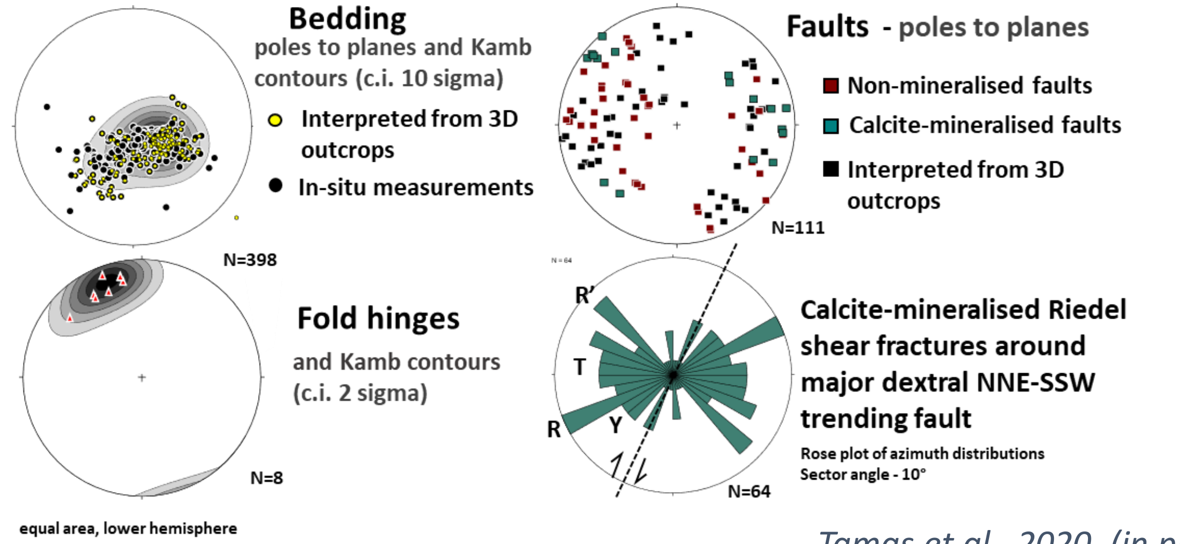
Examples of faulting and associated structures cross-cutting Devonian sandstones (New Aberdour Bay, southern coast of Moray Firth). a) Top view orthomosaic obtained from UAV photography, illustrating dextral reactivated NNE-SSW striking faults (red), sinistal NW-SE striking faults (white) and gentle to b) tight folds. Bedding is highlighted in orange. Fault panel showing c) early dip-slip slickenlines and d) overprinting oblique-dextral calcite slickenfibers (Tamas et al., 2020 in prep.).

Turriff Basin – evidence of Upper Jurassic reactivation of Devonian structures

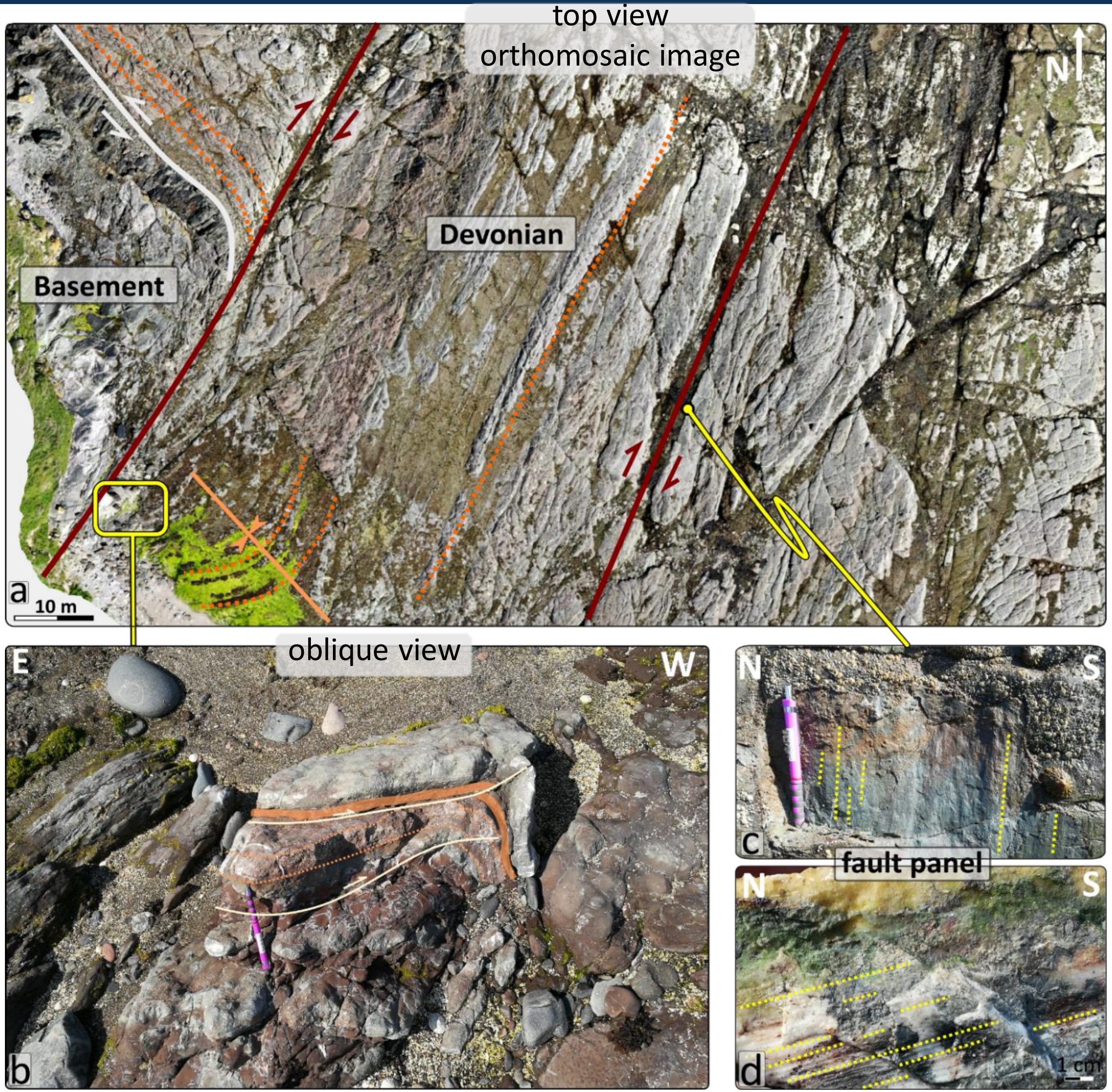
Also NW-SE sinistral faults (a) and NNW-SSE to NW-SE trending folds (b) are present in the area.

Normal-dextral slip along N-S to NNE-SSW and sinistral slip along NW-SE faults are consistently later and associated with calcite mineralization (e.g. as slickenfibres or in Riedel shear fractures).

Selected structural data from Turriff Basin

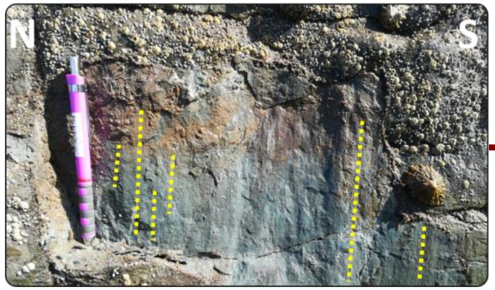


Tamas et al., 2020 (in prep.)

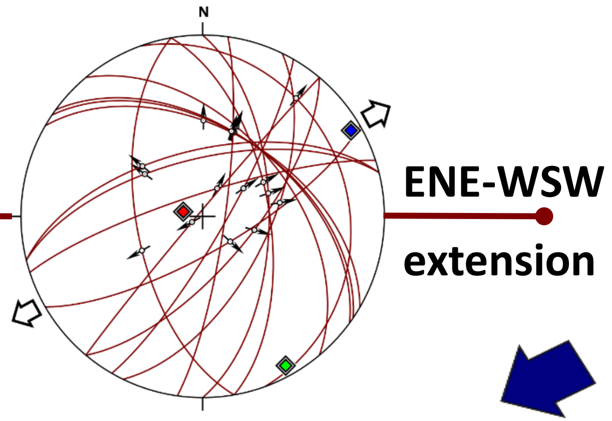


Turriff Basin – evidence of Upper Jurassic reactivation of Devonian structures

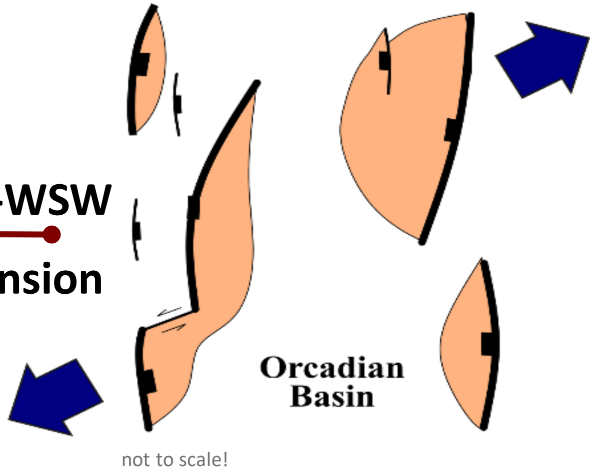
Devonian faults



clean breaks, gouges or breccia.
dip-slip, oblique-sinistral

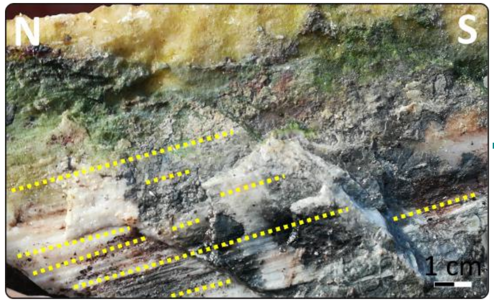


(after Angelier, 1990)

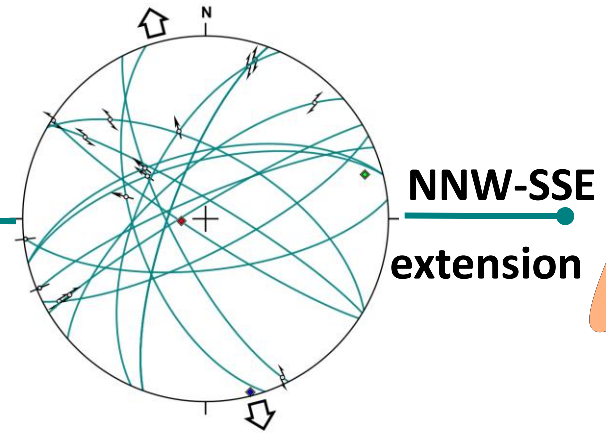


Our results suggest that the N-S to NNE-SSW striking growth faults developed during ENE-WSW extension and are related to the **opening of the Orcadian Basin**.

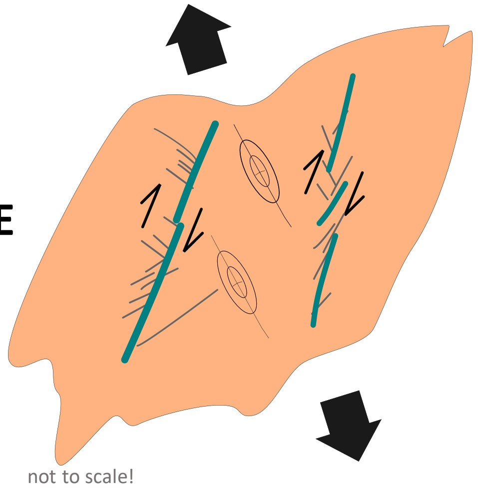
Upper Jurassic faults



calcite mineralised
N-S to NNE-SSW show evidence of dextral reactivation



(after Angelier, 1990)

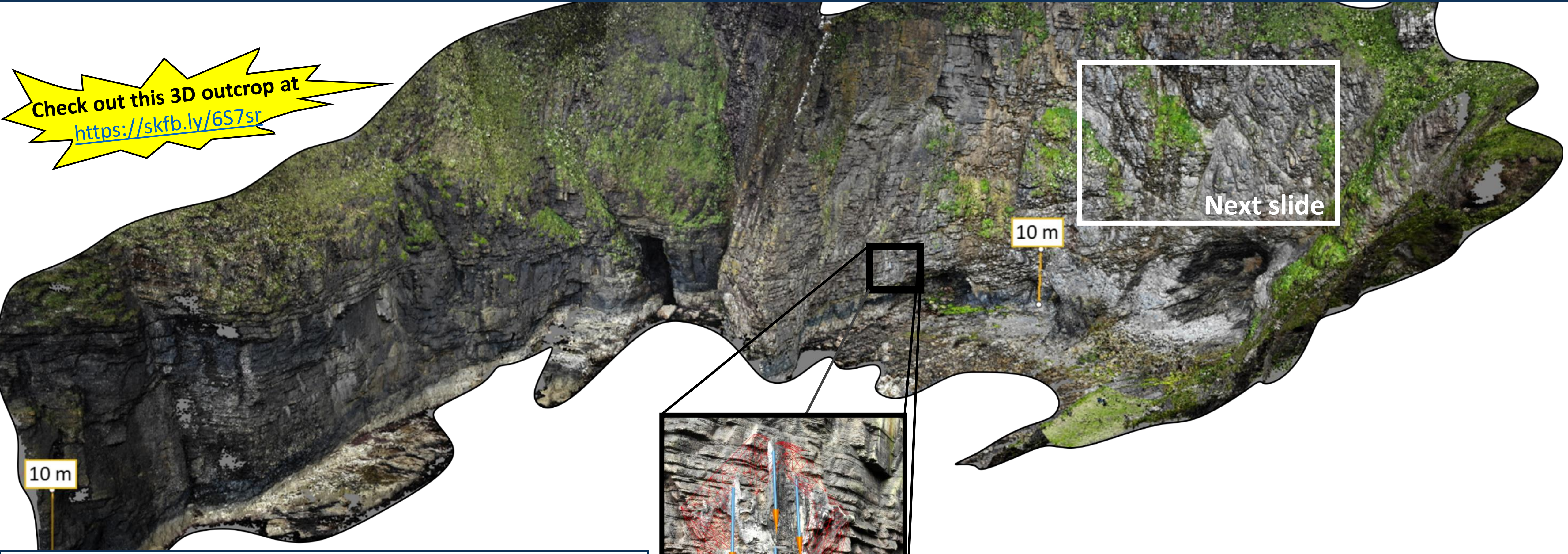


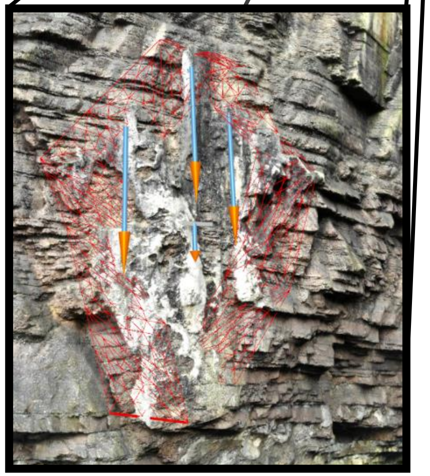
Devonian trends have then been **dextrally reactivated** during NNW-SSE extension.

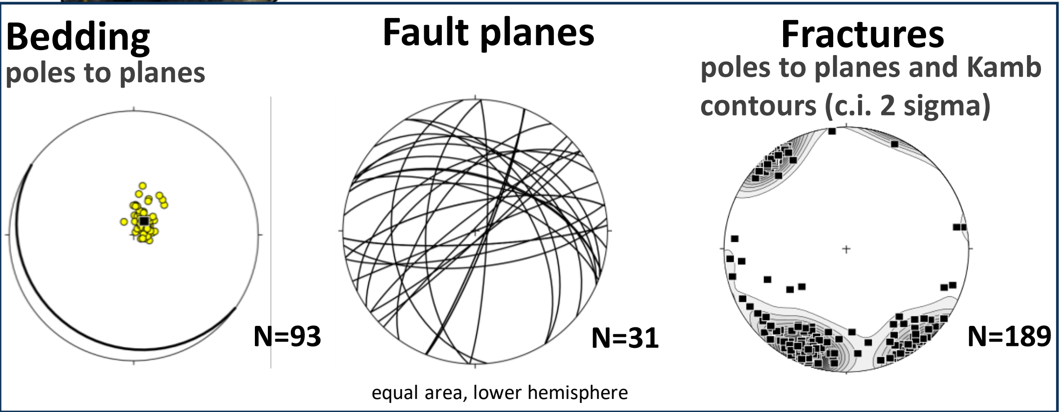
U-Pb dating of syn-kinematic calcite veins yield <u>Upper Jurassic (Kimmeridgian) ages,</u> which coincides with the main stage of IMFB opening seen offshore.

Tamas et al., 2020 (in prep.)

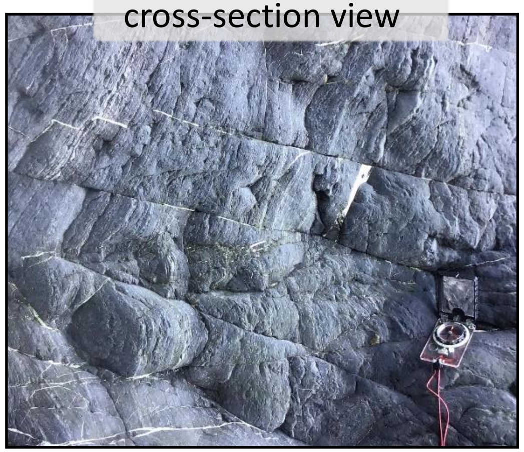
Whaligoe Steps, SE Caithness

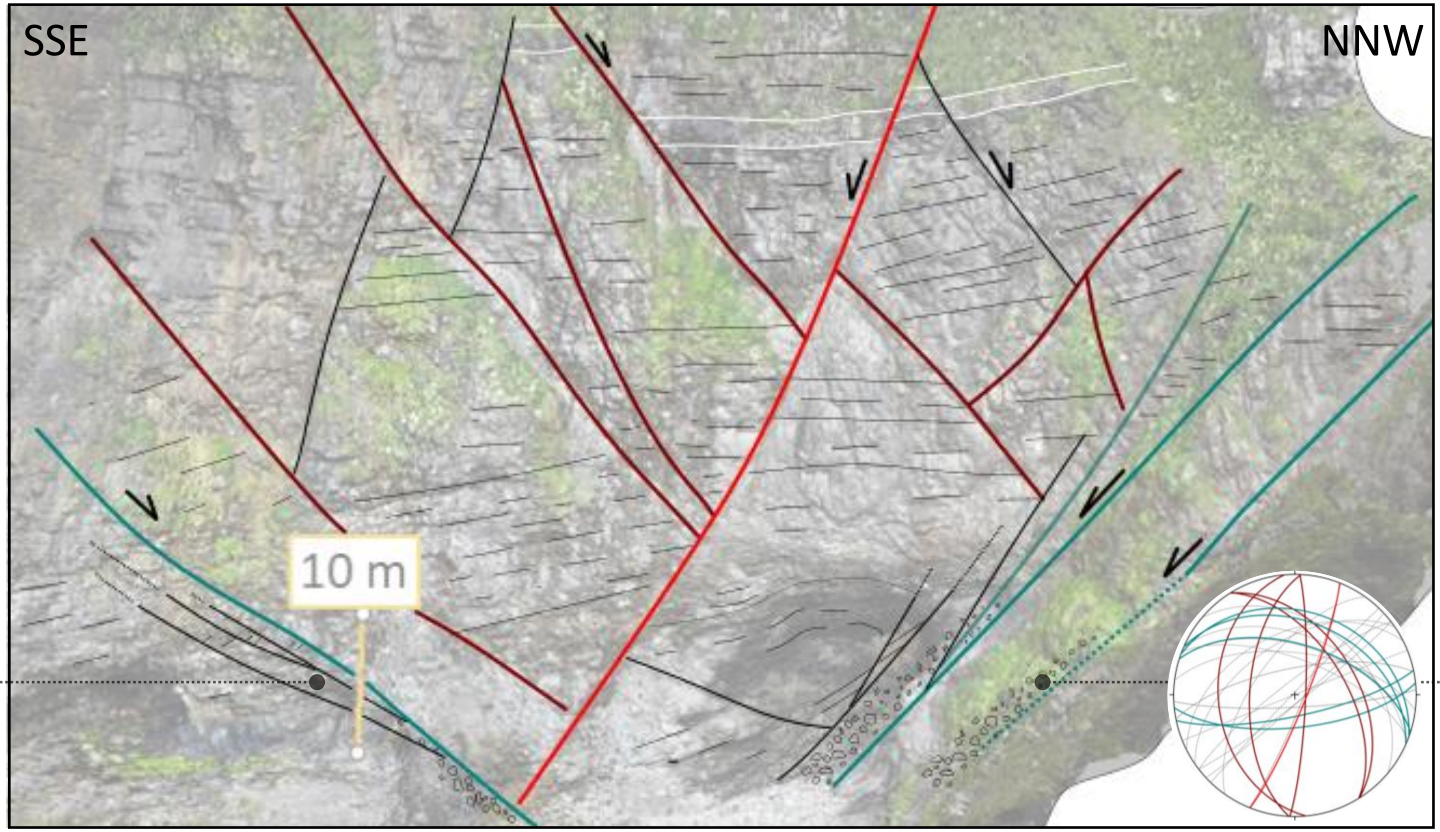


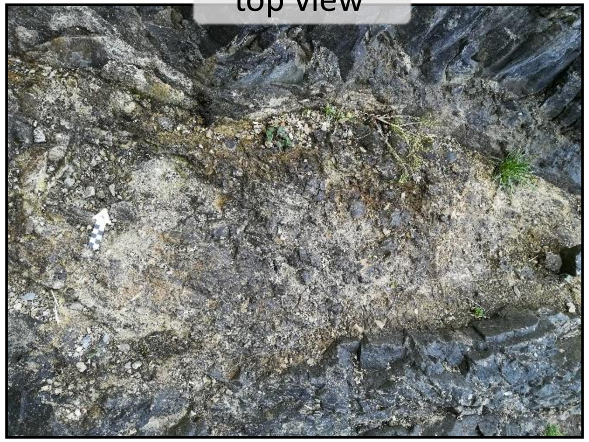




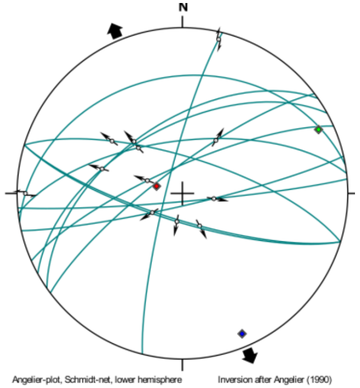
- Mainly ESE-WNW to NE-SW trending structures. Fault panels show dip-slip to oblique-sinistral lineations or slickenfibres.
- NNW-SSE to NNE-SSW striking faults are often cross-cut by later ESE-WNW to NE-SW trending faults (see next slide).







stress inversion of calcite mineralised faults in the area



- **ESE-WNW to NE-SW trending structures are constantly associated with calcite mineralisation.**
- **They developed during NNW-SSE extension, similar to the extension direction related to the Upper Jurassic reactivation of the NNE-SSW Devonian structures.**
- **This trend also coincided with the major Upper Jurassic offshore structures.**

(inferred)

Upper Jurassic

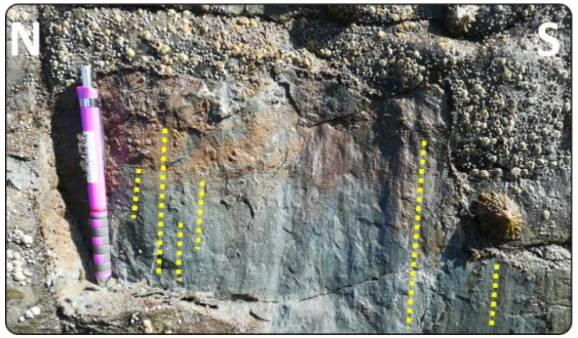
- **The NNW-SSE to NNE-SSW trending faults are earlier, Devonian, structures and are rarely associated with calcite mineralisation. The presence of mineralisation could indicate Upper Jurassic reactivation.**

(inferred)

Devonian

Conclusions

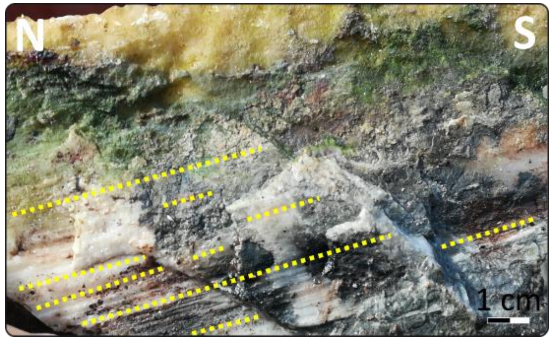
Devonian deformation



dip-slip, oblique-sinistral

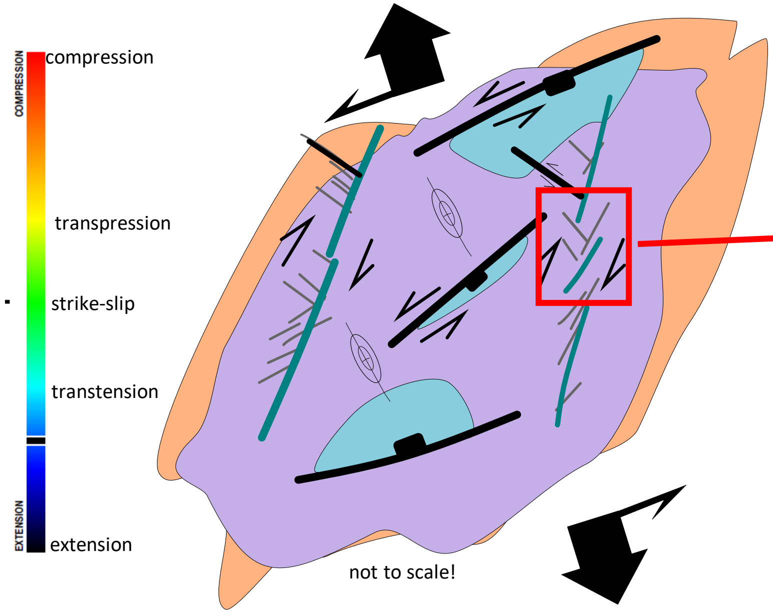
Our results suggest that the NNW-SSE to NNE-SSW striking growth faults are related to the opening of the Orcadian Basin. This implies that the regional sinistral transtensional model developed in Caithness (e.g. Dichiarante et al., 2016) extends to the southern limits of the Orcadian Basin in the Central Highlands.

Upper Jurassic Deformation



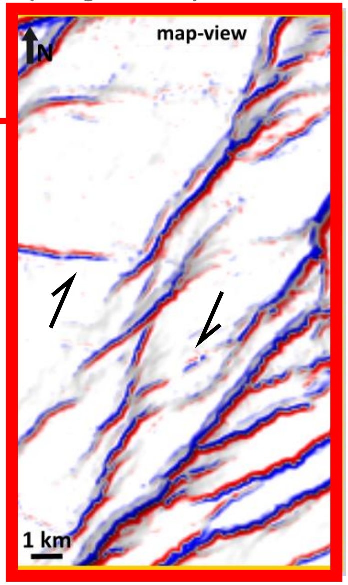
Dextral reactivated N-S to NNE-SSW trending faults

Dip-slip to oblique-sinistral NE-SW to ESE-WNW trending faults



stress regime computed (after Delvaux et al., 1997) based on stress inversion of major calcite mineralised faults

Structural map with 'influential data' property highlighting areas of rapid 3D geometric variations, exposing the fault pattern.



Upper Jurassic deformation is associated with complex fault pattern where dip-slip, oblique-sinistral and oblique-dextral faults coexist. This may suggest a transtensional opening of the basin.

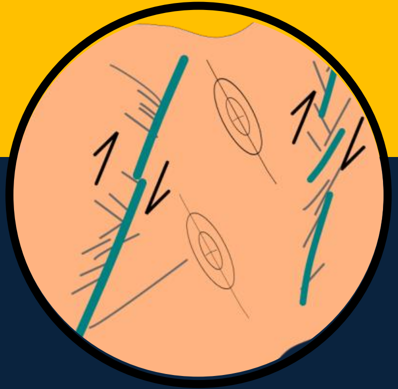
Devonian trends have then been dextrally reactivated during Upper Jurassic. Thus, NNW-SSE extension leads to reservoir-scale structural complexity due to widespread oblique reactivation of earlier Orcadian Basin structures. This pattern is widely recognised onshore and extends offshore as en-echelon Upper Jurassic N-S to NNE-SSW trending faults, consistent with dextral slip have been recognised on 3D seismic data .

Tamas et al., 2020 (in prep.)

Implications

¯_(ツ)_/¯ **'New information adds value, not from changing pre-drill risk, but from decisions made as a consequence.'**

(Peel and Brooks, 2015)



reconstruct deformation history | critical to **basin modelling**
improves **risk analysis**

sub-seismic structural style | fracture characterisation
heterogeneities
compartmentalisation

Relevant to any subsurface activity in the IMFB as well as providing a better understanding of superimposed basins.

Integration of fieldwork with subsurface interpretations have the ability to unlock the full potential of the area

Thank You and Stay Safe!

Many thanks to Dan Tamas for the help provided in acquiring and processing the drone images.
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We are also grateful to Spectrum, OGA and NDR for the access to the subsurface data.

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References

Allmendinger et al., 2012, https://doi.org/10.1017/CBO9780511920202

Andrews et al, 1990 http://pubs.bgs.ac.uk/publications.html?pubID=B01844

Cardozo & Allmendinger, 2013: https://doi.org/10.1016/j.cageo.2012.07.021

Davies et al., 2001 https://doi.org/10.1144/petgeo.7.4.371

Dichiarante et al., 2016 https://doi.org/10.1144/jgs2015-118

Zanella E. & Coward M.P. 2003. Structural framework. In: Evans D., Graham C., Armour A. & Bathurst P. (eds) The Millennium Atlas: Petroleum Geology of the Central and Northern North Sea, Geological Society, London, 45–59

Frostick et al., 1988 https://doi.org/10.1144/gsjgs.145.2.0235

Guariguata-Rojas and Underhill, 2017 https://doi.org/10.1190/INT-2017-0009.1

Lapadat et al., 2018 https://doi.org/10.1144/SP439.18

Le Breton et al., 2013 https://doi.org/10.1144/jgs2012-067

Long & Imber 2010 https://doi.org/10.1016/j.jsg.2009.11.009

McQuillin, et al., 1982 https://doi.org/10.1016/0012-821X(82)90028-0

Peel and Brooks, 2015 https://doi.org/10.1306/070615045

Roberts et al, 1990 https://doi.org/10.1144/gsjgs.147.1.0087

Sasvári and Baharev, 2014 https://doi.org/10.1016/j.cageo.2013.12.010

Thomson and Underhill, 1993 https://doi.org/10.1144/0041167

Underhill, 1991 https://doi.org/10.1016/0264-8172(91)90089-J

Wilson et al., 2010 https://doi.org/10.1144/SP335.32