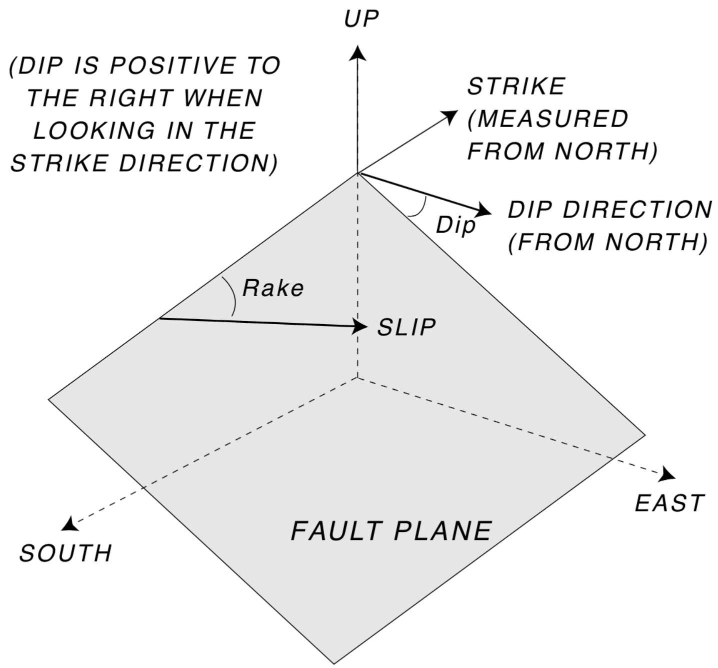
Faults and fractures at depth



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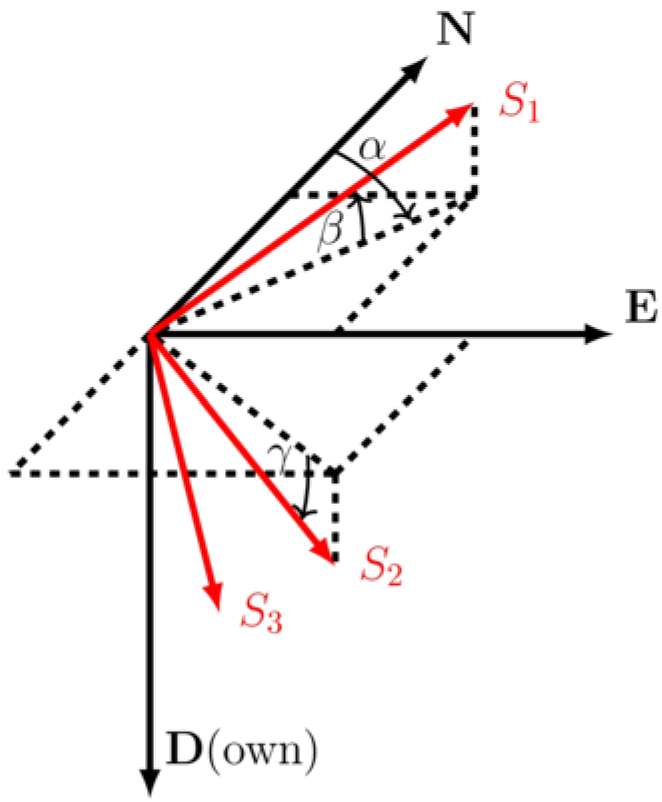
Geographical coordinate system



$$\mathbf{R}_G = \begin{bmatrix} \cos\alpha\cos\beta & \sin\alpha\cos\beta & -\sin\beta \\ \cos\alpha\sin\beta\sin\gamma - \sin\alpha\cos\gamma & \sin\alpha\sin\beta\sin\gamma + \cos\alpha\cos\gamma & \cos\beta\sin\gamma \\ \cos\alpha\sin\beta\cos\gamma + \sin\alpha\sin\gamma & \sin\alpha\sin\beta\cos\gamma - \cos\alpha\sin\gamma & \cos\beta\cos\gamma \end{bmatrix}$$

Interactive widget

Stress in geographical coordinate system

$$\mathbf{S}_G = \mathbf{R}_G^T \mathbf{S} \mathbf{R}_G$$

Example: Strike-slip faulting

$\mathbf{S} = \begin{bmatrix} 30 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 20 \end{bmatrix}$		$\alpha = 0^\circ$ Azimuth of S_{Hmax} $\beta = 0^\circ$ $S_1 = S_{Hmax}$ $\gamma = 90^\circ$ $S_2 = S_v$

$$\mathbf{R}_G = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & -1 & 0 \end{bmatrix}$$

$$\mathbf{S}_G = \begin{bmatrix} 30 & 0 & 0 \\ 0 & 20 & 0 \\ 0 & 0 & 25 \end{bmatrix}$$

Example: Normal faulting

$$\mathbf{S} = \begin{bmatrix} 30 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 20 \end{bmatrix}$$

$\alpha = 0^\circ$ Azimuth of S_{hmin}

$\beta = -90^\circ$ $S_1 = S_v$

$\gamma = 0^\circ$

$$\mathbf{R}_G = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \end{bmatrix}$$

$$\mathbf{S}_G = \begin{bmatrix} 20 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 30 \end{bmatrix}$$

Example: Reverse faulting

$$\mathbf{S} = \begin{bmatrix} 30 & 0 & 0 \\ 0 & 25 & 0 \\ 0 & 0 & 20 \end{bmatrix}$$

$$\alpha = 90^\circ \qquad \text{Azimuth of } S_{Hmax}$$

$$\beta = 0^\circ \qquad S_1 = S_{Hmax}$$

$$\gamma = 0^\circ \qquad S_2 = S_{hmin}$$

$$\mathbf{R}_G = \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\mathbf{S}_G = \begin{bmatrix} 25 & 0 & 0 \\ 0 & 30 & 0 \\ 0 & 0 & 20 \end{bmatrix}$$

Example: Strike-slip faulting

$$\mathbf{S} = \begin{bmatrix} 60 & 0 & 0 \\ 0 & 40 & 0 \\ 0 & 0 & 35 \end{bmatrix}$$

$\alpha = 135^\circ$ Azimuth of S_{Hmax}

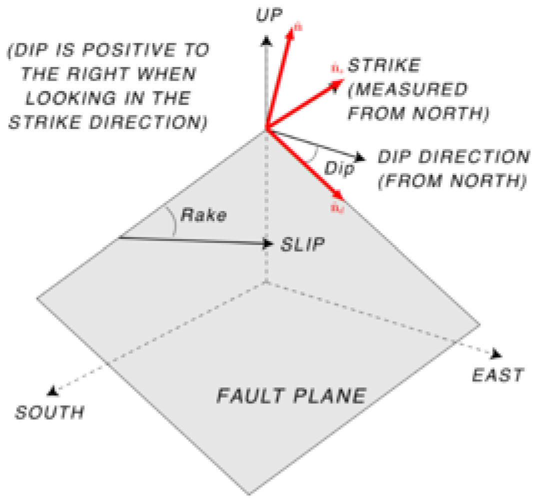
$\beta = 0^\circ$ $S_1 = S_{Hmax}$

$\gamma = 90^\circ$ $S_2 = S_v$

$$\mathbf{R}_G = \begin{bmatrix} -\frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \\ 0 & 0 & 1 \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 \end{bmatrix}$$

$$\mathbf{S}_G = \begin{bmatrix} 47.5 & -12.5 & 0 \\ -12.5 & 47.5 & 0 \\ 0 & 0 & 40 \end{bmatrix}$$

Fault orientation



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Fault traction and stress

Traction on fault plane

$$\vec{t} = \mathbf{S}_G \cdot \hat{\mathbf{n}}$$

Normal stress to plane

$$S_n = \vec{t}^{\intercal} \cdot \hat{\mathbf{n}}$$

Shear stress in dip direction

$$\tau_d = \vec{t}^{\intercal} \cdot \hat{\mathbf{n}}_d$$

Shear stress in strike direction

$$\tau_s = \vec{t}^{\intercal} \cdot \hat{\mathbf{n}}_s$$

Example: Strike-slip faulting

$$\mathbf{S}_G = \begin{bmatrix} 30 & -8.66 & 0 \\ -8.66 & 40 & 0 \\ 0 & 0 & 30 \end{bmatrix}$$

$$strike = 60^\circ$$
$$dip = 90^\circ$$

$$\hat{\mathbf{n}} = \begin{bmatrix} -0.866 \\ 0.5 \\ 0 \end{bmatrix} \quad \hat{\mathbf{n}}_s = \begin{bmatrix} 0.5 \\ 0.866 \\ 0 \end{bmatrix} \quad \hat{\mathbf{n}}_d = \begin{bmatrix} 0 \\ 0 \\ 1.0 \end{bmatrix}$$

$$S_n = 40 \quad \tau_d = 0 \quad \tau_s = 8.66$$

Example: Normal faulting

$$\mathbf{S}_G = \begin{bmatrix} 4000 & 0 & 0 \\ 0 & 3000 & 0 \\ 0 & 0 & 5000 \end{bmatrix}$$

$$strike = 45^\circ$$
$$dip = 60^\circ$$

$$\hat{\mathbf{n}} = \begin{bmatrix} -0.612 \\ 0.612 \\ -0.5 \end{bmatrix} \qquad \hat{\mathbf{n}}_s = \begin{bmatrix} 0.707 \\ 0.707 \\ 0 \end{bmatrix} \qquad \hat{\mathbf{n}}_d = \begin{bmatrix} -0.3535 \\ 0.3535 \\ 0.866 \end{bmatrix}$$

$$S_n = 3875 \quad \tau_d = -650 \quad \tau_s = -433$$

Example: Normal faulting

$$\mathbf{S}_G = \begin{bmatrix} 5000 & 0 & 0 \\ 0 & 4000 & 0 \\ 0 & 0 & 3000 \end{bmatrix}$$

$$strike = 225^\circ$$
$$dip = 60^\circ$$

$$\hat{\mathbf{n}} = \begin{bmatrix} 0.612 \\ -0.612 \\ -0.5 \end{bmatrix} \qquad \hat{\mathbf{n}}_s = \begin{bmatrix} -0.707 \\ -0.707 \\ 0 \end{bmatrix} \qquad \hat{\mathbf{n}}_d = \begin{bmatrix} 0.3535 \\ -0.3535 \\ 0.866 \end{bmatrix}$$

$$S_n = 4125 \quad \tau_d = -650 \quad \tau_s = -433$$

Example: Revese faulting

$$\mathbf{S}_G = \begin{bmatrix} 2100 & -520 & 0 \\ -520 & 1500 & 0 \\ 0 & 0 & 1000 \end{bmatrix}$$

$$strike = 120^\circ$$
$$dip = 70^\circ$$

$$\hat{\mathbf{n}} = \begin{bmatrix} -0.814 \\ -0.470 \\ -0.342 \end{bmatrix} \qquad \hat{\mathbf{n}}_s = \begin{bmatrix} -0.5 \\ 0.866 \\ 0 \end{bmatrix} \qquad \hat{\mathbf{n}}_d = \begin{bmatrix} 0.2961 \\ -0.1710 \\ 0.9396 \end{bmatrix}$$

$$S_n = 1441 \quad \tau_d = 161 \quad \tau_s = 488$$

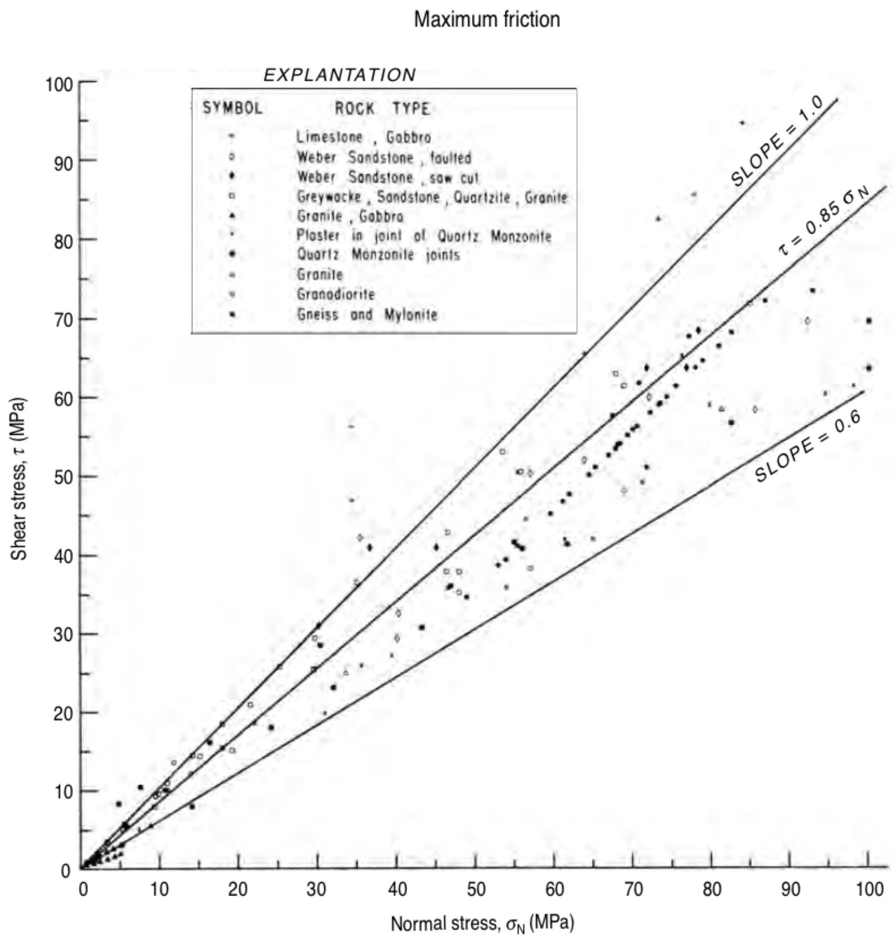
Shear failure (slip on faults)

$$\frac{\tau}{\sigma_n} = \mu$$

Coulomb failure function

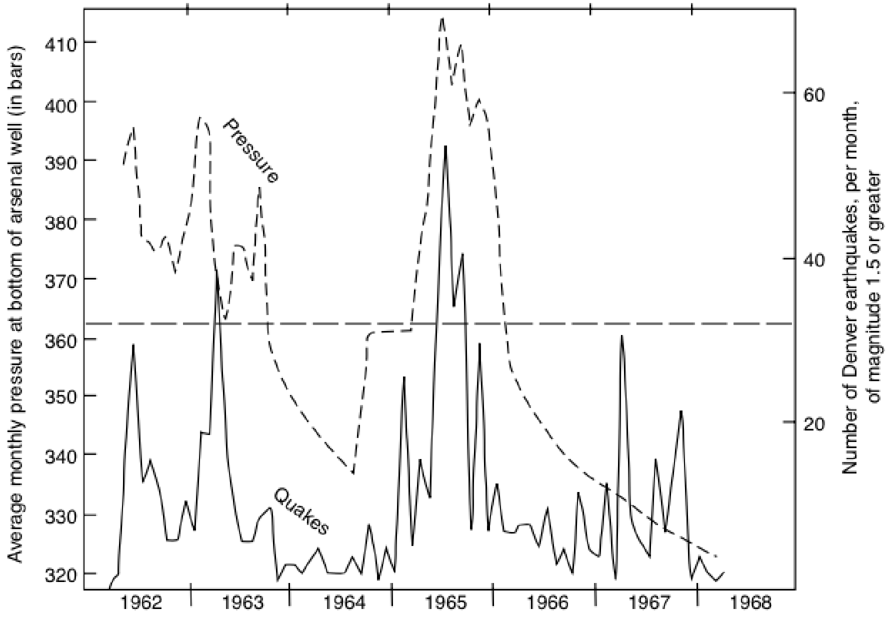
$$f = \tau - \mu\sigma_n \leq 0$$

Frictional strength of faults



 Zoback, *Reservoir Geomechanics* (Fig. 4.23, pp. 126)

Induced seismicity



Fluid injection and seismicity at the Rocky Mountain Arsenal

 Zoback, *Reservoir Geomechanics* (Fig. 4.22a, pp. 125)