Characterization of fault zones

Constraints and challenges to description and modelling

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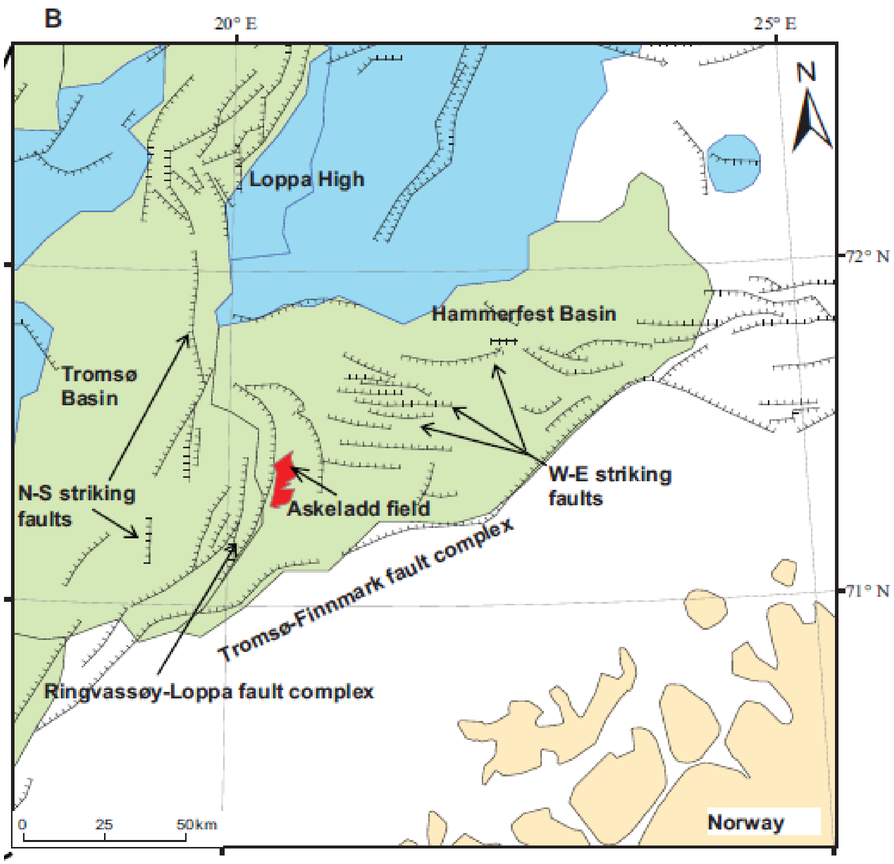
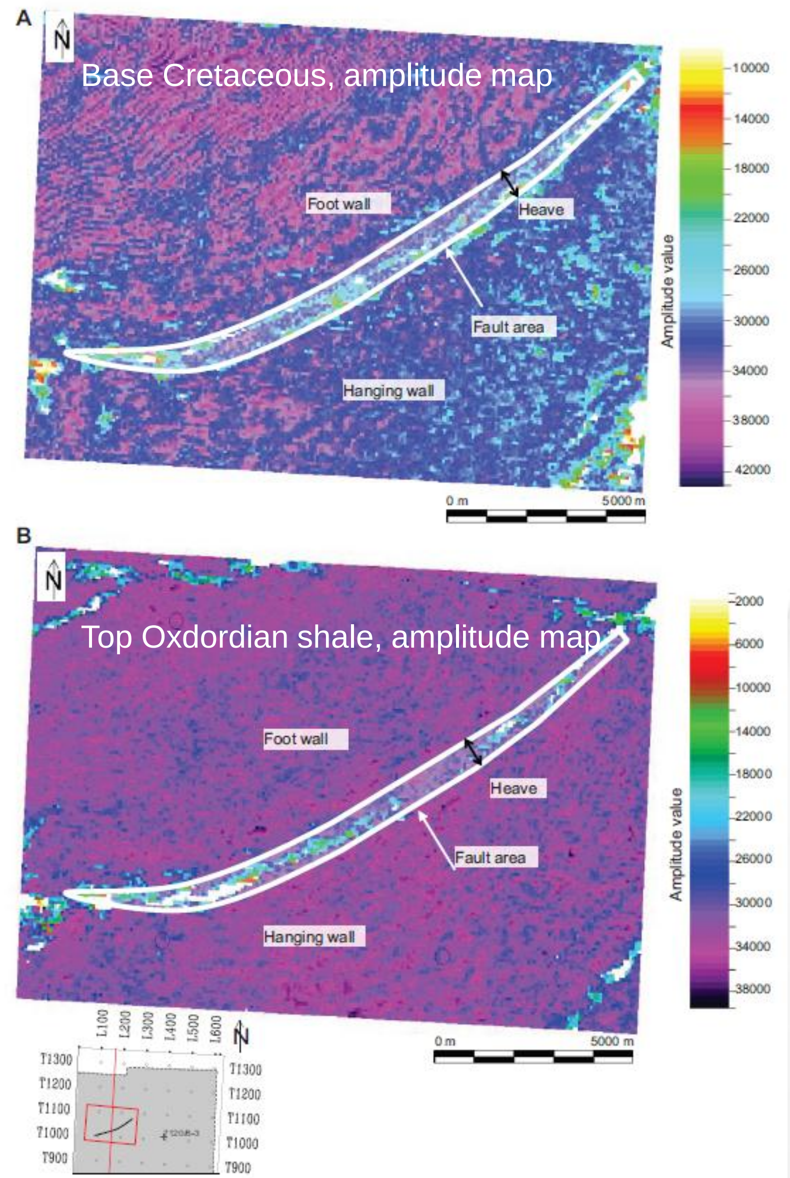
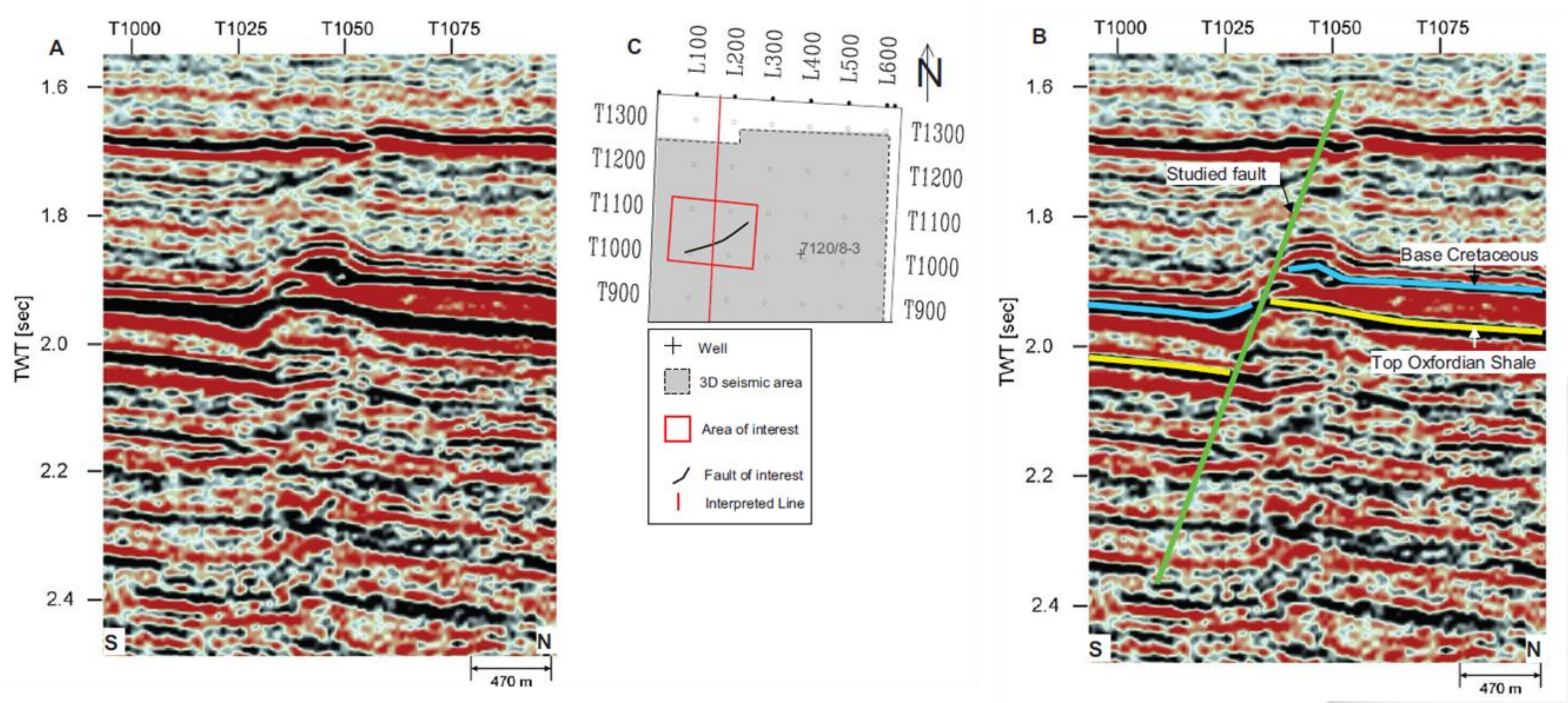
Nicolaisen, (2009). Dataset from Askeladden field.
3D seismic survey from 1983



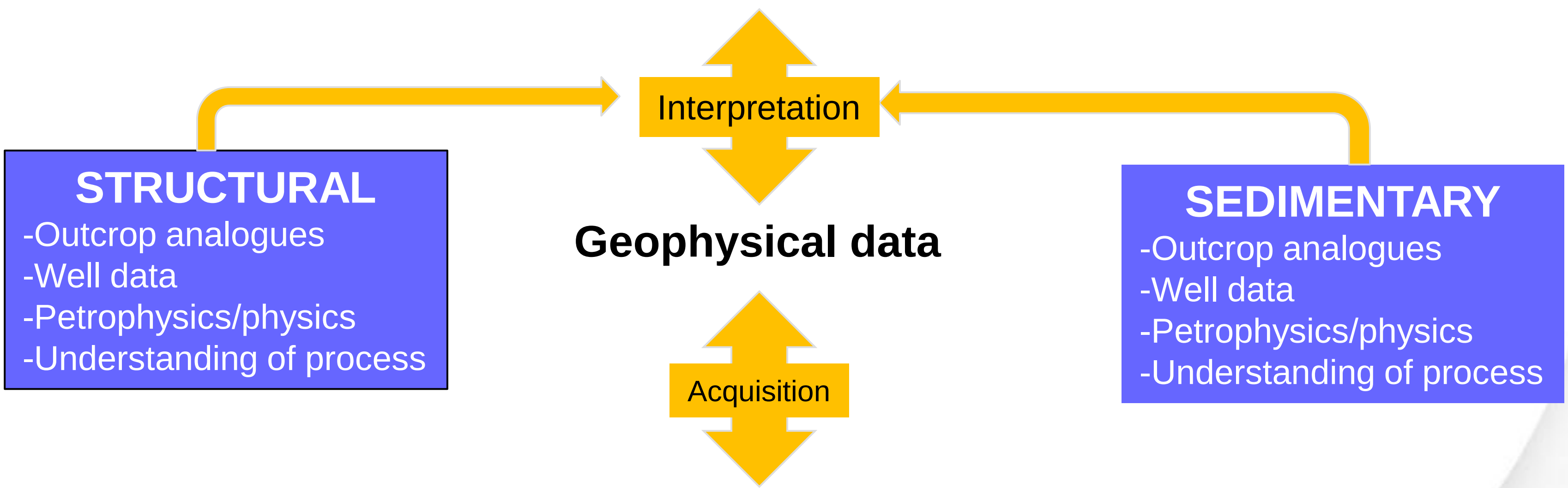




Nicolaisen, (2009)

Context

Rendering of subsurface geology



Subsurface geology

-What is shown in geophysical data-sets reflects actual geology features and properties

-How these data-sets are interpreted is closely related to our understanding of actual geology

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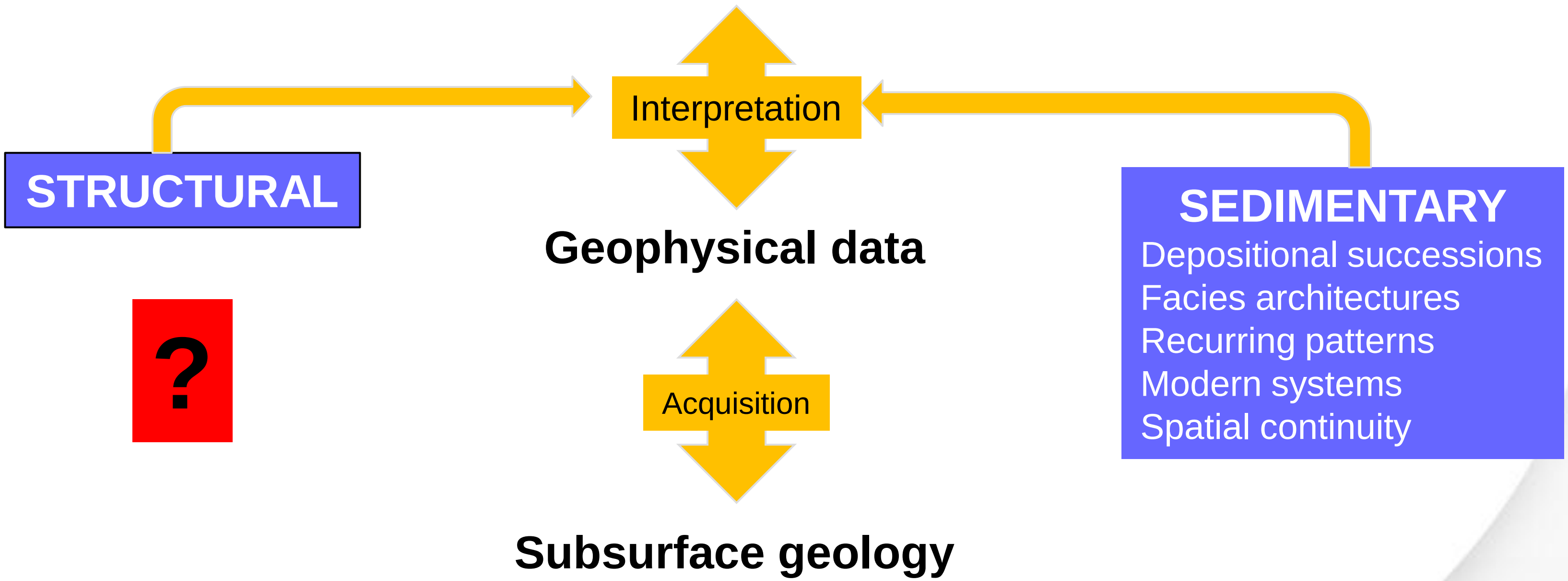
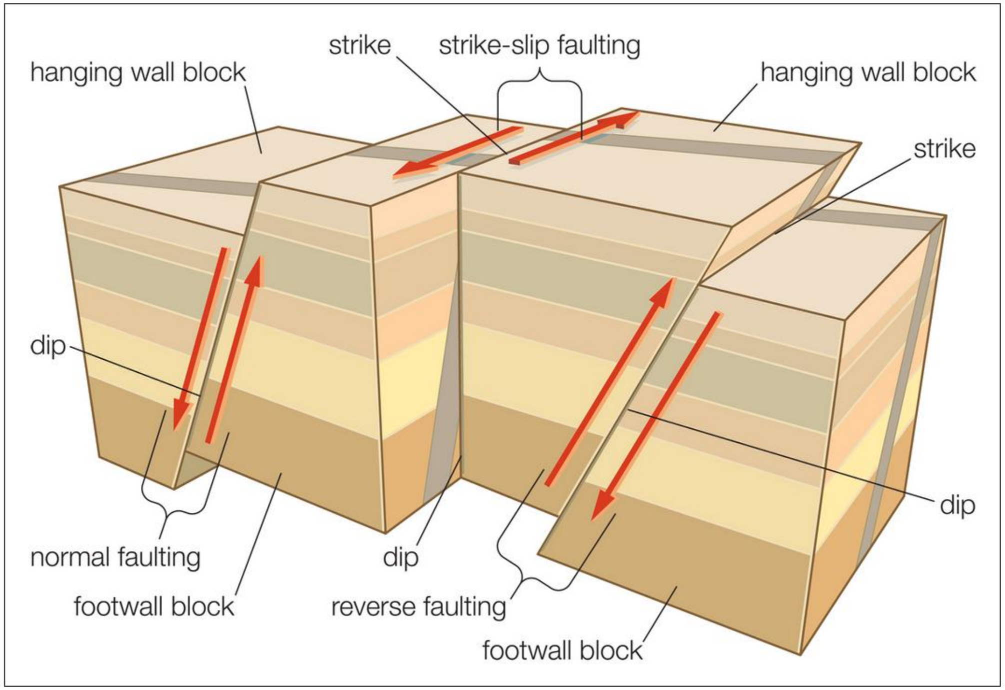
Rendering of subsurface geology



-What do we actually know about structural features and properties?

-Can we describe fault zones in a manner that allows reliable geological understanding to support seismic interpretation of them?

Faults



“A planar or gently curved fracture in the rocks of the Earth’s crust, where compressional or tensional forces cause relative displacement of the rocks on the opposite sides of the fracture”.

Encycl. Britt.

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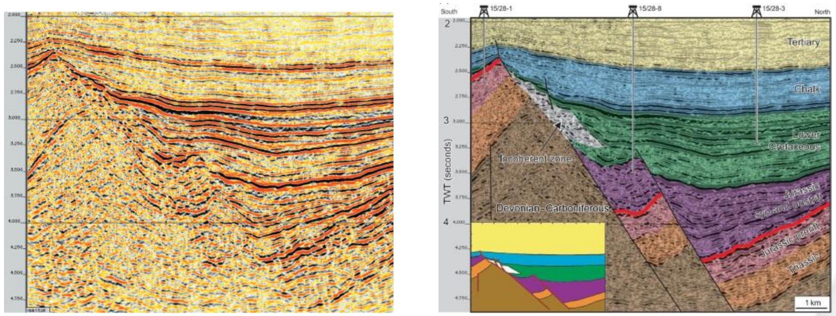
Significance of faults

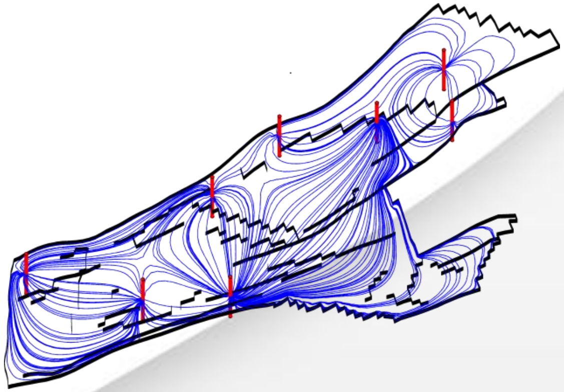
- Geohazards
  - Earthquakes
  - Tsunamis
  - Mass movement
  - Construction

- Deposition
  - Extent
  - Geometry

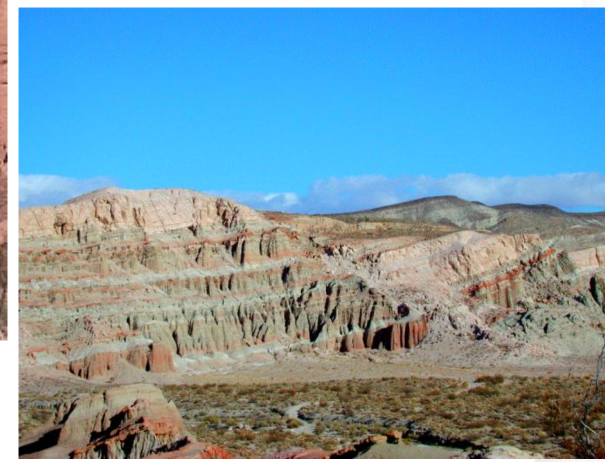
- Subsurface fluid flow
  - Petroleum E & P
  - CO_2 storage
  - Groundwater flow



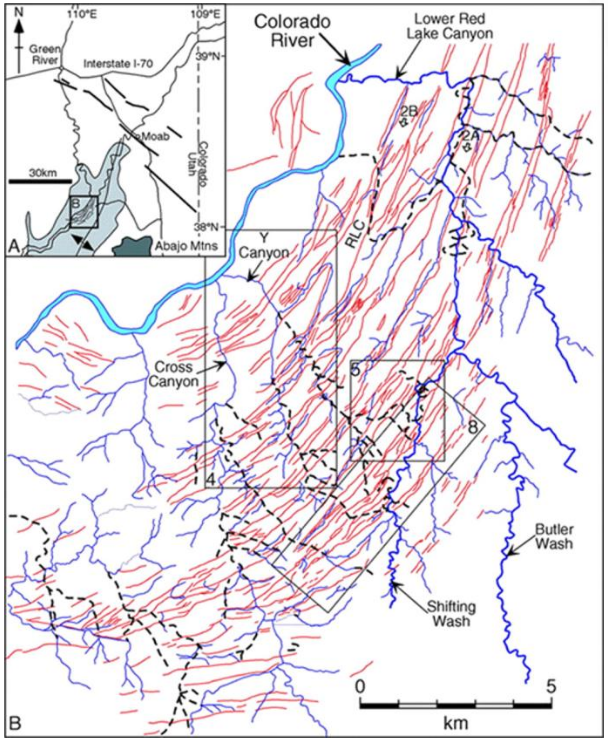
Stewart and Reeds (2003)

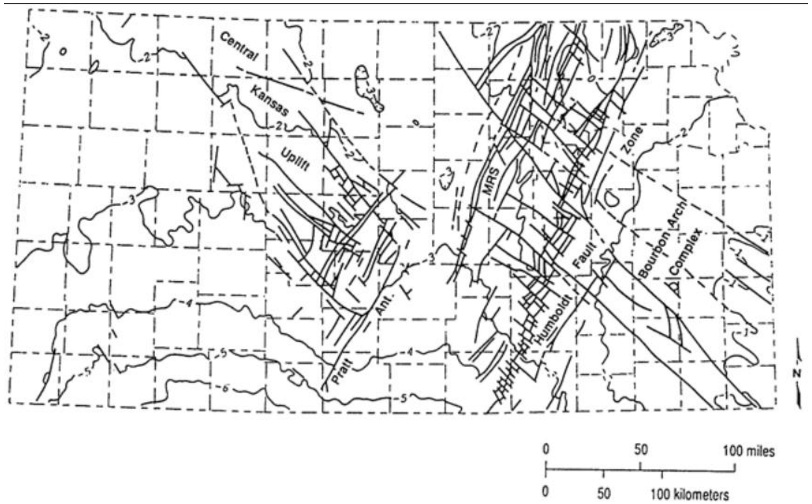


Geometry – Texbook examples



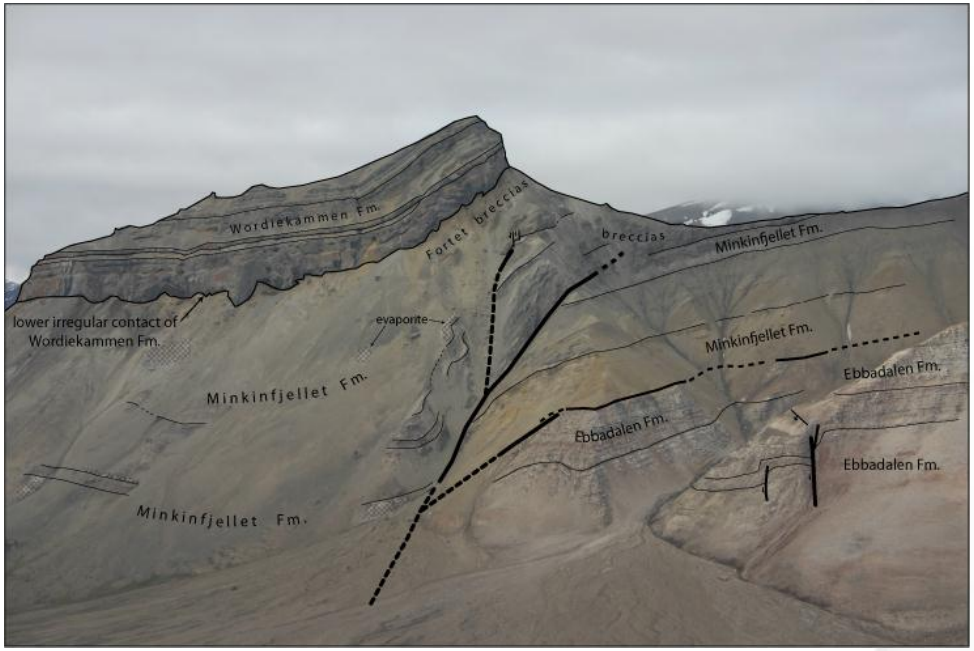
Geometric complexity





Associated geometries

Folding, drag, rotation



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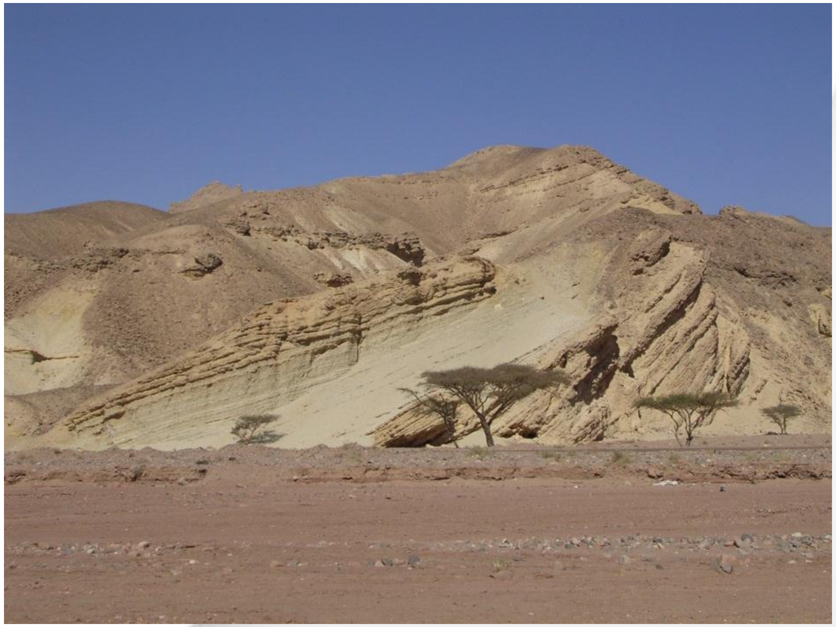
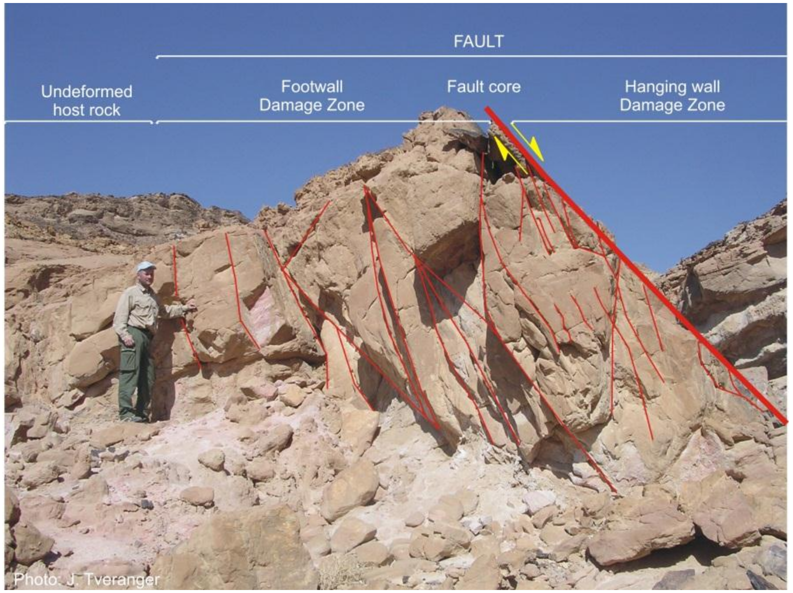
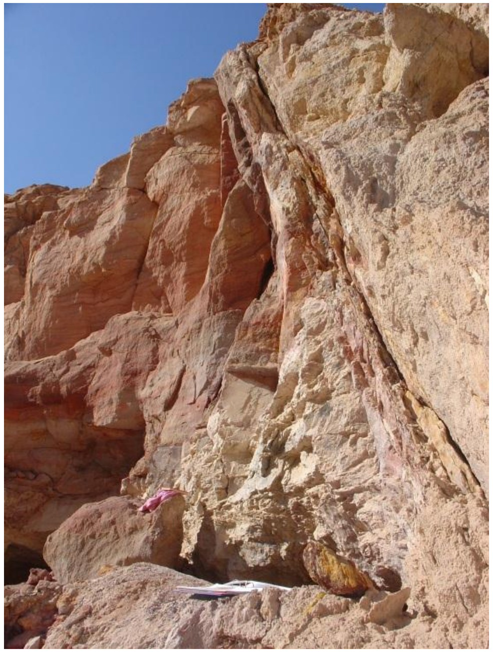


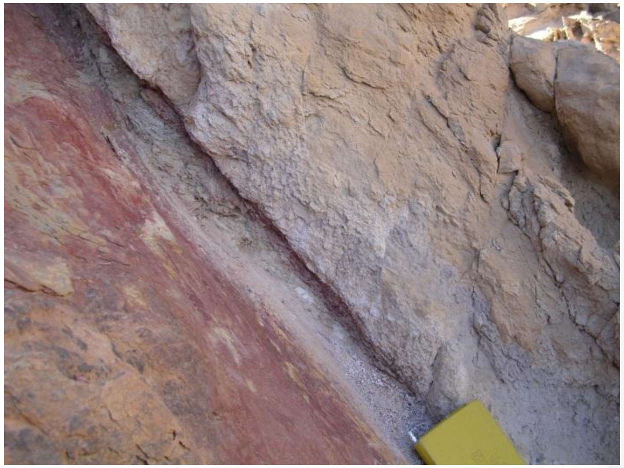
Associated structures



Associated structures

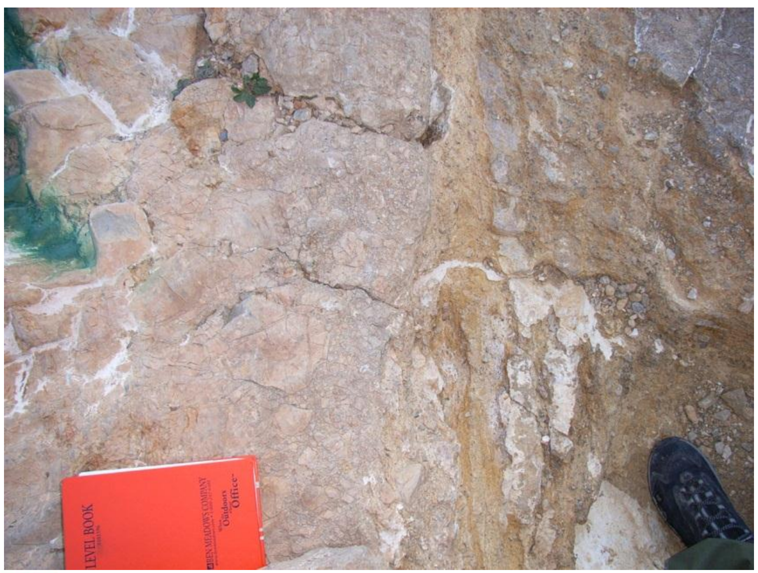
Realignment, crushing, fracturing, smearing





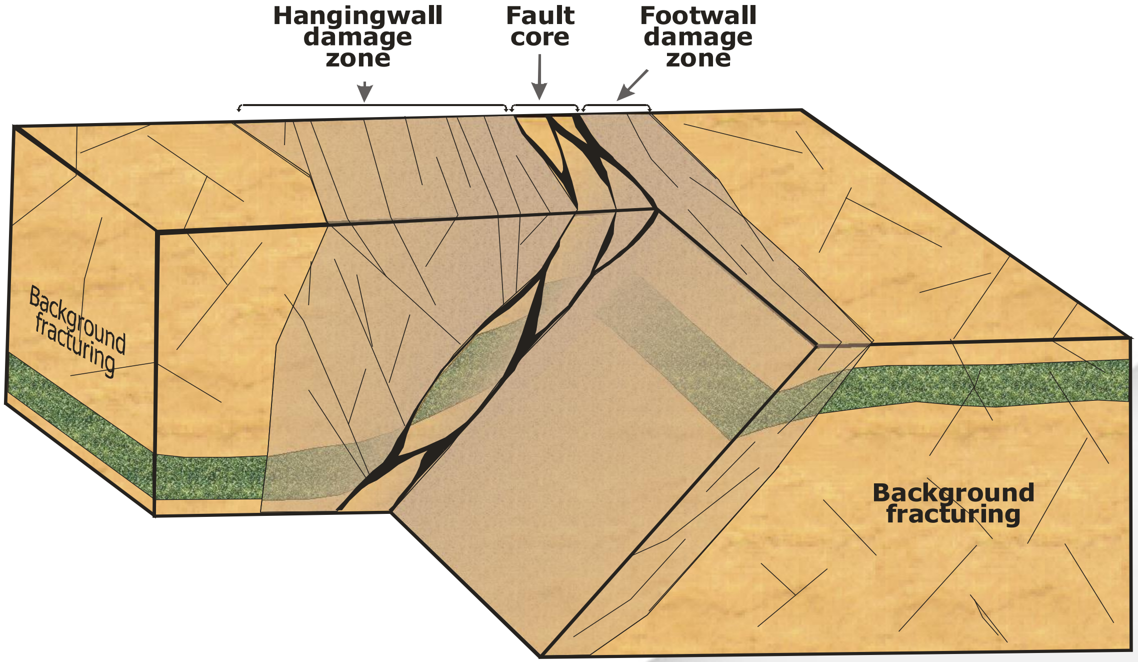
Associated structures

Associated structures

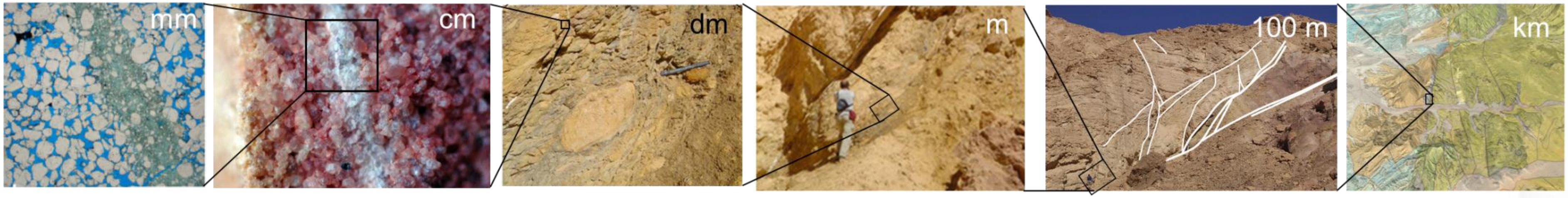


Faults in two sentences

- A fault represents:
  - A displacement and deformation of stratigraphy
  - A modification of the original petrophysical properties and structure in a volume surrounding the fault



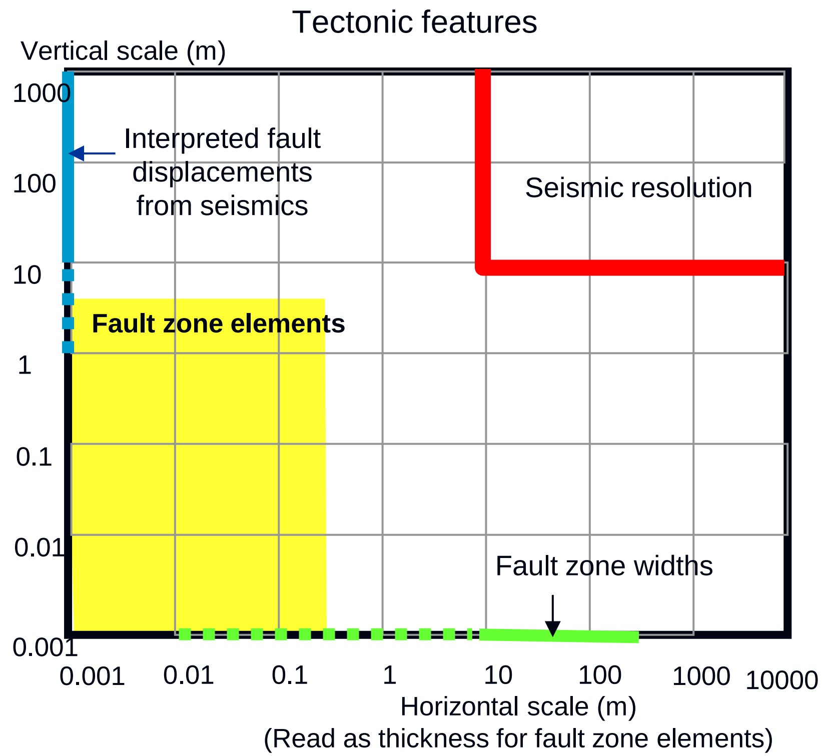
Scales



- Heterogeneity on all scales
- Wide range of structures and geometries
- Composite features

- …most of these features are sub-seismic….

- Description of sub-seismic elements relies on outcrop data and core



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Outcrop limitations

Erosion/weathering

Degradation/cover

Accessability

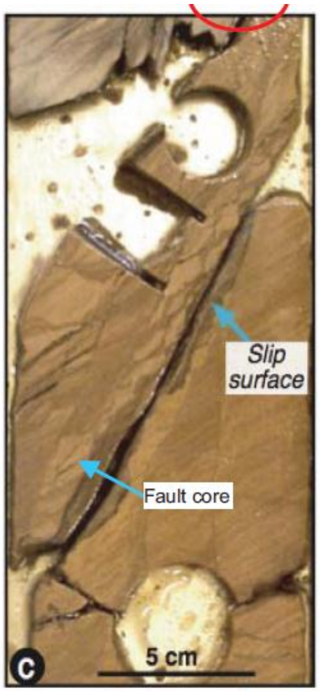
Limited spatial exposure

Safety aspects

Decompaction and weathering may change petrophysical properties….

Core limitations

- Core samples are rare
- Risk of jamming while drilling
- Pressure problems
- Non-cohesive rocks
- Point data



Core from a fault zone in the Triassic Stockton Fm, (USGS)

Characterization

Structural geology

- Traditionally focused on
  - Understanding processes
  - Geometric parameters
  - Outcrops as «unique» specimens
  - Regional tectonic understanding
- Limited attention to
  - Quantification of fault zone properties
  - Requirements of modelling

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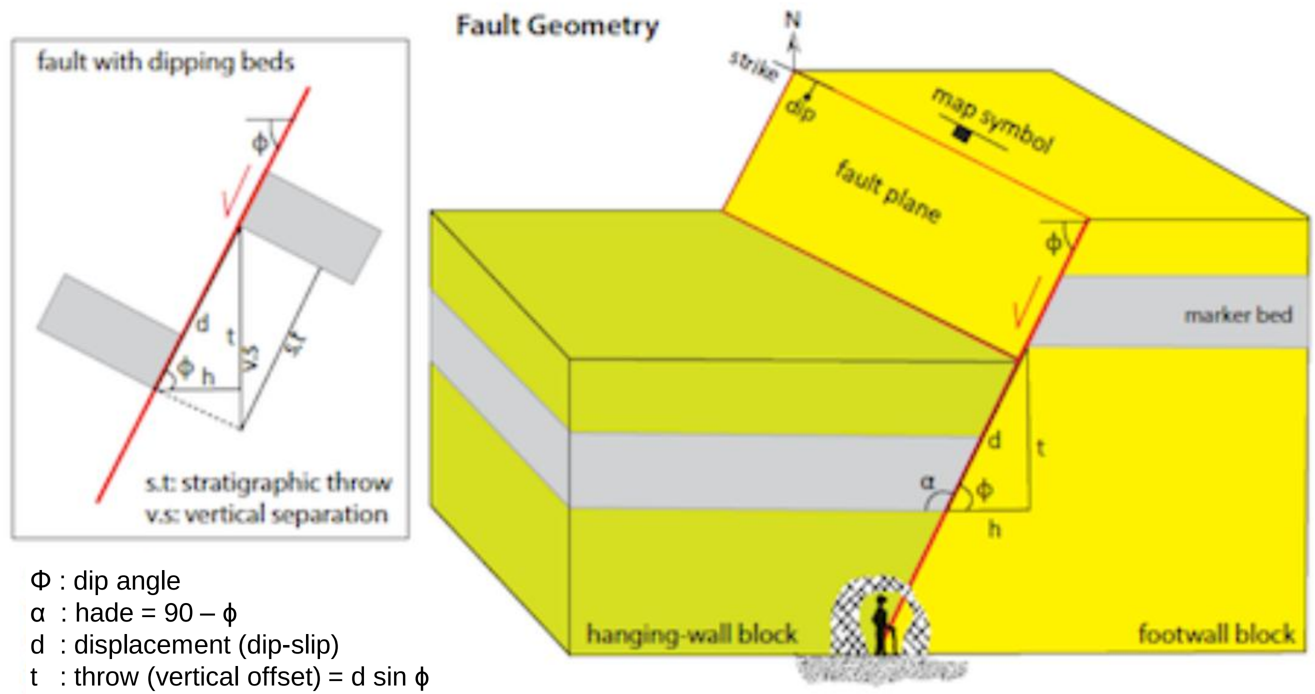
Geometrical characterization of single fault planes



Φ : dip angle
α : hade = 90 – ϕ
d : displacement (dip-slip)
t : throw (vertical offset) = d sin ϕ
h : heave (horizontal offset) = d cos ϕ
Slip rate = d/(time termination- time initiation)

Rasoul Sorkhabi (2012)

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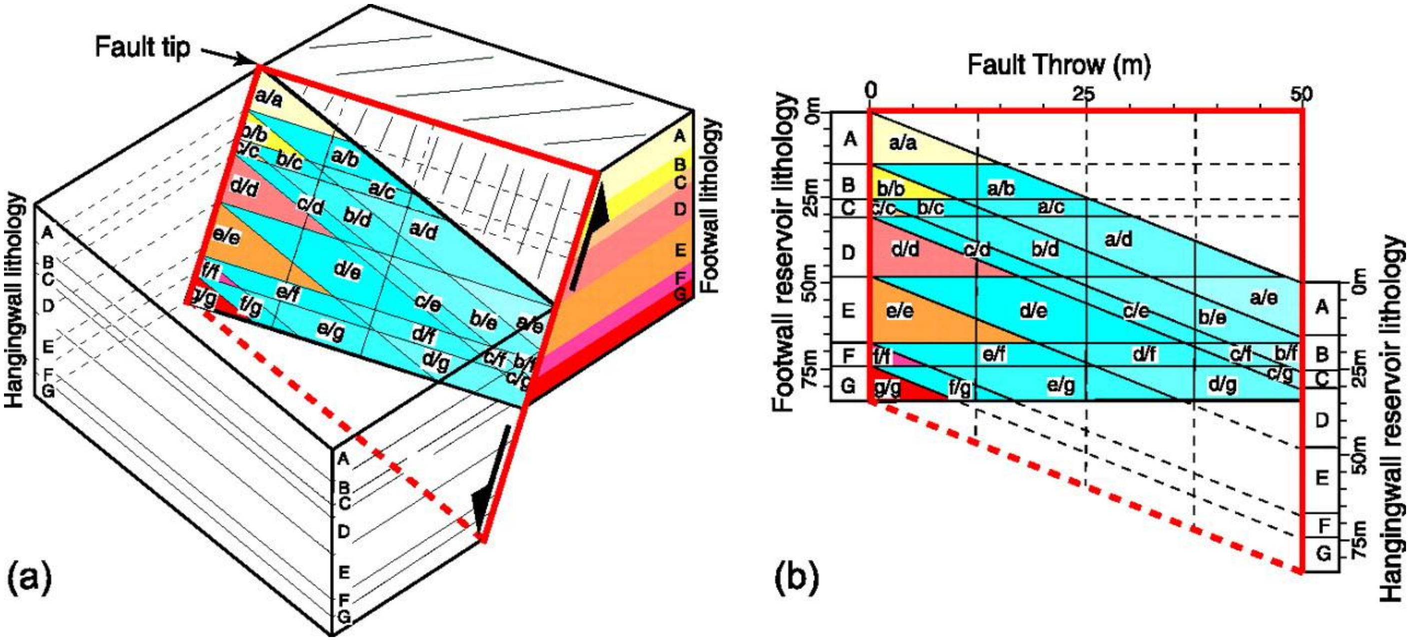
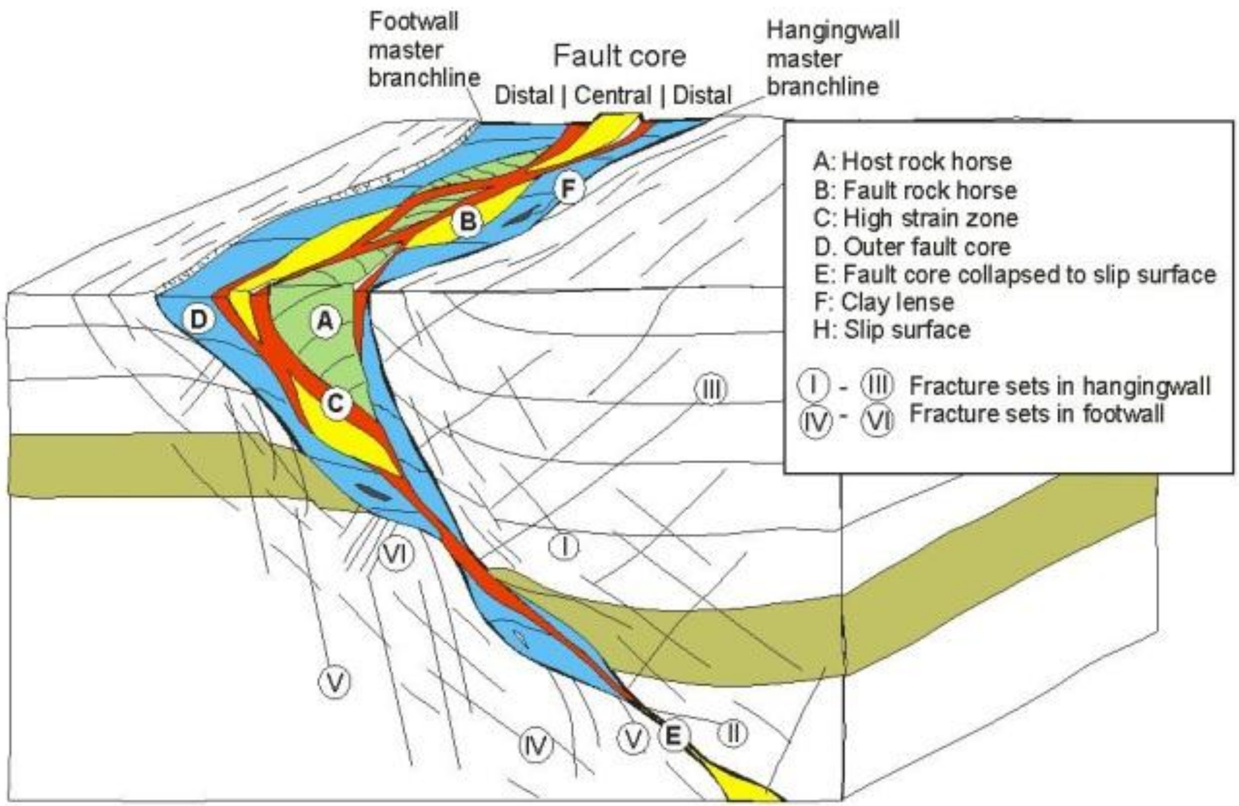
Juxtaposition



Porter et al. (2000)

Fault zone features



Gabrielsen et al. 2010

Terminology

- Different schools
- Different practices
- Multiple names for same feature
- Element of subjectivity

Fault bridges
Fracture
Slip surface
Vein
Fault propagation folding
Fault core
Griffith cracks
Rock flour
Brittle fault
Joint
Microbreccia
Stylolite
Flinty crush rock
Mode II crack
Horse
Cement membrane
Cataclasite
Sand smear
Crack
Relay ramps
Conjugate Joints
Deformation band
Shear band
Mode III crack
Fault-related folding
Displaced zones
Shattered zones
Braided shear fractures
Dyke
Gouge
Tectonite
Luder's bands band
Dilational deformation band
Fault rock
Mode I crack
Damage zone
Healed brittle faults
Compaction band
Clay membrane
Slip zone
Breccia
Lens
Sigmoidal Joints
Exfoliation joints
Shear lenses
Fault rock
Shear fracture
Ductile shear zone
Unhealed brittle faults
Relay zones
Cleavage
Filled brittle faults
Fault breccia
Shale gouge
Master joints
Phyllosilicate deformation band
Pinnate joints
Columnar Joints
Slipped deformation band
Orthogonal Joints

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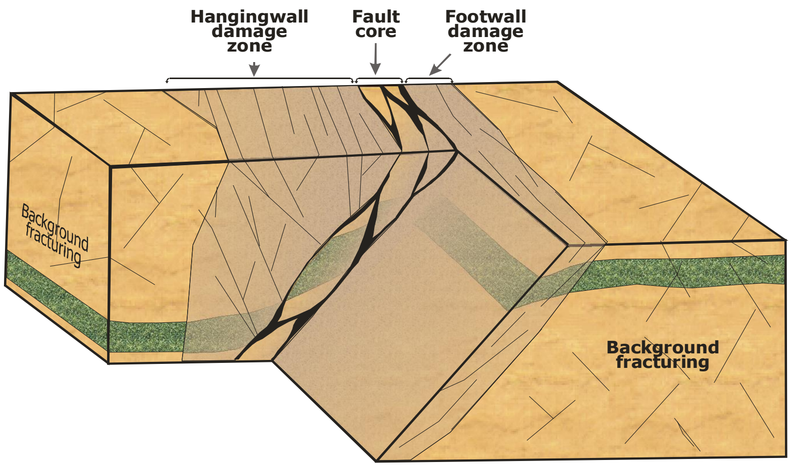
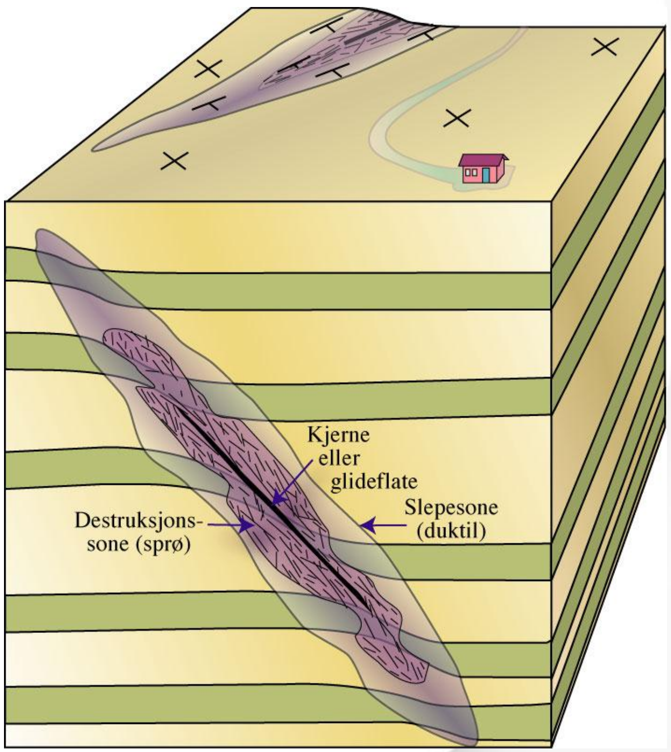
The whole picture?

No one has ever seen a complete fault zone in outcrop….





Fossen & Gabrielsen 2005

A complete 3D rendering of fault zone properties can only be achieved through modelling using compilations of empirical observations.

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What is there and what is needed

- Very fragmentary record
- High complexity
- No two faults are 100% identical

Empirical data

- Compile and systematize records
- Ensure consistent use of terminology
- Quantification !
- Statistical handling to identify patterns in
  - Spatial distribution of specific features
  - Properties of specific features

Required processing

- Geological models

Tools

- Forecasting

Products

…so how are the tools coping?

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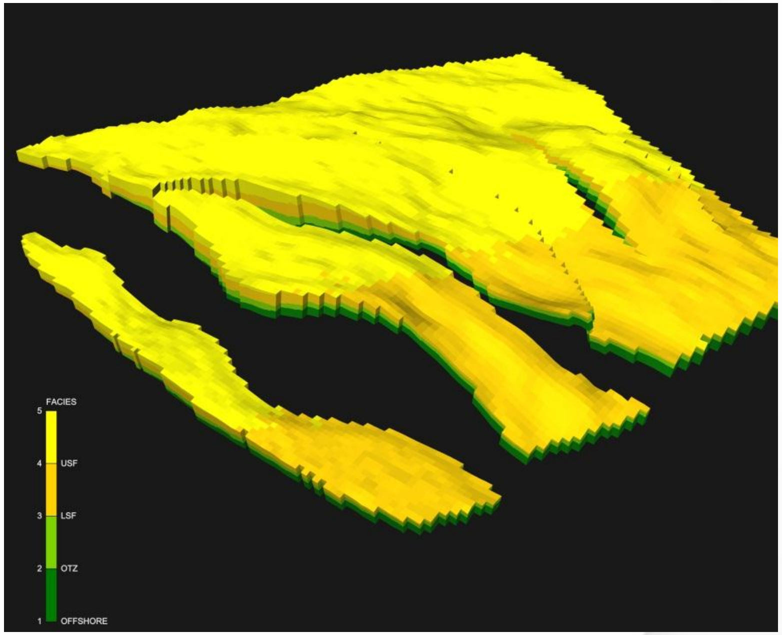
Modelling

Reservoir models

- Size ranging from a few to tens of square km (field or play size)
- Exploration and production purposes
- Corner-point grids – adaptable to fault traces/sticks
- Common resolution of 20-100m (XY) and 0,2-5 m (Z)
- Normally serve as input to flow simulation models with even coarser grids
- Originally designed to handle stratigraphic properties



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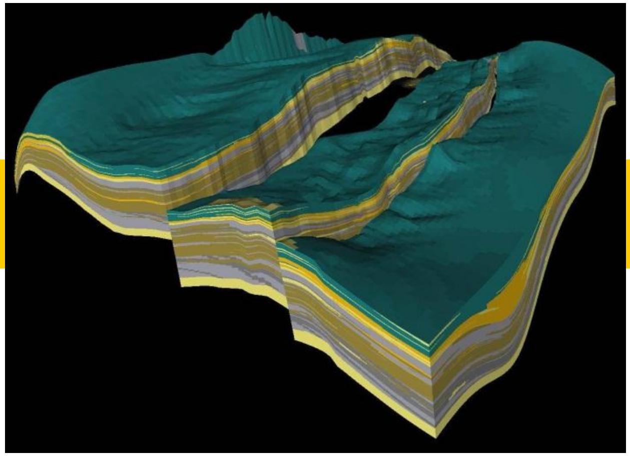
Industry-type reservoir geo-models

INPUT
Well data
Seismic data
Geological know-how
Exposed field analogues

Field/trap

Sedimentary heterogenities

Depositional structures and their properties



Structural heterogenities

Tectonic structures and their properties

Spatial distribution of petrophysical properties

OUTPUT
Property distributions for fluid flow simulation purposes

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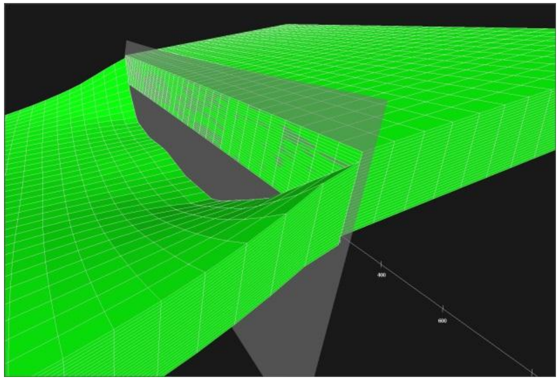
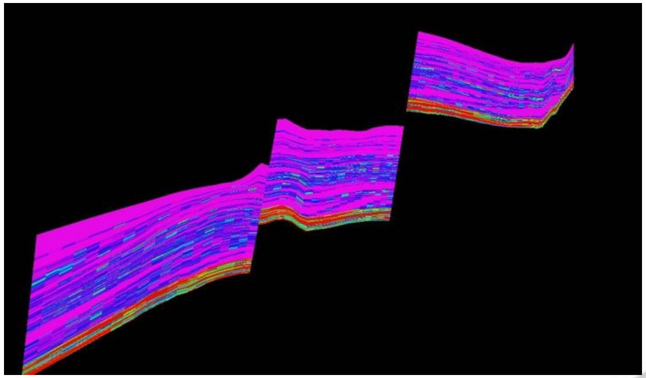
Current fault modelling practice

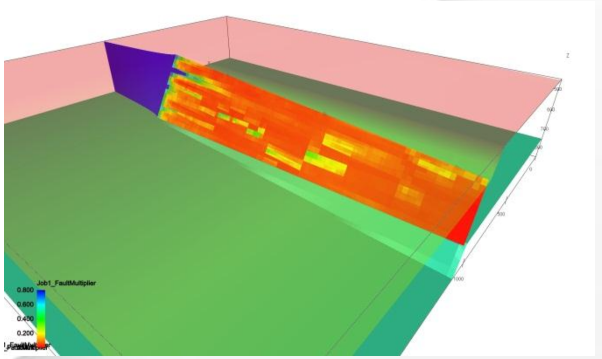
- Seismic interpretation – fault plane/fault sticks
  - Grid displacement (except sub-seismic faults which are included using implicit methods)

- Impact on fluid flow is included in the simulation model using transmissibility coefficients across grid splits. These can be derived from:

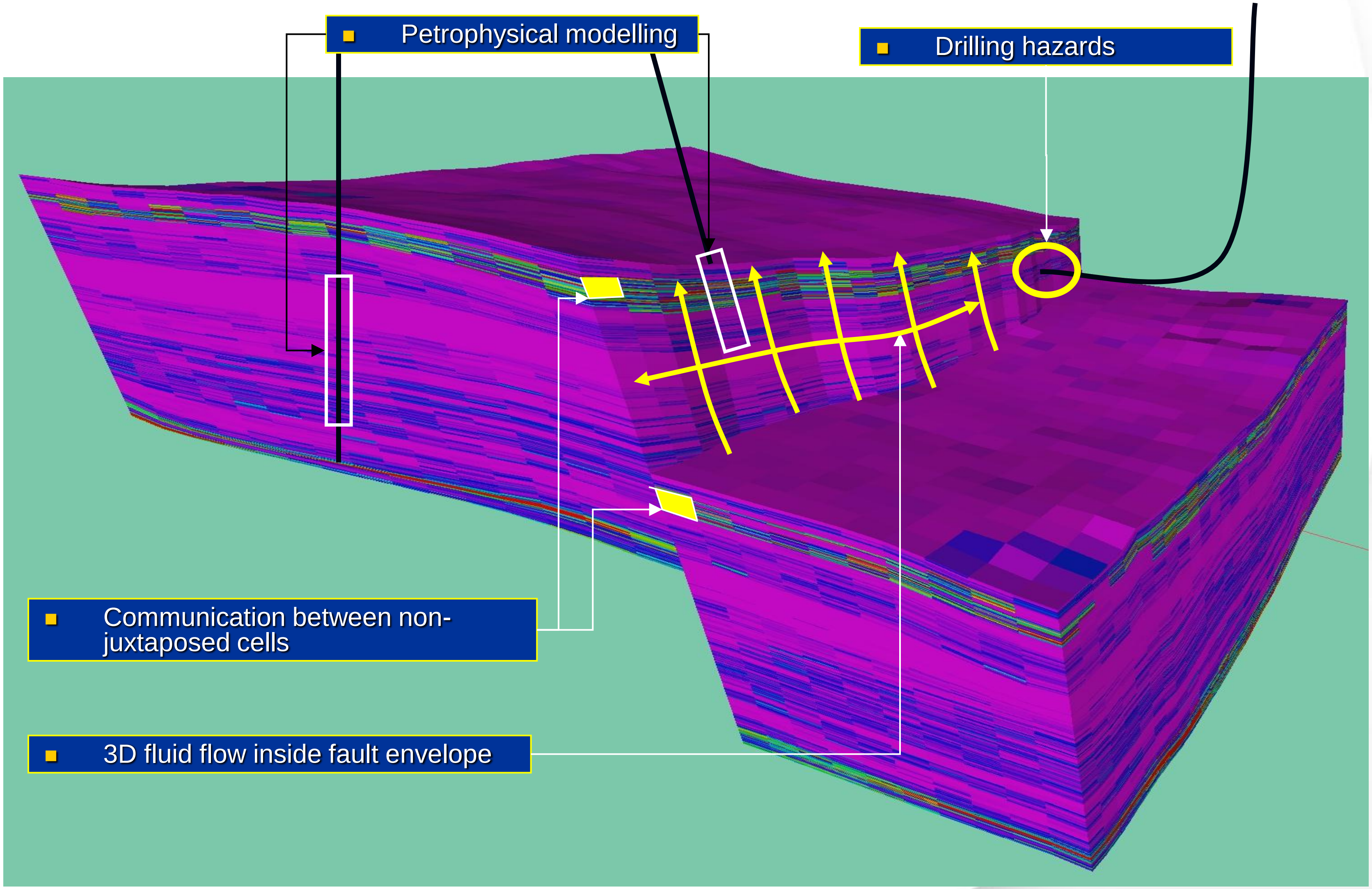
  - History matching of model using production data
  - Specialized software applications (HAVANA™, Juxtaposition™, TransGen™, a.o.) calculating permeability across fault planes as a function of lithology and displacement







Problematic features



- Severe limitations for explicit representation of the geology of the fault zone!
- ….but workers adapt to the limitations of the tools….

Shortcomings

Nature

- Seismic scale faults exhibit complex architectures
- Fault related changes in rock properties occur throughout a **volume** of host rock (fault envelope)
- Flow through faults is a result of how these petrophysical changes are distributed in the fault affected rock volume

Model rendering

- Faults as planes with displacements of model grid
- Fault related spatial property changes in volume surrounding faults commonly not included
- Fluid flow through faults approximated as 2D effect. Flow along faults and between reservoir zones with no juxtaposition can only be modeled deterministically (i.e. ”best guess”)

Consequences for simulation model

- Actual **3D flow** inside and through fault zones is not captured
- **In-place volumes** may be overestimated
- **Fault sealing** is simplified by handling fault zones as homogenized at any given position along the fault plane
- **Communication along faults can not be forecast** as the fault description does not include a Perm Z description. It can only be set ad hoc using history matching (no predictive value)
- Discrepancy between observed well behavior and modeled behavior is often assigned to fault impact (makes it impossible to distinguish between effects caused by the sedimentary model and the structural model) – **contribution of model components (sedimentological and structural) to overall model uncertainty can not be properly evaluated**

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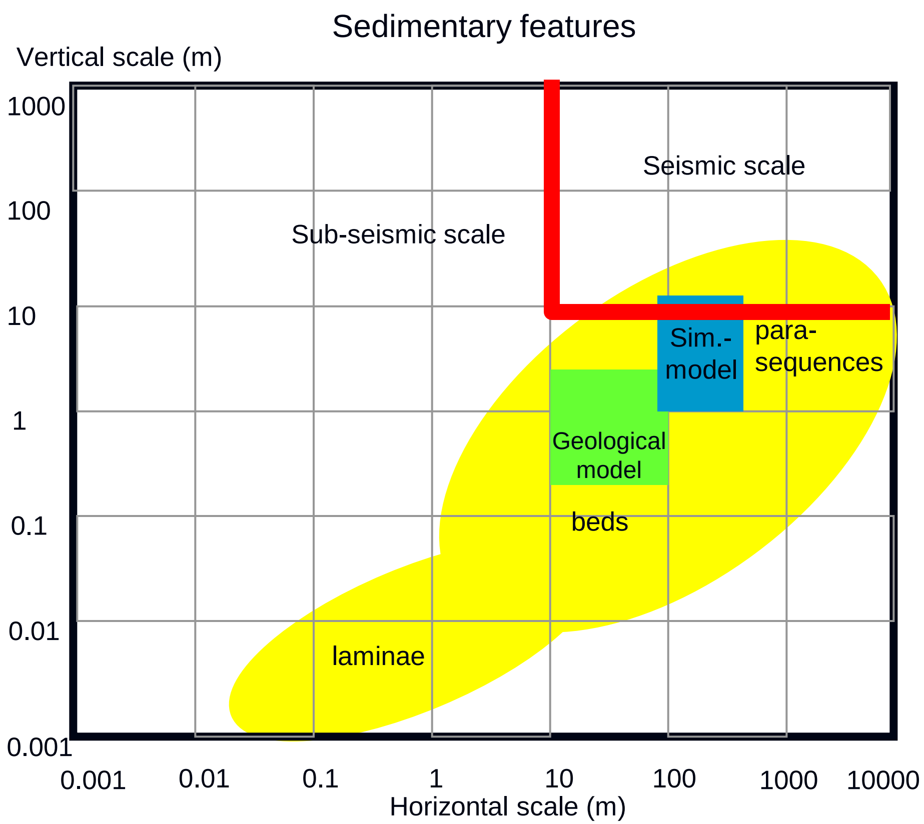
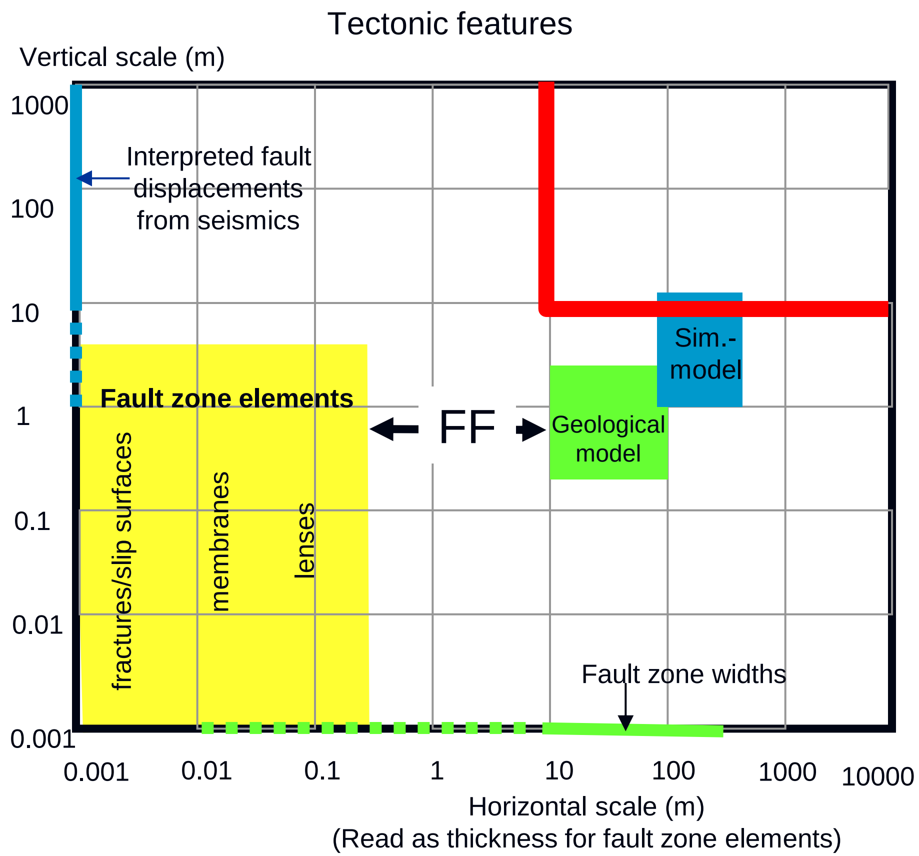
Model scales & model elements





Adapted from Pickup & Hern (2002)

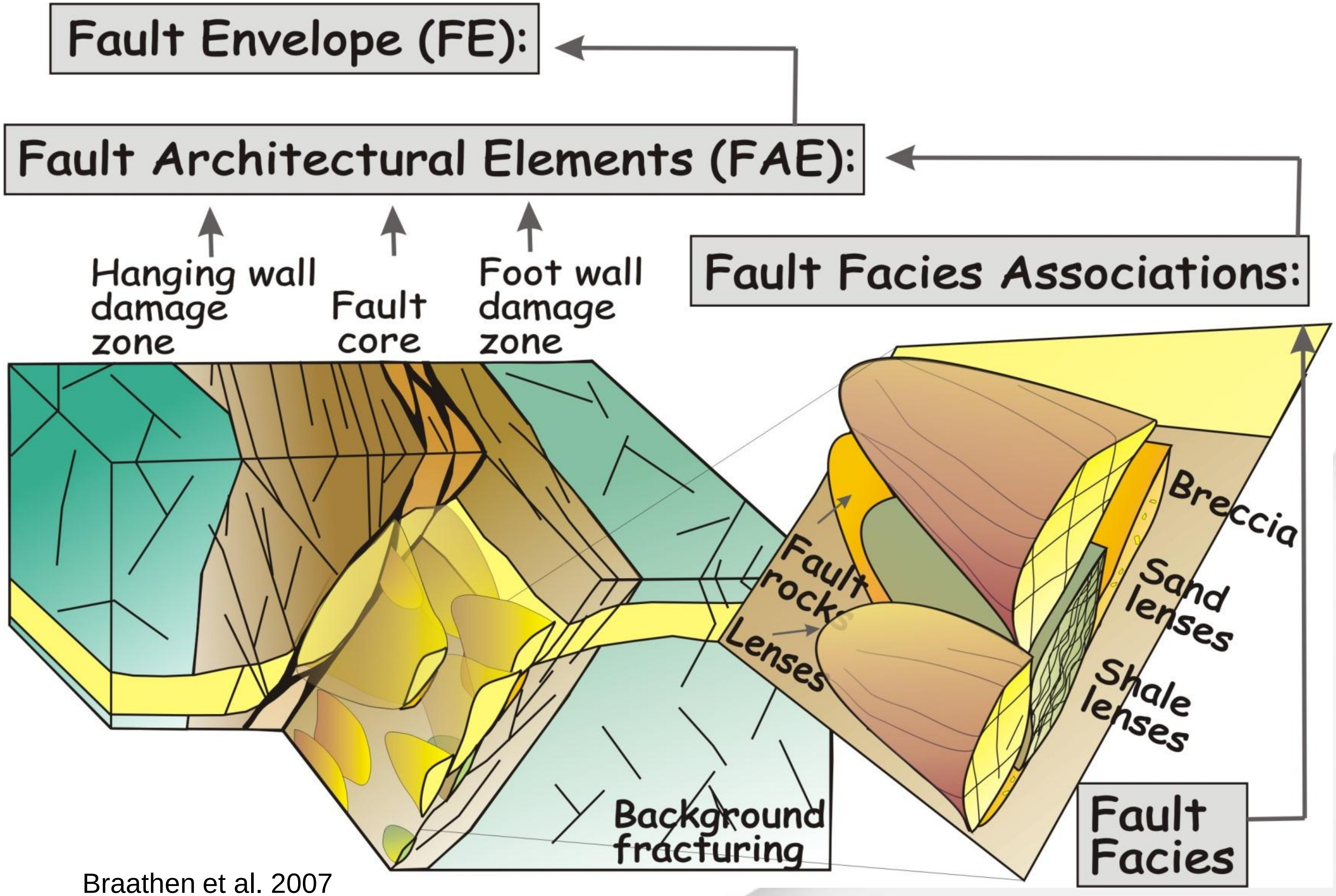
- Reservoir model scale is not inherently adapted for fault zone modeling; Current practice skips scales.
- Present fault modeling is largely dictated by software limitations
- Using facies as building blocks for fault zone architectures may be a means to bridge the gap and enable industrial reservoir models to incorporate more detailed geological descriptions of fault zone properties

FF=Fault Facies: Informally defined as any feature or body of rock with properties derived from tectonic deformation

Fault facies

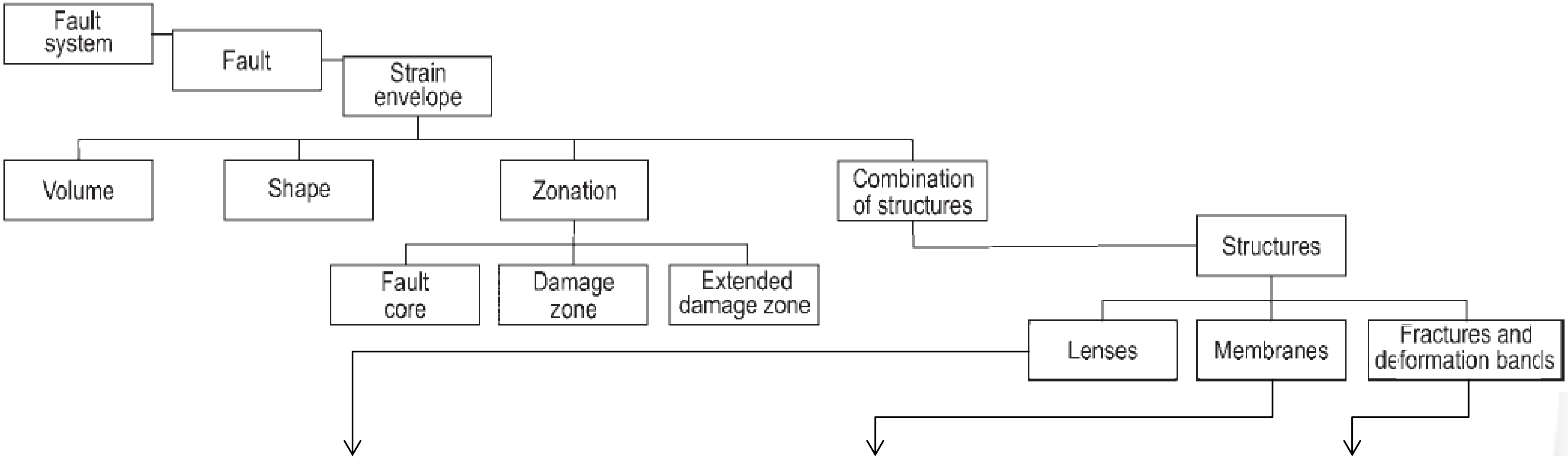
Facies is a well-developed concept for scale independent systematic description

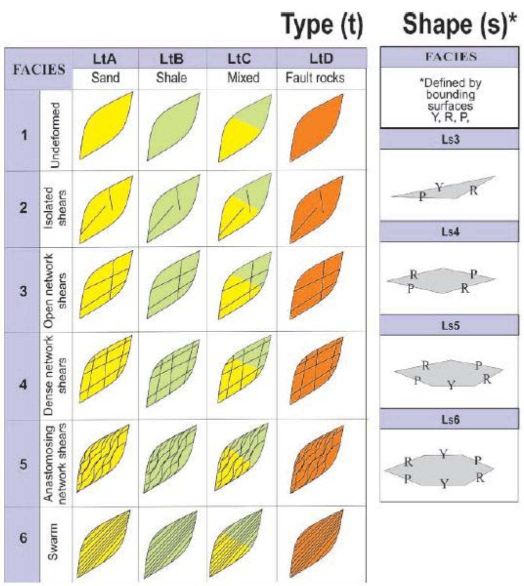
- **tool for systematic description of fault zone element on any chosen scale**
- **flexible window of observation**



Braathen et al. 2007

Fault description scheme





A) Type (t), with Cement (-C)

	FACIES
Breccias (with clasts)	Mt1
Sand gouge	Mt2
Shale gouge	Mt3
Sand smear	Mt4
Shale smear	Mt5

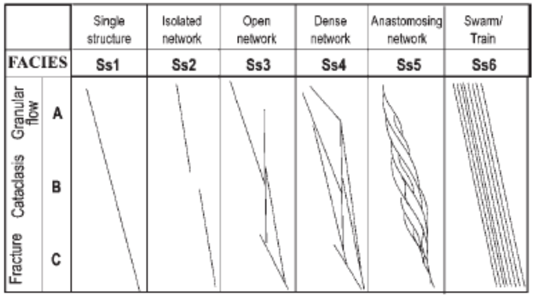
B) Appearance / Shape (f, c)

Continuity / Appearance	%	Fault rock	Cement
		FACIES	
Continuous	100	Mf1	Mc1
Semicontinuous	90–100	Mf2	Mc2
Ruptured	50–90	Mf3	Mc3
Patchy	10–50	Mf4	Mc4
Pocket	< 10	Mf5	Mc5

A) Type (Ssl = slip surface, Sfr = fracture, Sdb = deformation band)

Fractures	Sharp		Tabular	Deformation bands
	FACIES			
	Ssl	Sfr	Sdb	
R	Ssl1	Sfr1	Sdb1	Extensional shear band
R'	Ssl2	Sfr2	Sdb2	
Y	Ssl3	Sfr3	Sdb3	Shear band
P	Ssl4	Sfr4	Sdb4	Contractional shear band
Joint	T	Sfr5	Sdb5	Dilation band
Solution surface	So	Sfr6	Sdb6	Compaction band

B) Shape (s)

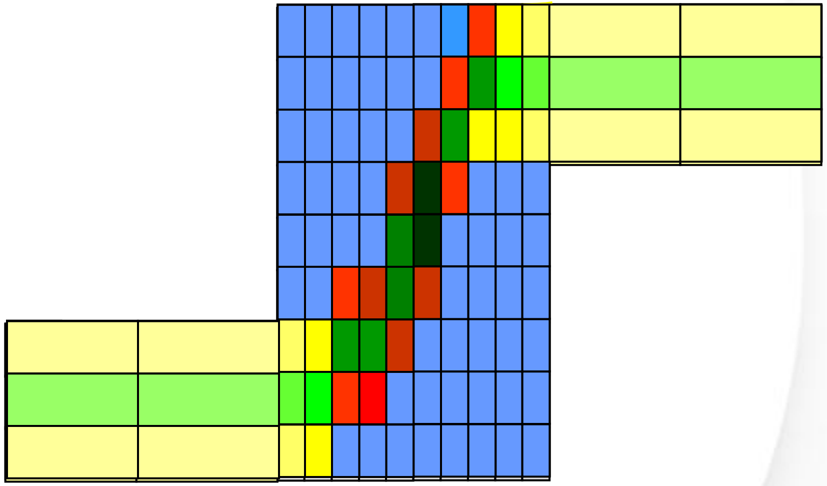


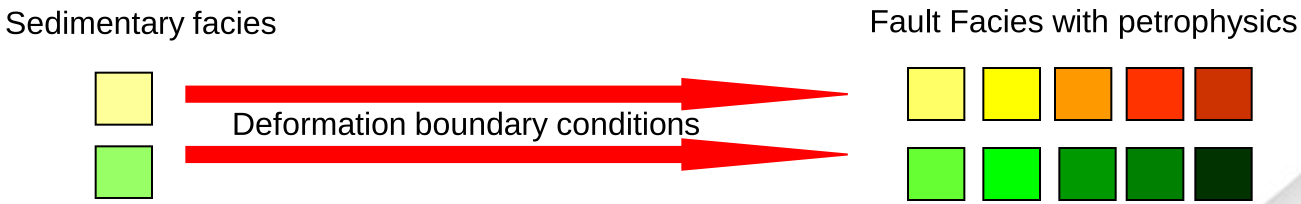
Adapted from Braathen et al. 2009

Fault zone models

Required elements

- Volumetric representation of fault envelope (i.e. FZ grid) in reservoir model
- Description and classification system for elements occurring inside fault envelope and their petrophysical properties under given sets of boundary conditions
- Conditioning factors for position and distribution of fault facies inside the fault envelope; room for complex displacement trends
- Up-scaling methods





- As for sedimentary facies, fault facies can be applied on any model scale defined by the user; facies definitions can be adapted to the available data and purpose of the model

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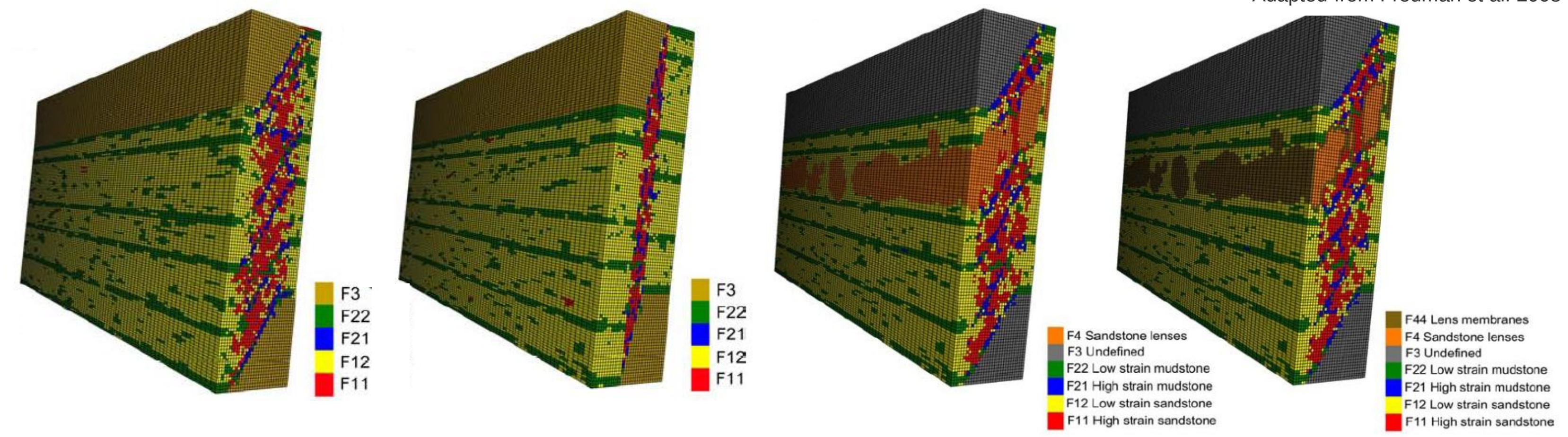
Geological input

- Outcrop analogues
- Empirical databases
- Statistic models
- Strain modelling tools
- Seismic parameters ?

- Stochastic modelling approach input data define boundary conditions
  - Define case specific elements
    - FF types
    - FF properties
      - Geometry
      - Dimensions
      - Frequency distribution, variograms
      - Petrophysical properties
  - Trends and conditioning parameters
    - Displacement distribution inside fault envelope
    - Strain distribution
    - Intra-facies petrophysical property trends

Adapted from Fredman et al. 2008

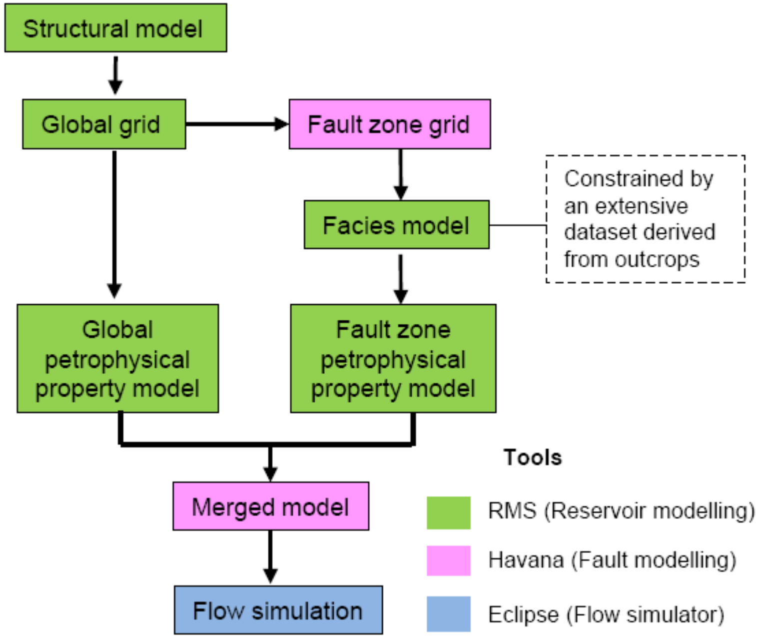


Example: Qu, D., Tveranger, J. and Røe, P. (submitted): Explicit modelling of fault damage zone properties. AAPG Bull.

Aims

- Explicit capture of realistic deformation band damage zone features in reservoir models.
- Investigate the impact of damage zone properties on fluid flow.

Workflow



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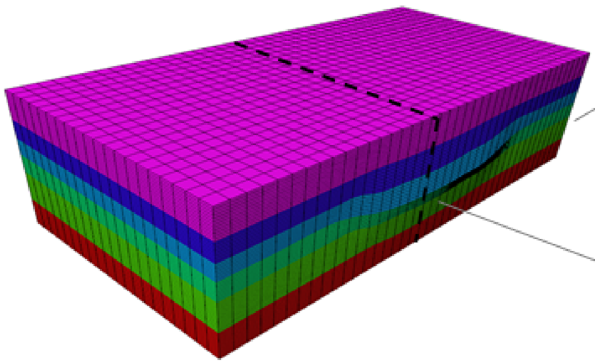
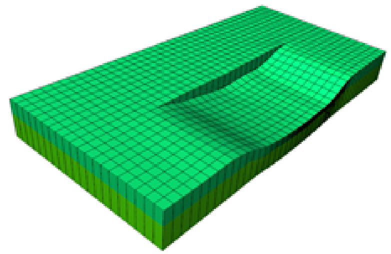
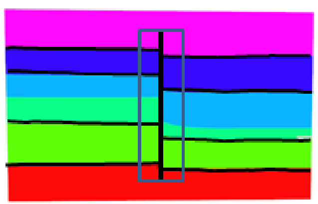
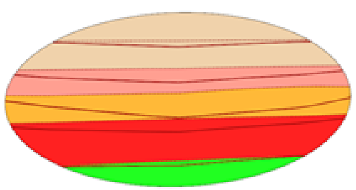
Model set-up

- **Global grid**



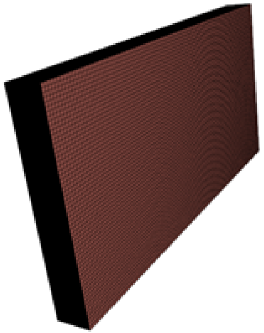






Model information
Dimension:1000m*1600m*600m
Maximum fault throw:100m
Fault length:1000m
Grid resolution: 50m*50m*10m
Number of cells: 38400

- **Fault zone grid**



- The volume around the fault is extracted from the global grid by using HAVANA.
- The fault zone grid can be refined to required resolution.

Fault zone grid
Fault zone width: 100m
Grid resolution: 1m*10m*5m
Number of cells: 1440000

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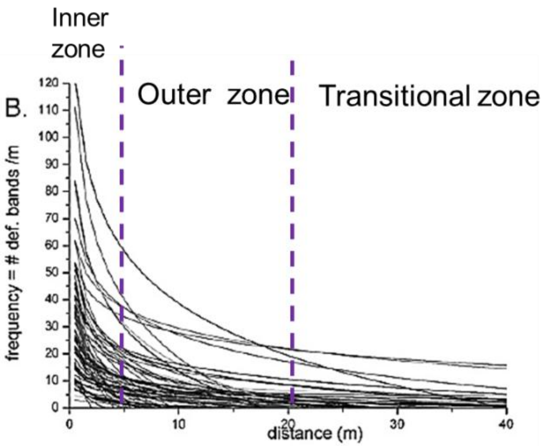
Describing the fault zone - 1

(a) Deformation bands are commonly developed in fault damage zones of porous sandstones. Deformation band densities and permeabilities have been collected from outcrops worldwide.

** Deformation band density: number of deformation band per meter.*



Schueller et al. (2013)

(b) The decrease of deformation band density with the increasing distance from the fault core is a significant feature of the damage zone structures. For modelling purposes we discretize this into three sub-zones.

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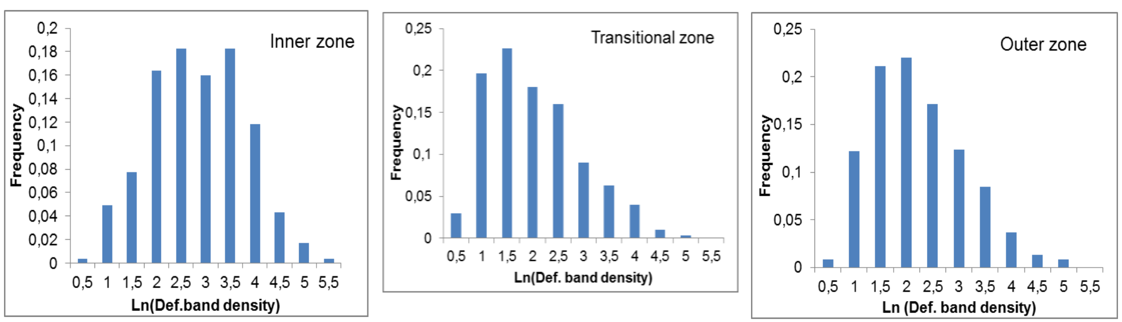
Describing the fault zone - 2

Sub-Damage zones	Proportion	
	undeformed sst	deformed sst
Inner zone	0.1	0.9
Outer zone	0.3	0.7
Transitional zone	0.5	0.5

(c) Proportions of undeformed sst and deformed sst in three sub-zones.

- *Deformed sst: sandstone associated with deformation band. Undeformed sst: sandsone without deformation band.*



(d) Frequency of deformation band densities of deformed sst in the three sub-zones.

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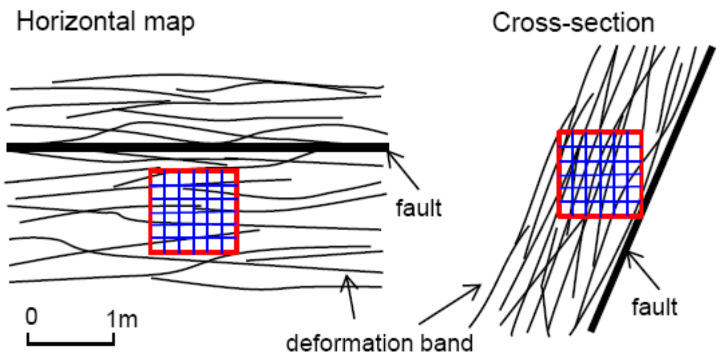
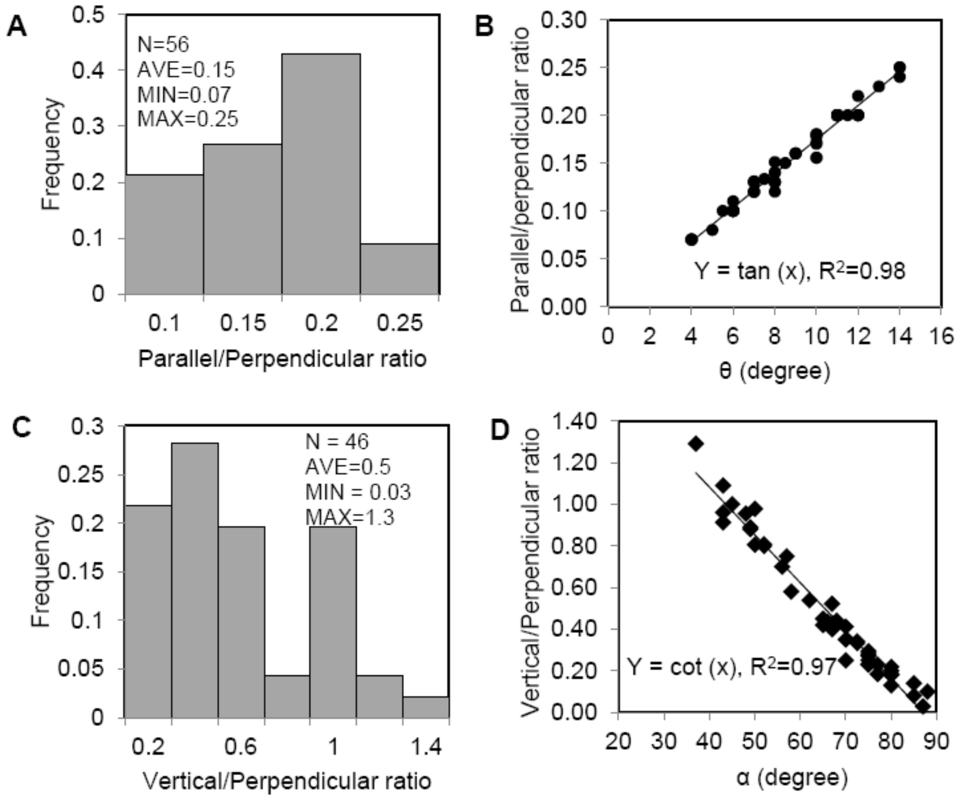
Describing the fault zone - 3





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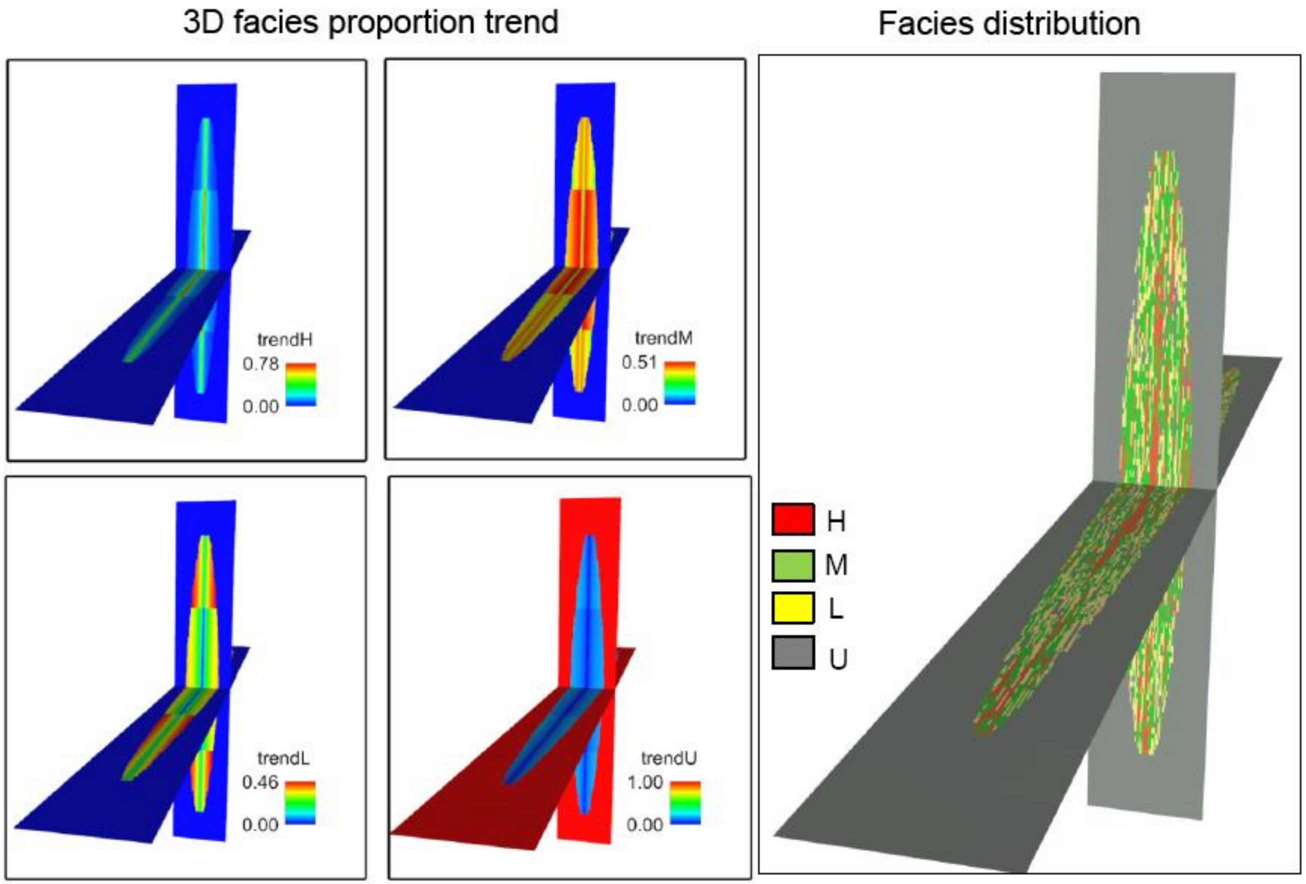
Modelling



(a) Extent of fault envelope and subdivision of the damage zone in the fault zone grid.

(b) Proportion of deformed sst at sub-zones, used as a trend for fault facies modeling

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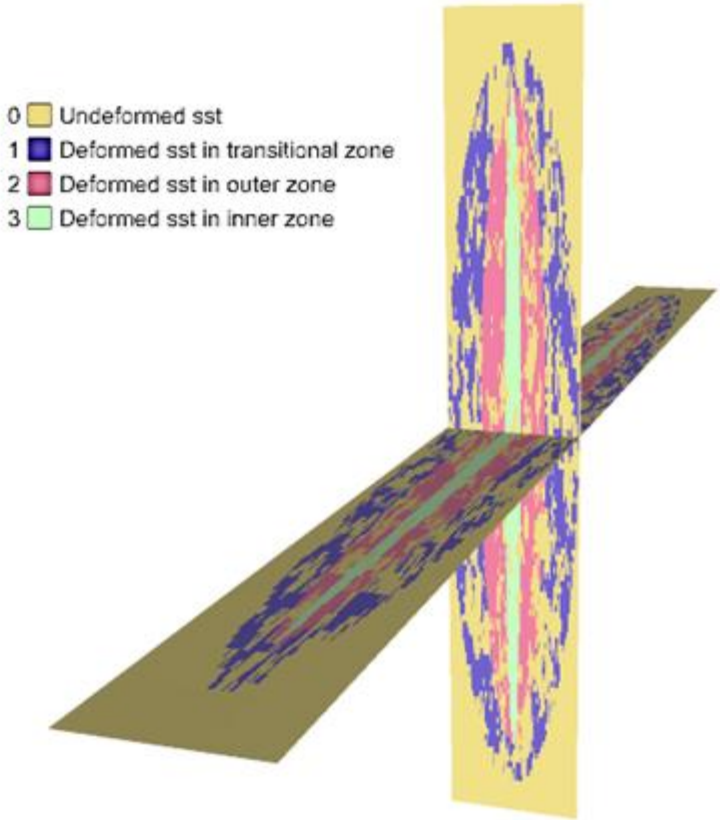
Modelling - 2



(c) Stochasitic distribution of deformed sst and undeformed sst in different sub-zones.

- Generated by the 'Facies modeling' module in RMS. The trend shown in (b) is used as a conditioning parameters.

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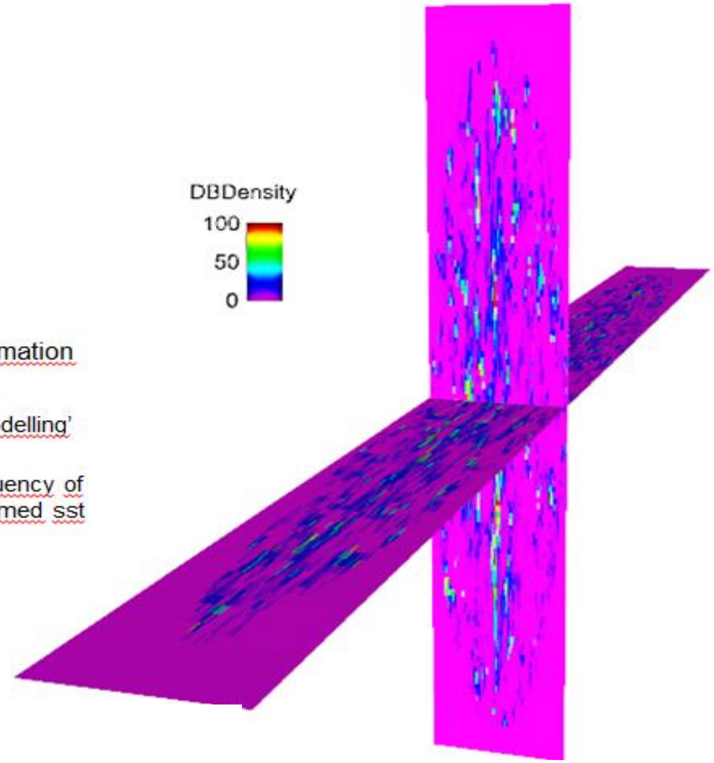
Modelling - 3



(d) Stochasitic distribution of deformation band density.

- Generated by the 'petrophysical modelling' module in RMS.
- The input data is the statistical frequency of deformation band densities of deformed sst in three sub-zones.

Cataclastic band

Dilation band

Type of features present their volumetric fraction and orientation will influence petrophysical properties

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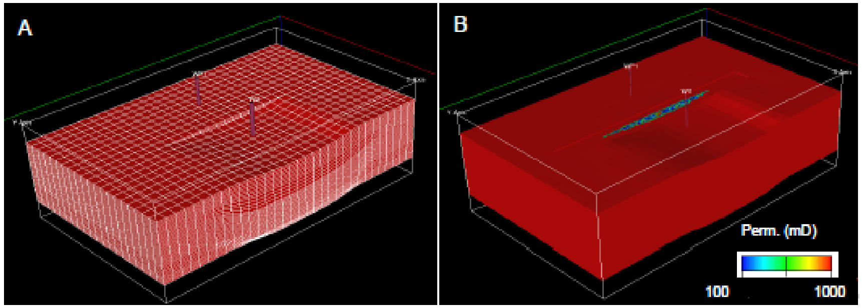
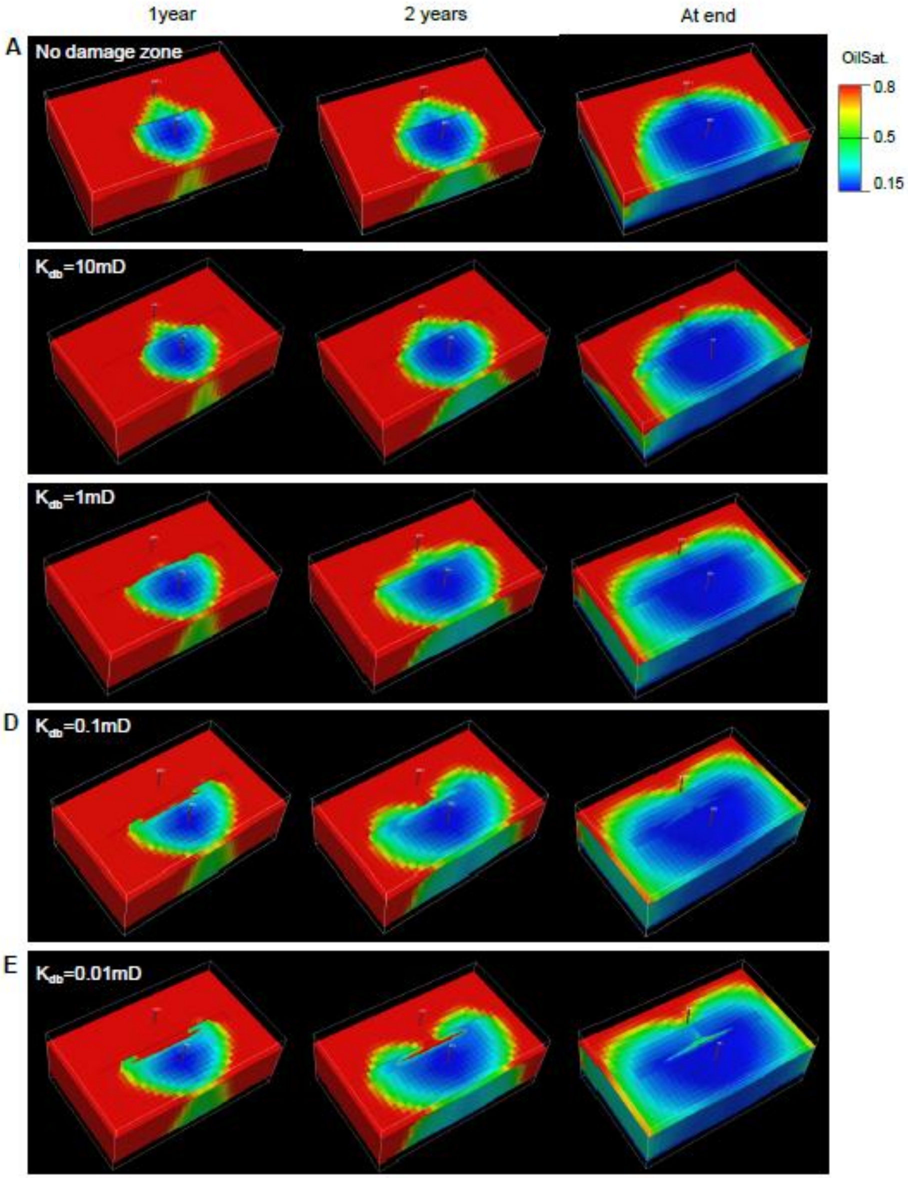
Improved fluid flow simulation

Injector/producer pair positioned on opposite sides of the fault





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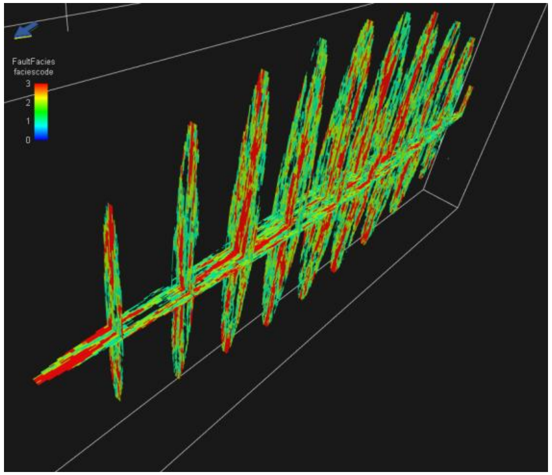
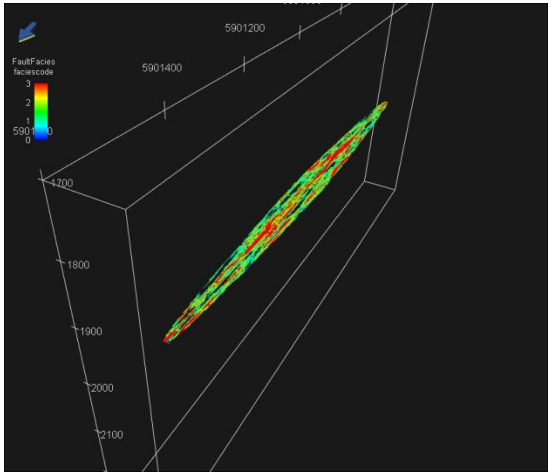
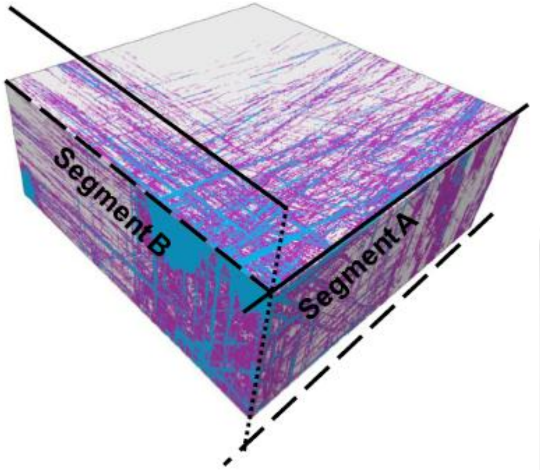
Seismic characterization

- Given petrophysical characterization of fault facies, explicit 3D fault zone models can provide input to forward seismic modelling of fault zones
- Potential for improving interpretation of faults in subsurface seismic data







0: undeformed rock, deformation band density=0;
1: deformation band density 1-5/m
2: deformation band density 6-20/m
3: deformation band density >20/m

Fachri et al. 2013

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Conclusions

- Improved characterization of fault zone properties requires more systematic manners of description and analysis targeted for 3D modelling purposes

- Employing fault facies modelling facilitates explicit modelling of fault zone features on any given scale

- The method opens up potential for:
  - Improved fluid flow simulation
  - providing realistic input for geophysical forward modelling on relevant scales
  - interpretation of fault zones structure in geophysical data

- Key geological challenges include
  - Databases for petrophysical properties of fault facies
  - Upscaling procedures for fault facies properties

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Thank you for your attention