Chapter One

Introduction

Overview of Geomechanics
RTS Geomechanics Services

Topics

- **Baker Hughes Geomechanics Services**
- **Building the geomechanical model**
- **Applications overview**
  - –Wellbore stability
  - –Sand production prediction
  - –Fracture permeability
  - –Fault leakage
  - –Hydraulic fracturing
  - –Compaction and faulting
  - –Casing shear and collapse

Baker Hughes

Reservoir Technical Services - Geomechanics

Baker Hughes

Expertise and Experience

Global experience

- Over 250 projects worldwide per year
- More than 6,000 projects total

Services and technology

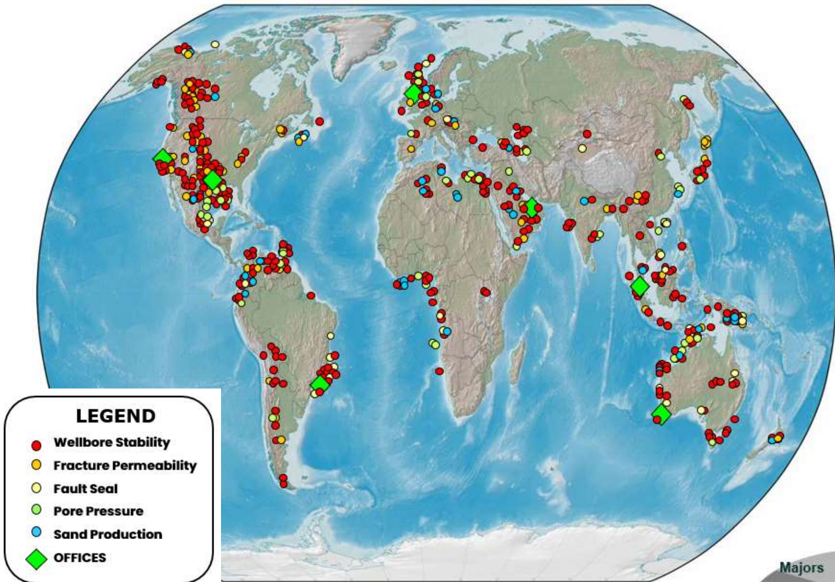
- Consulting studies – From single-well to region scale projects
- Software – JewelSuite contains most geomechanics applications
- Training – Provide training both as "public" and on-site courses

Over 50 geomechanics professionals

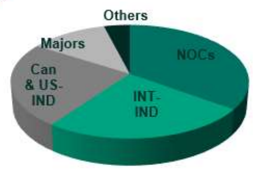
- More than half have a Ph.D.
- Backgrounds include: geology, geophysics, engineering, and rock mechanics, with specialization in various applications

Baker Hughes

Geomechanics Projects Map



GMI is a specialist provider of Geomechanics related products and services spanning
❖Consulting
❖Training
❖Software



- ❑ Multiple hubs around the globe with 40+ technical staff
- ❑ 2,000+ projects completed since incorporation.
- ❑ 300+ projects in Middle East – UAE, Oman, Kuwait, Iraq, KSA, India , Pakistan

Baker Hughes

GMI•SFIB™

(Stress and Failure of Inclined Boreholes) drilling and wellbore stability software:

- •Determines in situ stress-state for reservoir characterization
- •Computes optimal mud weights to limit wellbore failure
- •Designs optimally stable wellbore trajectories
- •Reduces sand production
- •Evaluates the stability of uncased wells and multilaterals over time.

•GMI•WellCheck™

- •SFIB streamlined for well design
- •Wellbore stability tools for drilling engineers
- •Quickly determines casing points
- •Models complex geological structures
- •Evaluates stability along the entire well path from surface to reservoir

Setting of offshore platforms in the most optimal location for directional drilling

Optimal placement of wellbores in fractured reservoirs to maximize well productivity

Elimination of casing strings

Reduction in Drilling Trouble Time

Allows for Drilling With Lighter Mud Weights

Optimized directional drilling planning

GMI•MohrFracs™

- •Identifies location and direction of most permeable fracture sets in a rock formation
- •Integrates stress and fracture data from dipmeter and image logs

GMI•Imager™ interactive image analysis software which allows users to:

- •Easily enhance, interpret and analyze acoustic, electrical and optical wellbore image data
- •Characterize natural and drilling-induced fracture and fault systems
- •Characterize hydrocarbon migration through determination of the permeability of fracture sets
- •Detect and measure wellbore failures to quantify the stress state

1D Geomechanics

3D/4D Geomechanics

Wellbore Stability Analysis

Fault and Fracture Stability Analysis

GMI•SFIB™

(Stress and Failure of Inclined Boreholes) drilling and wellbore stability software:

- •Determines in situ stress-state for reservoir characterization
- •Computes optimal mud weights to limit wellbore failure
- •Designs optimally stable wellbore trajectories
- •Reduces sand production
- •Evaluates the stability of uncased wells and multilaterals over time.

•GMI•WellCheck™

- •SFIB streamlined for well design
- •Wellbore stability tools for drilling engineers
- •Quickly determines casing points
- •Models complex geological structures
- •Evaluates stability along the entire well path from surface to reservoir

Setting of offshore platforms in the most optimal location for directional drilling
Optimal placement of wellbores in fractured reservoirs to maximize well productivity
Elimination of casing strings
Reduction in Drilling Trouble Time
Allows for Drilling With Lighter Mud Weights
Optimized directional drilling planning **GMI•MohrFracs™**

- •Identifies location and orientation of most permeable fracture sets in a rock formation
- •Integrates stress and fracture data from dipmeter and image logs

GMI•Imager™ interactive image analysis software which allows users to:

- •Easily enhance, interpret and analyze acoustic, electrical and optical wellbore image data
- •Characterize natural and drilling-induced fracture and fault systems
- •Characterize hydrocarbon migration through determination of the permeability of fracture sets
- •Detect and measure wellbore failures to quantify the stress state

Stresses are constrained in SFIB using several observations. The black polygon represents the range of stresses consistent with the frictional strength of the Earth's crust. All stresses possible in the Earth should plot inside the polygon. The red and blue contours represent the values of SHmax and Shmin that are consistent with breakouts (red) and tensile fractures (blue) for the given rock strength shown on each contour.

GMI•SFIB™

(Stress and Failure of Inclined Boreholes) drilling and wellbore stability software:

- •Determines in situ stress-state for reservoir characterization
- •Computes optimal mud weights to limit wellbore failure
- •Designs optimally stable wellbore trajectories
- •Reduces sand production
- •Evaluates the stability of uncased wells and multilaterals over time.

•**GMI•WellCheck™**

- •SFIB streamlined for well design
- •Wellbore stability tools for drilling engineers
- •Quickly determines casing points
- •Models complex geological structures
- •Evaluates stability along the entire well path from surface to reservoir

Setting of offshore platforms in the most optimal location for directional drilling
Optimal placement of wellbores in fractured reservoirs to maximize well productivity
Elimination of casing strings
Reduction in Drilling Trouble Time
Allows for Drilling With Lighter Mud Weights
Optimized directional drilling planning **GMI•MohrFracs™**

- •Identifies location and direction of most permeable fracture sets in a rock formation
- •Integrates stress and fracture data from dipmeter and image logs

GMI•Imager™ interactive image analysis software which allows users to:

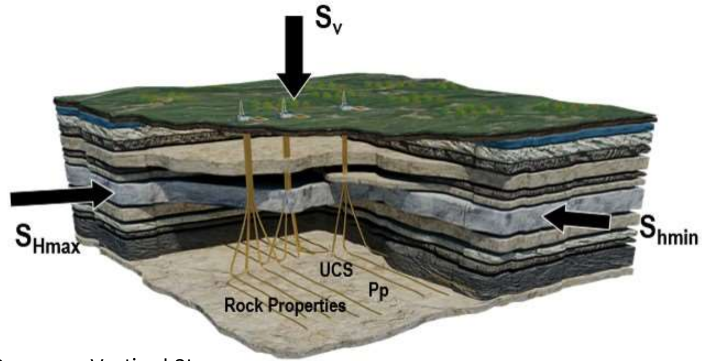
- •Easily enhance, interpret and analyze acoustic, electrical and optical wellbore image data
- •Characterize natural and drilling-induced fracture and fault systems
- •Characterize hydrocarbon migration through determination of the permeability of fracture sets
- •Detect and measure wellbore failures to quantify the stress state

Building the Geomechanical Model

Baker Hughes

Geomechanics Definition

- **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



S_v – Vertical Stress
S_{Hmax} – Maximum Horizontal Stress
S_{hmin} – Minimum Horizontal Stress
P_p – Pore Pressure
UCS – Unconfined Compressive Rock Strength
Rock Properties – Cohesion, Friction, Elastic Moduli

Baker Hughes

The geomechanical model begins by defining the principal stress tensor. The principal stress tensor resolves the in situ stresses into three mutually perpendicular vectors, S1, S2 and S3, that are the maximum, intermediate, and minimum stresses, respectively. The stresses measured in the earth can typically be defined by a vertical stress (Sv) and two mutually perpendicular horizontal stresses (SHmax, Shmin). Depending on the stress regime the values of Sv, Shmin, and SHmax can be S1, S2, or S3. The pore pressure acts against the principal stresses and must be defined to fully describe the stresses in the earth. Rock strength and other rock properties must also be known to fully define the geomechanical model. The geomechanical model is therefore two models: 1) the applied load (stress) and 2) the resistance to the applied load (strength). When these parameters are known, the geomechanical model is defined and predictions can be made of wellbore stability, fracture permeability, etc.

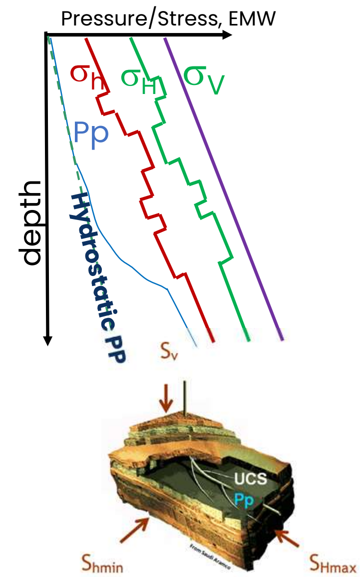
Required Data, with Baker Hughes Technologies

Vertical Stress, S_v
- Density (**LithoTrak, ZDL**)
- Pseudo density from acoustic (**SoundTrak, XMAC**)
- Pseudo density from seismic (**SeismicTrak, VSP**)

Pore Pressure, P_p
- Acoustic (**SoundTrak, XMAC, SeismicTrak, VSP**)
- Resistivity (**OnTrak, AziTrak**)
- Direct measurements (**FasTrak, RCI/RCX**)
- DFIT; surface seismic velocities; kicks/inflows
- Petrophysics (**ZoneTrakG**, **FLeX/RockView, MReX, MagTrak**)

Horizontal Stress (Orientation & Magnitude), S_{Hmax} azi
- Image (**ImageTrak, StarTrak, EARTH Imager, STAR HD**, **UltrasonicXplorer, GeoXplorer**)
- Multi-arm oriented caliper (**WGI, Image logs**)
- Azimuthal anisotropy (**XMAC**)
- Seismic structural data, MicroSeismic data
- Wellbore Failure Inversion (**JewelSuite GMI-SFIB**)

Horizontal Stress (Magnitude), S_{hmin}
- LOT/XLOT, ECD (**AccuFIT**), loss events, MicroFrac (**RCX™**)



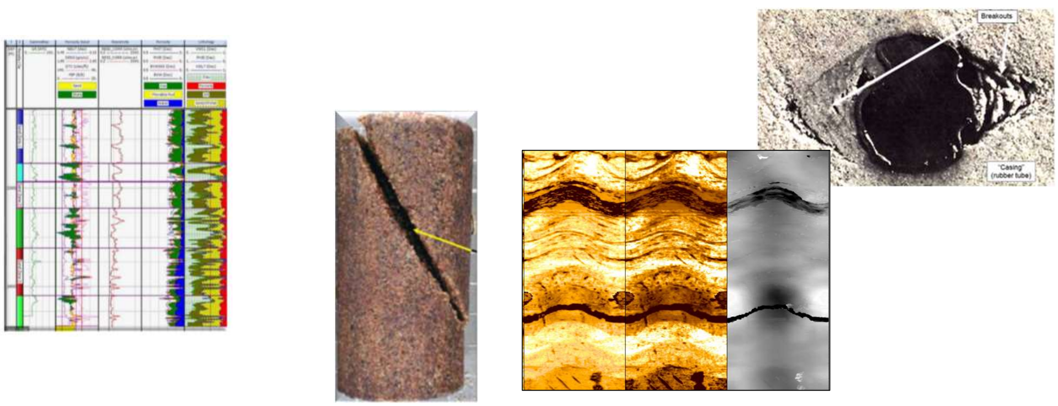
Baker Hughes

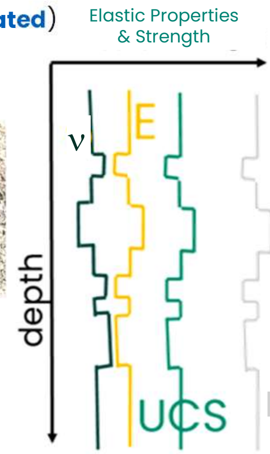
The data requirements for building a geomechanical model cover a broad suite of measurements. While this list shows some of the data needed to build a model, it is generalized and not sufficient to do a complete analysis of the geomechanics in a field. Most data required for building geomechanical models has already been collected in a field for other purposes. The geomechanical analysis pulls this data from disparate sources to create an internally consistent model of the stresses acting in the Earth and the ability of the Earth to resist those stresses.

Required Data, with Baker Hughes Technologies

Rock Strength & Rock Properties

- Lab measurements (**Baker Hughes Labs**)
- Petrophysics (**ZoneTrakG**, **FLeX/RockView, MReX, MagTrak**)
- Coring (**MaxCore, PCore, CoreGrad, HydroLift for Unconsolidated**)
- Acoustic (**SoundTrak, XMAC**)
- Wellbore failure-based modeling (**Image logs**)

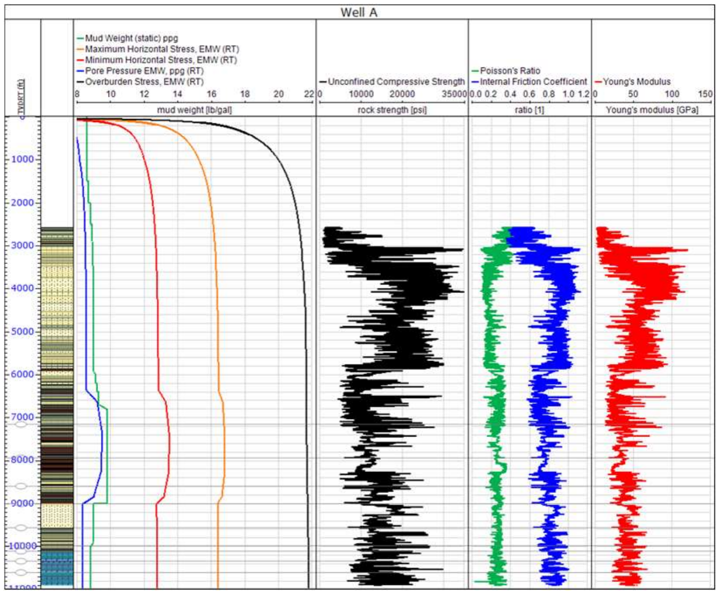




Baker Hughes

The data requirements for building a geomechanical model cover a broad suite of measurements. While this list shows some of the data needed to build a model, it is generalized and not sufficient to do a complete analysis of the geomechanics in a field. Most data required for building geomechanical models has already been collected in a field for other purposes. The geomechanical analysis pulls this data from disparate sources to create an internally consistent model of the stresses acting in the Earth and the ability of the Earth to resist those stresses.

Geomechanical Model Introduction



Geomechanical Model Example

Baker Hughes

Each curve shown here is discussed in the course either as a section or an entire chapter; and in many cases an exercise is associated with the curve to illustrate at least one method by which it can be calculated.

Vertical stress can be calculated by integrating density logs. It is very important to get at least one density log to surface or as shallow as practical. A power law relationship can then be extrapolated to the surface to fill in the missing data. Vertical stress data is especially important to acquire in deepwater environments, because of the decreased density of sediments in the shallow section of the well.

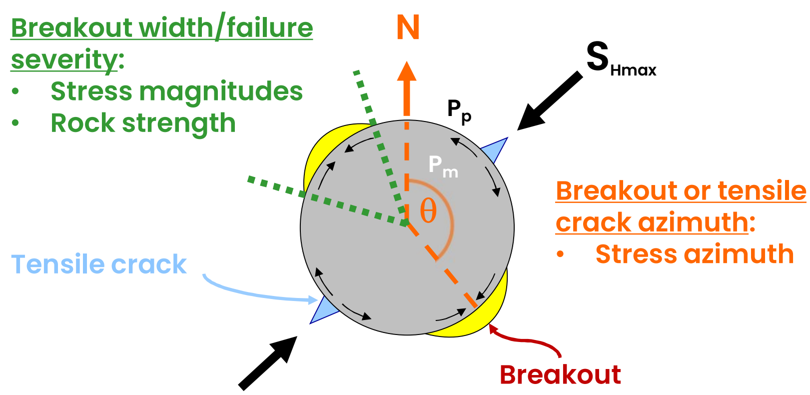
Pore pressure can come from seismic or logs. The pore pressure is highly correlated to the wellbore collapse and the fracture gradient, so the better this information is, the better the geomechanical model will predict borehole collapse conditions.

The minimum principal stress can generally be derived from extended leak-off tests (XLOT's), ideally using the fracture closure pressure.

Rock Strength is an important factor in determining the bore hole collapse pressure, or conversely, the mud weight required to prevent wellbore collapse. The log based data gives us a range of values.

Stress Orientation and Magnitude from Borehole Failure

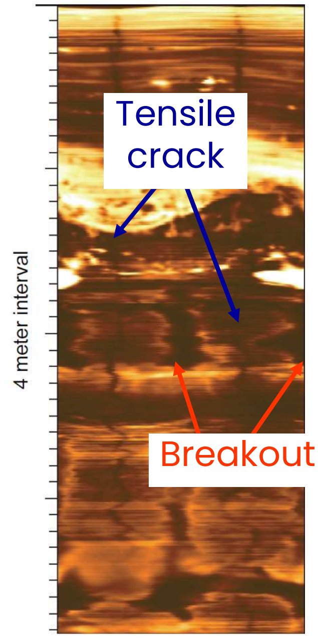
The mechanical interaction of the borehole in a given lithology with the current stress field governs borehole failure



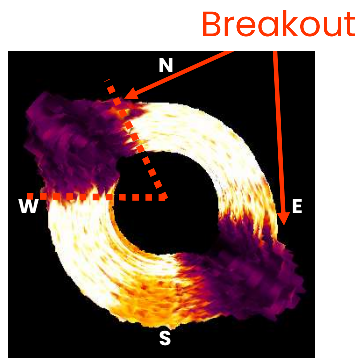
Baker Hughes

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.

Baker Hughes

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.

Applications Overview

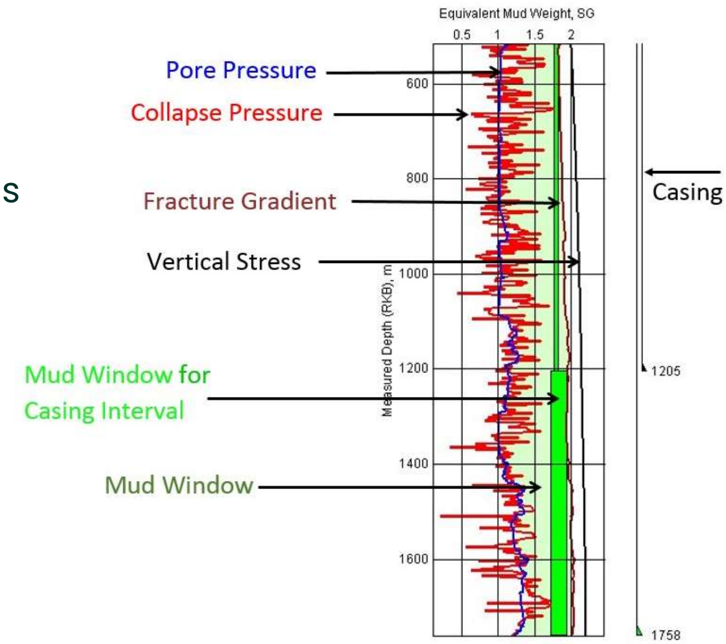
Baker Hughes

Wellbore Stability

Wellbore stability determination is one of the primary applications of the geomechanical model.

It is used to determine the optimal:

- Mud weight ranges
- Trajectories
- Casing set points



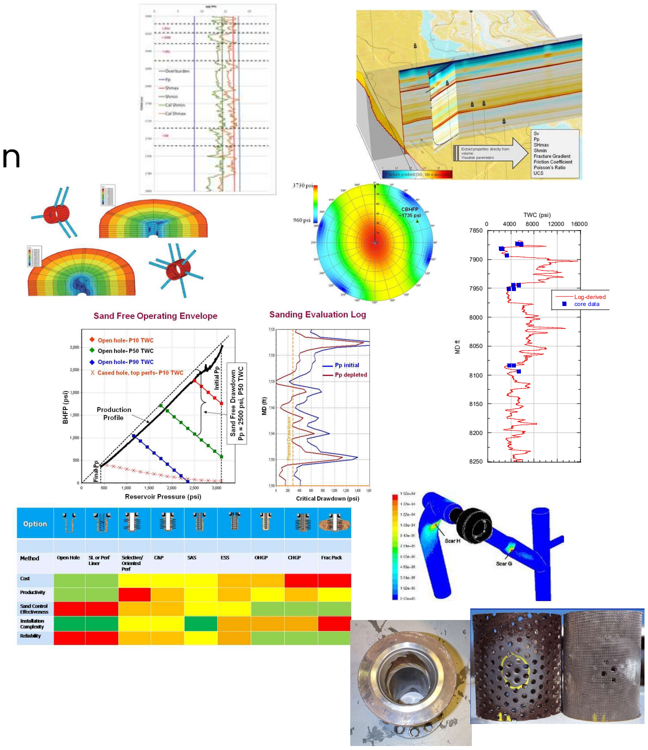
Mud Window Inputs

Baker Hughes

A good casing design should take into account the borehole collapse pressure as well as the pore pressure and fracture gradient.

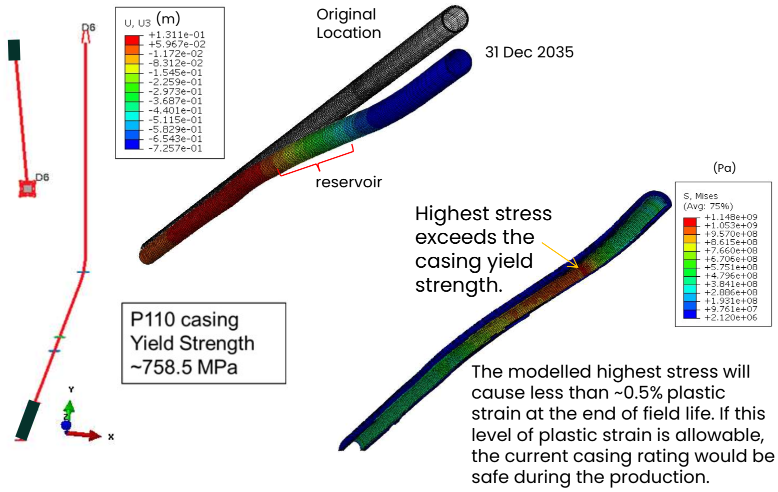
Sand Production Prediction

- Sand Quantification – volume estimation
  - Open hole
  - Cased & perforated
  - Maximum drawdown & depletion
  - Optimized well trajectories & perforating
- Production inflow models
- Sand Transport models
- Sand Erosion models (flow lines)
- Sand Completion Selection Process
- Sand Management Surveillance
- Sand Management Planning



Sand production can erode surface facilities as well as completions, and therefore requires an holistic approach to solving the problem.

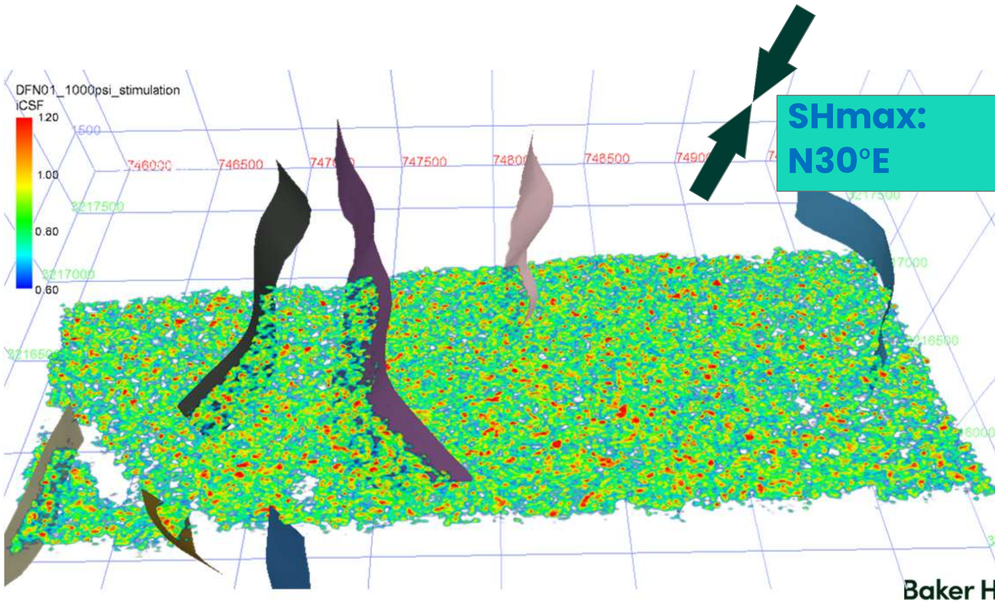
Casing Deformation



Baker Hughes

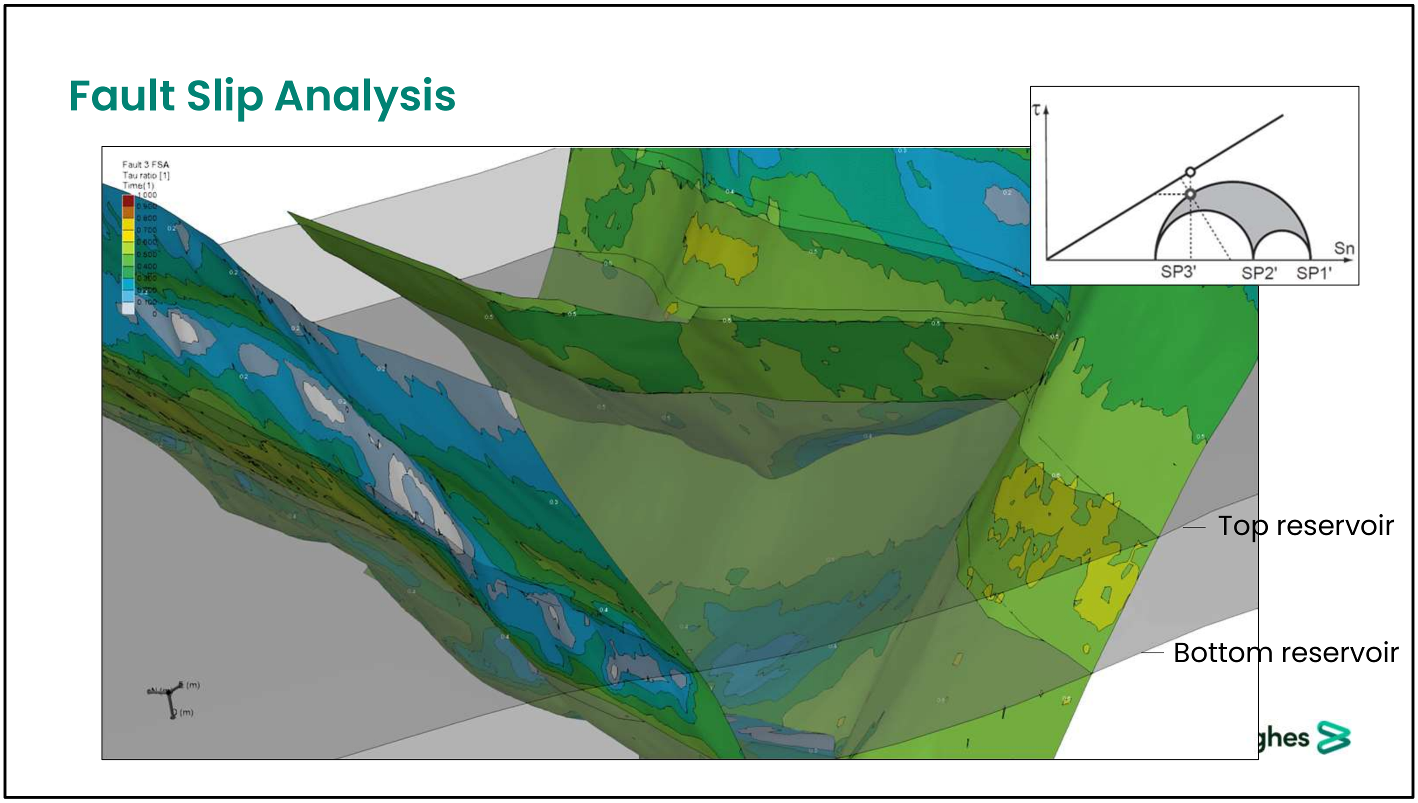
Casing can fail by a number of means, either above the reservoir or within the reservoir.

Fracture Permeability



Baker Hughes

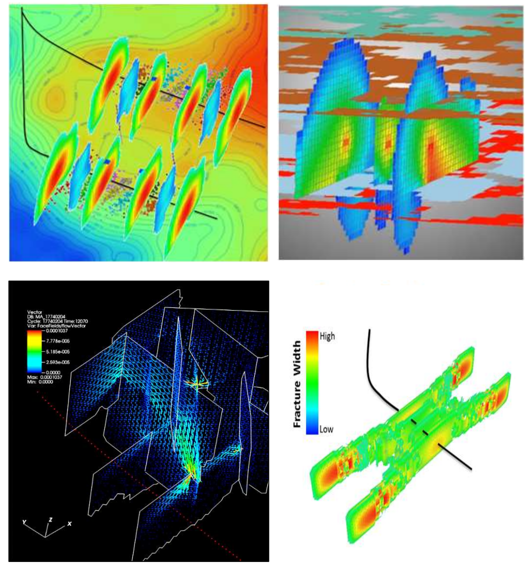
Fractures with high ratios of shear stress to normal stress tend to be hydraulically conductive, while fractures with lower ratios of shear stress to normal stress tend not to be hydraulically conductive. Statistically, the hydraulically conductive fractures are more likely to be critically stressed. By mapping the connectivity of these critically-stressed fractures, sweet spots can be identified in the reservoir.



Parts of faults that are likely to be stabilized or destabilized by injection are shown. Results of destabilization may be hydrocarbon leakage, sheared wellbores, stress changes, and earthquakes.

Hydraulic Fracturing

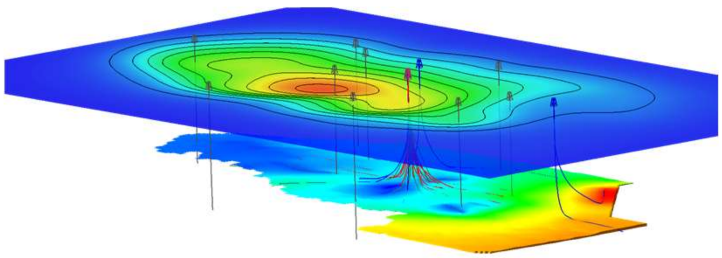
- Fully 3D multi-physics approach
- Single well to full reservoir scale models
- Optimized stimulation planning and engineering



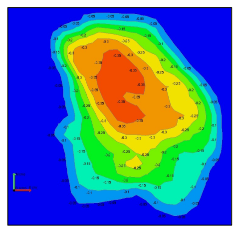
Baker Hughes

Hydraulic fracture propagation may be influenced by more than the far-field stresses. Near wellbore complexity of the stress field as well as the fabric of the rock - including faults, fractures, bedding, joints, and other hydraulic fractures - can strongly influence fracture growth.

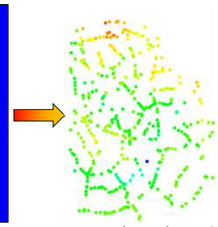
Compaction and Subsidence



From USGS Professional Paper 1401-A, "Ground water in the Central Valley, California- A summary report" Photo by Dick Ireland, USGS, 1977



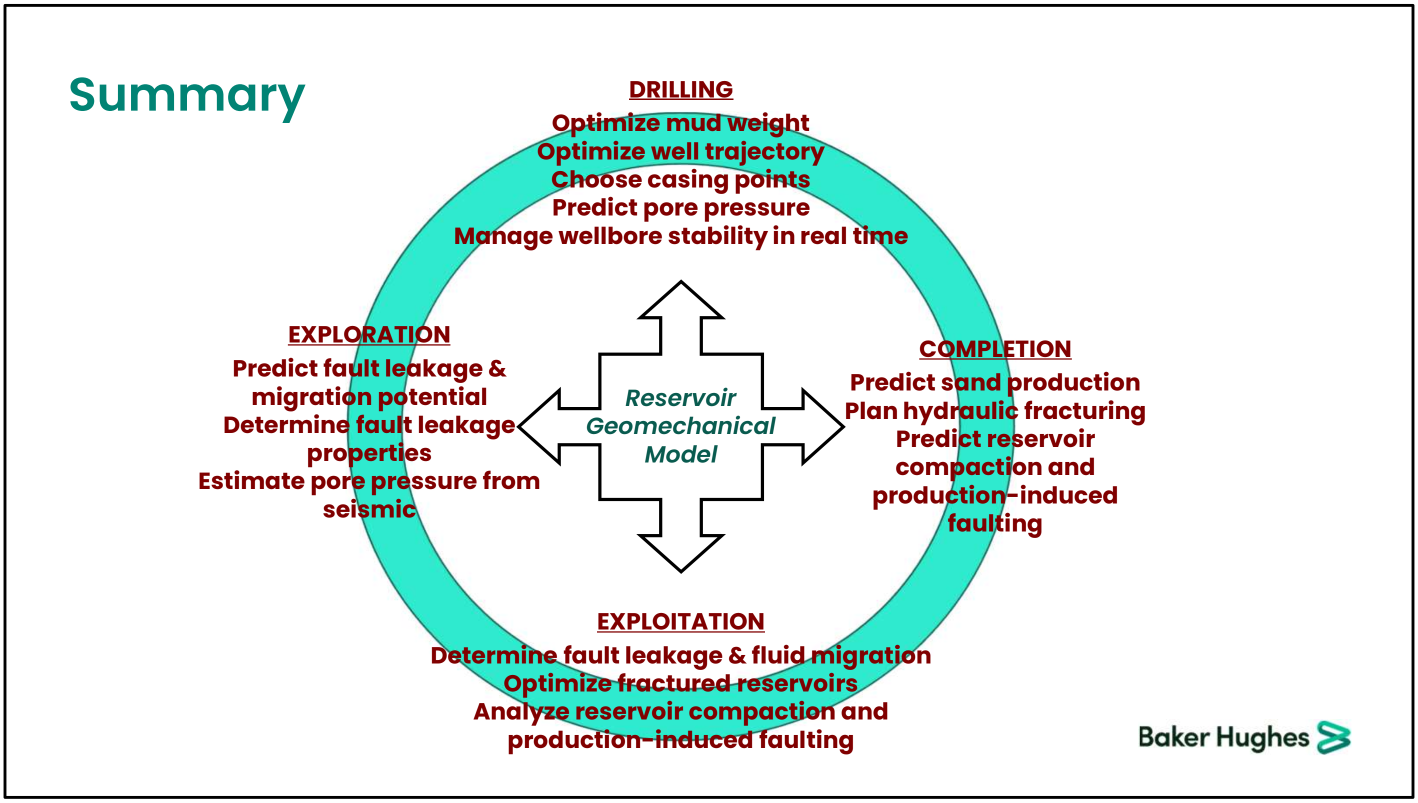
Modelled subsidence



Comparison with surface data

Baker Hughes

The problem with designing the completion after the drilling phase is that most life of well issues such as depletion and sand production are not optimized in the initial plan. Severe loss in productivity can occur with reactivation of faults (shearing and collapsing casing and liners) or dramatic loss of permeability due to localized reservoir compaction. The subsidence that often accompanies compaction may impact surface facilities and populations in unforeseen and dramatic ways.



Collapse of the wellbore is one of the leading causes of stuck pipe, resulting in sidetracks, packoffs, and collapsed completions. As the mud window shrinks, it becomes difficult to reach target depth without sufficient casing strings. Running out of "mud window" leads to loss of reserves, which could be avoided by careful upfront planning and consideration of wellbore stability effects in the initial plan.

We add significant value through improvements in completion design. Underbalanced drilling can be investigated and well design suited to ensure wellbore integrity during the underbalanced drilling operation. The proper azimuth is essential to maintain stability in open hole completions in horizontal wells and multilateral junctions. Knowledge of the direction and magnitude of S_{Hmax} enables optimal hydro frac design. The natural fracture system can also be exploited by drilling in directions that intersect the critically stressed (and therefore conductive) fractures.

The geomechanical model can have a significant impact on all aspects of field development from the exploration and appraisal phases through development and harvest of the field, to the final abandonment of the field. An optimized field development plan using geomechanics can result in very large cost savings over the life of the field.

Baker Hughes