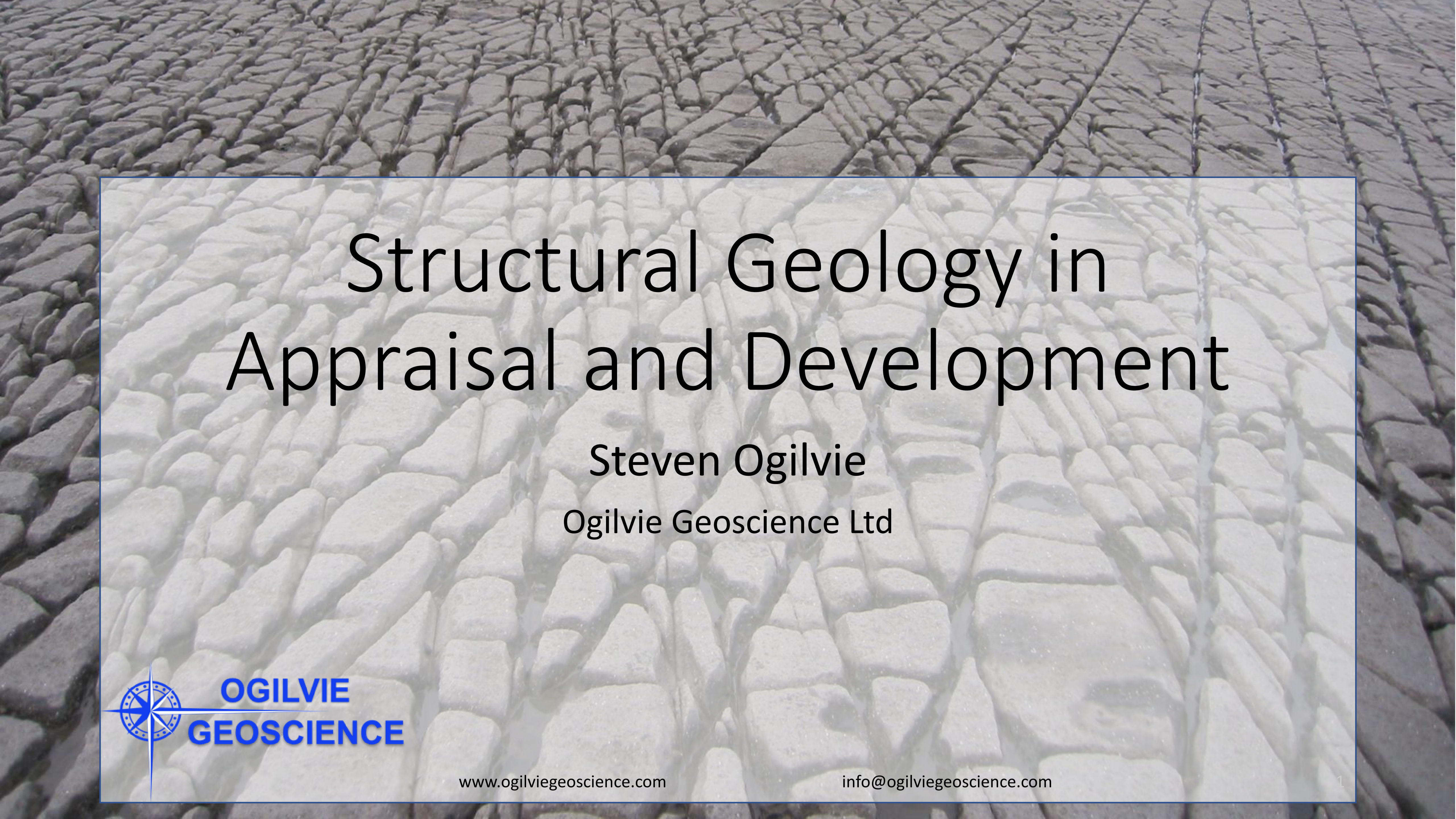

Structural Geology in Appraisal and Development

Steven Ogilvie

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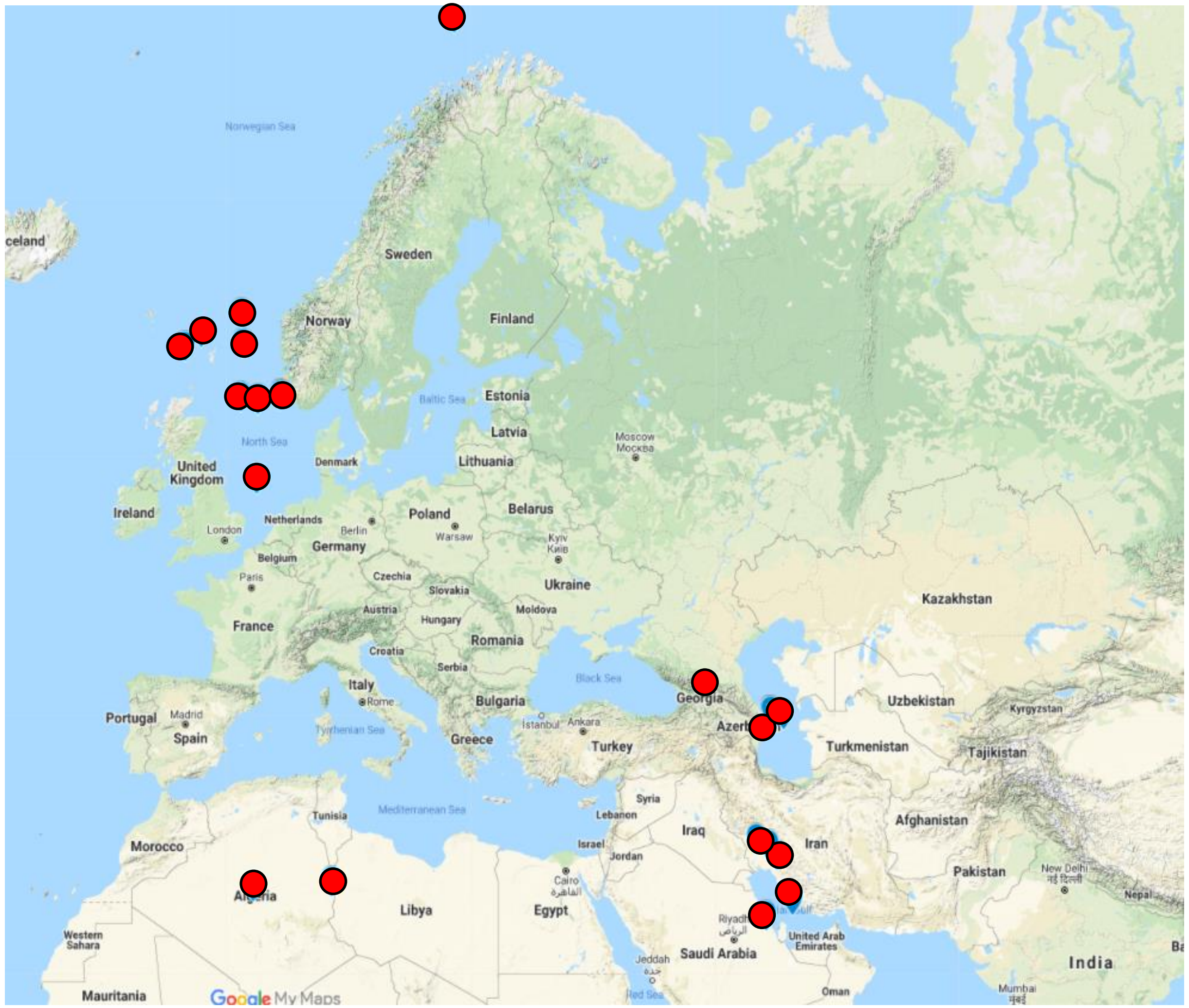
About us

- We specialise in the provision of Fractured Reservoir, Structural Geology and Geomechanics services to the Energy Industry

- Our focus is on in-field structural geology and geomechanics in the hydrocarbon **appraisal** and **development** phases



Objective

- To provide examples of where structural geology has added value and reduced uncertainty/risk throughout hydrocarbon appraisal and development

Key texts

Role of geology throughout the value chain….

Gluyas, J & Swarbick, R. 2004. Petroleum Geoscience, Blackwell publishing.

Industry focused structural geology…..

Fossen, H. 2016. Structural Geology 2nd Ed, Cambridge Univ. Press

Contents

Issue
Workflow
Outcome

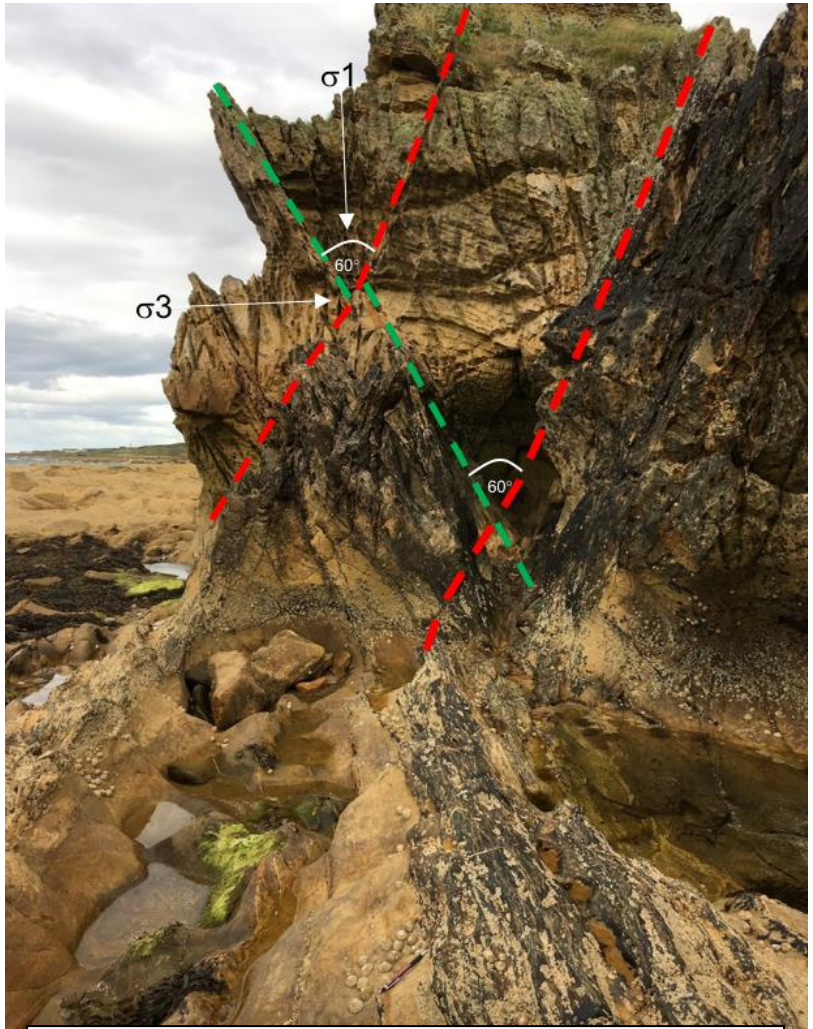
1. Structural Interpretation

1.1 Anderson’s (1951) classification

- Normal faults tend to form at 60°
- Reverse faults tend to form at 30°
- Strike slip faults at 90°

When Interpreting

- Make sure you’re seismic section is 1:1
- Best to use greyscale



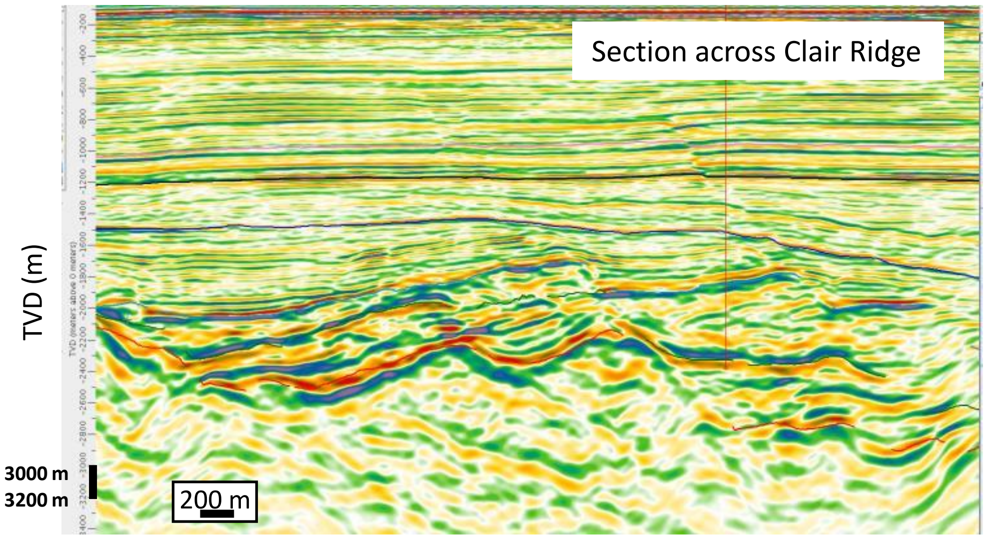
Normal faults in the Hopeman Sandstone, Inner Moray Firth

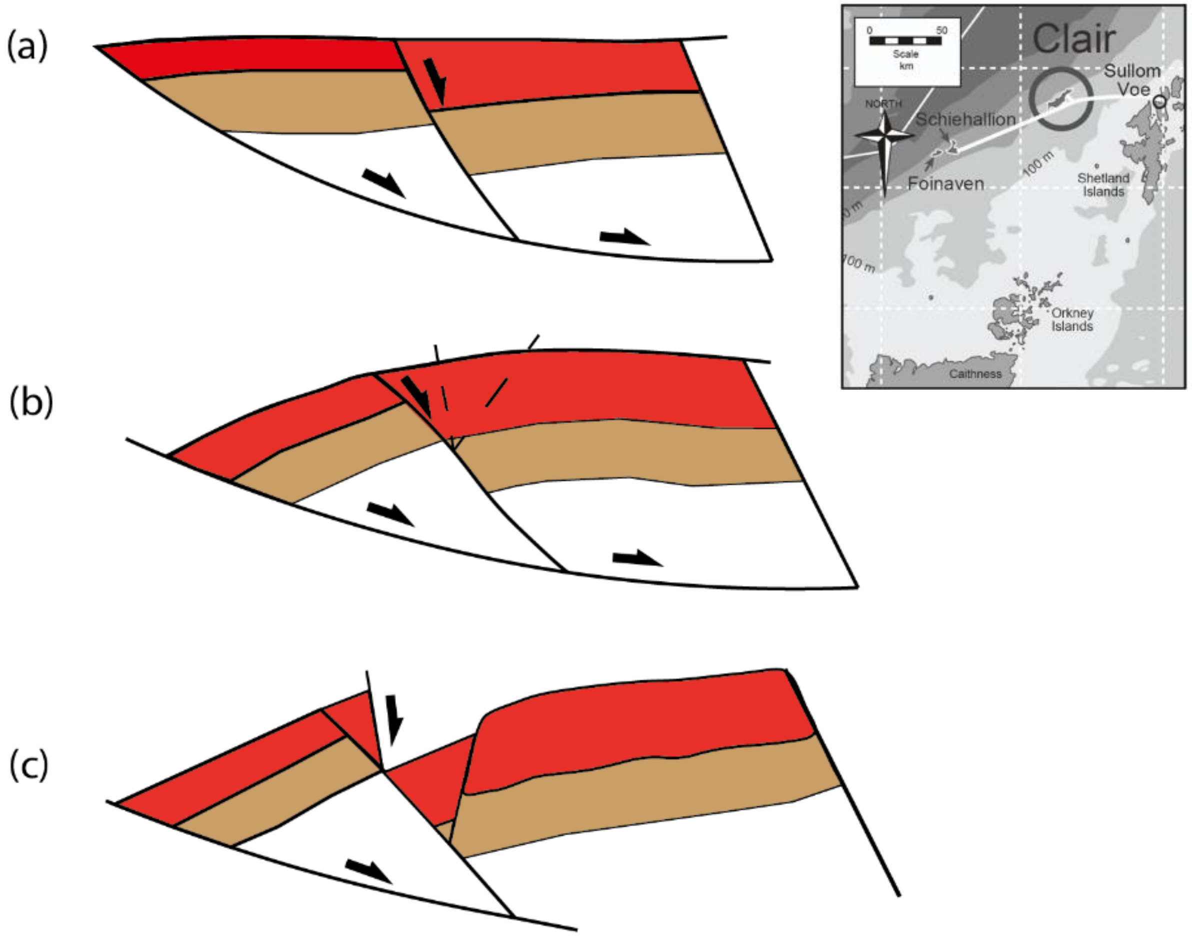
1.1 Low angle normal faults

Can form directly along a pre-existing weakness

OR

by fault block rotation

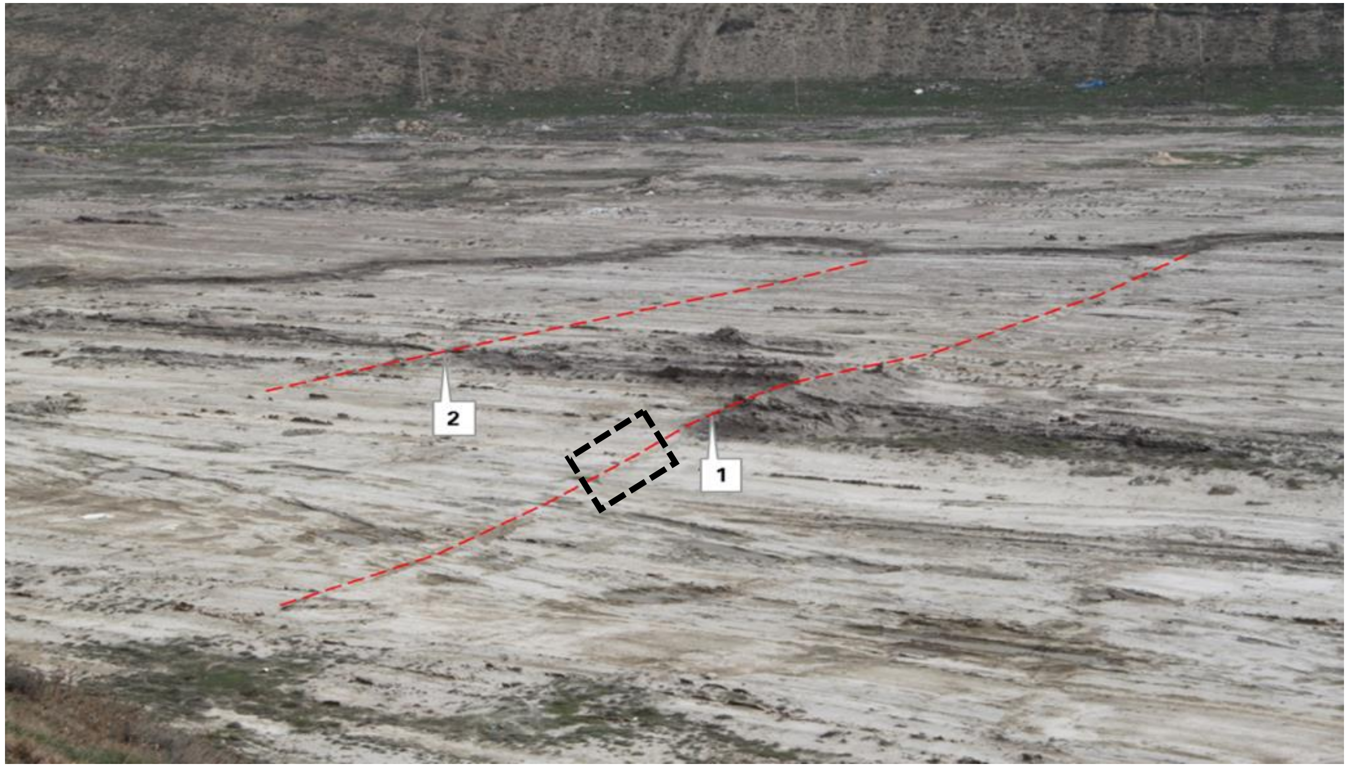




Ogilvie et al. (2015)

1.1 Strike-Slip Faults

- Often not interpreted on seismic
- Can be significant barriers to flow



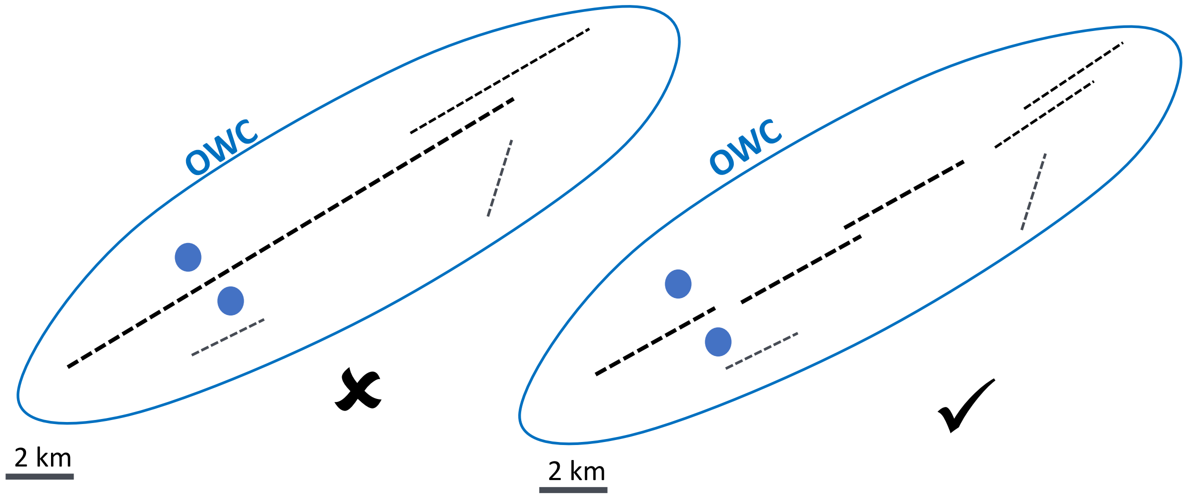
SS faults on the floor of Kirkmaky Valley, Azerbaijan

Dextral Strike-slip fault, Kirkmaky Valley
1. Drag folding in shaley sand (good kinematic indicator)
2. Cataclastic deformation bands in clean sandstone

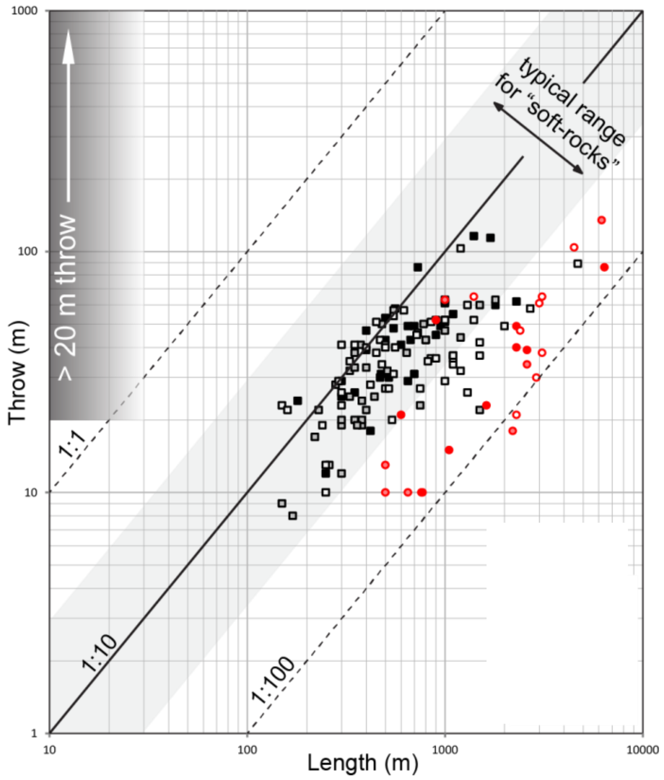
1.1 Fault length

Issue: Faults often mapped longer than they should be.

Workflow: Length vs. throw – typical range for sedy rocks is 1:10 to 1:30 (Shultz et al. 2006)



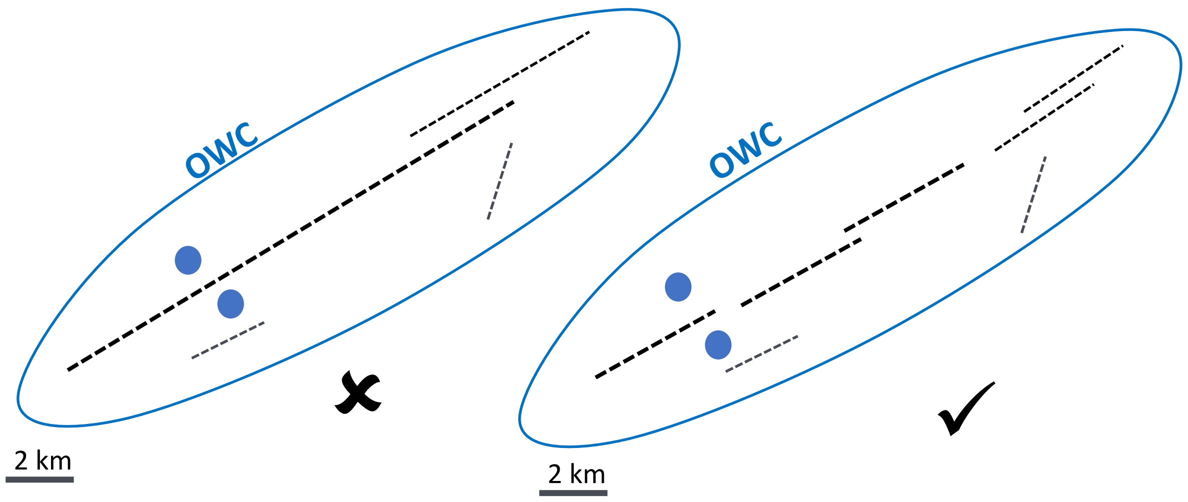
Map view of different fault interpretations on giant anticline



Throw vs Length

1.1 Fault length

Outcome: Shorter faults consistent with well data

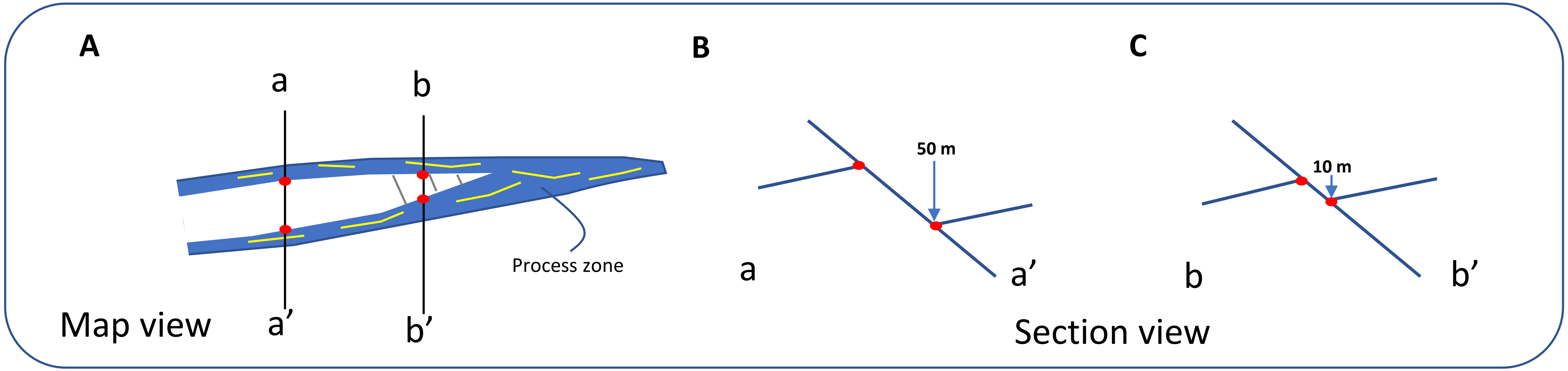


Map view of different fault interpretations on giant anticline

Short faults linked by relay ramps in Limestone, Kilve, Somerset

1.1 Fault tips

Issue: Tip extent can be misjudged. Ahead of the tip is a process zone of fractures – weak zones prone to mud invasion = risk of losses. Avoid drilling here as may need to sidetrack !

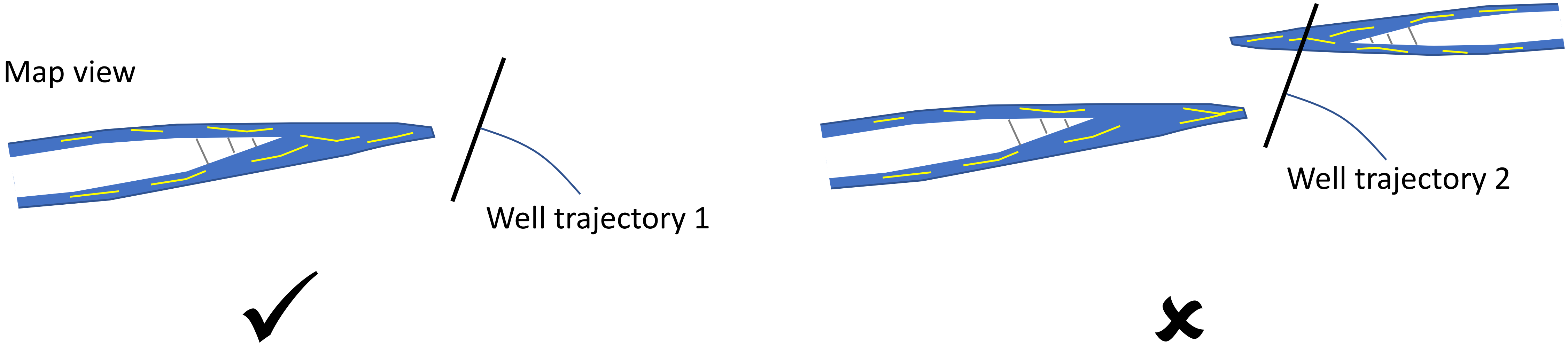


Workflow: Blank out fault where throw close to resolution, continue it based upon throw gradient, add process zone.

1.1 Fault tips

Outcome

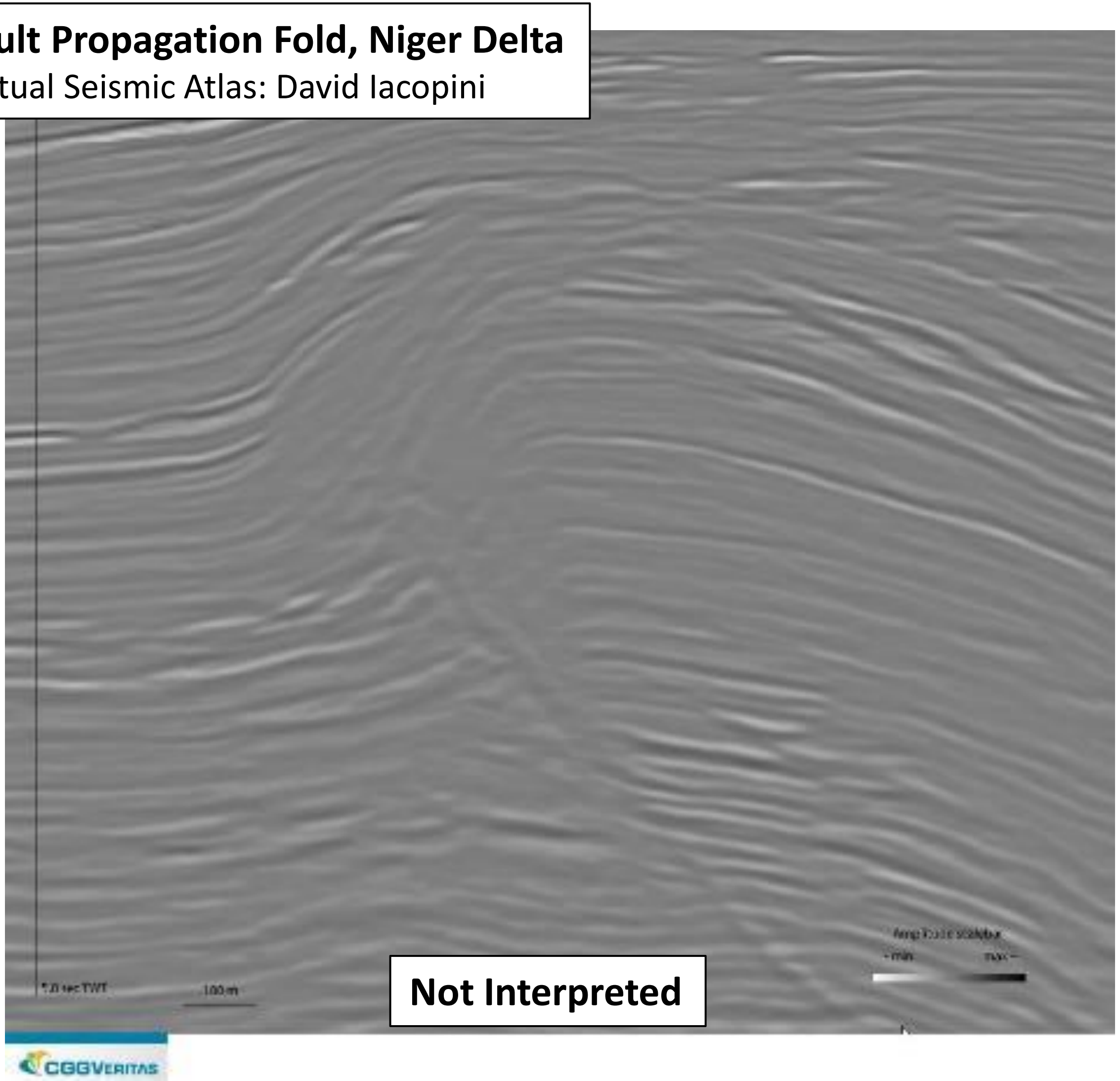
- 1 well drilled without losses
- Next one had issues – did it hit another fault that was poorly imaged ?



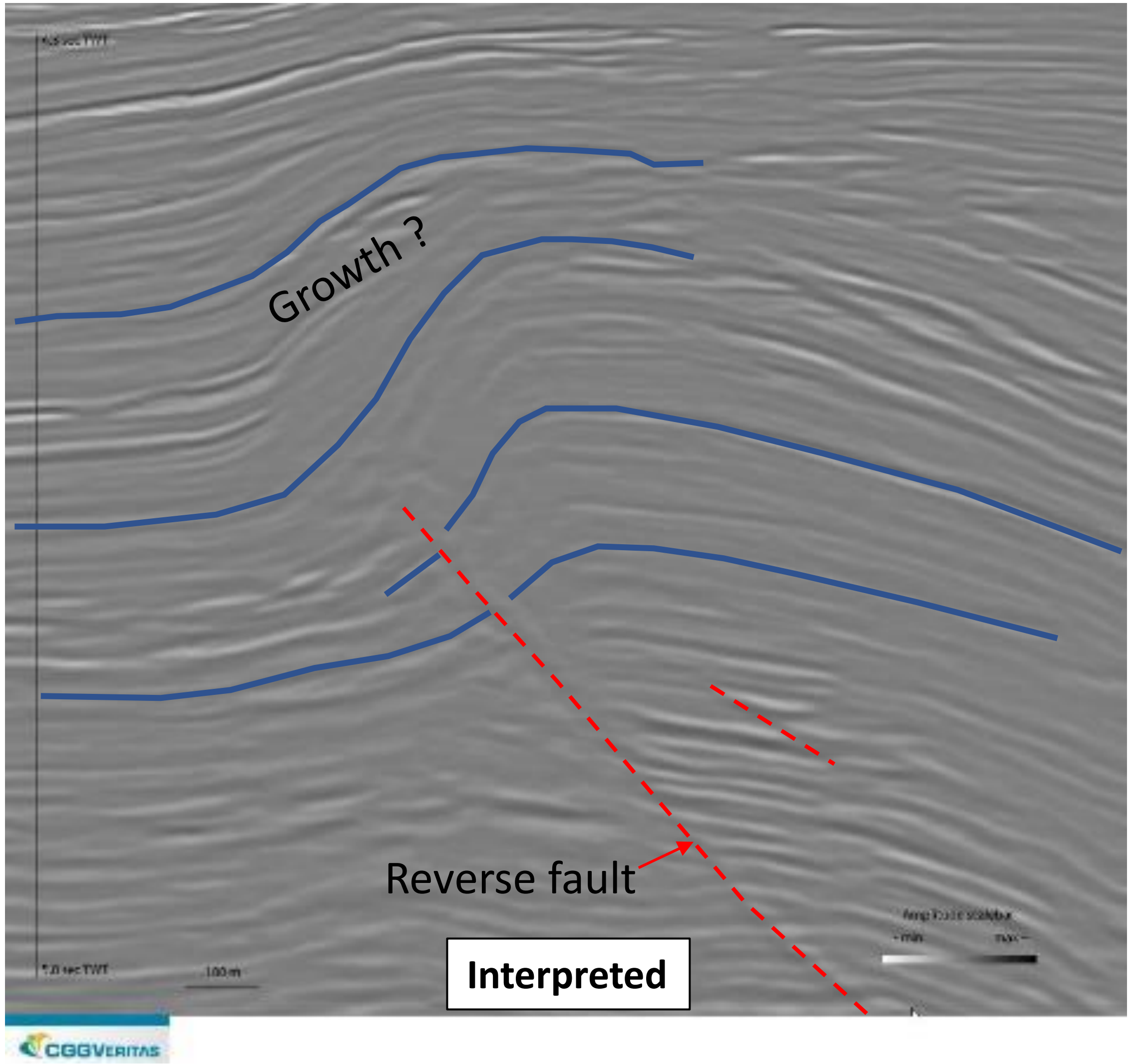
Can also try to aim for the centre of the fault

1.2 Steeply Dipping Beds

Fault Propagation Fold, Niger Delta
Virtual Seismic Atlas: David Iacopini



Not Interpreted

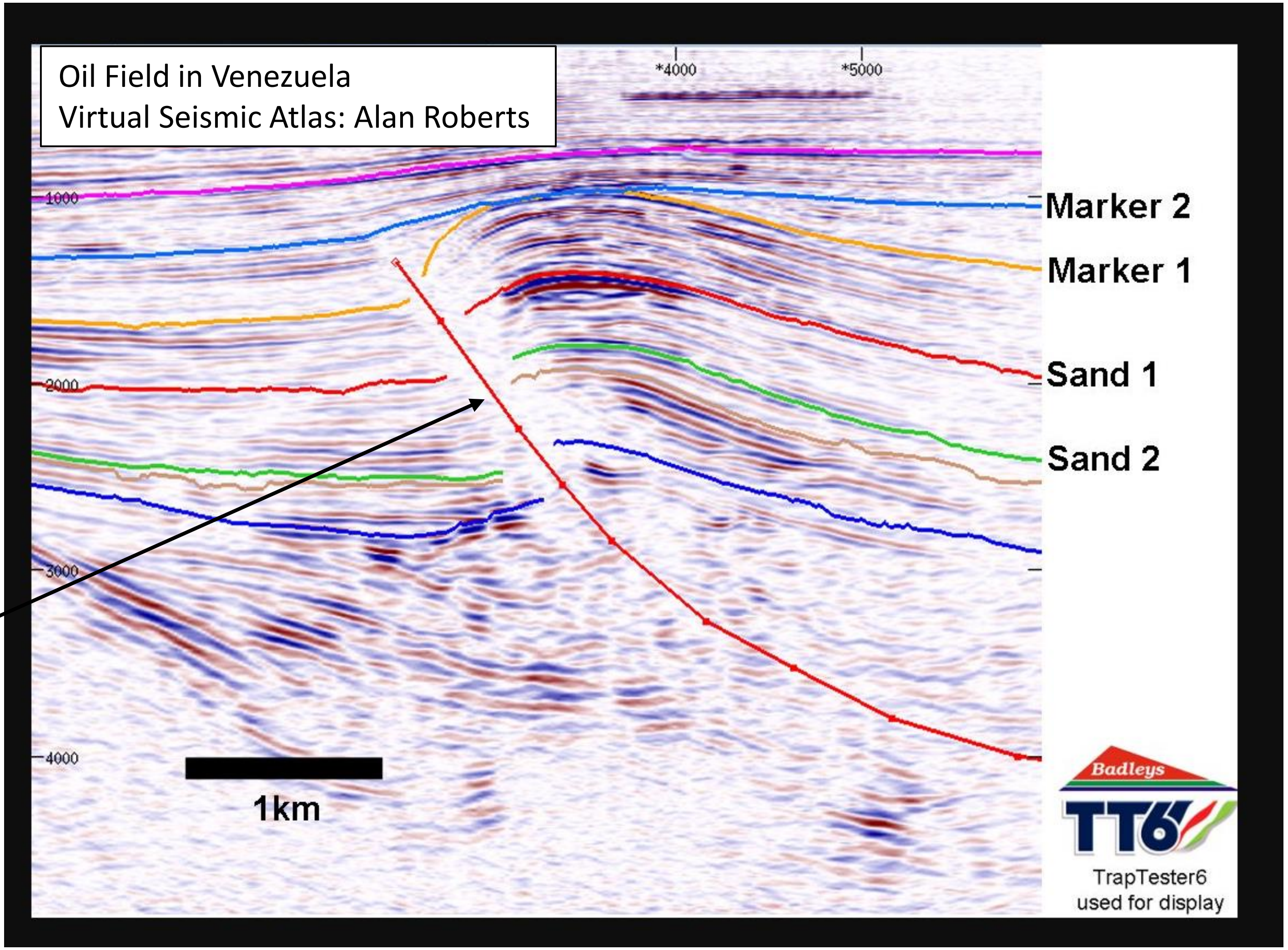


Interpreted

1.2 Steeply Dipping Beds

Issue: Structural Interpretation of poorly imaged zones as impacts reserves, well planning, production.

Deformation bands in sandstone
Permeability reduction



Oil Field in Venezuela
Virtual Seismic Atlas: Alan Roberts

1.2 Steeply Dipping Beds

Fault propagation fold in dolomite, Marsden Bay, England

1.2 Steeply Dipping Beds

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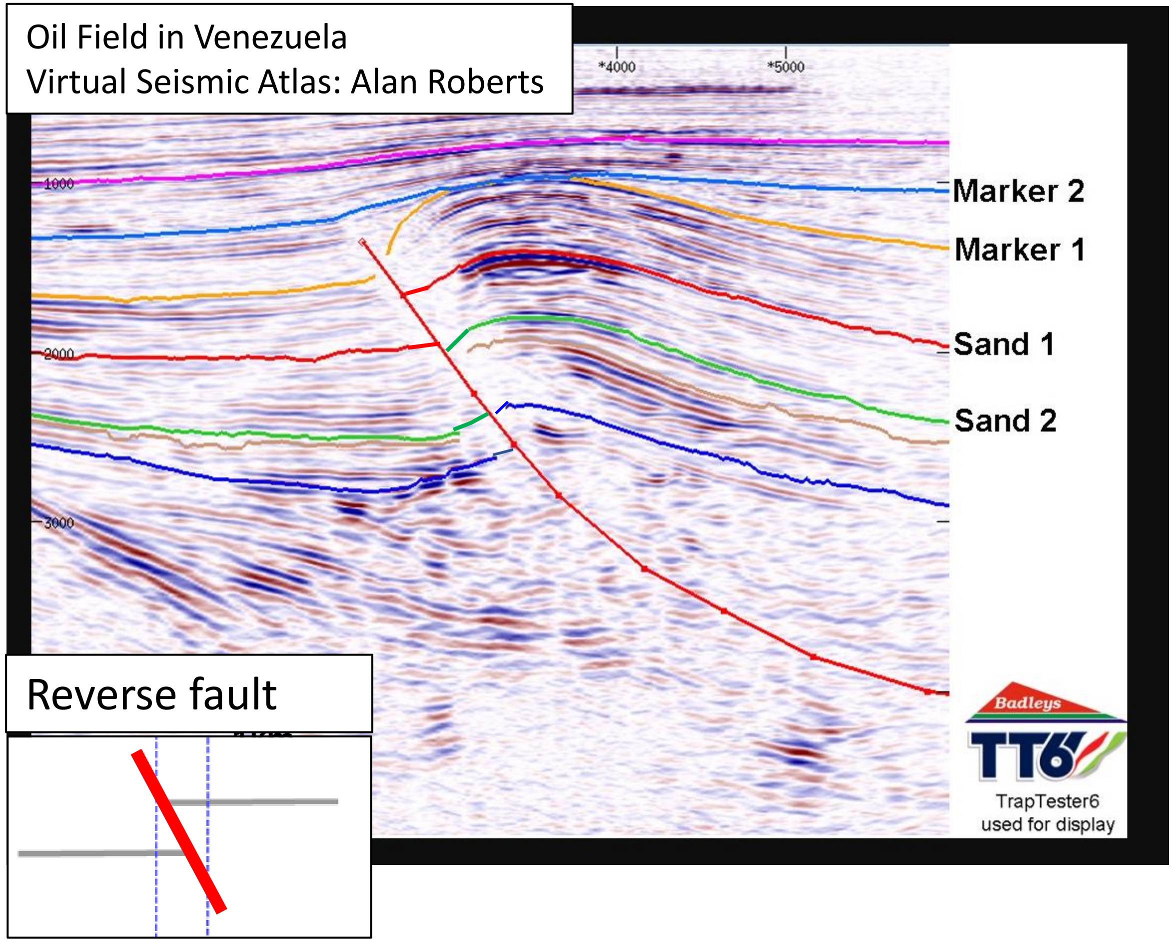
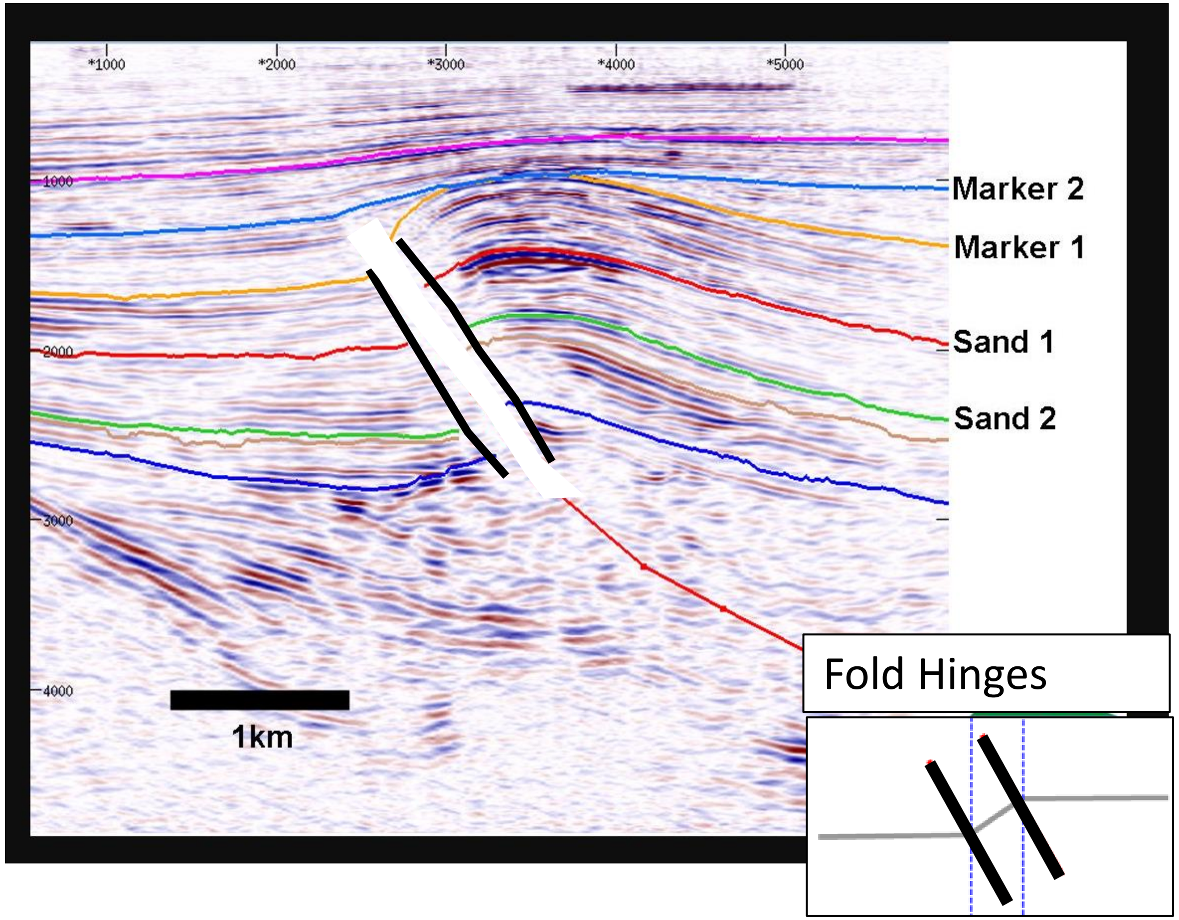
2 interpretations

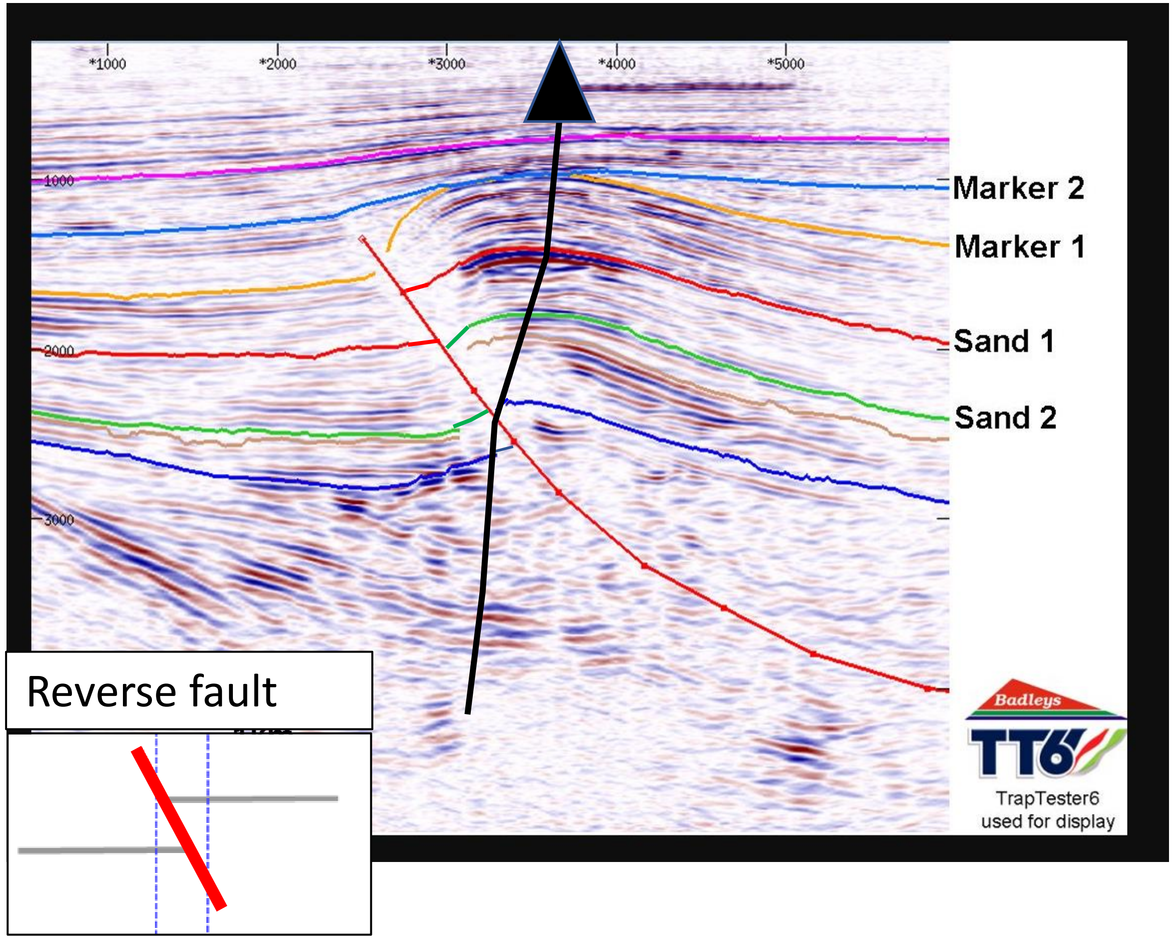

Oil Field in Venezuela
Virtual Seismic Atlas: Alan Roberts

Reverse fault

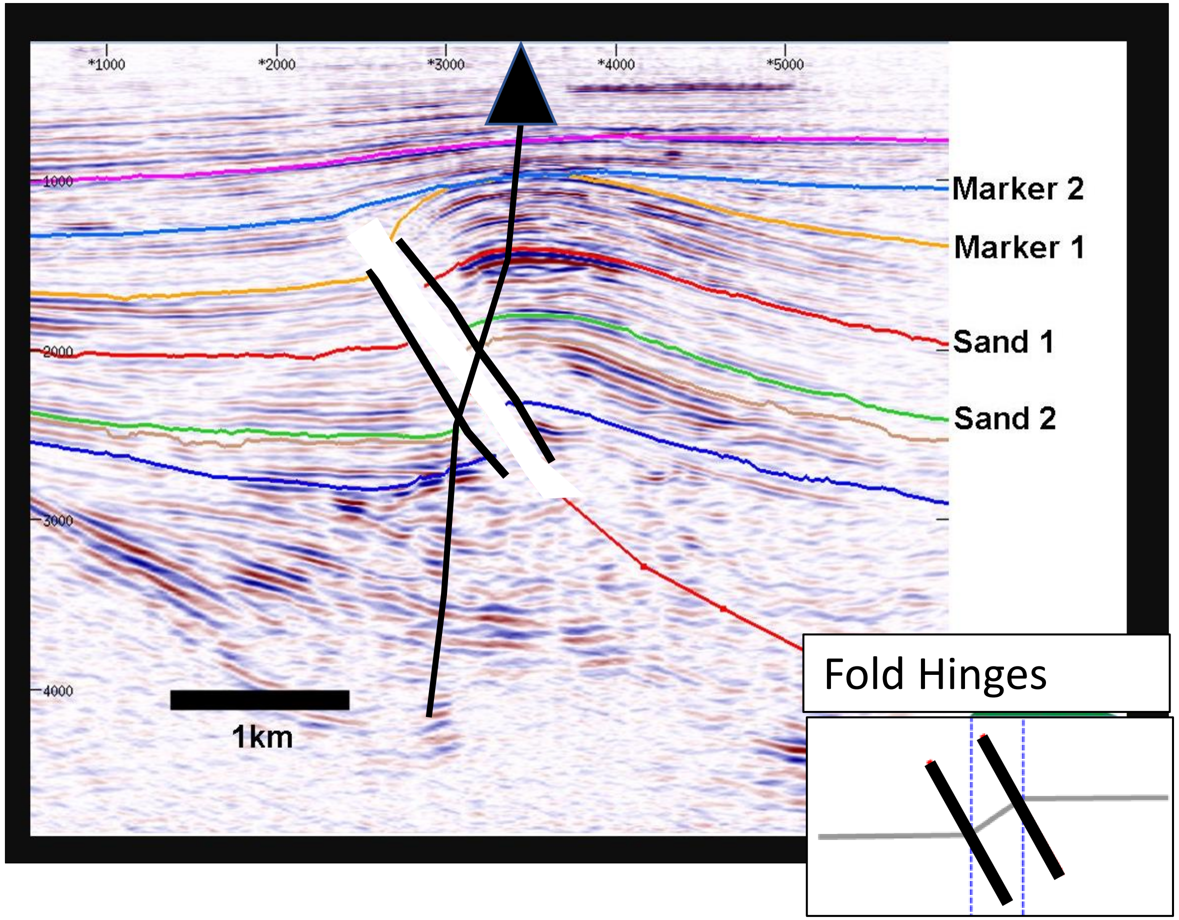

Fold Hinges

1.2 Steeply Dipping Beds

Workflow: Dipmeters, outcrop analogues



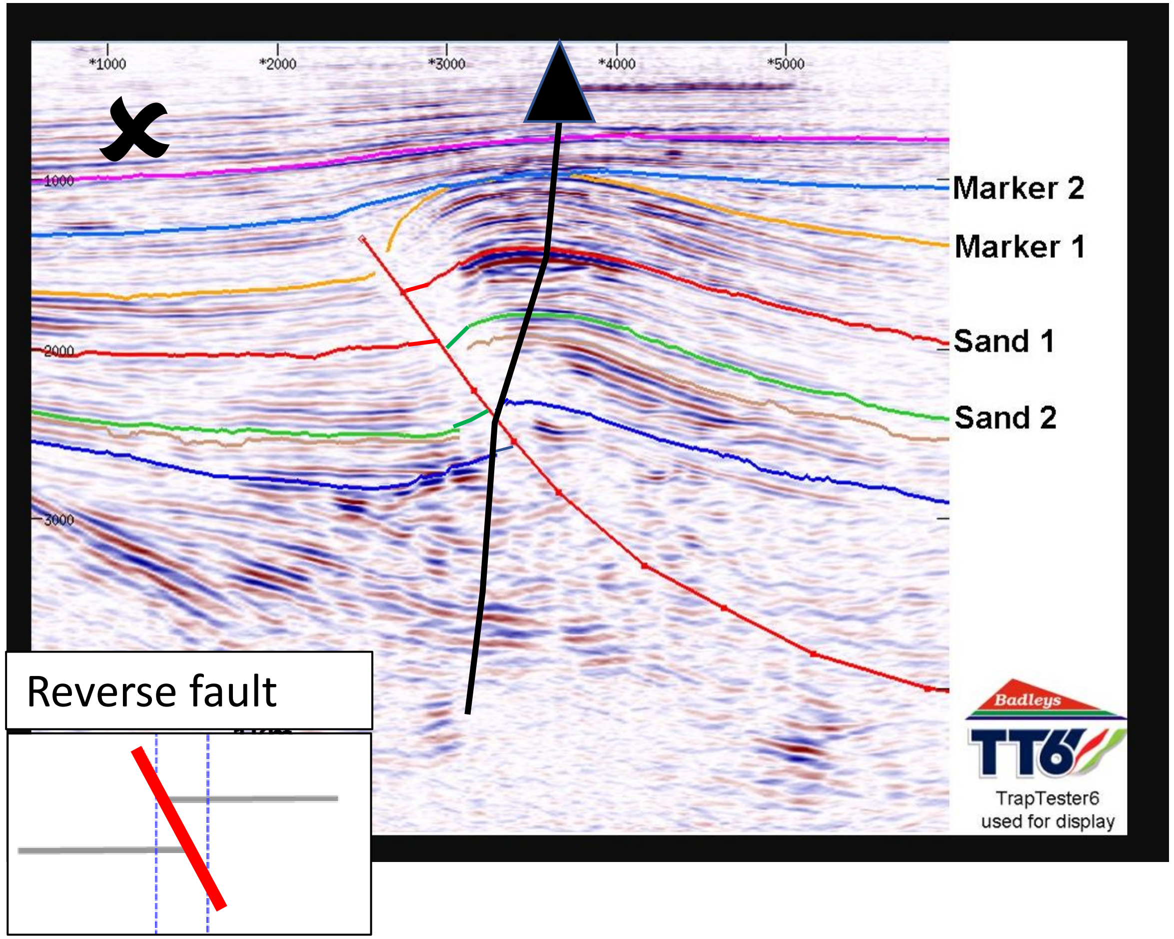
Reverse fault



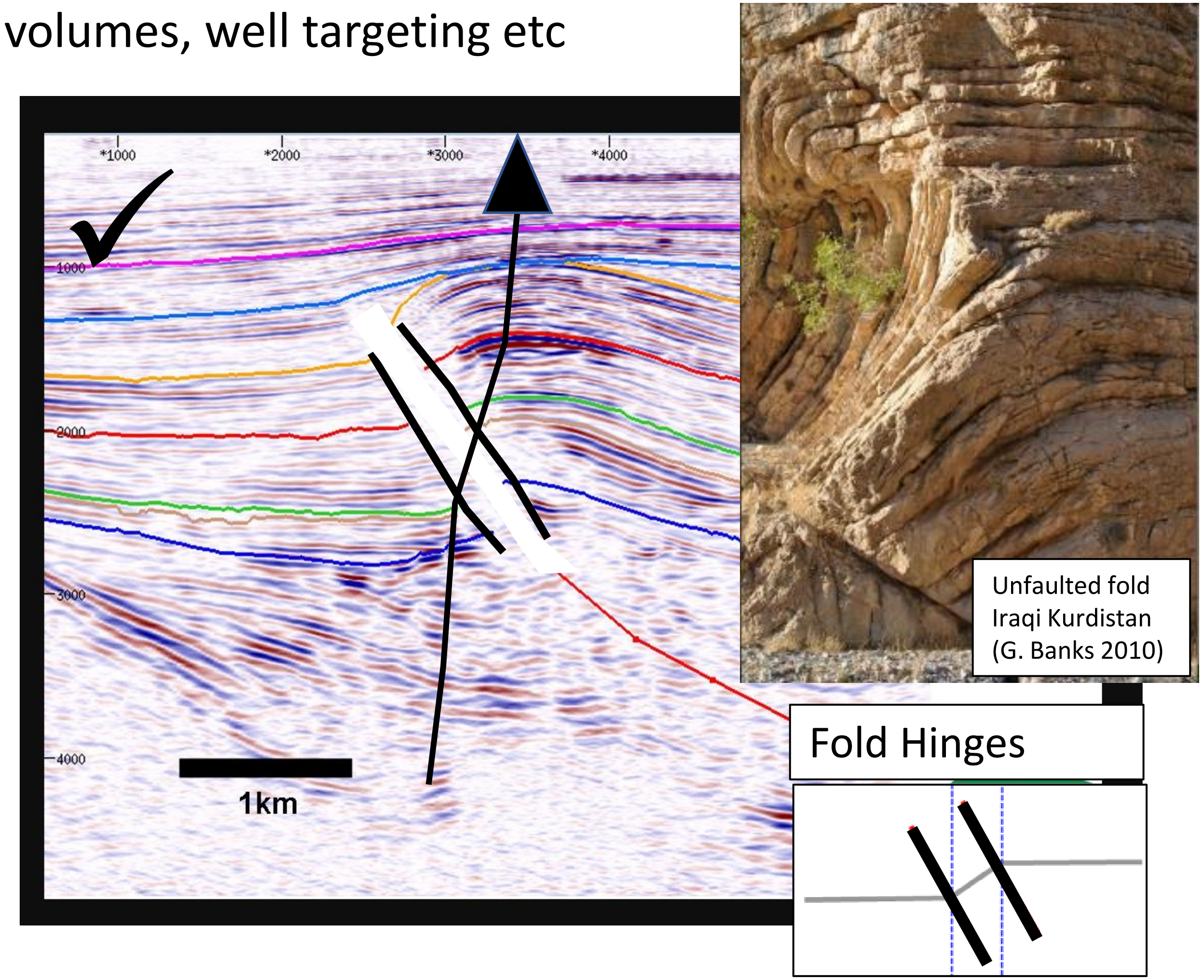
Fold Hinges

1.2 Steeply Dipping Beds

Outcome: Fold hinge interpretation, impacts accessible volumes, well targeting etc



Reverse fault

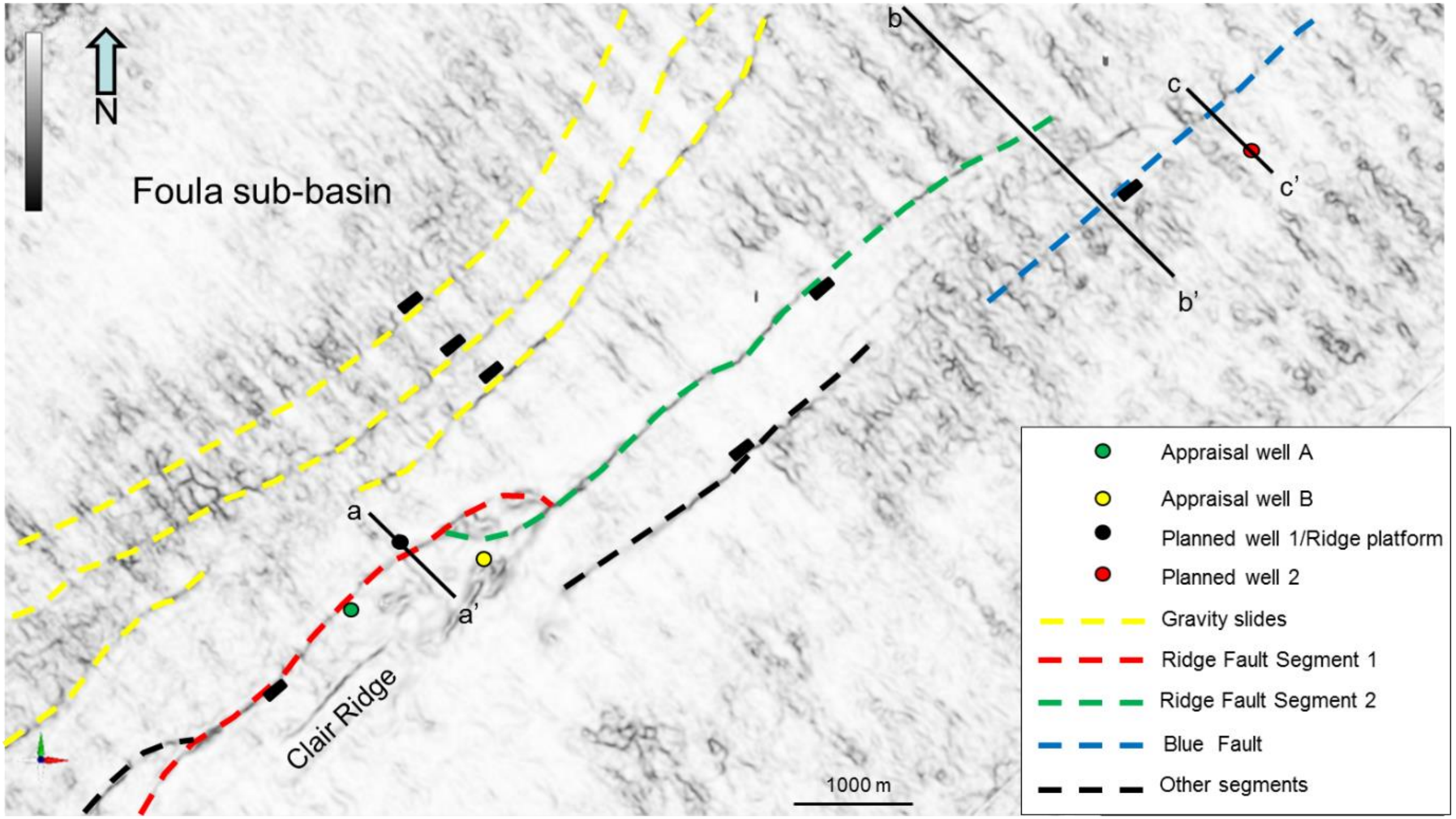


Unfaulted fold
Iraqi Kurdistan
(G. Banks 2010)

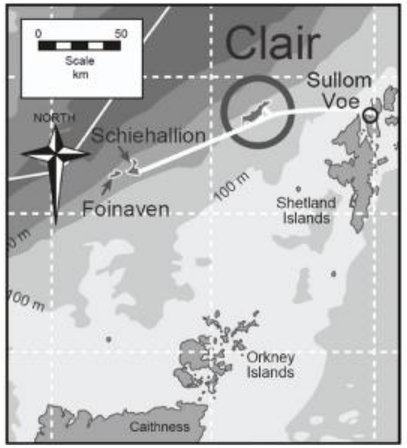
Fold Hinges

1.3 Standoff to Faults

Issue: Faults can cause wellbore instability, adverse impact upon production.
How close can we place wells to the Clair Ridge Fault ?



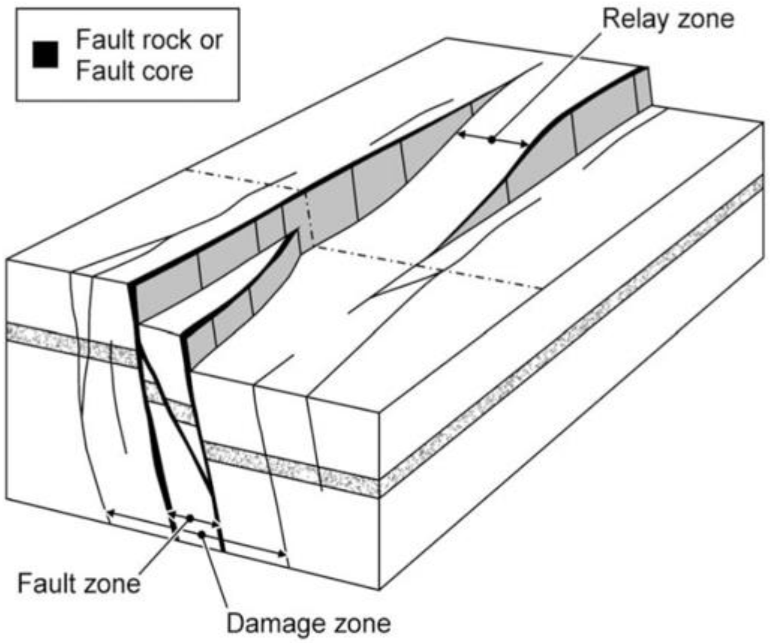
Map view (coherency)
Tertiary (570 m TVDSS)
Coherency



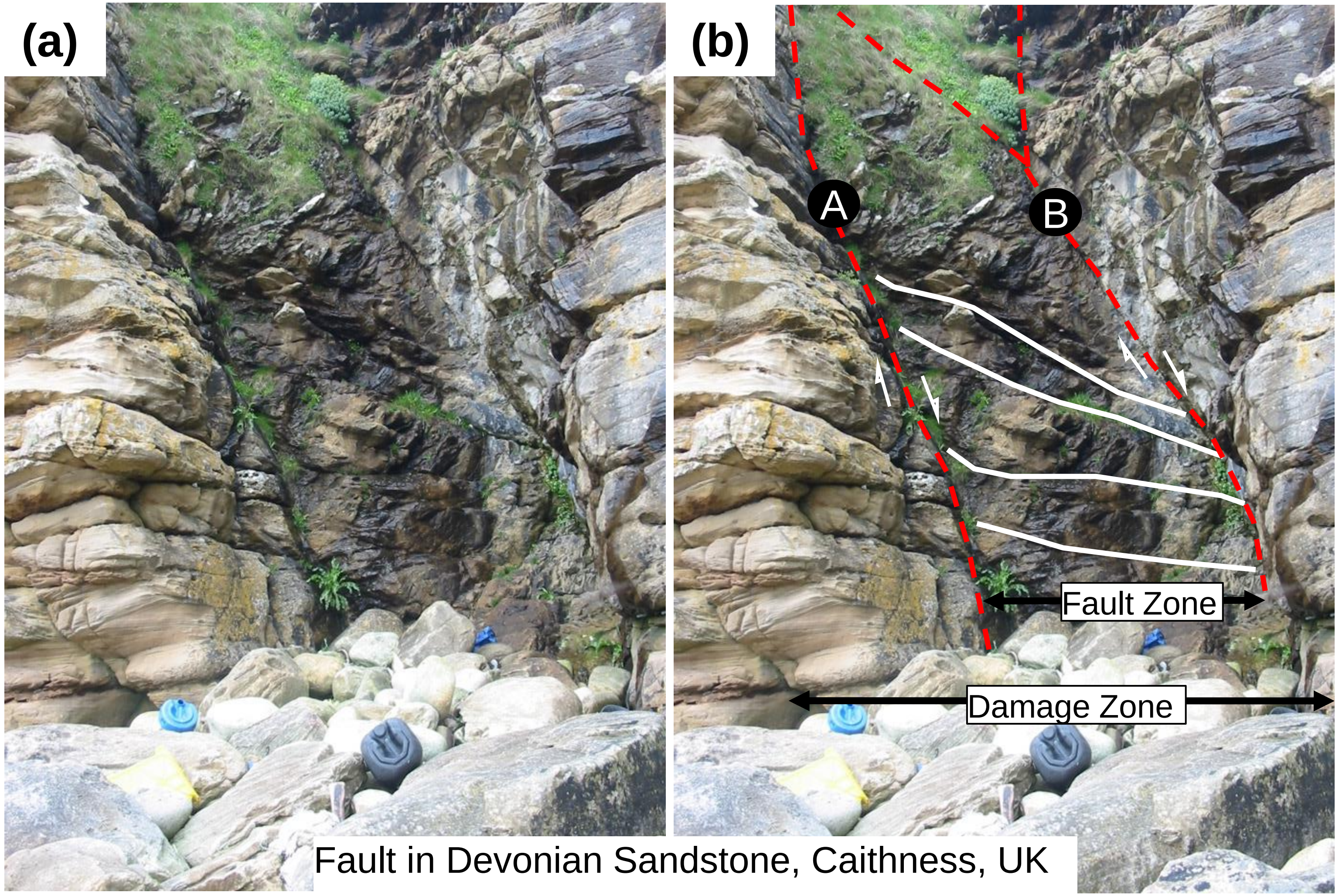
Ogilvie et al. (2015)

1.3 Standoff to Faults

Workflow



Childs et al. (2009)

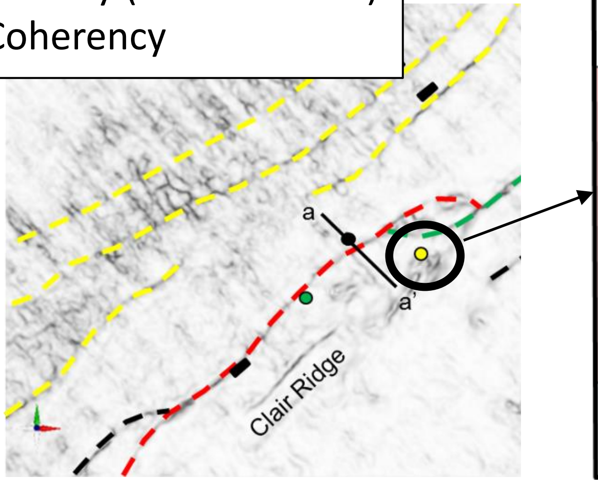


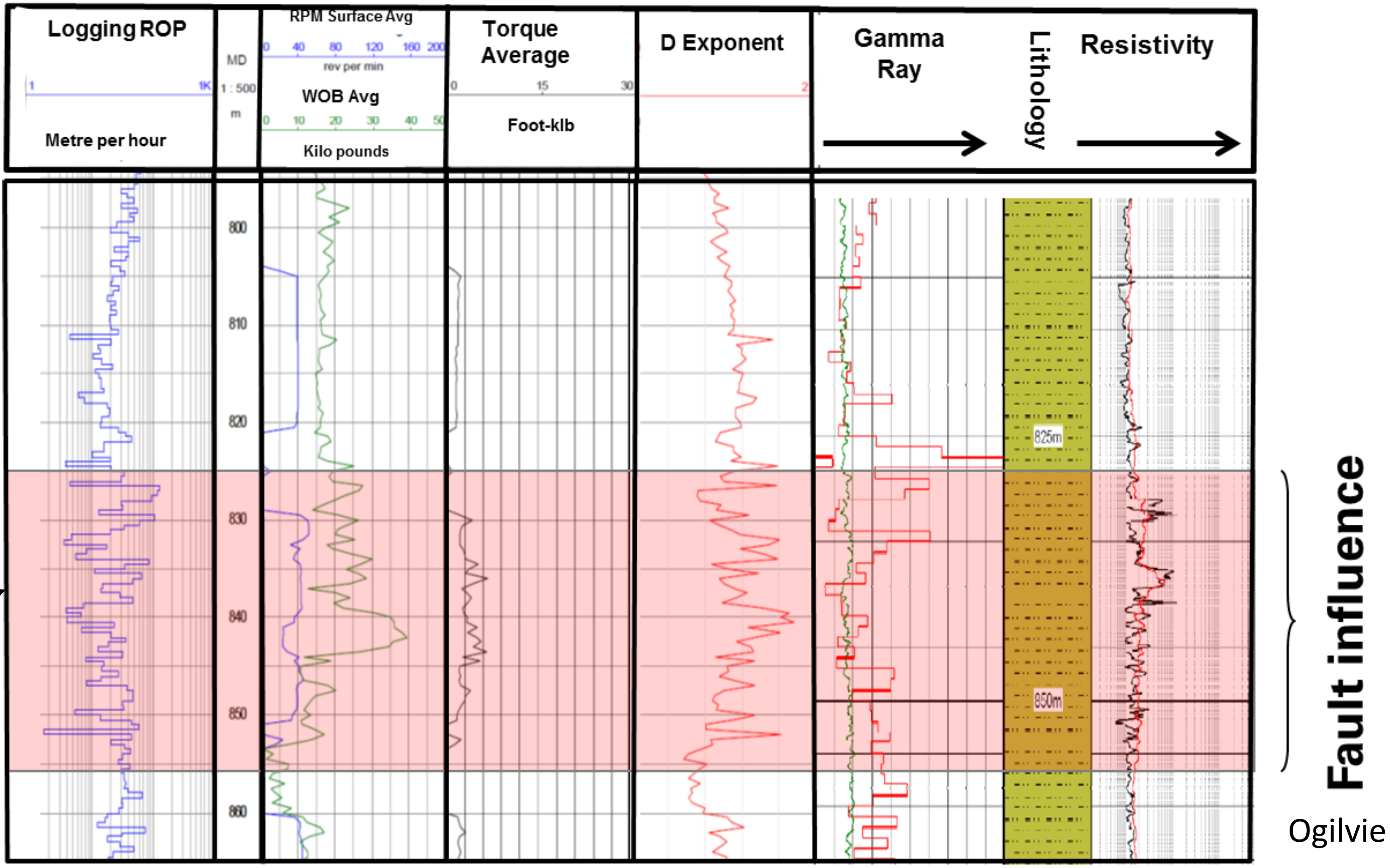
Fault in Devonian Sandstone, Caithness, UK

1.3 Standoff to Faults

Workflow: Use literature plots (Childs et al. 2009) as a guide but best to use existing wells

Map view (coherency)
Tertiary (570 m TVDSS)
Coherency



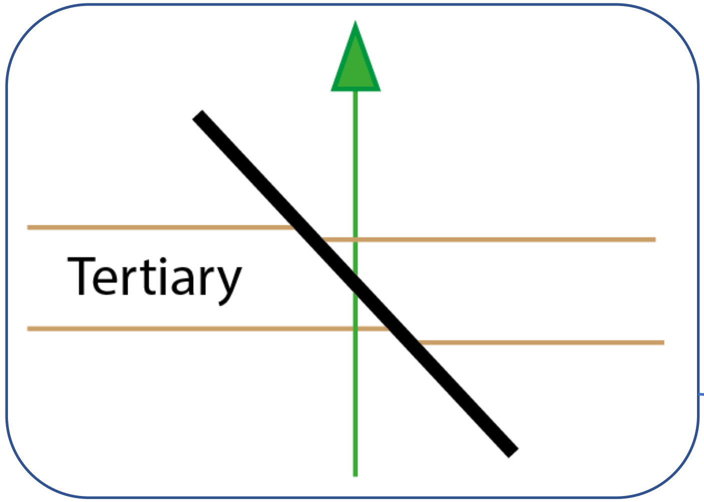


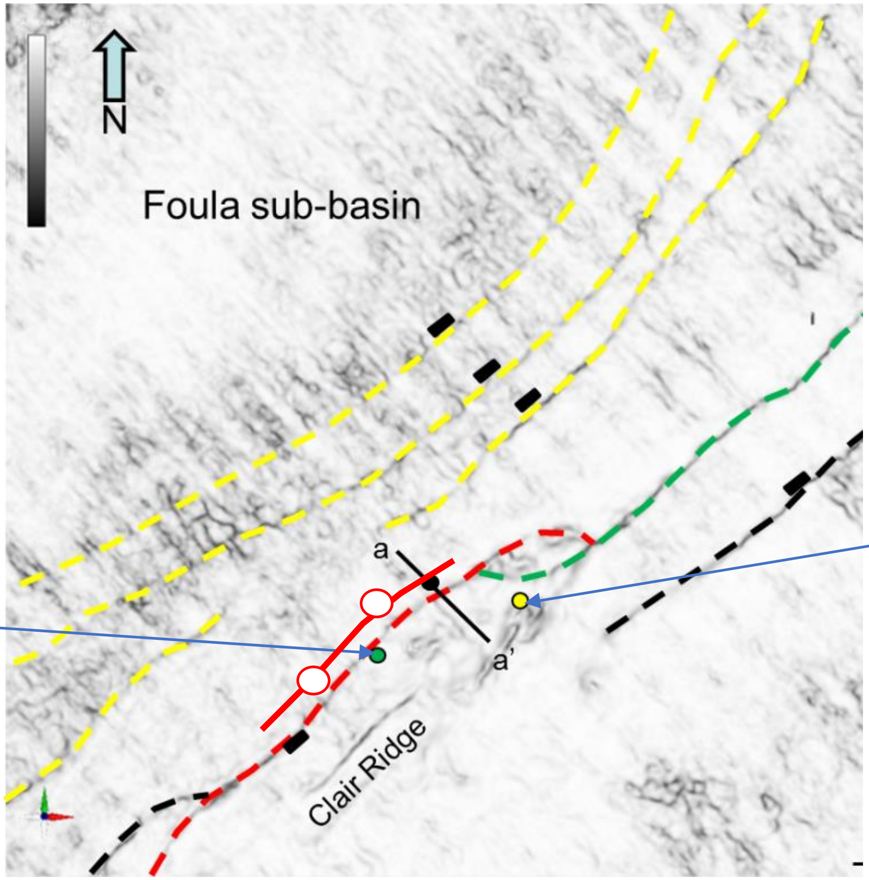
Ogilvie et al. (2015)

1.3 Standoff to Faults

Outcome: Early wells drilled at c. 40 m standoff (15m DZ + lateral fault uncertainty) = no issues

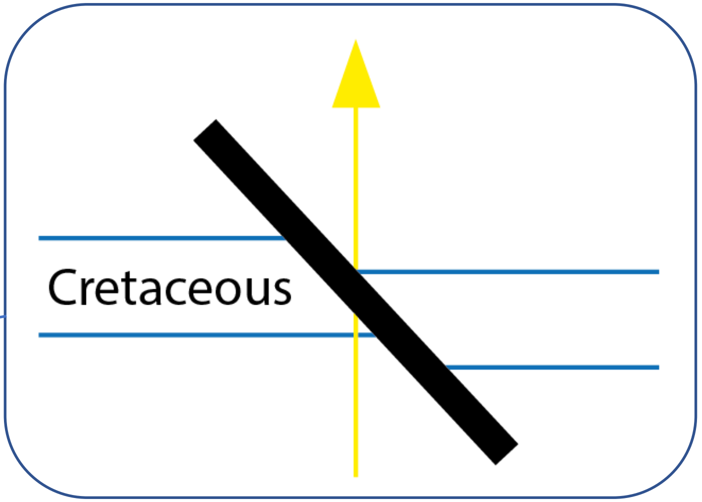
5 m "damage zone" at
seismic throw of c. 25 m





Ogilvie et al. (2015)

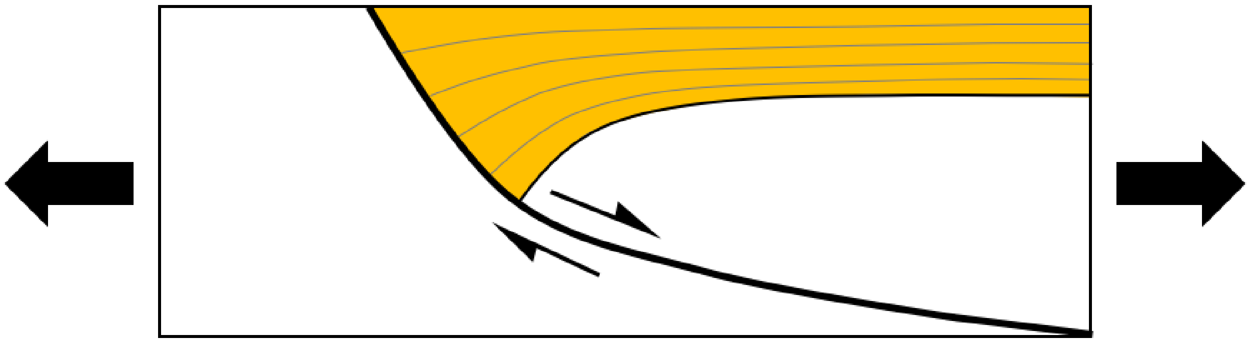
15 m "damage zone"

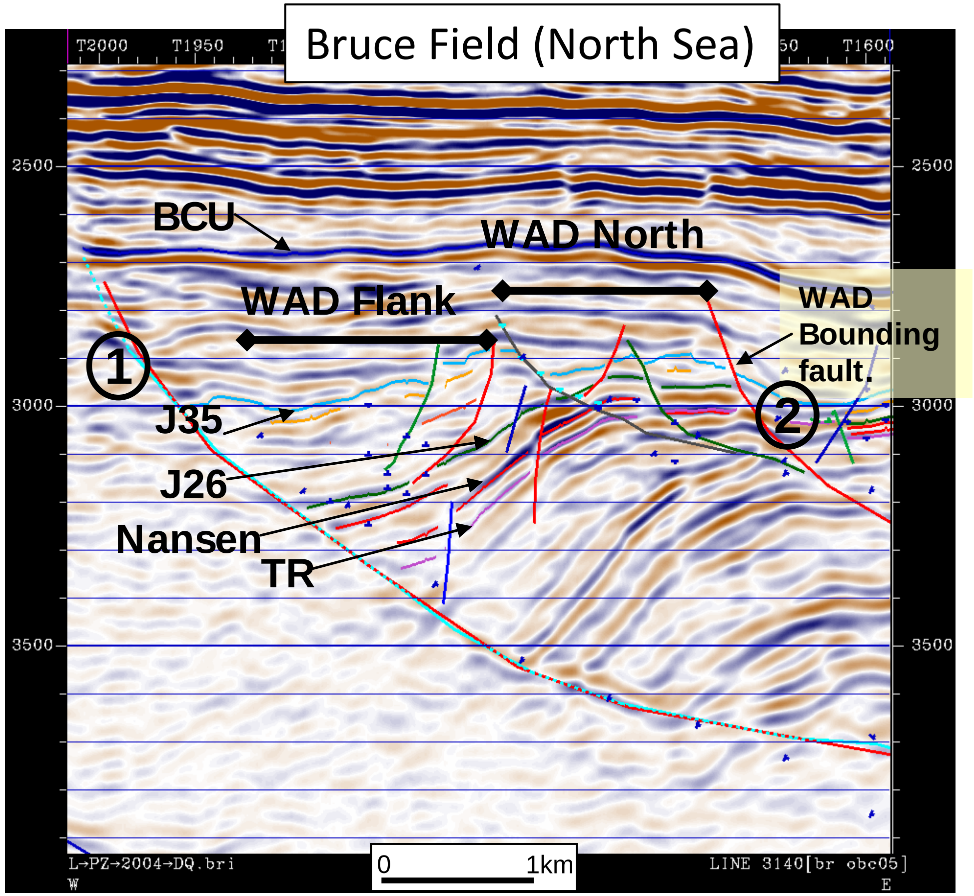


2. Restoration

2.1 Construct Fault at Depth

Rollover anticlines are a common type of folding in extensional basins



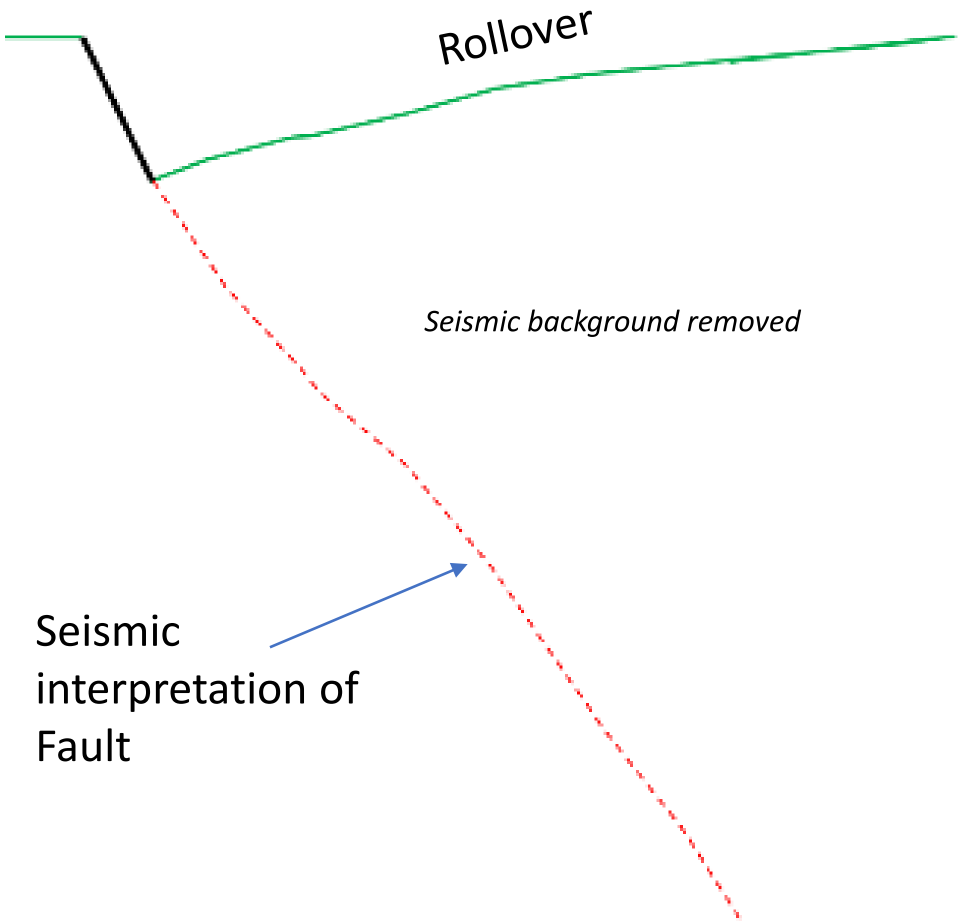


Bruce Field (North Sea)

EAGE presentation
Ogilvie et al. (2007)

2.1 Construct Fault at Depth

Issue: Given poor quality seismic, how do the faults extend/look with depth ?

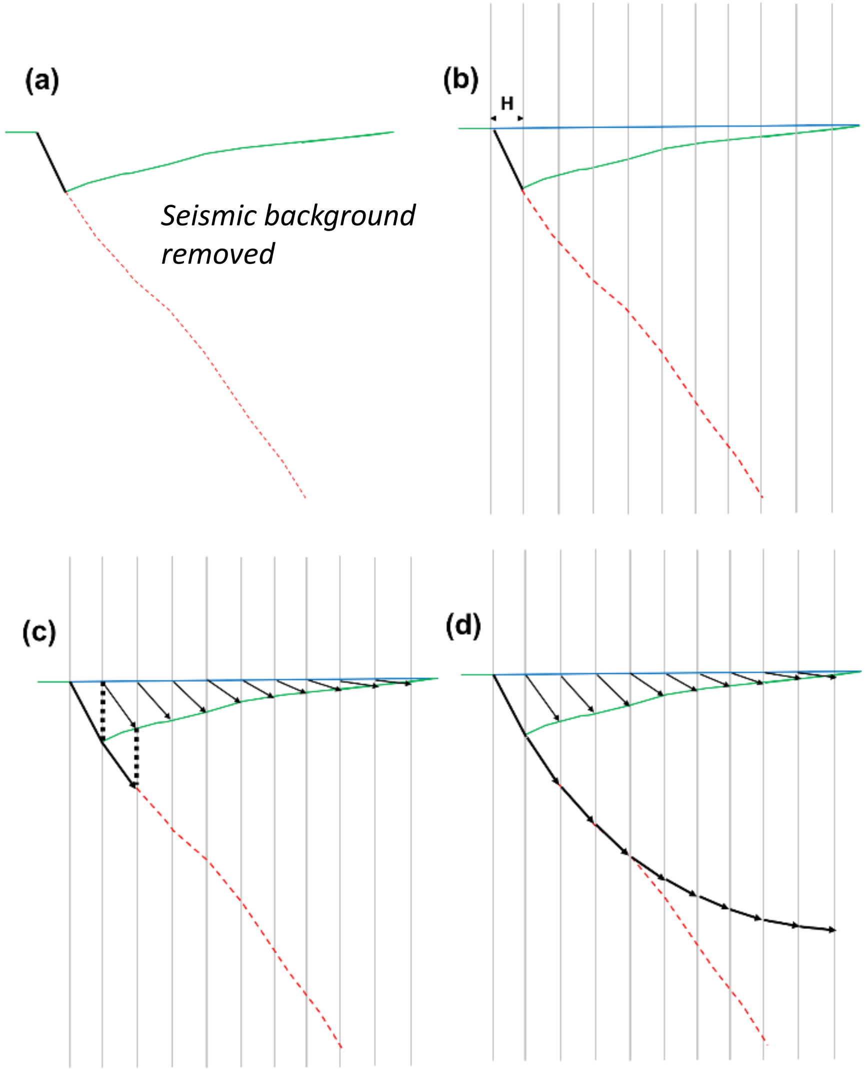


2.1 Construct Fault at Depth

Workflow: As the shape of the fault is related to the shape of rollover

- Can construct the fault at depth - using a **Chevron construction**.
- Do this by hand for a simple **vertical shear** case.

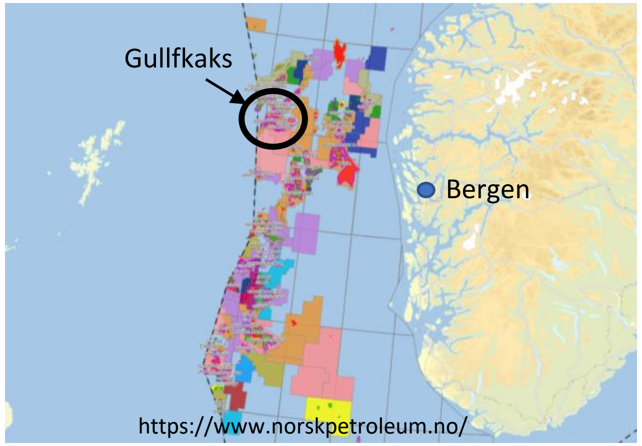
Outcome: structurally more robust interpretation of fault with depth



2.2 Restoration in the North Sea

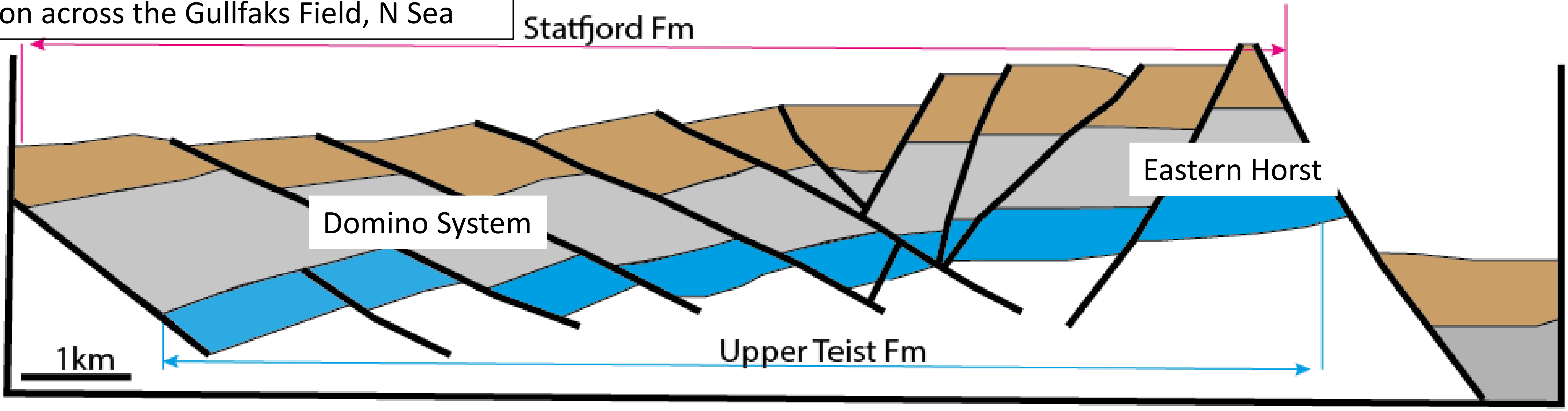
Issue: Validate structural interpretation for a model build

Workflow: Rotate and translate blocks (by hand) – rigid block restoration



https://www.norskpetroleum.no/

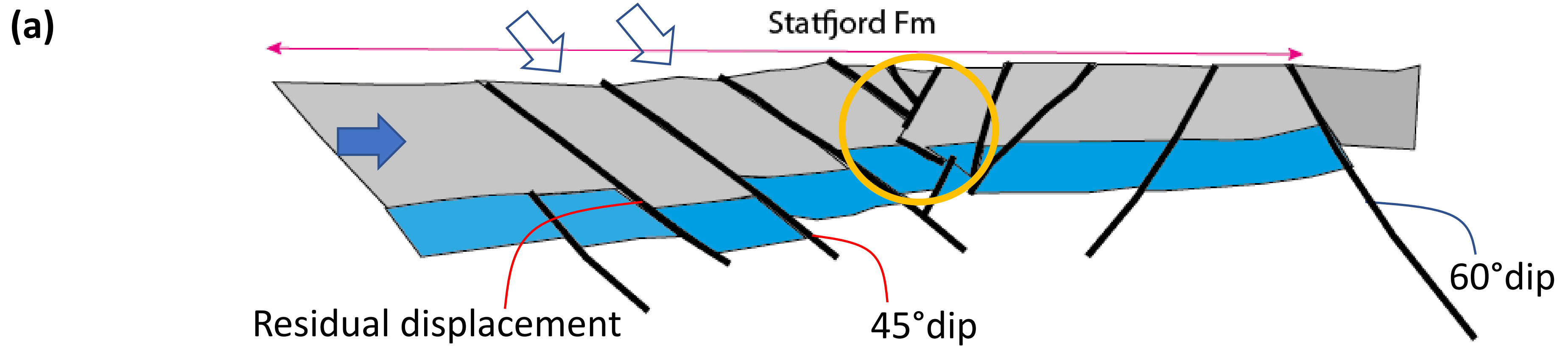
Section across the Gullfaks Field, N Sea



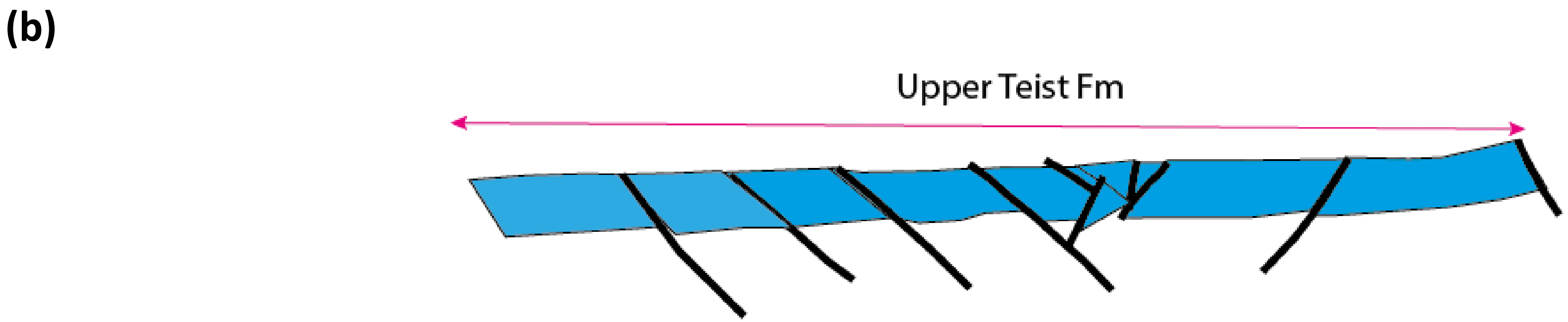
Redrawn from Fossen (2016)

2.2 Restoration in the North Sea

Outcome: We can quickly arrive at a number of observations. Rigid body rotation not suitable here as there is evidence of ductile deformation (a chevron reconstruction required ?)



- Pre-Statfjord faulting
- Thickening of grey unit
- Bumpy surfaces
- 45° fault dip
- Messy, reverse faults

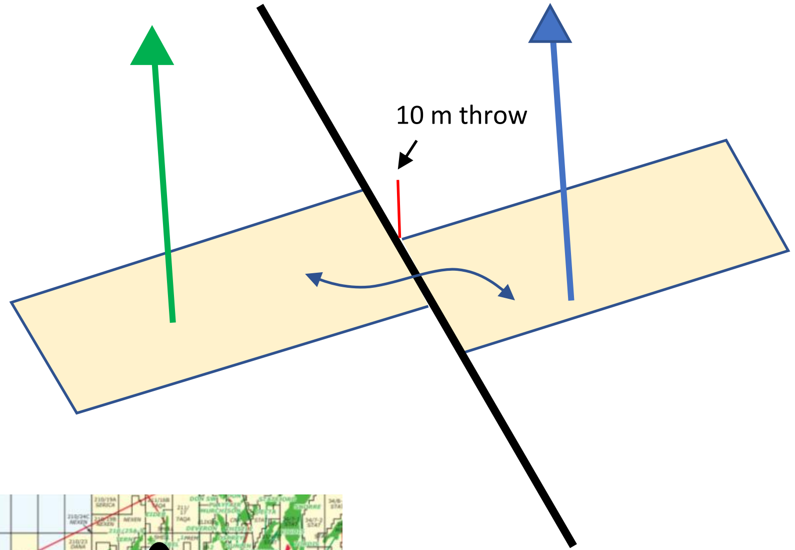


- Cannot restore to perfectly horizontal

3. Fault Seal

3.1 Fault Seal

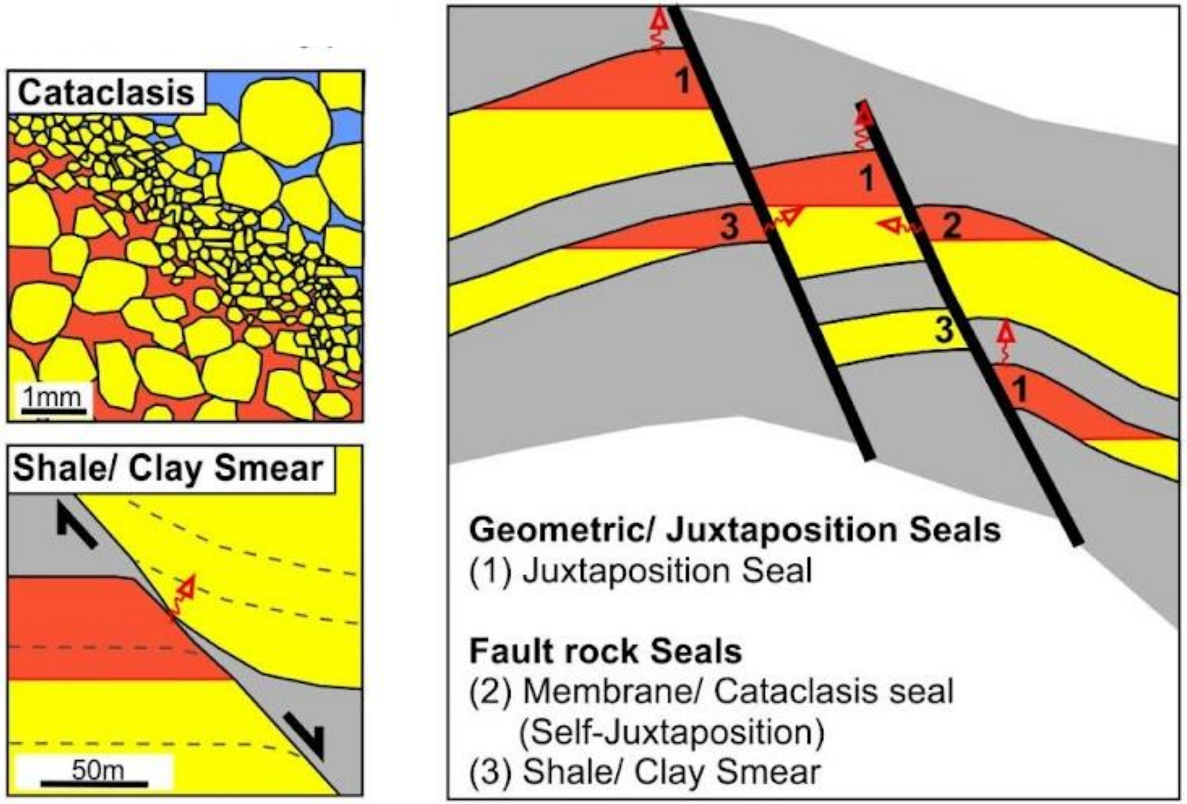
Issue: Faults are commonly permeability barriers during field development.



Cormorant Field type issues

Stiles & McKee (1986)

Juxtaposition vs. Process Seal



Ogilvie et al. (2020)

3.1 Fault Seal

How do we assess their impact in sandstones ?
Minimum size of fault we need to handle ?

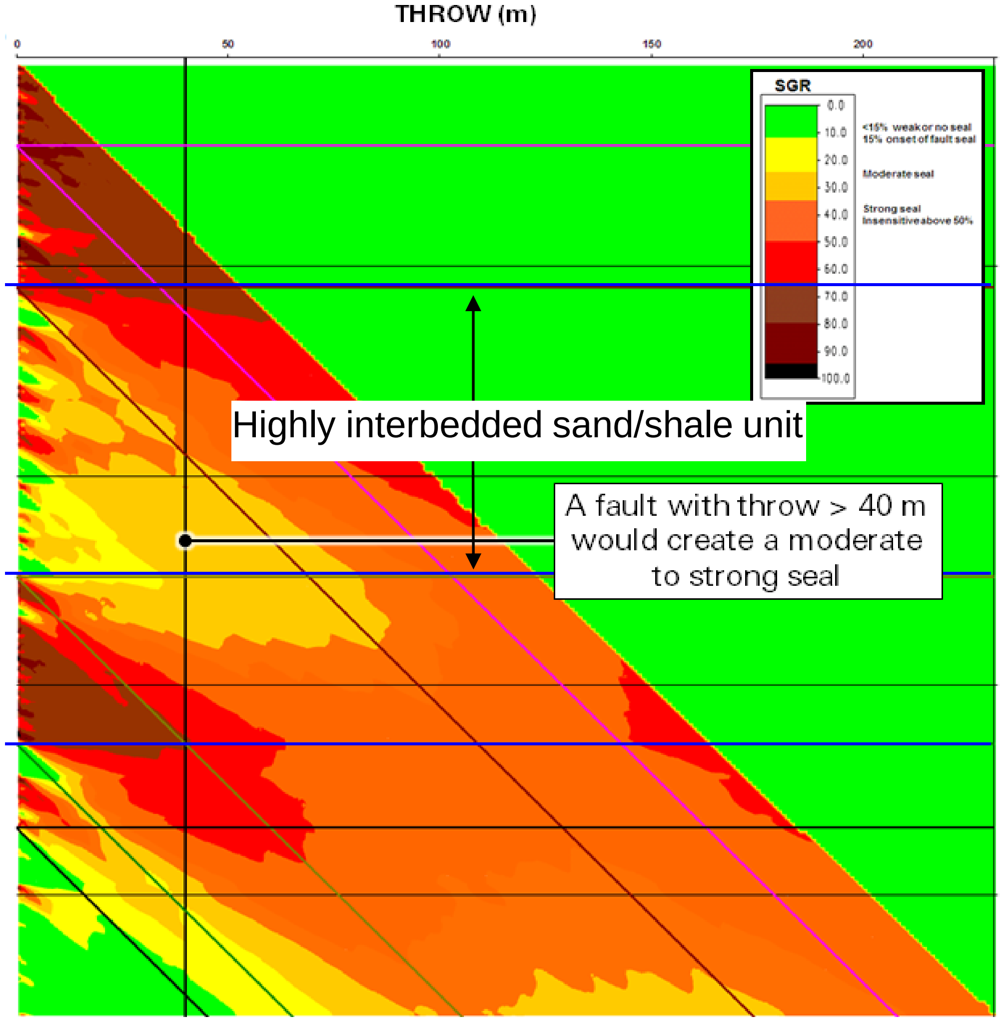
Workflows most advanced in clay – rich sandstones, less so in clean sandstones and carbonates

- Allan diagrams for what’s juxtaposed across an interpreted fault
- Juxtaposition diagram
- Fault geometry
- Geo-history

3.1 Fault Seal – Juxtaposition diagram

Outcome

- Juxtaposition diagram (Knipe, 1997) is a rapid way of telling us which size of fault matters
- In this example, a fault with throw > 40 m would create a moderate – strong seal



Highly interbedded sand/shale unit

A fault with throw > 40 m would create a moderate to strong seal

From Ogilvie (2019) FORCE presentation, Stavanger.

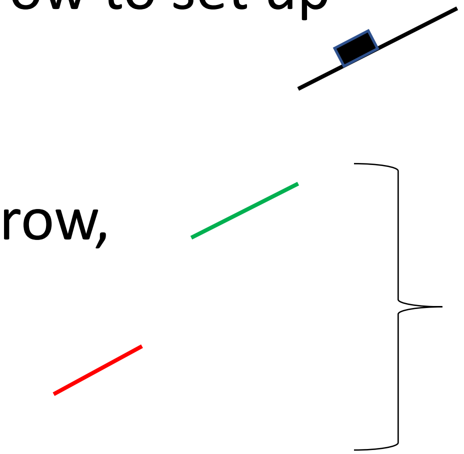
3.1 Fault Seal – Juxtaposition diagram

Our structural framework has

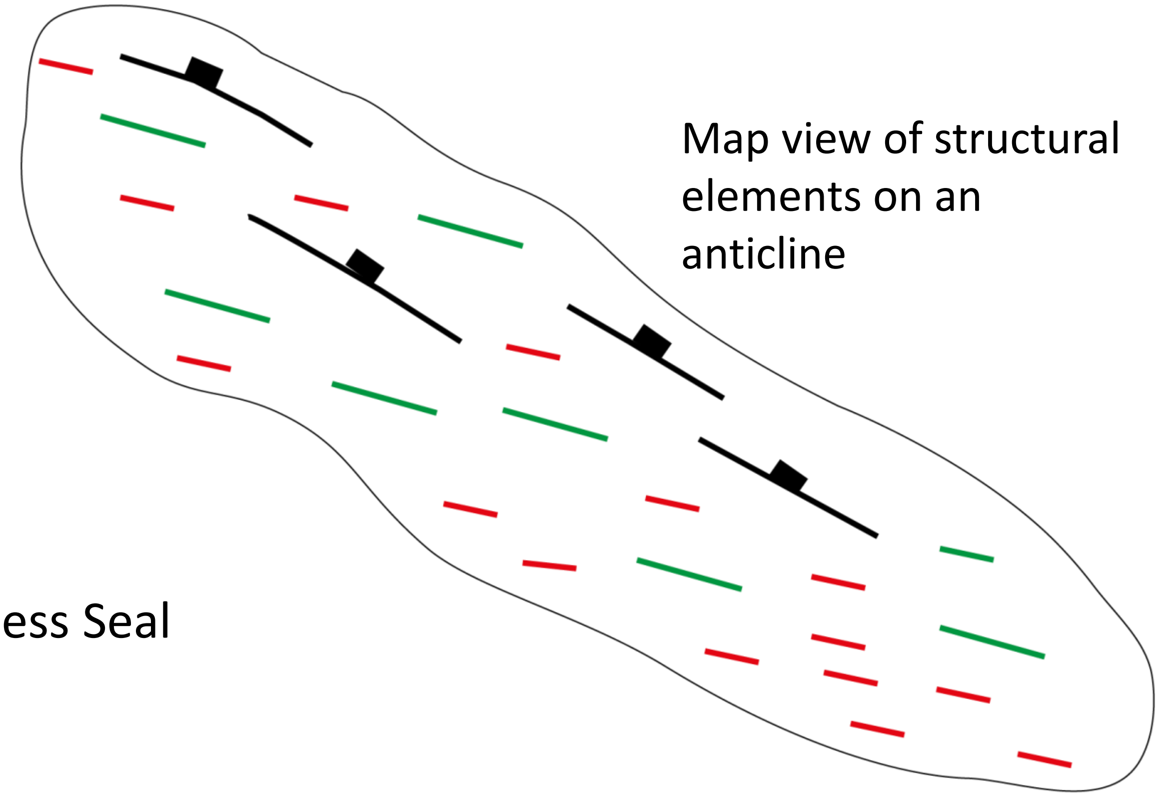
(i) faults with sufficient throw to set up juxtaposition seal,

(ii) faults with > 40 - 60 m throw,

(iii) faults with < 40 m throw



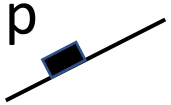
Process Seal



Map view of structural elements on an anticline

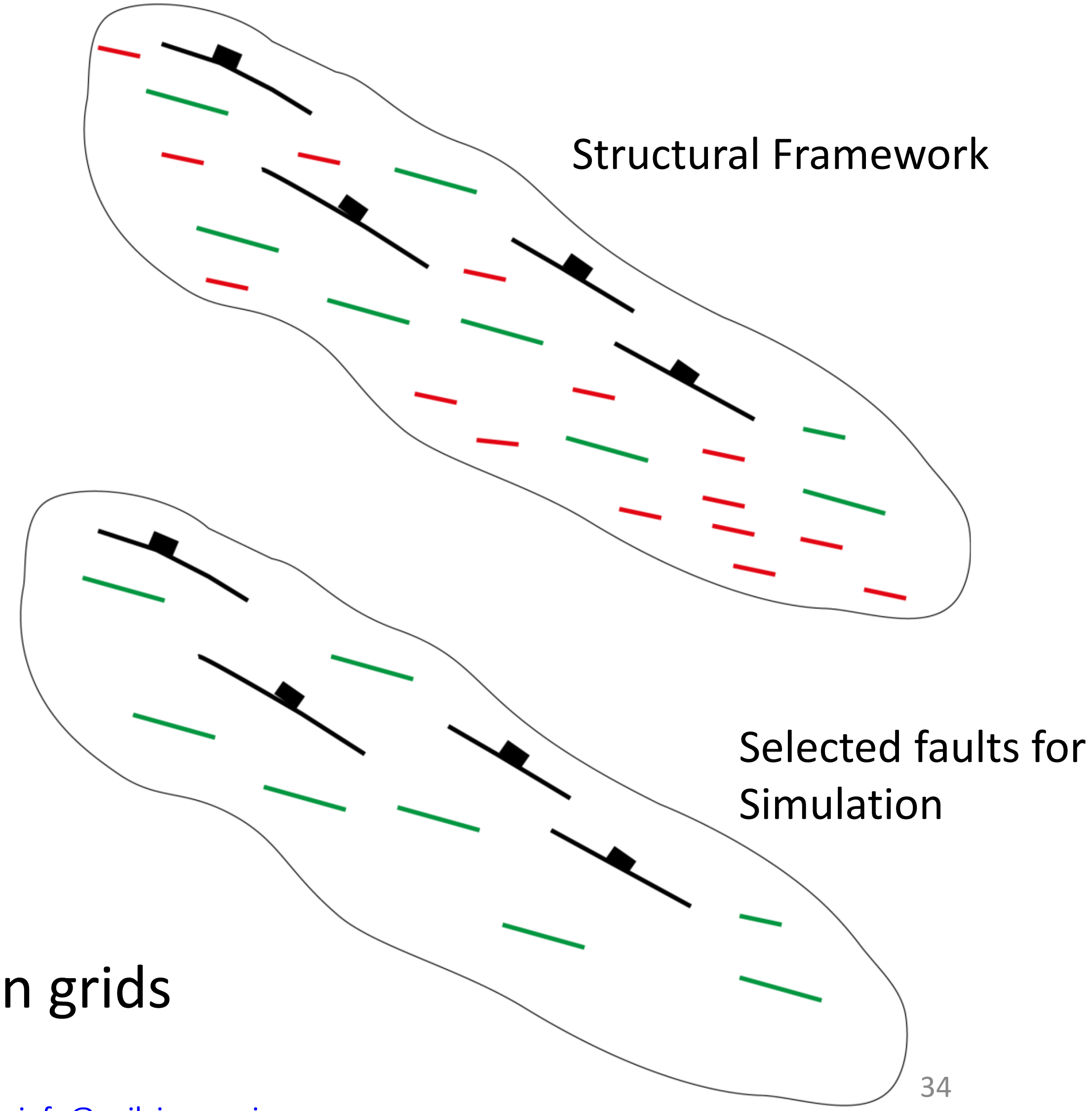
3.1 Fault Seal – Effective Framework

For initial simulation, we keep..

(i) Faults with sufficient throw to set up juxtaposition seal 

(ii) Faults with throw 40 – 60 m 

- We leave out (but may need later) those < 40 m throw 

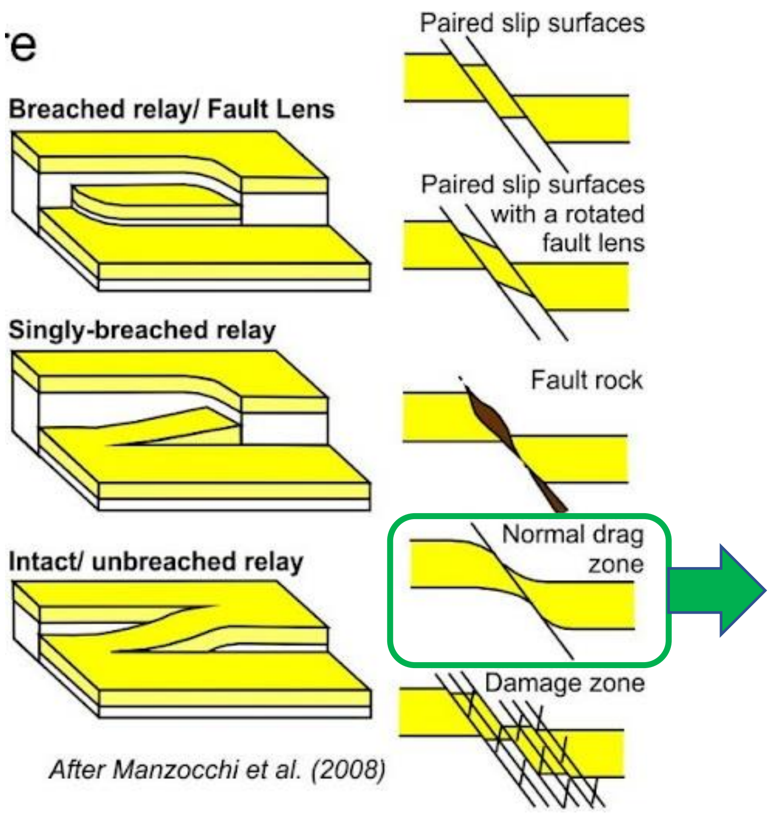

Structural Framework

Selected faults for Simulation

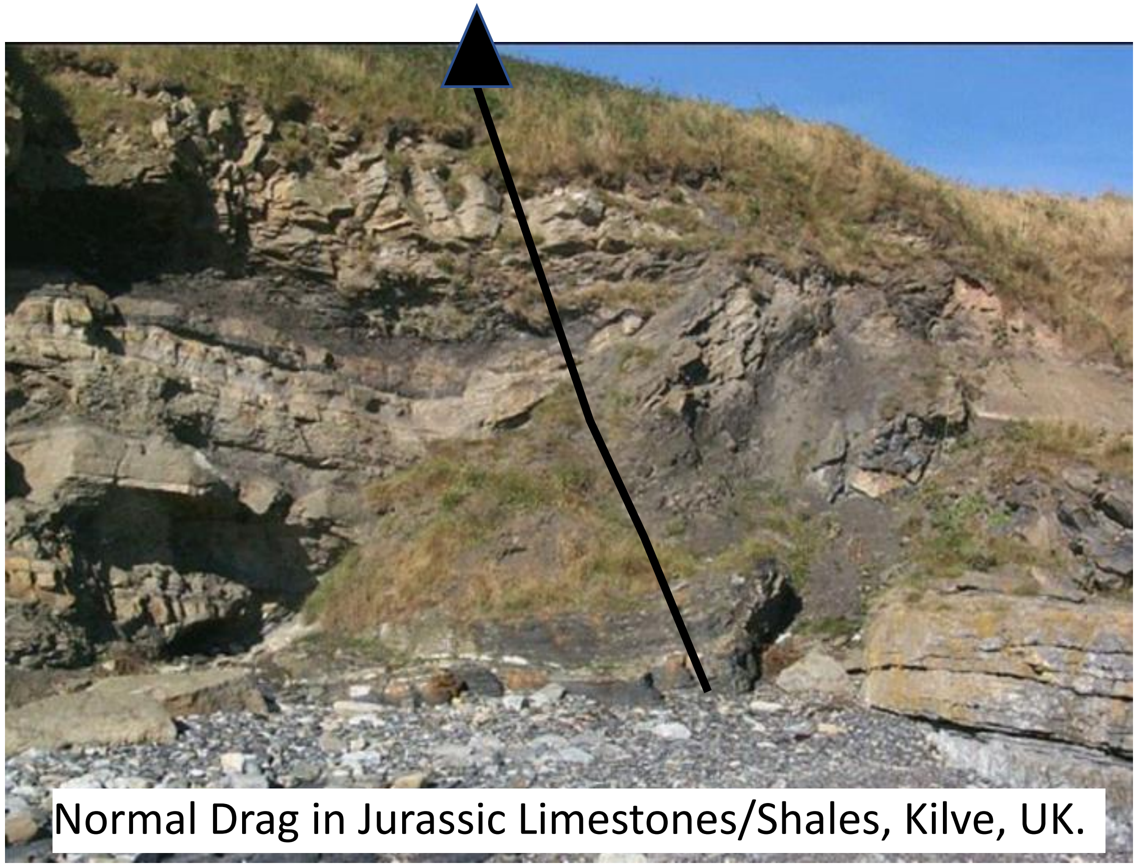
Use to support throw criteria for inclusion of faults in grids

3.2 Fault Drag

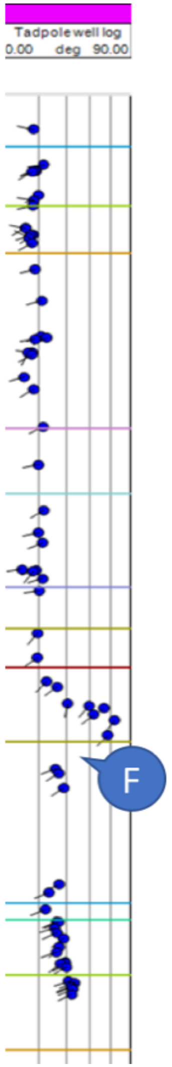
- Soft rocks develop more drag than stiff rocks.
- Distinctive pattern of bedding dip on image log interpretations



After Manzocchi et al. (2008)



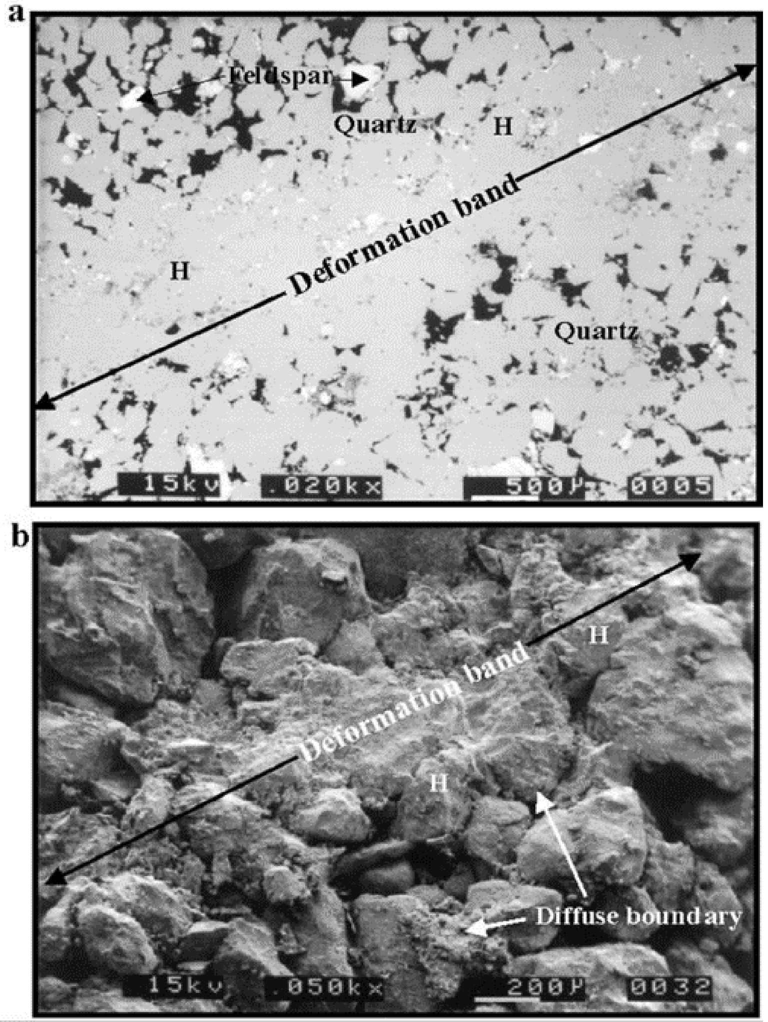
Normal Drag in Jurassic Limestones/Shales, Kilve, UK.



3.3 Low clay content

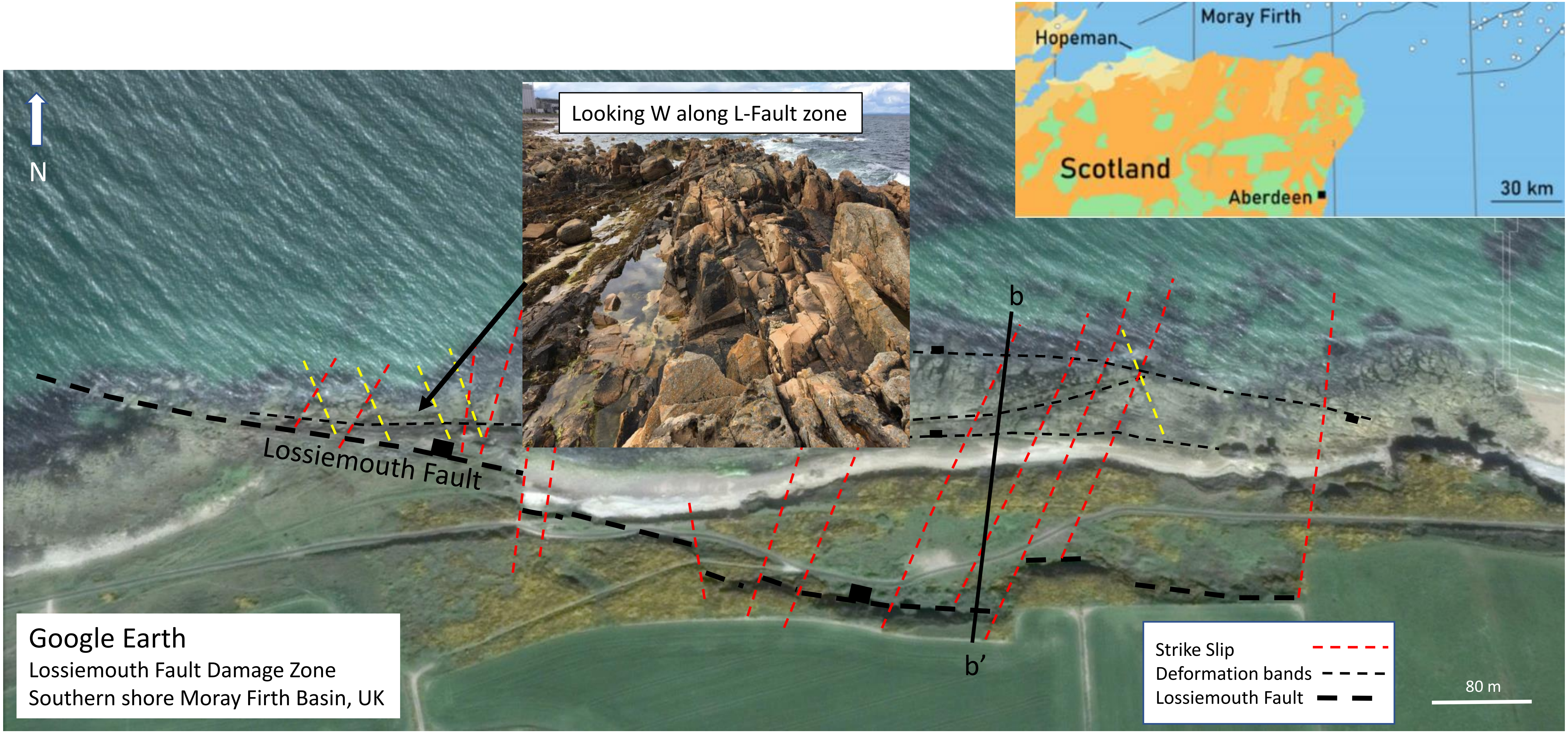
- Cannot use clay-based algorithms
- Understand geo-history - burial depth at time of faulting e.g., Deformation bands in S North Sea created at > 3 km burial depths – mechanical reduction in grain size creates large reductions in por/perm.
- Also form at shallow burial - some Gulf of Mexico Fields have large reductions in permeability – related to preferential crushing of weak lithic fragments etc ?


Rotliegende Sst, Southern N Sea



Hopeman Sandstone (age equivalent)

3.3 Hopeman Sandstone, Inner Moray Firth

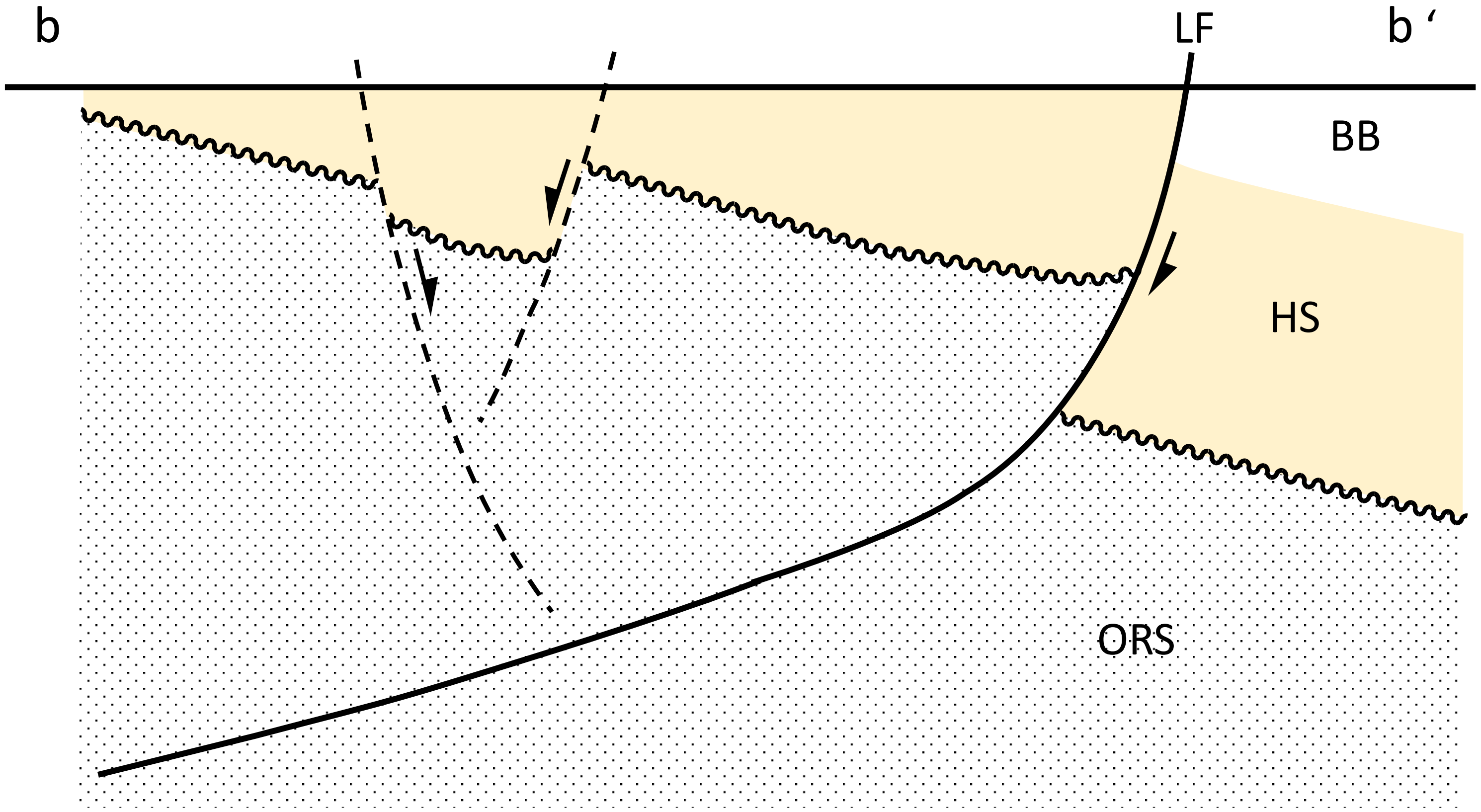


Looking W along L-Fault zone

Google Earth
Lossiemouth Fault Damage Zone
Southern shore Moray Firth Basin, UK

Strike Slip - - - -
Deformation bands - - - -
Lossiemouth Fault ▬ ▬

3.3 Hopeman Sandstone, Inner Moray Firth



BB : Burghead Beds

HS : Hopeman Sandstone

ORS : Old Red sandstone

LF : Lossiemouth Fault

3.3 Hopeman Sandstone, Inner Moray Firth

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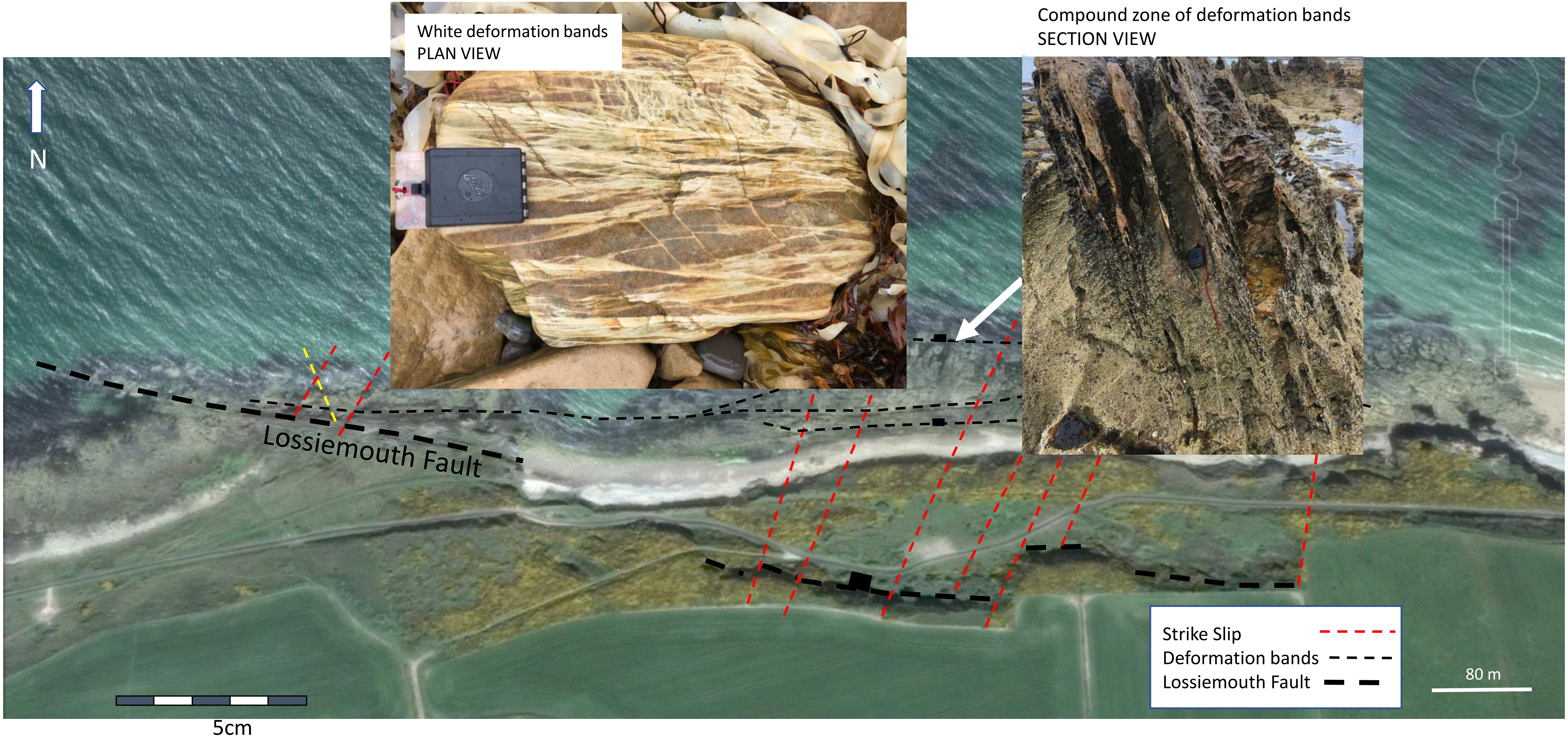


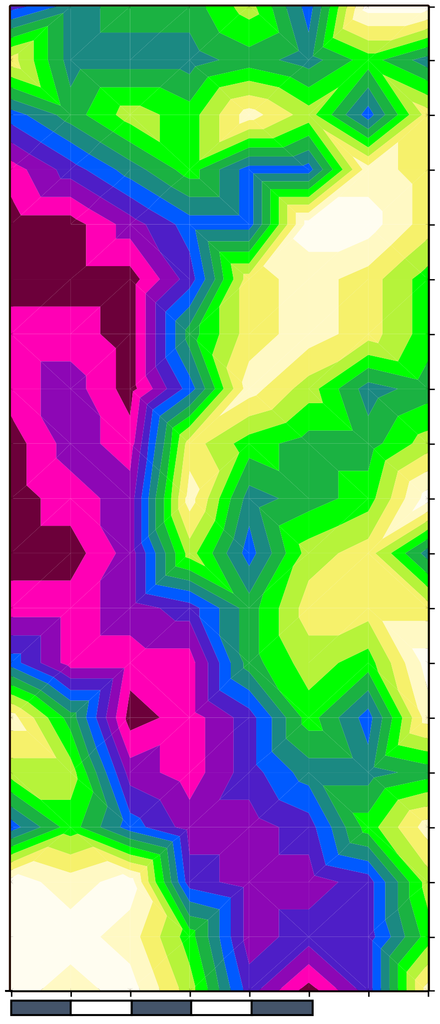
White deformation bands
PLAN VIEW

Compound zone of deformation bands
SECTION VIEW

Strike Slip - - - -
Deformation bands - - - -
Lossiemouth Fault ▬ ▬

3.3 Hopeman Sandstone, Inner Moray Firth

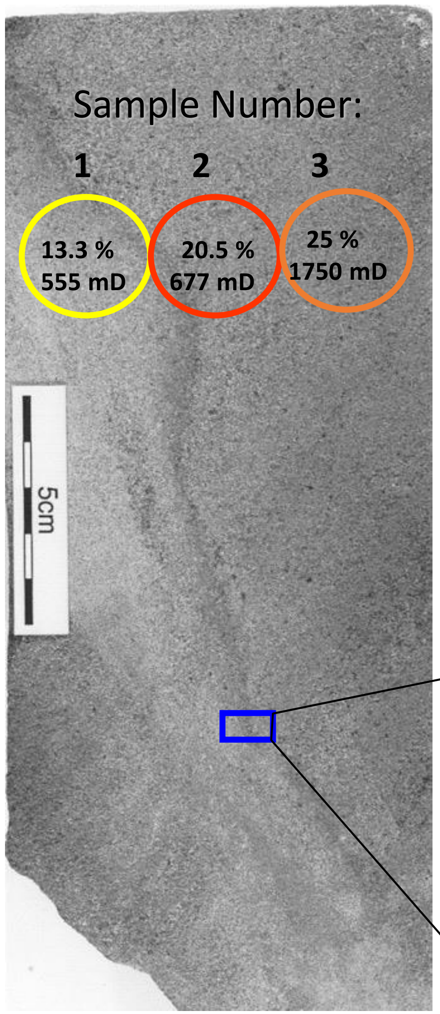
Gas Permeability image



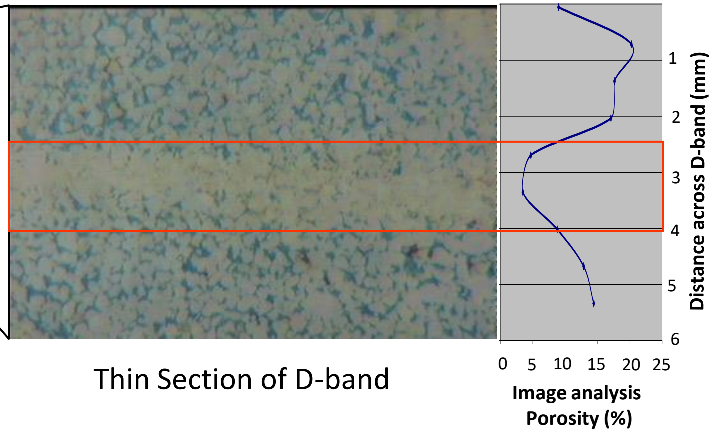
Legend (mD)

🟫	0.0034	to	2.35
🟪	2.35	to	29.6
🟪	29.6	to	192
🟦	192	to	397
🟦	397	to	682
🟩	682	to	785
🟩	785	to	899
🟩	899	to	1090
🟨	1090	to	1220
🟨	1220	to	1420
⬜	1420	to	1850
⬜	1850	to	3080

Core image



- Significant reduction in petrophysical properties

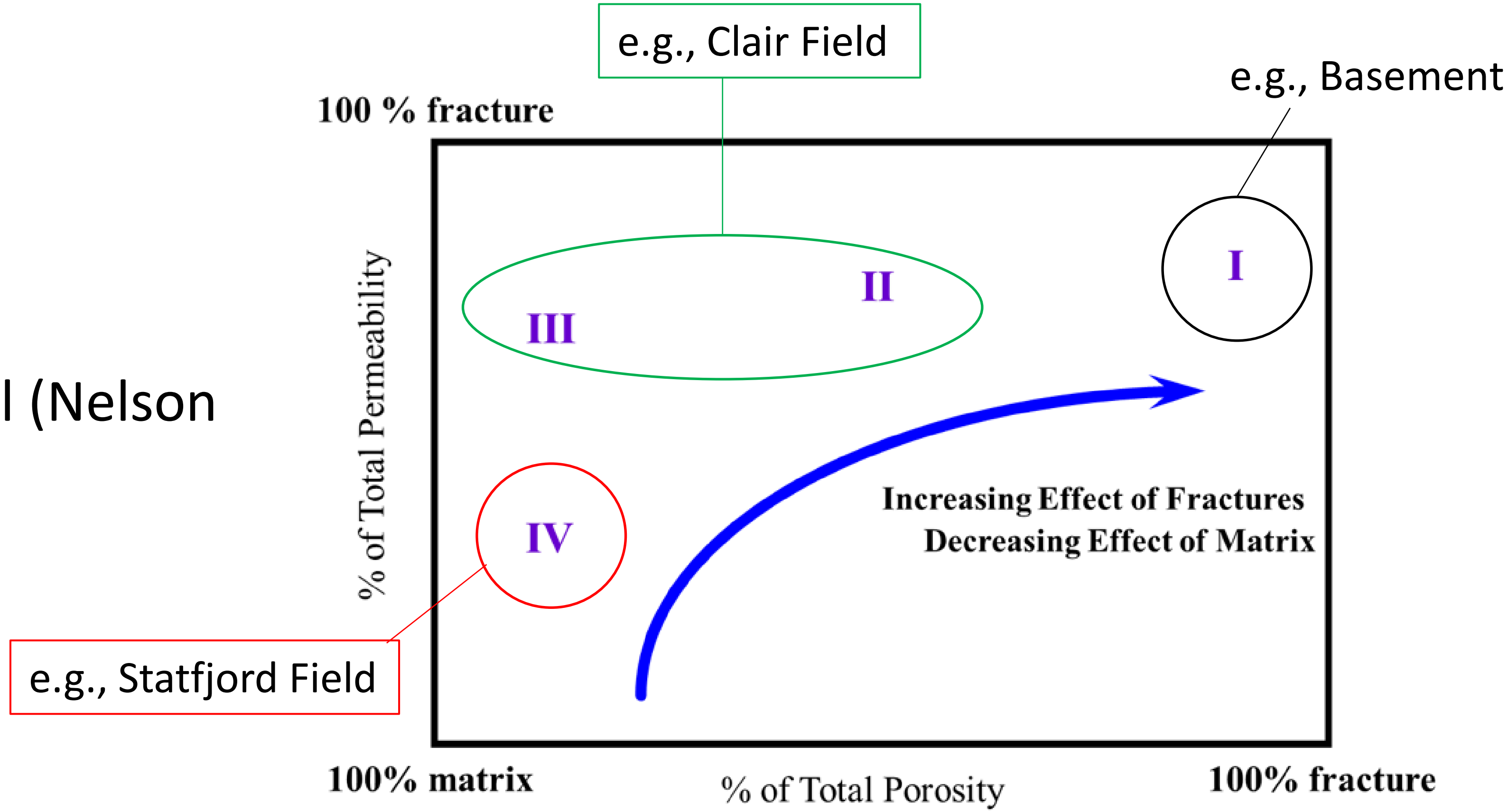


Thin Section of D-band

4. Fractured Reservoirs

4.1 Fractured Reservoir

- Naturally fractured reservoirs
- Permeability assist or essential (Nelson classification)
- Knowing which type is key to development strategy



4.1 Fractured Reservoir

- Below seismic resolution – joints and shear fractures
- Large uncertainty from whereabouts to dynamic performance
- Larger engineering/geomechanics element to their characterisation than in fault seal studies.

Jointed flagstones, Caithness, Scotland

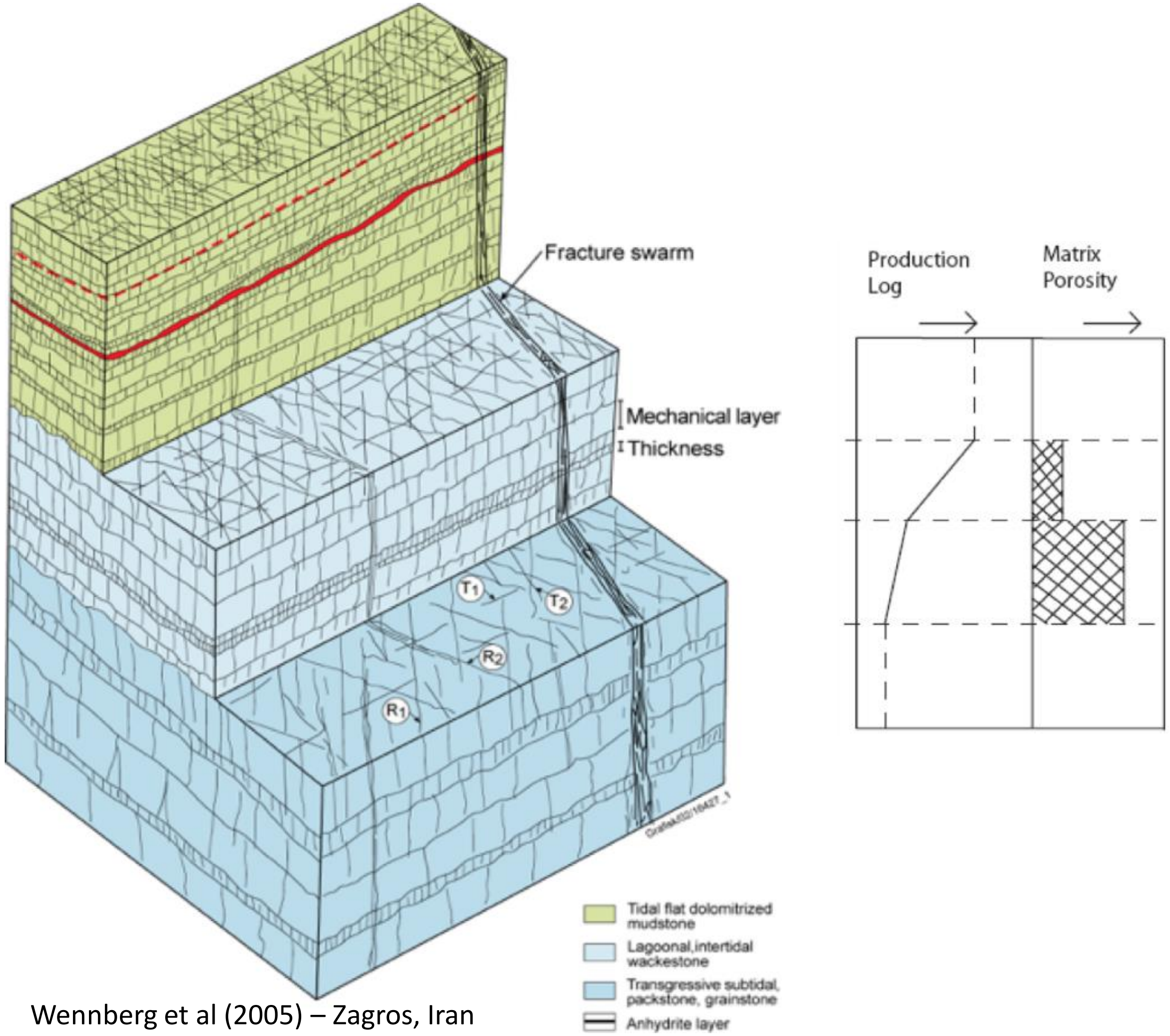
4.1 Fractured Reservoir

Diffuse Fractures

Joints in Limestone, Kilve Pill, Somerset (Map view)

Swarms

Fractured Dolomites, Marsden Bay, NE England (Cliff view)



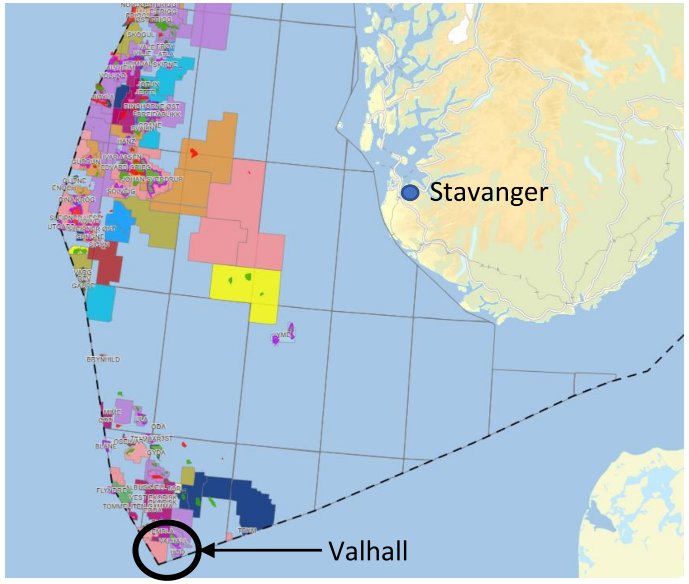
Wennberg et al (2005) – Zagros, Iran

4.2 Appraisal Case

Workflow: Create appraisal plan for oil bearing, fractured ? Mudstone in shallow section of Valhall Field.

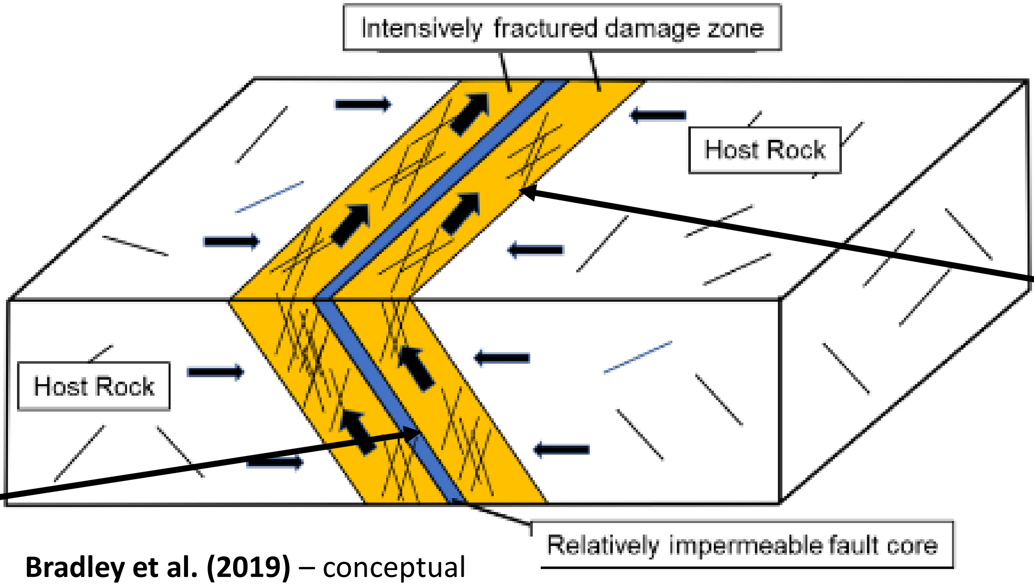
In-situ stress and core/image logs

Outcome: Shear fractures in damage around seismic scale faults.



https://www.norskpetroleum.no/

19 m Fault Core Zone



Bradley et al. (2019) – conceptual model modified from Johri et al (2014)

8 m Damage Zone

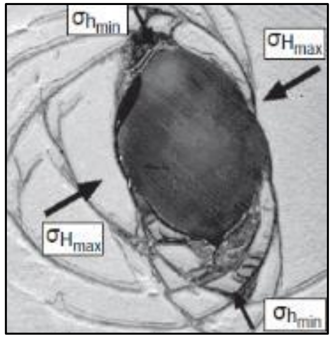
Slickenlined Shear Fractures in intact core

Extends below cored section (image log)

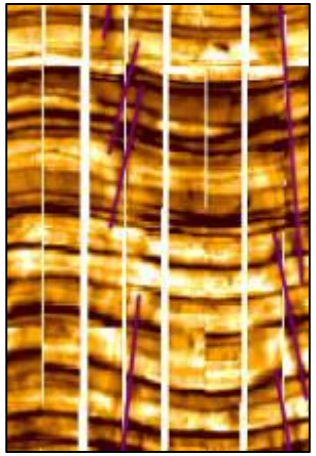
4.2 Appraisal Case

- But we don't know much about their flow potential !
- In-situ stress data allows us to display conductive orientation

Breakouts

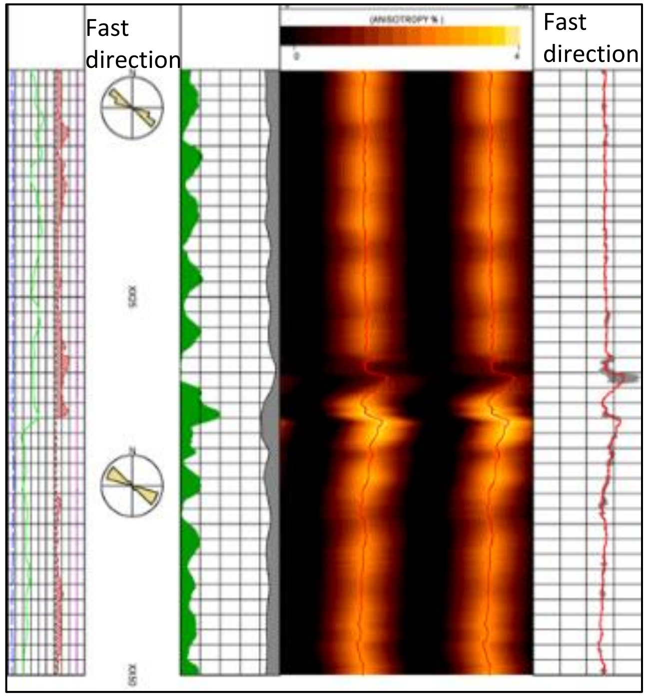


Holford & Tassone (2015)

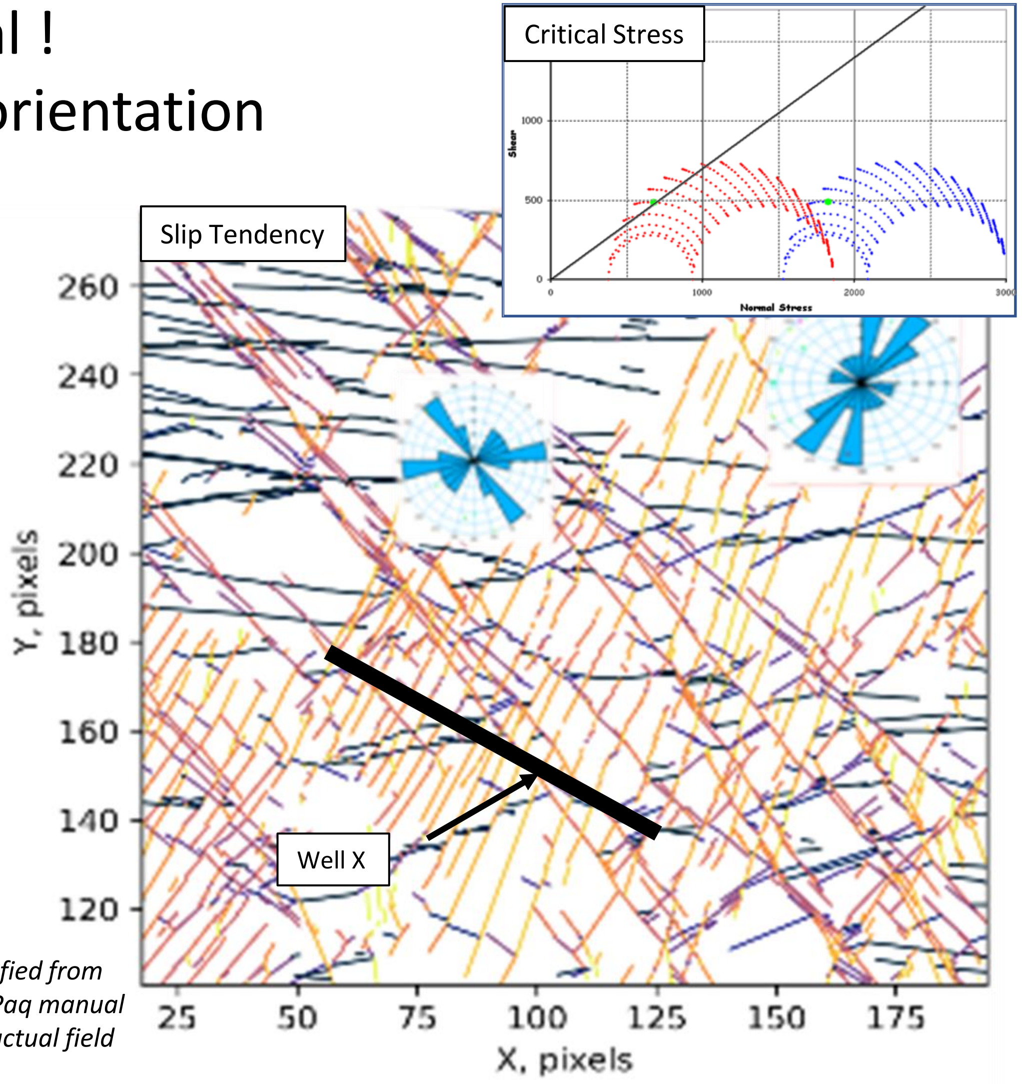


Drilling induced tensional fractures

Log data – Dipole Sonic



Bradley et al. (2019)

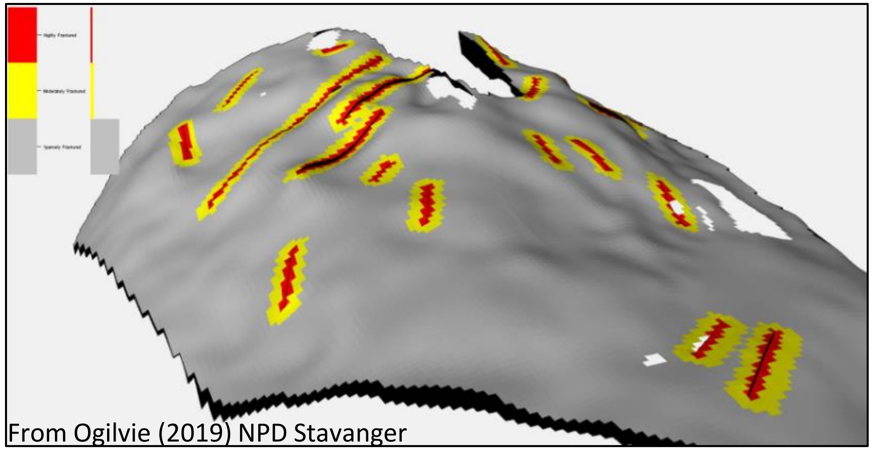


Modified from FracPaq manual Not actual field data

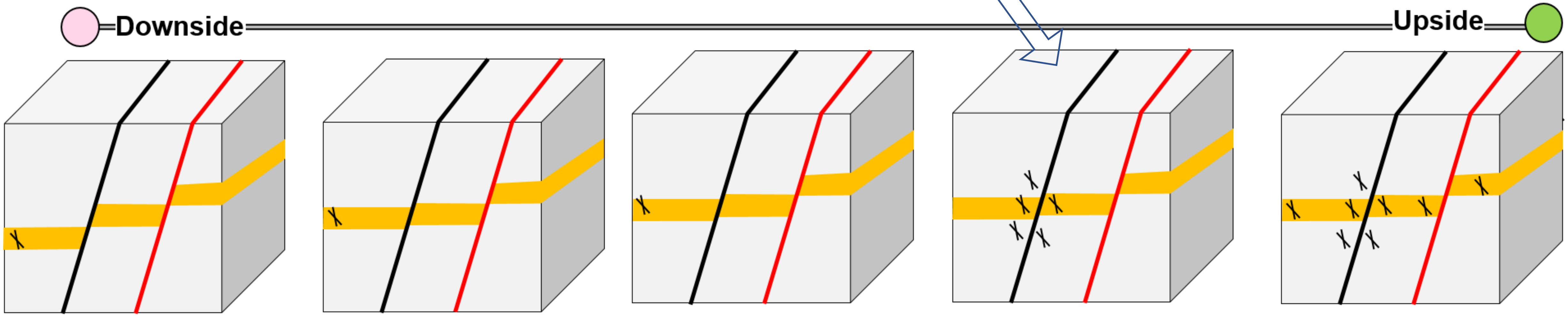
4.2 Appraisal Case

- This is a likely scenario for appraise value case
- Carry a range of reservoir descriptions for appraise value case

Fractures around seismic scale fault



From Ogilvie (2019) NPD Stavanger



Juxtaposition Seal

Process Seal

Sand on sand

Fractures around fault

Pervasive fracturing

From Ogilvie (2019) NPD Stavanger

5. Conclusions

Examples of where Structural Geology can and has reduced uncertainty and added value to various appraisal and development projects

1. Structural Interpretation

- Guidelines to create/QC a robust structural model for geomodelling, reduce drilling risk.
- Reduce structural uncertainty in steep limb area to reduce uncertainty in reserves, improve well target (reduce risk of encountering poor quality rock)
- Correct standoff of wells to faults to reduce drilling risks, avoid poor quality rock

5. Conclusions – part 2

2. Restoration

- Construct fault with depth to reduce structural uncertainty for geomodelling
- Perform restoration to reduce structural uncertainty for geomodelling
- These can be carried out by general practitioners to provide a structurally valid interpretation

3. Fault Seal

- Faults can be barriers during development. Method shown to sort out what size (throw) matters creates effective fault framework for dynamic simulation
- Workflows relatively well established for sandstone, but not where low clay content and in carbonates.
- Geo-history especially key for clay free sandstones (same sand juxtaposed), illustrated using outcrop example

4. Fractured Reservoir

- Natural fractures can add permeability
- Large uncertainty, particularly in absence of well tests
- Data integration is key !
- Don't dive into DFN models – sketch out concepts, assess probabilities based upon available data – appraisal case study N Sea