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Chapter Three

In-situ Stresses & Modeling

Overview of Geomechanics

RTS Geomechanics Services

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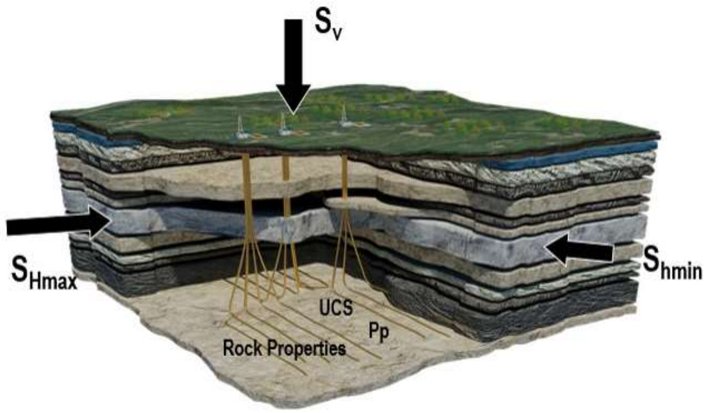
Geomechanics Modelling (1D / 3D)

Geomechanics deals with rock under stress. When these stresses exceed the rock strength, failures of some kind will occur.

- **Description of a geomechanical model for a reservoir involves detailed knowledge of:**
  - *In situ stress orientations*
  - *In situ stress magnitudes*
  - *Pore pressure*
  - *Rock mechanical properties*
- **Other considerations:**
  - *Mud chemistry*
  - *Weak bedding planes*
  - *Fractures*
  - *Thermal effects*



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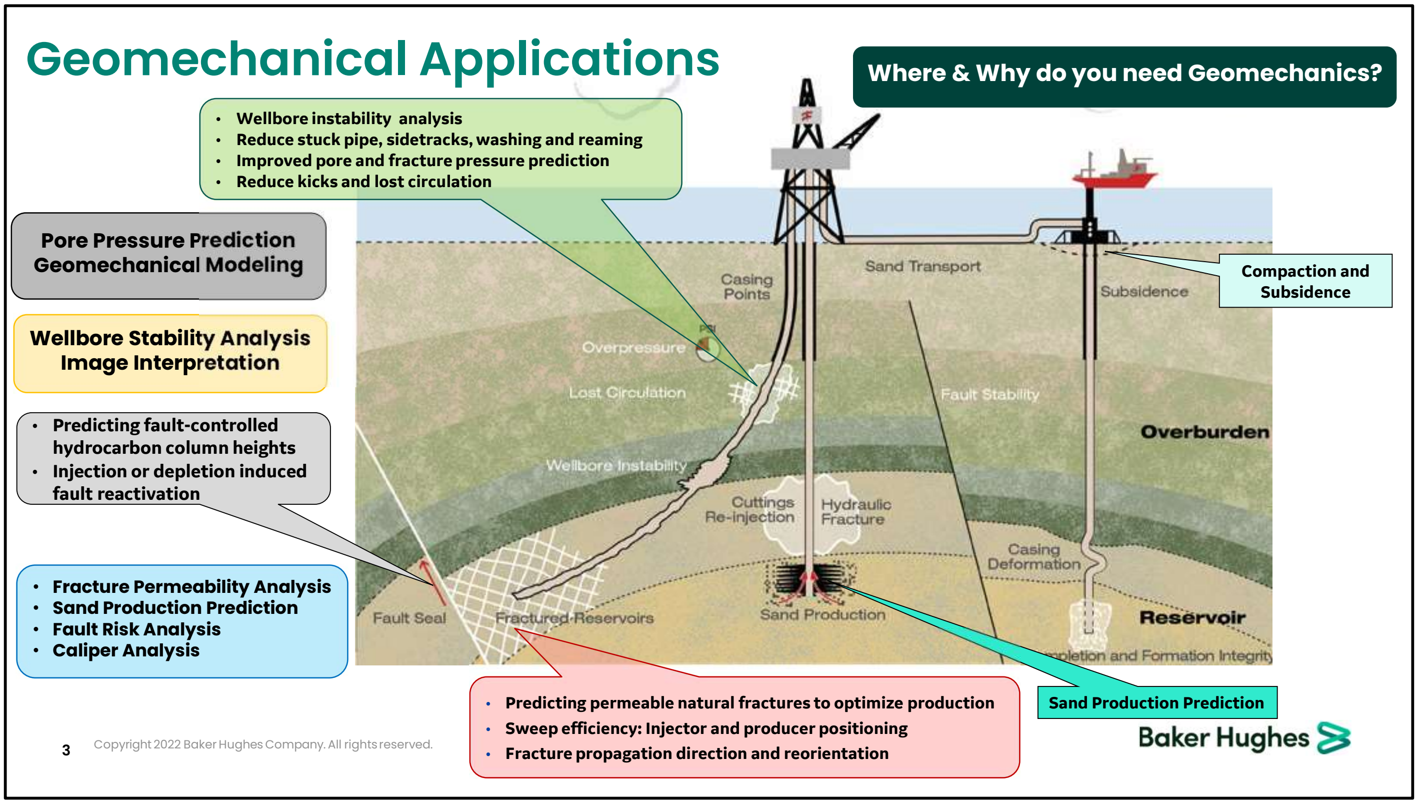


Geomechanics Challenges:

Touches Drilling – Completion – Stimulation – Production – Geology – Geophysics – Petrophysics -Reservoir

Wellbore stability problems alone cost the industry ~ $7,000,000,000 p.a. globally

Solutions:

Geomechanical models and workflows

(1D to 4D)

Baker Hughes GMI Software, JewelSuite™

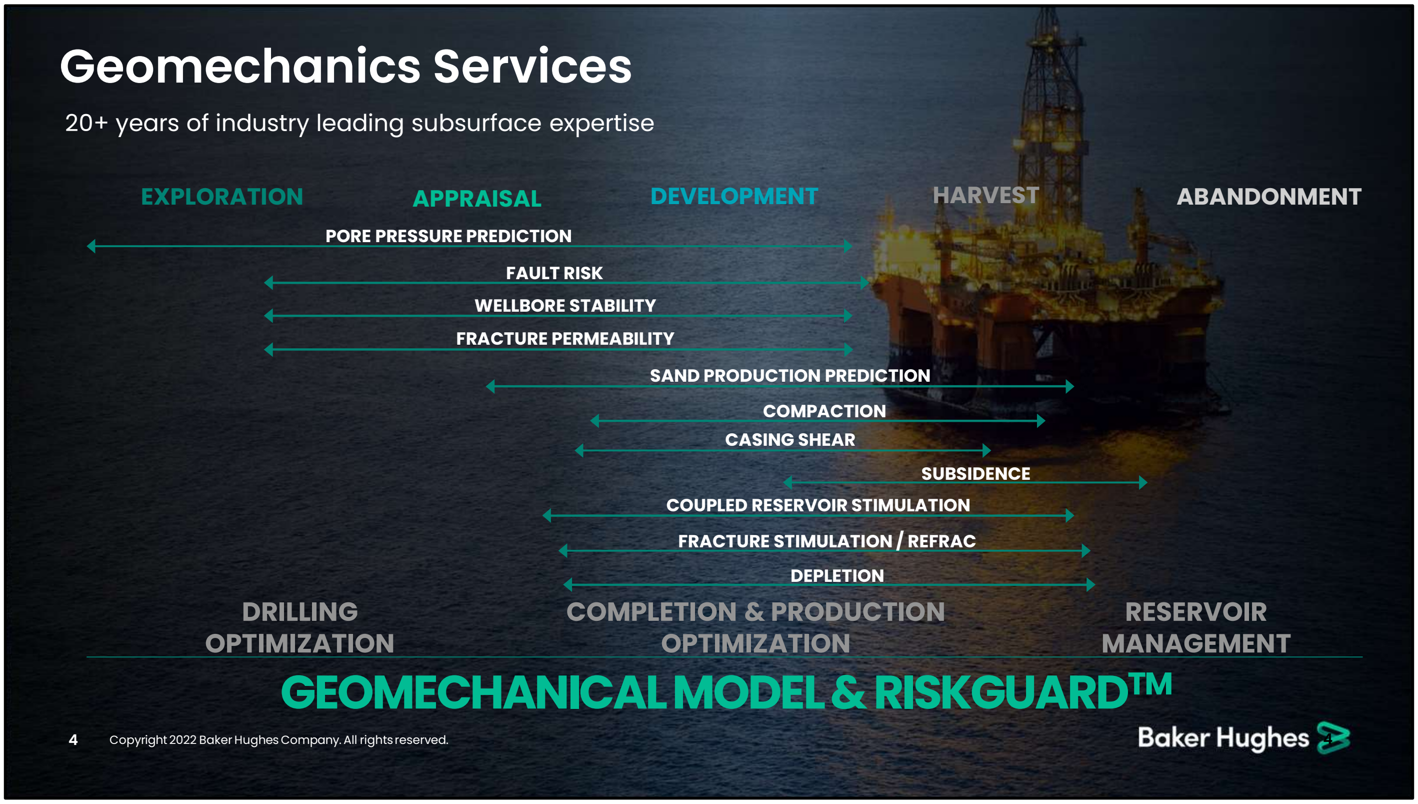
Value:

Reduce the risk of unexpected costs and

non-productive drilling time

Optimised well trajectories and mud weight window optimisation for well integrity

Reduce risks and improve production and recovery for field management


Geomechanics Services
20+ years of industry leading subsurface expertise
EXPLORATION
APPRAISAL
DEVELOPMENT
HARVEST
ABANDONMENT
PORE PRESSURE PREDICTION
FAULT RISK
WELLBORE STABILITY
FRACTURE PERMEABILITY
SAND PRODUCTION PREDICTION
COMPACTION
CASING SHEAR
SUBSIDENCE
COUPLED RESERVOIR STIMULATION
FRACTURE STIMULATION / REFRAC
DEPLETION
DRILLING OPTIMIZATION
COMPLETION & PRODUCTION OPTIMIZATION
RESERVOIR MANAGEMENT
GEOMECHANICAL MODEL & RISKGUARD™
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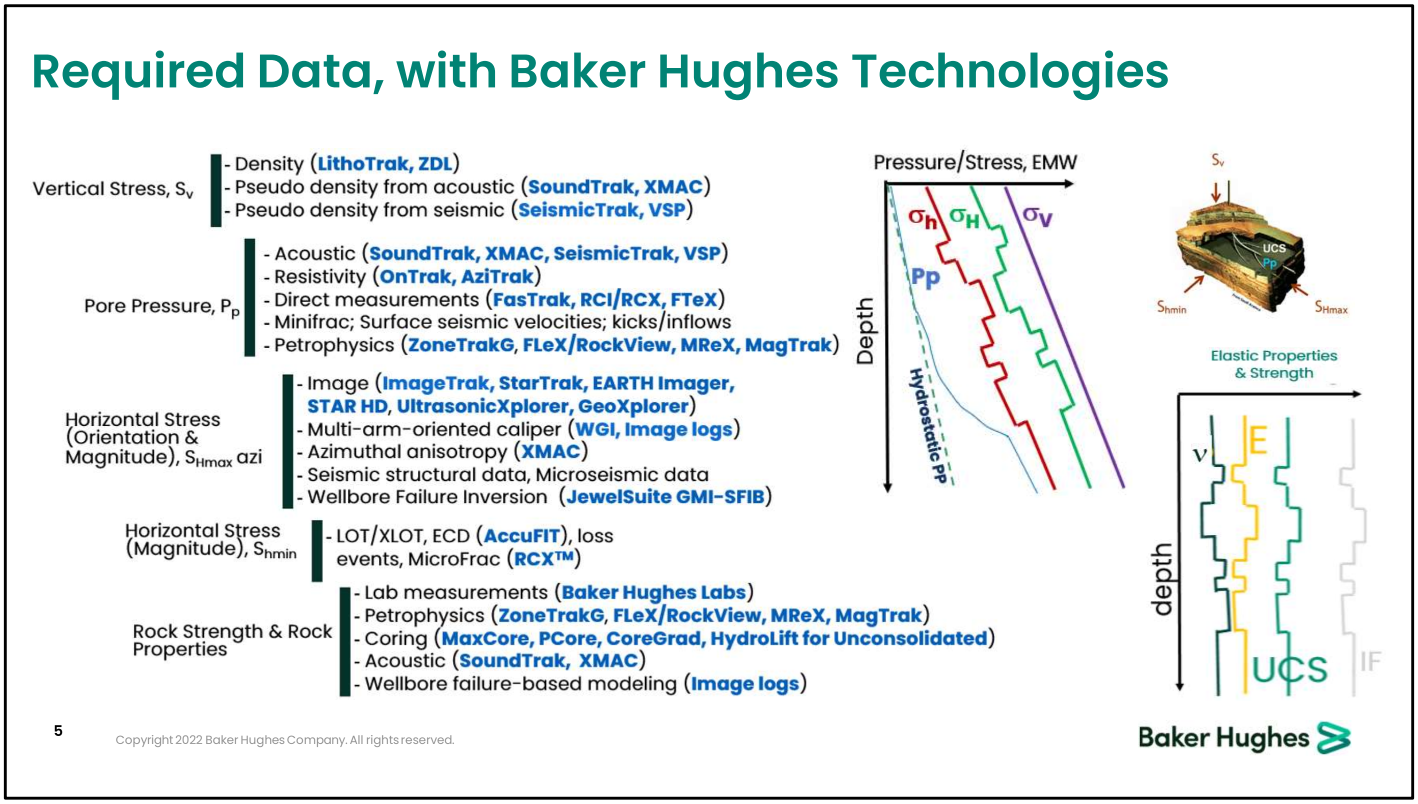


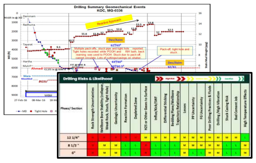
1D Geomechanics

3D Geomechanics

Wellbore Stability Analysis

Fault and Fracture Stability Analysis

Workflow: 1D Geomechanical Modelling

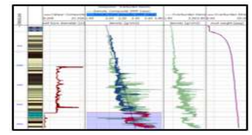


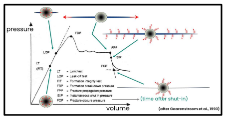
Drilling Reports Review

Drilling events

Vertical Stress (S_V)

Density and pseudo-density from sonic/seismic



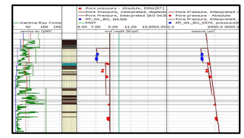


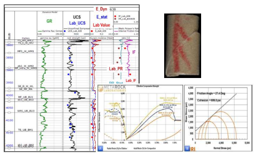
Shmin: Least Principal Stress

XLOT /LOT/FITs, frac data, total Lost Circulation.

P_p prediction

Direct measurements Log-based (acoustic, resistivity)
Seismic (ITT, velocity, Formation tests & drilling experiences)



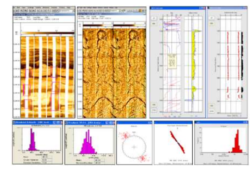


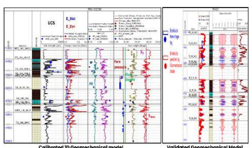
UCS: Rock Strength

Core tests, logs, cuttings analysis, wellbore failure analysis

S_{Hmax} Orientation

Analysis of wellbore failure in image/caliper



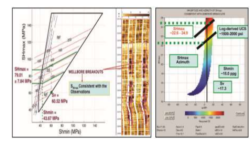


Model Verification

Drilling experiences and image/caliper

S_{Hmax} Magnitude

GMI•SFIB-assisted modeling



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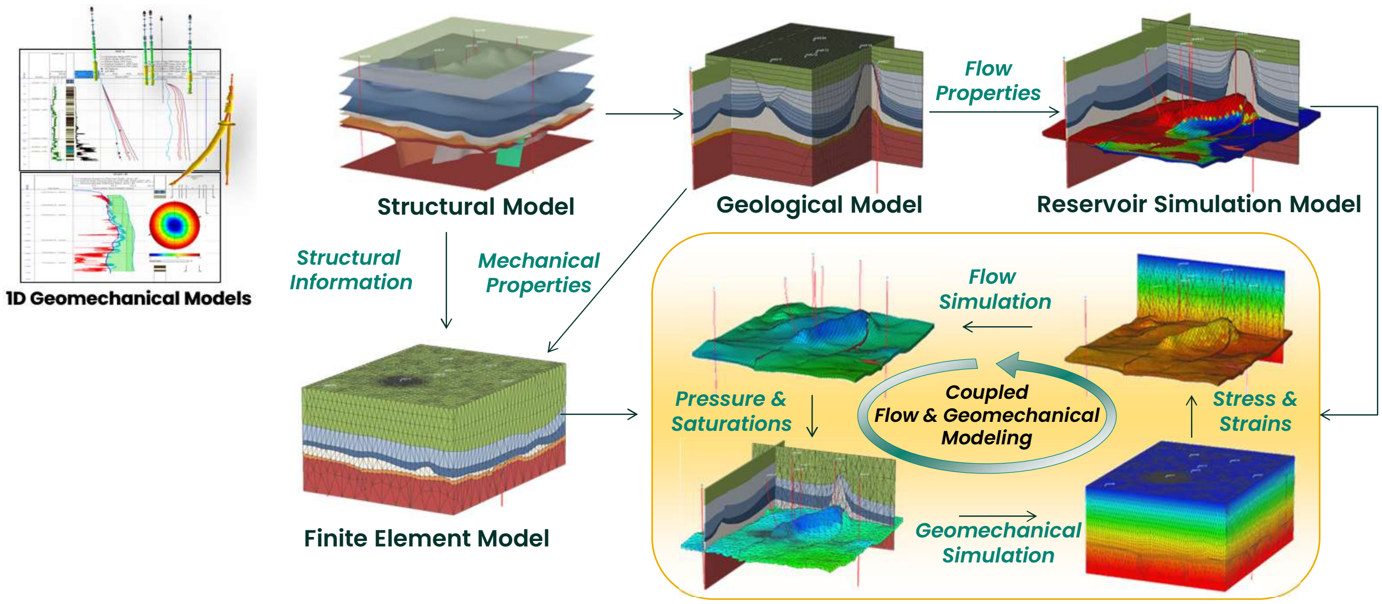
Workflow: 3D/4D Geomechanical Modelling



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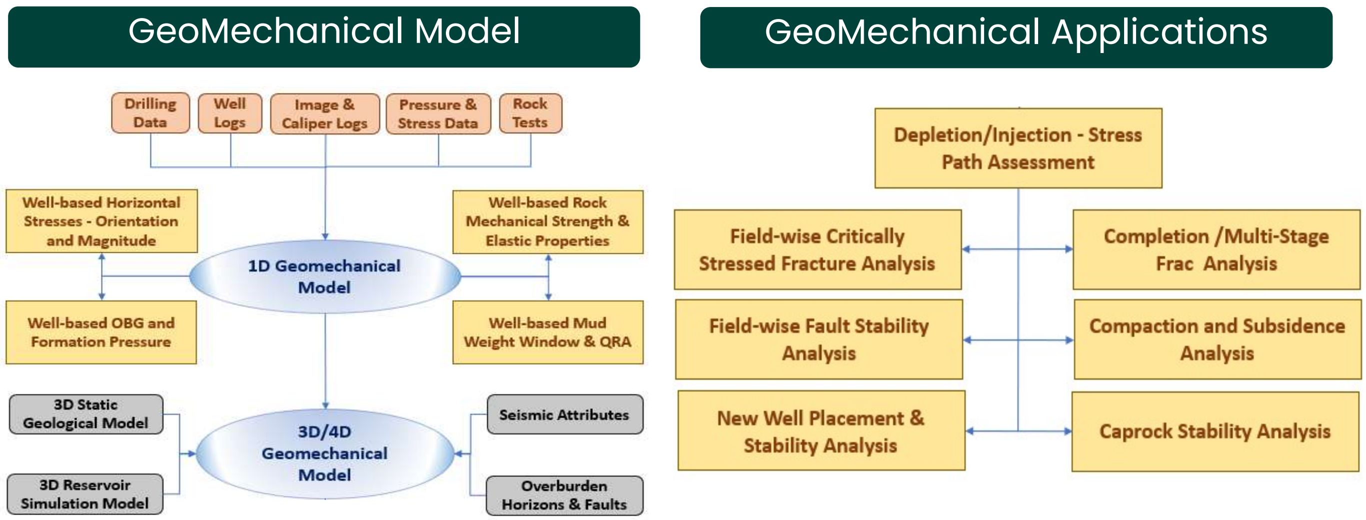
Stress & Strains relates to porosity and permeability changes; for two-way coupling, this changes are updated regularly to perform the flow simulations

Geomechanics Workflow of a Typical Study



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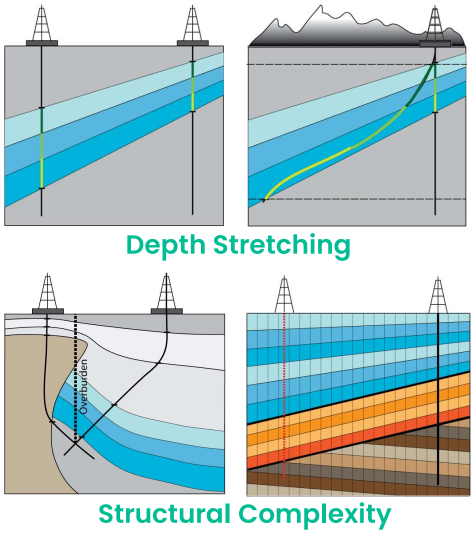
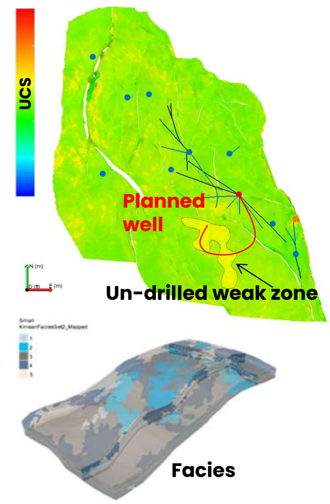
3D Geomechanics – Static Model



1D vs 3D Geomechanics

Challenges:
- Depth stretching will not work in complex settings
- 1D models do not capture property variations along highly deviated well paths
- Integration of Subsurface models & interpretations

Solution:
- Workflow to construct & fill the 3D grid with geomechanical properties
- Integrate specialized geophysical analysis (Elastic Inversion)



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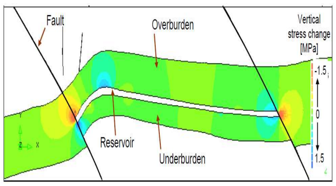
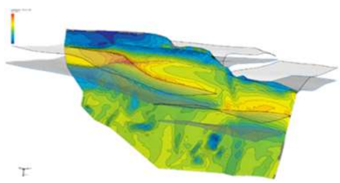
4D Geomechanics – Dynamic Model

Cost estimate:
*"…Due to seabed subsidence, the Ekofisk complex in the North Sea was sinking by approximately 40cm/yr and had reduced the safety air gap of 20m to 16.3m between the platform decks and storm waves. In order to compensate for the subsidence of six platforms, the 'jack up' project was born with a criteria to create a 23m 100 year 'design wave' by extending the platform legs and raising the decks 6m. This was the largest lift and most prestigious project in the world at the time with a total value of **£400 million**, and for IMH Commissioning Engineers the most challenging and rewarding undertaken at that time…"*

http://www.conocophillips.no/PublishingImages/Ekofisk_Complex_Press-Photo3.jpg
http://subseaworldnews.com/2012/08/15/subsea-7-to-conduct-underwater-operations-on-norwegian-ekofisk-field/
http://www.imh-uk.com/wp-content/uploads/2012/10/Deck-Elevation-Project-for-Ekofisk-Oil-Platform-Field-Subsidence.pdf



Field



Faults

3D Static vs 4D Geomechanics

Challenges:
- Complex material behavior
- Load transfer at the flanks of reservoirs
- Stress field around creeping materials (e.g. salt)
- The change in stress magnitudes with reservoir depletion ('Stress Path', $A=\Delta S/\Delta P_p$)
- Reservoir compartmentalisation
- Stress continuity across faults

Solution:
- Get rid of invalid assumptions
- Finite Element Analysis (3D stress analysis) using Abaqus/FEA (Simulia, Dassault Systèmes) and JewelSuite™ (Baker Hughes Inc.)

Value:
- Realistic models for stress changes, surface subsidence, fault-reactivation, sand production prediction, casing deformation

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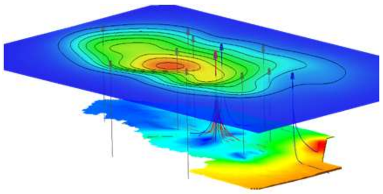
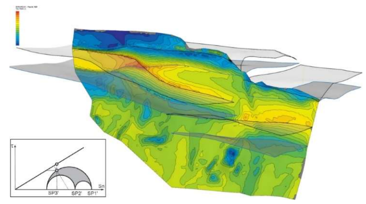
Geomechanics - Applications

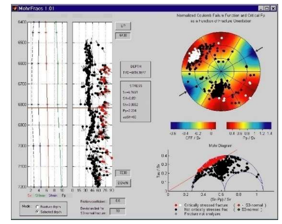
Compaction & Surface Subsidence



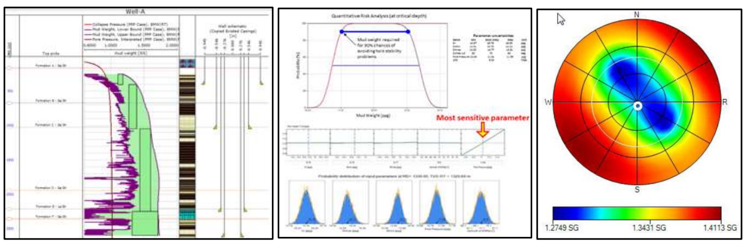
Fault Stability Analysis



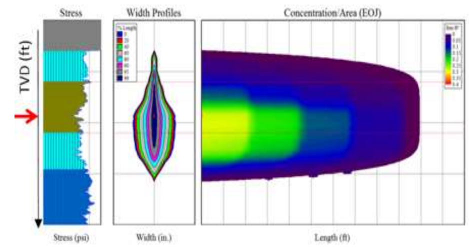
Critically-Stressed Fracture Analysis



Wellbore Stability Analysis



Hydraulic Fracturing Analysis



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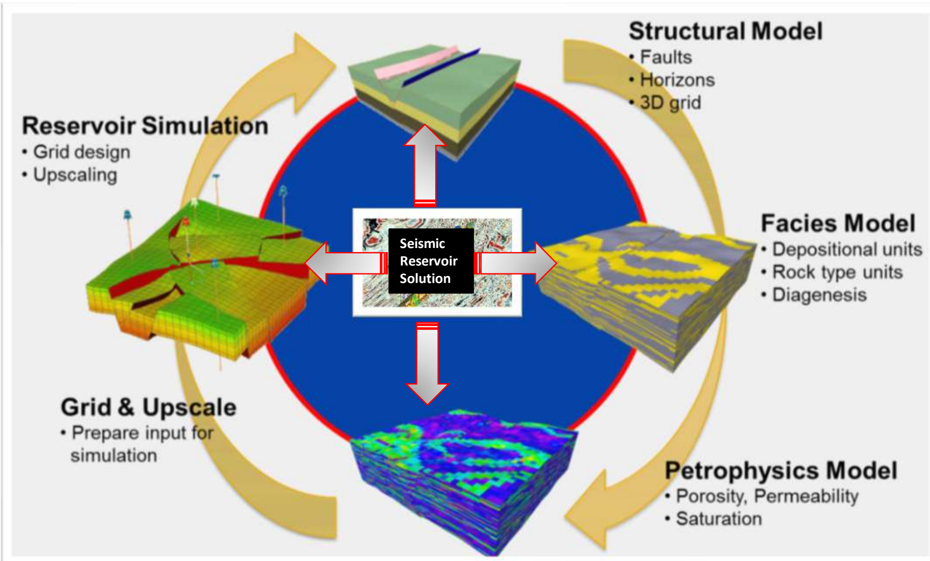
Seismic Reservoir Solution Support



Different elements of the 3D Seismic contribute to multiple disciplines within Baker Hughes Reservoir Technical Services

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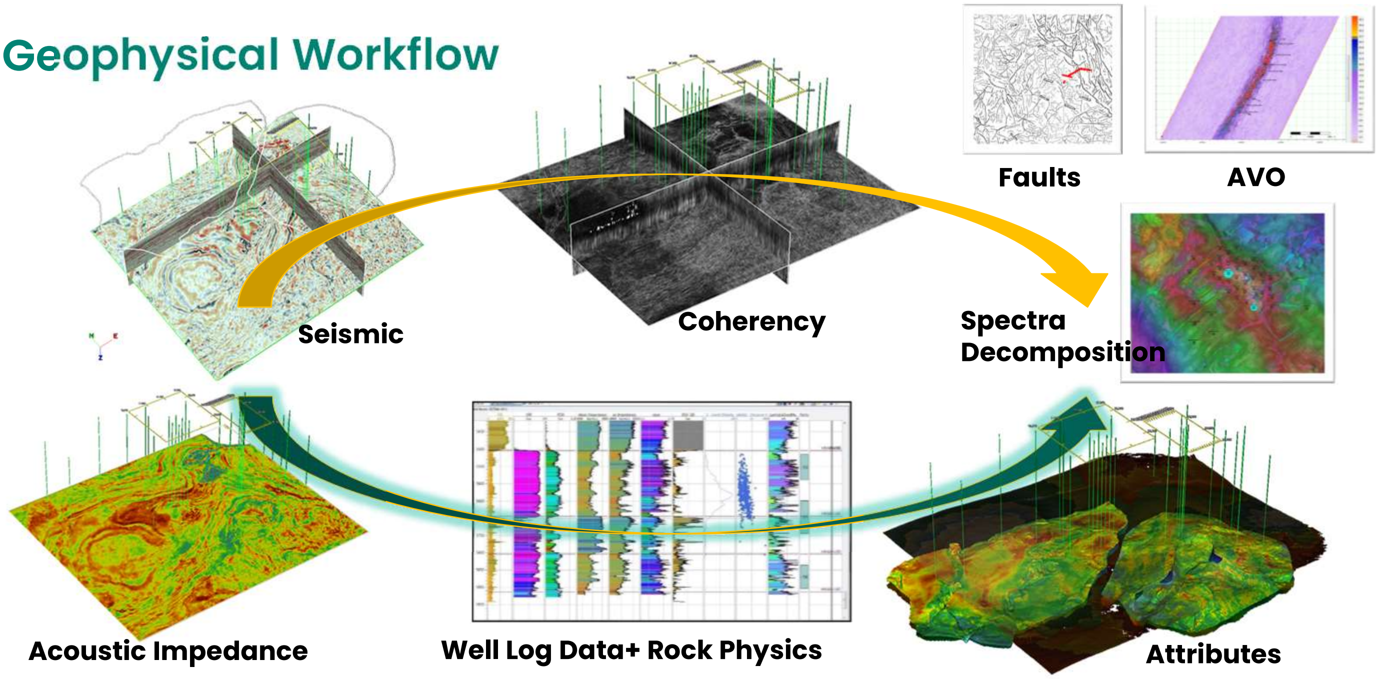
Geophysical Workflow

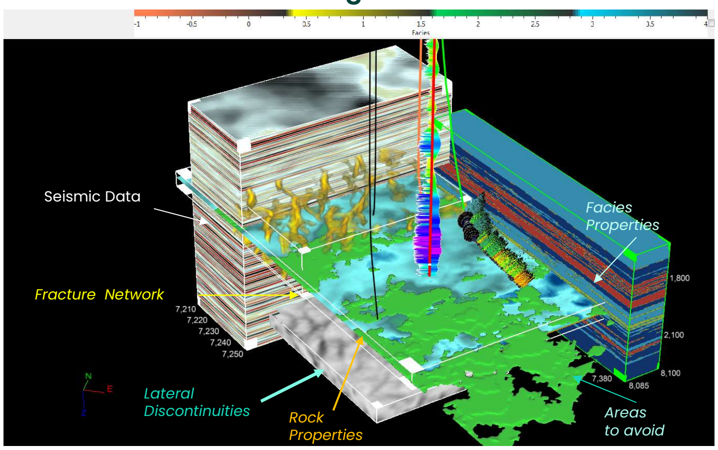


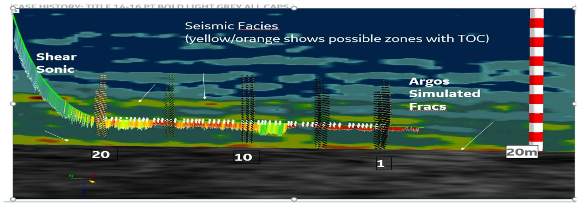
One path for Faults, AVO, Fractures, geometry attributes (independent of wells)
Another path for Inversion, Seismic rock classification, Seismic derived properties

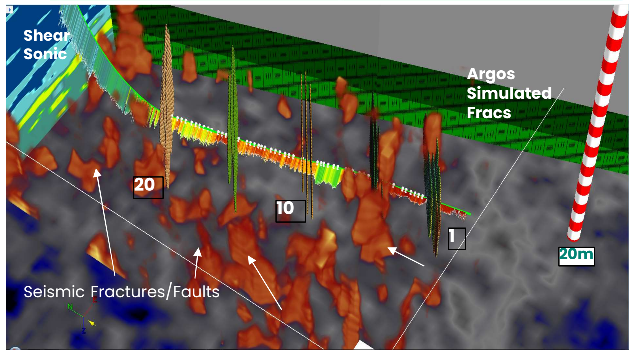
Pre-stack

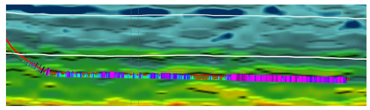
Seismic Attributes from PSTM elastic inversion and other Image results were generated to incorporated together with the Structural components into the geo modeling for fracking simulation and prediction of the wells to be drill

Seismic Integration









Rock Types using
P-wave, S-fast and S-slow
S-impedance seismic

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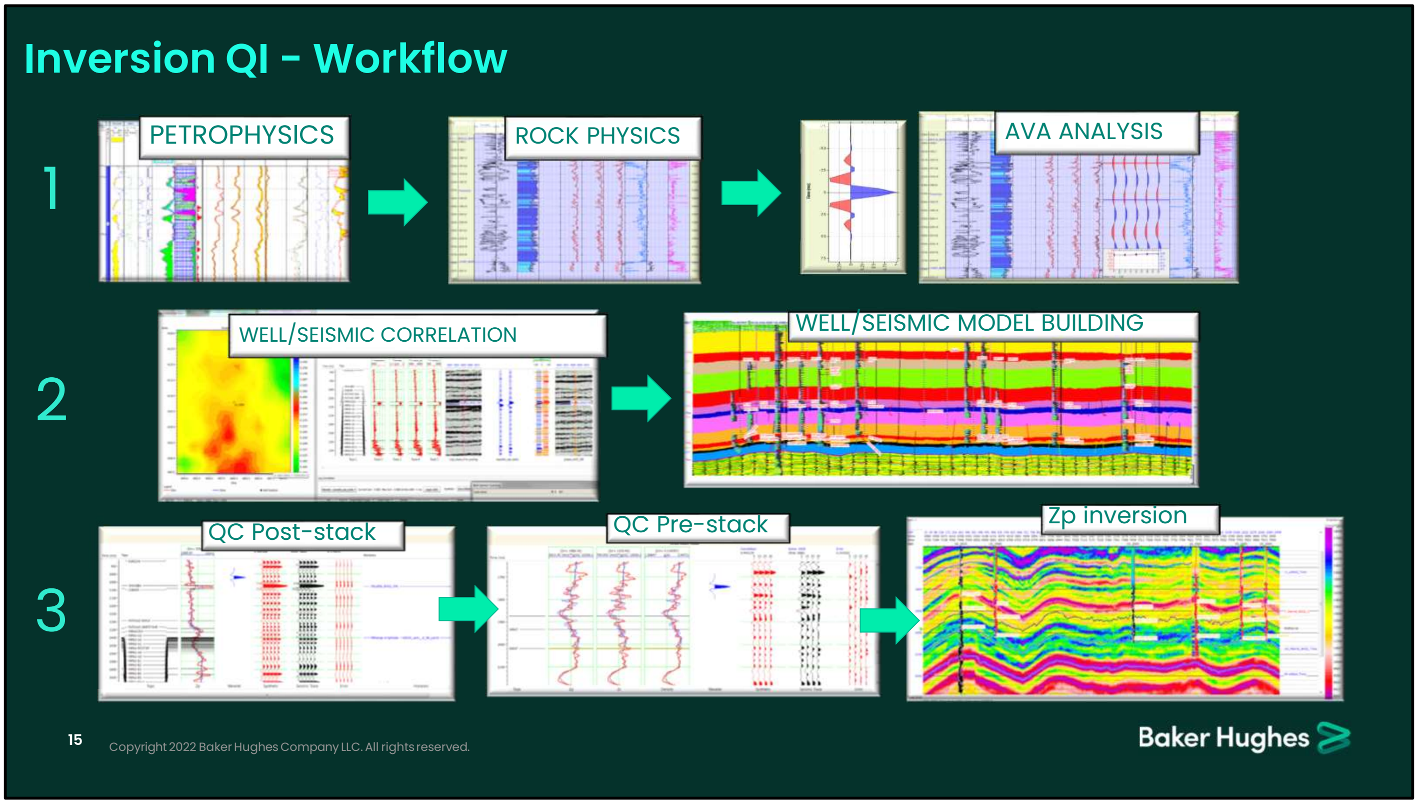
Inversion QI - Workflow
1
PETROPHYSICS
ROCK PHYSICS
AVA ANALYSIS
2
WELL/SEISMIC CORRELATION
WELL/SEISMIC MODEL BUILDING
3
QC Post-stack
QC Pre-stack
Zp inversion
15
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Sources of Stress in the Crust

Plate driving stresses

- Ridge push force at mid ocean ridges
- Slab pull force from negative buoyancy of down-going slabs
- Collision resistance forces
- Transform faults resist plate motion
- Suction force acting on continental lithosphere near subduction zones

Topography

- Large mountain chains can cause significant stress at depth
- Stress perturbations can occur from the removal of topographic loads such as ice sheets

Lithospheric Buoyancy

- Lateral variations in the thickness and density of the lithosphere

Lithospheric Flexure

- Bending occurs in the lithosphere as a result of localized loads

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Sources of Stress

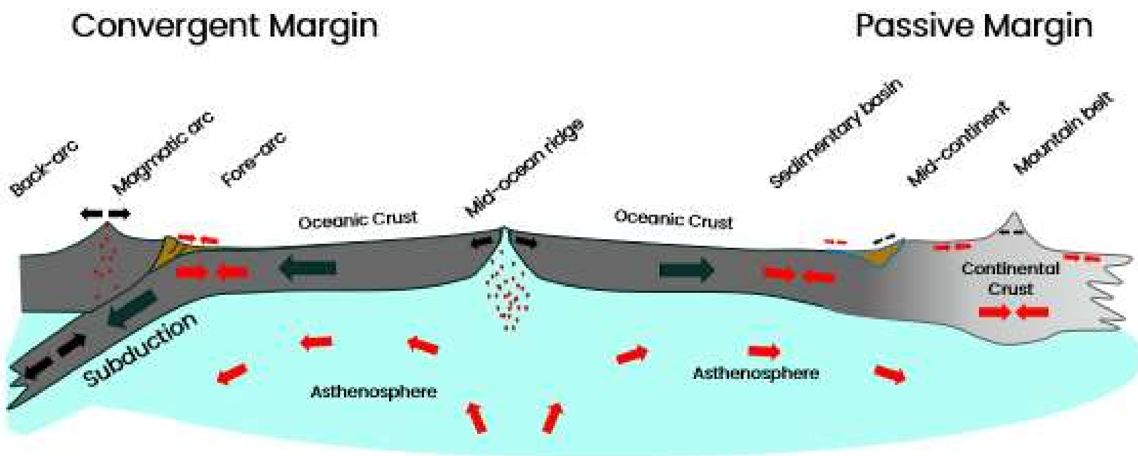

Plate Tectonic Stresses

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Broadly, plates are driven by the cooling lithosphere away from ocean spreading ridges and by the descent of cooled lithosphere back toward the center of the earth. Other driving forces include collision resistance forces, topographically-induced forces, and lithospheric bending and flexure.

Plate Boundaries and Associated Seismicity

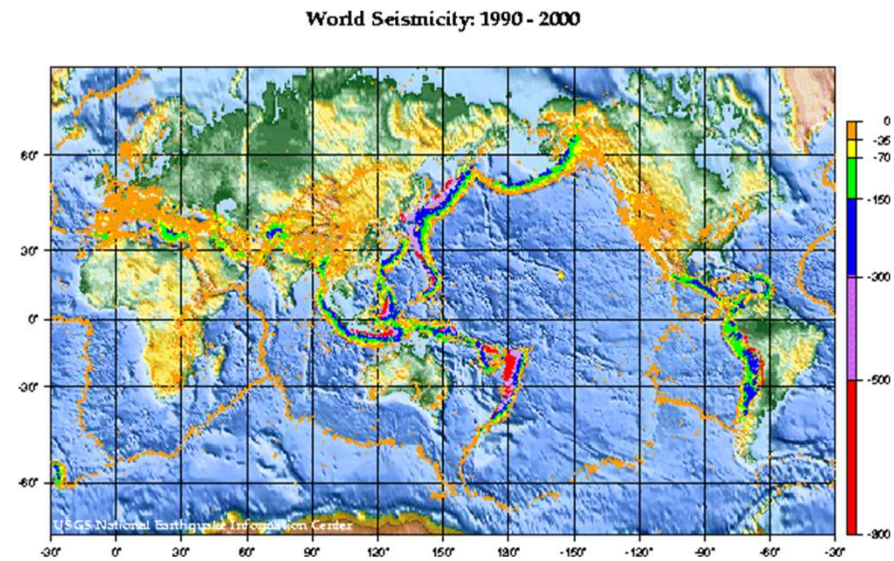

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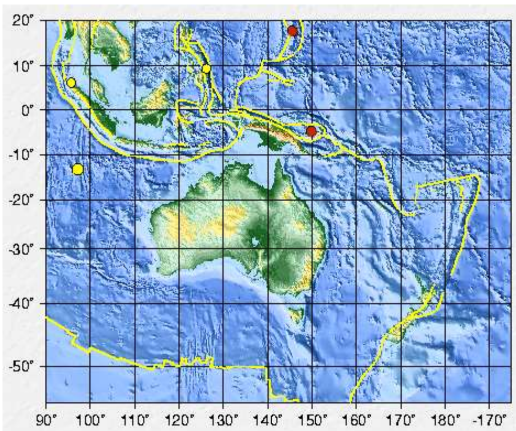
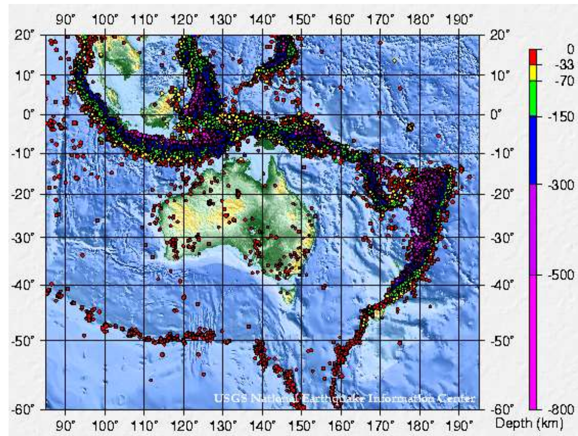
Plate Boundaries and Associated Seismicity





1977-1997

Earthquakes reflect internal deformation due to stress in the crust

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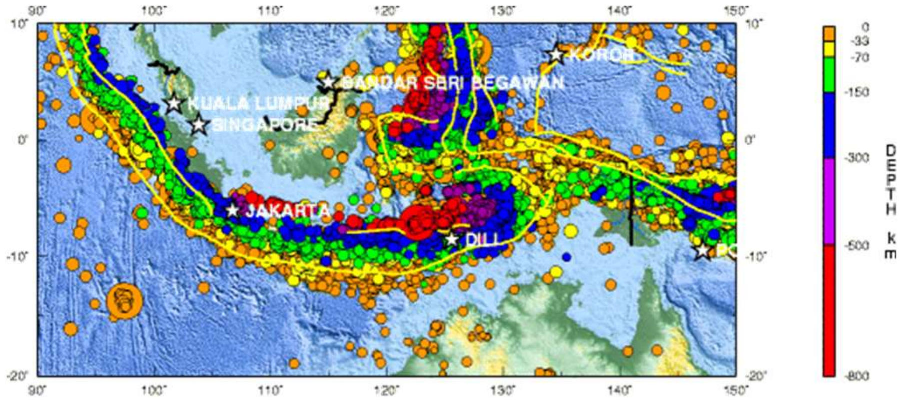
Seismicity of Indonesia (1990-2000)



Seismicity of Indonesia, 1990 - 2000

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Active subduction occurs along much of the Indonesian archipelago. The active tectonics of the area defines much of the observed stress orientations and magnitudes.

Global Stress Observations

- A uniform stress field exists through the upper brittle crust
  - ✓ Consistent orientations from different techniques which sample very different rock volumes and depth ranges
- Intraplate regions are dominated by compression
  - ✓ Thrust and strike-slip stress regimes
- Active extensional tectonism
  - ✓ Normal faulting stress regimes occur in topographically high areas
- Regional consistency of both stress orientations and relative magnitudes
  - ✓ Broad scale regional stress provinces may be defined, many of which coincide with physiographic provinces, particularly in tectonically active regions.

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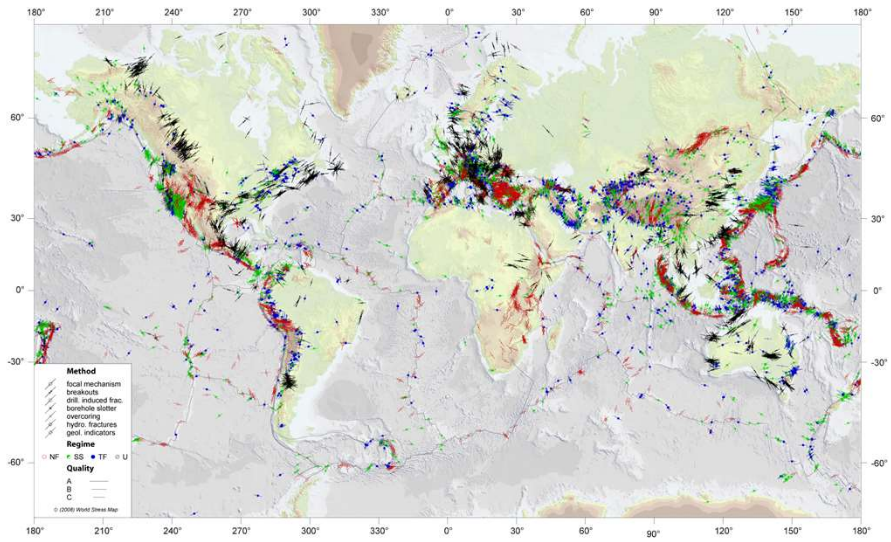
World Stress Map

The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.
(Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B.)



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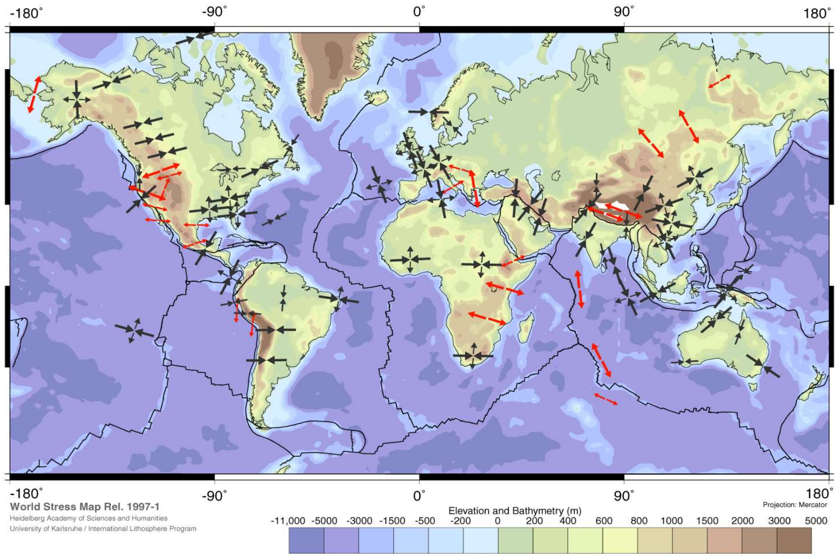
The world stress map is a publicly available database of maximum horizontal stress orientations throughout the world. Pre-made maps can be downloaded and the user can also create a custom stress map of a specific region using data from the database as well as the user's own private stress orientation data. These data may be used as a starting point for stress orientation and relative stress magnitudes if no other data exist. However, caution should be exercised, as the noise in the data due to possible poor quality control may lead to erroneous conclusions.
(http://www-wsm.physik.uni-karlsruhe.de/pub/home/index_noflash.html)

Generalized World Stress Map



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Generalized Global Stress Map. It delineates provinces of approximately uniform constant stress orientation and relative magnitude. In addition to stress orientations, relative stress magnitudes (stress regimes) are indicated using the following definitions: extensional stress regime ($S_v > S_{Hmax} > S_h$) (normal dip slip), includes categories NF and NS (rakes generally >50°); strike-slip stress regime ($S_{Hmax} > S_v > S_h$) (dominant horizontal slip), SS category (rakes generally >40°); and thrust stress regime ($S_{Hmax} > S_h > S_v$) (reverse dip slip), includes categories TF and TS (rakes generally >50°).. Stress regime was inferred primarily from earthquake focal mechanisms and style of Quaternary faulting. Thick inward pointing arrows indicate S_{Hmax} orientations in areas of compressional (strike-slip and thrust) stress regimes. Thick outward pointing arrows give S_{hmin} orientations in areas of normal faulting regimes. Regions dominated by strike-slip tectonics are distinguished with the thick inward pointing and orthogonal, thin outward pointing arrows.

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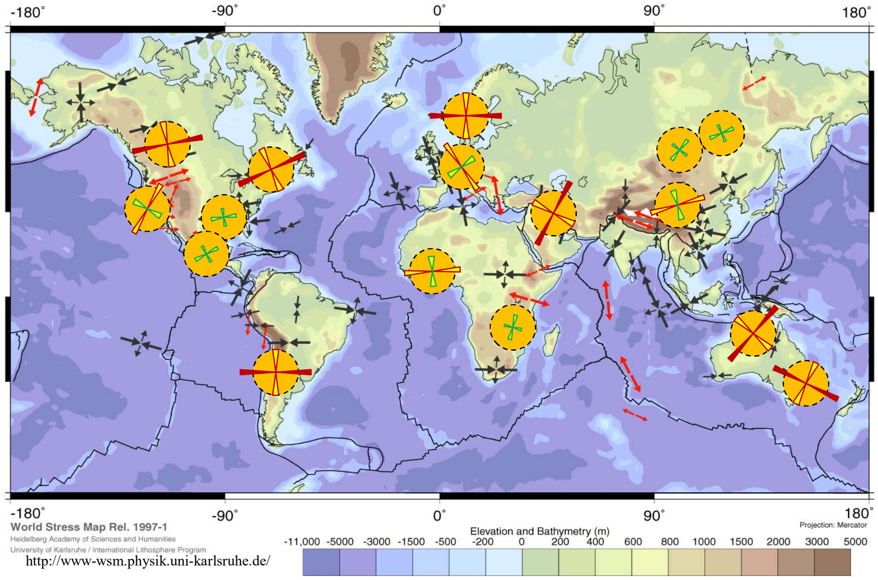
Relative Stress Magnitudes Vary



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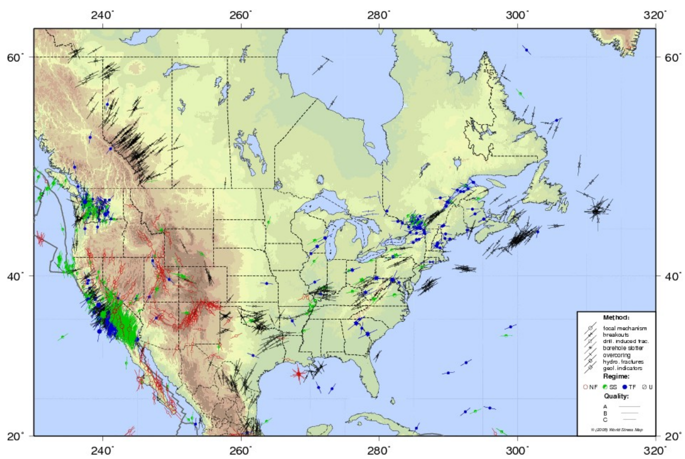
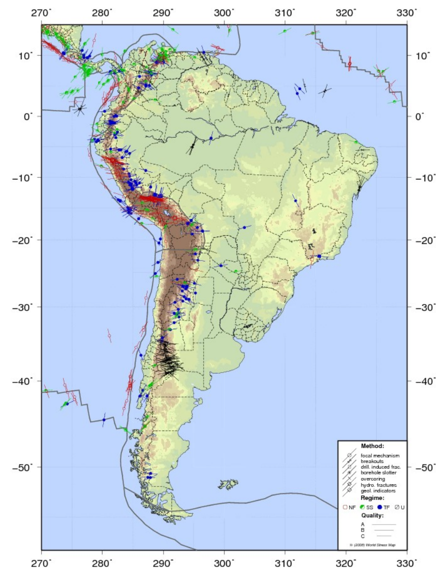
World Stress Maps



North America



South America

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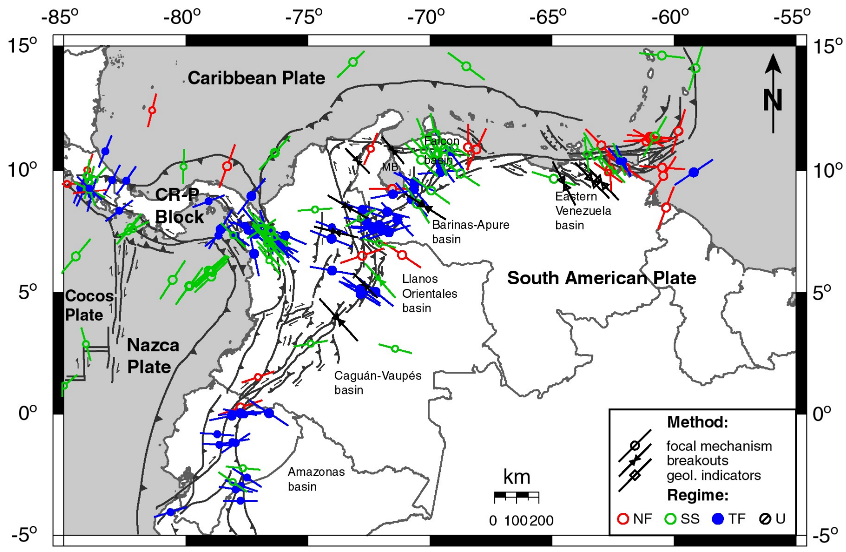
Stress Orientations in Northern South America



Colmenares and Zoback (2003)

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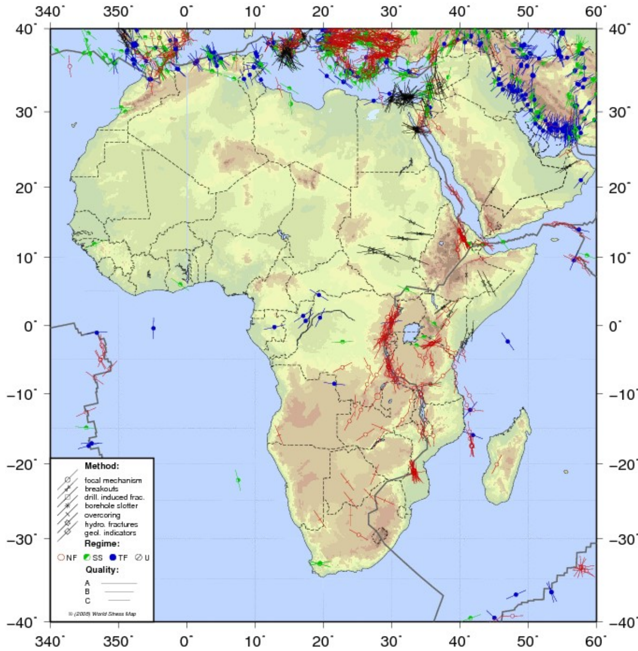
Stress orientations from earthquake focal plane mechanisms generally show a thrust faulting stress regime in the Andes that transitions to a strike-slip faulting stress regime east of Lake Maracaibo, and that further transitions to a normal faulting stress regime offshore eastern Venezuela. The stress orientations, relative magnitudes, and styles of faulting observed in the region are consistent with the overall direction of plate motion.

World Stress Map – Africa & Mideast



Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

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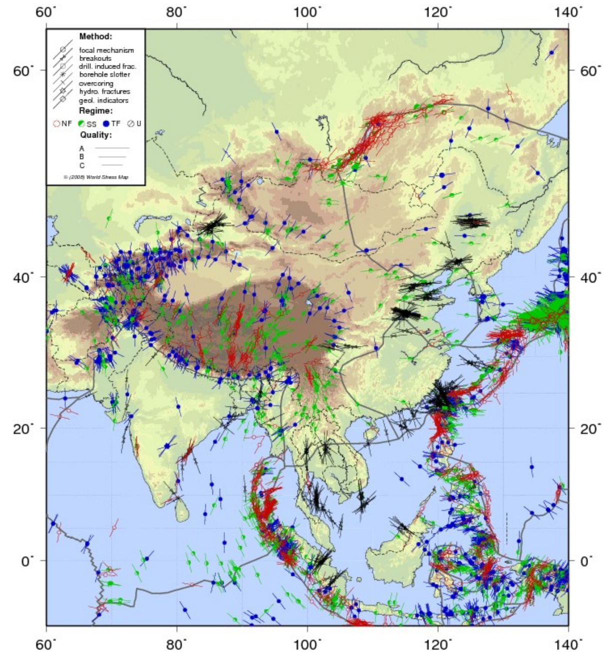
World Stress Map – Eastern Asia



Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

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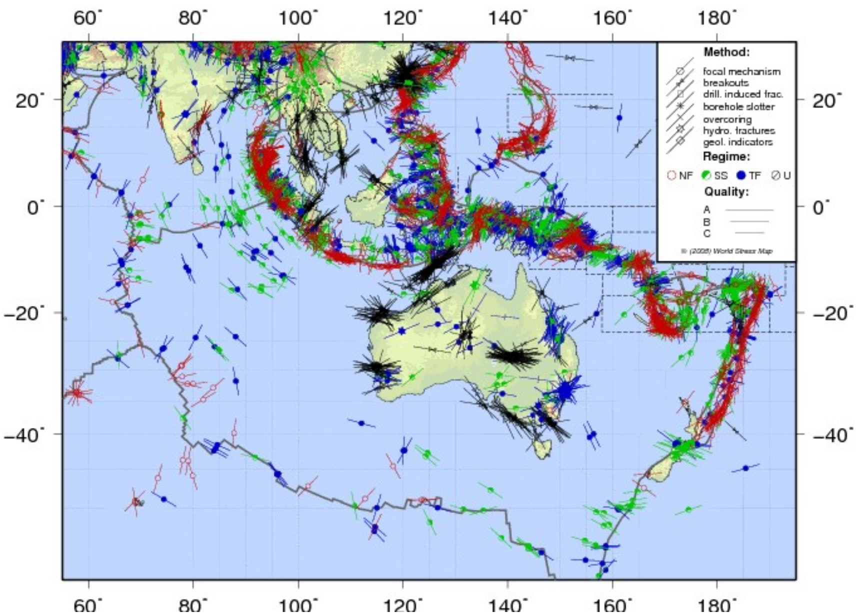
World Stress Map – Australia



Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. and Müller, B., The World Stress Map database release 2008 doi:10.1594/GFZ.WSM.Rel2008, 2008.

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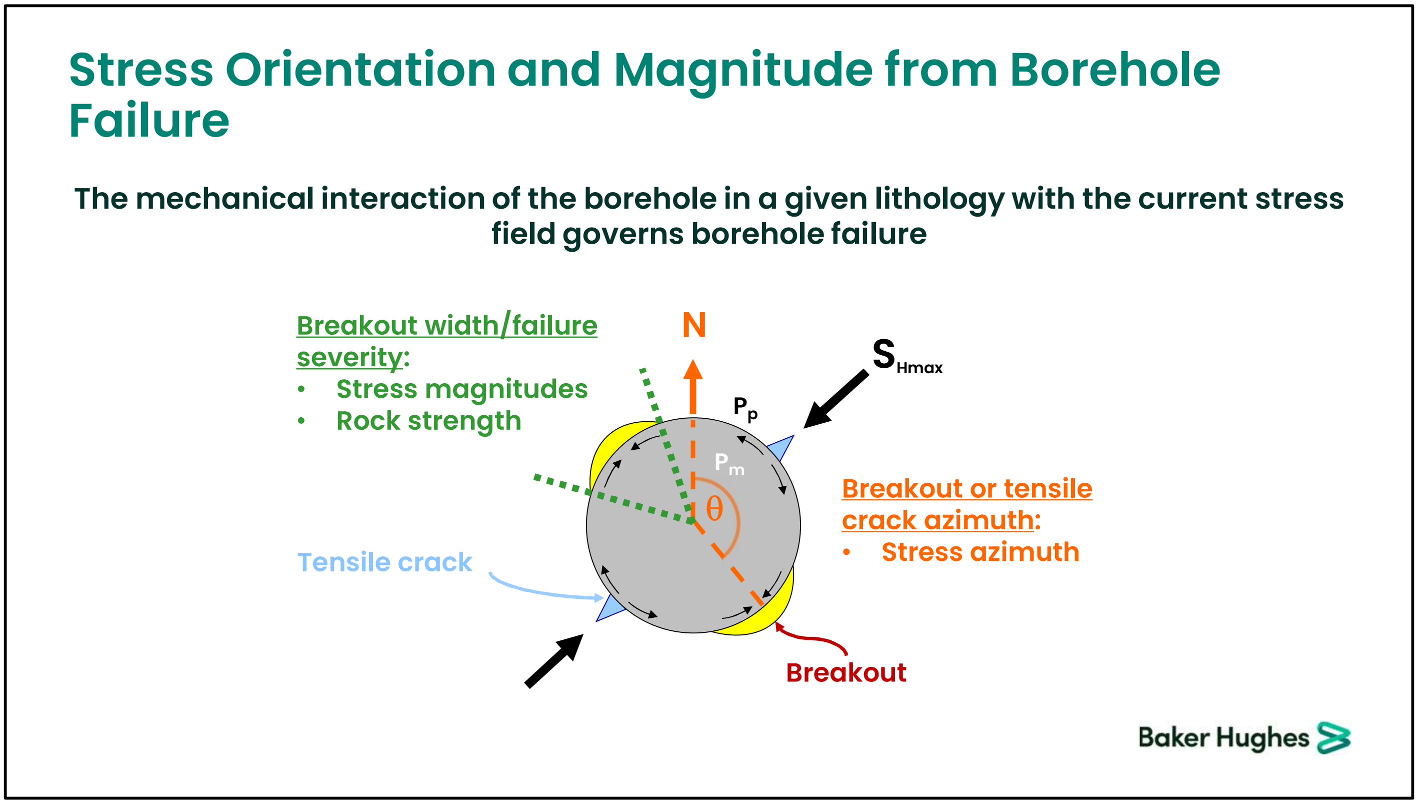
The world stress map is a publicly available database of maximum horizontal stress orientations throughout the world. Pre-made maps can be downloaded and the user can also create a custom stress map of a specific region using data from the database as well as the user’s own private stress orientation data. (http://www-wsm.physik.uni-karlsruhe.de/pub/home/index_noflash.html)

Methods for Estimation of Maximum Horizontal Stress Azimuth

S_{Hmax} azimuth can be obtained from:

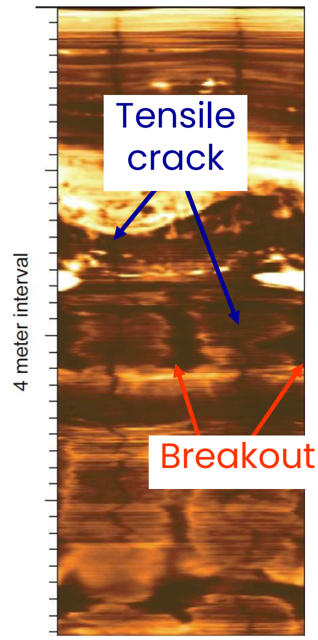
- Orientation of drilling-induced tensile fractures in vertical wells (image logs)
- Breakout orientation in vertical wells provides S_{hmin} azimuth (image logs or oriented 4- or 6-arm caliper data). S_{Hmax} azimuth = S_{hmin} azimuth $\pm$ 90°
- Inferences from ACTIVE structures (seismic, bathymetry maps, outcrop data, etc.)
- Earthquake focal plane mechanisms (inversion of multiple earthquake events is required for accurate S_{Hmax} azimuth)
- Stress-induced acoustic anisotropies – problematic because acoustic anisotropies are caused by a variety of factors, not just stress (cross dipole acoustic, multi-component seismic)

Baker Hughes

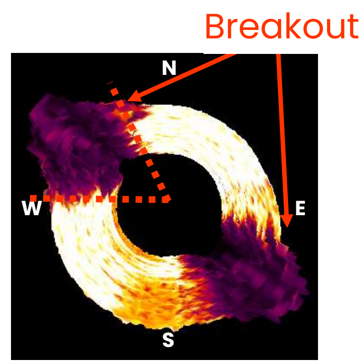


A stress concentration is set up around the wellbore when the rock that previously supported the far-field stresses is removed. The mud weight in the hole must support the stresses previously supported by the removed material. The stresses are concentrated at the wellbore wall, with the stresses becoming less compressive in the orientation of the maximum horizontal stress and more compressive in the orientation of the minimum horizontal stress. If the stresses in the orientation of SHmax exceed the tensile strength of the rock then a small tensile crack will form. If the stresses in the orientation of Shmin exceed the compressive strength of the rock then a compressive failure or "breakout" will form.

Examples of Wellbore Failure



This well is failing in both compression and in tension



Important: This failure is often not catastrophic and does not adversely affect drilling.

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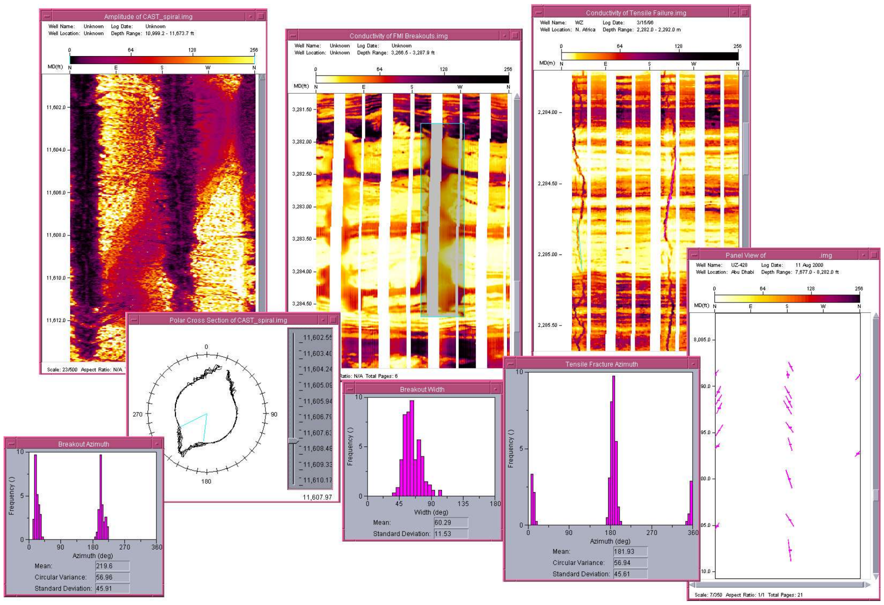
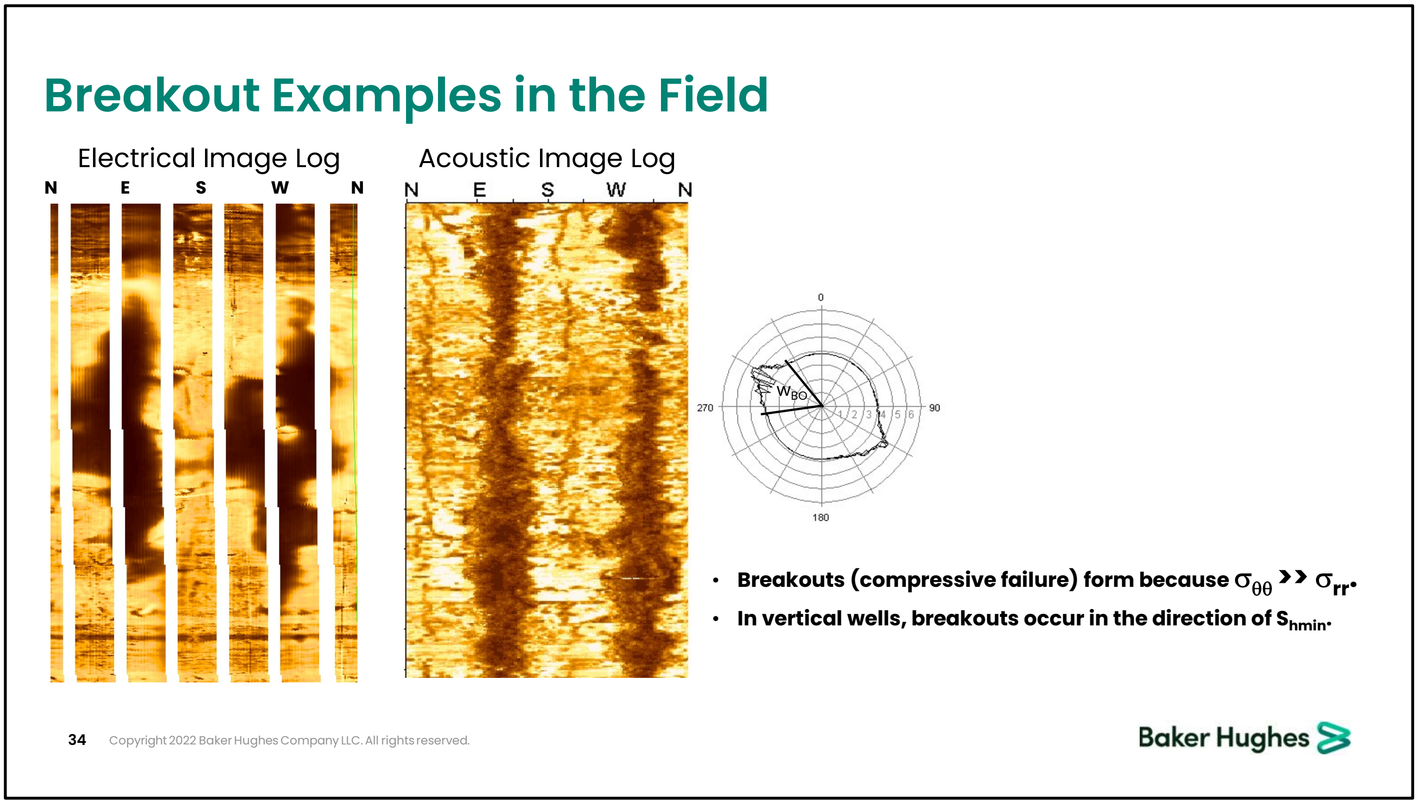
This is a view of acoustic wellbore image data showing the development of both compressional (wellbore breakouts) and tensile (tensile wall fractures) failures developed over the same well interval. As theoretically predicted, the tensile wall fractures form at 90° to wellbore breakouts. The polar cross-sectional view of the breakouts clearly shows the width and depth of these wellbore features. Breakout orientation provides information on the direction of the least horizontal principal stress in vertical wells, and breakout width gives us a way to constrain stress magnitude. The width of a breakout is a function of the stress magnitudes in the vicinity of the well and the strength of the rock. The weaker the rock the larger the breakouts. It is important to note that breakouts and tensile wall fractures provide important information on the state of stress in the reservoir. Wellbore breakout development can usually be controlled (breakout width <90 °) by drilling with the proper mud weight. Some breakout development helps in building accurate geomechanical models.

GMI•Imager™ Wellbore Failure Analysis



Baker Hughes

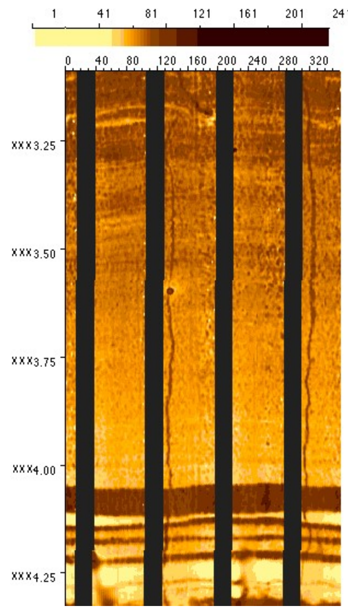
GMI-Imager is a fully-featured wellbore imaging analysis software tool with unique capabilities to measure and analyze compressional (breakouts), tensile (tensile wall fractures) wellbore failures.



Breakouts appear as out of focus zones in electrical image log data due to the pad being out of contact with the wellbore wall (left). In acoustic image data the breakouts appear as dark bands of varying width (middle). Acoustic data allows for the analysis of the wellbore in cross-section (right).

Drilling-Induced Tensile Fractures

- Drilling-induced tensile fractures form because $\sigma_{\theta\theta}$ is lower than the tensile strength of the formation.
- In vertical wells, drilling-induced tensile fractures occur in the direction of S_{Hmax}.



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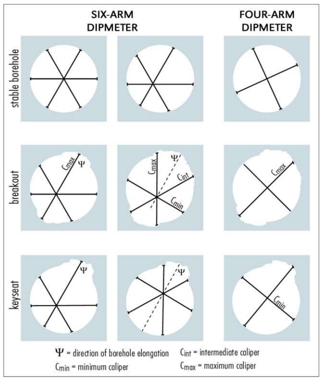
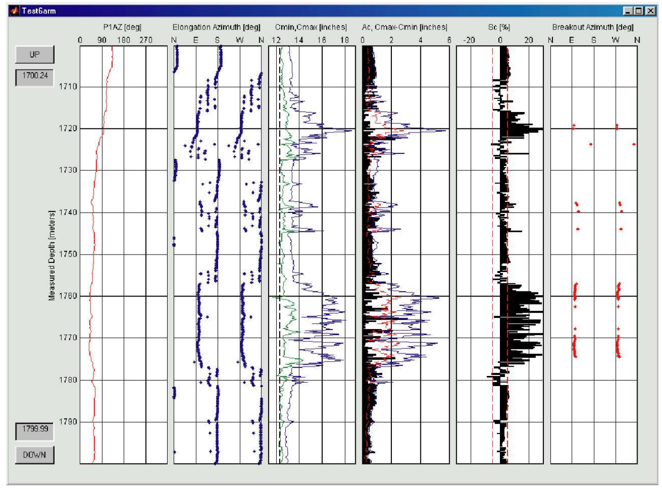
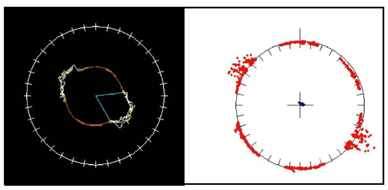
Drilling-induced tensile fractures appear as thin dark bands approximately parallel with the axis of a vertical wellbore occurring 180 degrees apart in the image.

GMI•Caliper™ Wellbore Failure Analysis





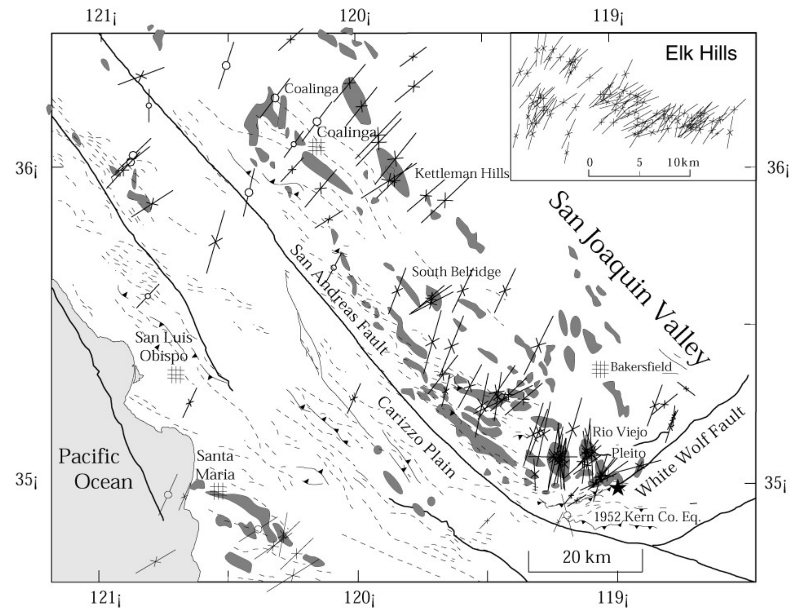


Rapid, accurate 4 and 6-Arm caliper analysis for wellbore failure

Baker Hughes

GMI-Caliper provides a rapid accurate analysis of 4 and 6 arm caliper data. The interpretation of six-arm caliper data for breakout identification is significantly more complicated than the interpretation of four-arm data. GMI•Caliper implements an innovative new analysis technique for detecting breakouts in six-arm caliper data. Our proprietary algorithm utilizes the individual caliper measurements from each arm to align the tool center with the borehole axis and differentiate between symmetrical elongations (wellbore breakouts) and asymmetrical elongations (keyseats).

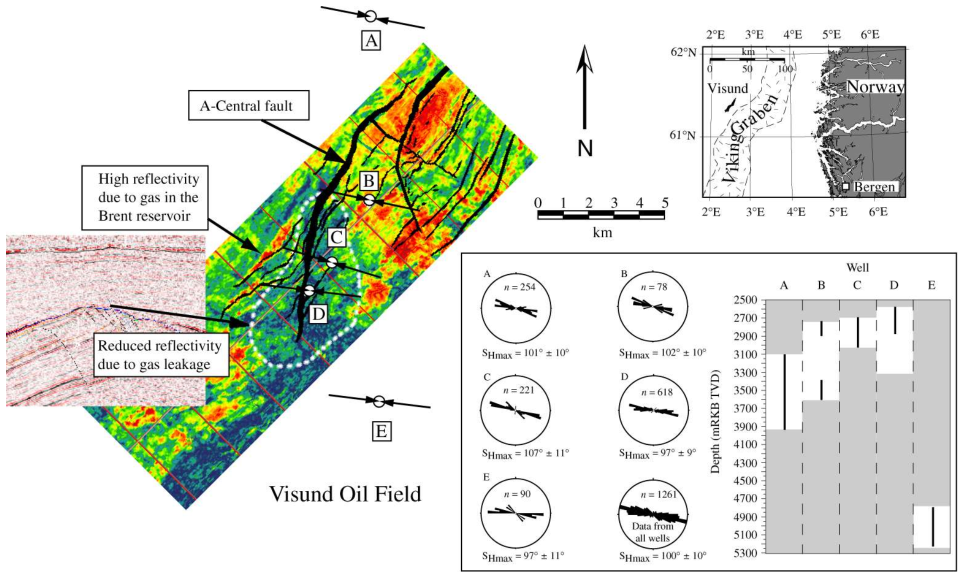
S_{Hmax} Azimuths in Central California (From Breakouts and Earthauakes)



Baker Hughes

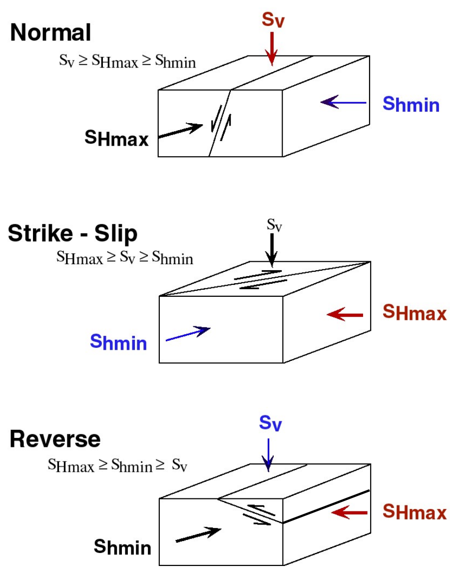
High-quality measurements of the orientation SHmax from observations of wellbore failure from individual wells and from well-located earthquake focal mechanism provide understanding of the regional tectonic stress field. Stress orientation can be regionally consistent over broad areas as they are in the upper San Joaquin Valley or they can deviate from the regional trend as they do in close proximity to he White Wolf fault in the Southern San Joaquin Valley. The cause of the rotation of the stresses in the southern San Joaquin Valley is the stress drop associated with the 1952 Kearn County earthquake that caused a local perturbation of the regional stress field in the vicinity of the White Wolf Fault.

S_{Hmax} Azimuths From Tensile Fractures



Map view of the Visund field showing the seismic reflectivity of the reservoir horizon as well as the mean orientation of the maximum horizontal stress in five wells (A-E). High seismic reflectivity is shown with hot colors and is interpreted to be the result of gas trapped at the top of the reservoir. Low reflectivity is interpreted to be the result of gas leakage from the reservoir. The absence of gas in the low reflectivity region was confirmed by the observation of no free gas cap in wells C and D. Well B did encounter a free gas cap.

Stress from ACTIVE Structures



$S_1 = S_v$
$S_2 = S_{Hmax}$
$S_3 = S_{hmin}$

$S_1 = S_{Hmax}$
$S_2 = S_v$
$S_3 = S_{hmin}$

$S_1 = S_{Hmax}$
$S_2 = S_{hmin}$
$S_3 = S_v$

Fault geometries can provide important information on present-day stress state if they are representative of present-day tectonic processes.

Fault geometries can provide:

- Stress orientation
- *Relative* stress magnitudes

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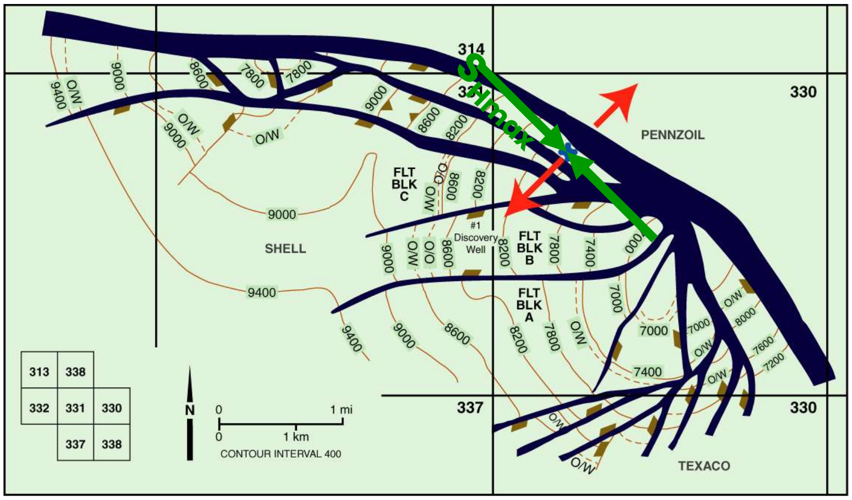
The relative magnitudes of the vertical stress (Sv), maximum horizontal stress (SHmax) and minimum horizontal stress (Shmin) define the stress regime. In a normal faulting stress regime Sv is the maximum principal stress, SHmax is the intermediate principal stress and Shmin is the least principal stress. In a strike-slip faulting stress regime SHmax is the maximum principal stress, Sv is the intermediate principal stress and Shmin is the least principal stress. In a reverse faulting stress regime Sv is the least principal stress, Shmin is the intermediate principal stress and SHmax is the maximum principal stress. The stress regimes define types of faulting that would be likely if the stress differences are high enough.

S_{Hmax} azimuths Inferred from Active Structures (Normal Faulting)



The measured S_{Hmax} orientation is roughly parallel to the strike of a major active growth fault.

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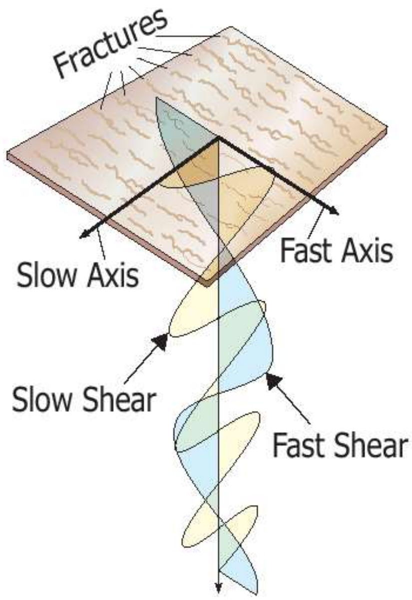
Active growth faults bounding a GOM minibasin constrain the orientation of the stress field around the fault.

The stress orientation from breakouts varies significantly across this field in a tectonically-active area.

Shear Wave Splitting in an Anisotropic Medium



(illustration from Boness and Zoback, 2003)

Baker Hughes

This vertically fractured block represents an idealized anisotropic medium where the fracture strike is perpendicular to the borehole axis. The tool induced shear wave will split as it enters this block into two shear waves. The two shear waves will propagate with different wave speeds. The faster one is called the fast shear wave and the slower is called the slow shear wave. The difference in speed between the two shear waves is a measure of formation anisotropy. The shear wave speed will be different around the borehole depending on the direction it is measured - this is what defines the shear wave azimuthal anisotropy around the borehole.

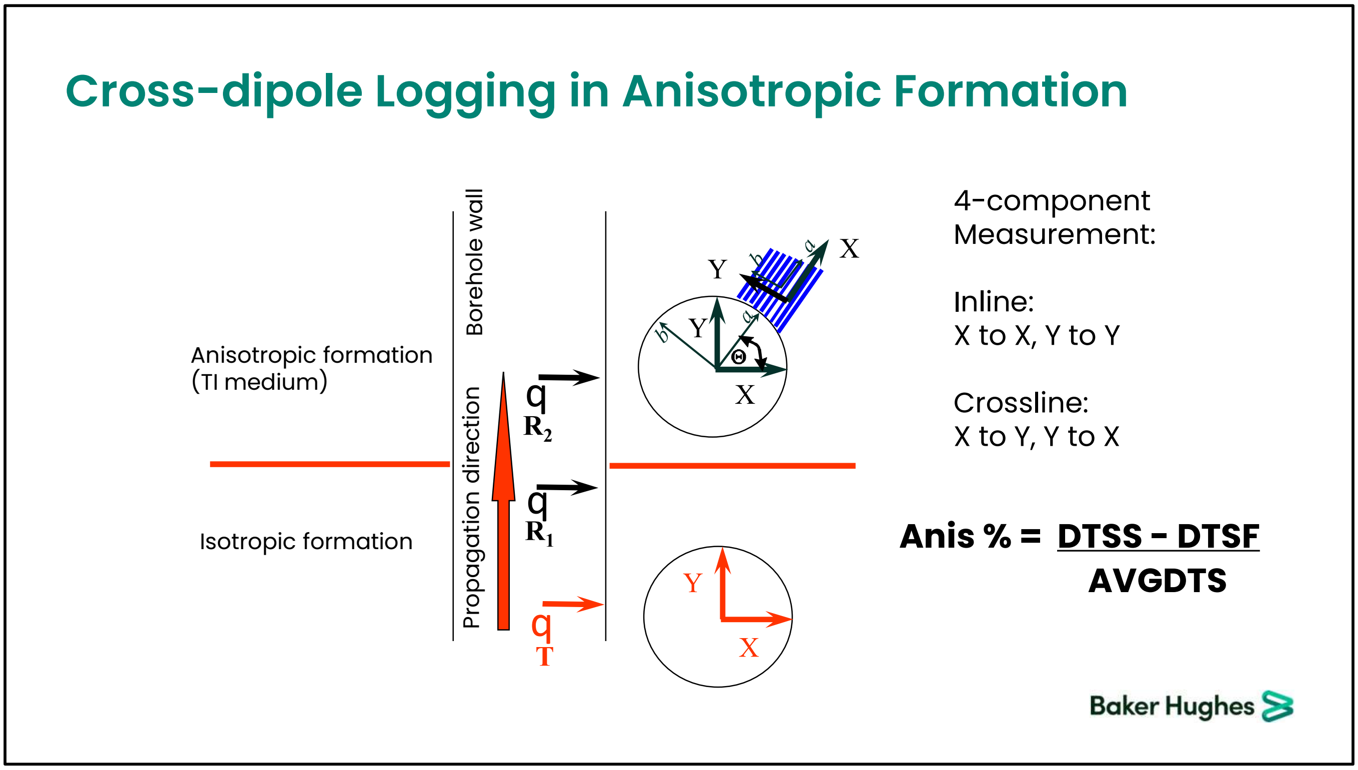
Cross Dipole Sonic (Theory)

Definition: Anisotropy is the variation of material property depending on the direction in which it is measured

Dipole tools generate bending modes

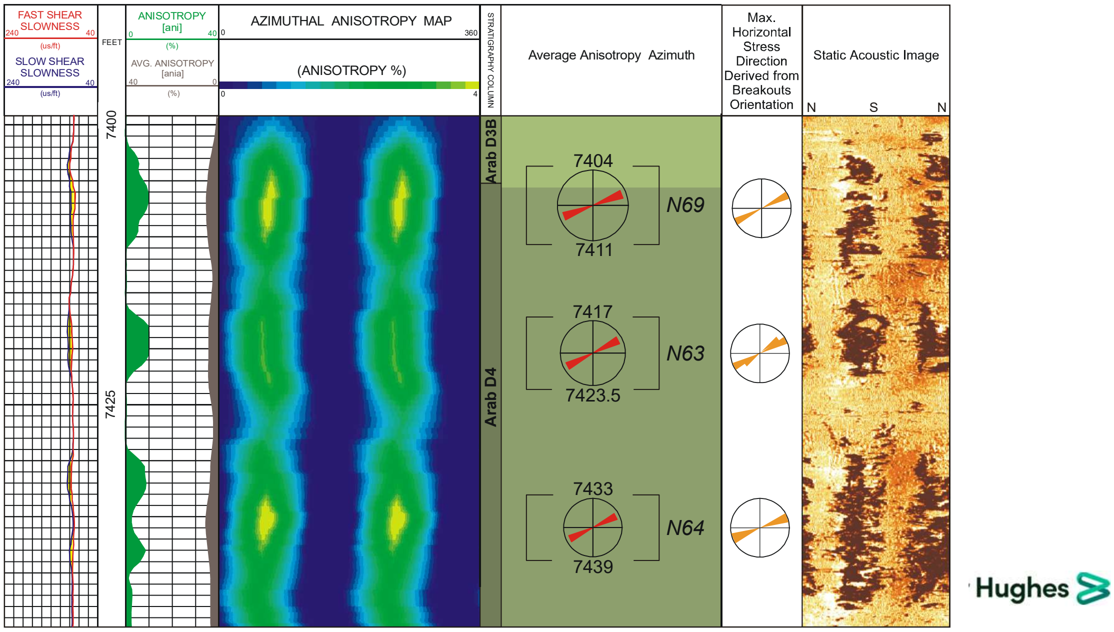
- In anisotropic rock one mode travels faster
  - anisotropy can be intrinsic (bedding; fractures; stratigraphy)
  - anisotropy can be stress-induced
- If anisotropy is stress-induced, the fast mode particle motion in a vertical well is parallel to S_{Hmax} (at low frequency)
- Velocity difference is a function of stress difference among other things
- Anisotropy is significant mostly in sands (but not all sands!)
- Dipole data is less sensitive to anisotropy induced by stresses in shales. This is due to lower horizontal stress differences and larger amounts of intrinsic anisotropy

Baker Hughes



Measurement of this type of anisotropy has become possible with the new generation of acoustic tool, namely the cross-dipole tool, using the physics of shear-wave splitting. This tool possess two set of transmitters (X & Y) that are perp. to each other and two set of receivers (X & Y) that are per. to each other. The X receivers are aligned with the source X , so that their maximum sensitivity is in the X transmitter direction and the same for the Y receivers.

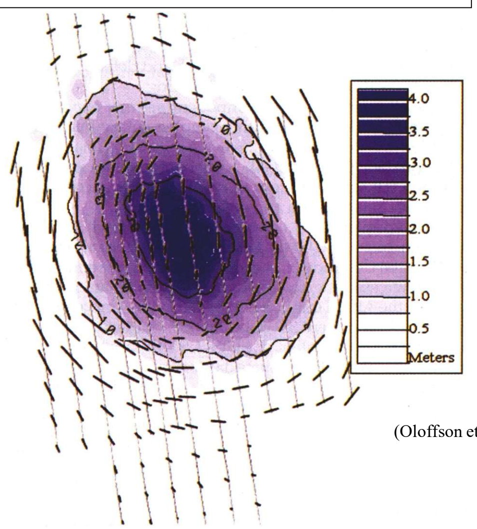
Stress Induced Acoustic Anisotropy and Borehole Breakout Orientations



Stress induced acoustic anisotropy has been shown in some cases to provide reliable stress orientations. In areas where the anisotropy is high the orientation is measured and compared to the orientation of the maximum horizontal stress determined from breakouts. The stress orientations are closely aligned using the two different methods.

Can Stress Orientations be Determined from Seismic?

Acoustic Anisotropy Directions in Valhall Field
Based on Multi-Component Seismic
(Near Surface Compared to Subsidence)



(Oloffson et al., 2003)

Challenges:

- As with cross dipole acoustic, is anisotropy due to stress?
- Difficult to obtain accurate anisotropy directions near reservoir depth (shear-wave splitting analysis has to be performed layer by layer, starting with the shallowest, so errors are cumulative with depth)
- Stress orientation from seismic remains an unproven methodology with many potential pitfalls

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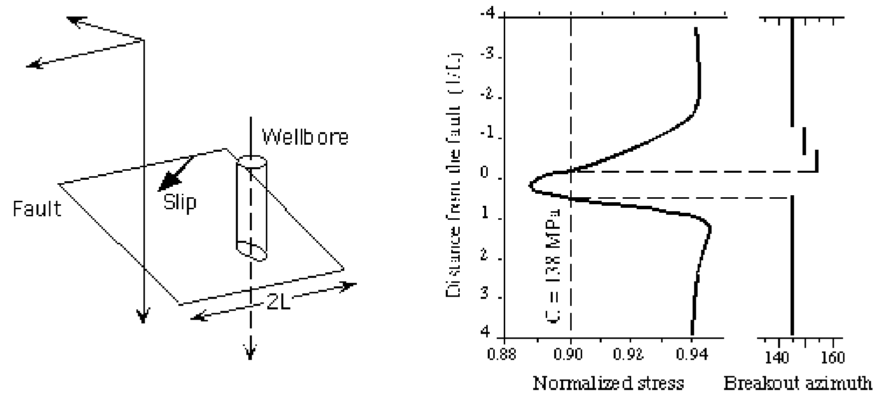
The stress orientation from multi-component seismic data is compared to the magnitude of subsidence measured above the Valhall Field in the Norwegian sector of the North Sea. Anisotropy measurements of this type may be measuring the stress orientation, or fractures caused by the subsiding crest of the structure. The cause is unclear and use of this technique to determine stress orientation can lead to erroneous conclusions.

Fault-Induced Stress Changes



Fault slip and impact on borehole stresses can be predicted

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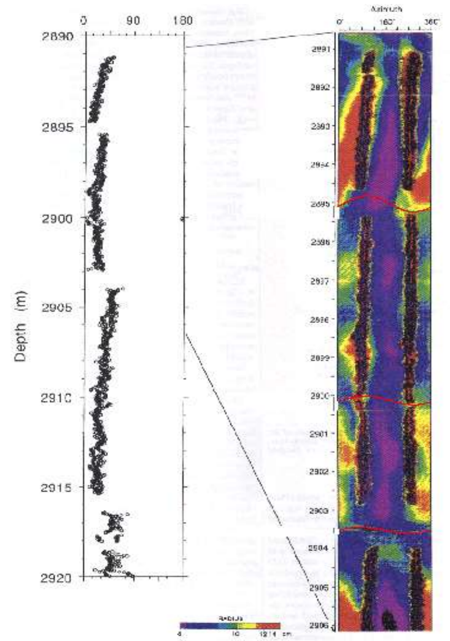
The stress drop around the fault as a result of slip can be modeled. The resulting rotation of breakouts can be modeled as well and matched to observed breakout rotations.

Anomalous Breakout Orientations



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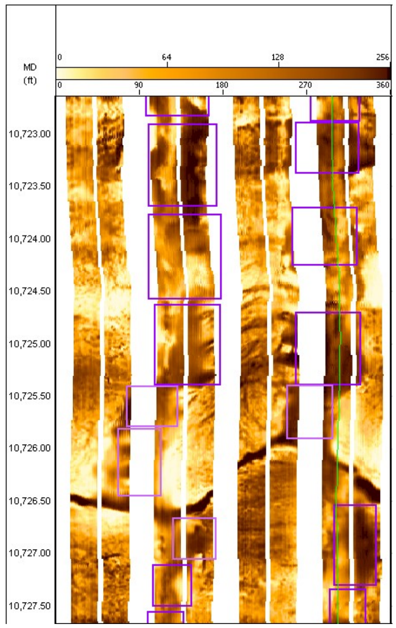
The observed breakout rotations can be modeled to determine the magnitude of fault slip and size of fault.

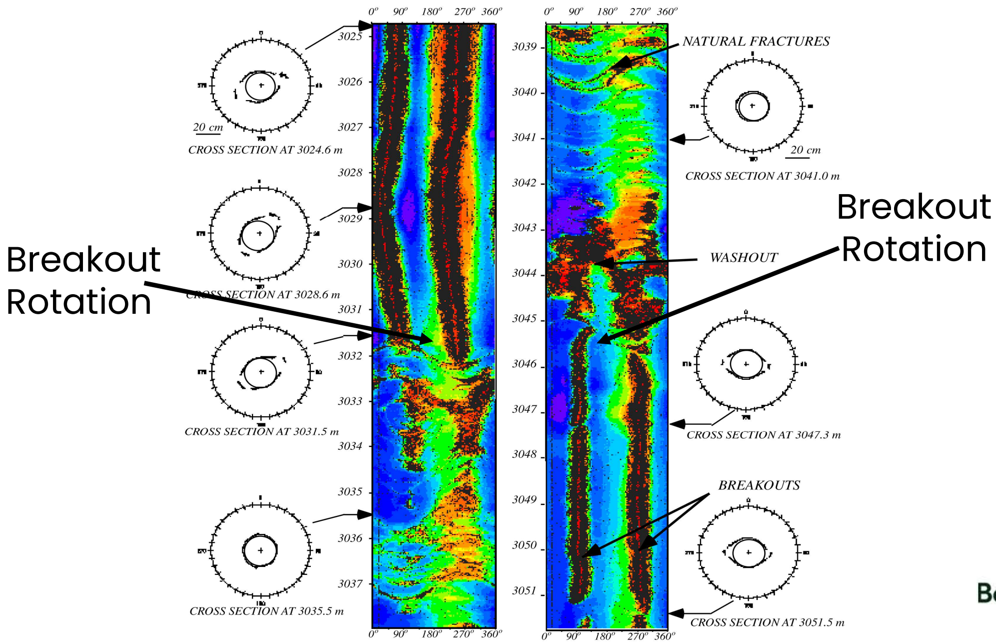
Breakout Rotations Near a Fracture



Baker Hughes

The observed breakout rotations can be modeled to determine the magnitude of fault slip and size of fault.

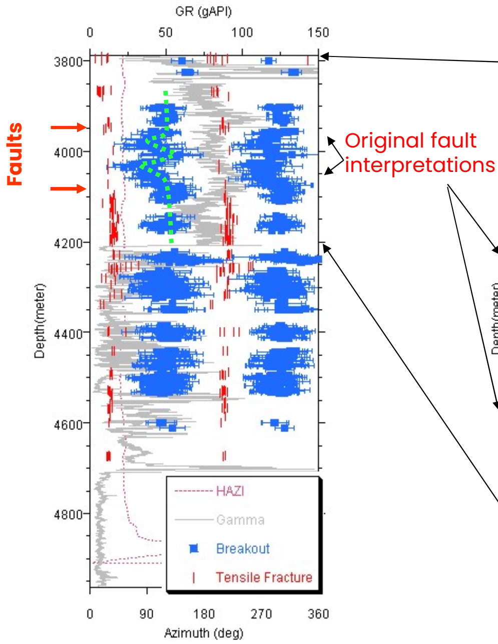
Wellbore Breakout Rotations Due to Fault Slip

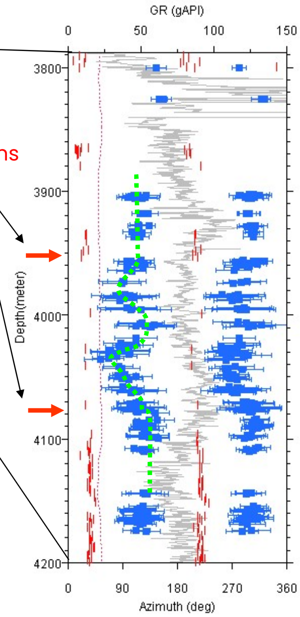


Baker Hughes

The observed breakout rotations can be modeled to determine the magnitude of fault slip and size of fault.

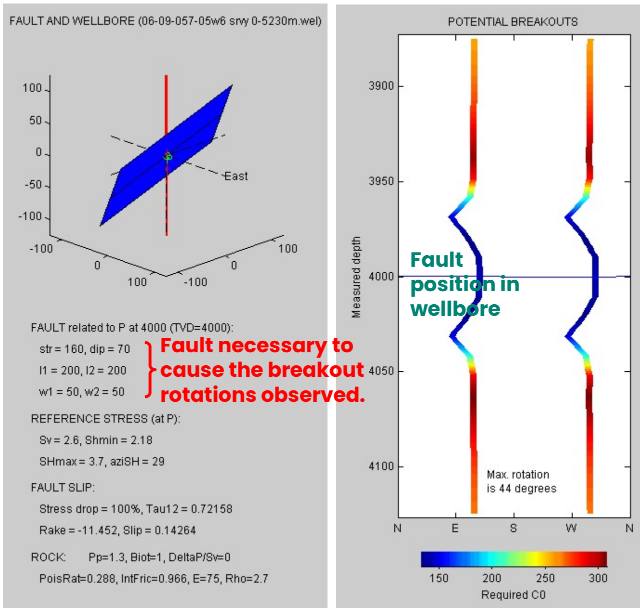
Breakout Rotation Observations

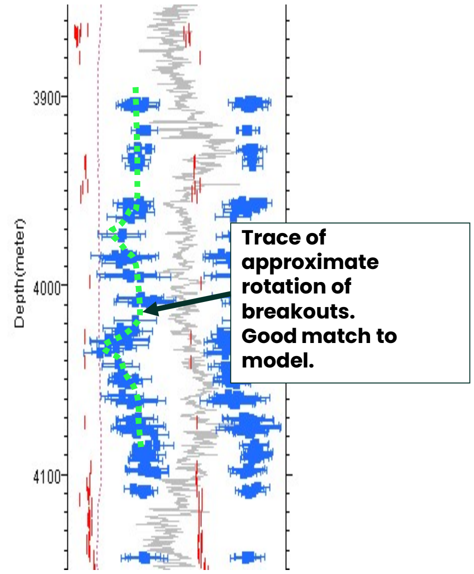




Expanded view as indicated. Dotted green line traces approximate rotation of breakouts throughout the fault zone. This is the pattern we try to replicate in the model.

Breakout Rotation Analysis: Results





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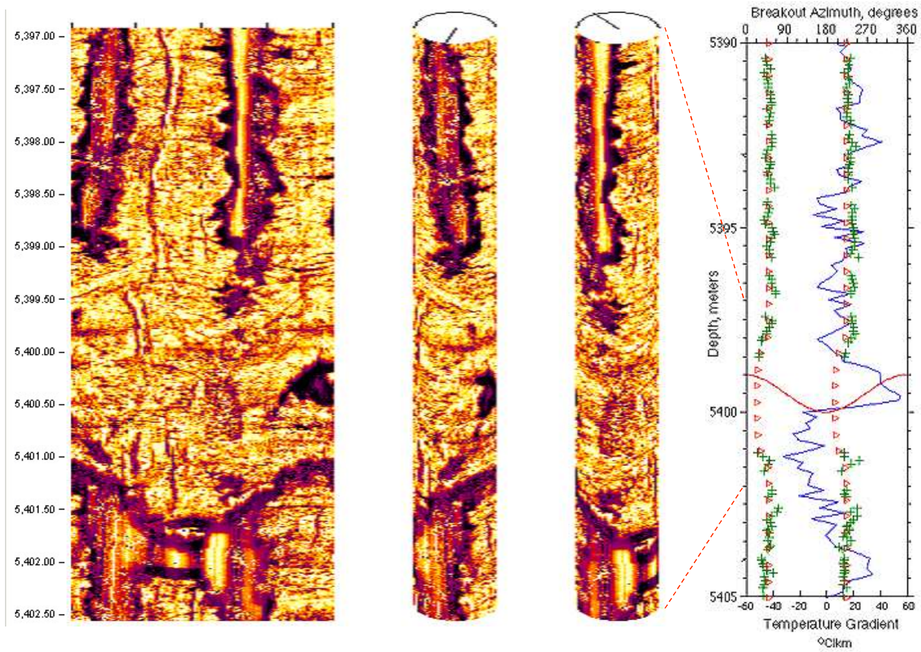
Breakout Rotation at Active Faults



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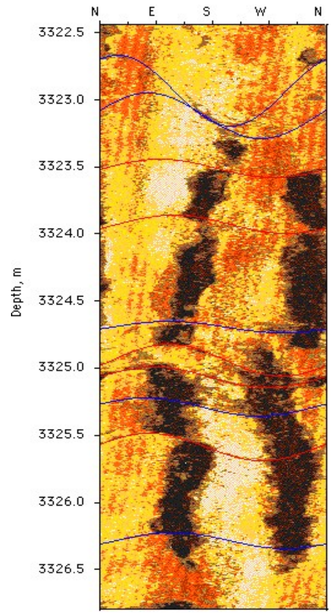
Breakout Rotation at Active Faults



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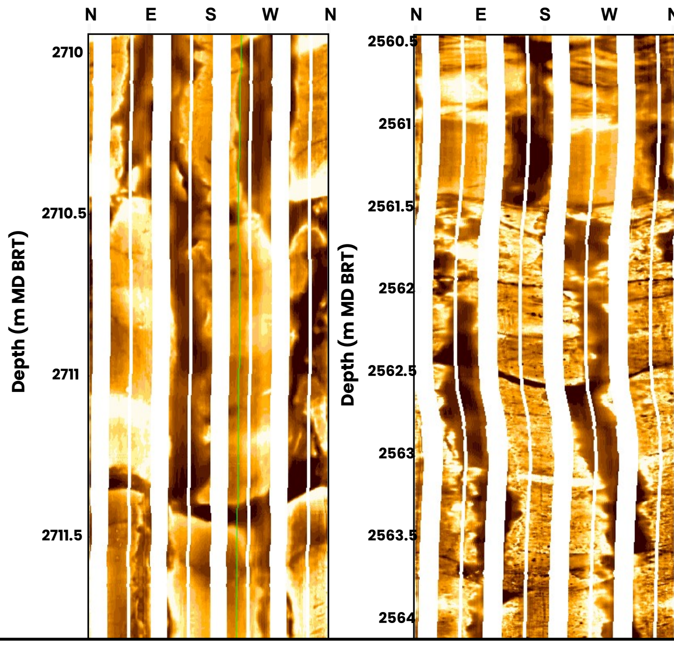
Breakout Rotation at Active Fault



Breakouts rotating across fractures.

- Indicate fractures are active in the current stress field and cause stress perturbations.
- Fractures may be conduits for lost circulation.

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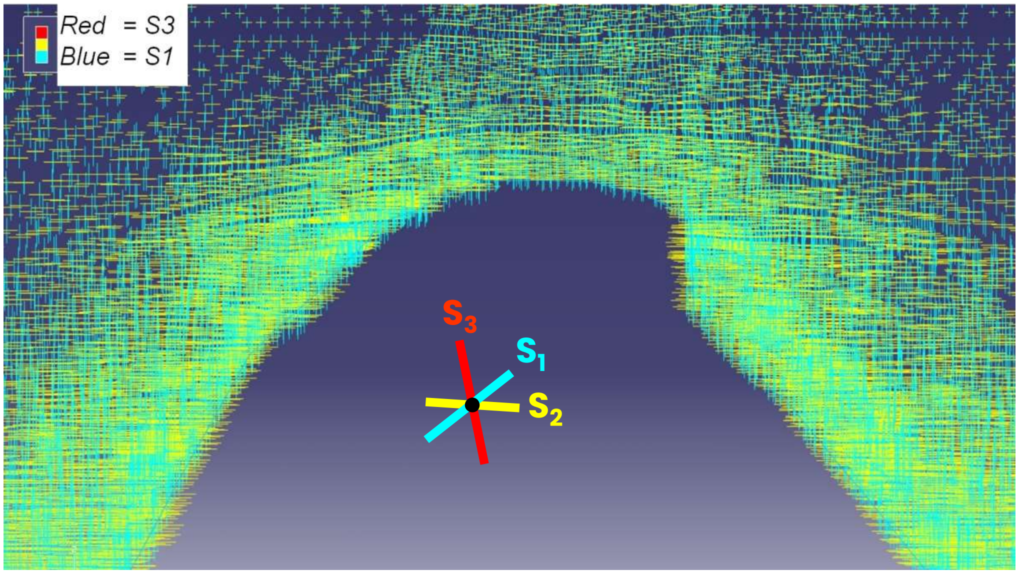
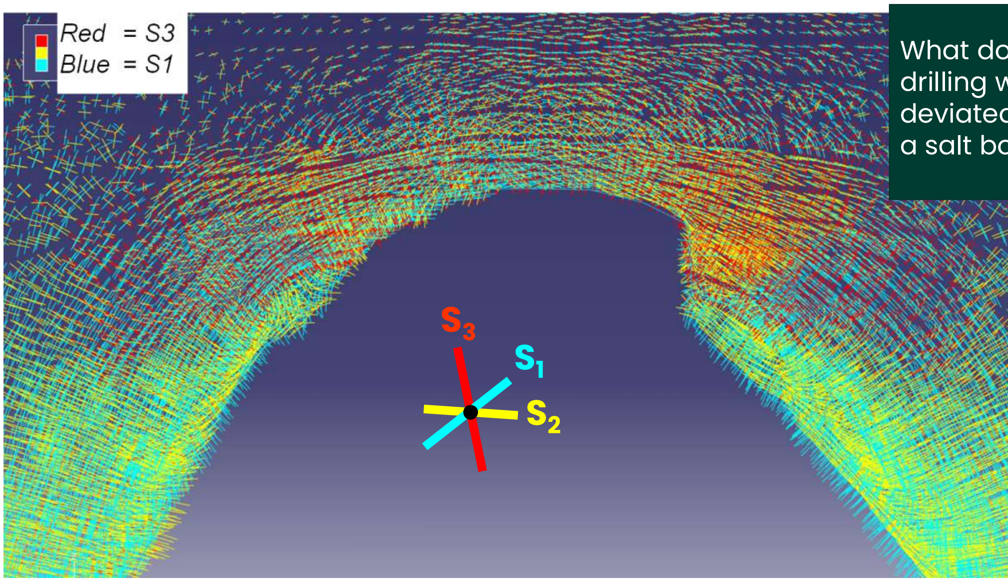
Salt and Stresses (I)



Baker Hughes

Salt and Stresses (II)



What does this mean for drilling wells (straight or deviated) near or through a salt body?

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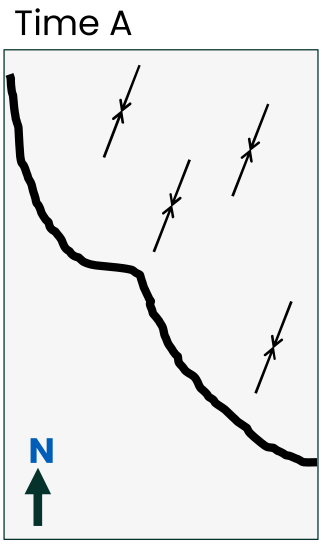
Stress Orientation



These represent the stresses in the same field at two different times in history. Is it possible for the stress orientations to change? If so, how?

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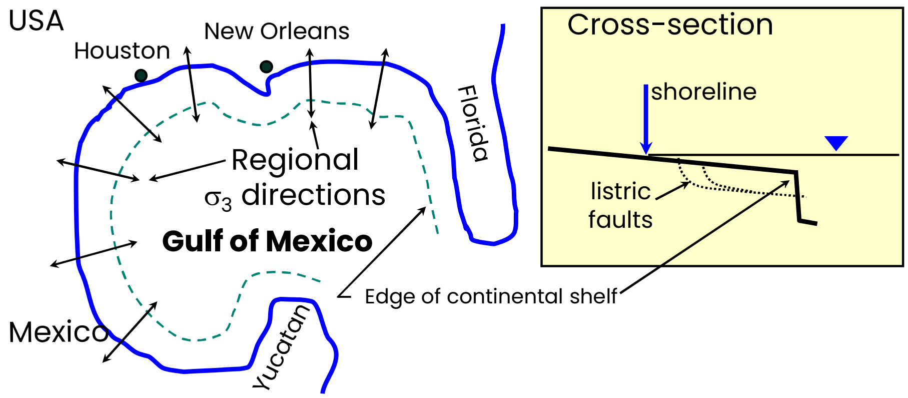
Stresses and Basin Shape



GoM example: regional stress directions are dominated by the continental slope, except locally near salt domes and a few structures such as the Mississippi canyon

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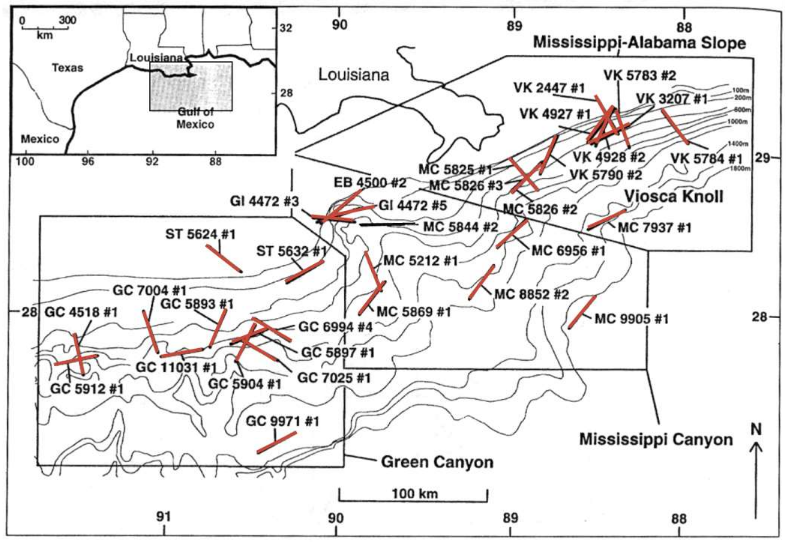
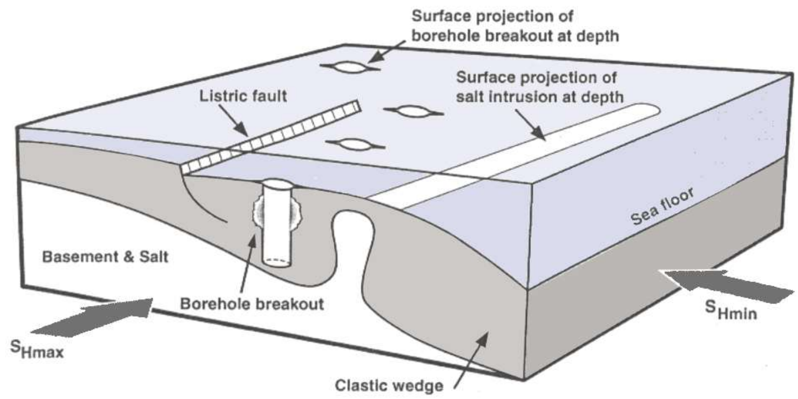
In general, stresses in the Gulf of Mexico are perpendicular and parallel to the coastline. This is due to the continuous slumping of material into the deeper parts of the gulf. Cartoon from Dusseault.

GOM Stress Orientations



Stress orientations in the Gulf of Mexico are generally parallel to the coastline and perpendicular to the slope of the sea floor. There are significant variations from this trend that are caused by local perturbations around salt domes and active faults.

Offshore Gulf of Mexico Stress Orientations



Yassir and Zerwer (1997)

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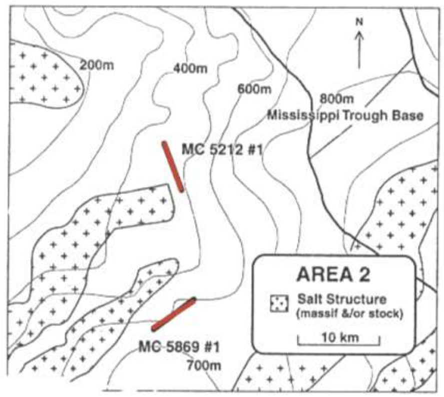
Conceptually, slumping of sediment into the deeper Gulf of Mexico occurs against the least principal stress, and allows the formation of normal faults and salt diapirs aligned with the maximum horizontal stress direction. Borehole breakouts will align with the direction of slope movement, in the direction of the minimum horizontal stress.

S_{Hmax} Orientations and Locations



Stress orientations are affected by salt.

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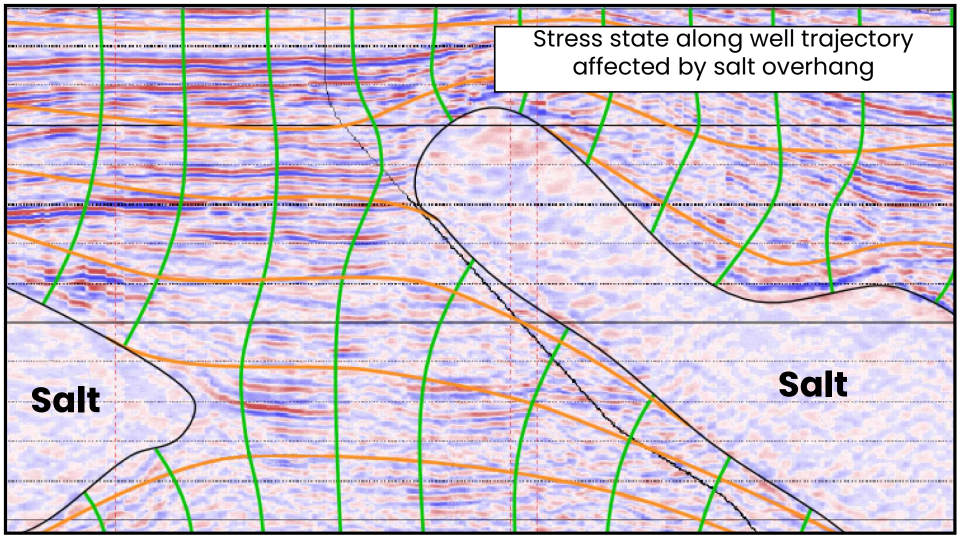
Locally around salt domes the stress orientations are affected by, and sometimes align with, the surface of the salt because the salt acts like a free surface.

Principal Stresses Near Salt Bodies



- **Near salt bodies the vertical stress IS NOT a principal stress.**
- **Prediction of stress near salt is very difficult. (requires 6 instead of 4 independent parameters)**

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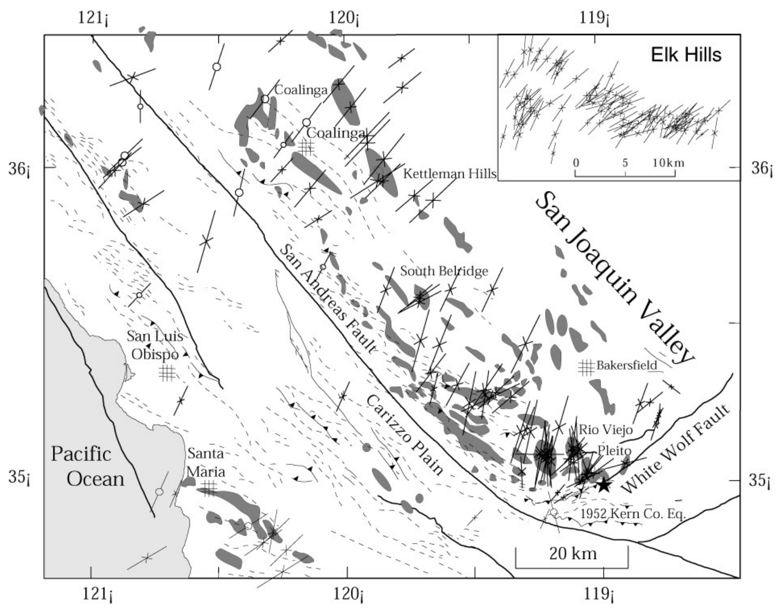
The vertical stress (green) and horizontal stress (orange) are perturbed around the salt bodies. The stresses will tend to align perpendicular and parallel to the surface of the salt.

Stress Map of Central California



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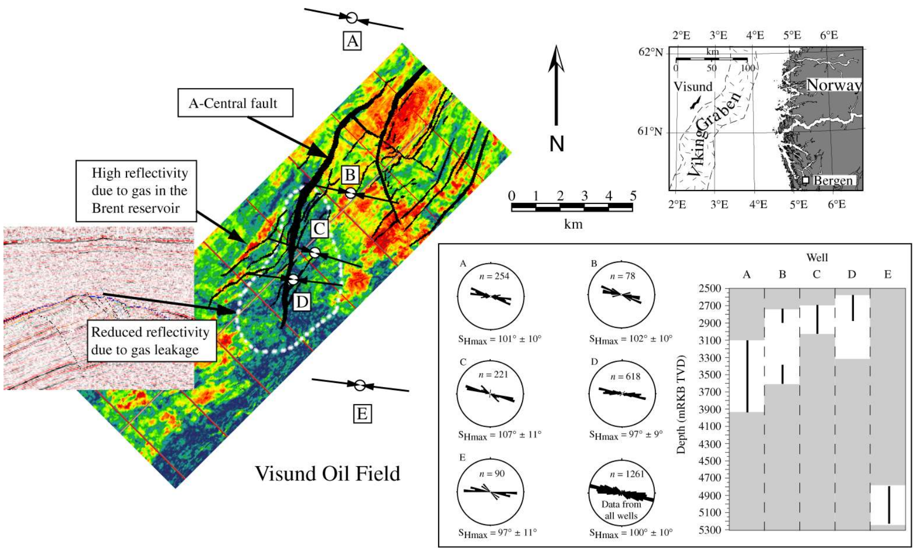
The stress field in Central California near the San Andreas fault (an actively deforming fold and thrust belt in a transpressional plate tectonic setting) is remarkably uniform (Castillo and Zoback). Note that NE-SW maximum horizontal stress directions implied by wellbore breakouts (inward pointed arrows) and earthquake focal plane mechanisms (lines with open circles) correlate extremely well, in general, and are consistently oriented orthogonal to trend of currently active fold axes (dashed lines) and thrust faults. At the scale of a single oil field in Central California (inset), stress orientation data obtained from analysis of stress-induced wellbore breakouts in numerous wells illustrates an overall uniform NE-SW maximum compressive stress with gradual changes of stress orientation occurring on the scale of several km.

Stress orientations between structures and within individual structures show a significant variation. The regional orientation is consistently NE-SW. The fields are in an actively deforming region that causes the structures to locally control stress orientations.

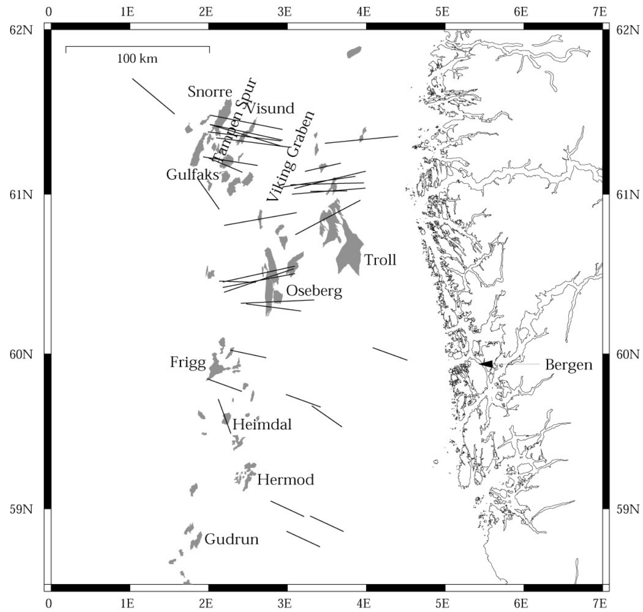
Visund Field Orientations



Baker Hughes

Map view of the Visund field showing the seismic reflectivity of the reservoir horizon as well as the mean orientation of the maximum horizontal stress in five wells (A-E). High seismic reflectivity is shown with hot colors and is interpreted to be the result of gas trapped at the top of the reservoir. Low reflectivity is interpreted to be the result of gas leakage from the reservoir. The absence of gas in the low reflectivity region was confirmed by the observation of no free gas cap in wells C and D. Well B did encounter a free gas cap.

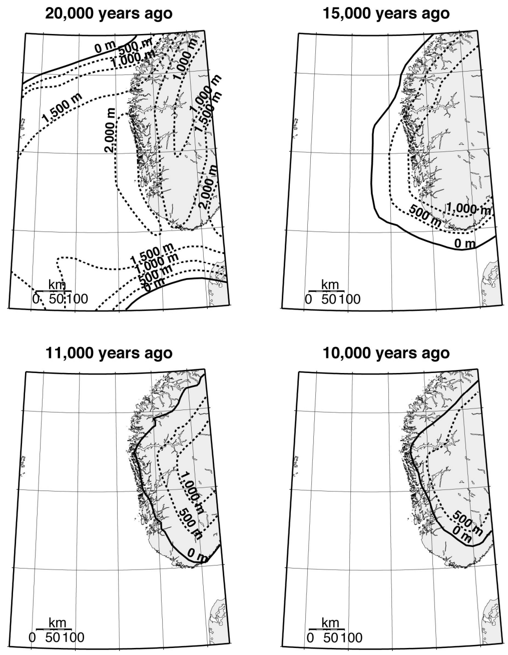
Stress Map of the Northern North Sea



Baker Hughes

Drilling-induced tensile wall fractures reveal a consistent picture of stress orientation is also observed in the oil fields in the northern North Sea (after Wiprut).

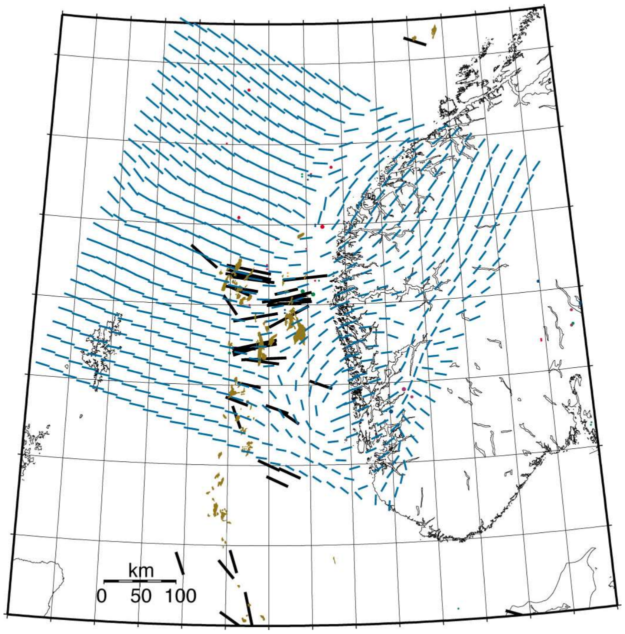
Glacial Ice Sheet Size Over Time in S. Norway

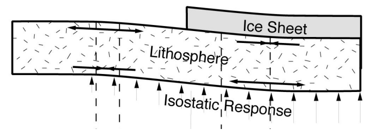


Baker Hughes

Melting of the glacial ice sheet from the last ice age proceeded from the maximum thickness ~20,000 years ago to the end of the ice age ~10,000 years ago. This glacial melting caused a perturbation of the stresses in the region.

Modeled Stress Orientation Rotations





Stress orientations are affected by lithospheric bending due to advance and melting of ice sheet

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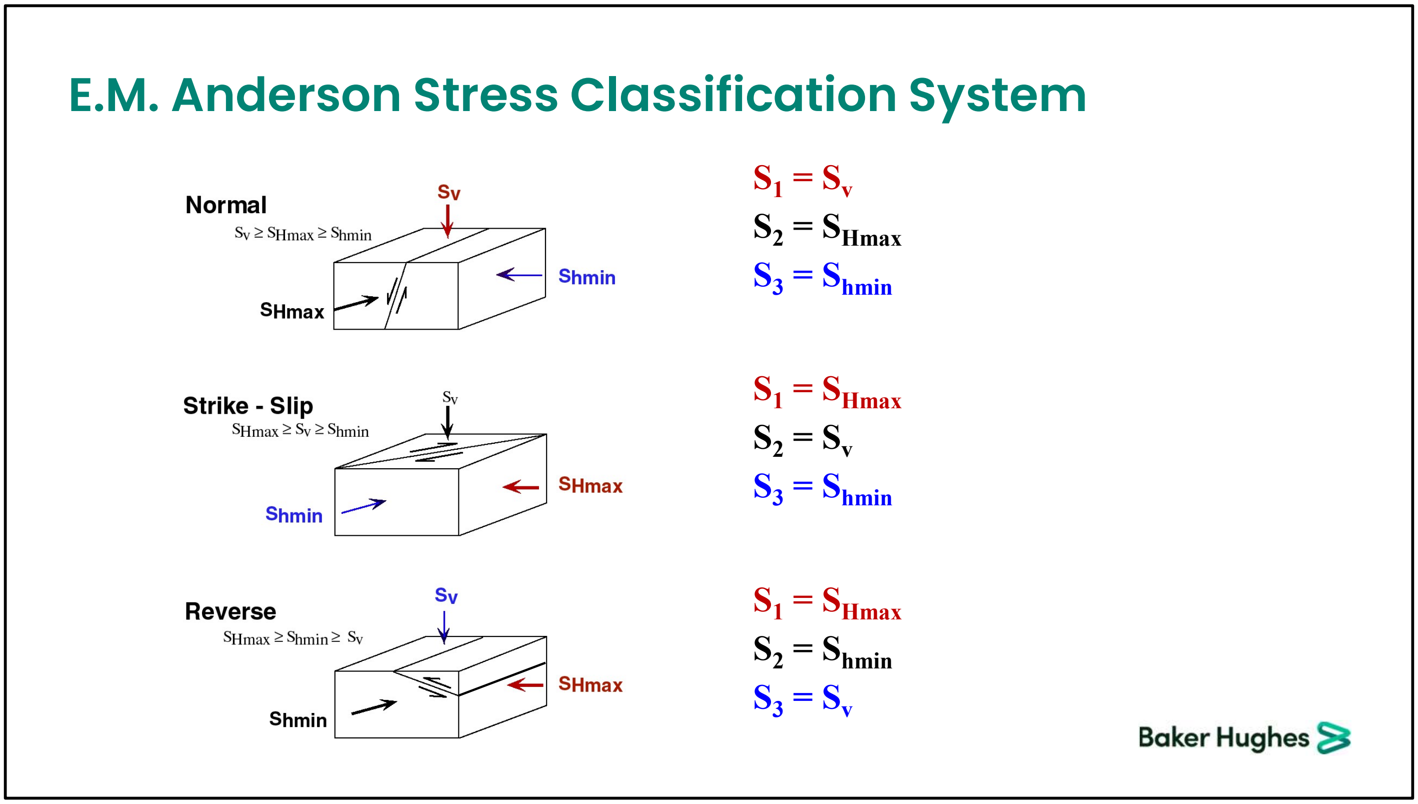
Stress orientations modeled from finite element analysis are shown with blue ticks, and match well with measured stress orientations shown with black lines.



The relative magnitudes of the vertical stress (Sv), maximum horizontal stress (SHmax) and minimum horizontal stress (Shmin) define the stress regime. In a normal faulting stress regime Sv is the maximum principal stress, SHmax is the intermediate principal stress and Shmin is the least principal stress. In a strike-slip faulting stress regime SHmax is the maximum principal stress, Sv is the intermediate principal stress and Shmin is the least principal stress. In a reverse faulting stress regime Sv is the least principal stress, Shmin is the intermediate principal stress and SHmax is the maximum principal stress. The stress regimes define types of faulting that would be likely if the stress differences are high enough.

Relating Relative Stress and Faulting Regimes

Regime /Stress	S_1	S_2	S_3
Normal	S_v	S_{Hmax}	S_{hmin}
Strike-Slip	S_{Hmax}	S_v	S_{hmin}
Reverse	S_{Hmax}	S_{hmin}	S_v

In general:
$S_1 \equiv$ Maximum principal stress
$S_2 \equiv$ Intermediate principal stress
$S_3 \equiv$ Minimum principal stress

In the earth:
$S_{Hmax} \equiv$ Maximum horizontal stress (can be S_1 or S_2)
$S_{hmin} \equiv$ Minimum horizontal stress (can be S_2 or S_3)
$S_v \equiv$ Vertical stress (can be S_1, S_2, or S_3)

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The relative magnitudes of the vertical stress (Sv), maximum horizontal stress (SHmax) and minimum horizontal stress (Shmin) define the stress regime. In a normal faulting stress regime Sv is the maximum principal stress, SHmax is the intermediate principal stress and Shmin is the least principal stress. In a strike-slip faulting stress regime SHmax is the maximum principal stress, Sv is the intermediate principal stress and Shmin is the least principal stress. In a reverse faulting stress regime Sv is the least principal stress, Shmin is the intermediate principal stress and SHmax is the maximum principal stress. The stress regimes define types of faulting that would be likely if the stress differences are high enough.

Normal Faulting

Arches National Park, Photo Courtesy of Dr. David Castillo

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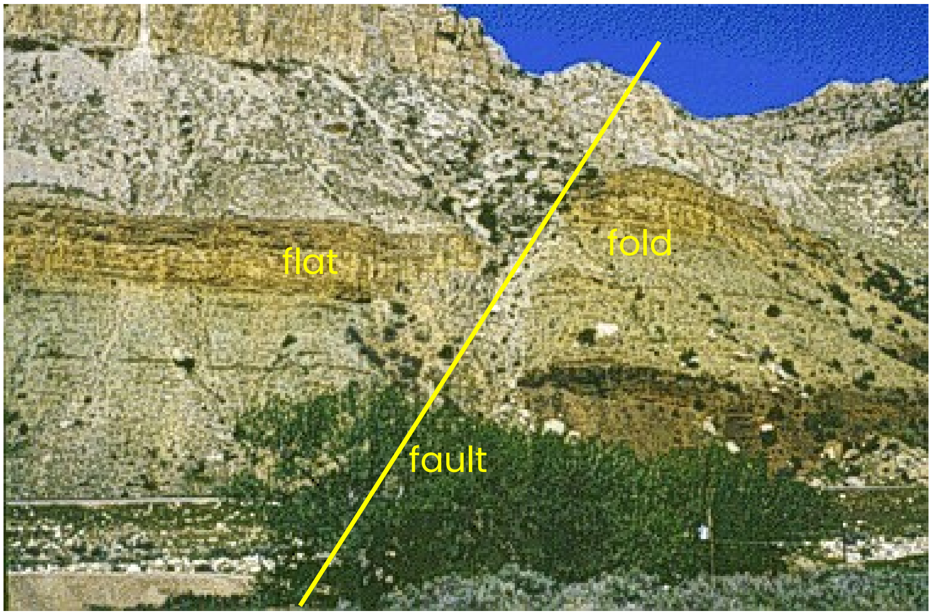
Relict Normal Fault



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The stresses that created this normal fault may not be the stresses acting on the rock today. (Courtesy, Unocal)

Active Strike-Slip Fault

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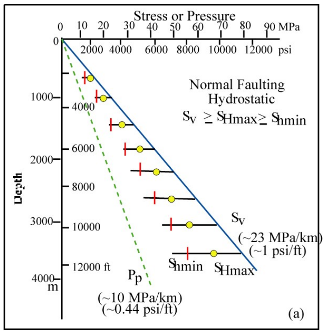
Offsets in stream channels show the sense of motion along the San Andreas Fault. (University of California, Santa Cruz, http://emerald.ucsc.edu/~es10/classnotes/images/S.A.fault,CarrizoPlain.wo.jpg)

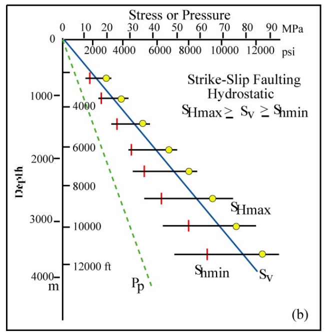
Relict Thrust (Reverse) Fault

Note in a thrust faulting environment the thickness of the formation being drilled may be much more than in the zone beyond the faulting. (**Conor Watkins And J. David Rogers, http://web.umr.edu/~rogersda/cp_megalandslides/1162-fault_with_drag_folds_preserved_in_boulder_near_granite_park_fault_in_205_mile_canyon.jpg)**

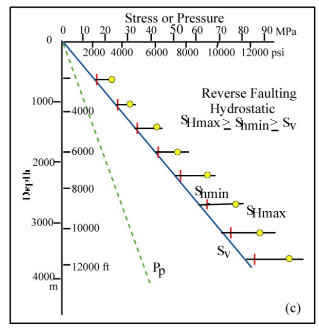
Range of Stress Magnitudes at Depth

Hydrostatic P_p





With hydrostatic pore pressures, large differences in stress magnitudes exist.



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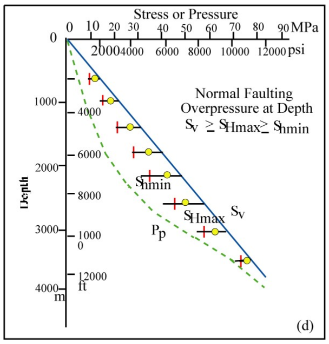
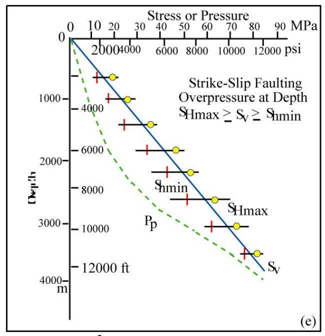
Schematically demonstrates possible stress magnitudes for normal, strike-slip and reverse faulting environments when pore pressure is hydrostatic (a-c) and when it approaches pore pressure approaches lithostatic pressure at depth (next slide). At each depth the range of possible values of S_{hmin} and S_{Hmax} are limited by Anderson faulting theory (which defines the relative stress magnitude) and Coulomb faulting theory which determines maximum values of the differences between the maximum and minimum principal stresses in terms of the frictional strength of faulted rock at a given depth and pore pressure. Note in Fig. a, that if pore pressure is close to hydrostatic and the least principal stress is significantly below the vertical stress, an extensional, or normal faulting, regime is indicated and the maximum horizontal stress is less than or equal to the vertical stress. Alternatively, for the same pore pressure conditions, if S_{hmin} increases more rapidly with respect to S_v as shown in Fig. b, a more compressional strike-slip stress state may be indicated and S_{Hmax}

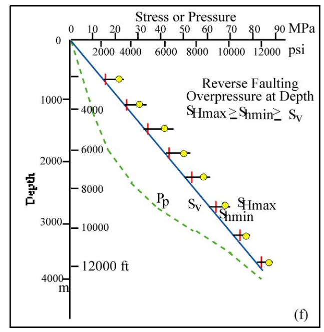
may exceed S_v. When the least principal stress is equal to the overburden, a reverse faulting regime is indicated and both horizontal stresses will be greater than the vertical stress (Fig. c). The differences between the three principal stresses can be large and can grow rapidly with depth when pore pressure is close to hydrostatic.

Range of Stress Magnitudes at Depth

Overpressure at Depth







With high pore pressures the horizontal stresses approach the overburden.
The three principal stresses are almost identical.

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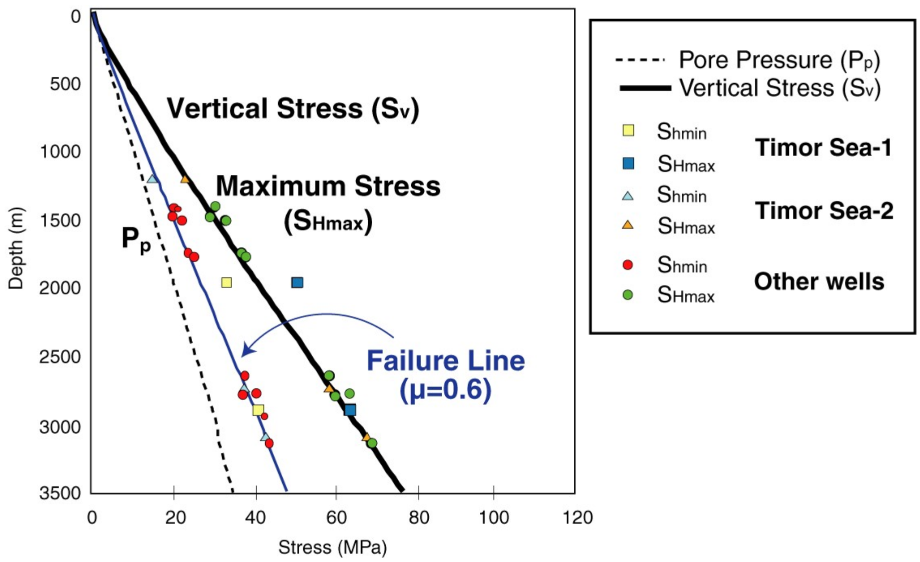
Severely overpressured formations are characterized by relatively small differences between the three principal stresses because the frictional strength of the crust is severely reduced by high pore pressure. Note that when pore pressure is very close to the vertical stress, the both horizontal stresses must also be close to the vertical stress, regardless of whether it is a normal, strike-slip or reverse faulting environment.

Transitional Normal/SS Faulting Stress State



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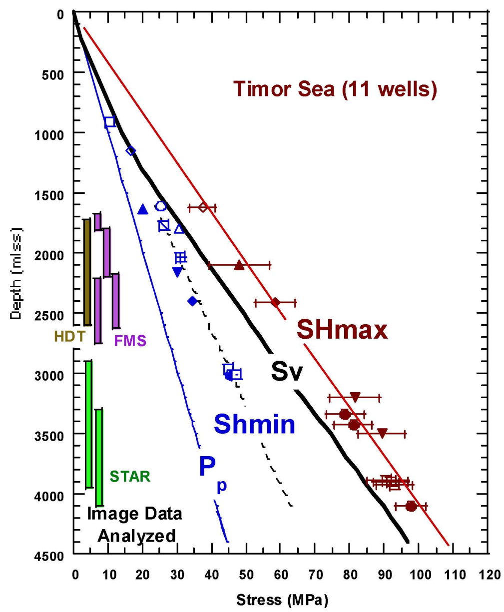
A transitional Normal/Strike-Slip faulting stress regime is shown where SHmax ~ Sv > Shmin.

Strike-Slip Faulting Stress State



- Similar observations can provide detailed stress and pore pressure profiles for entire fields.
- Overburden from density
- Shmin from leakoff tests
- Pore pressure from well tests and velocity analysis in shales
- SHmax from analysis of breakouts and tensile failures in image data

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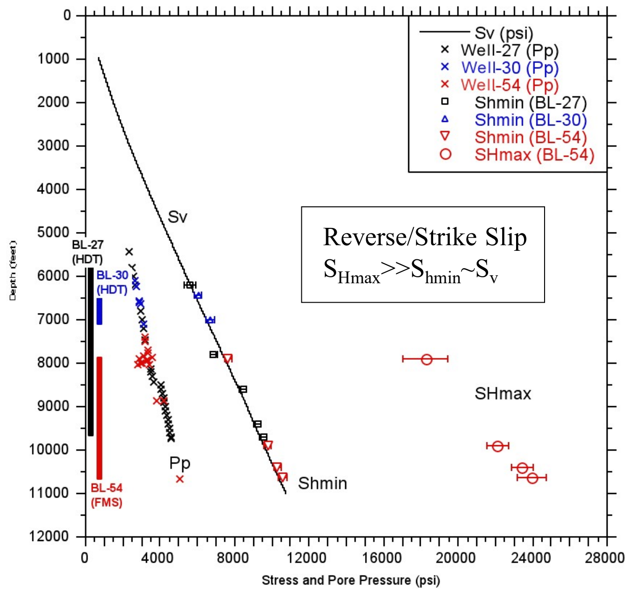
A strike-slip faulting stress regime is shown where SHmax > Sv > Shmin.

Transitional SS/Reverse Faulting Stress State



The area is in a transitional strike-slip/reverse stress regime with S_{hmin} approximately equal to S_v or slightly greater than S_v.

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A transitional strike-slip/reverse faulting stress regime is shown where SHmax >> Shmin ~ Sv. Because leakoff tests measure the least principal stress, they measure the vertical stress in a reverse faulting stress regime and the value of Shmin is not constrained. Therefore, it is seldom possible to determine whether a well is being drilled into a purely reverse faulting stress regime.

Summary of Methods for Estimation of Maximum Horizontal Stress Azimuth

S_{Hmax} azimuth can be obtained from:

- Orientation of drilling-induced tensile fractures in vertical wells (image logs)
- Breakout orientation in vertical wells provides S_{hmin} azimuth (image logs or oriented 4- or 6-arm caliper data). S_{Hmax} azimuth = S_{hmin} azimuth $\pm$ 90°
- Inferences from ACTIVE structures (seismic, bathymetry maps, outcrop data, etc.)
- Earthquake focal plane mechanisms (inversion of multiple earthquake events is required for accurate S_{Hmax} azimuth)
- Stress-induced acoustic anisotropies – problematic because acoustic anisotropies are caused by a variety of factors, not just stress (cross dipole acoustic, multi-component seismic)

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Summary of Methods for Estimation of Maximum Horizontal Stress Azimuth

S_{Hmax} azimuth can also be obtained from breakouts in deviated wells:

- Observations of wellbore failure (breakouts and tensile fractures) in deviated wells DO NOT directly indicate the S_{Hmax} azimuth. This is because the orientation of wellbore failure in deviated wells depends on in situ stress orientations AND magnitudes.
- The upside of this is that failure orientations in deviated wells can provide information on in-situ stress orientations AND magnitudes but modeling of stress concentrations in deviated wells is required (e.g. through use of GMI•SFIB™)

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