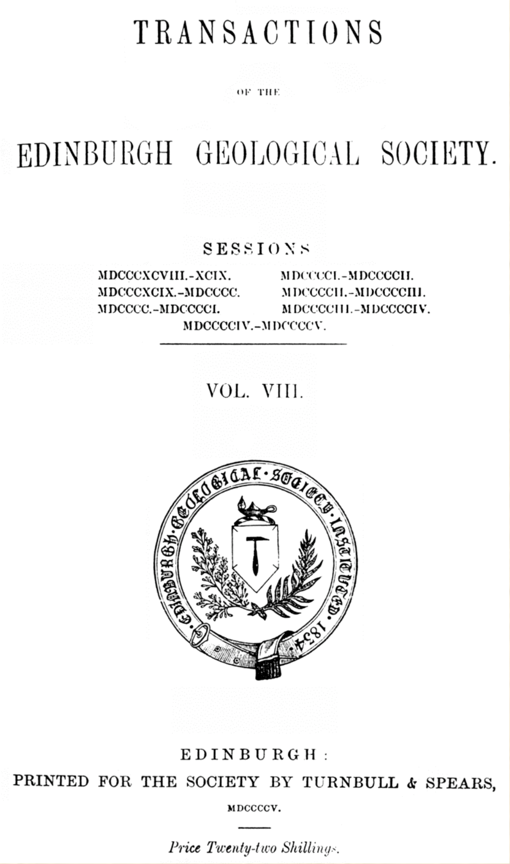
Que nous disent les mécanismes au foyer sur l'état de contrainte dans la croûte et sur la théorie d'Anderson ?

- Anderson's faulting
  - ConJugate planes
  - Optimal stress orientation
- Frictional reactivation:
  - Makes it irrelevant or not ?
- Focal Mechanisms
  - P, B, T
  - Frohlich's triangular diagrams
  - Global CMT
  - Quality
- GCMT analysis
  - By depth
  - By Rake (fault type)
  - Interpretation
- Conclusions

Bernard Célérier
Géosciences Montpellier
Université de Montpellier II - CNRS

Anderson's faulting



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OF THE

EDINBURGH GEOLOGICAL SOCIETY.

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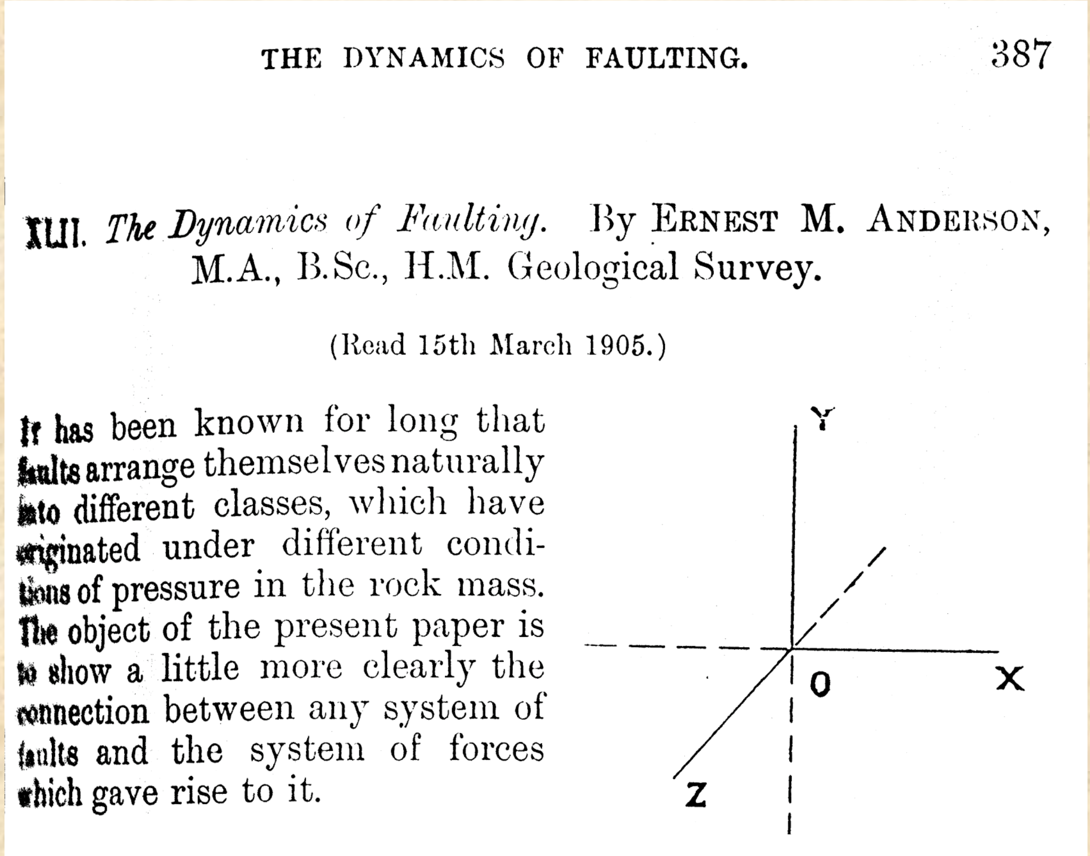


THE DYNAMICS OF FAULTING. 387

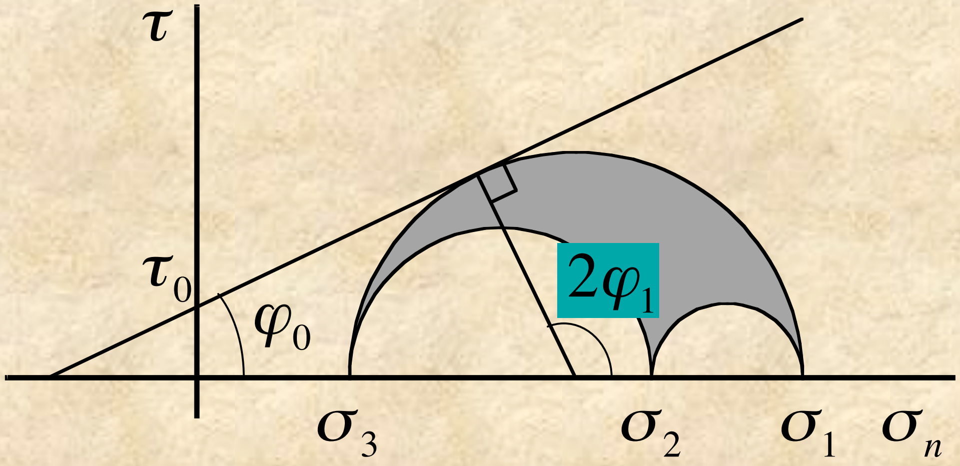
XLII. *The Dynamics of Faulting.* By ERNEST M. ANDERSON, M.A., B.Sc., H.M. Geological Survey.

(Read 15th March 1905.)

It has been known for long that faults arrange themselves naturally into different classes, which have originated under different conditions of pressure in the rock mass. The object of the present paper is to show a little more clearly the connection between any system of faults and the system of forces which gave rise to it.

- Coulomb criterion for rupture
- Rupture occurs on optimal planes
- A principal stress direction is vertical

Stress orientation -> optimal conjugate faults



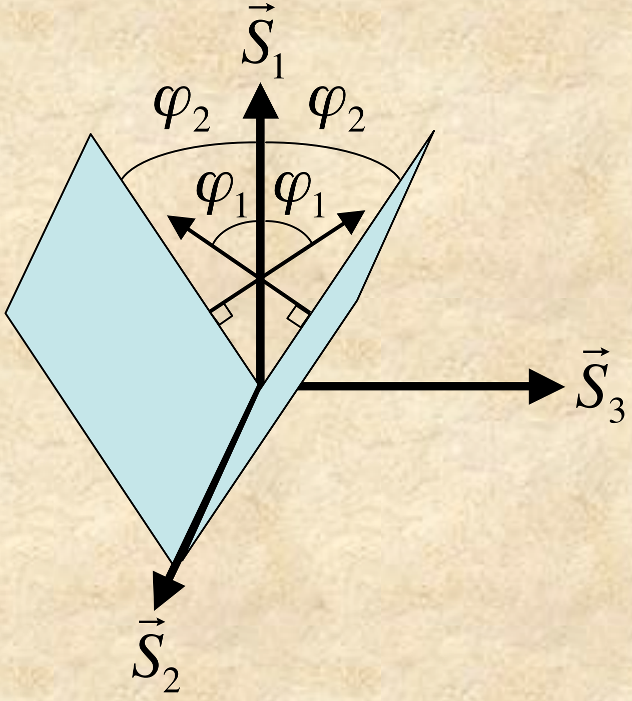
- Coulomb criterion for rupture
- Rupture occurs on optimal planes

$$\mu = \tan(\varphi_0) \approx 0.6$$

$$\varphi_0 \approx 30°$$

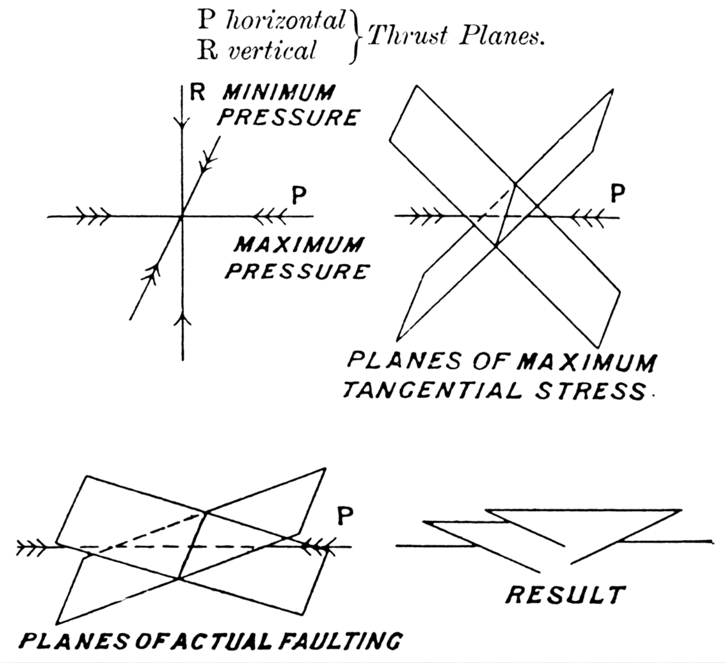
$$\varphi_1 = \frac{\varphi_0}{2} + \frac{\pi}{4} \approx 60°$$

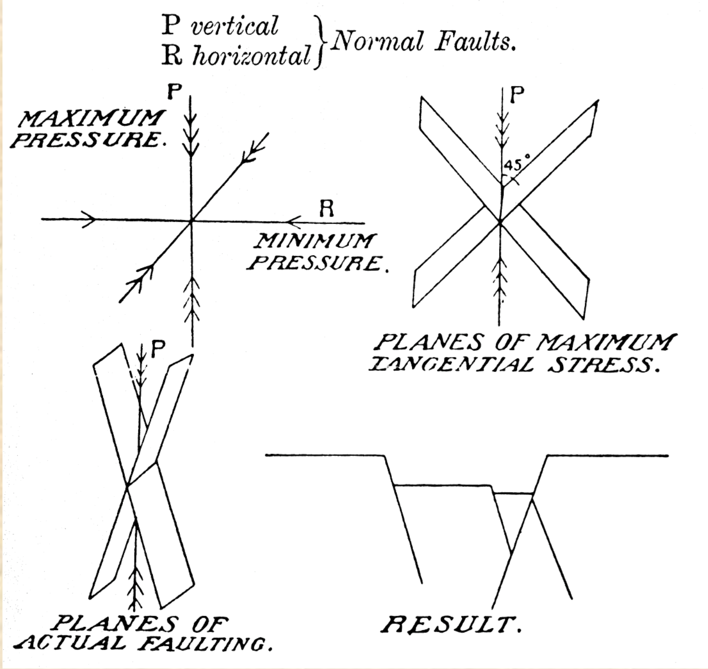
$$\varphi_2 = \frac{\pi}{4} - \frac{\varphi_0}{2} \approx 30°$$

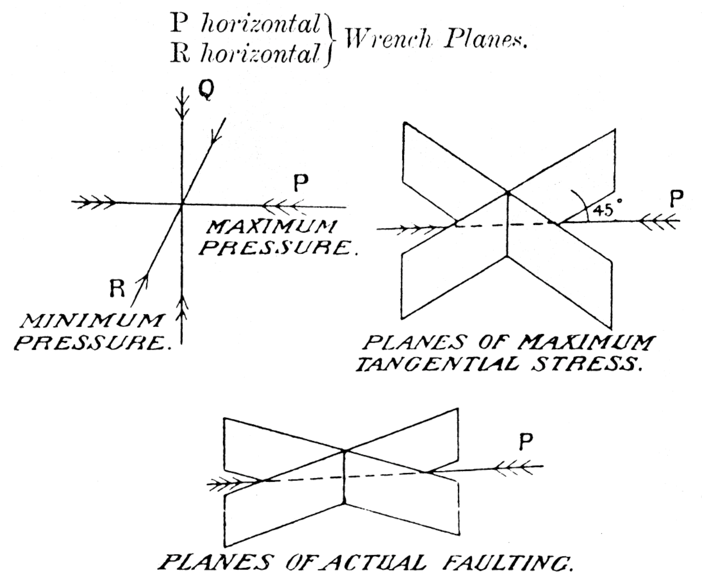


Stress orientation -> optimal conjugate faults
Fault & slip datum -> optimal stress orientation

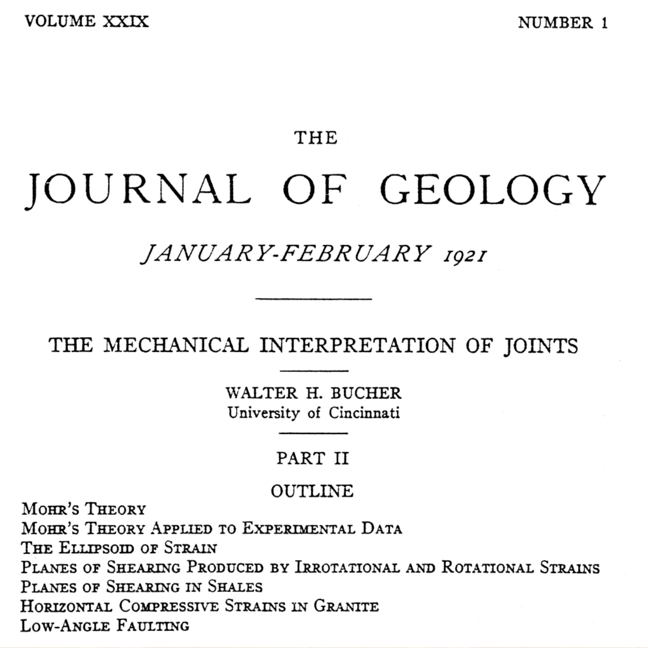
The vertical is a principal stress direction







Anderson, 1905



VOLUME XXIX NUMBER 1

THE JOURNAL OF GEOLOGY

JANUARY-FEBRUARY 1921

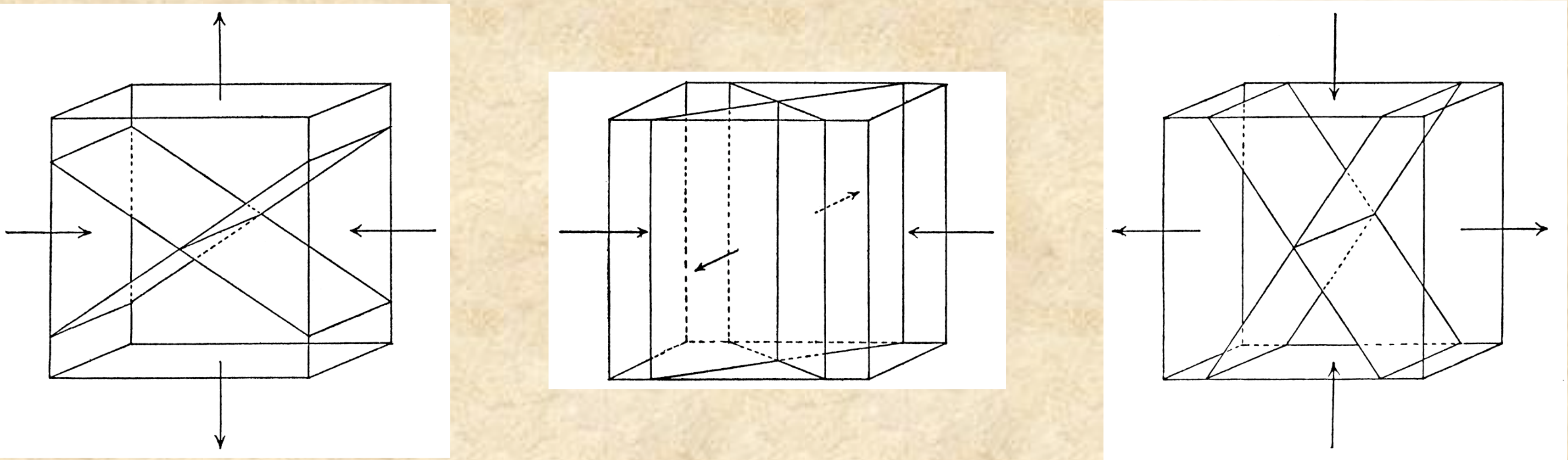
THE MECHANICAL INTERPRETATION OF JOINTS

WALTER H. BUCHER
University of Cincinnati

PART II

OUTLINE

Mohr's Theory
Mohr's Theory Applied to Experimental Data
The Ellipsoid of Strain
Planes of Shearing Produced by Irrotational and Rotational Strains
Planes of Shearing in Shales
Horizontal Compressive Strains in Granite
Low-Angle Faulting



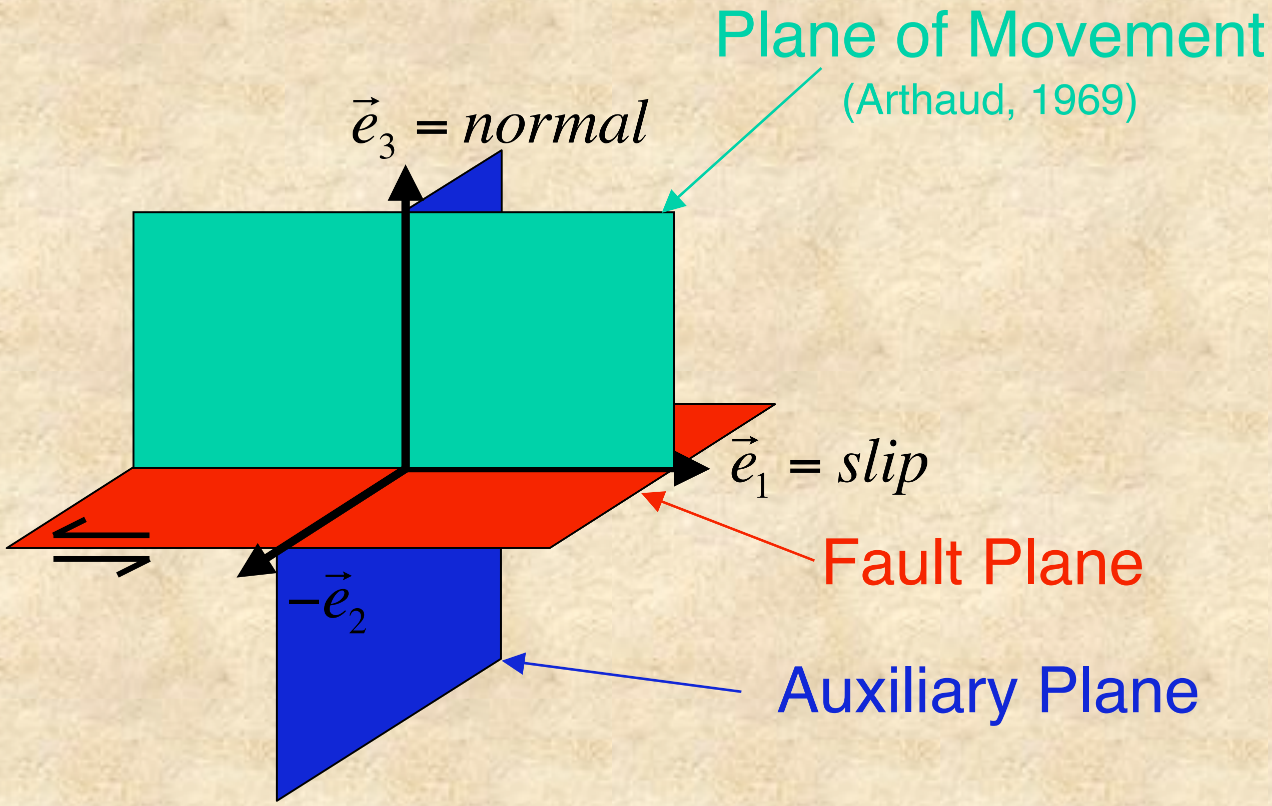
Eastern Kentucky, road cut, 1917
Hartmann (1896): Luder's lines,
Karman (1911), Daubree (1879).

Bucher, 1920-21

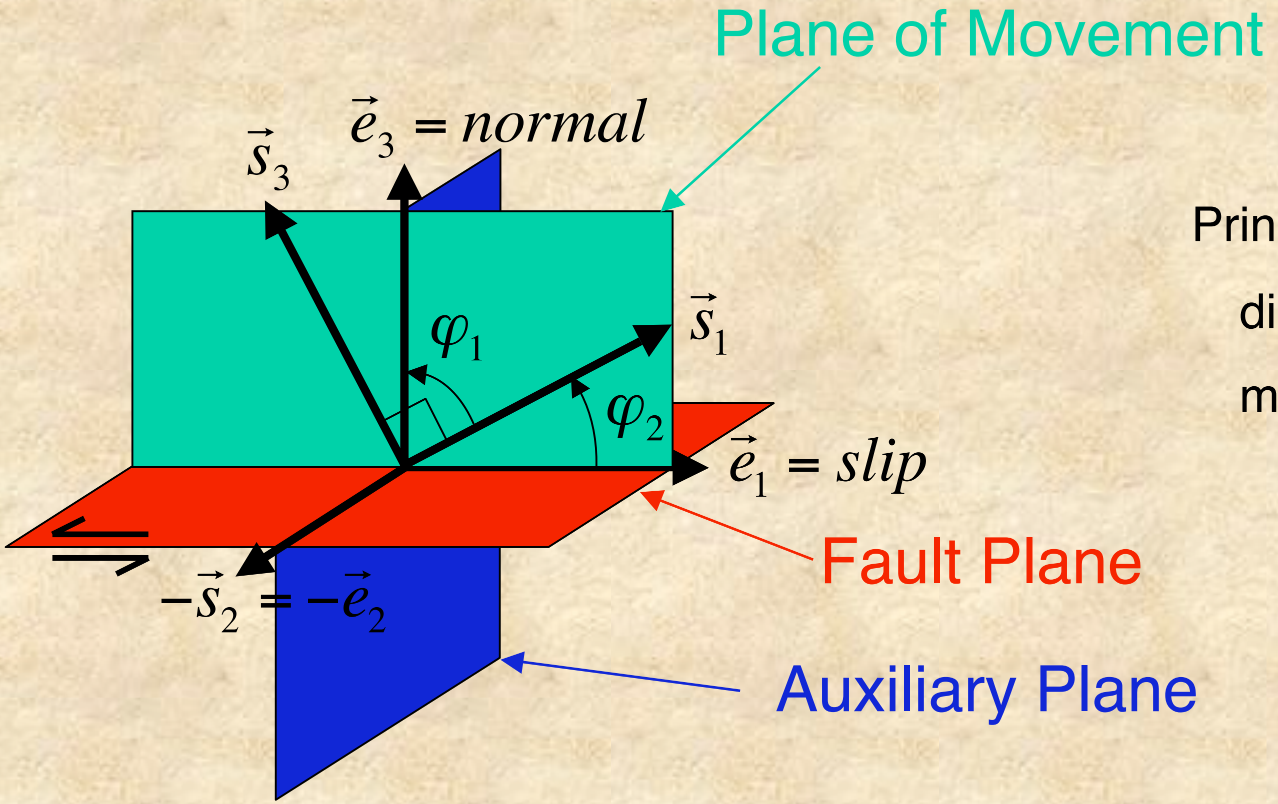
3 planes

Conjugate faults -> optimal stress orientation

Single fault & slip datum -> optimal stress orientation



optimal stress orientation



Principal stress

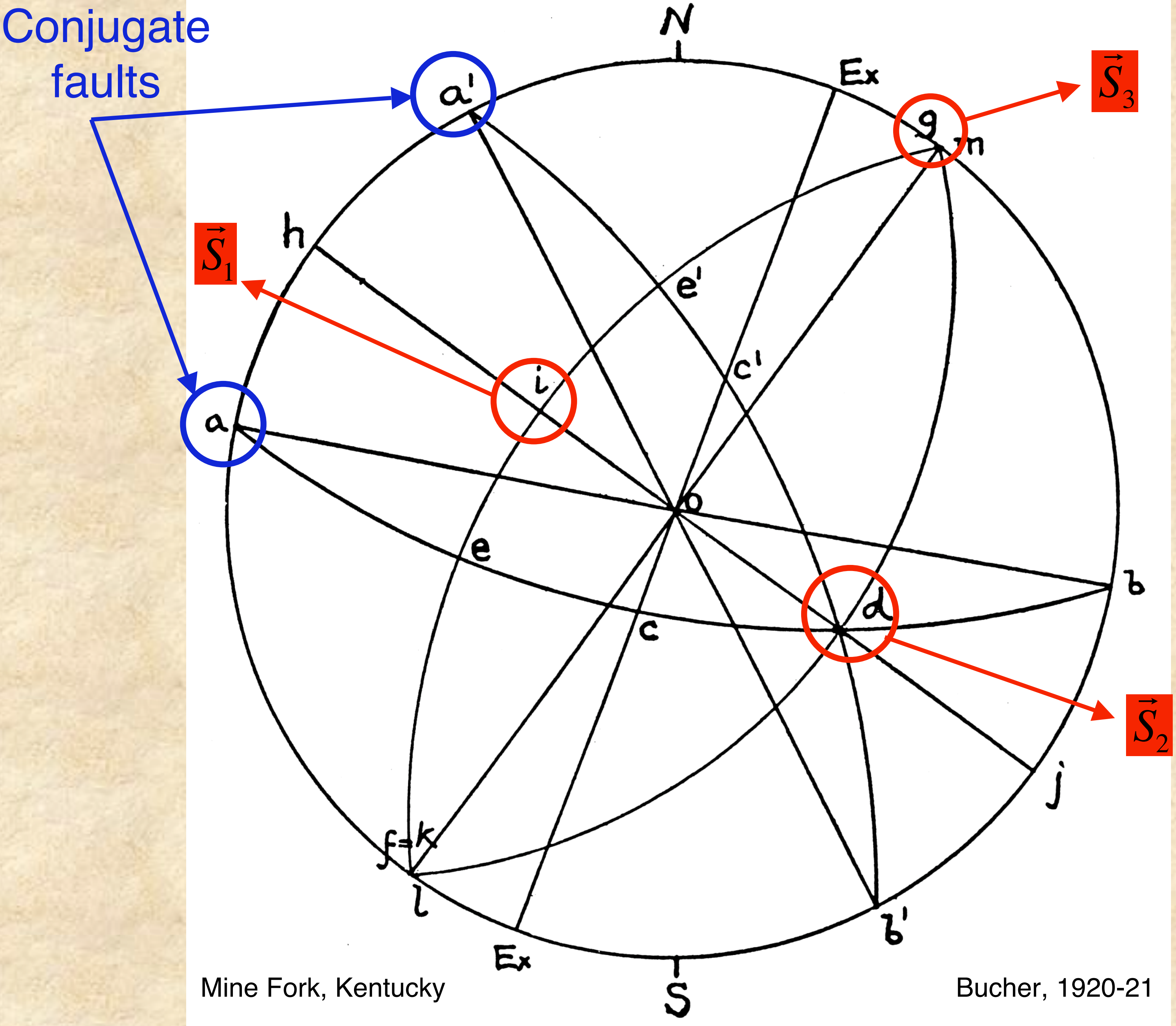
directions: $\vec{s}_1, \vec{s}_2, \vec{s}_3$

magnitudes: $\sigma_1 \geq \sigma_2 \geq \sigma_3$

$\varphi_0 \approx 30°$

$$\varphi_1 = \frac{\varphi_0}{2} + 45° \approx 60°$$

$$\varphi_2 = 45° - \frac{\varphi_0}{2} \approx 30°$$



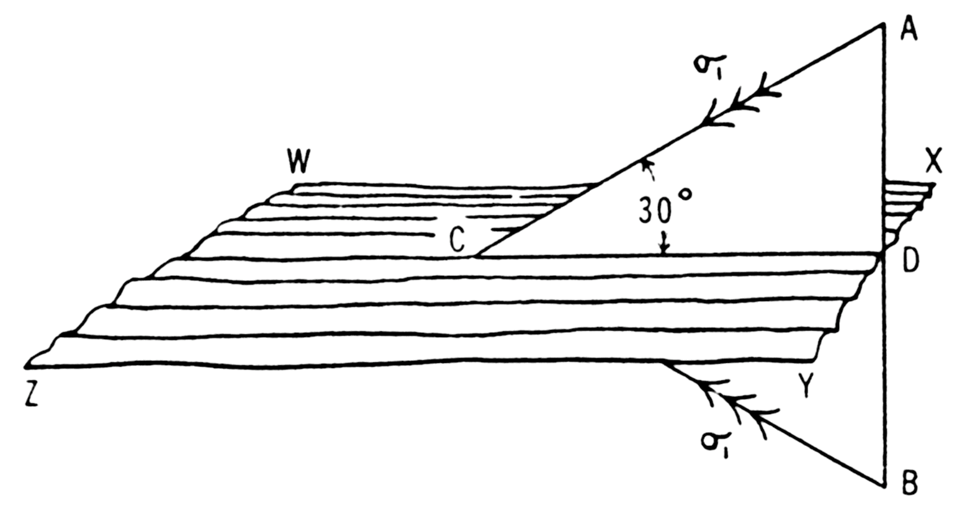
Conjugate faults

Mine Fork, Kentucky

Bucher, 1920-21

Single fault & slip datum -> optimal stress orientation

Anderson (1905)
Bucher (1921)
Turner (1953)
Compton (1966)
Raleigh et al. (1972)
Etchecopar (1984)



Compton,1966, GSAB

Problem: non optimally oriented plane reactivation

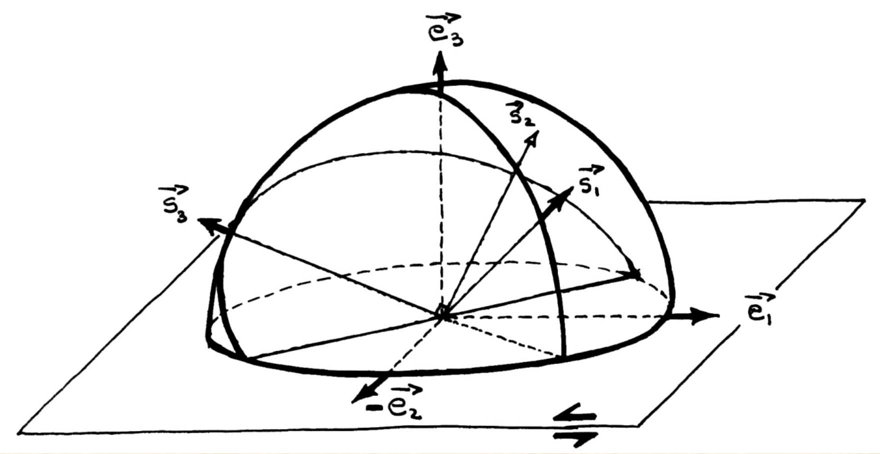
Reactivation on non-optimally oriented planes McKenzie (1969):

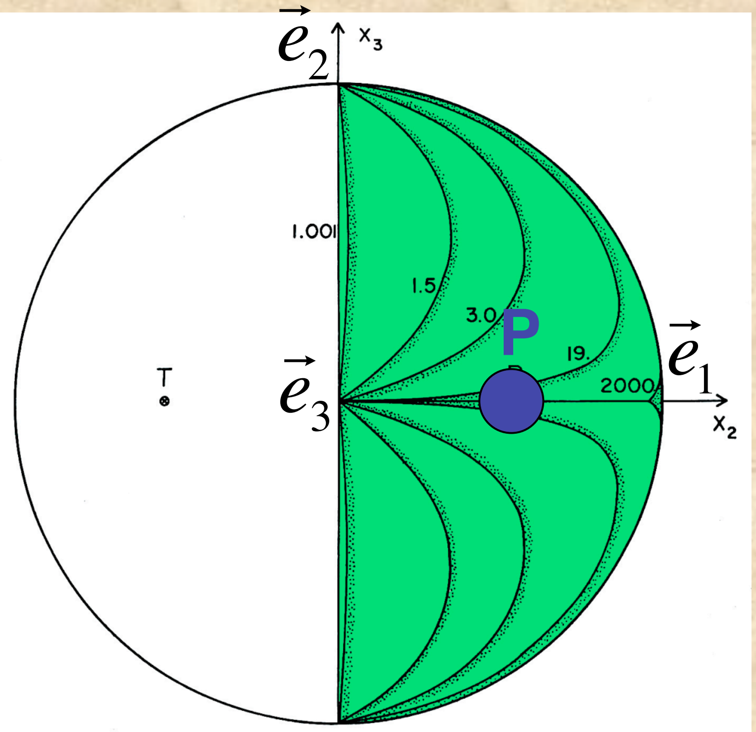
> Shear stress along slip can be accommodated with s_1 anywhere within the dilatational quadrant
>
> In the worst case, s_1 may be at right angle from P.

However (Jaeger, 1959, 1960):

> Reactivating non-optimally oriented planes requires higher stress difference, or pore pressure, or lower friction coefficient.

Question: how frequent ?

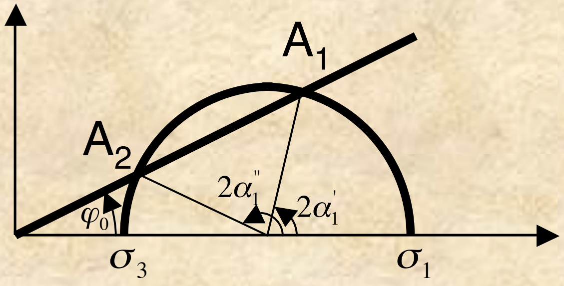




Jaeger, Geophys. Pura. Appl., 1959; Geol. Mag., 1960

McKenzie, BSSA,1969

2D frictional sliding

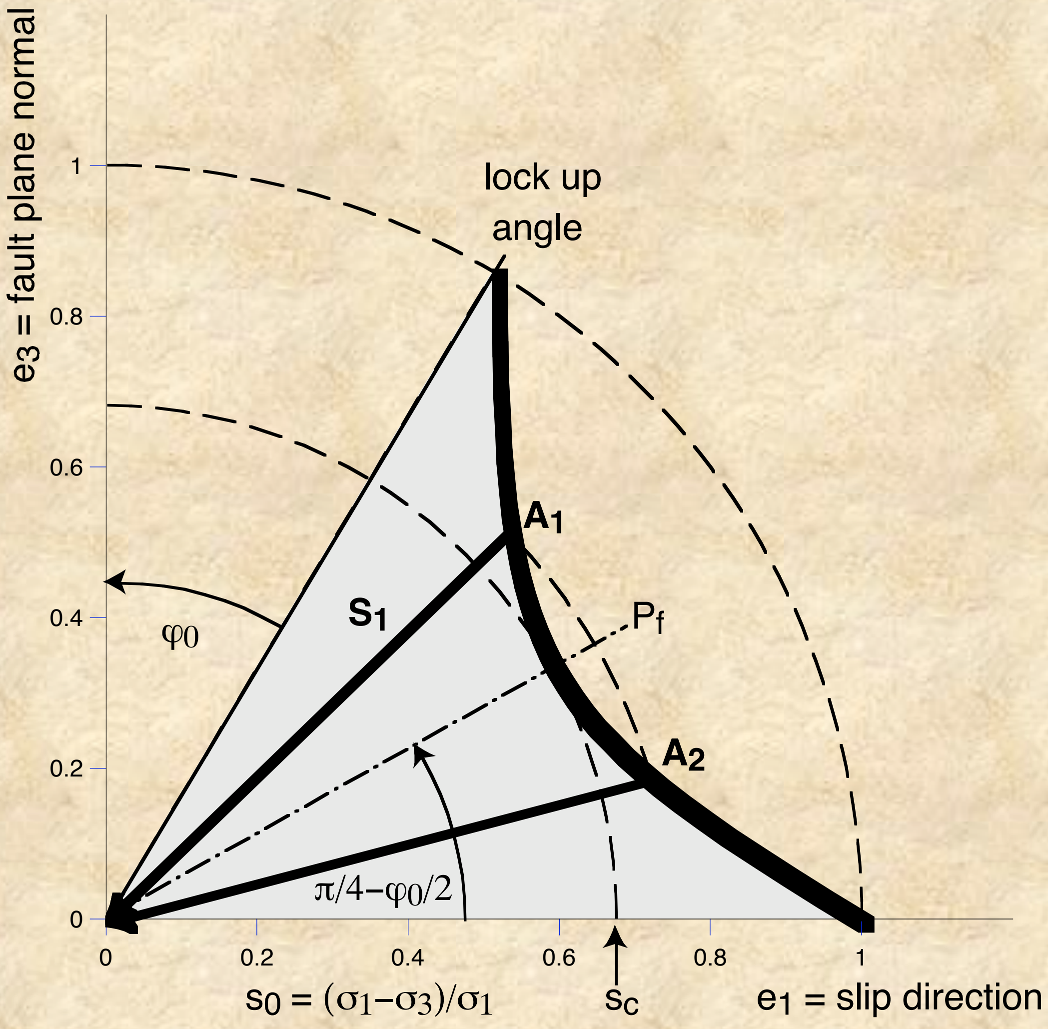


$$s_0 = \frac{\sigma_1' - \sigma_3'}{\sigma_1'}$$

$$s_0 = \frac{2\sin\varphi_0}{\sin(2\beta_1+\varphi_0)+\sin\varphi_0}$$

$$s_c = \frac{2\sin\varphi_0}{1+\sin\varphi_0}$$

$$\varphi_0 = 31^\circ \qquad s_c = 0.68$$

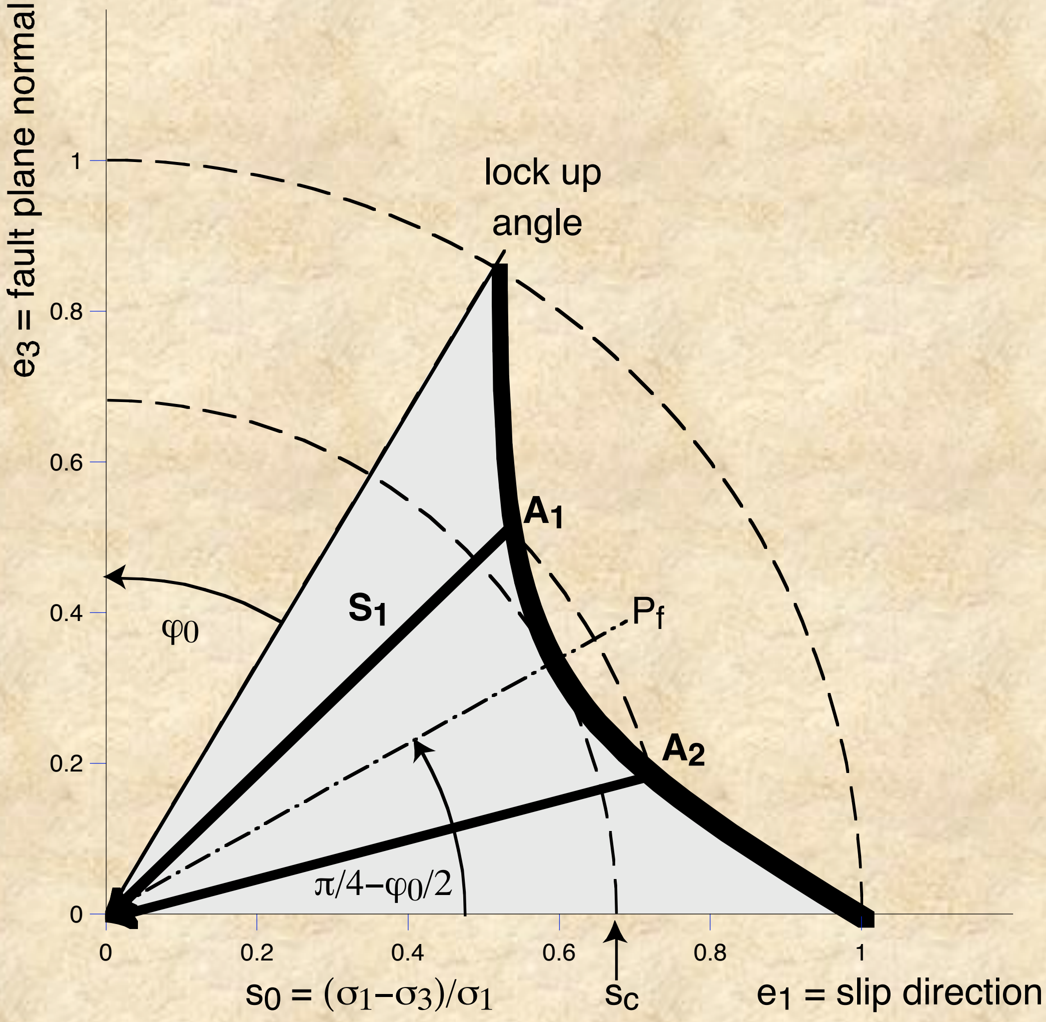


Jaeger, Geophys. Pura. Appl., 1959; Geol. Mag., 1960; Célérier, Tectonics, 1988

2D frictional sliding

Conclusions:

- S_1 away from Pf requires higher s_0:
  either higher stress difference
  or higher pore pressure (lower σ'_1)
- Optimal stress direction Pf is relevant.



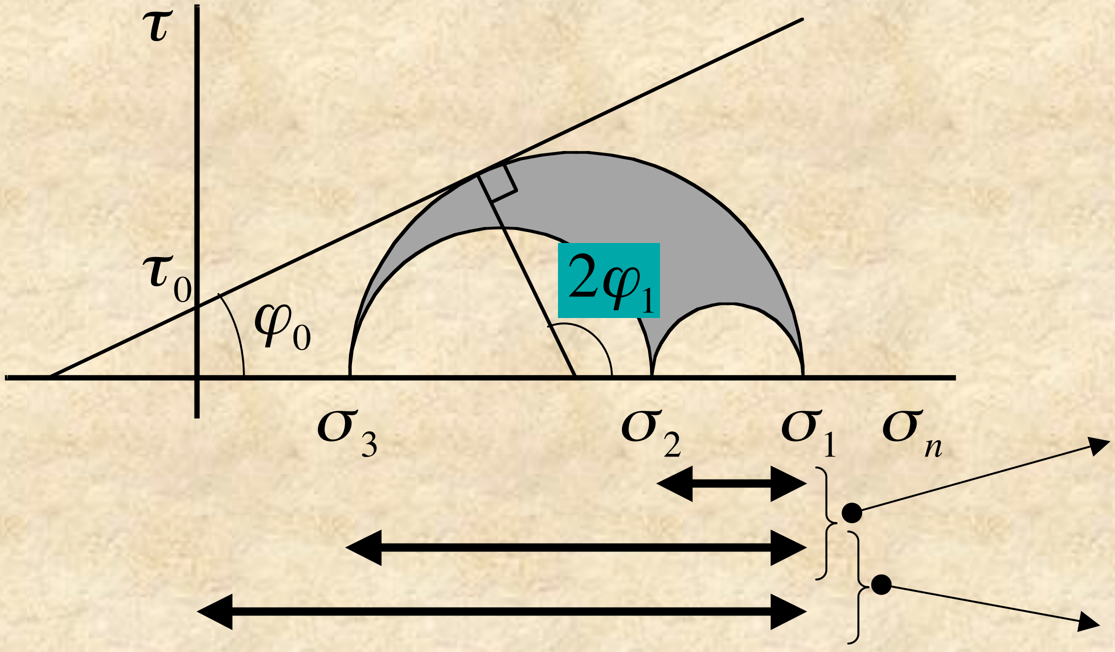
Jaeger, Geophys. Pura. Appl., 1959; Geol. Mag., 1960; Célérier, Tectonics, 1988

3D frictional sliding

Requirements:

- slip along shear stress
- satisfy a friction law

Define two parameters:



$$r_0 = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$

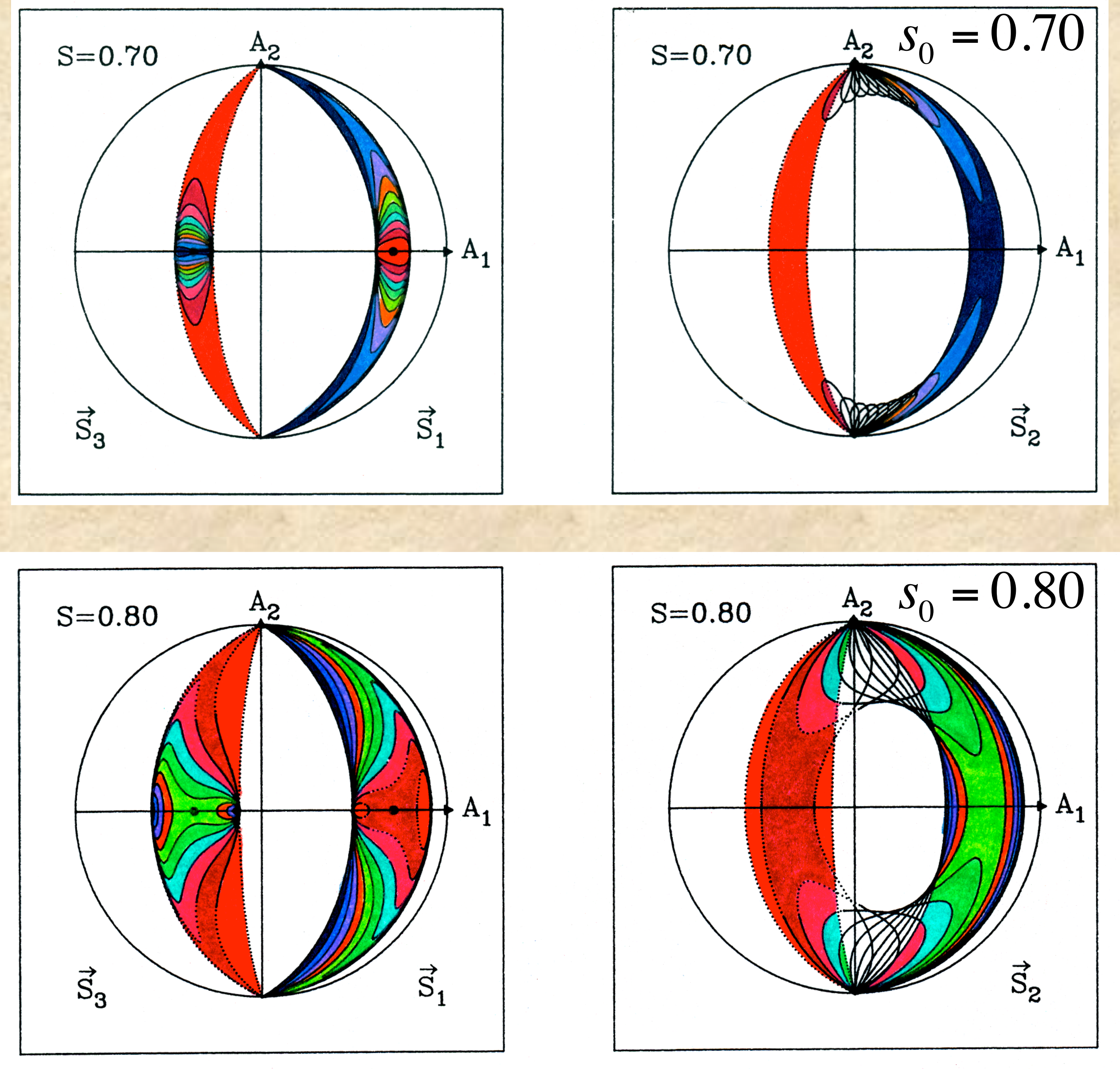
$$s_0 = \frac{\sigma_1' - \sigma_3'}{\sigma_1'}$$

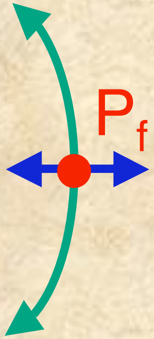
Can reduce the study to $\tau_0 = 0$ (Jaeger & Rosengren, 1969)

Celerier, 1988

Trajectories of S_1,S_2,S_3, satisfying both

- shear stress along slip
- friction law





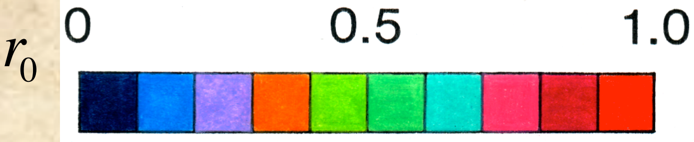
r_0 -> 0.0

P_f

s_0 -> 1.0

$$s_0 = \frac{\sigma_1' - \sigma_3'}{\sigma_1'}$$

$$r_0 = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$



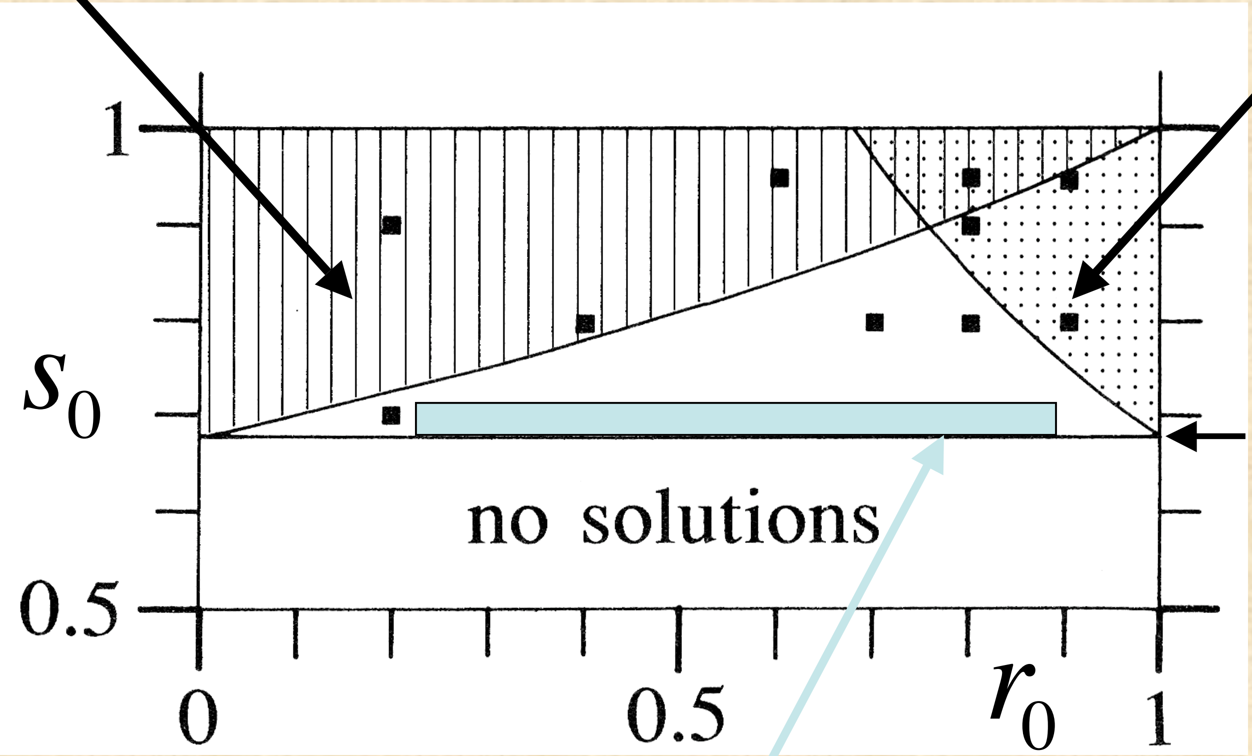
Celerier, 1988

$\vec{S}_1$ can lie in the fault plane

$\vec{S}_3$ can lie in the fault plane

$$s_0 = \frac{\sigma_1' - \sigma_3'}{\sigma_1'}$$

$$r_0 = \frac{\sigma_1 - \sigma_2}{\sigma_1 - \sigma_3}$$



$$s_c = \frac{2\sin\varphi_0}{1+\sin\varphi_0}$$

s_c

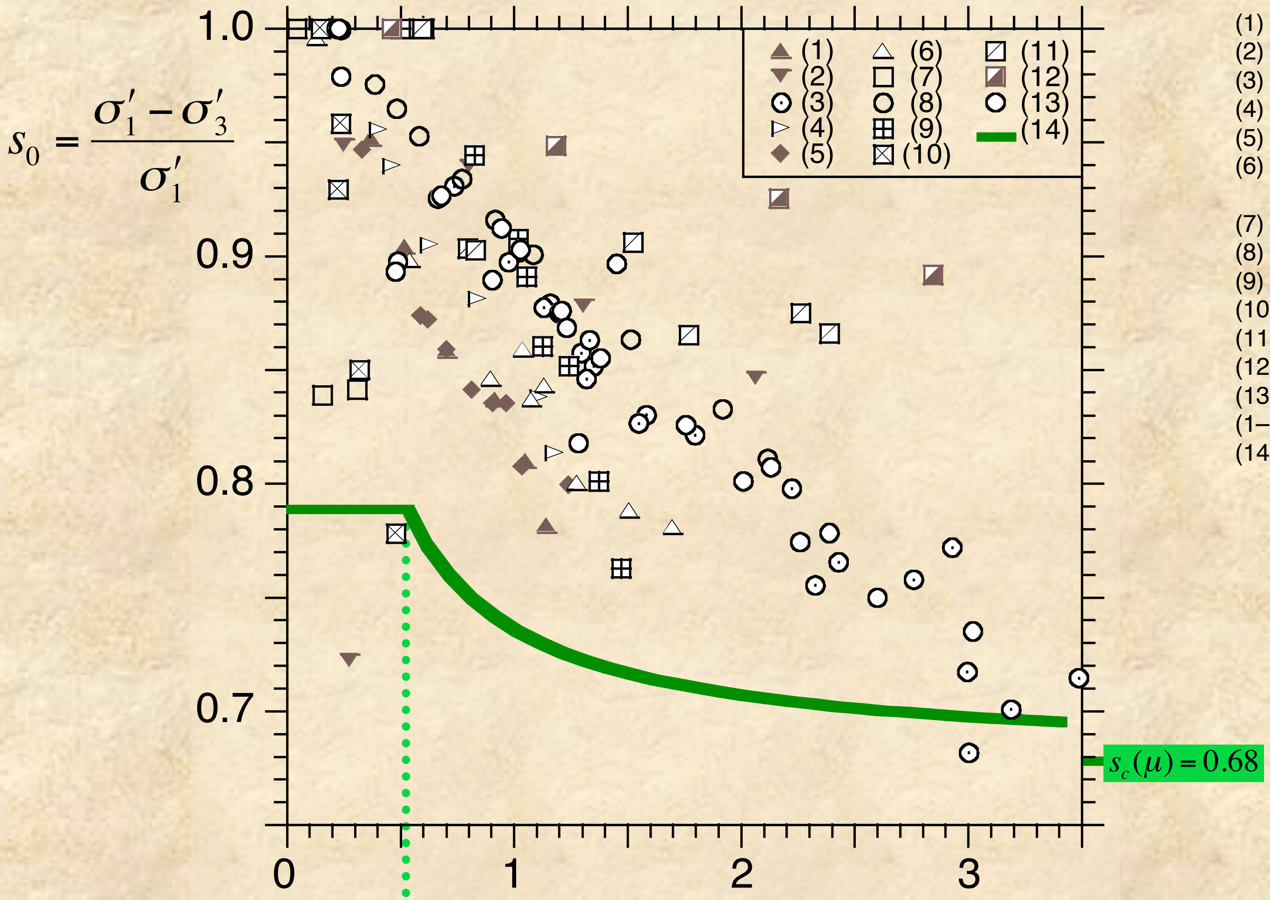
$\varphi_0 = 31°$

$s_c = 0.68$

Conclusion:
in states of stress where
- s_0 close to s_c
- r_0 remote from 0 or 1

optimal stress are relevant for faults with
- μ close to 0.6

Celerier, 1988



(1) Orikabe Diorite [Mogi, 1965]
(2) Frederick Diabase [Brace, 1964]
(3) Westerly Granite [Byerlee, 1967]
(4) Mannari Granite [Mogi, 1965]
(5) Haruyama Peridotite [Mogi, 1965]
(6) Kitashirakawa Granite [Matsushima, 1959, 1960]
(7) Marble [Brace et al., 1966]
(8) Westerly Granite [Mogi, 1966a, 1966b]
(9) Blair Dolomite [Brace, 1964]
(10) Webatuk Dolomite [Brace, 1964]
(11) Aplite [Brace et al., 1966]
(12) Cheshire Quartzite [Brace, 1964]
(13) Westerly Granite [Brace et al., 1966]
(1–13) Also in Ohnaka [1973] & Sheorey [1997]
(14) Reactivation of optimally oriented fracture with standard frictional properties [Byerlee, 1978]

Without cohesion:

$$s_c(\mu) = \frac{2\sin\varphi_0}{1+\sin\varphi_0} = 2\mu\left(\sqrt{1+\mu^2} - \mu\right)$$

With cohesion:

$$s_t(\mu,\tau_0,\sigma_1) = \left(1 + \frac{\tau_0}{\mu\sigma_1}\right) s_c(\mu)$$

$s_t(\mu,\tau_0,\sigma_1) = 0.79$

$s_c(\mu) = 0.79$

$\sigma_1 \le 500\ MPa$

$\varphi_0 = 40°$

$$\left.\begin{aligned} &\mu = 0.85 \\ &\tau_0 = 0 \\ &\sigma_n \le 200\ MPa \end{aligned}\right\}$$

$s_t(\mu,\tau_0,\sigma_1) = 0.68 + \dfrac{56.7}{\sigma_1\ [in\ MPa]}$

$s_c(\mu) = 0.68$

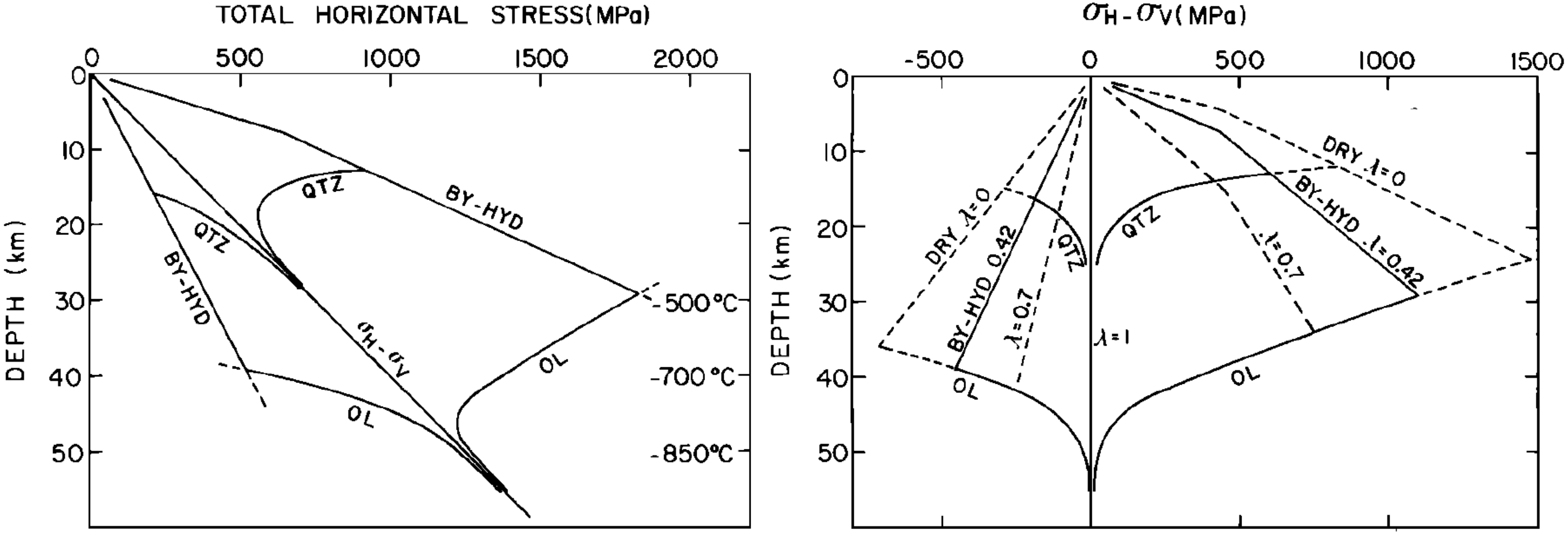
$\sigma_1 \ge 500\ MPa$

$\varphi_0 = 31°$

$$\left.\begin{aligned} &\mu = 0.6 \\ &\tau_0 = 50\ MPa \\ &\sigma_n \ge 200\ MPa \end{aligned}\right\} \text{[Byerlee, 1978]}$$

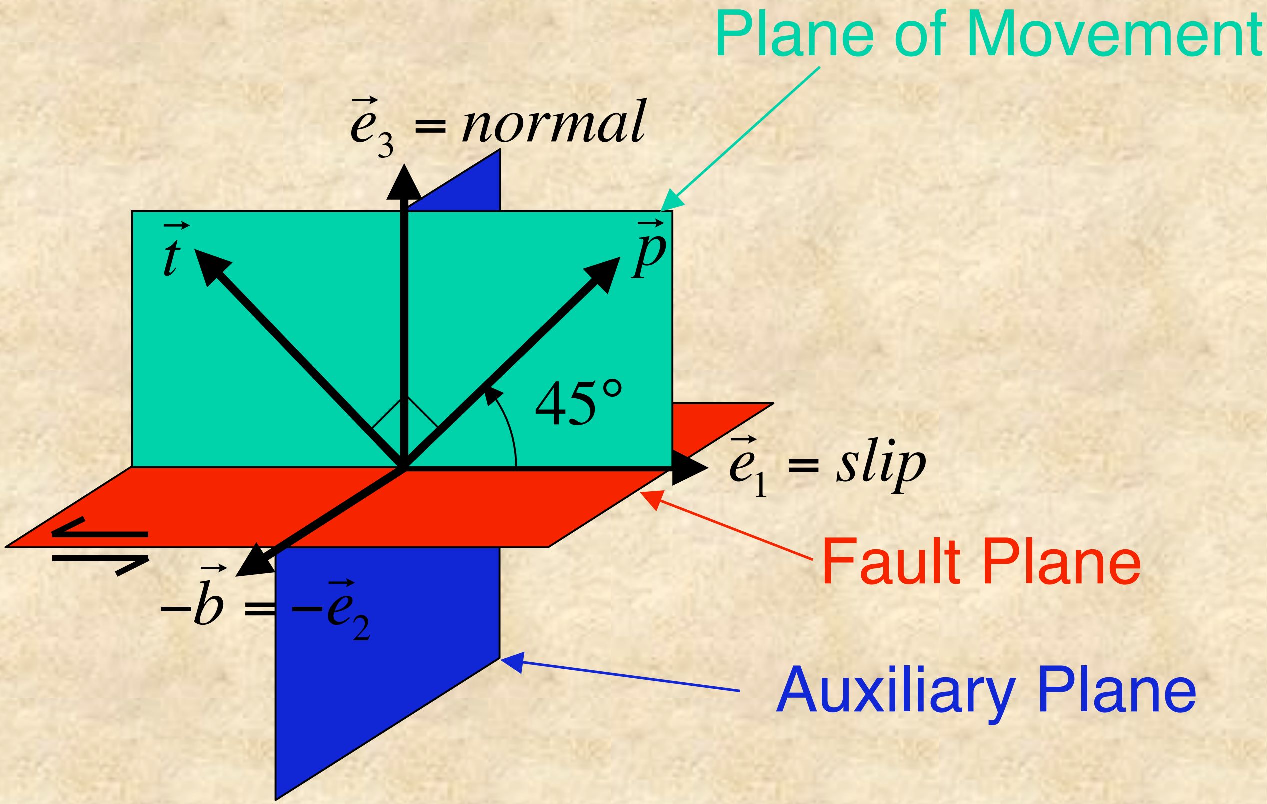
$\sigma_v = \sigma_1$
α 0 - 1
120 - 180 km

Célérier, Rev. Geophysics, 2008

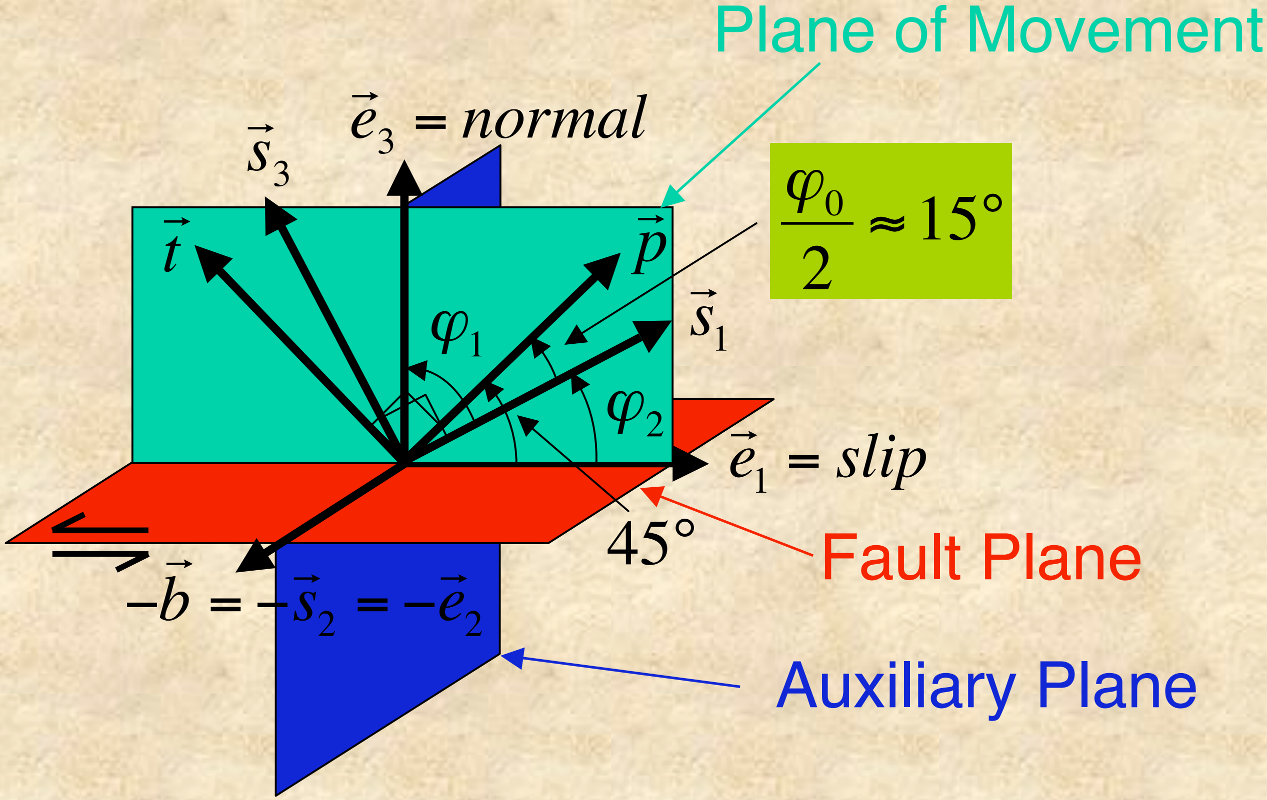


Brace & Kohlstedt, JGR Nov. 1980

P, B, T


Plane of Movement
$\vec{e}_3 = normal$
$\vec{t}$
$\vec{p}$
45°
$\vec{e}_1 = slip$
Fault Plane
$-\vec{b} = -\vec{e}_2$
Auxiliary Plane

optimal stress orientation close to P, B, T



$\varphi_0 \approx 30°$

$\varphi_1 = \frac{\varphi_0}{2} + 45° \approx 60°$

$\varphi_2 = 45° - \frac{\varphi_0}{2} \approx 30°$

Triangular diagrams

Original definition (Frohlich, 1992, 2001)

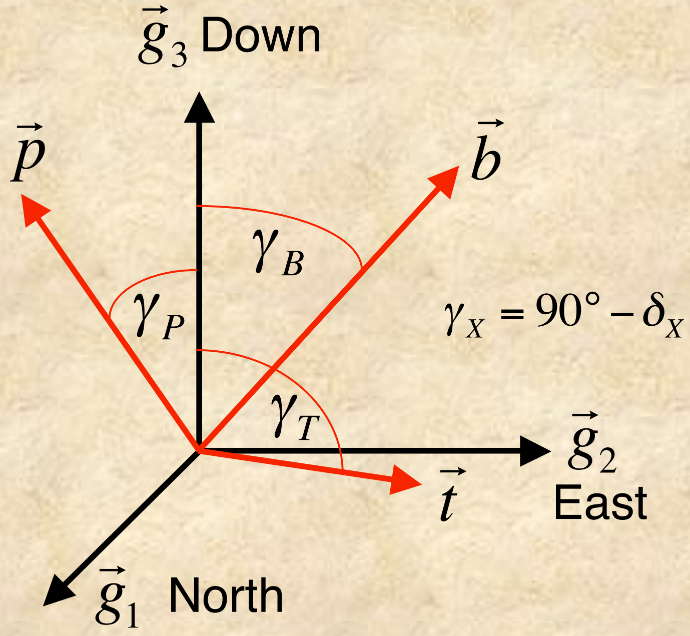
Geographical frame $G = (\vec{g}_1, \vec{g}_2, \vec{g}_3)$

P,B,T frame $Q = (\vec{p}, \vec{b}, \vec{t})$

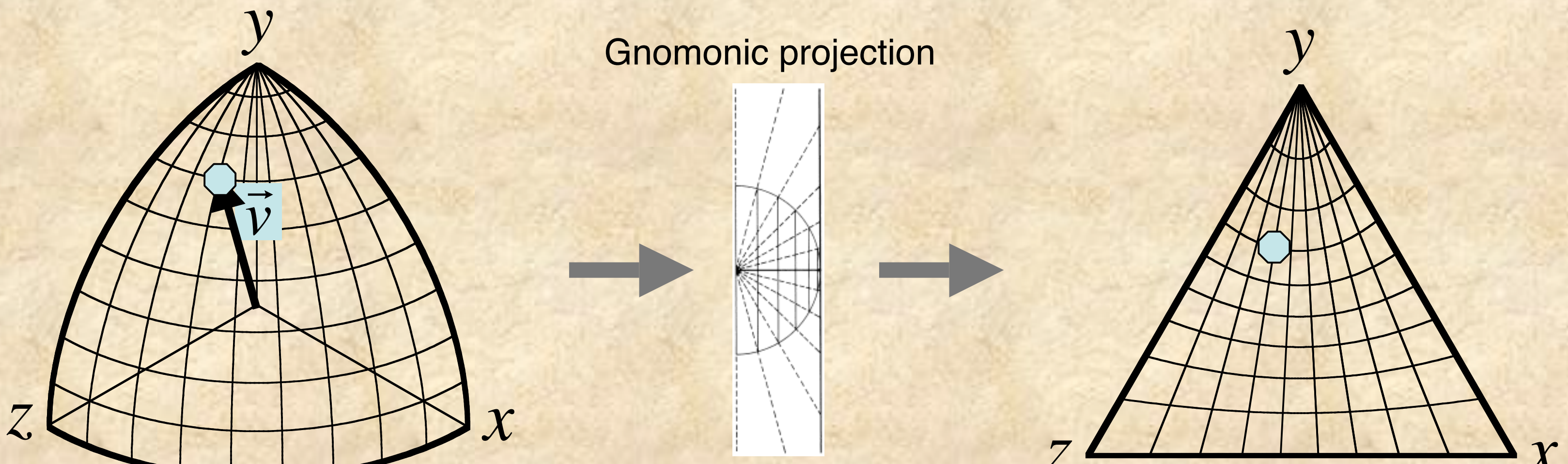
Plunges of P,B,T: $\delta_P, \delta_B, \delta_T \ in \left[0, 90°\right]$

$$Q^G = \begin{array}{c} \begin{array}{ccc} \vec{p} & \vec{b} & \vec{t} \end{array} \\ \left[\begin{array}{ccc} q_{11} & q_{12} & q_{13} \\ q_{21} & q_{22} & q_{23} \\ \hline q_{31} & q_{32} & q_{33} \\ \hline \end{array}\right] \end{array} \longrightarrow \vec{v} = \begin{bmatrix} \sin\delta_P \\ \sin\delta_B \\ \sin\delta_T \end{bmatrix} = \pm \begin{bmatrix} q_{31} \\ q_{32} \\ q_{32} \end{bmatrix}$$

$$\|\vec{v}\| = 1$$



$\gamma_X = 90° - \delta_X$



Gnomonic projection

Great circles -> lines
Seismic rays -> lines

Frohlich, Phys. Earth Planet. Int., 1992; Geophys. J. Int., 2001

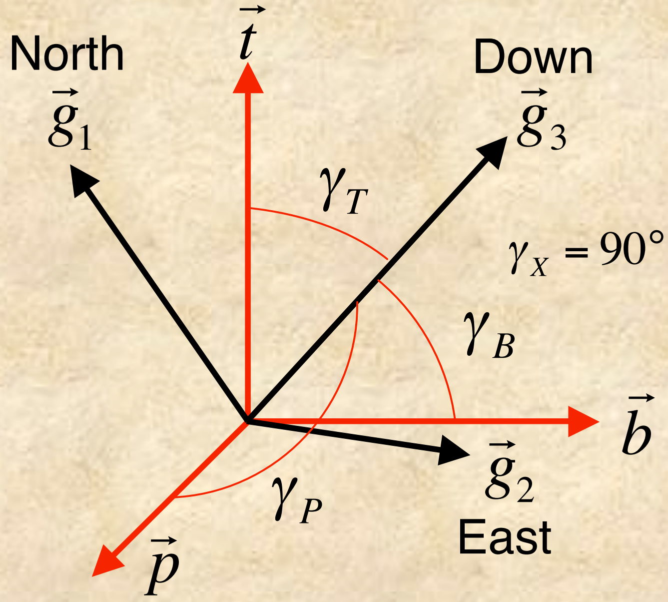
Triangular diagrams

Alternate interpretation

$$G^Q = \left[\begin{array}{ccc} & & \vec{g}_3 \\ g_{11} & g_{12} & \boxed{g_{13}} \\ g_{21} & g_{22} & \boxed{g_{23}} \\ g_{31} & g_{32} & \boxed{g_{33}} \end{array}\right]$$

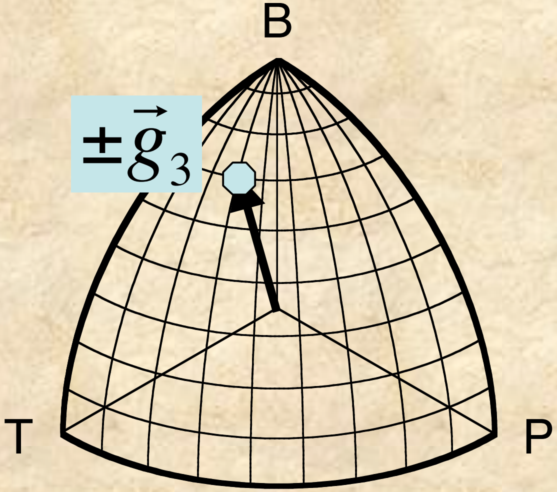
$$\vec{g}_3 = \begin{bmatrix} g_{13} \\ g_{23} \\ g_{33} \end{bmatrix} = \begin{bmatrix} q_{31} \\ q_{32} \\ q_{33} \end{bmatrix} = \pm \begin{bmatrix} \sin\delta_P \\ \sin\delta_B \\ \sin\delta_T \end{bmatrix}$$

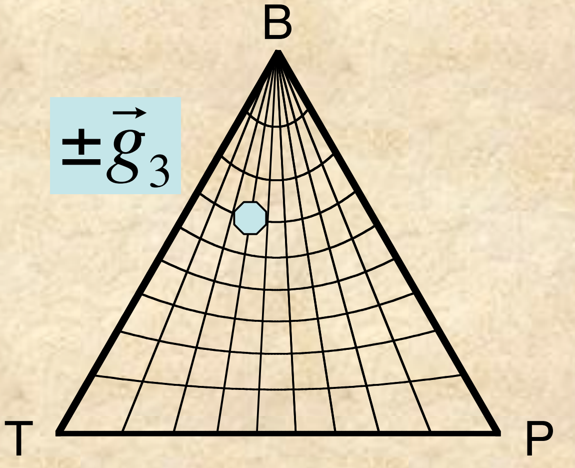
$$G^Q = \left(Q^G\right)^{-1} = {}^tQ^G$$



$$\gamma_X = 90° - \delta_X$$

$\vec{v} = \pm\vec{g}_3$ ⇒ The triangular diagram represents the upgoing or downgoing vertical within the P,B,T frame

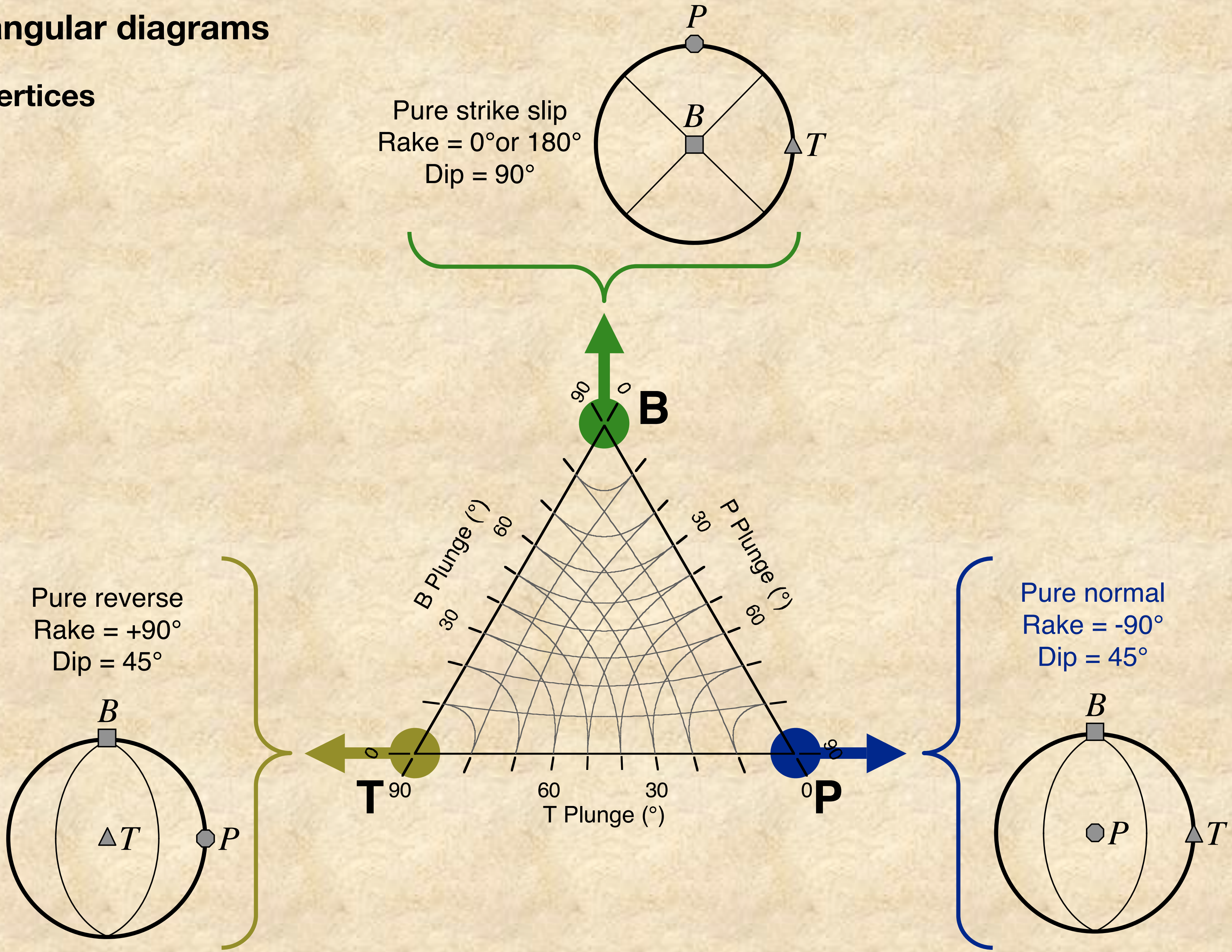




Célérier, Rev. Geophysics, 2008

Triangular diagrams

Vertices



Pure strike slip
Rake = 0°or 180°
Dip = 90°

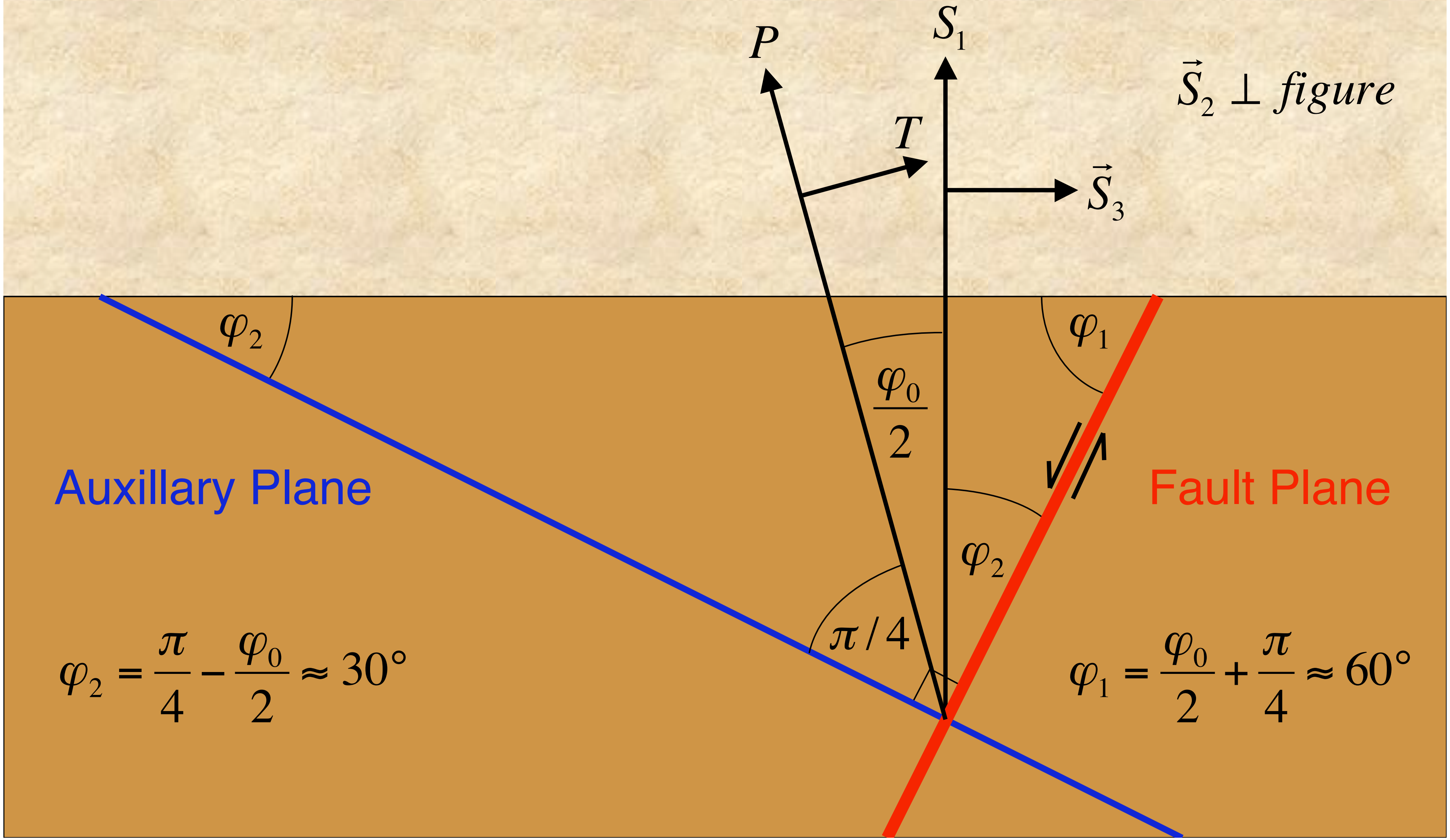
Pure reverse
Rake = +90°
Dip = 45°

Pure normal
Rake = -90°
Dip = 45°

Anderson’s Normal Faulting

Cross section

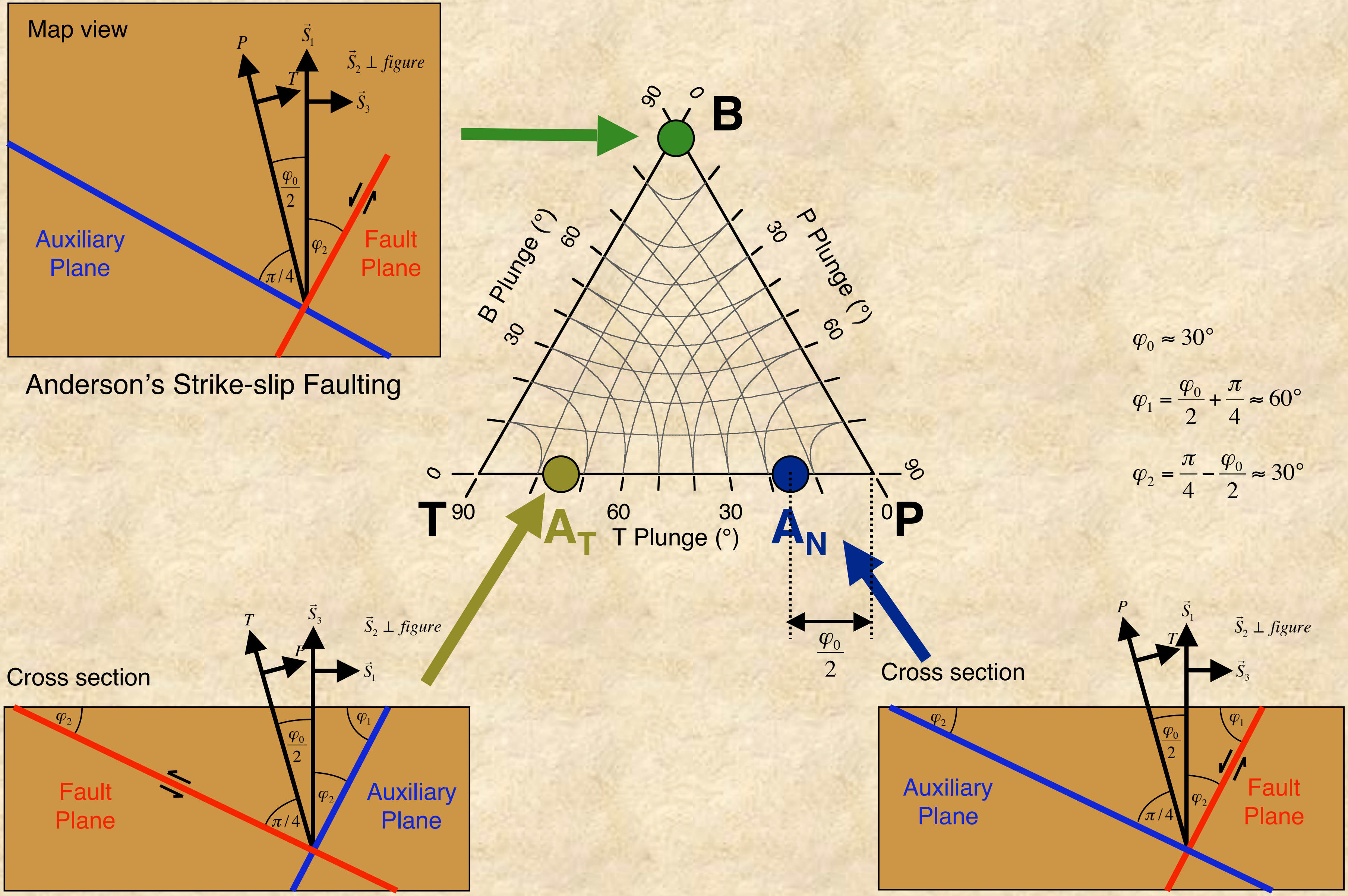
$\varphi_0 \approx 30°$



$$\varphi_2 = \frac{\pi}{4} - \frac{\varphi_0}{2} \approx 30°$$

$$\varphi_1 = \frac{\varphi_0}{2} + \frac{\pi}{4} \approx 60°$$

location of Anderson faulting



Anderson's Strike-slip Faulting

$$\varphi_0 \approx 30°$$

$$\varphi_1 = \frac{\varphi_0}{2} + \frac{\pi}{4} \approx 60°$$

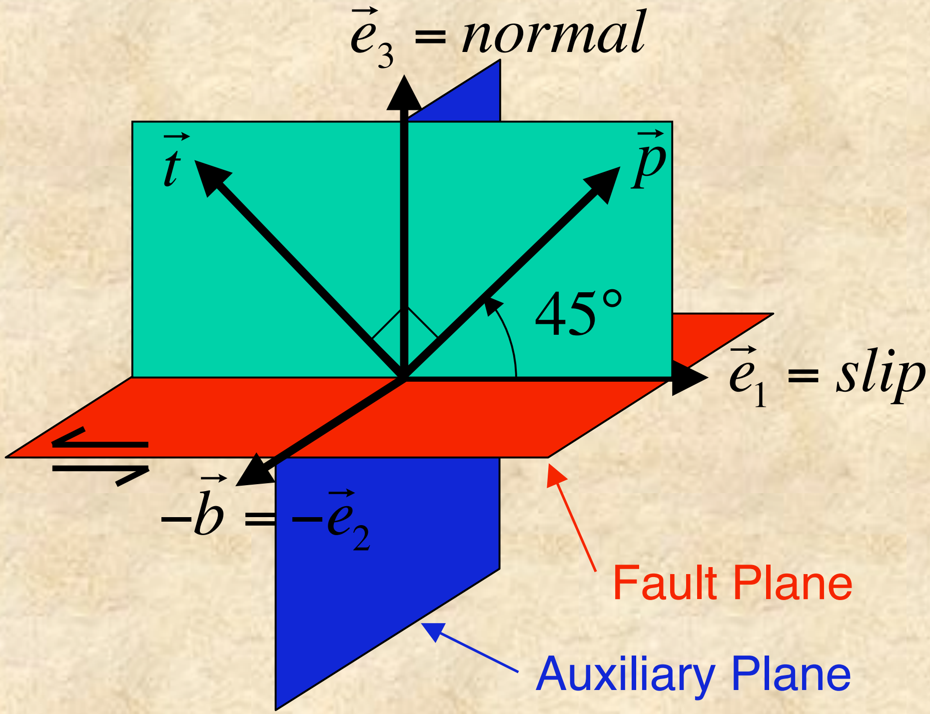
$$\varphi_2 = \frac{\pi}{4} - \frac{\varphi_0}{2} \approx 30°$$

Anderson's Reverse Faulting

Anderson's Normal Faulting

Frohlich, Geophys. J. Int., 2001
Célérier, Rev. Geophysics, 2008

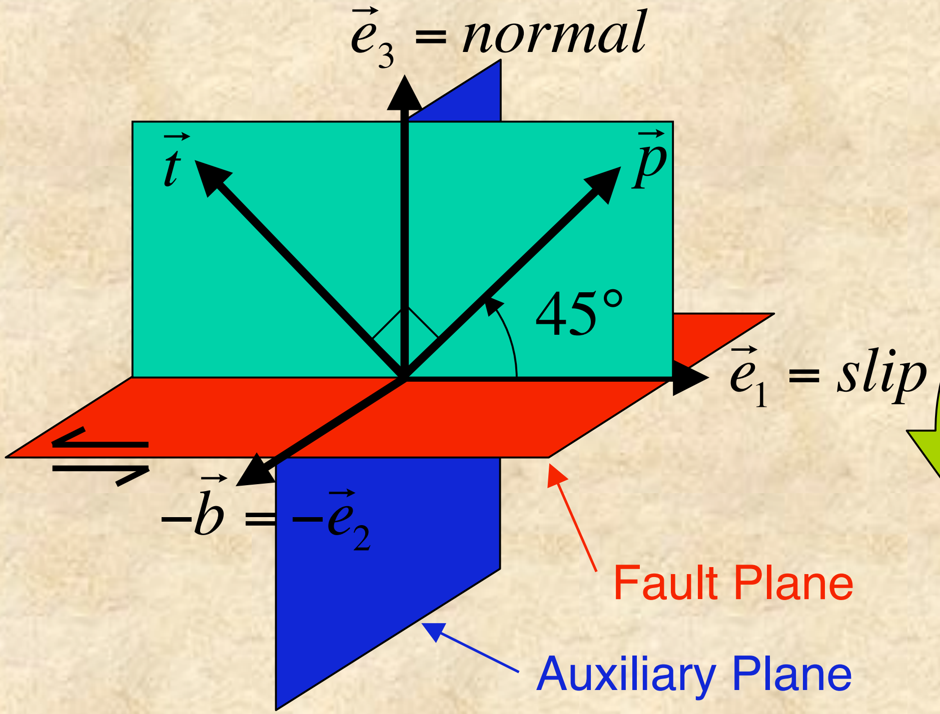
P,B,T plunges versus slip: geometry

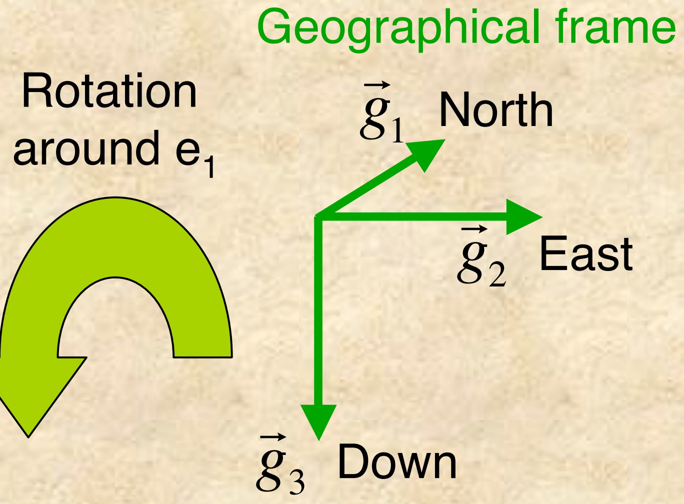


Fault Plane

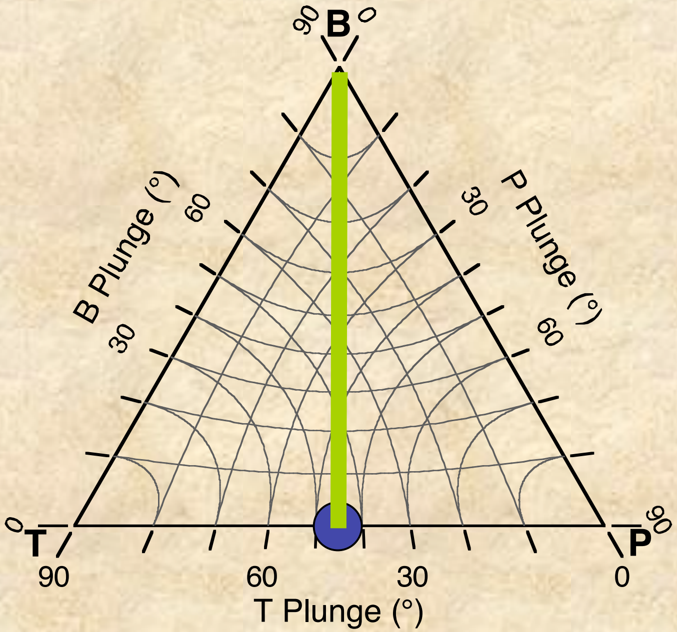
Auxiliary Plane

P,B,T plunges versus strike-slip

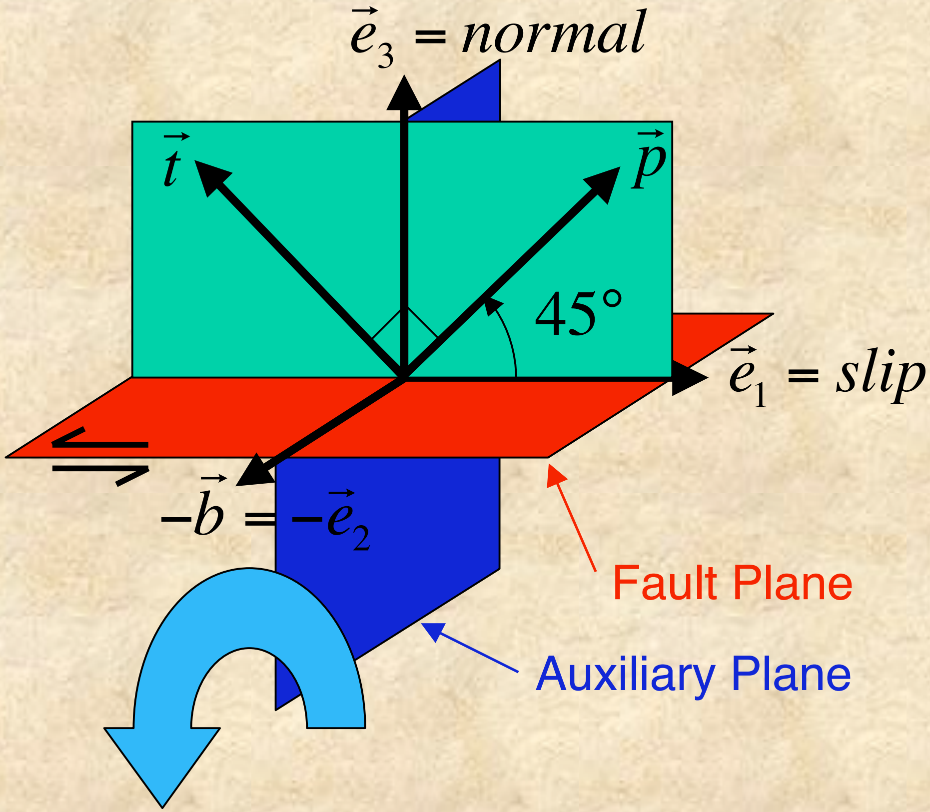




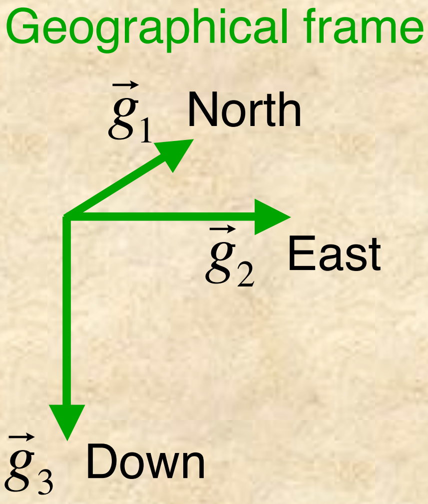
B plunge varies from 0° to 90°
P and T plunges remain equal
Fault plane remains pure strike-slip

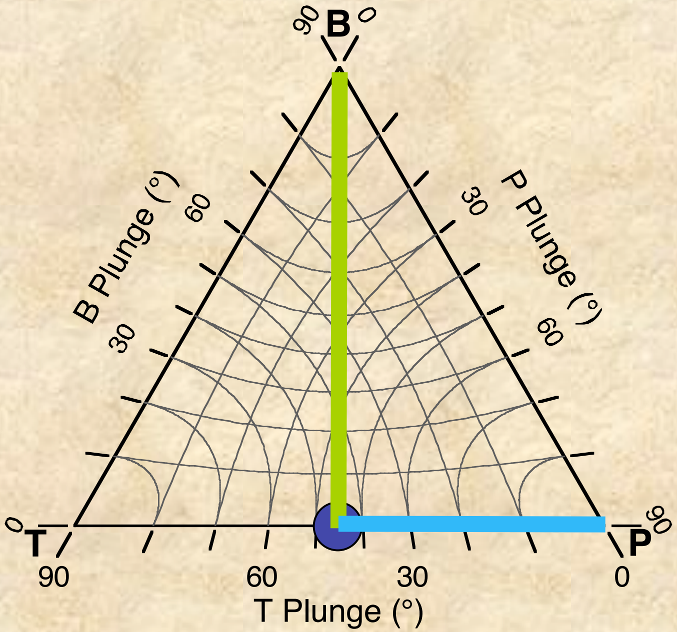


P,B,T plunges versus normal slip



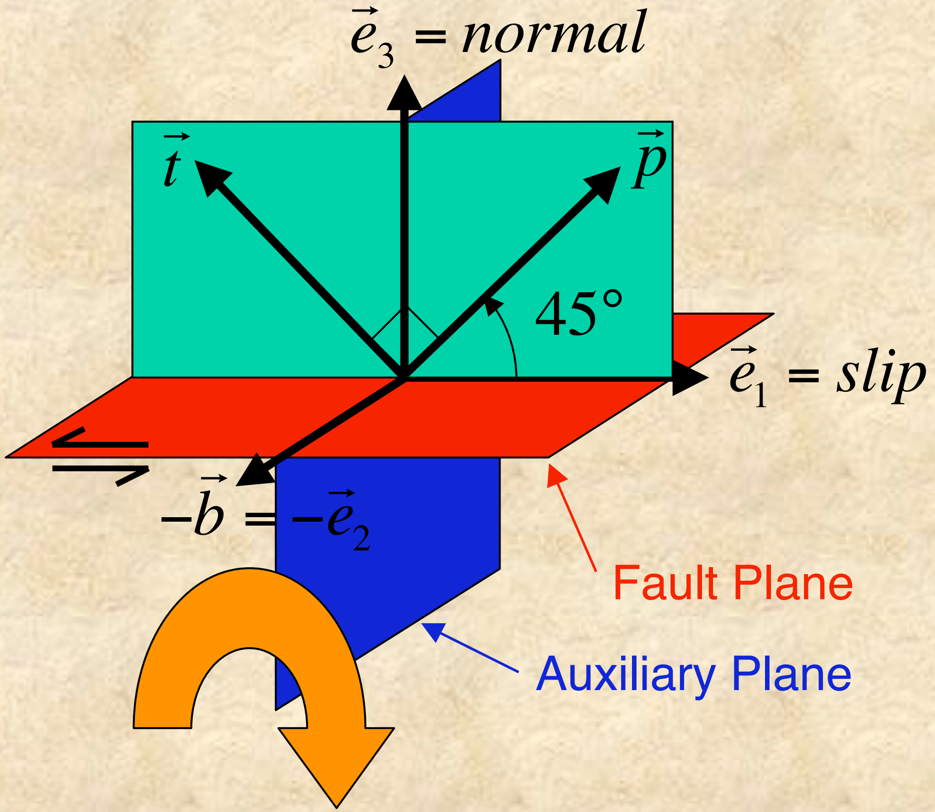
Rotation
around e_2





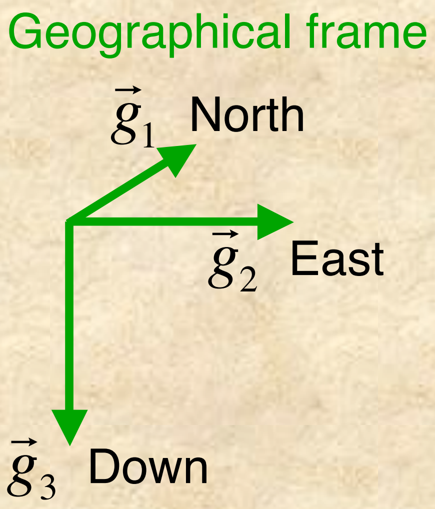
B plunge remains 0°
P plunge varies from 45° to 90°
Fault plane is pure normal slip

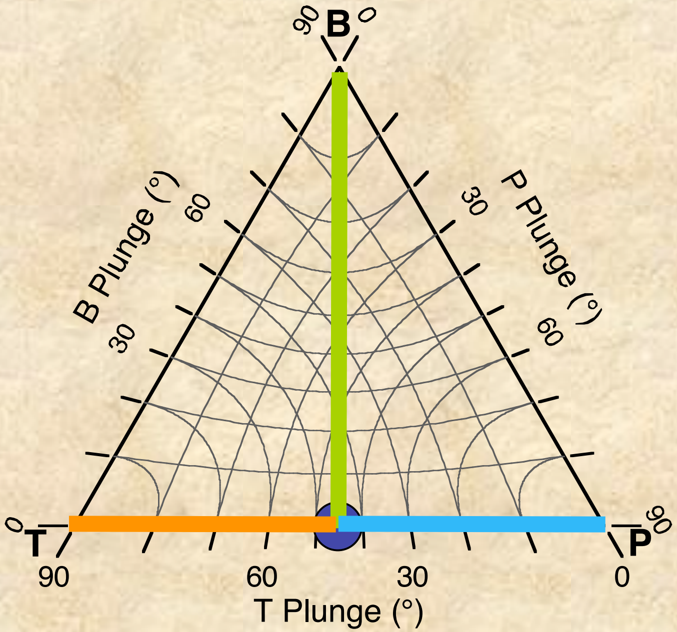
P,B,T plunges versus reverse slip



Rotation around e_2

B plunge remains 0°
T plunge varies from 45° to 90°
Fault plane is pure reverse slip





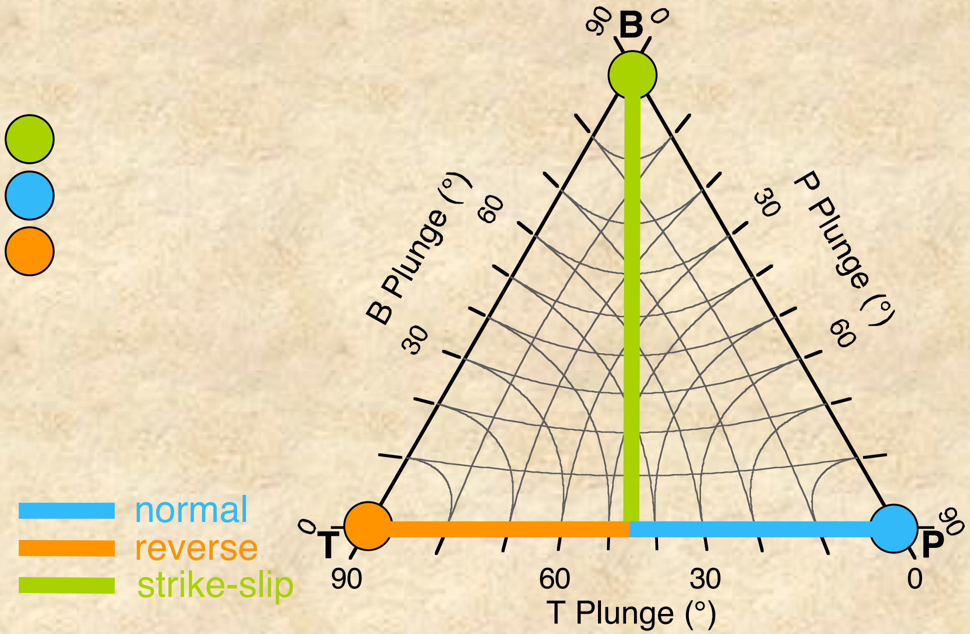
P,B,T plunges versus dip or strike slip: conclusions

Both nodal planes:

strike slip <=> B plunge = 90° ●
normal slip <=> P plunge = 90° ●
reverse slip <=> T plunge = 90° ●

One nodal plane :

dip slip <=> B plunge = 0°
strike slip <=> P plunge = T plunge

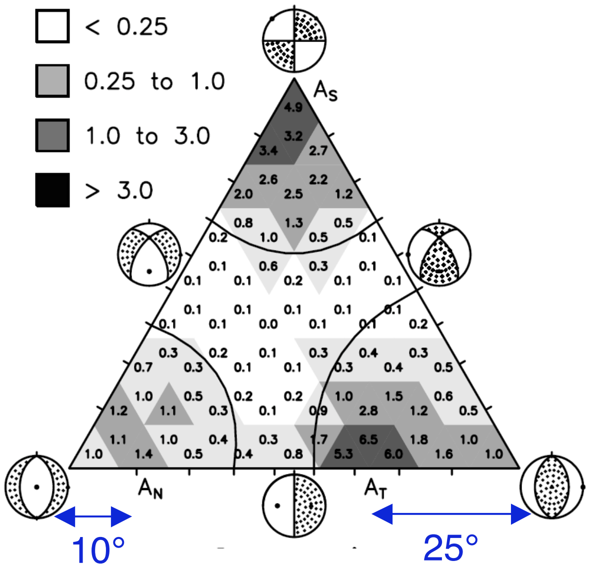


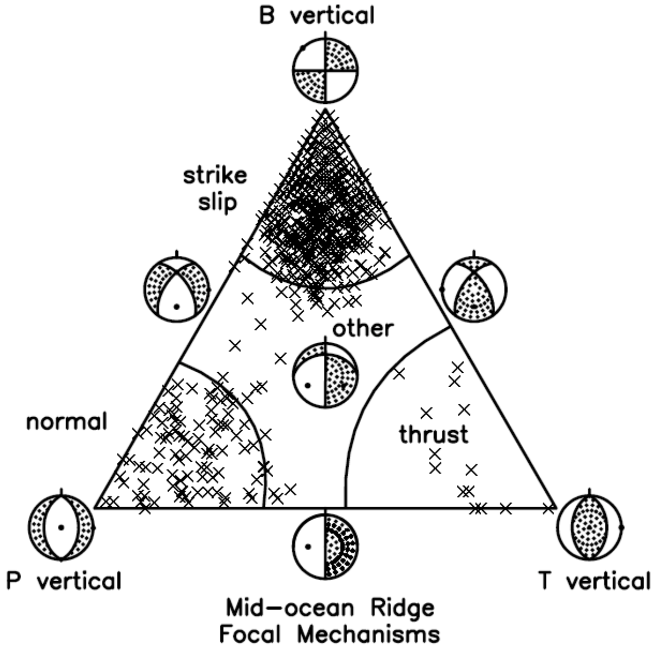
strike slip **does not require** steep B plunge
dip slip **does not require** steep P or T plunge

shallow B: best proxy for dip slip
steep B: not a good proxy for strike slip

Frohlich , GJI, 2001

• CMT 1977-Oct 1999	16410
• Focal depth (centroid ?) ≤ 30 km	8687
• Reliability standards (Frohlich & Davis (1999))	3625
• fclvd ≤ 0.2	
• llDMll/llMll ≤ 15%	
• nfree = 6	
• Near oceanic ridge earthquake	637



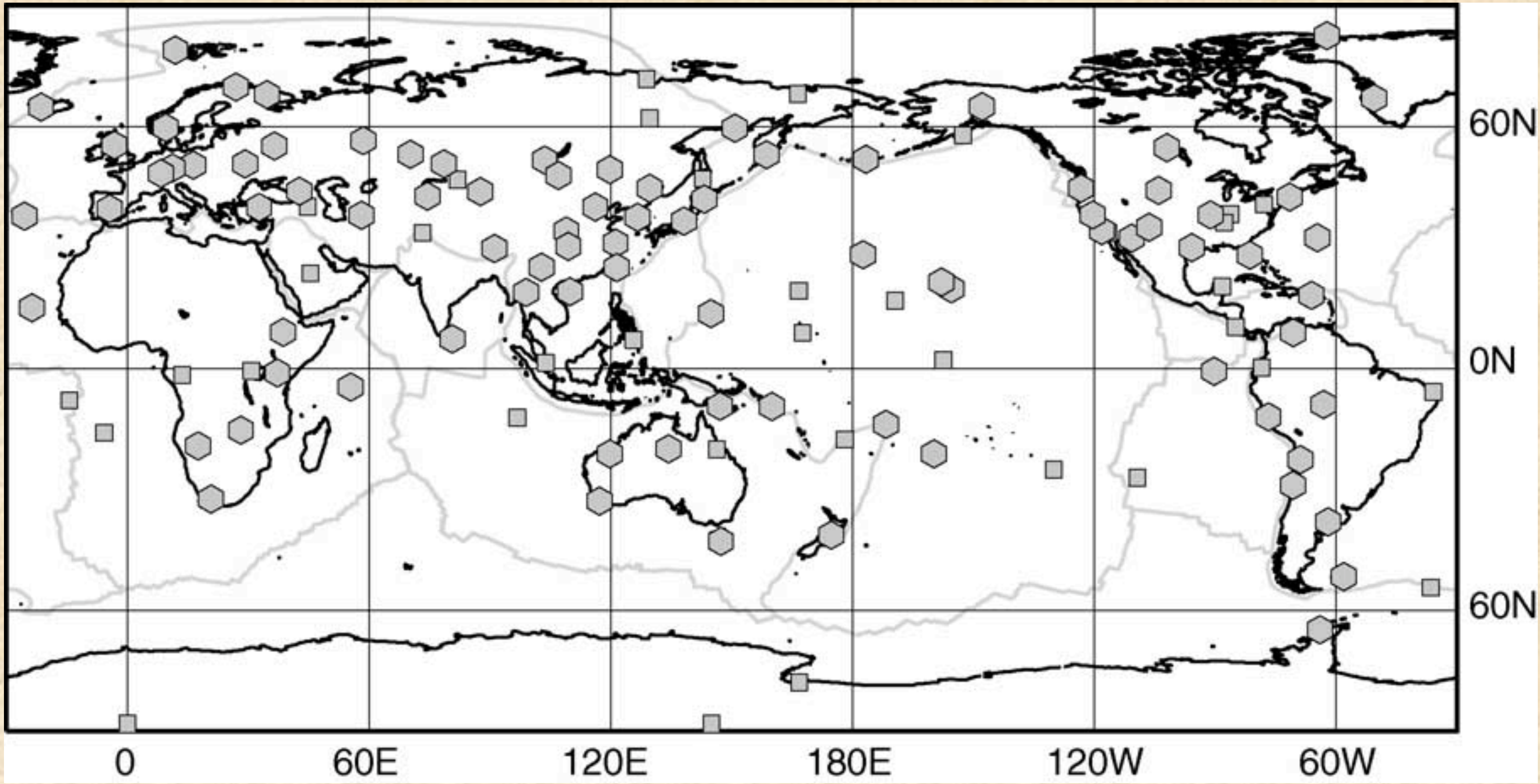


Global Centroid Moment Tensors (GCMT)

- **Global catalog of moment tensors**
  - Hosted at Lamont Doherty Earth Observatory: www.globalcmt.org
  - Ex Harvard CMT
  - Funded by the National Science Foundation since its inception
- **Method: Dziewonski et al. (1981)**
  - Digital stations => Filtered T > 45s + Sampled 1 Hz
  - Coupled inversion for moment tensor and hypocenter
- **Dziewonski et al. (1983):**
  - Centroid location different from PDE hypocenter
  - $\Delta h \sim 50$ km, $\Delta z \sim 12$ km
  - $Z < 15$ km => $Z = 15$ km (PDE $Z = 10$ km or 33 km)
  - $M_w \geq 5.2$ $M_o \geq 10^{17}$ Nm
- **History**
  - systematic since 1981 (Dziewonski & Woodhouse, 1983)
  - 2003 report: Ekström et al., PEPI, 2005
  - backtrack to 1977: 5 digital stations (Dziewonski et al., 1987)
  - 1976 for $M_w \geq 6$ (Ekström, & Nettles, 1997)
  - Deep earthquakes 1907-1976 (Huang et al., 1994, 1997, 1998)
- **Database used**
  - 1976-2004 for analysis
  - Use also 2003 report: Ekström et al., PEPI, 2005

GCMT

Digital seismic network

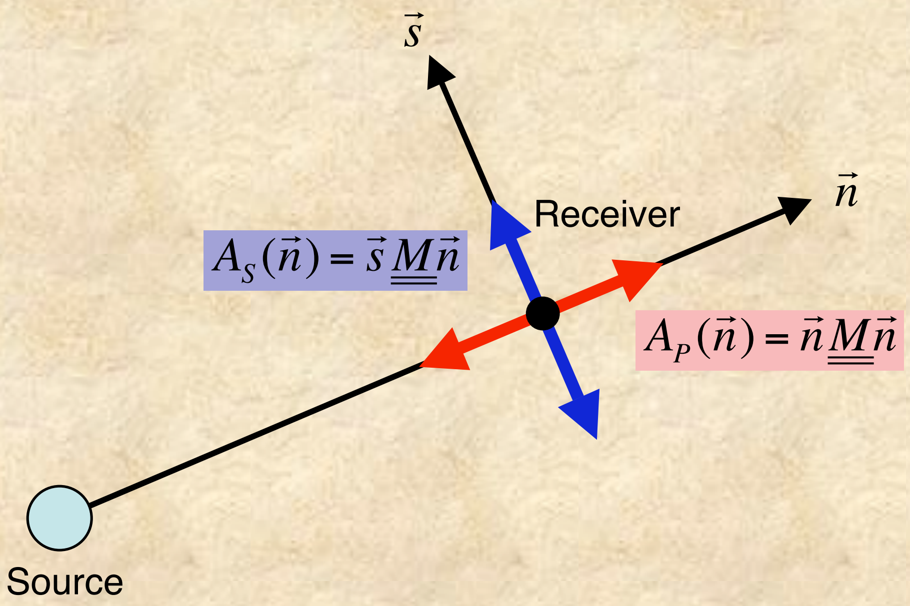


Stations   (octogon > 200 events)

Ekstrom et al, PEPI , 2005

GCMT

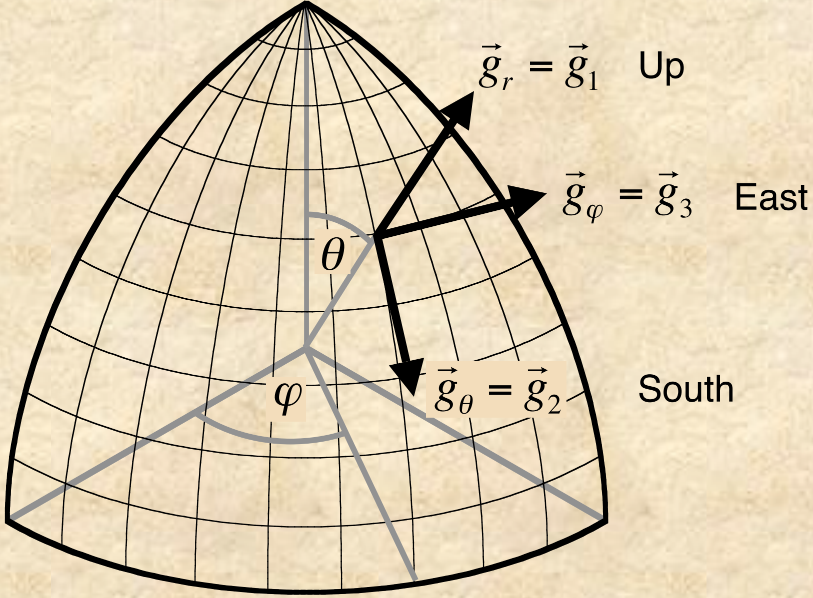
Moment Tensor M



$$A_S(\vec{n}) = \vec{s}\,\underline{\underline{M}}\,\vec{n}$$

$$A_P(\vec{n}) = \vec{n}\,\underline{\underline{M}}\,\vec{n}$$

$$G = (\vec{g}_r, \vec{g}_\theta, \vec{g}_\varphi)$$



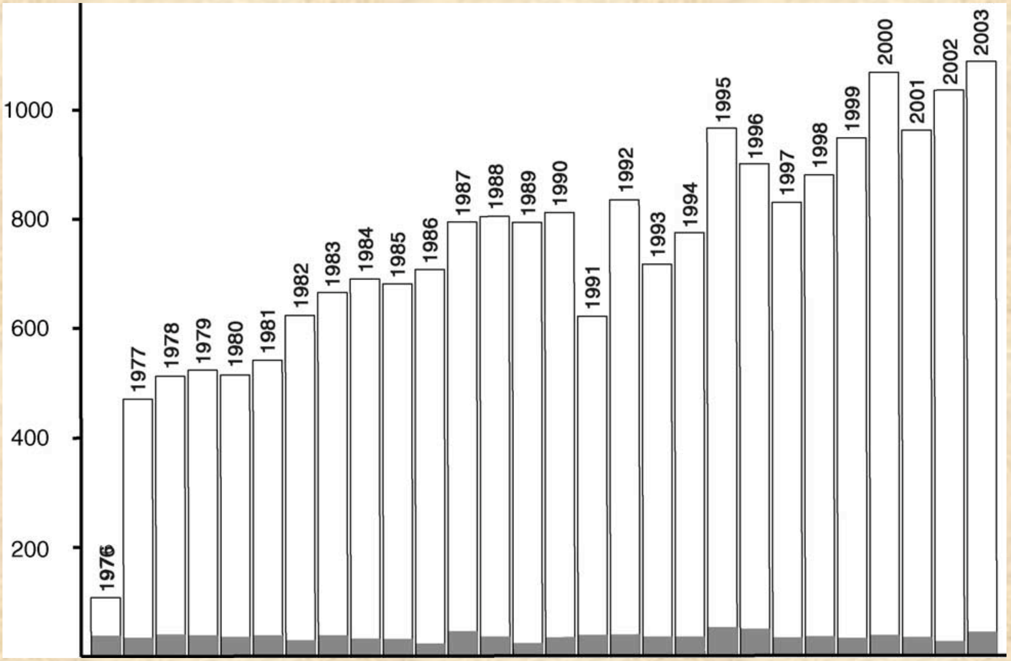
$$M^G = \begin{bmatrix} m_{rr} & m_{rs} & m_{re} \\ m_{rs} & m_{ss} & m_{se} \\ m_{re} & m_{se} & m_{ee} \end{bmatrix}$$

$$M_0 = \frac{1}{\sqrt{2}}\sqrt{\sum_{ij} m_{ij}^2}$$

$$= \mu \Delta \bar{u} S \; (dble\ cple)$$

GCMT Catalog

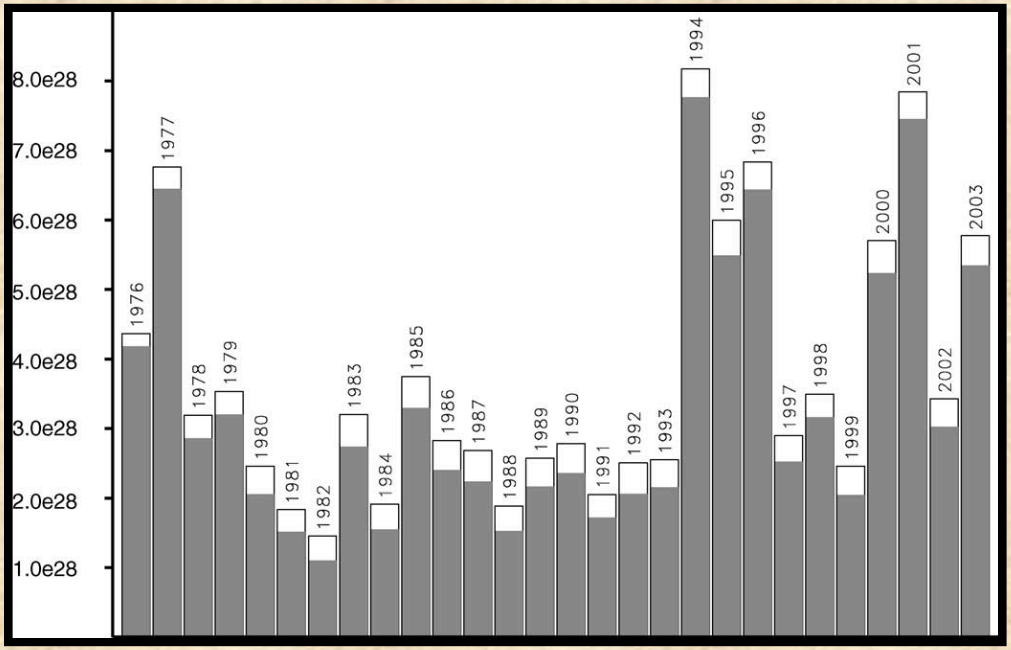
Number of events



Grey => Mw ≥ 6.5

2003: 43 events

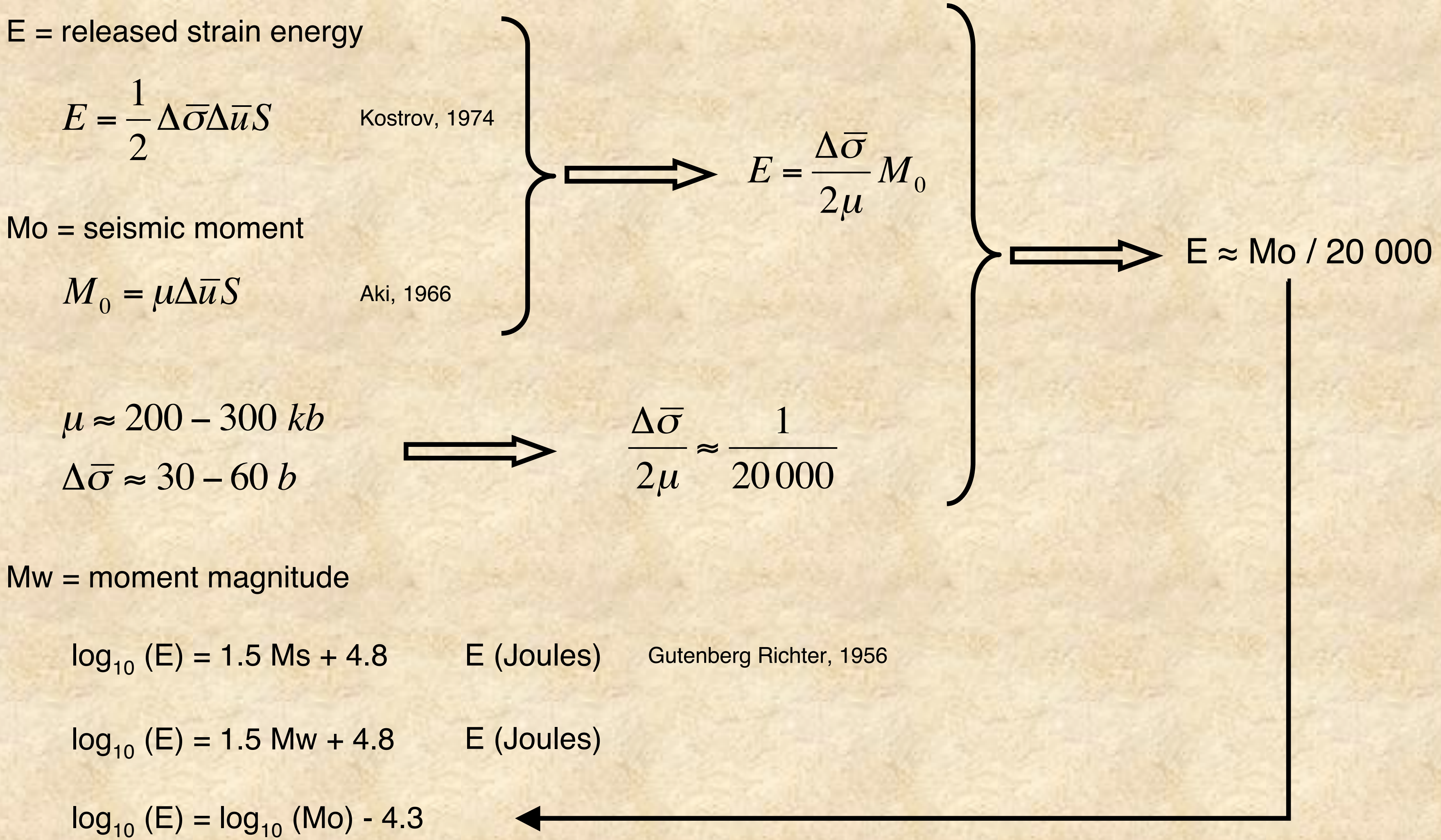
Mo (dyne.cm)



Ekstrom et al, PEPI , 2005

Relate M_0 to E and M_w

Kanamori, JGR, 1977



E = released strain energy

$$E = \frac{1}{2}\Delta\overline{\sigma}\Delta\overline{u}S$$ Kostrov, 1974

Mo = seismic moment

$$M_0 = \mu\Delta\overline{u}S$$ Aki, 1966

$$\Longrightarrow E = \frac{\Delta\overline{\sigma}}{2\mu}M_0$$

$$\mu \approx 200 - 300\ kb$$

$$\Delta\overline{\sigma} \approx 30 - 60\ b$$

$$\Longrightarrow \frac{\Delta\overline{\sigma}}{2\mu} \approx \frac{1}{20\,000}$$

$\Longrightarrow$ E ≈ Mo / 20 000

Mw = moment magnitude

$\log_{10}$ (E) = 1.5 Ms + 4.8 E (Joules) Gutenberg Richter, 1956

$\log_{10}$ (E) = 1.5 Mw + 4.8 E (Joules)

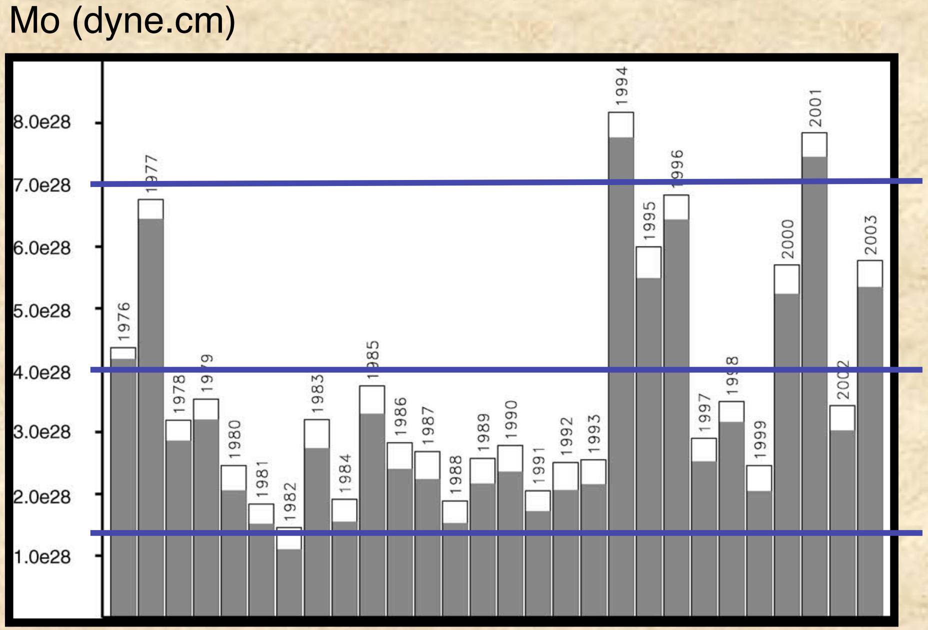
$\log_{10}$ (E) = $\log_{10}$ (Mo) - 4.3

Mw = 2/3 $\log_{10}$ (Mo) - 6.1 Mo (N m)

GCMT

Relate M_0 to E and M_w

erg = dyne cm
Joule = Newton m
1 erg = 10^{-7} Joule



Ekstrom et al, PEPI , 2005

— Mo = 4 10^{29} Mw = 9

5 x (Mw = 8)

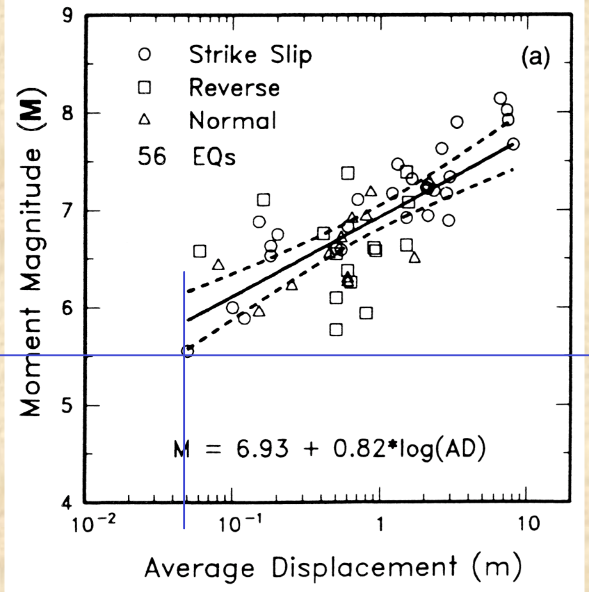
∑Mo ≈ 4 10^{28} dyne cm = 4 10^{21} N m
∑E ≈ ∑Mo/20000 = 2 10^{17} Joules
≈ 8 nuclear power plants (2003: 43 events Mw ≥ 6.5)

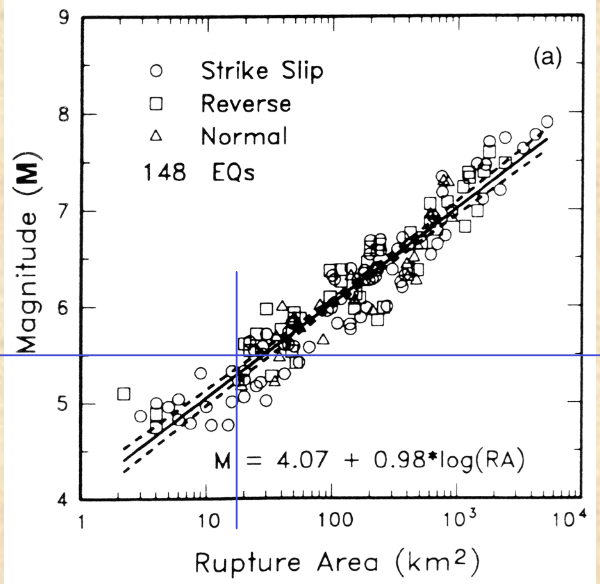
Mo = 1.4 10^{28} Mw = 8

800 MW nuclear power plant one year production:
1 year = 3.15 10^7 s
E ≈ 8 10^8 x 3.15 10^7 = 2.5 10^{16} J

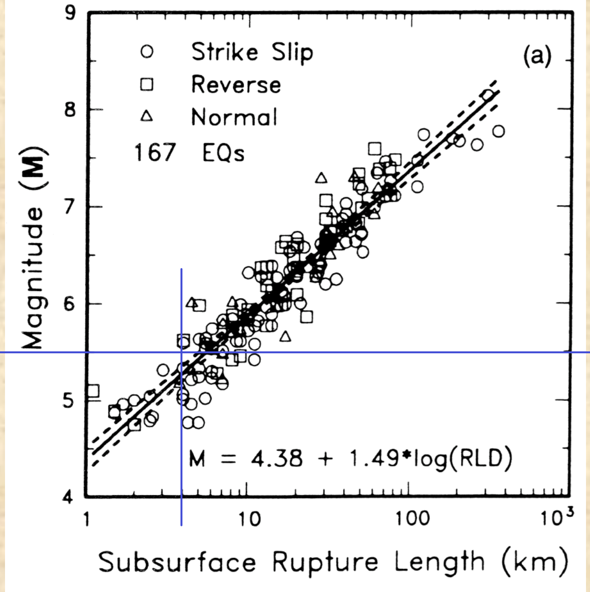
GCMT

Threshold





Wells & Coppersmith, BSSA, 1994



GCMT catalog is complete for
Mw ≥ 5.5

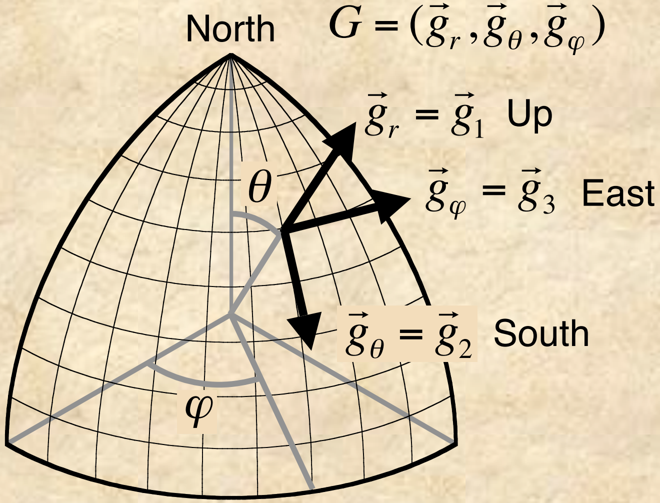
Δu ≥ 5 cm
L ≥ 4 km
A ≥ 20 km^2

Quality selection

Frohlich & Davis, JGR, 1999

- Full or partial inversion ? (nfree)
- Error range (Erel)
- Double couple or not ? (fclvd)

Full or partial inversion ? (nfree)

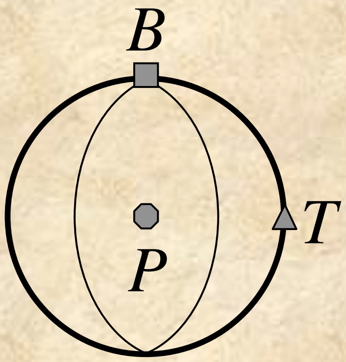


$$M^G = \begin{bmatrix} m_{rr} & m_{rs} & m_{re} \\ m_{rs} & m_{ss} & m_{se} \\ m_{re} & m_{se} & m_{ee} \end{bmatrix}$$

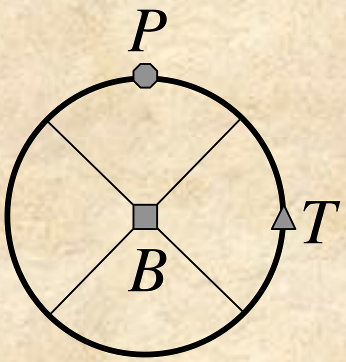
Shallow earthquakes (depth < 30 km)
m_{rs} & m_{re} poorly constrained => set to 0

$$M^G = \begin{bmatrix} m_{rr} & 0 & 0 \\ 0 & m_{ss} & m_{se} \\ 0 & m_{se} & m_{ee} \end{bmatrix}$$

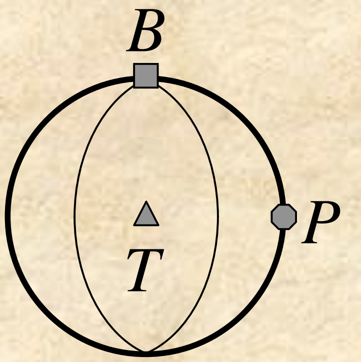
=> 1 vertical, 2 horizontal principal axes



Pure normal
Rake = -90°
Dip = 45°



Pure strike-slip
Rake = 0°or 180°
Dip = 90°

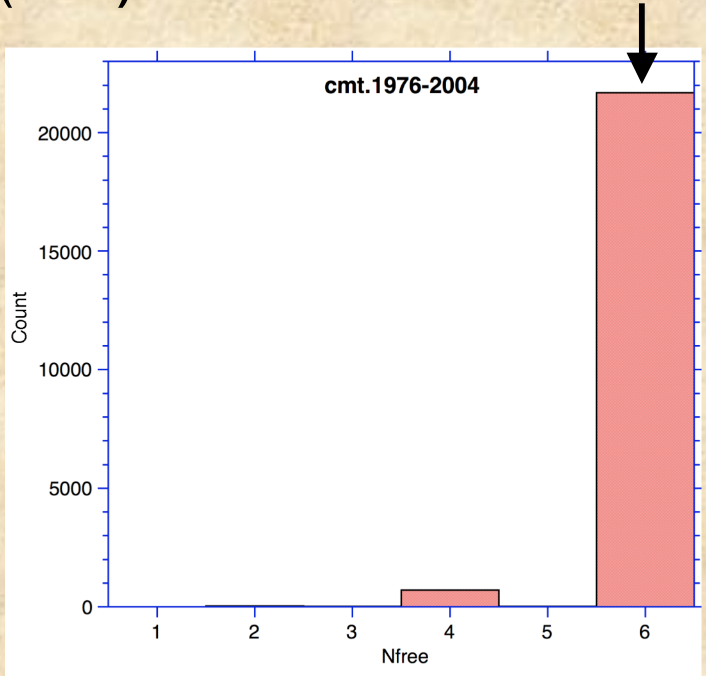


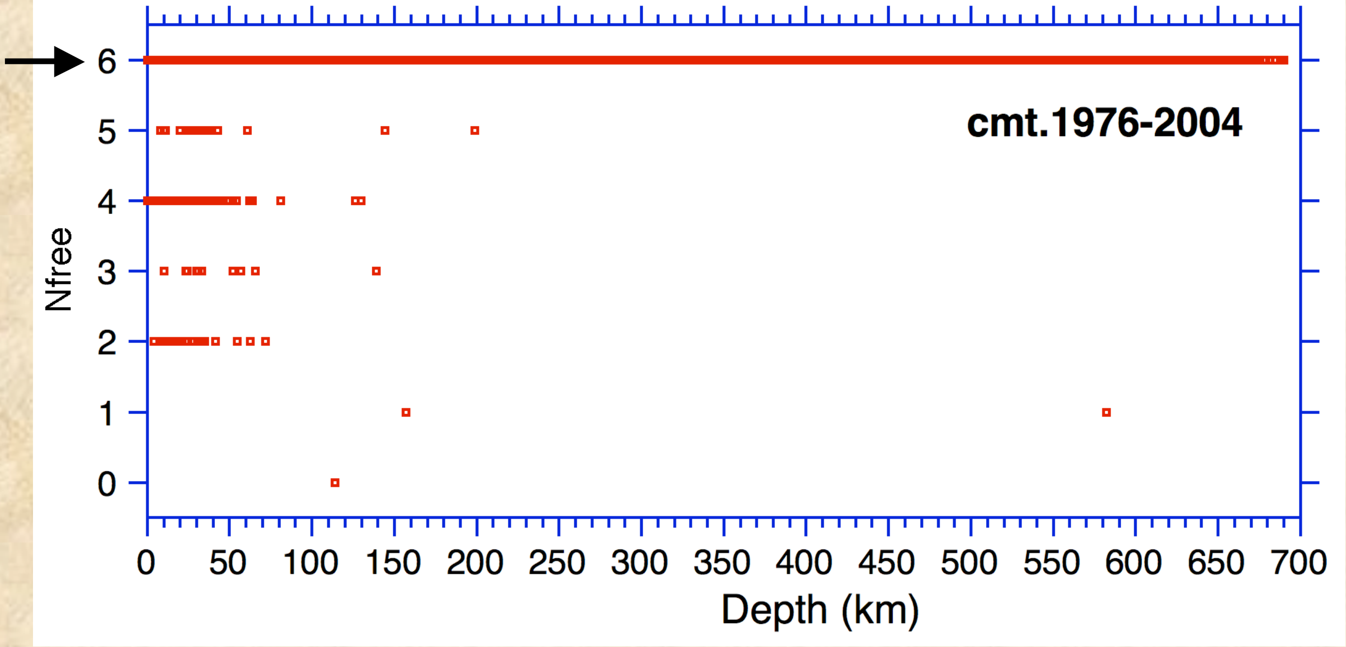
Pure reverse
Rake = +90°
Dip = 45°

Selection

Full or partial inversion ? (nfree)

Define
nfree = number of components really inverted for
Retain only
nfree = 6 Frohlich & Davis, JGR, 1999





Selection

$$M^G = \begin{bmatrix} m_{11} & m_{12} & m_{13} \\ m_{12} & m_{22} & m_{23} \\ m_{13} & m_{32} & m_{33} \end{bmatrix}$$

$$DM^G = \begin{bmatrix} dm_{11} & dm_{12} & dm_{13} \\ dm_{12} & dm_{22} & dm_{23} \\ dm_{13} & dm_{32} & dm_{33} \end{bmatrix}$$

Error range (Erel)

Define relative error:

$$\|M\| = \sqrt{\sum_{i=1}^{3}\sum_{j=1}^{3} m_{ij}^2}$$

$$\|DM\| = \sqrt{\sum_{i=1}^{3}\sum_{j=1}^{3} dm_{ij}^2}$$

$$E_{rel} = \frac{\|DM\|}{\|M\|}$$

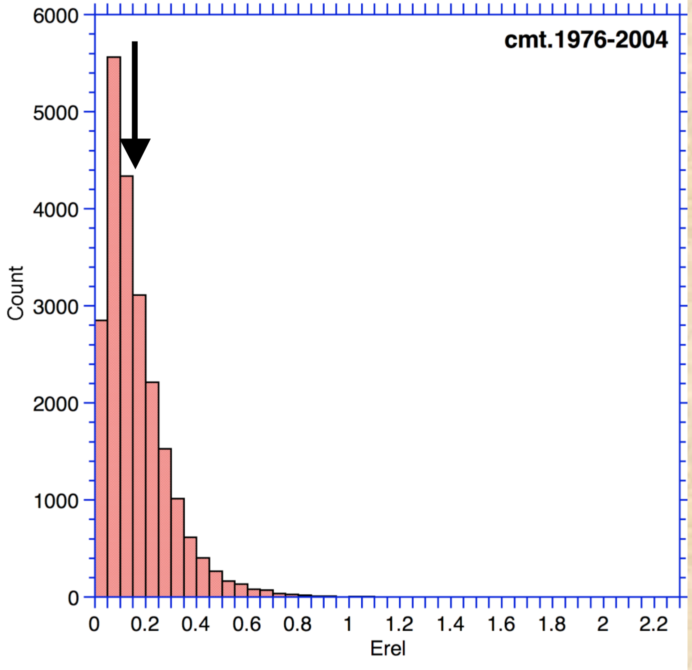
$$E_{rel} \leq 15\%$$

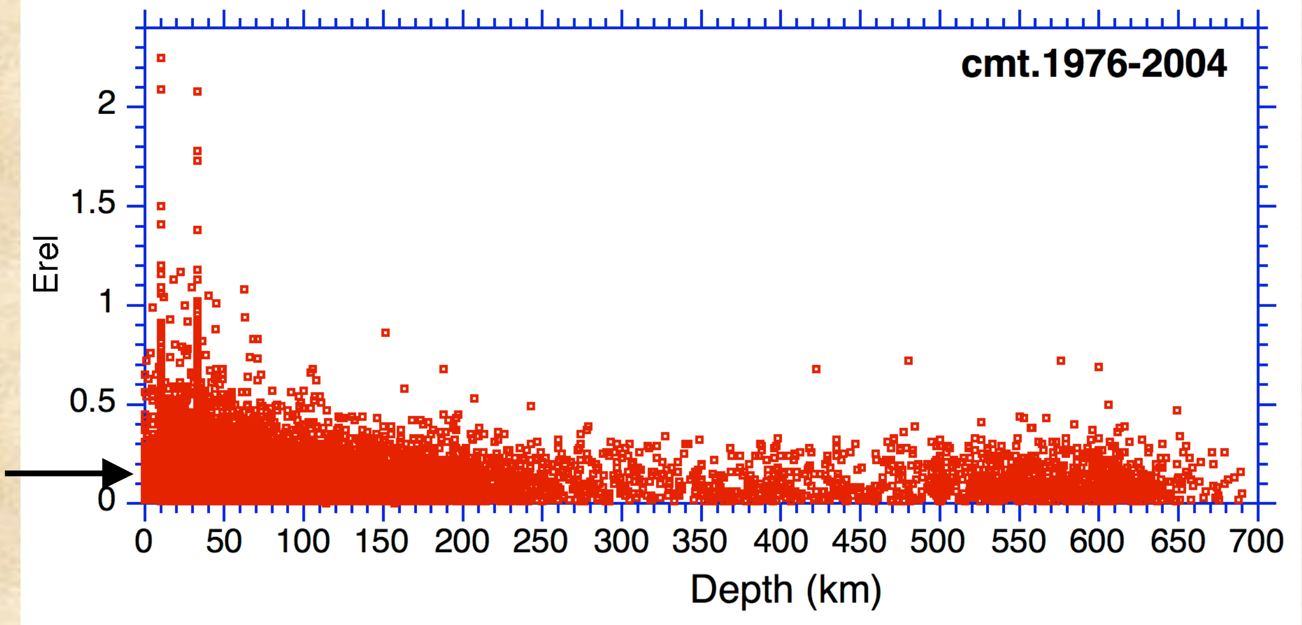
Frohlich & Davis, JGR, 1999

Selection

Error range (Erel)

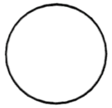
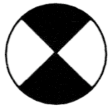
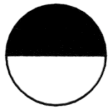
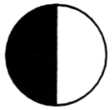
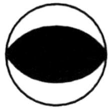
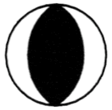
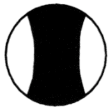
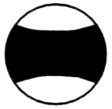
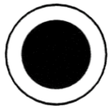
$E_{rel} \leq 15\%$ Frohlich & Davis, JGR, 1999





Selection

Double couple or not ? (fclvd)

Moment tensor	Beachball	Moment tensor	Beachball
$\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$		$-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$-\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&-1\\0&0&0\\-1&0&0\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&-1\\0&-1&0\end{pmatrix}$	
$\frac{1}{\sqrt{2}}\begin{pmatrix}-1&0&0\\0&0&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&-1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$		$\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$	
$\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$		$-\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$	

Explosion
Implosion

Double
Couple

CLVD

Stein & Wysession, Textbook, 2003

Selection

Double couple or not ? (fclvd)

Eigenvectors frame $A = (\vec{a}_1, \vec{a}_2, \vec{a}_3)$

$$M^A = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix}$$

$$|m_1| \geq |m_2| >> |m_3|$$

$$m_1 + m_2 + m_3 = 0$$

Decomposition into
- Double couple
- CLVD = Compensated Linear Vector Dipole

$$m_B = m_3$$

2 cases:

$$M^A = \begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{bmatrix} = m_1(1-2F)\underbrace{\begin{bmatrix} +1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{bmatrix}}_{\text{Double couple}} + m_1 F \underbrace{\begin{bmatrix} 2 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}}_{\text{CLVD}}$$

$$m_1 \geq 0:$$

$$m_P = m_2$$

$$m_T = m_1$$

$$A = (T, P, B)$$

$$F = -\frac{m_3}{m_1}$$

F = 0 => Pure double couple
F = 0.5 => Pure CLVD

$$m_1 \leq 0:$$

$$m_P = m_1$$

$$m_T = m_2$$

$$A = (P, T, B)$$

$$f_{clvd} = -\frac{m_B}{\max(|m_P|, |m_T|)}$$

$f_{clvd} = 0$	Pure double couple
$\lvert f_{clvd} \rvert = 0.5$	Pure CLVD
$\lvert f_{clvd} \rvert \leq 0.2$	Quality threshold

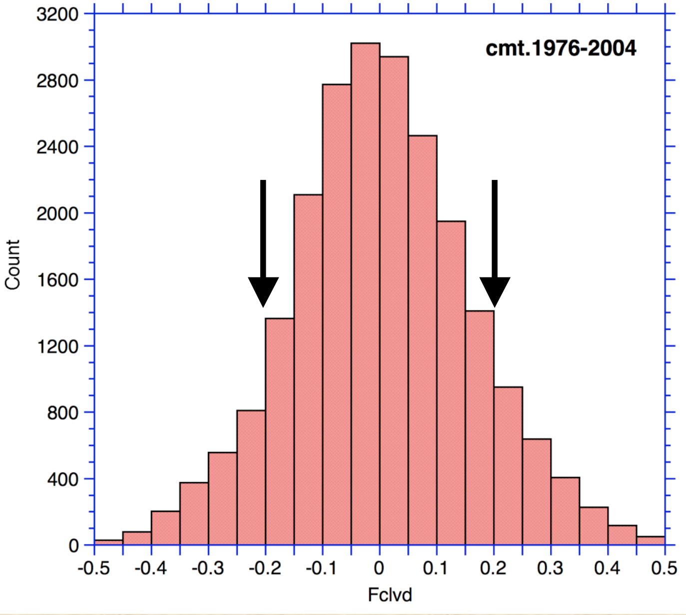
Frohlich & Davis, JGR, 1999

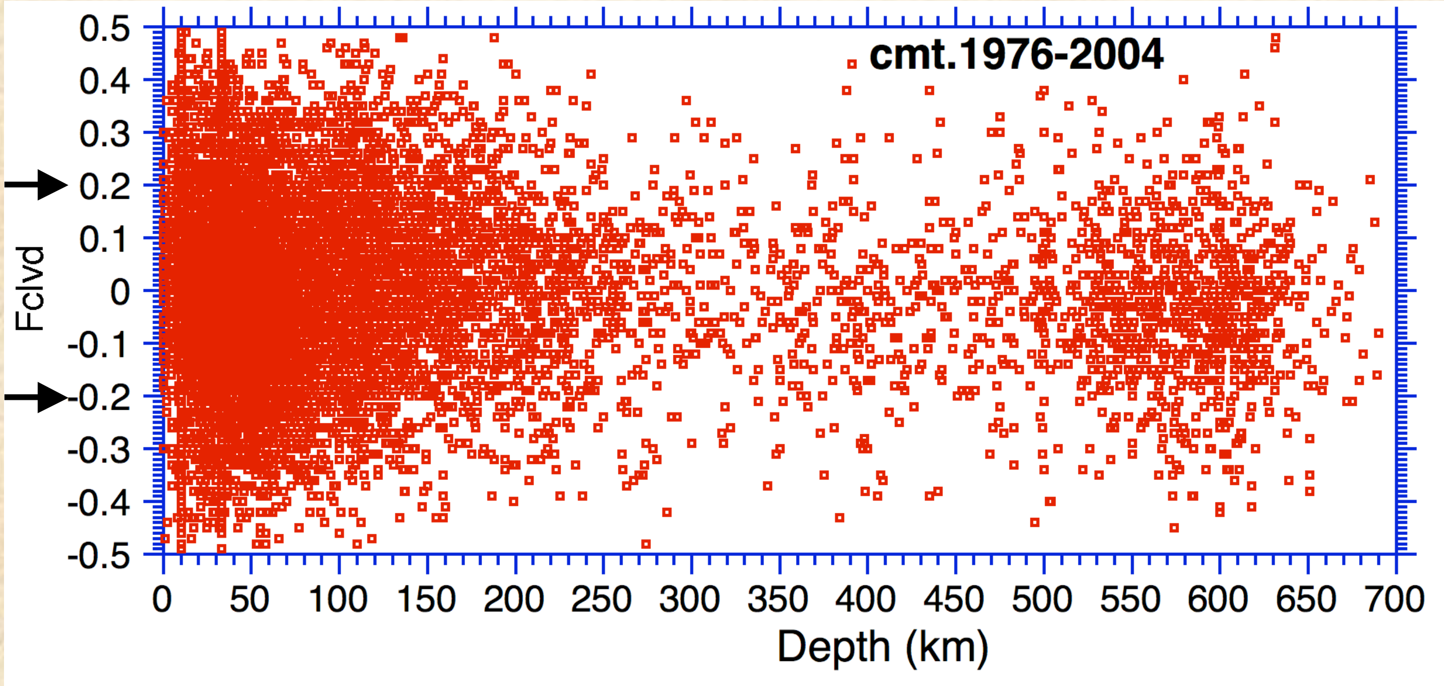
Selection

Double couple or not ? (fclvd)

$$f_{clvd} = -\frac{m_B}{\max(|m_P|,|m_T|)}$$

$$|f_{clvd}| \leq 0.2$$





Summary

Parameter	**Quality threshold**
nfree = inverted components	nfree = 6
$E_{rel} = \frac{\lVert DM \rVert}{\lVert M \rVert}$	$E_{rel} \leq 15\%$
$f_{clvd} = -\frac{m_B}{\max(\lvert m_P \rvert, \lvert m_T \rvert)}$	$\lvert f_{clvd} \rvert \leq 0.2$

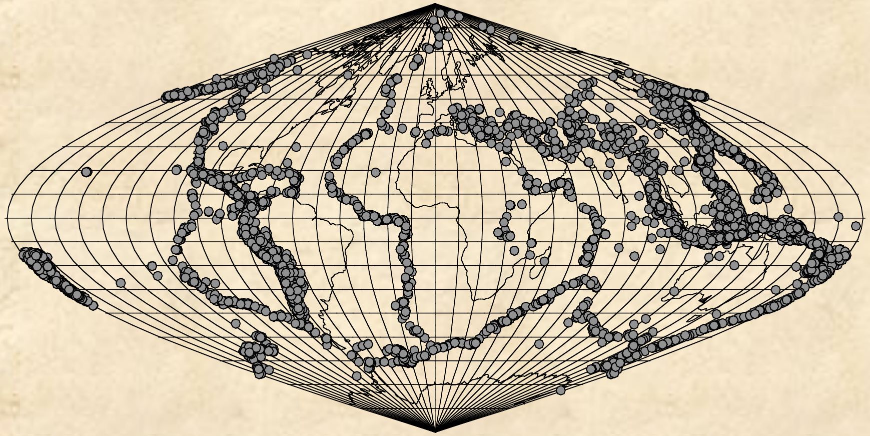
= > Angular uncertainties: 5-10°

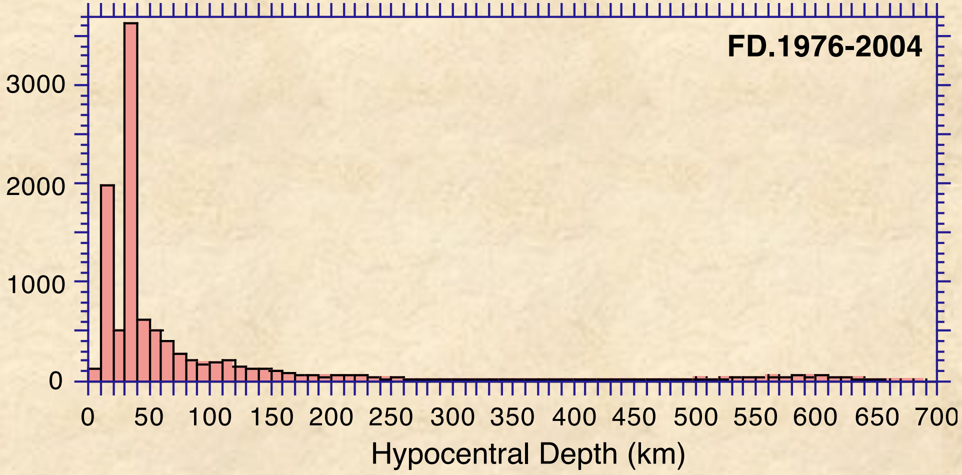
Frohlich & Davis, JGR, 1999

Results

FD 0-700 km 1976-2004

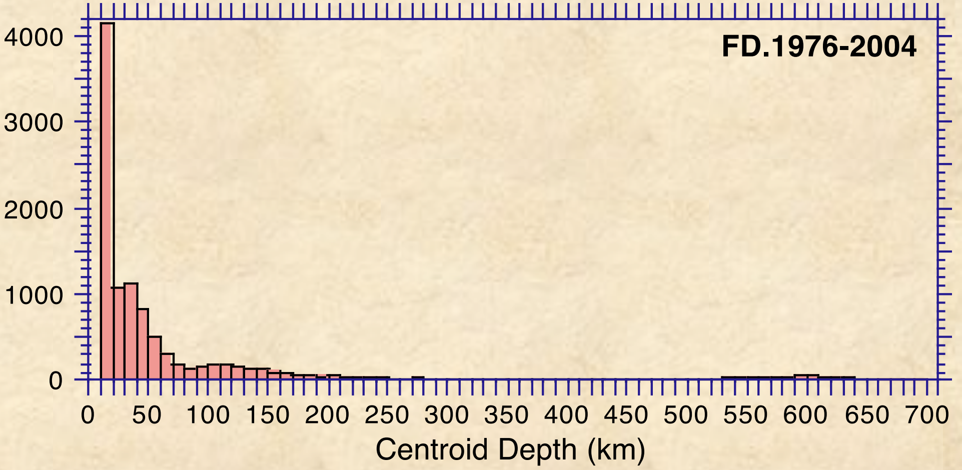
N = 10709





Hypocenter depth (km)	CMT	FD (selection)	
[0,30]	6355	2685	42%
] 30,40]	8018	3619	45%
] 40,300]	6798	3609	53%
] 300,700]	1306	796	61%
[0,700]	22477	10709	48%

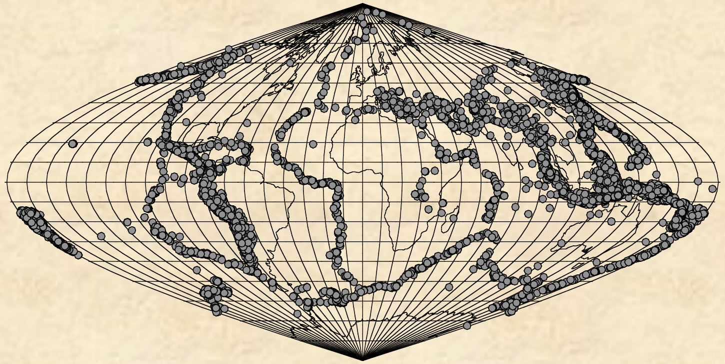
1976-2004

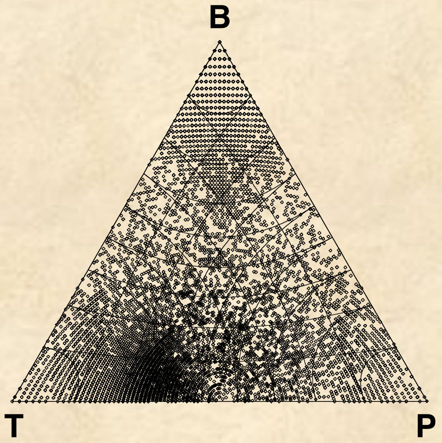


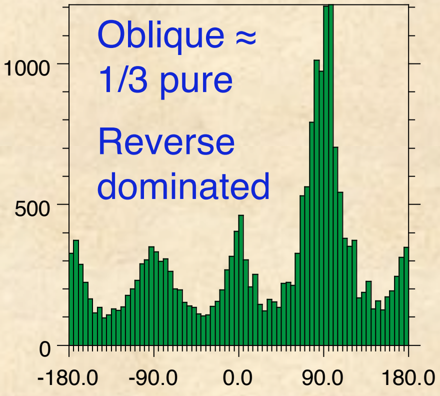
Results

FD 0-700 km 1976-2004

N = 10709

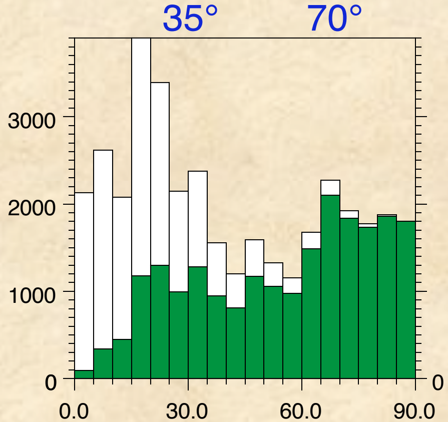


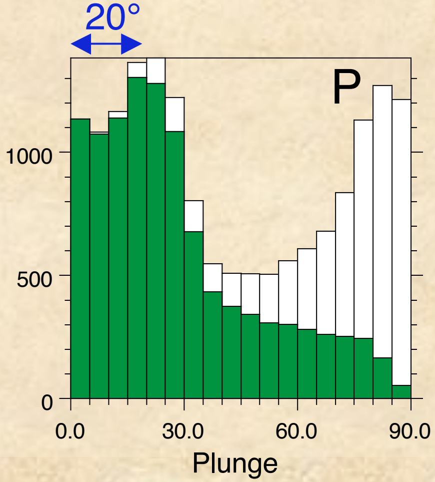


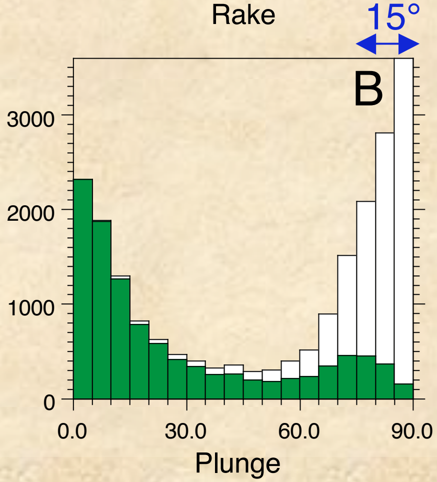


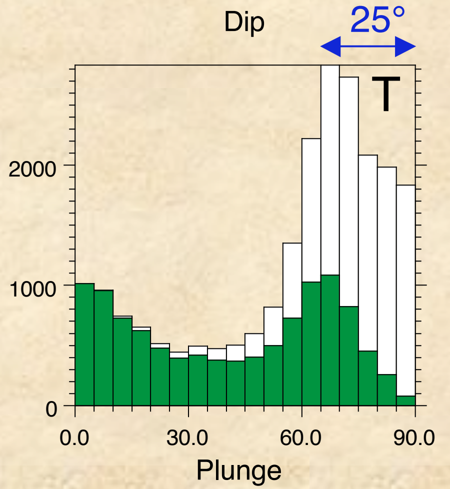
Oblique ≈ 1/3 pure

Reverse dominated





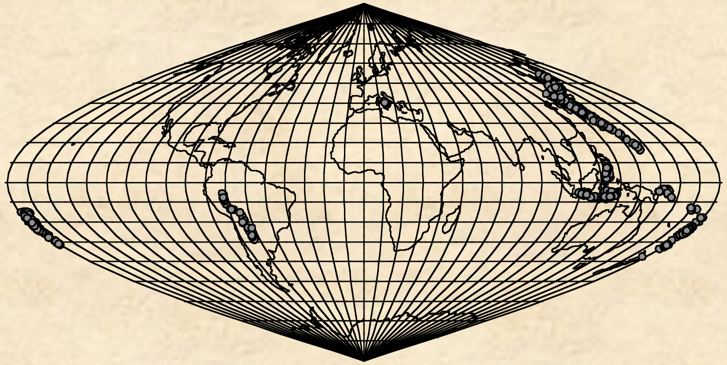


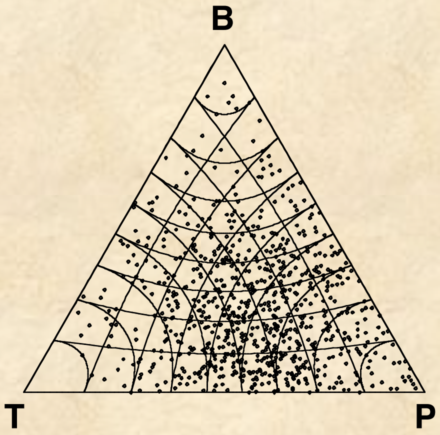


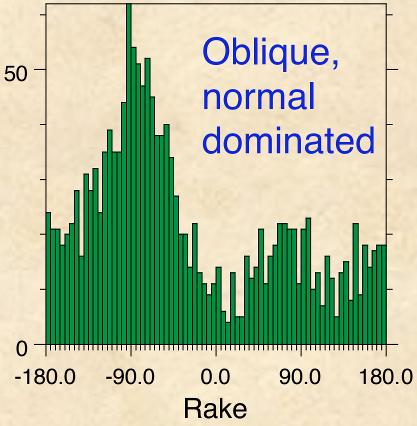
Results

FD 300-700 km

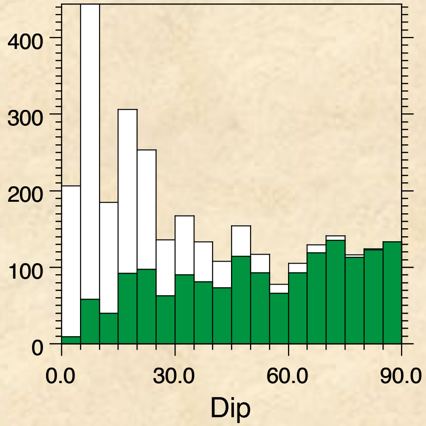
N = 796

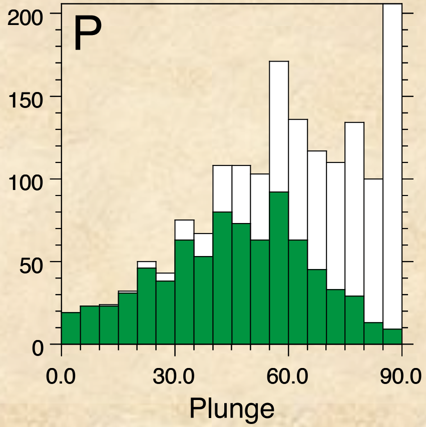


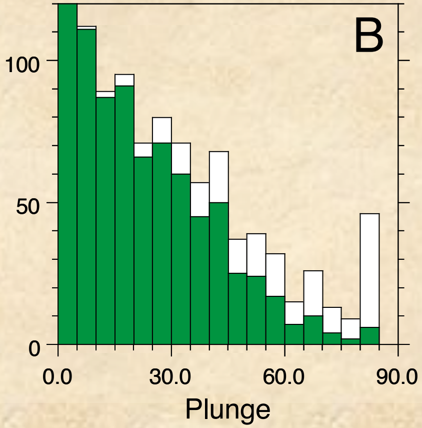


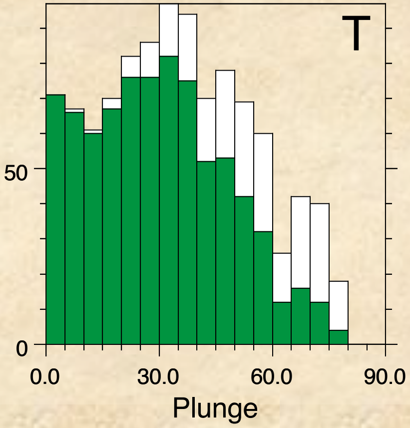


Oblique, normal dominated





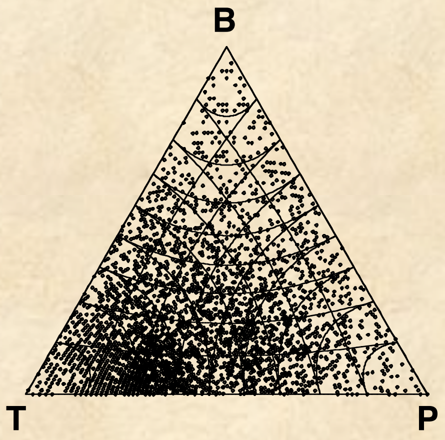


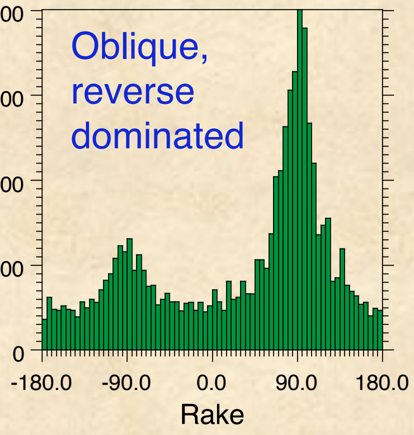


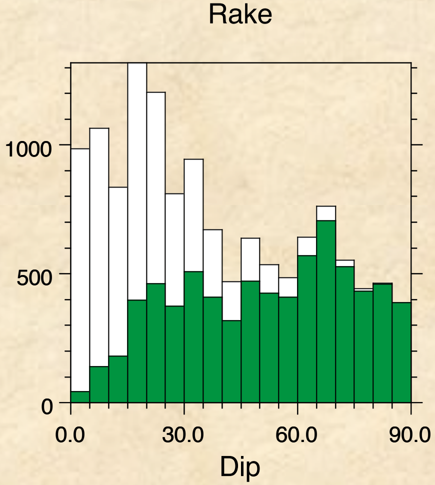
Results

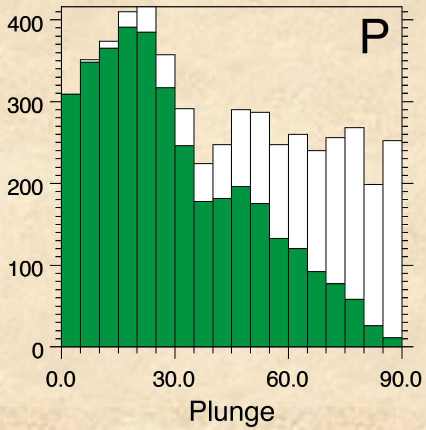
FD 40-300 km

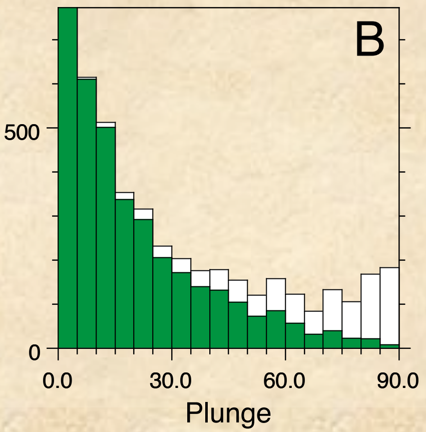
N = 3609

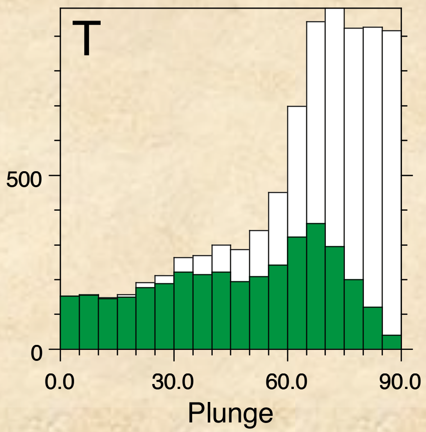



Oblique, reverse dominated





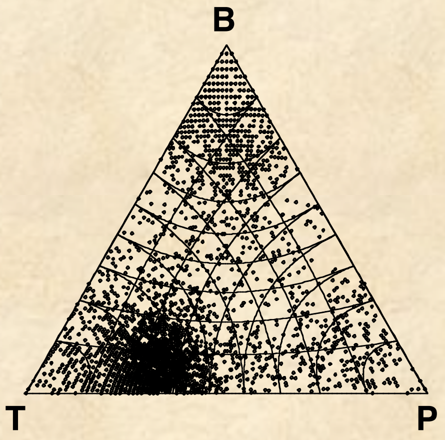


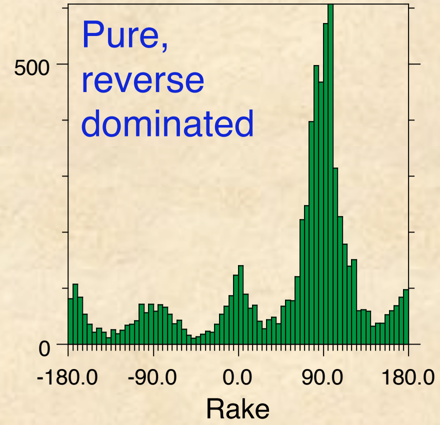


Results

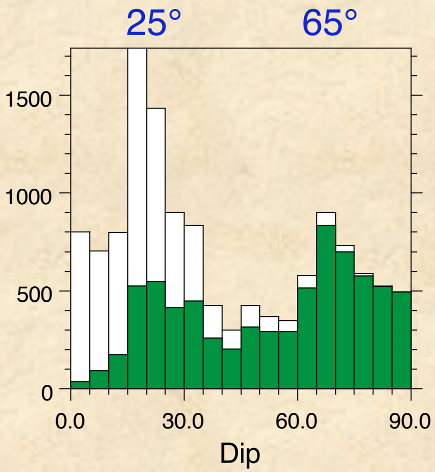
FD 30-40 km

N = 3619



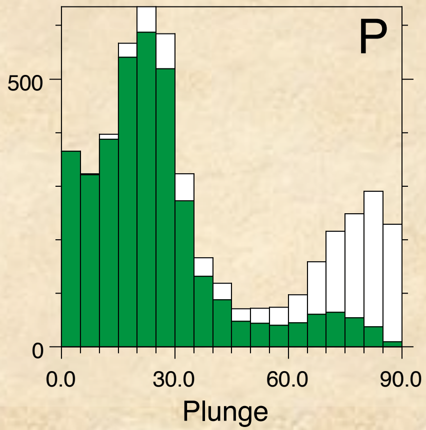


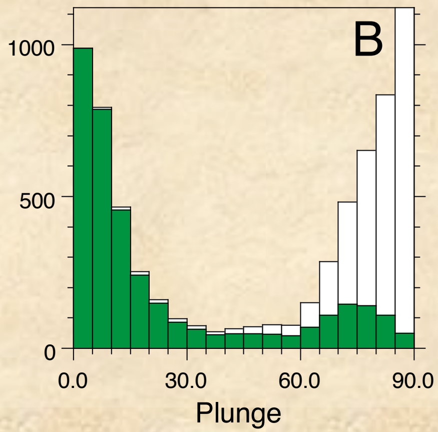
Pure, reverse dominated

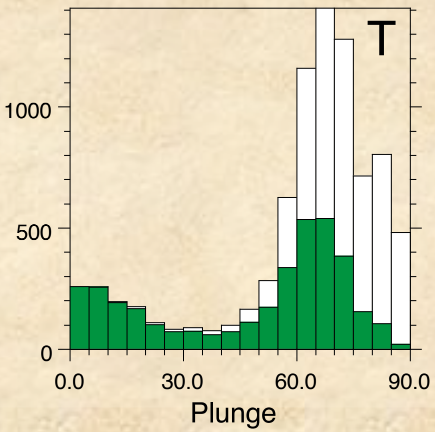


25°

65°



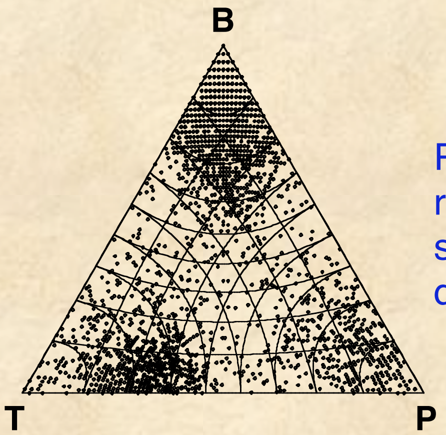




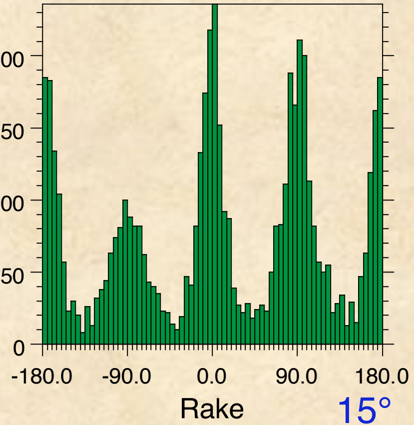
Results

FD 0-30 km

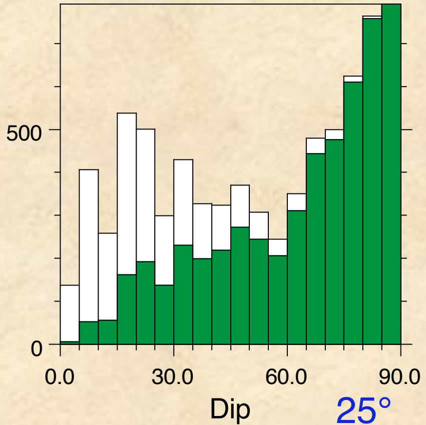
N = 2685



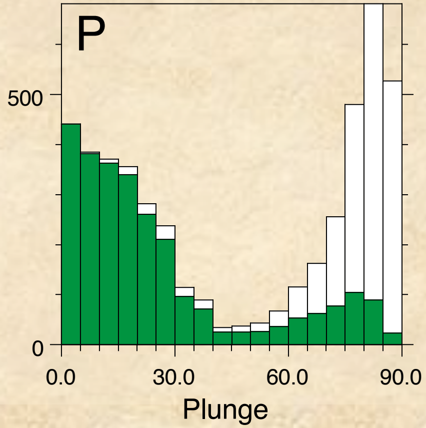
Pure,
reverse +
strike-slip
dominated



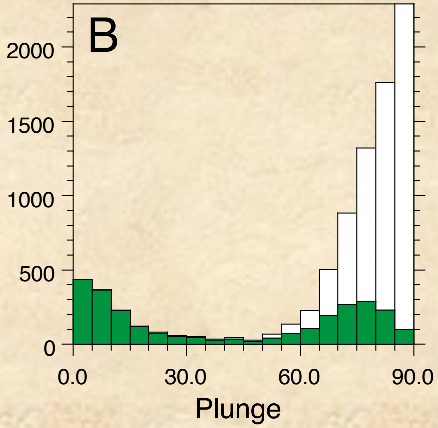
? ? 90°



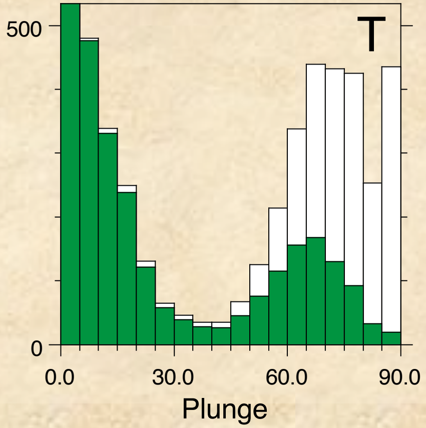
15°



15°



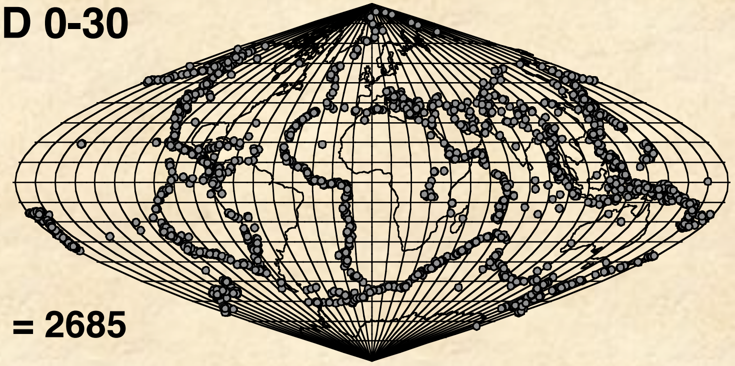
25°



Results

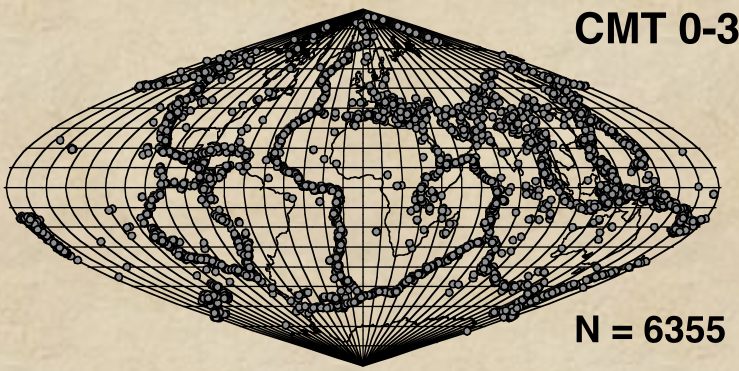
FD versus CMT 0-30 km

FD 0-30

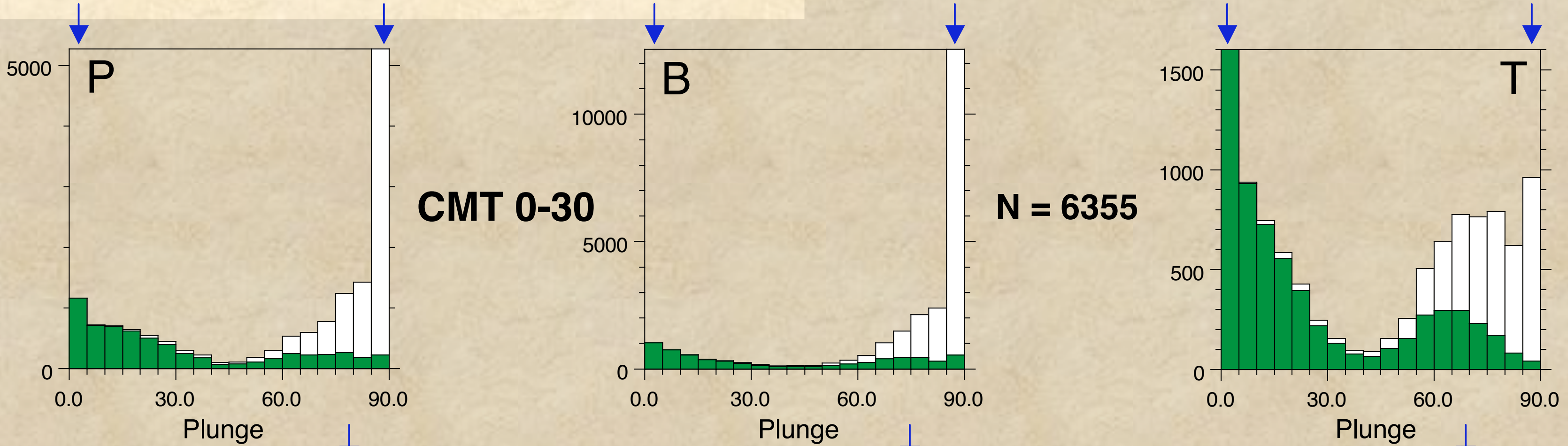


N = 2685

CMT 0-30

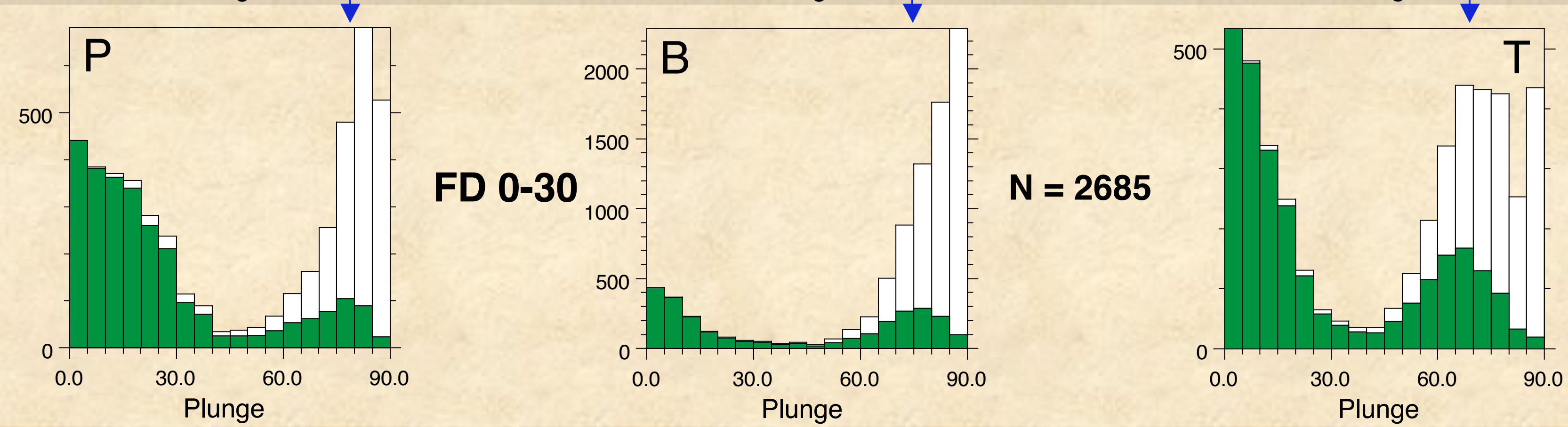


N = 6355



CMT 0-30

N = 6355

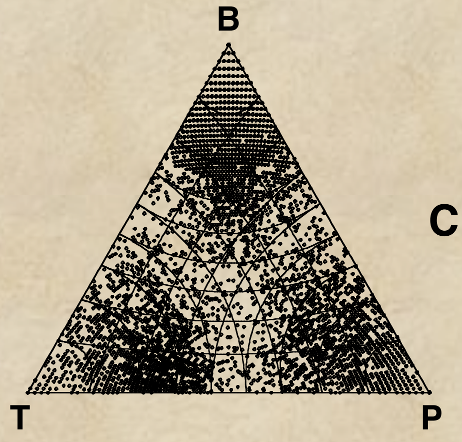


FD 0-30

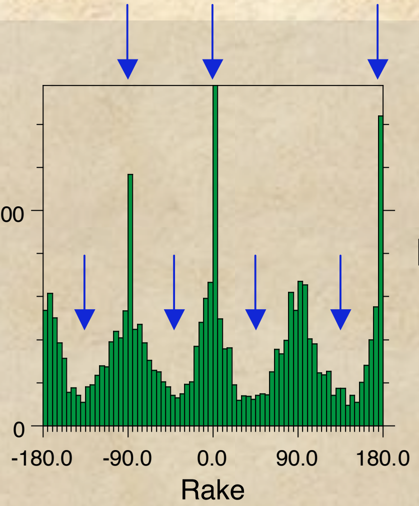
N = 2685

Results

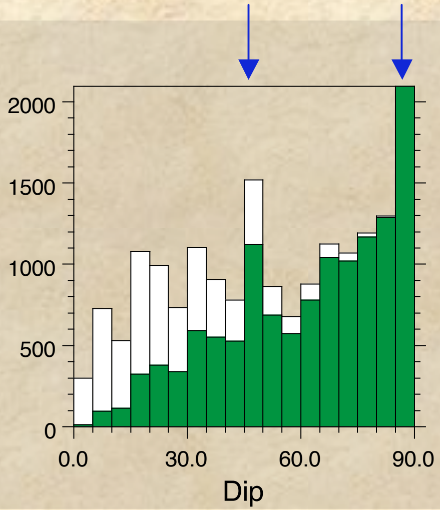
FD versus CMT 0-30 km

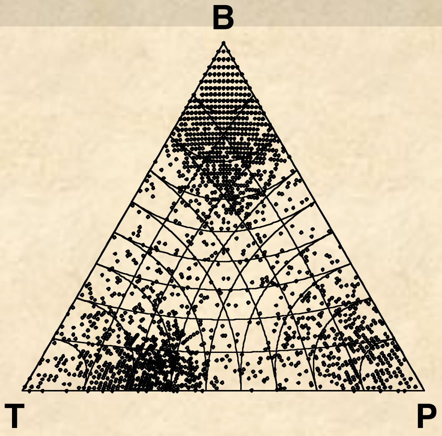


CMT 0-30

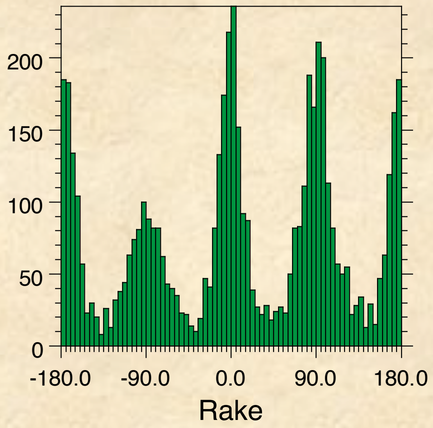


N = 6355

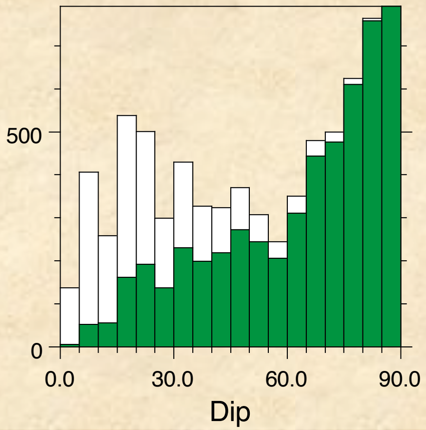




FD 0-30



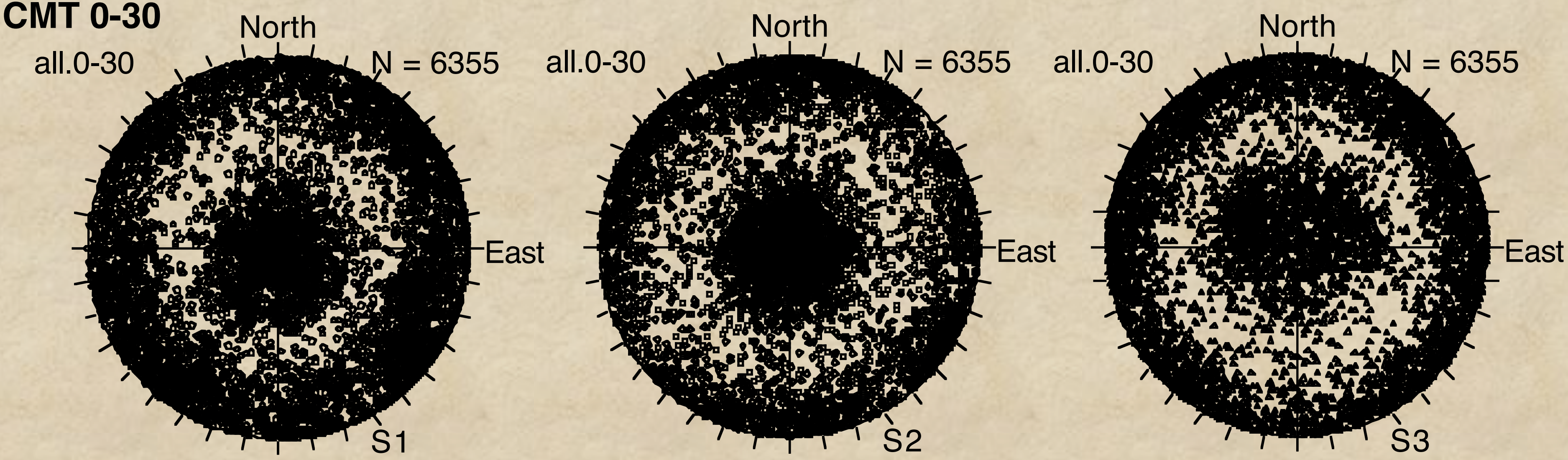
N = 2685



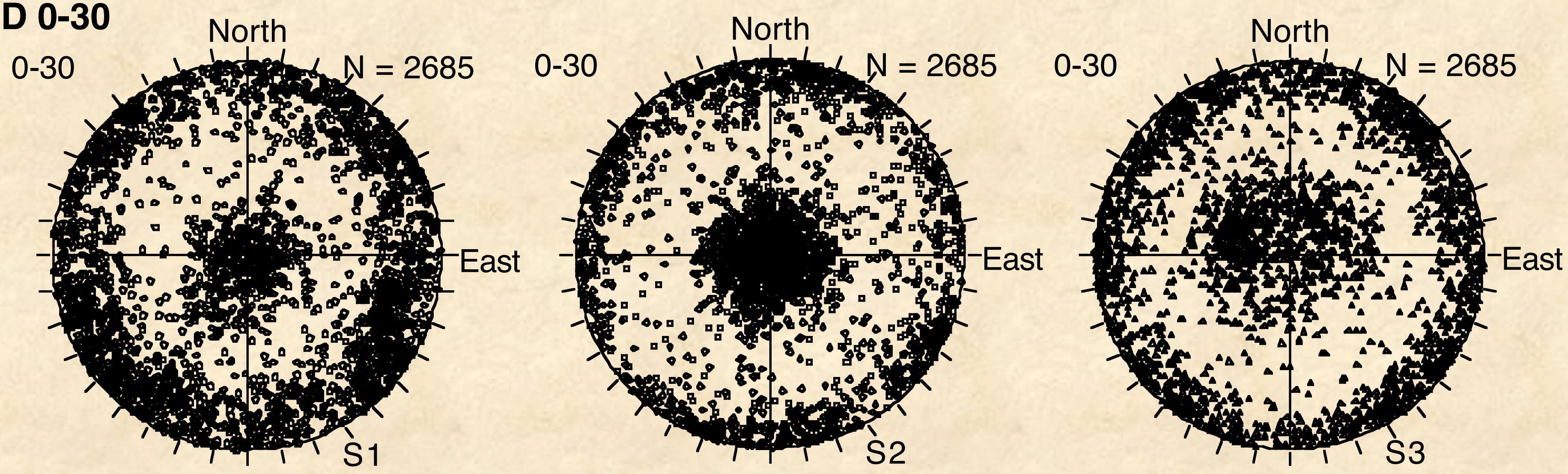
Results

FD versus CMT 0-30 km

CMT 0-30



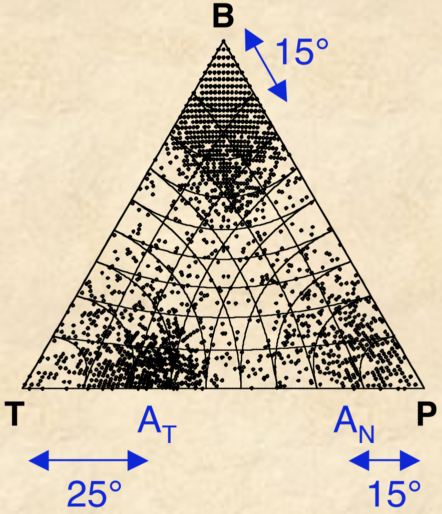
FD 0-30

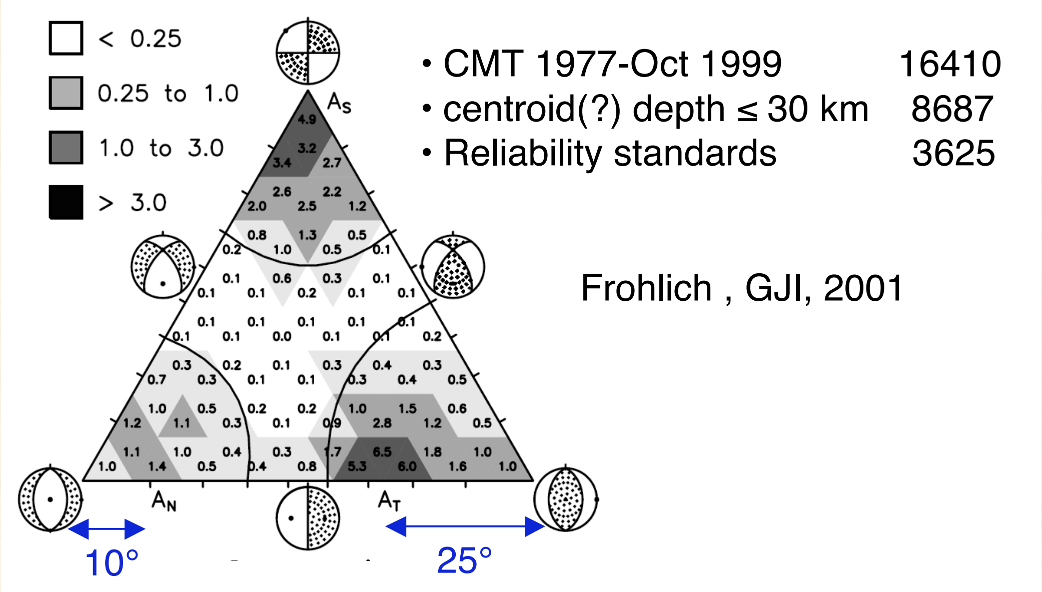


Results

FD 0-30 km versus Frohich (2001)

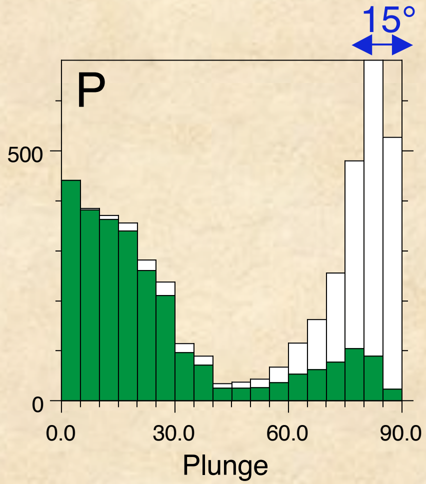
N = 2685

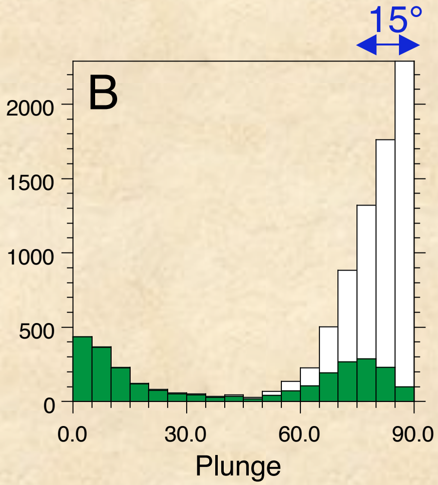


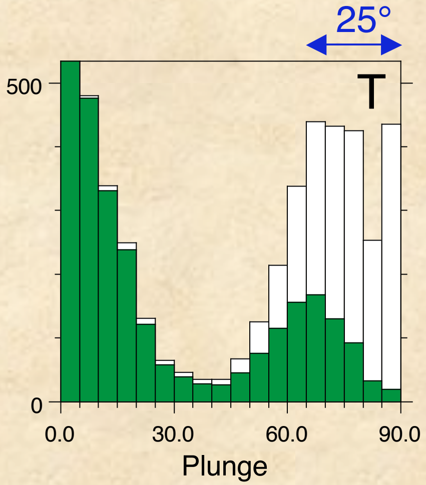


- CMT 1977-Oct 1999 16410
- centroid(?) depth ≤ 30 km 8687
- Reliability standards 3625

Frohlich , GJI, 2001



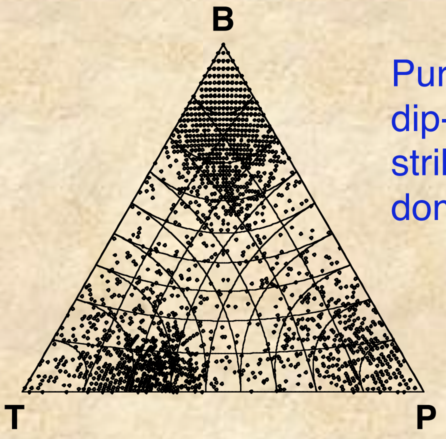




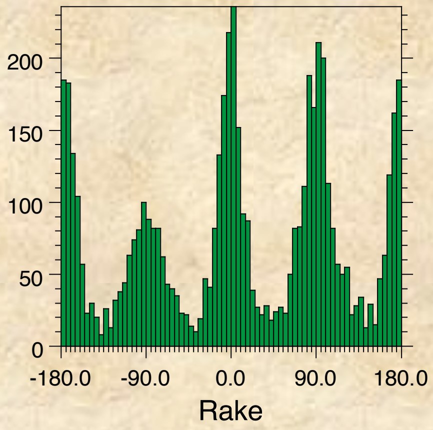
Results

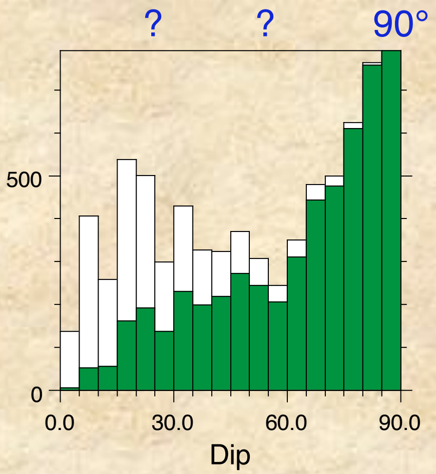
FD 0-30 km

N = 2685



Pure,
dip-slip and
strike-slip
dominated





Rake, P, B, T: consistent with dominant Anderson
Dip: inconclusive for dip-slip, ok for strike slip ?

⇒ Isolate pure strike and dip-slip events
Question: selection on both nodal planes or on one at least ?

Selection

One or two nodal planes: dip slip case

Consider two slightly different mechanisms where

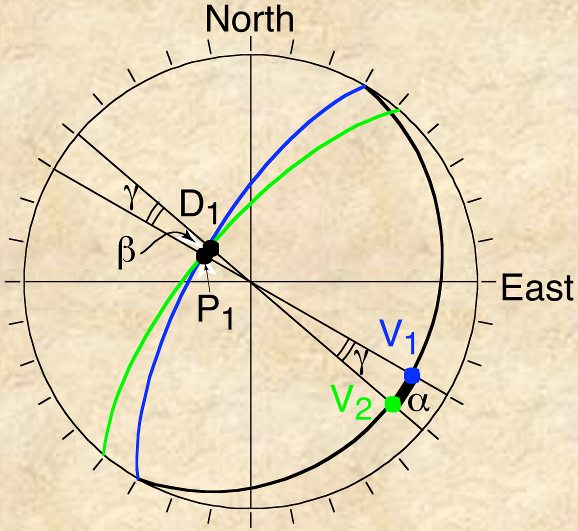
- Case 1: the first nodal plane is pure dip-slip (P1,V1)
- Case 2: the same nodal plane is near dip-slip (P1,V2)

and look at the second nodal plane.

	Nodal planes	
	1st	**2nd**
Pole	P1	V1
Slip	V1	P1
Pole	P1	V2
Slip	V2	P1

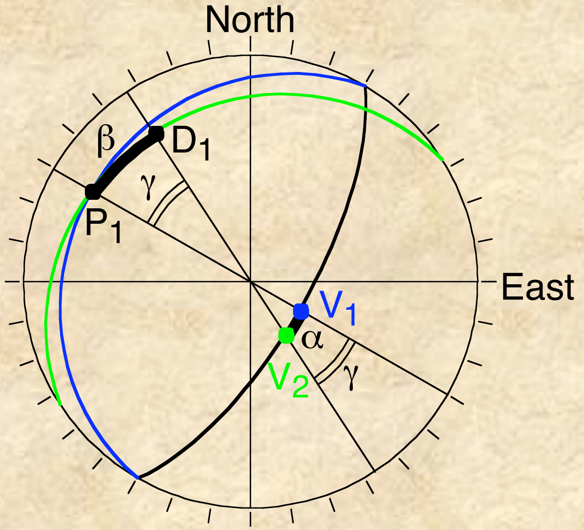
D1: down dip for plane 2, case 2

The first nodal plane has a shallow dip:



- Case 1: the second nodal plane is pure dip-slip
- Case 2: the second nodal plane is near dip-slip

The first nodal plane has a steep dip:



- Case 1: the second nodal plane is pure dip-slip
- Case 2: the second nodal plane has an oblique slip

Selection

One or two nodal planes: strike slip case

	Nodal planes	
	1st	**2nd**
Pole	P1	V1
Slip	V1	P1
Pole	P1	V2
Slip	V2	P1

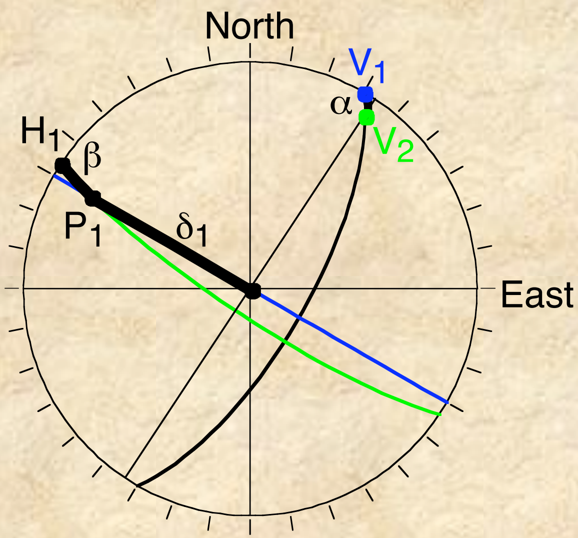
H1: along strike for plane 2, case 2

Consider two slightly different mechanisms where

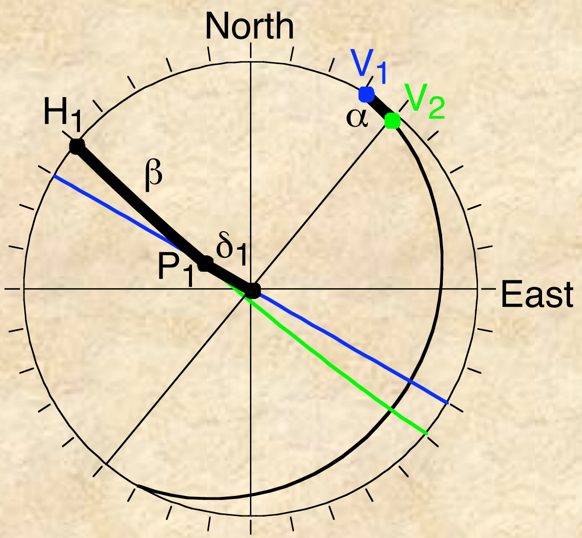
- Case 1: the first nodal plane is pure strike-slip (P1,V1)
- Case 2: the same nodal plane is near strike-slip (P1,V2)

and look at the second nodal plane.

The first nodal plane has a steep dip:



The first nodal plane has a shallow dip:



- Case 1: the second nodal plane is near strike-slip
- Case 2: the second nodal plane is near strike-slip

- Case 1: the second nodal plane is near dip-slip
- Case 2: the second nodal plane is near dip-slip

Selection

One or two nodal planes ?

One near dip-slip nodal plane:

- Steep dip => oblique slip on second nodal plane
- Shallow dip => near dip-slip second plane

One near strike-slip nodal plane:

- Steep dip => near strike-slip second nodal plane
- Shallow dip => oblique slip on second plane

Select near dip-slip or strike-slip rake on at least one nodal plane:

- includes all actual fault planes with that rake
- includes also actual oblique slip fault planes

Select rake on both nodal plane:

- excludes fault planes with that rake
- includes only fault planes with that rake

Conclusions:

- no perfect solution
- investigate both 1 (1P) and 2 planes (2P)

Results

Rake within 10° of pure dip or strike slip

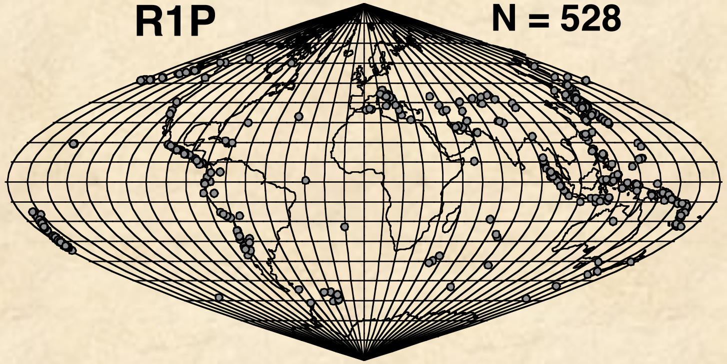
1976-2004 FD 0-30 km

Rake range	**1 or 2 planes ?**	Data set	Number of data
[80,100]	1 plane	R1P	528
[80,100]	2 planes	R2P	267
[-180,-170] U [-10,10] U [170,180]	1 plane	S1P	1130
[-180,-170] U [-10,10] U [170,180]	2 planes	S2P	437
[-100,-80]	1 plane	N1P	217
[-100,-80]	2 planes	N2P	147

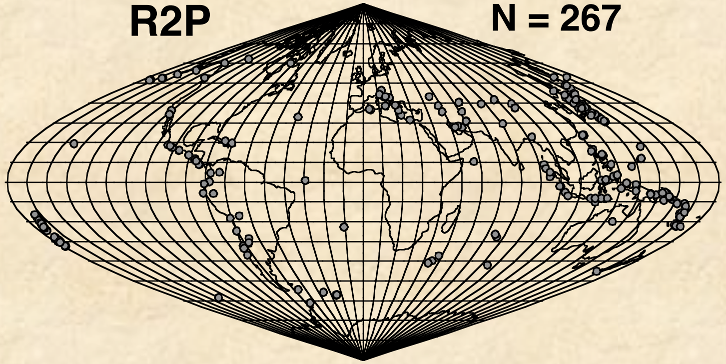
Results

Localisation

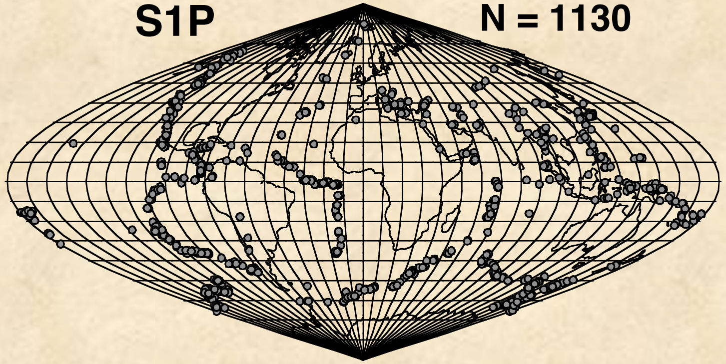
R1P N = 528



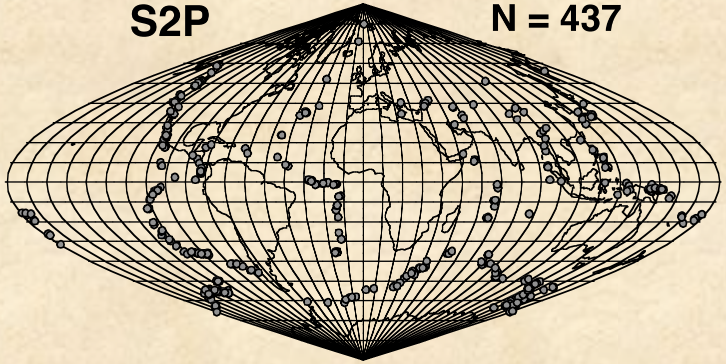
R2P N = 267



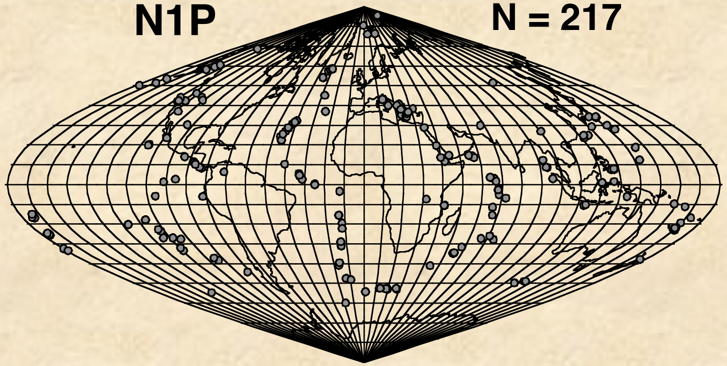
S1P N = 1130



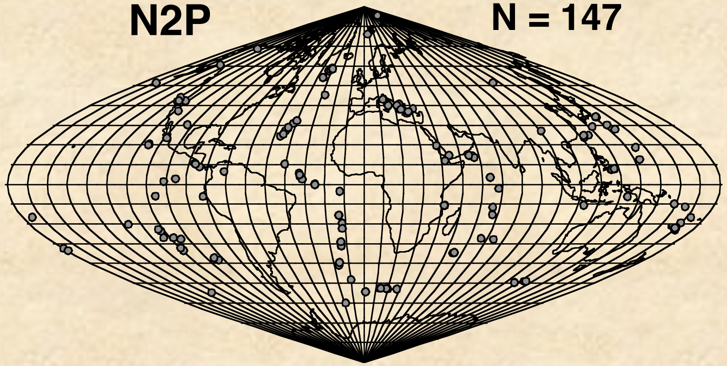
S2P N = 437



N1P N = 217



N2P N = 147



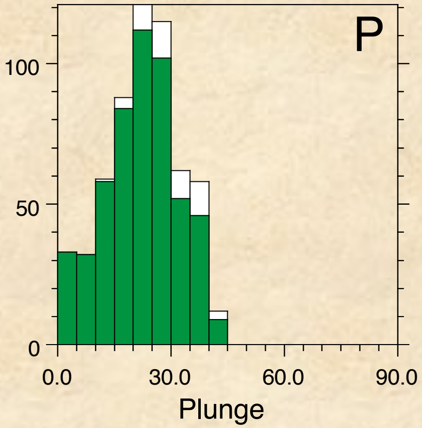
Results

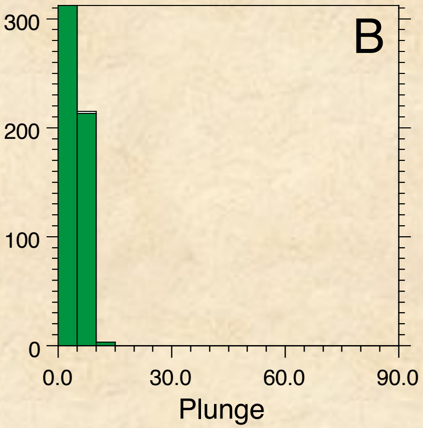
Reverse

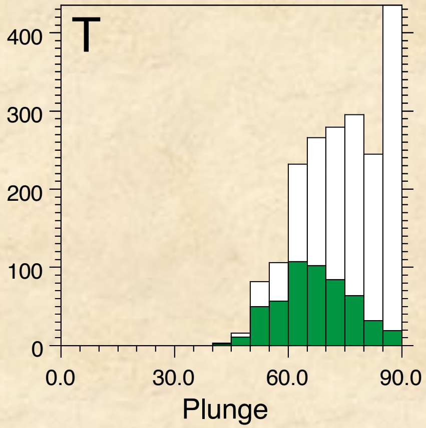
20-30°

60-90°

R1P





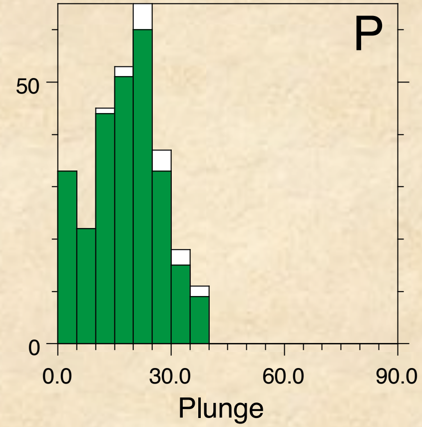


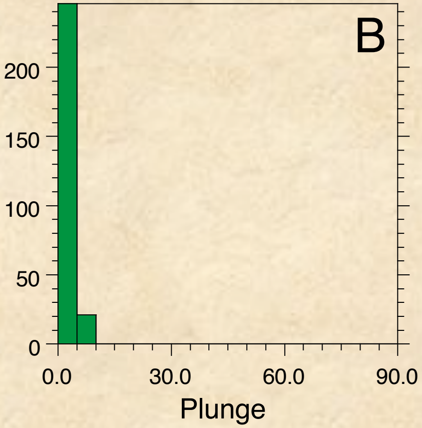
N = 528

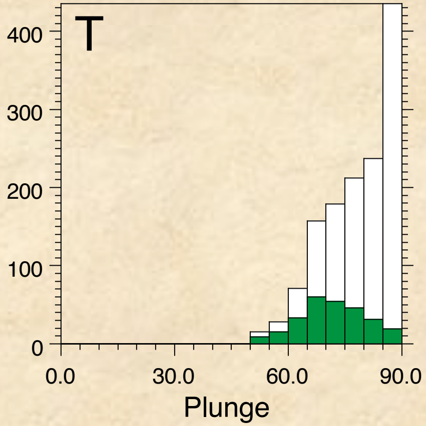
20-25°

65-90°

R2P





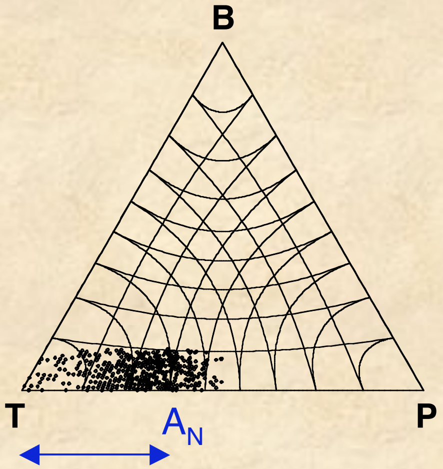


N = 267

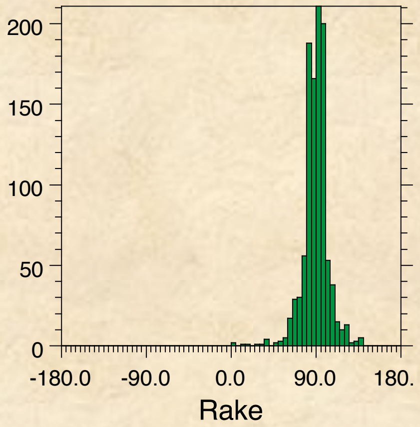
Results

Reverse

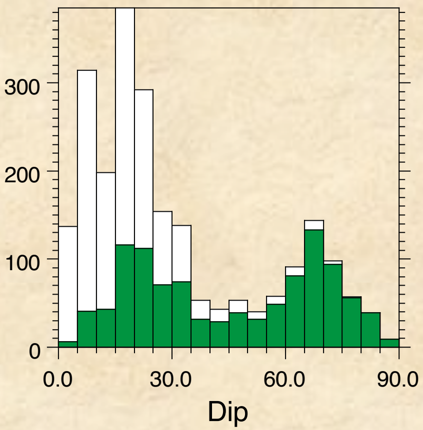
R1P



30°

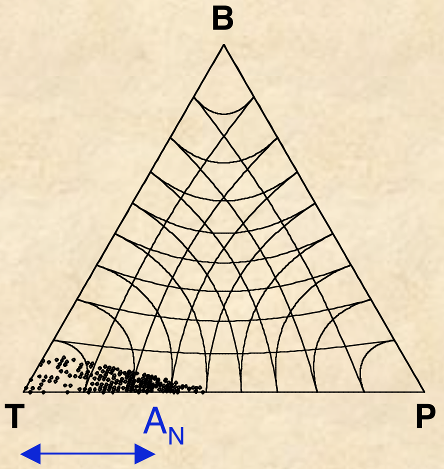


15-25° 65-70°

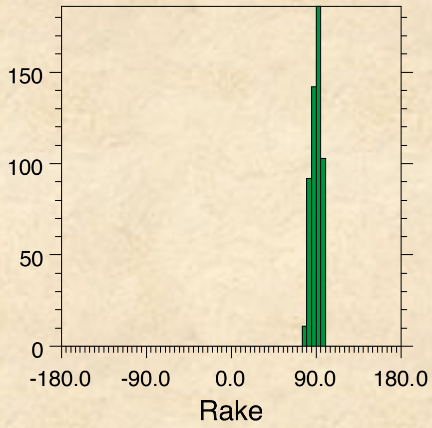


N = 528

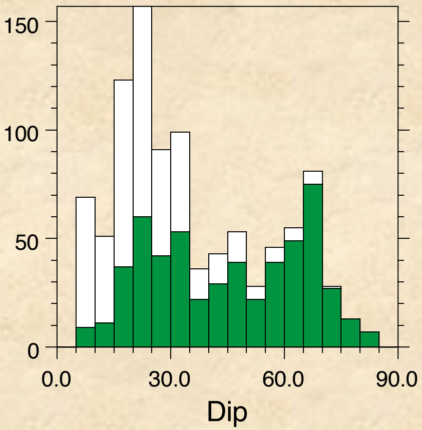
R2P



25°



20-25° 65-70°

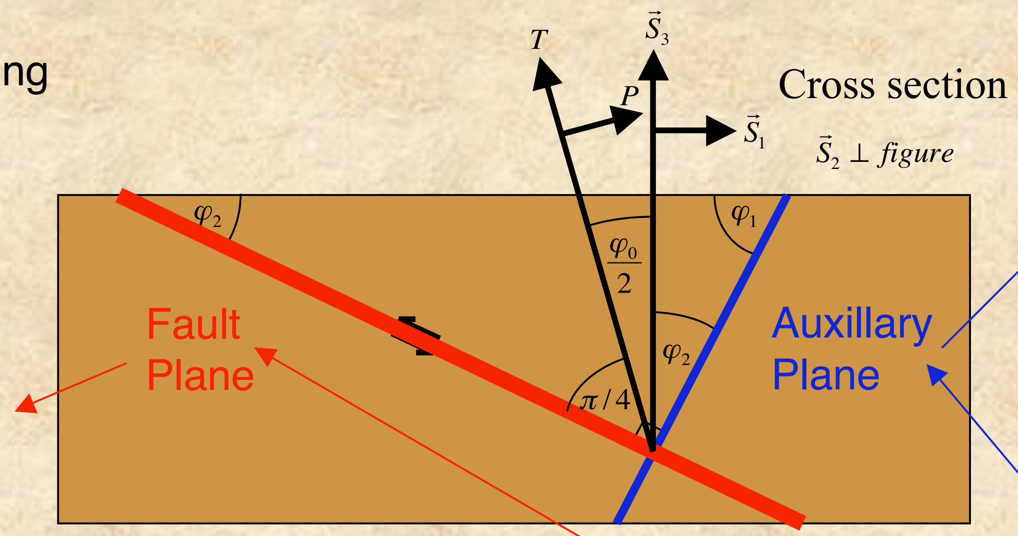


N = 267

Pure Reverse Faulting

N=528

R1P



$\varphi_2 = 45° - \varphi_0/2$

$\varphi_0 = 40\text{-}60°$

$\varphi_1 = \varphi_0/2 + 45°$

$\varphi_0 = 40\text{-}50°$

$\varphi_0 = 40\text{-}60°$

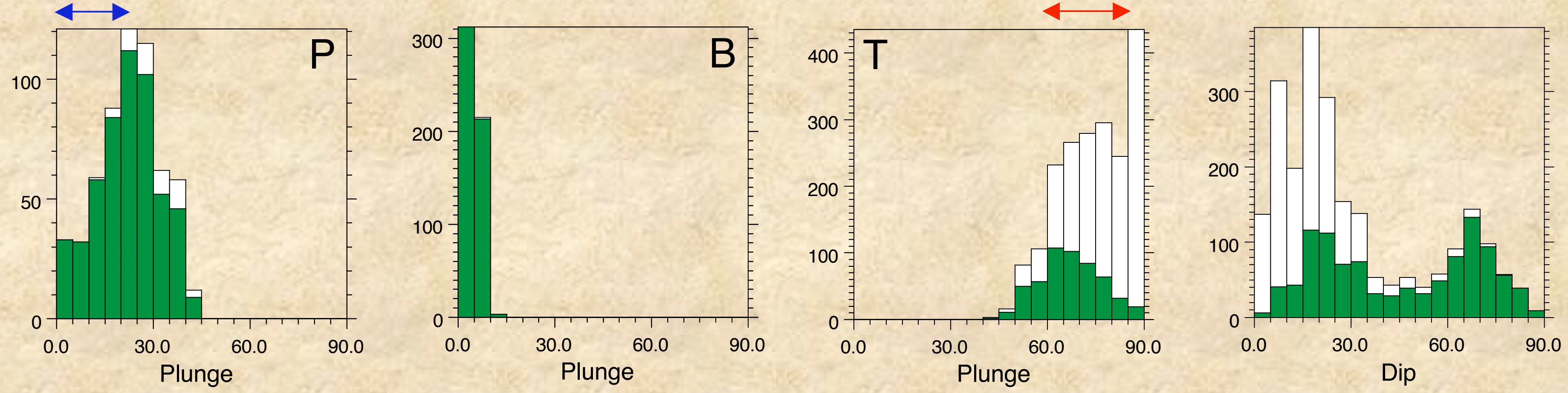
$\varphi_0 = 0\text{-}60°$

20-30°

0-30°

15-25°

65-70°

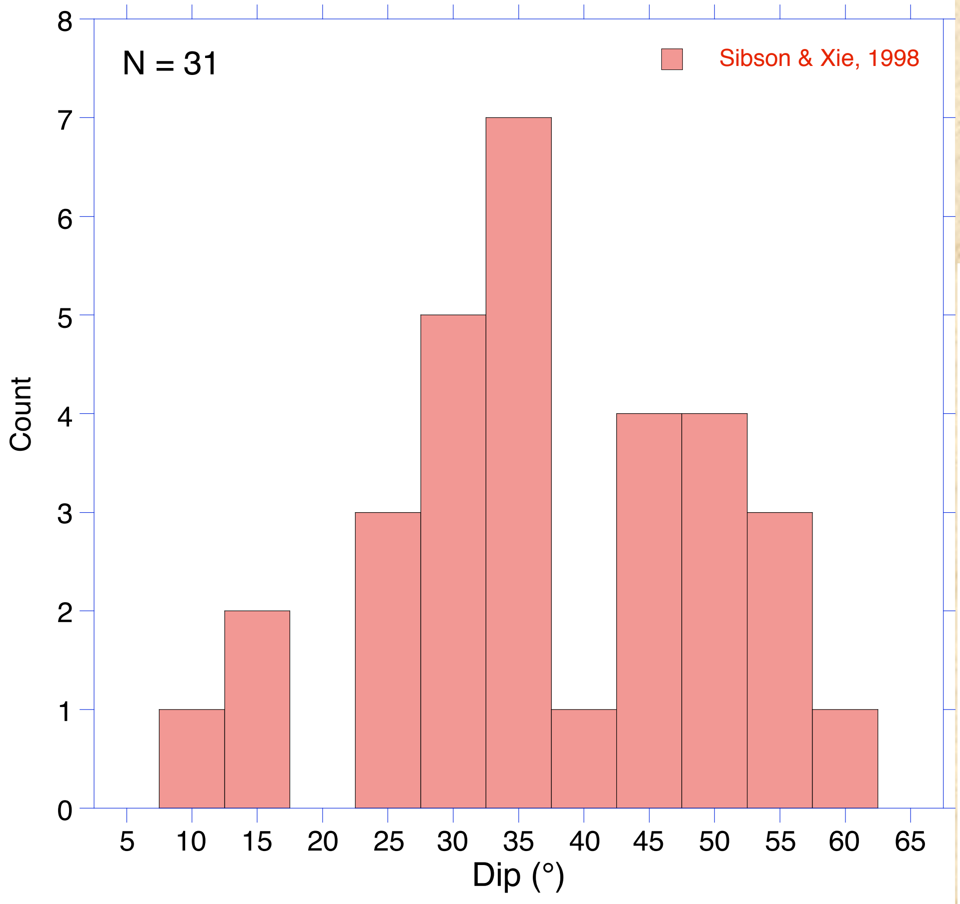


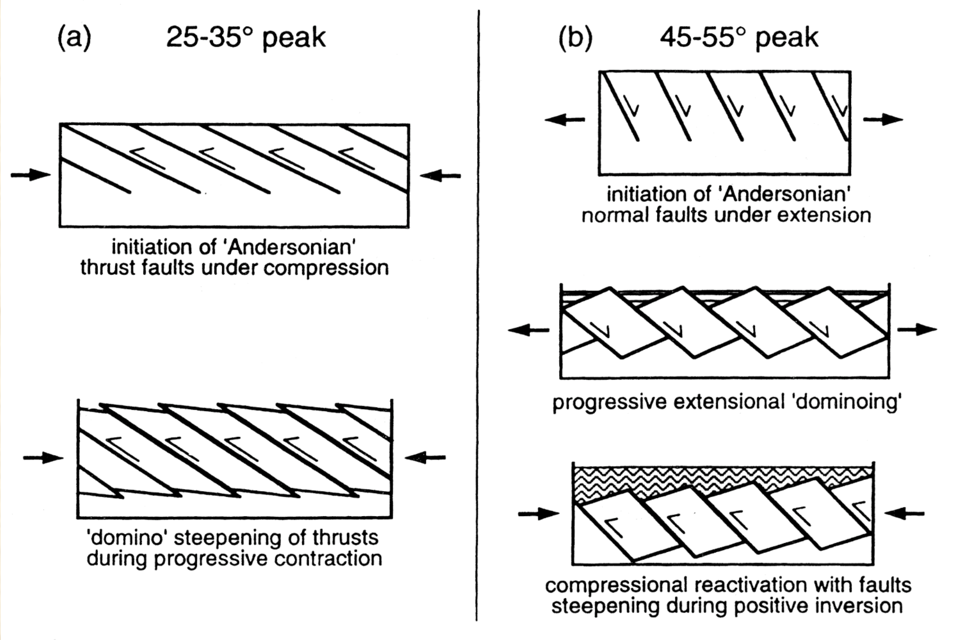
Sibson & Xie, 1998

M > 5.5
Fault plane (known)
Rake = +90±30°

Optimal & lock up angles
2D frictional sliding

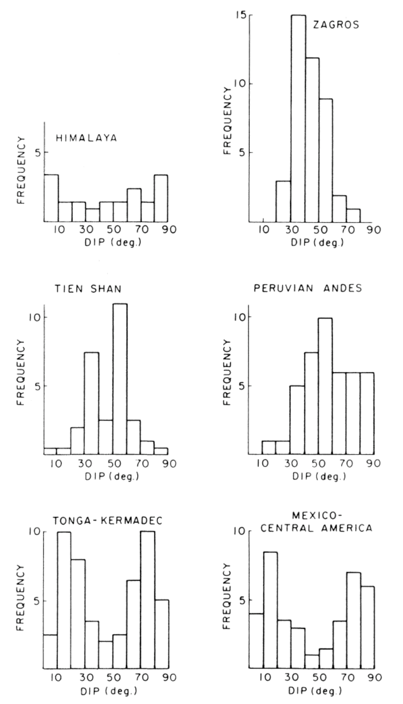
Conclusions:
- Bimodal 25-35°, 45-55°
- 25-35°-> φ_0 = 20-40°
- Paucity of $\delta < 20°$
- Lock up angle $\delta = 60°$ consistent with $\mu = 0.6$
- Domino rotation to high dip (45-55°)?
- Reactivation of normal faults (45-55°)?





Molnar & Chen,
1982

Both
nodal
planes

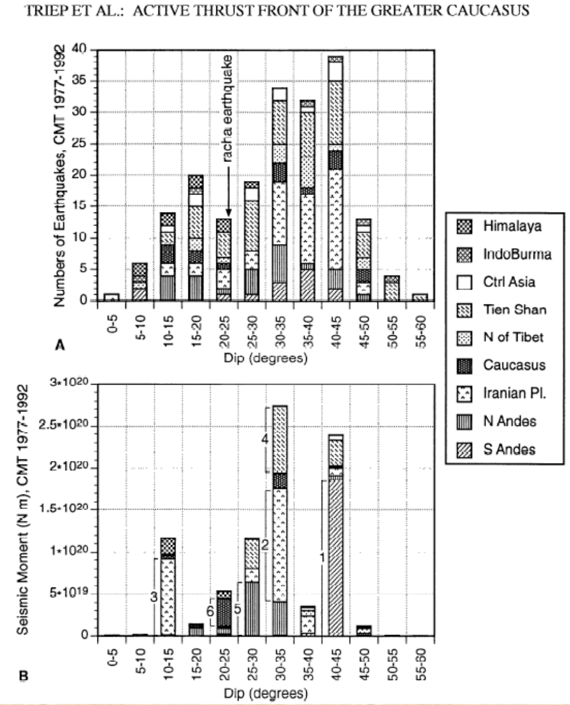


Triep et al, JGR, 1995

CMT 1977-1992
0-40 km
Plunge P < plunge T

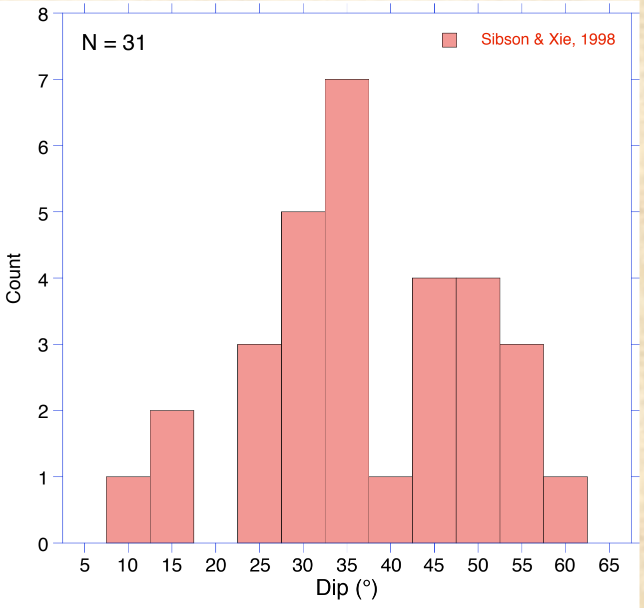
$$\sqrt{(plunge\ P)^2 + (plunge\ T)^2} > 45°$$

Assume
Shallower dip = Fault
⇒maximum estimate
of shallow dip

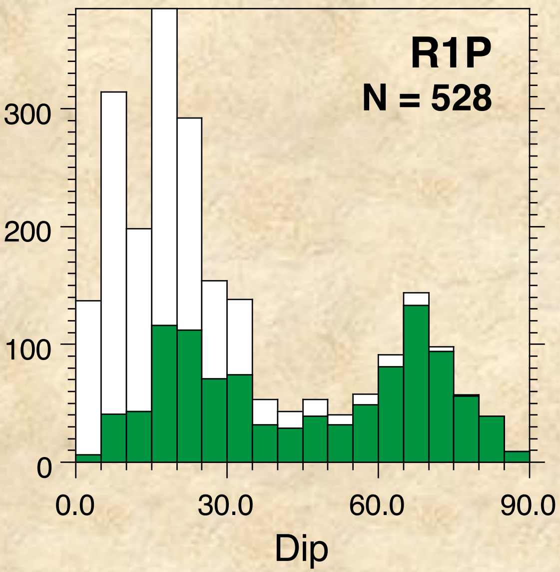


Sibson & Xie,
1998

M > 5.5
Fault plane
(known)
Rake = +90±30°



15-25°
65-70°

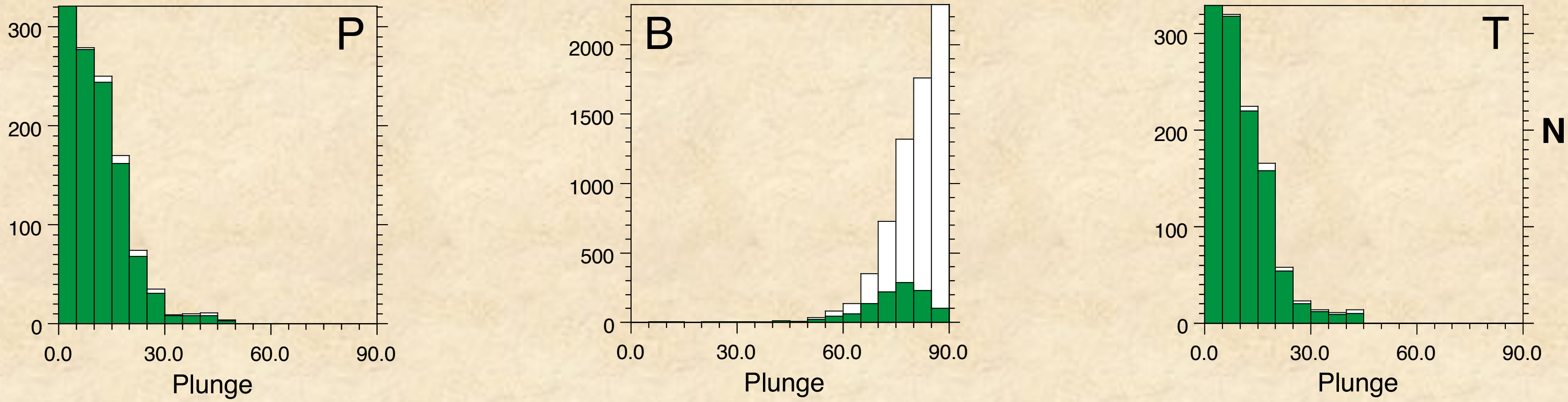


Results

Strike-slip

75-90°

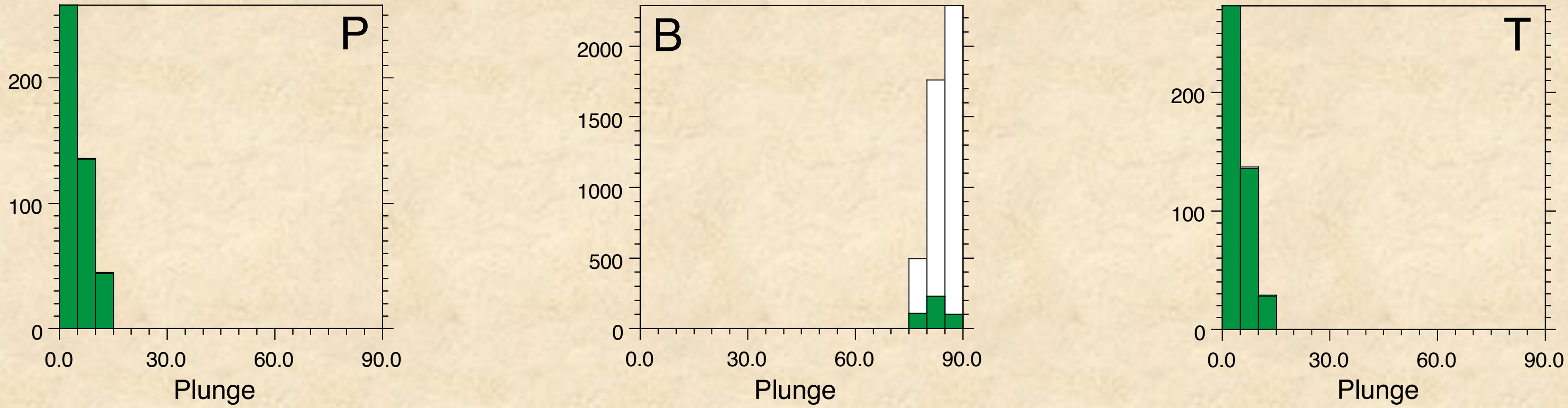
S1P



N = 1130

80-90°

S2P

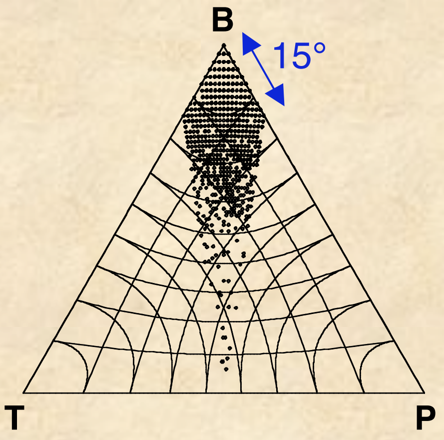


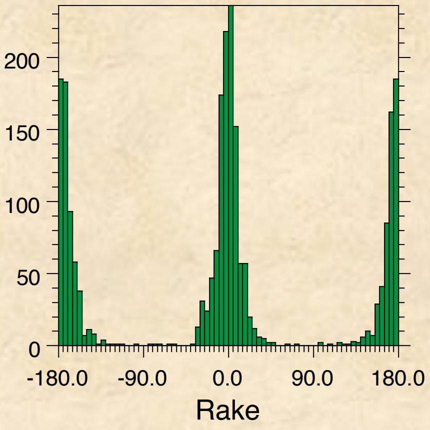
N = 437

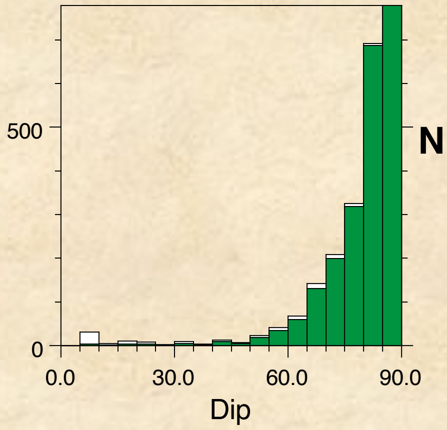
Results

Strike-slip

S1P

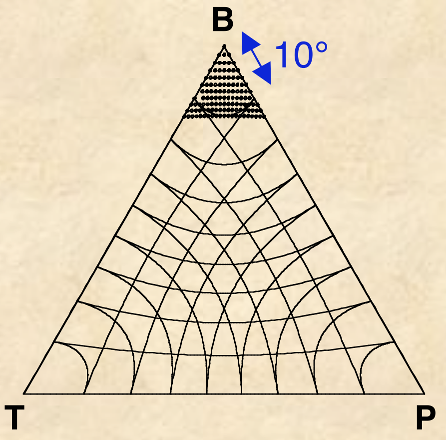


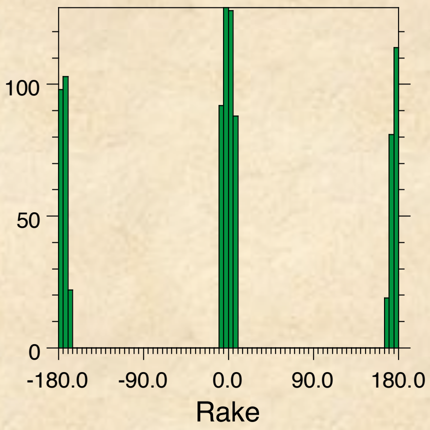


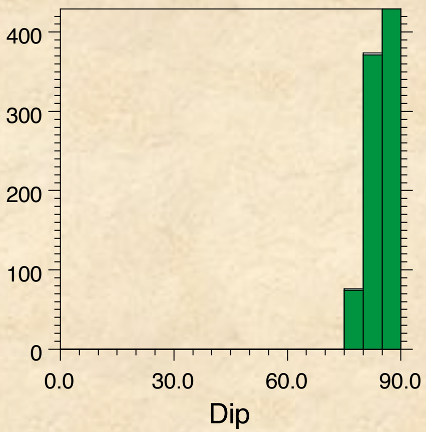


N = 1130

S2P





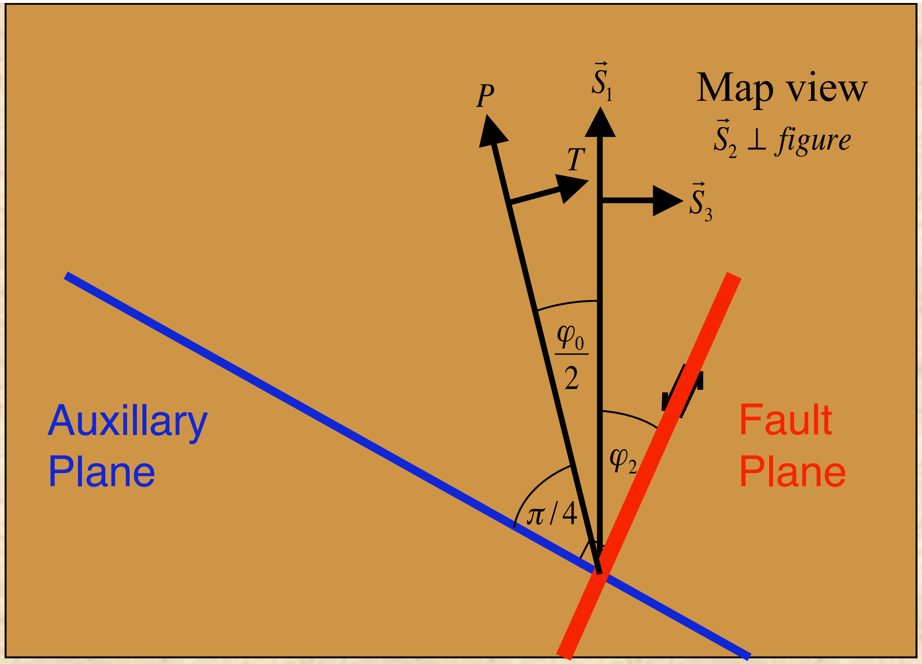


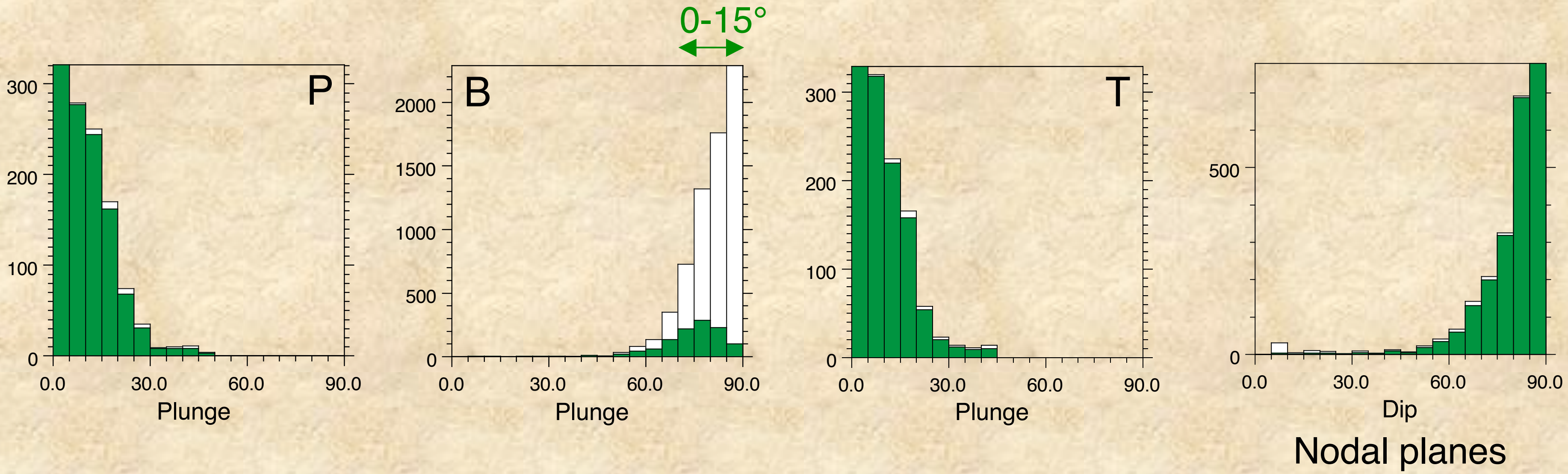
N = 437

Pure Strike Slip Faulting

N=1130

S1P





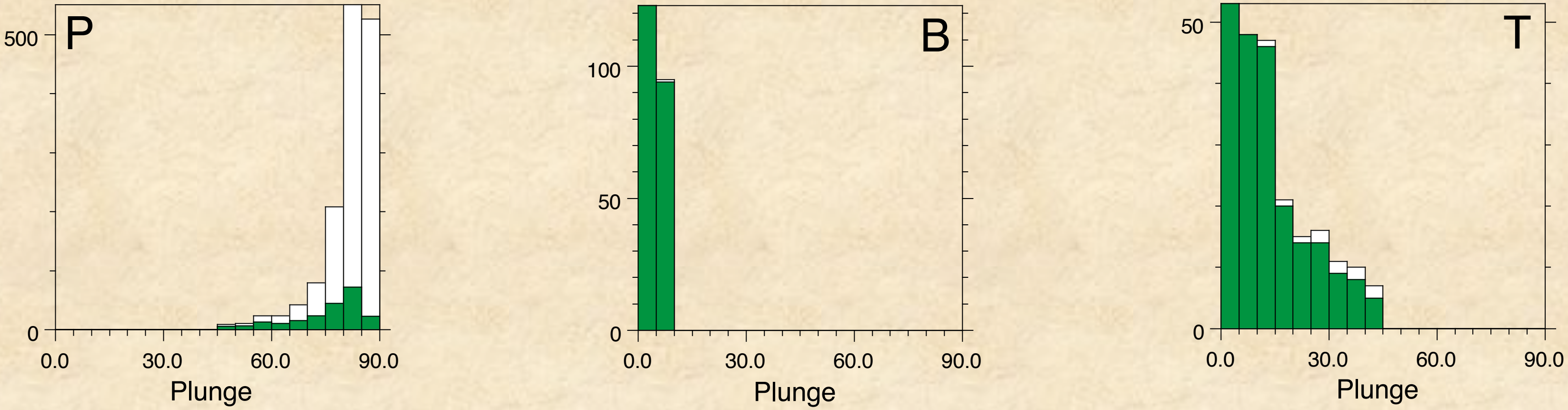
Results

Normal

N1P

80-90°

0-5°

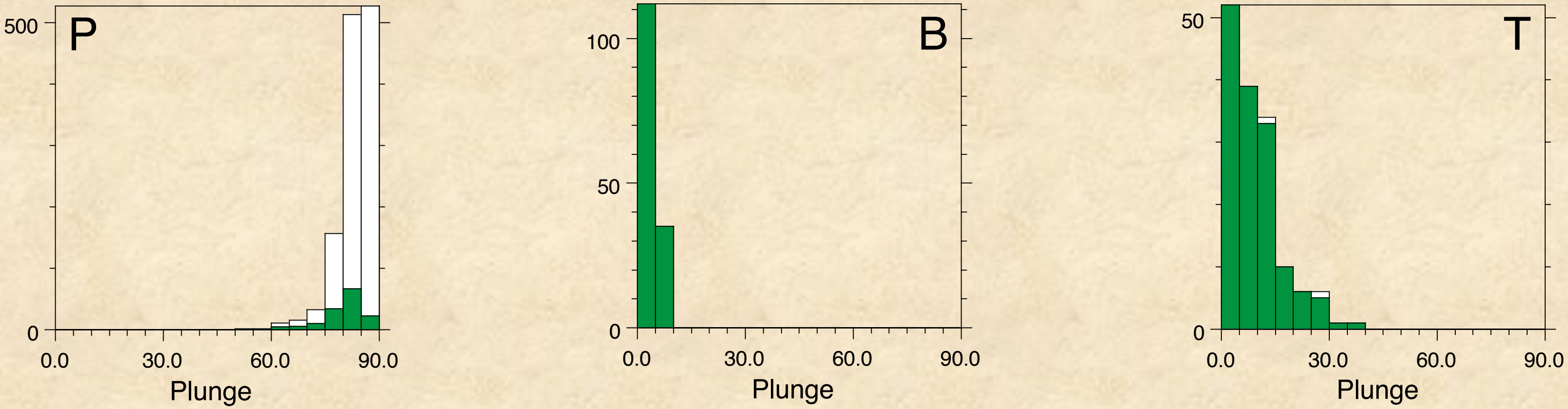


N = 217

N2P

80-90°

0-5°

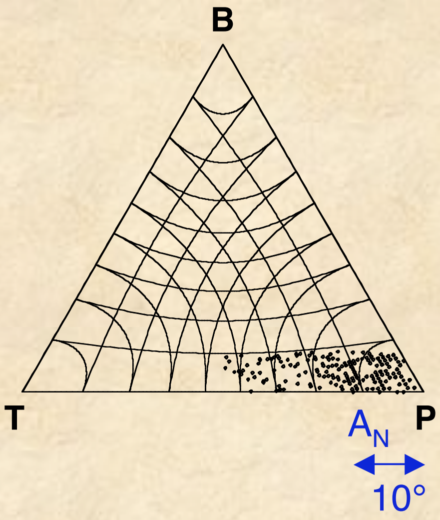


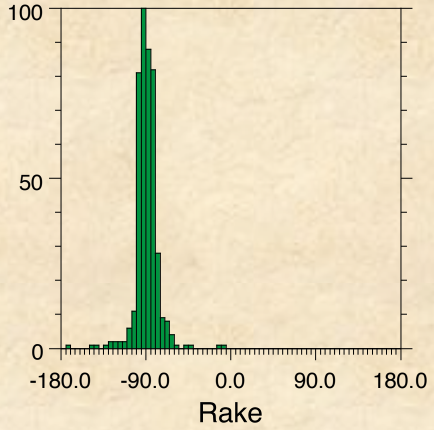
N = 147

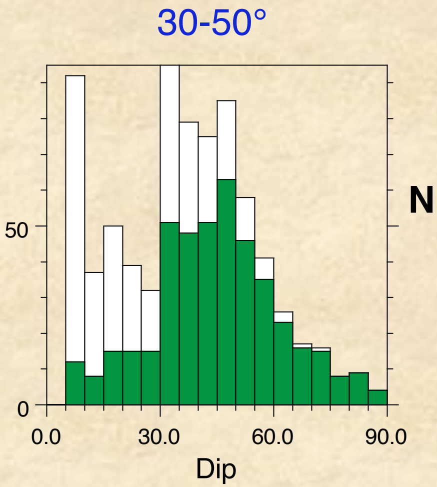
Results

Normal

N1P

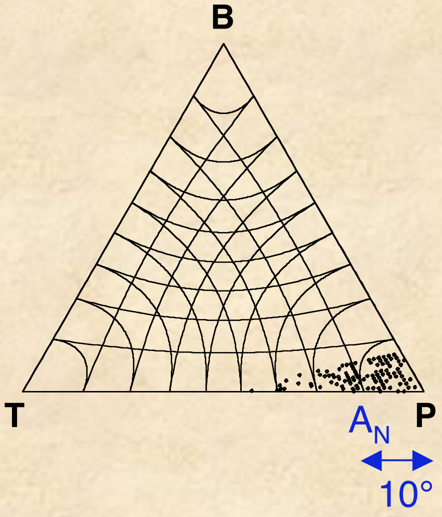


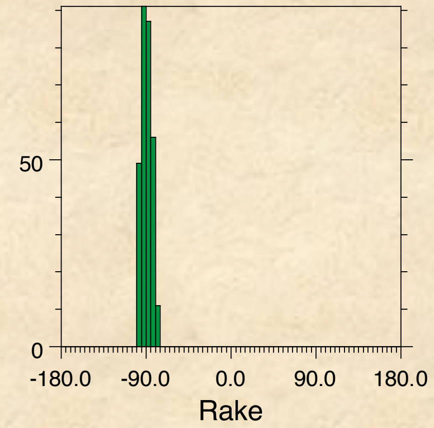


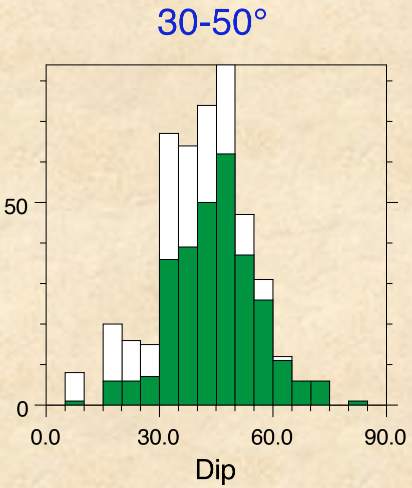


N = 217

N2P





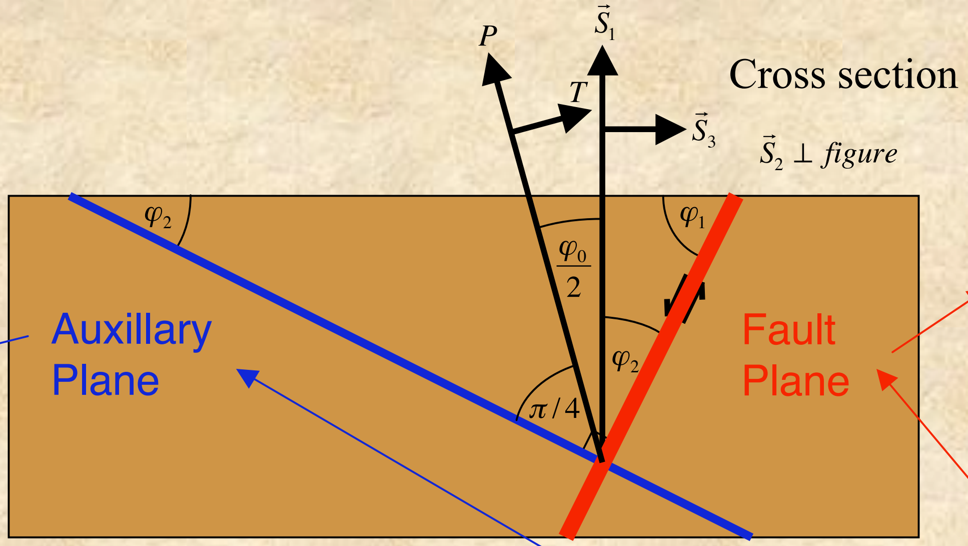


N = 147

Pure Normal Faulting

N=217

N1P



$\varphi_1 = \varphi_0/2+45°$

$\varphi_0 = 0\text{-}10°$

$\varphi_2 = 45°\text{-}\varphi_0/2$

$\varphi_0 = 0\text{-}30°$

$\varphi_0 = 0\text{-}20°$

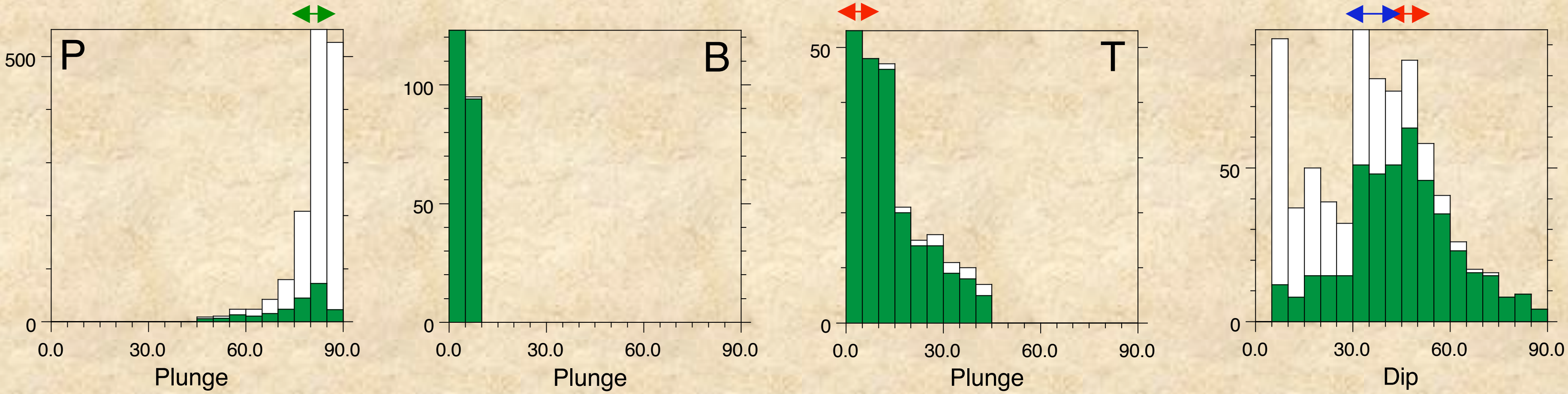
Other interpretation:

$\Rightarrow \varphi_0 < 0$

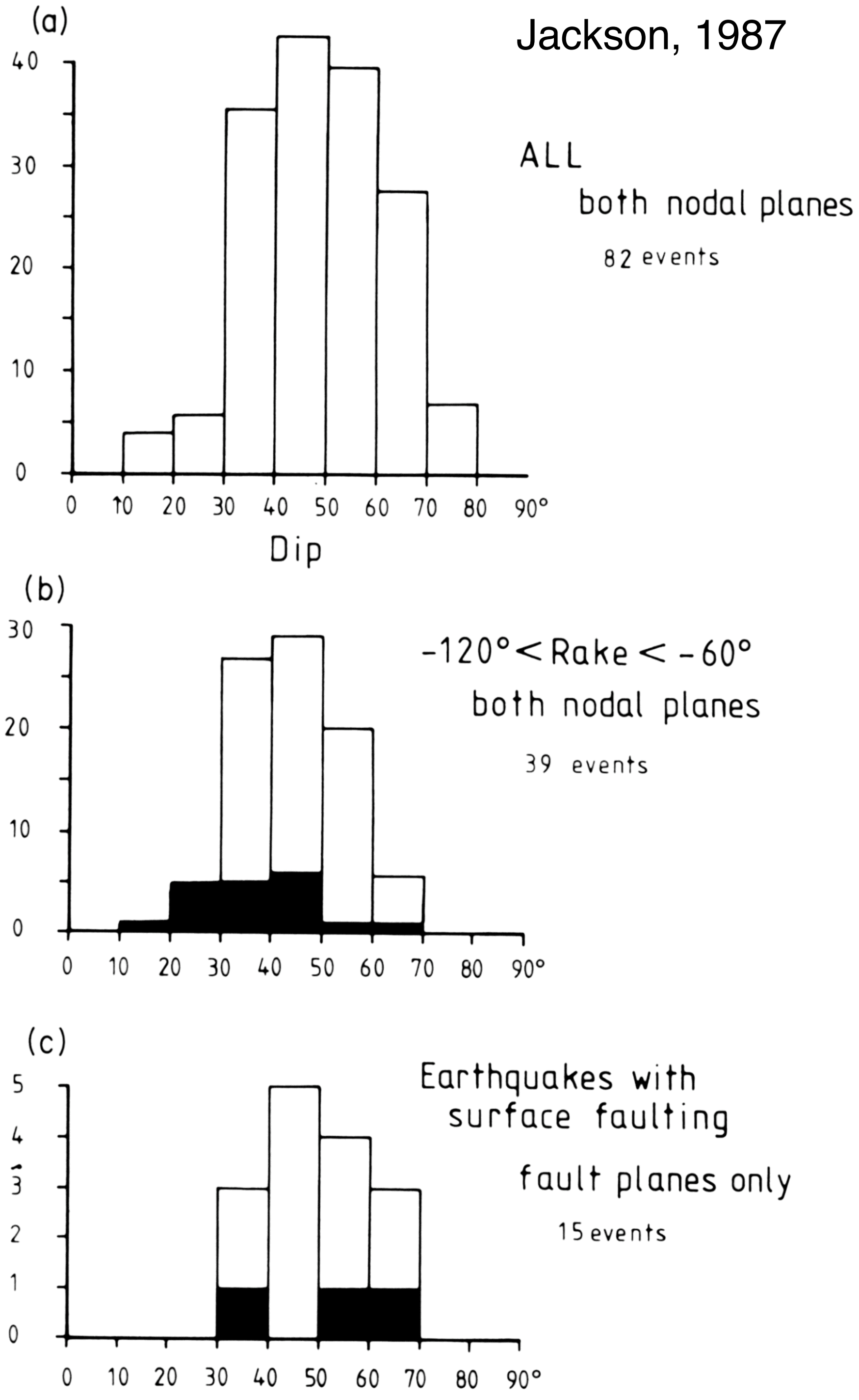
0-10°

0-5°

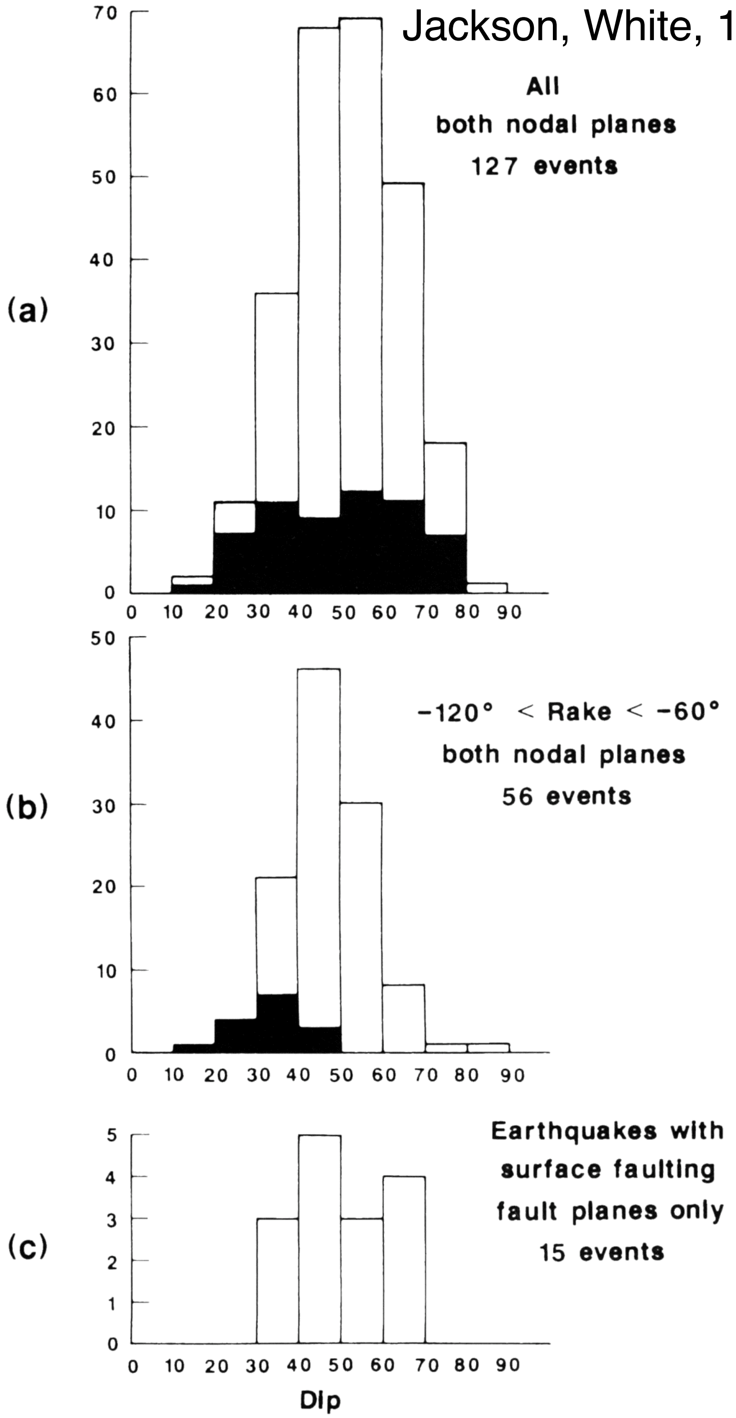
30-45° 45-50°



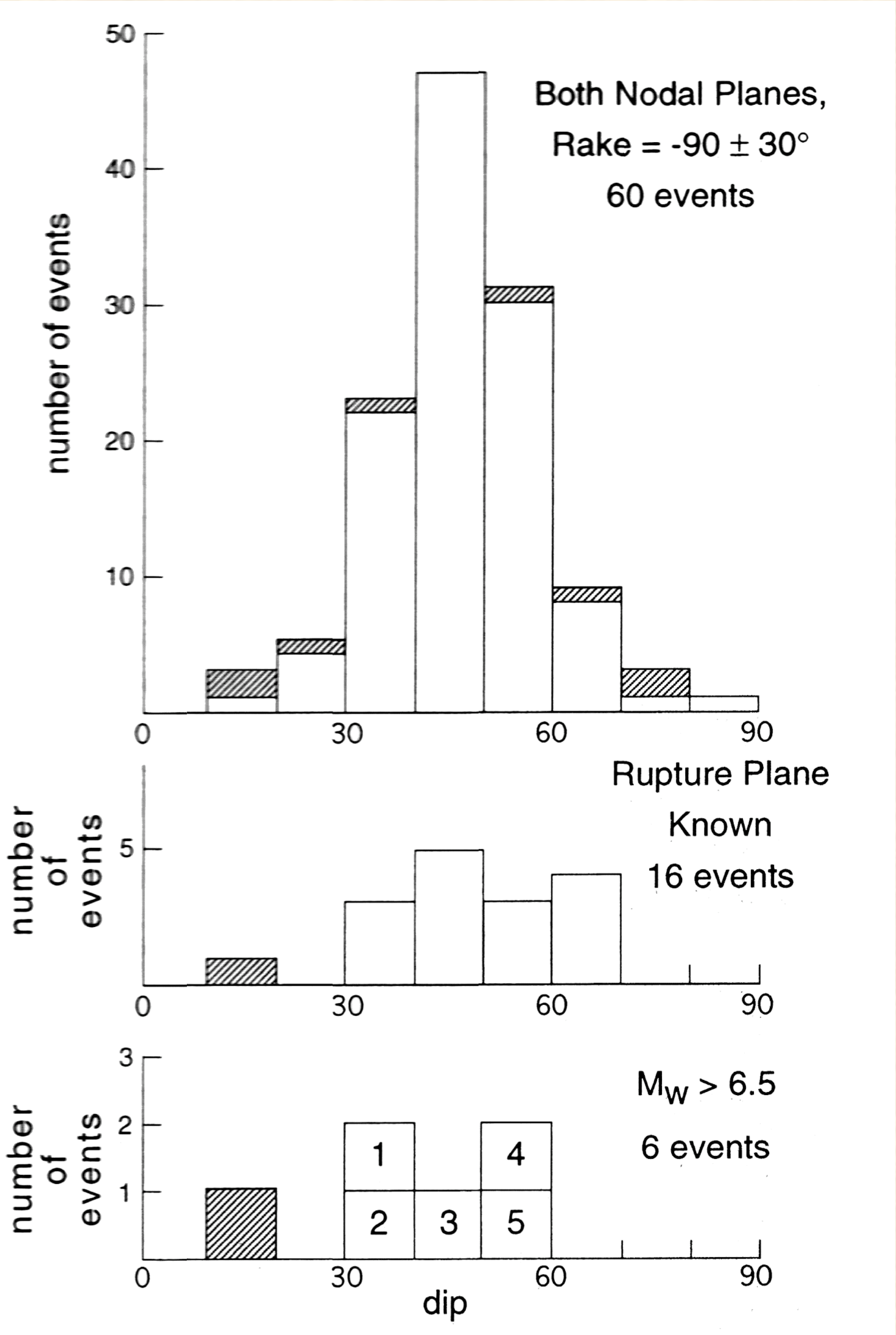
Jackson, 1987



Jackson, White, 1989



Wernicke, 1995, JGR



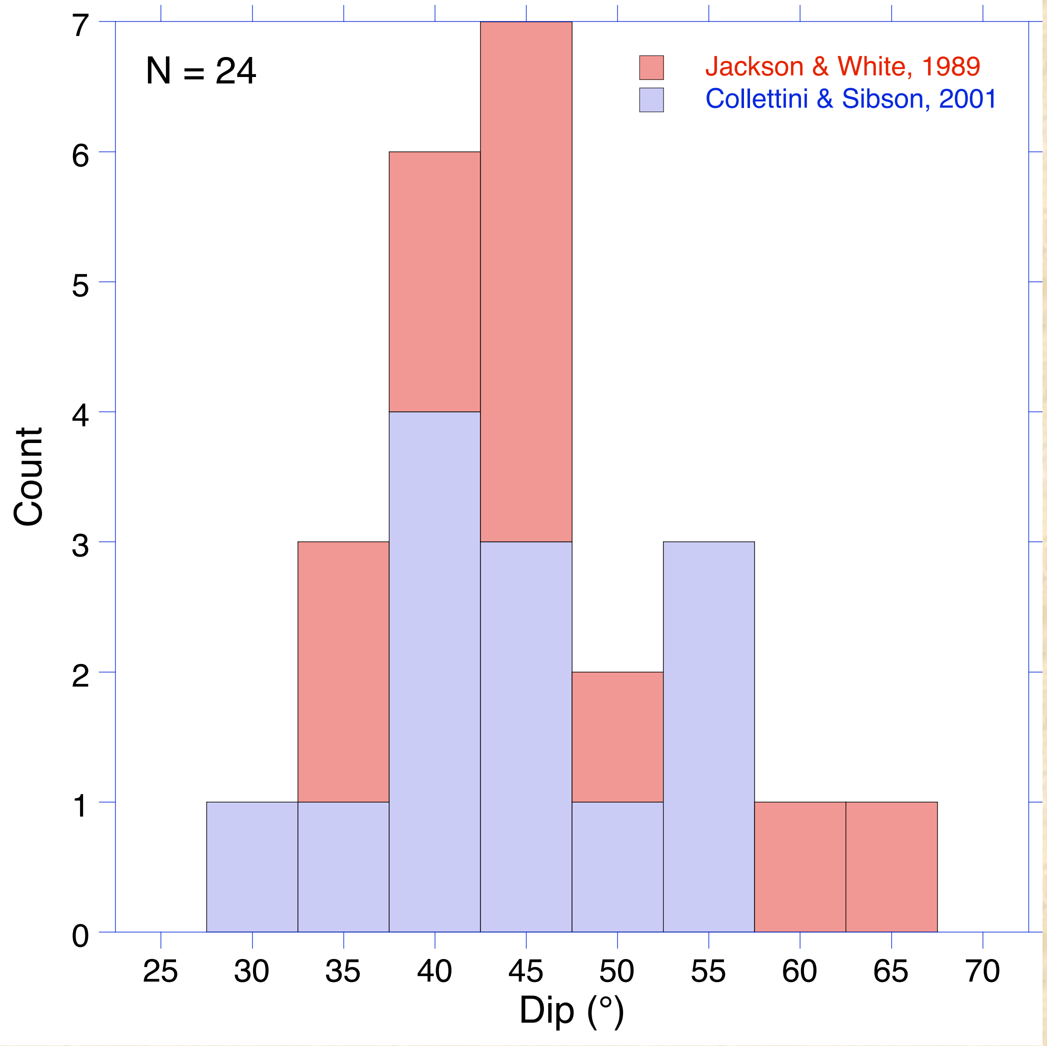
Jackson & White, 1989
Abers, 1991 (hatched)

Jackson & White, 1989
Abers, 1991 (hatched = Woodlark basin)

Doser & Smith, 1989
Jackson & White, 1989
Abers, 1991 (hatched)

1 Aegean Sea 1970
2 Aegean Sea 1969
3 Hebgen Lake, 1959
4 Borah Peak, 1983
5 Italy, 1980

Colletini & Sibson, 2001

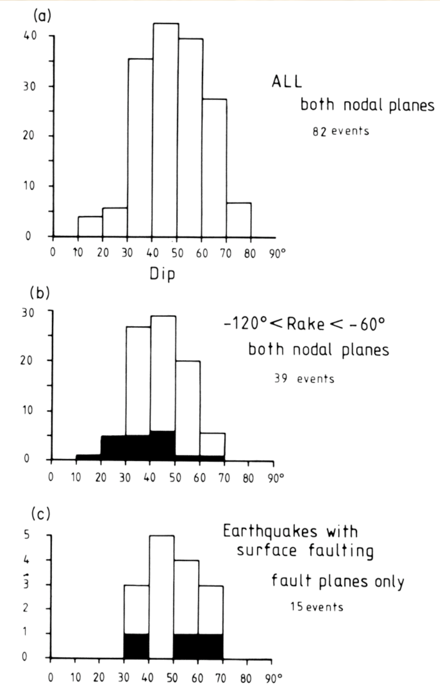


M > 5.5
Fault plane (known)
Rake = -90±30°

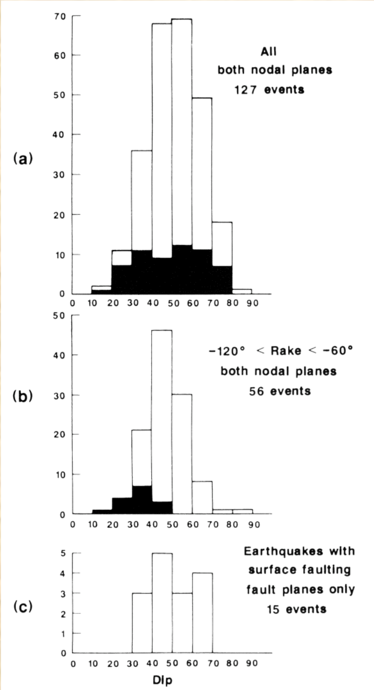
Conclusions:

- Lock up angle $\delta = 30°$ consistent with $\mu = 0.6$
- Peak at 45° unexplained
- Domino rotation to low dip ?
- Reactivation of reverse faults ?

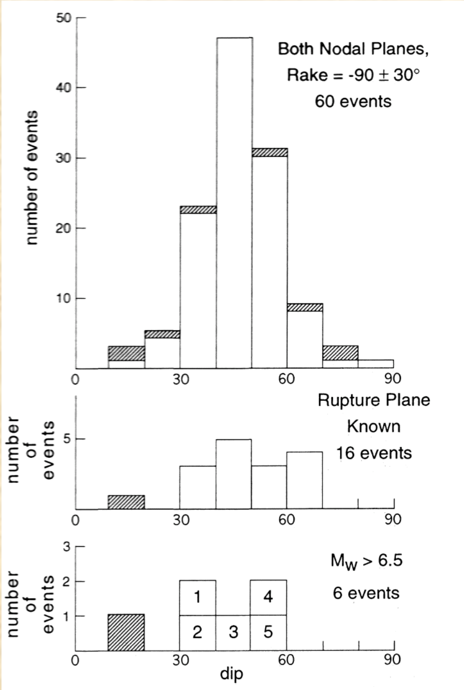
Jackson, 1987



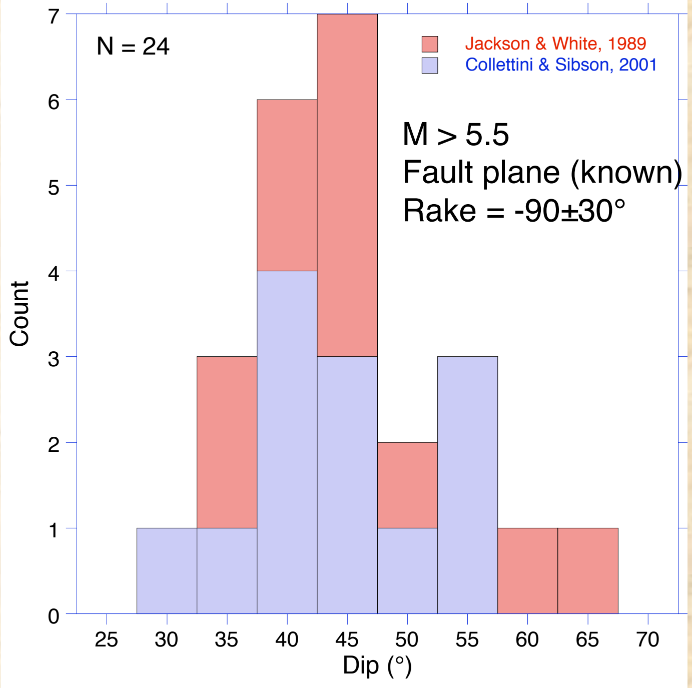
Jackson, White, 1989



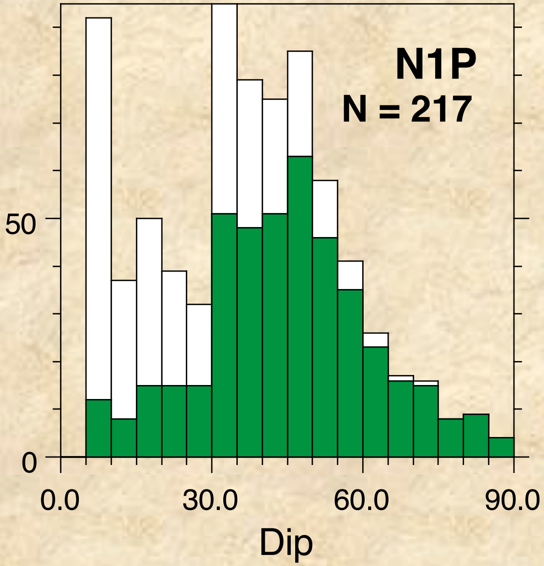
Wernicke, 1995



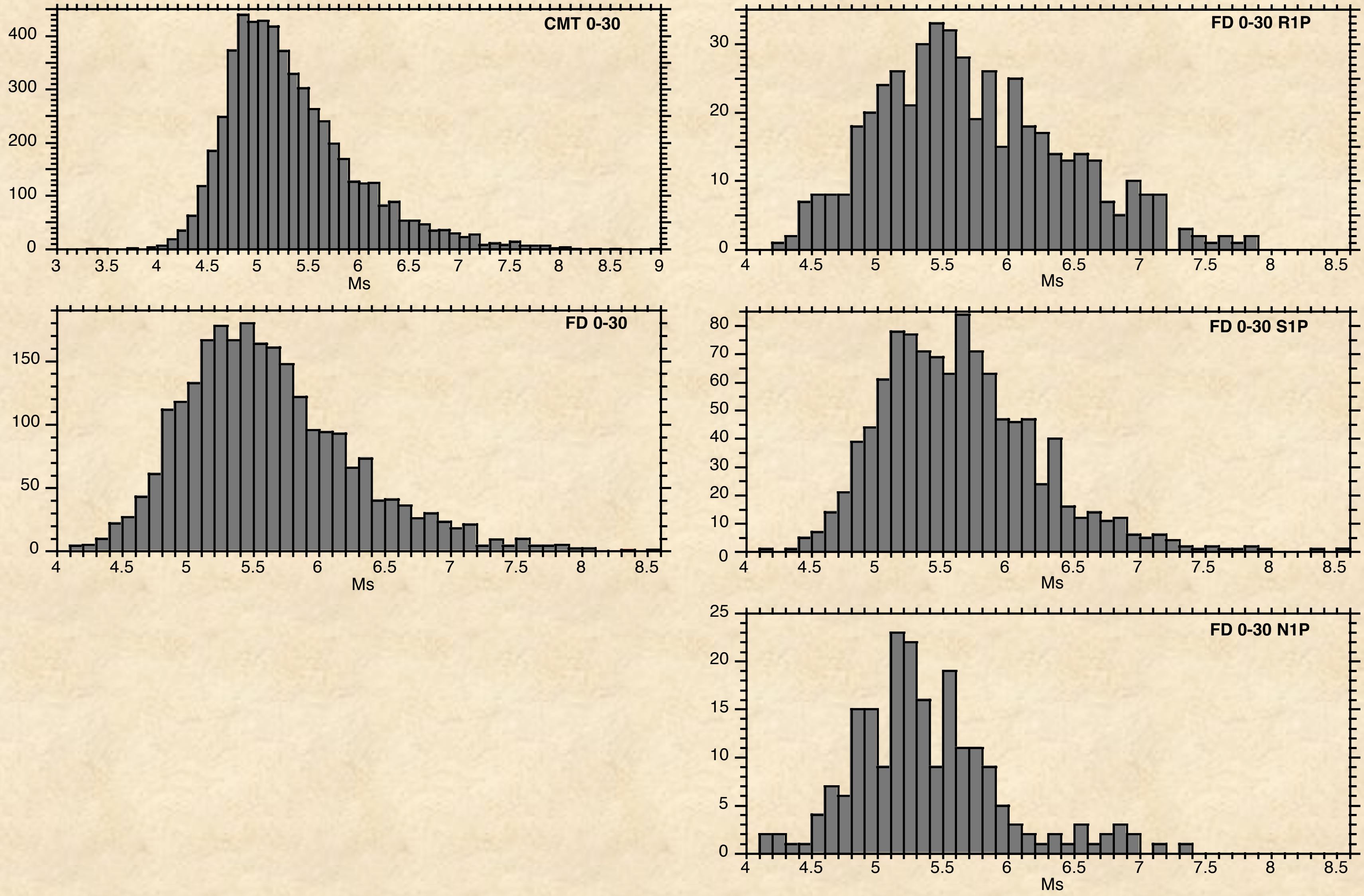
Colletini & Sibson, 2001



30-50°



Catalog completeness / Magnitudes



Conclusions

- Shallow earthquakes dominated by pure dip or strike slip events.
- Simplest interpretation: dominant 'near Anderson' faulting.

  supports crustal strength hypothesis of Brace & Kohlstedt (1980) to crustal depths
- Dissymetry between normal and thrust events
- Thrust events compatible with Andersonian conditions but with φ_0 = 40-60°.
- Normal events nodal planes dipping around 45°, suggesting φ_0 -> 0°, φ_0 = 0-30°.
- Highlights how much complete global catalogs can reveal
- How much more could be learnt from catalog complete to lower magnitude (x10/M),

  more precise depth determinations and fault plane identification.