$$P_{mud} = P_W$$

S_{Hmax}

		Sigh_3	
	6000	psi	12000
		SigH_3	
	6000	psi	12000
		SigV	
	6000	psi	12000
		PPRS_3	
	6000	psi	12000

Mechanical stratigraphy	Calcite	Minifrac_closure_Pressure	Perforations
	Calcite_QE		
	0 1	6000 psi 12000	

Depth A
Depth C
Depth D
Depth B
Depth E

p

J_2

σ_n

| **Un-wrapped image** (ultrasonic) | **3D-representation** | **Interpretation** |
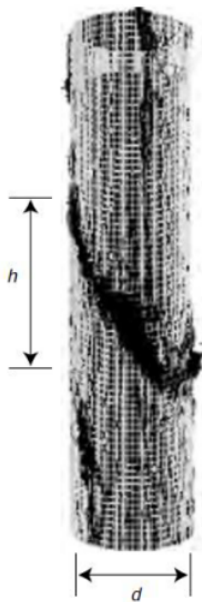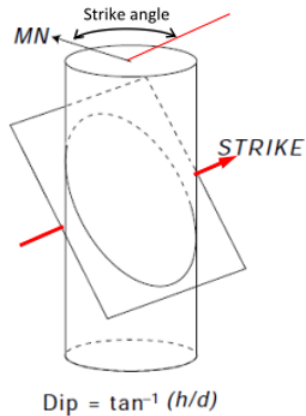
Un-wrapped image (ultrasonic):
- N E S W N
- Depth [meters]: 133, 137, 141, 145
- PARTIAL SINUSOID
- FRACTURES
- h
- strike

3D-representation:
- h
- d

Interpretation:
- Strike angle
- MN
- STRIKE
- Dip = $\tan^{-1}(h/d)$

(Zoback 2013, RM, Ch 5.3)

(σ_n, τ)

τ/σ_n

$\mu = 0.5 \pm 0.1$

$60° \pm 10°$

$80° \pm 5°$

$10° \pm 10°$

$60° \pm 5°$

(a) Structural map with fault blocks labeled F1 through F9.

(b) 3D grid top model (ft) showing stress orientations.

$$S_{hmin} \approx 0.76 \times S_V$$
$$S_{Hmax} \approx 0.79 \times S_V$$

Gradient in S_V:
≈ 1.00 psi/ft

S_{hmin}

σ_n/σ_v

τ/σ_v

$P_p/$

$z = 0.44$

$\mu = 0.6$

$$E_{static} = 0.65 \cdot E_{dynamic}$$

$$E'_{static} = E_{static}/(1 - \nu^2)$$

$$\varepsilon_{Hmax} = 0.0015$$

$$\varepsilon_{hmin} = 0$$
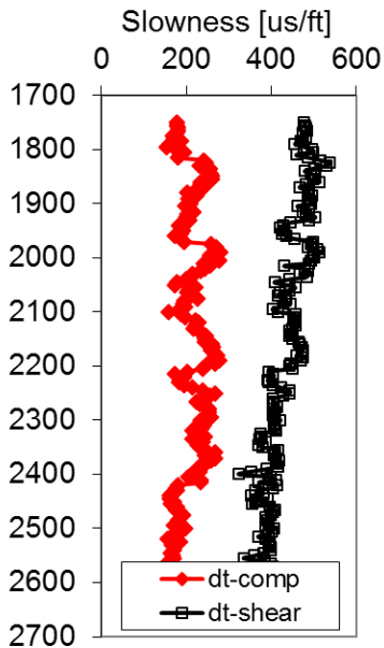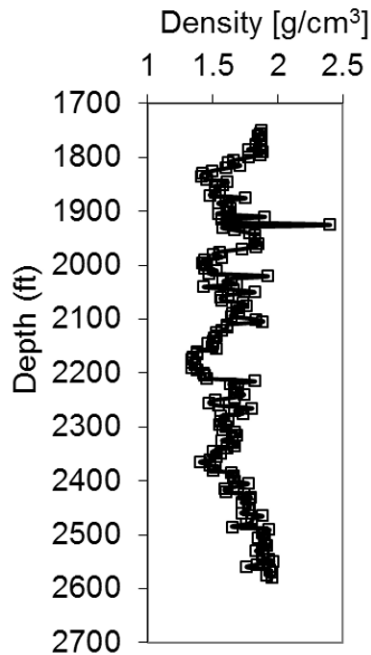
$$
\begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ 2\varepsilon_{23} \\ 2\varepsilon_{13} \\ 2\varepsilon_{12} \end{bmatrix} = \begin{bmatrix} +\dfrac{1}{E_h} & -\dfrac{\nu_h}{E_h} & -\dfrac{\nu_v}{E_v} & 0 & 0 & 0 \\ -\dfrac{\nu_h}{E_h} & +\dfrac{1}{E_h} & -\dfrac{\nu_v}{E_v} & 0 & 0 & 0 \\ -\dfrac{\nu_v}{E_v} & -\dfrac{\nu_v}{E_v} & +\dfrac{1}{E_v} & 0 & 0 & 0 \\ 0 & 0 & 0 & \dfrac{1}{G_v} & 0 & 0 \\ 0 & 0 & 0 & 0 & \dfrac{1}{G_v} & 0 \\ 0 & 0 & 0 & 0 & 0 & \dfrac{1}{G_h} \end{bmatrix} \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{23} \\ \sigma_{13} \\ \sigma_{12} \end{bmatrix}
$$

$$G_h = \frac{E_h}{2(1 + \nu_h)}$$

G_v

$$E_h = \frac{(C_{11} - C_{12}) \left[C_{33}(C_{11} + C_{12}) - 2\,C_{13}^2 \right]}{C_{11}C_{33} - C_{13}^2}$$

$$E_v = C_{33} - \frac{2\,C_{13}^2}{C_{11} + C_{12}}$$

$$\nu_h = \frac{C_{13}}{C_{11} + C_{12}}$$

$$\nu_v = \frac{C_{12}C_{33} - C_{13}^2}{C_{11}C_{33} + C_{13}^2}$$

$$G_v = C_{44}$$

$$G_h = C_{66} = \frac{C_{11} - C_{12}}{2}$$

$$
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\sigma_{23} \\
\sigma_{13} \\
\sigma_{12}
\end{bmatrix}
=
\begin{bmatrix}
C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\
C_{12} & C_{11} & C_{13} & 0 & 0 & 0 \\
C_{13} & C_{13} & C_{33} & 0 & 0 & 0 \\
0 & 0 & 0 & C_{44} & 0 & 0 \\
0 & 0 & 0 & 0 & C_{44} & 0 \\
0 & 0 & 0 & 0 & 0 & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
2\varepsilon_{23} \\
2\varepsilon_{13} \\
2\varepsilon_{12}
\end{bmatrix}
$$

$$C_{11} = \left[\frac{1}{(1 - \nu_h)E_v - 2\nu_v^2 E_h} \right] \left(\frac{E_h E_v - \nu_v^2 E_h^2}{1 + \nu_h} \right)$$

$$C_{33} = \left[\frac{1}{(1 - \nu_h)E_v - 2\nu_v^2 E_h} \right] (E_v^2 - \nu_h E_v^2)$$

$$C_{12} = \left[\frac{1}{(1 - \nu_h)E_v - 2\nu_v^2 E_h} \right] \left(\frac{\nu_v^2 E_h^2 + \nu_h E_h E_v}{1 + \nu_h} \right)$$

$$C_{13} = \left[\frac{1}{(1 - \nu_h)E_v - 2\nu_v^2 E_h} \right] (\nu_v E_h E_v)$$

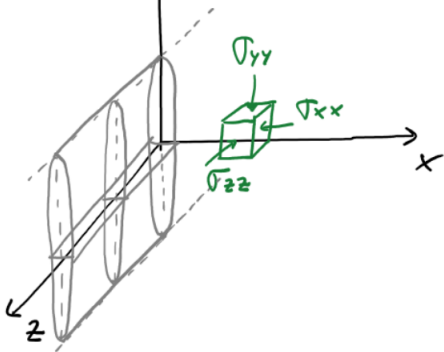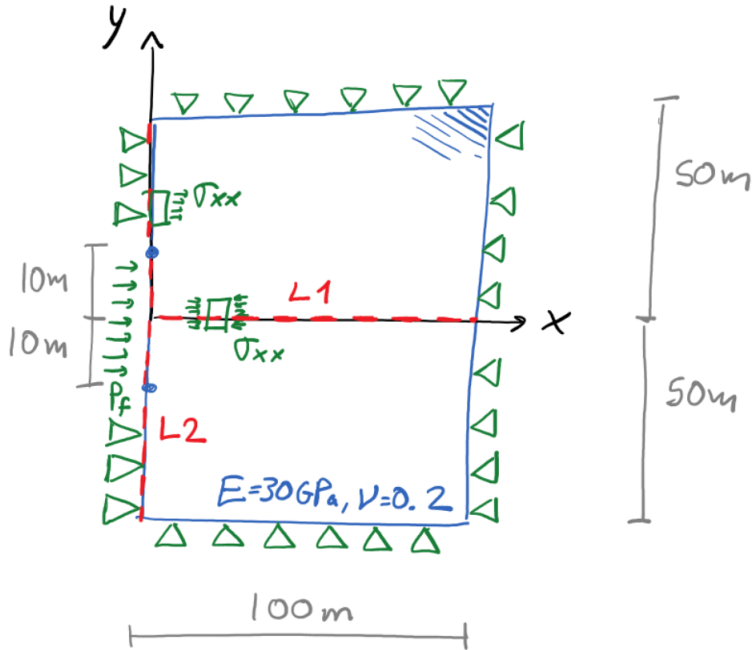$$C_{66} = \frac{C_{11} - C_{12}}{2} = G_h = \frac{E_h}{2(1 + \nu_h)}$$

C_{44}

σ_{xx}

σ_{yy}

ν

UCS

T_s

σ_{rr}

$\sigma_{\theta\theta}$

$\sigma_{r\theta}$

x

y

(r, θ)

r

σ_{xy}

c

$$(x, y) =$$

Fracture length in z
>> fracture length in y
$\Rightarrow$ Plane strain in (x,y)

σ_{yy}

σ_{xx}

σ_{zz}

$\equiv$

σ_{xx}

L1

σ_{xx}

P_f

L2

$E = 30\,GPa, \nu = 0.2$

50m

50m

100m

10m

10m

$y =$

P_c

P_p

T_{ch}

ε_{vol}
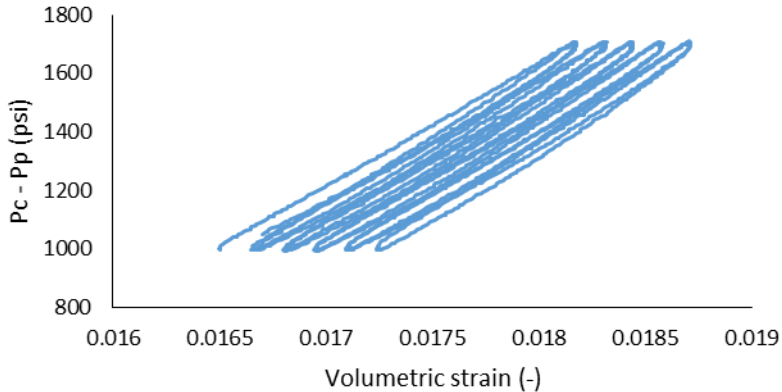
σ_{mean}

α

α_h

α_v

Production : 120 bbl/day
Min. BHP : 240 psi

1000 ft

S_v =1200 psi

Zero displacements
except for vertical
direction

Permeability : 50 mD
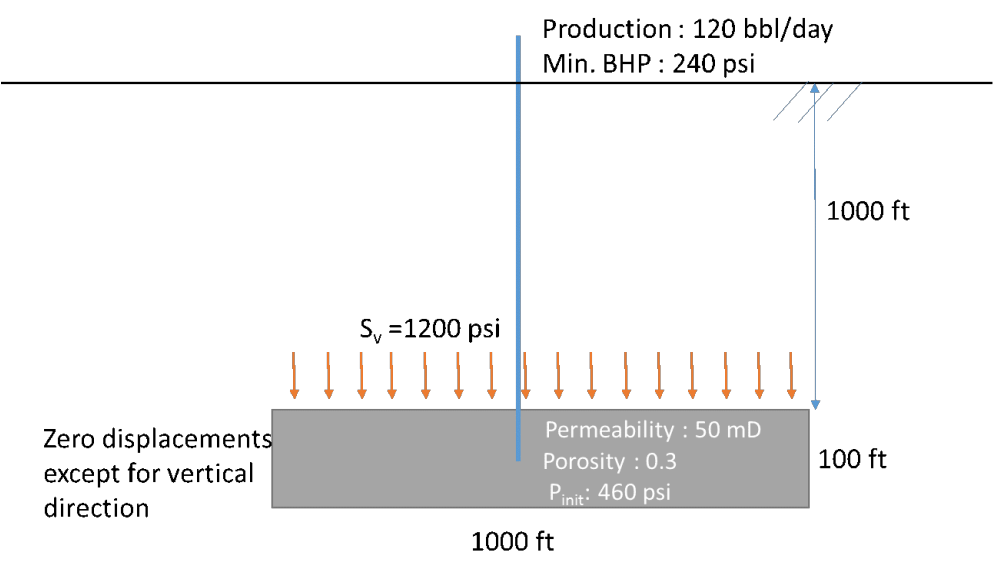Porosity : 0.3
P_{init} : 460 psi

100 ft

1000 ft

$$\alpha\frac{(1-2\nu)}{(1-\nu)}$$

(p', q)

$P_{pore\,fluid}$

$$\sigma_1 = UCS + q\sigma_3$$

S_0

$(J_2)^{1/2}$

$$P_W = P_p$$

P_W

dP_p/dz

$$dS_v/dz$$

$$\phi = \phi_0 \exp\left(-\beta \sigma_v\right)$$

$$e = e_0 - C_c \ln\left(\frac{\sigma_v}{1 \text{ MPa}}\right)$$

λ_p

S_v

$$dq = 3dp'$$

G

p'_o

$$\phi_{CS} = 24°$$

λ

e_o

p'

ε_q

e

$$dq = 0.9 \, dp'$$

$p' = 400$

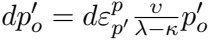$$d\varepsilon^e_{p'} = \frac{\kappa}{\upsilon}\frac{dp'}{p'}; \ d\varepsilon^e_q = \frac{dq}{3G}$$
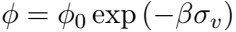
$$\begin{bmatrix} d\varepsilon_{p'}^p \\ d\varepsilon_q^p \end{bmatrix} = \frac{\lambda-\kappa}{vp'(M^2+\eta^2)} \begin{bmatrix} M^2-\eta^2 & 2\eta \\ 2\eta & \frac{4\eta^2}{M^2-\eta^2} \end{bmatrix} \begin{bmatrix} dp' \\ dq \end{bmatrix}$$

$$v = 1 + e$$

$$\eta = q/p'$$

$$de = -vd\varepsilon_p$$

$$dp'_o = d\varepsilon^p_{p'} \frac{v}{\lambda - \kappa} p'_o$$

$$\Delta S_{yy} = \nu(\Delta S_{xx} + \Delta S_{zz})$$

h_f

$$E' = 8.9 \times 10^6$$

x_f

$w_{w,0}$

−6

$$p' - q$$

$$10^{-6}$$

E_{sta}/E_{dyn}