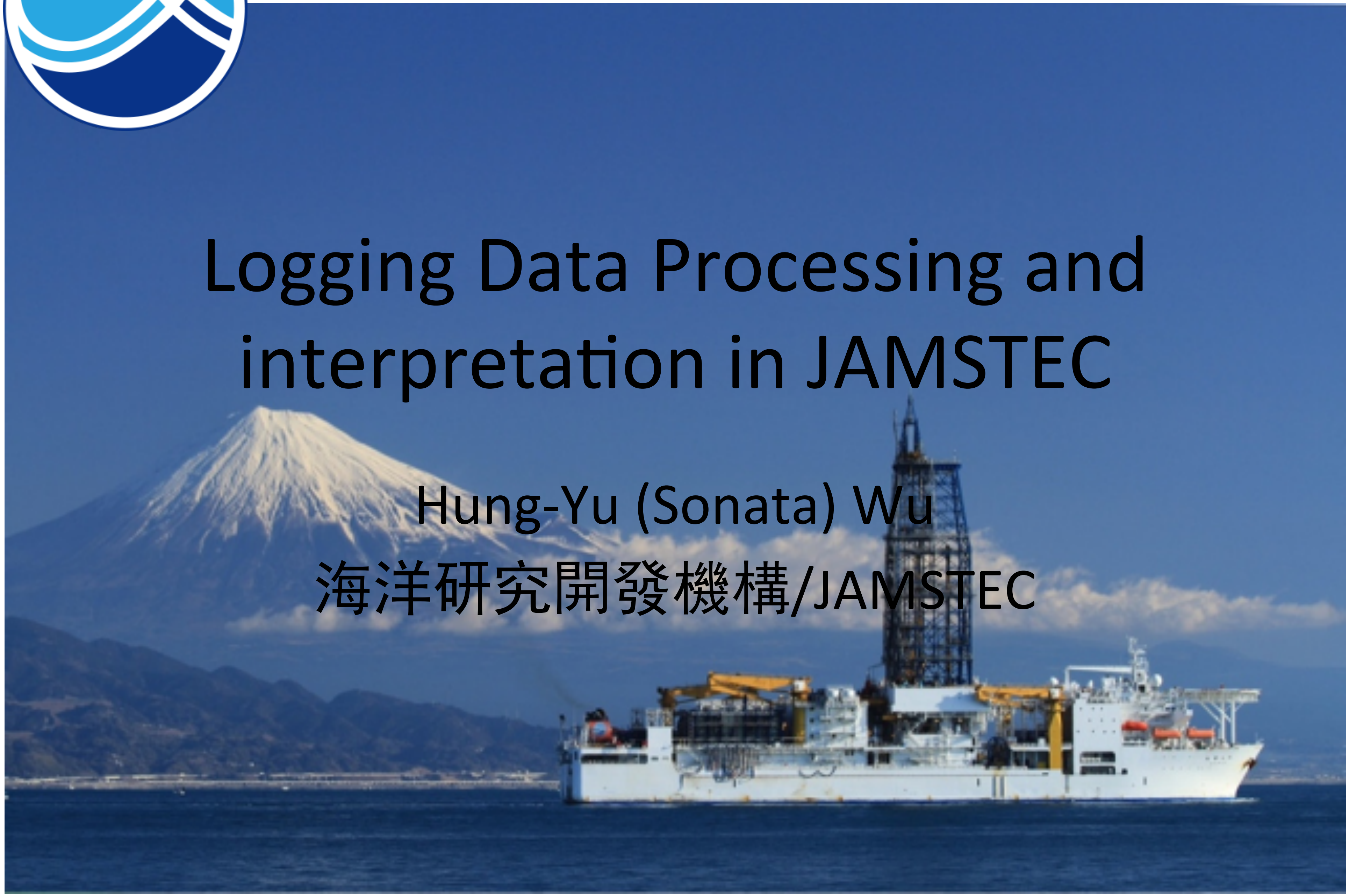
Logging Data Processing and interpretation in JAMSTEC

Hung-Yu (Sonata) Wu
海洋研究開發機構/JAMSTEC



About me

- 2006-2010 National Central Univ. ~PhD
- 2008-2009 Stanford Univ. ~ Visiting Scholar
- 2010-2010 National Central Univ. ~ Postdoc
- 2010-2013 JAMSTEC ~ Postdoc
- 2013-present JAMSTEC ~ Researcher

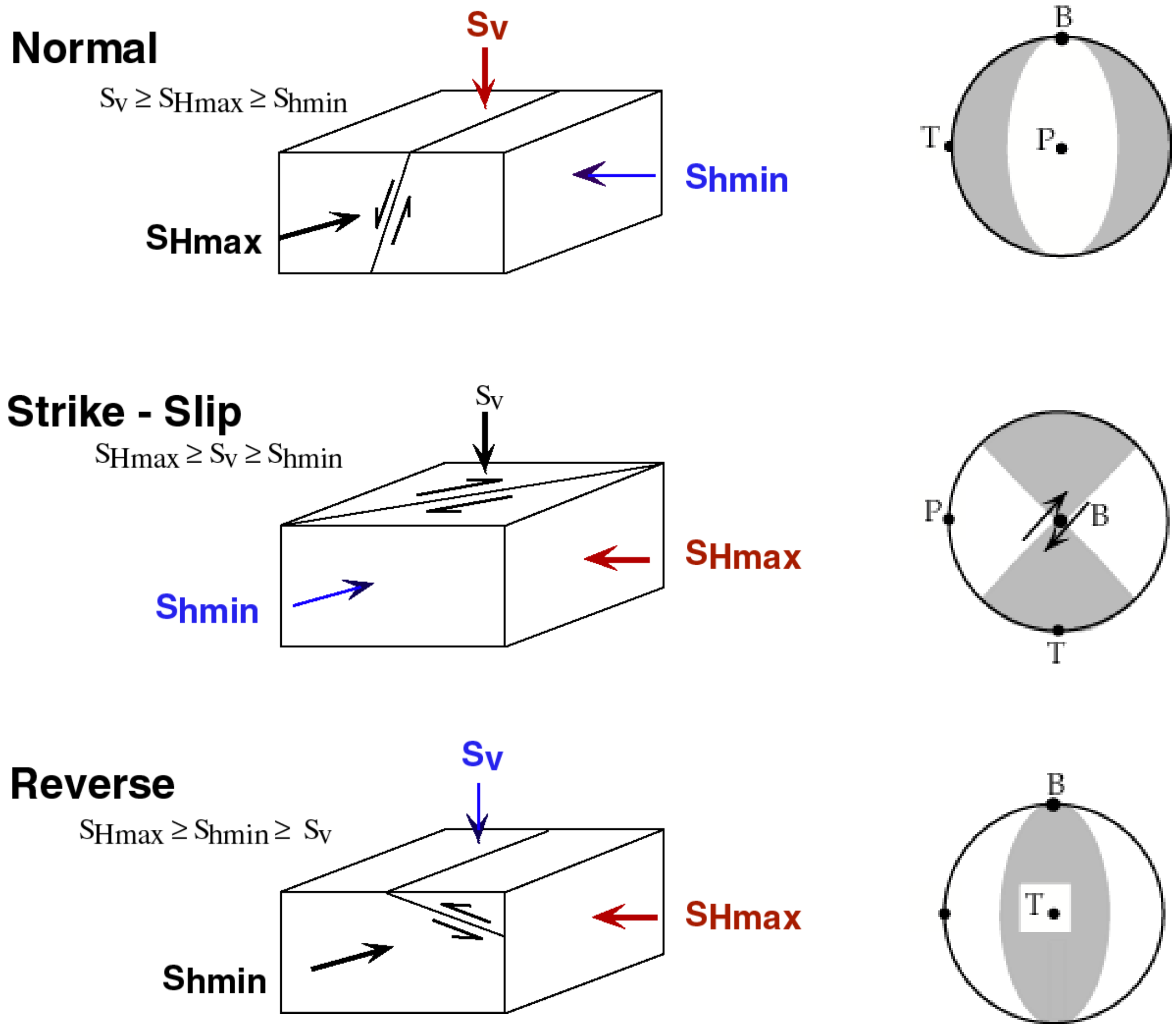
- Working for: Logging data interpretation, Geomechanism model, stress field evaluation, rock experiment, geothermal measurements.

- Participated projects: TCDP, SAFDO, NanTroSEIZE, JFAST, NGHP-2, SIP-2, TGDP

Outline

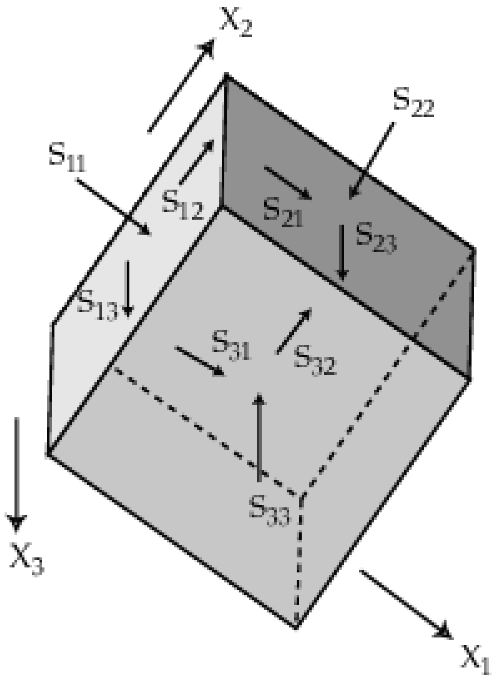
- NanTroSEIZE drilling project (C9, C2, C11, C4)
- Exp.337 Shimokita (CPP)
- JFAST
- SIP2 Okinawa
- NGHP-2, India
- Software reviews
- Summary

Anderson Classification of Relative Stress Magnitude



Zoback, 2007

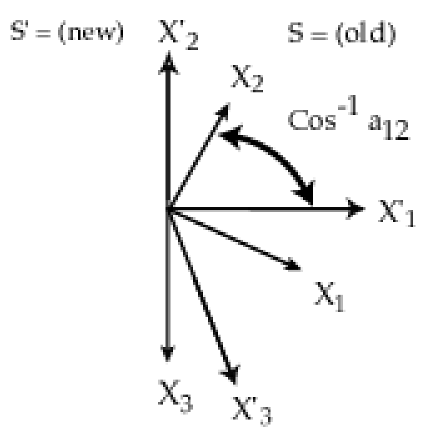
Definition of Stress Tensor
(arbitrary cartesian coordinate system)



$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

Tensor Transformation
(rotation of axes)

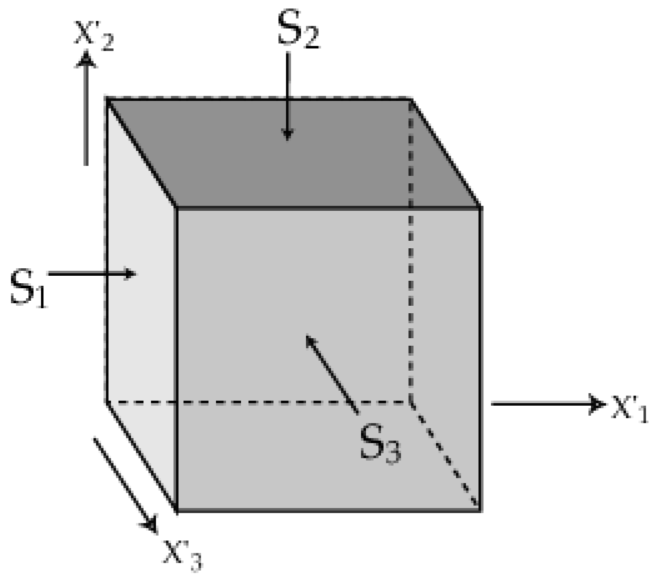
$$S' = A^T \; S \; A$$



$$\begin{array}{cc} \begin{array}{c} S' \\ \text{(new)} \end{array} & \\ A = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix} & \begin{array}{c} S \\ \text{(old)} \end{array} \end{array}$$

Directions Cosines

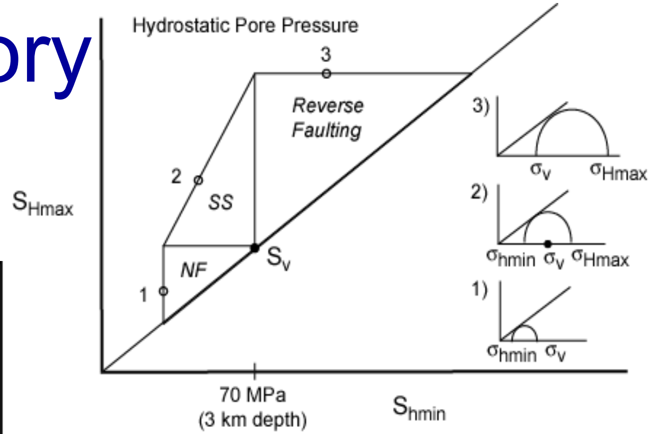
Principal Stress Tensor



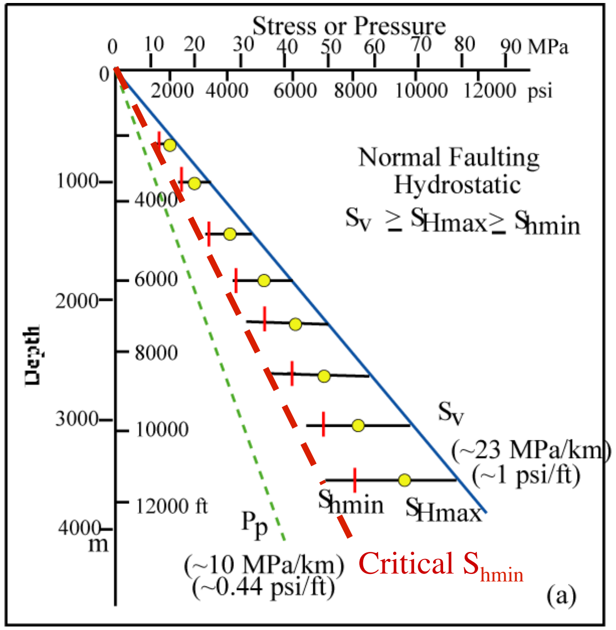
$$S' = \begin{bmatrix} S_1 & 0 & 0 \\ 0 & S_2 & 0 \\ 0 & 0 & S_3 \end{bmatrix}$$

Zoback, 2007

Estimation Stress Magnitudes by friction ~Anderson's faulting theory



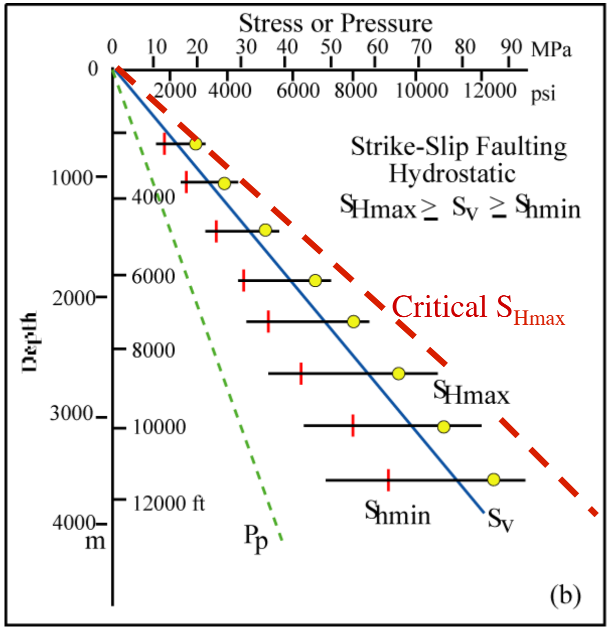
Hydrostatic P_p



$$\frac{S_v - P_p}{S_{h\min} - P_p} = 3.1$$

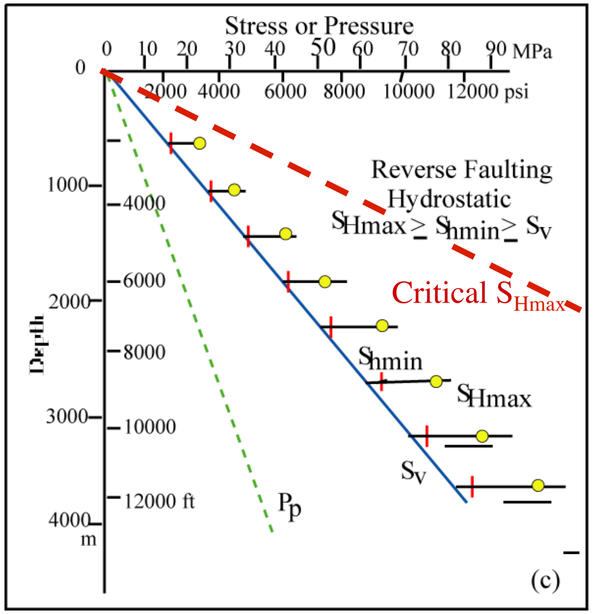
$$S_{h\min} = \frac{S_v - P_p}{3.1} + P_p$$

$$S_{h\min} \approx 0.6 S_v$$



$$\frac{S_{H\max} - P_p}{S_{h\min} - P_p} = 3.1$$

$$S_{H\max} = 3.1\left(S_{h\min} - P_p\right) + P_p$$



$$\frac{S_{H\max} - P_p}{S_v - P_p} = 3.1$$

$$S_{H\max} = 3.1\left(S_v - P_p\right) + P_p$$

$$\frac{\sigma_1}{\sigma_3} = \frac{S_1 - P_p}{S_3 - P_p} = \left[\sqrt{\mu^2 + 1} + \mu\right]^2$$

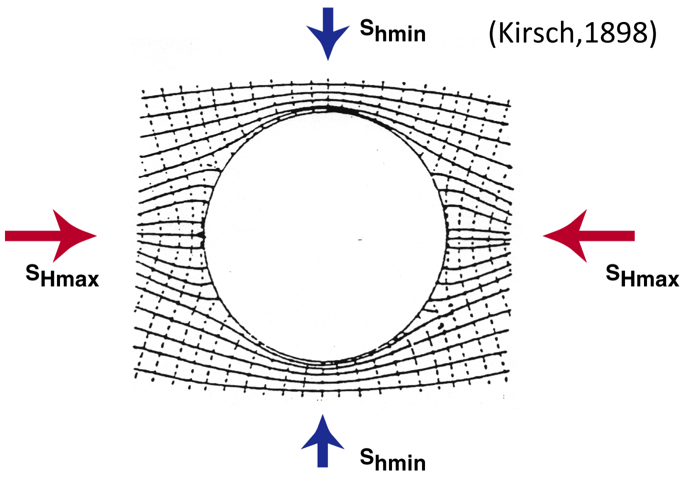
Determine Stress in the homogenous plane

- Stress Orientation:

  Breakout azimuth, tensil

  Caliper diameter

(Kirsch,1898)



$$\sigma_{rr} = \frac{1}{2}(S_{H\max} - S_{h\min} - 2P_0)\left(1 - \frac{R^2}{r^2}\right) + \frac{1}{2}(S_{H\max} - S_{h\min})\left(1 - \frac{4R^2}{r^2} + \frac{3R^4}{r^4}\right)\cos 2\theta + \frac{P_0 R^2}{r^2}$$

- Stress Magnitude

$$\sigma_{\theta\theta} = \frac{1}{2}(S_{H\max} + S_{h\min} - 2P_0)\left(1 + \frac{R^2}{r^2}\right) - \frac{1}{2}(S_{H\max} - S_{h\min})\left(1 + \frac{3R^4}{r^4}\right)\cos 2\theta - \frac{P_0 R^2}{r^2} - \sigma^{\Delta T}$$

$$\sigma_{zz} = S_v - 2\nu(S_{H\max} - S_{h\min})\frac{r^2}{R^2}\cos 2\theta$$

$$\tau_{r\theta} = \frac{1}{2}(S_{H\max} - S_{h\min})\left(1 + \frac{2R^2}{r^2} - \frac{3R^4}{r^4}\right)\sin 2\theta$$

Local stress field perturbed due to the borehole

Hoop Stress around Borehole wall

$$\sigma_{\theta\theta} = S_{h\min} + S_{HMAX} - 2(S_{HMAX} - S_{h\min})\cos 2\theta - 2P_0 - \Delta P - \sigma^{\Delta T}$$

- At the point of minimum compression around the wellbore (i.e, at $\theta = 0$, parallel to S_{Hmax}), Equations reduces to
- $\sigma_{\theta\theta}^{min} = 3S_{hmin} - S_{Hmax} - 2P_0 - \Delta P - \sigma^{\Delta T}$
- Whereas, at the point of maximum stress concentration around the wellbore (i.e, at $\theta = 90°$, parallel to S_{hmin}),
- $\sigma_{\theta\theta}^{max} = 3S_{Hmax} - S_{hmin} - 2P_0 - \Delta P - \sigma^{\Delta T}$

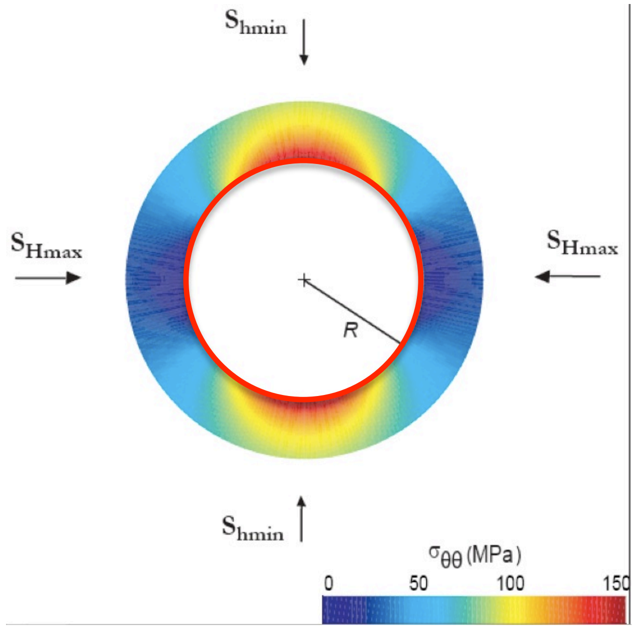
- $\sigma_{\theta\theta}^{max} - \sigma_{\theta\theta}^{min} = 4\,(S_{Hmax} - S_{hmin})$

- In general,

  Pore pressure = hydrostatic

  ΔP measured by MDT

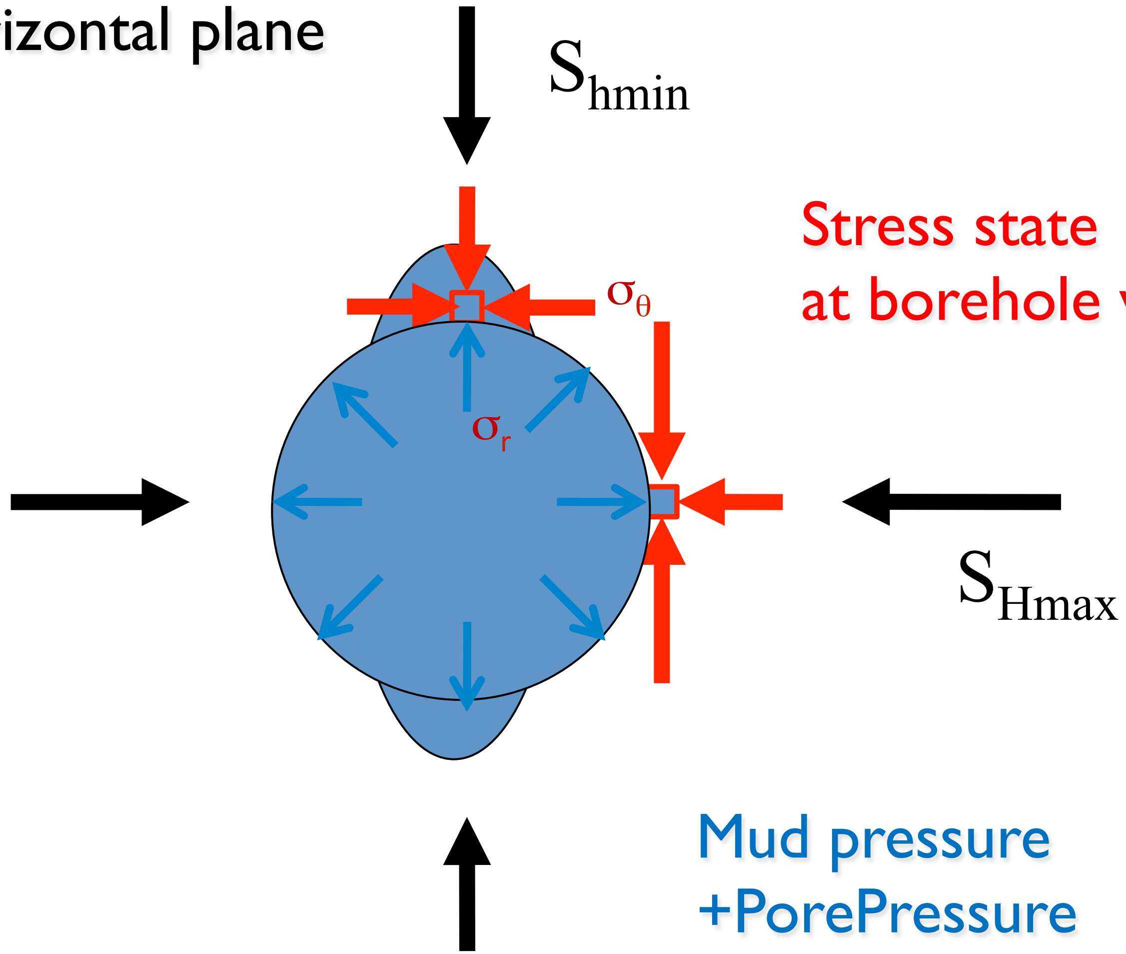
  $\sigma_{\theta\theta}$? Why Rock Strength?



What is breakouts?

Far field stress in horizontal plane

- •Before drilling
- •After drilling

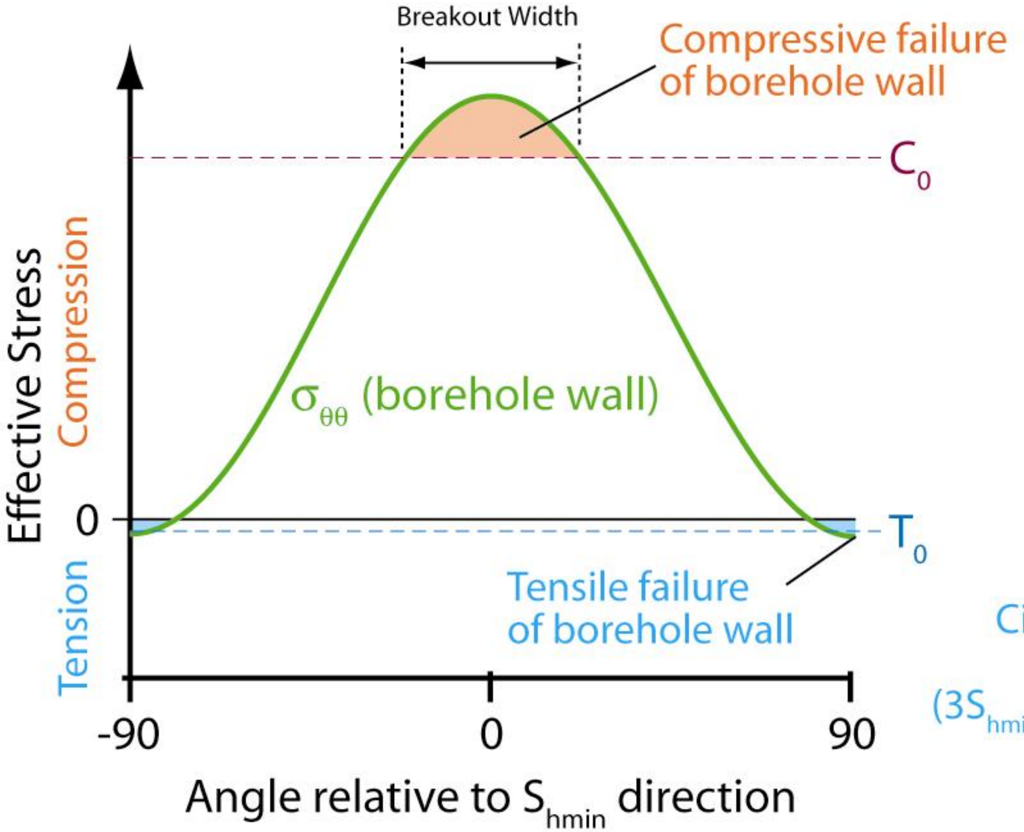


If $\sigma_{\theta\ max}$>compressive strength, compressive failure occurs

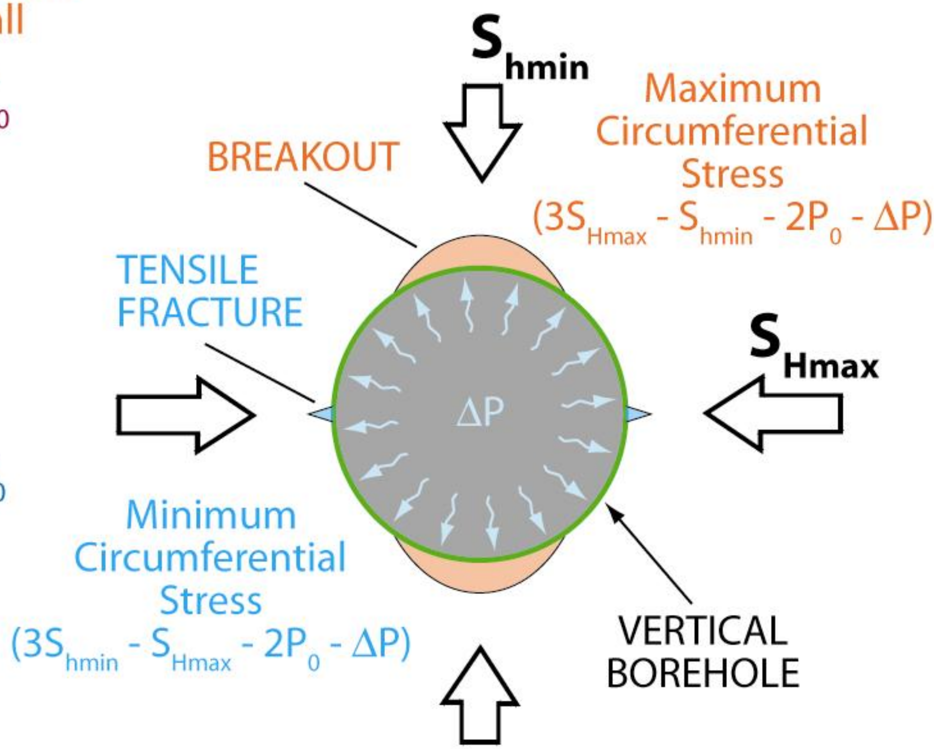
Stress induced compressive failure = Breakout

Geomechanical model
Stress observation from borehole failure

Stress Concentration At Borehole Wall

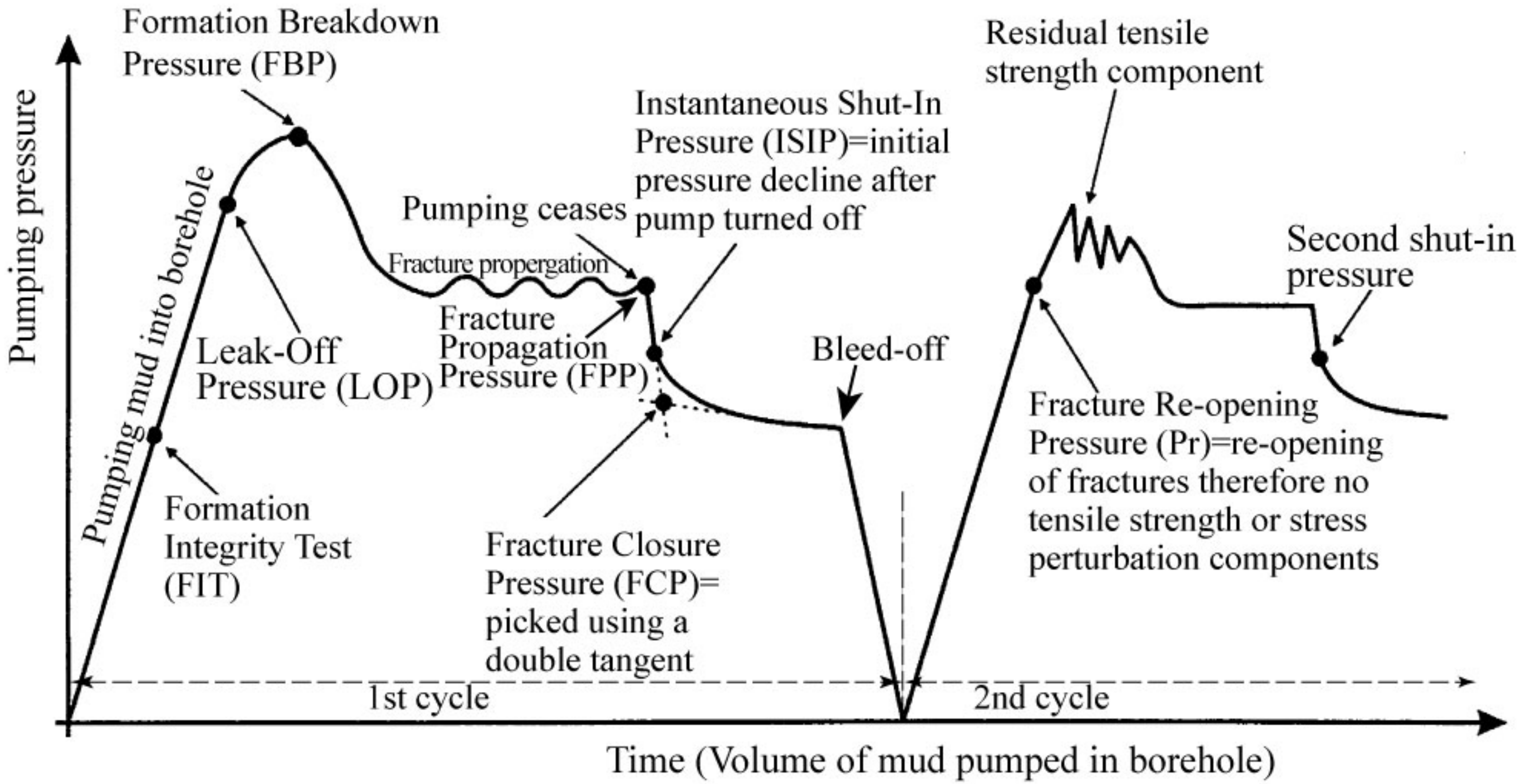


Borehole Structures & Stress
(Vertical Borehole)



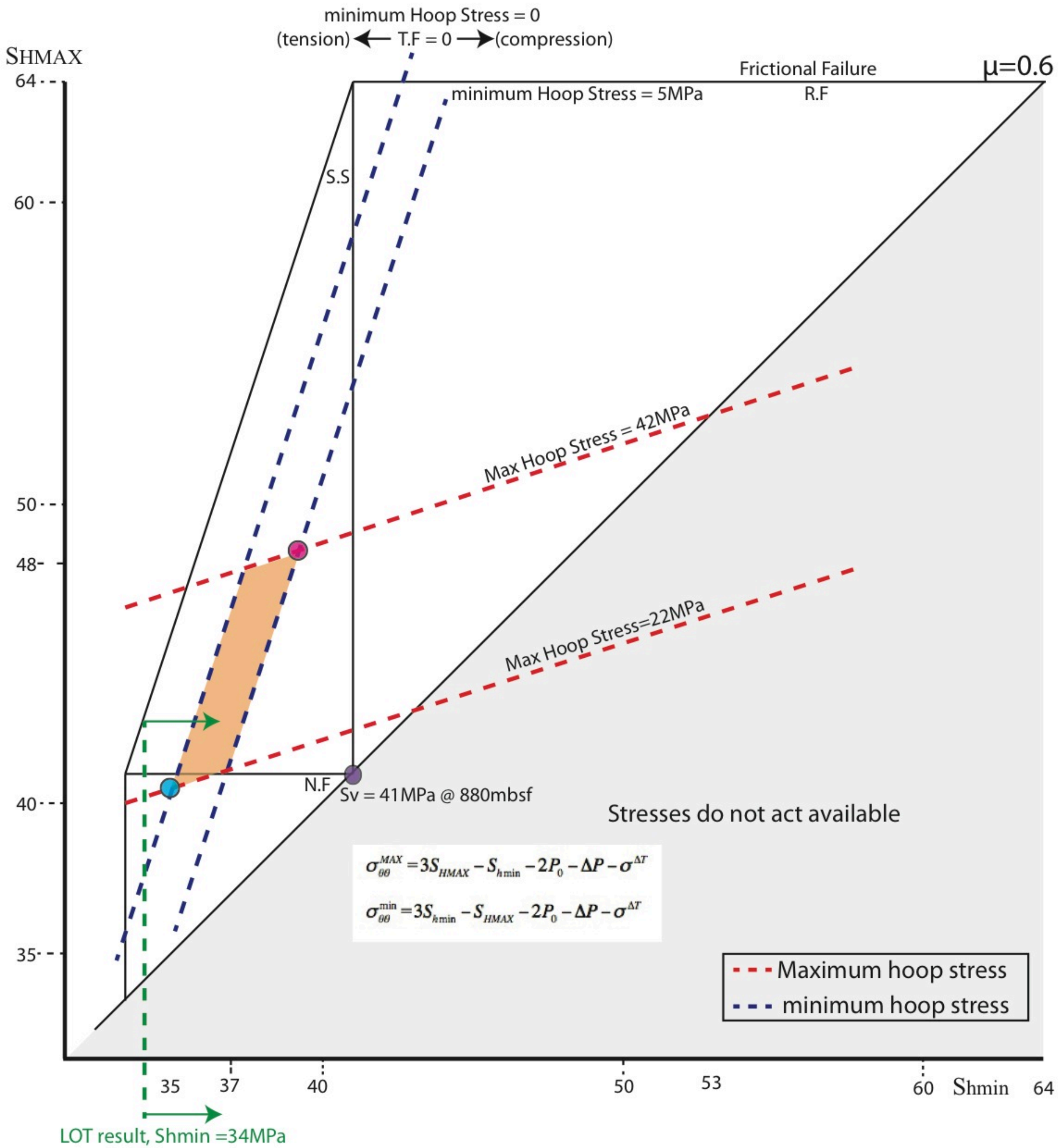
From N.C. Davatzes

MDT (Leak-off tests)

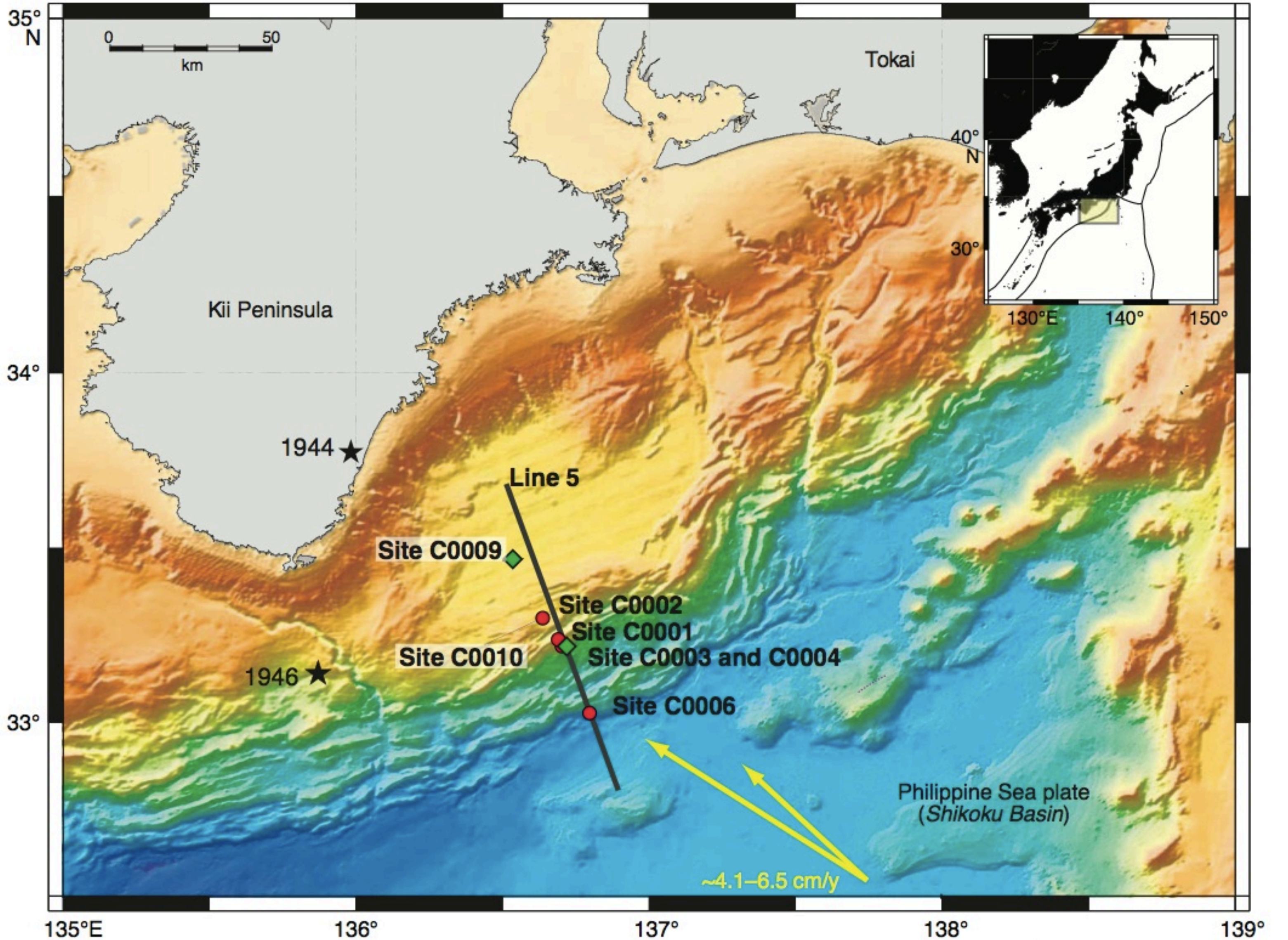


(after White et al., 2002)

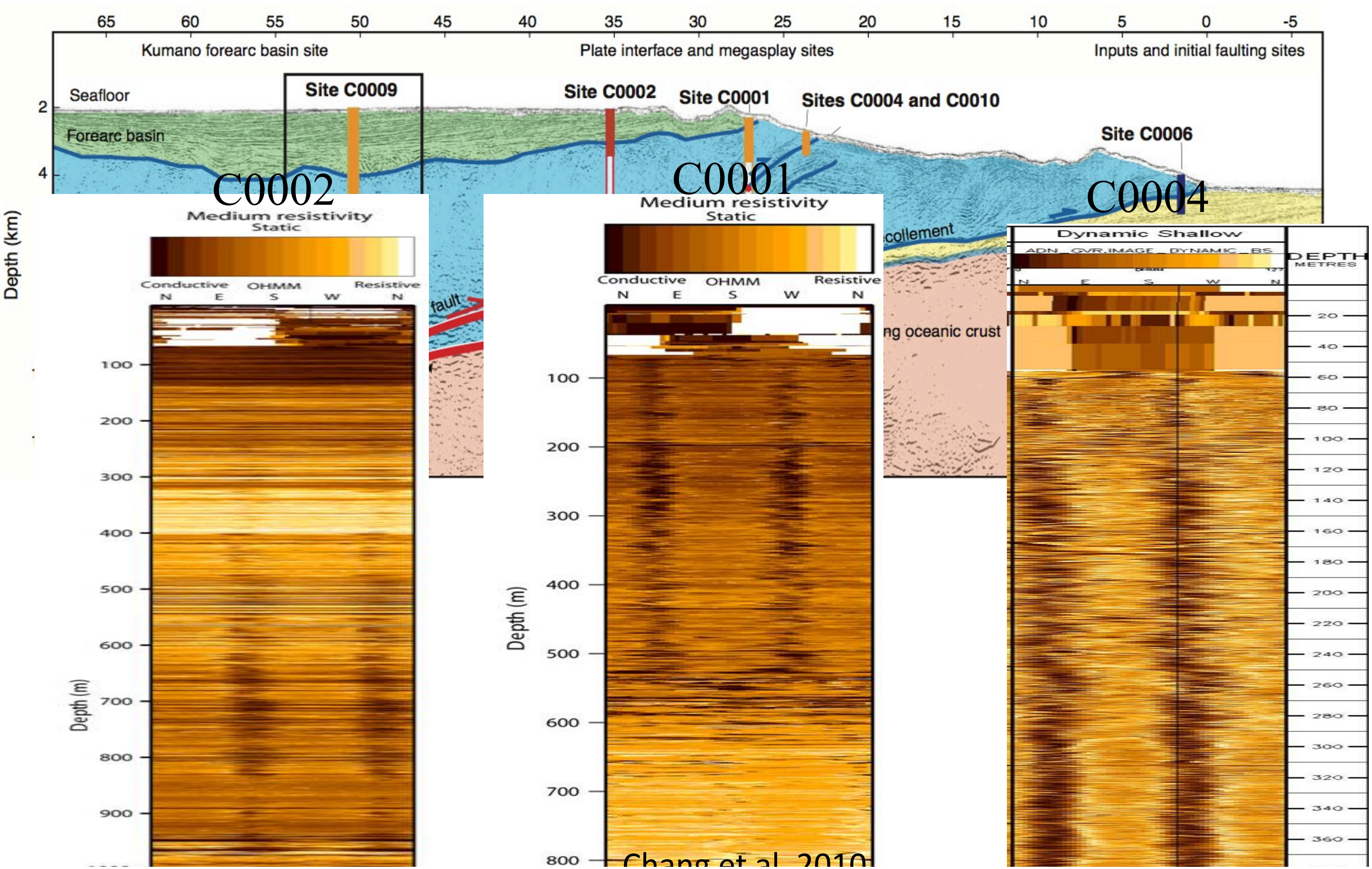
Stress polygon



Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE)



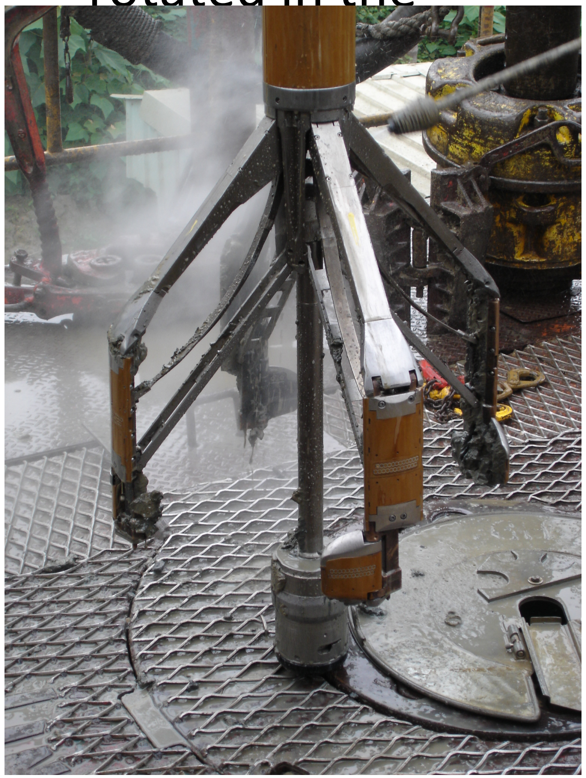
LWD IMAGES in NanTroSEIZE

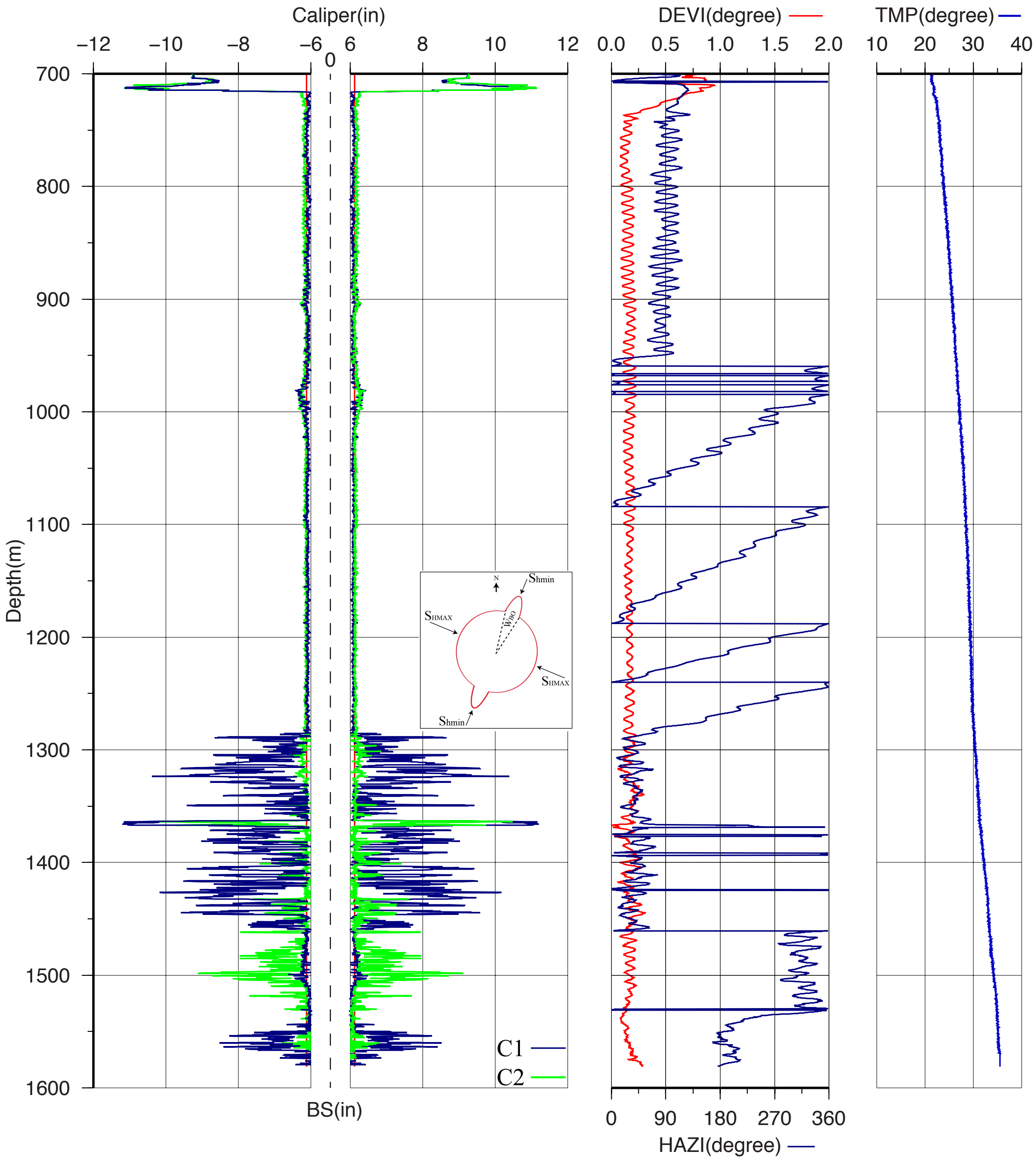


Borehole Condition ~ caliper

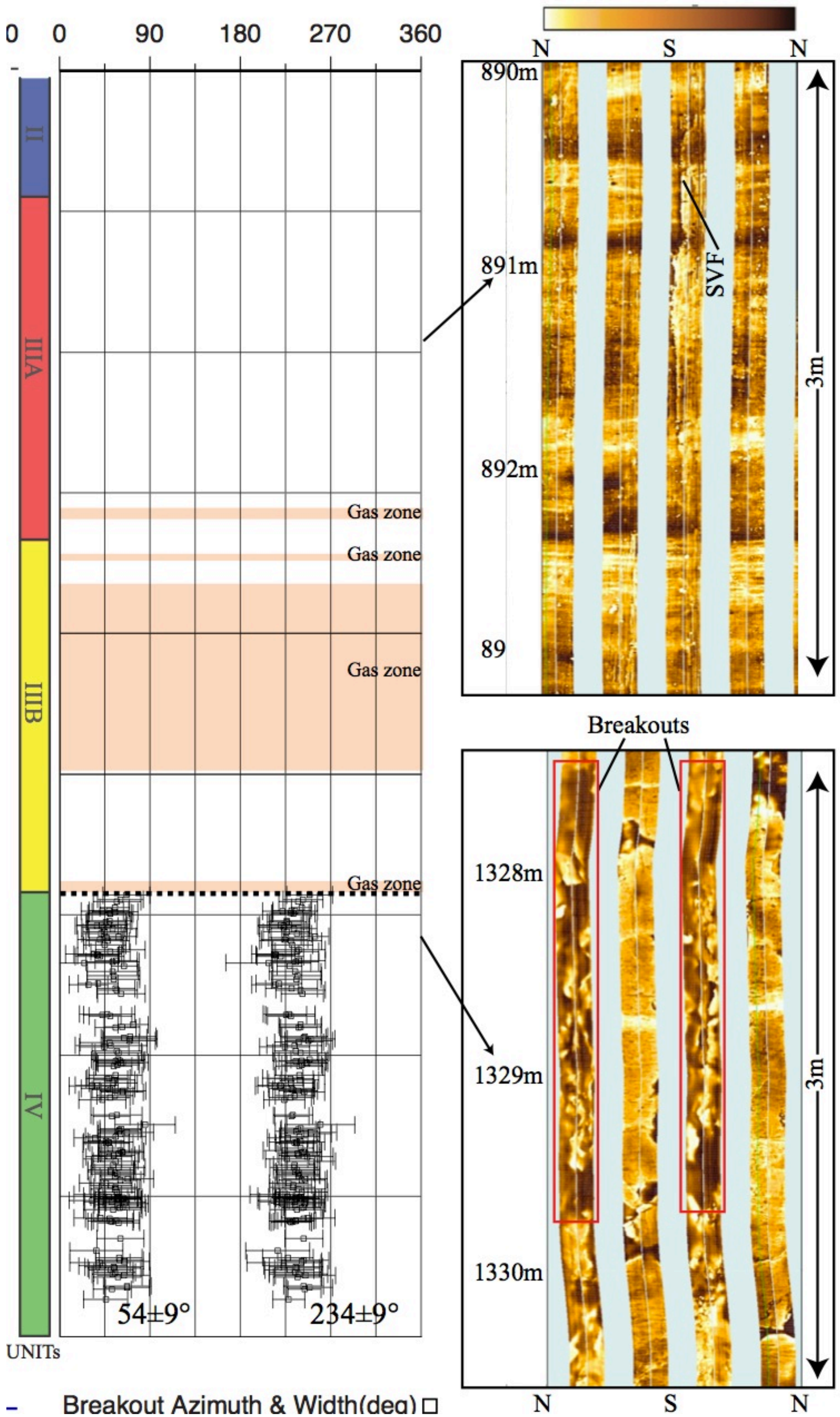
Breakout & Tensile Fractures

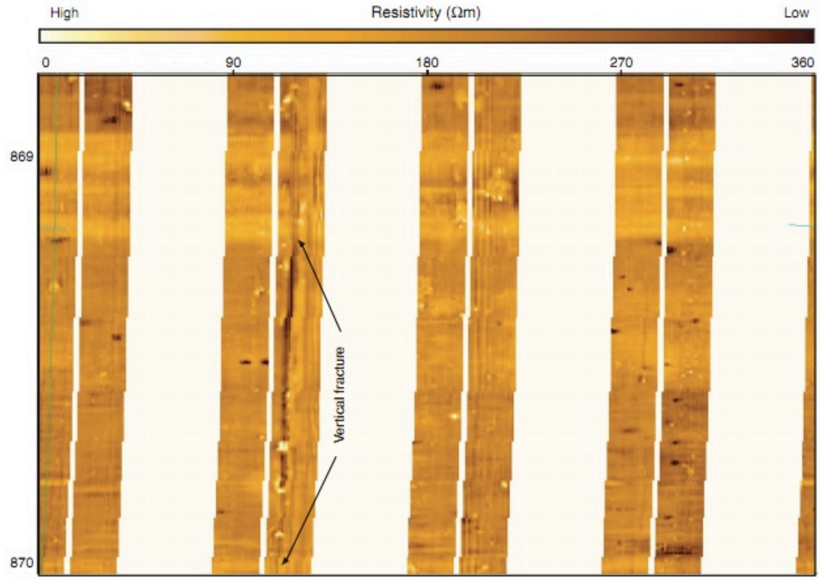
- The caliper data show the well-round circle fit the bit size(No failure)
- No breakout above depth 1285 mbsf
- FMI Tool is free rotated in the



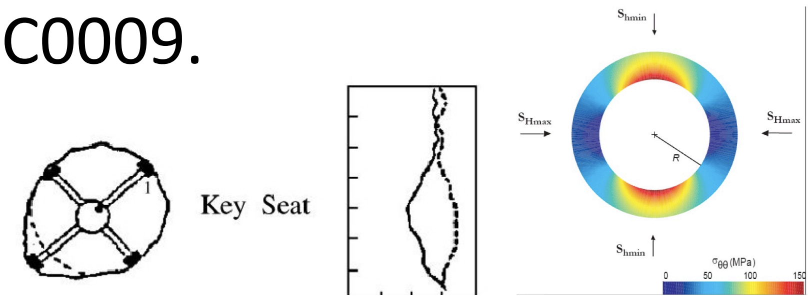


Breakout & SVF Azimuth



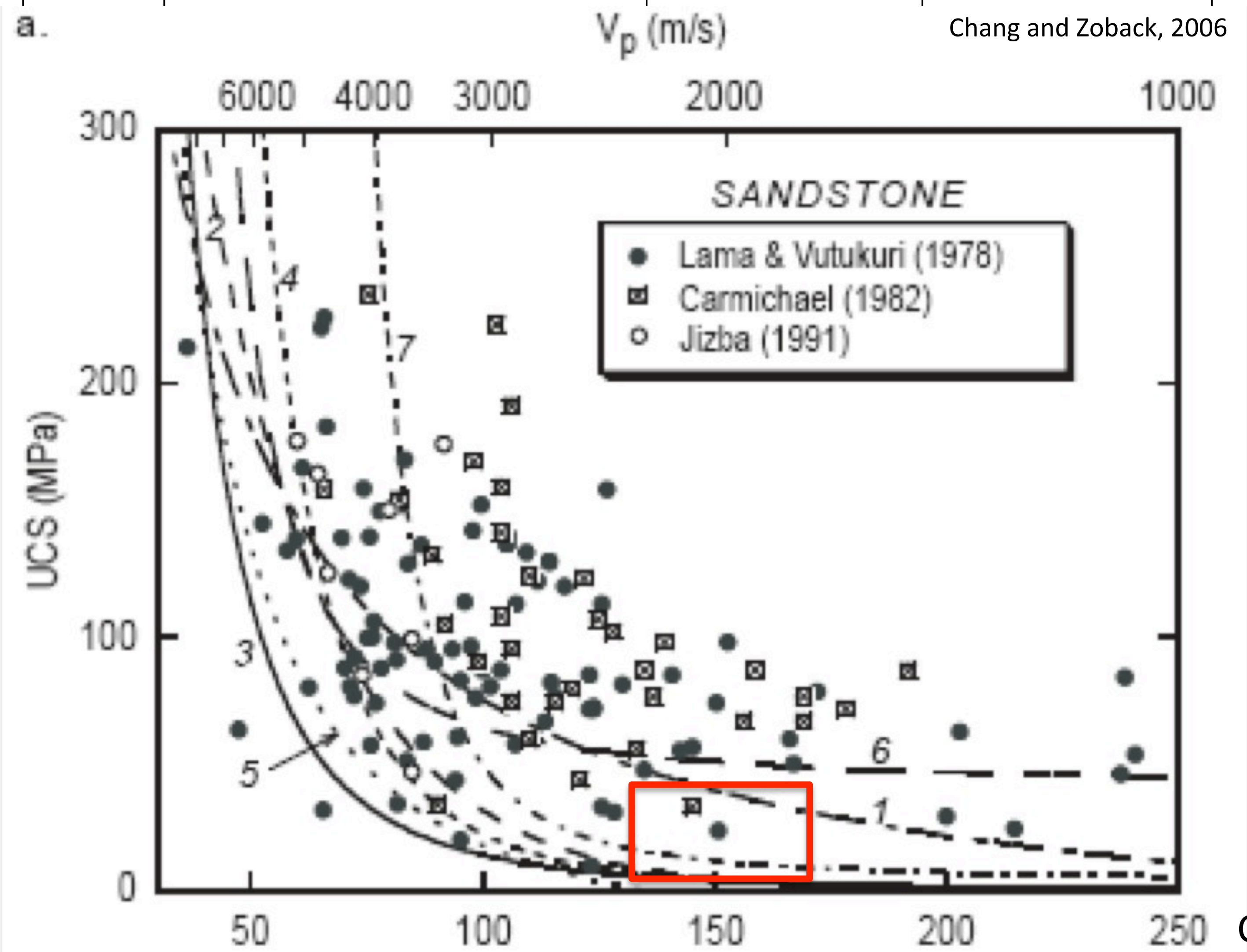


- Single vertical fracture (SVF)does not represent the direction of S_{HMAX}.
- No pair, 180°-apart tensile fractures found in Site C0009.



Empirical Function for Sandstone

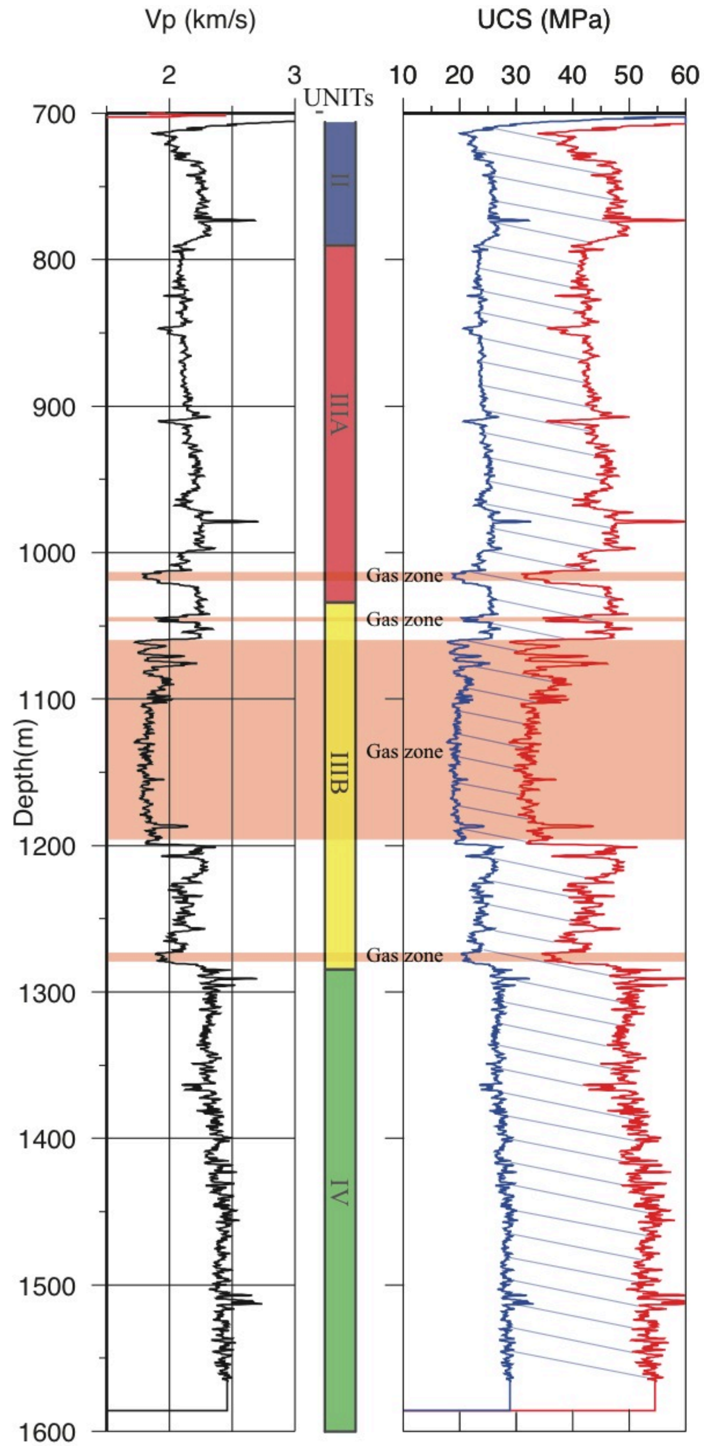
Eq. No.	UCS, MPa	Region Where Developed	General Comments	Reference
1	$0.035 V_p - 31.5$	Thuringia, Germany	-	(Freyburg 1972)
				IcNally 1987)
				npublished
				'jaer, Holt et al. 1992)
				Ioos, Zoback et al. 1999)
				npublished
				npublished
				npublished
				'ernik, Bruno et al. 1993)
				npublished



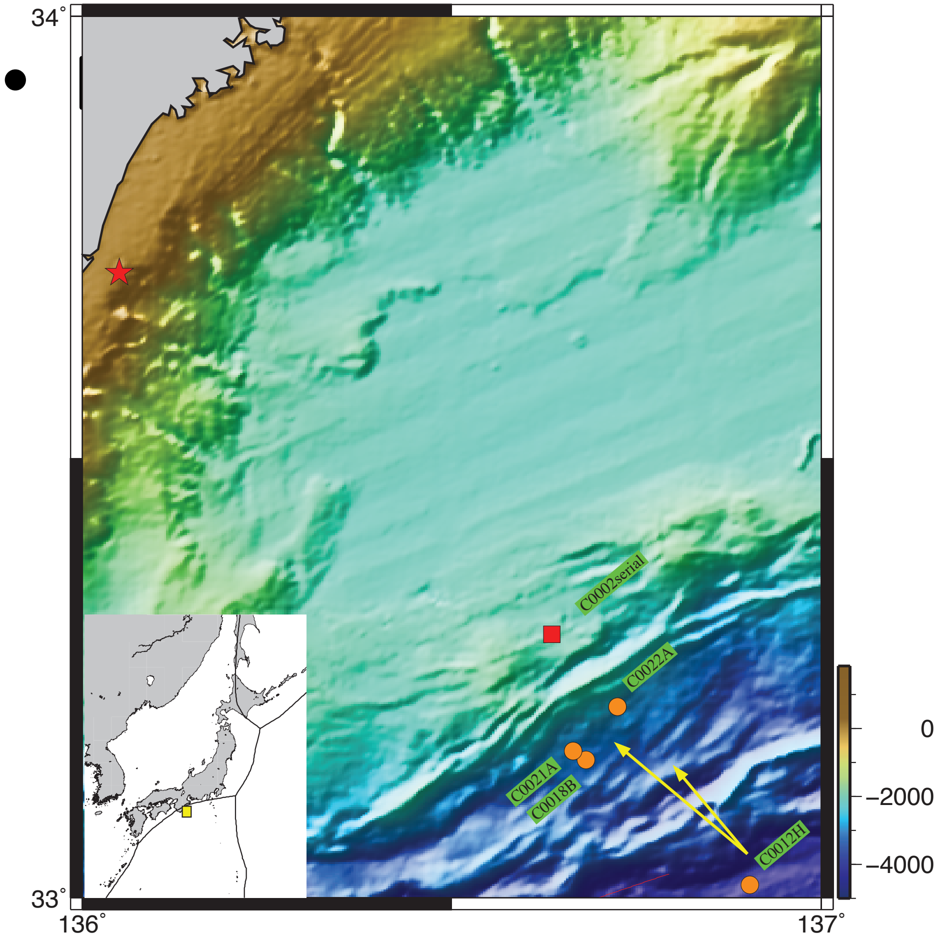
Chang and Zoback, 2006

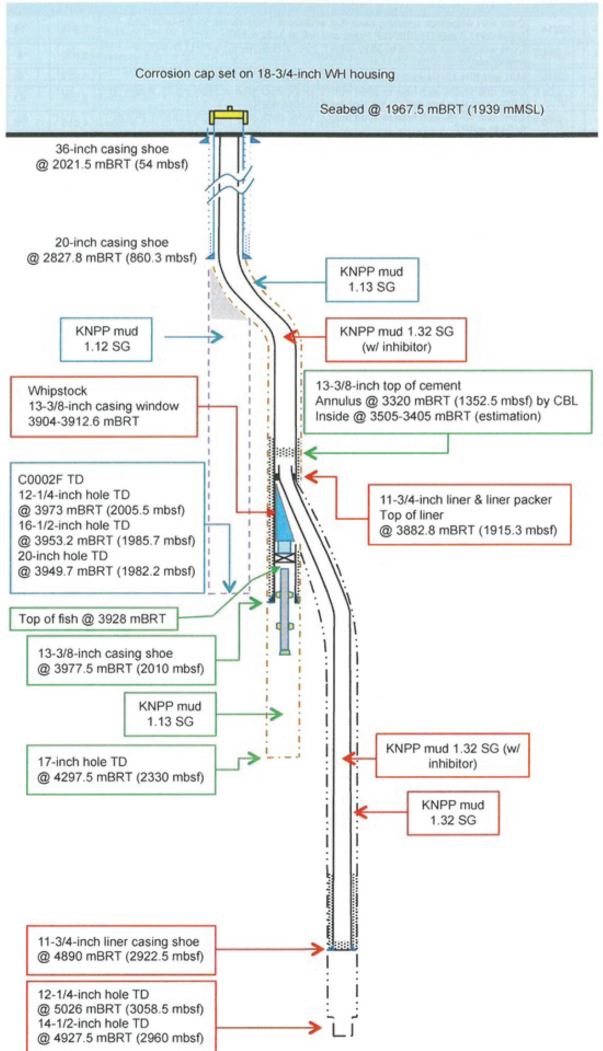
Estimated Rock strength

- P-wave and S-Wave velocities are slightly increasing with depth.
- P-wave velocity is sharp decreasing in the Gas zones.
- The high velocities below 1285 mbsf present the high rock strength in accretionary prism.
- The strength of rock is between 20Mpa to 60Mpa.



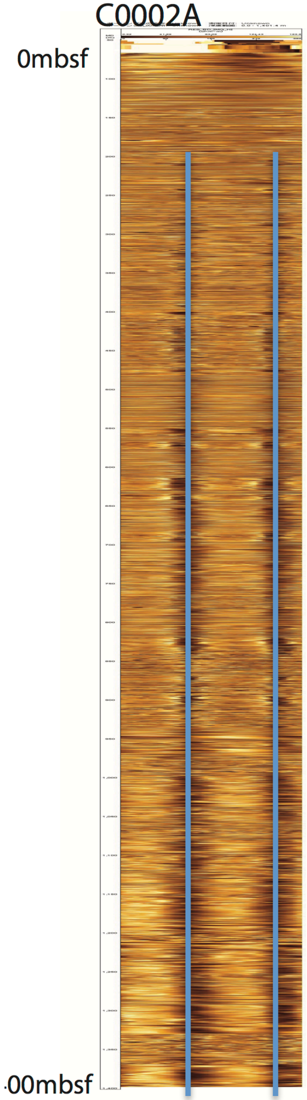
Site C2



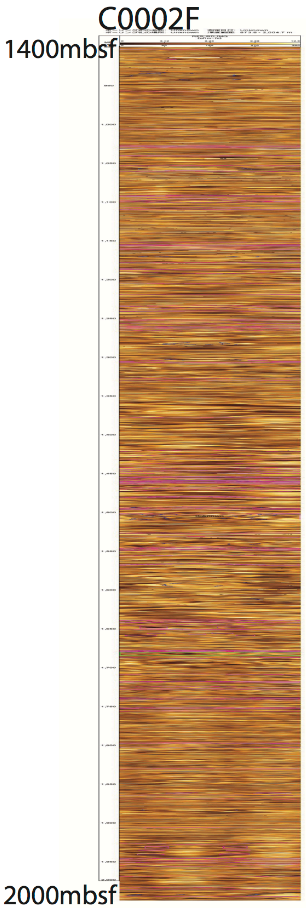


From CDEX Drilling Complietion Report

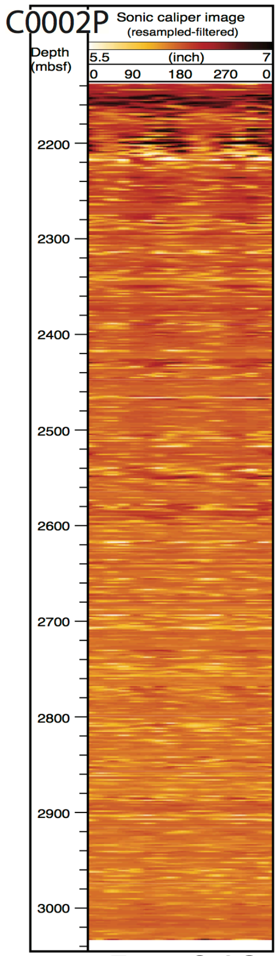
LWD images in C2 A,F and P



Exp:319



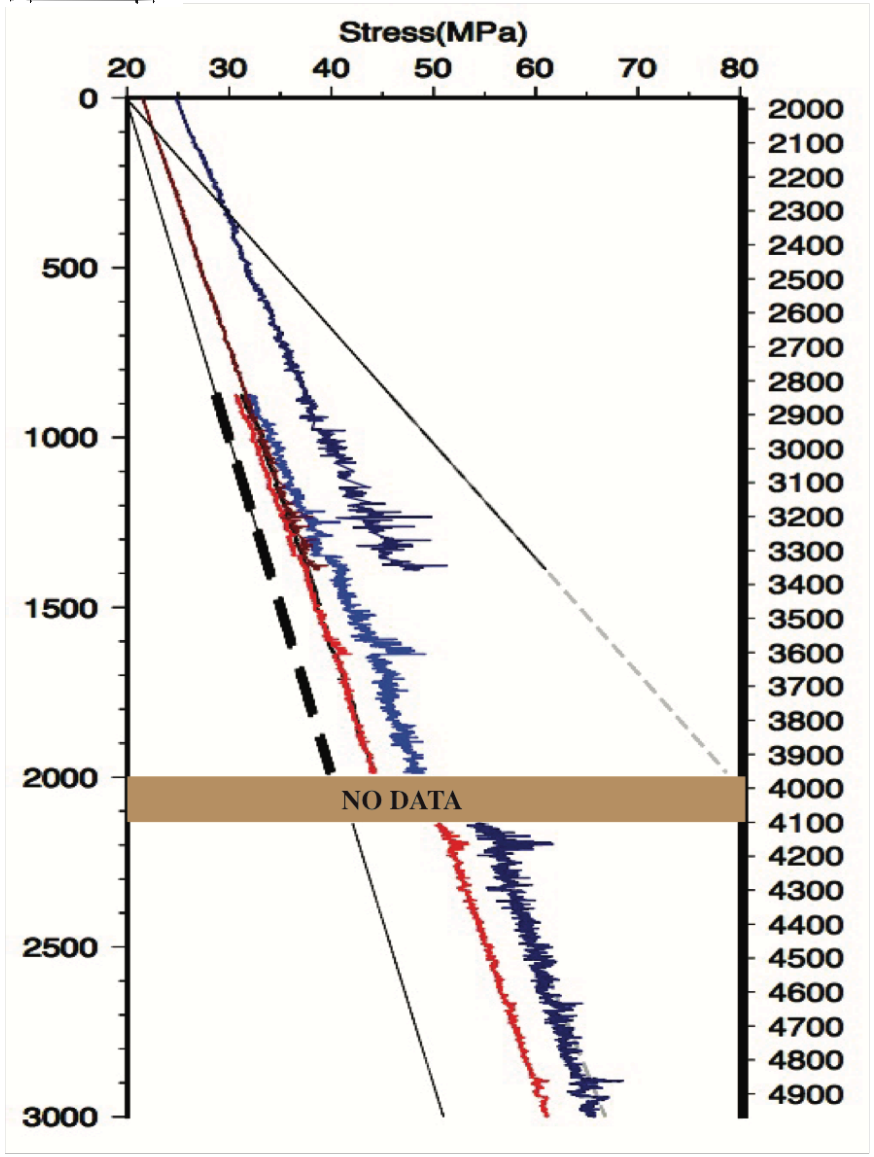
Exp:338

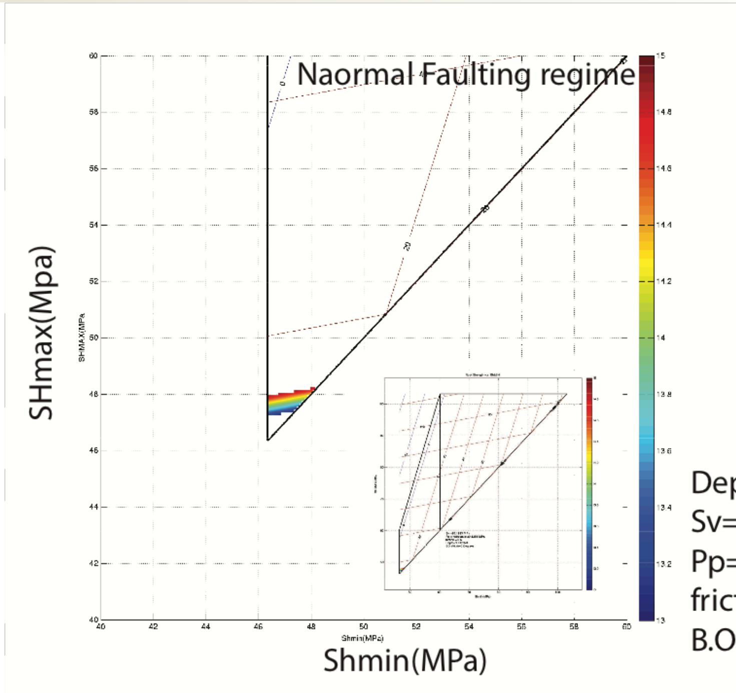


Exp:348

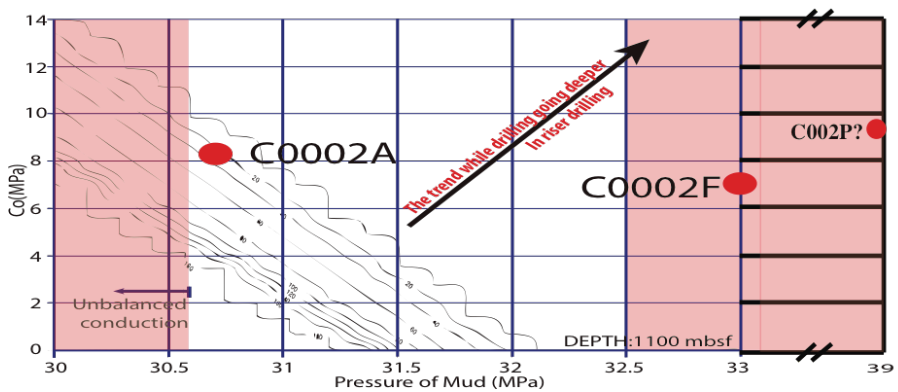
- C2A image showed the consistent borehole breakout azimuth. No tensile fractures recorded.
- C2F images indicated the no failure borehole state during the drilling. However, the drill difficulties took place in the bottom of this borehole (3.5km).
- C2P drilled in the very critical state. Few breakouts showed in the top of images. The drill difficulties happened in the bottom (5kmbsl)

Stress Profile

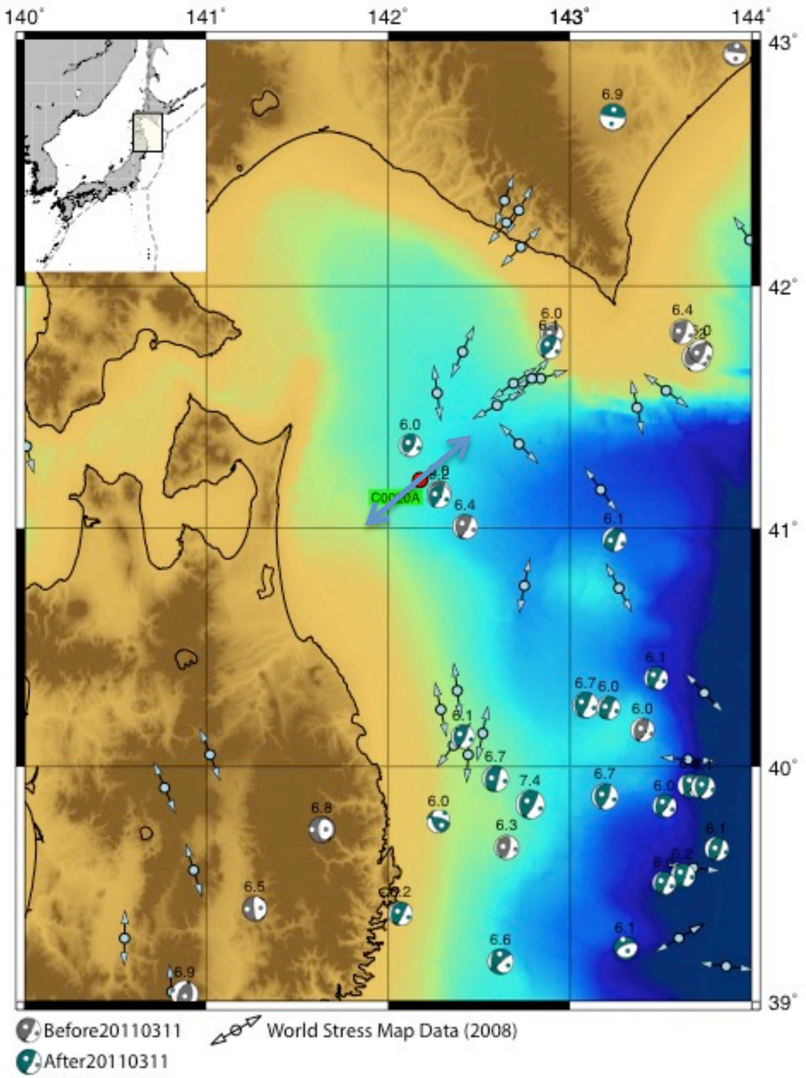




Depth=1.9mbsf
Sv=60.17MPa
Pp=39.84MPa
friction=0.6
B.O width =0

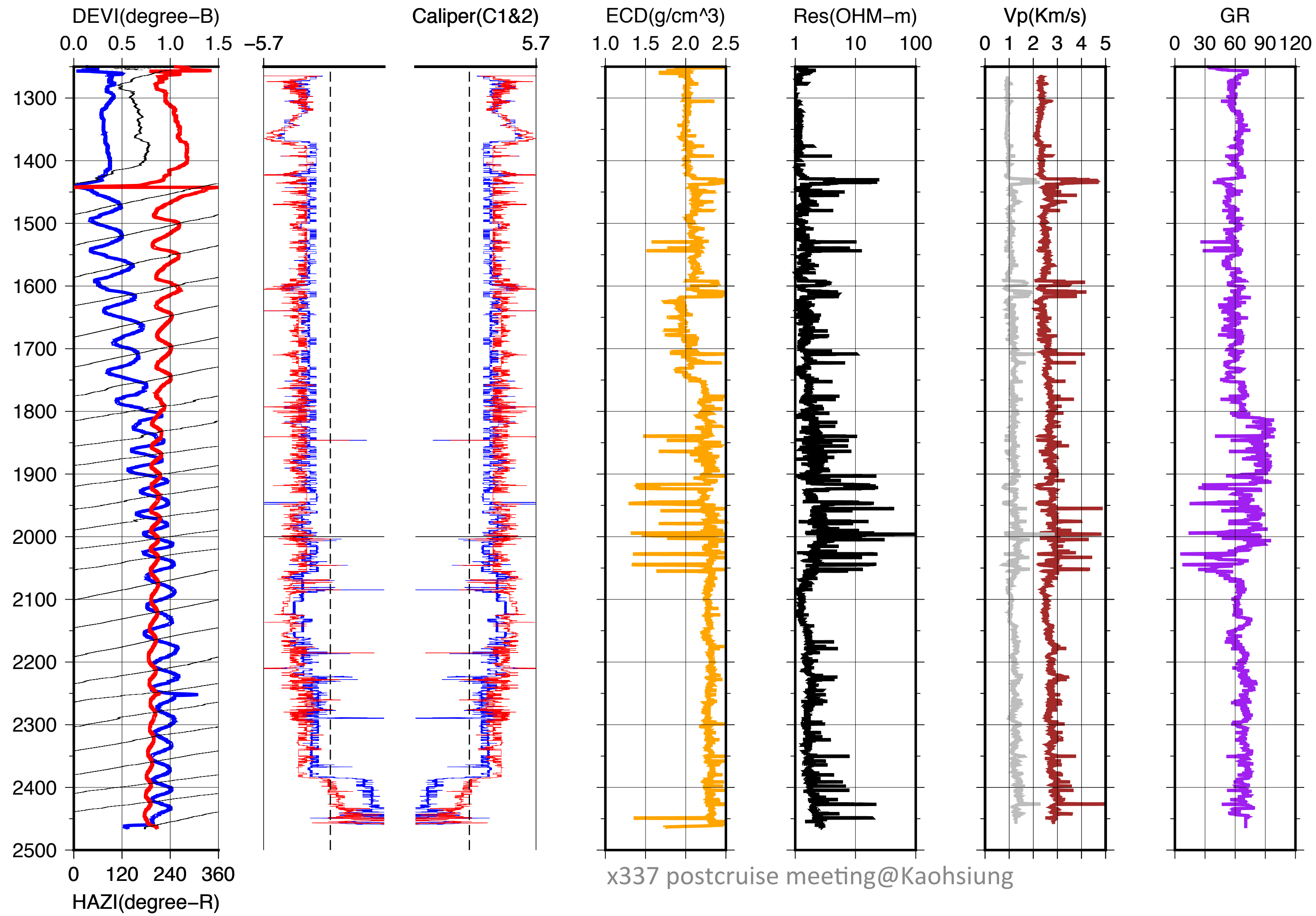


X337 C0020A Site Map



- Drilling depth: 1252~2461.4mbsf
- Focal mechanism indicated that the main stress direction is driven by the plate movement.
- World stress map(2008) showed the S_{HMAX} would vary in some events.
- However, the events near the drill site show the same trend of stress mechanism from 1999~2015.

Logging data & borehole conditions



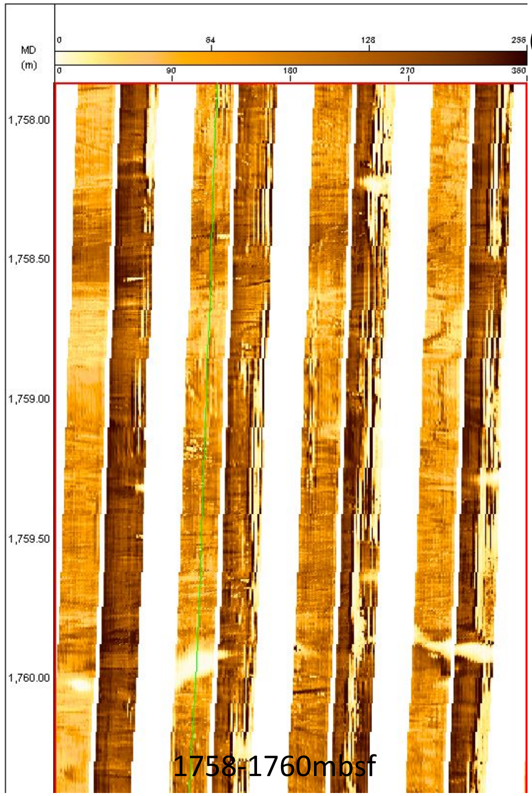
1.Logging of DEVI and HAZI, P1AZ displayed the good rotation of the tool and full cover of the borehole wall .

2. Caliper data shows enlargement in the borehole in all section but bottom of the hole.

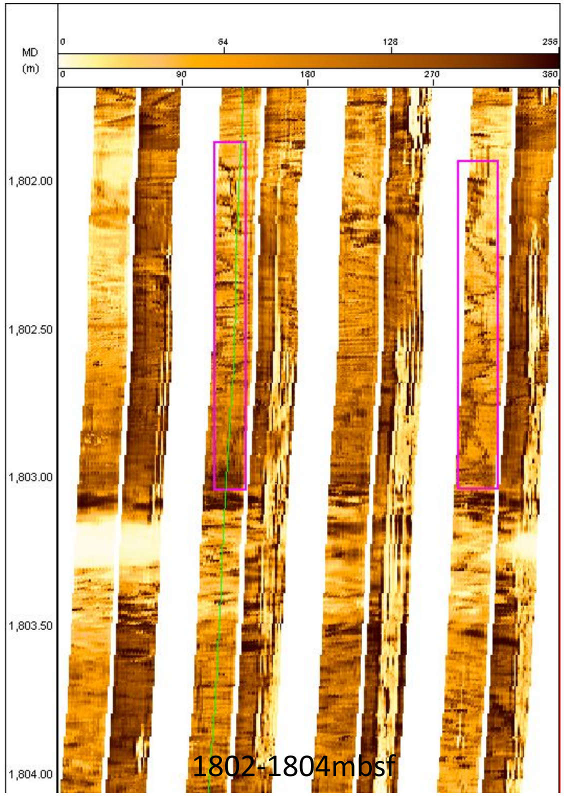
3.Density, resistivity, velocity and GR-ray are corresponded to each other well during 1900~2100mbsf

Breakout forming

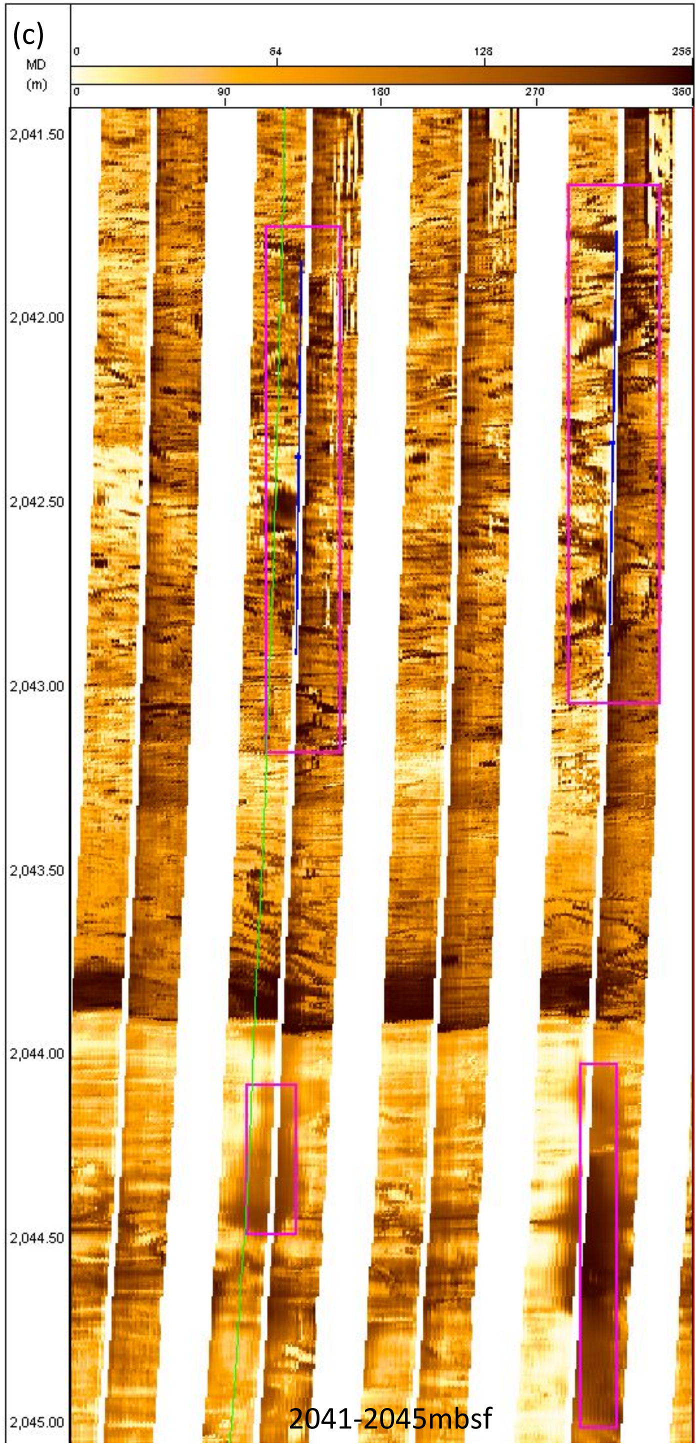
(a)



(b)

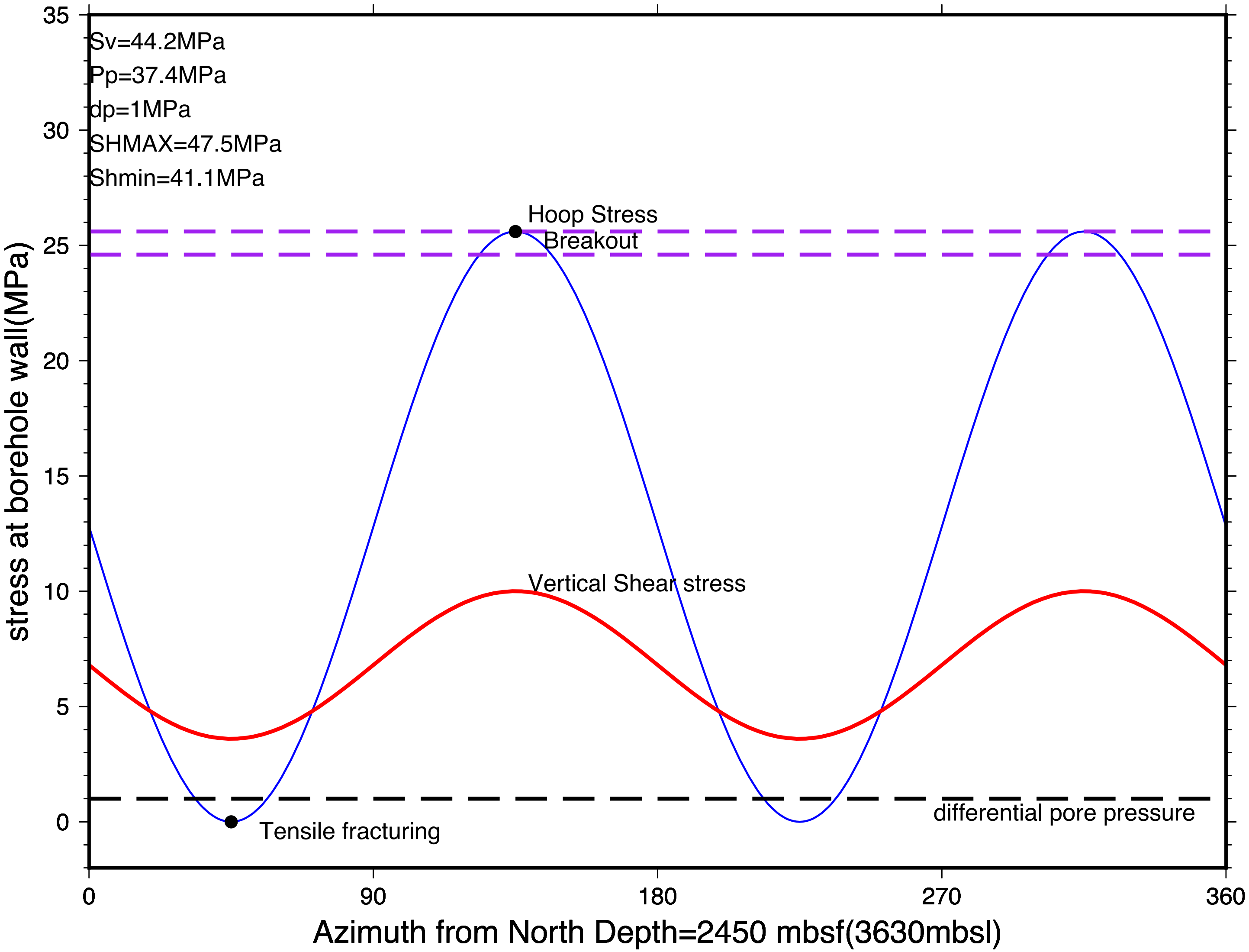


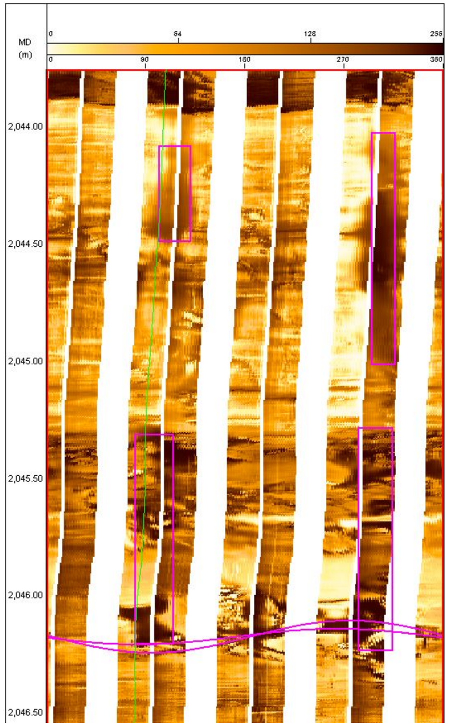
(c)

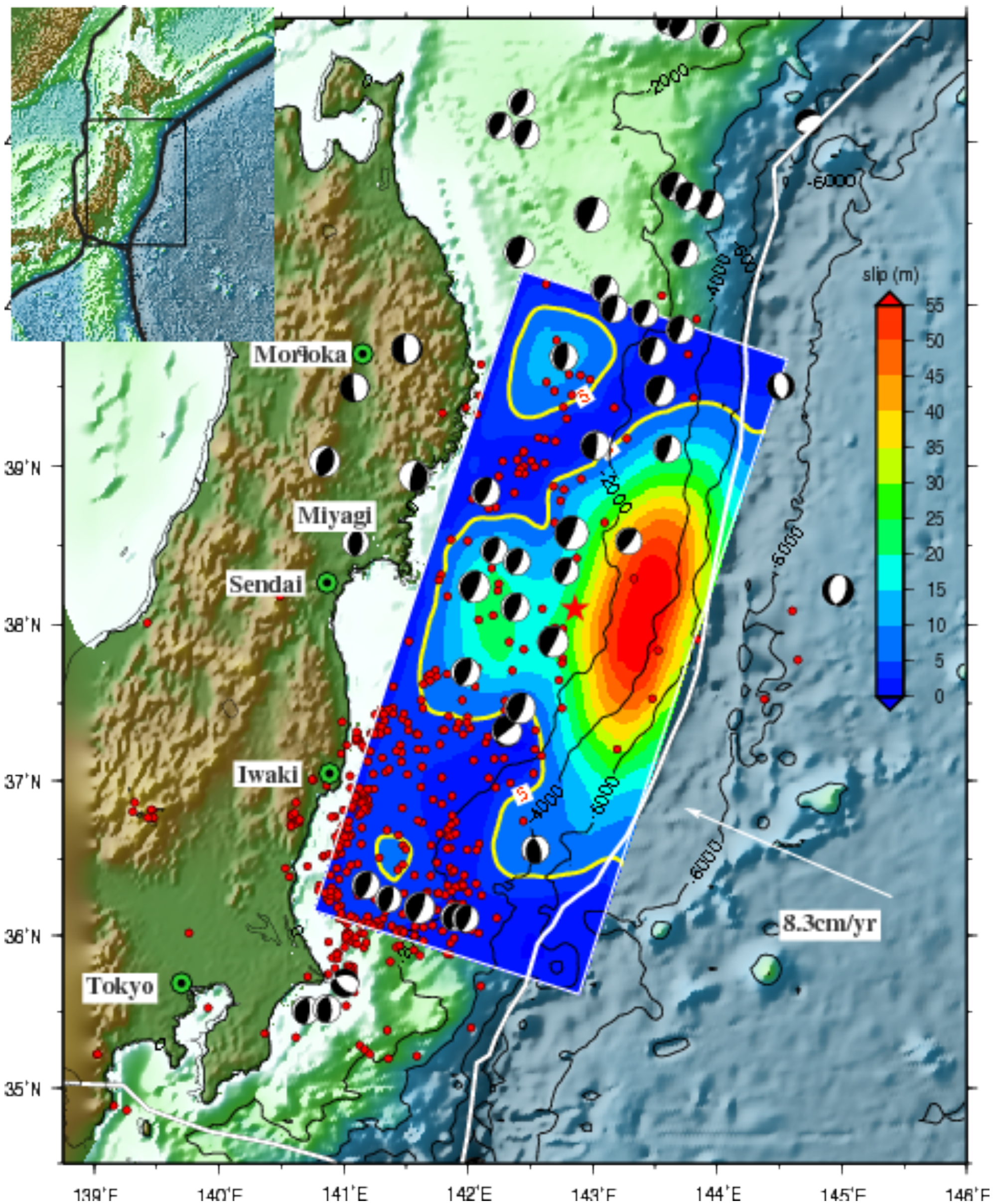


- It is an amazing example to show the evolution of breakout forming. B.O is forming from crack with shear fracturing, deepening fractures and collapsing.
- It may be the first time to find the evidence of breakout forming processes.

Hoop stress around the borehole







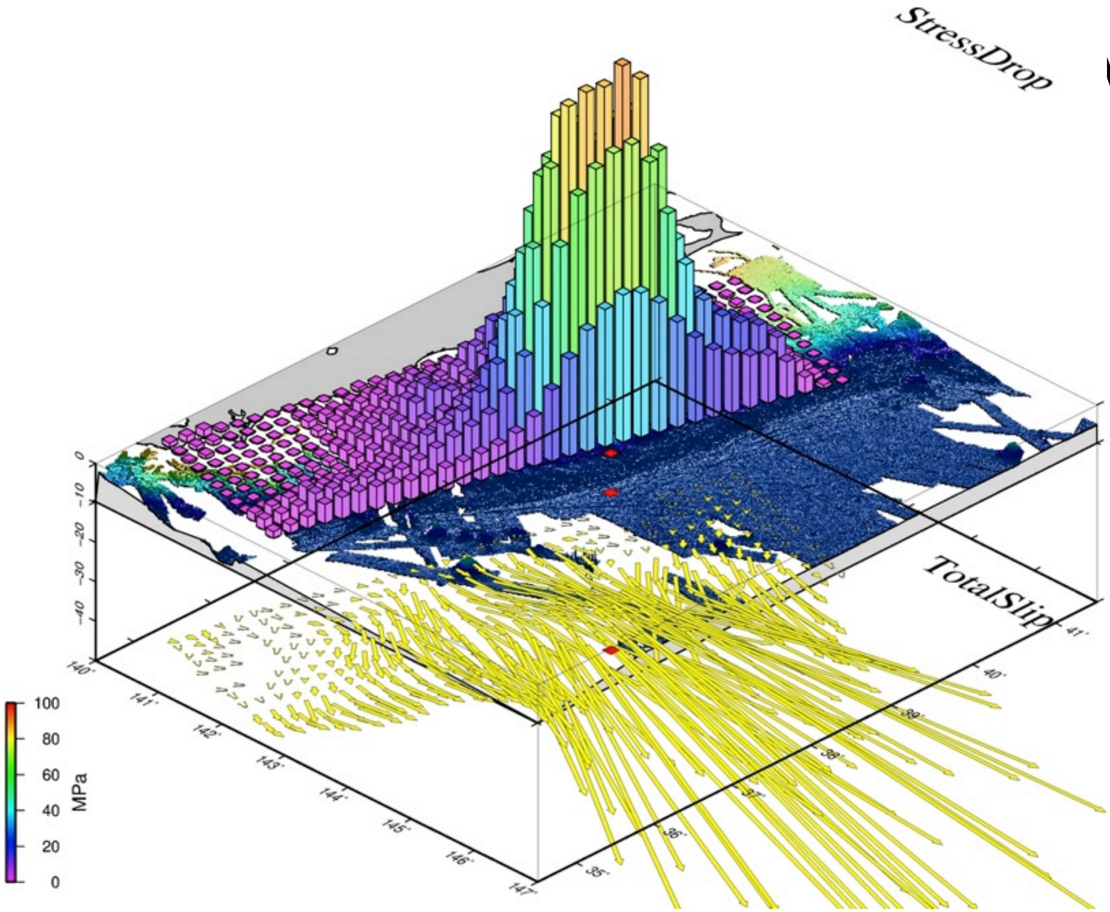
Seismogenic Zone Challenges ~ JFAST

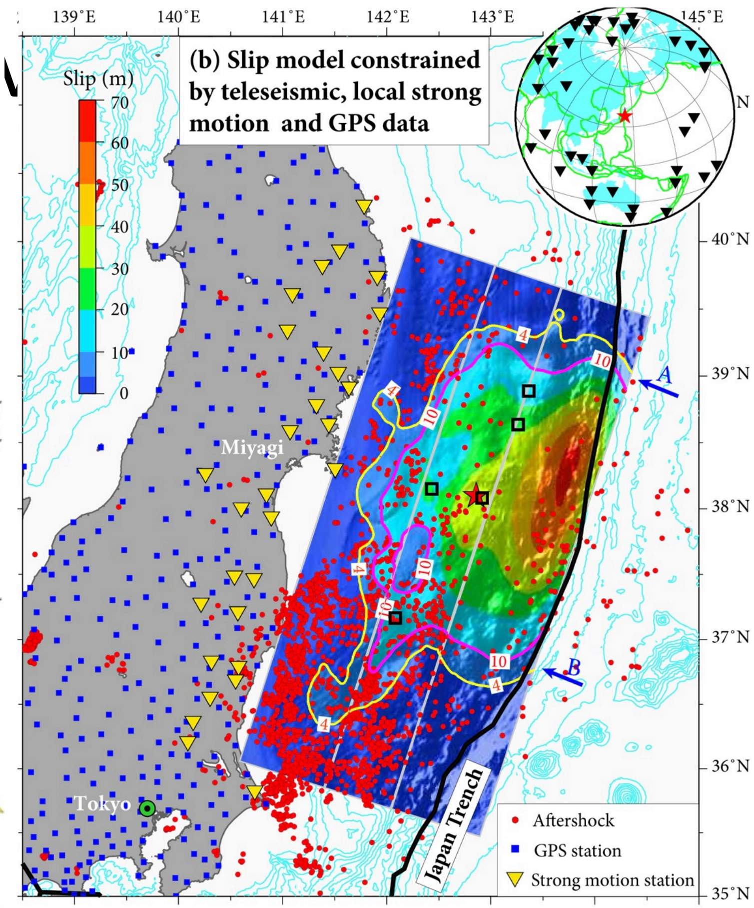
- What governs subduction zone seismogenic fault locking vs stable slip and/or transitional fault behavior?
- Does fault state evolve during interseismic and pre-seismic period? If so, how?
- What governs tsunami generation characteristics for a given great earthquake?

Stress analysis conceived to address these questions

Slip Model for 311 Tohoku earthquake

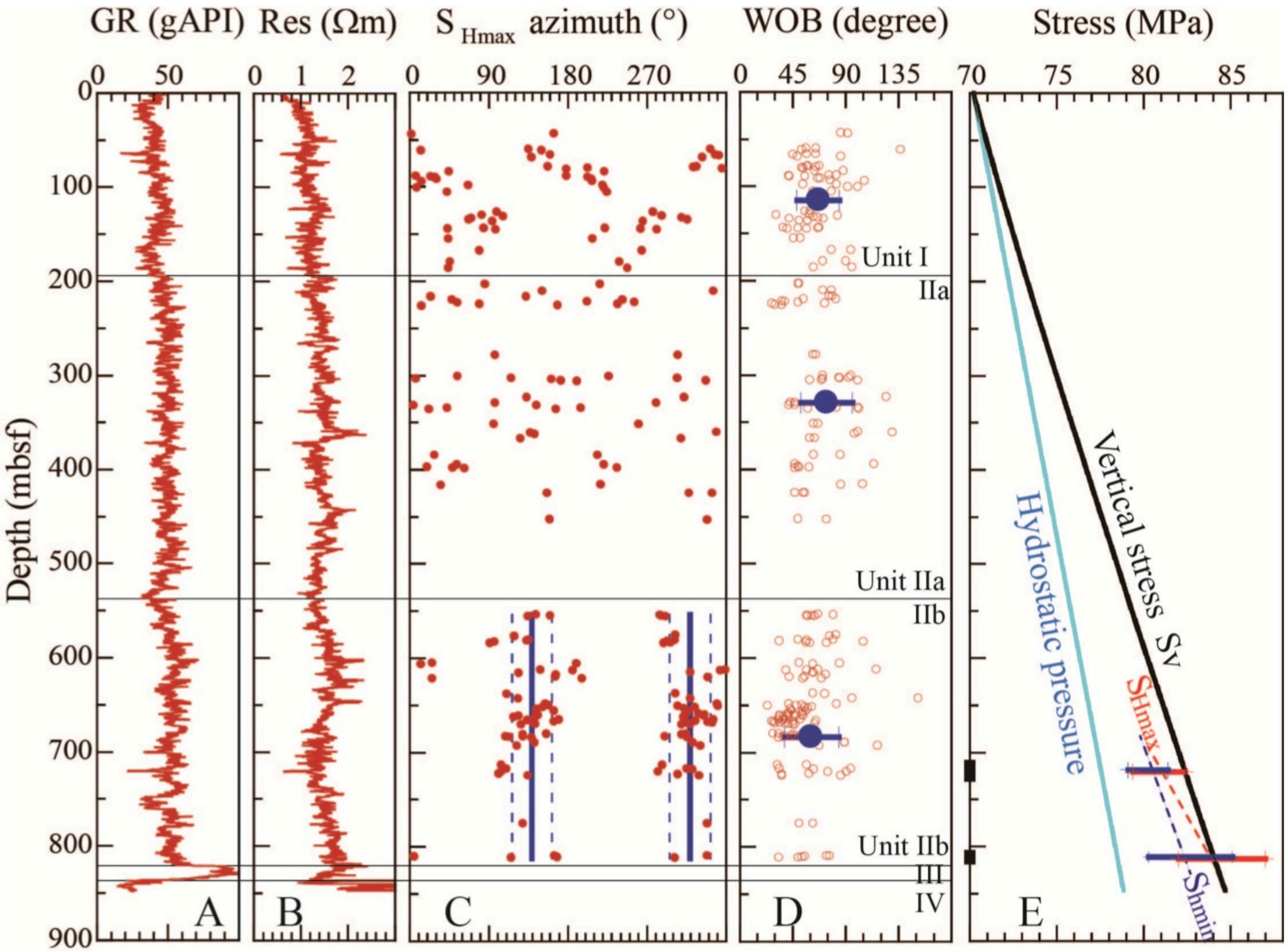
- The stress drop from slip model is ~100Mpa (+eq.)





Exp. 343 logging data and LWD images

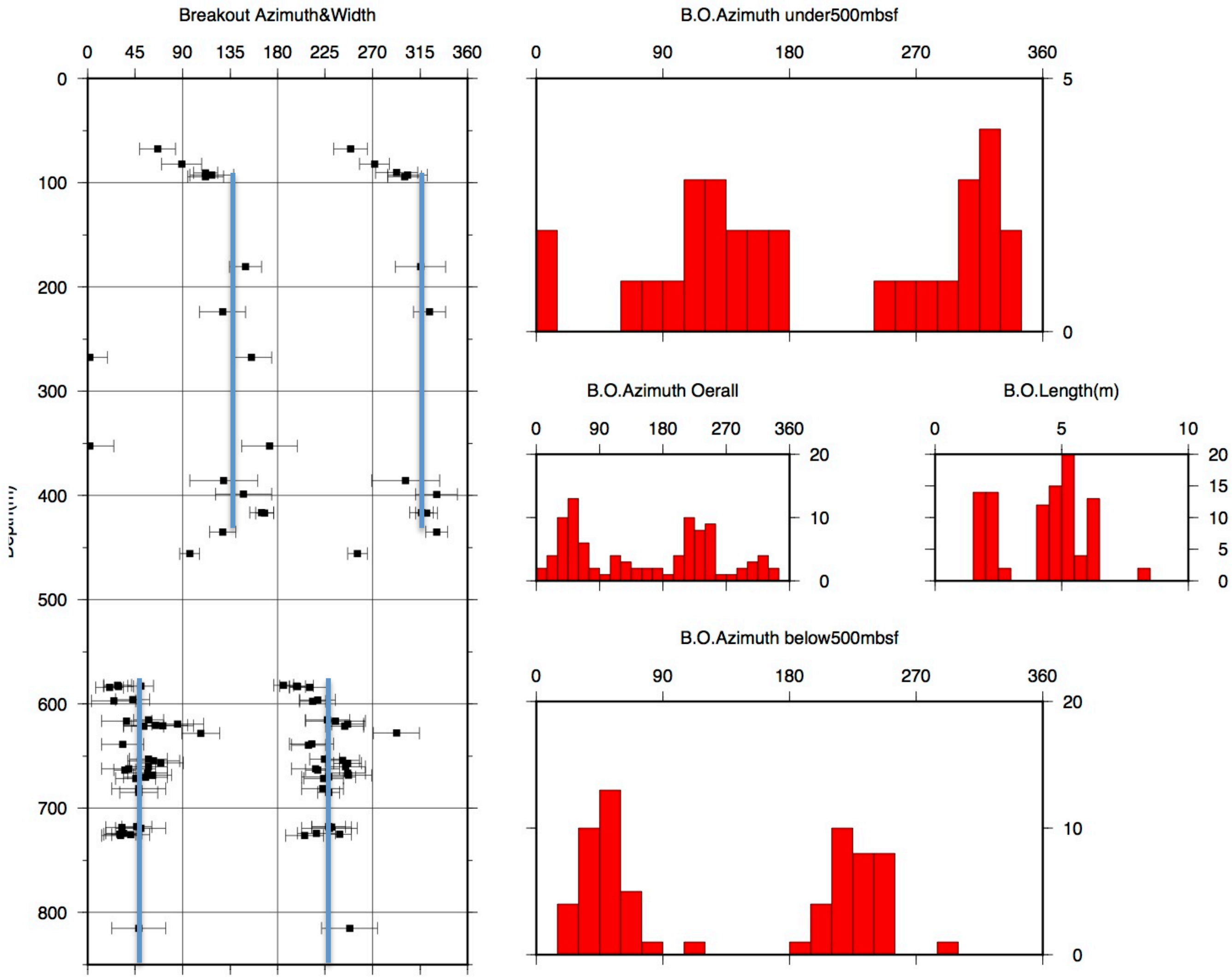
- The borehole breakout distribution can be recognized from LWD images. (Lin et al., 2012)
- The different lithology including plate boundary) can be found in this drilling. However, the stress variation is unknown.
- Density, velocity, friction, and rock strength hardly detected in exp. 343.

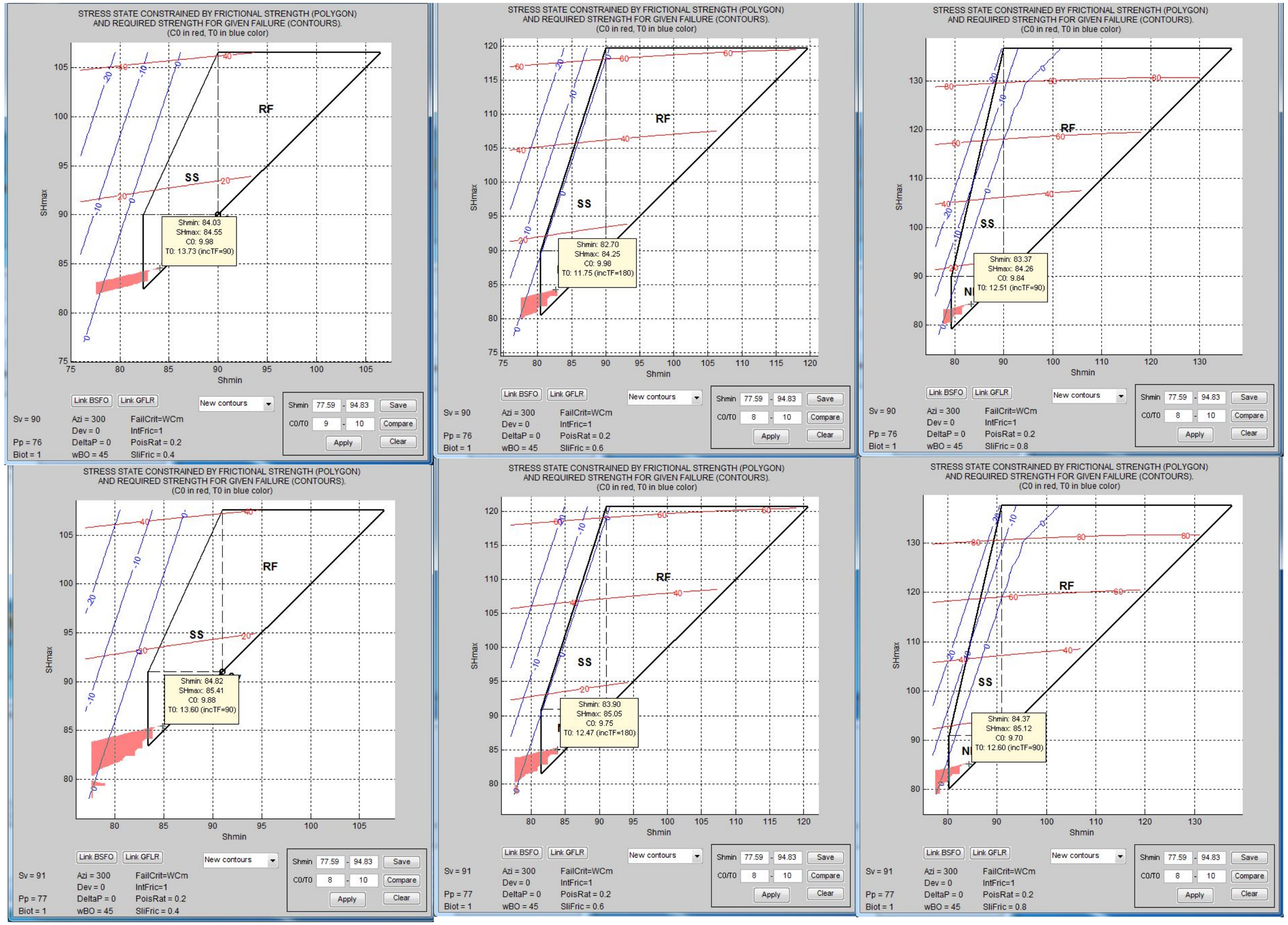


Lin et al., Science 2012

- Stress directions seem inconsistent above 500mbsf.
- Less constrain for the overburden weight (Sv).

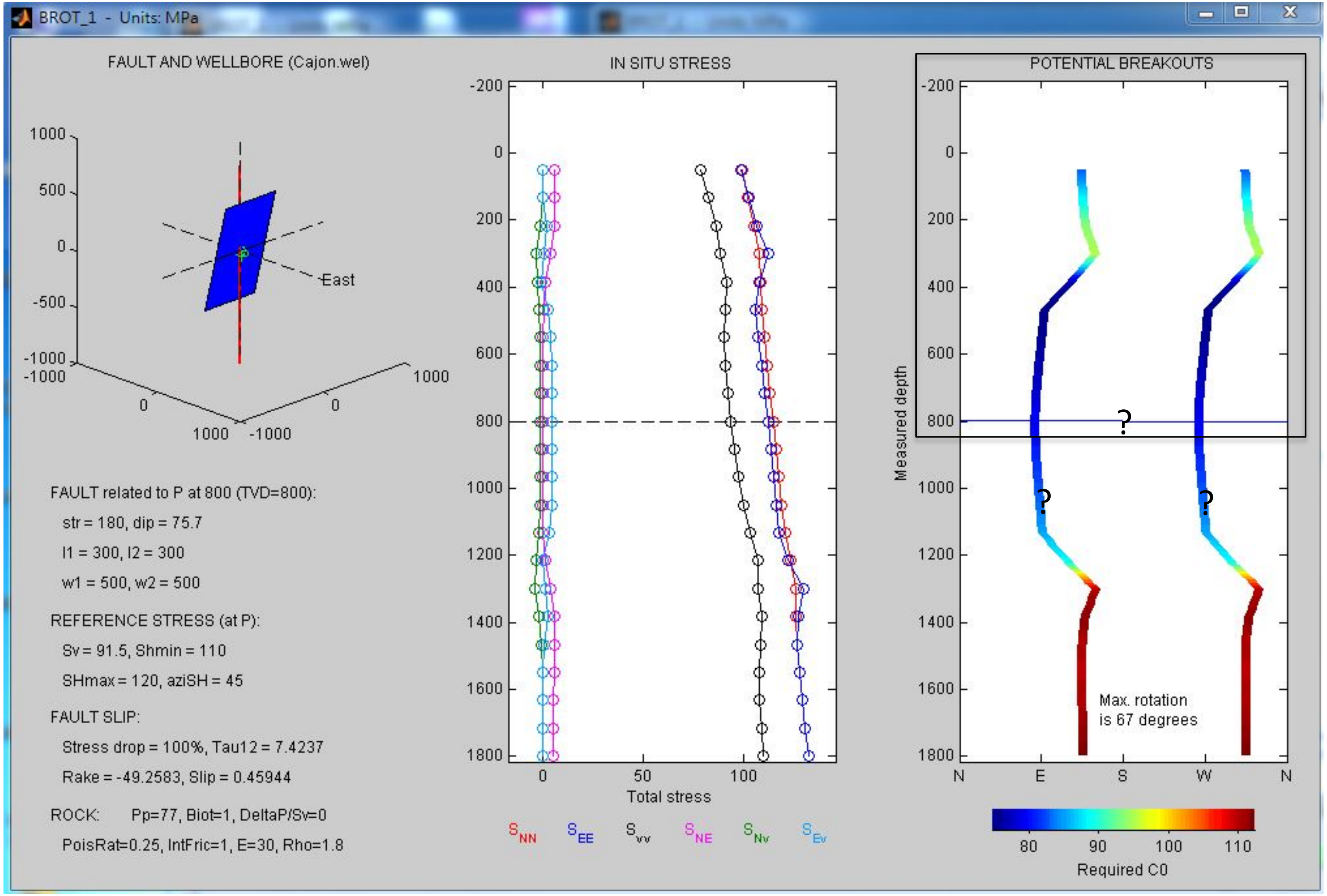
Re-evaluate the breakout azimuth in shallow portion



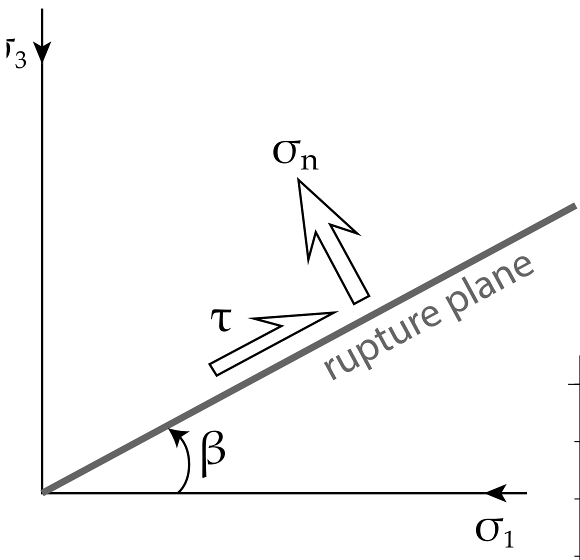


- The stress state after earthquake is in Normal-fault stress regime(friction=0.4;0.6 and 0.8)
- Rock strength should be in ~10Mpa or the normal-faulting slip occurs after the mainshock.
- Vertical stress equals to 90Mpa if the density 1.8g/cm^3 applied at 720mbsf.

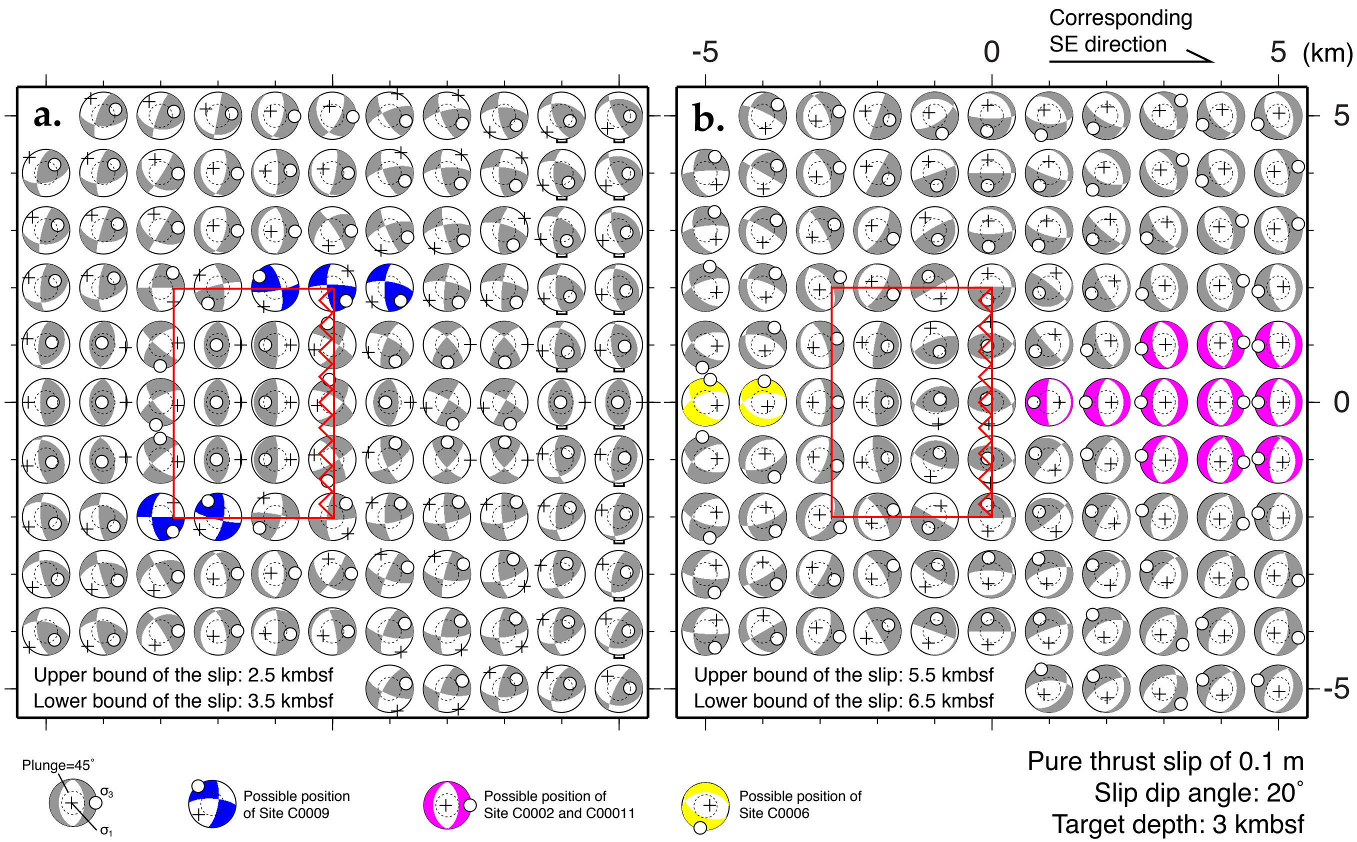
Geomechanical model for C0019B



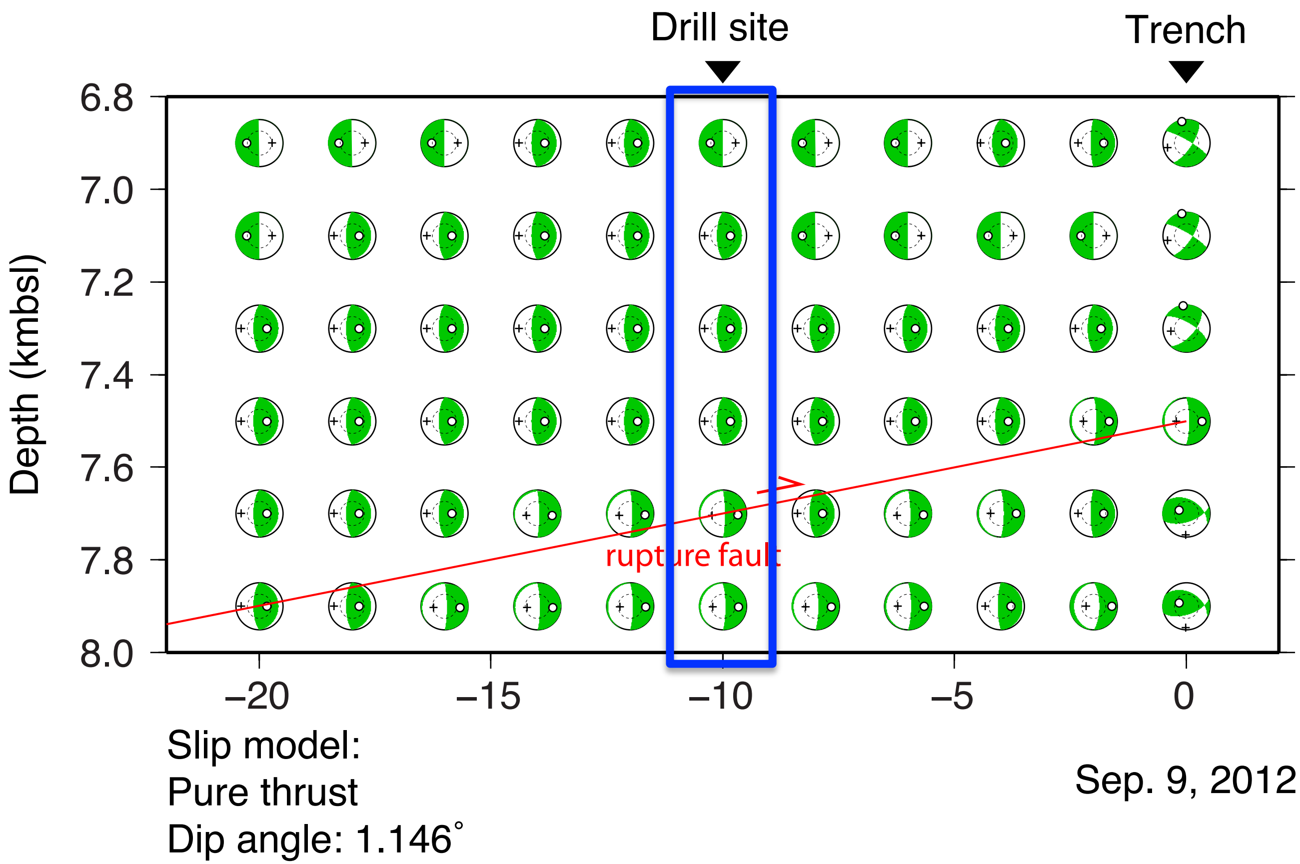
Optimal Oriented Plane model



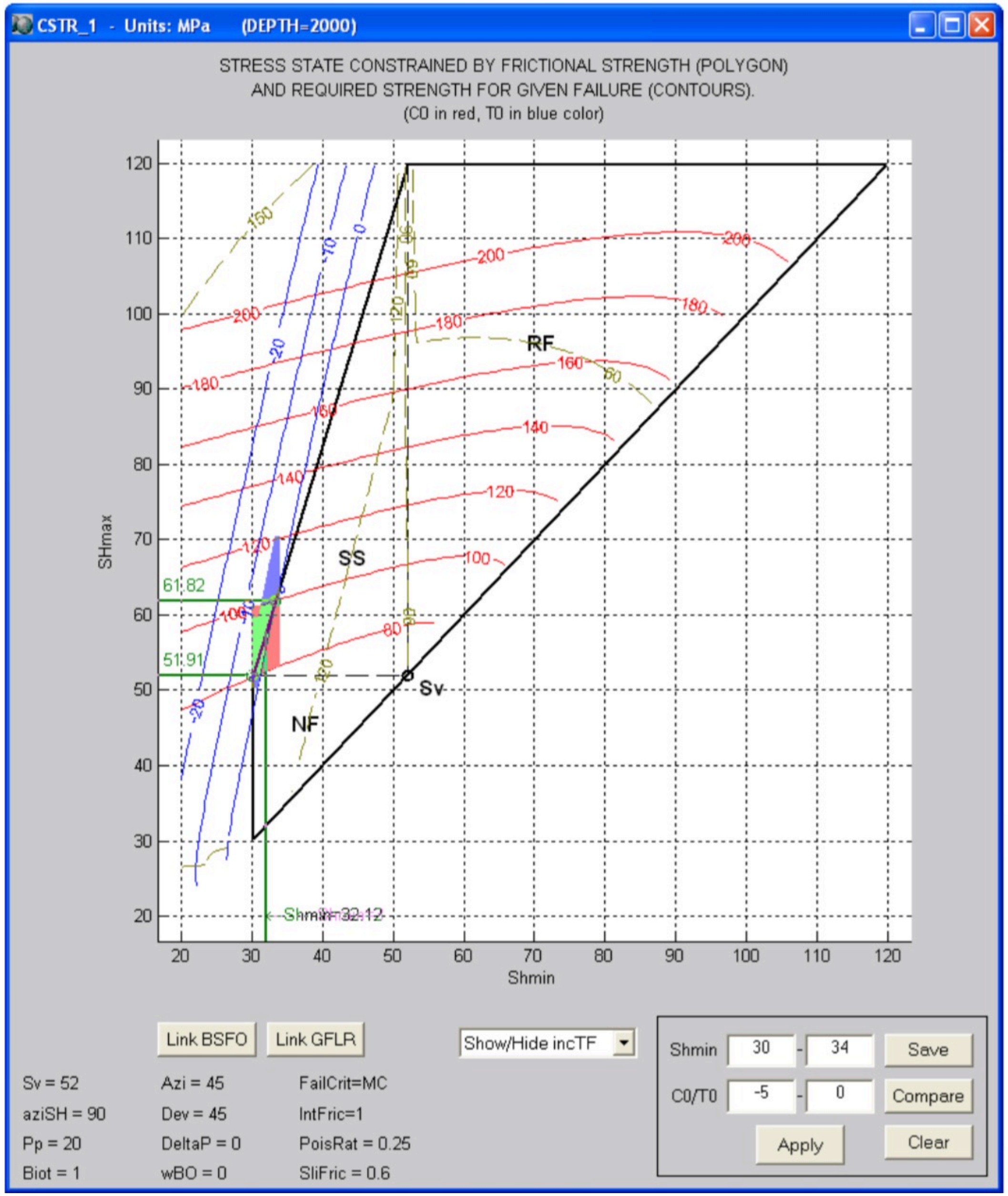
- Constrain by the borehole stress state
- Assume the fault patch in reasonable parameters



OOP model for site C0019B

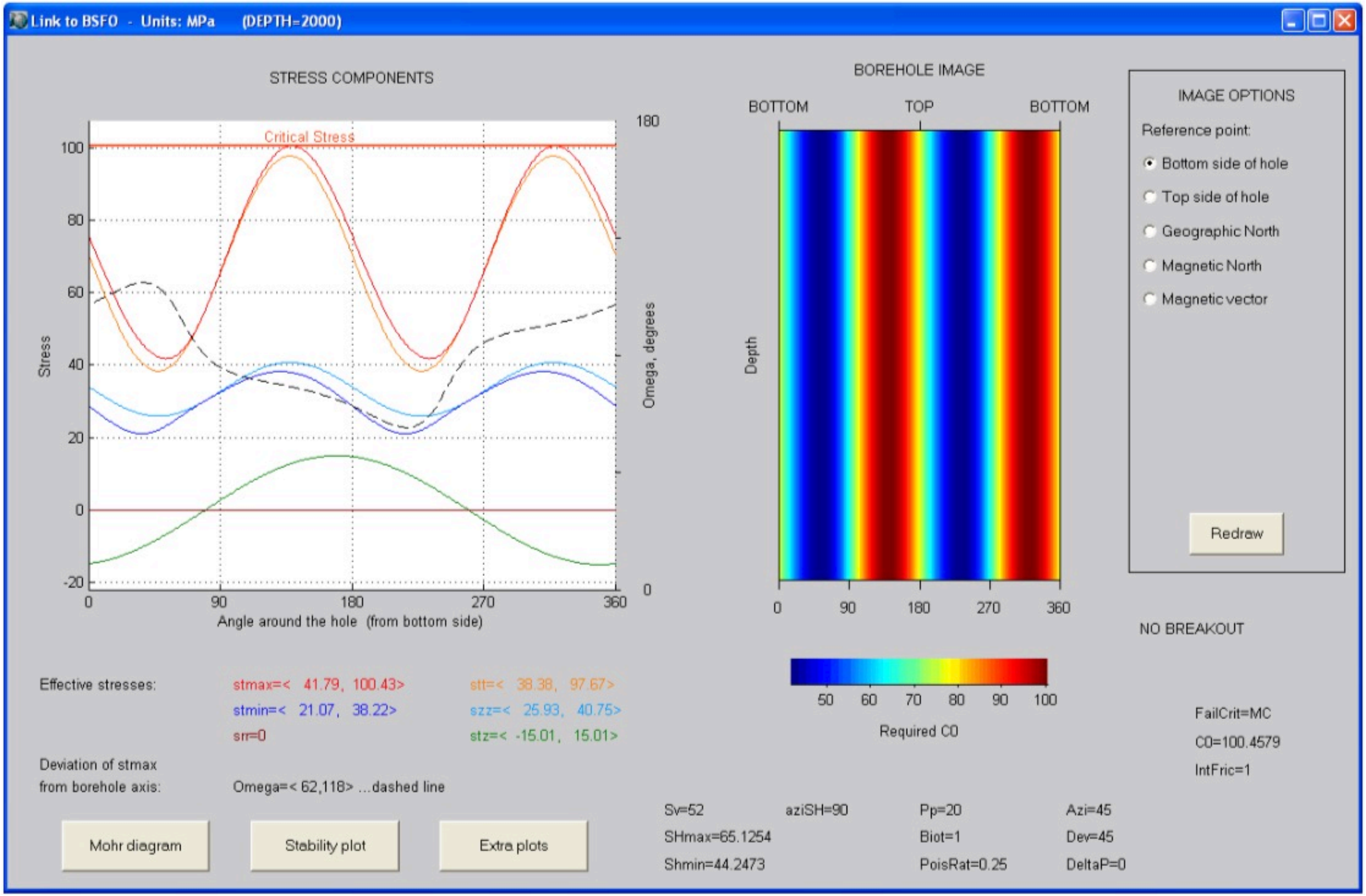


GMI- SFIB

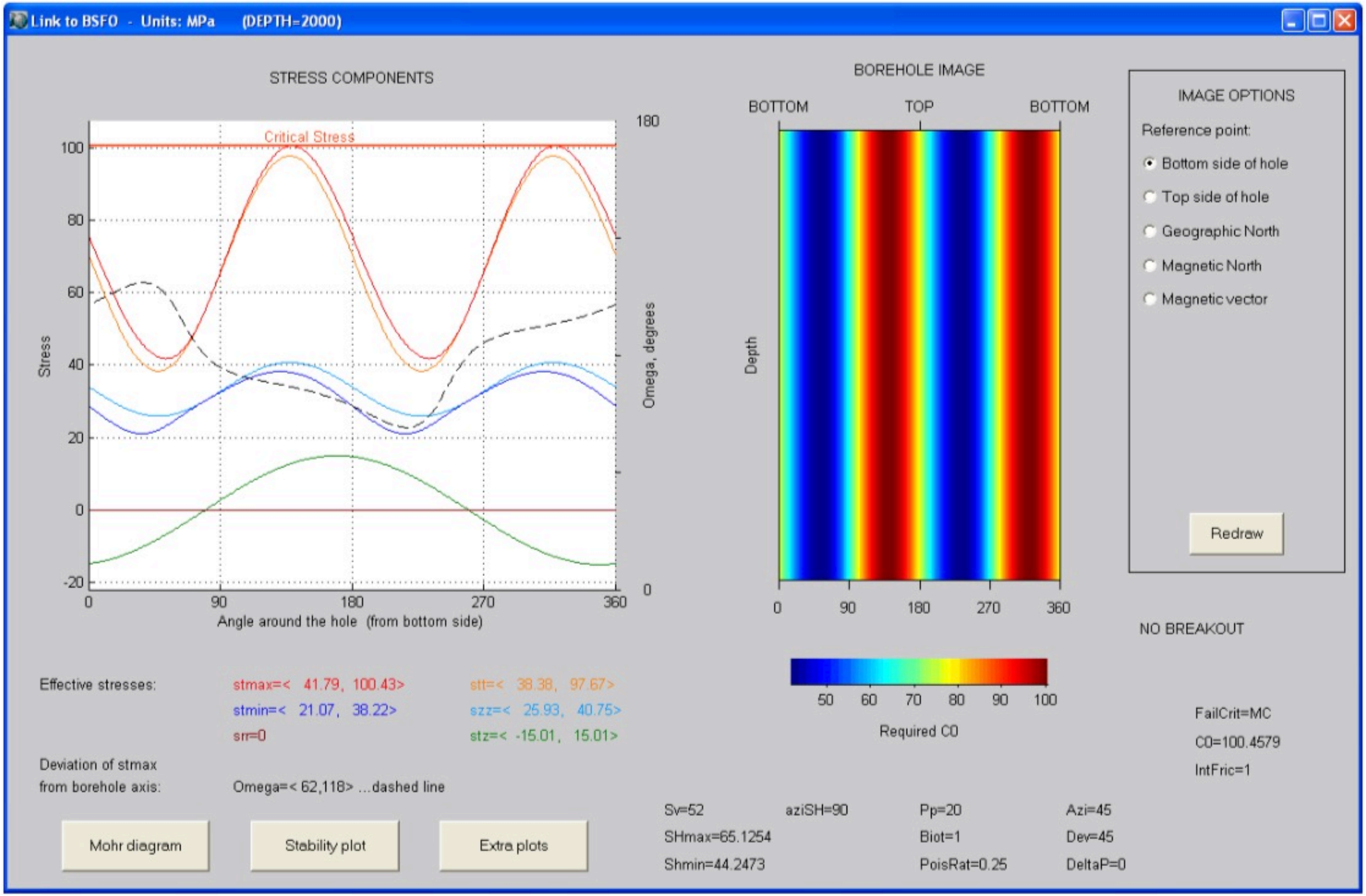


CSTR_1 - Units: MPa (DEPTH=2000)
STRESS STATE CONSTRAINED BY FRICTIONAL STRENGTH (POLYGON)
AND REQUIRED STRENGTH FOR GIVEN FAILURE (CONTOURS).
(C0 in red, T0 in blue color)
SHmax
Shmin
RF
SS
NF
Sv
61.82
51.91
Link BSFO
Link GFLR
Show/Hide incTF
Shmin 30 - 34
C0/T0 -5 - 0
Save
Compare
Apply
Clear
Sv = 52
aziSH = 90
Pp = 20
Biot = 1
Azi = 45
Dev = 45
DeltaP = 0
wBO = 0
FailCrit=MC
IntFric=1
PoisRat = 0.25
SliFric = 0.6

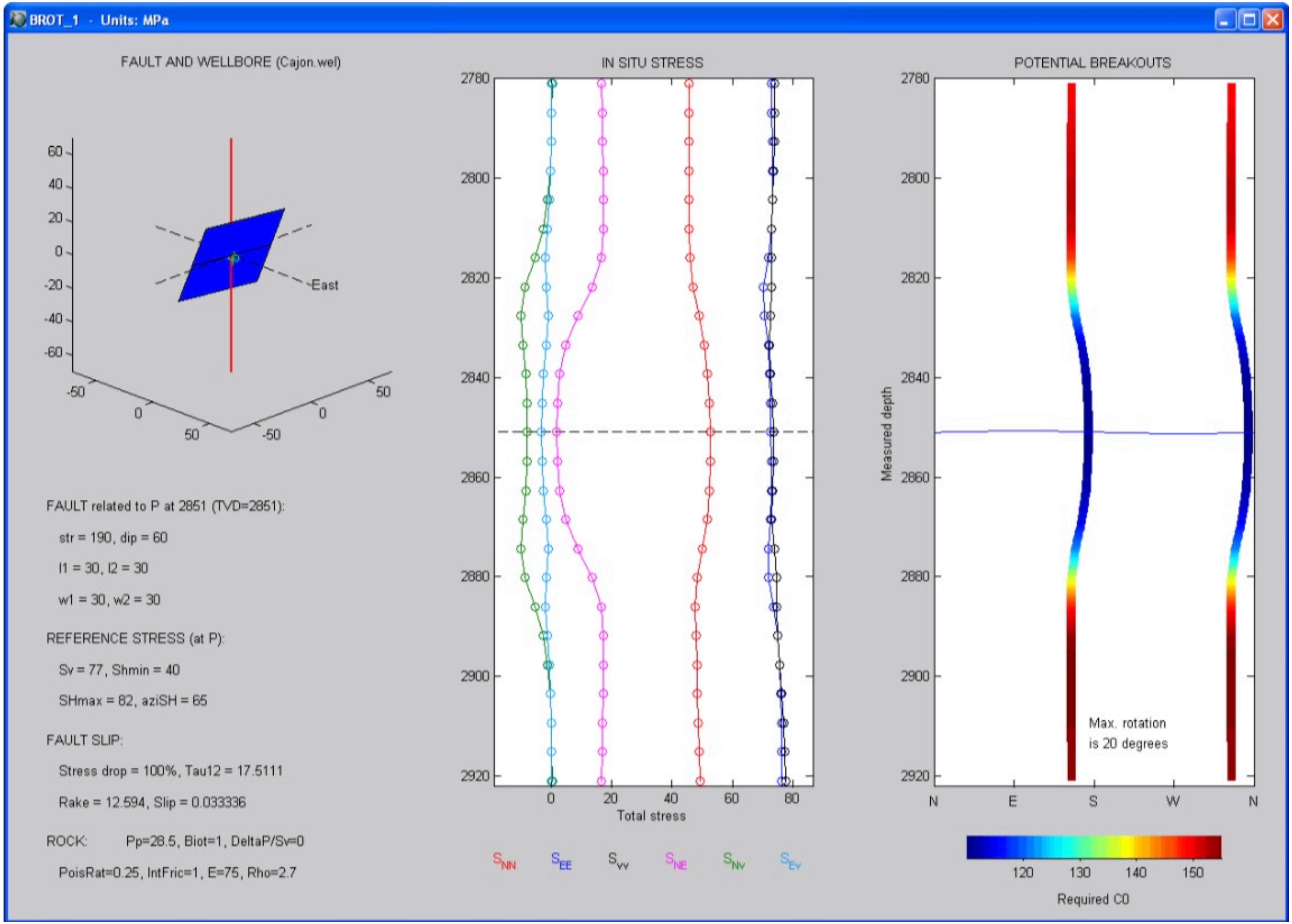
GMI-Breakout Simulation



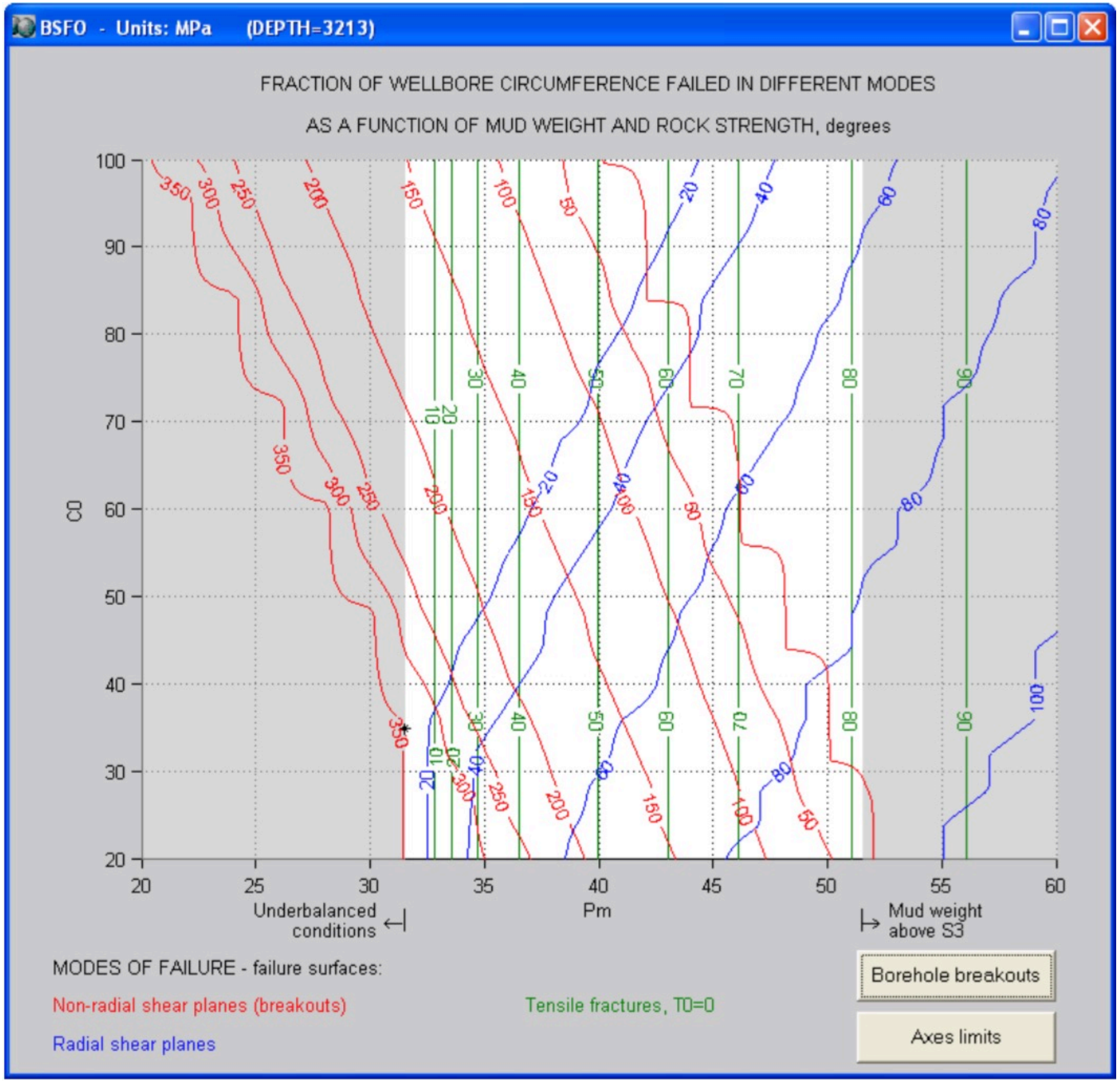
GMI-Breakout tendency



GMI-Breakout rotation



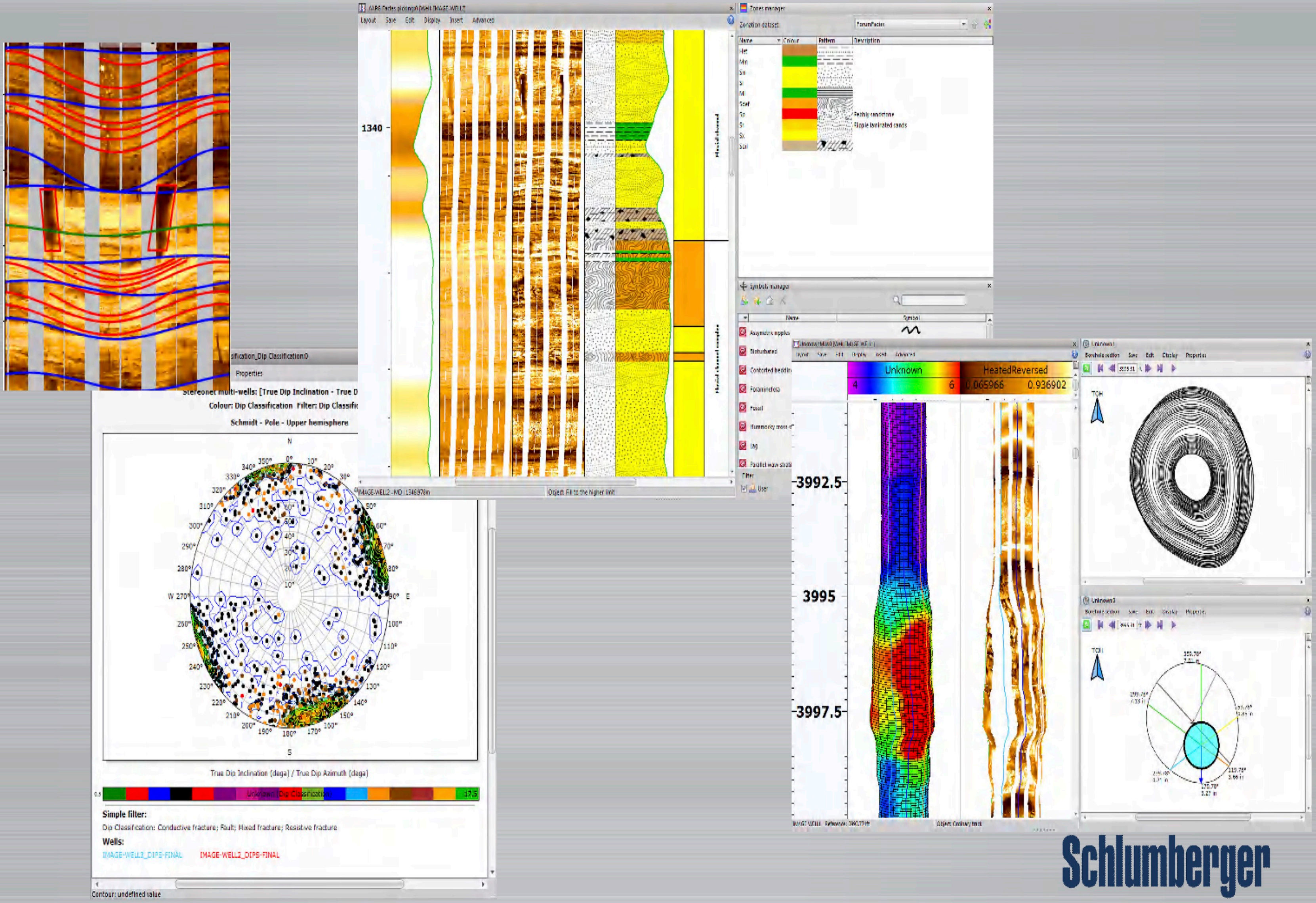
GMI-Borehole stability



Techlog- Well bore Imaging

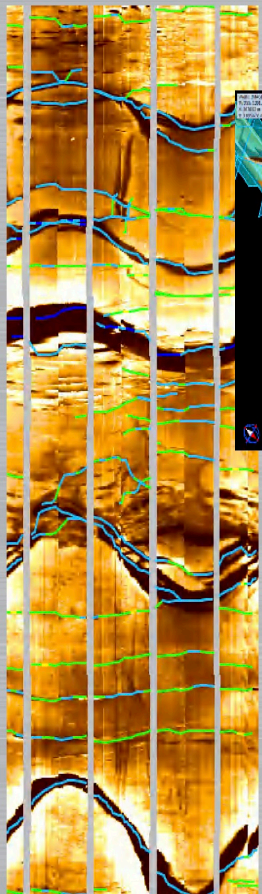
- Data Quality
- Extracting infomration from loggings
- Share between disciplines
- Data accessibility over lifetime of asset

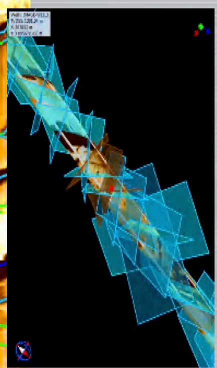
…to interpreting data with the best tools…

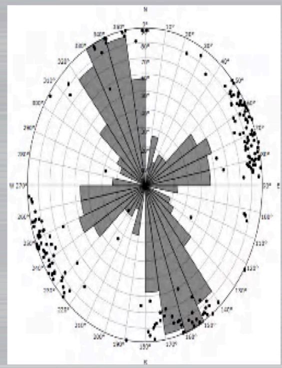


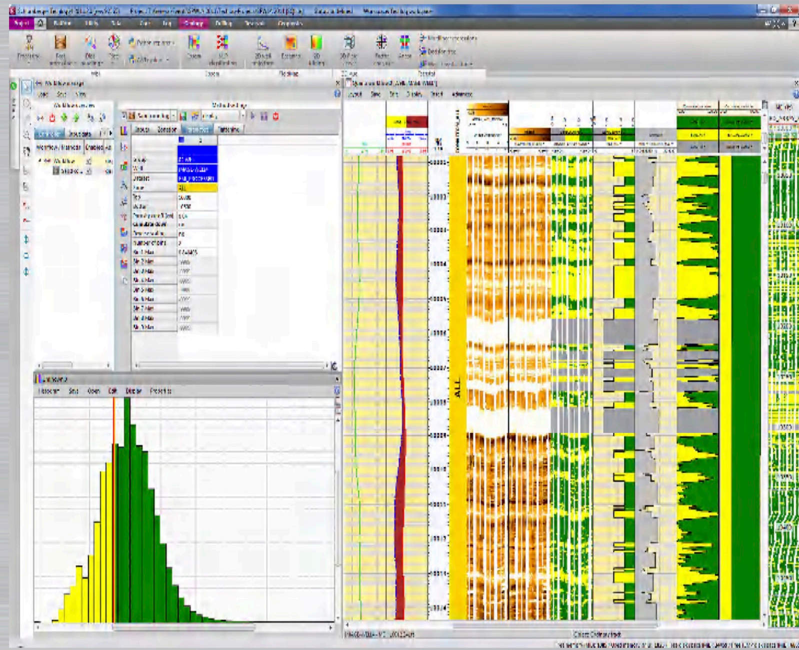
Schlumberger

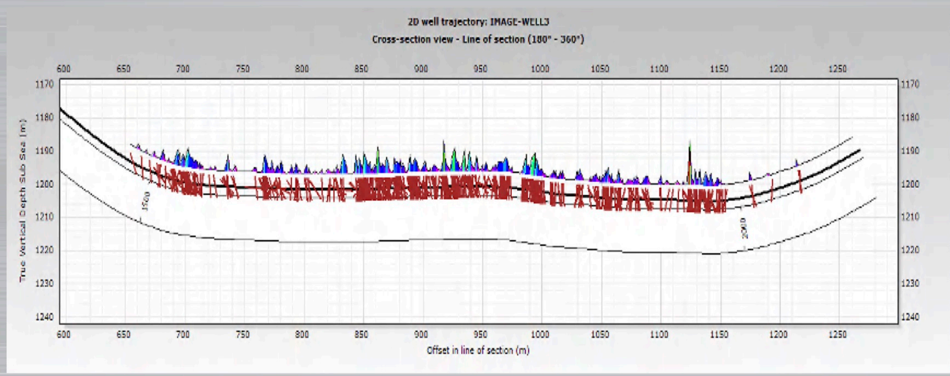
Understanding fracture and run sand counting





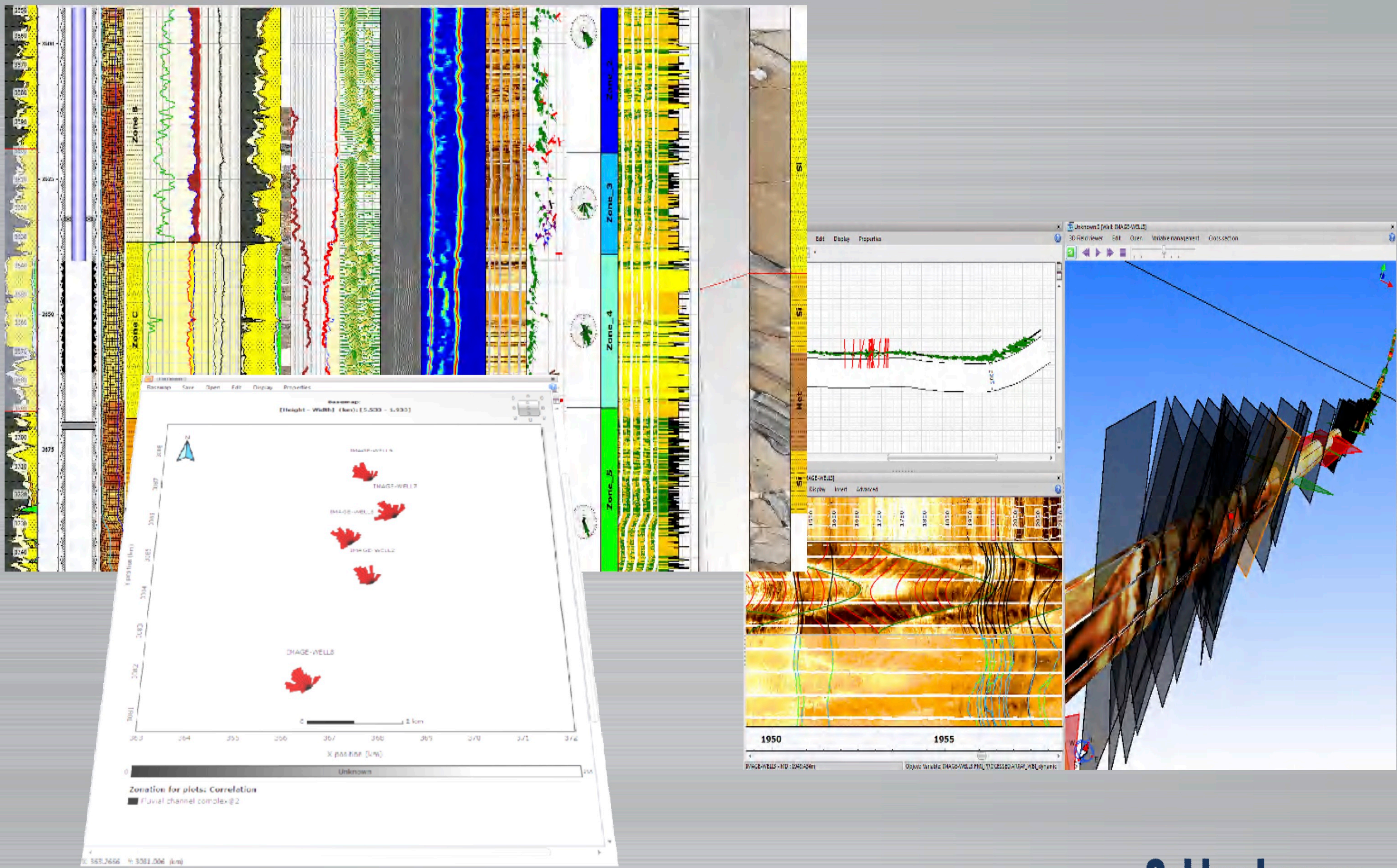






Schlumberger

..and sharing results with Techlog's visualisation power.



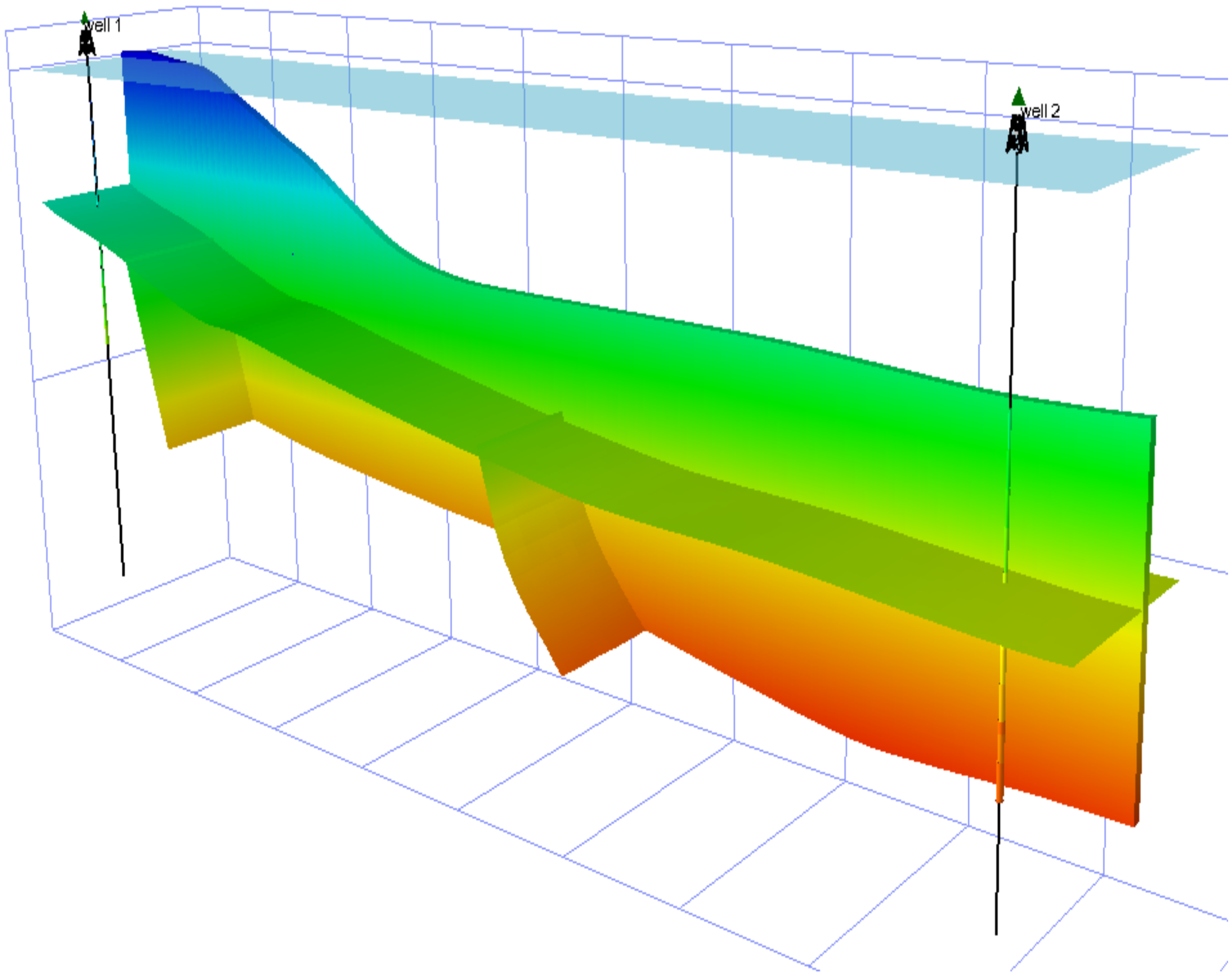
Schlumberger

Jewel Suites- Geomechanics

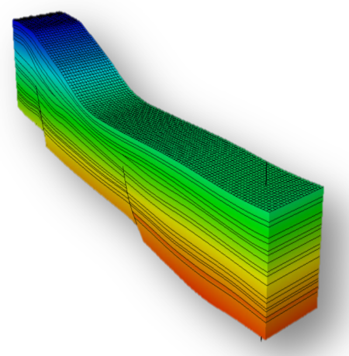
Advantages of static 3D geomechanical model

- Masters 1D depth stretching problems; Honors structural constraints
- Use of existing techniques/subsurface models
- Integrates multiple data sources (wells, seismic horizons and volumes)
- Fast and cost efficient 3D model
- High resolution model for WBS (~1m)
- Model build in an integrated environment (multiple user input)
- WBS analyses of arbitrary well trajectories possible

3D Geomechanical model – Well based method

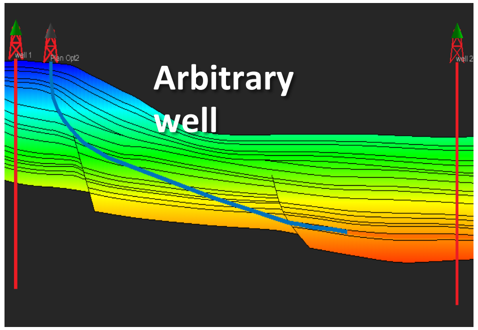


Extracting results

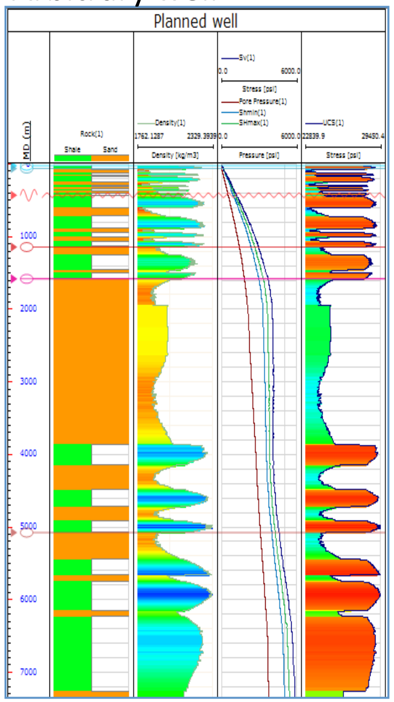


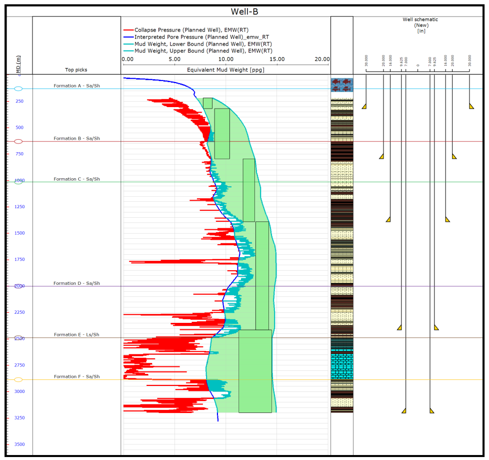
3D Hi-Res Geomechanical Model

- Rock Mechanical Properties
- Pore Pressures
- In-situ Stresses and
- Fracture Gradient

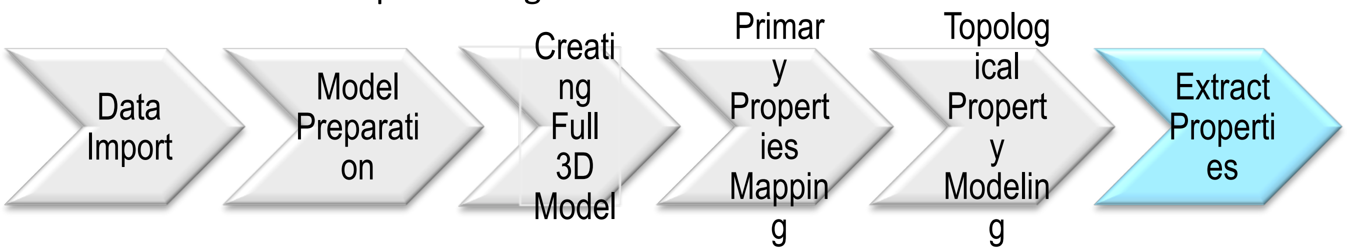


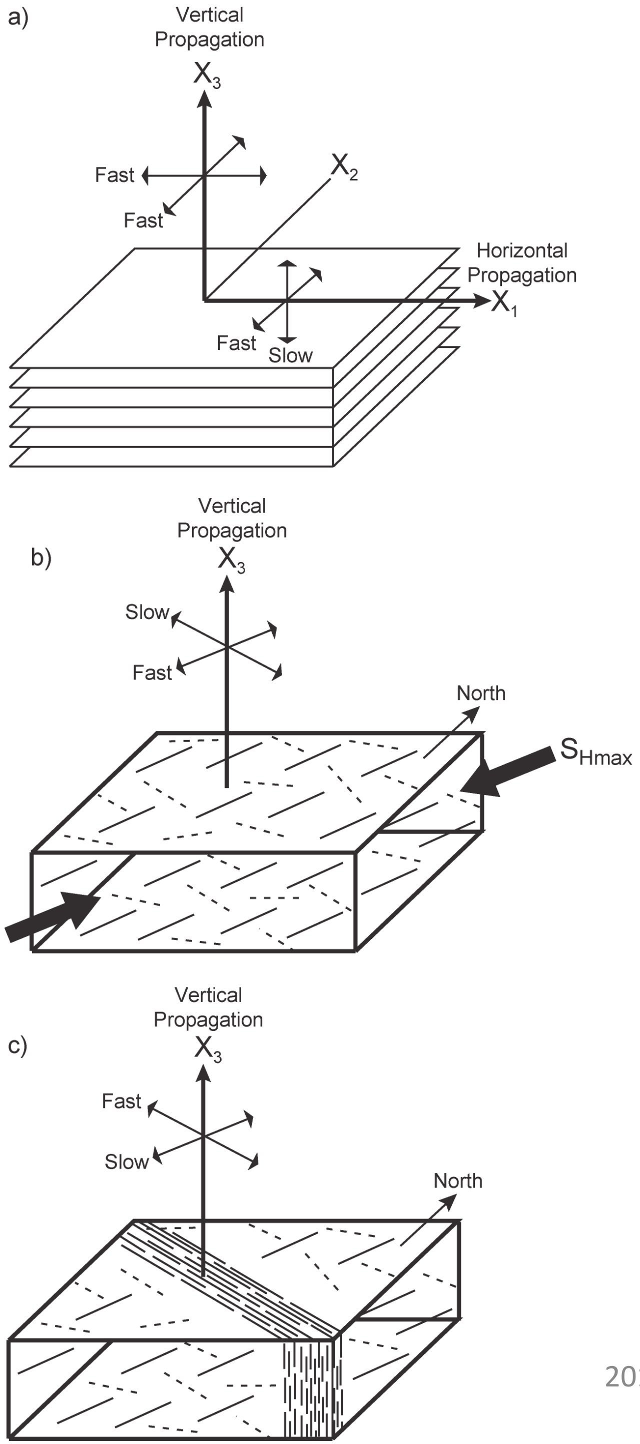
Pseudo logs from Arbitrary well





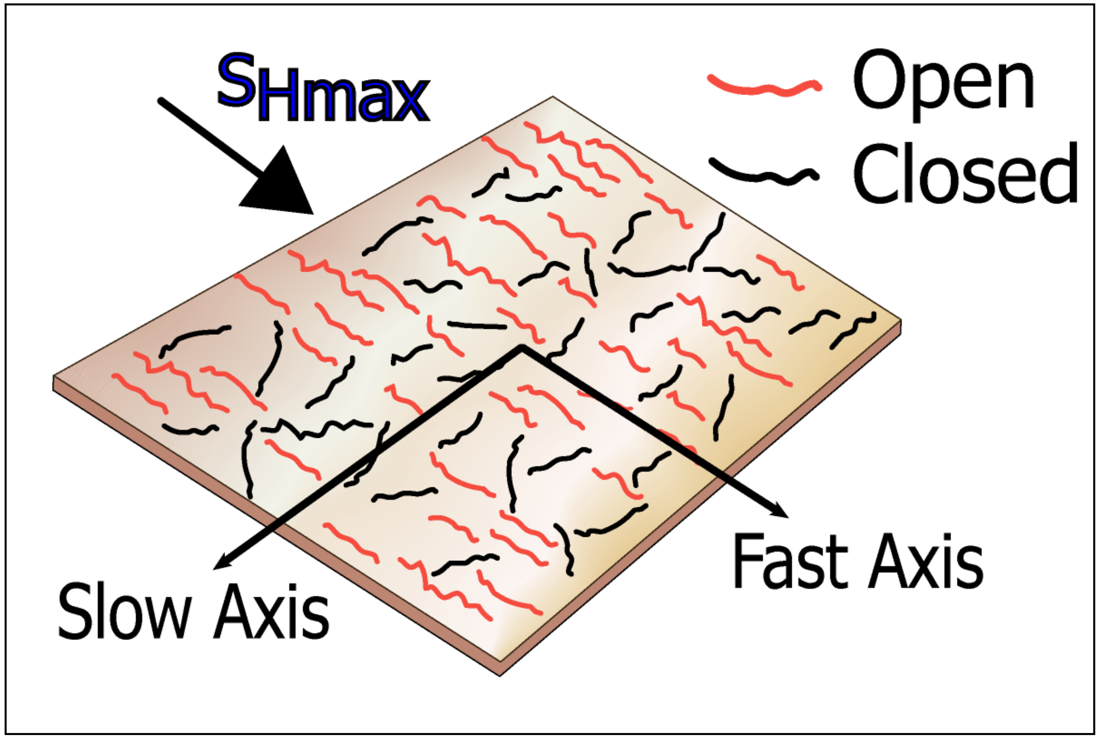
Wellbore stability Analysis from pseudo logs





Stress-induced anisotropy

Highly disordered system

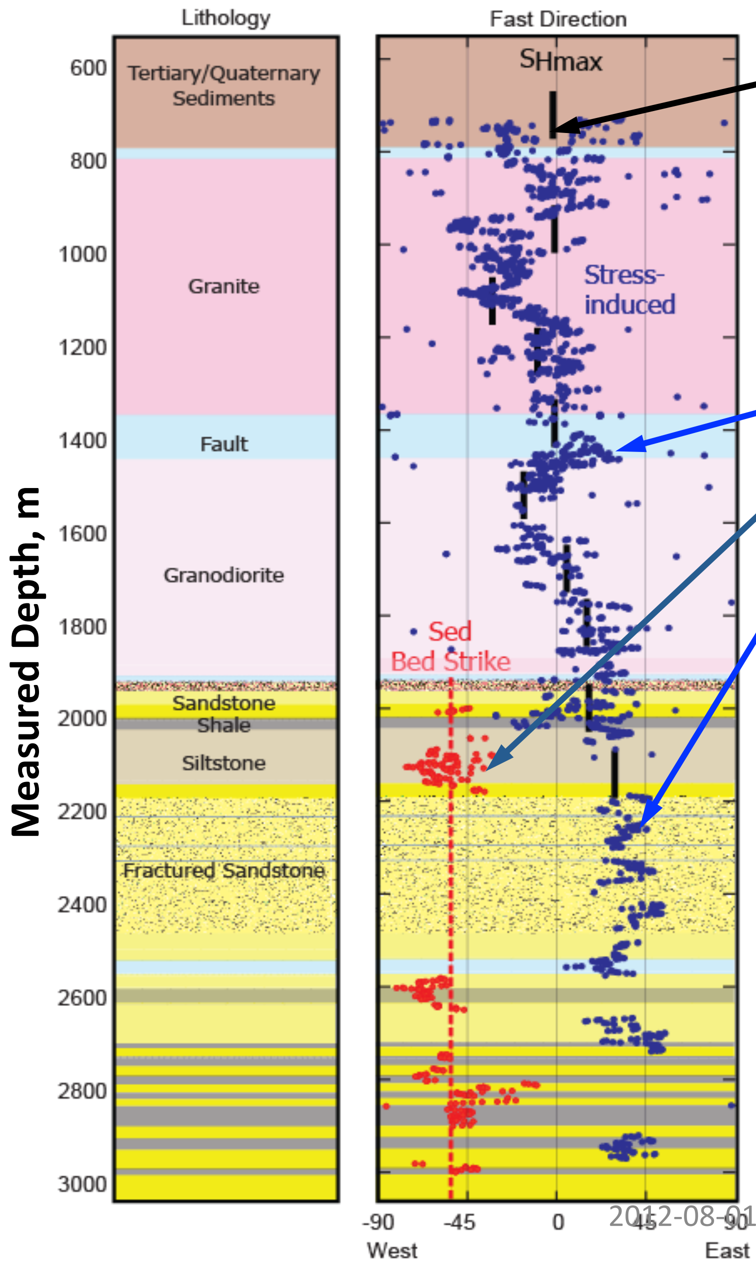


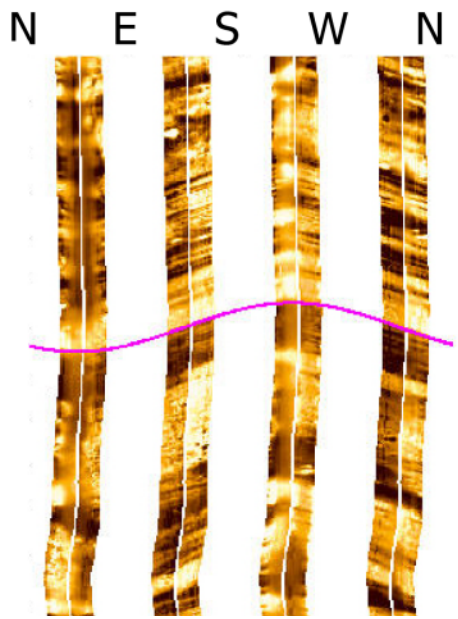
- Preferential closure of fractures in response to S_{Hmax}
- Stress parallel fast direction
- Decreasing anisotropy with depth as stress increases.

But How Do Stress Orientations Change as Fault is Approached at Depth?

S_{Hmax} Direction in Pilot Hole from Breakouts and Tensile Cracks (Hickman and Zoback, 2004)

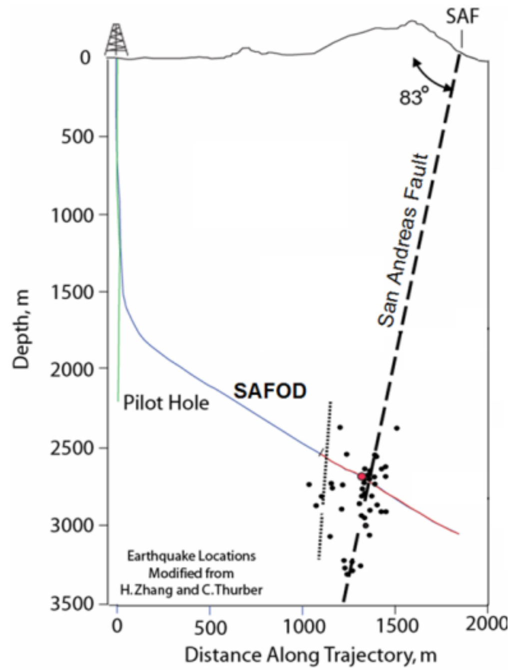
Fast Shear Wave Polarization Direction in SAFOD from Cross-Dipole Sonic Logs (Boness and Zoback, 2006)



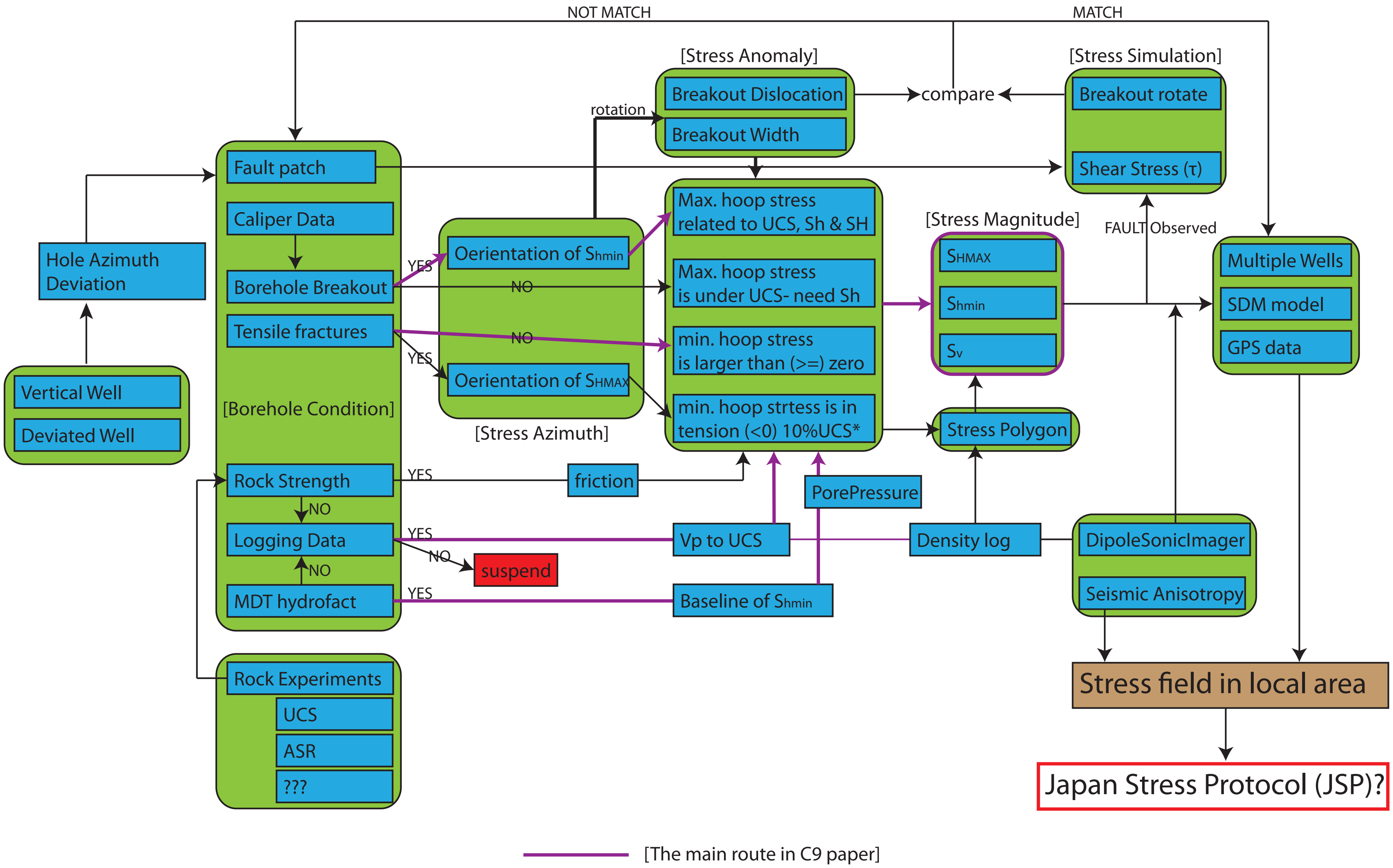


Bedded ss/shales

FMI Log



Future Work


NOT MATCH
MATCH
[Stress Anomaly]
Breakout Dislocation
Breakout Width
compare
[Stress Simulation]
Breakout rotate
Shear Stress (τ)
rotation
Fault patch
Caliper Data
Borehole Breakout
Tensile fractures
[Borehole Condition]
Rock Strength
Logging Data
MDT hydrofact
Hole Azimuth Deviation
Vertical Well
Deviated Well
YES
NO
Oerientation of Shmin
Oerientation of SHMAX
[Stress Azimuth]
Max. hoop stress related to UCS, Sh & SH
Max. hoop stress is under UCS- need Sh
min. hoop stress is larger than (>=) zero
min. hoop strtess is in tension (<0) 10%UCS*
[Stress Magnitude]
SHMAX
Shmin
Sv
Stress Polygon
FAULT
Observed
Multiple Wells
SDM model
GPS data
friction
PorePressure
Vp to UCS
Density log
DipoleSonicImager
Seismic Anisotropy
suspend
Baseline of Shmin
Rock Experiments
UCS
ASR
???
Stress field in local area
Japan Stress Protocol (JSP)?
[The main route in C9 paper]

SDM for Nankai Stress Field

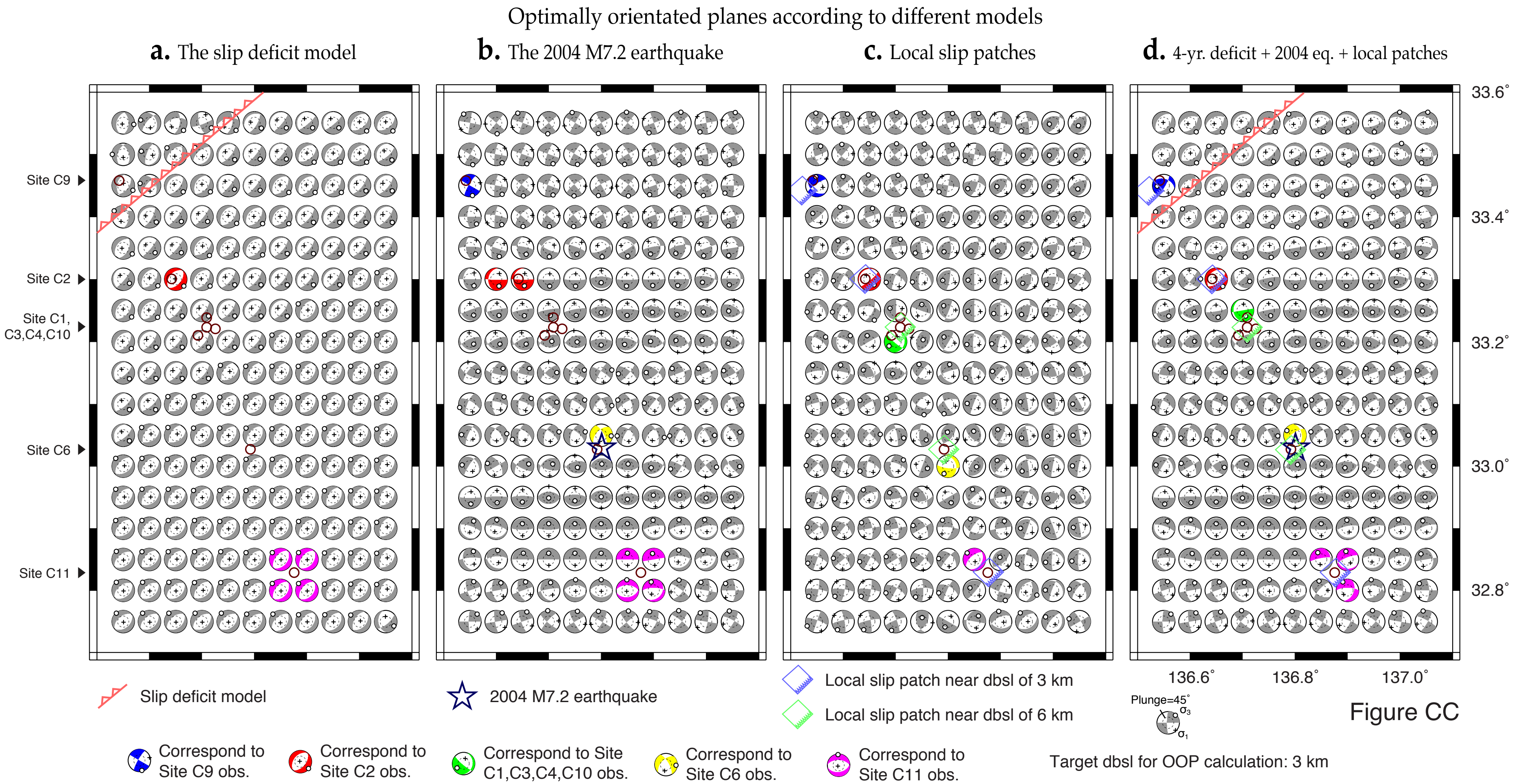


Figure CC

Summary

- No matter what software you use, you still need to do your research BY YOURSELF.
- 3D model of stress magnitudes over interval spanned by borehole tied to hard measurements, we need to collected the borehole condictionsm visible behaviors in imgaes logs and model of rock strength.
- Discrete measurements of static principal stress magnitudes and 3D model of their variation with depth help us map magnitude of stress rotations within the total stress field. (see beyond the images)


THANK YOU