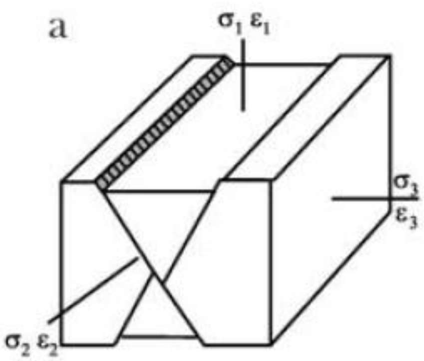
ConocoPhillips

Non-Andersonian Fault Analysis in Reservoirs

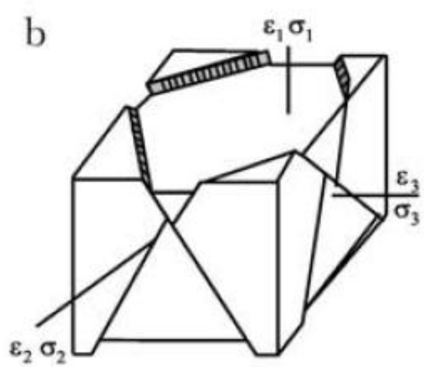
Seth Busetti, Bob Krantz, Justin MacDonald, and Peter Hennings

October 2013

3D Faulting: Some Combination of Polyphase and 3D Strain Fields



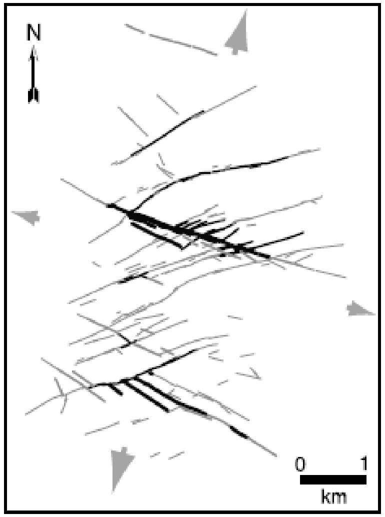
Anderson, 1951



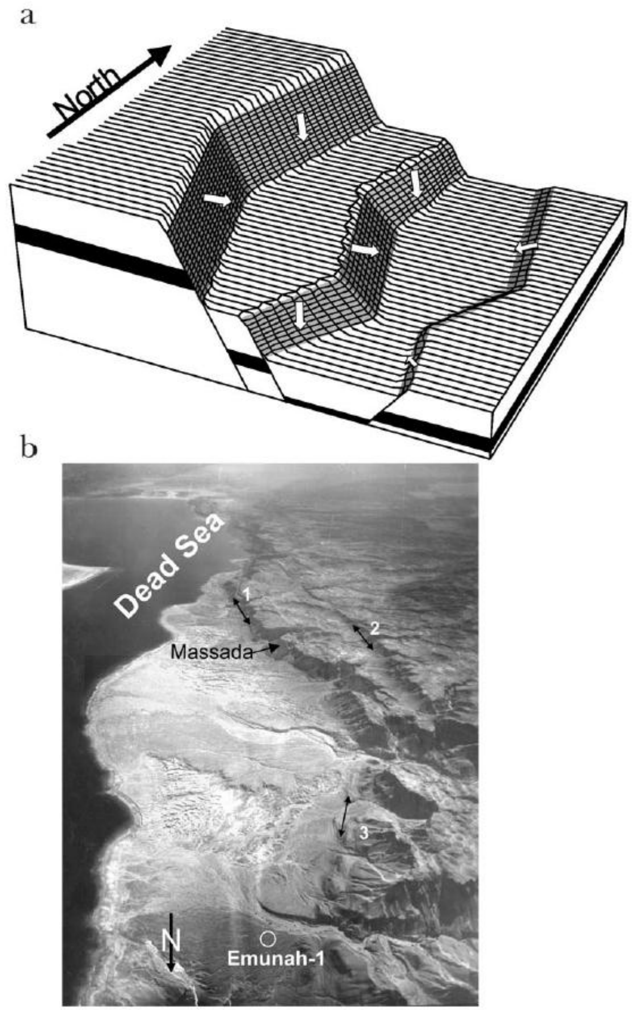
Reches ,1983

Phase 1: Deformation band dominated faulting

Phase 2: Joint dominated faulting

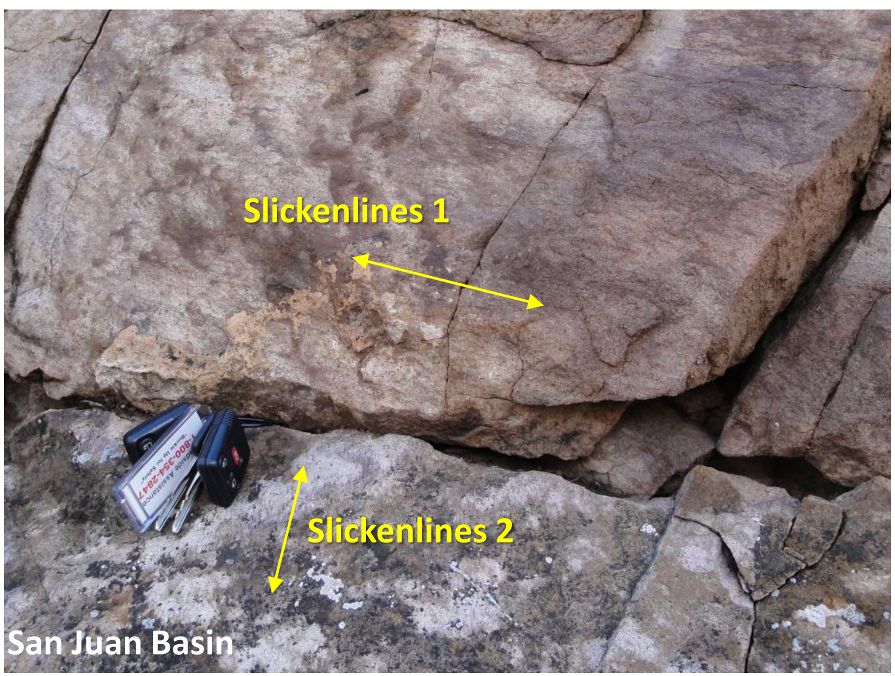


Davatzes et al. 2003

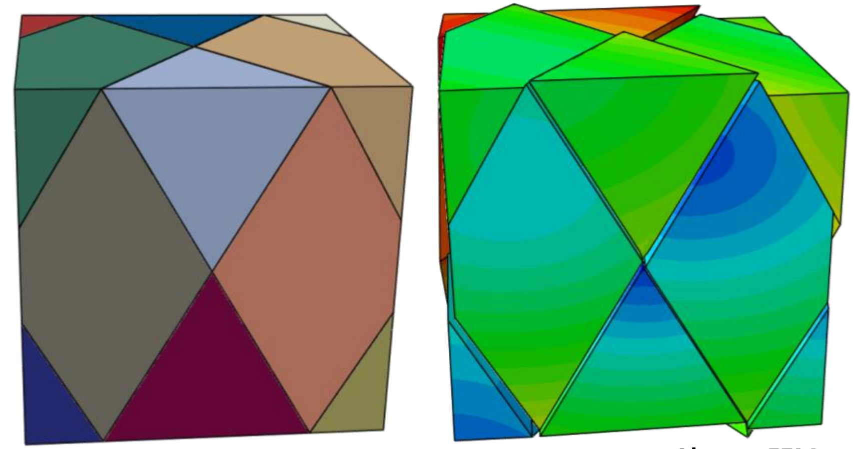


Sagy et al. 2003

3D Strain Compatibility: Kinematics, Slip Vectors (Resolved Shear)

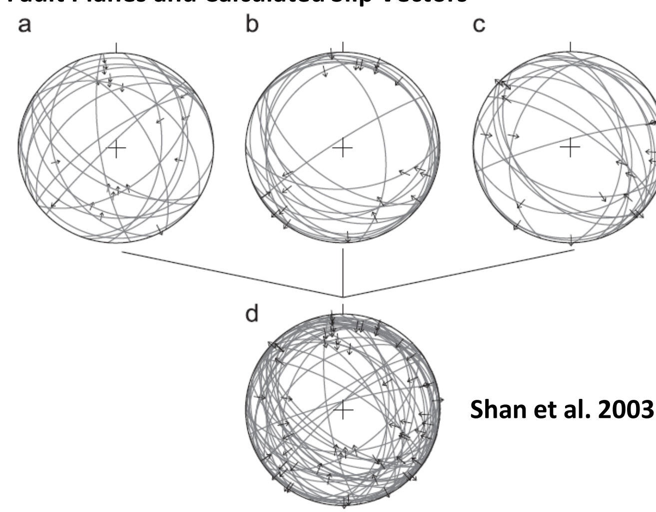


SS: SH>Sv>Sh



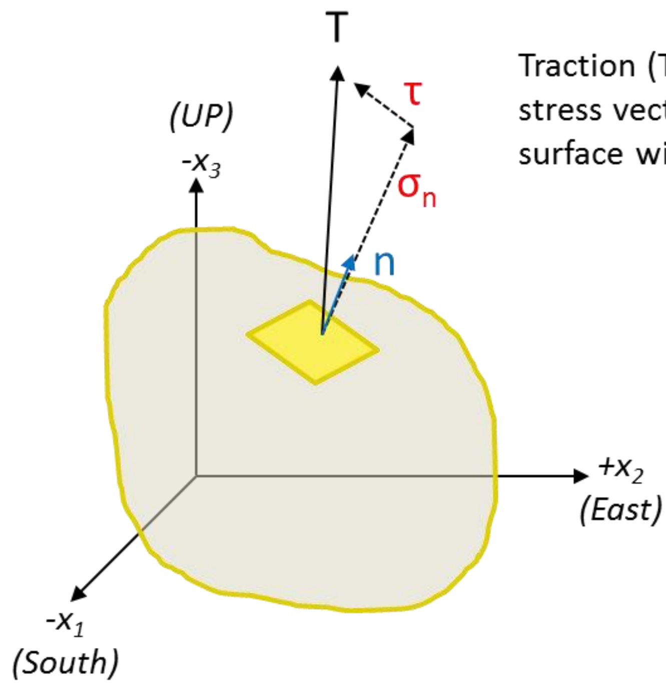
Abaqus FEM

Fault Planes and Calculated Slip Vectors

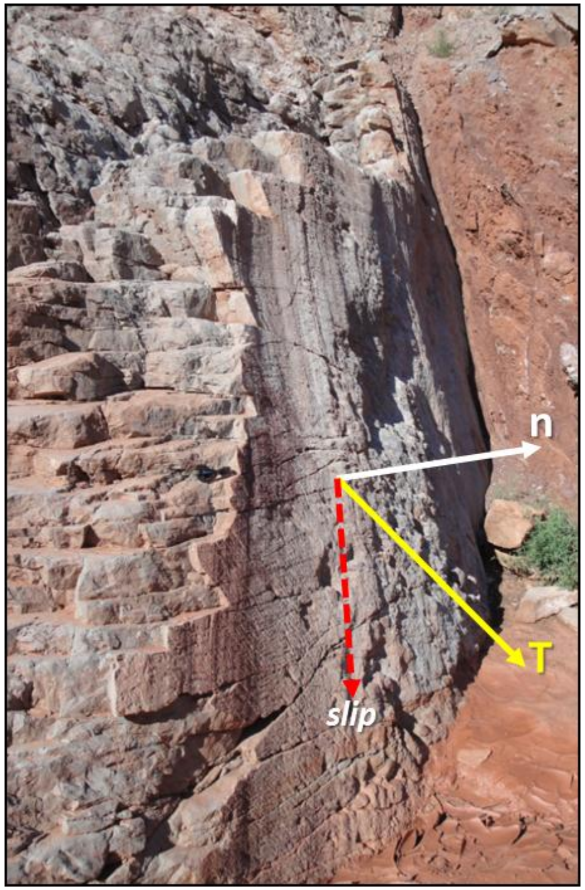


Shan et al. 2003

3D Fault Analysis For Reservoir Geomechanics: Resolved Stress



Traction (T) is the limiting stress vector acting on a surface with normal (n)



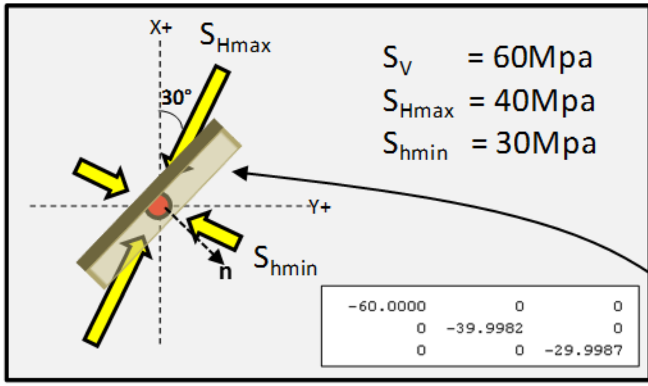
Stress principal: T = dF/dA — ΔF reaction force / ΔS surface element

Cauchy's formula: $T = [\sigma]_{ij} n_j$ — vector = tensor x vector

Traction Vector — Normal Vector — Stress Tensor

$$\begin{bmatrix} T_1^{(\mathbf{n})} & T_2^{(\mathbf{n})} & T_3^{(\mathbf{n})} \end{bmatrix} = \begin{bmatrix} n_1 & n_2 & n_3 \end{bmatrix} \cdot \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

3D Fault Analysis For Reservoir Geomechanics: Resolved Stress



$$\sigma_{rotated} = \begin{bmatrix} -37.4982 & -4.3300 & 0 \\ -4.3300 & -32.4987 & 0 \\ 0 & 0 & -60.000 \end{bmatrix}$$

Find the traction on a fracture/fault with strike = 44 ° and dip = 74°

Nx = cos(*dipdir*)*sin(*dip*) = cos(134)*sin(74) =

Ny = sin(*dipdir*)*sin(*dip*) = sin(134)*sin(74) =

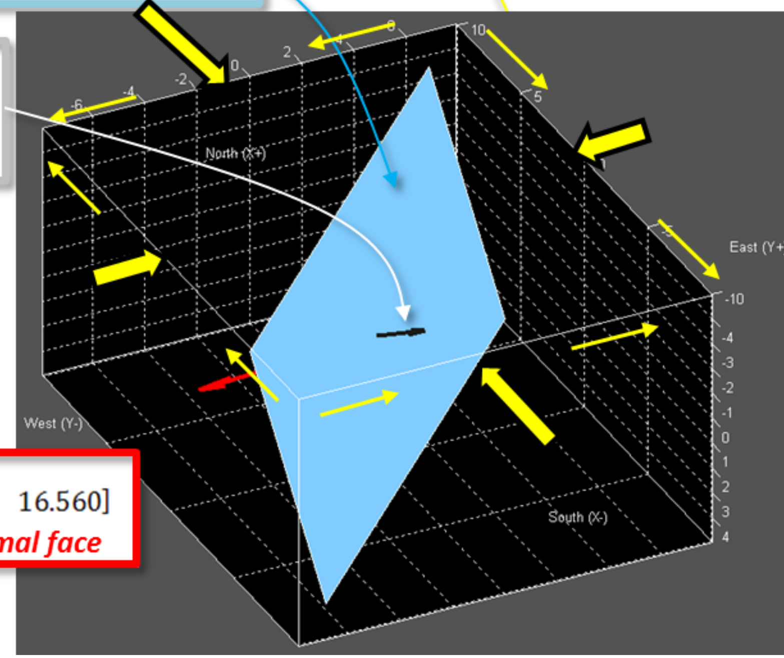
Nz = -cos(*dip*) = -cos(74) =

$$\mathbf{n}_j = \begin{bmatrix} -0.668 \\ 0.692 \\ -0.276 \end{bmatrix}$$

$$\begin{bmatrix} T_1^{(\mathbf{n})} & T_2^{(\mathbf{n})} & T_3^{(\mathbf{n})} \end{bmatrix} = \begin{bmatrix} n_1 & n_2 & n_3 \end{bmatrix} \cdot \begin{bmatrix} \sigma_{11} & \sigma_{12} & \sigma_{13} \\ \sigma_{21} & \sigma_{22} & \sigma_{23} \\ \sigma_{31} & \sigma_{32} & \sigma_{33} \end{bmatrix}$$

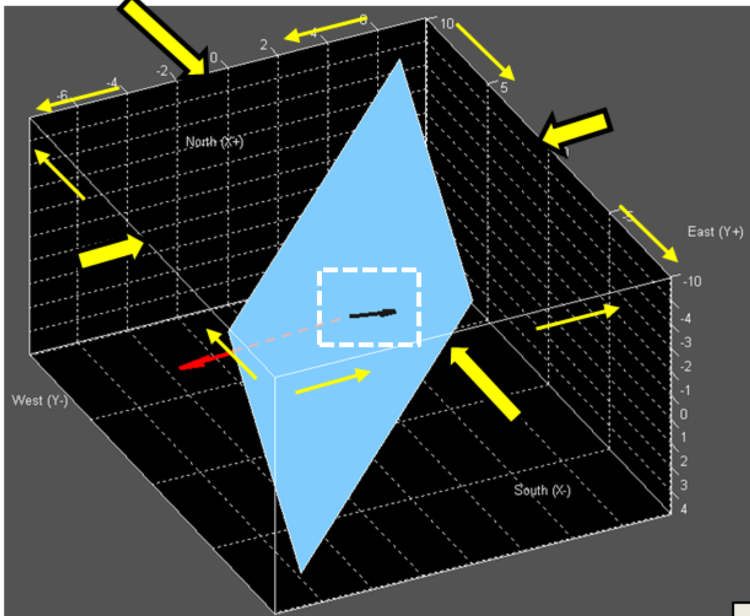
$$= \begin{bmatrix} -0.668 & 0.692 & -0.276 \end{bmatrix} \cdot \begin{bmatrix} -37.498 & -4.330 & 0 \\ -4.330 & -32.4987 & 0 \\ 0 & 0 & -60.000 \end{bmatrix} = \begin{bmatrix} 22.052 & -19.597 & 16.560 \end{bmatrix}$$

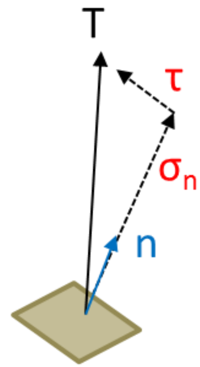
Traction on normal face



3D Fault Analysis For Reservoir Geomechanics: Critical Stress

Tectonic Stress and Resulting Traction





$\sigma_n = n \cdot T$ (Dot Product)

```
>> dot([-.668 .692 -.276],[22.052 -19.597 16.560])
```

$\tau^2 = T^2 - \sigma_n^2$ (Pythagorean)

```
>> ((norm([22.052 -19.597 16.560]))^2-(-32.8624)^2)^.5
```

$\sigma_n = 32.88$ MPa

$\tau = 8.04$ MPa

Fault/Fracture Instability from Traction

Coulomb Failure:

Shear Stress → $\tau = C + \mu\sigma_n$ ← *Normal Stress*

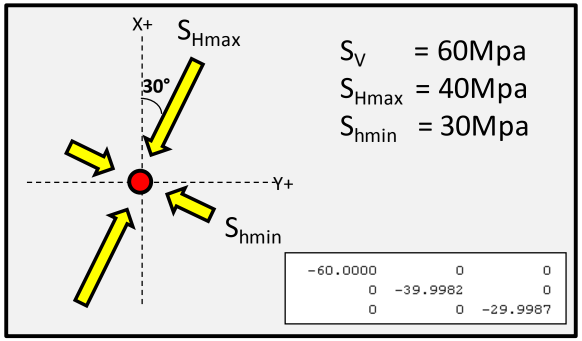
Cohesion — *Coefficient of Friction*

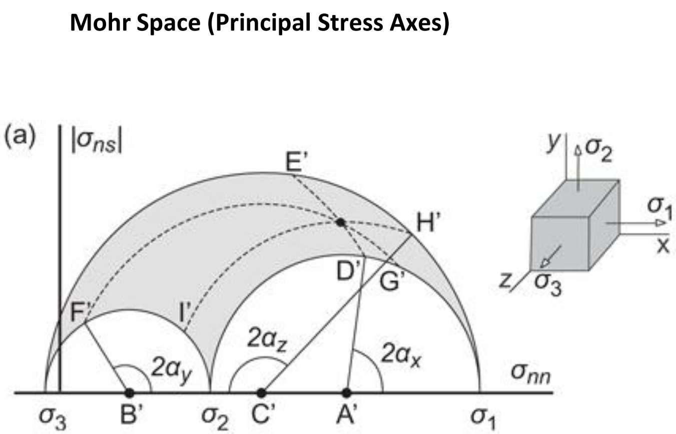
Shear and Normal Stress: Calculated
Cohesion and Friction: Laboratory Tests

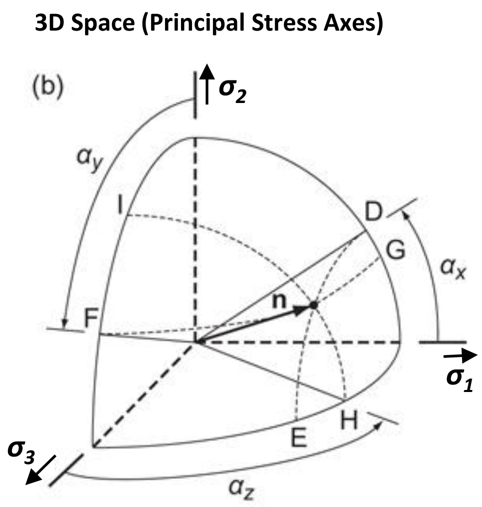
Some Useful Instability Parameters

		$C = 0; \mu = 0.6$
Fluid Pressure to Fail: (Pore or Internal Fracture)	$\sigma_n - \tau/\mu$	= 19.48 Mpa
Fluid Pressure to Dilate: (set μ high to give ~90° angle)	$\sigma_n - \tau/\mu$	= 32.74 Mpa
Critical Friction to Fail:	$(\tau - C)/\sigma_n$	= 0.2445 (14°)
Critical Cohesion to Fail: (Coulomb Failure Function)	$\tau - \mu\sigma_n$	= -11.69 MPa

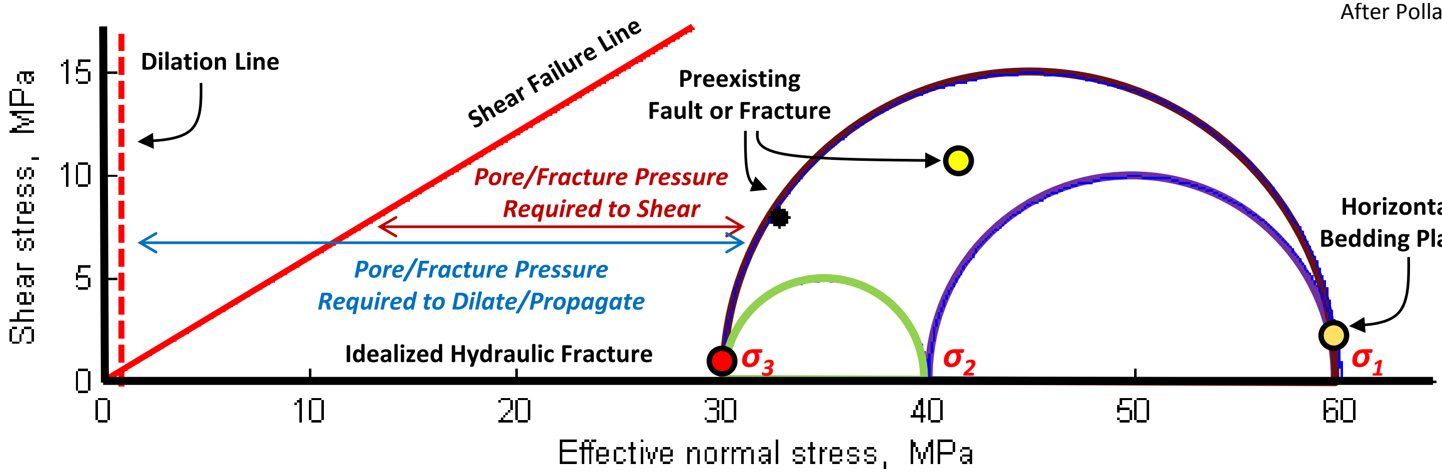
3D Fault Analysis For Reservoir Geomechanics: Critical Stress





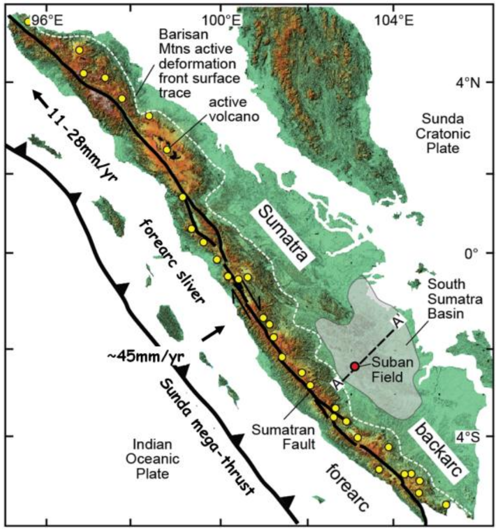


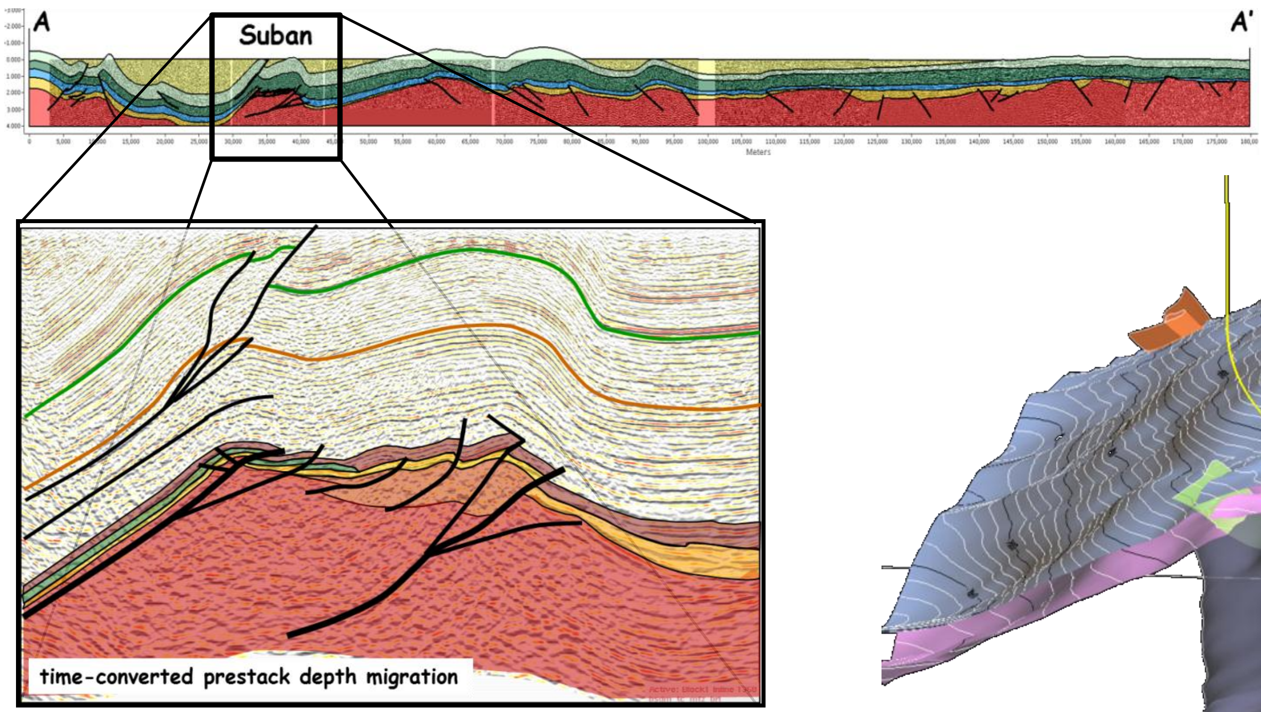
After Pollard and Fletcher, p.223

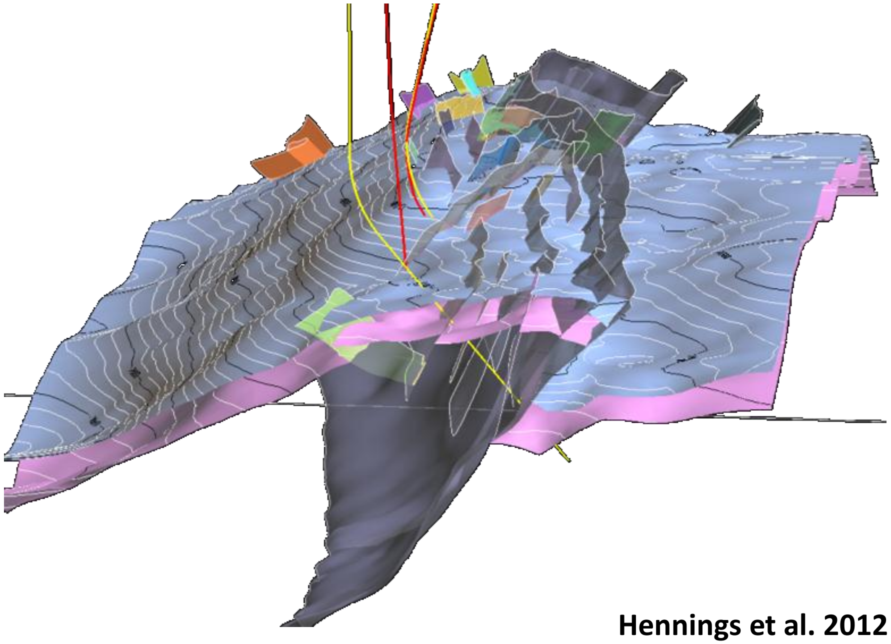


Reservoir Examples of 3D Faulting – Suban, Sumatra, Indonesia

- Located at oblique converging Indo-Australian plate boundary
- Complex structure, highly faulted and fractured
- Fracture enabled production
  - 0.5-2% of fractures are hydraulically significant
  - Flow associated with critically stressed fractures
- Strike slip domains are hydraulically more enhanced

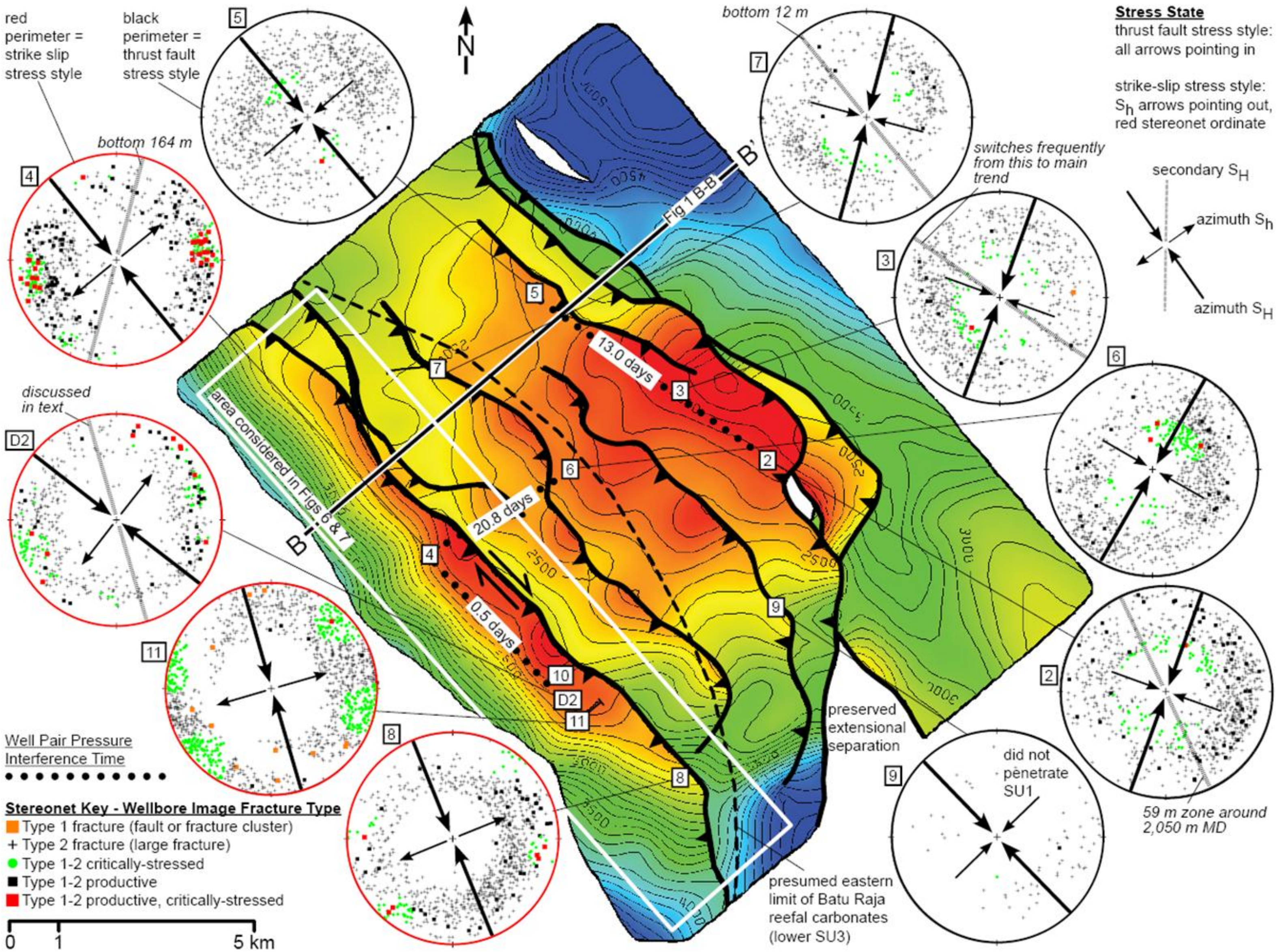






Hennings et al. 2012

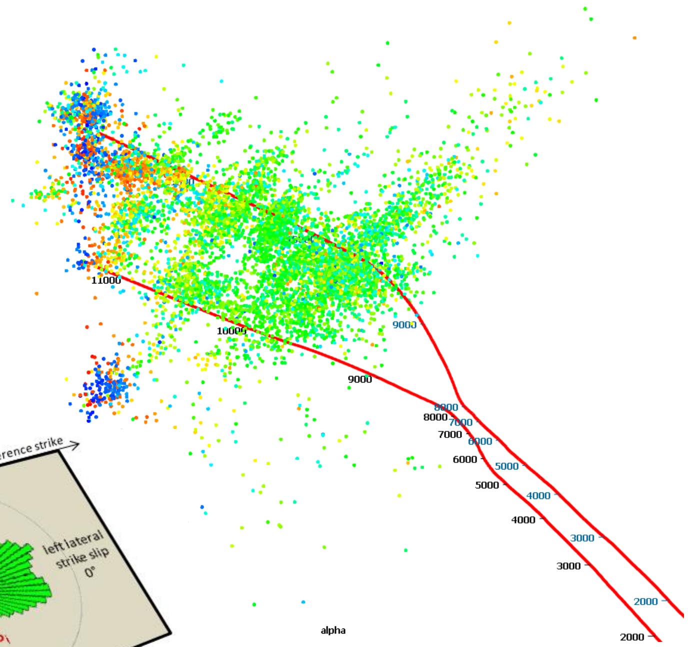
Reservoir Examples of 3D Faulting – Suban, Sumatra, Indonesia

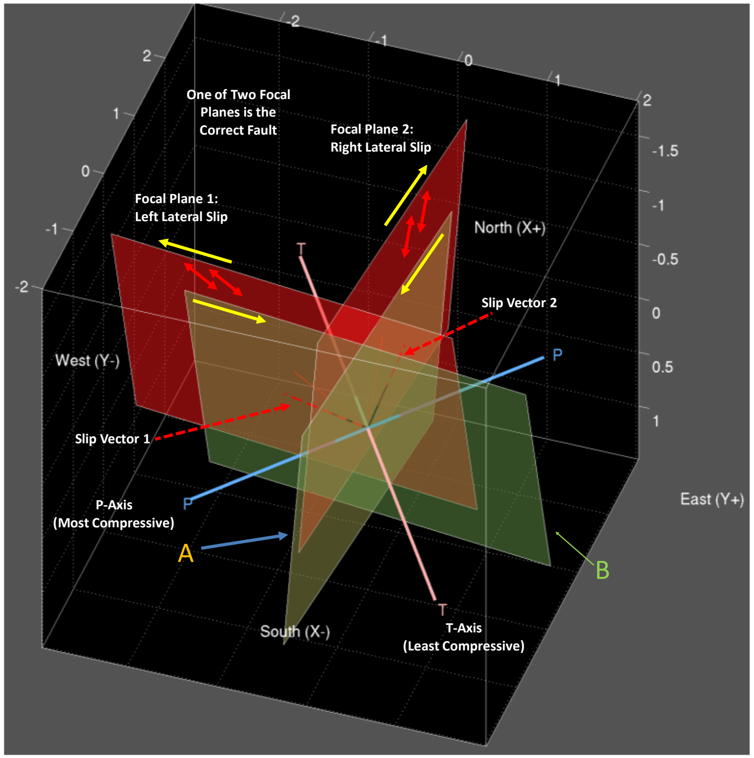


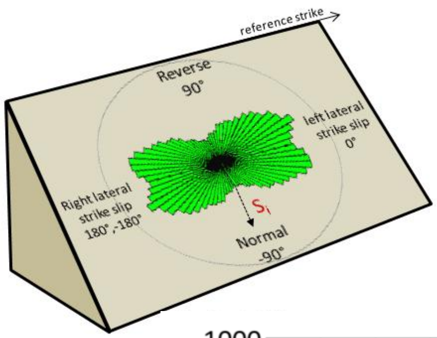
Hennings et al. 2012

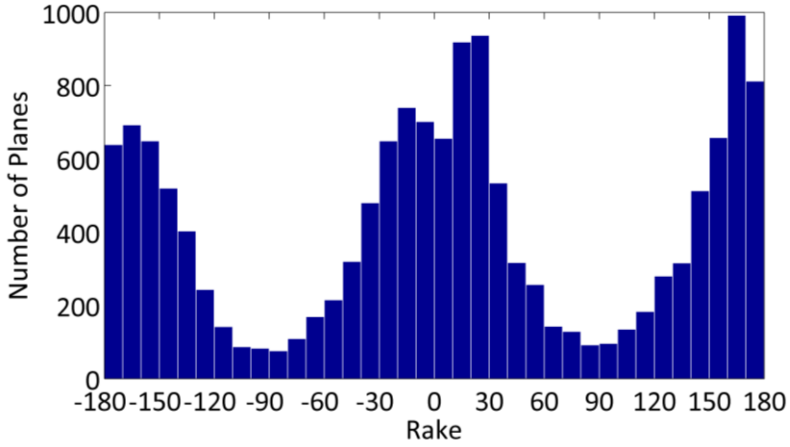
Reservoir Examples of 3D Faulting – Barnett Shale Microseismic

- Geomechanically enhanced source rock play
- Pervasive N-S and NE-SW natural faults and fractures
  - Regional tectonic structures
  - Rectilinear karst collapse features
- Microseismic focal mechanisms Indicates
  - Activation of natural fractures and faults
  - A range of oblique fault slip directions

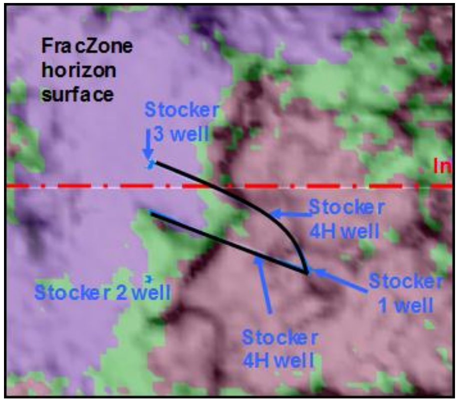


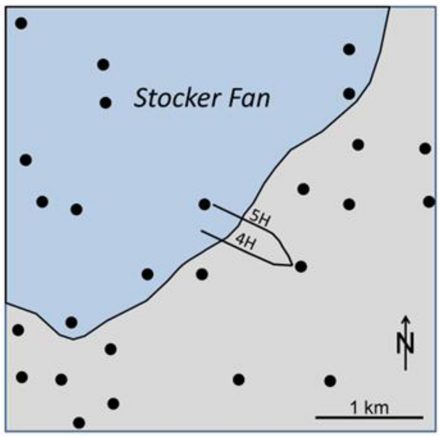




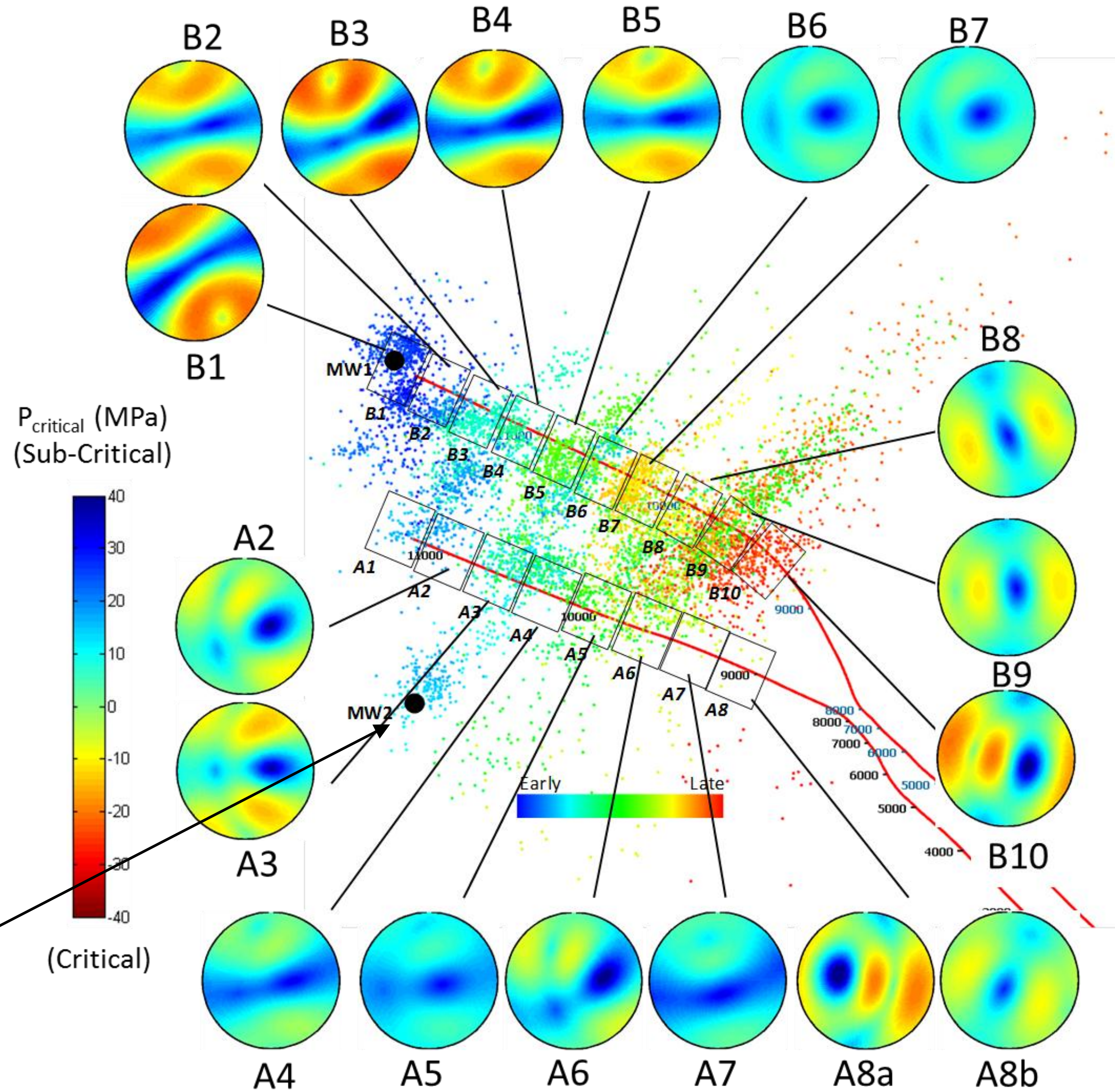


Reservoir Examples of 3D Faulting – Barnett Shale Microseismic





Focal Planes → Stress Inversion → Critical Stress Stereonets



Microseismic activation of natural fractures and faults

Busetti and Reches 2013 (AAPG Bulletin in Review)

Summary

- Andersonian faulting assumes simplified conditions
    - Principal stress/strain axes aligned vertically
    - Faults aligned with principal stress/strain axes
- Reservoir settings often are not simple
    - Multiple phases of deformation
    - 3D strain fields (complex kinematics)
    - *In situ* conditions differ from geologic ones
- 3D geomechanical analysis requires non-Andersonian conditions
    - Mis-aligned or inoptimally oriented faults and fractures
    - 3D and 4D heterogeneous stress fields (*in situ* and operational)
    - Fracture permeability requires 2D and 3D anisotropy
- Reservoir characterization paradigm shift (growth opportunity)