From Borehole Images to Fracture Permeability and Fracturing Pressure*

Bernd Ruehlicke[1]

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[1]Eriksfiord Inc., Houston, Texas (bernd.ruehlicke@eriksfiord.com)

Abstract

Borehole imagers and dipole sonic tools form the ideal pair of instruments for detailed borehole image interpretation including the evaluation of structural tilt, faulting, and fracturing. In addition, the stress field (orientation and magnitude of principal stresses) can be inverted based on both analytical and FEM methods leveraging the image logs in combination with rock mechanical and formation pressure data. Borehole images can be generated from oriented high-resolution measurement of various rock parameters, such as electrical conductivity/resistivity, acoustic reflectivity, and density. Fullwave sonic can be obtained from a range of sonic tools, while rock mechanical data usually requires laboratory testing on core plugs.

This presentation will demonstrate the suitability of bore-hole image and sonic logs for geological and geomechanical studies through an integrated workflow using examples from recently drilled wells.

Reference Cited

Luthi, S.M., and P. Souhaité, 1990, Fracture Apertures from Electrical Borehole Scans: Geophysics, v. 55/7, p. 821-833.

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Bernd Ruehlicke

Eriksfiord

Agenda

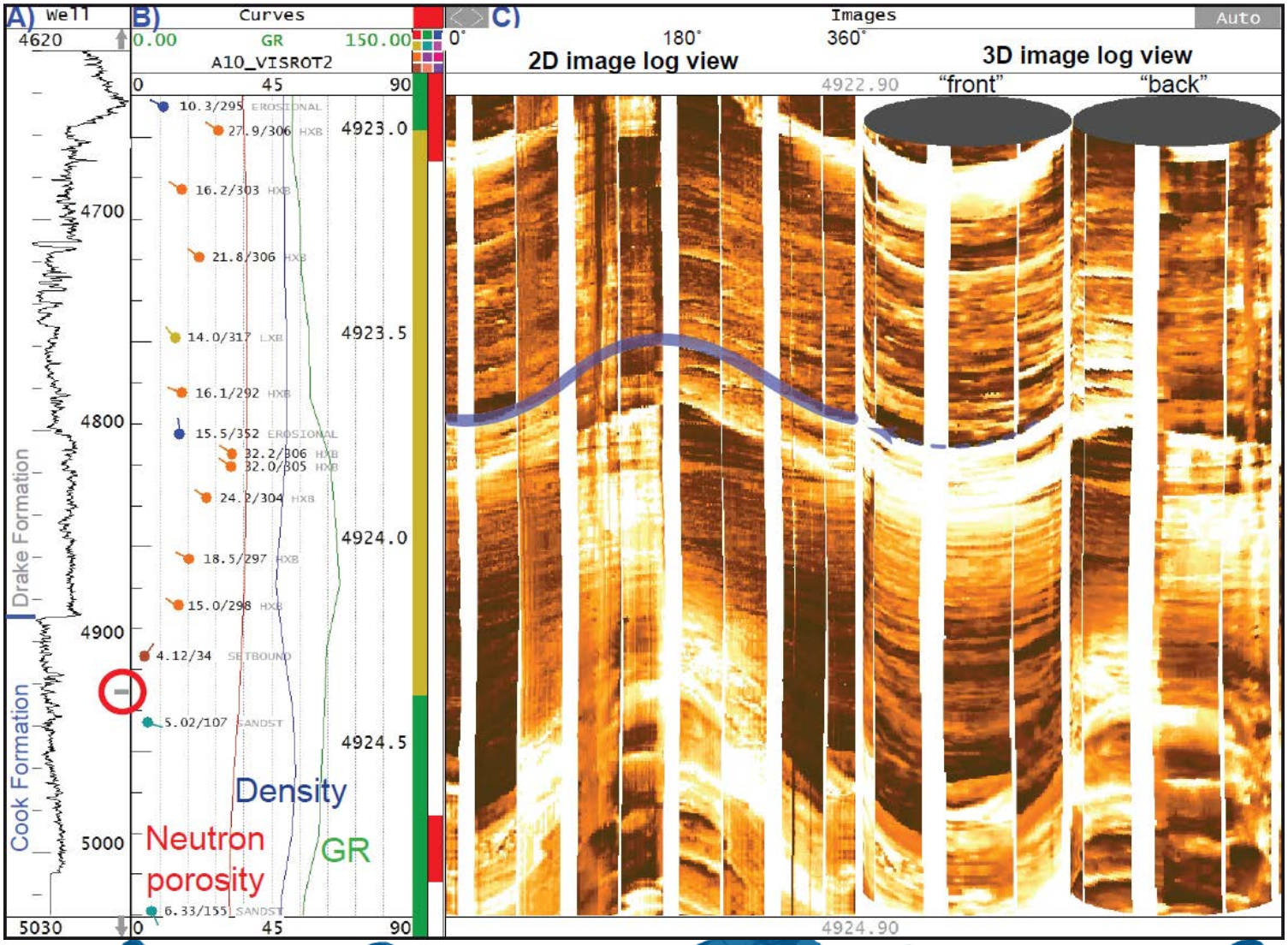
1) Image logs and fracture examples

2) Semi-quantitative results from fractures

3) Stress: how do we measure it

4) Apply calculated stresses

Borehole image interpretation

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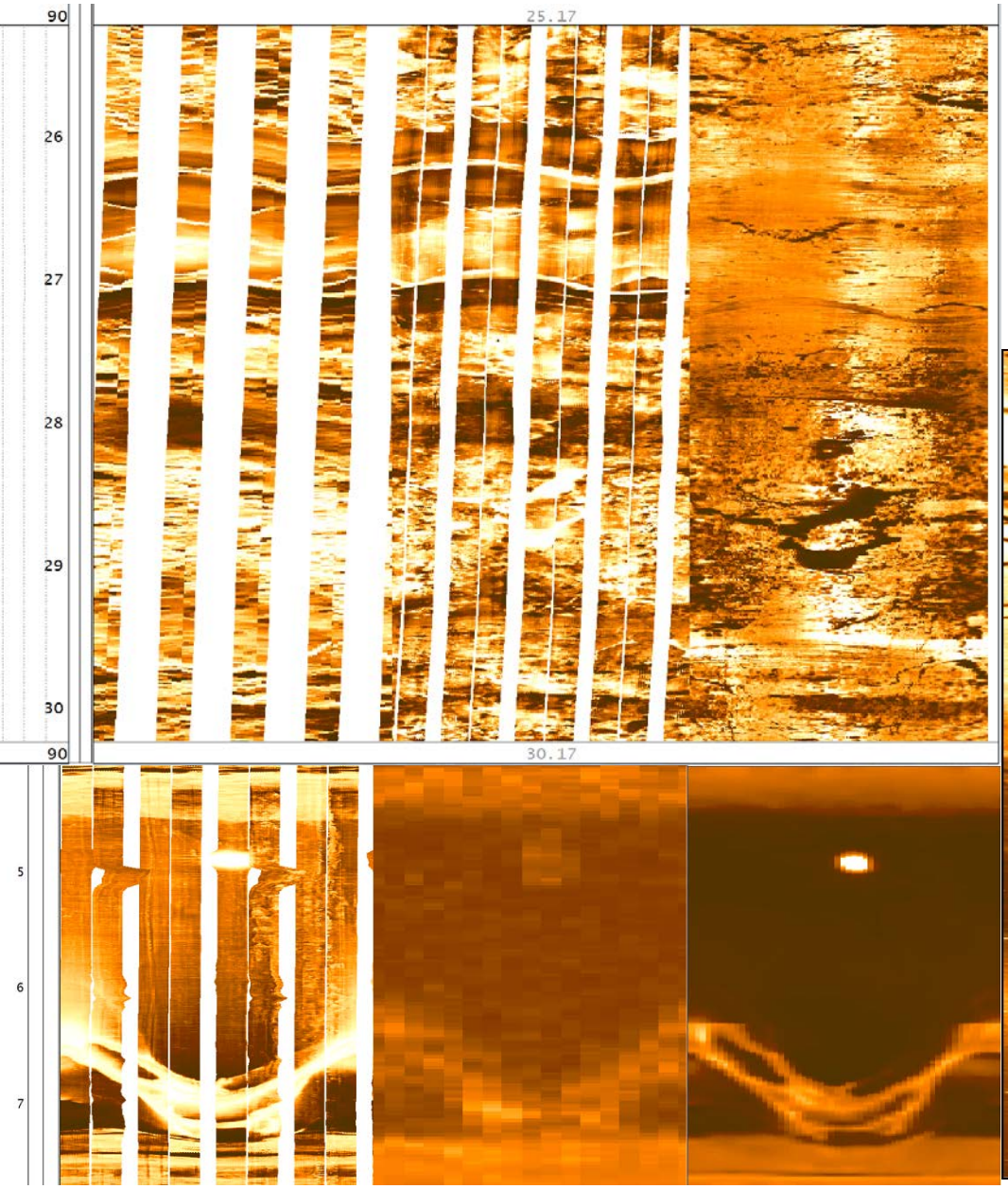
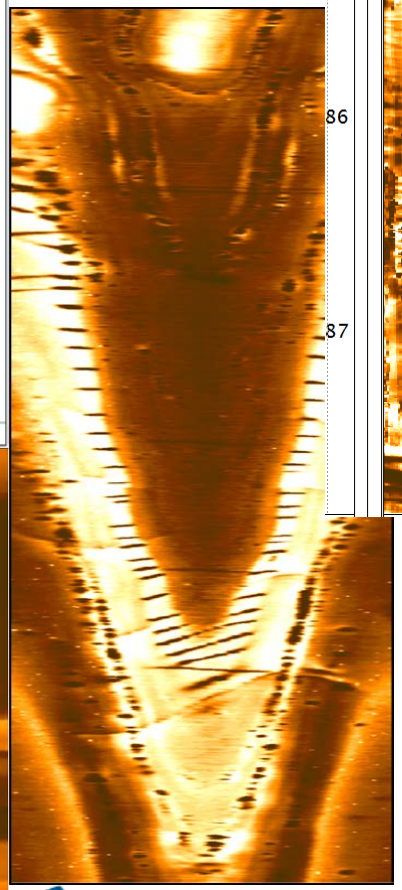
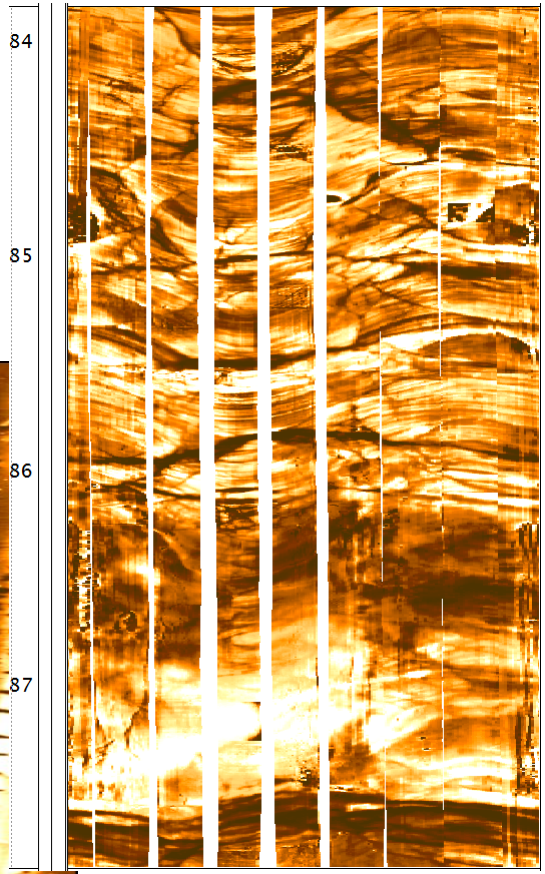
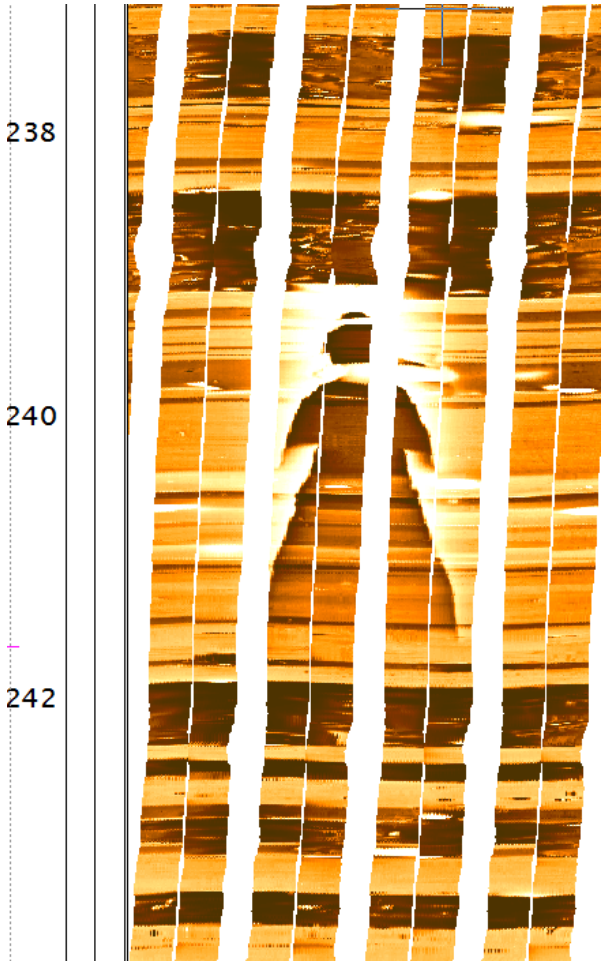
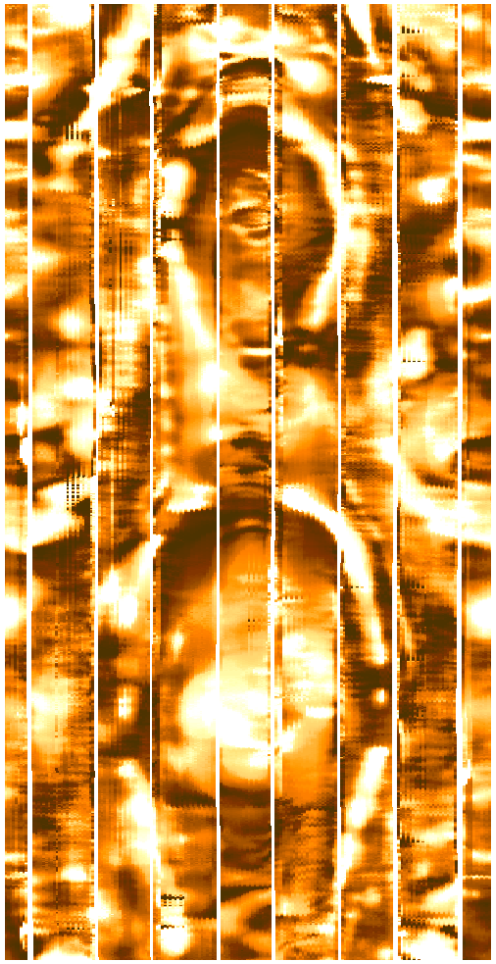
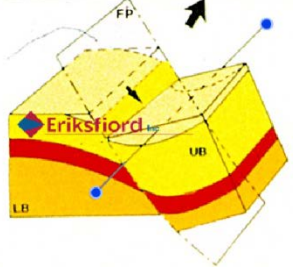


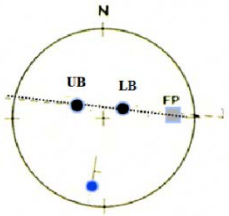


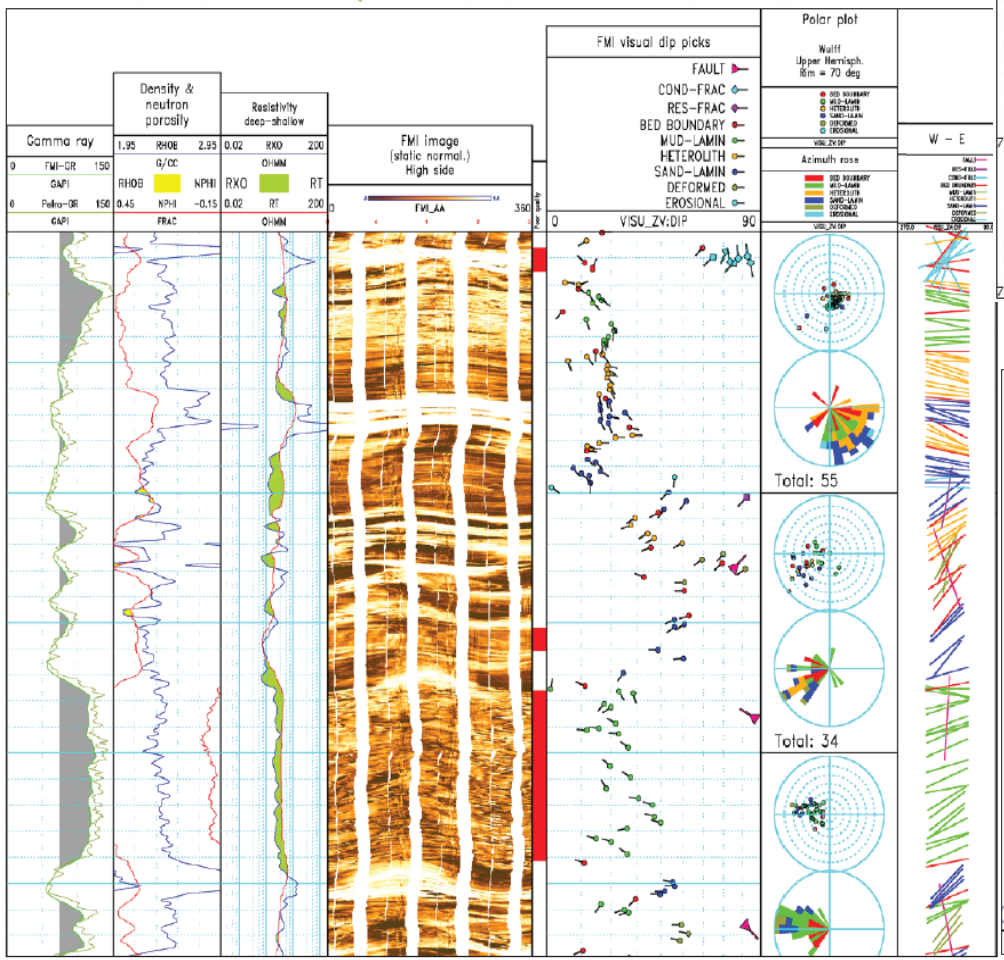


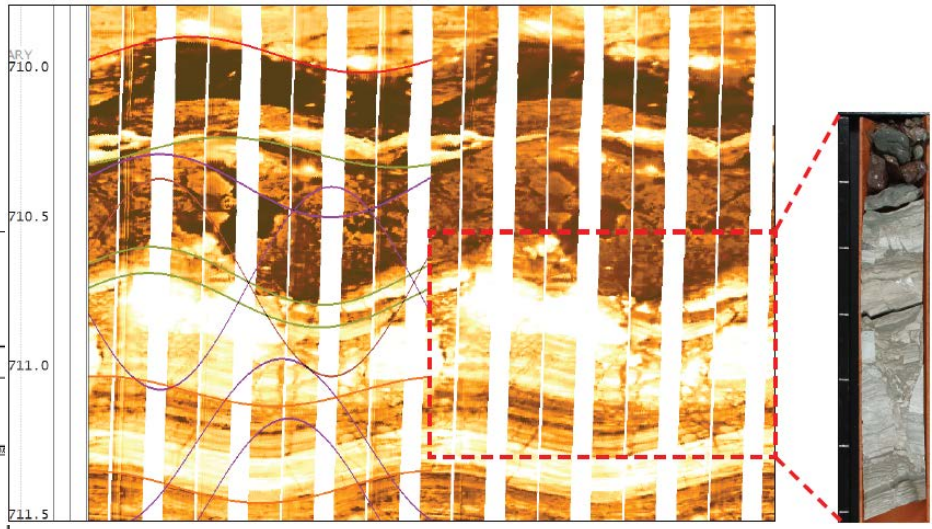


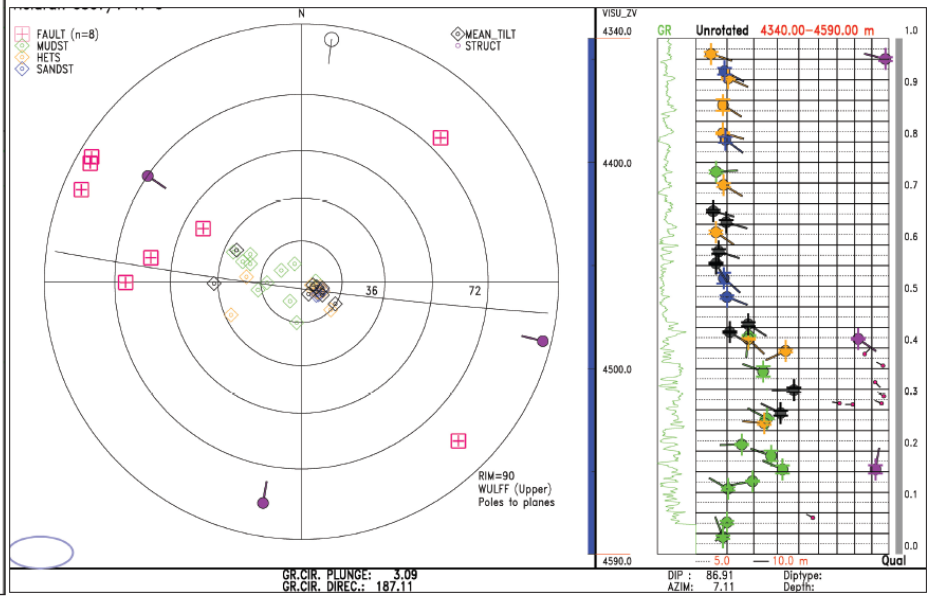


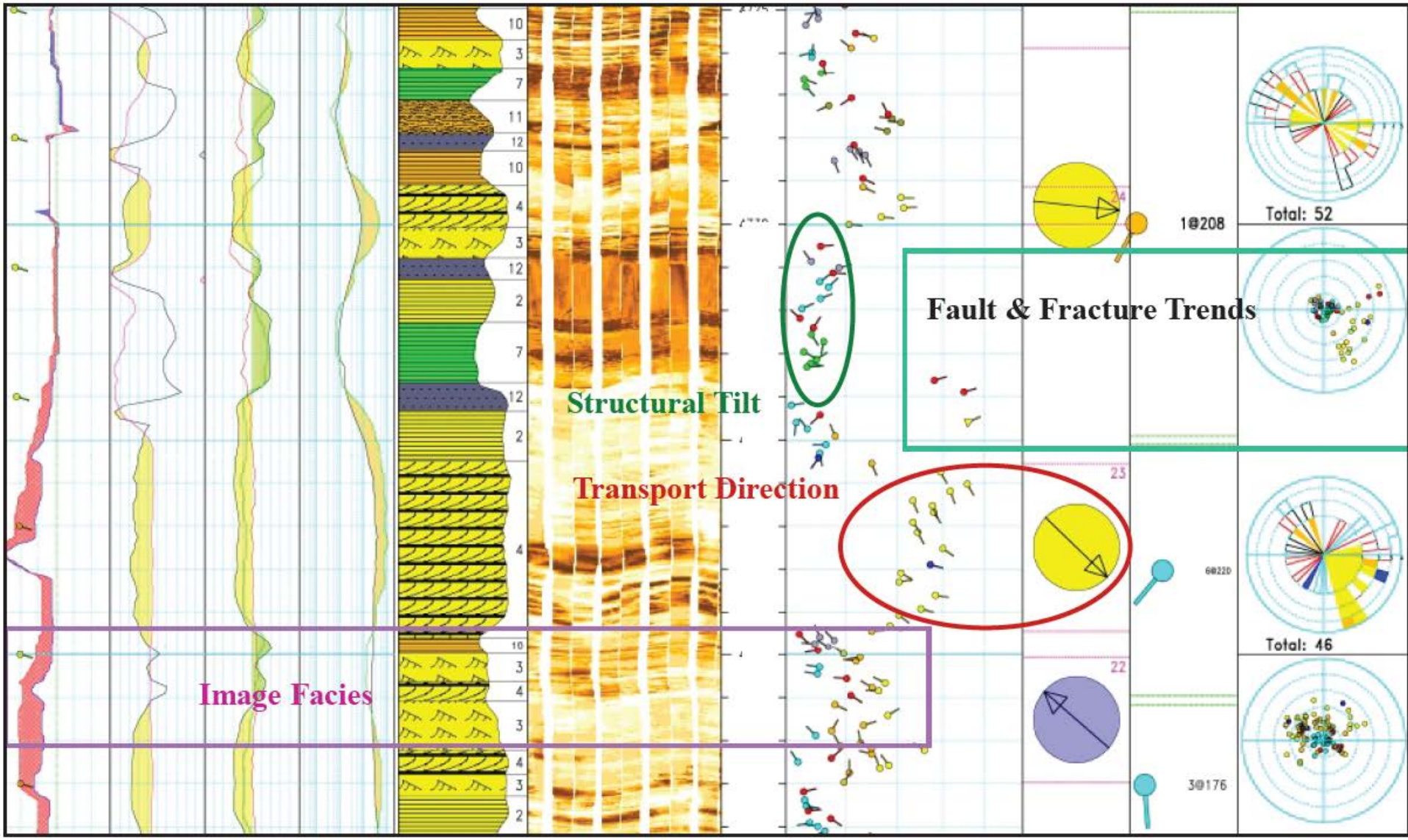




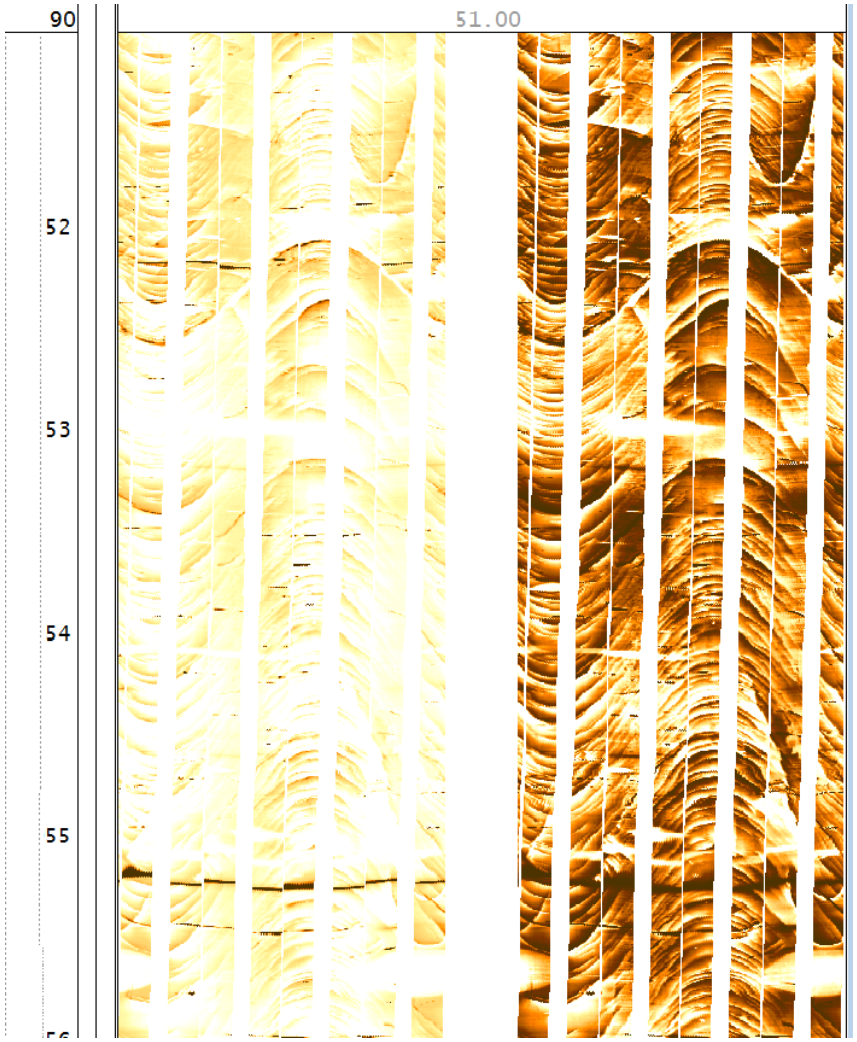






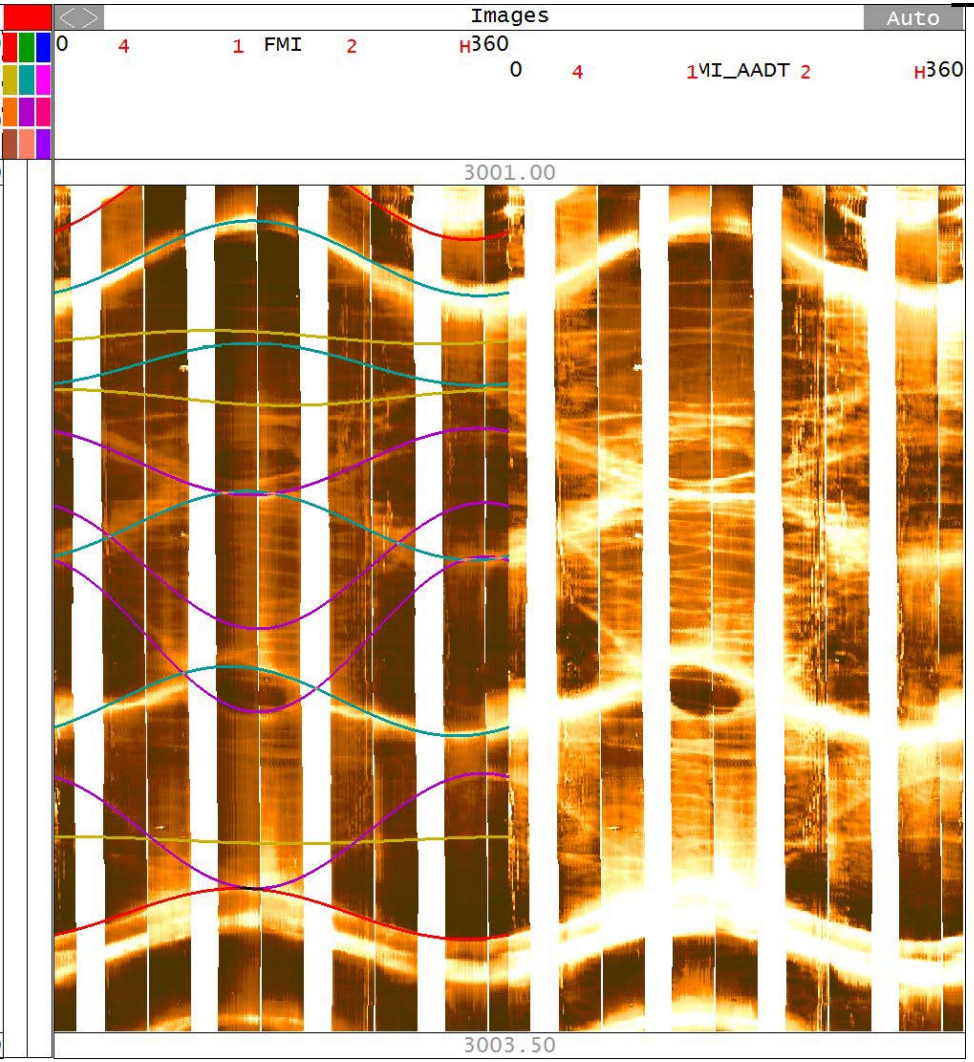


Fractures

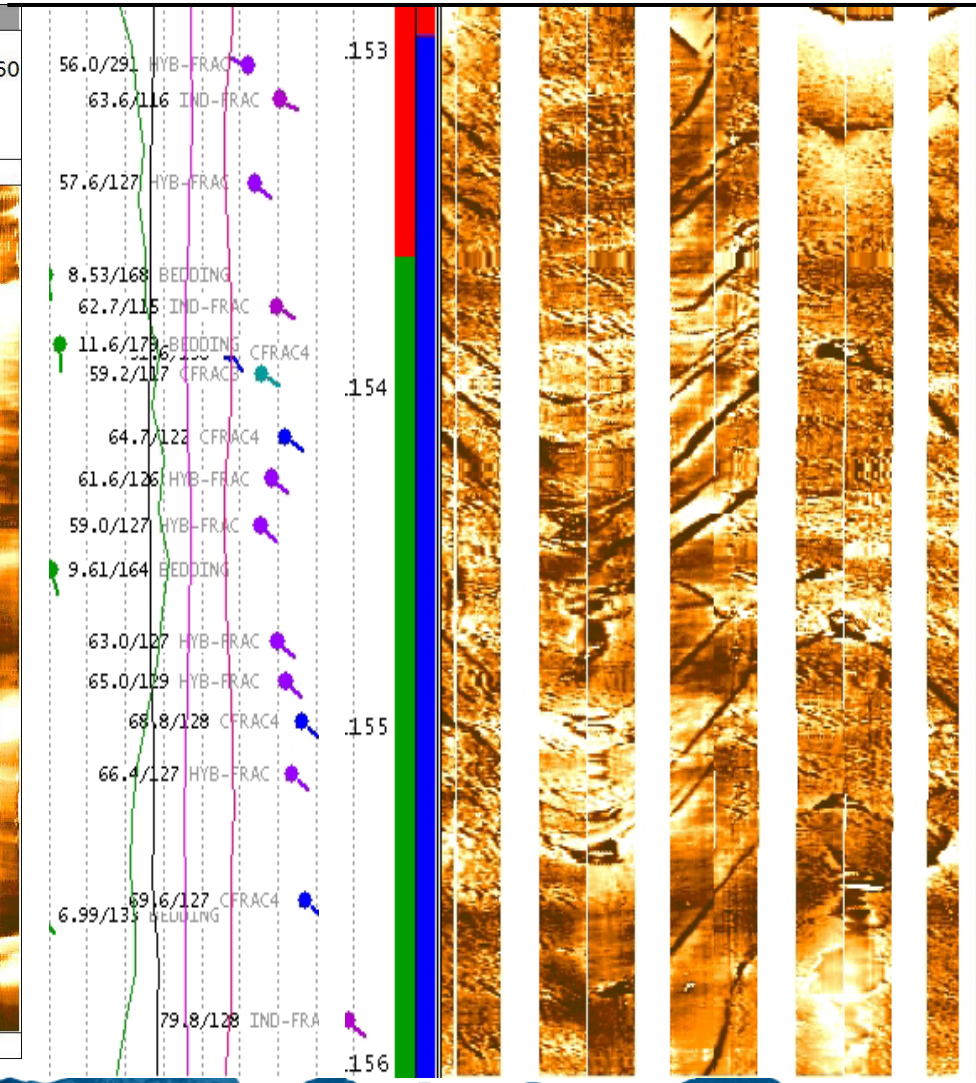


Fracture examples

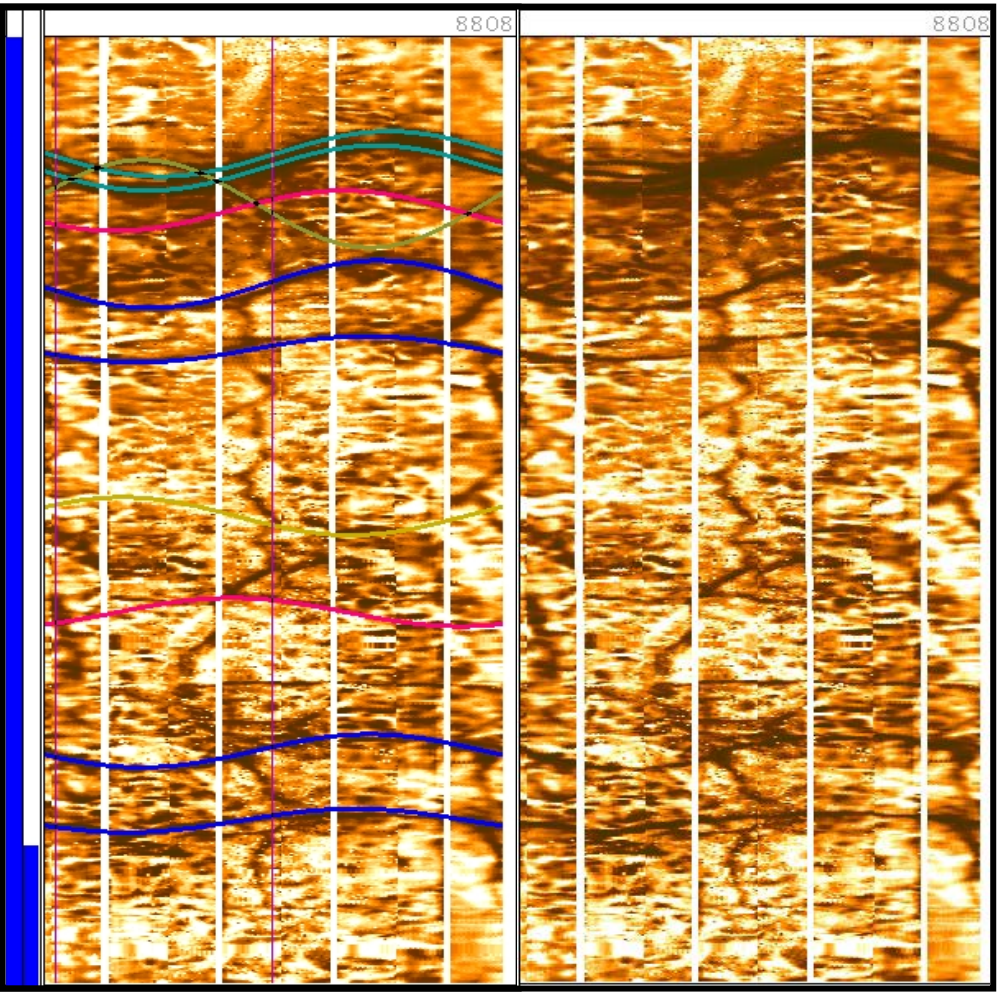
Resistive

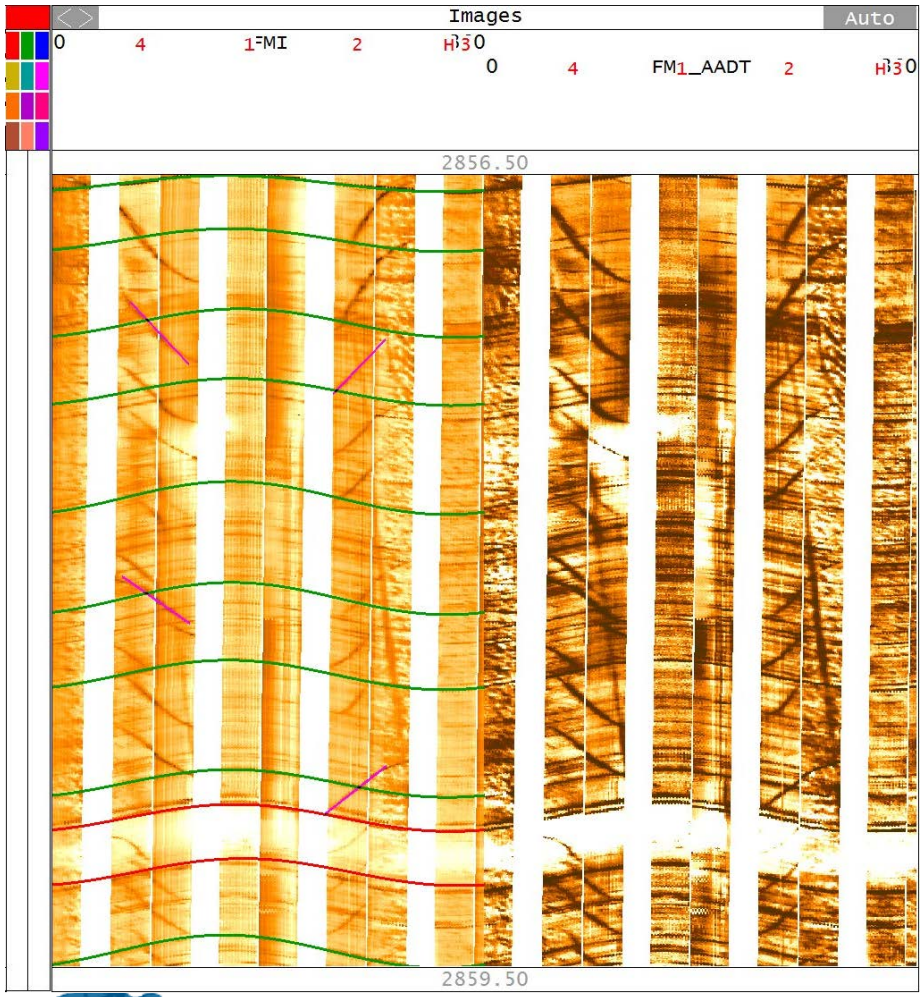


Conductive



Natural and induced fractures





Fracture cluster analysis

… based on high-resolution image logs such as FMI, HMI, etc.

→ Each fracture plane is described by type, relating to STYLE, CONTINUITY and QUALITY as seen on the borehole image

→ Degree of fracturing is then described by:
1) Density (number of planes per meter)
2) Corrected density for borehole bias
3) Cluster subdivision

→ Fracture porosity

→ Relative fracture permeability

Fracture cluster analysis

Fracture Clusters

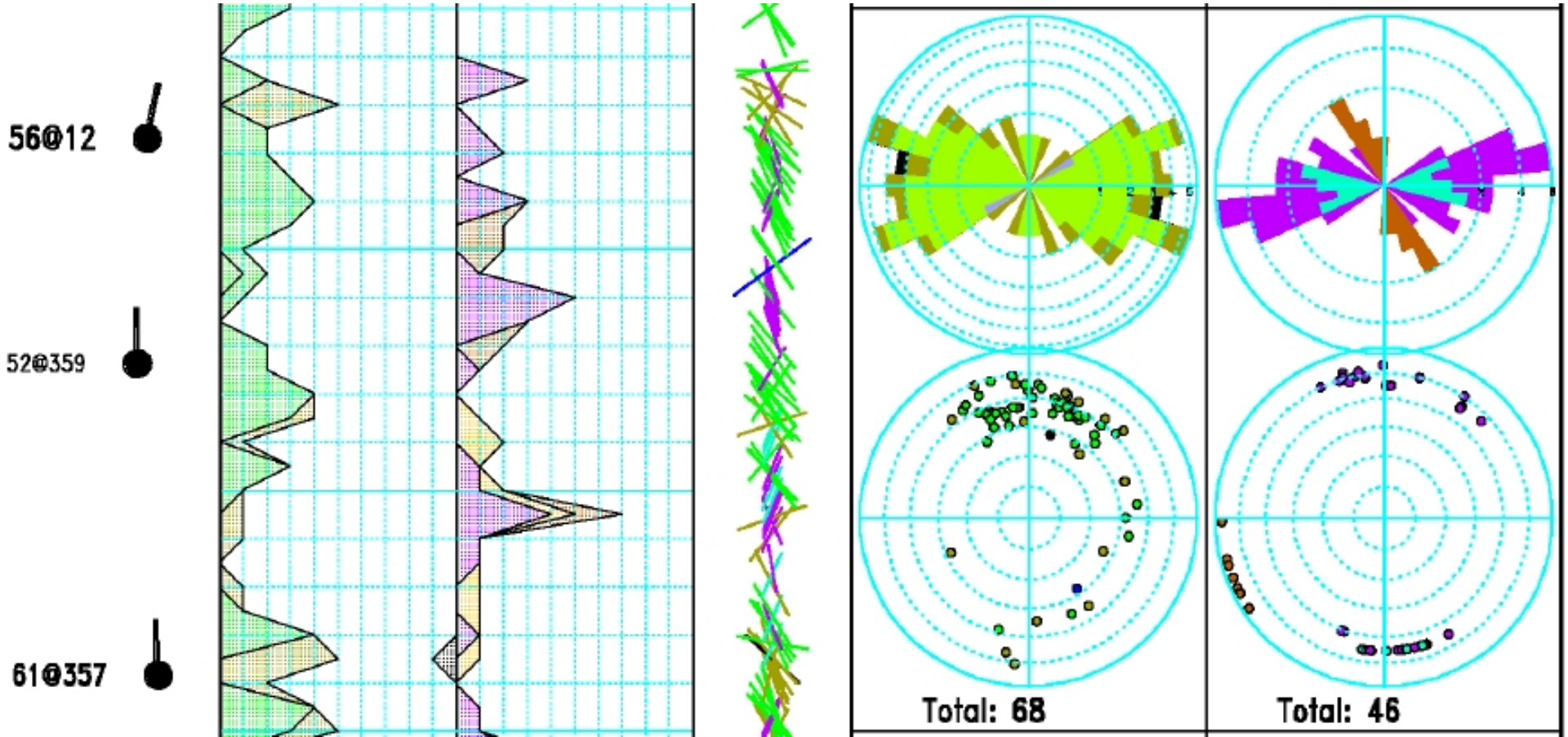
Conductive fracture frequency

Resistive fracture frequency

S-N projection

Conductive fracture strike/ stereogram

Resistive fracture strike/ stereogram



Quantification of fracture aperture from BHI

Three schools: 1) Can't be done

2) Fixed at mean value per fracture type, calib. against prod. testing

3) Luthi&Souhaite method (Geophysics, 1990) $W = c\ A\ R_m^b\ R_{X_0}^{(1-b)}$

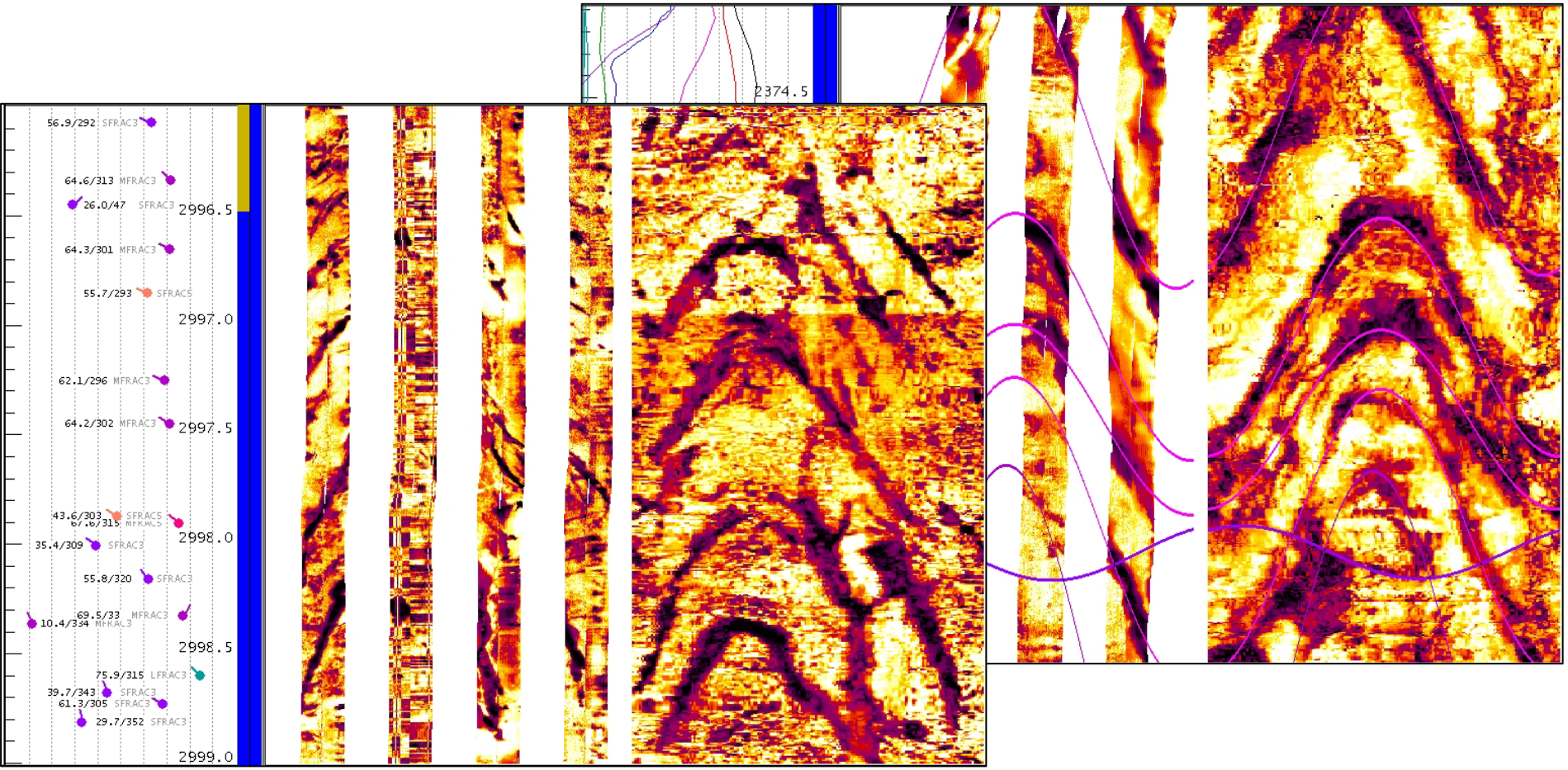
W= aperture, A= excess conductivity, Rm/Rx= mud res/flushed resist

L-S themselves mention a long list of requirements, some of which are:

- only FMS (Static, Emex corrected – voltage current & gain)
- constant lithology (Rx) over fracture length,
- dip <45º rel.to well
- perfect image quality,
- fracs have to be planar,
- b & c are tool and environment-dependant and poorly defined
- In addition: no fracture crossing, full circumferential, edge effect, isotropic stresses …

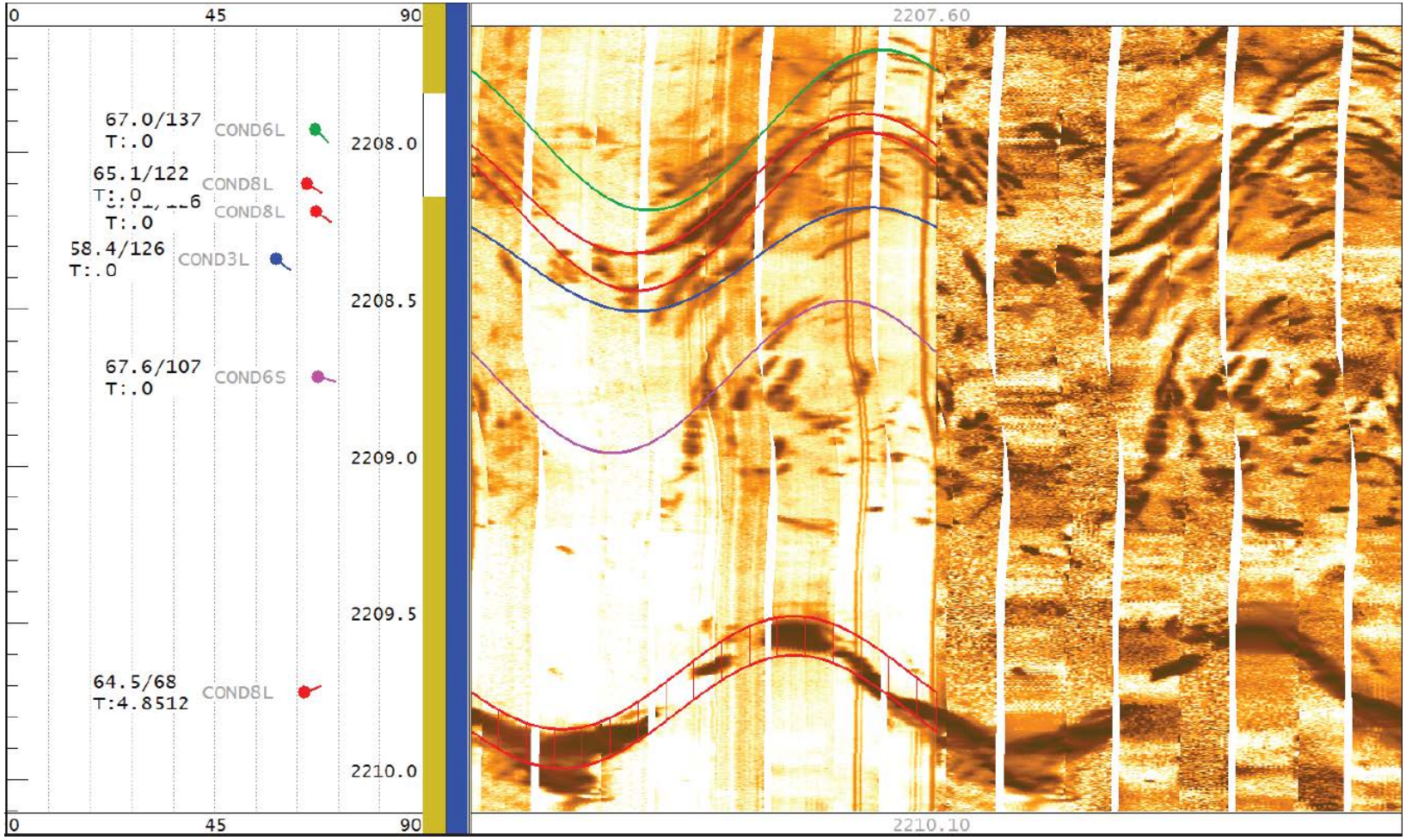
➔ Not a single fracture that does not violate some of the requirements

Quantification of fracture aperture from BHI



Limitation due to tool type, log quality, borehole quality (throat chipping), current sucking…

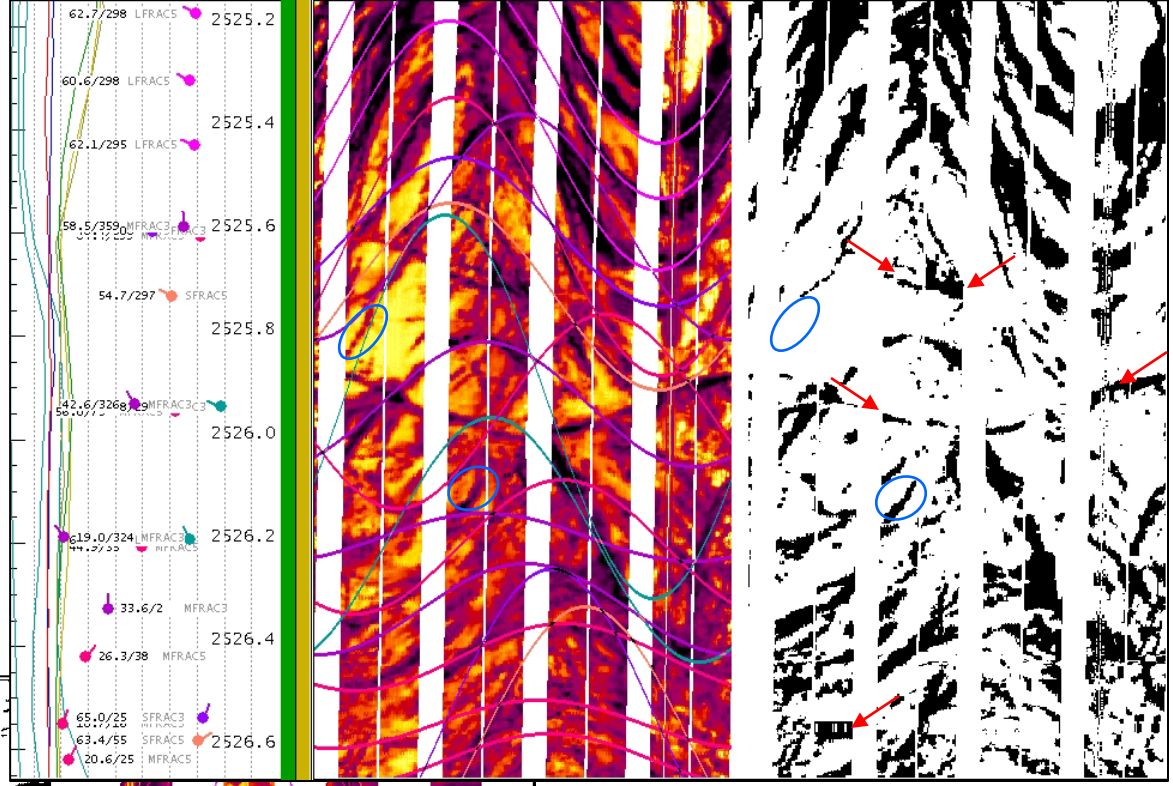
Quantification of fracture aperture from BHI

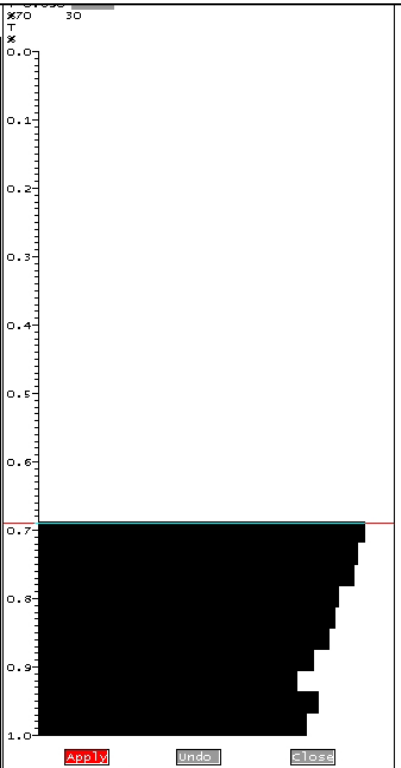


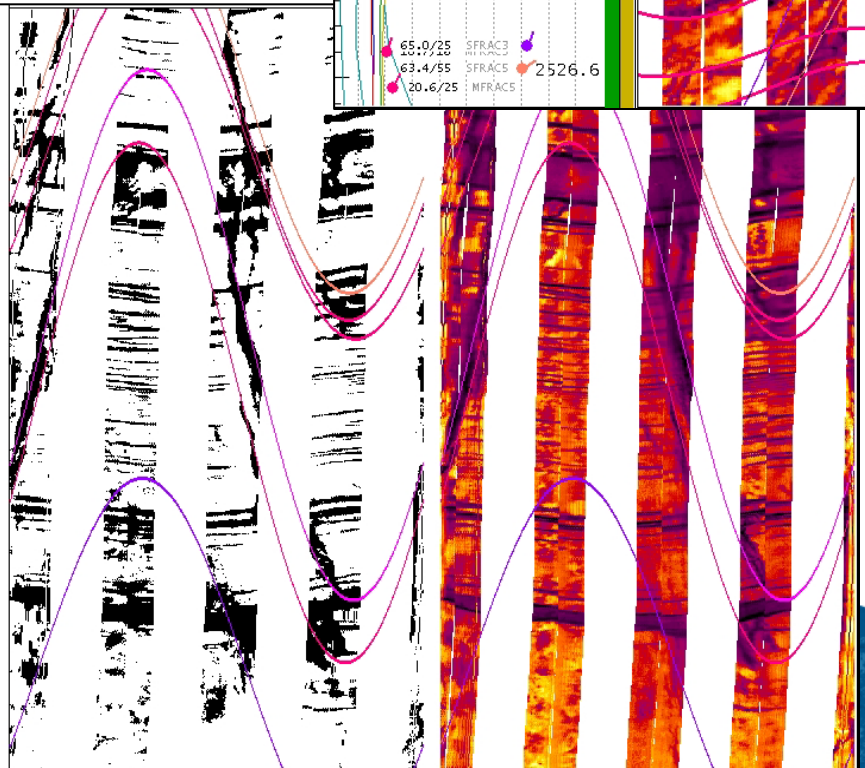
Manual picking of large apparent fracture apertures (correction for orientation, edge effect etc.)

Quantification of fracture aperture from BHI

Thresholding

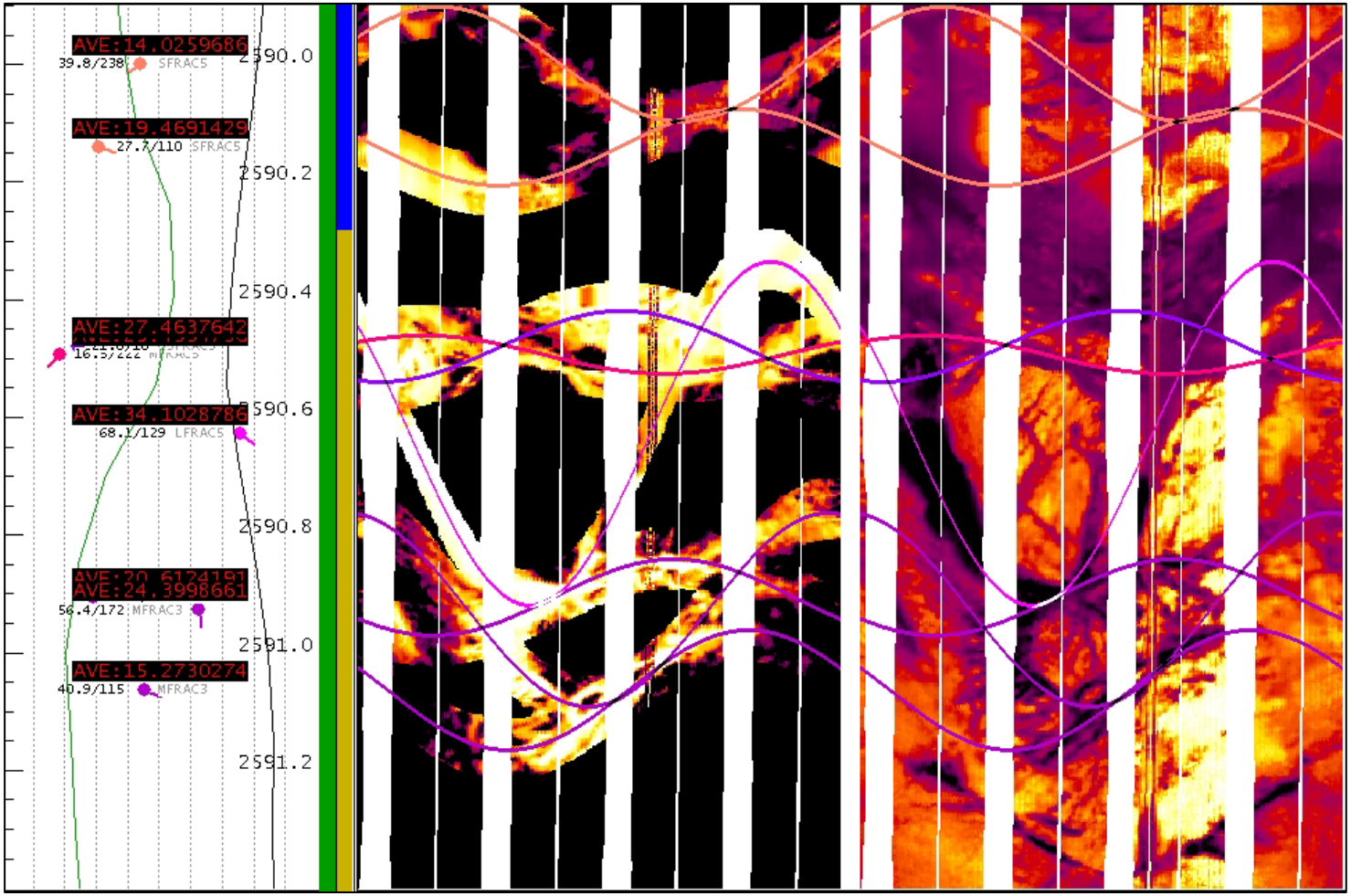






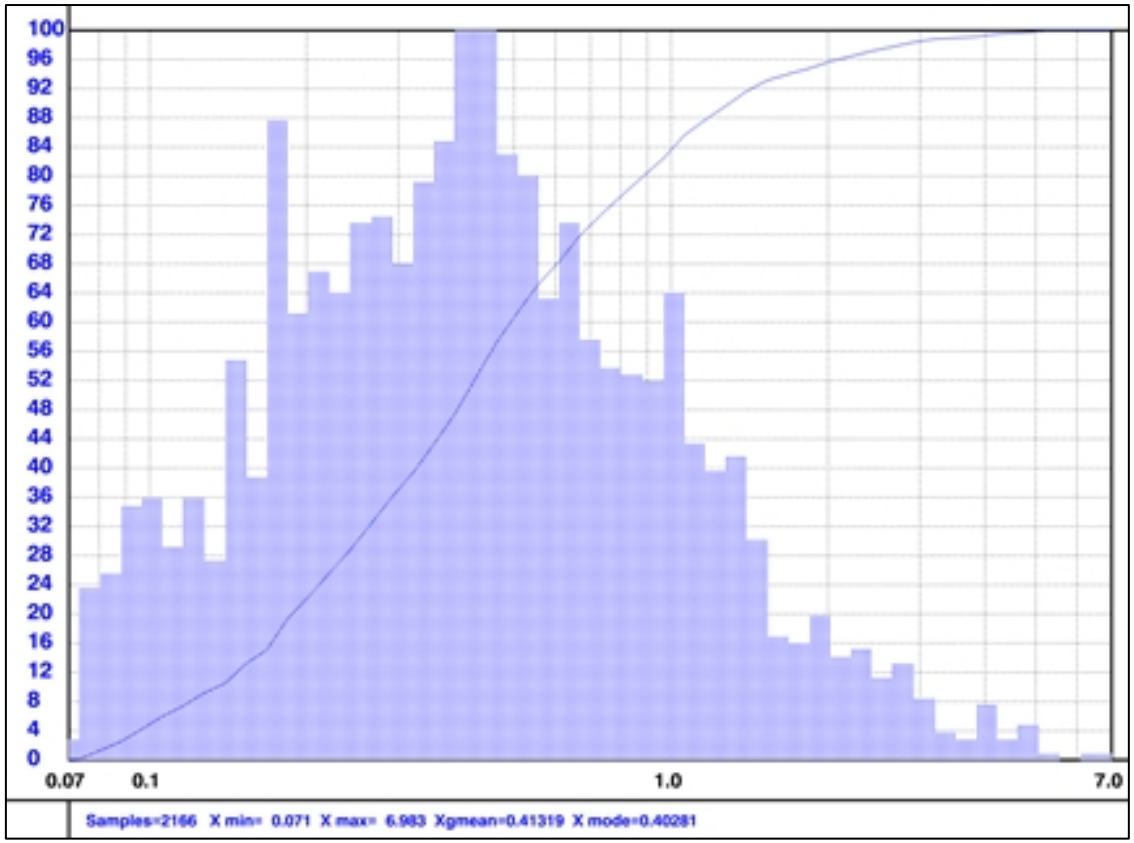
Pollution of excess conductivity by conductive beds or artefacts

Quantification of fracture aperture from BHI



Counting of excess conductivity (fracture intersections/muddy beds)

Quantification of fracture aperture from BHI



Distribution of calculated fracture apertures (n=2166, range 0-7mm, mean=0.4mm)

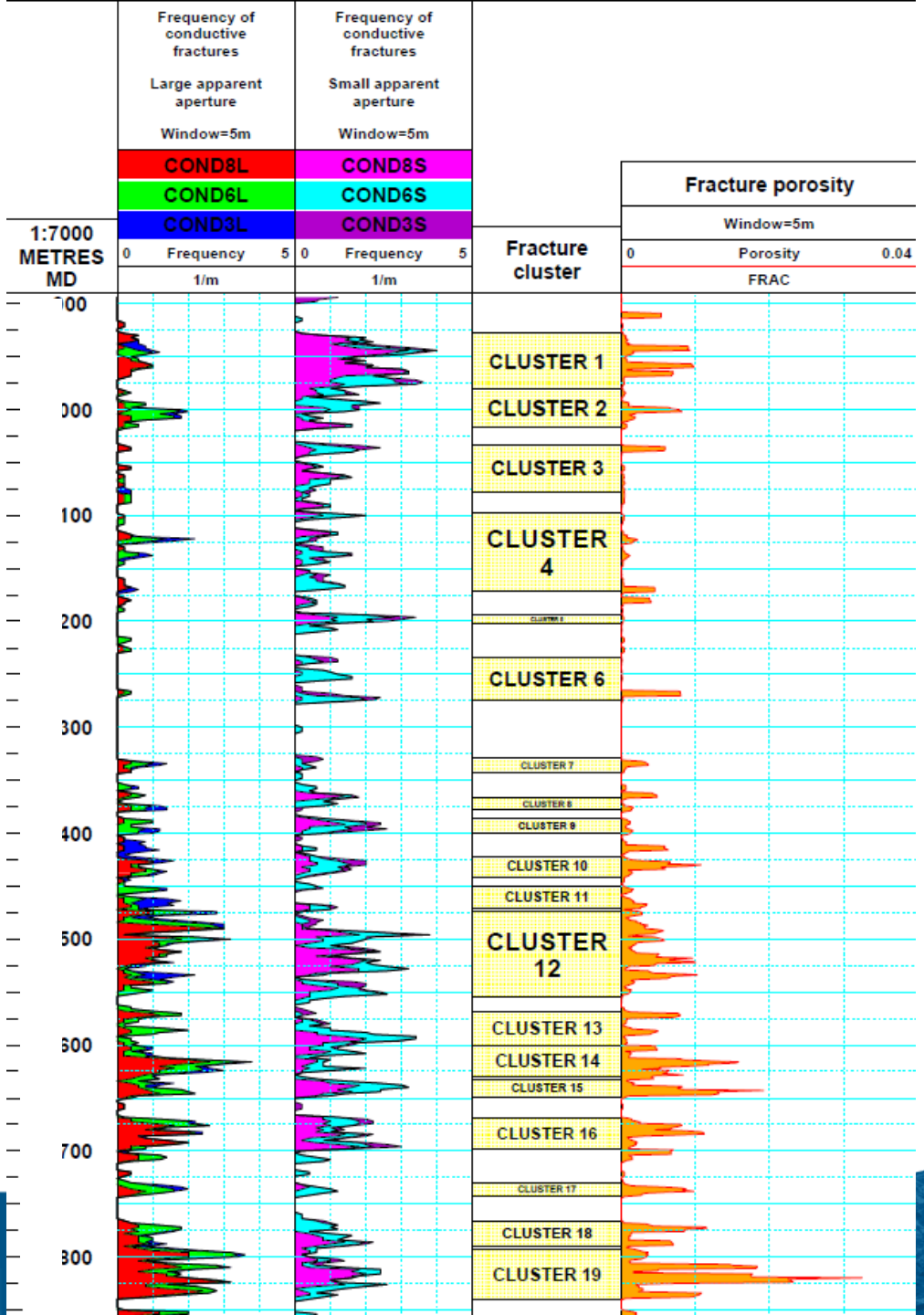
Combined method: Subdivision into different fracture classes with fixed mean reference apertures (calibration to core…).

Measuring excess conduct. over matrix.

Correlation of manually picked thickness to excess conductivity.

Correcting for current sucking (edge effect, throat chipping).

Fracture porosity



Summing up of fracture apertures per meter relative to matrix. Multiplied with a factor depending on apparent aperture & continuity.

Sanity check against Neutron Por.

... all nice, but fractures are stressed

STRESS – How to measure it ?

Vinland Software Suite® 1.7.611 - Release 1.7 Update 2 - Eriksfiord, Inc.

File Edit View Navigate Tools Window Help

Projects | Files | Services

softwaredemo
15/9-3 ST3
Stress; 1
2903 Sand Brk_CLONE_1367959850409; 1
2903 Sand Brk; 1

Tensile Fracture X-Section Window

Drag this to move

Borehole X-Section Tensile

HIGH SIDE

Scale = min Tangential - To (MPA)

To	Fail...	Strike	BA...	RB	Width	Om...	Hazi	Devi	Mx...
0	Yes	86.325	87.669	120	36	153....	327....	18.821	32.406

Start page | Stress Analyzer Window - Well: 15/9-3 ST3

FMIS; 1; 2900.00 - 2940.00 BAZIM/RB/Depth:85.3/117.5/2904.6076 2902.03

2903.0

2904.0

Palette

Planes

BED-BOUND, BEDDING, BED_BOUNDARY, CLOSED_FRAC, COND-FRAC, COND6L, COND8L, COND8S, FRAC_C, FRAC_COND, FRAC_CP, FRAC_CT, FRAC_CX, FRAC_H, FRAC_R

Breakout X-Section Window

Drag this to move

Borehole X-Section Breakout

HIGH SIDE

Scale = UCS - Required Strength [Mogi-Coulomb] (MPA)

UCS	Fric...	Fail...	Strike	BA...	RB	Width	Hazi	Devi	Min...
32	26.5	Yes	179....	357....	30	28	327....	18.821	38.25

Weakplane Picker Window

Weak Plane Calculator

μ = .50

τ [Shear Stress] (MPA)

Sn - pp [Effective Normal Stress] (MPA)

Tensile Fracture Predictor Window

SH 55.2

SH Azi 86.4

RB	Width	Omega	Strike	BAZIM
120.0	36.0	153.2	86.3	87.7

Insert SH/SHAzi to Stress Tensor

Auto Insert to Tensor

Breakout Predictor Window

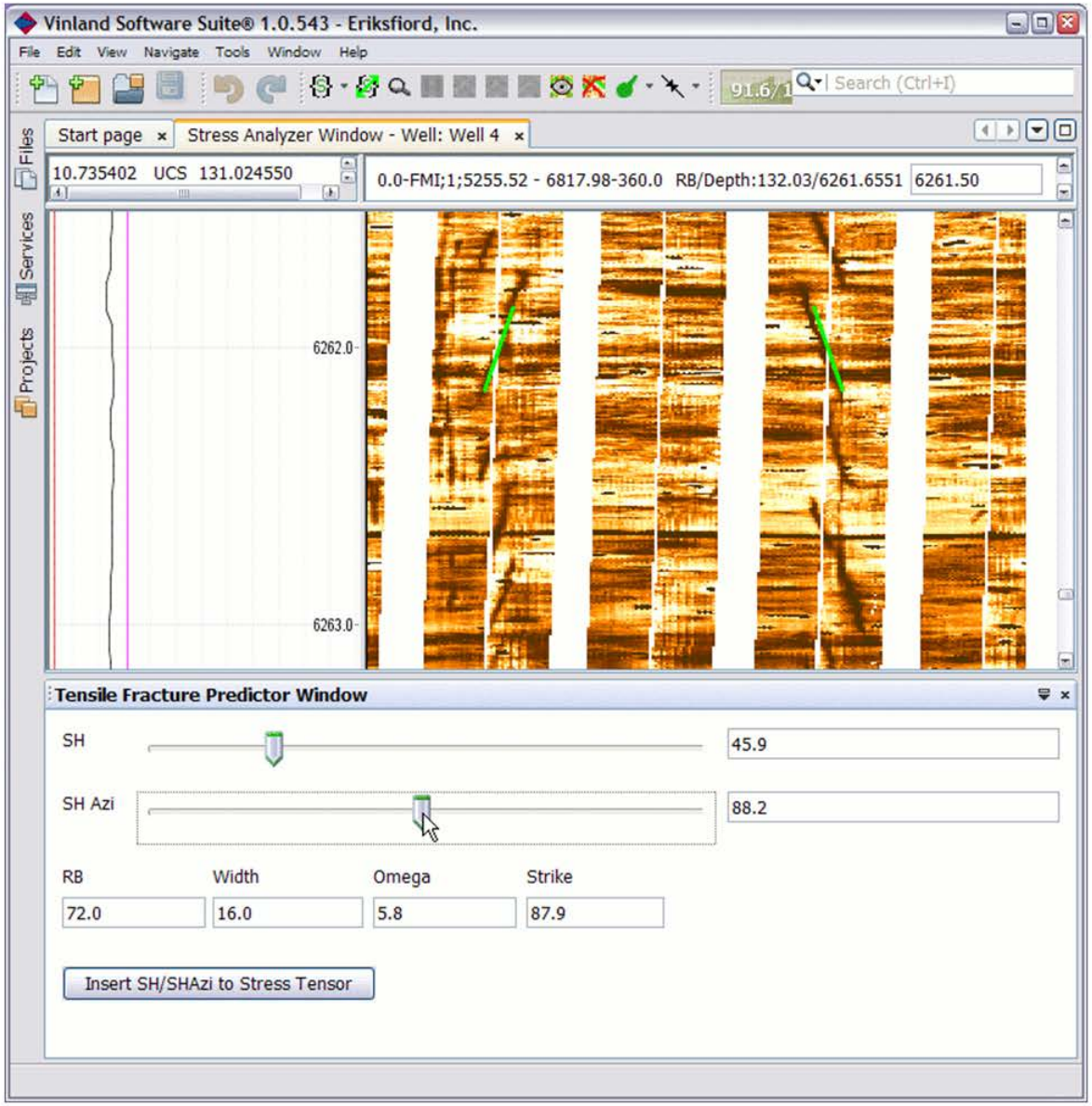
SH 55.2

SH Azi 86.4

RB	Width	Strike	BAZIM
30.0	28.0	179.1	357.7

Insert SH/SHAzi to Stress Tensor

Auto Insert to Tensor



The test is to assume a stress field and predict the position, azimuth and angle of incidence of the resulting crack.

Induced fractures are skin-deep and only lead to mudloss when propagating into the far field with $P>S_3$

Creating a Stress log along hole.

Vinland Software Suite® 0.33.52 - Eriksfiord, Inc.

File Edit View Navigate Tools Window Help

Projects | Files | Services

- COBRA_sand;1;2049.98 - 3003.85
- COBRA_sand_HAZI_0;1;2049.98 - 3003.85
- COBRA_shale;1;2049.98 - 3003.85
- COBRA_shale_HAZI_0;1;2049.98 - 3003.85
- FMI_3;1;2160.00 - 2560.00
- STRESS_TVDSS;1;2049.98 - 3003.85
- STRESS_sand;1;2049.98 - 3003.85
- STRESS_sand_HAZI_0;1;2049.98 - 3003.85
- STRESS_shale;1;2049.98 - 3003.85
- STRESS_shale_HAZI_0;1;2049.98 - 3003.85
- Well 4
- Prospect A1
- Friction
- System
- shale_gas
- test2

Cobra Window

Property	Type	Curve	Value	Unit
SV	CURVE	SV	0.0	MPA
SV Azimuth	CONSTANT	SV	0.0	DEG
SV Deviation	CONSTANT	SV	0.0	DEG
Sh	CURVE	SHMN	0.0	MPA
SH	CURVE	SHMX	0.0	MPA
SH Azimuth	CURVE	SHMXAZI	0.0	DEG
Poisson	CURVE	POISSON	0.28	FRAC
Biot	CURVE	BIOT	0.85	FRAC
UCS	CURVE	UCS	0.0	MPA
Int. Fric. Angle	CURVE	FRICANGLE	30.0	DEG
Tensile	CURVE	TENSILE	-1.0	MPA
Pp	CURVE	PP	0.0	MPA
Pw	CURVE	PW	0.0	MPA
Hole Azimuth	CURVE	HAZI	0.0	DEG
Hole Deviation	CURVE	DEVI	0.0	DEG
TVD(Datum)	CURVE	TVDSS	0.0	M
g	CONSTANT	N/A	9.81	M/S2
KB Elevation	CONSTANT	N/A	25.0	M
Top Depth	CONSTANT	N/A	2200.0	M
Bottom Depth	CONSTANT	N/A	2400.0	M

Cancel | Start COBRA Algorithm

Stress Analyzer Window - Well: Well 2 | 2200.0-2400.0 M

Drag this to move

Depth [M]: 2200.0, 2225.0, 2250.0, 2275.0, 2300.0, 2325.0, 2350.0, 2375.0, 2400.0

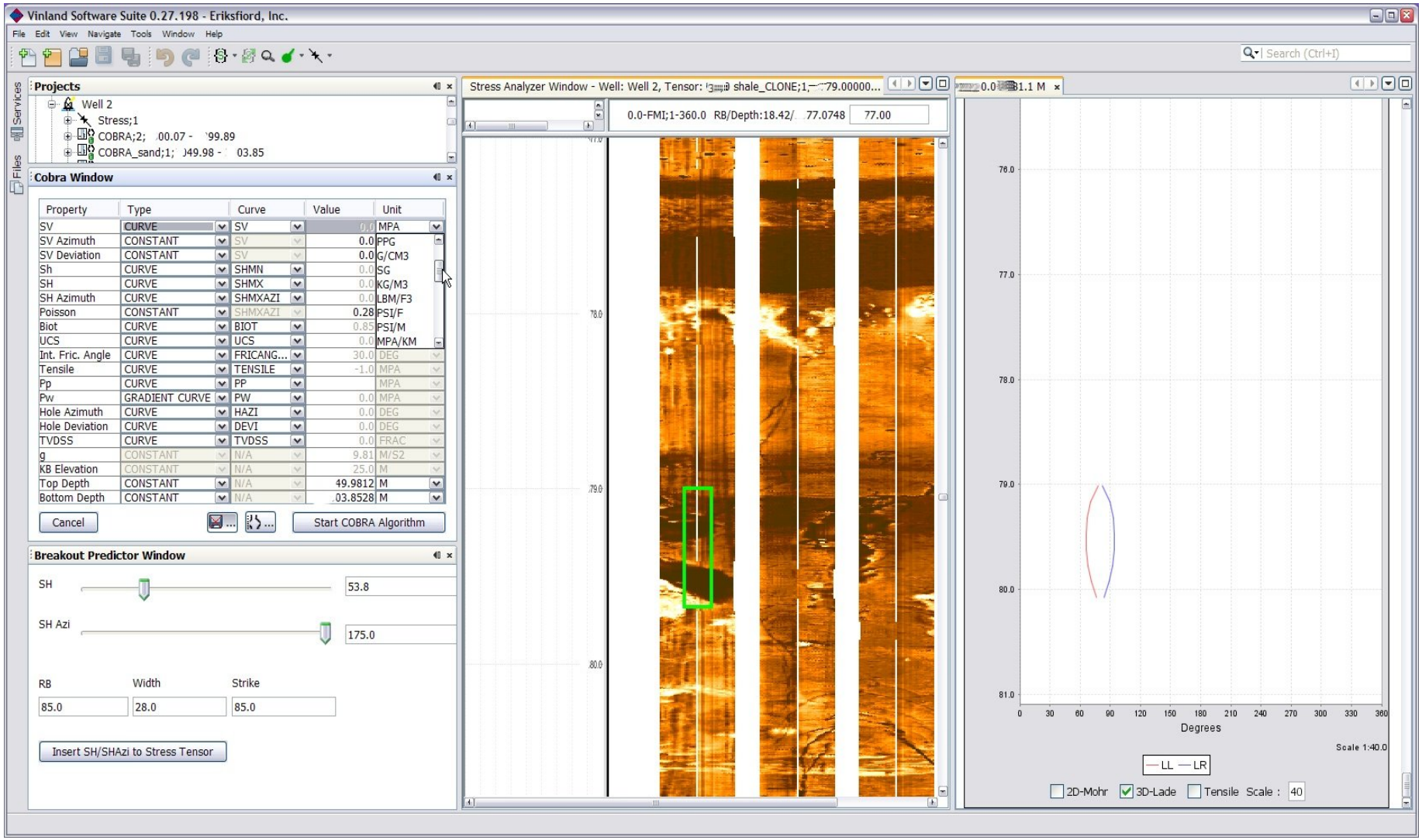
Degrees: 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, 330, 360

Scale 1:1000.0

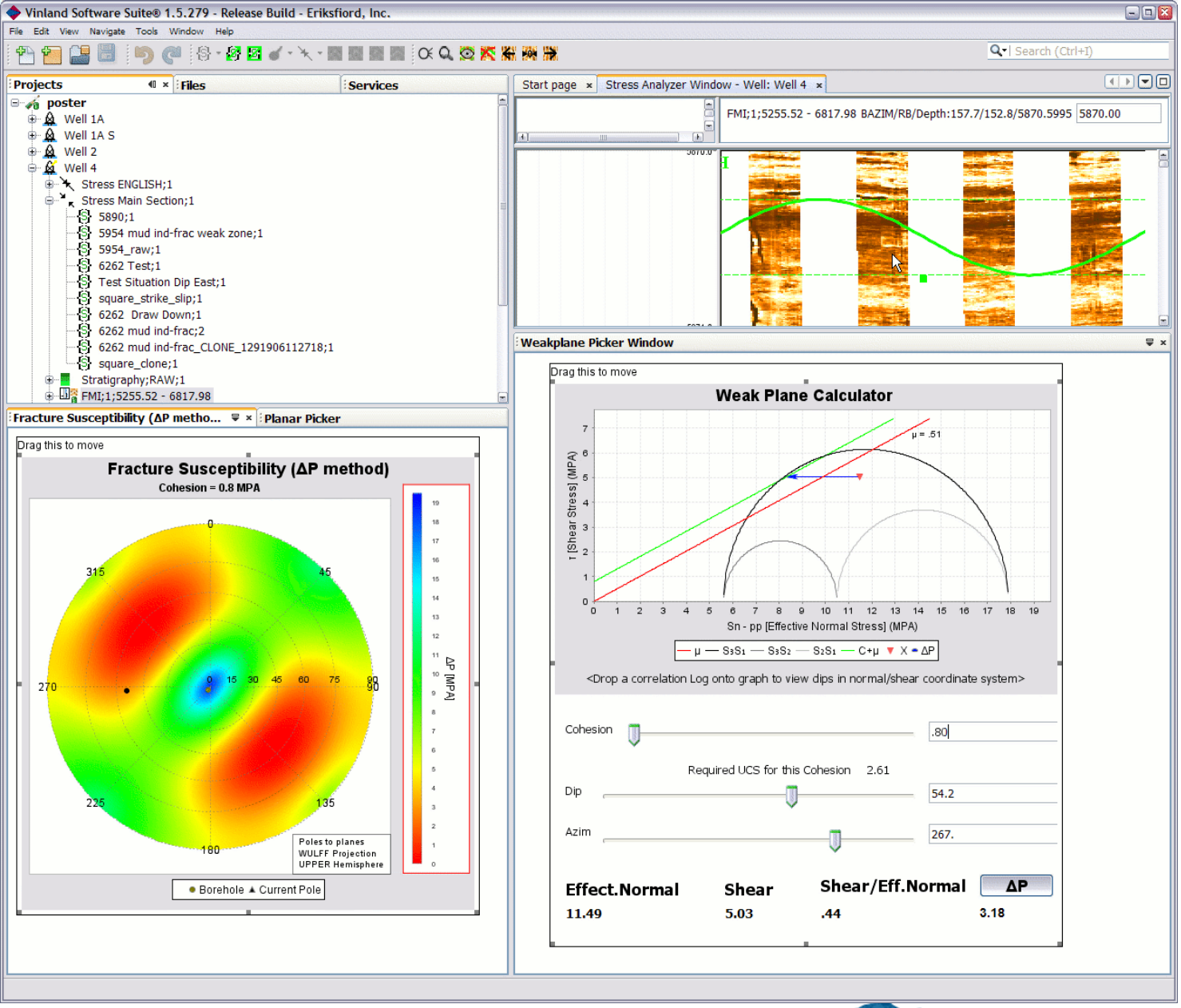
LL LR

2D-Mohr | 3D-Lade | Tensile Scale : 1000

Verify stress log against reality.



Stresses on fractures



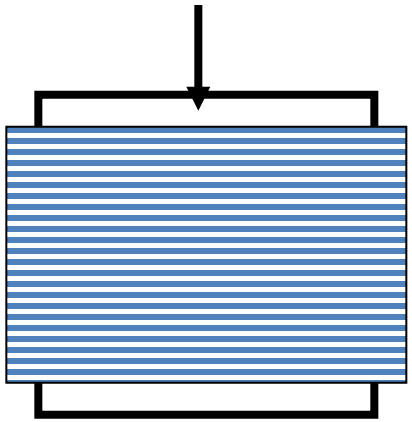
Now it is possible to calculate the stresses acting on each fracture.

Fracture permeability

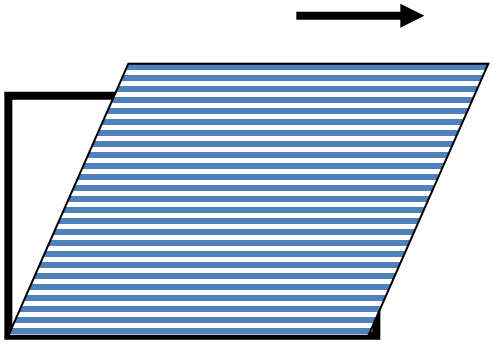
as function of both normal and shear stress

… possible in combination with a geomechanical evaluation (stress tensor and rock strength data)

$$\frac{\Delta k}{k_0} = \left[1 + \frac{\Delta\varepsilon}{b}\left(\frac{K_n}{E} + \frac{1}{s}\right)^{-1} + \frac{\Delta\gamma}{b}\left(\frac{K_{sh}}{G} + \frac{1}{s}\right)^{-1} \tan(u) \right]^3$$



k decreases



k increases

k (k_0) = Permeability (at zero stress)

s = Fracture spacing

b = Aperture

u = Shear angle

Kn, Ksh = normal and shear stiffness

E, G = Young's and shear modulus

$\Delta\varepsilon$, $\Delta\gamma$ = Normal and shear strain

Fracture behaviour away from the borehole

The shear stability of a fracture depends on shear stress relative to effective normal stress.

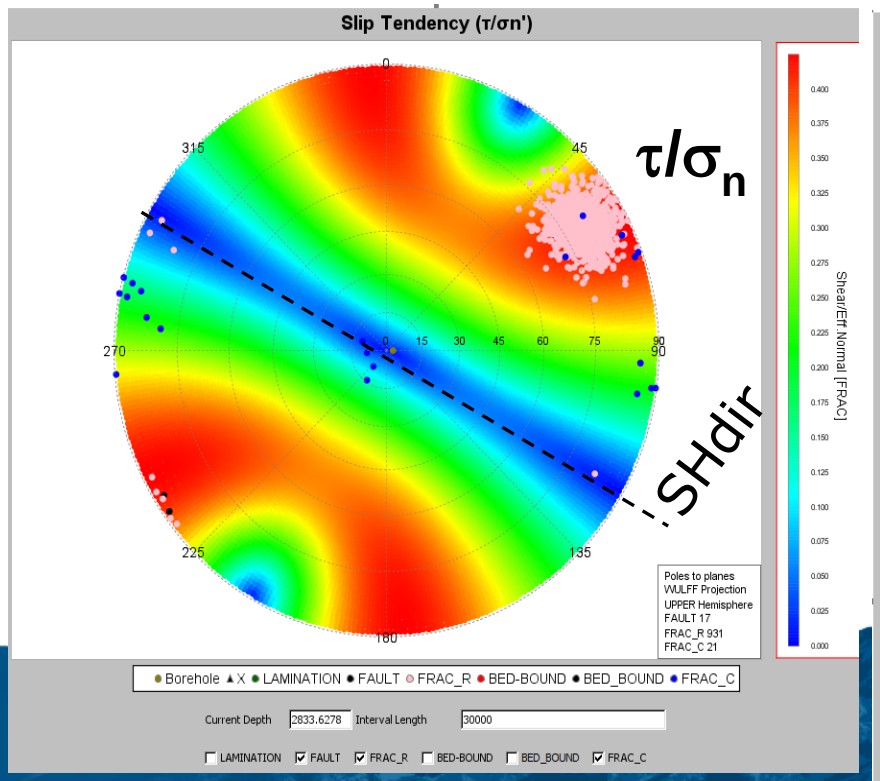
When it exceeds the friction co-efficient of the fracture, the fracture slips and the shear stress drops.

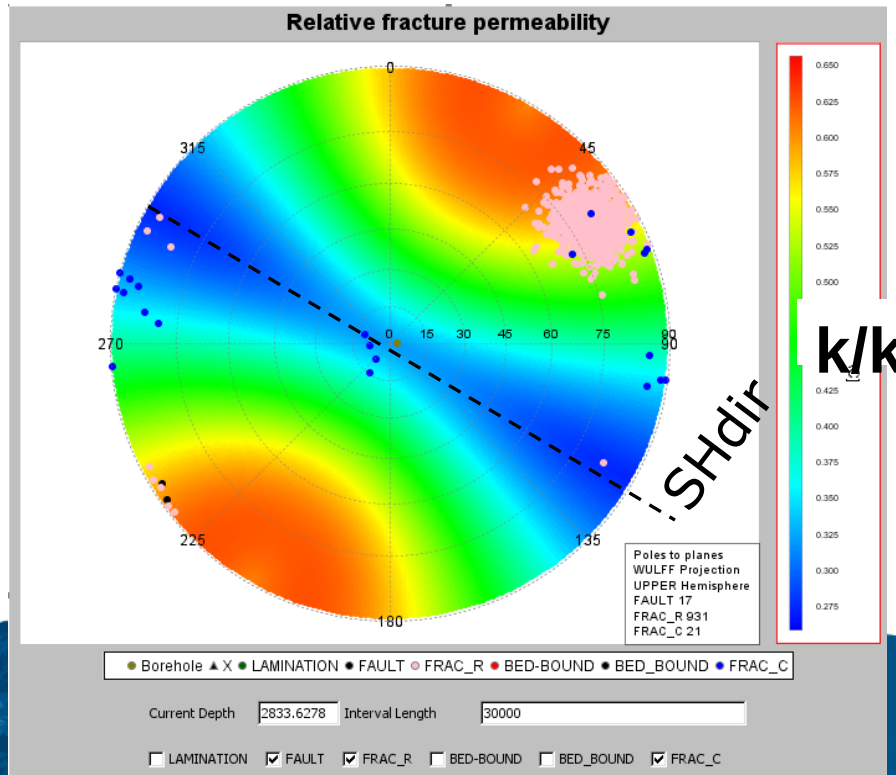
This is an irreversible mechanism.

k/k0 is stressed fracture permeability relative to unstressed state. It depends on

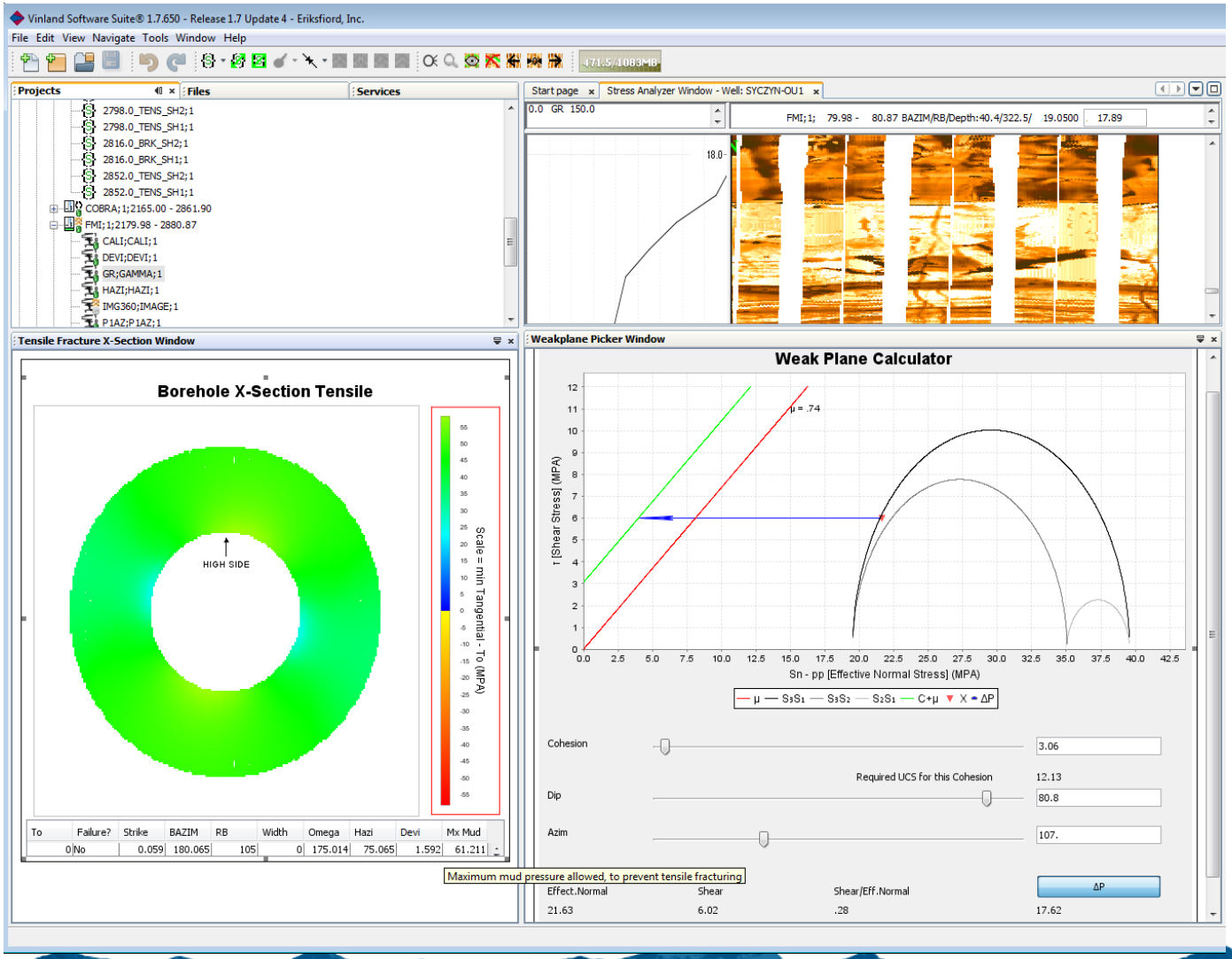
- fracture and stress orientation
- aperture and spacing
- fracture shear modulus
- fracture Young's modulus
- shear dilation angle

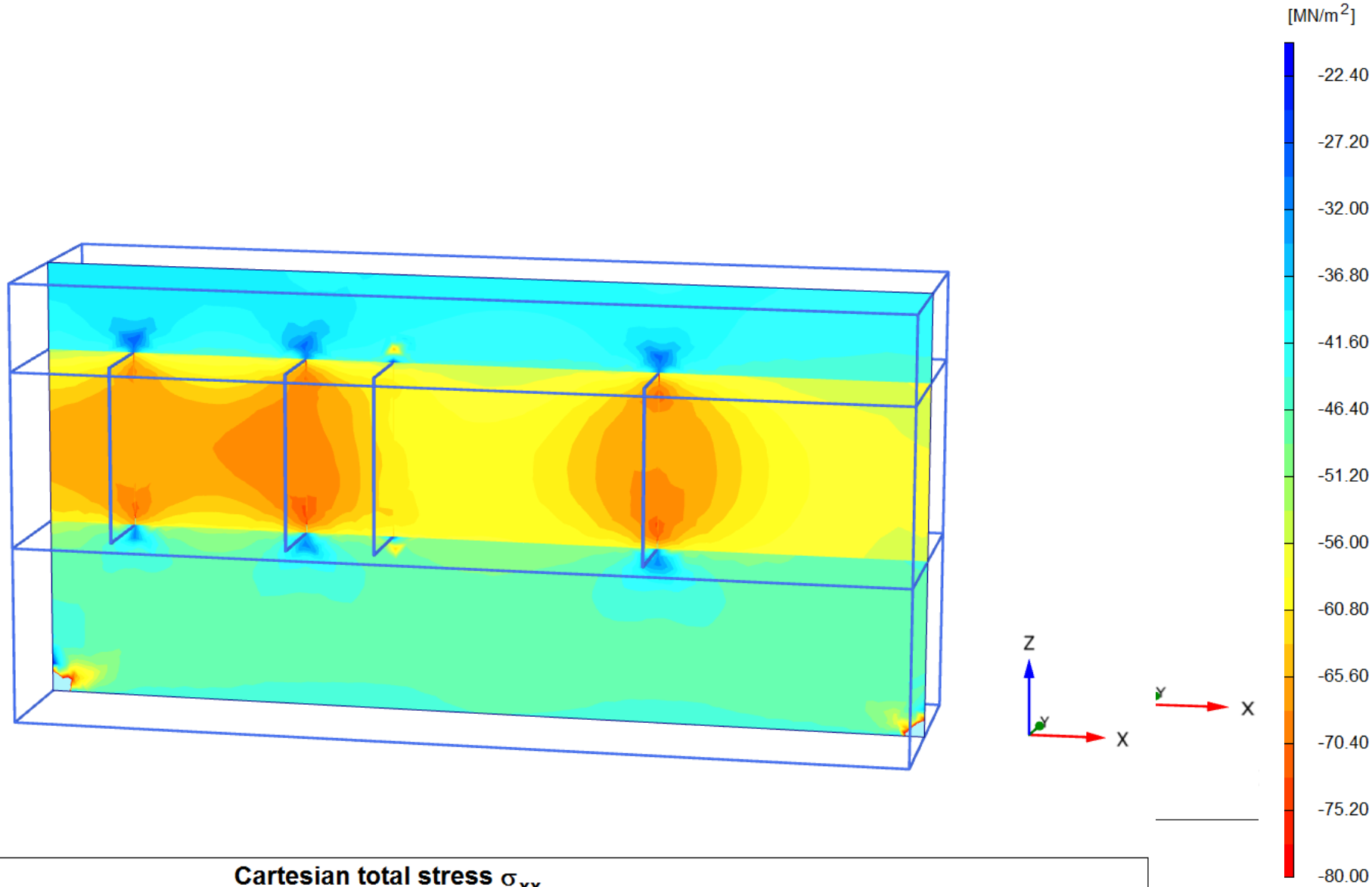
The model is reversible also for shear as it expresses dilation instead of slip.





Fracturing pressure





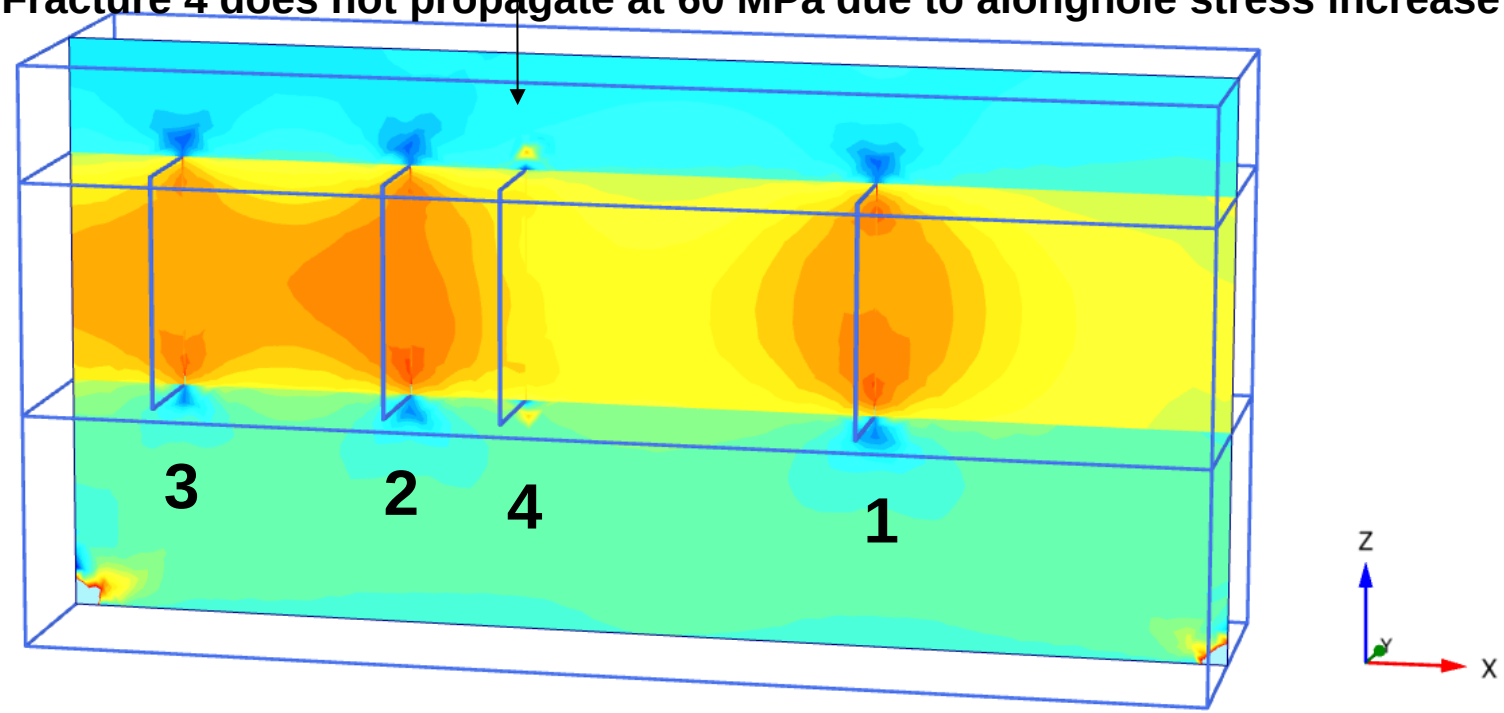
Cartesian total stress σ_{xx}

Cartesian total stress $\hat{\sigma}_{xx}$

Effect of fracturing sequence on opening pressure

1) Fracture 1 is opened at P=60 MPa, then propped
2) Fracture 2 is opened at P=60 MPa, then propped
3) Fracture 3 is opened at P=60 MPa, then propped

Fracture 4 does not propagate at 60 MPa due to alonghole stress increase



Cartesian total stress σ_{xx}

Conclusions

1) Geological interpretation of BHI yields semi-quantitative permeability and porosity contribution from fractures (and vugs).

2) Fracture seen in borehole is deformed by anomalous stress. Indirect methods required to predict fracture behavior in the far field.

3) Reversible model for combined shear and normal stress influence on fracture permeability exists but requires calibration

4) The far stress field is perturbed by artificial fracturing but the effect on opening pressure and propagation direction is predictable.

Thanks to

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Christian Ottesen

Eriksfiord