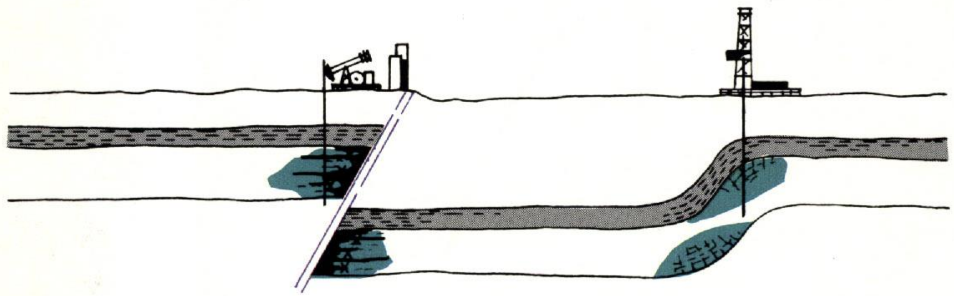

Fracture characterization using seismic

# Fractured Reservoirs

Dr. Abdelwahab Noufal

anoufalus@yahoo.com

Ab_noufal@yahoo.com



# FRACTURED RESERVOIR

Fractures add porosity and greatly enhance reservoir rock permeability. Fine-grained sedimentary rocks such as shales and chalks have porosity but lack permeability, except where fractured. Fractures occur where the rock has been folded or moved along a fault.

# Stages of Deformation

Introduction

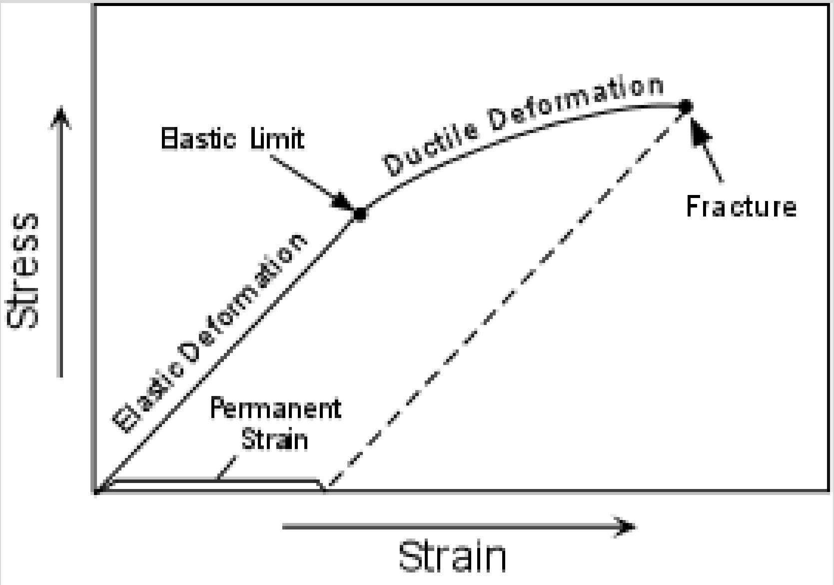
Stress is a force applied over an area. One type of stress that we are all used to is a uniform stress, called pressure. A uniform stress is a stress wherein the forces act equally from all directions. In the Earth the pressure due to the weight of overlying rocks is a uniform stress, and is sometimes referred to as confining stress.

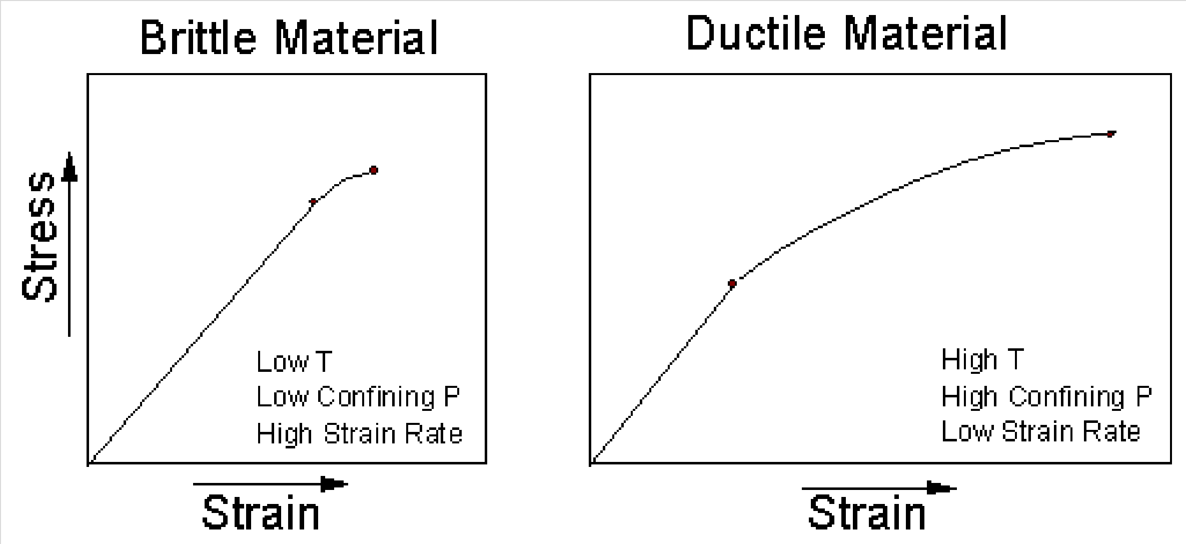
If stress is not equal from all directions then we say that the stress is a differential stress. Three kinds of differential stress occur.

1. Tensional stress (or extensional stress), which stretches rock;
2. Compressional stress, which squeezes rock; and
3. Shear stress, which result in slippage and translation.

When rocks deform they are said to strain. A strain is a change in size, shape, or volume of a material.

# Stages of Deformation



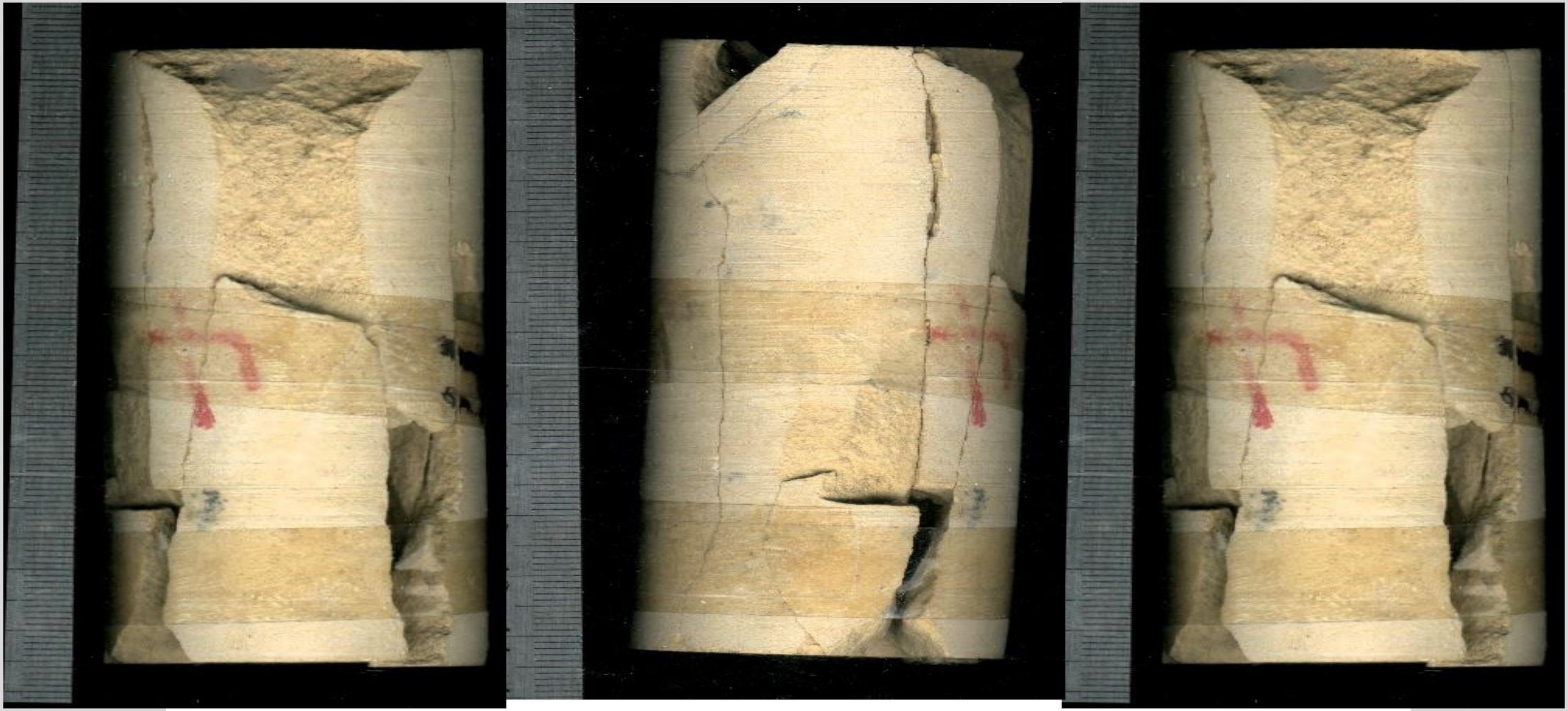




Stages of Deformation

When a rock is subjected to increasing stress it passes through 3 successive stages of deformation.

- Elastic Deformation -- wherein the strain is reversible.
- Ductile Deformation -- wherein the strain is irreversible.
- Fracture

# Rheology



Rheology is the study of relationships between stress and strain under various environmental conditions (e.g. temperature, confining pressure, pore fluid pressure, strain rate, composition, and grain size). The aim is two-fold: 1) to predict a rock's response to stress. 2) to interpret structures resulting from stress. The approach is also two-fold: 1) theoretical models. 2) experimental studies using (a) rocks or (b) rock analogs.

- what is the relationship between stress and strain?
- cannot have strain without stress…relationship not easy to define
- rheology: study of response of rocks to stress; how rocks flow;

- *what strain will result from given applied stress depends on rheology*
- …relationship among stress, strain and time
- flow is everyday phenomenon…even in rocks

- *geologic time is very long*…
- • displacements on San Andreas accumulate stresses over
- tens to hundreds of thousands of years
- • deformation in Appalachians occurred over millions of years
- *on these time scales, rocks may flow*
- examine glass in old windows: may distort your view
- why? glass has sagged (flowed downward) from gravity;
- in very old windows, glass may be thinner at top than bottom
- related terms:
- strength: stress that a material can support before failure
- competency: resistance of materials to flow

# General behavior:  the creep curve

compression tests on rocks show behavior not simple

…yields *creep curves*…(strain as function of time)




three creep regimes:

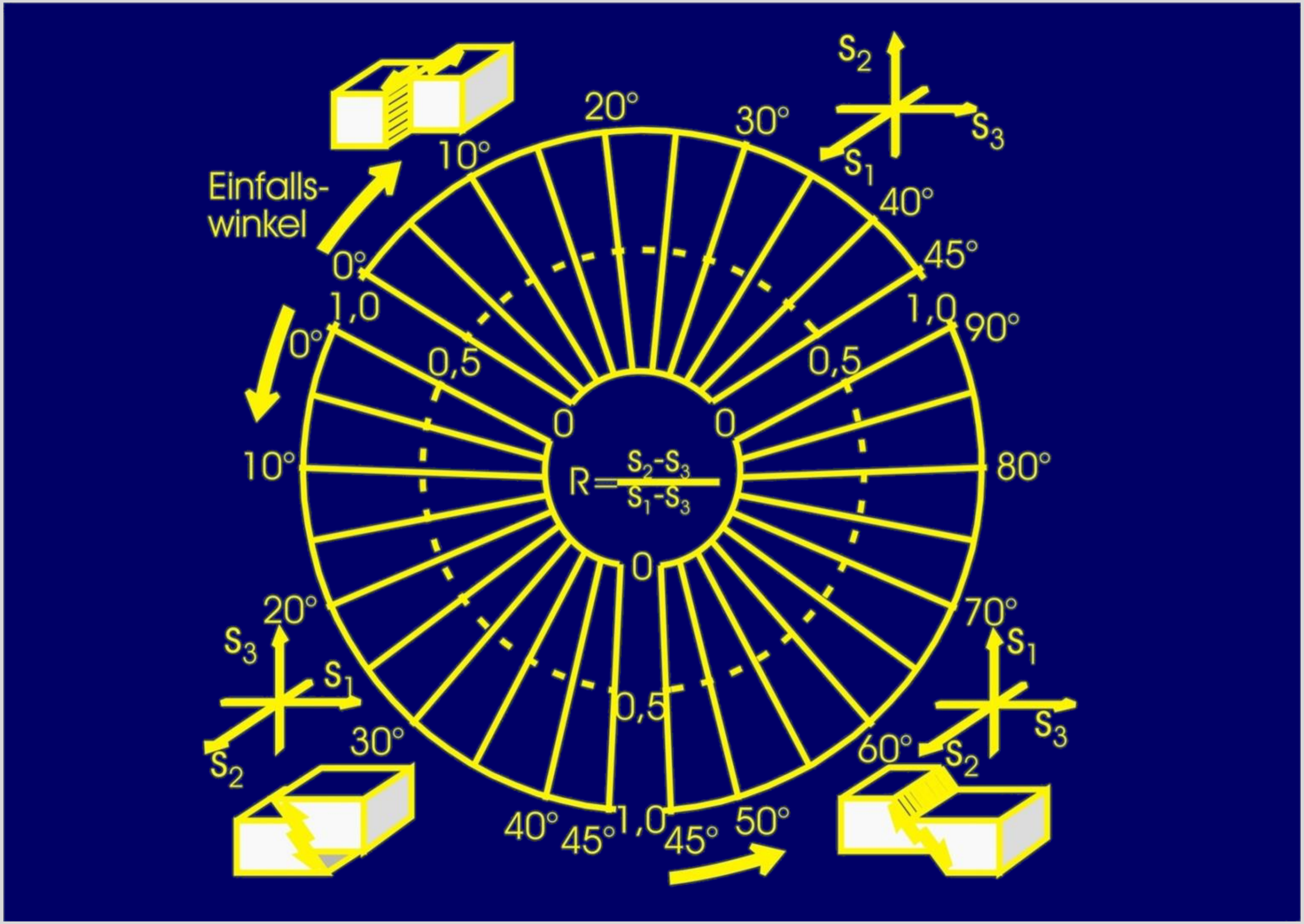
I: primary, or transient creep: strain decreases with time following very rapid initial accumulation

II: secondary, or steady-state creep: strain accumulation approximately linear with time

III: tertiary, or accelerated creep:  strain increases with time and failure eventually results

# Structure Analysis

# Paleostress Analysis



# Paleostress Analysis

Paleostress analyses

- According to the two-dimensional Mohr-Coulomb theory (Jaeger and Cook,  nehw srucco pils tluaf ,(1979 sserts raehsτ across a fault plane equals the frictional resistence to slip : $\tau = \tau) \mu + {}_0\sigma_n - P($

where $\tau_0$is the cohesive shear strength of the fault, μ is the friction coefficient ,$\sigma_n$ the normal stress across the fault, and P is the fluid pressure of water in the fault zone and its surroundings. In unfaulted material, the two conjugate planes on which failure and slippage occur at the lowest differential stress) $\sigma\text{-}_1\sigma$ ($_3$are perpendicular to the plane containing the greatest and least principal stresses) $\sigma_1$and $\sigma_3$respectively); they intersect in the intermediate principal stress) σ ,($_2$and are inclined at angles of $\pm \theta_0$to σ ,$_1$where

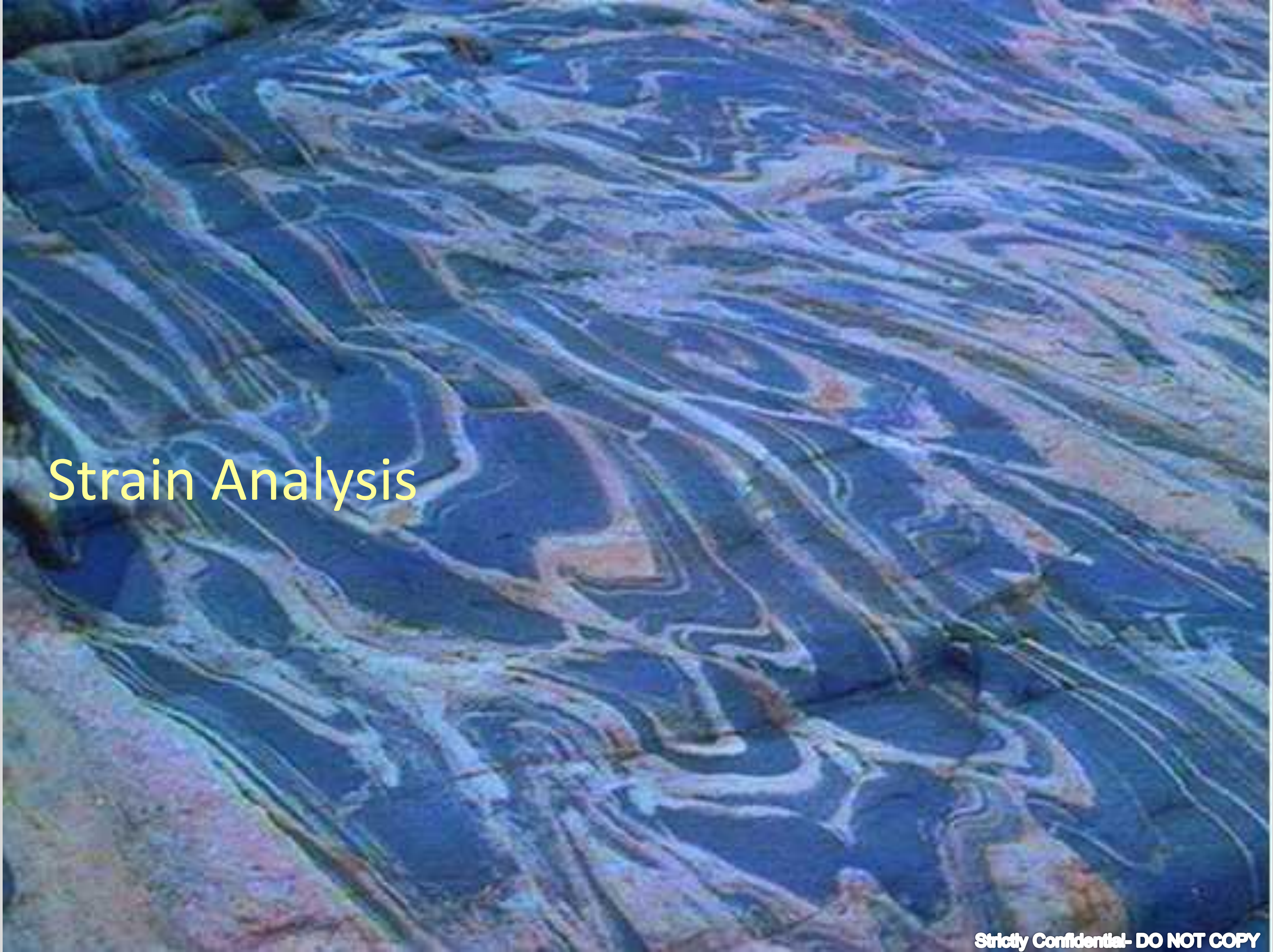
$\theta$ 1/2-°45 = $_0\tan^{-}\mu^{1}$

Laboratory-derived values of internal rock friction yield μ =  taht ylpmi dna ,(1978 ,eelreyB) 0.9-0.6θ.°30-°25=$_0$

Determination of principal axes and stress ratio:

To obtain the direction of the principal compressional axes $\sigma\_{}_1\sigma\_{}_2\sigma$ , $_3$and the ratio R =$\sigma\text{-}_2\sigma/_3\sigma\text{-}_1\sigma$ $_3$of the paleostress tensors, a number of graphical and numerical methods were used namely, pressure/tension axes method, numerical dynamic analysis, right dihedra method, direct inversion method, and iterative grid search method. Since Anderson ( fo snotialupop eht fo scimanyd eht terpretni ot deirt evah stsigoloeg ,(1951 eht no sserts raehs devloser eht fo noticerid eht neewteb ecnednopserroc a gnimussa senalp tluaf detairts .notiairts edisnekcils eht dna enalp tluaf

# Strain Analysis

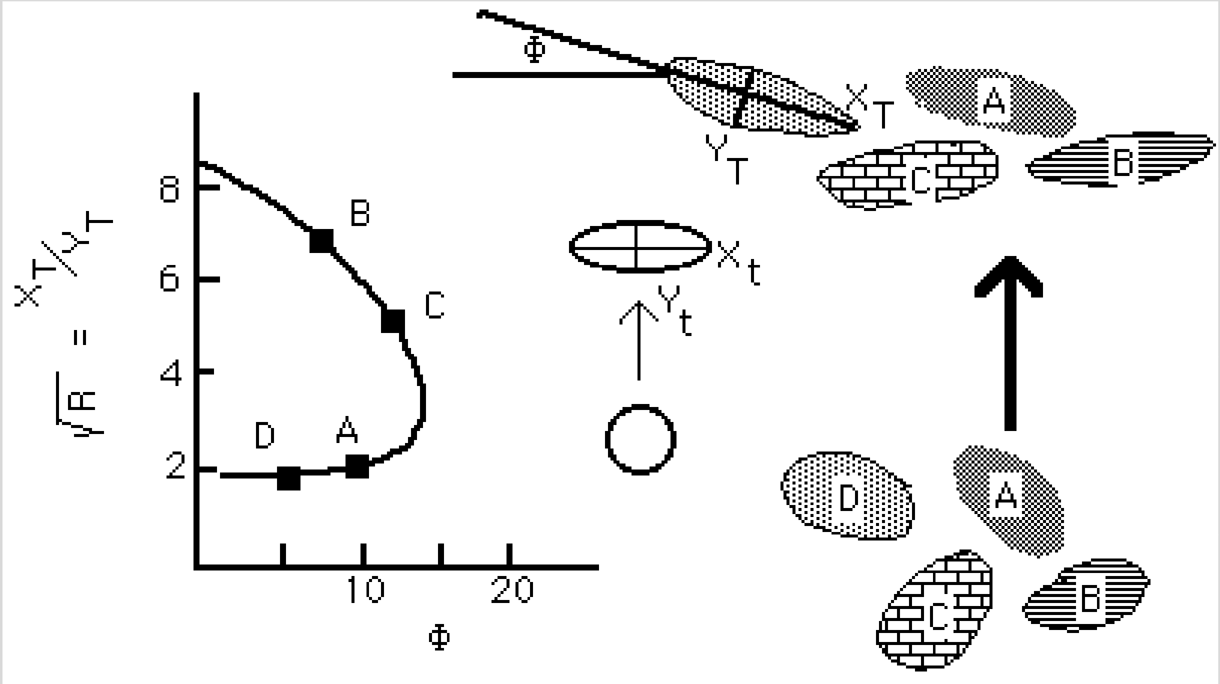


# Strain Analysis

## Strain Markers

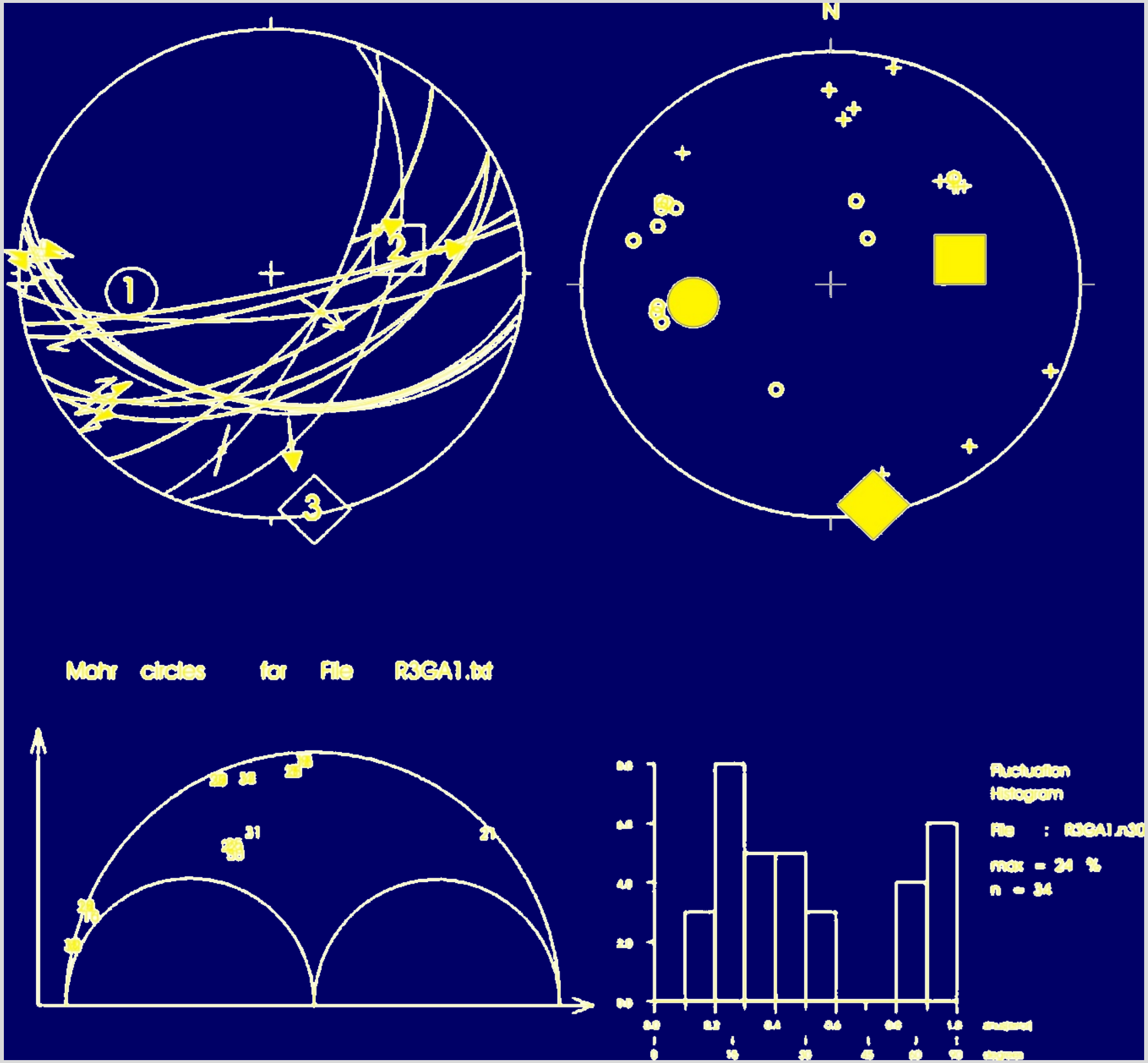
Strain in rocks is measured using objects of known initial shape. The initial shapes can vary from round crinoid columnals to the irregular shape of breccia fragments. In two dimensions initially round objects include scolithus tubes, crinoid columnals, reduction spots, vesicules, concretions, and oolites. Initially elliptical objects include congolmerate pebbles. Fossils are usually irregular in shape but some such as leaves, brachiopods and trilobites may have a bilateral symmetry. More complicated shapes include the spiral of the ammonite, cavities of the coral, belemnites, and the branches of the graptolite. Other markers are deposited with centers at uniform distances from their nearest neighbours. In this lecture we are going to consider the analysis of four situations where rock strain can be inferred from the shape or position of deformed markers.

# Strain Analysis

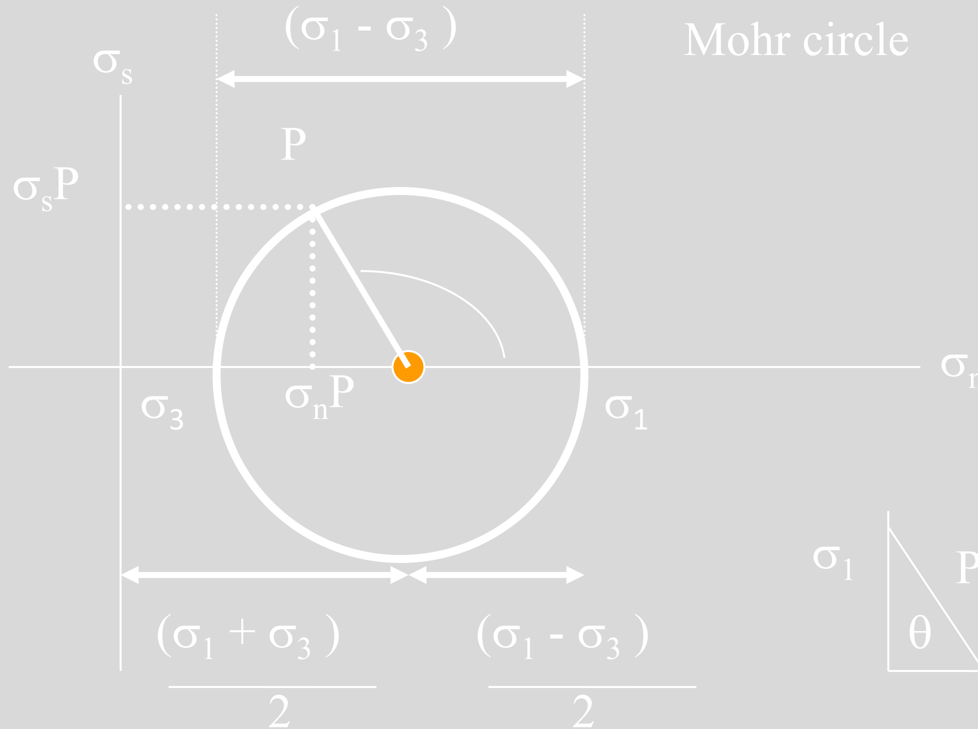



Ri and the strain ellipse Rs. The Rf /Φ plots have two shapes depending on whether Ri > Rs or Ri < Rs. In the former case the data envelope is symmetric about the orientation of the long axis of the strain ellipse and shows maximum and minimum Rf values. In the latter case the data envelope is closed and the data points shown a limited range of orientations defining the fluctuation F.

# Stress tensor; Mohr circles; states of stress; strain

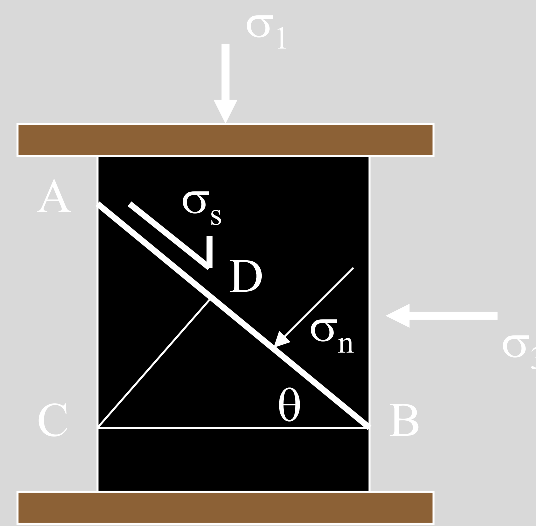


**2θ**










original diagram

point P represents a plane that is θ degrees from $\sigma_3$

…plots 2θ clockwise from $\sigma_1$ (note our original diagram on the upper right)

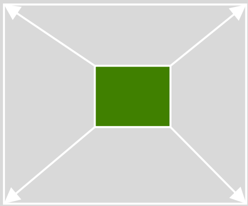
*textbook does the Mohr circle in terms of $\sigma_1$ and plots planes as -2θ from $\sigma_1$*

*remember that the expression for the circle was done in terms of 2θ*

normal and shear stresses on point P are $\sigma_n$P and $\sigma_s$P, respectively

$$\sigma_n P = 1/2(\sigma_1 - \sigma_3) + 1/2(\sigma_1 - \sigma_3)\cos 2\theta$$
$$\sigma_s P = 1/2(\sigma_1 - \sigma_3)\sin 2\theta$$

non-rigid body deformation:



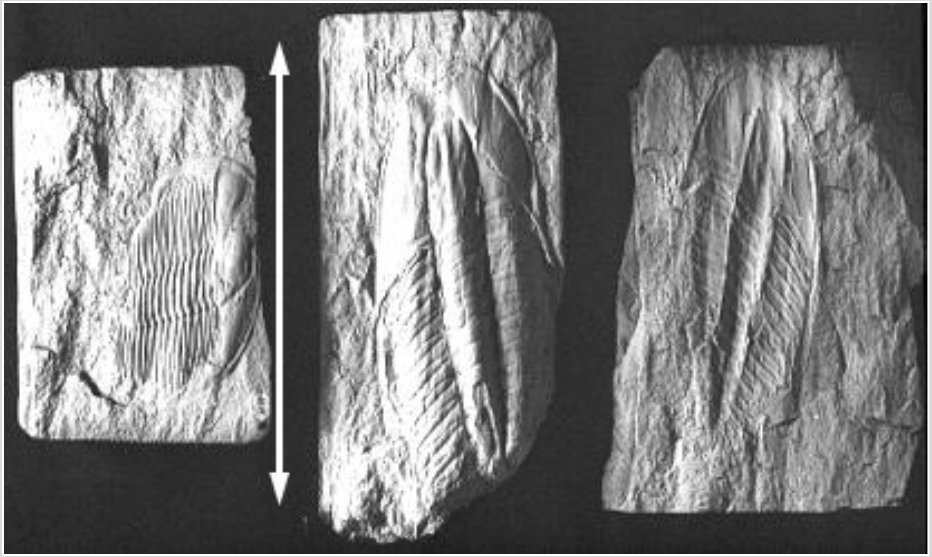
dilation: change in size of body

distortion: change in shape of body
(blue square becomes red)



*dilation and distortion are strain*

note that strain describes displacement field of points relative to each other; requires only internal reference frame



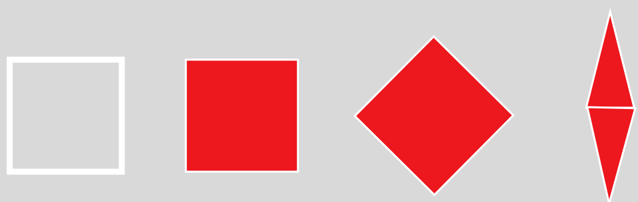
strained trilobites

# Original square and its deformed counterpart…

deformation involved:
translation, rotation,
and distortion (strain)




order of processes matters:



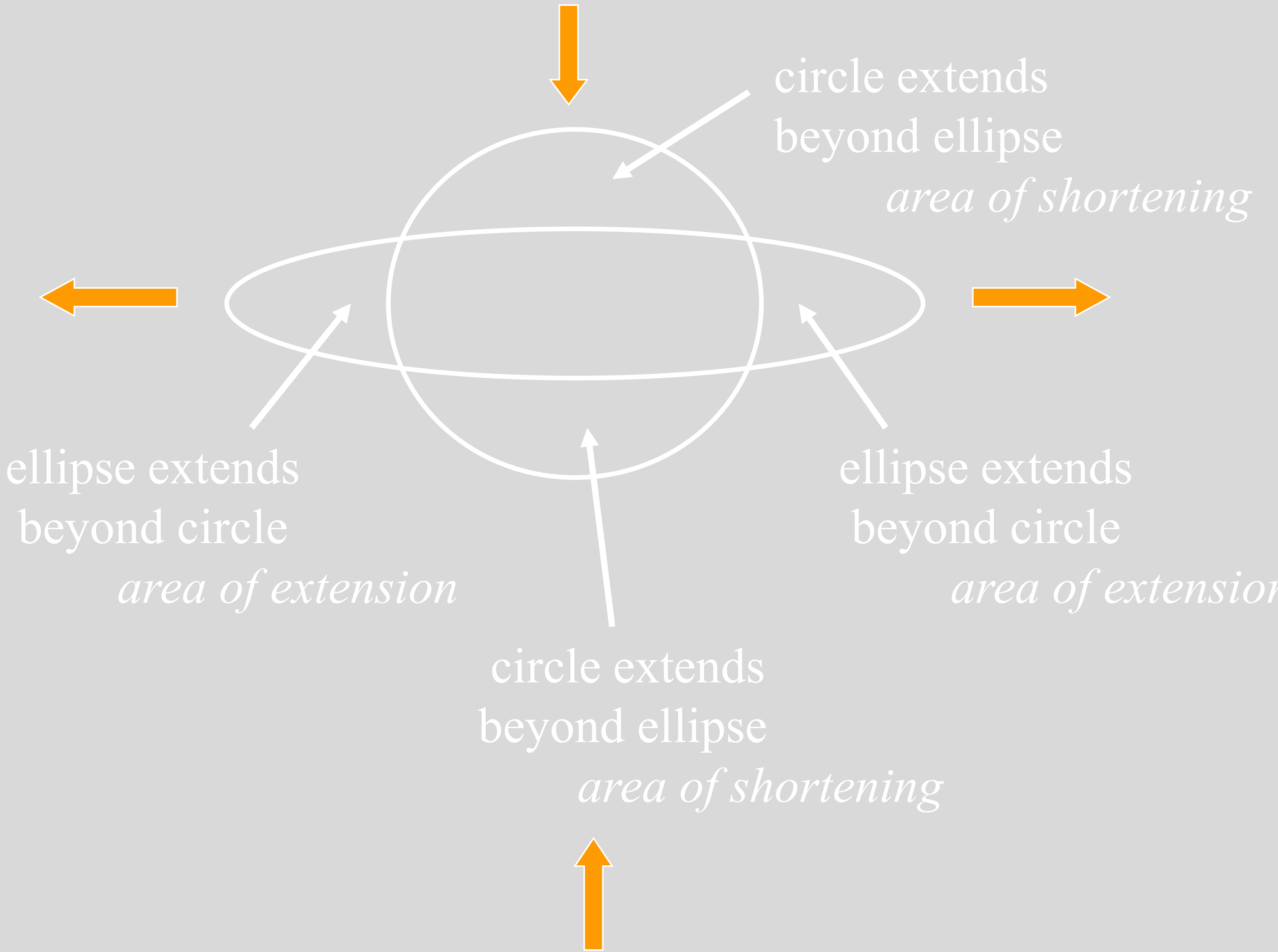
trans rot dis

dis trans rot

*important: deformation does not equal strain*
*…strain only part of deformation*

most of the time, strain is all we can measure…
need external reference frame to determine translation, rotation
(can use paleomagnetism to infer)

*what does the strain ellipse tell us?*



# Basement Fabrics: foliations and lineations

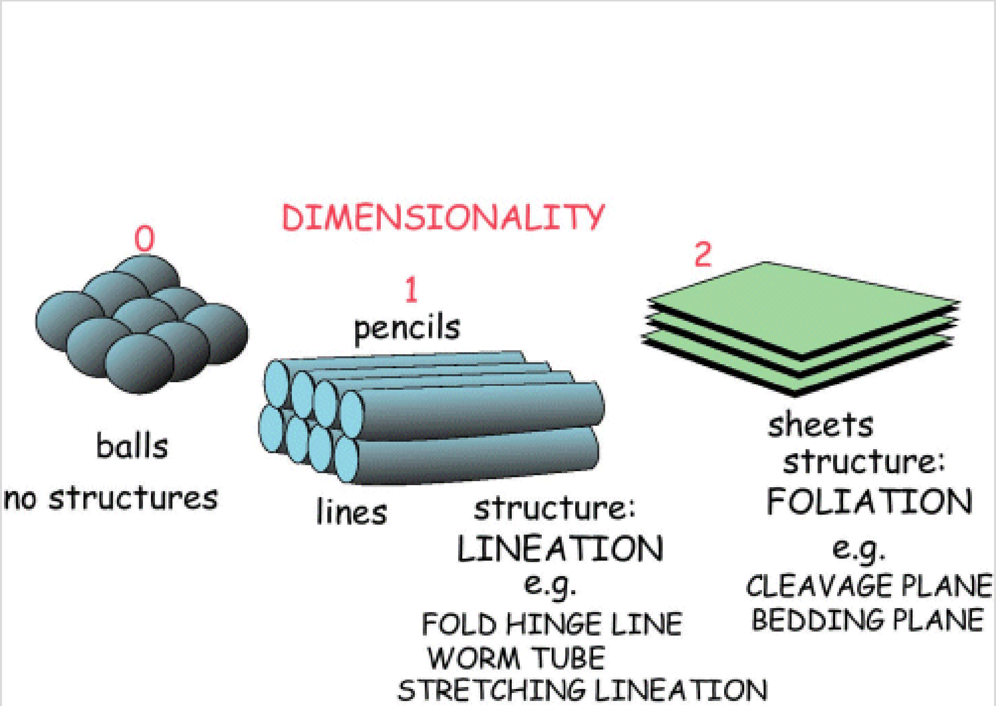
# Fabrics: foliations and lineations

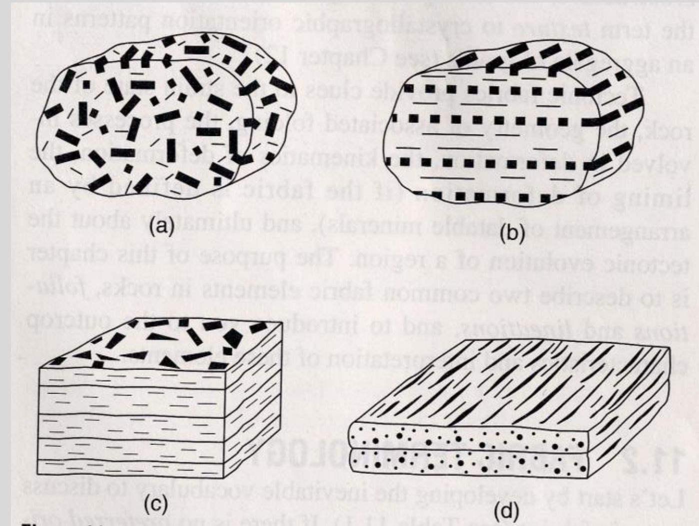
fabric: geometrical arrangement of component features in rock
(grain shape, grain size, grain configuration);
…features are fabric elements….
mineral grains, clasts, layers, fold hinges, etc.

primary fabric: form during formation of rock
tectonic fabric: form as consequence of tectonic deformation

two common tectonic fabric elements: foliations and lineations

No preferred orientation (0 and a): random fabric
undeformed sandstone, granite, basalt, etc.



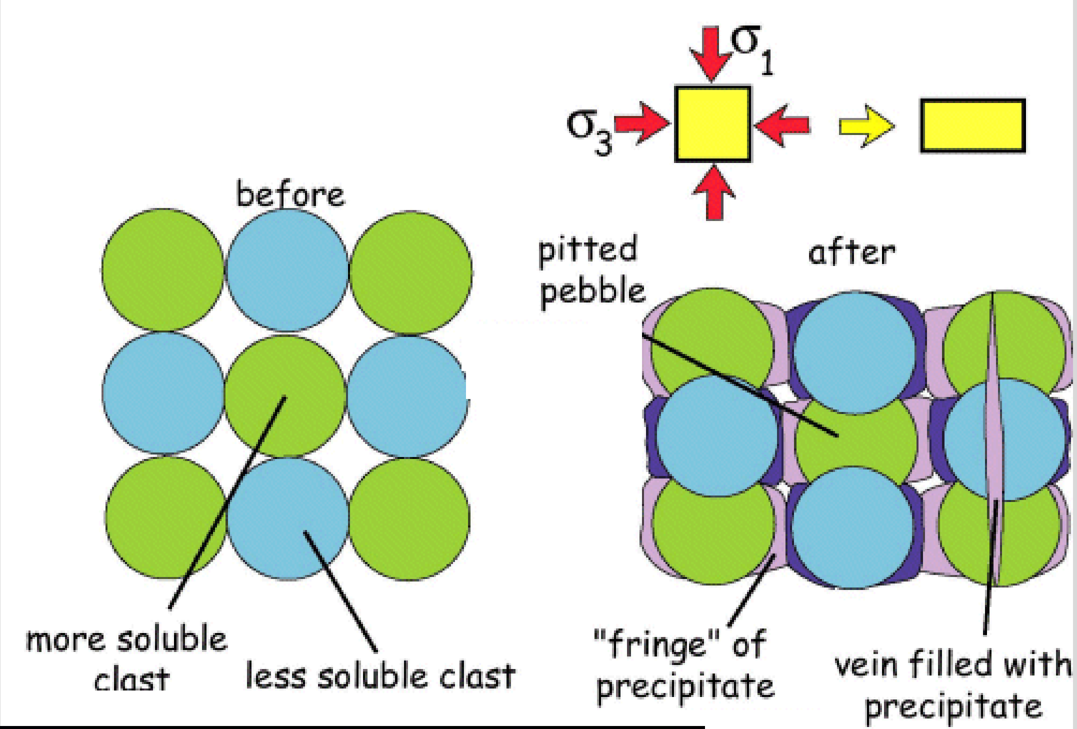



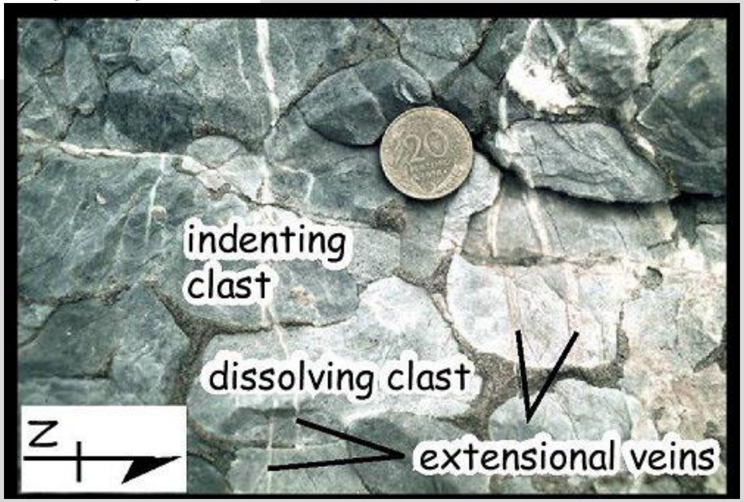

nonrandom, or, preferred fabric: deformed rocks where elements are aligned in some way (b)…

…lineation is a linear fabric (1 and d)

…foliation is a planar fabric (2 and c)

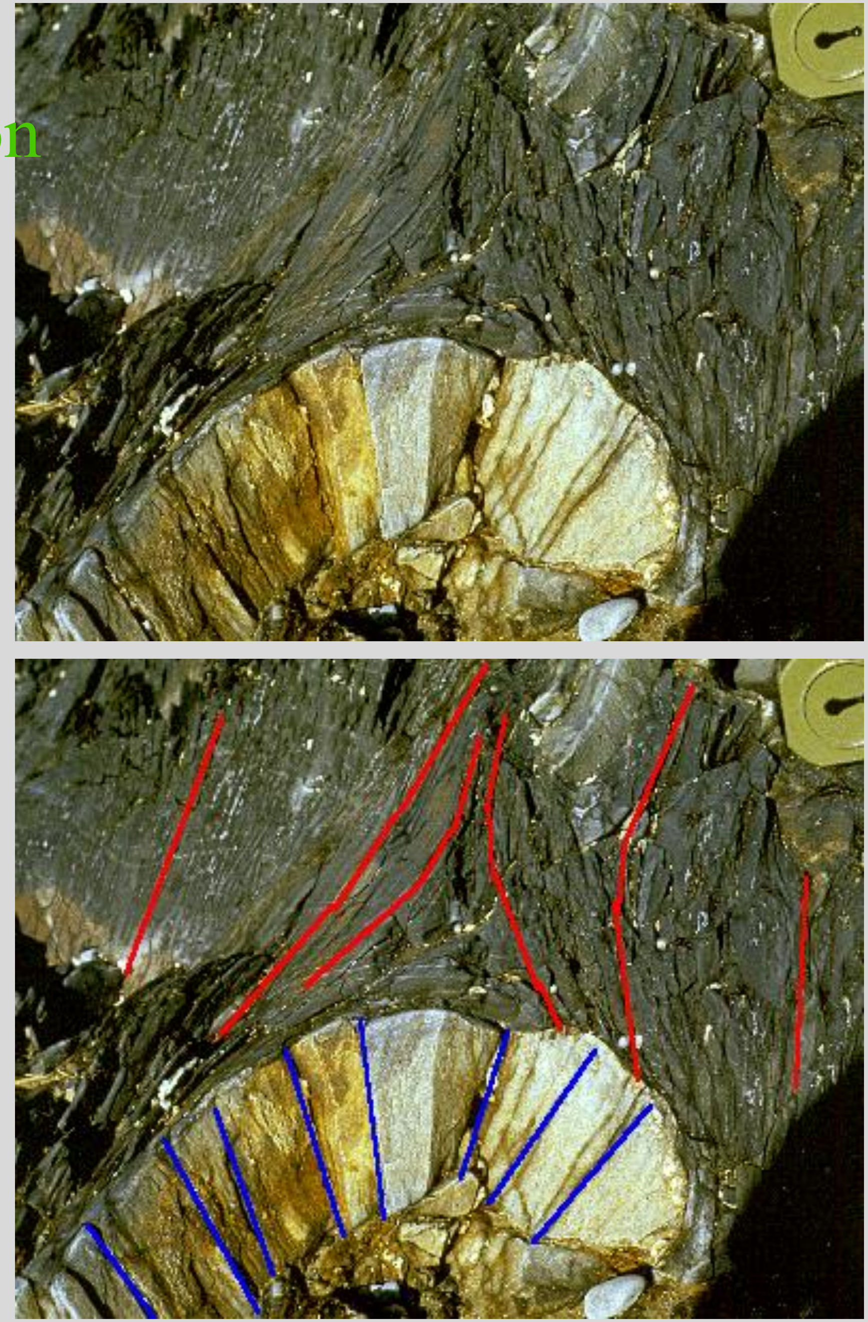
# Pressure solution

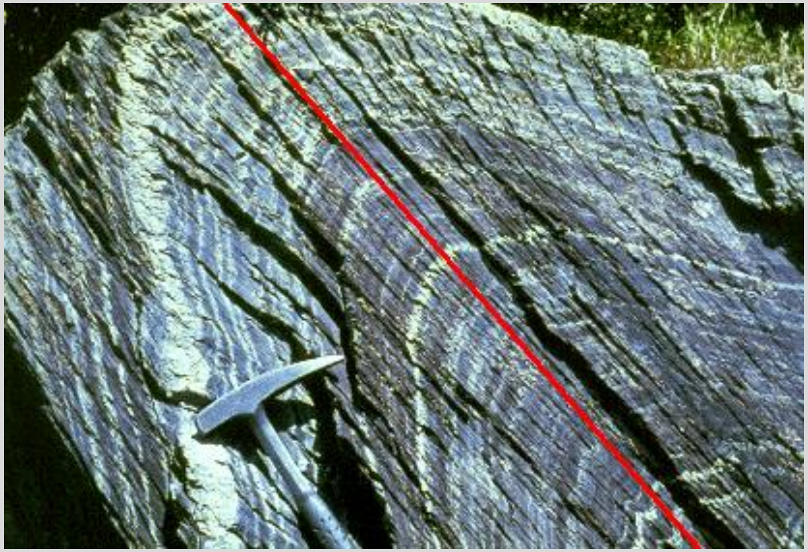


# Cleavage fans and refraction

*sandstone and shale*

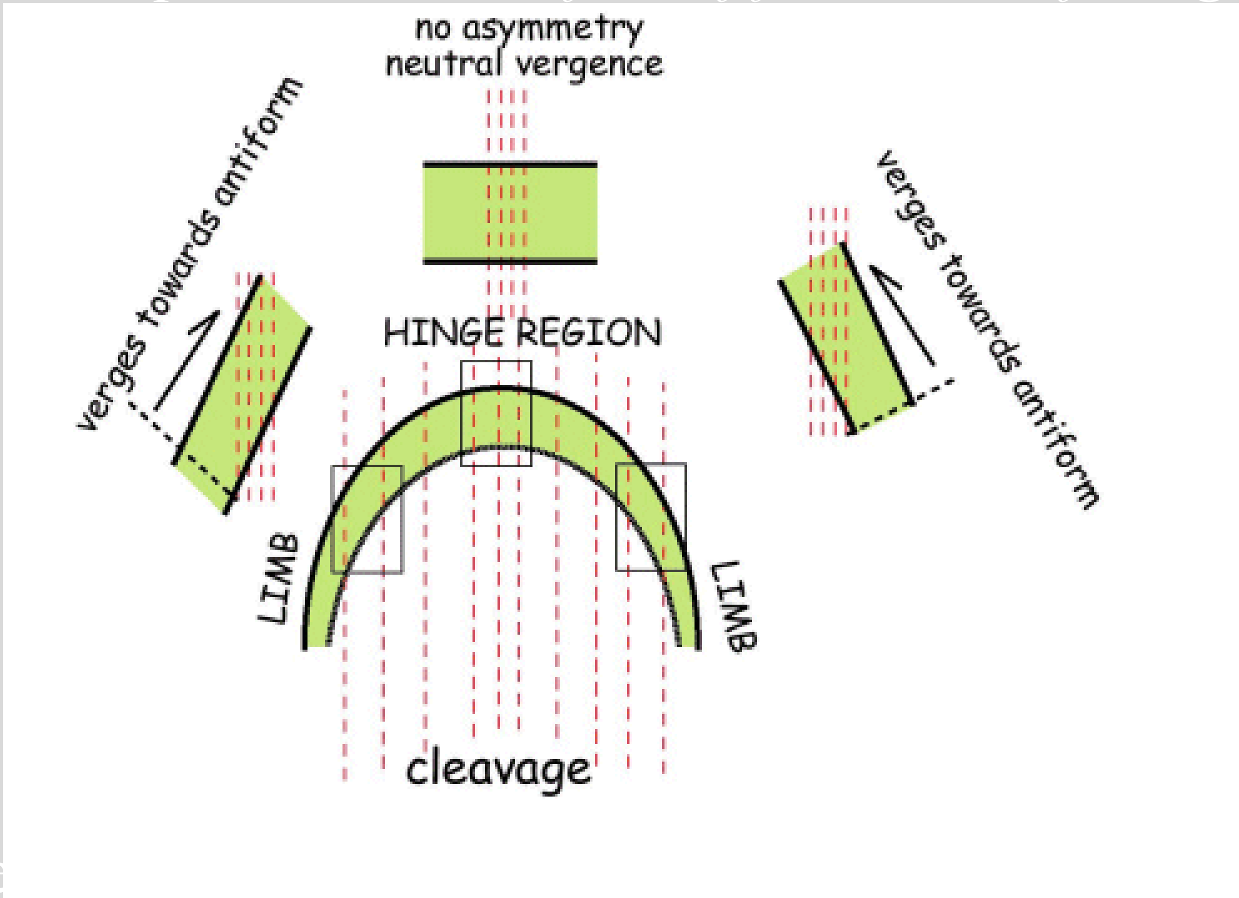




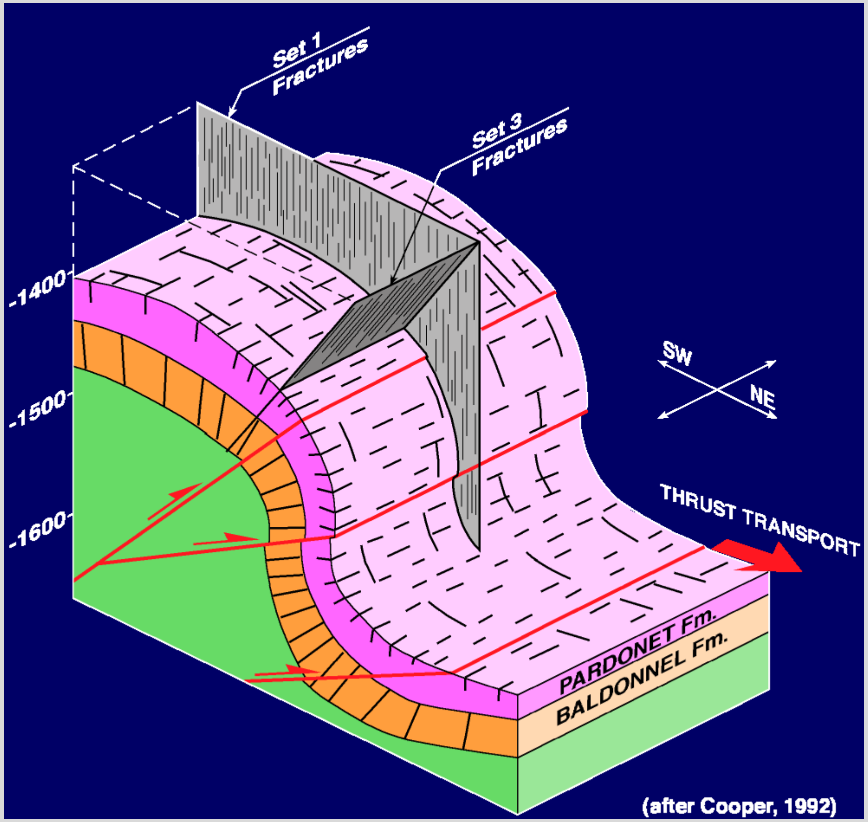
*axial planar cleavage in shale (little fanning)*

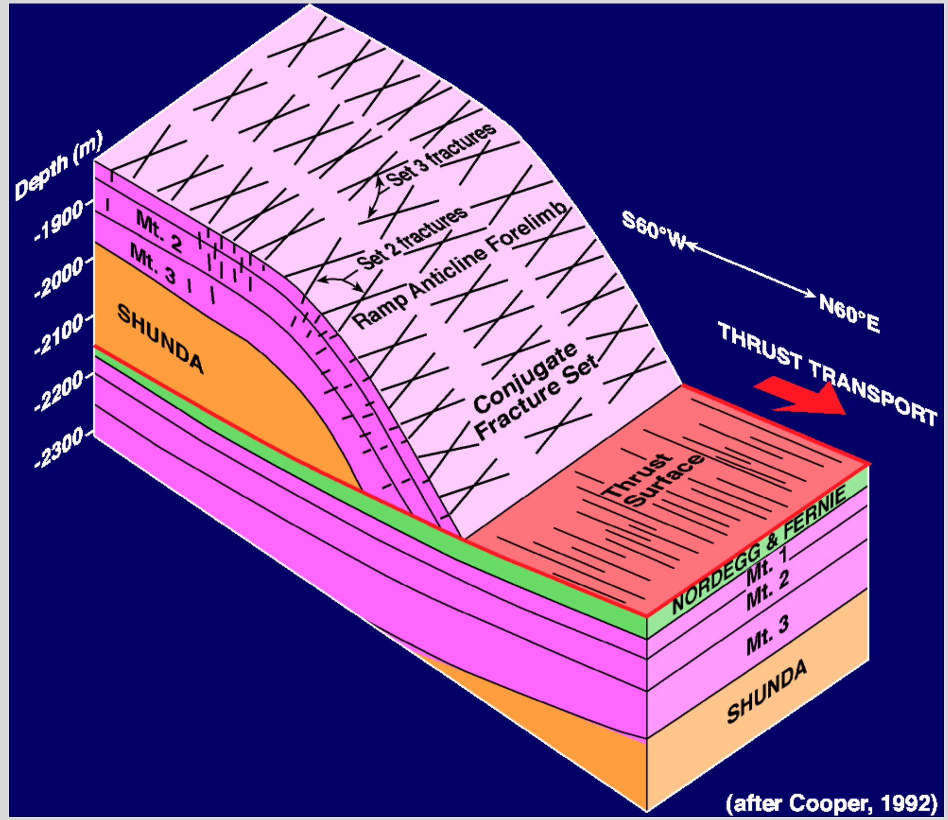
# Cleavage-bedding geometry

*cleavage "vergence" relative to bedding*
*yields information on position of rocks*
*with respect to axial surface of fold and on facing of folds*




(note: inte … old axis;
…must be because cleavage is parallel to axial surface)


Set 1
Fractures
Set 3
Fractures
-1400
-1500
-1600
SW
NE
THRUST TRANSPORT
PARDONET Fm.
BALDONNEL Fm.
(after Cooper, 1992)


Depth (m)
-1900
-2000
-2100
-2200
-2300
Mt. 2
Mt. 3
SHUNDA
Set 3 fractures
Set 2 fractures
Ramp Anticline Forelimb
Conjugate
Fracture Set
S60°W
N60°E
THRUST TRANSPORT
Thrust
Surface
NORDEGG & FERNIE
Mt. 1
Mt. 2
Mt. 3
SHUNDA
(after Cooper, 1992)

# Brittle Deformation; Fracture Mechanics

Bryce Canyon

Monument Valley

southeastern Utah has a spectacular landscape of pillars and arches

….defined by joints

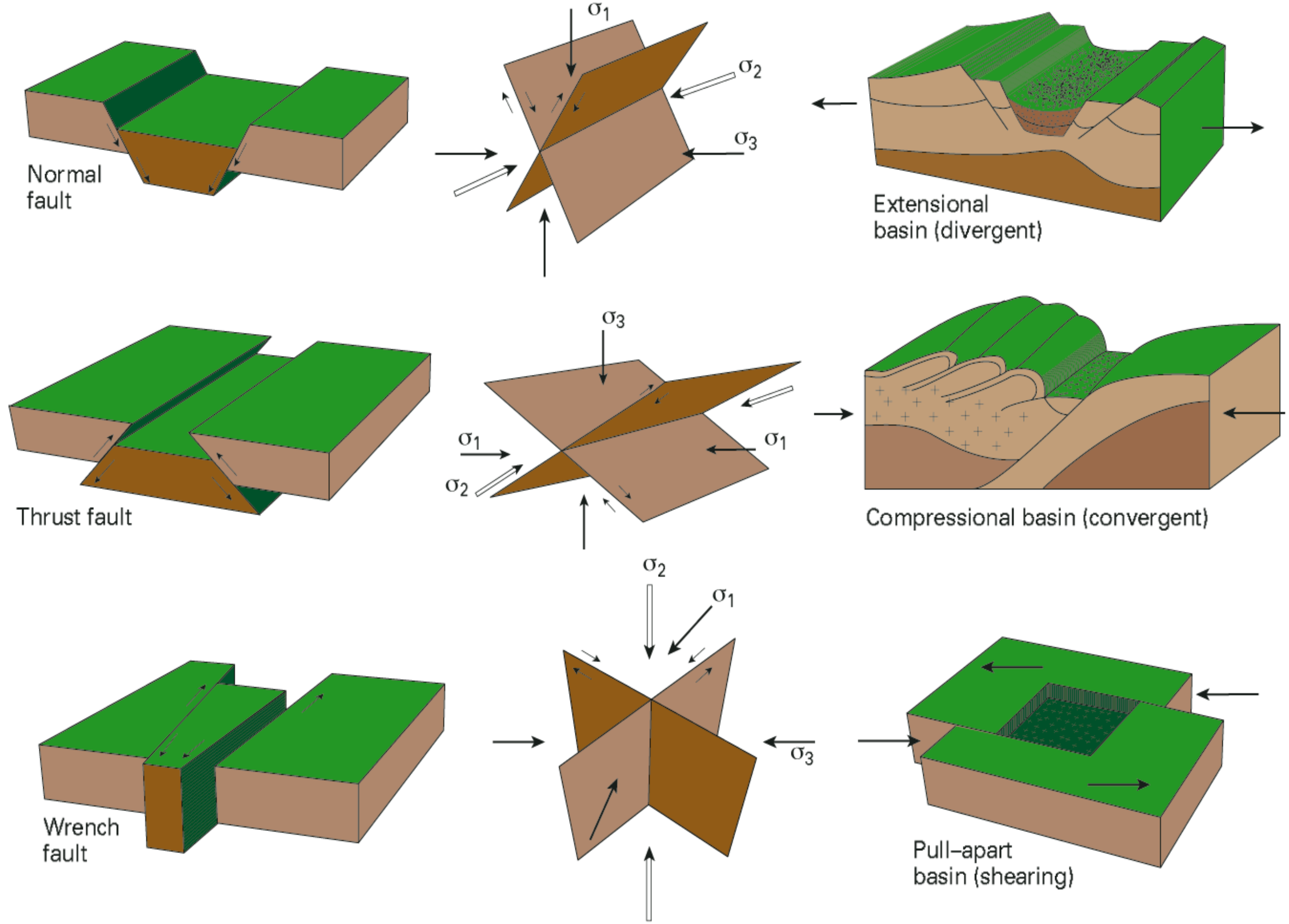
…natural fractures (cracks) in rocks which are

planar (or curviplanar) and unfilled and

across which no shear displacement has occurred

(shear displacement)

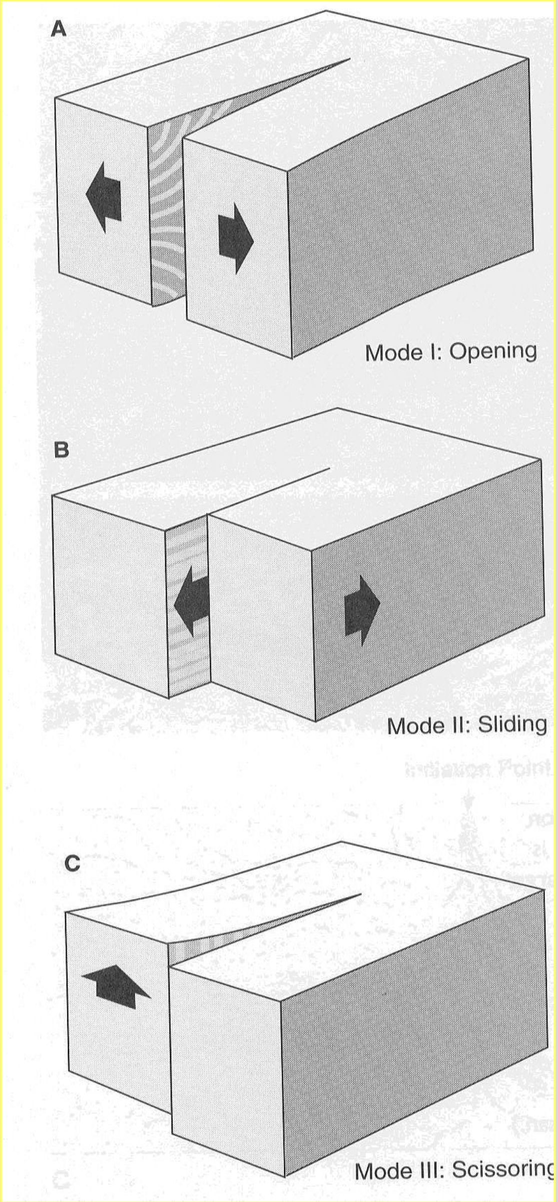
# Fracture Prediction ~ Fault related trends



# Types of fractures (cracks)

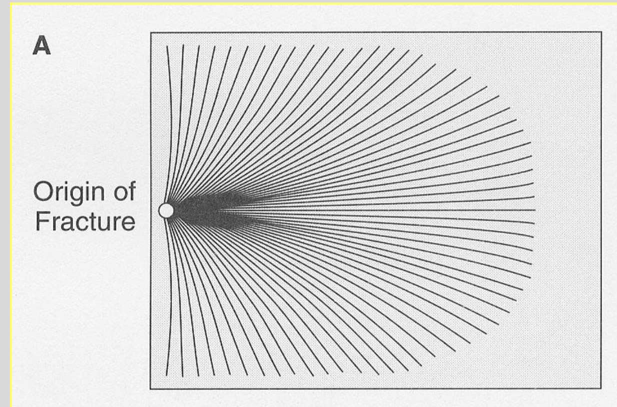
*three fundamental fracture modes*
*...end members to describe any*
*combination of motions*

Mode I: opening perpendicular to
fracture surface
…joints
Mode II: sliding in direction parallel
to fracture surface
…shear fractures
Mode III: scissoring parallel to fracture
surface and fracture front




from: Davis and Reynolds, 1996

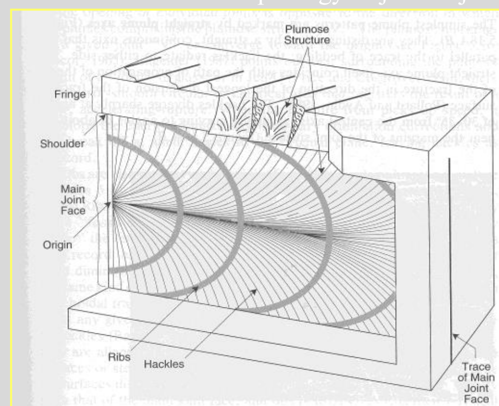
# Plumose structure




hackles

direction of propagation

surface morphology of joints:  joint face is not smooth




looks like
feather imprint
spreads outward
from origin
of joint

plumose structure
(ribs and hackles)

# Joint arrays are groups of joints

*systematic*: group of joints parallel to each other that maintain same spacing over region of observation

*non-systematic*: irregular spatial distribution; they are not parallel to neighboring joints; tend to be nonplanar



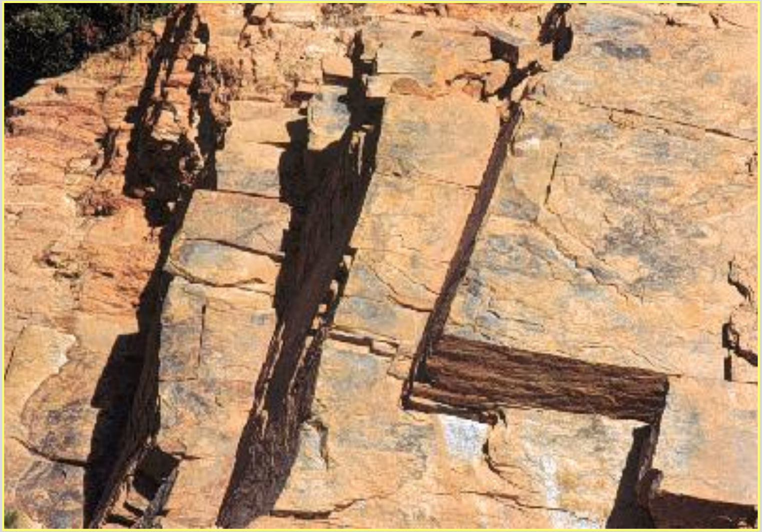

*joint set*: group of systematic joints

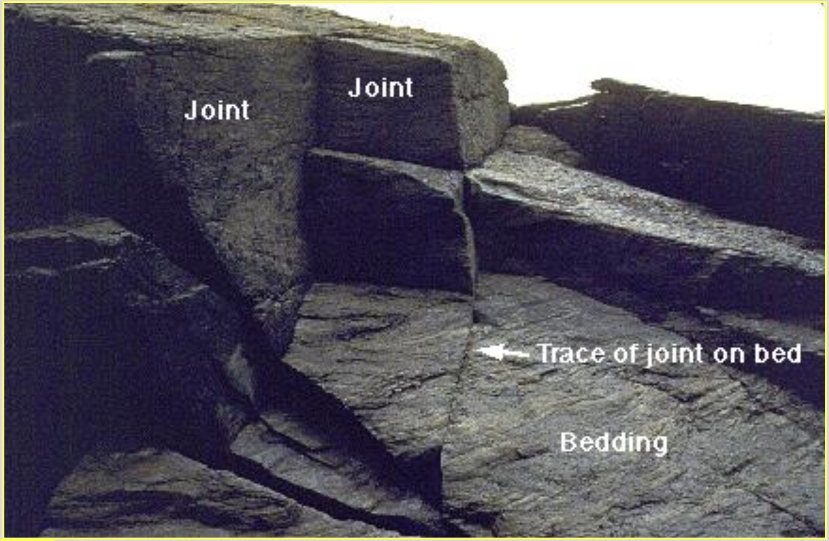
--two or more joint sets intersect at constant angles: *joint system*

--angle between two joint sets in system: *dihedral angle*

--two sets in system that are perpendicular (i.e. dihedral angle is 90°) they are an *orthogonal system*

--two sets in system that intersect at low angles (i.e. dihedral angle is 30-60°) they are a *conjugate system*



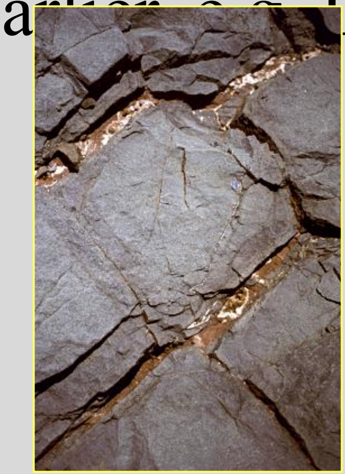



orthogonal joint sets

many different configurations of joint systems occur:

- orthogonal
- conjugate
- sigmoidal
- columnar (discussed earlier, e.g. Devil's Tower)

sigmoidal



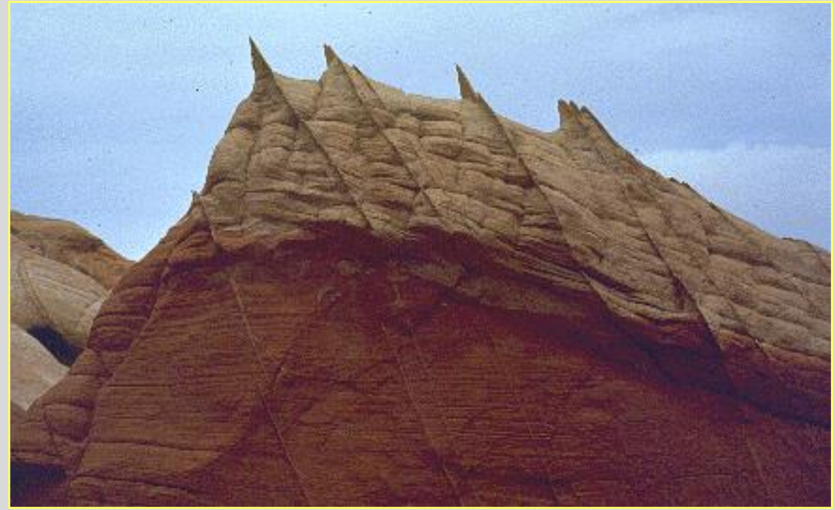
columnar (cooling)

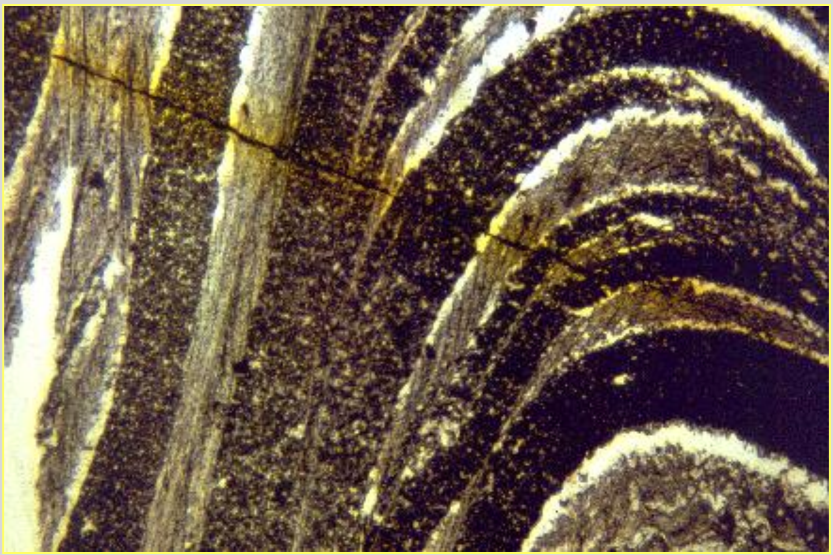
distinguished from each other by nature of intersections and length of joints in different sets

if one set cuts outcrop and is longer → master set

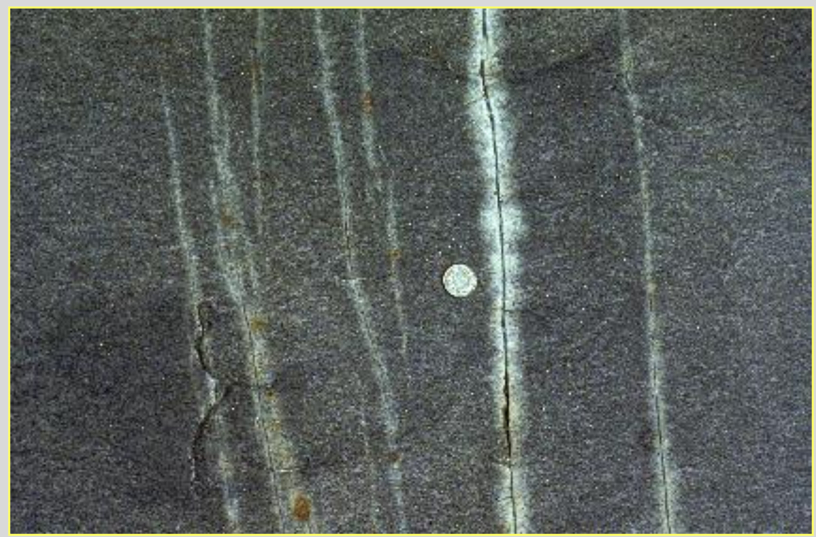
shorter set that terminates at longer → cross joints

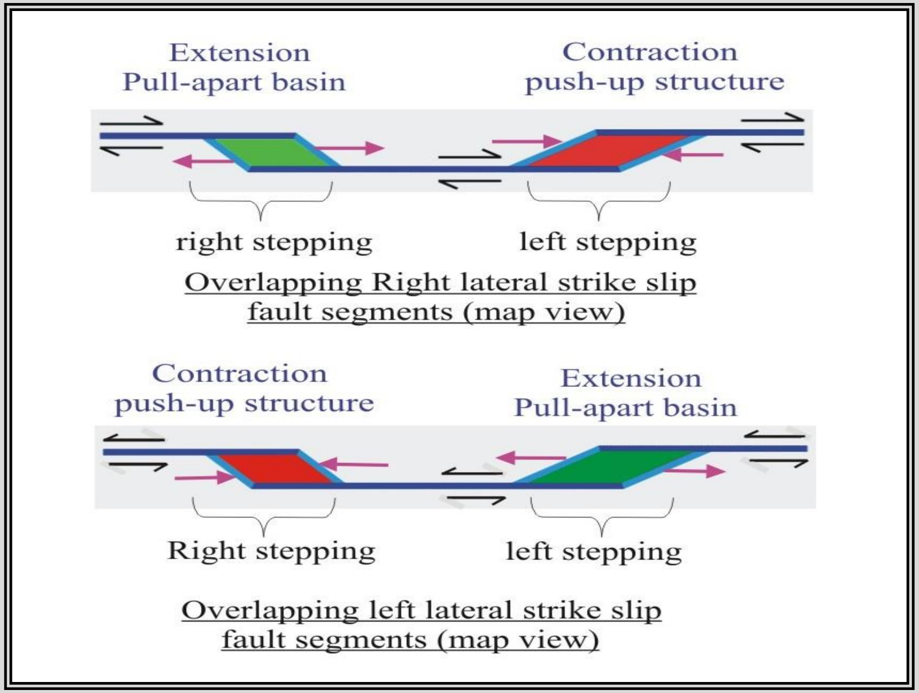
joints can fill with fluid….
formation of veins





yellow is iron-staining

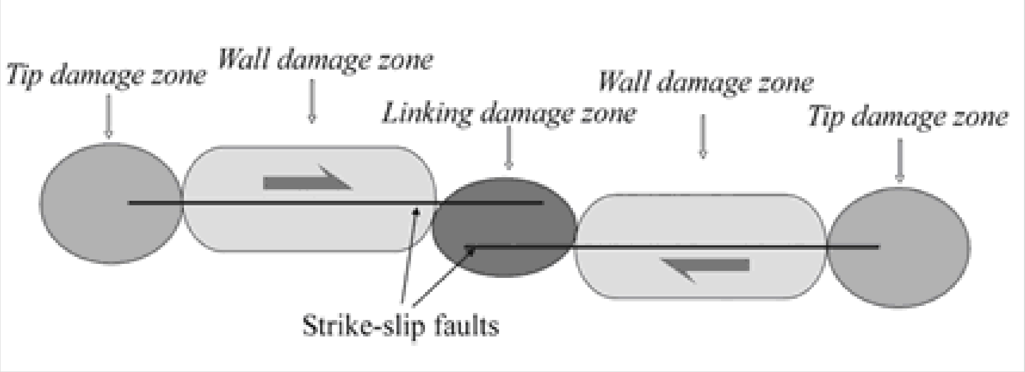


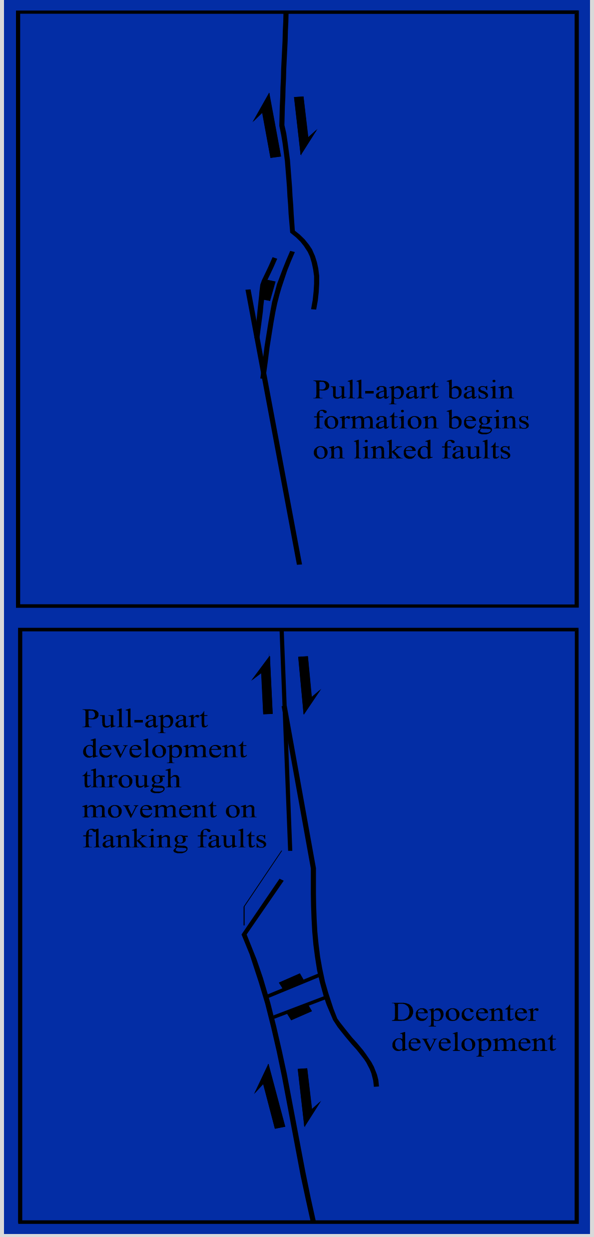


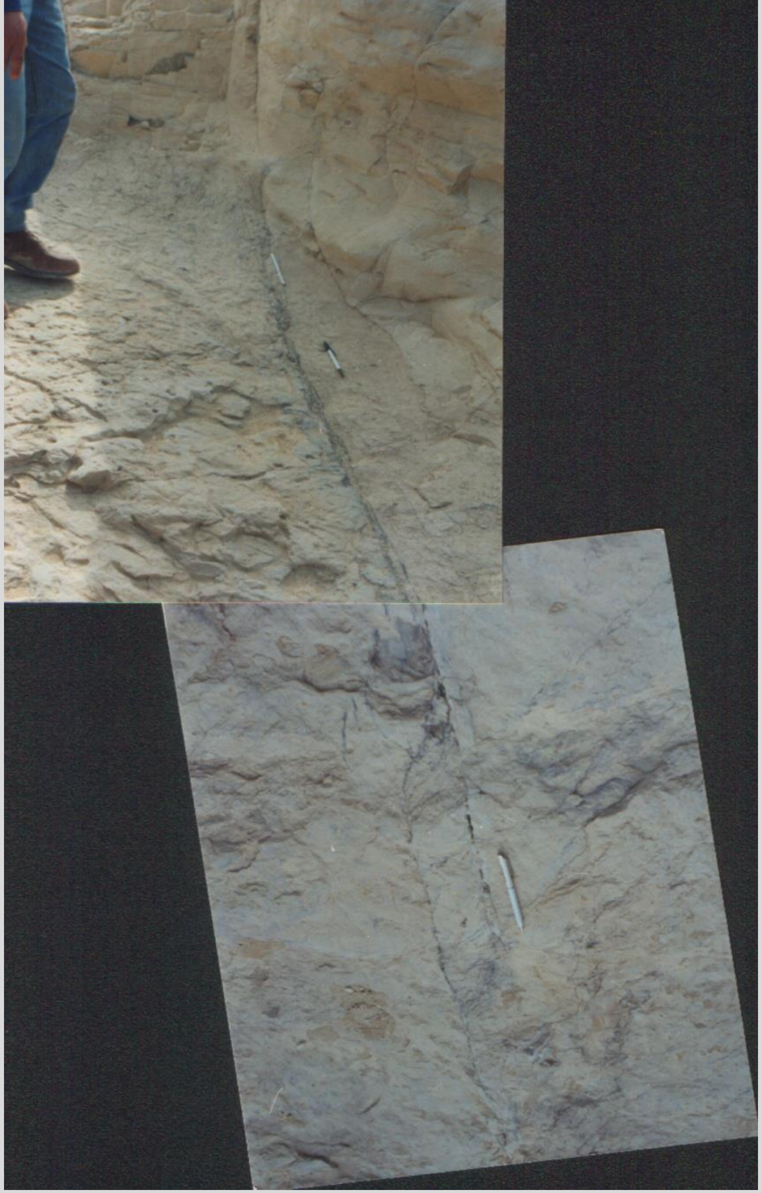

# Damage Zones

Schematic diagram of the principal locations of damage zones around a strike-slip fault zone in map view.

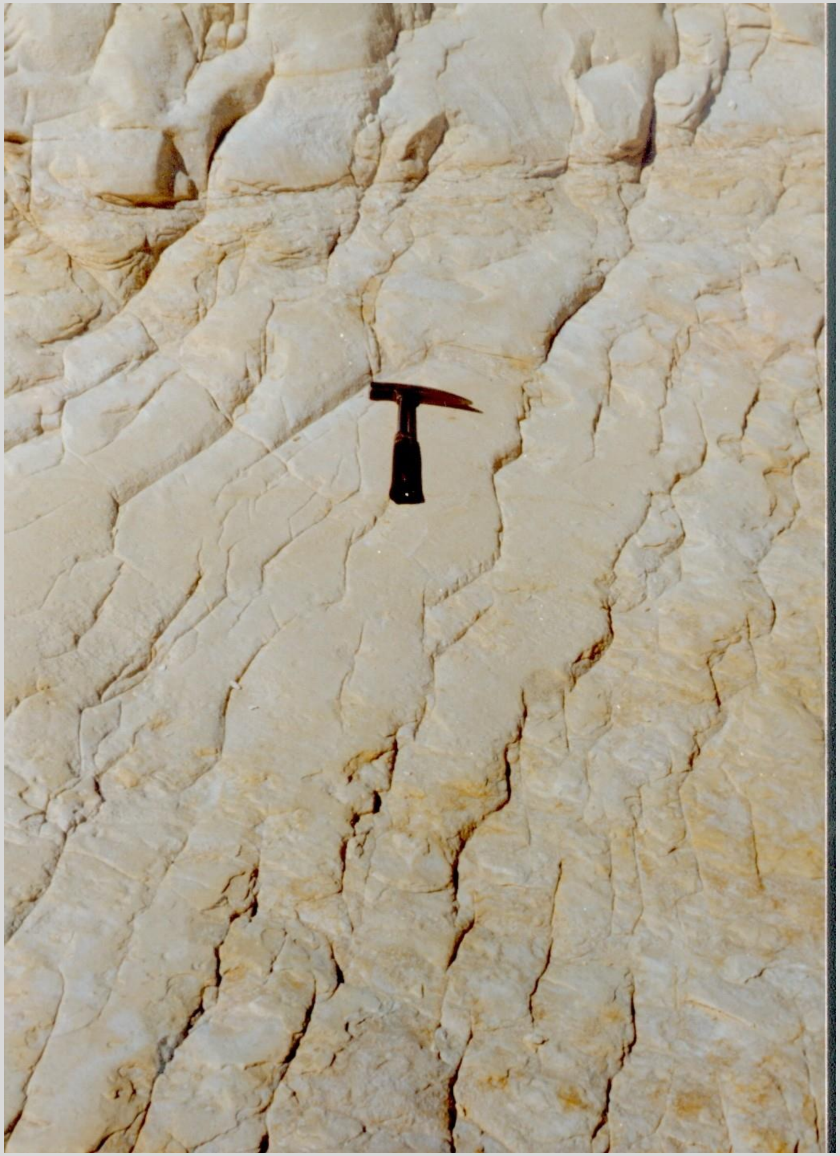
Fault damage zones are zones of intensive cracking and crushing along fault planes and in-between fault segments. Damage zone structures include enechelon extension fractures, antithetic faults, synthetic faults, and rotated blocks with associated triangular openings. The impact of such damage zones on the Aqaba-Amman district is as much important as that of the main faults themselves.





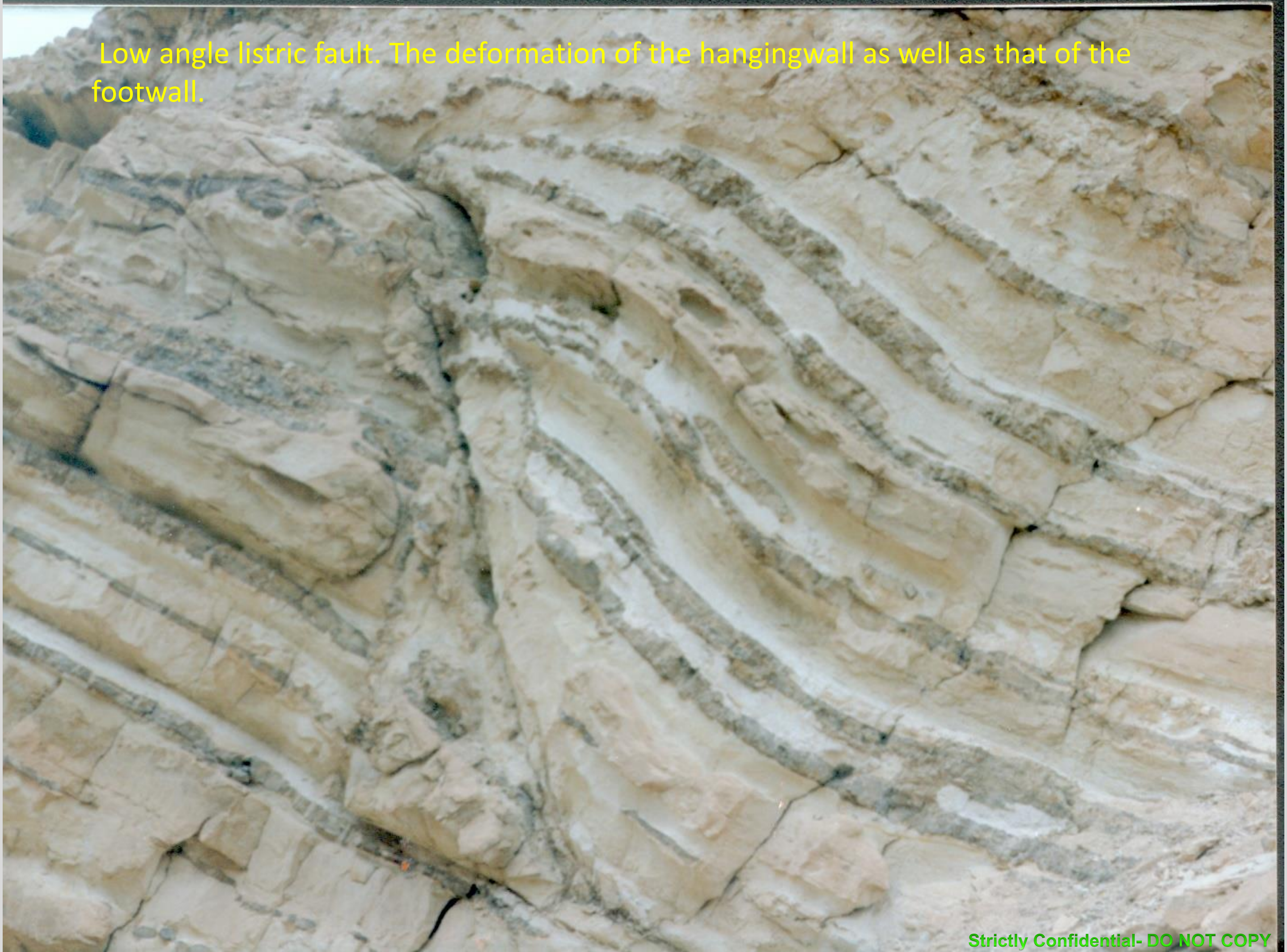
Two fracture systems propagate from the down point of the photo, and then one takes the response, whereas the other decays and dissipates its stresses along the major one. Note that at the point of linkage, many fractures will propagate due to the small difference of the stress trajectory.



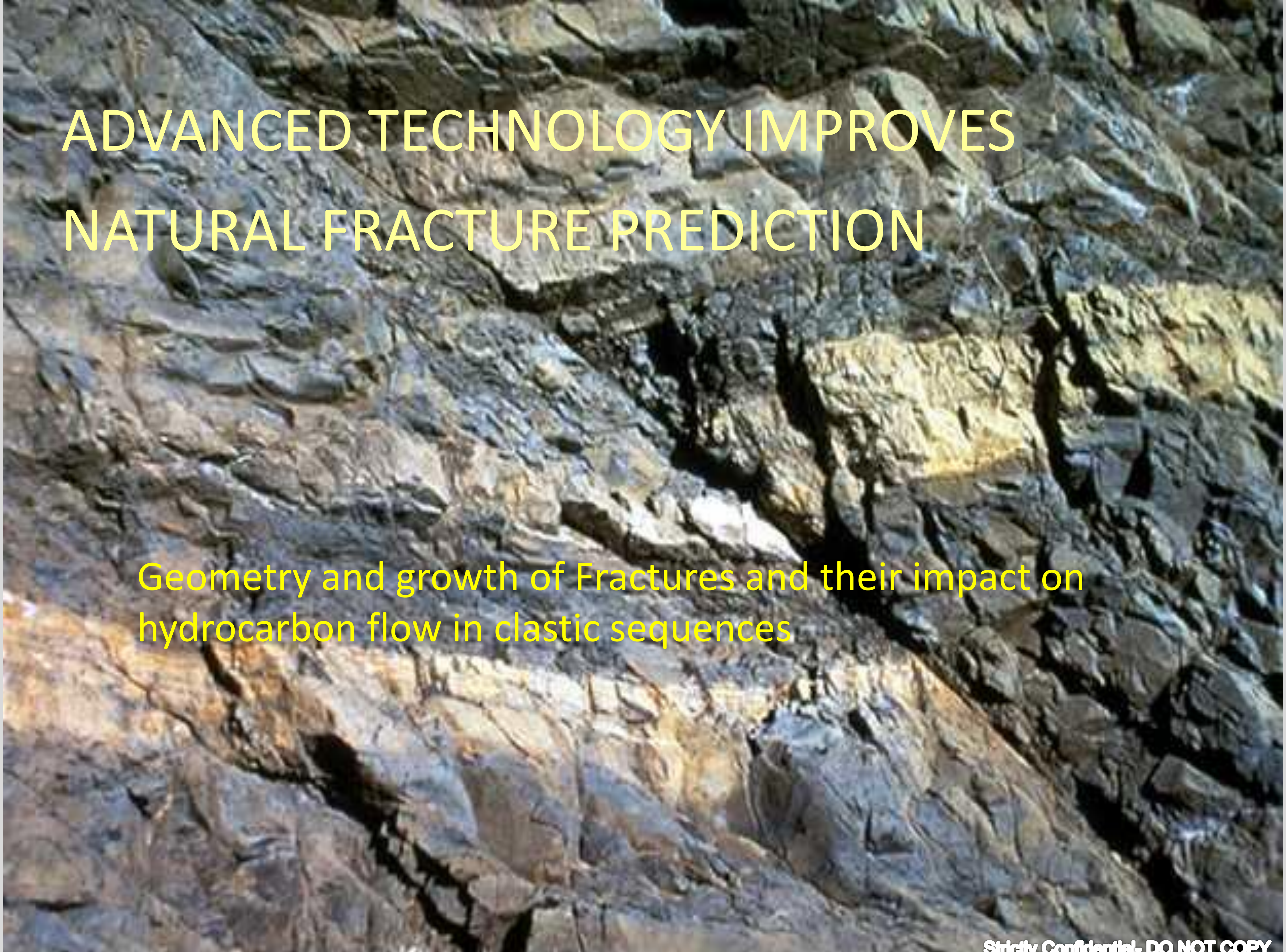
En-èchelon arrays of zigzag-shaped fractures.

# Exercise: Interpret

Twisted fractures. The fractures coalesce together and dissipate their stresses to one another.



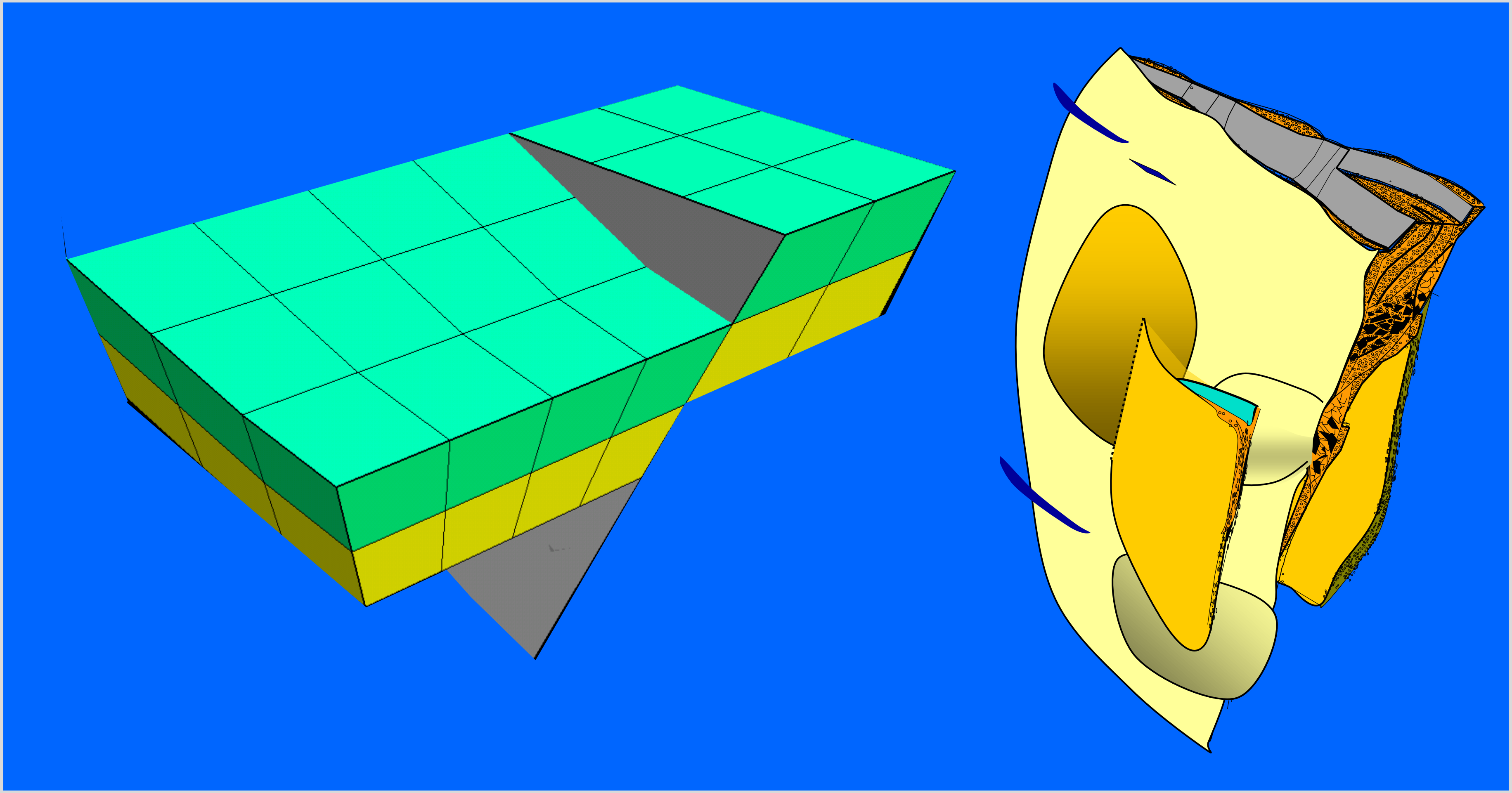
Low angle listric fault. The deformation of the hangingwall as well as that of the footwall.



# ADVANCED TECHNOLOGY IMPROVES NATURAL FRACTURE PREDICTION

Geometry and growth of Fractures and their impact on hydrocarbon flow in clastic sequences

If faults were planes, flow assessment would be relatively easy!

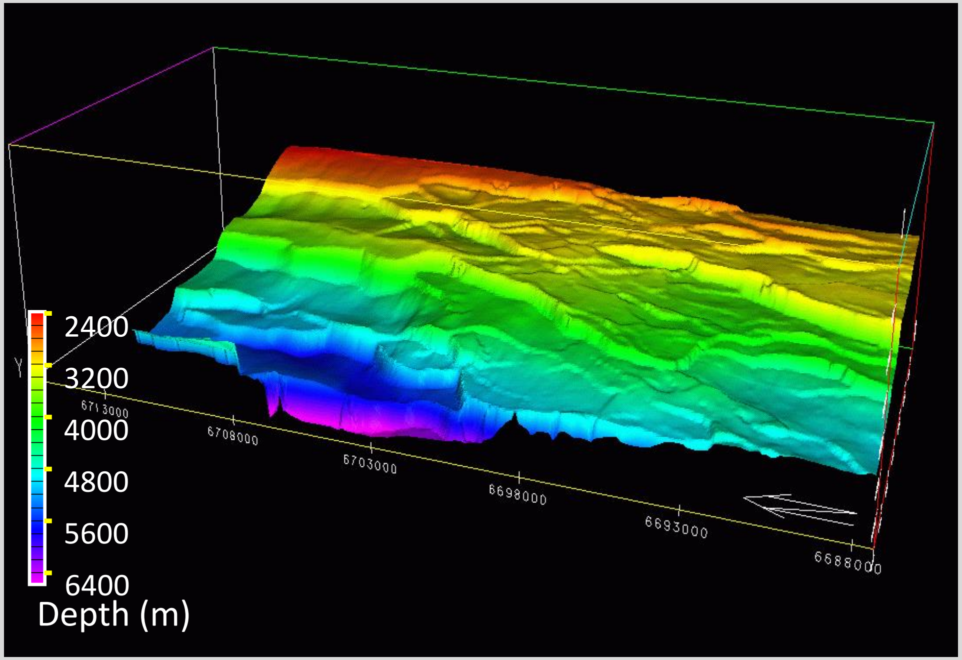


Fault zones include fault rocks that can severely impact flow.

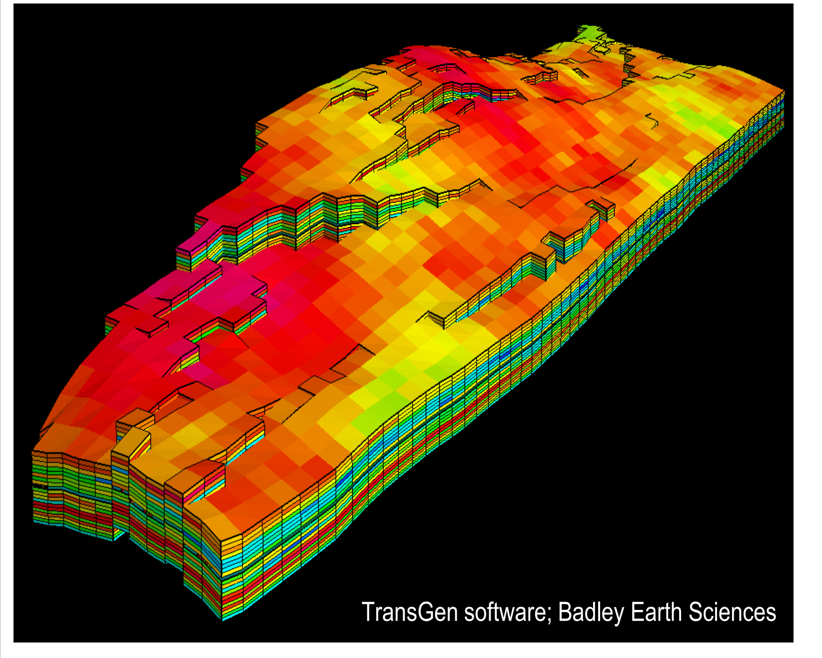
Fault rocks in high permeability clastics decrease flow.

So whatever the hydrocarbon flow issue we require predictive and modelling capabilities.

Migration - Traps




Production - Reservoir




Purpose of talk is to describe fault zones and methods for their inclusion in flow models.

Three separate talks:

(i) Internal structure, growth and properties of fault zones in siliciclastic sequences.

(ii) Faults in migration modelling.

(iii) Faults in production modelling.

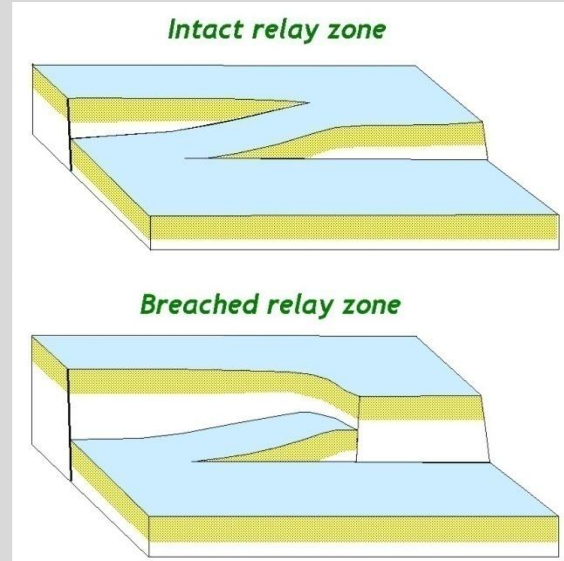
# Factors important for controlling flow

Fault zone structure & fault rock thickness

Fault rock continuity

Fault rock poroperm properties

# Fault zone widening – tip-line bifurcation

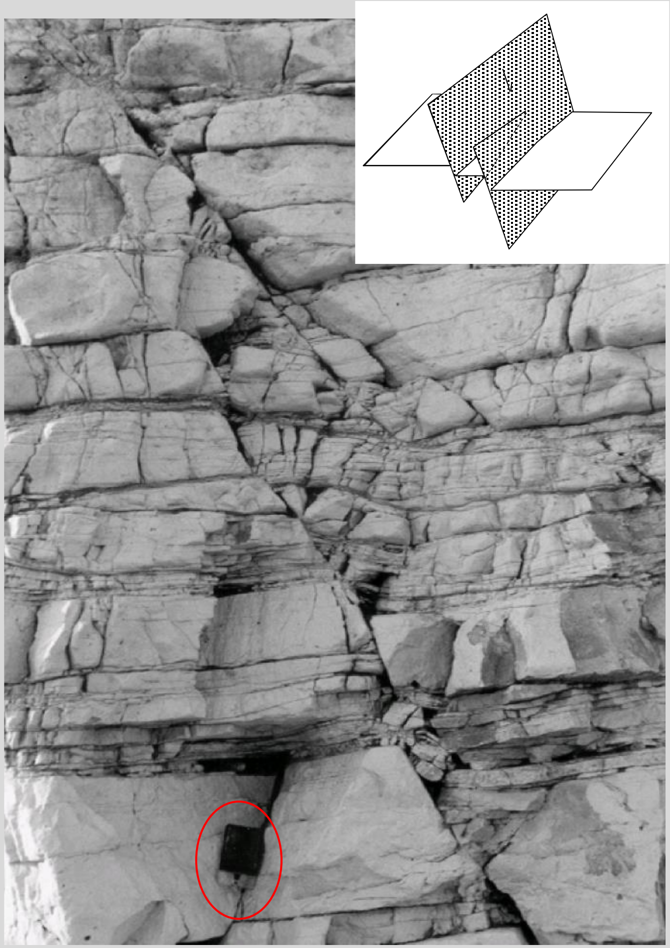






Segmentation will ultimately generate lenses of variably deformed fault rock.

# 3-D segmentation and refraction - promote fault zone widening.

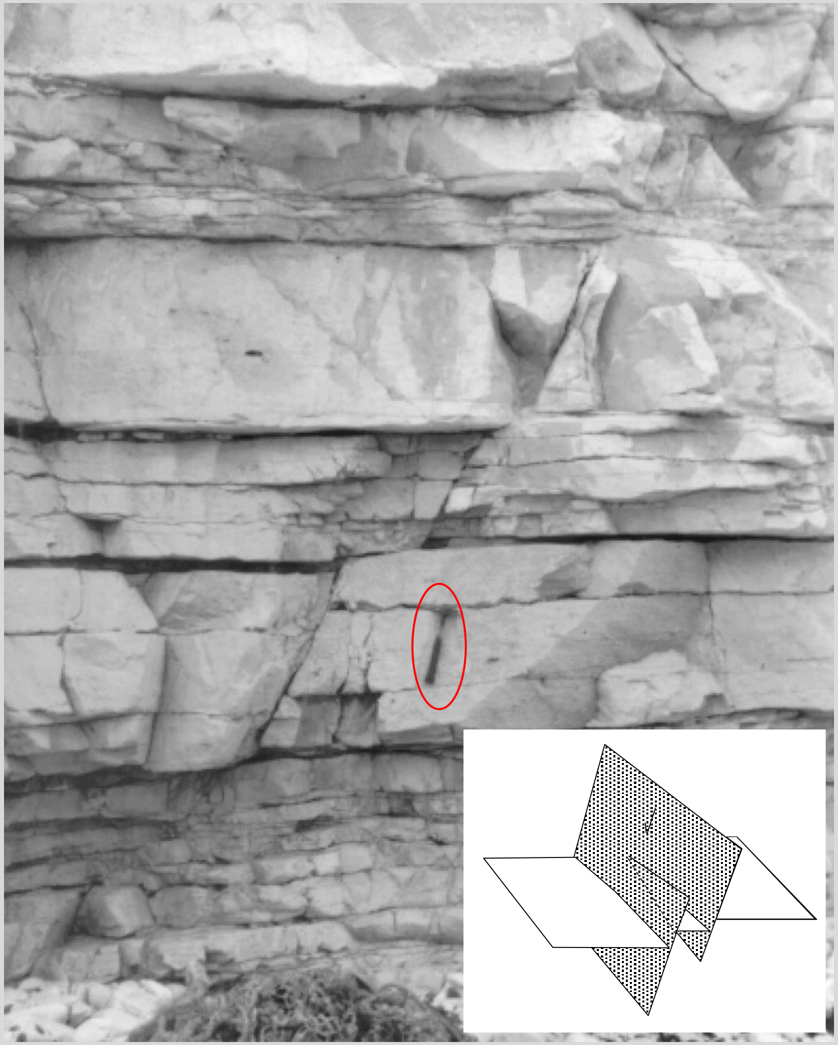


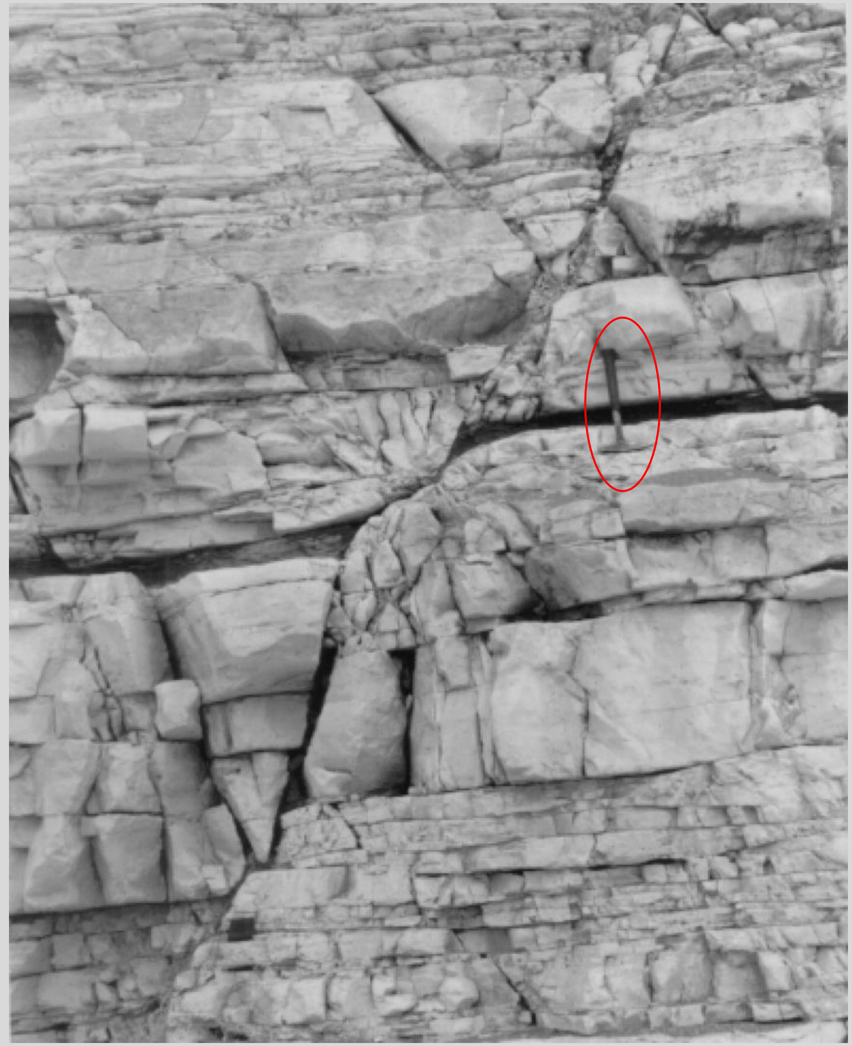
Danes Dyke, Flamborough Head, UK

Kilve, Somerset, UK

Refraction through different layers plays important role.

# Refraction/segmentation and fault zone widening





Danes Dyke, Flamborough Head, UK

# Factors important for controlling flow

Fault zone structure & fault rock thickness

Fault rock continuity

Fault rock poroperm properties

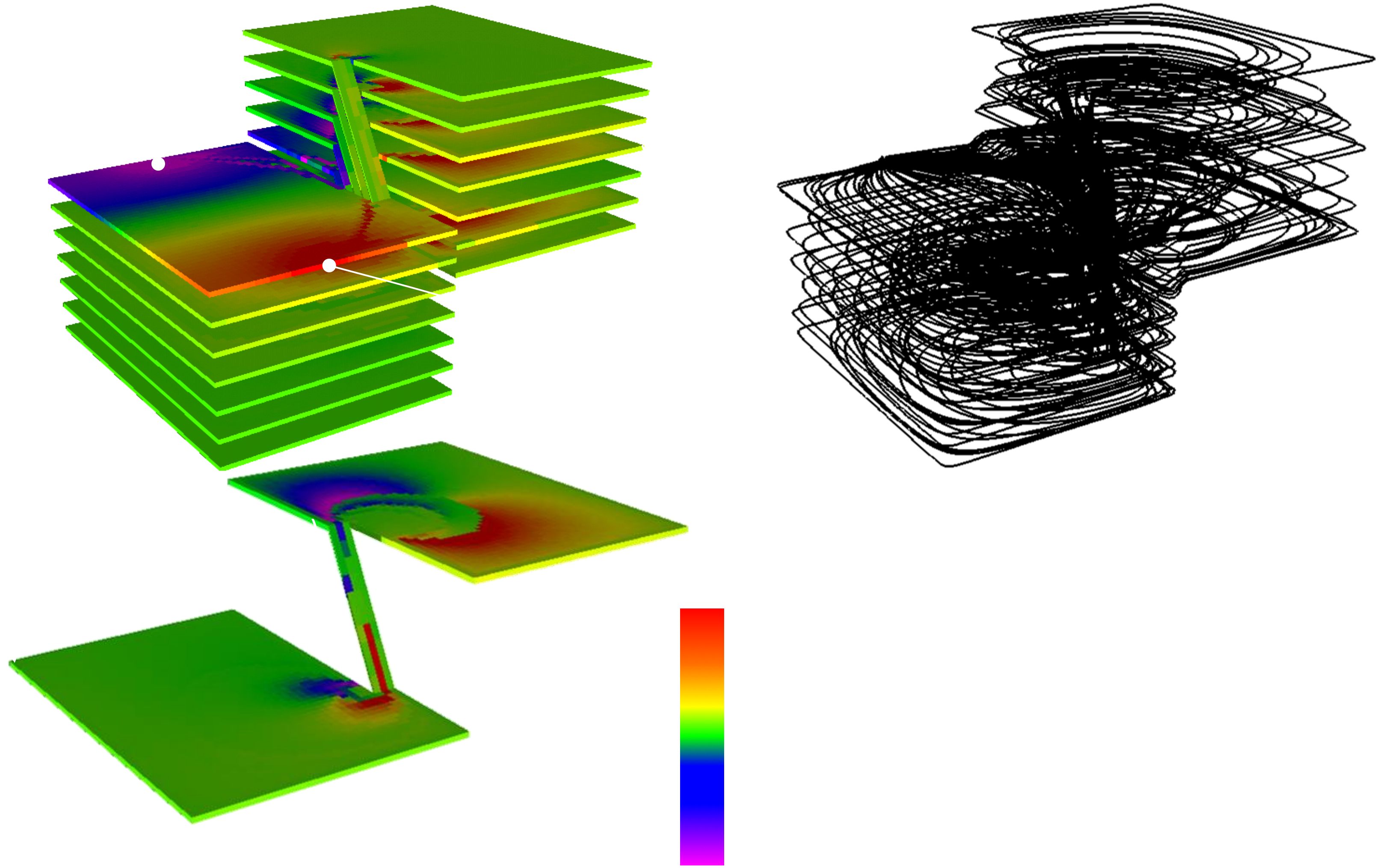
Fault rock thickness is related to fault displacement.

Shaley fault rock is relatively continuous and its presence is either predictable or is amenable to stochastic modelling.

Fault shale fraction (Shale Gouge Ratio) is correlated to fault rock permeability and threshold pressures.

The above observations form the basis for the inclusion of faults in hydrocarbon migration and production models.

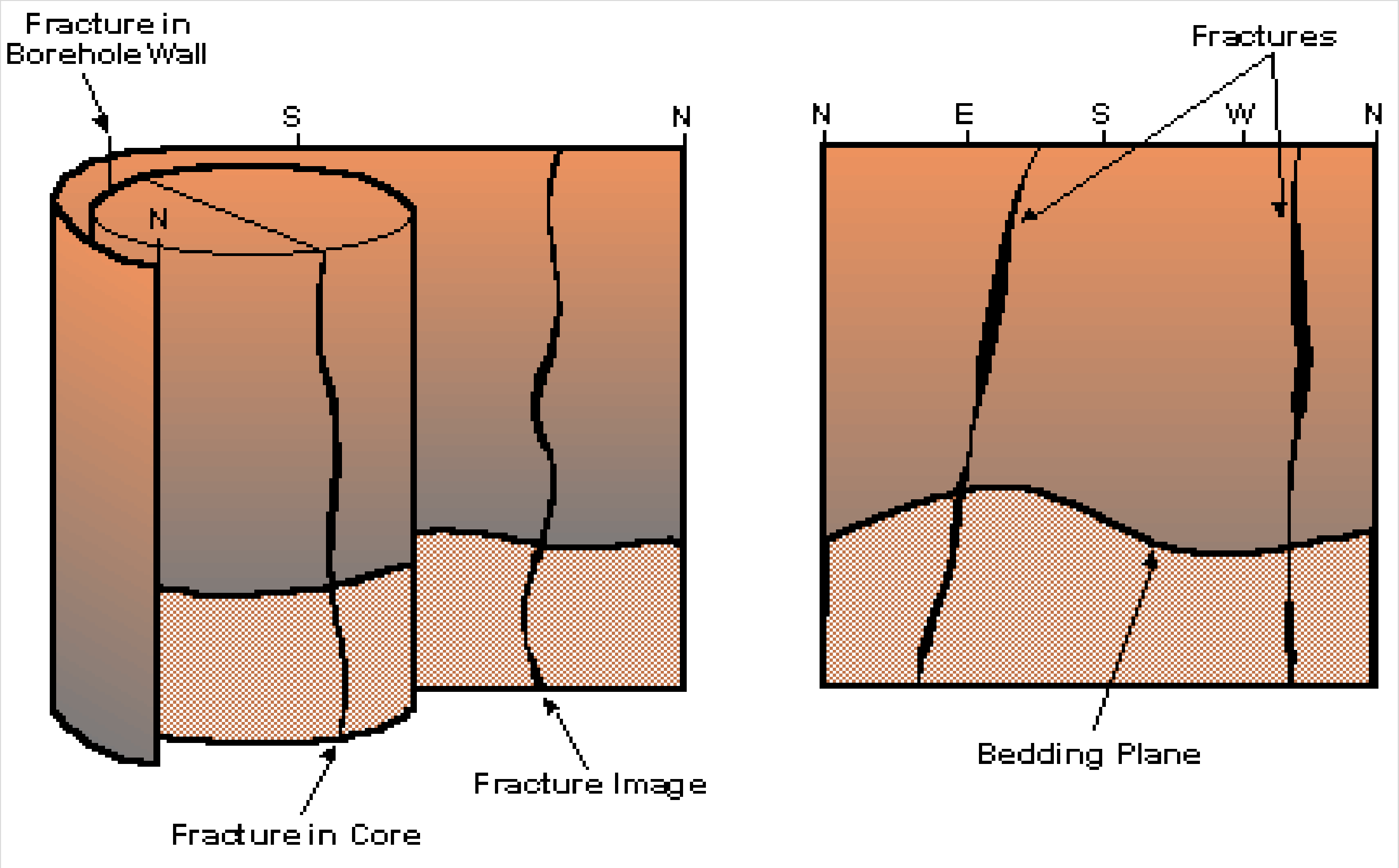
# Fault relay provides thoroughly 3D flow



# Fracture Identification

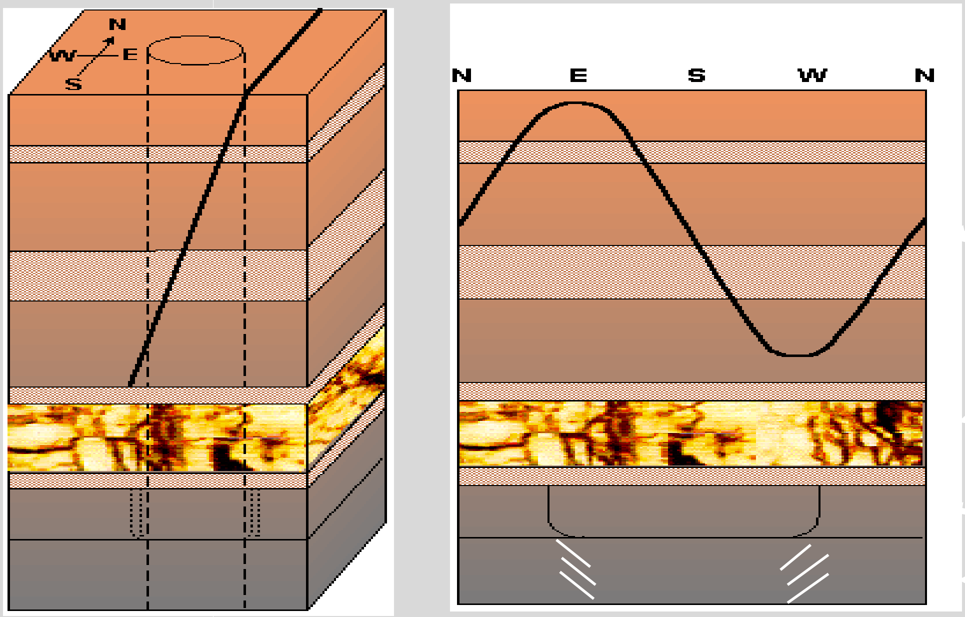
# Fractures

- Natural *open, mineral-filled, or vuggy* ;
- polygonal;
- mechanically induced.




Unwrapped Image of Borehole Wall

# Fracture Identification

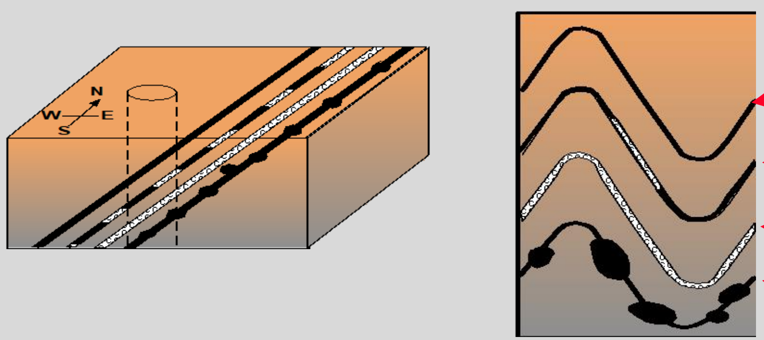



Natural - angles from 60° to vertical

Polygonal

Mechanical:
Hydraulic
Stress

Fracture Morphology (Open, Mineral-Filled, Vuggy)



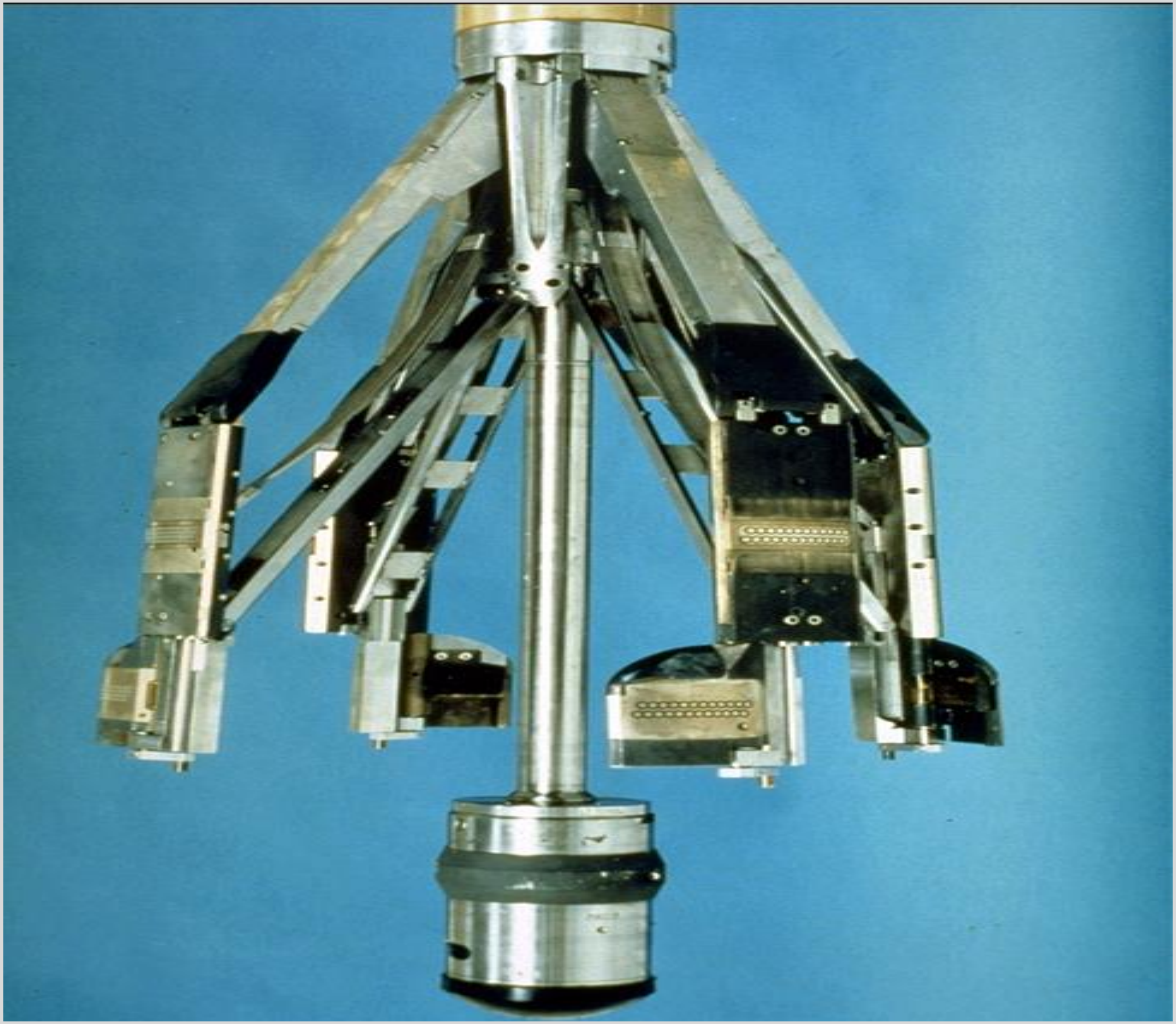

Open

Partially filled

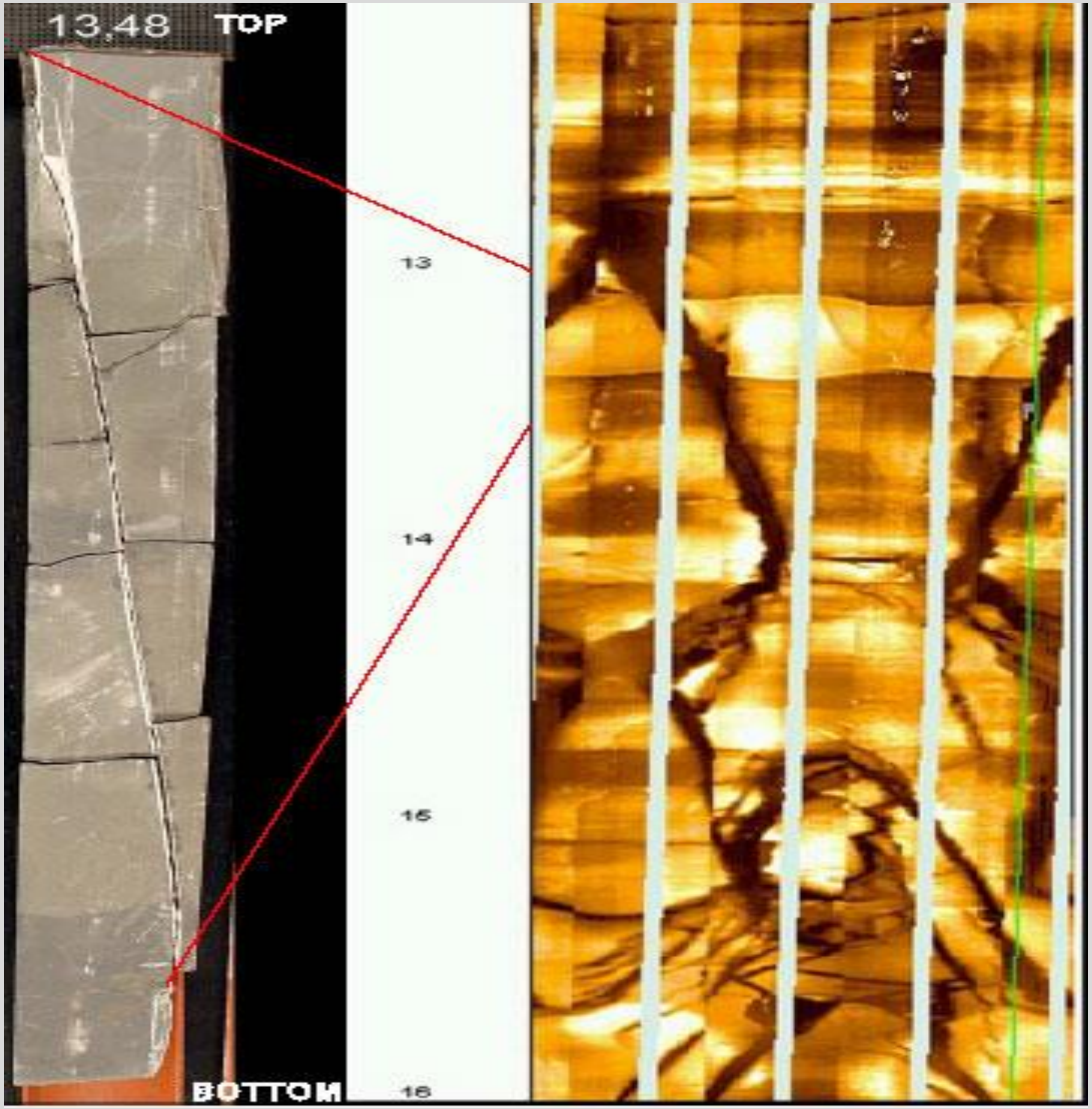
Mineral filled

Solution enhanced (vuggy)

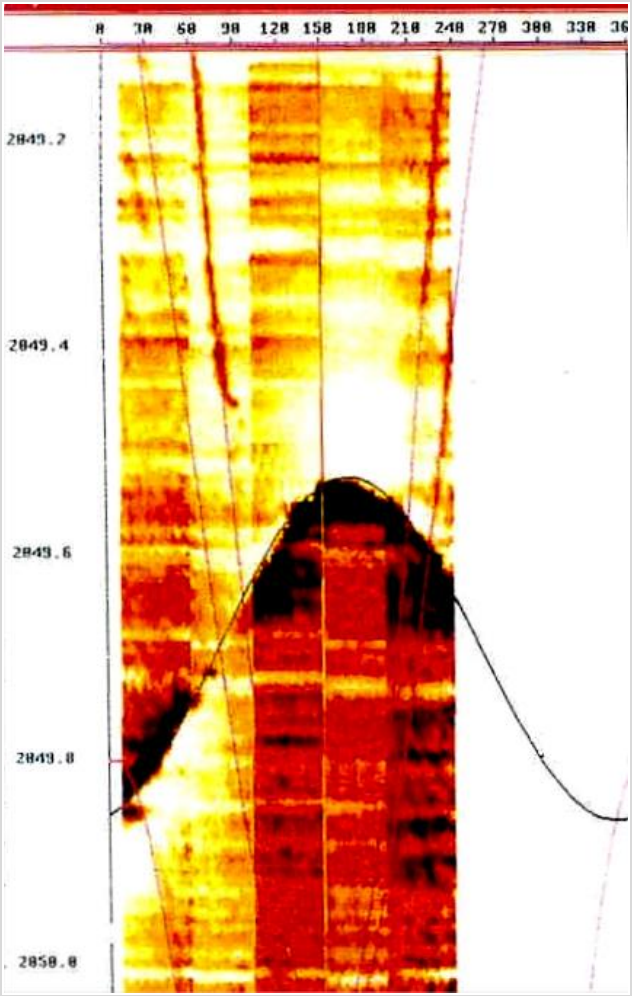
# Formation MicroScanner Tool

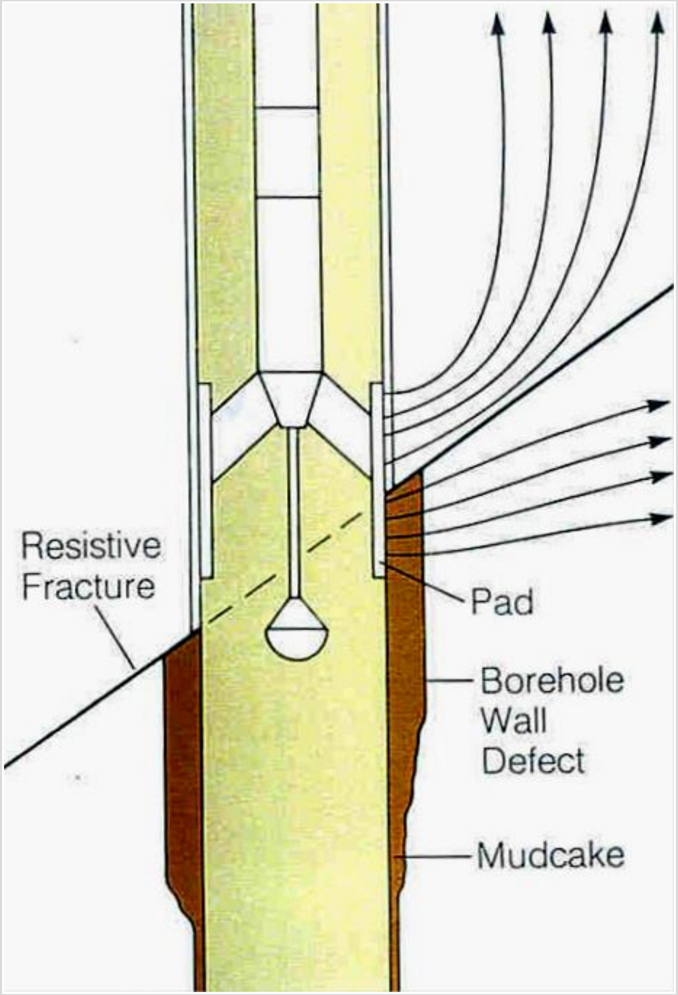


# FMI



# Fractures Resistive


Halo effect around a mineralized fracture in a Shale

# Fracture Aperture Calculation

$$W = c \cdot A \cdot Rm^{b} \cdot Rxo^{1-b}$$

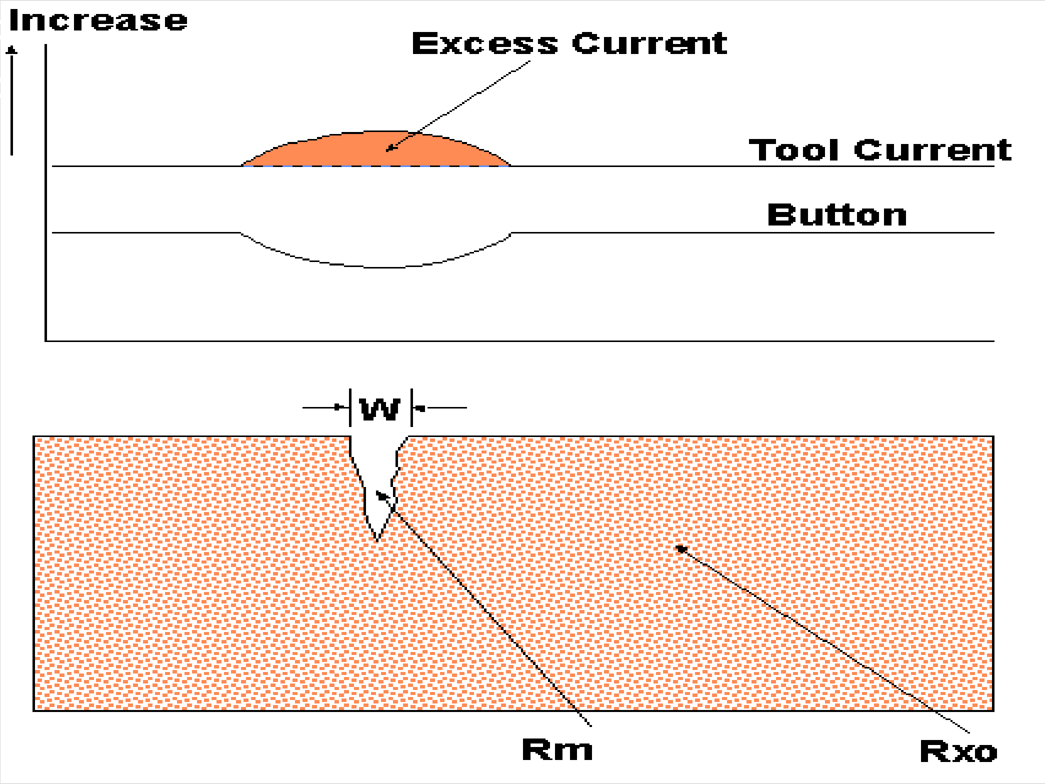
Where W = fracture aperture

b,c = constant from tool modeling

A = excess current divided by voltage and integrated along a line perpendicular to the fracture trace

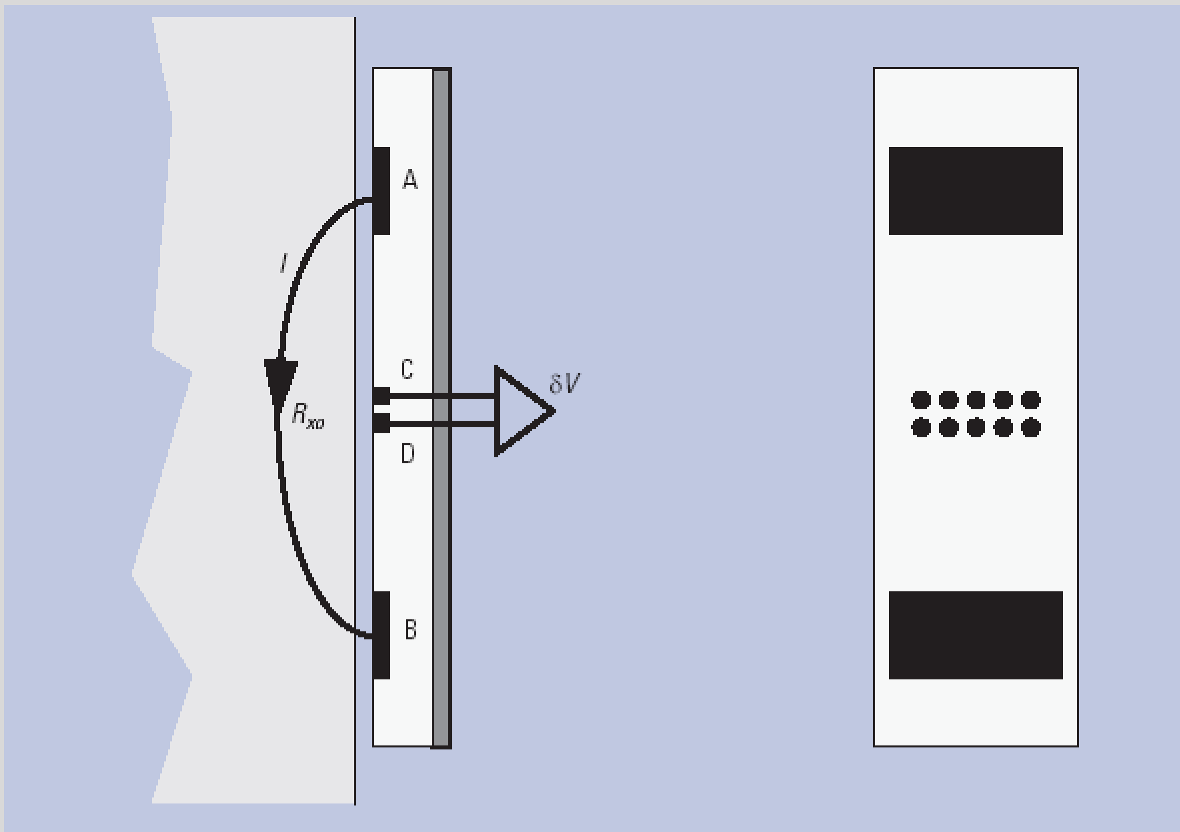
Rm = mud resist

Rxo = flushed zo

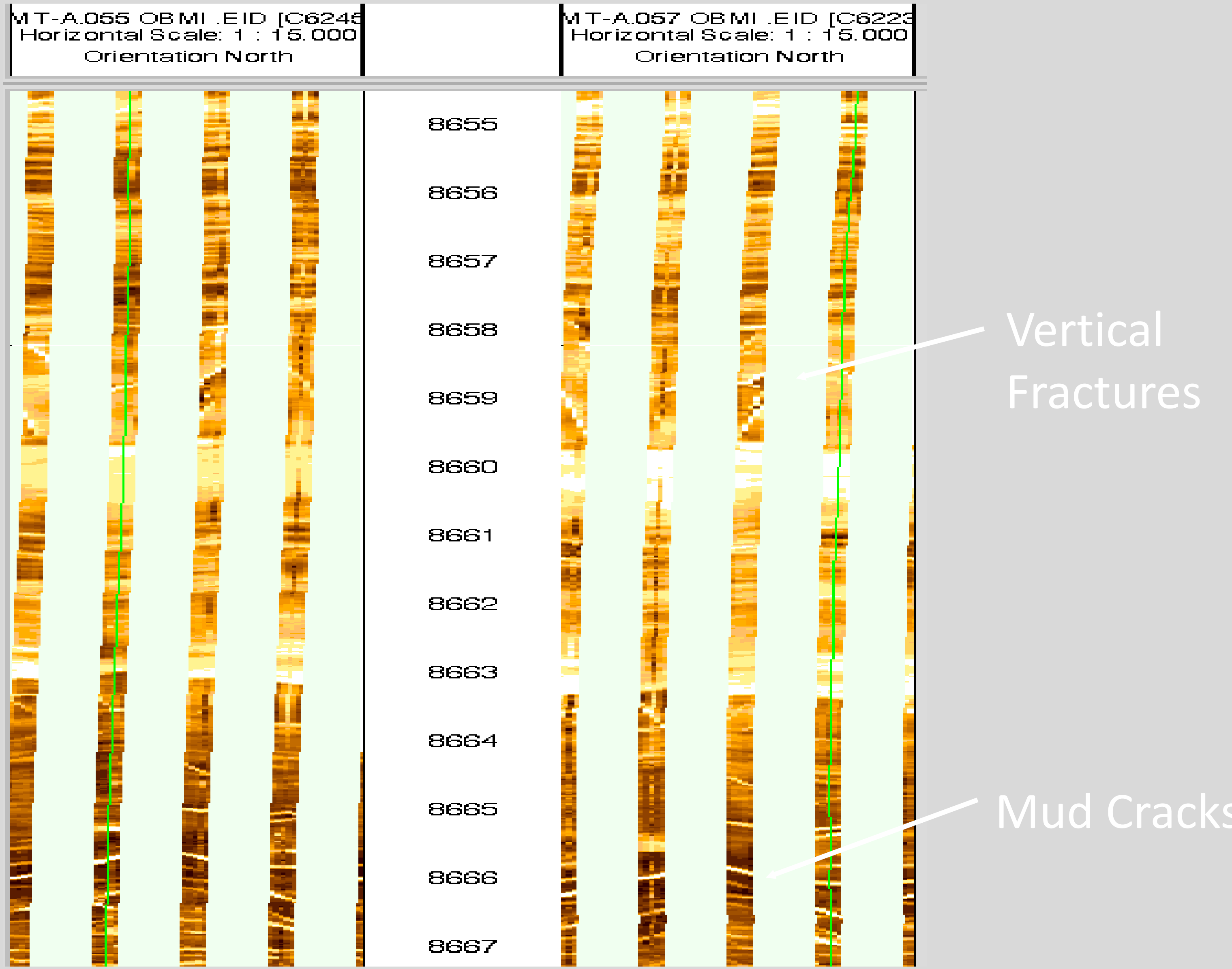


OBMI

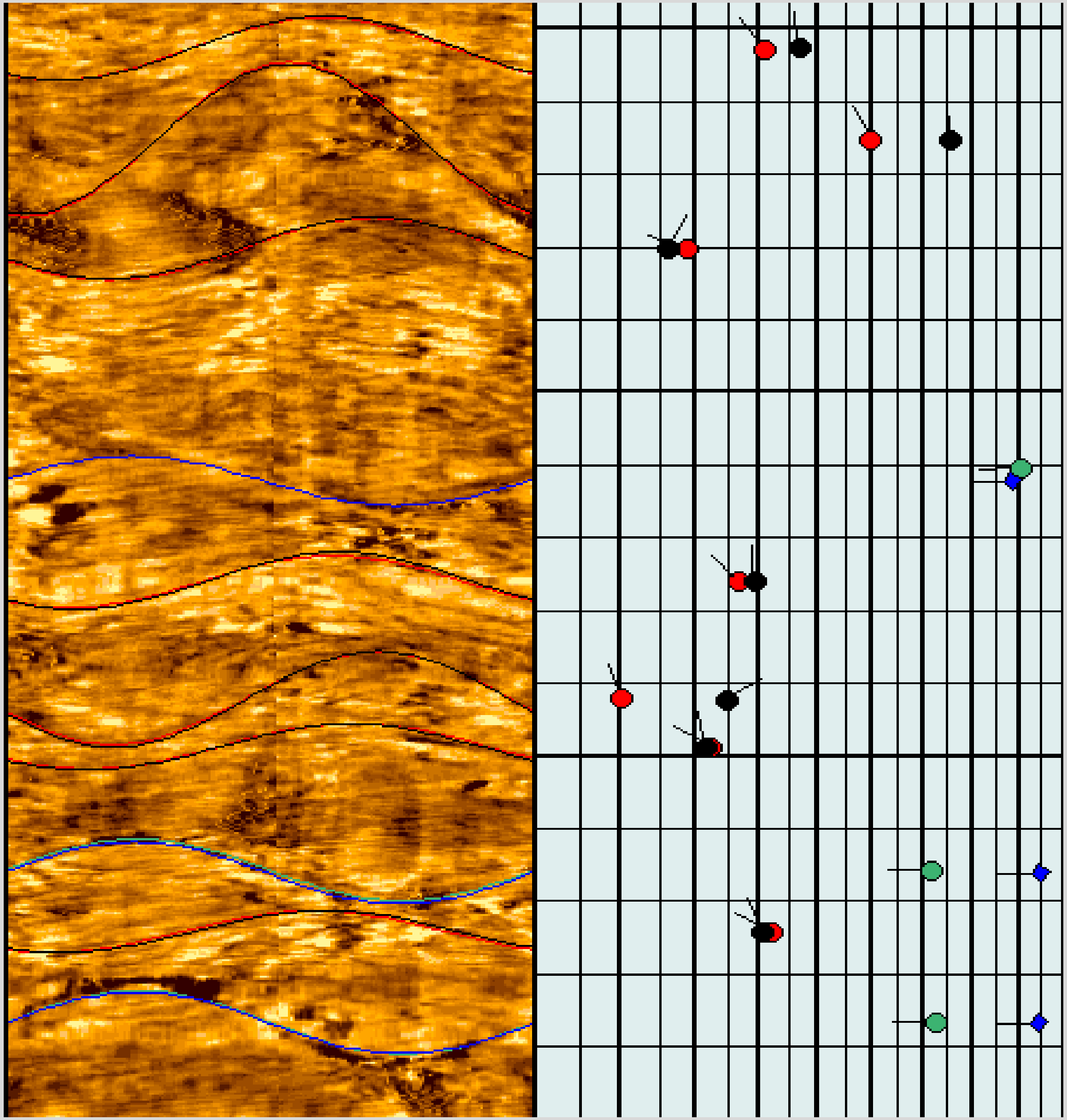
Oil Based Mud Imager



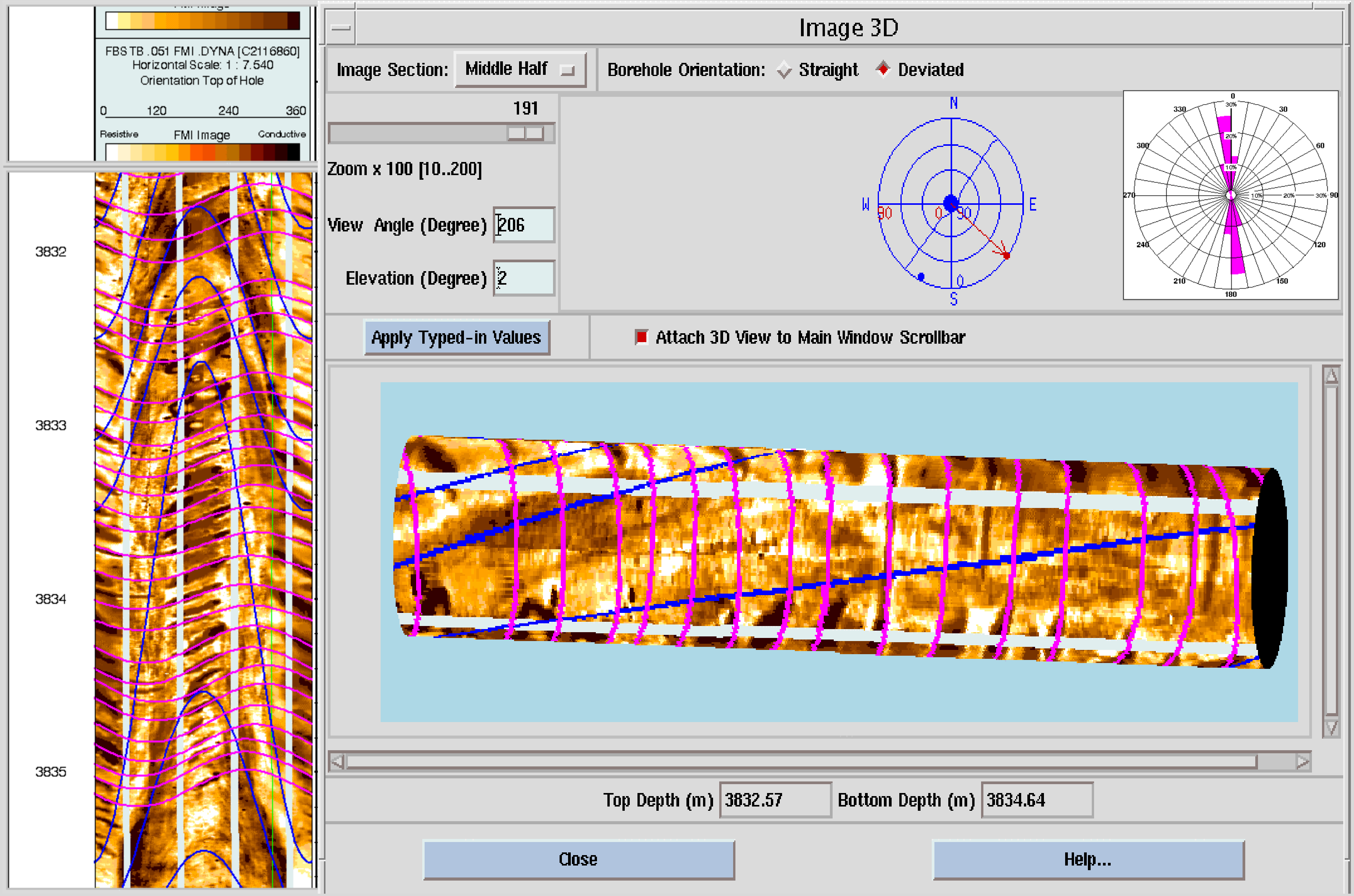
# OBMI

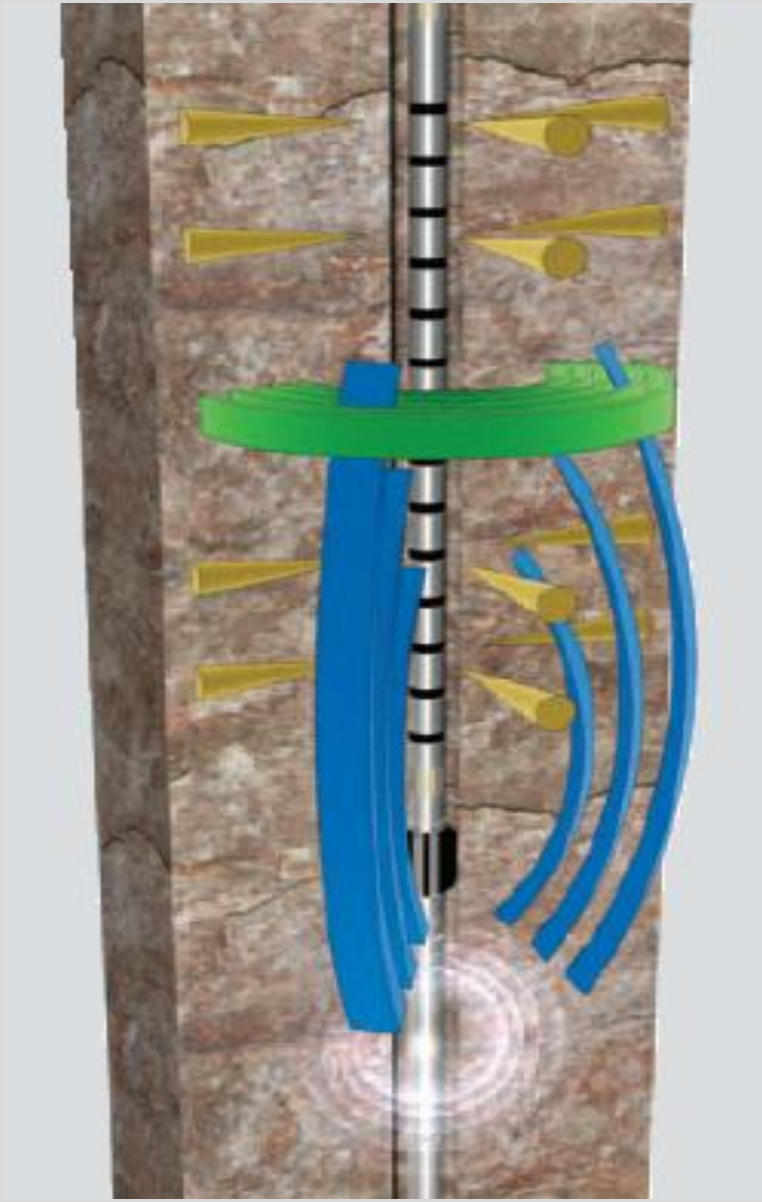

MT-A.055 OBMI .EID [C6245
Horizontal Scale: 1 : 15.000
Orientation North
MT-A.057 OBMI .EID [C6223
Horizontal Scale: 1 : 15.000
Orientation North
8655
8656
8657
8658
8659
8660
8661
8662
8663
8664
8665
8666
8667
Vertical Fractures
Mud Cracks

# UBI



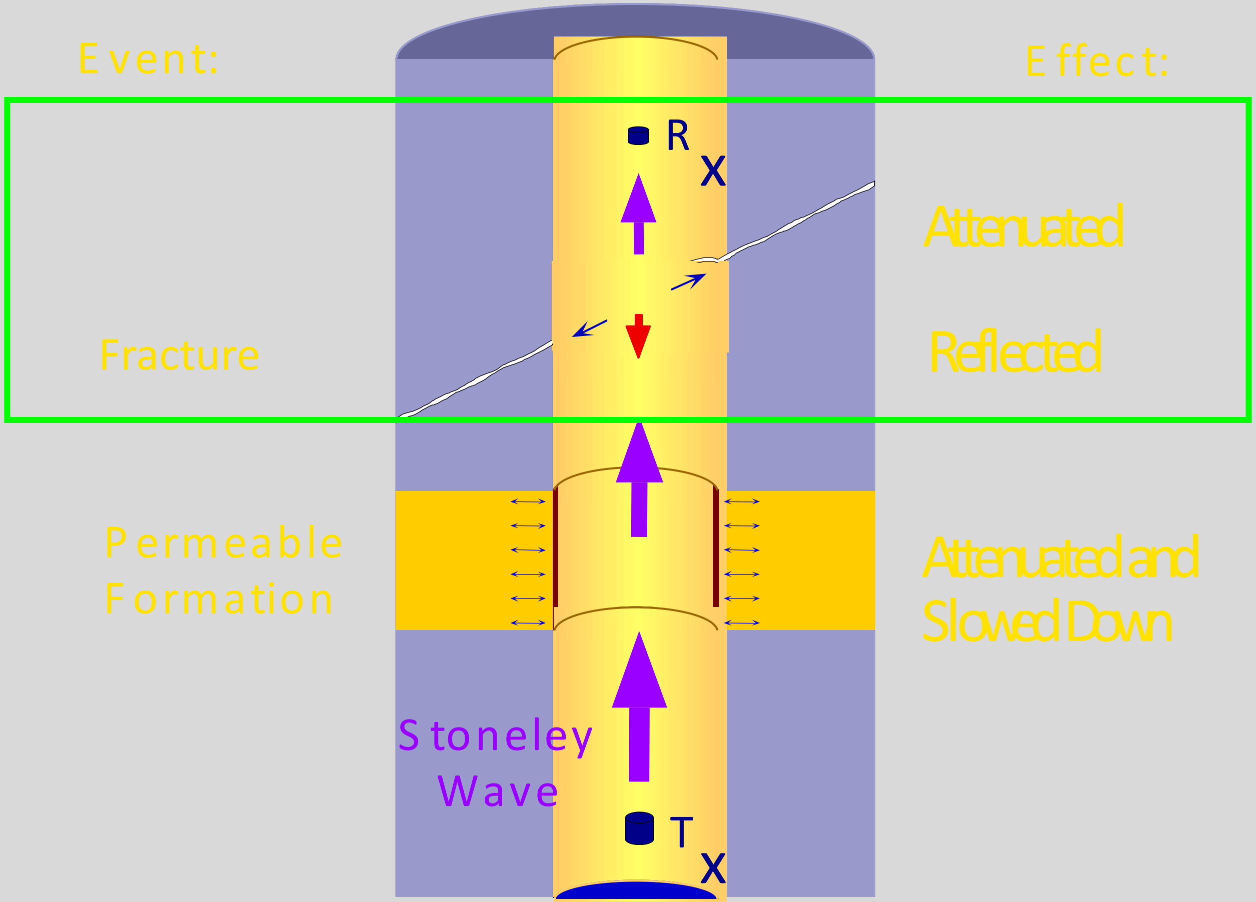
# Fractures in Horizontal Borehole





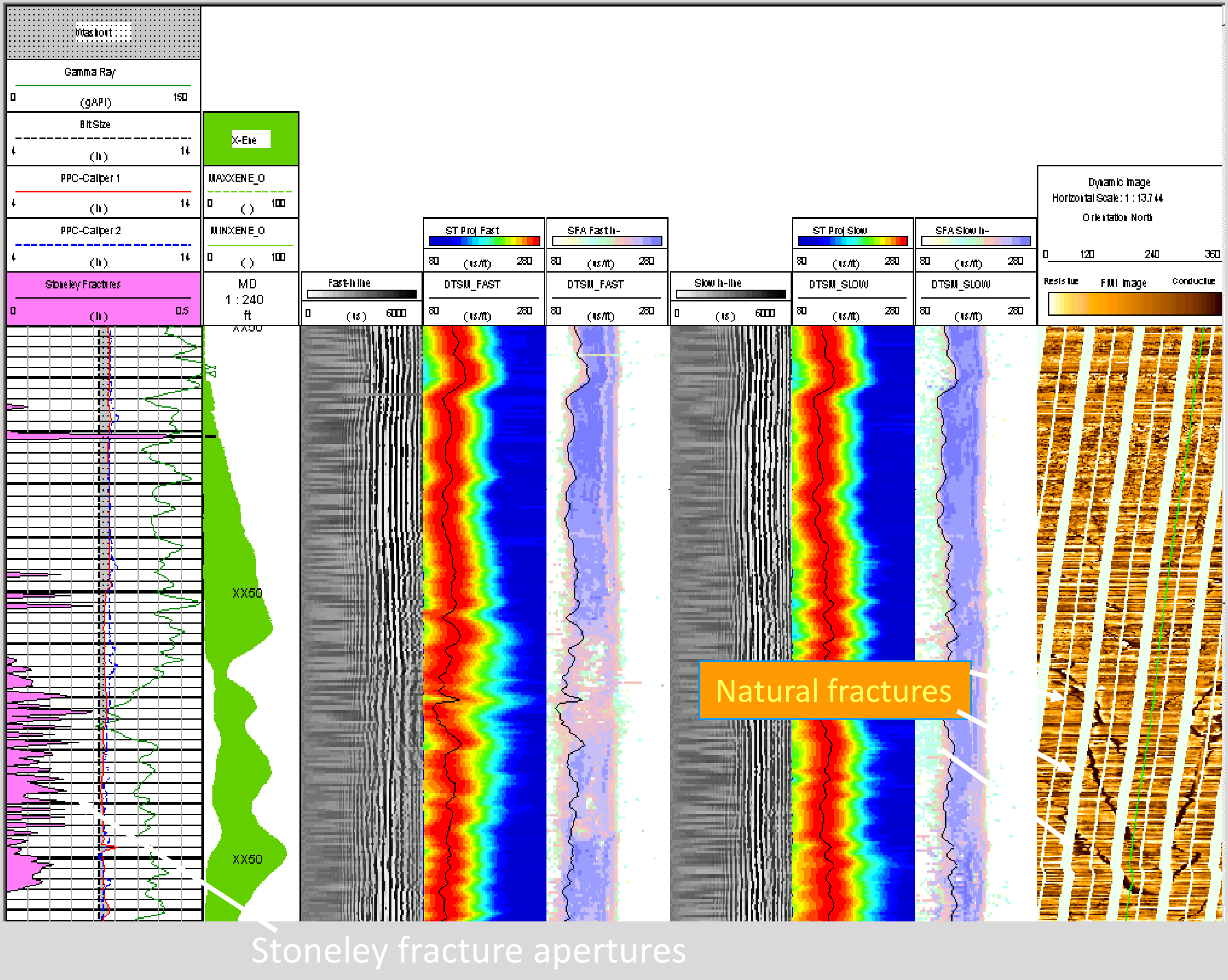
The Sonic Scanner tool provides the benefits of axial, azimuthal, and radial information from both the monopole and the dipole measurements for near-wellbore and far-field slowness information.

# Effect of Fractures on Stoneley



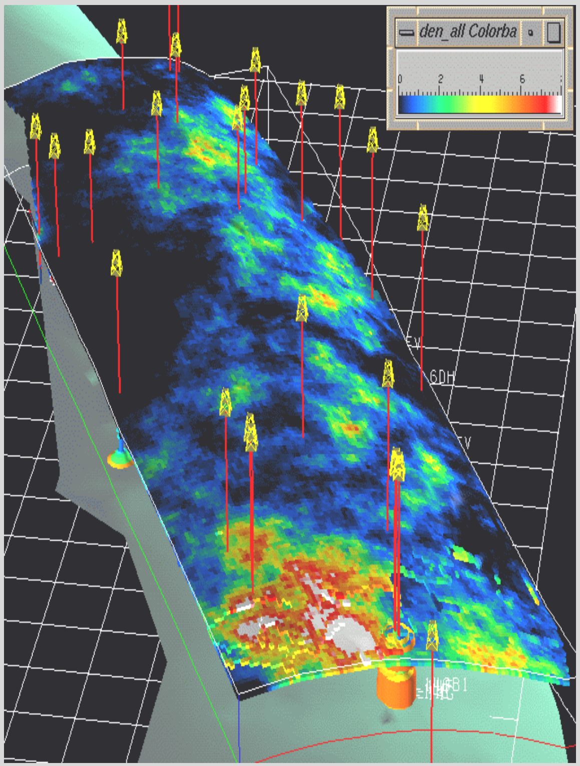

*The Stoneley is sensitive to the fluid mobility: k/h*

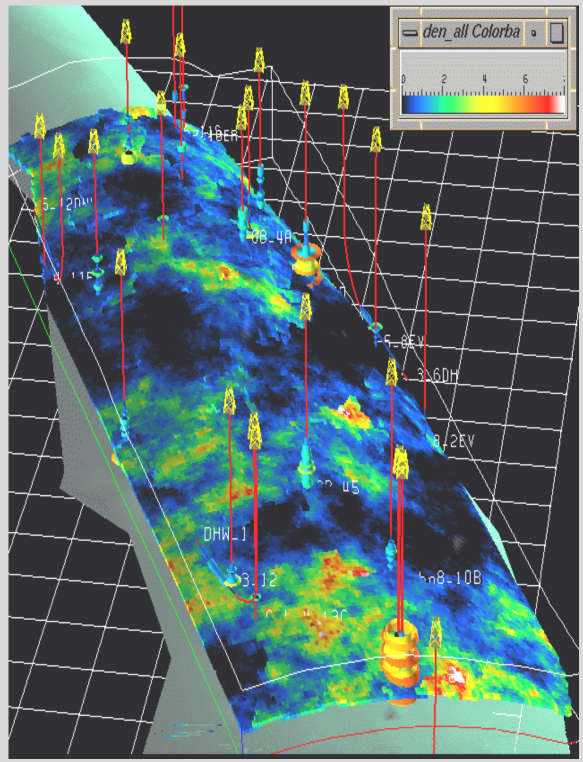
# Fracture Detection

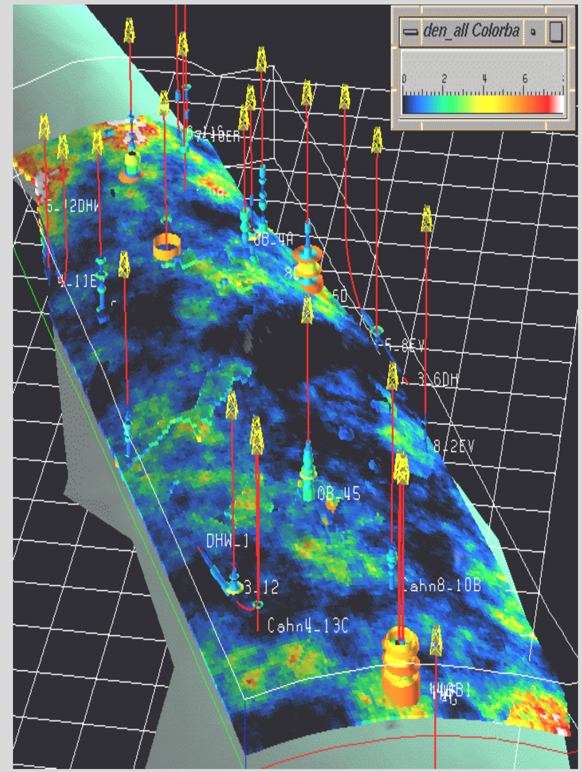


# 3D Fracture Model

## Examples of Fracture Density for Different Layers in the 3D Model



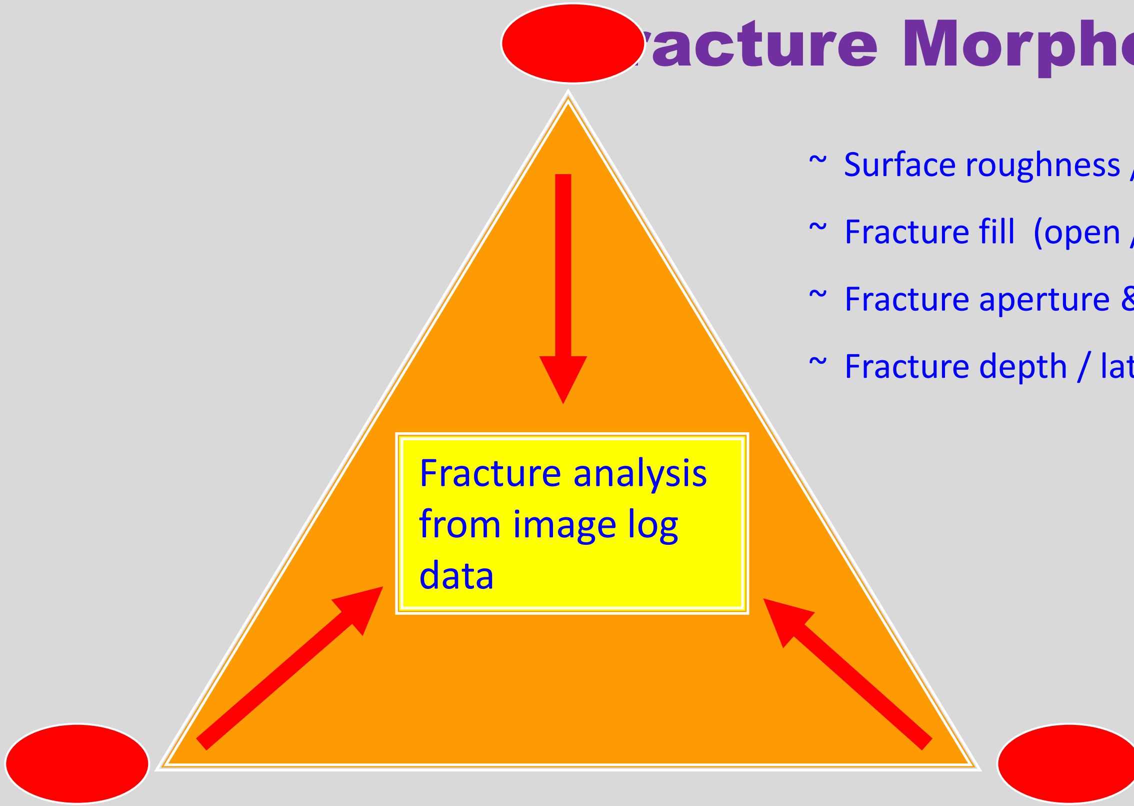
## Fracture Morphology

~ Surface roughness / planarity

~ Fracture fill (open / cemented)

~ Fracture aperture & porosity

~ Fracture depth / lateral & vertical extent




## Fracture orientation

~ Define directional fracture sets

~ Analysis of fractures by set

~ Relation to present-day in-situ stress

~ Relation to structural axis

## Fracture distribution

~ Clustered or dispersed

~ Fractured zones in the well

~ Fracture density per zone

~ Relation to lithology type

~ Relation to structural boundaries (Faults)

# Fracture Analysis Workflow

Stage1. Classification

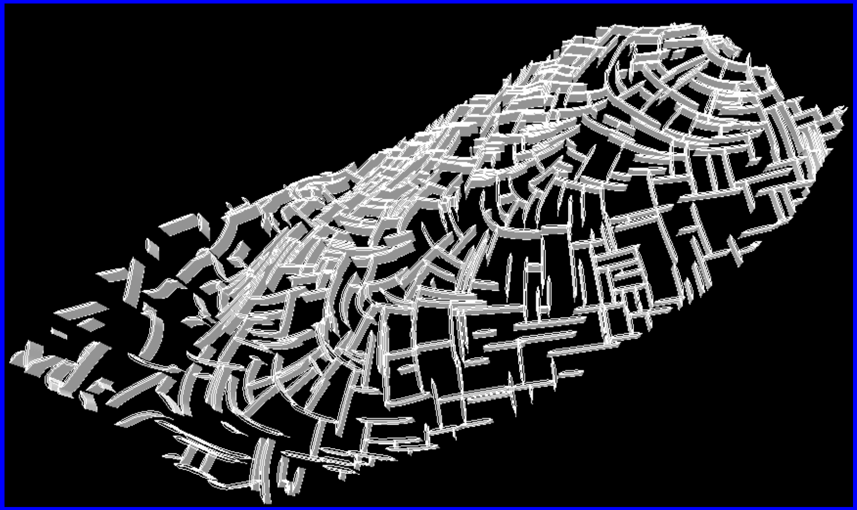
Stage2. Description

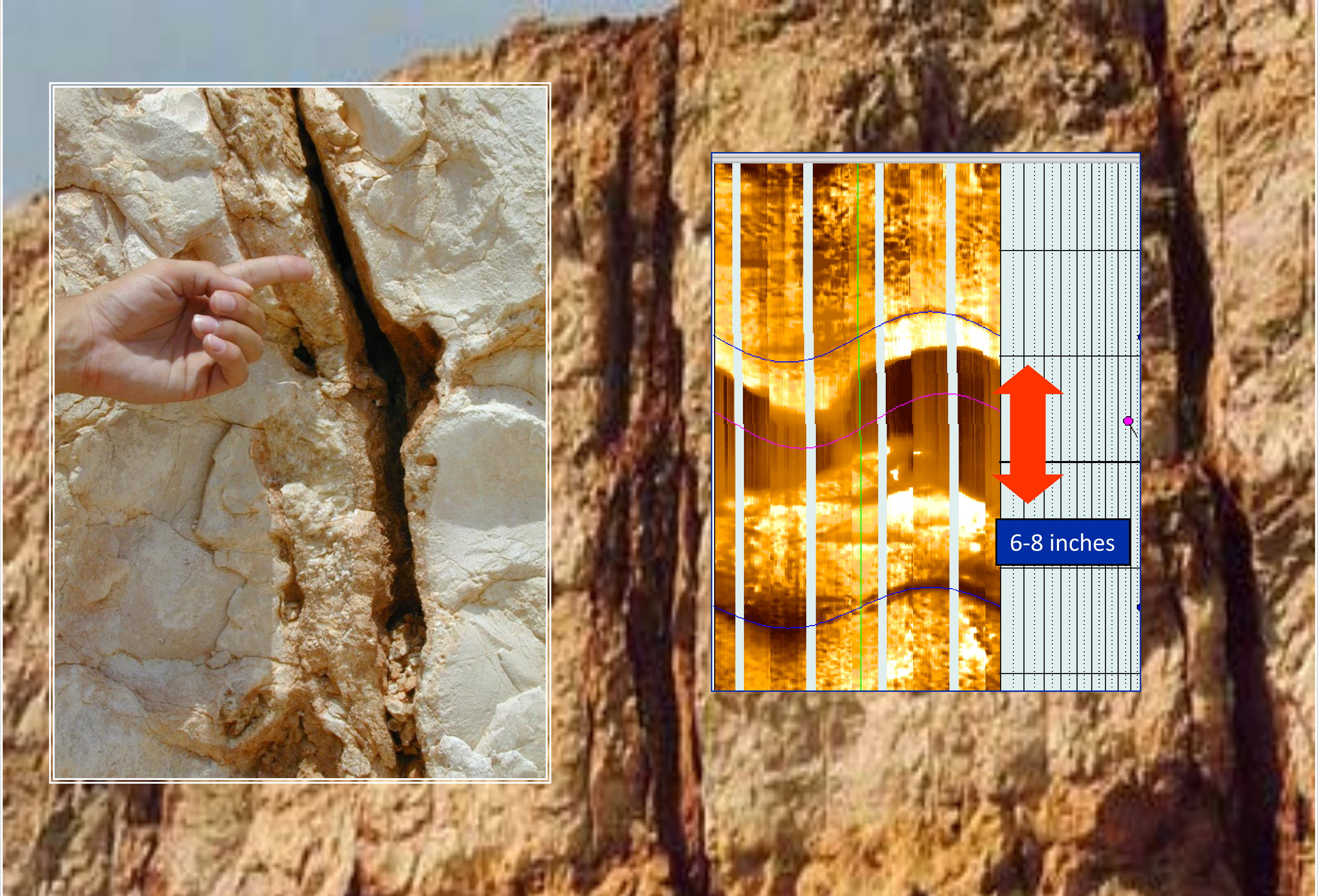
Stage3. Direction

Stage4. Distribution

Stage5. Enhanced Permeability

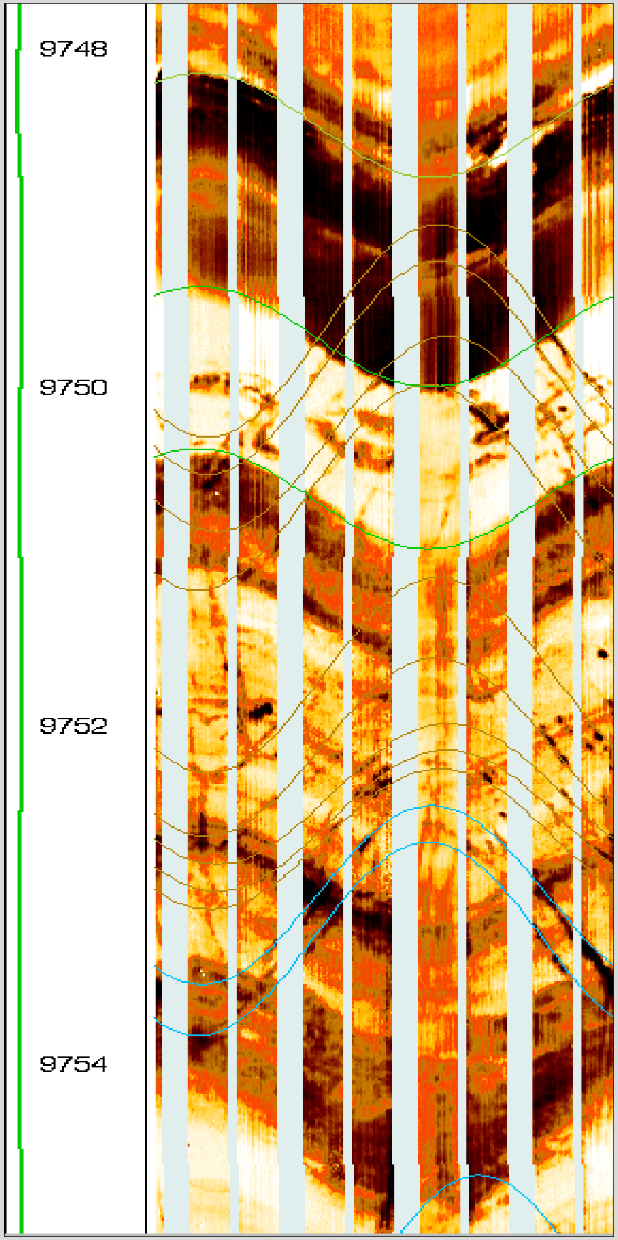
Stage6. Field-wide Fracture Distribution / Model






Fractures in Outcrop ~ Major Conductive fractures

# Minor Conductive Fractures




Probable
Open fracture
types

## Criteria :

~ Moderate to low contrast ,dark linear trace with moderate to narrow apparent aperture

~ Usually with discontinuous trace around the borehole. They may form single continuous sections or multiple short fissures isolated by partial mineralisation

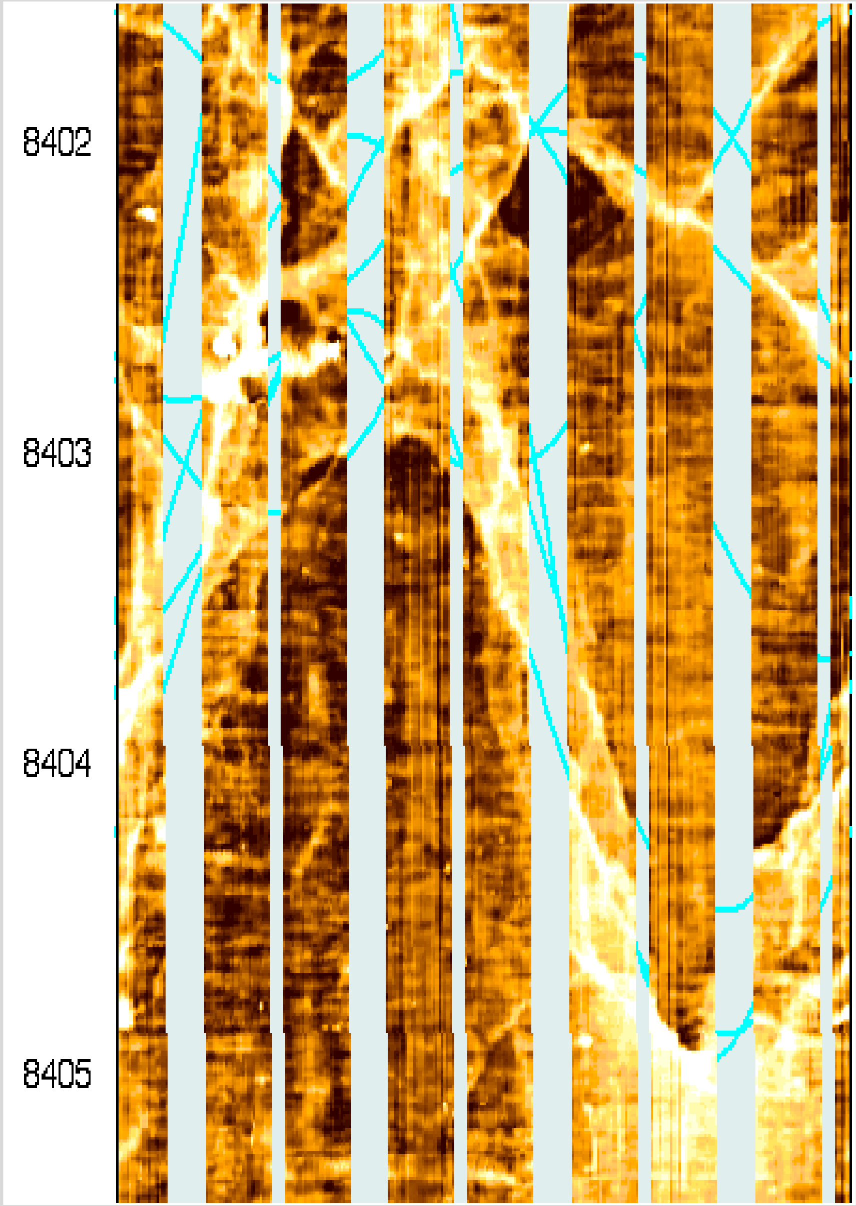
~ Clear angular relation with the bedding trends, ie cross-cutting sedimentary structure

~ With variable planarity, both irregular & planar surfaces likely

# Fractures in core ~ Minor fracture type

# Major Resistive Fractures

Probable Closed fracture types




## Criteria :

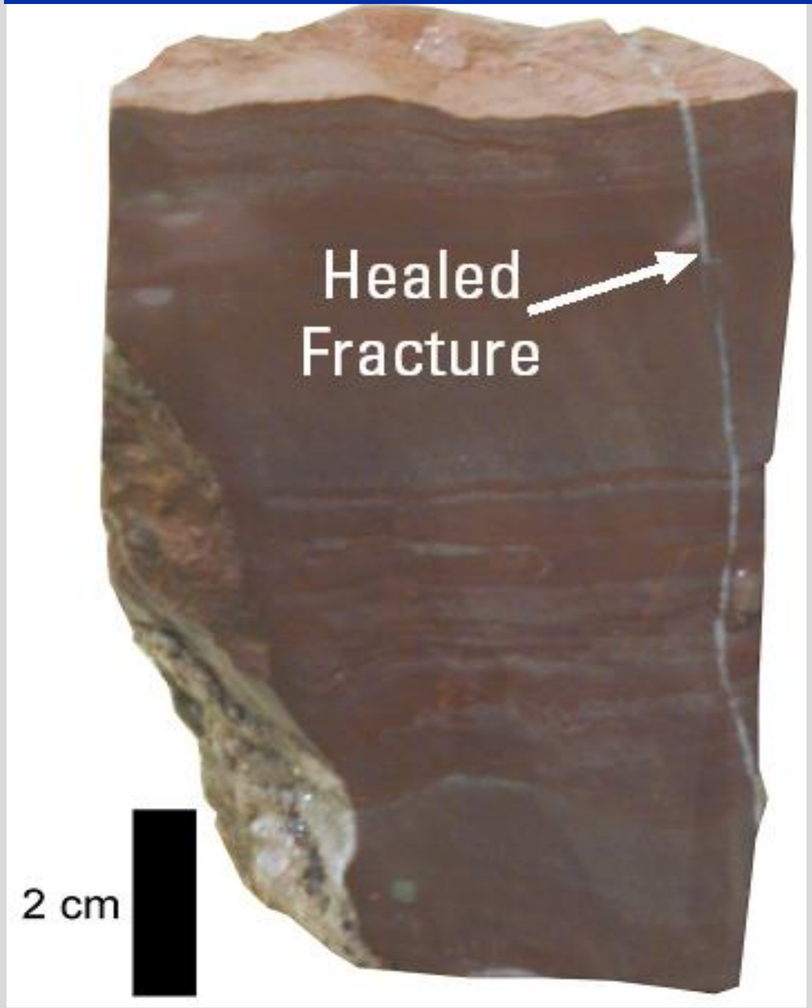
~ High contrast , light linear trace with moderate to wide apparent aperture

~ Usually with a continuous trace around the borehole except when strata bounded or when terminated against another fracture or fault

~ Clear angular relation with the bedding trends, cross-cutting the sedimentary structure

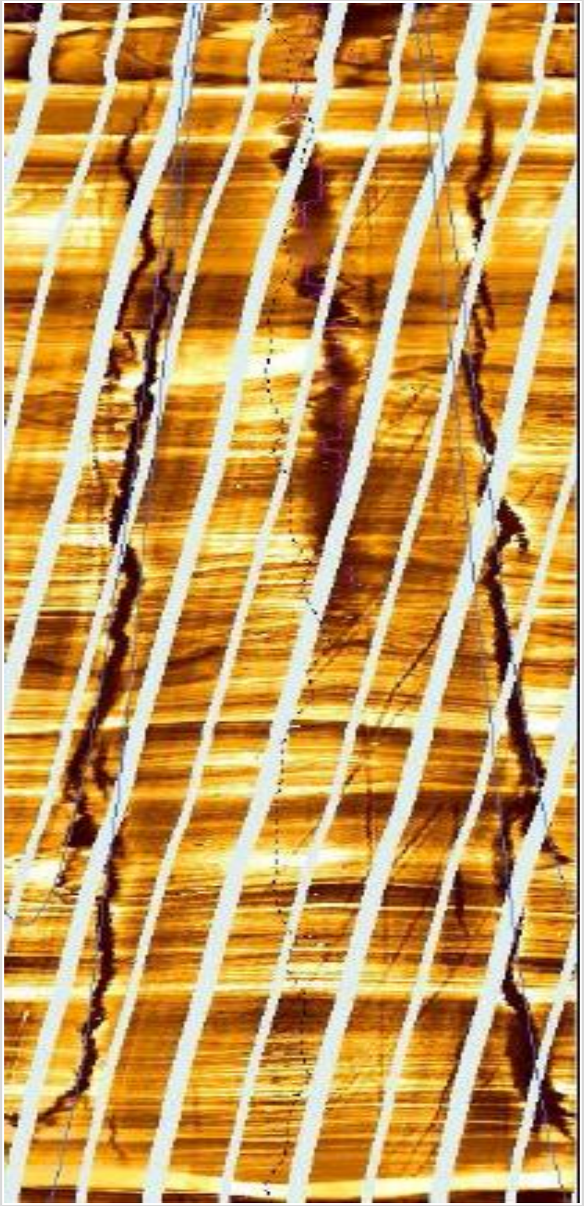
~ Often associated with development of a white shadow zone in the dip direction of the fracture plane

# Fractures in Outcrop ~ Resistive fractures



# Drilling Induced Fractures

In-situ stress features



## Criteria :

~ High contrast, dark linear and curvilinear traces, moderate to wide apparent aperture

~ Geometry is related to the well trajectory. In near vertical wells they appear as sub-vertical symmetrical traces. They can also appear as a series of short en-echelon tensional features on either side of the borehole (next slide).

~ They will be aligned (strike) in the direction of maximum horizontal stress.

~ Clear angular relation with the bedding trends, ie cross-cutting all the natural structures.

~ Often discontinuous and with low planarity

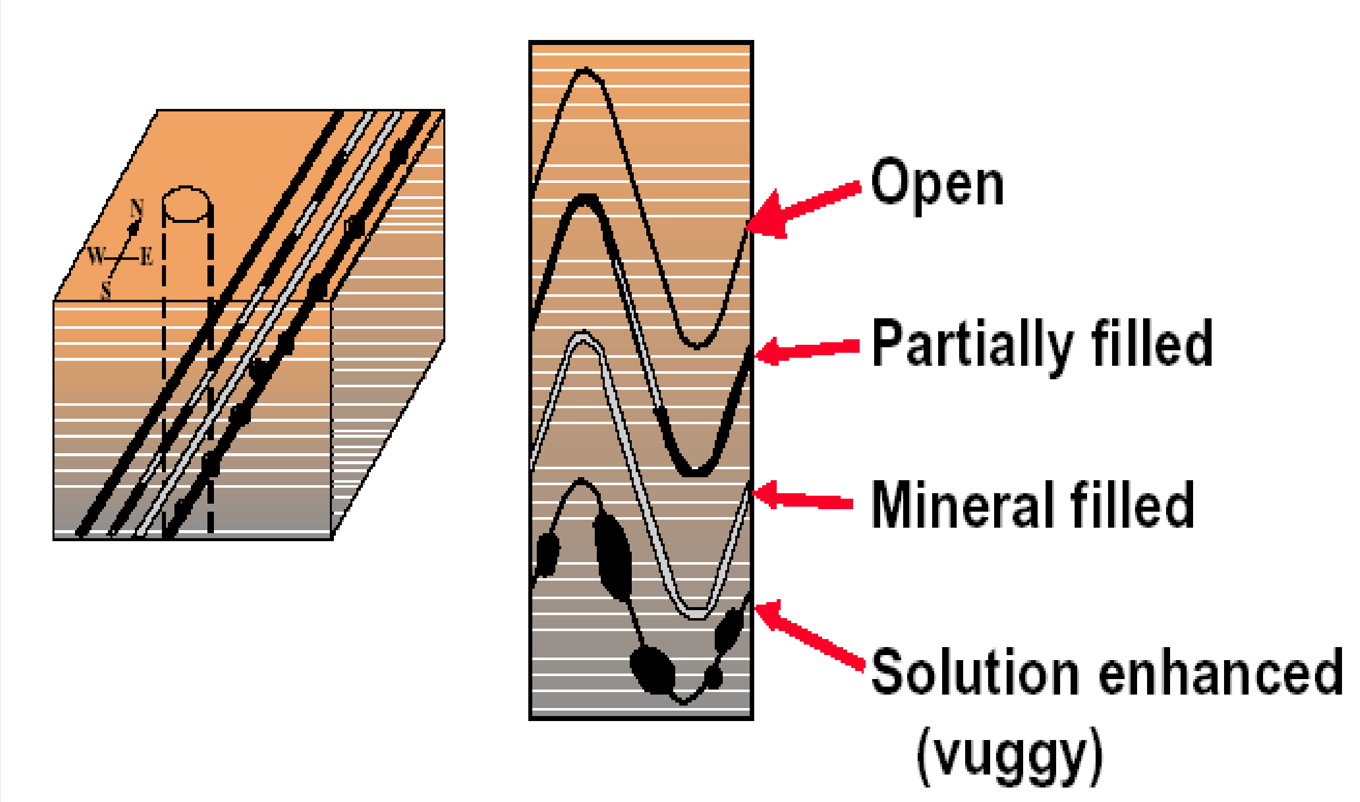
~ Not observed on the deep investigation logs or on core

# Fracture Types ~ Natural vs Induced

How do you know if the fractures are natural or drilling induced ?

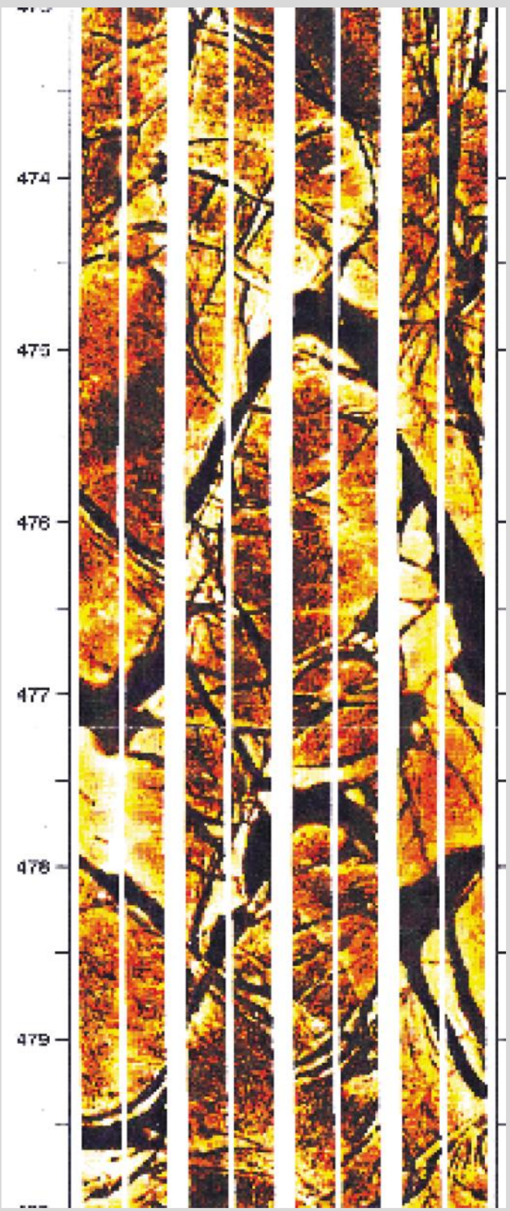
1. **Orientation** (unimodal in Max horizontal stress)
2. **Relationship to borehole geometry**
3. **Log response** (Conductive / Low Acoustic amplitude)
4. **Cross-cutting all other structures**
5. **Visible on core & deep investigation logs**
6. **Indications of mineralisation (natural)**

# Description of Fracture Morphology



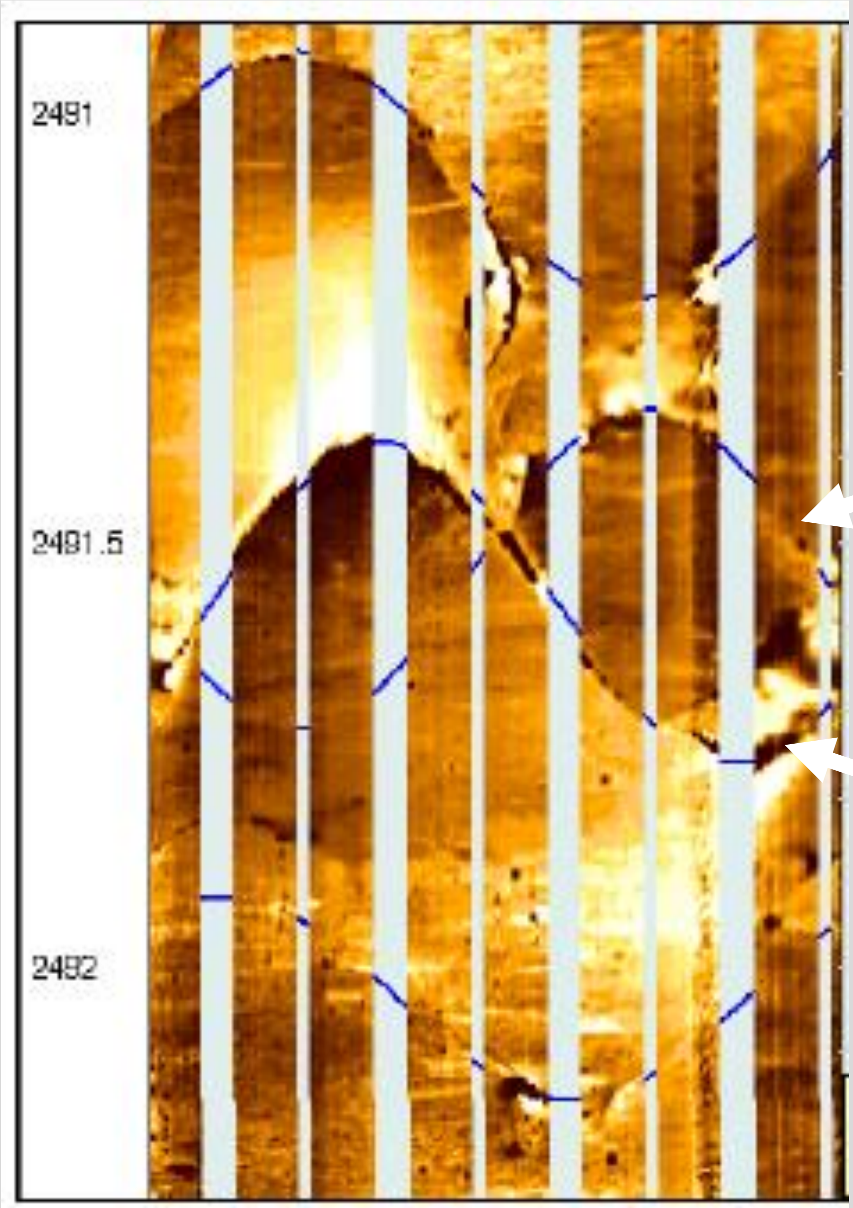

1. Surface roughness / planarity
2. Fracture fill material (open / cemented)
3. Fracture aperture & trace length
4. Fracture intersection / relative age

# Fracture Morphology – Network




Cross-cutting fractures

# Fracture Morphology – Network

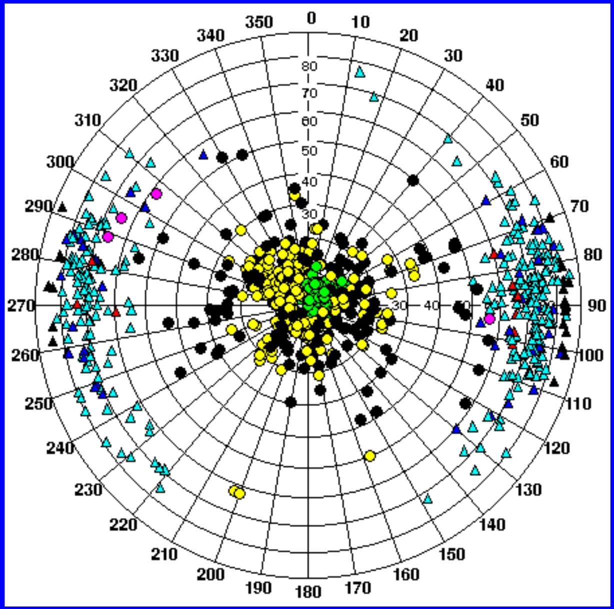


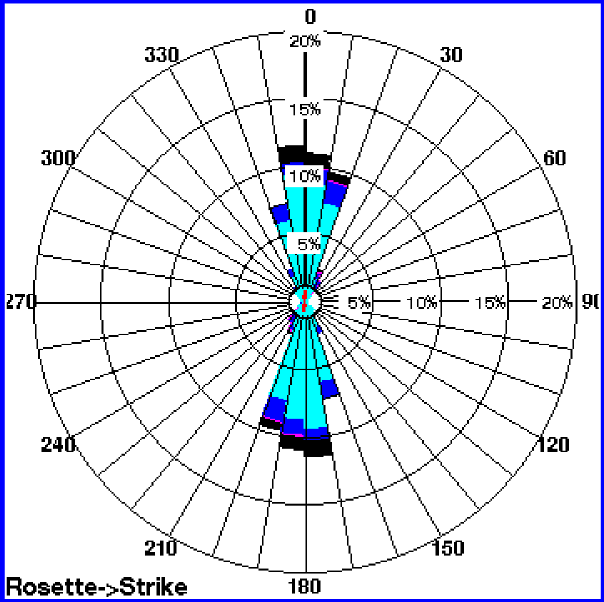

**Cross-cutting fractures**

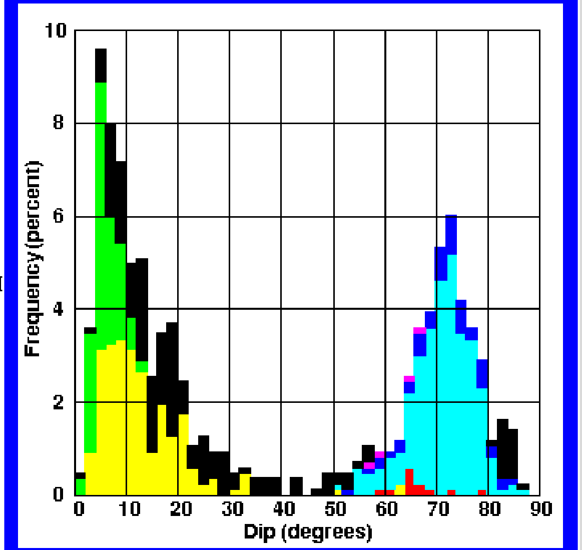
Phase2 fractures

Phase1 fractures

# Analysis of fracture direction




Schmidt stereonet

Strike Rosette

Dip histogram

# Analysis of fracture distribution

1. Continuous log of fractures

2. Fracture Density curves highlight distribution

3. Controls on fracture development

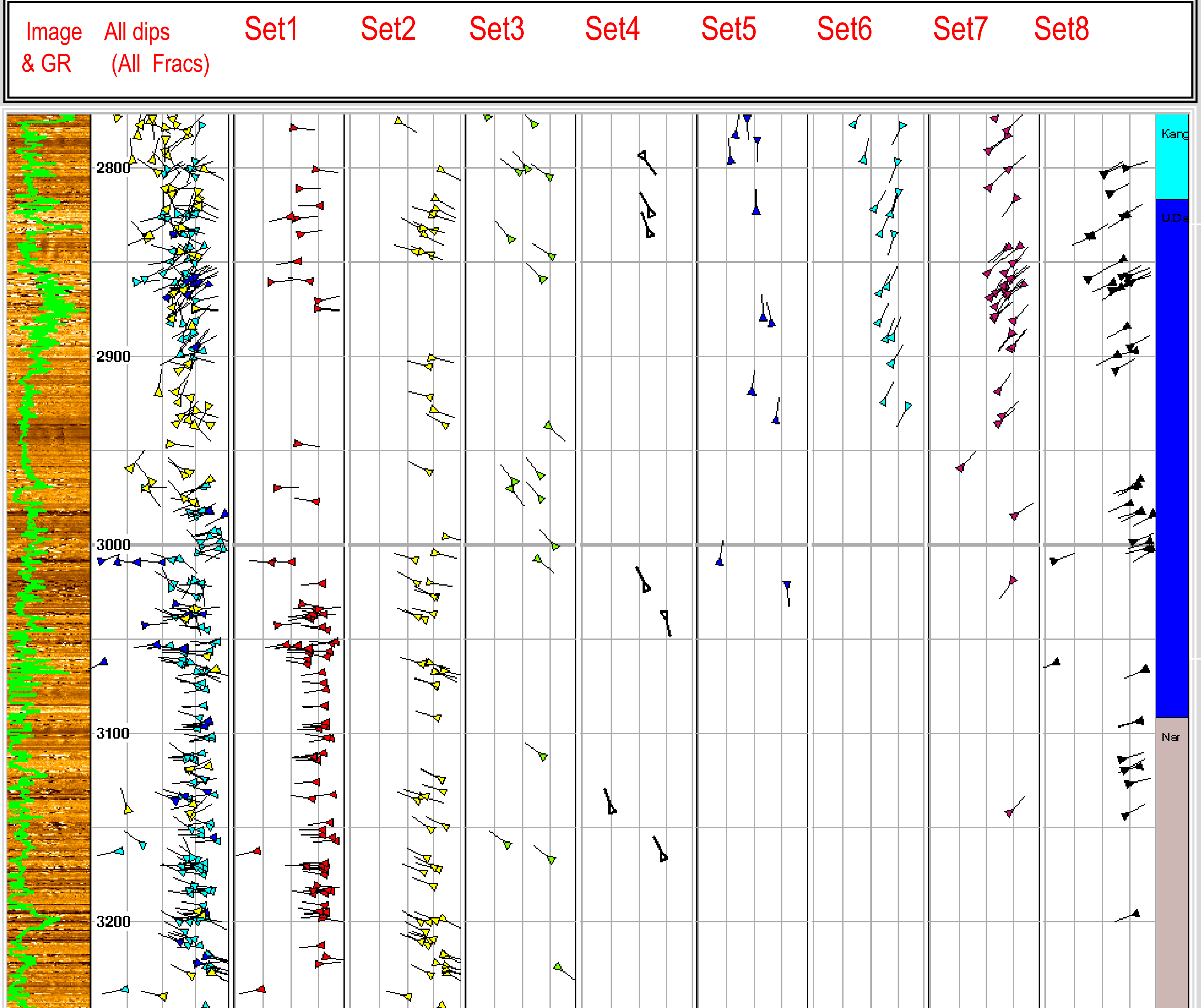
~ Lithology type

~ Bed thickness

~ Formation dip

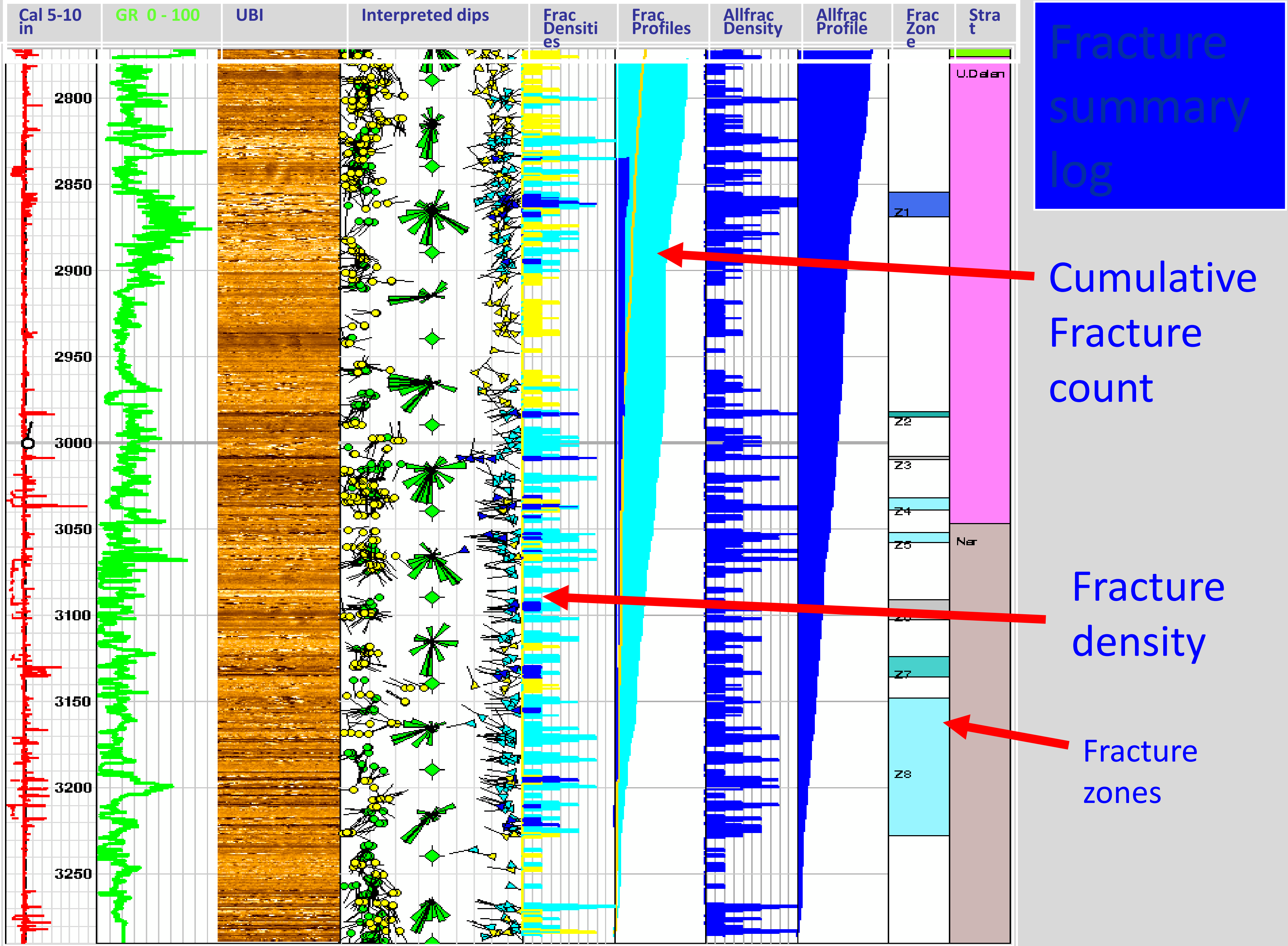
~ Structural boundaries

~ Borehole condition and wellbore stability




Relation between fracture direction and measured depth

Fracture Directions ~ Colour coded fracture sets




# Fracture summary log

# Estimation of Fracture Enhanced Permeability

| | |
|---|---|
| **A - High** | ~ Well developed conductive fractures with continuous trace and wide apparent aperture, also where there are interconnected directional fracture sets, faults and a favourable fracture orientation with respect to the regional stress trends. |
| **B - Moderate** | ~ Numerous minor conductive fractures and occasional major fracture types |
| **C - Low** | ~ Rare Major fractures, moderate conductive fractures, also an unfavourable orientation with respect to the regional stress trends. |
| **D - Poor** | ~ Low fracture count and/or the presence of significant resistive features |

~ Fracture Type / Morphology

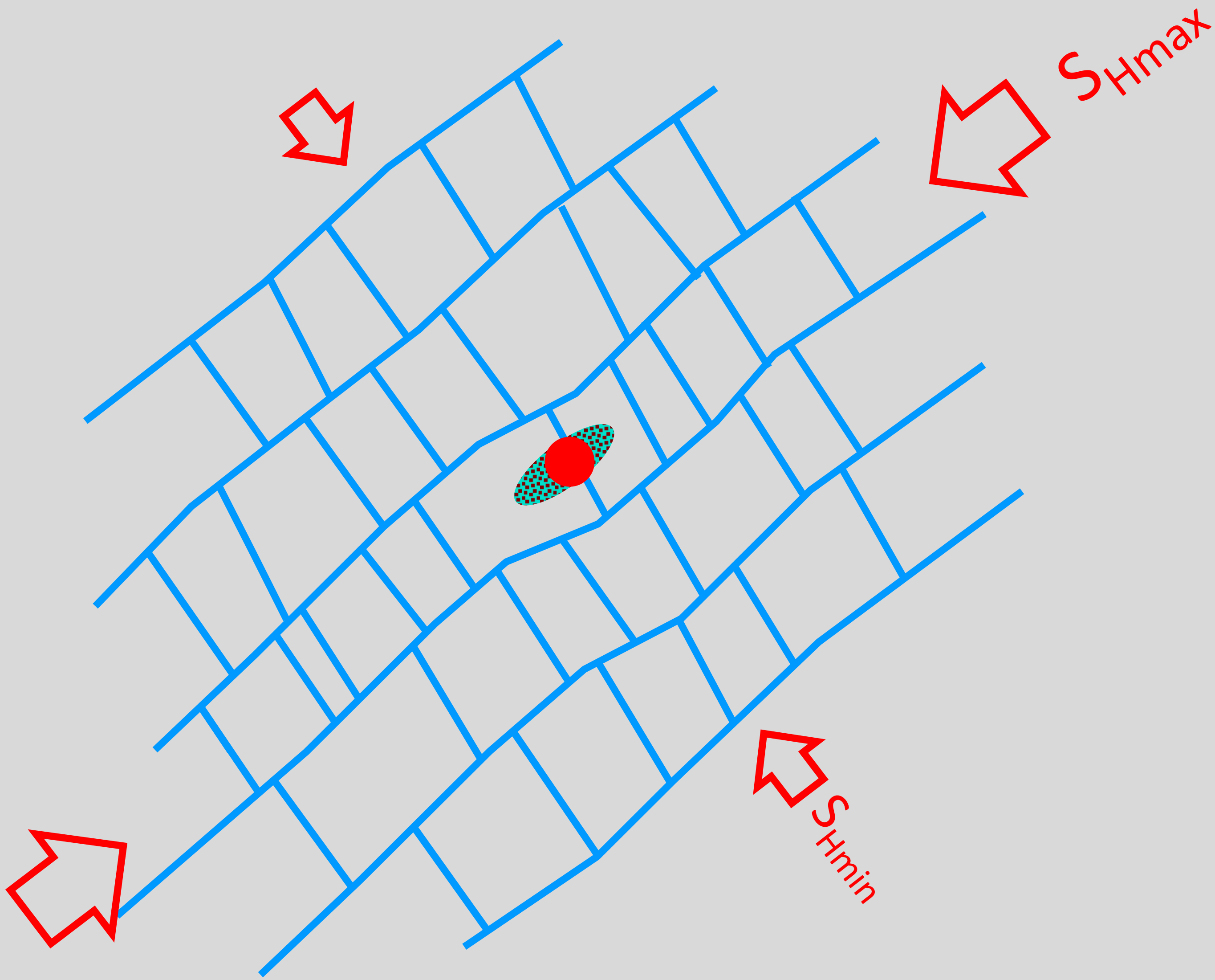
~ Fracture direction relative to present-day in-situ stress

~ Fracture dip angle and number of different fracture directional sets

~ Host rock lithology

~ Structural axis

# Fracture Permeability ~ In-situ stress direction



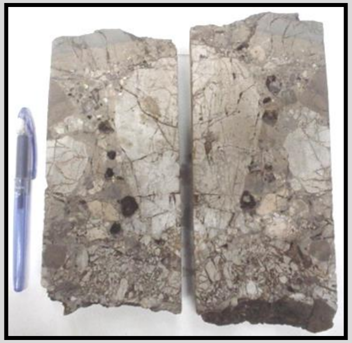
# Prediction of Field-wide fracture distribution

Regional ~ Joints

~ Cleats

Tectonic ~ Fault related

~ Fold related



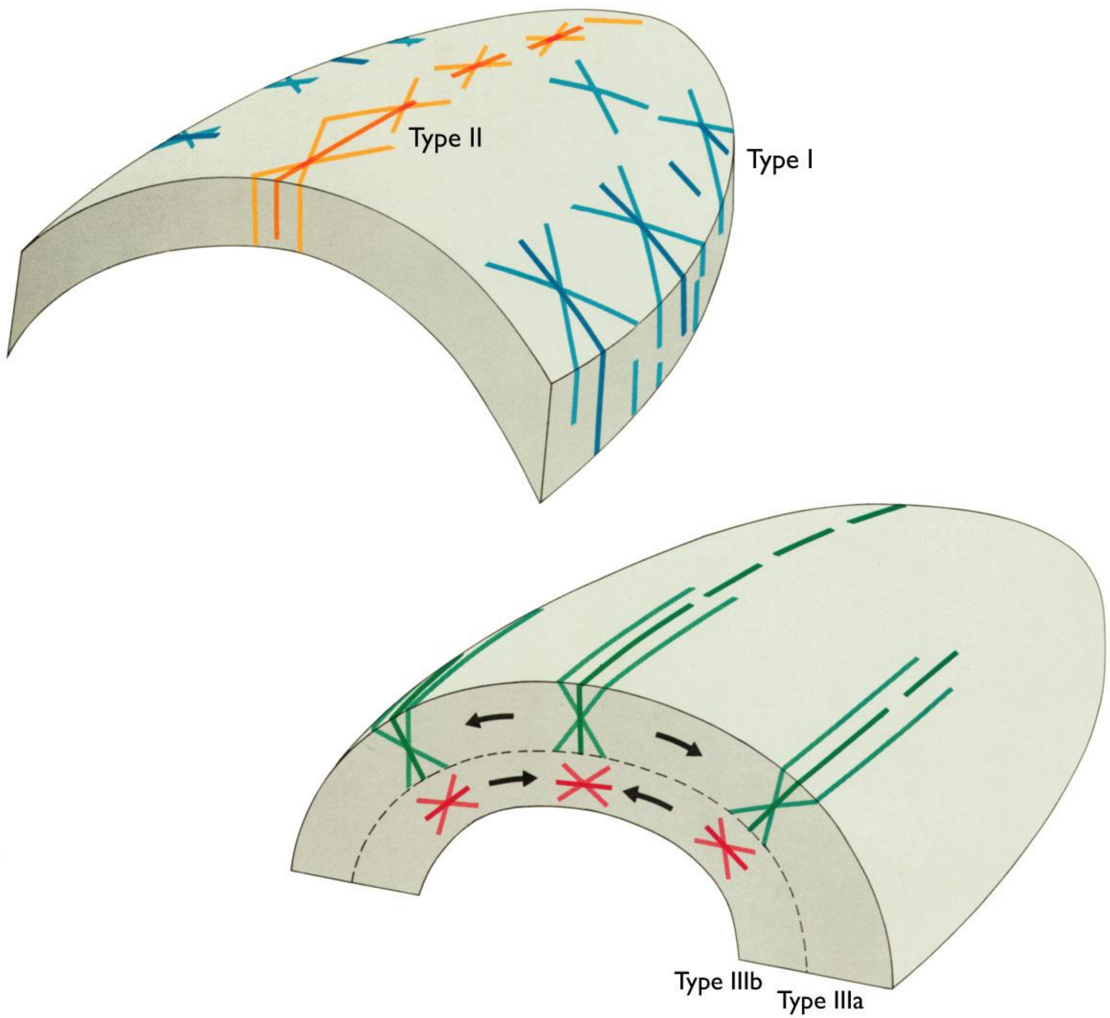
Contractional ~ Chickenwire

~ Diagenetic

~ Columnar joints

Aerial view of Cambro-Ordovician outcrops on the Tassilis N'Ajjer, Algeria illustrates the complexity of the fault/fracture network in the subsuface.

# Fracture Prediction ~ Fold-related trends




**Stearn's (1968) Fold-related Fractures**

## Fold-Related

Type 1 - Transverse

Type2 - Longitudinal

Six types of fold-related fracture can be expected :

Type 1 : Extension

Type 1 : Shear1

Type 1 : Shear2

Type 2 : Extension

Type 2 : Shear1

Type 2 : Shear2

# Case Studies

Fractured Basement Hydrocarbon Reservoirs

"Freak coincidence of nature…?

…..or under-explored potential?"

# Fractured basement reservoirs

## Some facts

Fractured basement reservoirs have low porosity 1-3%
High permeability

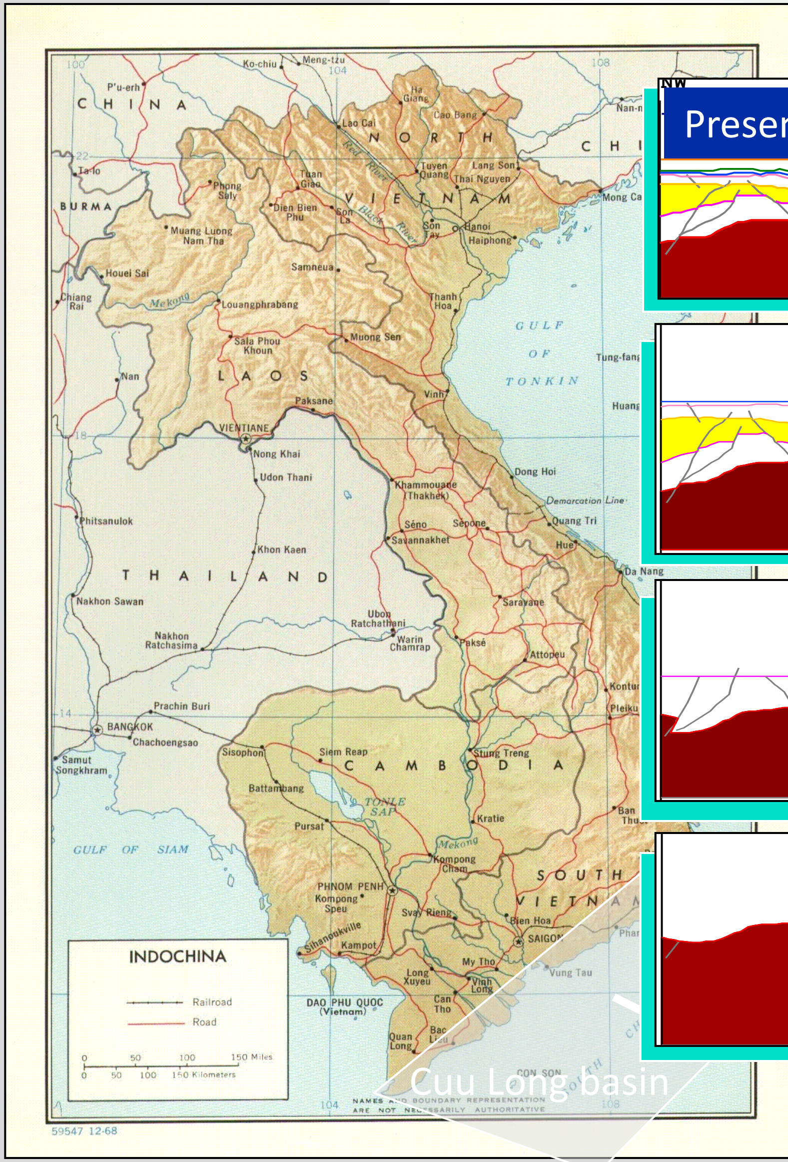
Granitoid/Metamorphic rock

Mostly oil
large oil columns (1000m)

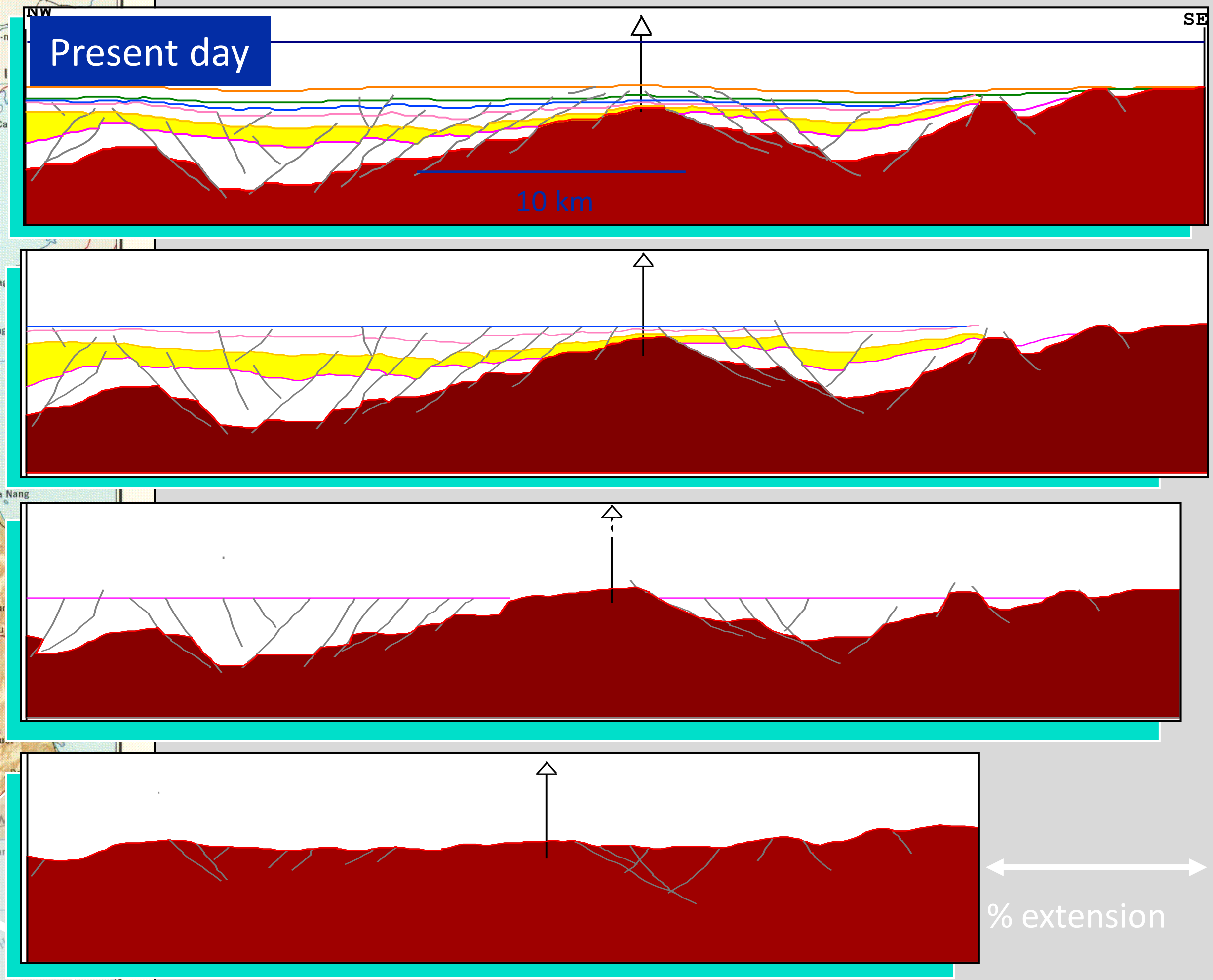
- La Paz, Venezuela 600MMBO recovered
- Bach Ho etc., Vietnam 500 MMBO recovered
- Zeit Bay/Ashrafi, Egypt, 25,000 BOPD

Can occur in all tectonic settings, but focus on Vietnam "extensional" setting

# Regional setting




Cuu Long basin



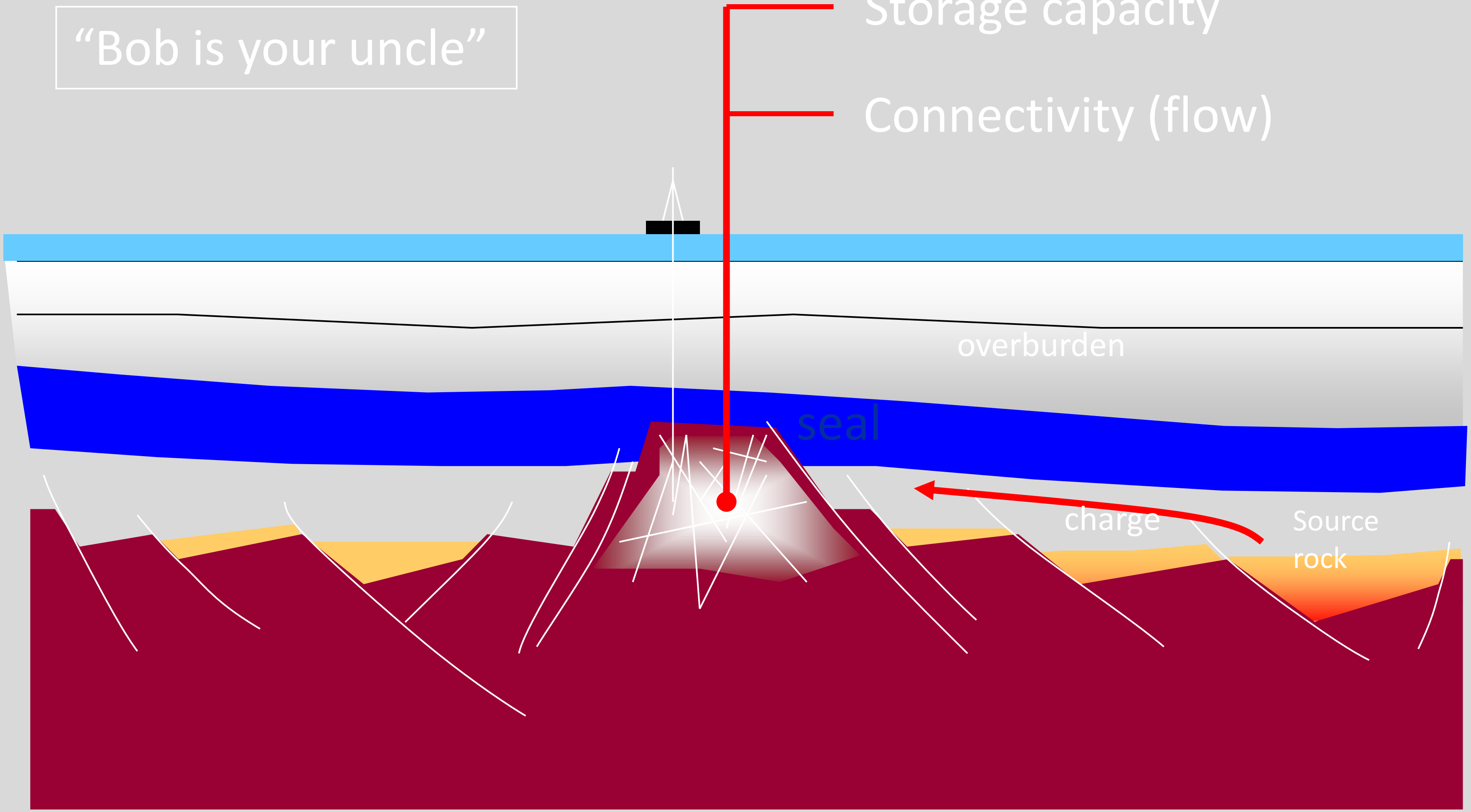

% extension

Geological history

# Fractured basement reservoirs

Petroleum play

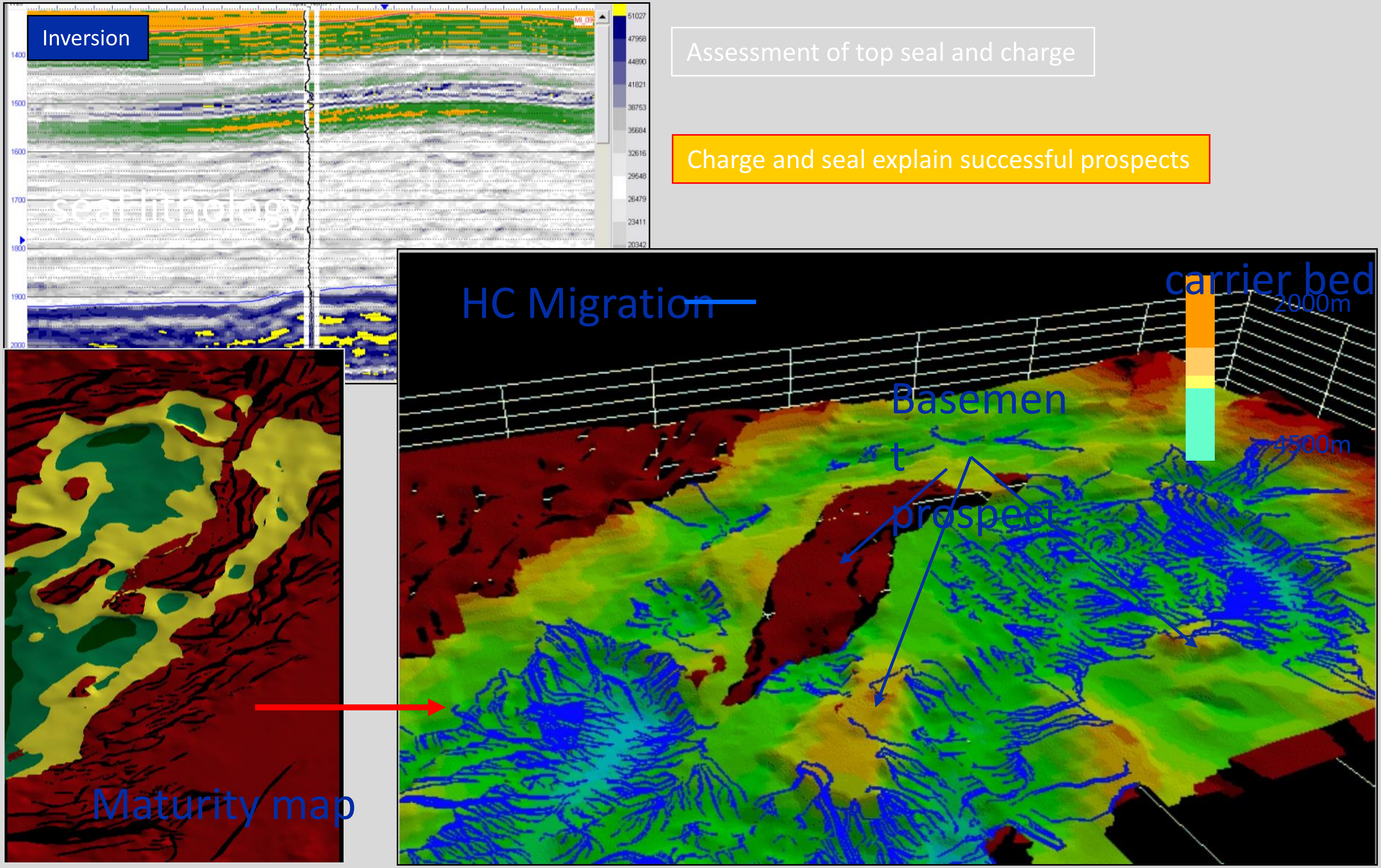
“Bob is your uncle”



# Fractured basement reservoirs

Assessment of top seal and charge

Charge and seal explain successful prospects



# Fractured basement reservoirs

## RESERVOIR

Fracture characterisation

- Seismic methods
- Structural modelling
- Fracture Modelling
- Stress modelling

Static Reservoir model

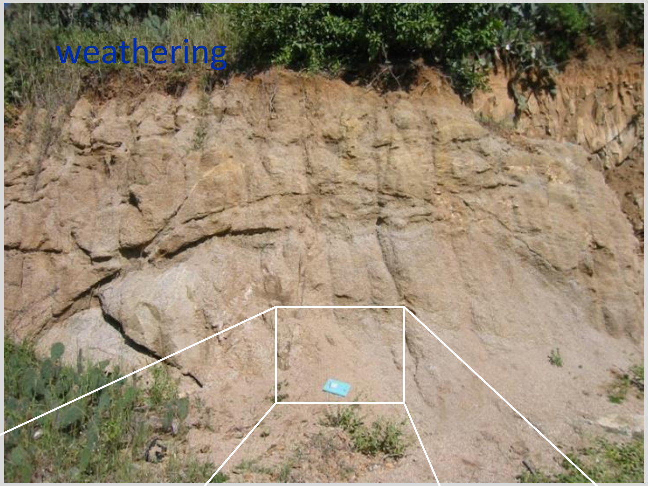
Dynamic flow?

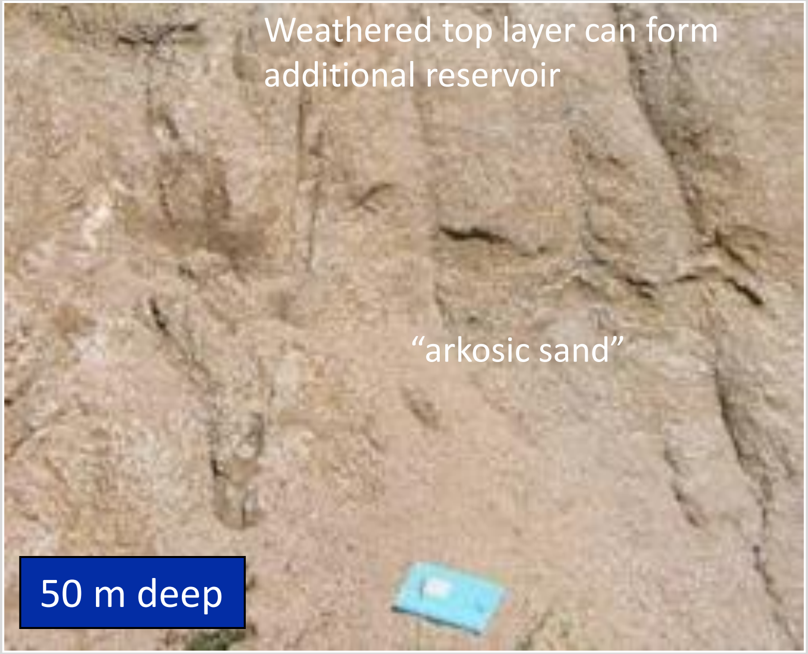
# Fractured basement reservoirs

Fractures define porosity
and permeability

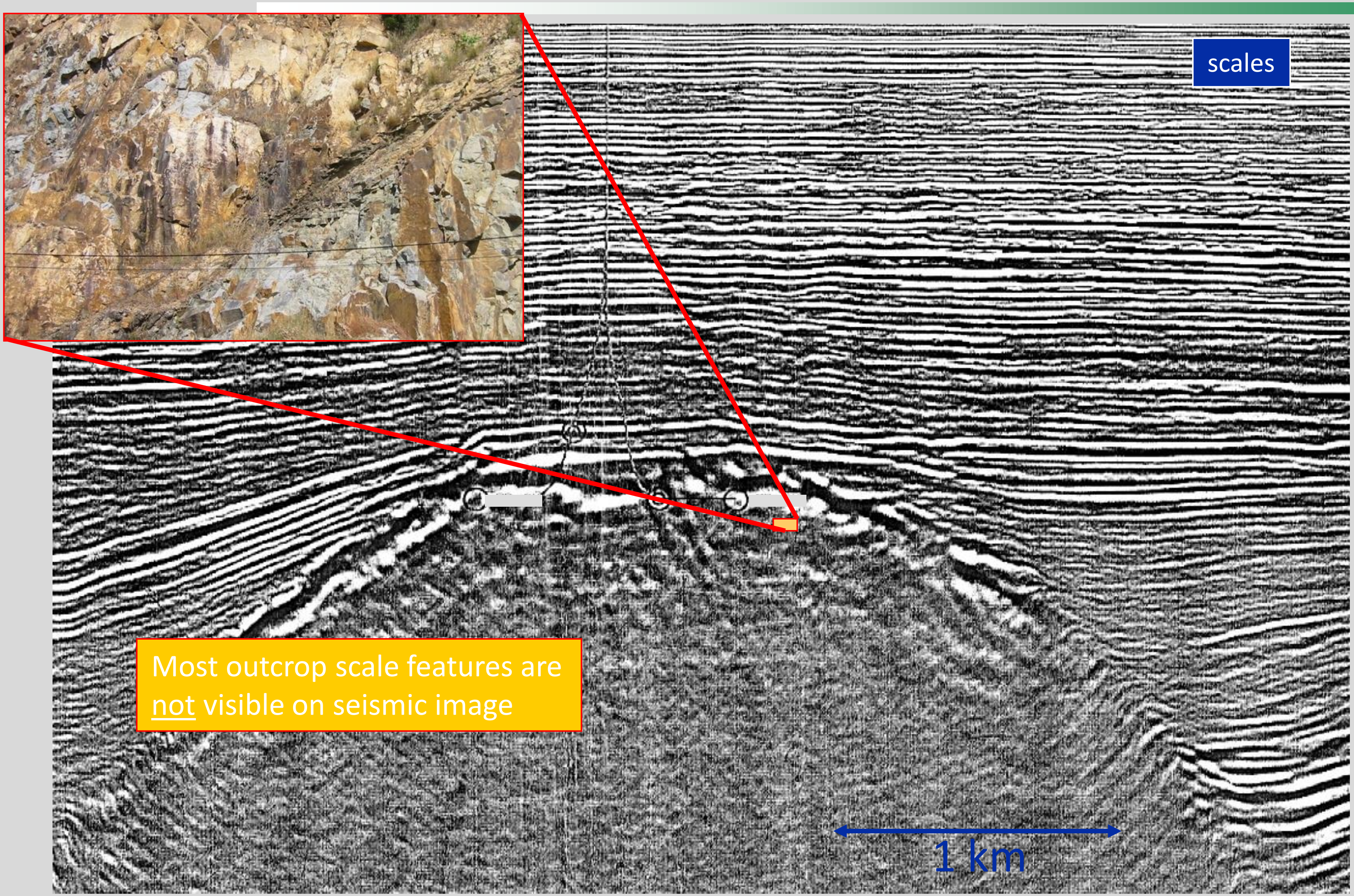
No matrix ø
in fresh basement

“The mother of all
fractured reservoirs”



# Fractured basement reservoirs



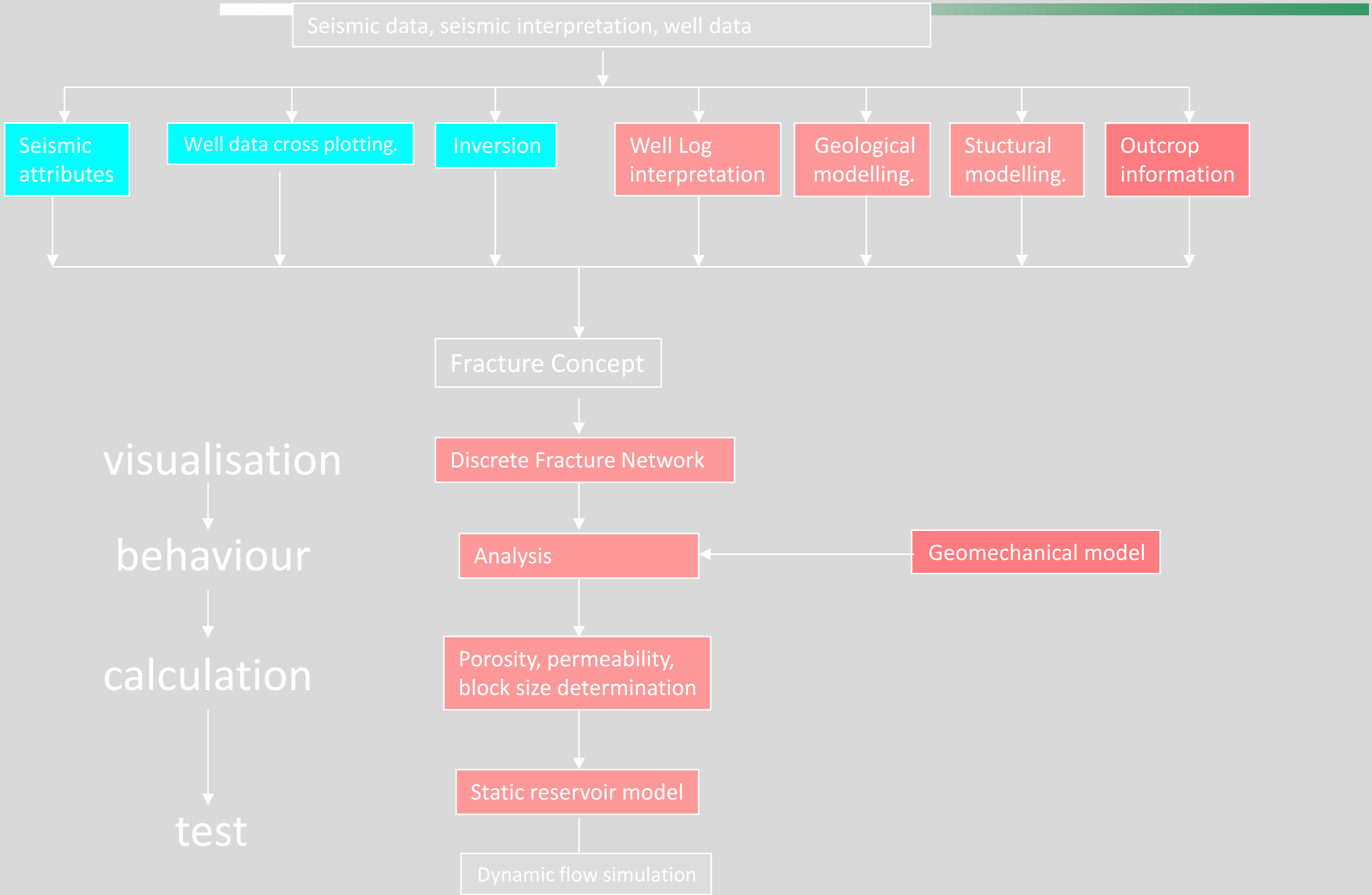
# Fractured basement reservoirs

Observations on different scales are difficult to relate,
As they have different spatial distributions, features etc.
Therefore, a

"Conceptual fracture model"

needs to be designed that describes those relationships.

# Fractured basement reservoirs workflow



# Fractured basement reservoirs

Fracture concept

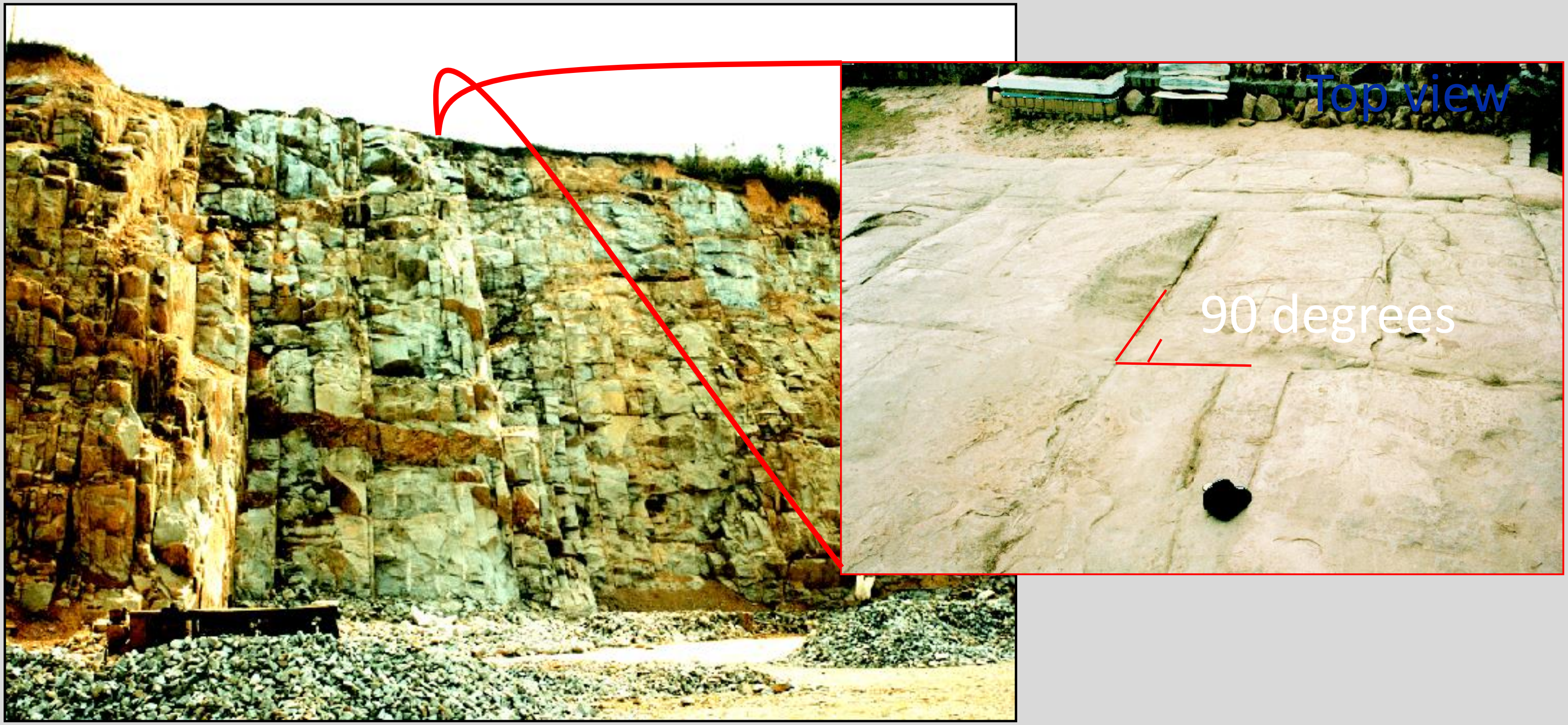
Describes:

- Classification & Generic origin of various fracture sets
- Spatial distribution of fracture sets
- Properties of each fracture set
  (length, aperture, permeability, etc)
- The mutual relationships between all 3 above

*"An educated guess consistent with observed data and comparative to well known analogues…."*

# Fractured basement reservoirs

Fracture creating processes

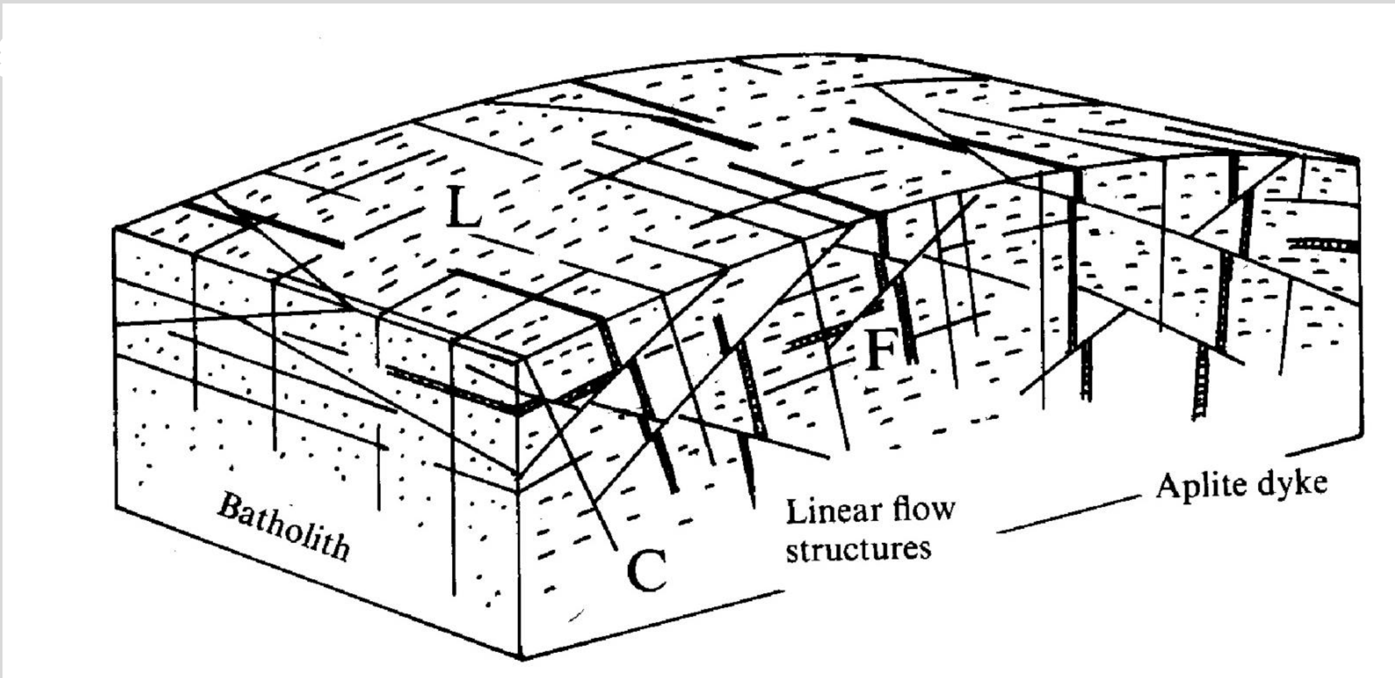



Undeformed granite shows equidistant, orthogonal fracture sets.
(Partly) filled with pegmatite (late melt) suggest they formed just after crystallisation of the magma.
Spacing typical 1-2 m

## Fracture creating processes

I Cooling & crystallisation

Analo

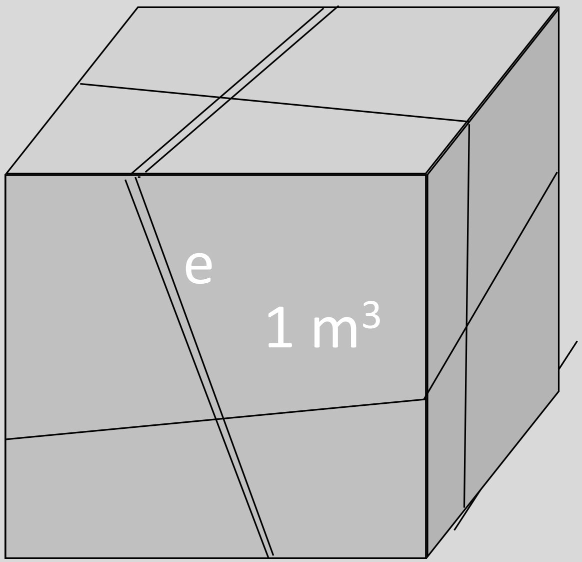



*After: Cloos, 1922*

Fracture sets commonly observed in granites, called primary (or "cooling") fractures,
Formed during the crystallisation of the magma. Mostly joints

# Fracture creating processes

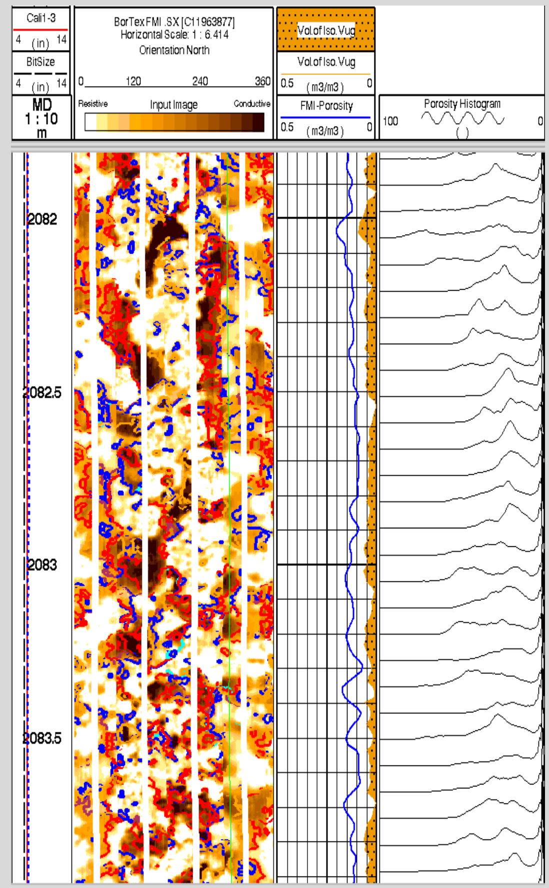
## Porosity estimate from outcrop




Apertures (e) typically: 0.25 mm (logs)
Fracture spacing (D) Ø →

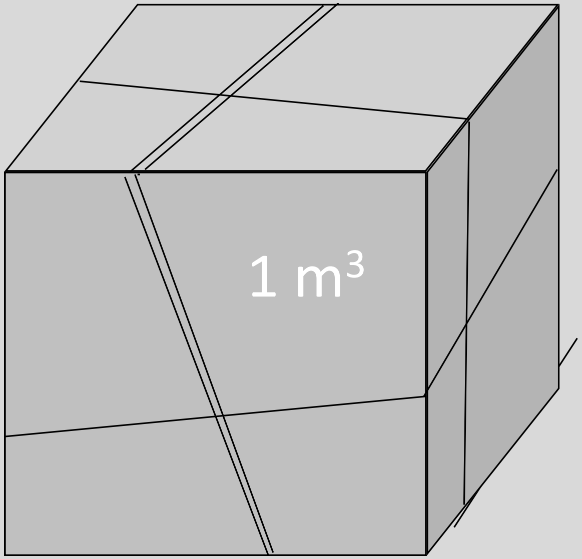
$$\phi = \frac{e}{D+e} \times 100$$

*After: Nelson (2001)*




Aperture/Ø estimates from logs
*From*

# Fracture creating processes

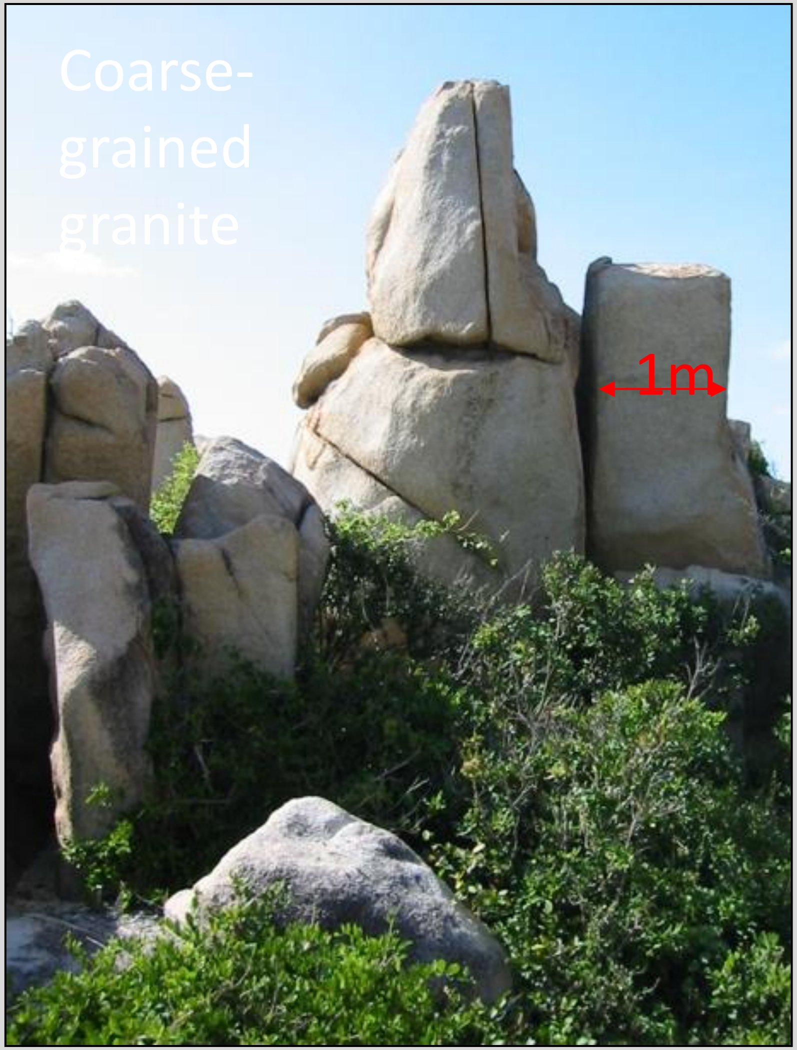



Cooling fractures in coarse grained granite on average create

< 0.1% porosity

assuming all fractures open

Spacing typically 0.5 - 2 m:



# Fracture creating processes

Influence of lithology:

Andesite usually fine grained and significantly higher fracture density. Both are attributed to rapid cooling process (solidifies close to surface).


Fracture spacing ~ 5- 10 cm

up to 1% porosity

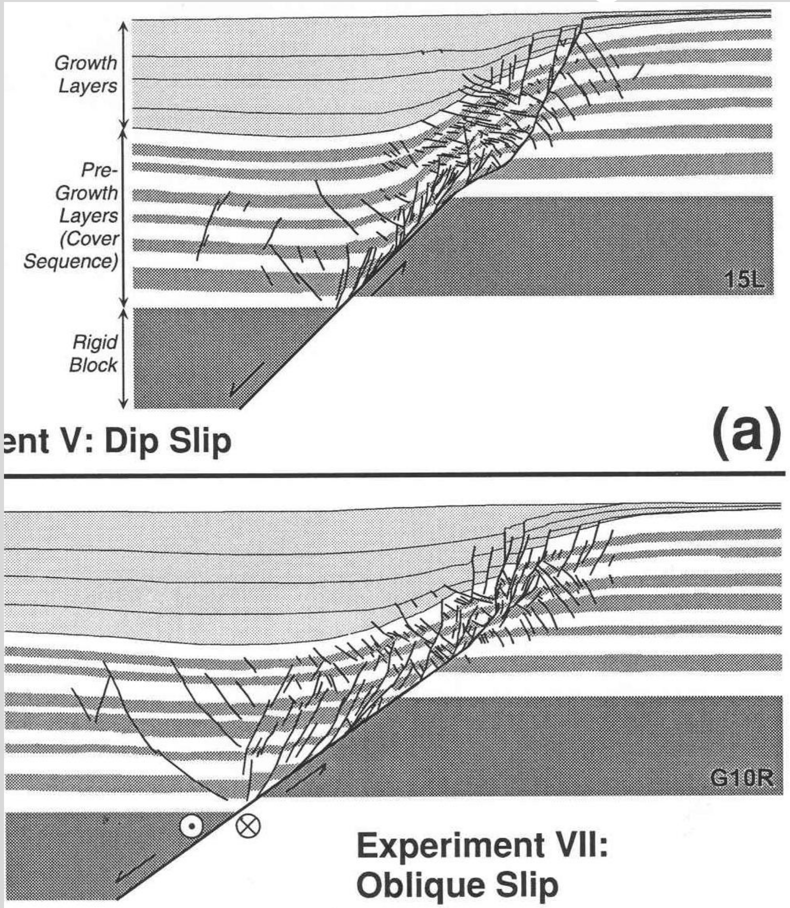
assuming all fractures open

Order of magnitude higher Ø!

# Fracture creating processes

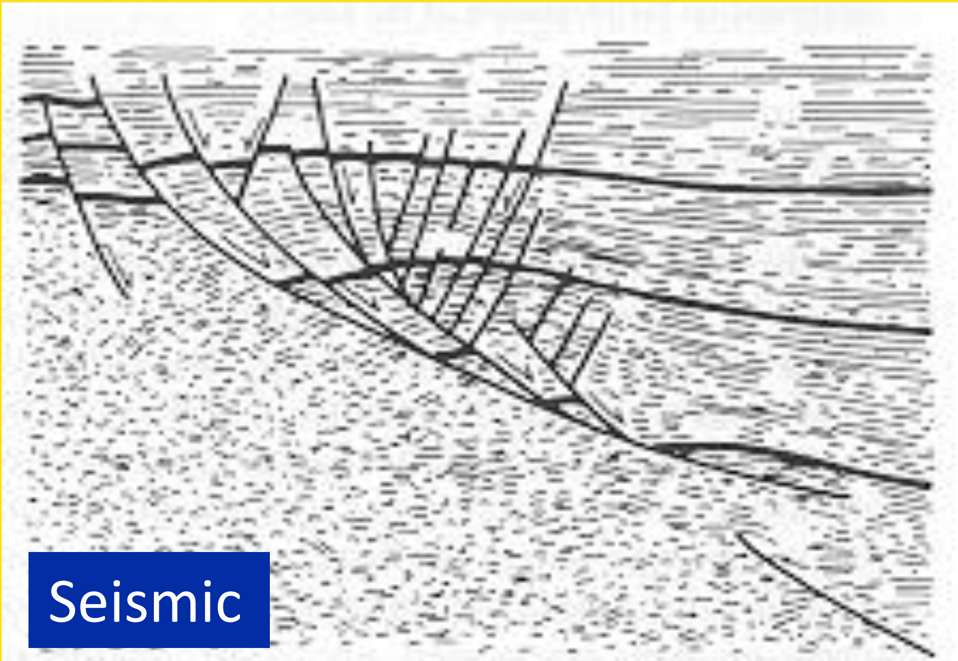
## II Deformation

Sandbox modelling




*From: Schlische et al., 2002*

Deformation of brittle rocks is cause of pervasive fracturing




*From: Dula 1991*

# Fracture creating processes

## Deformation creates shear fractures

Conjugate shear fractures
Here: randomly distributed "No clustering"

Fracture spacing ~ 5 cm
1-2 % porosity

## and "subseismic faults"

Or strain can be concentrated in discrete faults ("clustering")

Average porosity ??

# Fracture creating processes


Permeability contrast between cataclastic shear fracture (top detail)
And joint (below)

Shear fracture often forms highly brecciated core and surrounding fractured damage zone

Shear fractures create more Ø and permeability than joints

# Fracture creating processes


Discrete faultzone with pervasive cataclastic faultrock

Porosity locally up to 10% (?)

High permeability

"Fluid flow corridors"

Locally, fine-grained gouge in the core of the faultzone may act as fluid barrier

Faults are considered fluid corridors along the fault damage zone, not necessarily across faults

# Fracture creating processes

Primary fractures

Always present?
- Randomly distributed?
- Ø, perm = ƒ: lithology
- Ø poor in granite

Tectonic fractures

Dominate reservoir: (Ø and perm)
- High fracture density
- Long & wide (ƒ: displacement)
- Brecciated nature
- Clustered distribution

Exhumation fractures

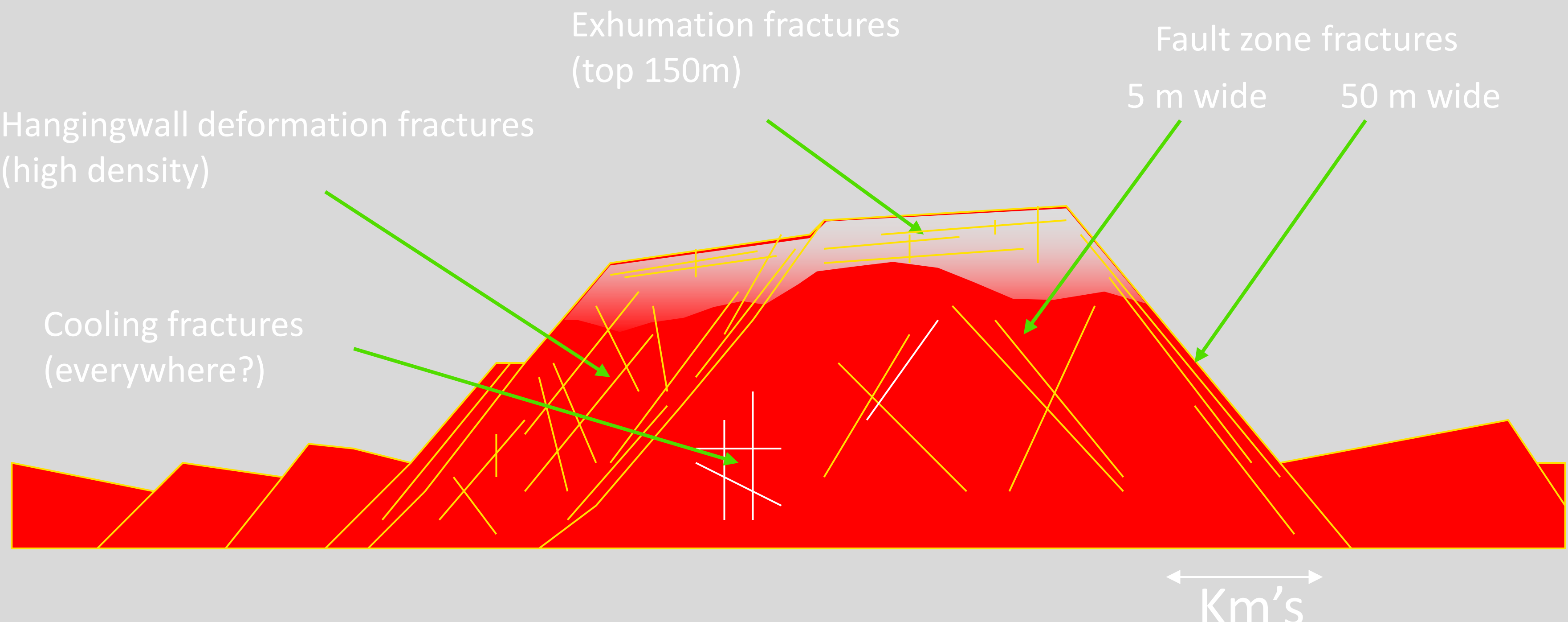
Top 150 m:
- Good Ø and perm
- Enhanced/blocked by weathering
- Density decreases with depth

# Fracture creating processes

## Exploration targets

Tectonic fractures are presumed to dominated the porosity and permeability of the fractured reservoir

The top 50-150 m maybe enhanced by weathering and sheet (exhumation-) fractures



# Fracture creating processes

## Fracture density-porosity-permeability

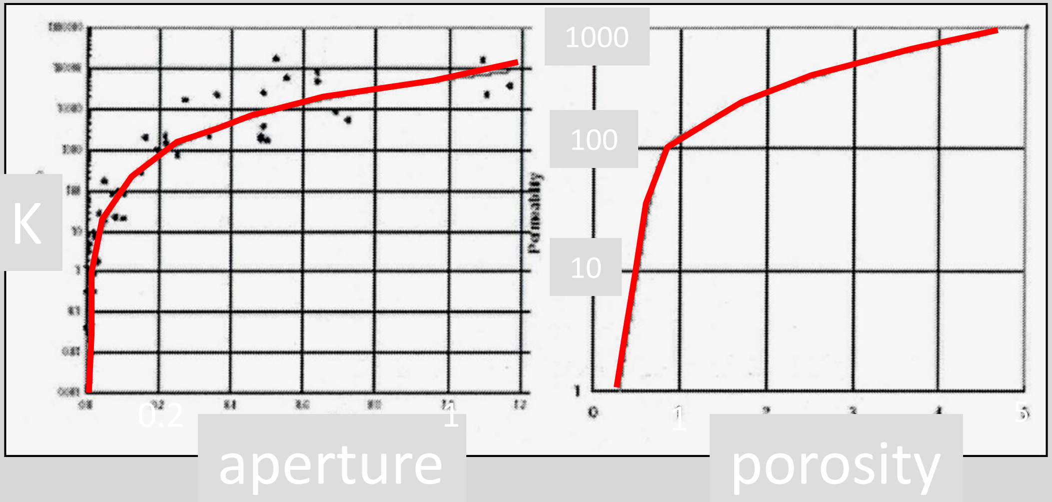
$$\phi = \frac{e}{D+e} \times 100$$

D= spacing
E=aperture

*After: Nelson (2001)*

$$K_f = \frac{e^3}{D} \times (8.35 \times 10^8)$$

*Only for homogeneous fracture sets*




*After: Shiomoto, 2003*

Exploration tool:

Fracture density // porosity & permeability

# Fracture creating processes

Identify productive structural domains ("sweetspots")

guides to
fracture density

$\emptyset_f$, $K_f$, connectivity

More fractures → more intersections → better connectivity → better flow

# Fracture creating processes

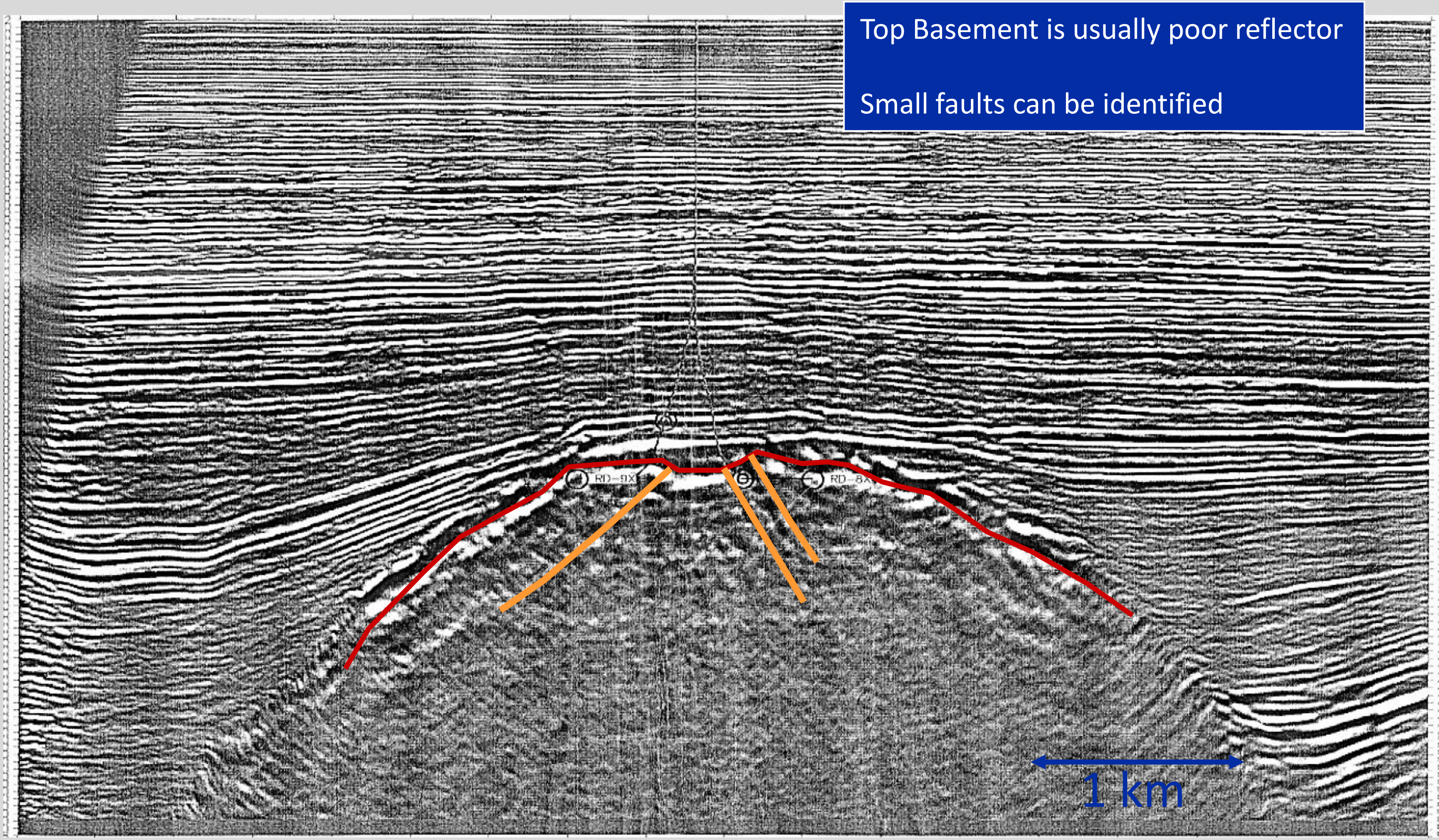
Defining fracture density with seismic methods:

- Identification of small discrete faults from detailed seismic interpretation
- Seismic attribute maps as fracture density prediction

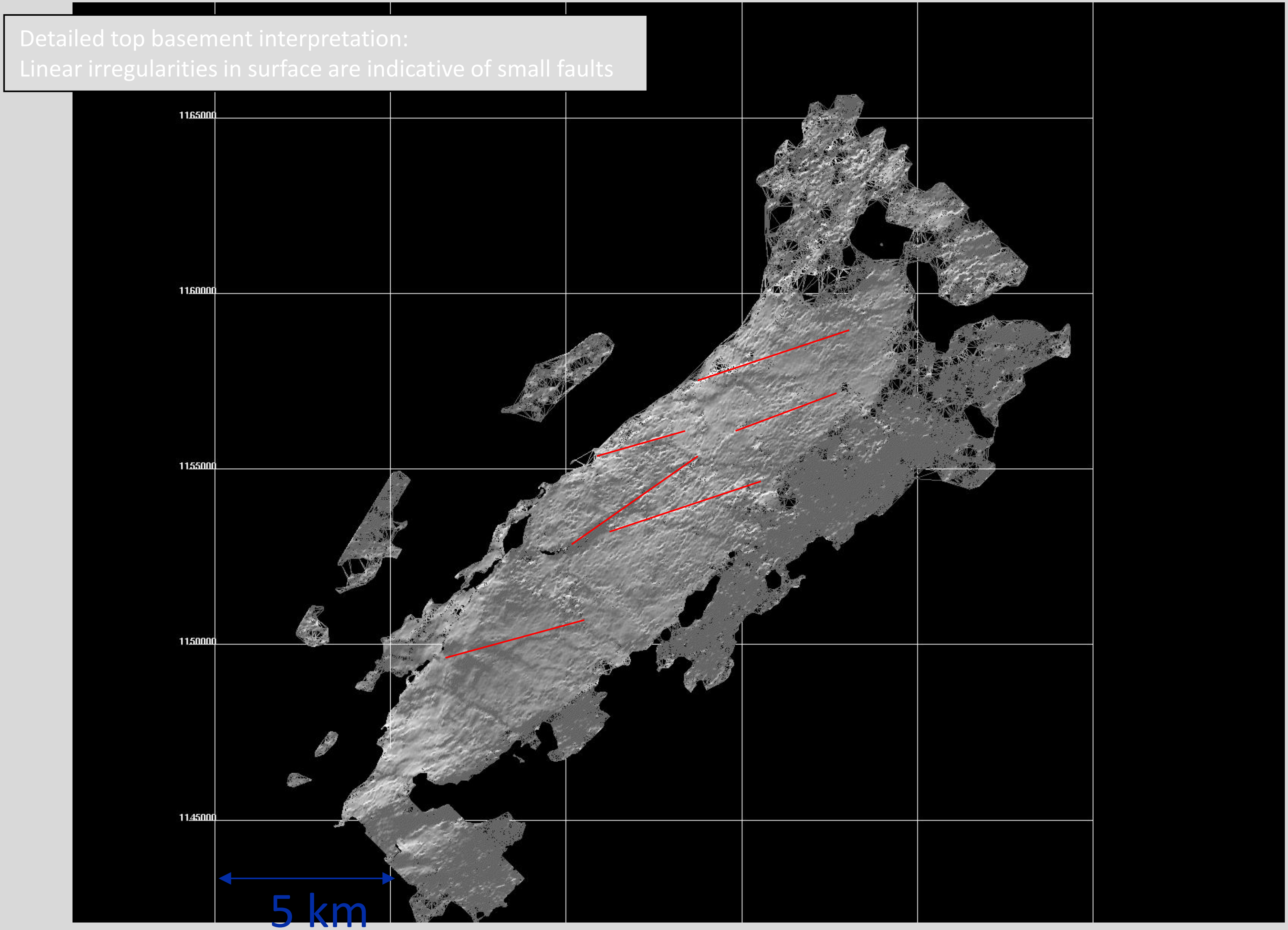
# Fracture creating processes

Top Basement is usually poor reflector

Small faults can be identified

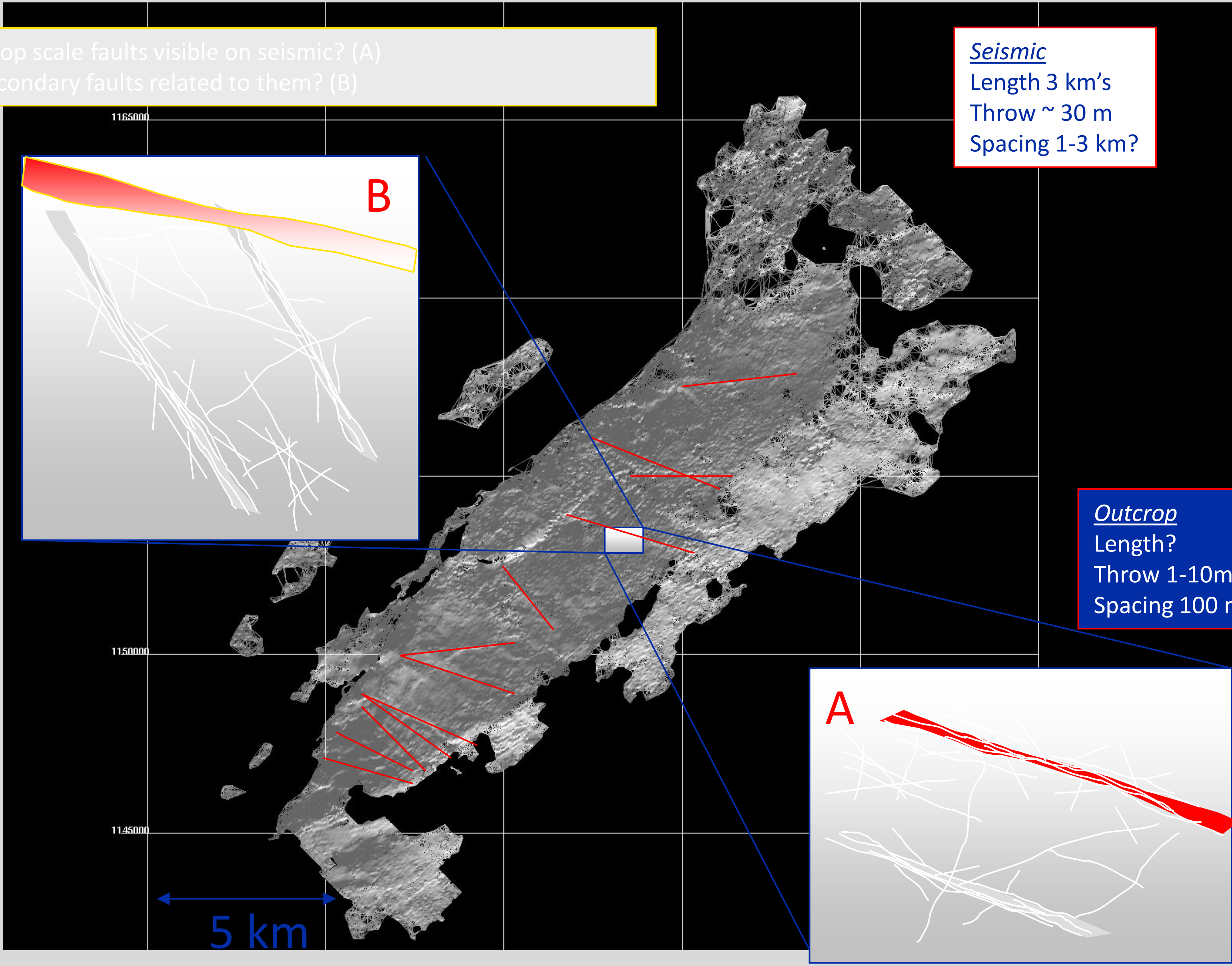


# Fracture creating processes



# Fracture creating processes

Outcrop scale faults visible on seismic? (A)
Or secondary faults related to them? (B)




*Seismic*
Length 3 km's
Throw ~ 30 m
Spacing 1-3 km?

*Outcrop*
Length?
Throw 1-10m?
Spacing 100 m

# Fracture creating processes

Seismic attribute maps:
Attribute values are indicative for subseismic fracture density


Coherency map

Low coherency indicator for high fracture density

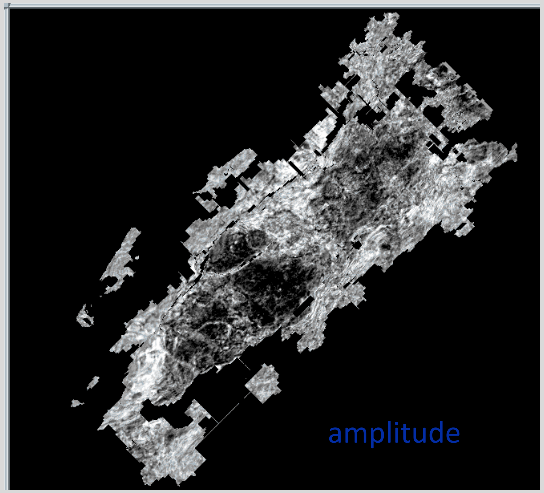
high
low

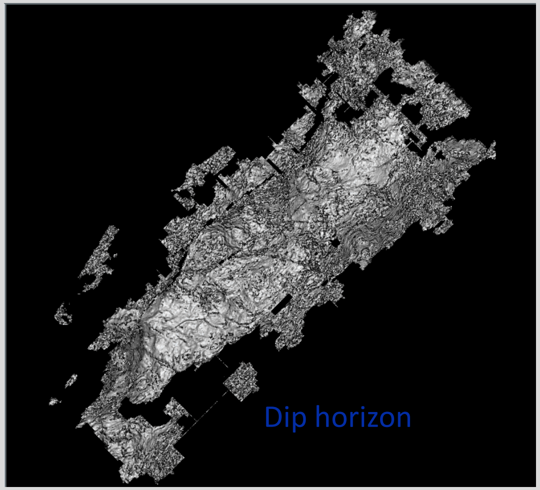
But what scale of fractures?

# Fracture creating processes

Geophysical methods

- Attribute maps (coherency, amplitude, instantaneous phase, dip, azimuth etc.)
- Seismic modelling
- AVO etc. for dominant fracture orientations



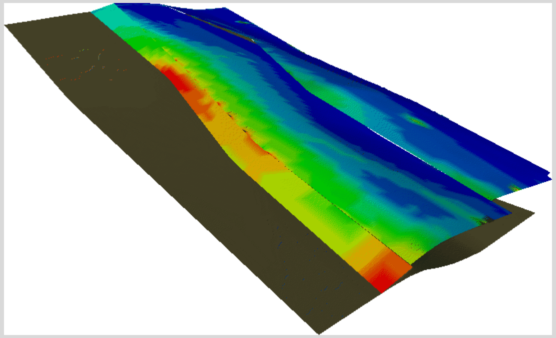

Attribute maps need to be quantitatively correlated to well data and must make geologically realistic patterns

# Fracture creating processes

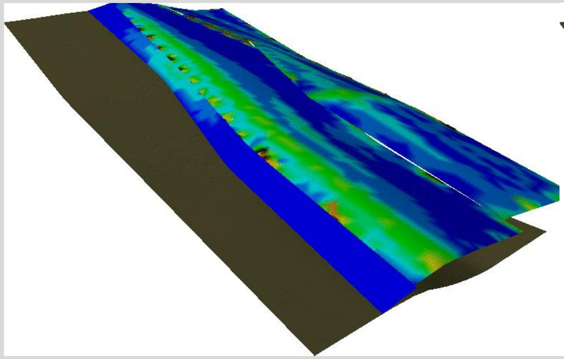
Defining fracture density from structural analysis

- Structural modelling/restorations identify areas of high deformation
- Curvature & strain maps as guides for fracture density
- Structural modelling can identify fracture sets and deformation processes

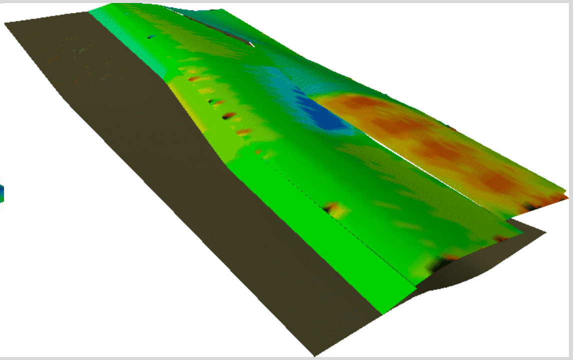
Techniques from layered fractured clastic reservoirs



strain

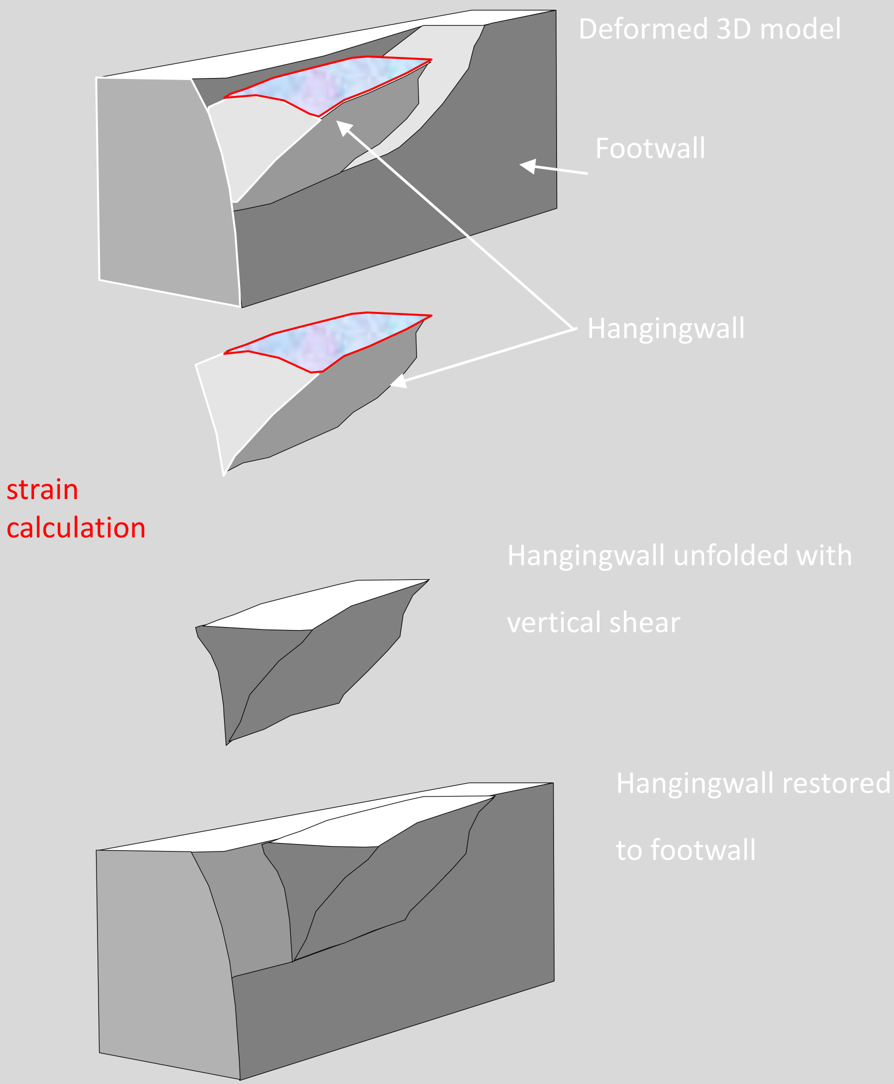


curvature



cylindricity

# Fracture creating processes




- Restorations
- Strain/curvature calculations

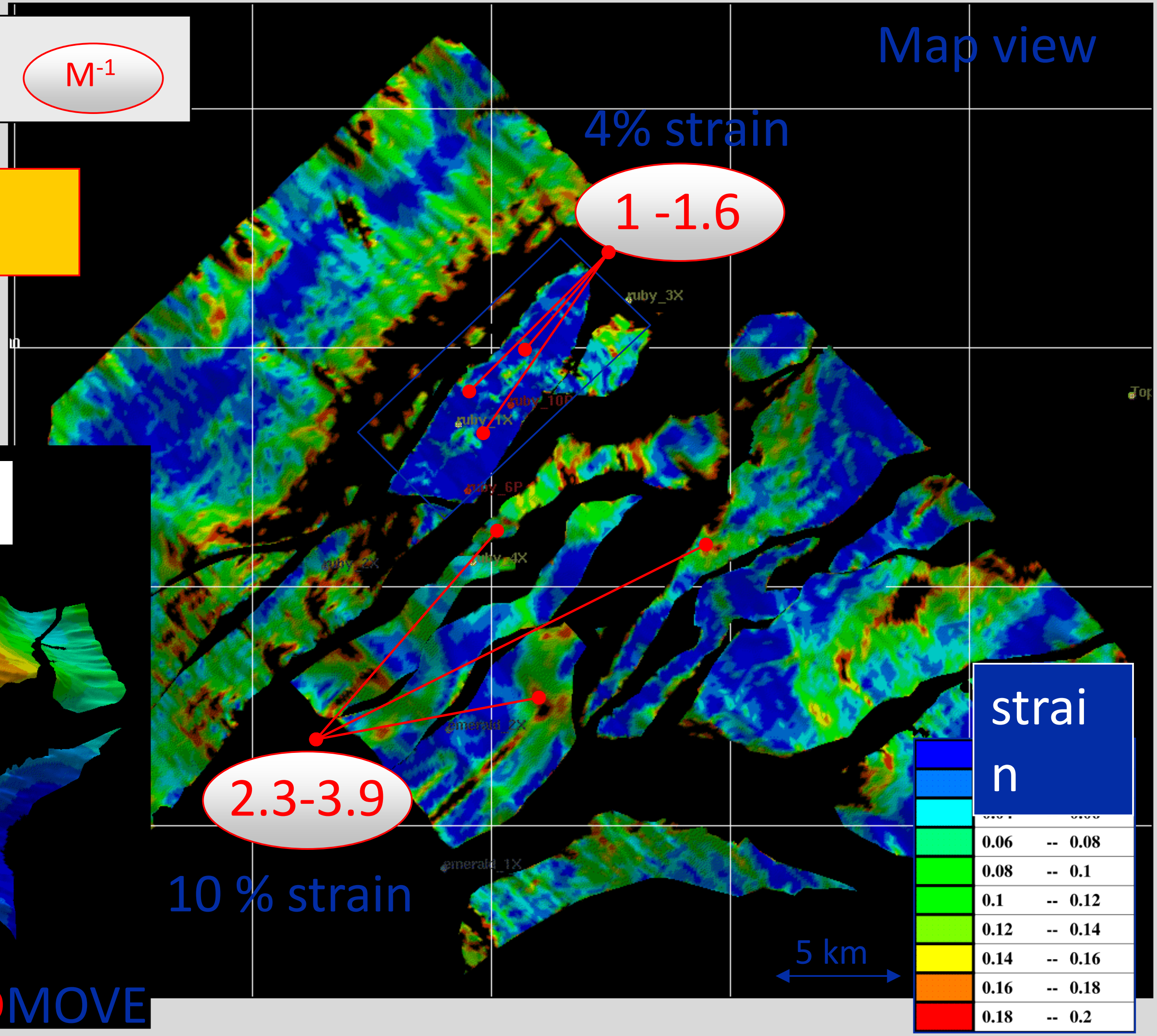
Top basement surface geometry is indicative of total deformation intensity

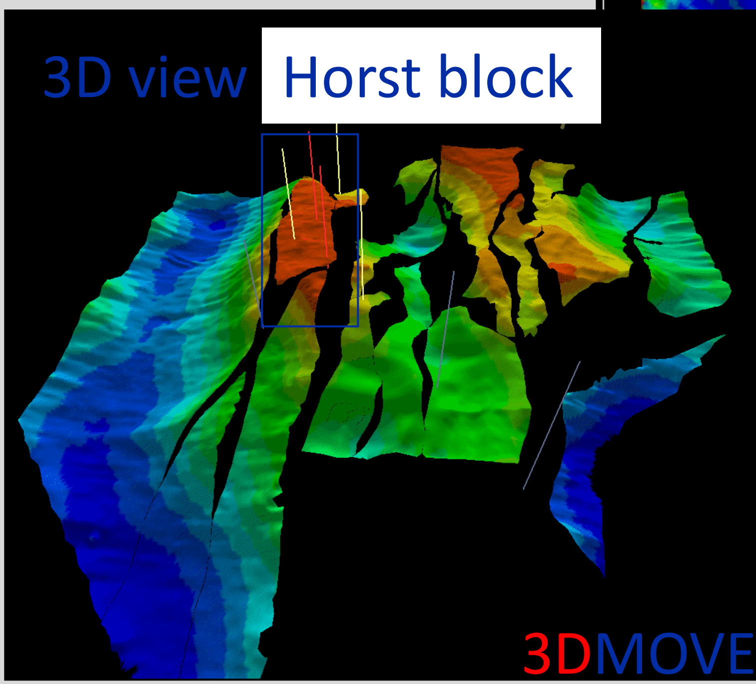
Fracturing accommodates the change in shape

# Fracture creating processes

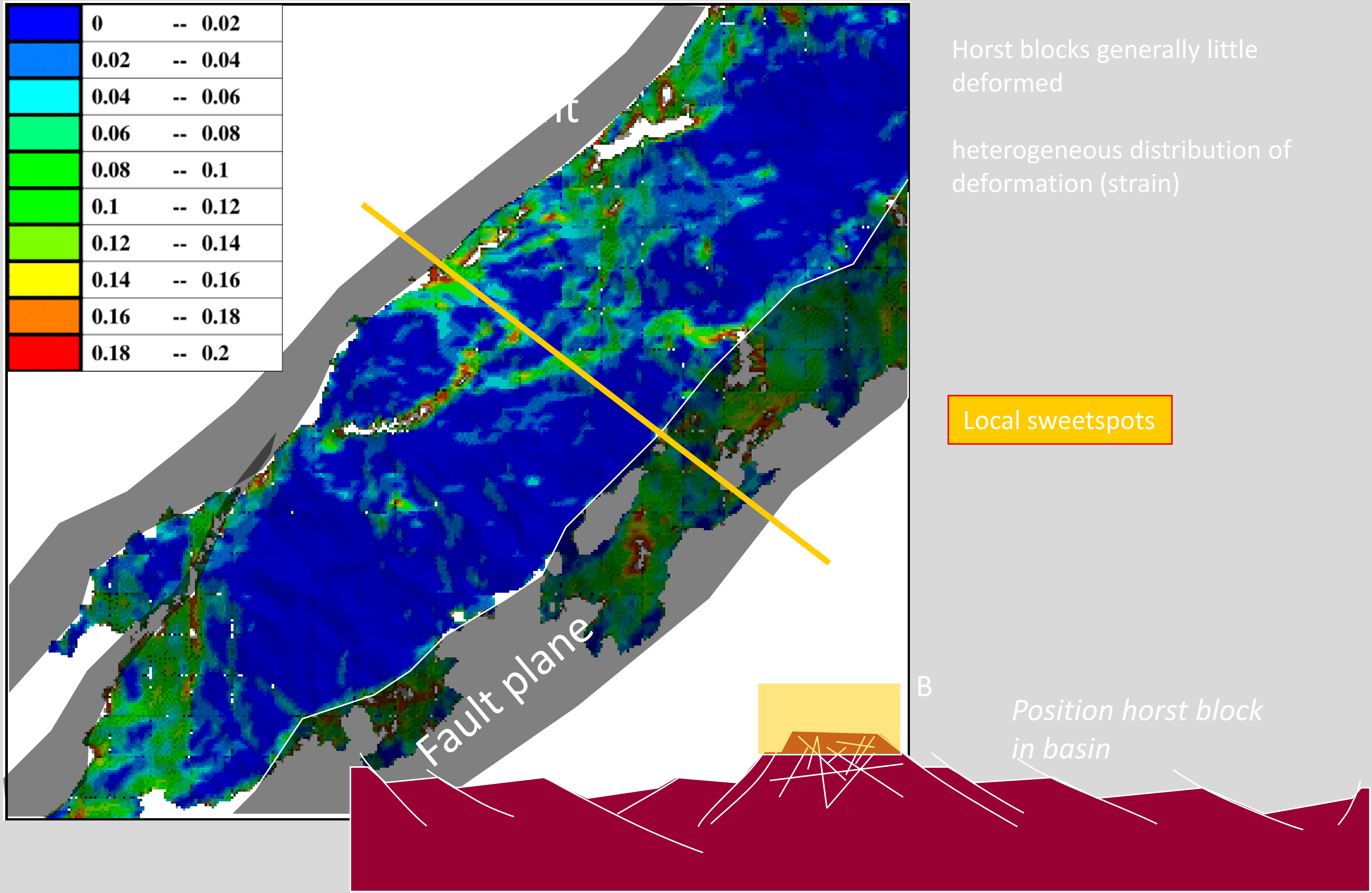
Strain map and average fracture density per meter $M^{-1}$

Hangingwalls more deformed than footwalls



# Fracture creating processes




Horst blocks generally little deformed

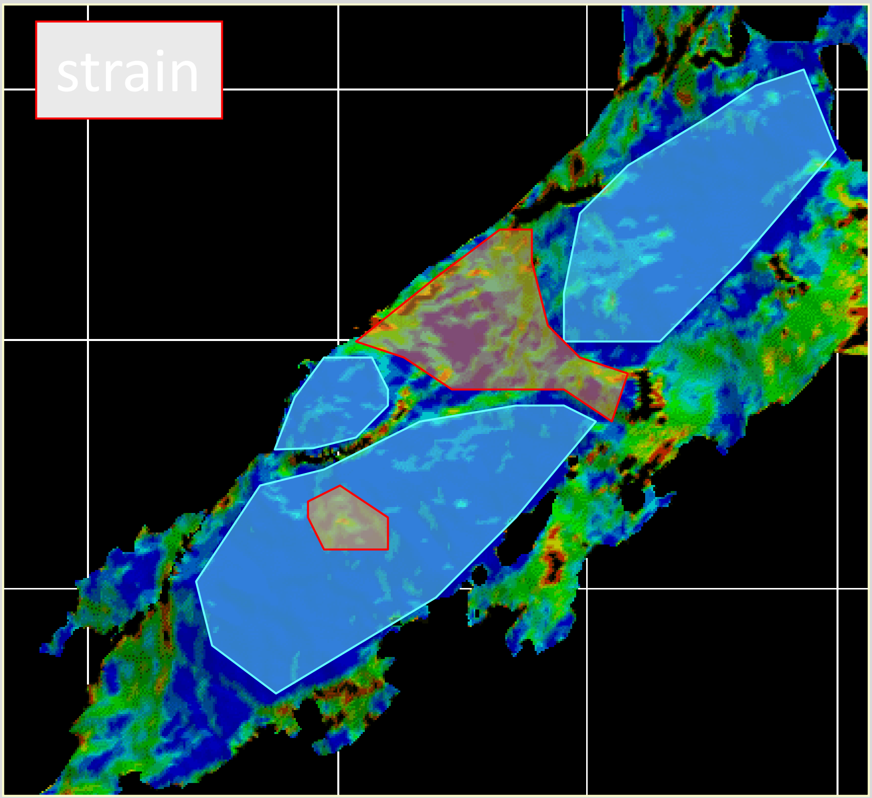
heterogeneous distribution of deformation (strain)

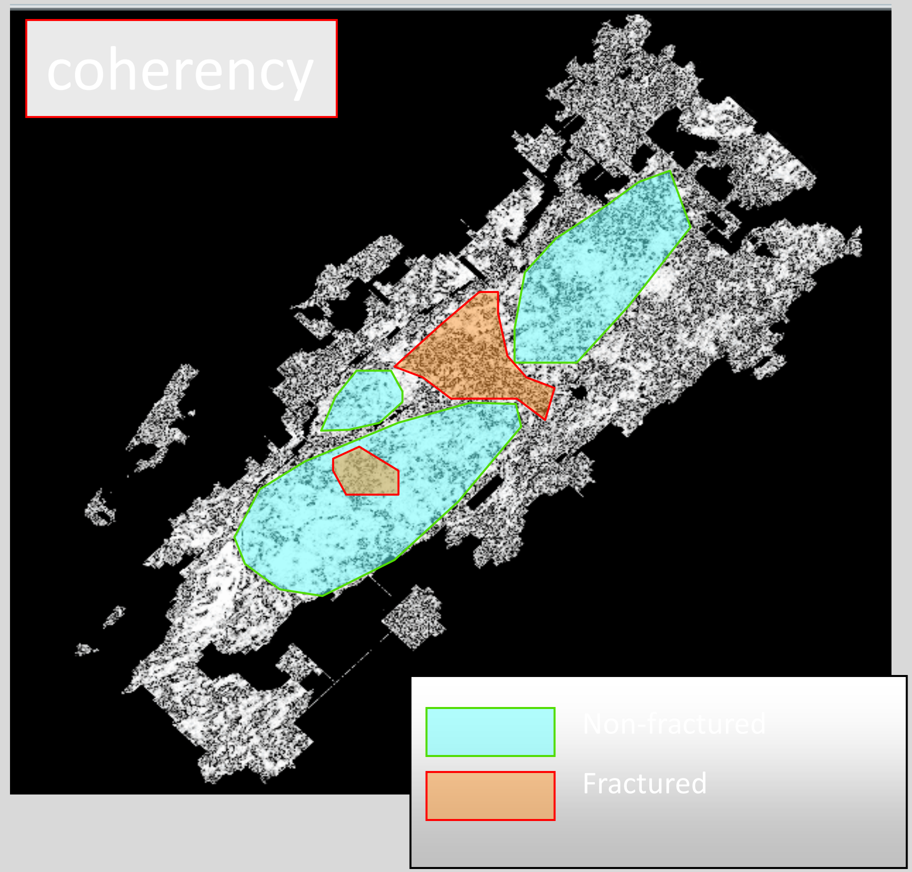
Local sweetspots

*Position horst block in basin*

# Fracture creating processes

Strain and coherency maps show very similar patterns
Areas of potentially productive domains



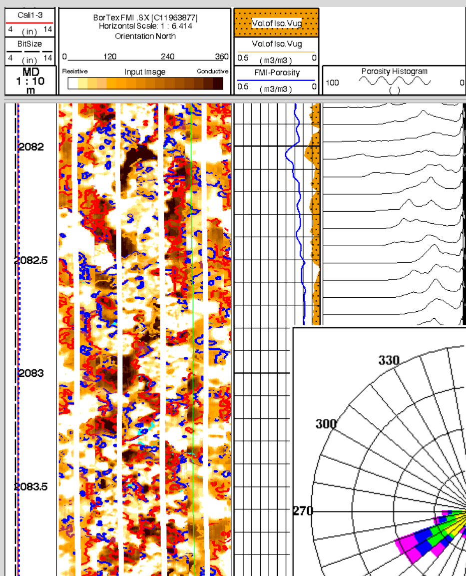



# Fracture creating processes

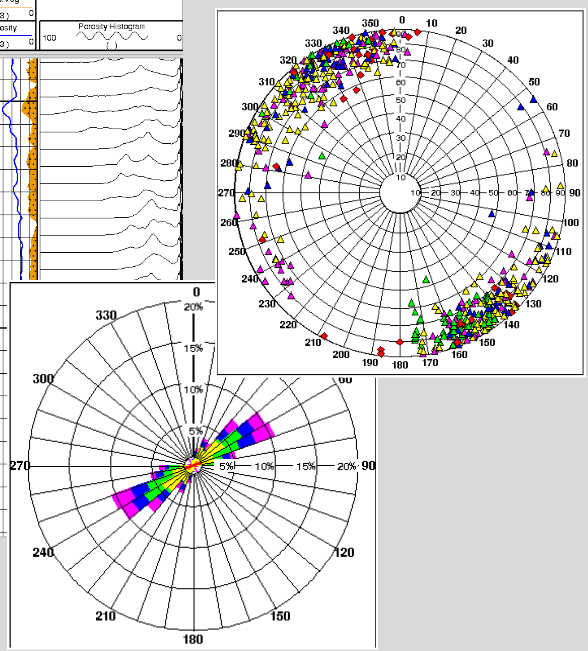
Well core/log data for:

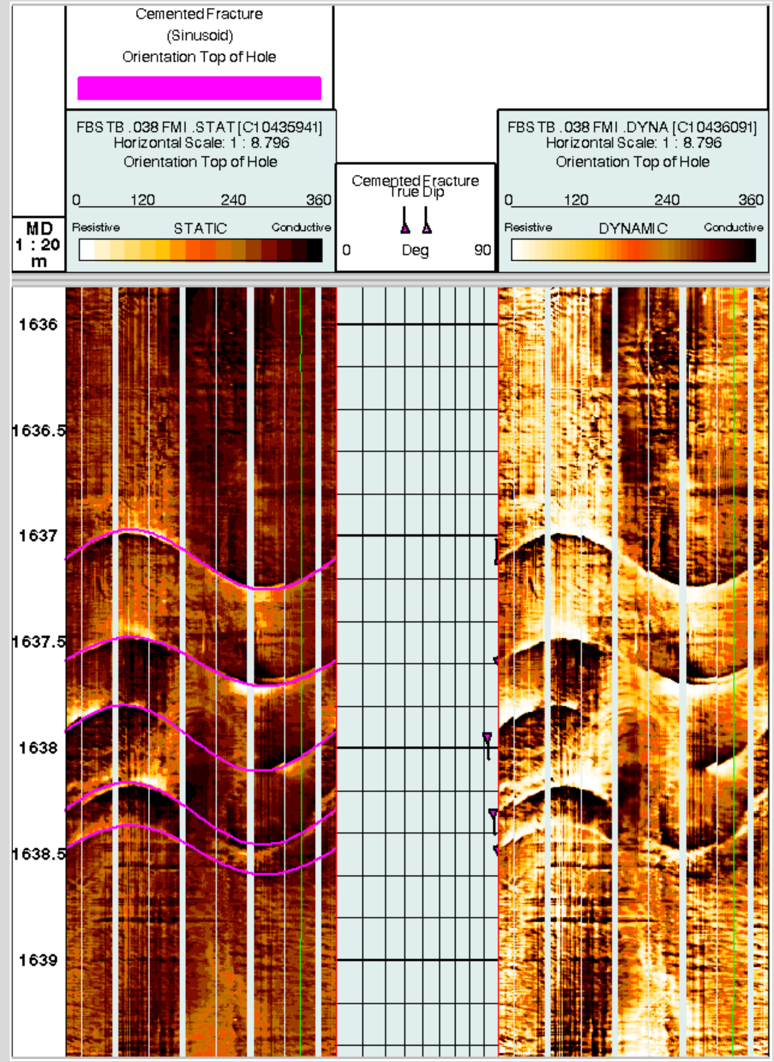
- fracture type (open, closed, brecciated, etc)
- spacing and orientations,
- estimates of aperture (?) and fluid content

Aperture estimates



Orientation distributions





# Fracture creating processes

Quantification Conceptual fracture model

related

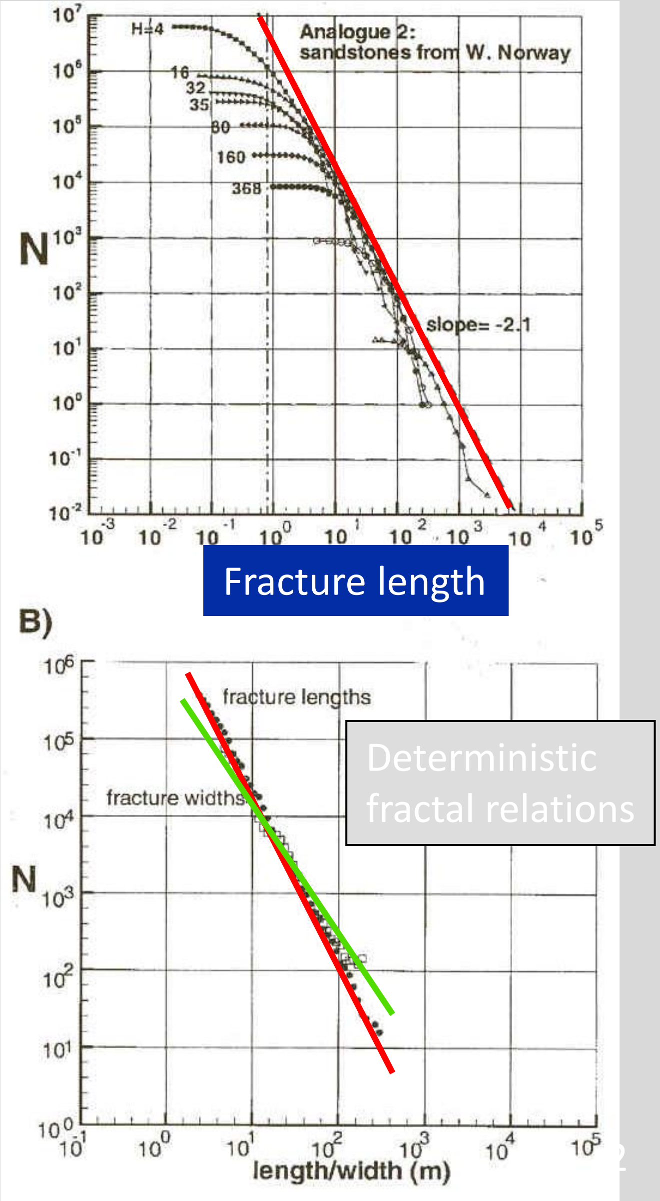
Fracture length ($z^{10}$, $z^{100}$)
Width ($z^{-10}$, $z^{-100}$)
Throw (z)

*From general multi-scale fracture studies*

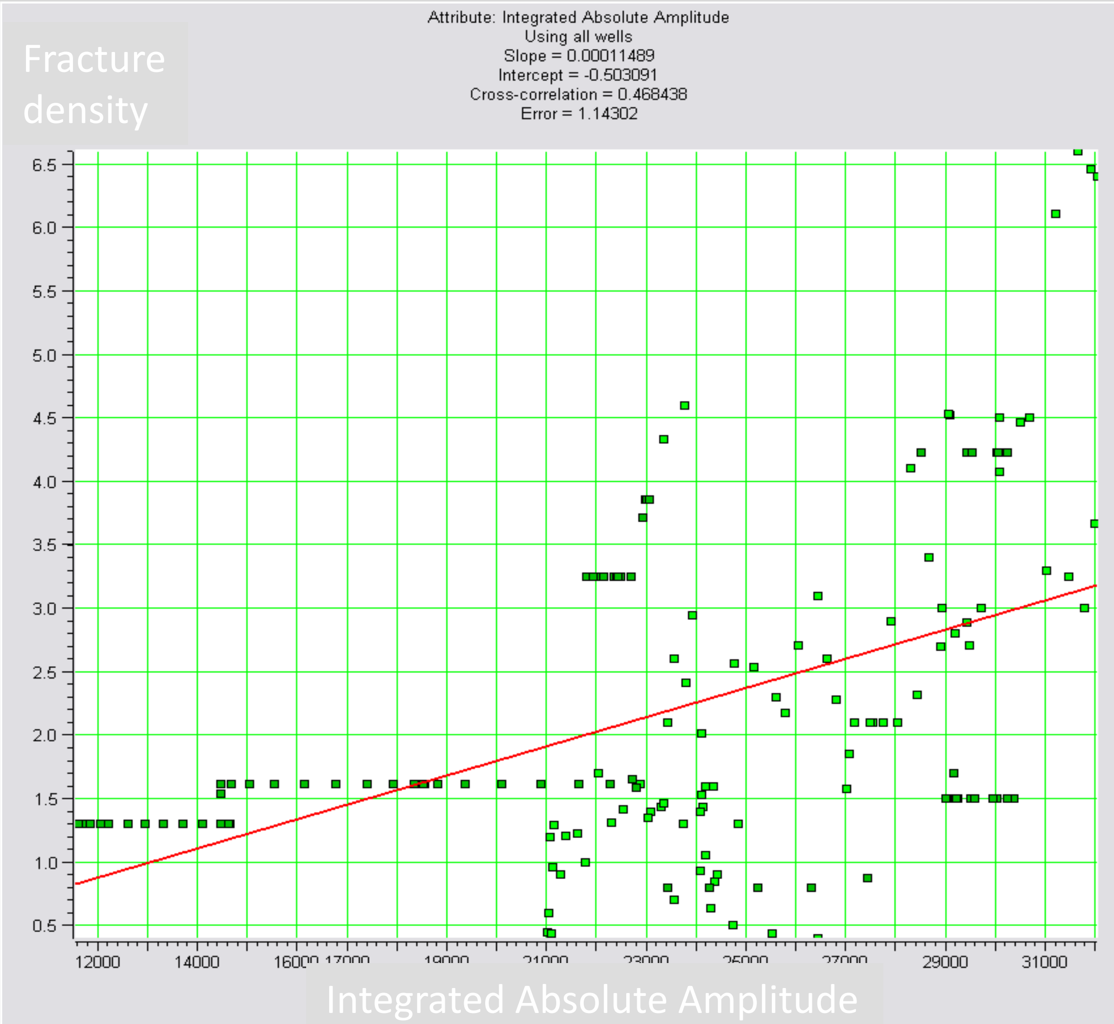
Measure fractures at different scales
- microscopic
- outcrop
- satellite image

Fracture spatial distribution?
Not deterministic?

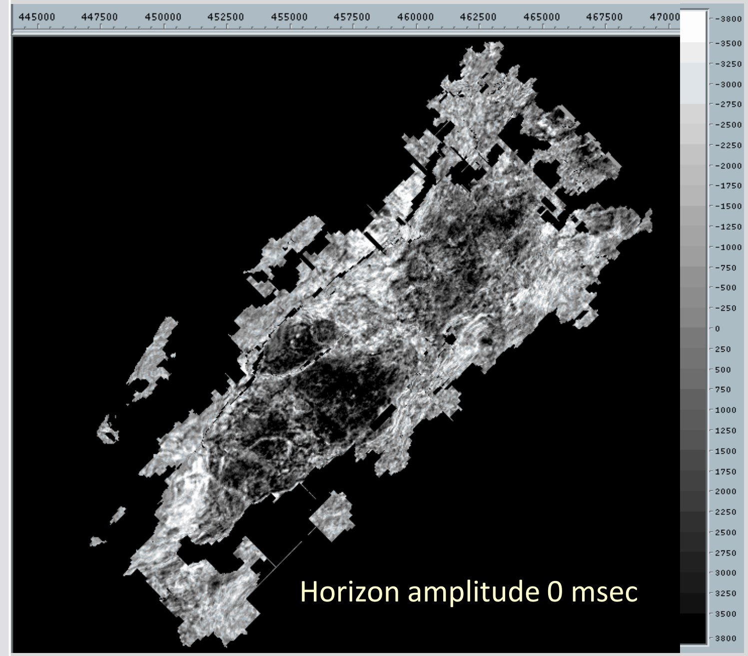
Clustering: distribution can be conditioned with attribute maps



# Fracture creating processes

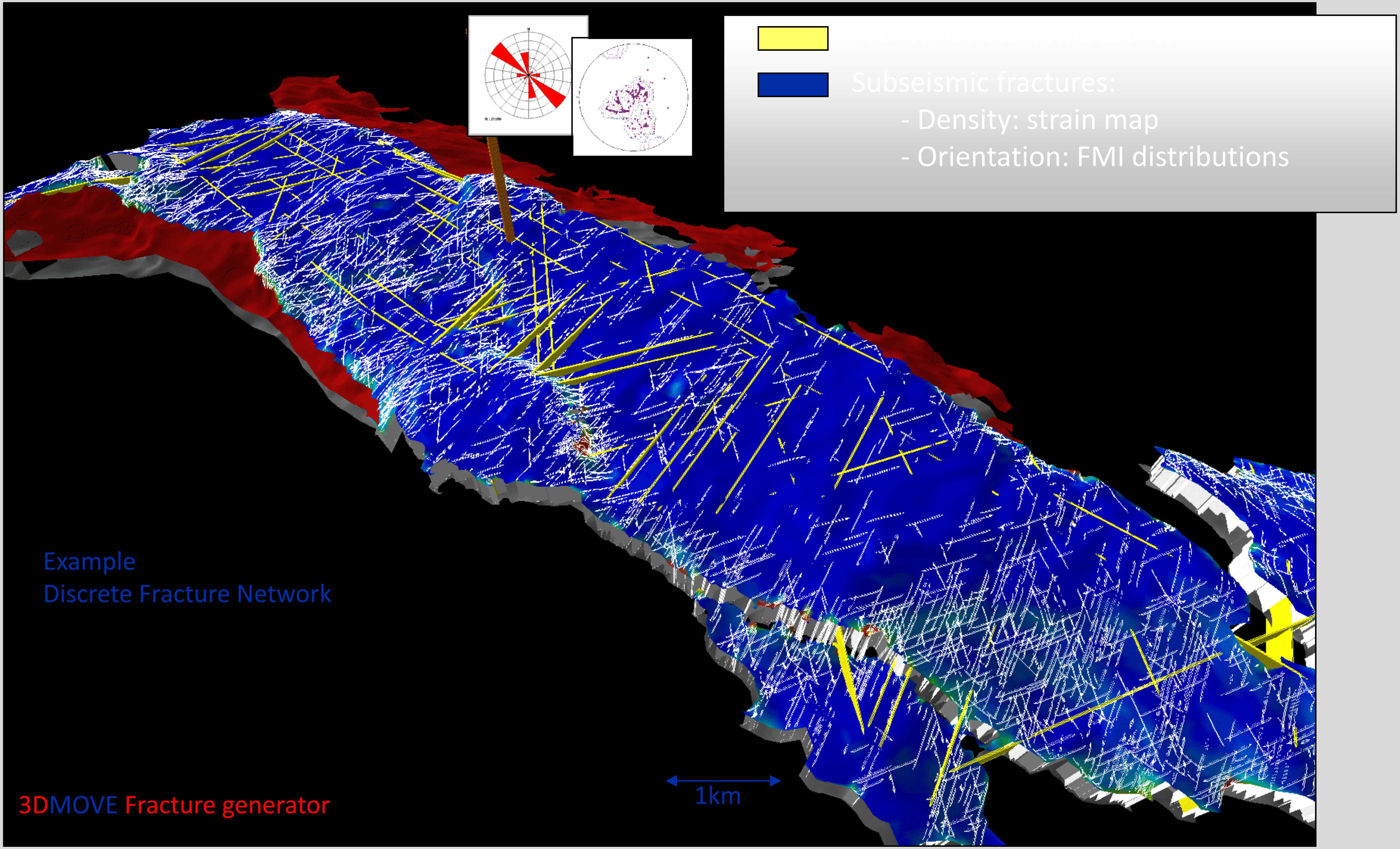



Seismic attributes checked against well observations for "subseismic" fracture density correlation

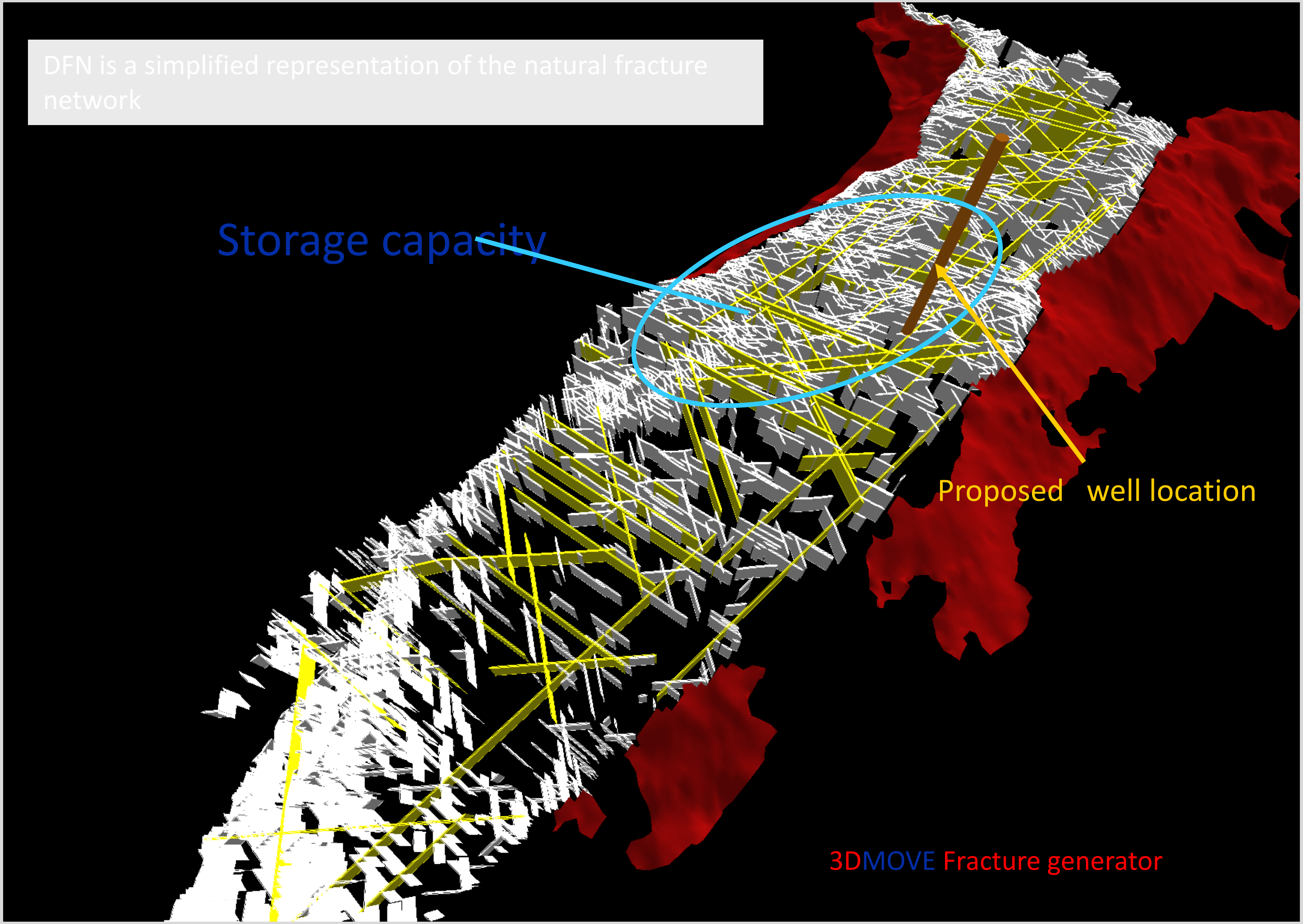



Cross plot and linear regression between basement fracture density
and the Integrated Absolute Amplitude attribute of the seismic migration trace at the well locations (M. Brewer).

# Fracture creating processes



# Fracture creating processes



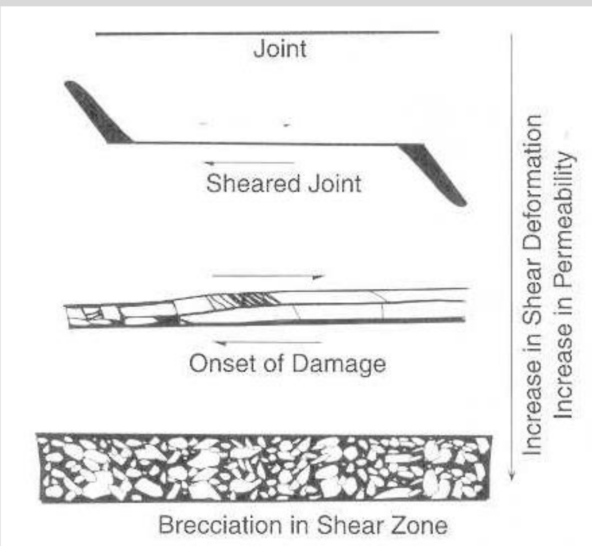
# Fracture creating processes

DFN behaviour

Conductive fractures?

Fracture properties:
- fault gouge, brecciation, cementation, roughness

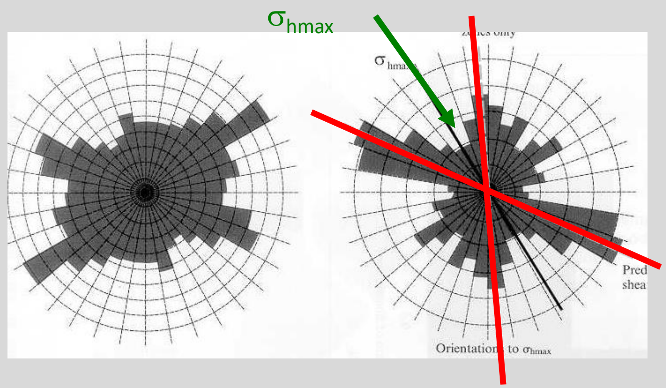
Present day regional stress state
Fluid pressure




*After Dholakia et al., 1998*

all

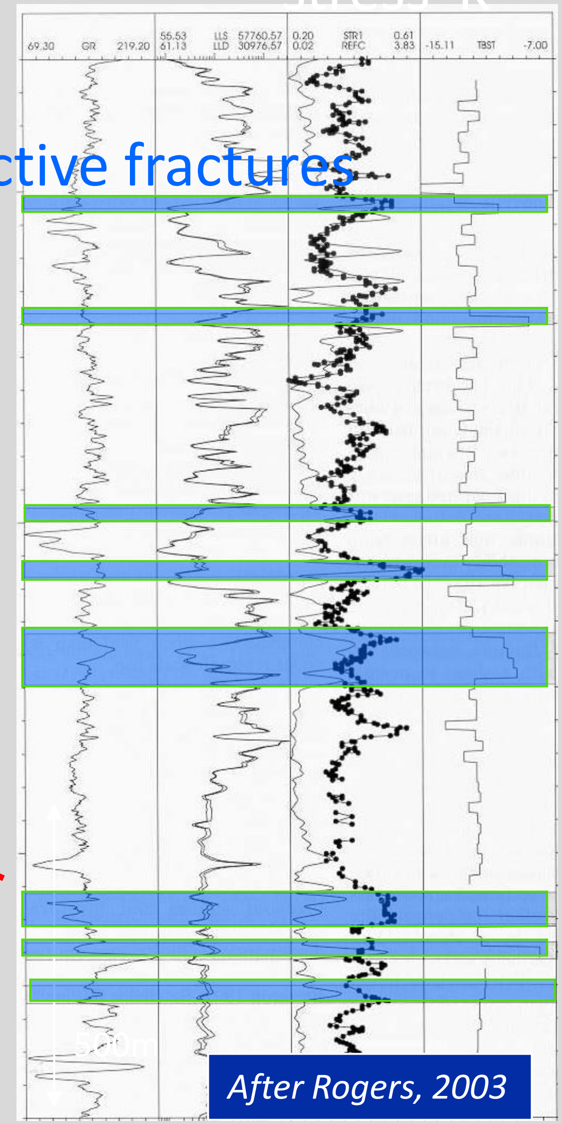
conductive




Critically stressed

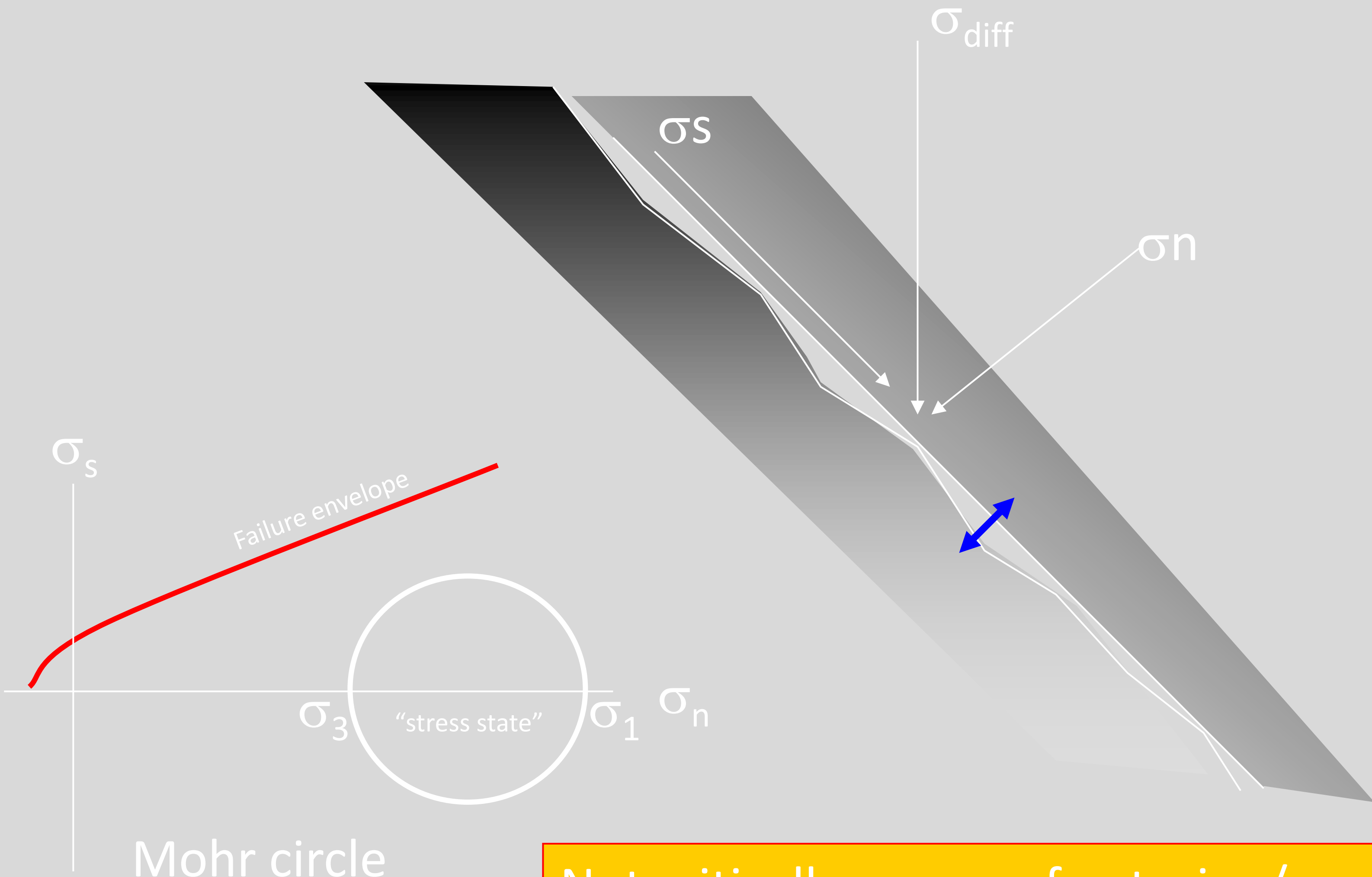
stress K

Conductive fractures



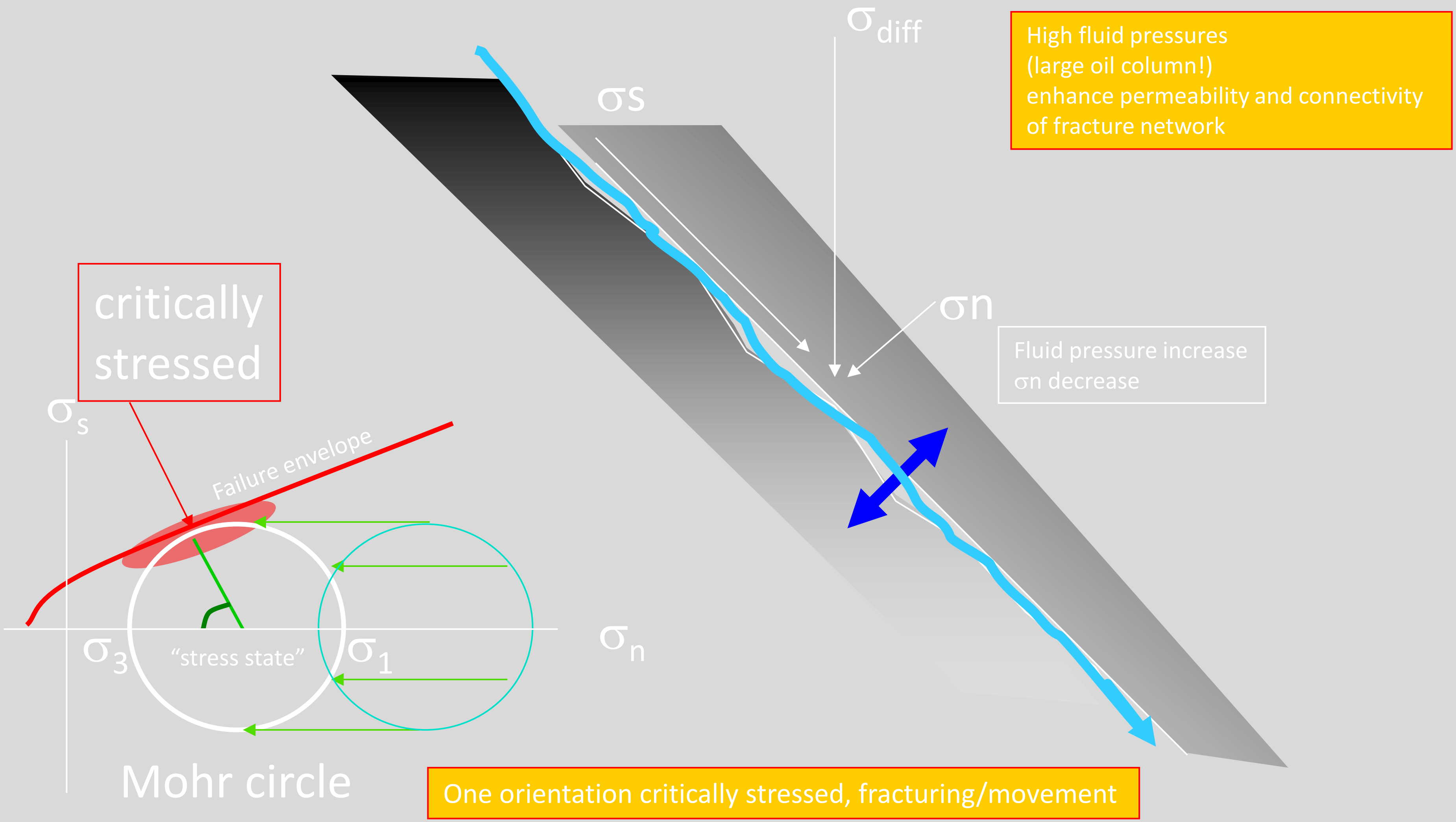

*After Rogers, 2003*

# Fracture creating processes

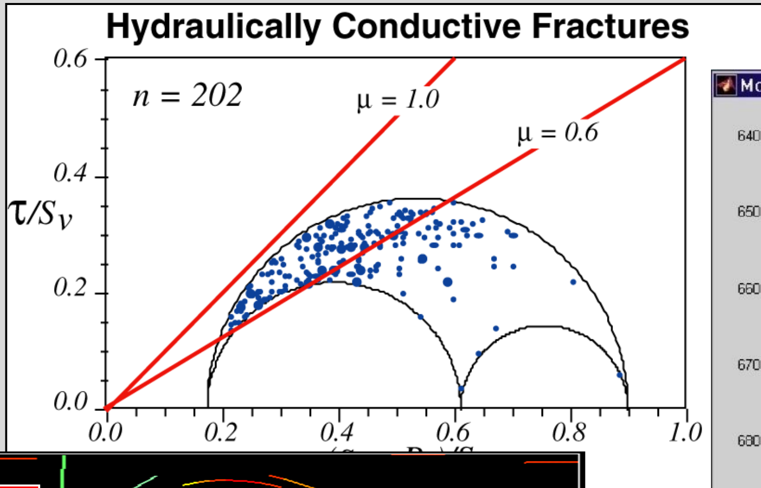


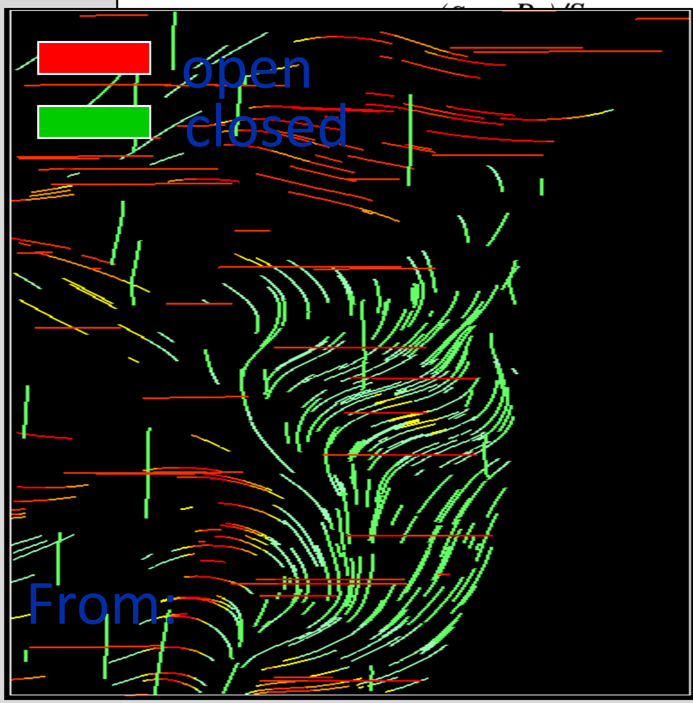

Not critically stressed, no fracturing/movement

# Fracture creating processes

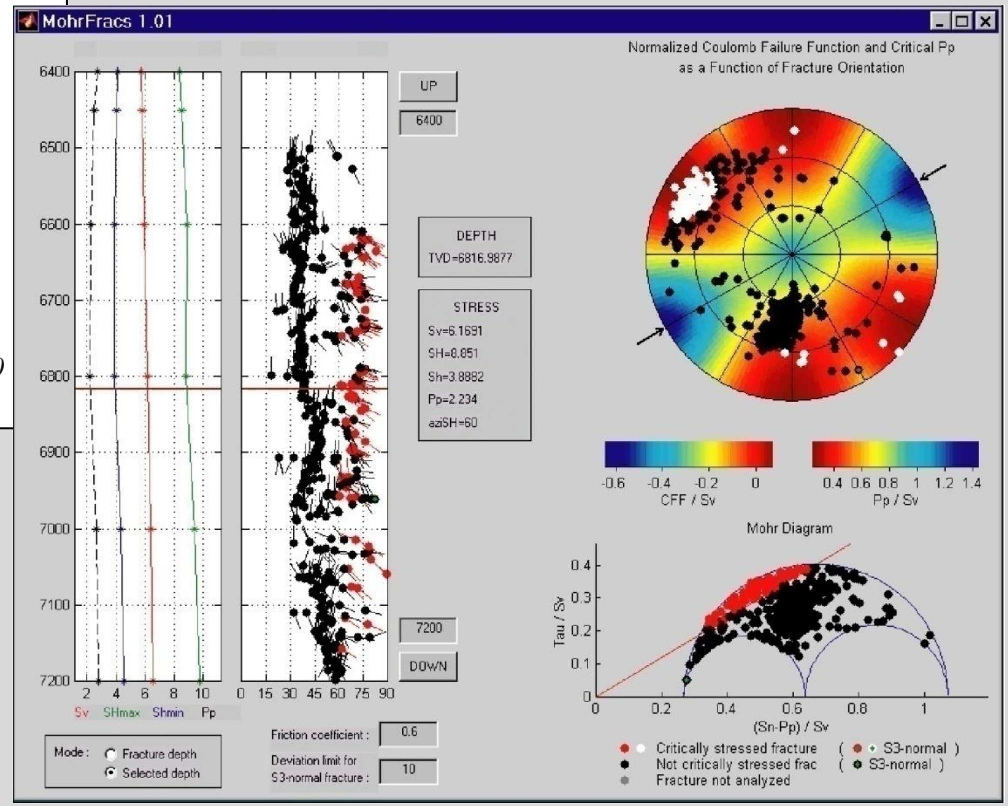


# Fracture creating processes



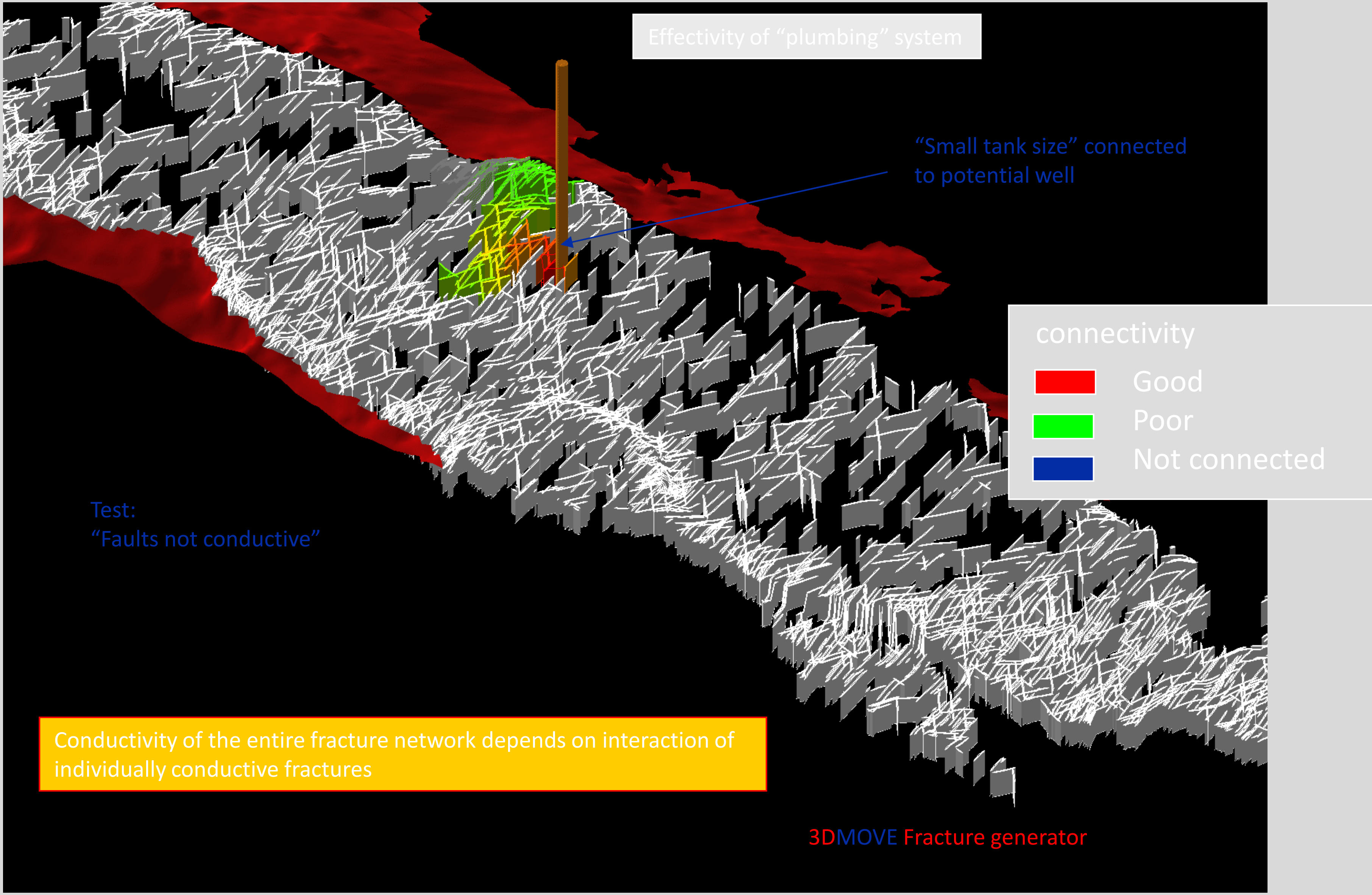




From: D. Castillo, GeoMechanics International

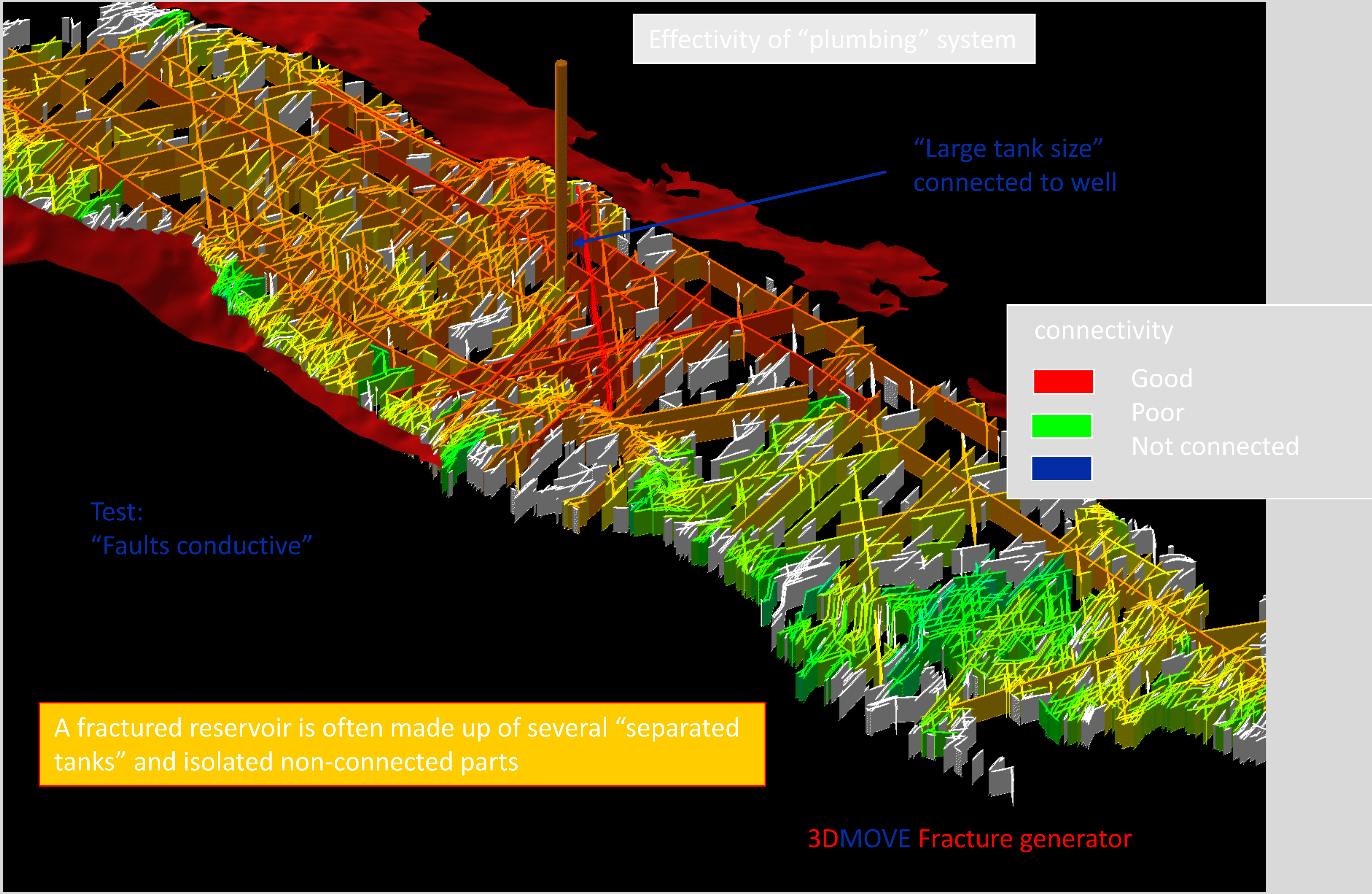



Geomechanical model → Conductive fractures → DFN

# Fracture creating processes



# Fracture creating processes



# Fracture creating processes

Why fractured basements?

Need new petroleum plays, new reservoir types

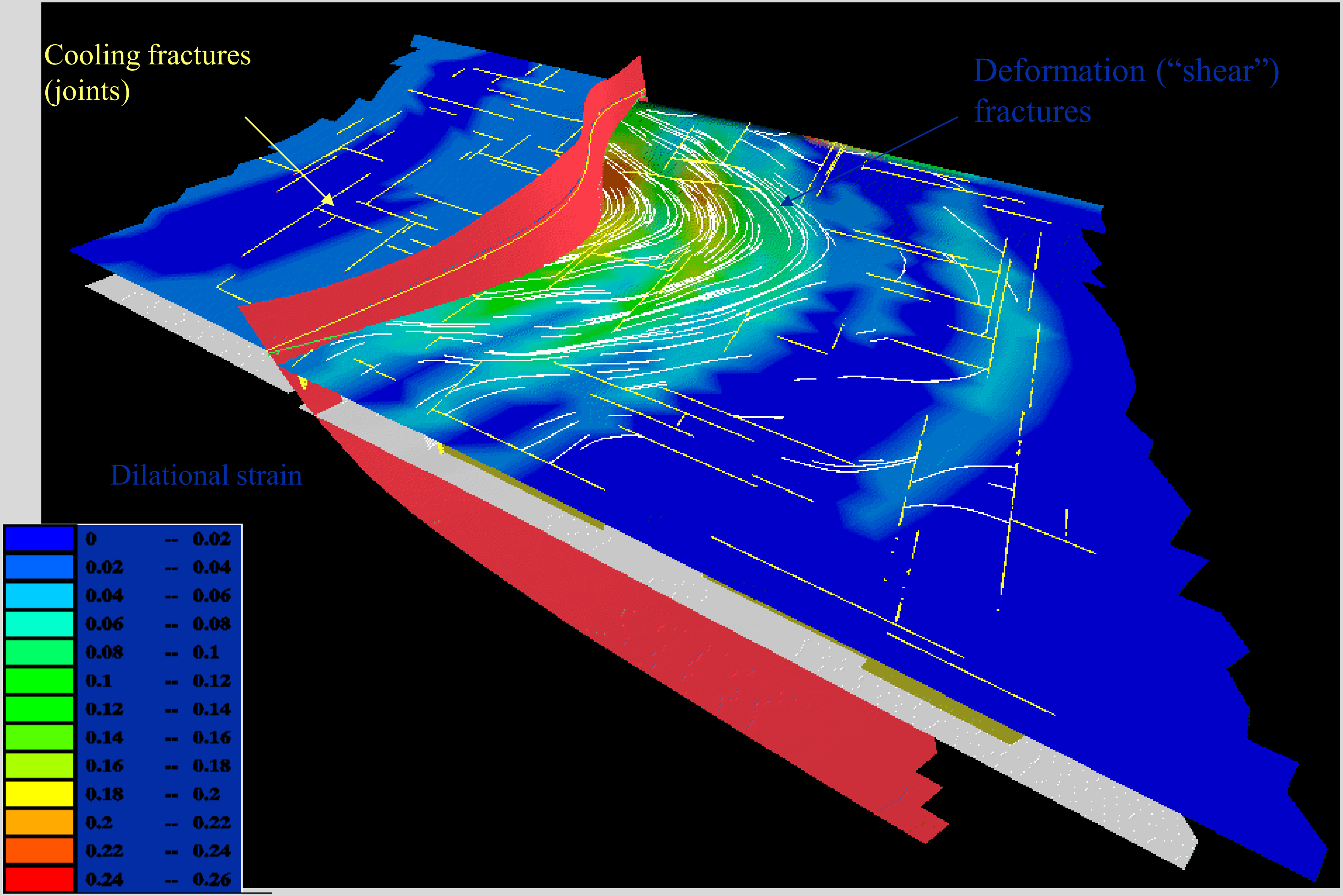
Many extensional basins have similar history as Vietnam

- Extensional crystalline basement (fractures)
- Lacustrine infill (source & seal)
- Marine infill (overburden)

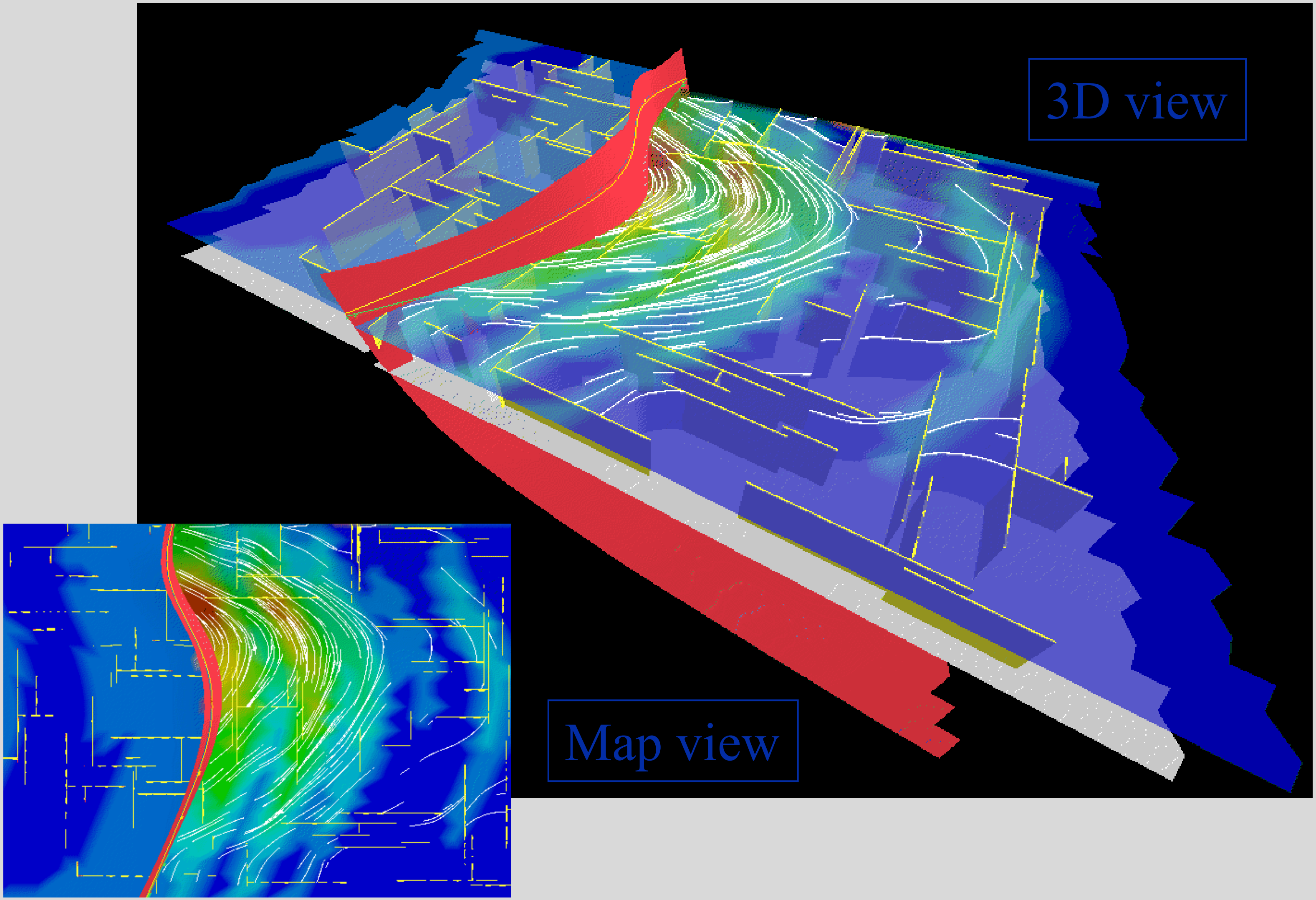
Can initially be explored as secondary target at relatively low cost due to occurrence of clastic traps over basement high (draping etc.)

Lots of unexplored potential in existing petroleum basin….

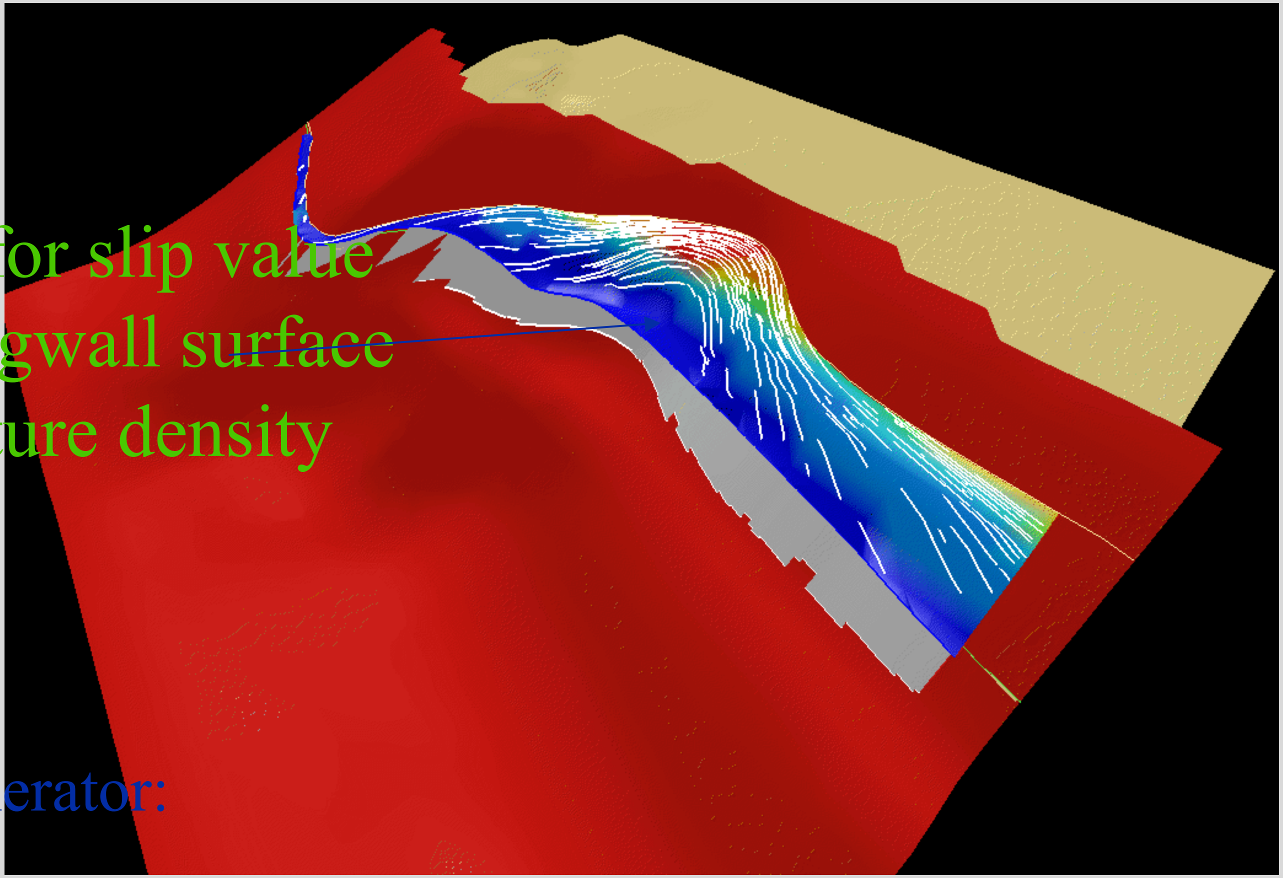
# Fracture network in extensional basement:



# Fracture network in extensional basement:



## Modelling fractures in fault damage zone:



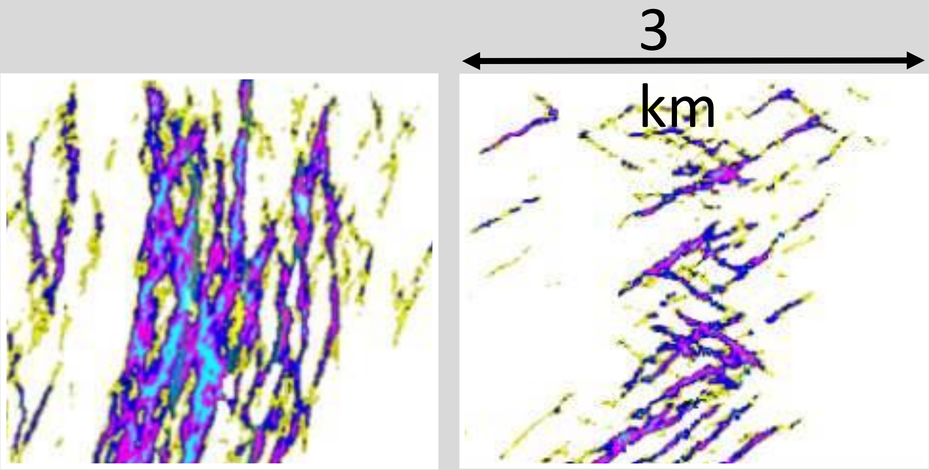
Colour map for slip value along hangingwall surface controls fracture density

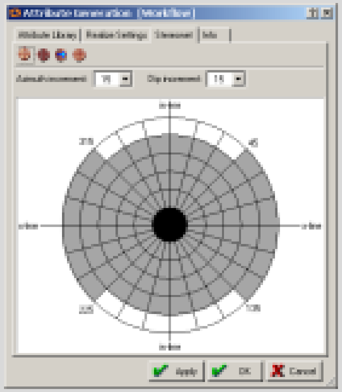
Input fracture generator:

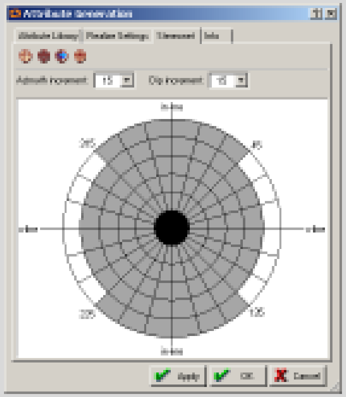
- Local slip value along fault controls density of fractures
- Orientation fractures parallel to local strike of fault
- Fracture density gradually decreasing away from the fault

# Fracture Cluster Mapping (FCM)  Workflow

- Main data source: **Seismic**
- Requires highest resolution and lowest noise level → **Q-Technology**
- Requires advanced 'discontinuity extraction algorithm' → **Petrel**
- Integrate log data to constrain algorithm for effective separation of fracture corridors from other discontinuities

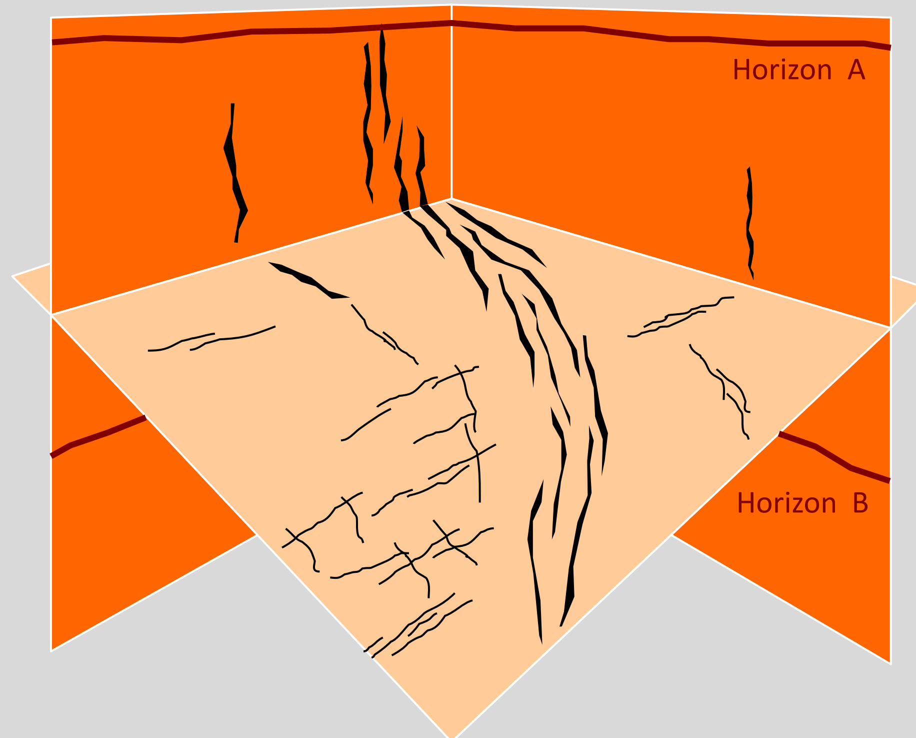




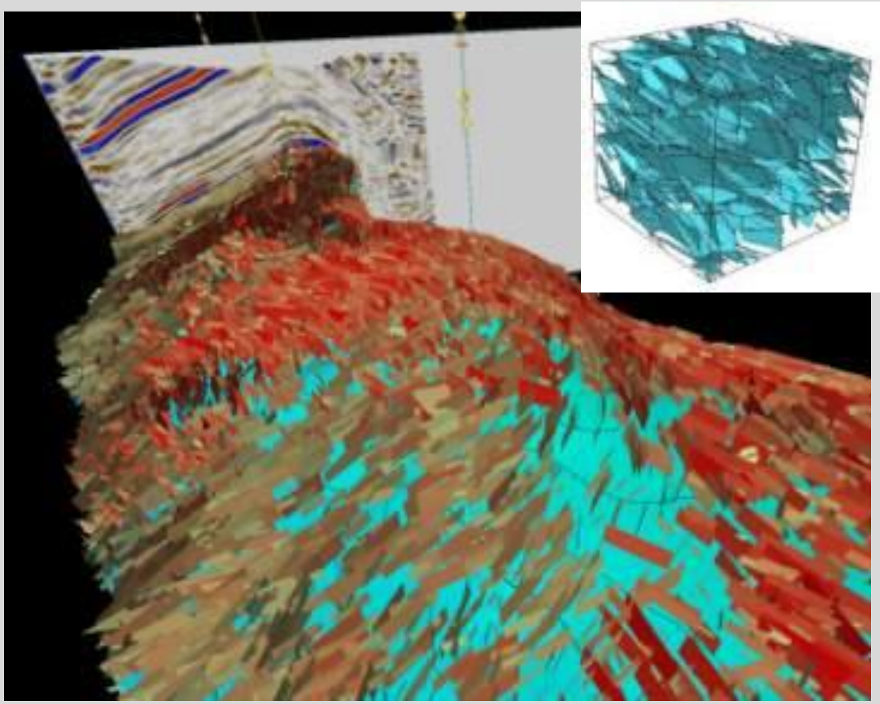
# Detection of Individual Fracture Corridors

- ‘Diffuse’ fractures can be modeled using geostatistics constrained by all available measurements and geological / geo-mechanical information
- Fracture corridors are highways for fluids in the reservoir:  They must be detected and placed at the correct position in the model



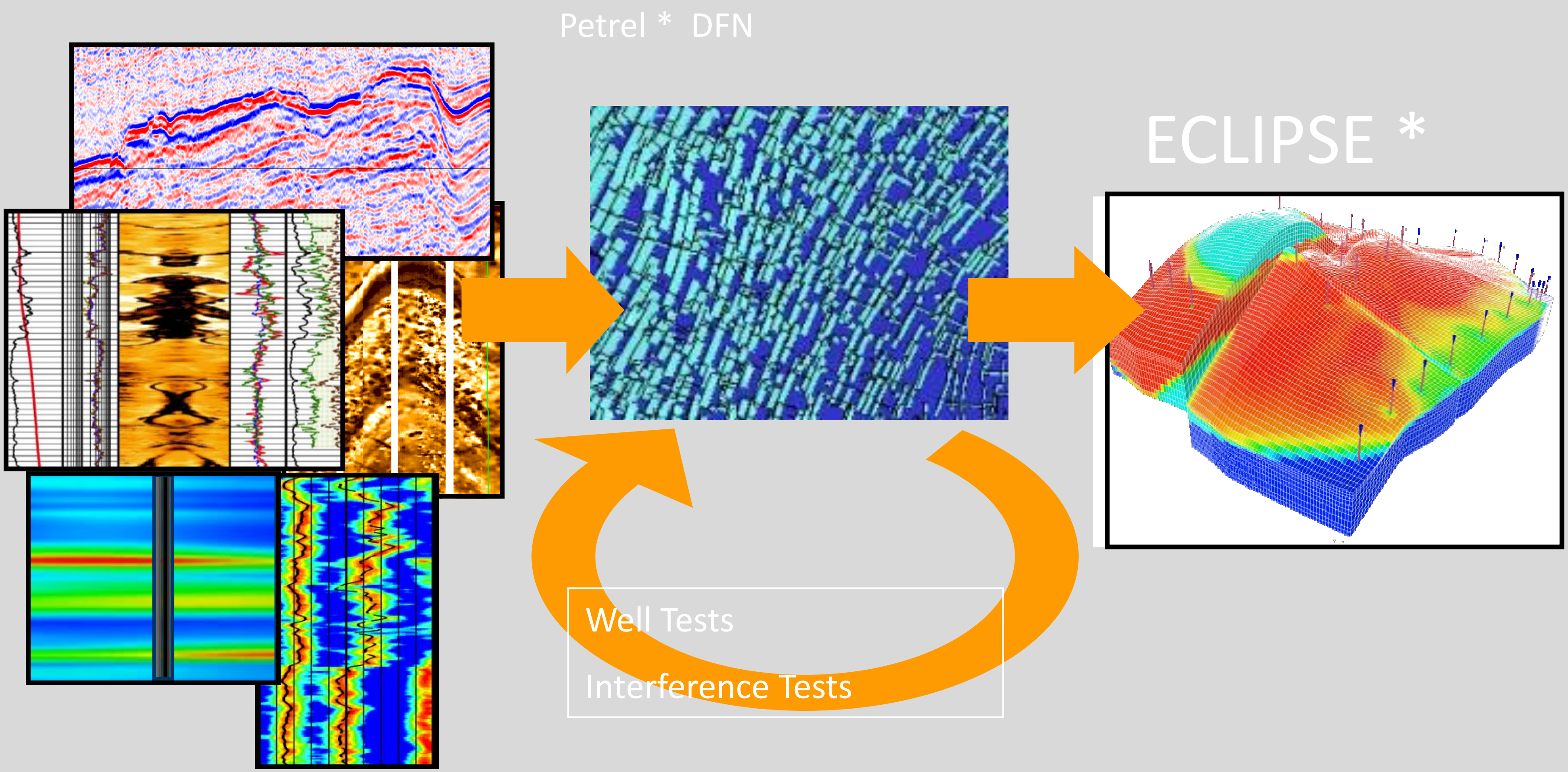
# Discrete Fracture Network Modeling

- Import / Export functionality of FracMan$^{TM}$ DFN format files
- DFN geo-statistical generation constrained by seismic data , log data and geological model
- DFN 3D visualization
- Upscaling program generates input data to ECLIPSE (Permeability tensor calculation for each grid block)



# The Key to Fractured Reservoirs Modeling

Data Integration Workflows (FCM + DFN) + People Expertise



## Fracture analysis considerations :

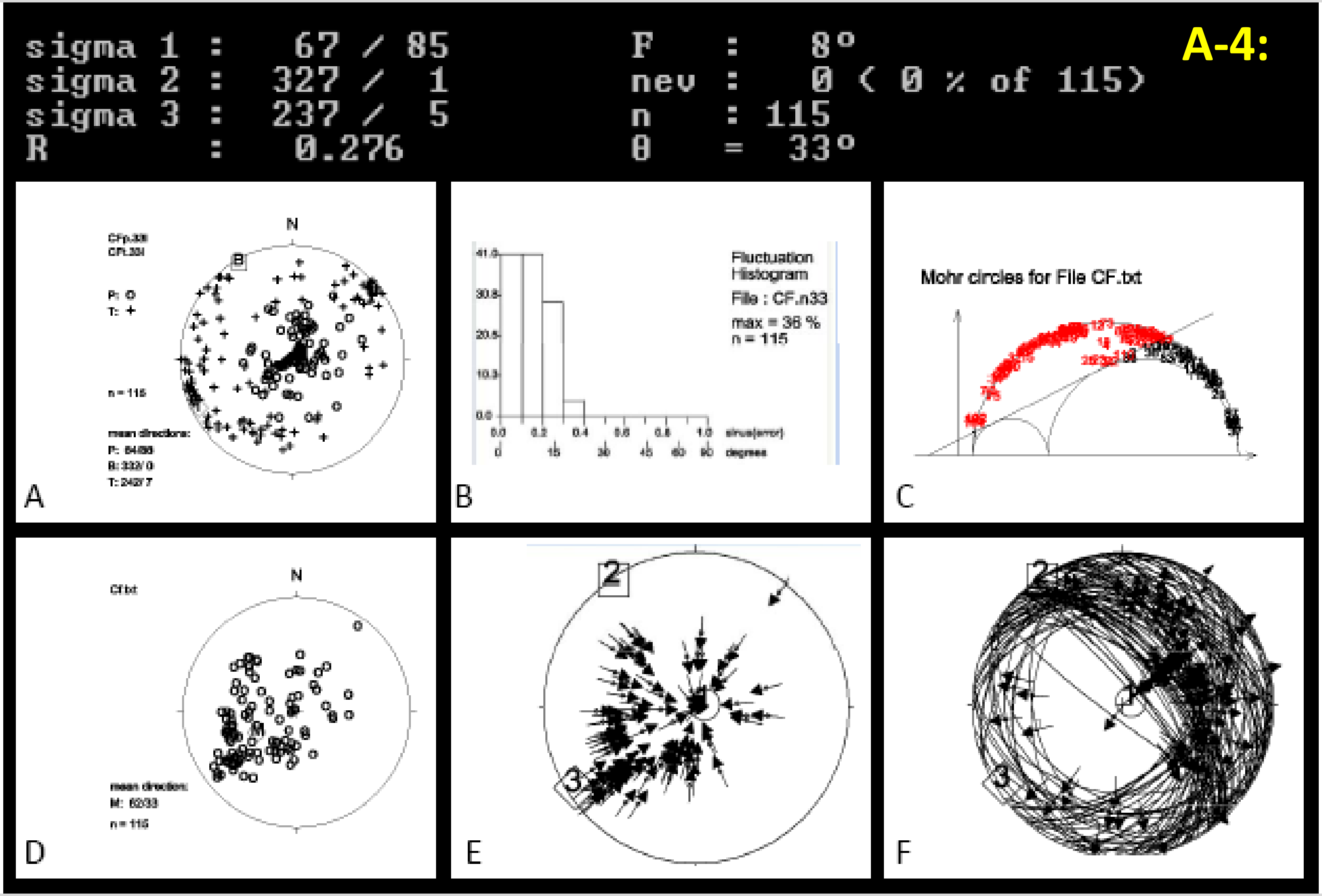
- ~ Which fractures will produce ?
- ~ Are fractures Natural or Drilling induced ?
- ~ Is there any solution enhancement of fractures ?
- ~ What was the timing of fracture development ?
- ~ Should deviated or horizontal wells be considered ?

# RESULTS OF THE FRACTURE ANALYSIS

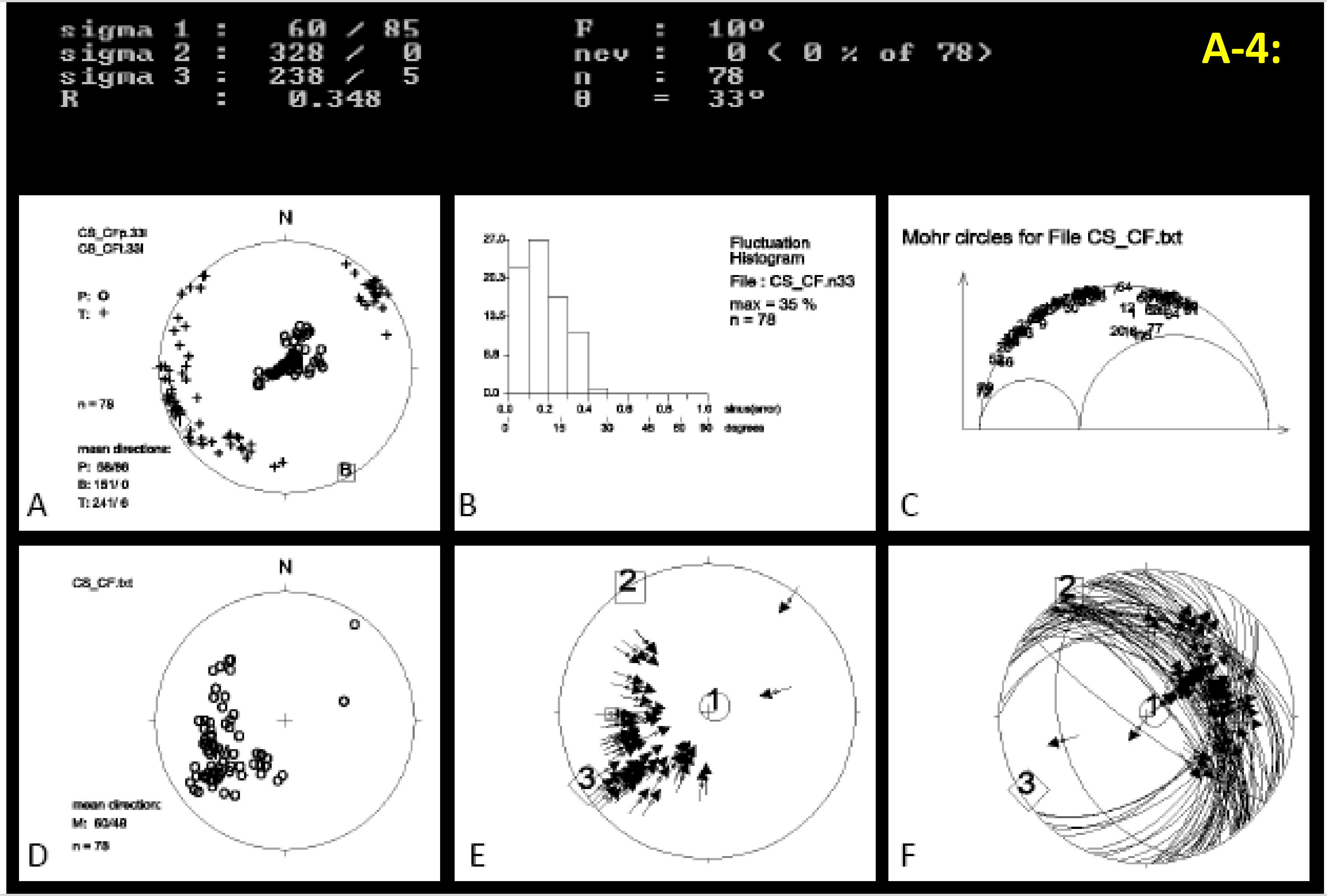
- Quantify the fractures
- Classify and categorize fractures
- Statistical analysis of fractures
- Analyze drilling data to capture mud loss events
- Geomechanics analysis to identify critically stressed fractures

# RUBY FIELD

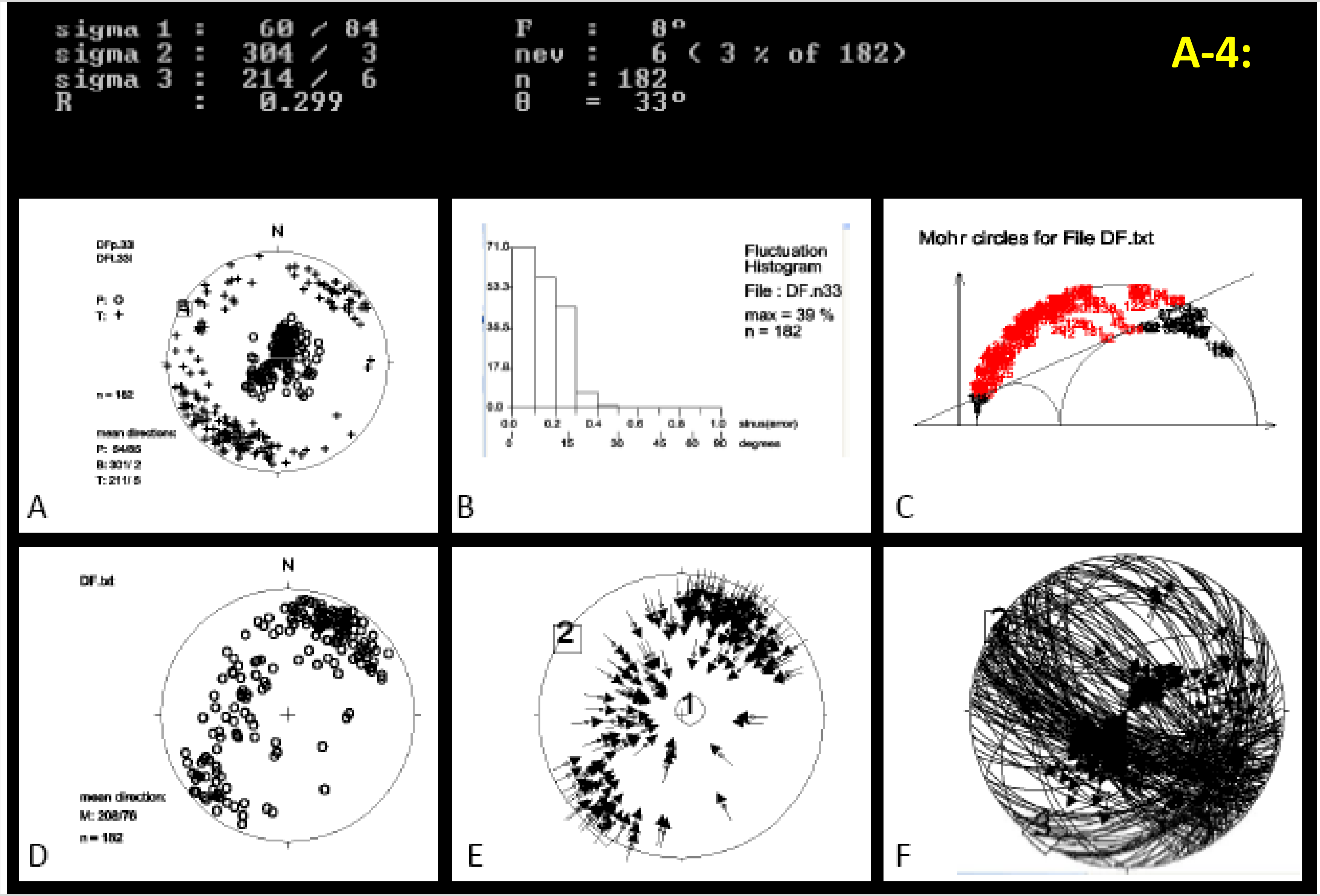
Continuous conductive fractures data set (great circles, arrows indicate sense of movement), compression (P) and tension (T) axes, Mohr circle (by numerical dynamic analysis, all in lower hemisphere projection).



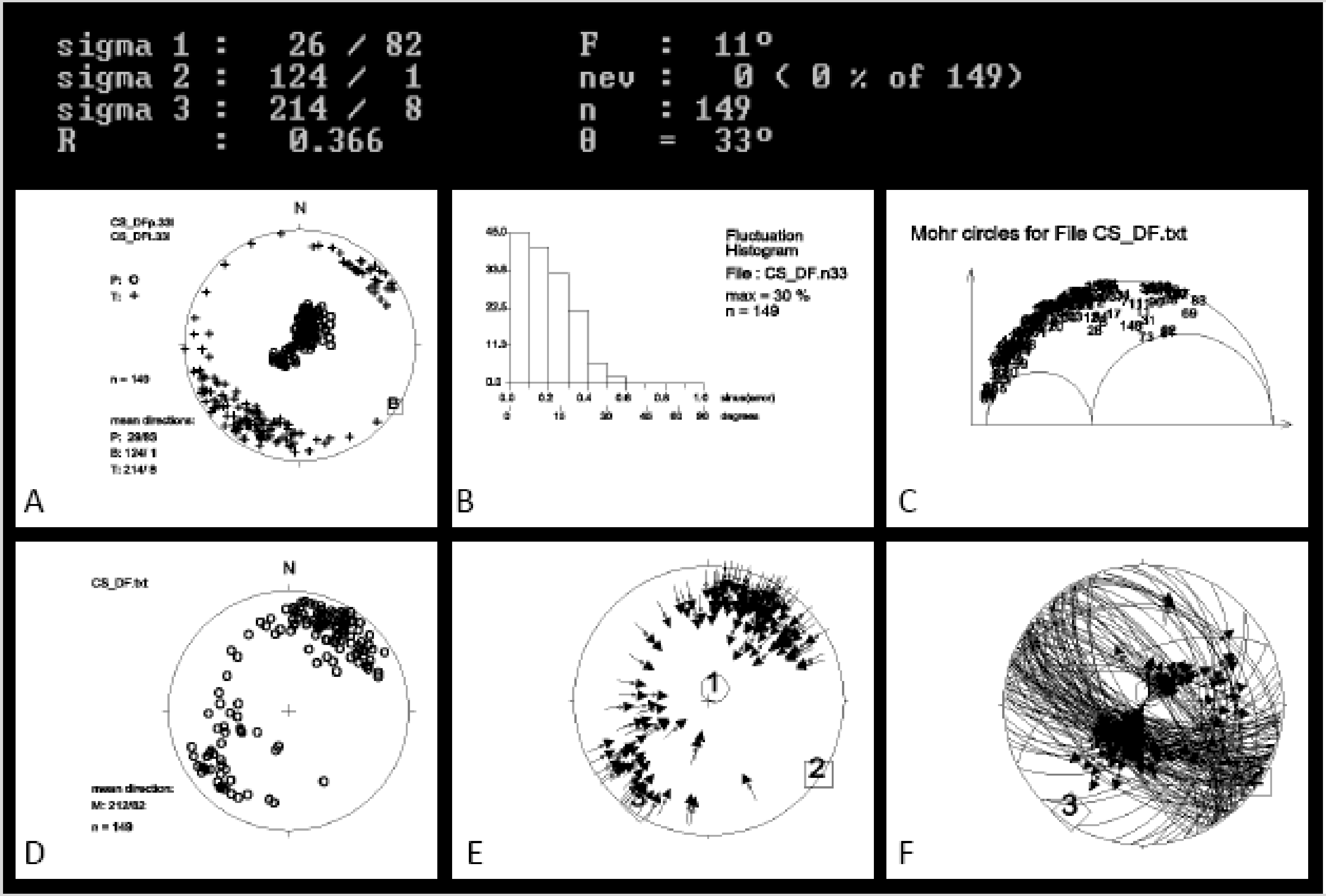
Critically stressed continuous conductive fractures data set (great circles, arrows indicate sense of movement), compression (P) and tension (T) axes, Mohr circle (by numerical dynamic analysis, all in lower hemisphere projection).



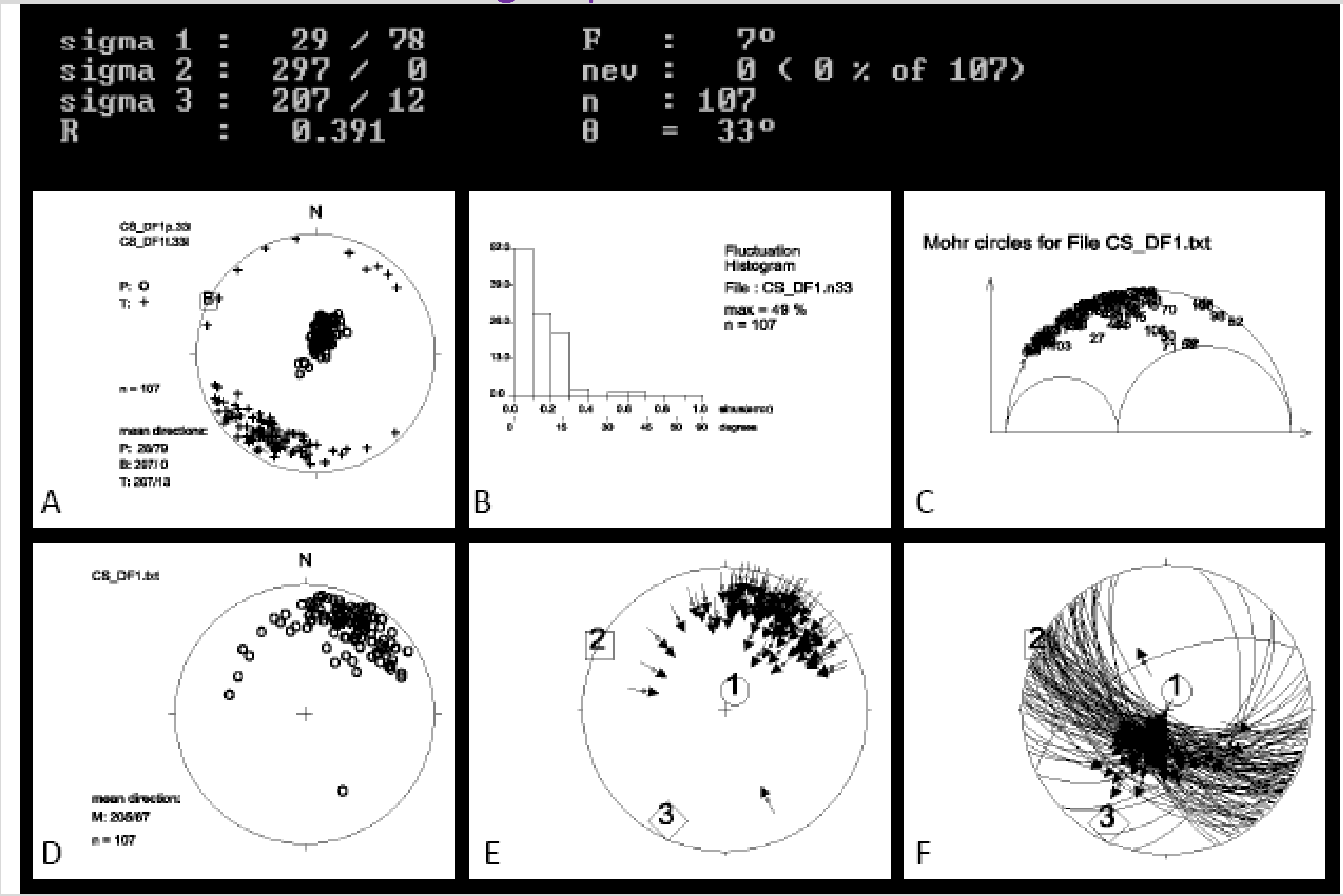
Discontinuous conductive fractures data set



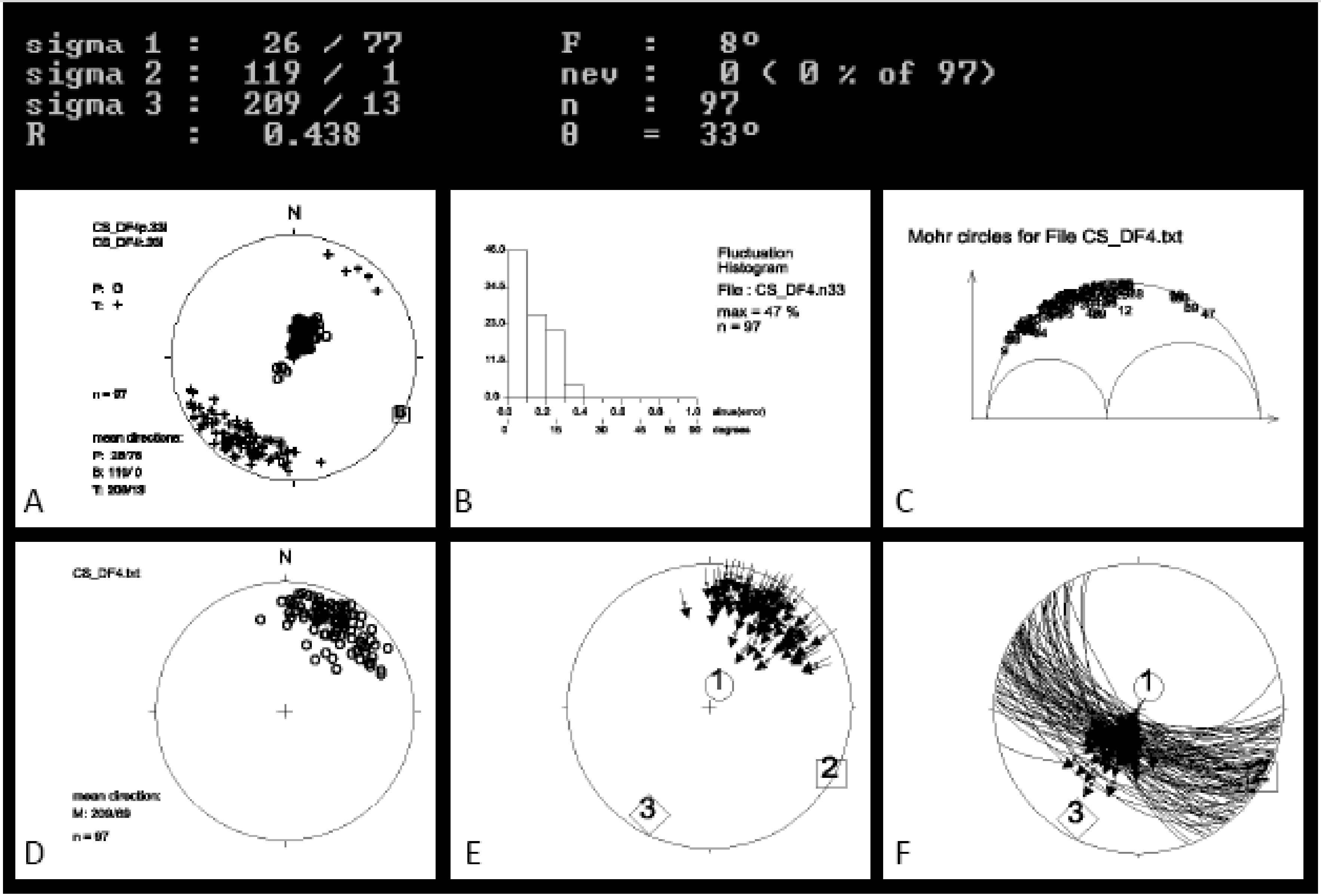
critically stressed discontinuous conductive fractures data set



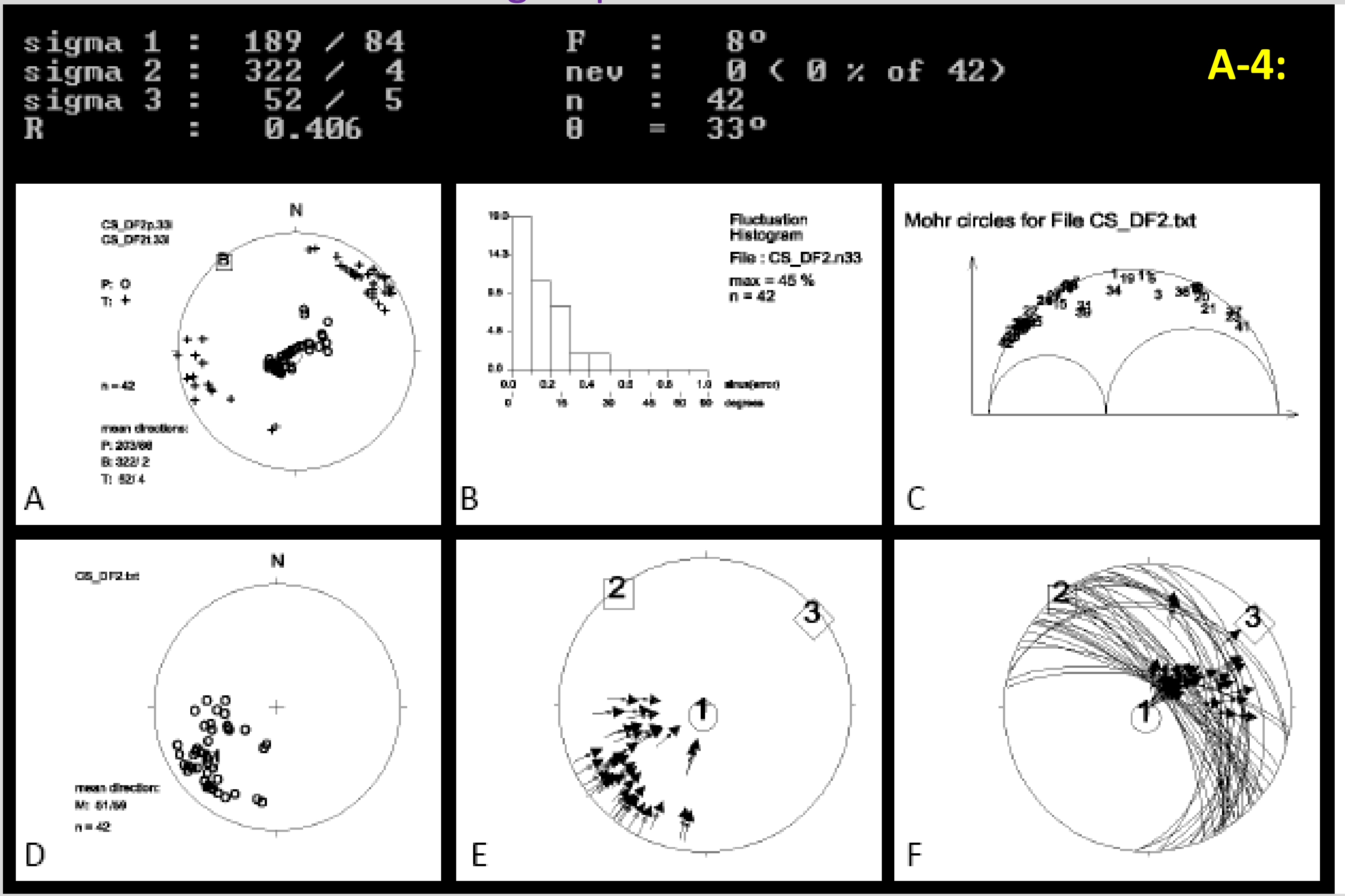
# critically stressed discontinuous conductive fractures data set of group 1



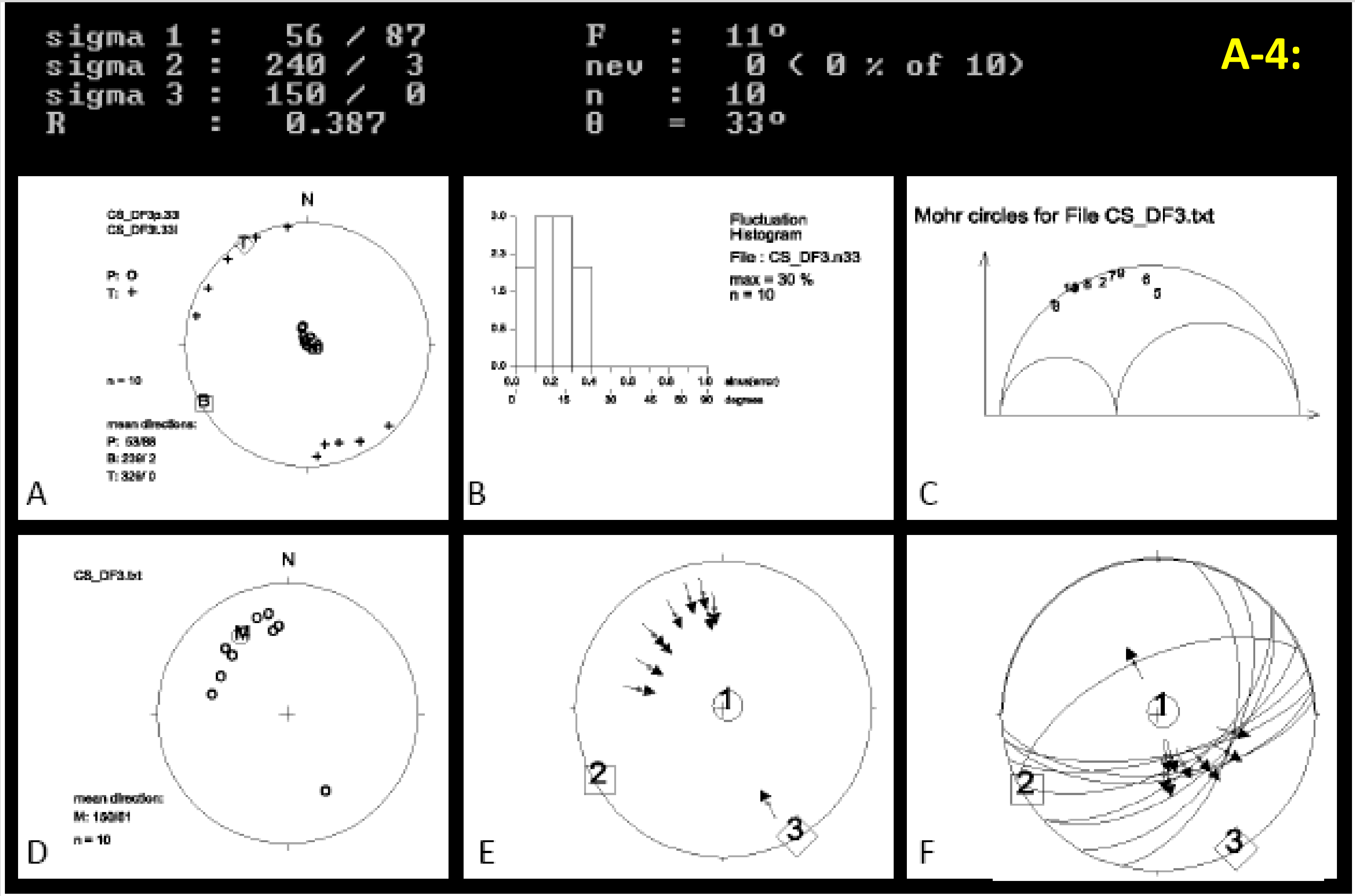
critically stressed discontinuous conductive fractures data set of group 2



critically stressed discontinuous conductive fractures data set of group 2



critically stressed discontinuous conductive fractures data set of group 4



## A-4:

# Observations from the analysis :

•Only fractures with certain dip and dip azimuth could be critically stressed. From the stereoplot it can be observed that only fractures with strike of zone 1, 2 and 3 and dip angle from 50° to 80° could be critically stressed

•Continuous fractures have two critically stressed zones, these are zone 2 of $\sigma_3$ due 238° and zone 5 of $\sigma_3$ due 303°

•Discontinuous fractures have three critically stressed zones; these are zone1, 2 and zone 4. Only zones 1 and 2 match with the present day stress field. Although zone 4 is critically stressed, but it will not contribute to production

•Vuggy fractures have two critically stressed zones, these are zone 2 of $\sigma_3$ due 53° and zone 6 of $\sigma_3$ due 151°, which is not contributed to production

•Brecciated fractures have one critically stressed zones, this is zone 3, which does not fit with the present day stress field and does not considered to be responsible for production

•Healed fractures have one zone critically stressed, this is group 1

•The present day stress field represents that the minimum horizontal stress is lying between zone 1 and group 2 and therefore the ideal well azimuth in the vicinity of A-4 is between this trend and because it is represented by a zone, this means both zones of one and two will be responsible for oil production.

# A-4:

•The group 1 & 2 are mainly continuous and vuggy fractures and this is the main reason, why A-4 is still producing without any problems.
•Additional observation is the non-presence of drilling induced fractures and this is most probably due to the presence of zone 2 which are very close to the present day stress field and therefore it is much easier to take the weak plane than initiating a new one.

•All the critically stressed fractures have the same strike direction NW-SE (parallel to the direction of the maximum horizontal stress in the field as observed from the module analysis applied on six wells across the field. With an dip magnitude between 50° to 80°
•There is no mud loss reported in zone 1&2. Statistical analysis gave the following information
•Average fracture density per foot is 0.41
•Average volcanic fracture density is 2.00
•Average fracture porosity is 0,0454 %
•Average fracture aperture is 0.196 mm
•Low to medium planar fractures surface morphology.
•Partially continuous fracture trace over few pads showing a connoted vuggy-like trace.
•Open Fractures strike direction NW-SE

| Fracture type | No. of fractures | Critically Stressed |
|---|---|---|
| Brecciated | 20 | 18 |
| Continuous | 115 | 78 |
| Discontinuous | 182 | 149 |
| Vuggy | 45 | 21 |
| Boundary | 75 | - |
| Healed | 18 | 4 |

## A-4:

**PRESENT DAY STRESS:**

The drilling induced fractures are abundant in majority of the wells within the basement section. All the drilling induced fractures showed a consistent striking orientation NW-SE with average strike at about 330-150 degrees indicating the horizontal maximum *in-situ* stress oriented at NW-SE. The

The drilling induced fractures are presented in A-1; A-3; A-6 and A-6-ST and there is no drilling induced fractures reported in A-4 and A-10.

The present day stress field for each well is analyzed and the data can summarized as follows:

- A-1: Maximum horizontal stress is 308°
- A-3: Maximum horizontal stress is 210°
- A-6: Maximum horizontal stress is 57°
- A-6-ST: Maximum horizontal stress is 52°

Studying the relationship between the present day stress field and those forming the critically stressed fractures, we can put a new well placement model to catch the best well trajectory for the development phase in the Ruby field and this is presented in the next section.

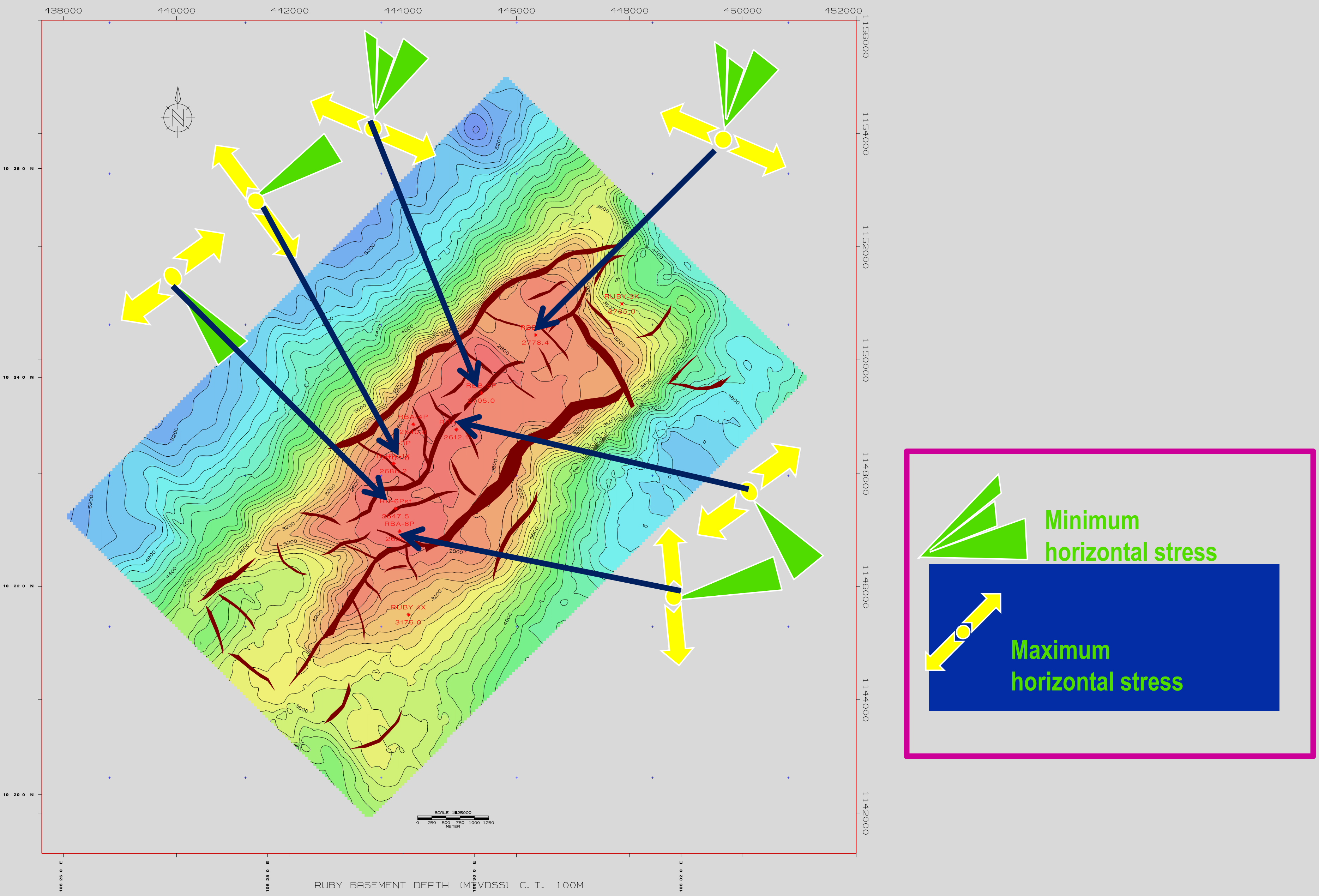
## A-4:

***The proposed trajectory***

* Horizontal drilling is proposed for the A field to catch most of the critically fracture sets.

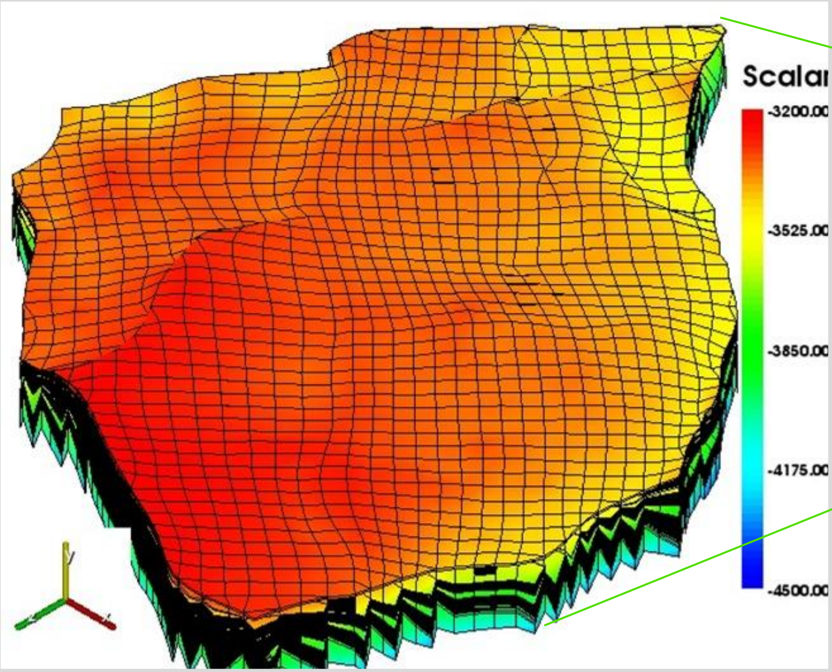
* The trajectory azimuth was aligned with the minimum horizontal stress direction that is N15-30 degree; which would give the maximum penetration of the critically fracture sets in the vicinity of these wells: A-4, A-1, A-3 and A-6. But in the vicinity of A-6-ST and A-10, it is recommended to drill in this direction N300-330.

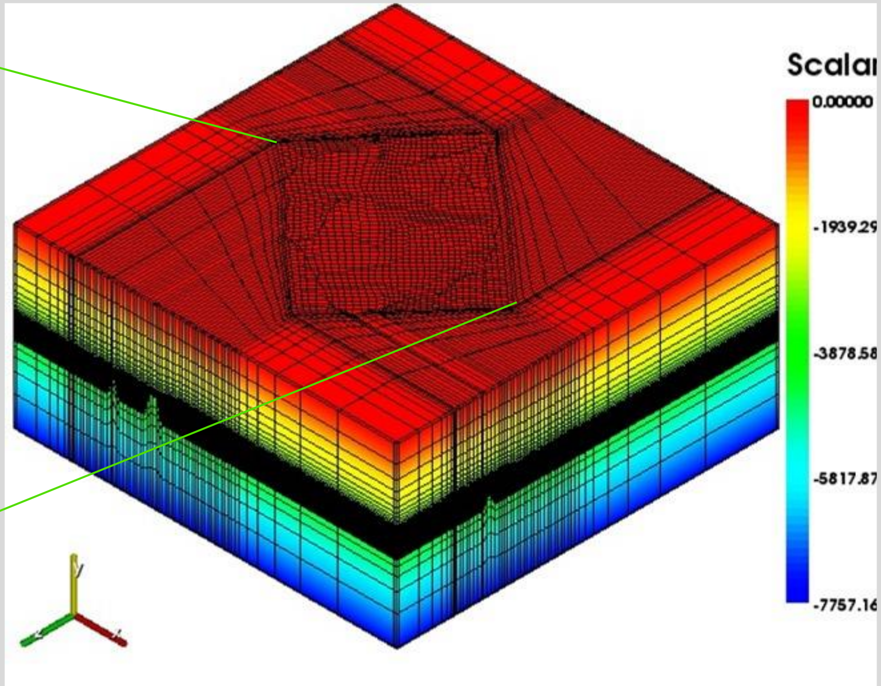
# Ruby Field



Minimum horizontal stress
Maximum horizontal stress
RUBY BASEMENT DEPTH (M TVDSS) C.I. 100M

# Embedding of an ECLIPSE Model

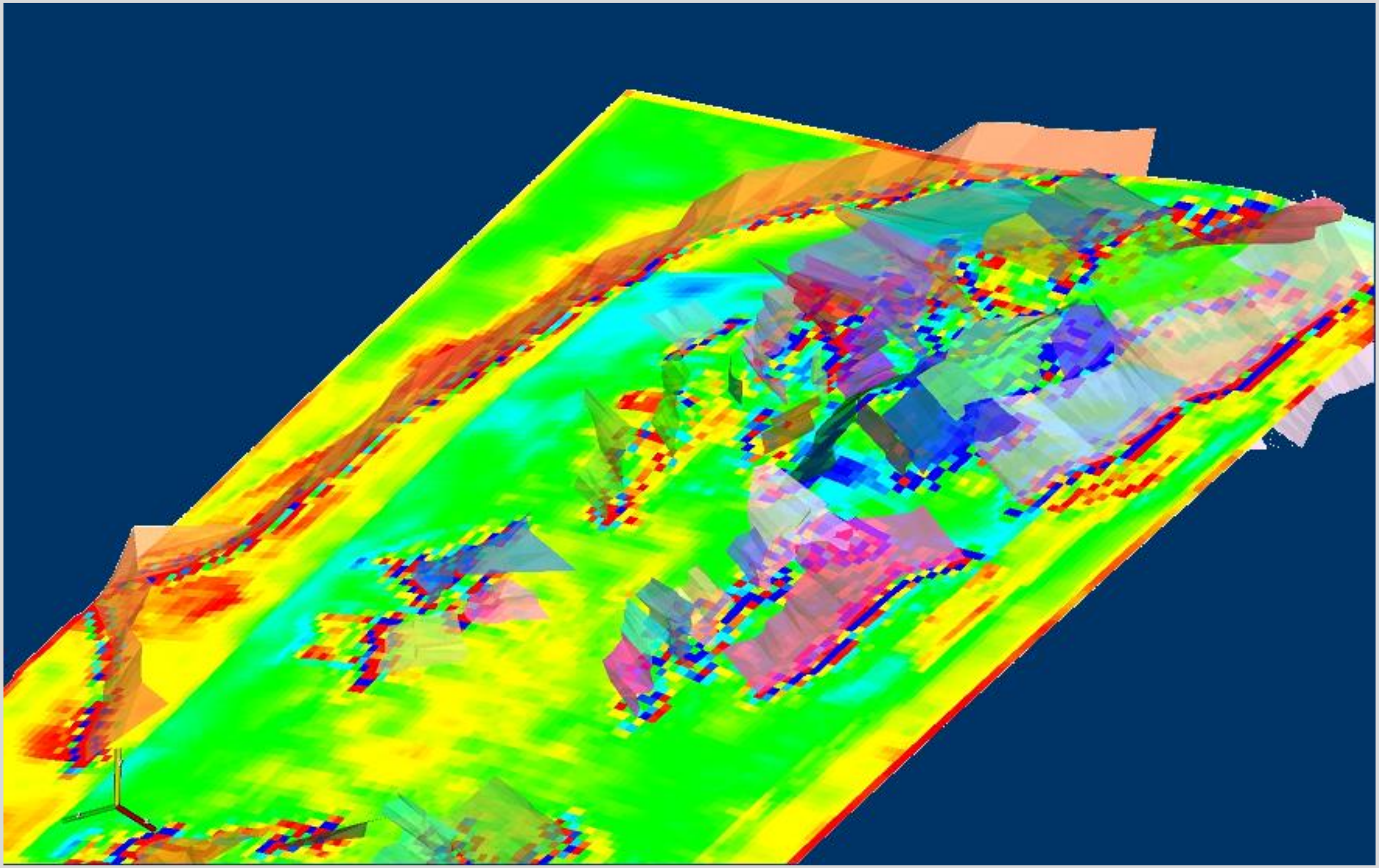


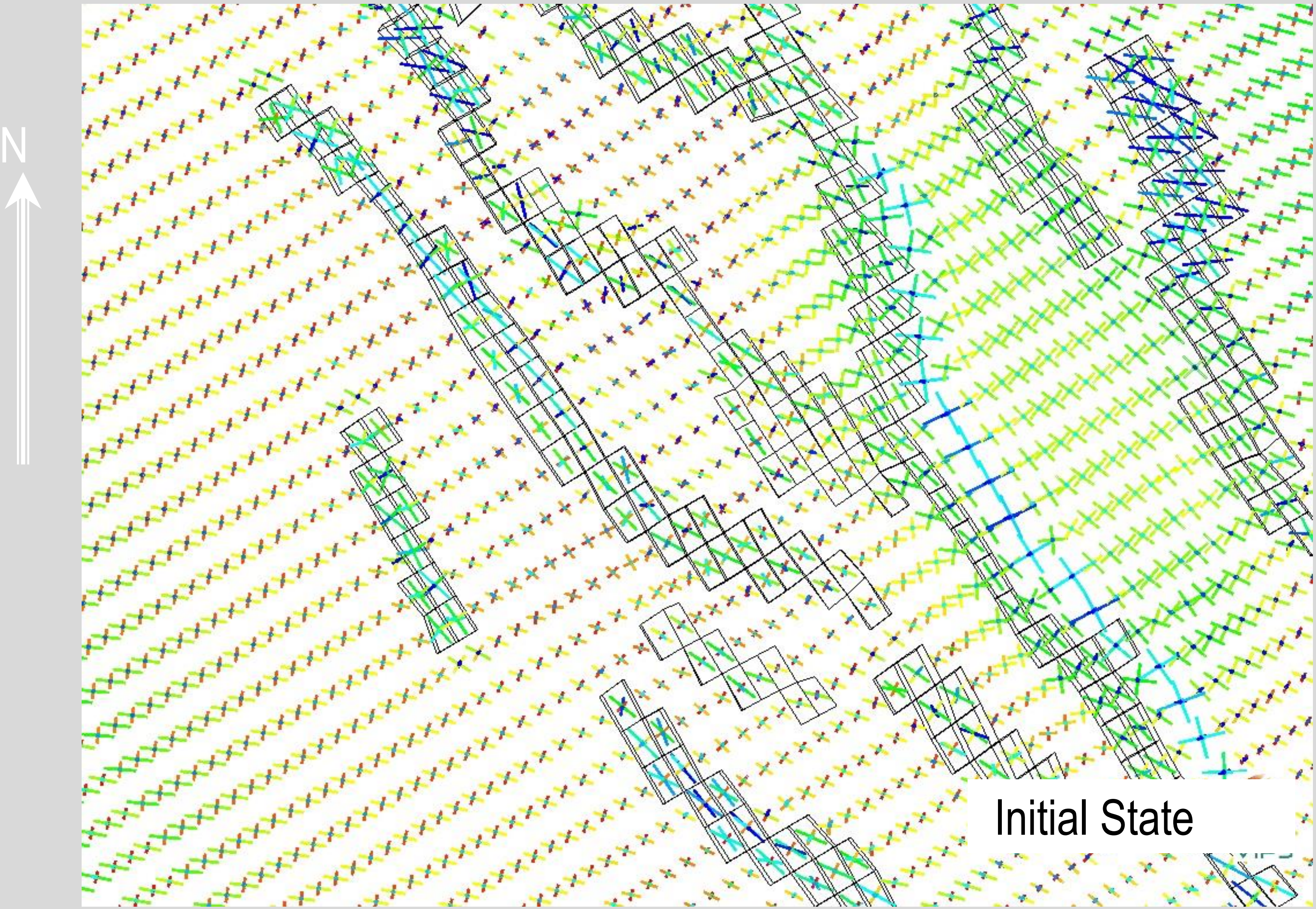

- **Original ECLIPSE model**

Embedded geo-mechanical model

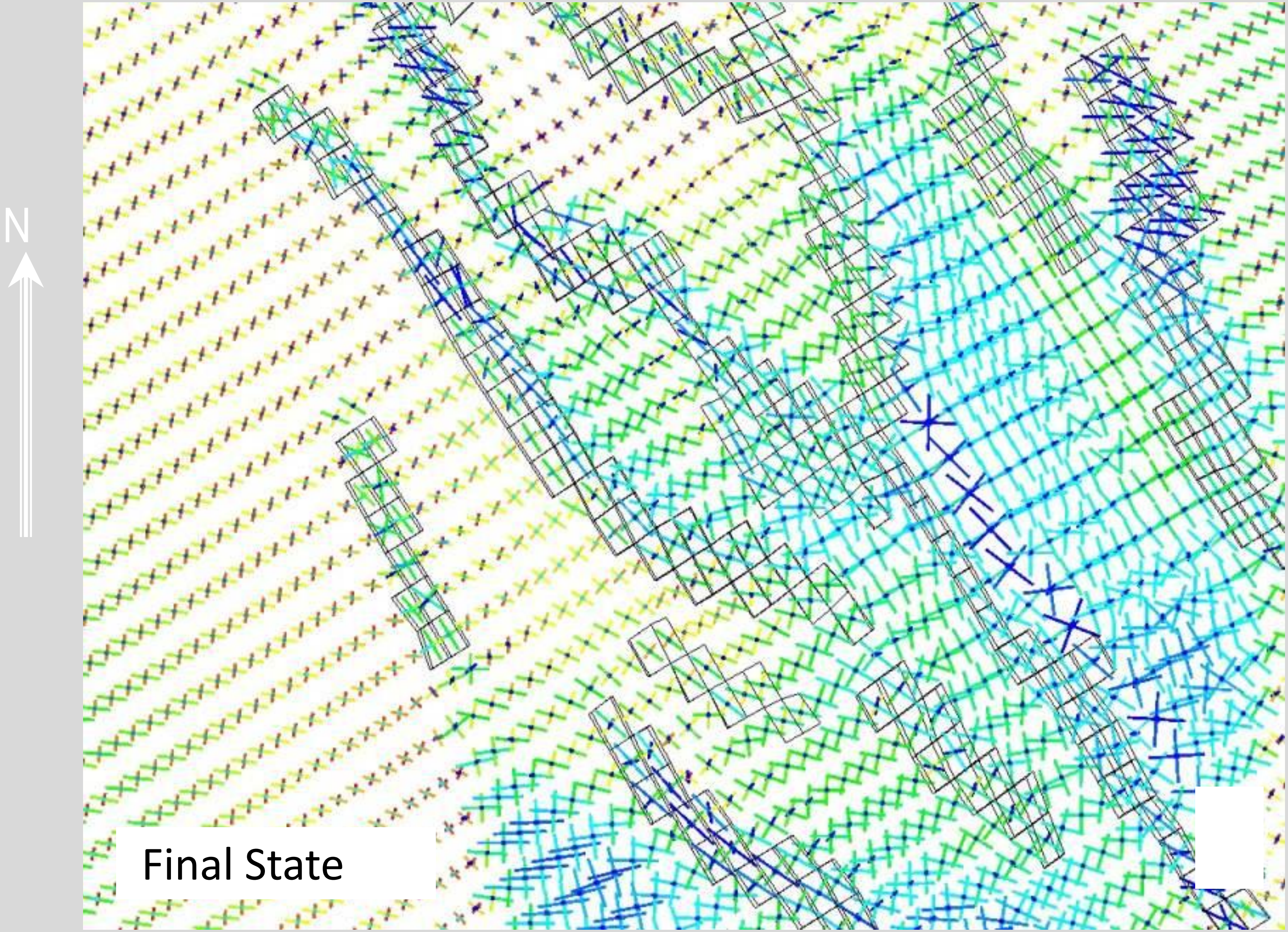
# Phase II: Initial Stress Distribution



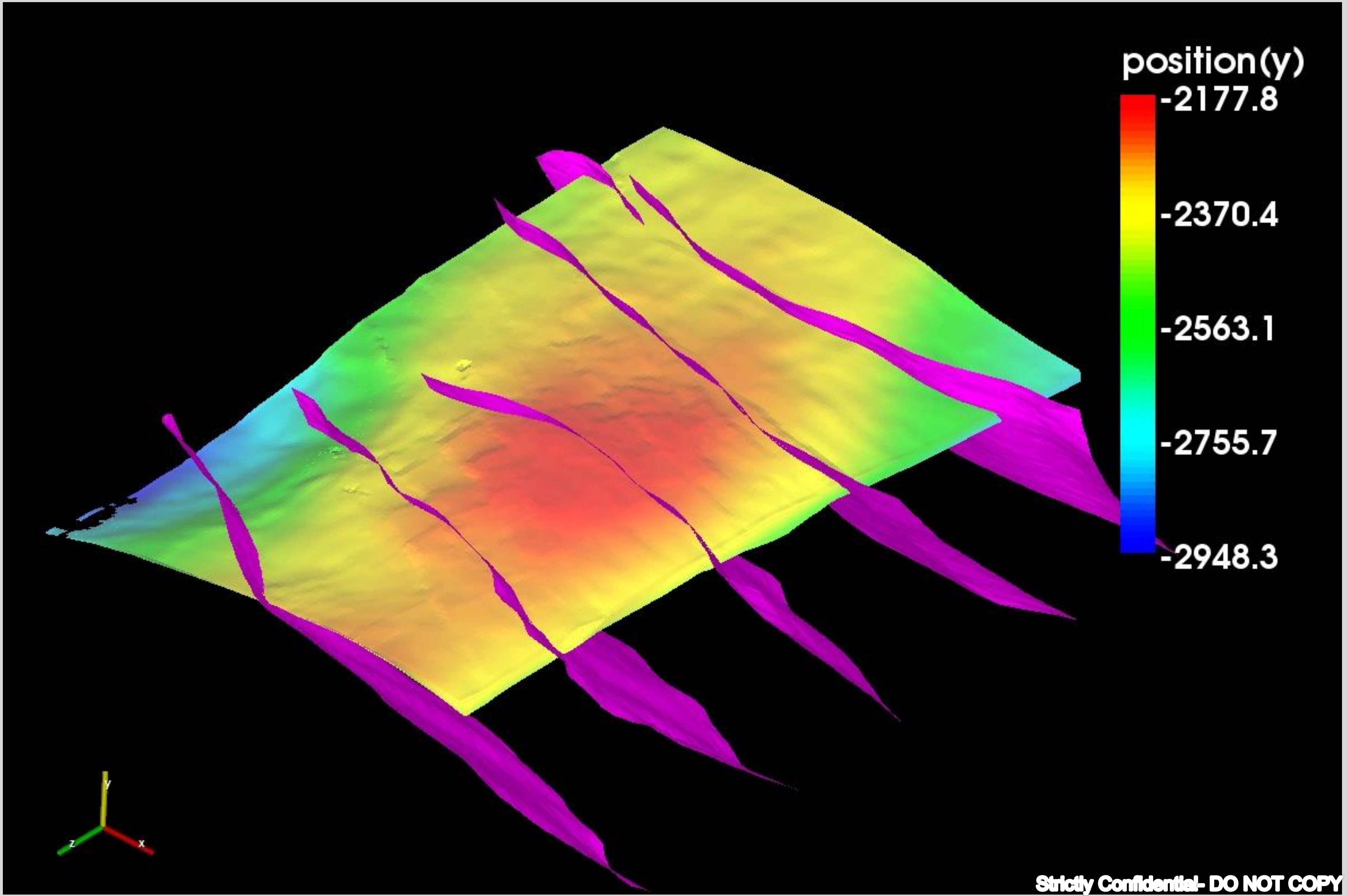
# Phase II: Initial Stress Orientation



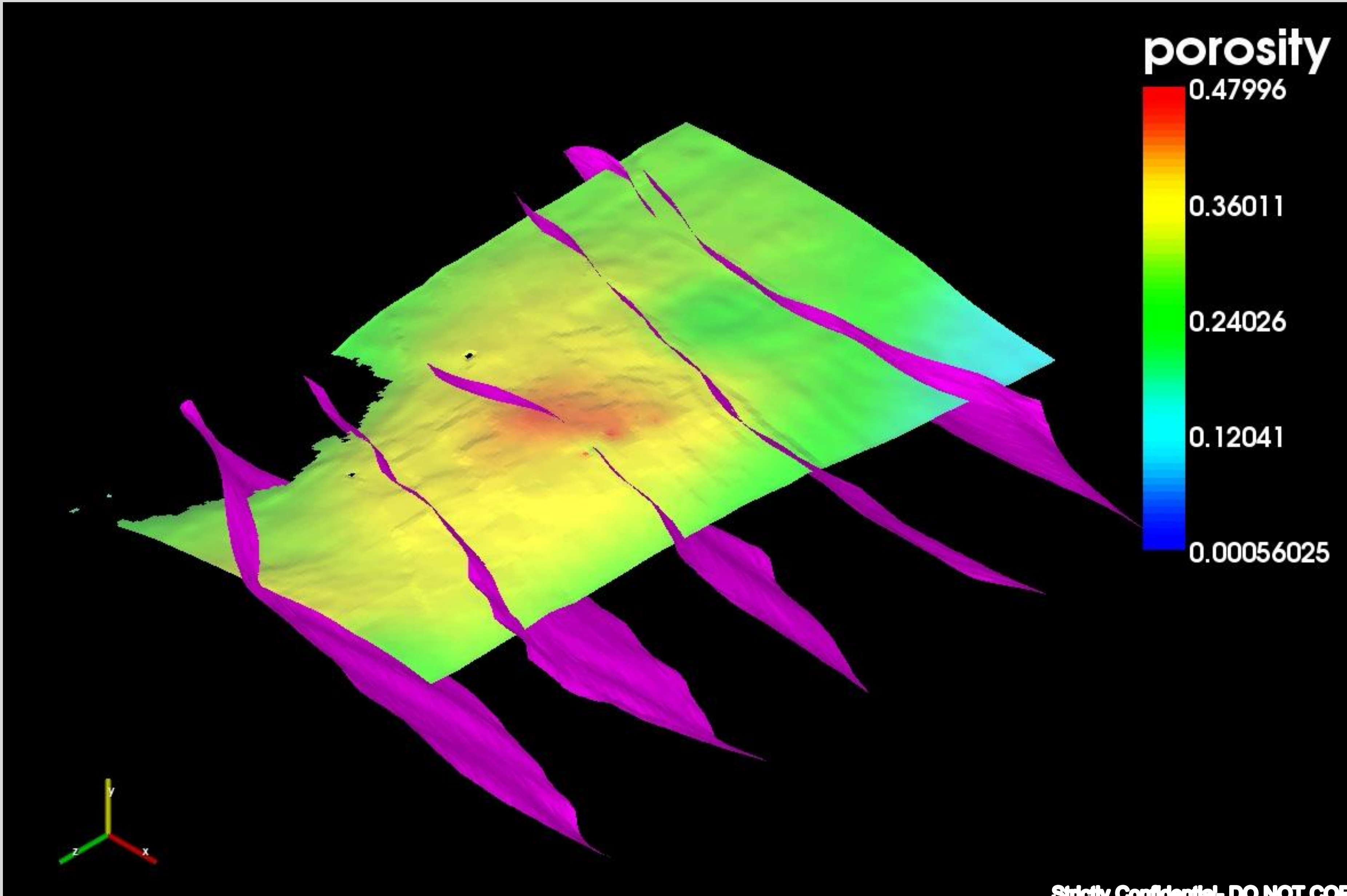
# Phase III: Stress Orientation



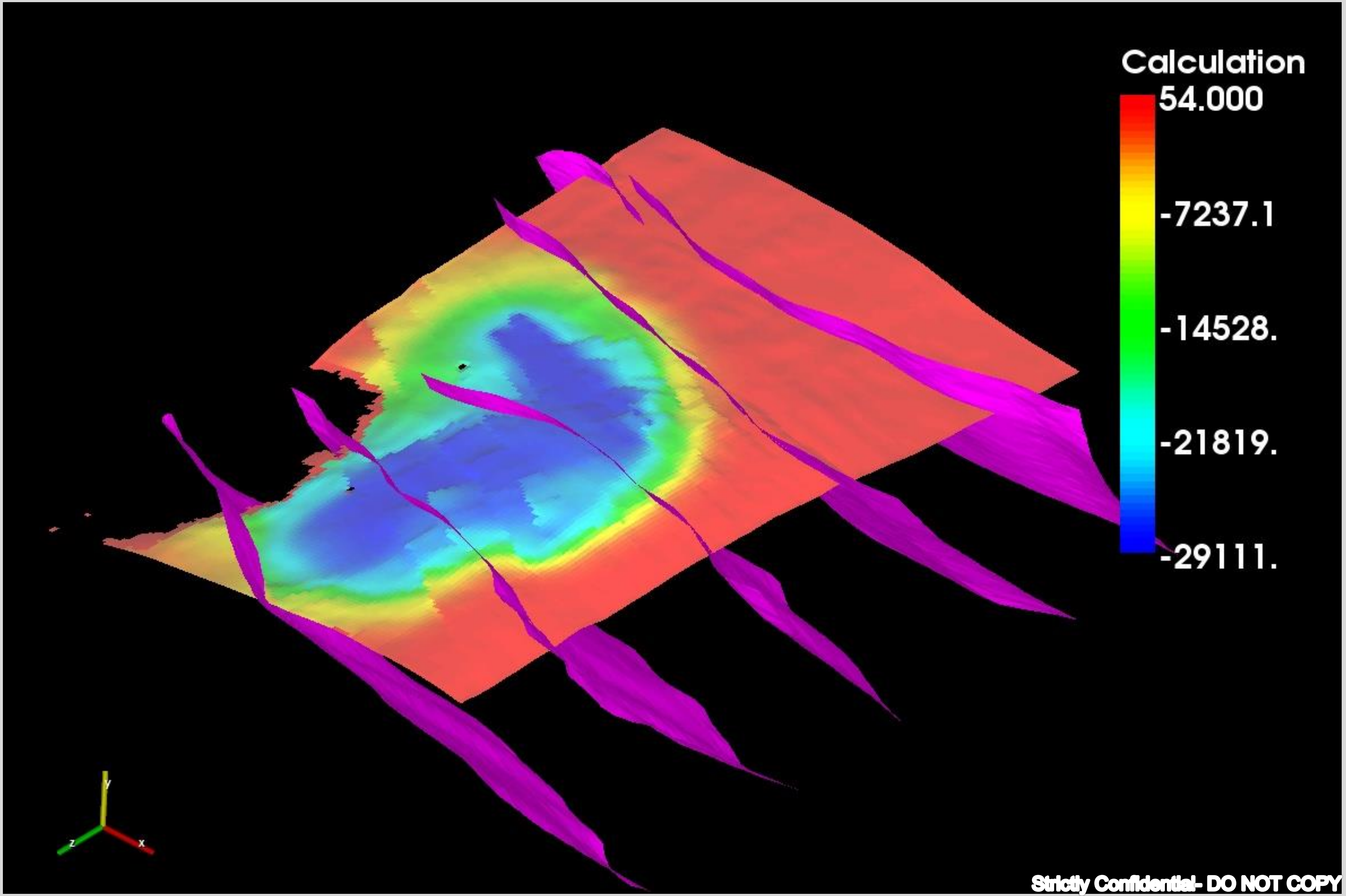
# Typical Layer



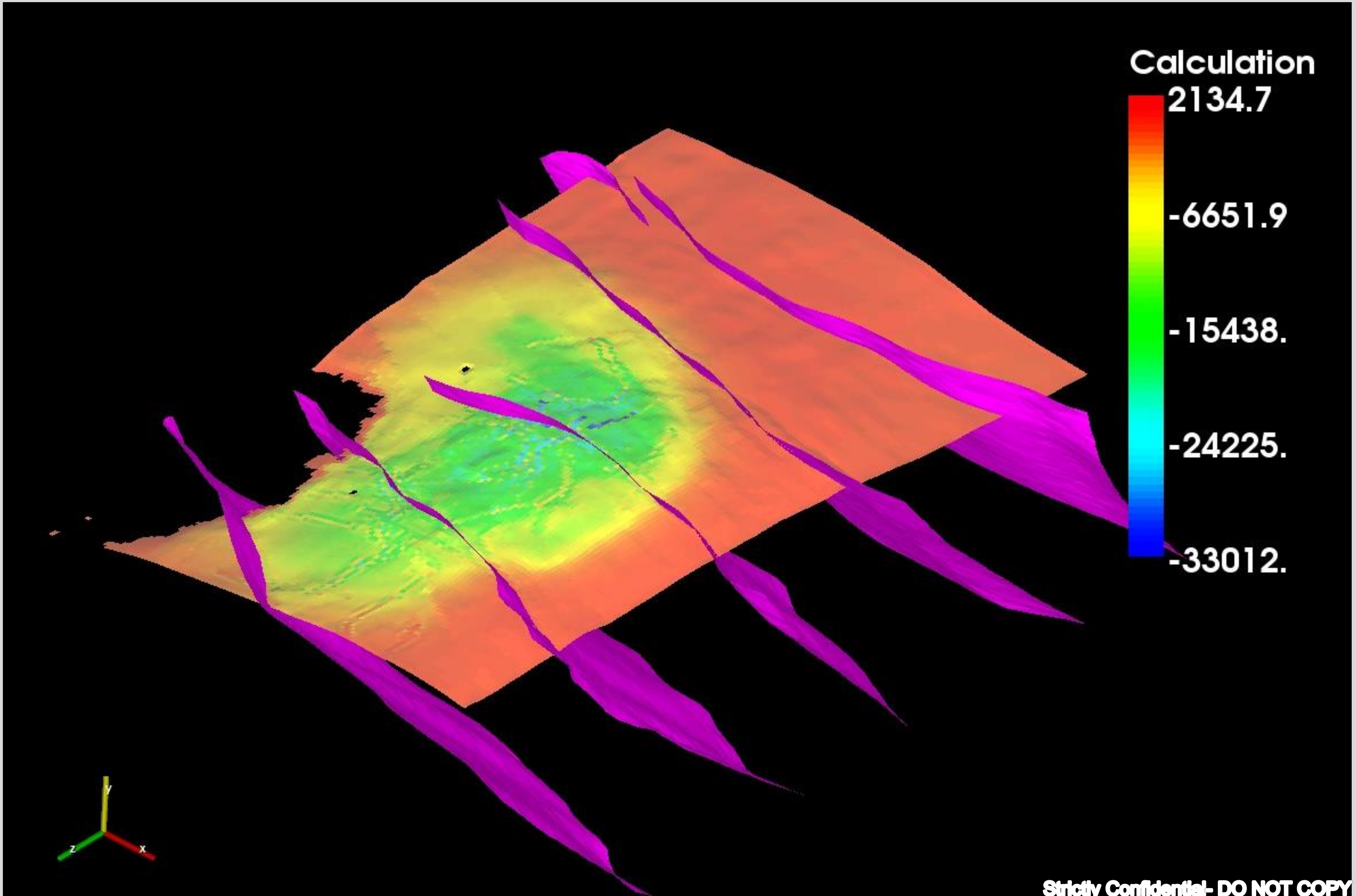
# Porosity Map



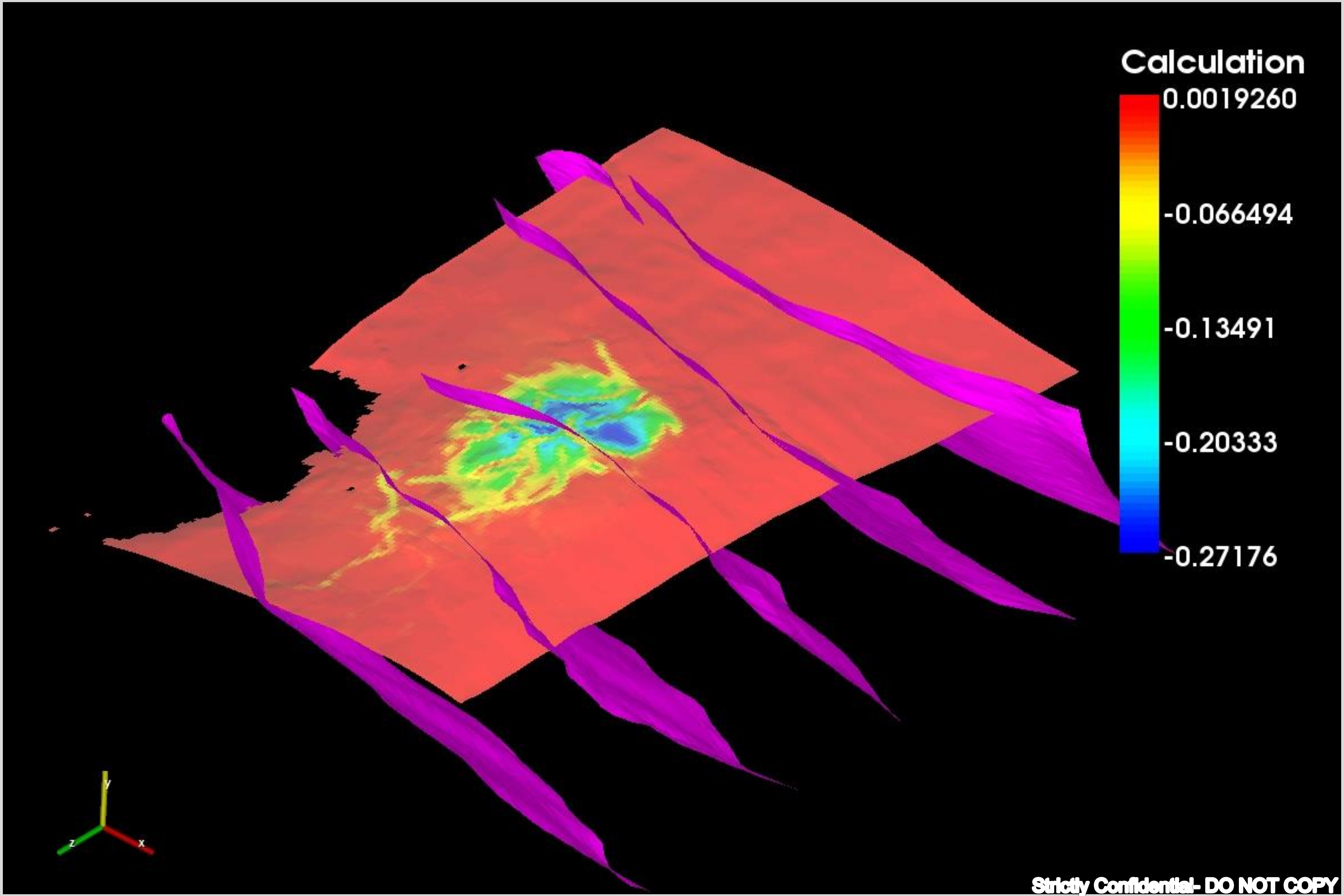
# Pressure Change



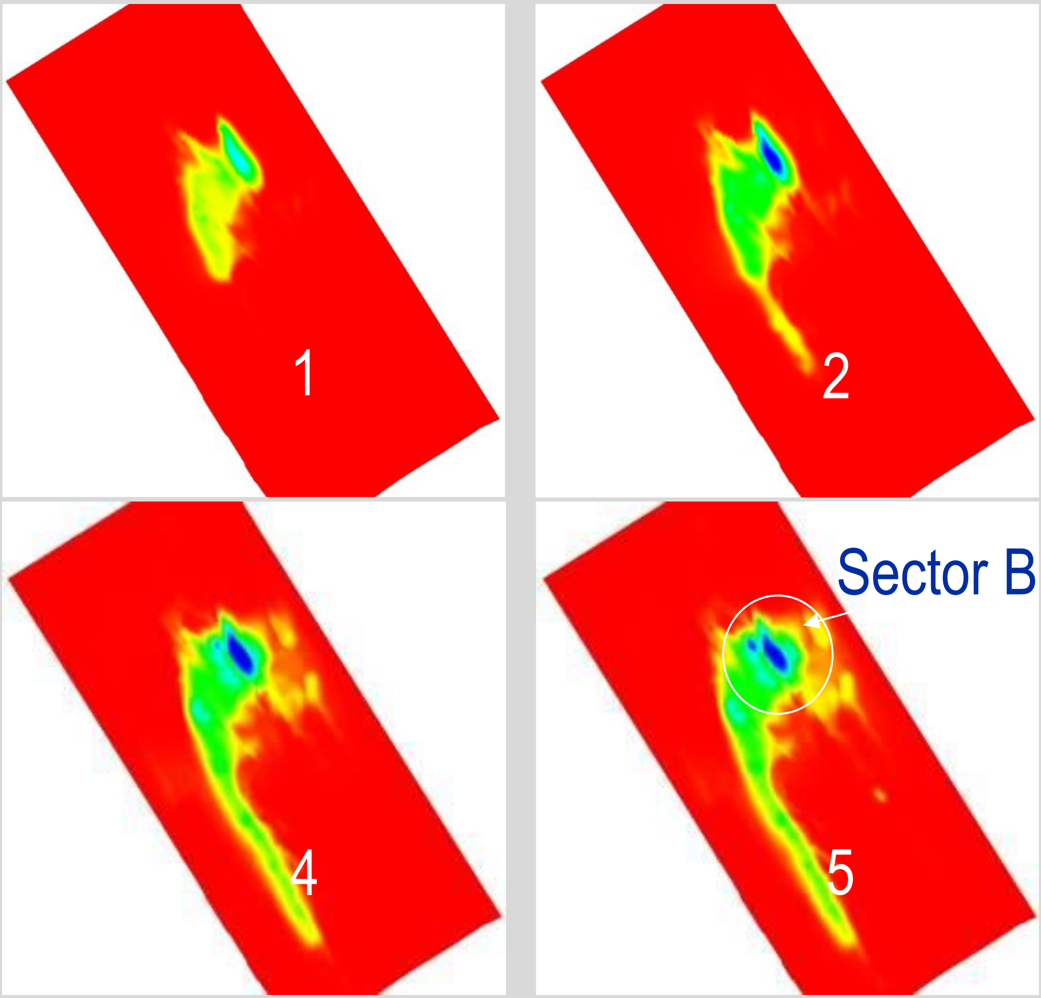
# Mean Effective Stress Change



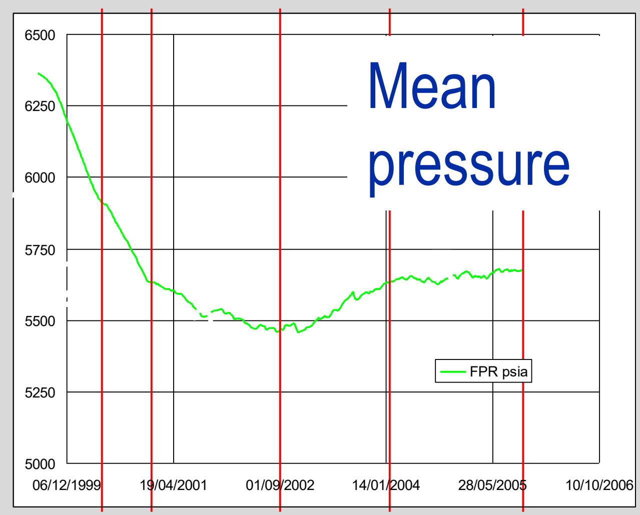
# Induced Deformation



# Compaction




Section A



# New Workflow