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Optimizing Asset Design - Cradle to Grave

“Bridging the Gap between the Earth Science & Engineering Disciplines using Mechanical Earth Modeling Technology”

Harvey E. Goodman

Chevron Fellow

Rock Mechanics & Mechanical Earth Modeling

Business Driver and Technical Focus Area Selection

Business driver:

Optimize well Design - Reliability and Placement through the life of the gas/oil field asset.

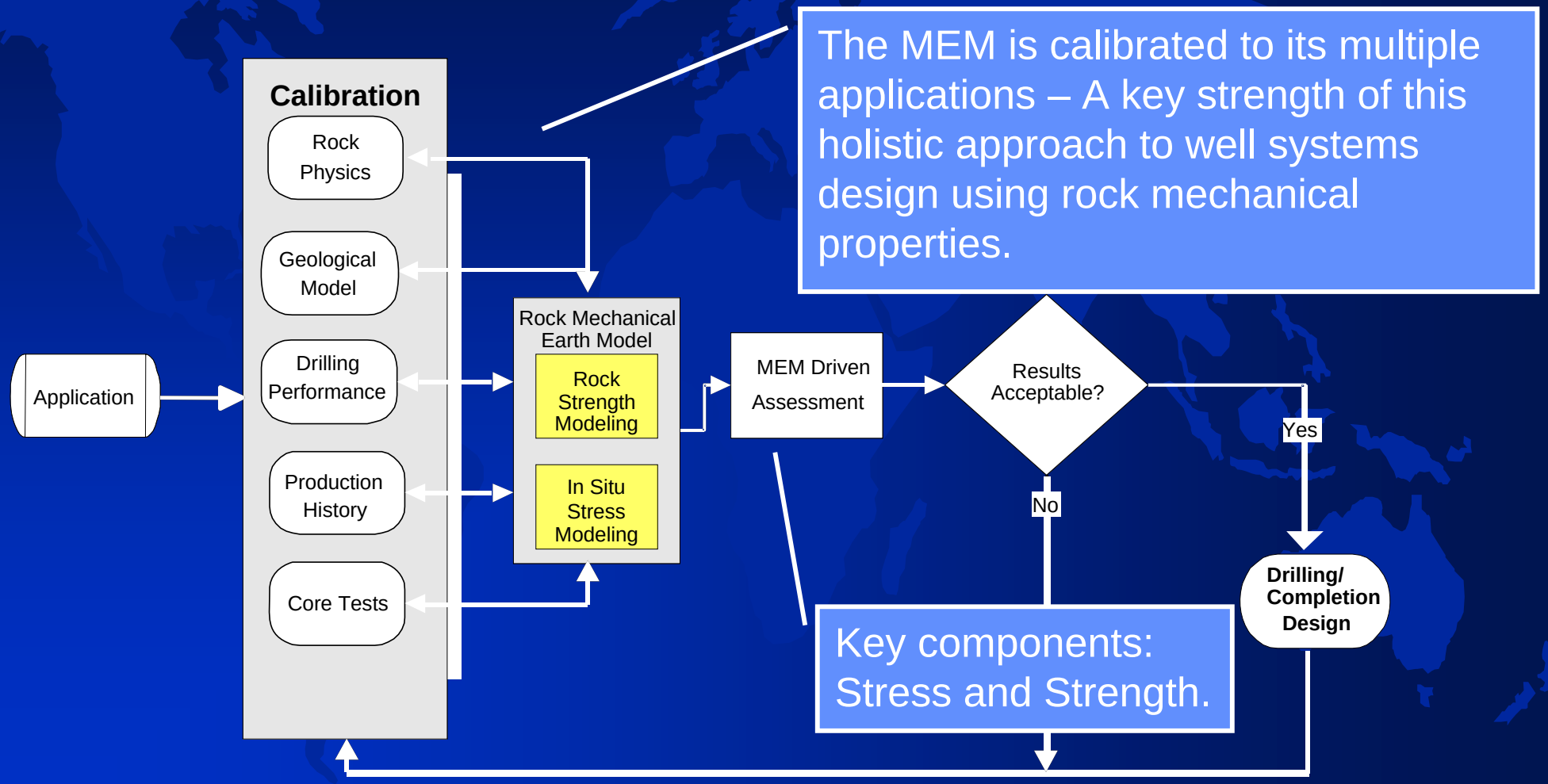
Technical focus:

Link the engineering disciplines necessary to build safe, reliable well systems with the geological and geophysical sciences involved in asset discovery.

Discussion Topics

1. The Mechanical Earth Model (MEM) approach to well systems design
   - What is it?
   - How can a MEM add value?
2. Building the MEM from Acoustics Data
   - Rock properties and acoustics predictions
   - Seismic techniques
   - Examples
3. Using the MEM to conceptualize development risks
   - Hole stability
4. Future Trends and Challenges

Mechanical Earth Model or MEM

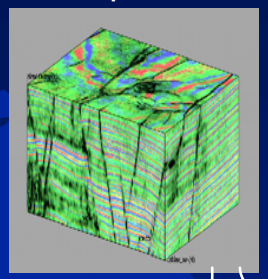


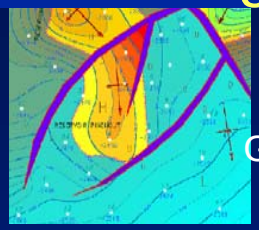
The MEM is calibrated to its multiple applications – A key strength of this holistic approach to well systems design using rock mechanical properties.

Key components: Stress and Strength.

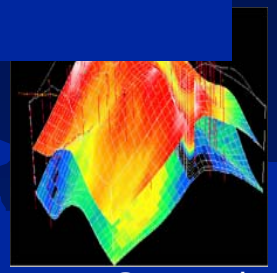
The Mechanical Earth Model
Big Picture

Seismic Interpretation



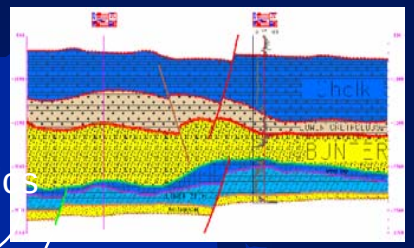


Geol. Maps



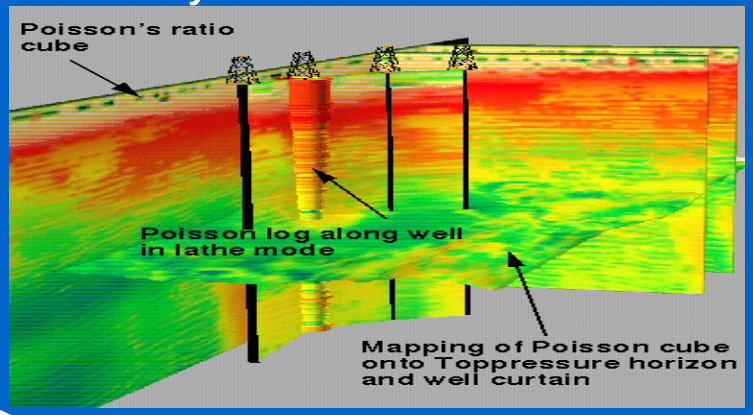
Geostatistics

Reservoir Characterization

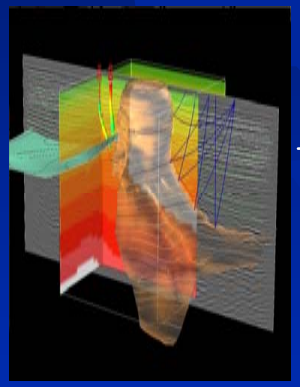


Cross -Sections

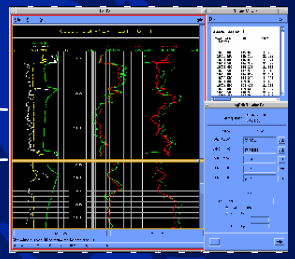
Dynamic Poisson's Ratio



G O C A D



Stratigraphic Modeling

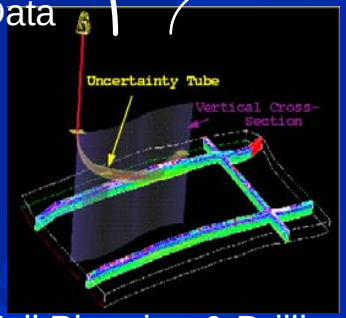


Petrophysics

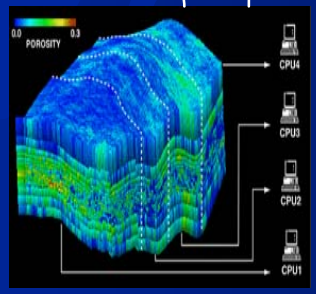
Historical Operational Data

Drilling

Real Time Drilling Data



Well Planning & Drilling Simulation



Reservoir Simulation

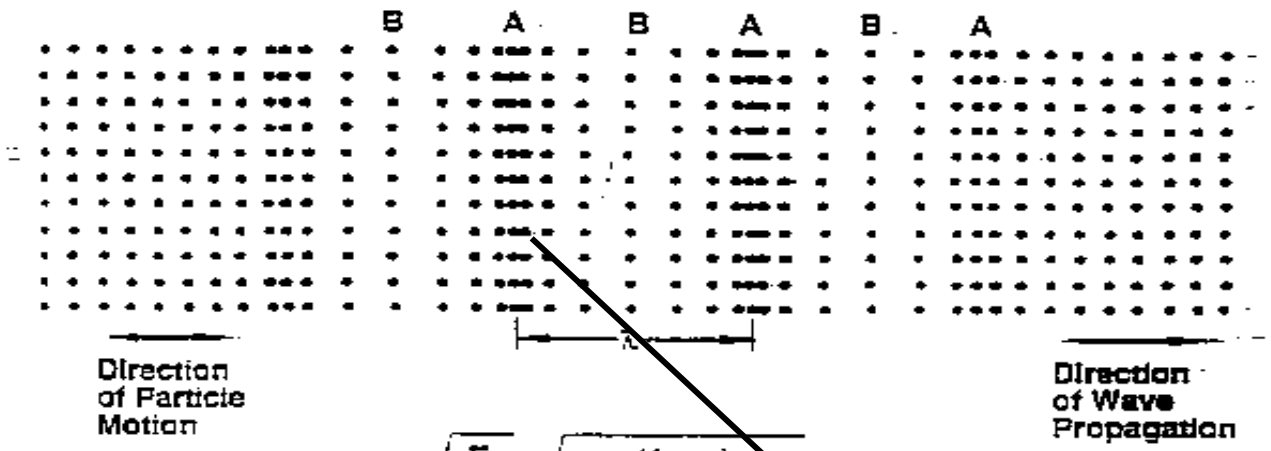
Historical Production Data

Production

Real Time Production Surveillance

How we use acoustics to define the MEM.
But first, some background:

The P Wave



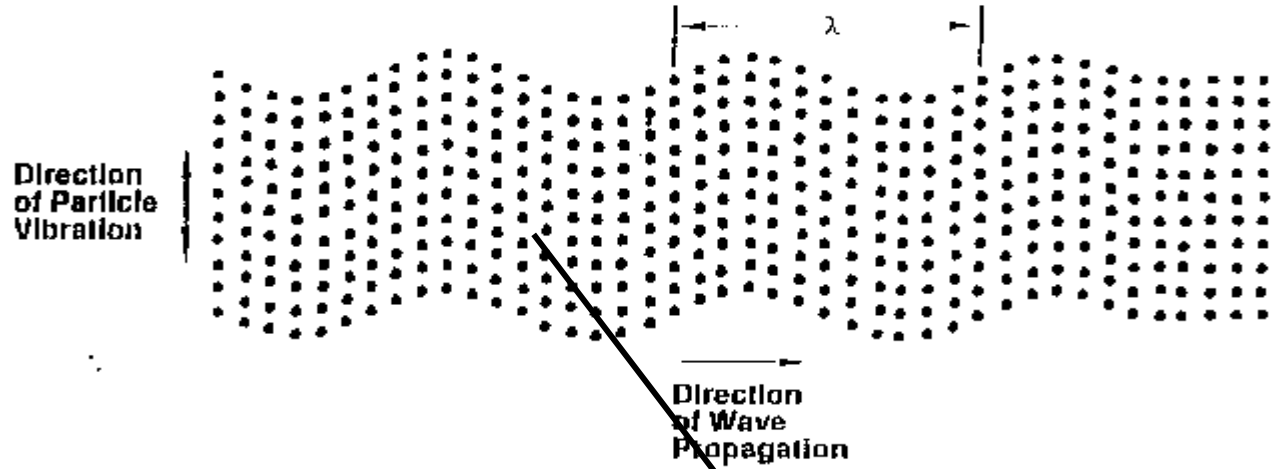
$$V_L = \sqrt{\frac{E}{\rho}} \sqrt{\frac{(1-\sigma)}{(1+\sigma)(1-2\sigma)}}$$

$$V_L = \lambda f$$

Figure 3
Longitudinal (Compressional or Pressure or P) Wa
(Krautkramer and Krautkramer, 1961)

Particle motion parallel to wave propagation.

The S Wave



$V_S = \lambda f \qquad V_S = \sqrt{\frac{G}{\rho}}$

Particle motion perpendicular to wave propagation.

Figure 4
Shear (Transverse or S) Wave
(Krautkramer and Krautkramer, 1961)

P & S Velocities

- Depend on the elastic properties of the travel medium
  - Hard rock has fast P & S velocities.
  - Soft rock has slow P & S velocities.

$$V_p = \sqrt{\frac{\frac{4}{3}G + K_b}{\rho_b}}$$

$$V_s = \sqrt{\frac{G}{\rho_b}}$$

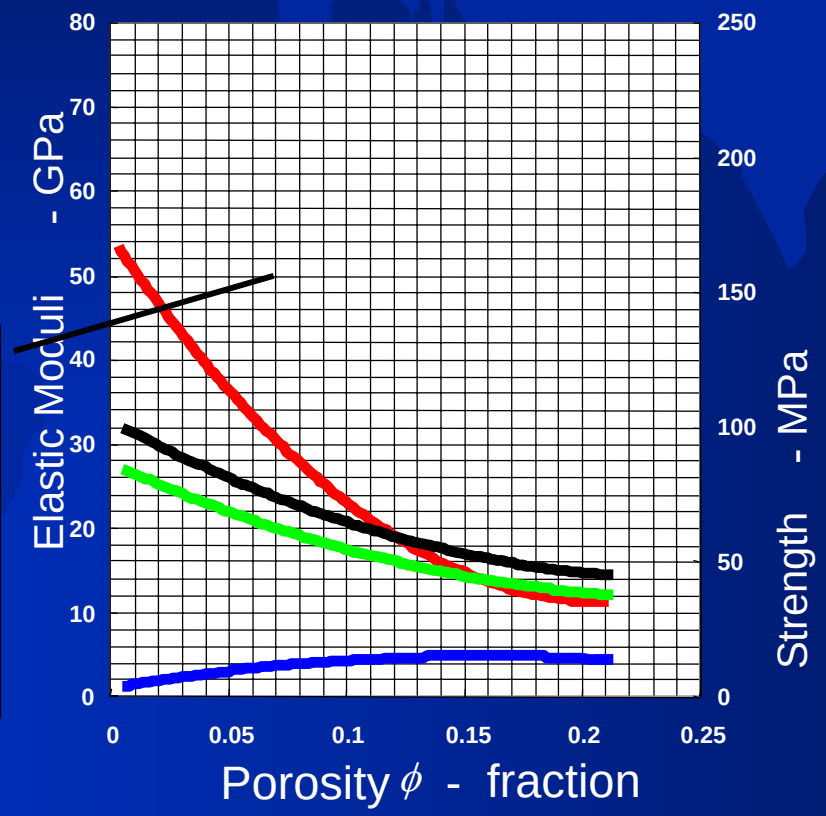
Shear (G) and bulk (K_b) moduli are rock stiffness terms; both inversely proportional to bulk density (ρ_b).

Rock Physics and Engineering Properties

- Frame properties are used to estimate rock strength and stress magnitude.

As porosity decreases rock stiffness increases effecting strength and stress propagation tendencies.

Porosity, Elastic Moduli & Compressive Strength



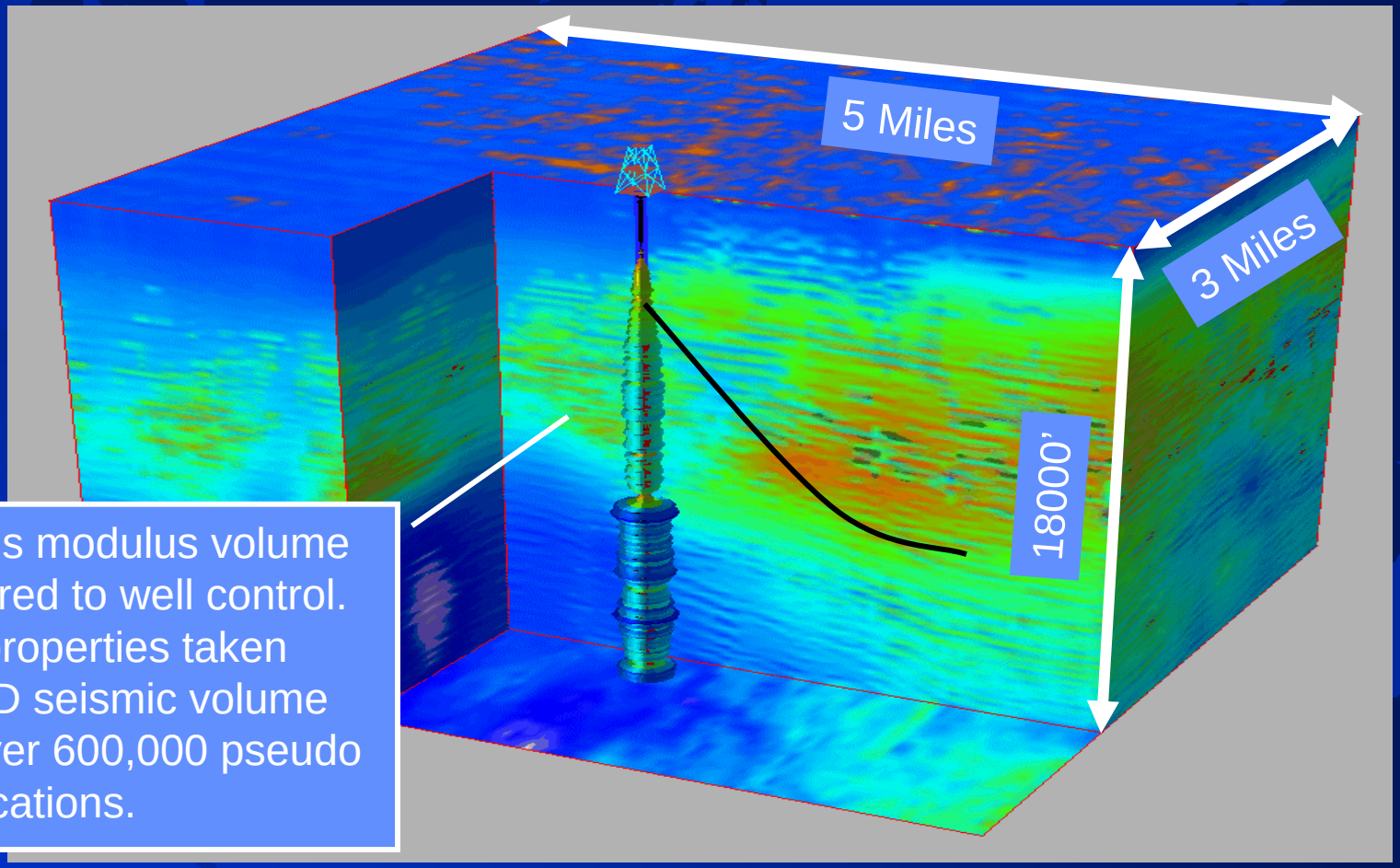
Comp Strength

Bulk Modulus Kb

Shear Modulus G

Pore Vol Modulus Kp

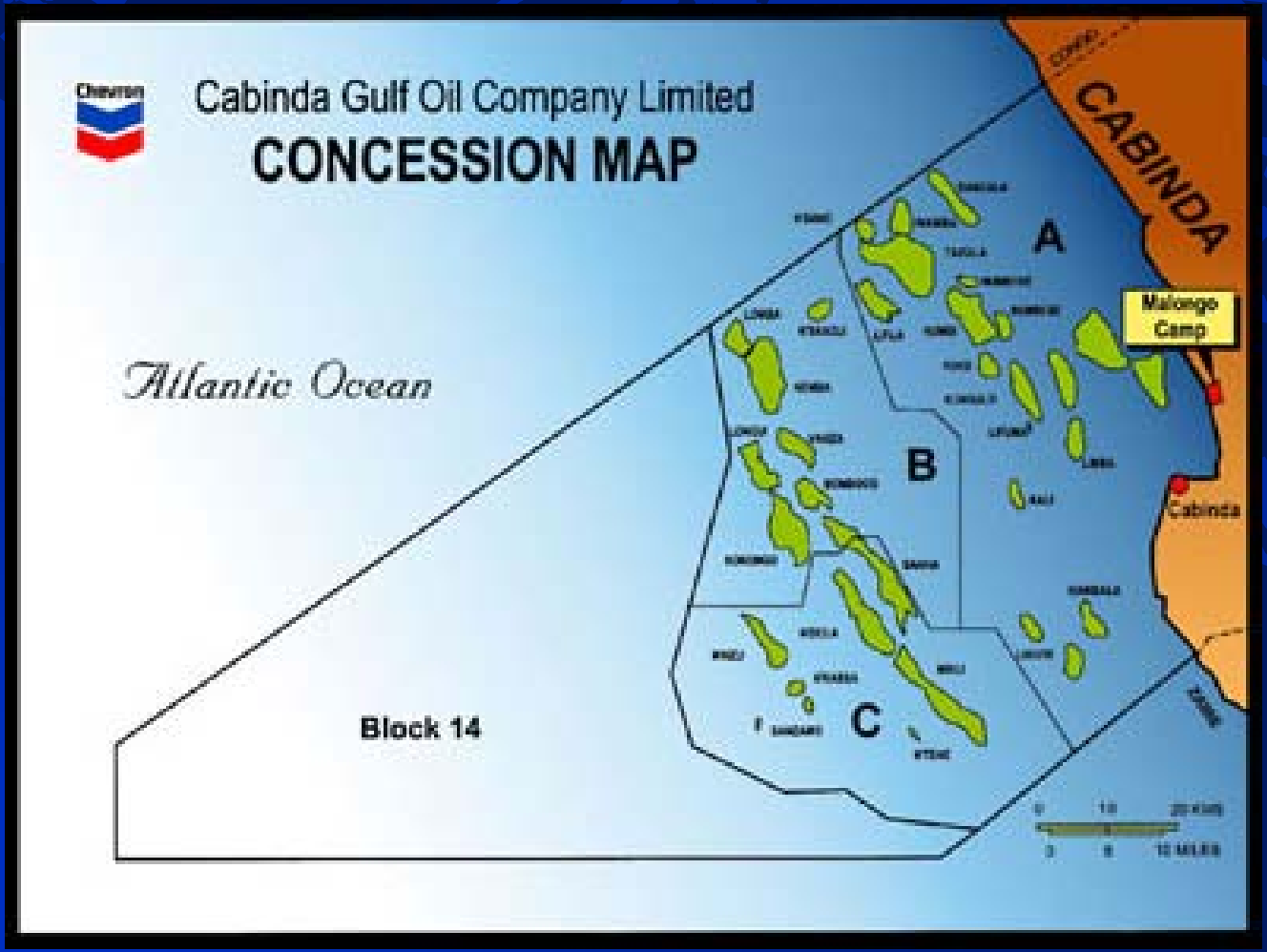
The Mature Mechanical Earth Model



Young's modulus volume compared to well control. Rock properties taken from 3D seismic volume with over 600,000 pseudo well locations.

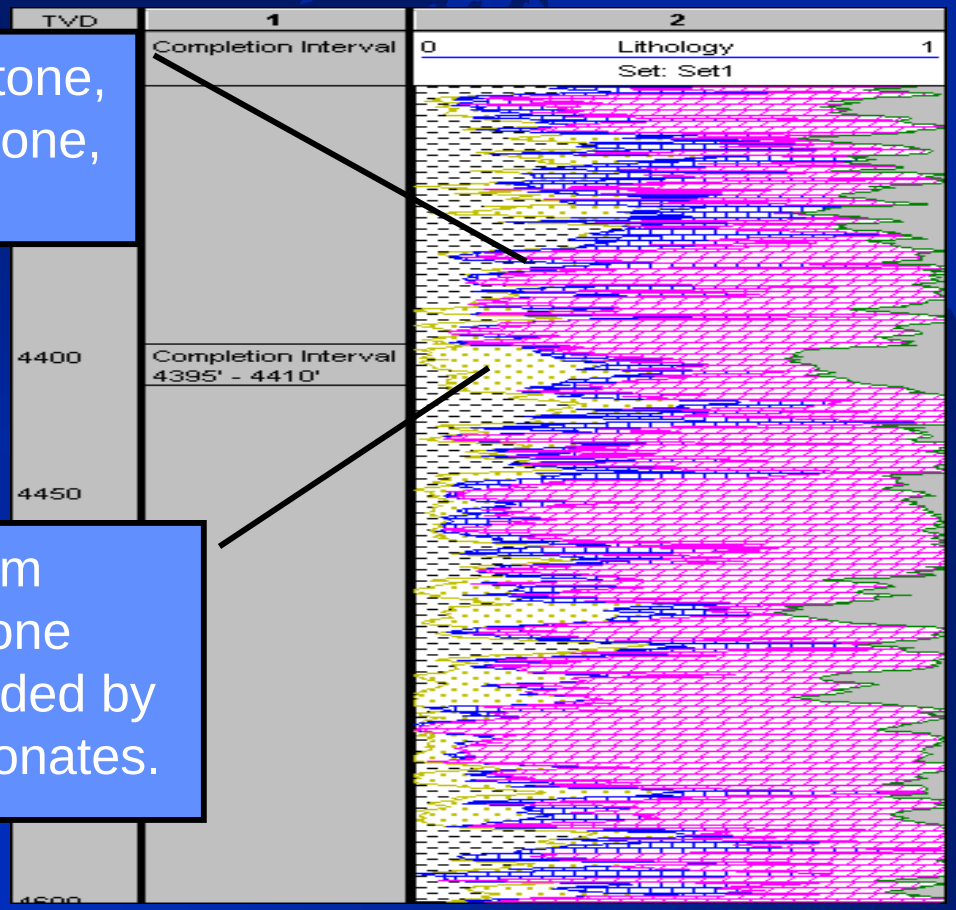
How well can we predict Shear wave velocity? What do we need to know first?

Angola Offshore



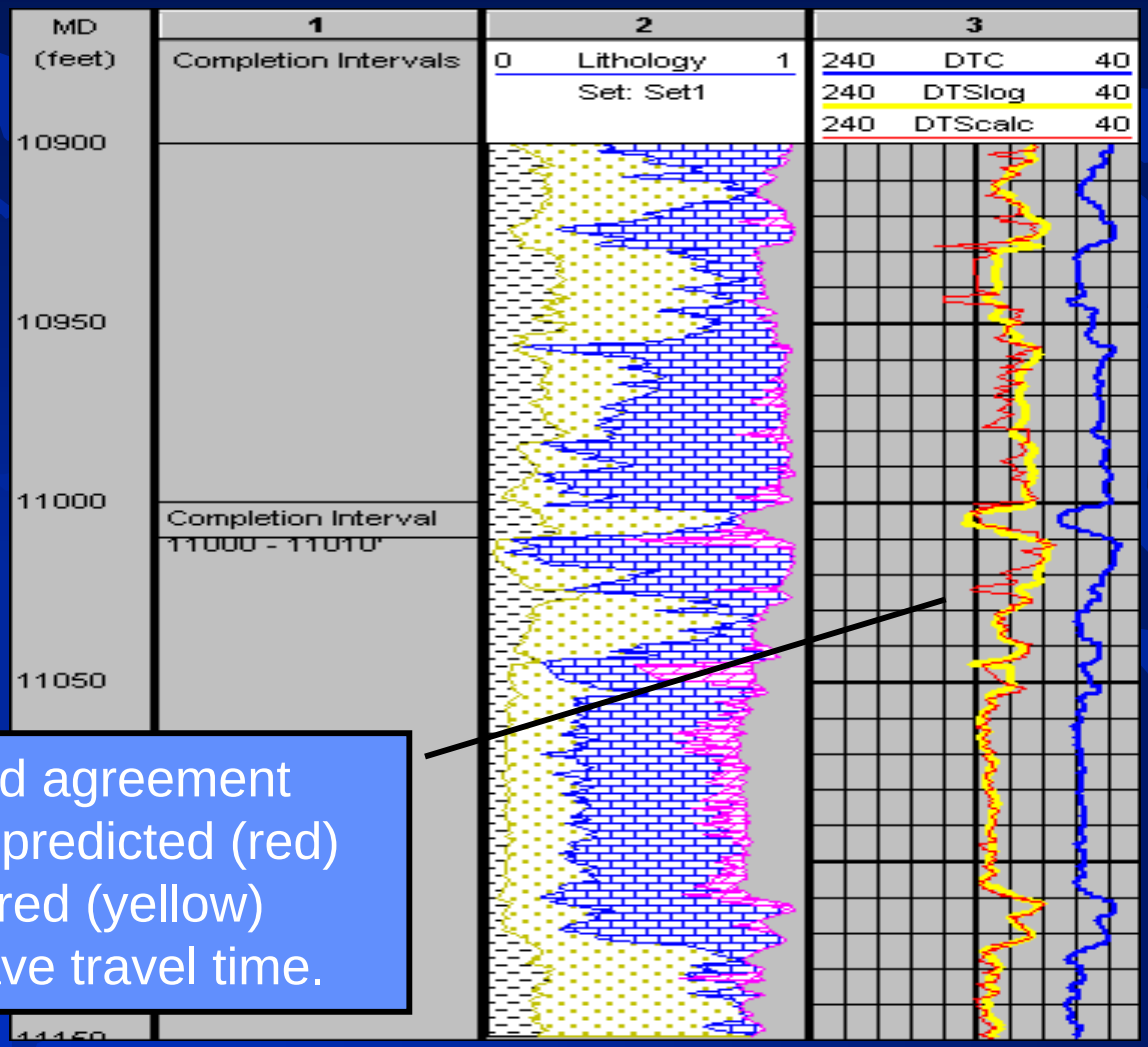
Complex Lithology, West Africa

Mixture of sandstone, dolostone, limestone, and minor shale.



Production from friable sandstone intervals bounded by hard stiff carbonates.

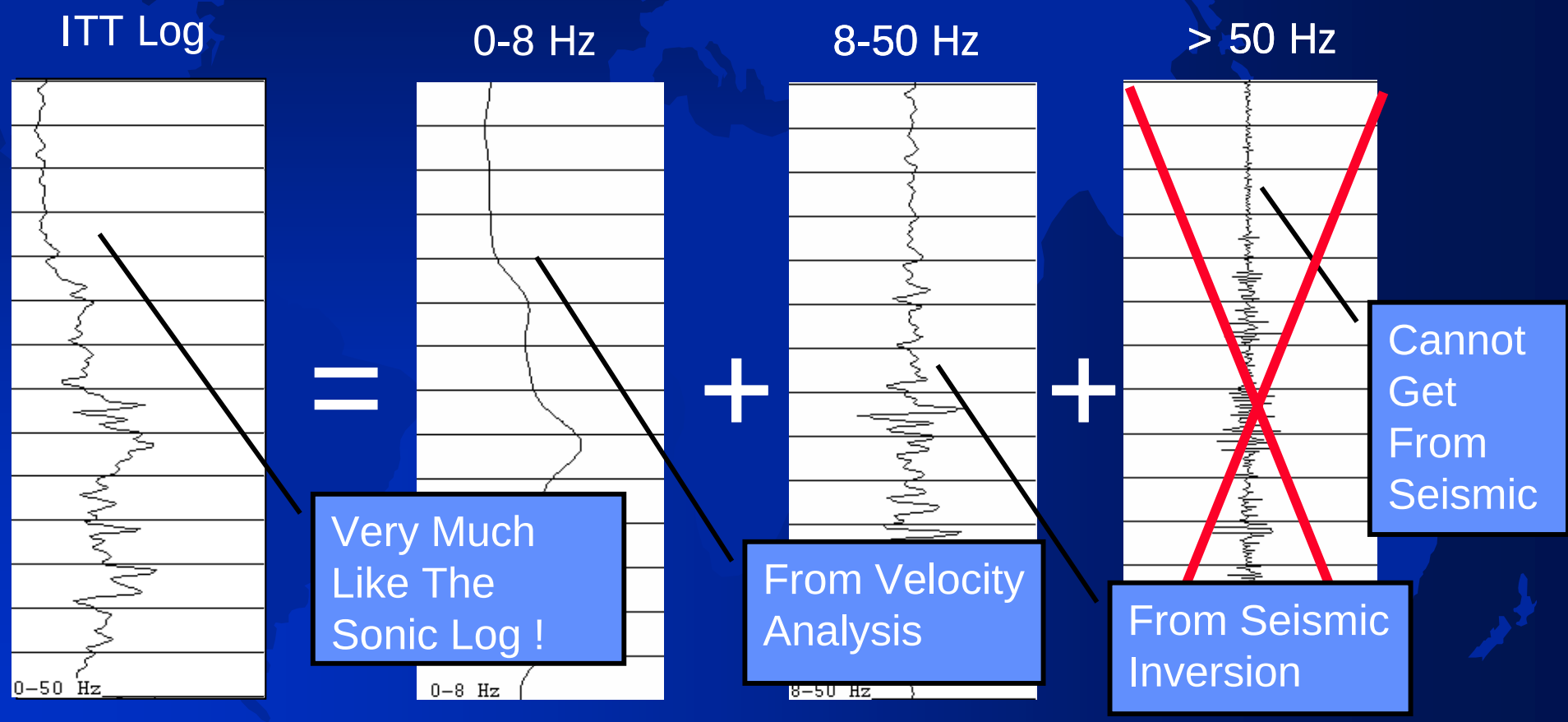
Complex Pinda Fm S-Wave Modeling



Very good agreement between predicted (red) & measured (yellow) shear wave travel time.

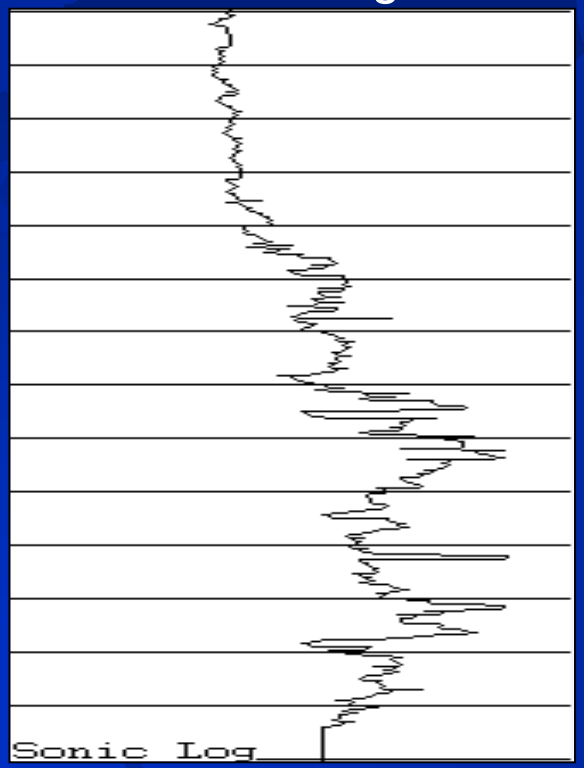
A brief look at how we manage to characterize P-wave velocity and lithology from seismic data sets.

ITT (interval travel time or pseudo-sonic log) as Sum of Seismic Velocities

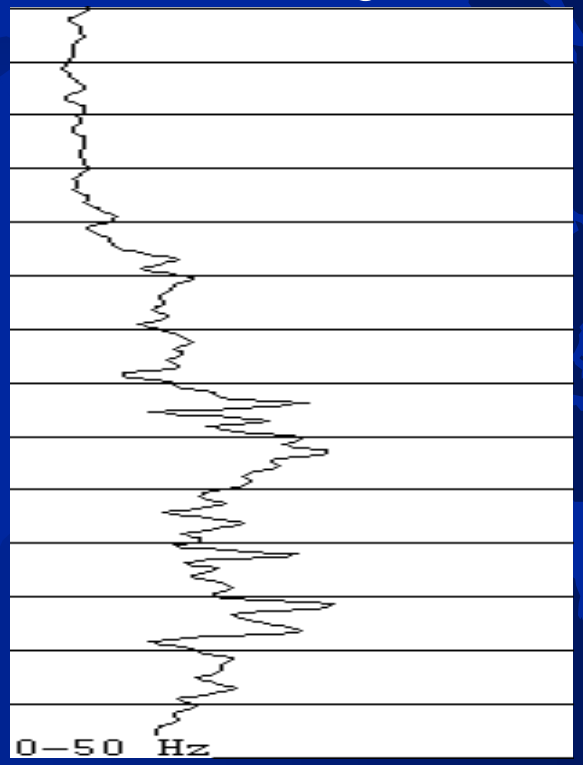


Not Perfect But Pretty Good !

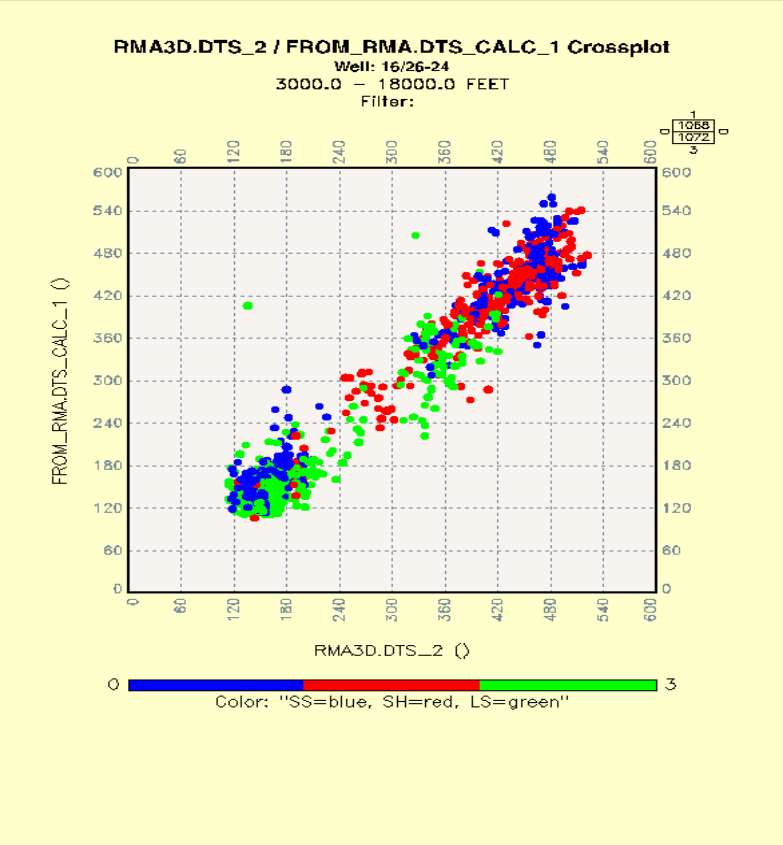
Sonic Log



ITT Log



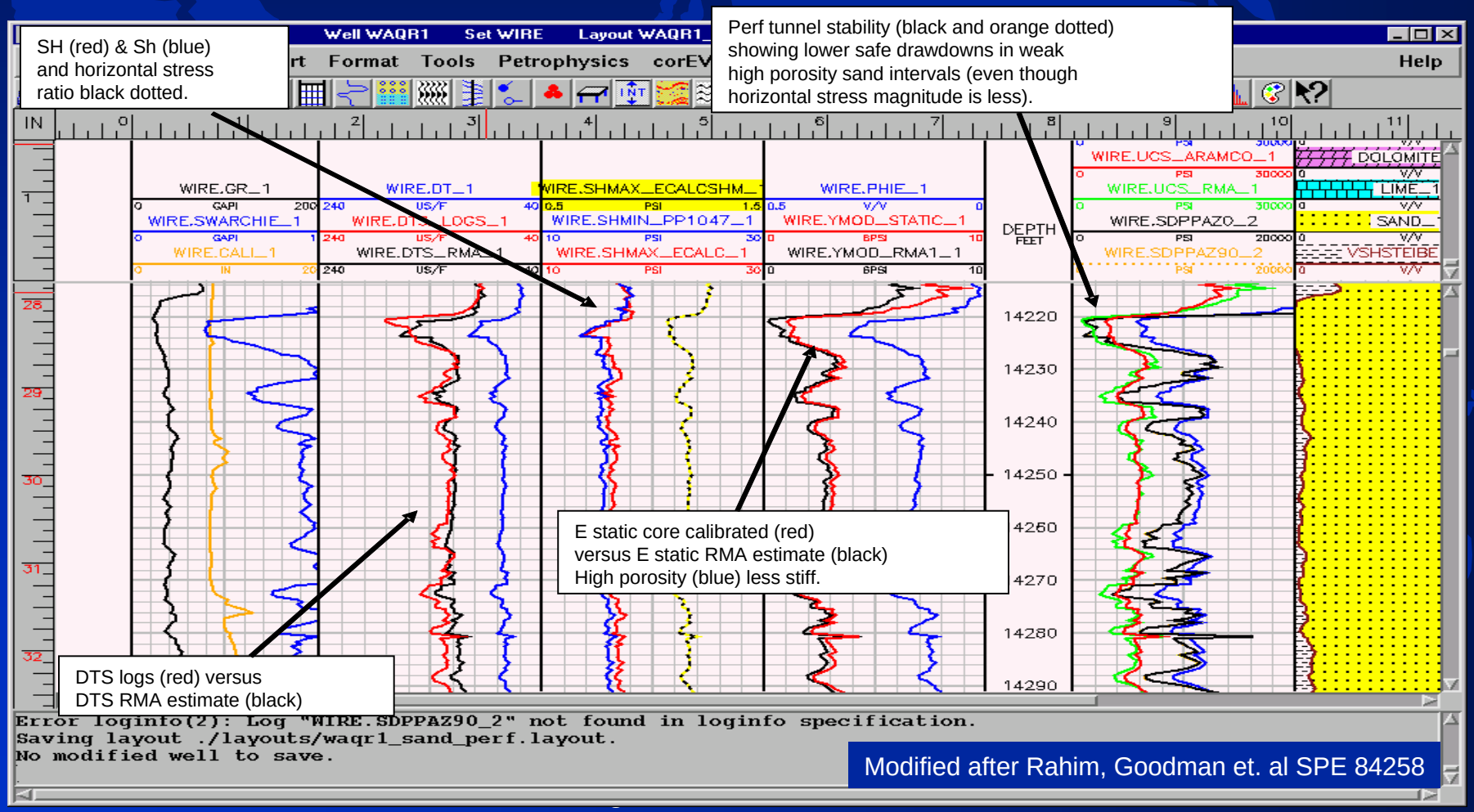
Seismic and Well Log Derived Shear Wave Velocity with Respect to Lithology



- Vertical axis is the shear slowness coming from sonic log and log based lithologies.
- Horizontal axis is the shear slowness from the seismic inversion.

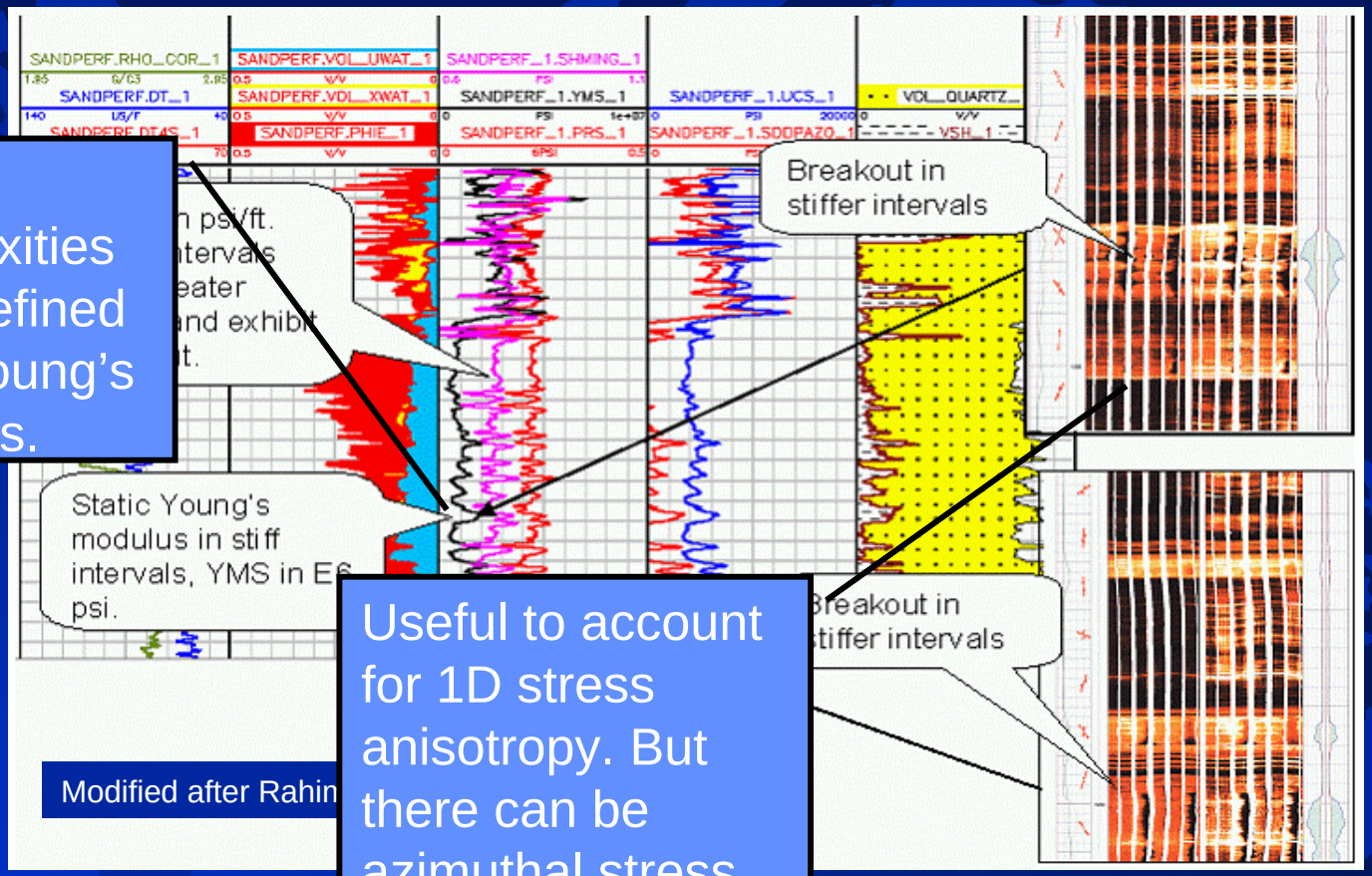
We Can Predict Rock Strength and Static Young's Modulus From Acoustics.

Formation Strength and Static Young's Modulus from Logs.



Modified after Rahim, Goodman et. al SPE 84258

Layer Dependent BO



Modified after Rahin

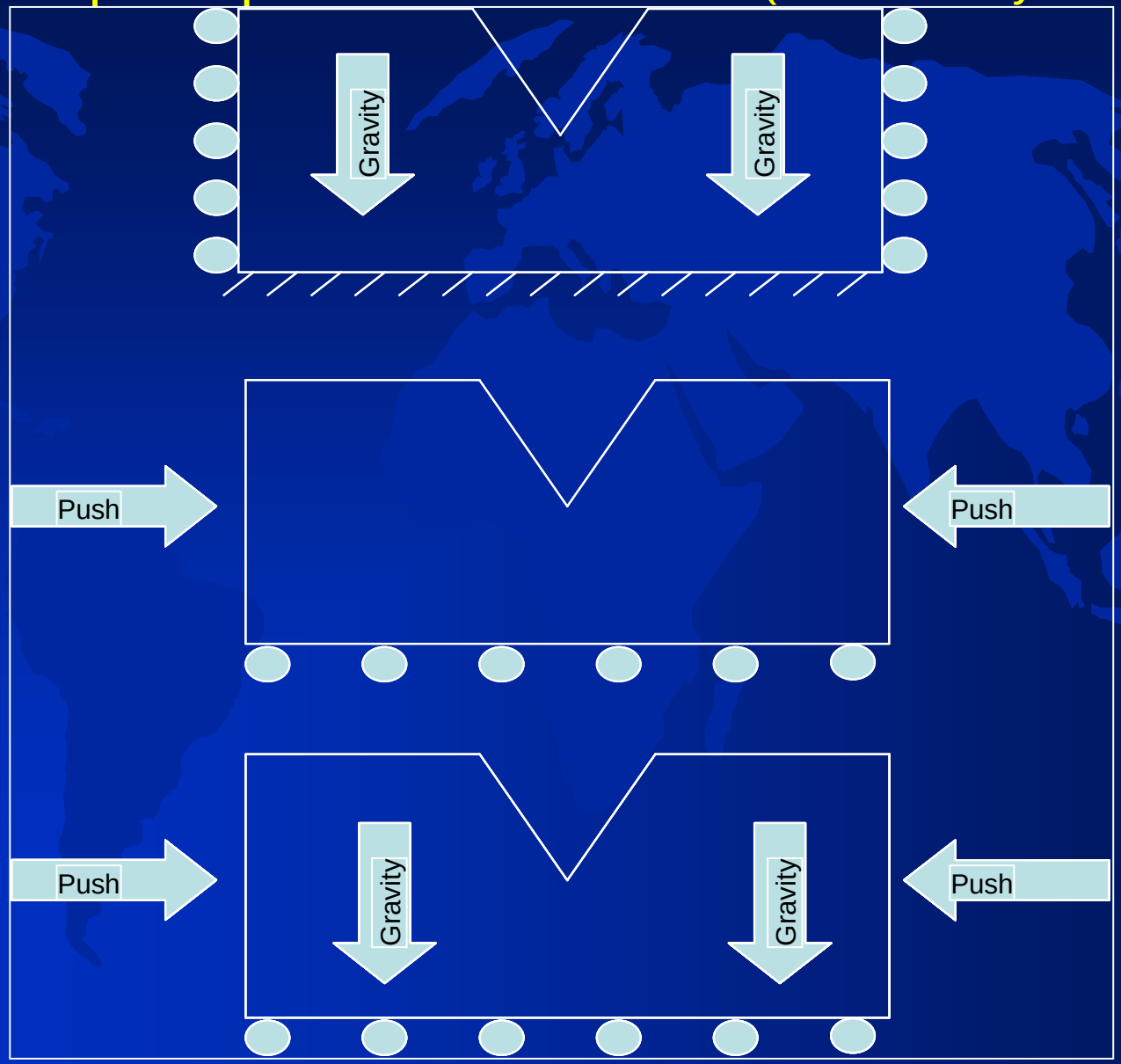
Stress complexities were defined from Young's modulus.

Useful to account for 1D stress anisotropy. But there can be azimuthal stress anisotropy too.

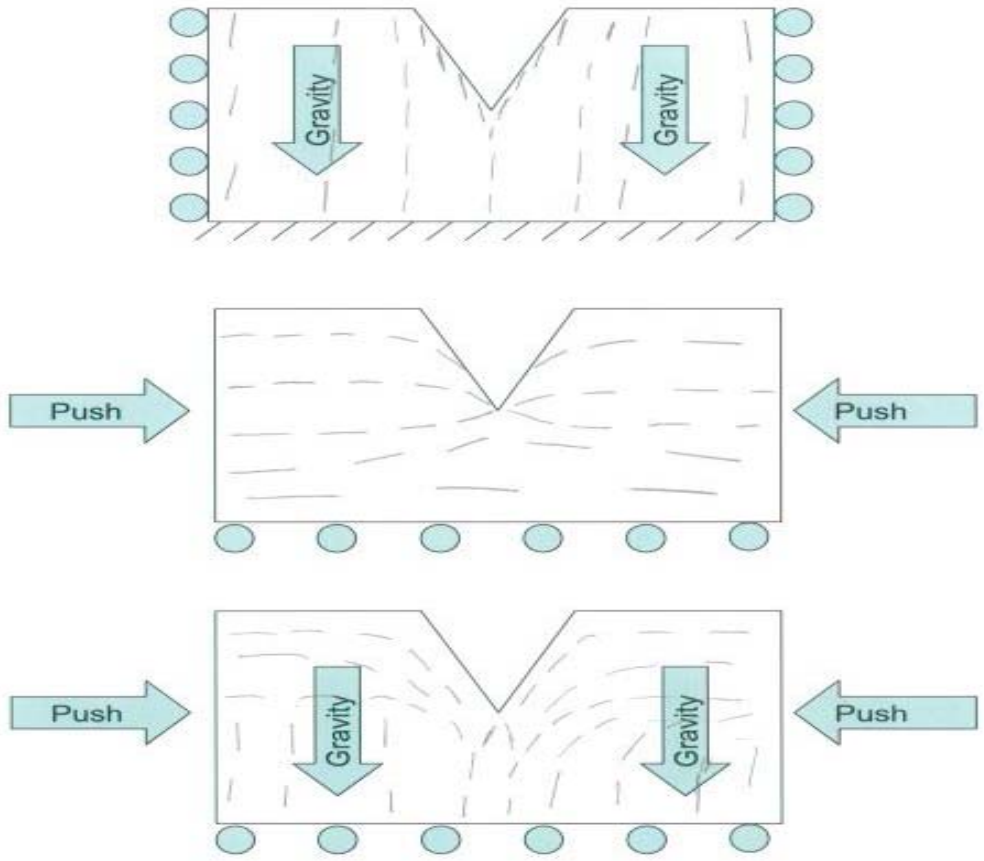
- We believe the stiffer formation layer intervals are more highly stressed; essentially the load bearing members of the geologic section.

- We now use this concept to predict stress character across the geologic structure using MEM properties & numerical modeling.

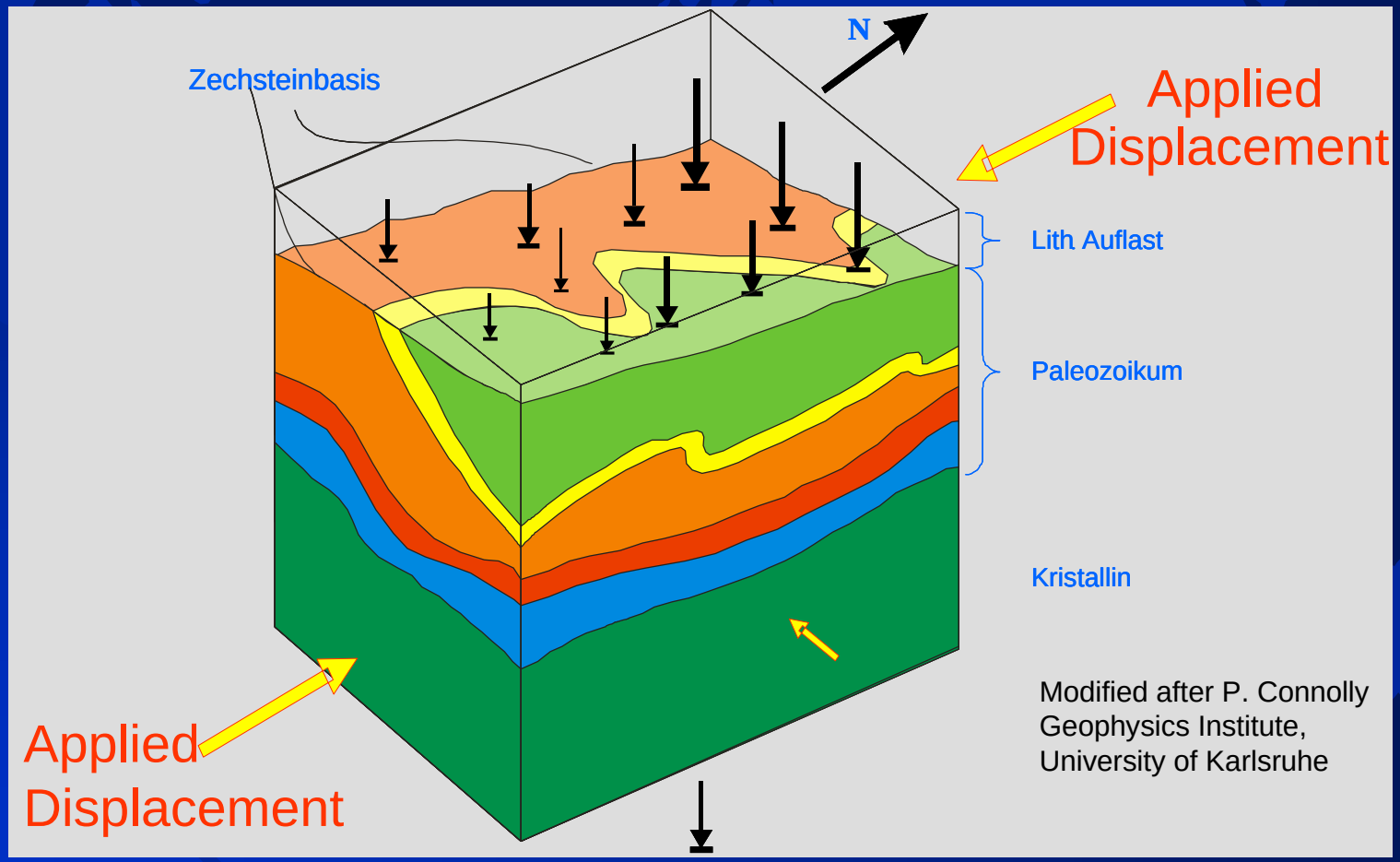
5. Annotate the following images with minimum and maximum principal stress vectors. (P. Connolly – 2008)



5. Answer to Max principle stress orientation question.



Stresses in the 3D Volume

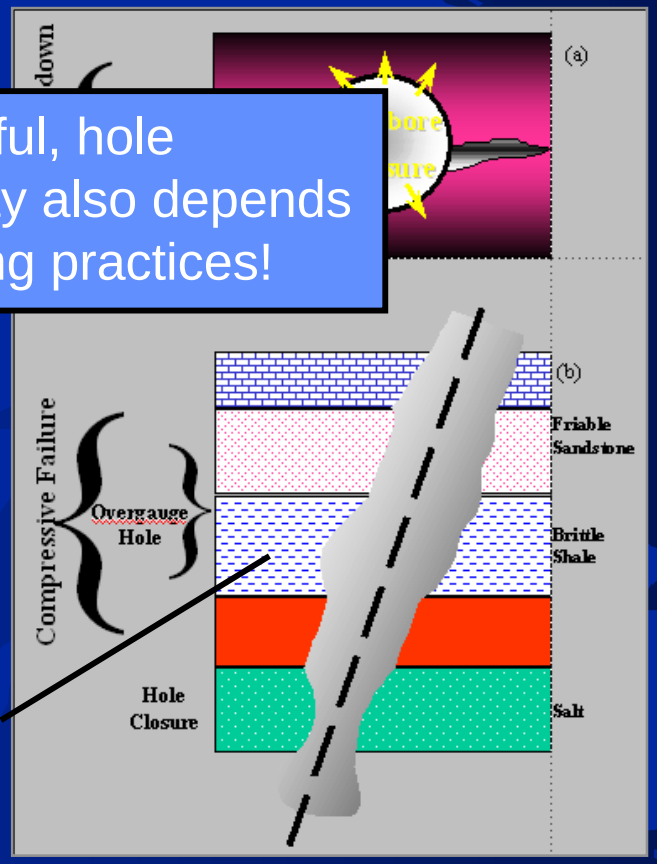


Rock Mechanics Of Hole Failure

Symptoms:

- Large size and volume of cavings/cuttings
- Oversize hole
- Stuck pipe by packing off
- Hole fill after tripping
- Restricted circulation/increase in pump pressure

Be careful, hole instability also depends on drilling practices!

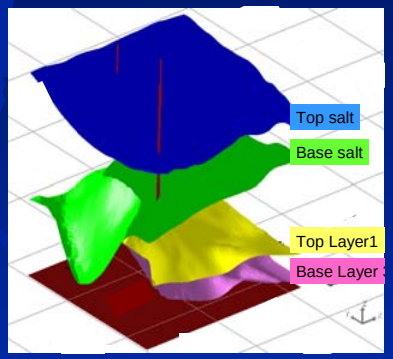


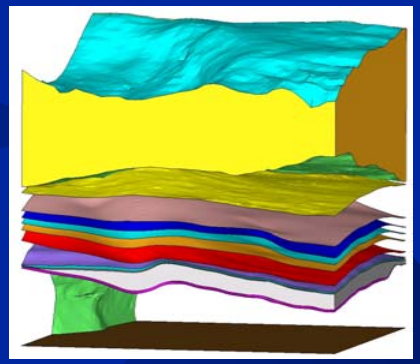
Common practice estimates stress and rock strength that caused hole failure.

Hole stability forecast for deepwater subsalt play

- Ocean bottom bathymetry overlying the massive salt sheet GOM
- Oil reservoirs have been in water depths greater than 6,000', overlain by greater than 10,000' of salt

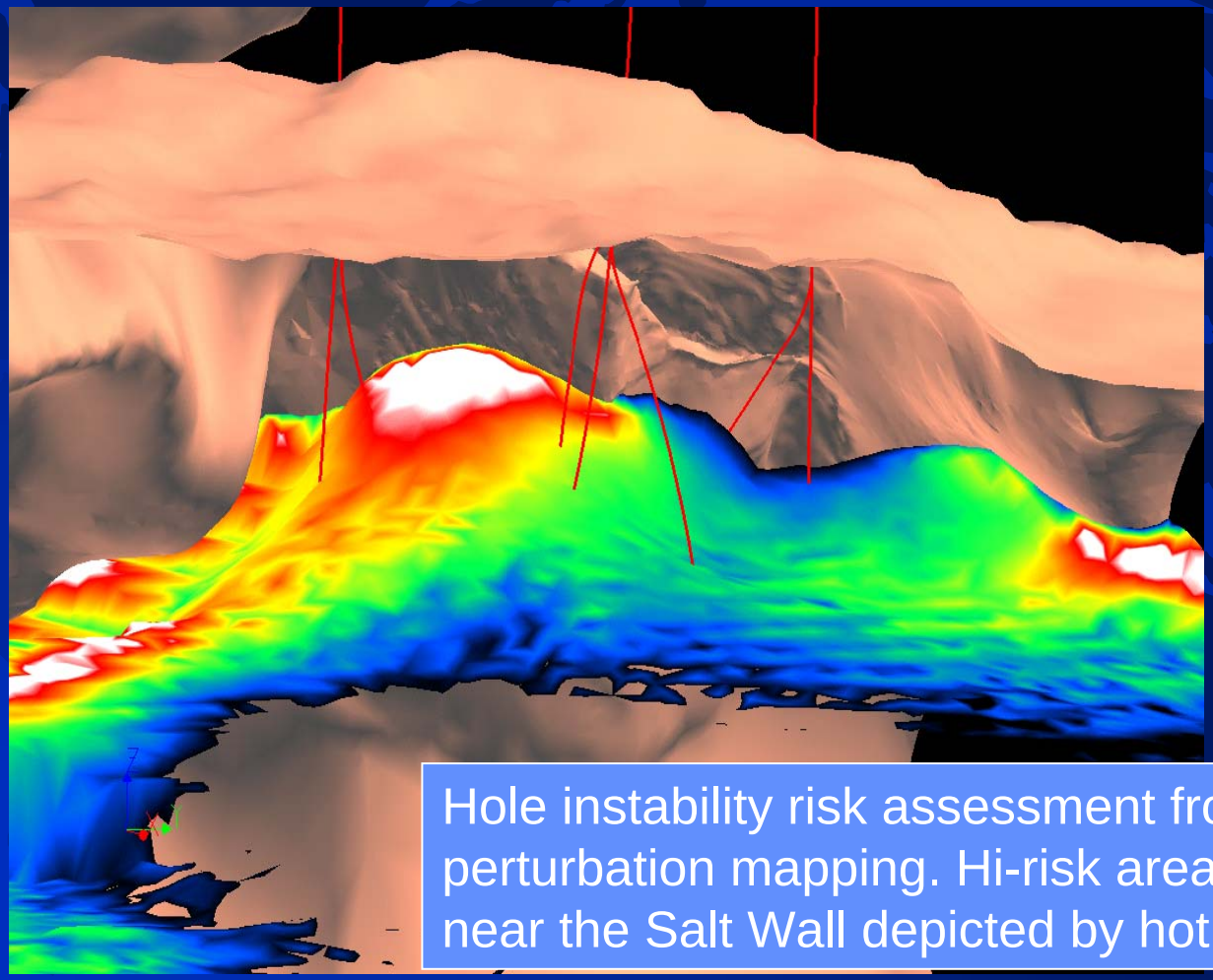
Deepwater subsalt MEM





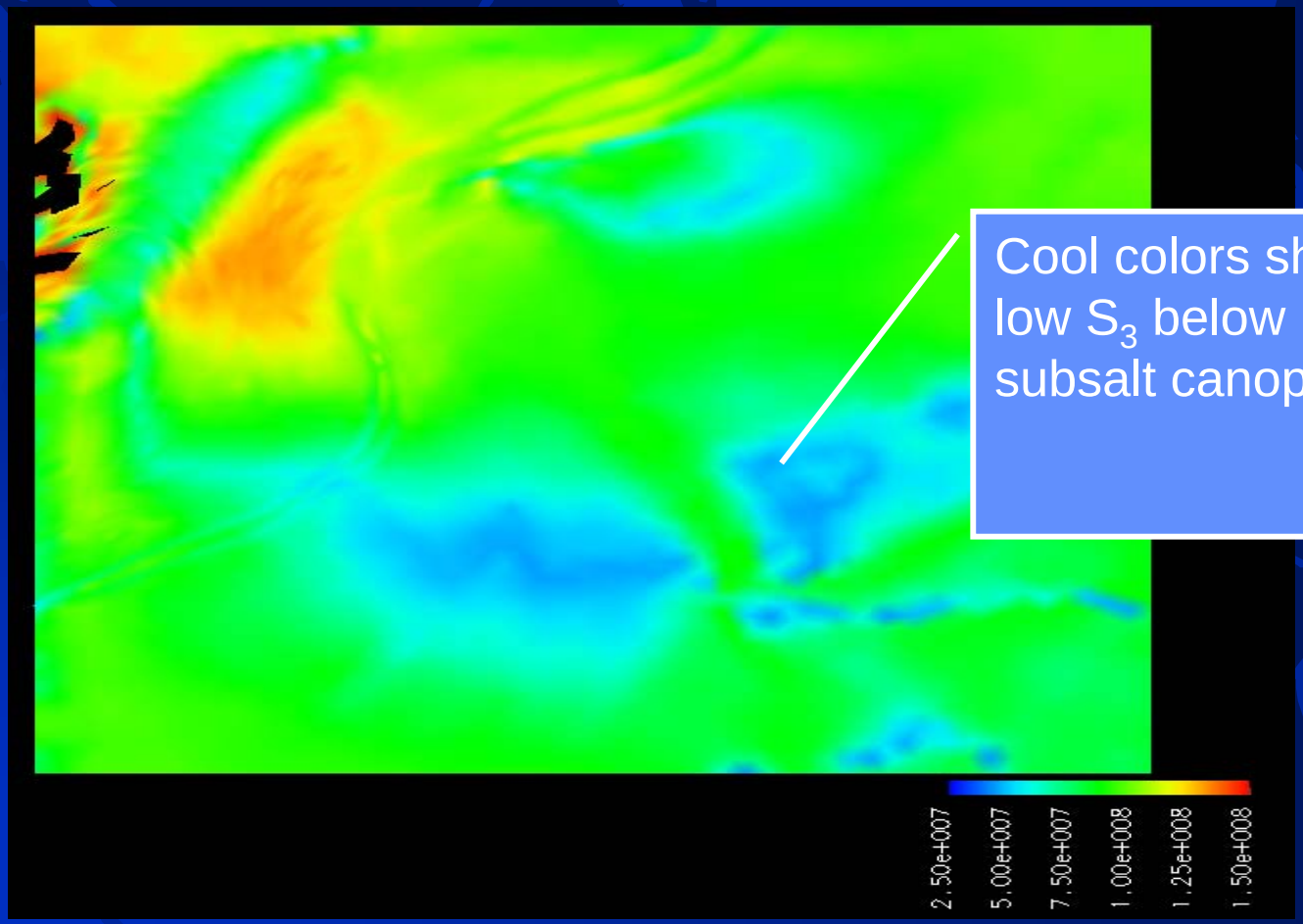
- Build earth model geometry that utilizes mapped salt and geological formation bed boundaries across the structure.
- Create FEA (finite element analysis) mesh that corresponds to geological model geometry.
- Build material model based on acoustics dominated data set that contains salt and non-salt elastic moduli (layer rheology).
- Apply far field loads constrained by the geological and structural model to produce in-situ stress field.

Stresses at Salt/Clastic boundaries



Hole instability risk assessment from stress field perturbation mapping. Hi-risk areas updip near the Salt Wall depicted by hot colors.

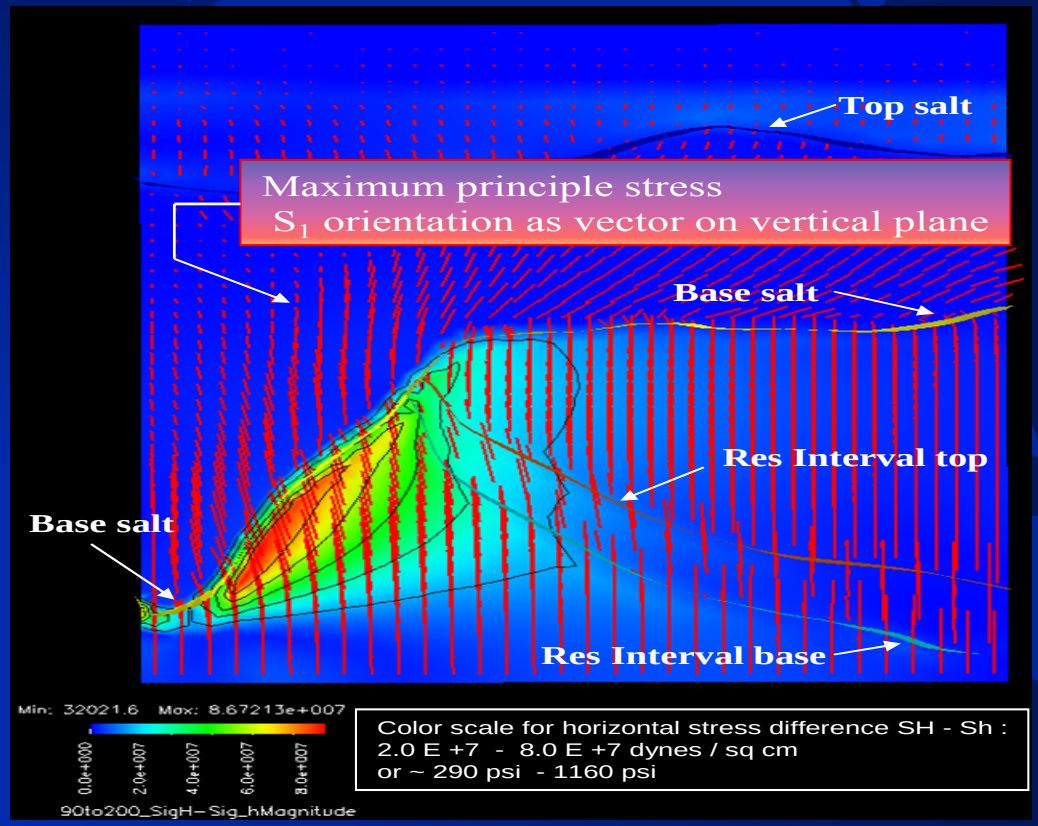
S_3 (minimum principle stress) along Base of Salt surface.



Cool colors show low S_3 below subsalt canopy.

In-situ stress complexity associated with the salt/clastic boundaries

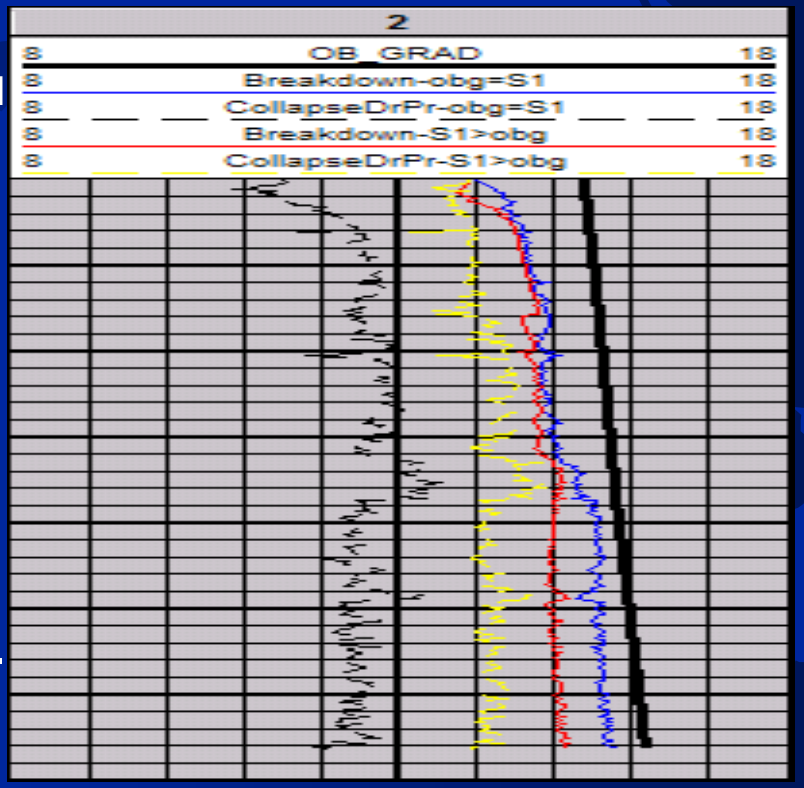
- Colors indicate difference in maximum horizontal stress σ_H and minimum horizontal stress σ_h
- Red lines show maximum principal stress S_1 rotation at subsalt boundary
- Can profoundly impact risk of drilling through this part of the subsalt structure.



Wellbore stability forecast profile
Principle Stress rotation effect

- Two principal stress regimes - $S_1 = \sigma_v$, $S_2 = \sigma_H$ and $S_3 = \sigma_h$ and $S_1 > \sigma_v$, $S_2 > \sigma_H$ and $S_3 < \sigma_h$.

- Safe drilling mud weight window decreased for rotated Principle Stress regime significantly:
  <u>from 2.6 ppg (15.1 – 12.5 ppg) to only 0.7 ppg (14.8 – 14.1 ppg)</u>



Future Trends & Challenges

- Applying this approach adds the most value when implemented early in project development.
- Delivery of this technology requires multidisciplined technical skill sets.
- Major challenge is MEM requires extensive work in the overburden.