Globale Seismizität I

Erdbebenquelle
Stressfeld

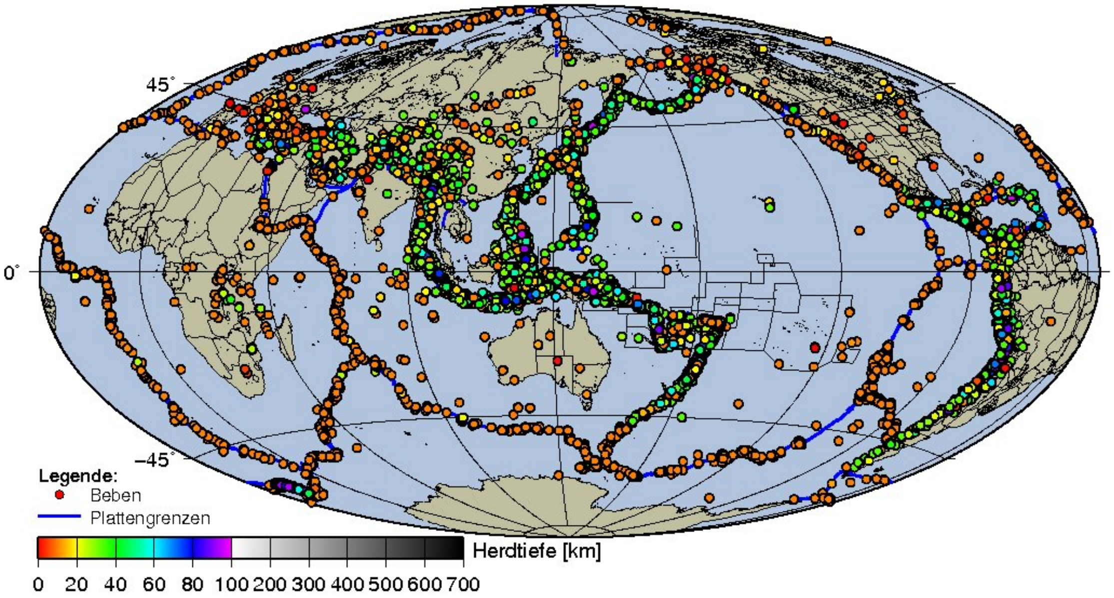
Literatur:

Berckhemer, H., Grundlagen der Geophysik, Wiss. Buchges. 1990.
Stüwe, K. Geodynamik der Lithospäre, Springer, 2000

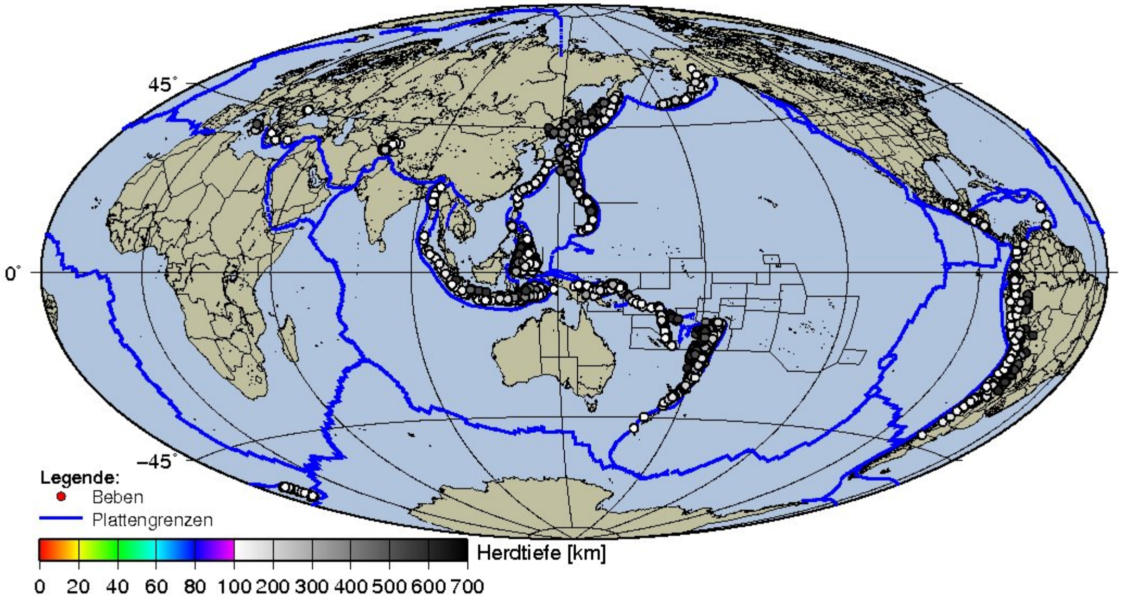
Sheaer, P., Introduction to Seismology, Cambridge University Press, 1999.

Lay, T. & T. Wallace, Modern Global Seismology, Academic Press, 1995.

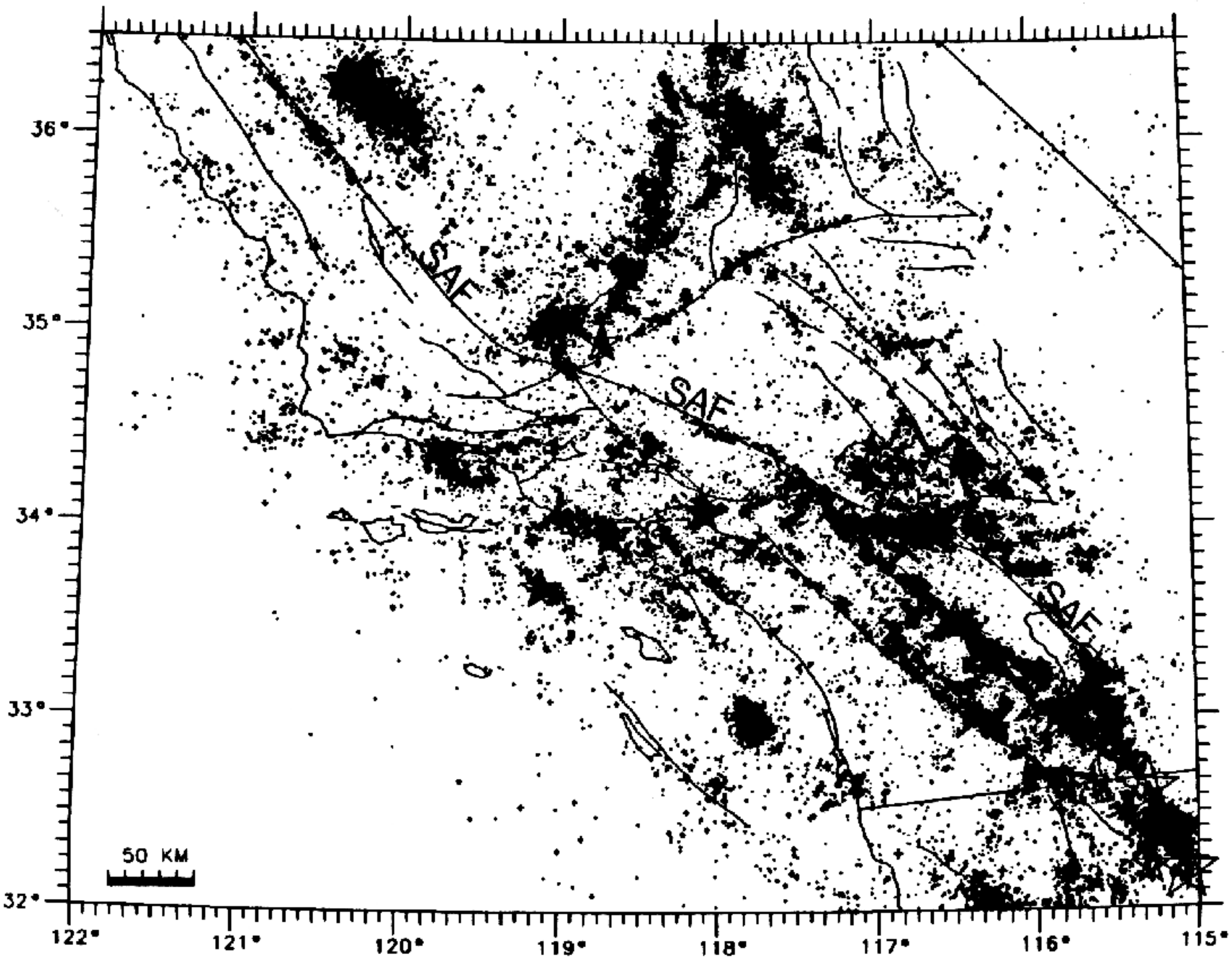
Global earthquake distribution 1995 – 2006



Source depth < 100 km



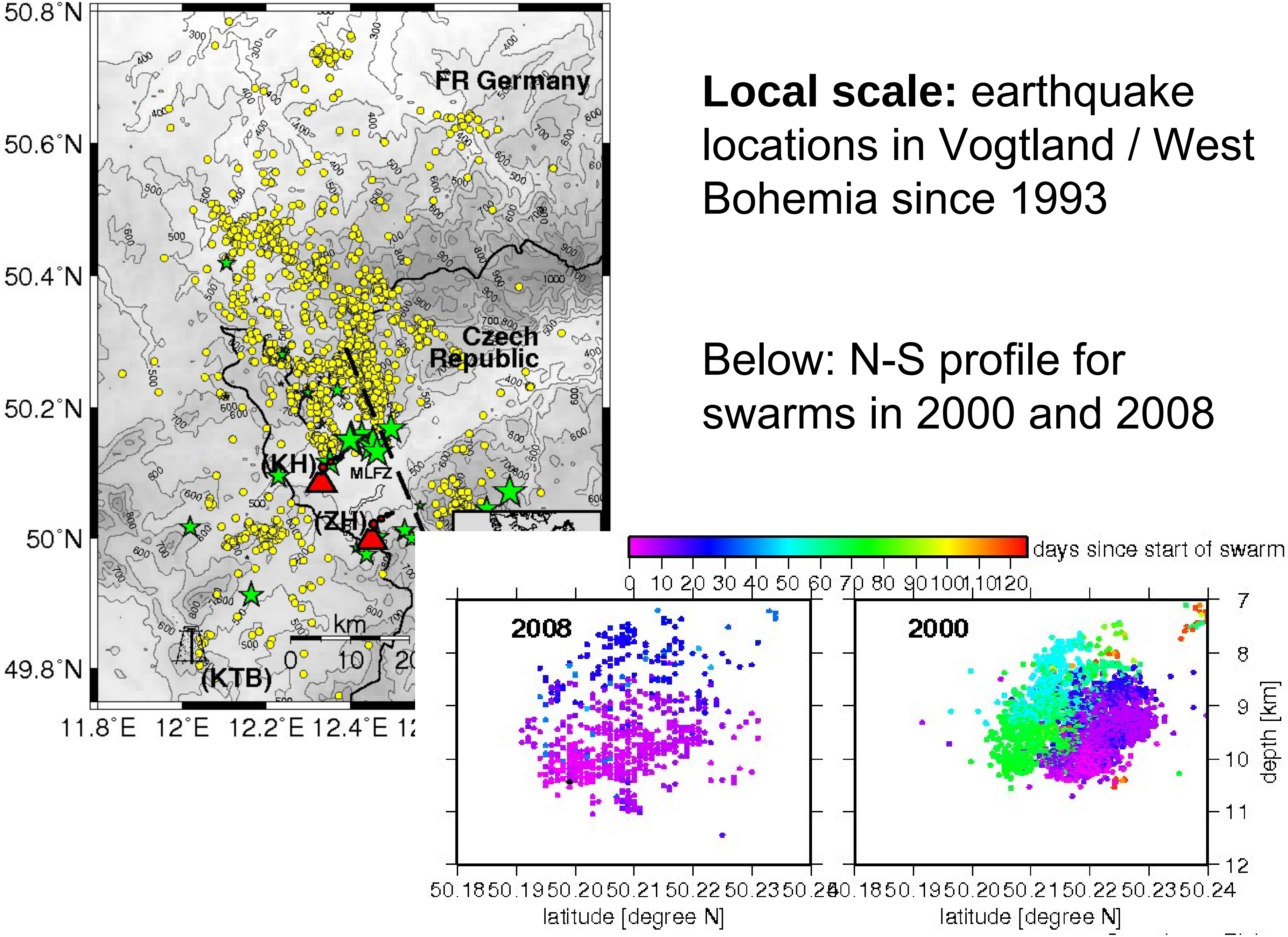
Source depth from 100 to 700 km



Regional scale: earthquake locations in Southern California 1978 – 1988 & active faults

Local scale: earthquake locations in Vogtland / West Bohemia since 1993

Below: N-S profile for swarms in 2000 and 2008



- Earthquakes mark currently active faults
- Deep earthquakes only at subduction zones
- Earthquake distribution greatly contributed to development of plate tectonics

Issues:

- What are earthquakes physically?
- How are they generated?
- What happens during an earthquake?

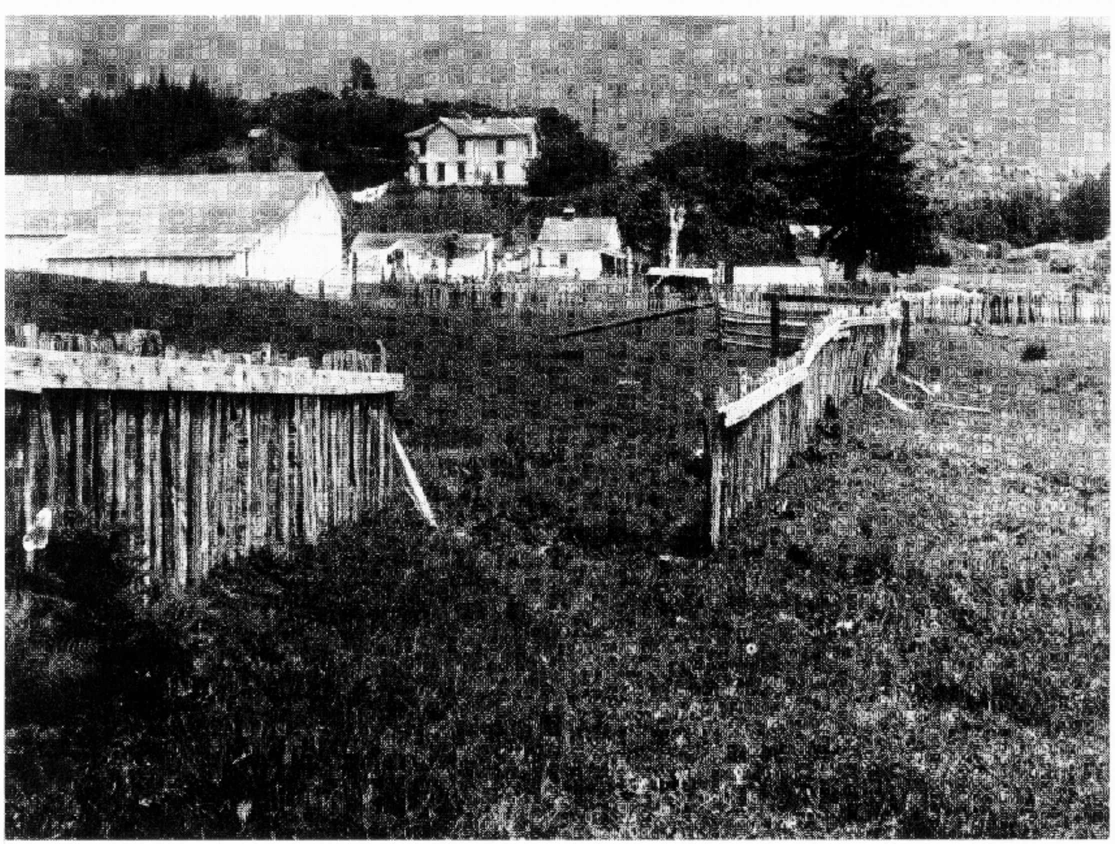
From myth to physics:

- Earthquakes due to drought or rain (Demokrit)
- 19th century: fire (plutonists) or water (neptunists)
- 1873, 1875: relation to tectonic faults (Edward Suess)
- 1910: Reid´s **elastic rebound hypothesis**

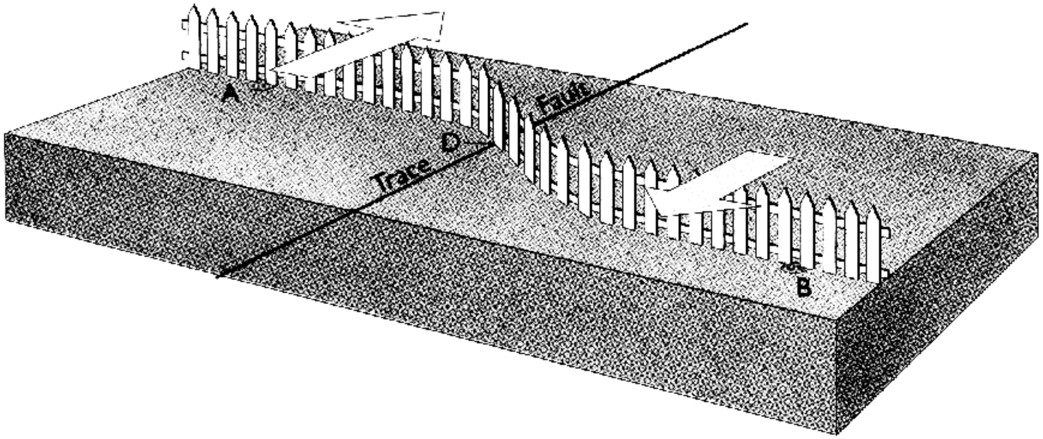
Elastic rebound hypothesis (Reid ´sche Scherbruchhypothese)

San Francisco earthquake (M_s = 8.3) 1906:

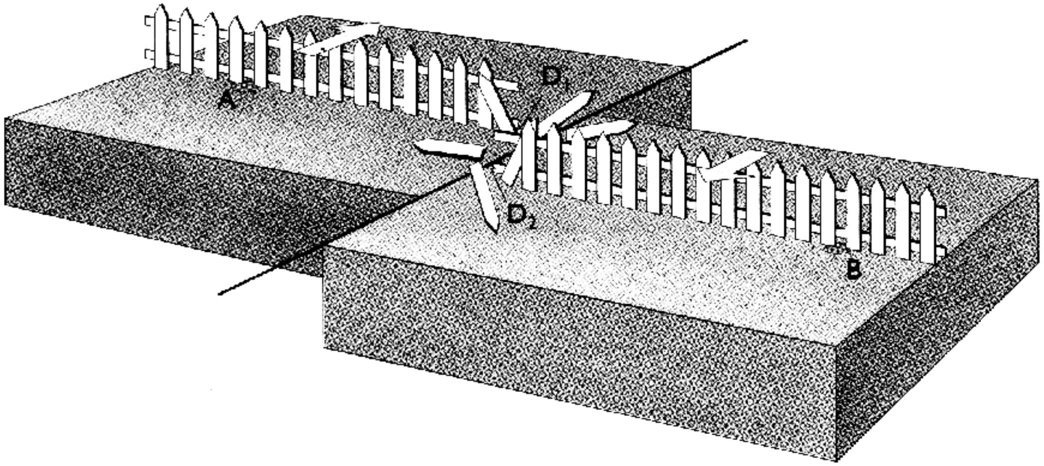
surface faulting up to 6 m at rupture of 300 km length



The earthquake process



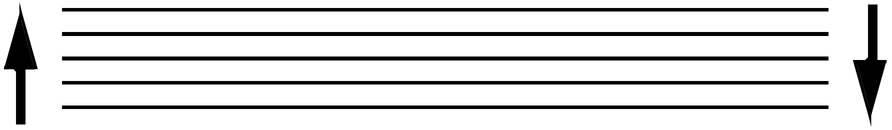
Tectonic forces bend the fence

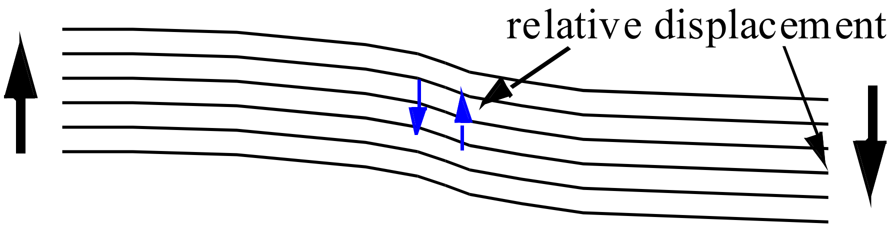


Rupture, strained rocks spring back

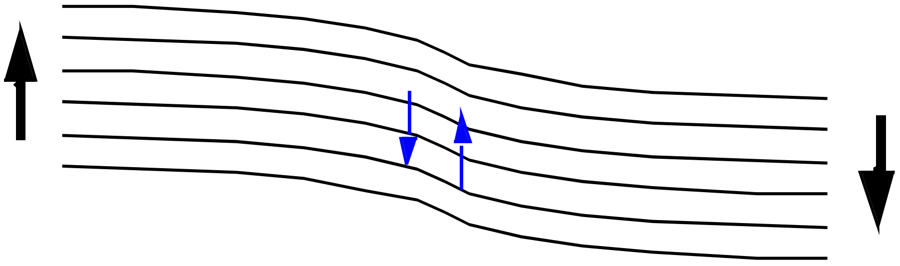
Earthquakes as shear fractures

Straight lines:



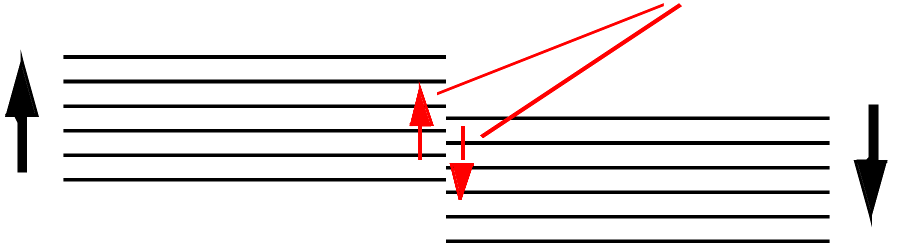


Elastic deformation accumulates:



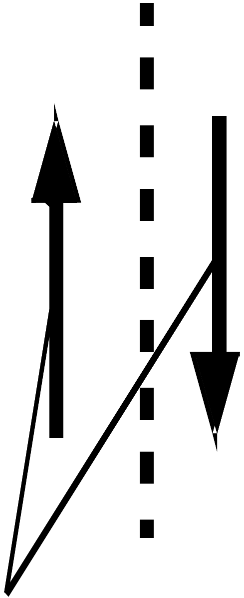
rigidity of rock exceeded => shearing fracture,
propagation on focal plane at 2-3km/s

rebound



deformation energy relaesed as seismic energy

Characteristic deformation in the vicinity of the focus



focal plane

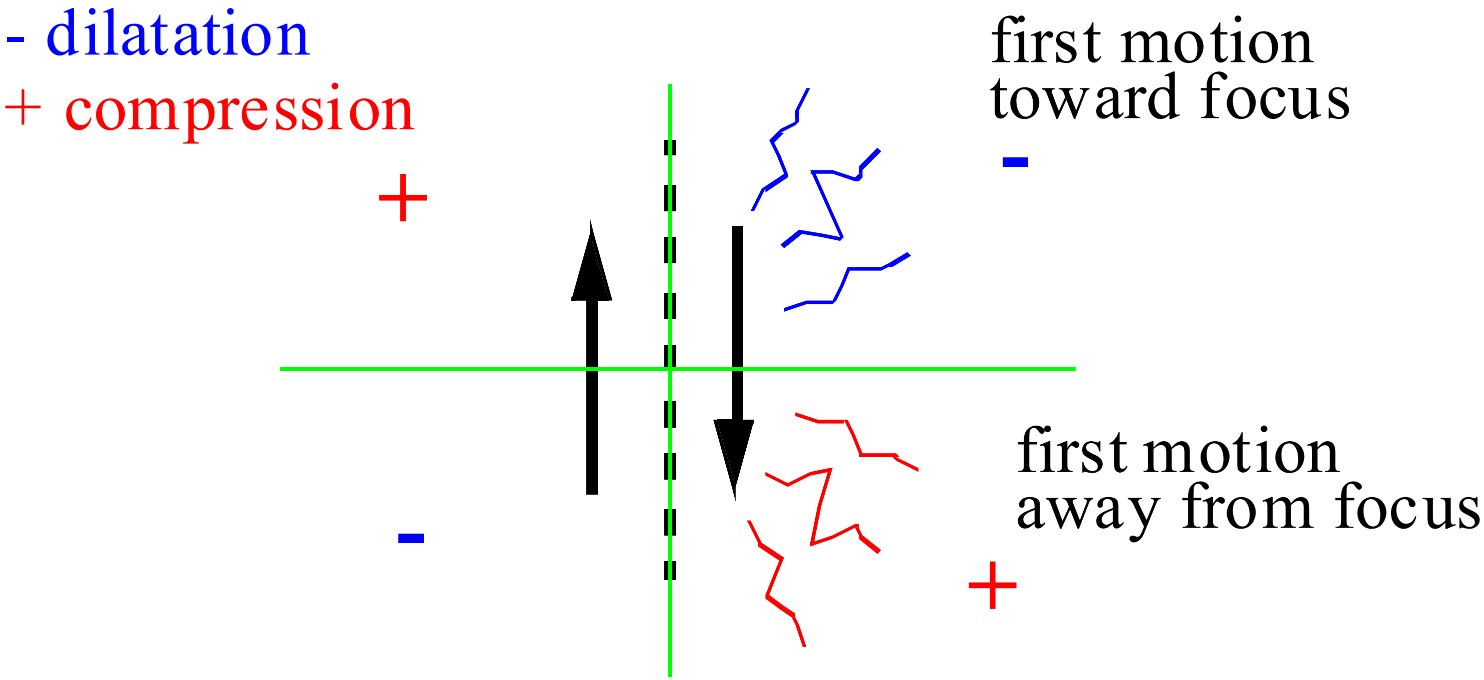
compression

extension

extension

compression

Rebound / dislocation



- dilatation
+ compression

first motion
toward focus

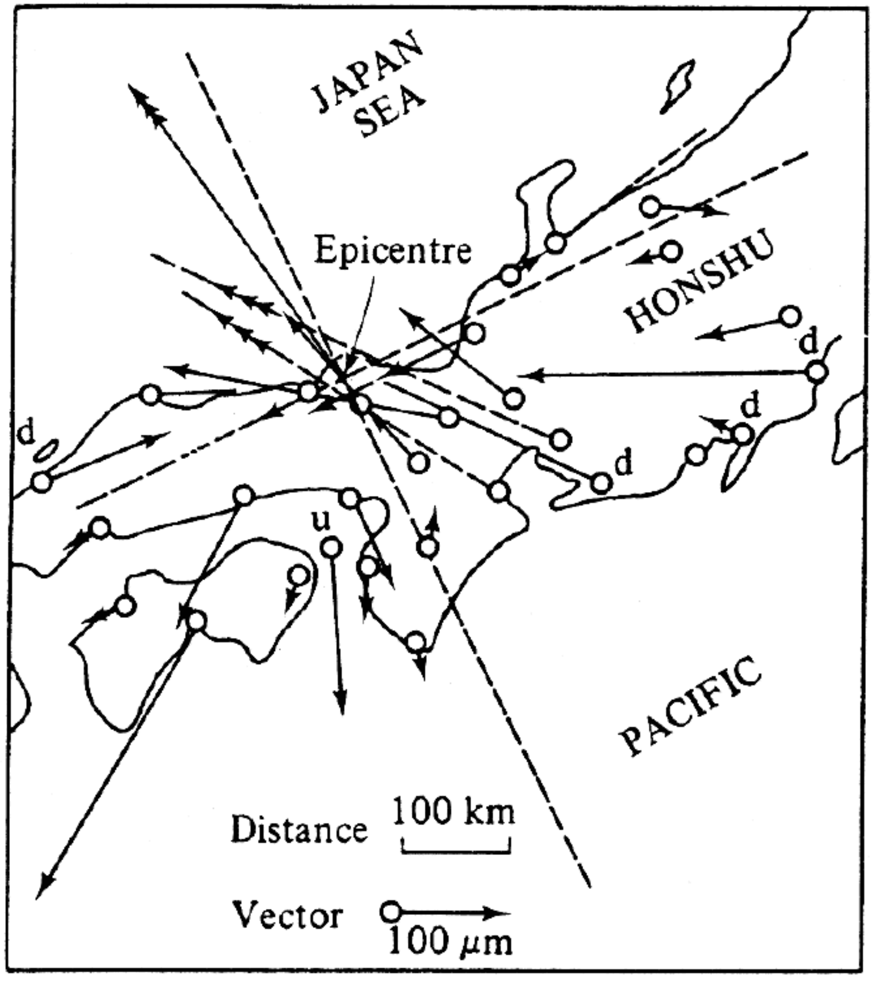
first motion
away from focus

Wavetype: **P-waves**

On nodal planes sign reversal → no displacement

P-wave motion equal for 2 conjugate faults

Distribution of initial ground movement during the Tango earthquake (1927, Japan)

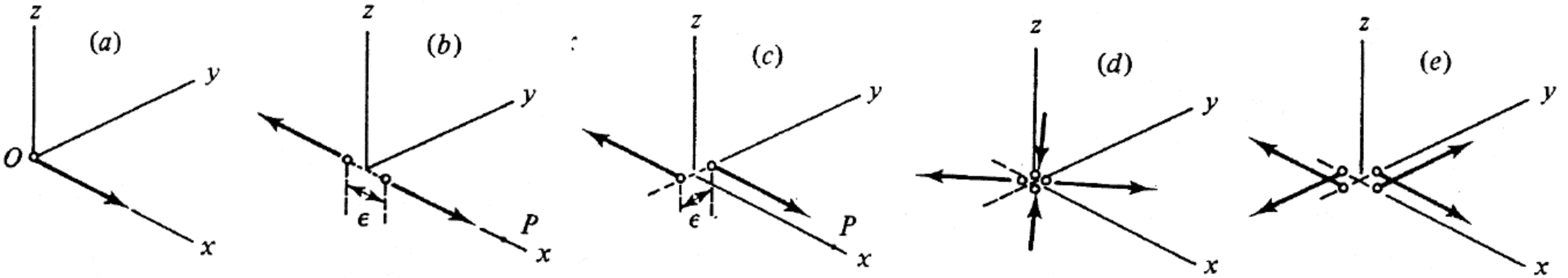


S-waves:

- similar distribution
- 4 domains of different first motions
- nodal lines offset by 45°
  against nodal planes of P-waves

Force models of earthquakes

- equivalent volume forces (Nakano 1923)
- radiation from punctually acting single forces and their combinations



Single force

Equal opposite forces, tension

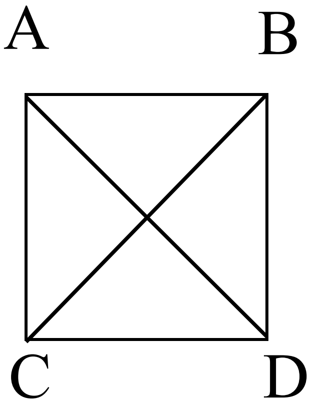
Equal opposite forces, torque

2 force pairs, tension and compression

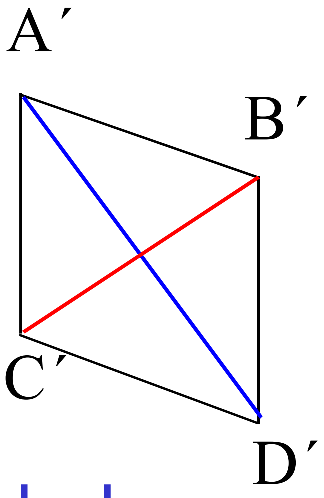
2 force pairs, torques

Influence of shear on an infinitesimal volume

Volume element



Shear parallel to sides BD, AC

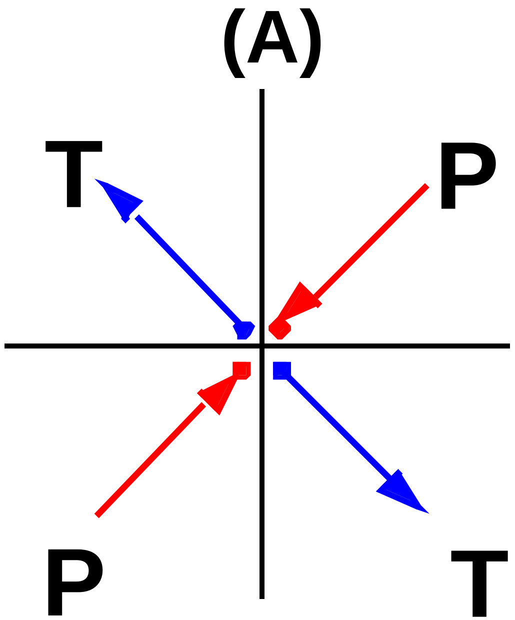


A'D' is extended

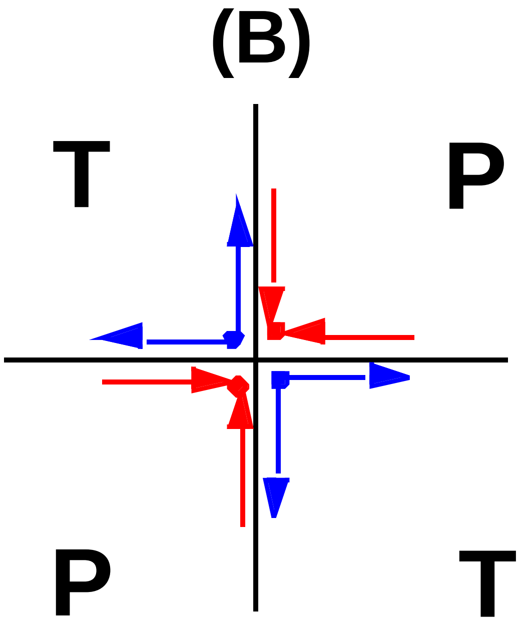
B'C' is compressed

Equal value of relative change in length, different signs

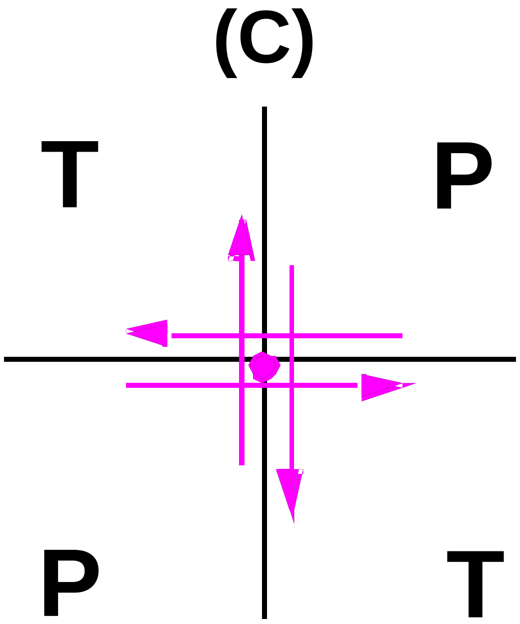
System of equivalent orthogonal pressure and tension (**P and T axes**):



Decomposition of forces into parts parallel to the axes



Two orthogonal force dipoles



For shear on horizontal line:
equivalent system of compression/extension
-> equivalent double couple

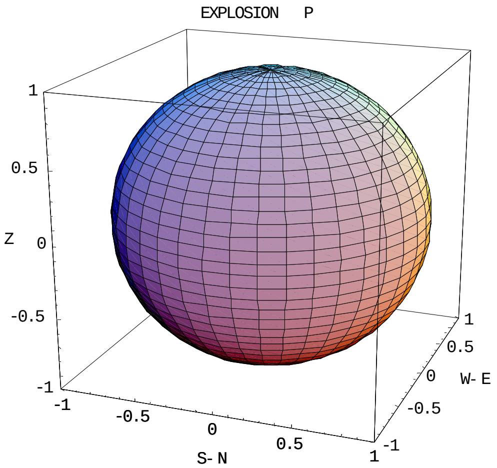
Symmetry - no discrimination between 2 orthogonal planes!

- **Caution**: simplified model of forces being equivalent to radiation process
- Theoretical connection between forces and displacement explained in fifties
- **Double-couple** force model required to explain wavefield due to **shear sources**

Radiation pattern

= amplitude of displacement due to the radiated wave on a unit sphere in direction of propagation

e.g. explosion (only P waves):



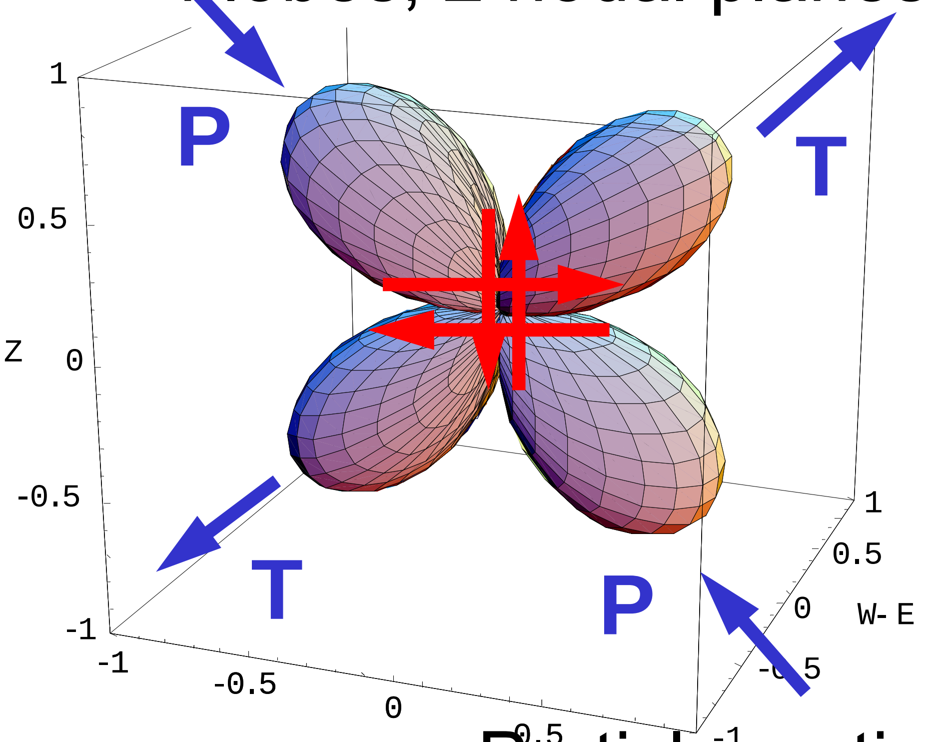
Interpretation:

- Line from origin to observation point cuts radiation pattern in a certain point
- Distance of this point from origin = measure of radiation strength
- Up: first motion = compression, down: dilatation

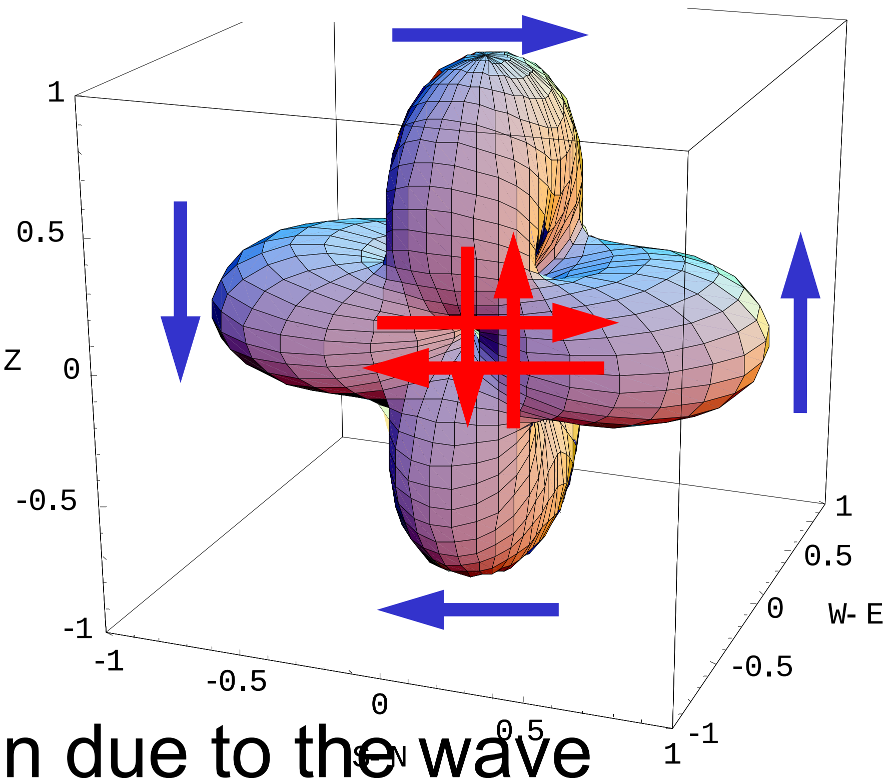
Radiation from Double couple

horizontal or vertical shear source

P waves:
4 lobes, 2 nodal planes



S waves:
2 nodal lines



→ Particle motion due to the wave

→ Rupture: displacement across the fault

Fault plane solutions

- Determination of fault and auxiliary plane
- Direction of motion
- Equivalent system of pressure and tension

Classical **method:**

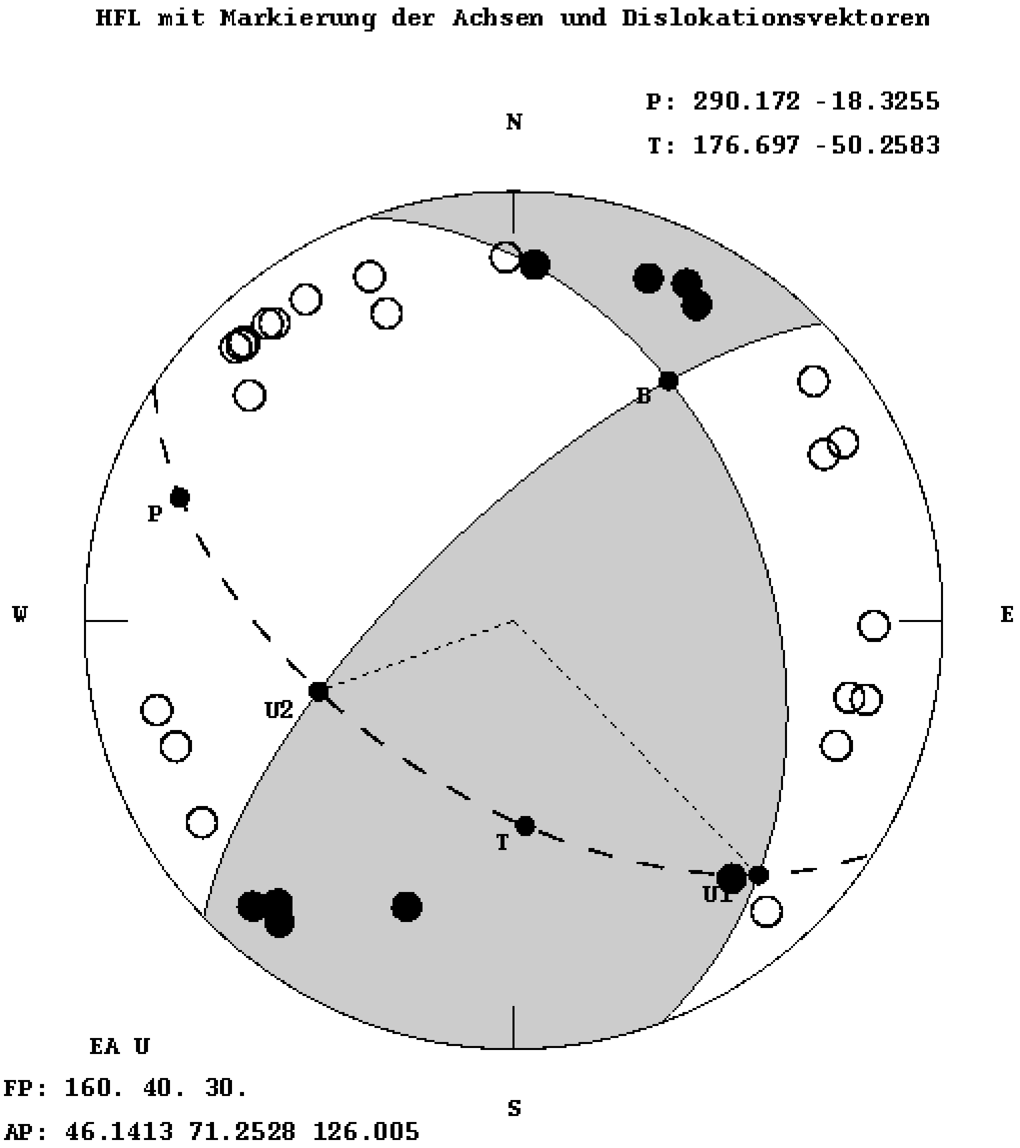
based on P-wave first motions

a) trace first motions back to focal sphere

b) determine quadrants of different first motion

c) thus P- and T-axes, dislocation vectors known

Result – Fault-Plane solutions



P- and T-axes

= directions of maximal compression/extension in radiation pattern

Generally P, T **NOT** equal tectonic stress axes, only under 45° - hypothesis

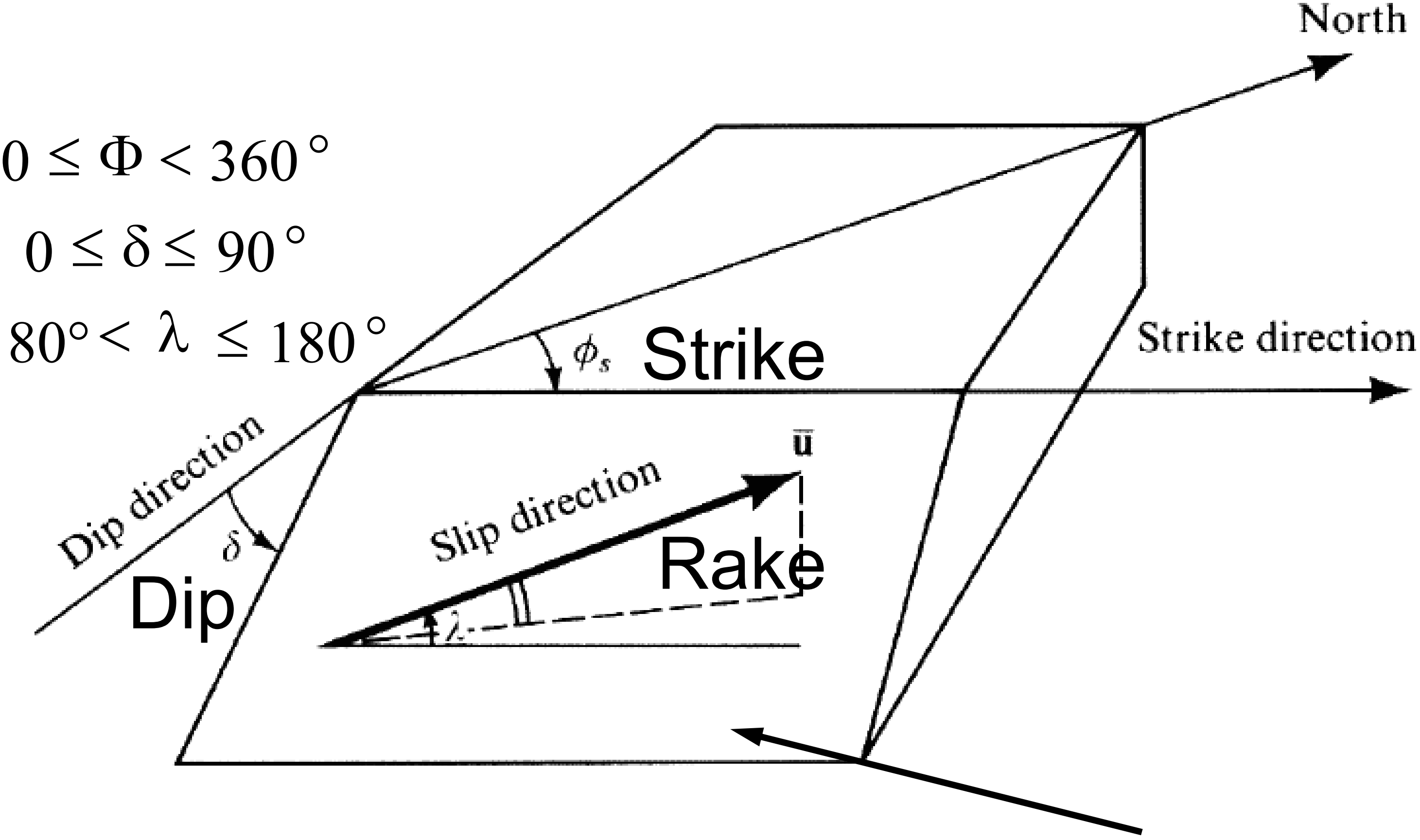
e.g. San-Andreas fault: max. principal stress ⊥ fault

Point source - shear dislocation Definition of strike, dip, slip (Streichen, Fallen, Neigung)

$0 \le \Phi < 360°$

$0 \le \delta \le 90°$

$-180° < \lambda \le 180°$



Strike

Dip

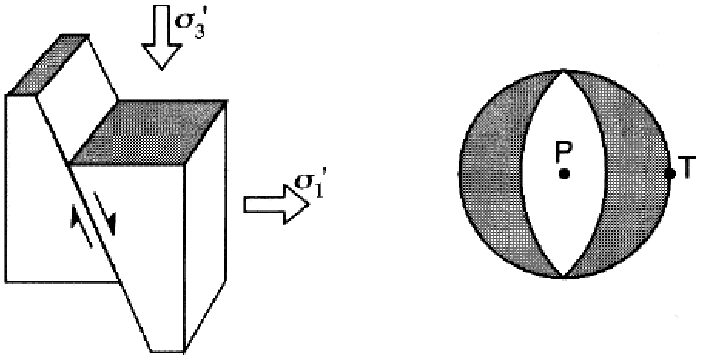
Rake

Rupture surface A_0

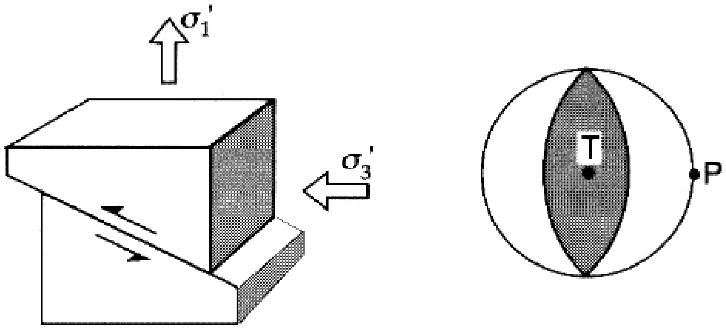
Interpretation of fault plane solutions - seismotectonics

- **Dynamic** interpretation of a single FPS problematic
- Combination of many FPS: stress tensor inversion
- FPS important for **kinematic** interpretation: sense of faulting, direction of motion, deformation pattern

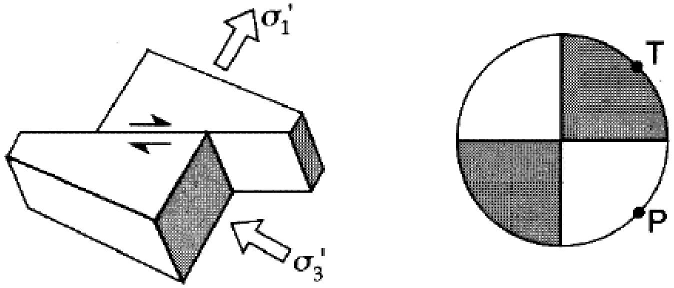
Main types of fault mechanisms



Normal fault



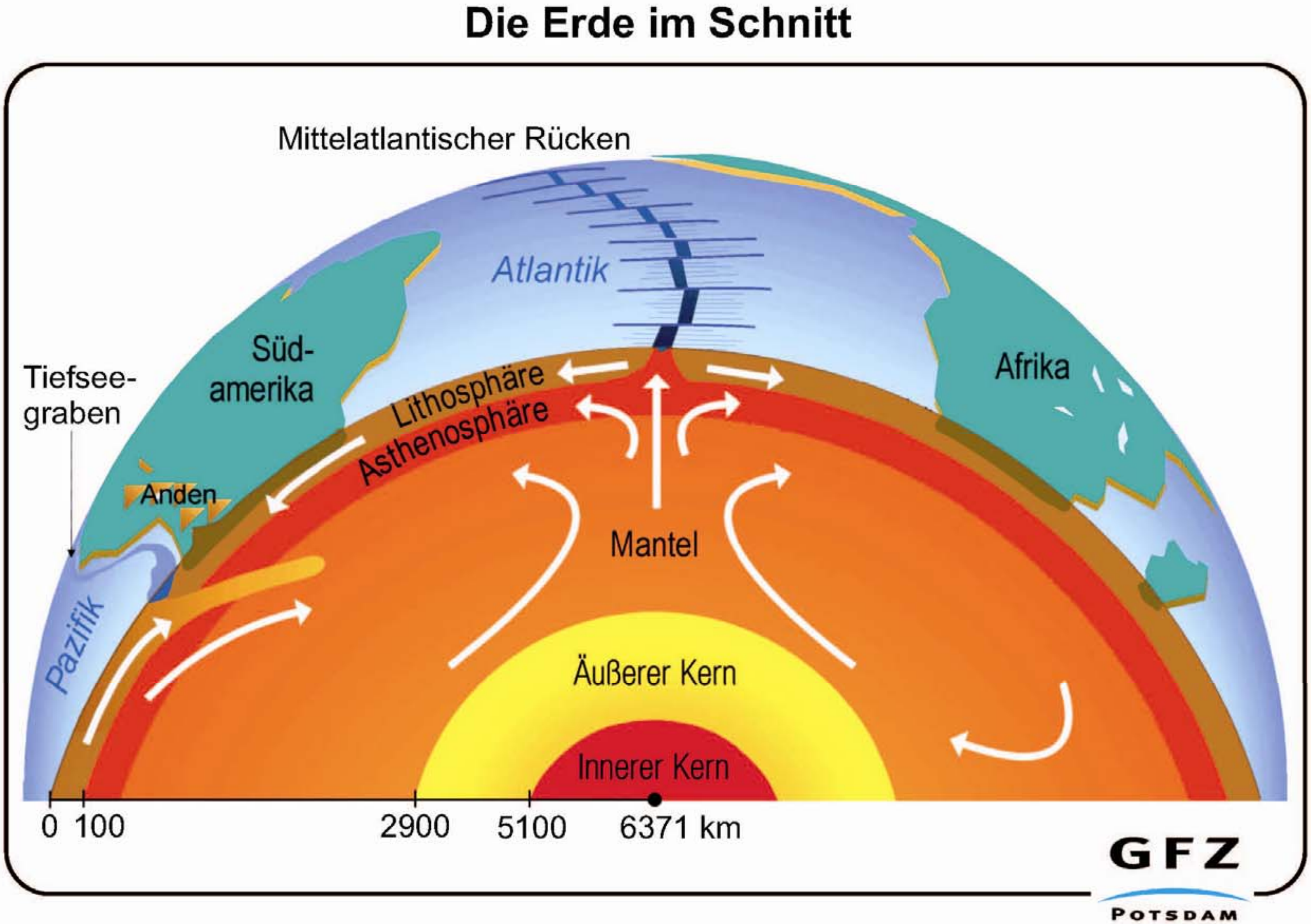
Reverse fault



Strike-slip fault

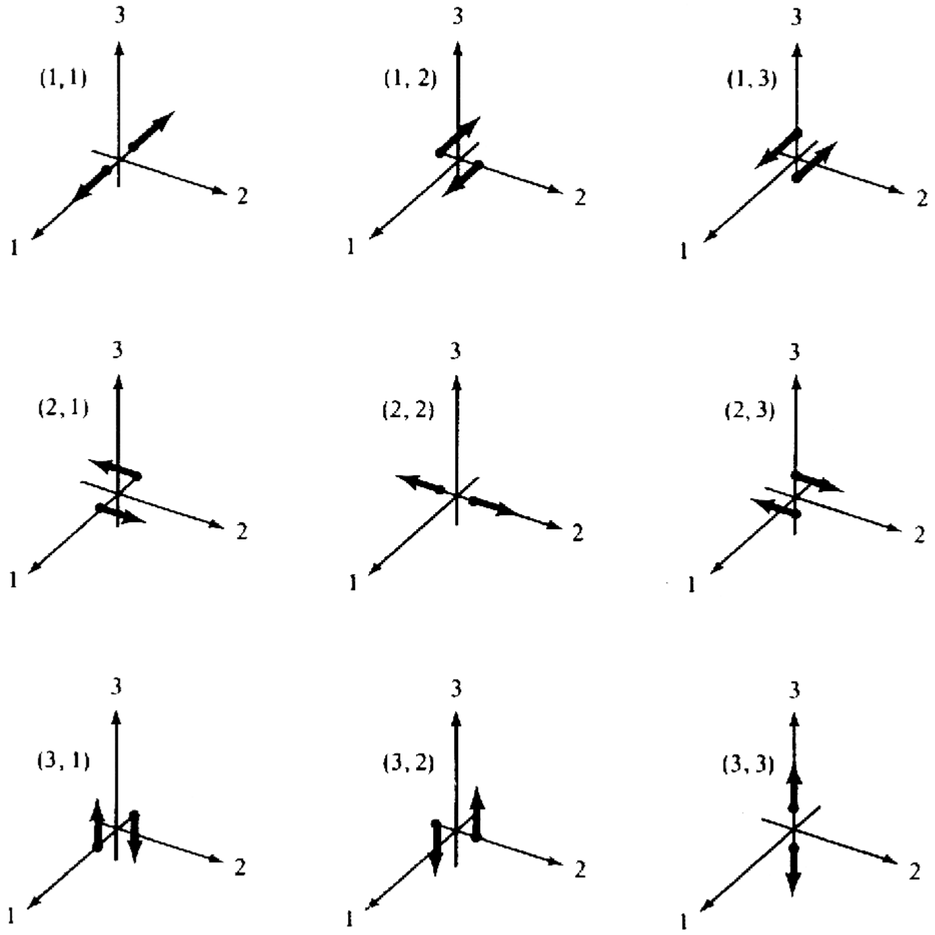
Active plate margins:

3 types: constructive, destructive, conservative



Double couple explains shear fracture, but no other seismic sources (explosions, implosions, hydrofrac)

→ Generalization: different dipole combinations



Seismic **moment tensor** $\mathbf{M_{jk}}$

Scalar Seismic moment:

$$M_T = \sqrt{\sum_{j,k} M_{jk} M_{jk} / 2}$$

$$\approx M_0 = \mu \overline{d_0} A_0$$

equal for shear sources

Point source → **Extended** source

Wavelength > focus dimension

Wavelength ~~>~~ focus dimension

Models for extended sources:

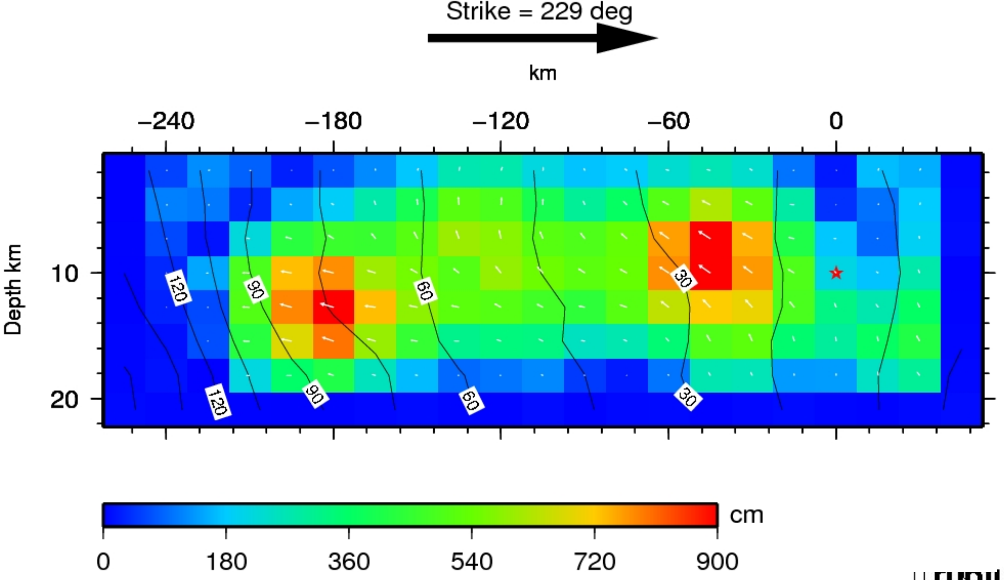
- Kinematic: prescribed dislocation on focal plane
- Dynamic: prescribed stress

Wanted:

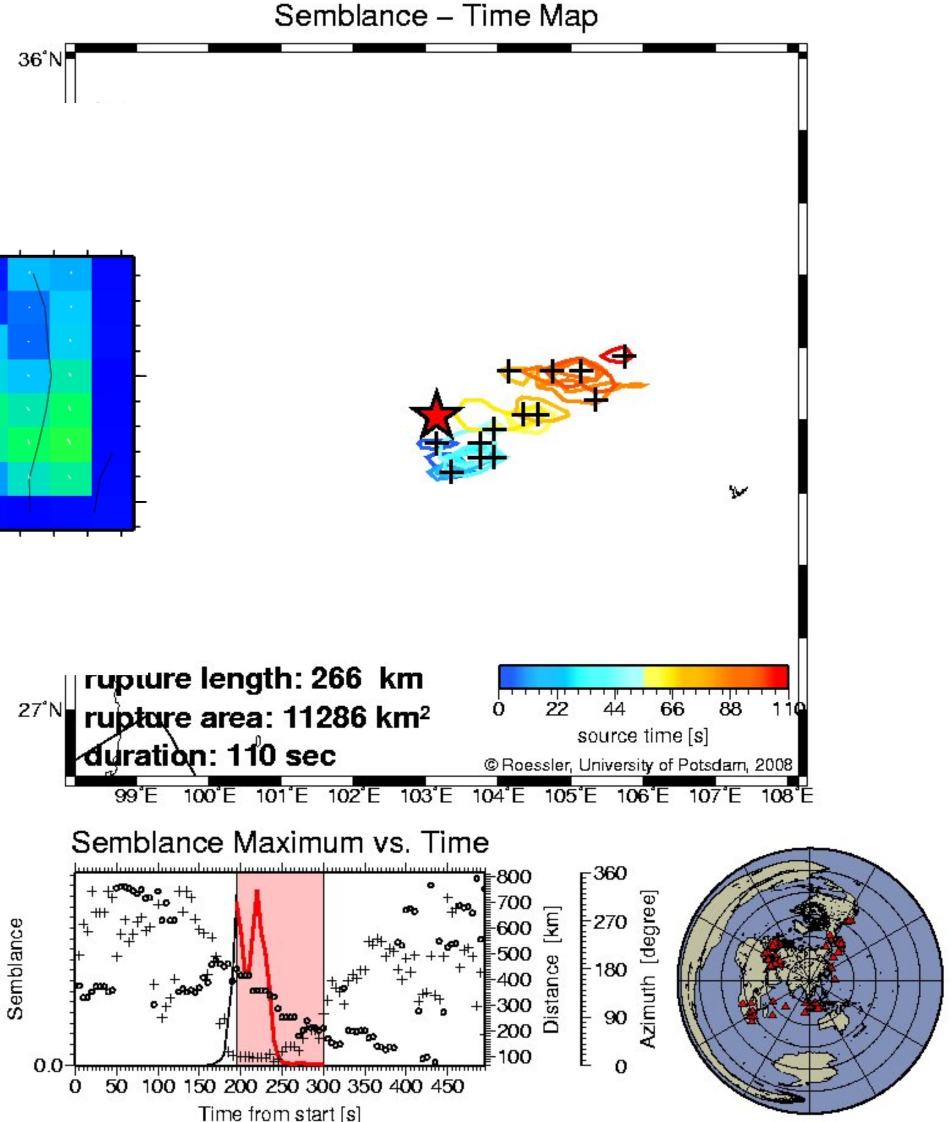
- dislocation at observation point
- spectral amplitudes

Sichuan earthquake (China)
12/05/2008, Mw8.0

Finite source model (Chen Ji, UCSB)



Rupture propagation


Semblance – Time Map

rupture length: 266 km
rupture area: 11286 km²
duration: 110 sec

© Roessler, University of Potsdam, 2008

Semblance Maximum vs. Time

www.geo.uni-potsdam.de/Forschung/Geophysik/GITEWS/tsunami.htm

Stress field

- So far: kinematics
- Stress field => **dynamics**
- Stress field ⬄ geological structures: What comes first?

⇨

a) **Fundamentals:** description of stress, stress tensor, principal stress axes

stress measurement

b) **Interpretation** of the stress field

in plate tectonic context

A. Fundamentals

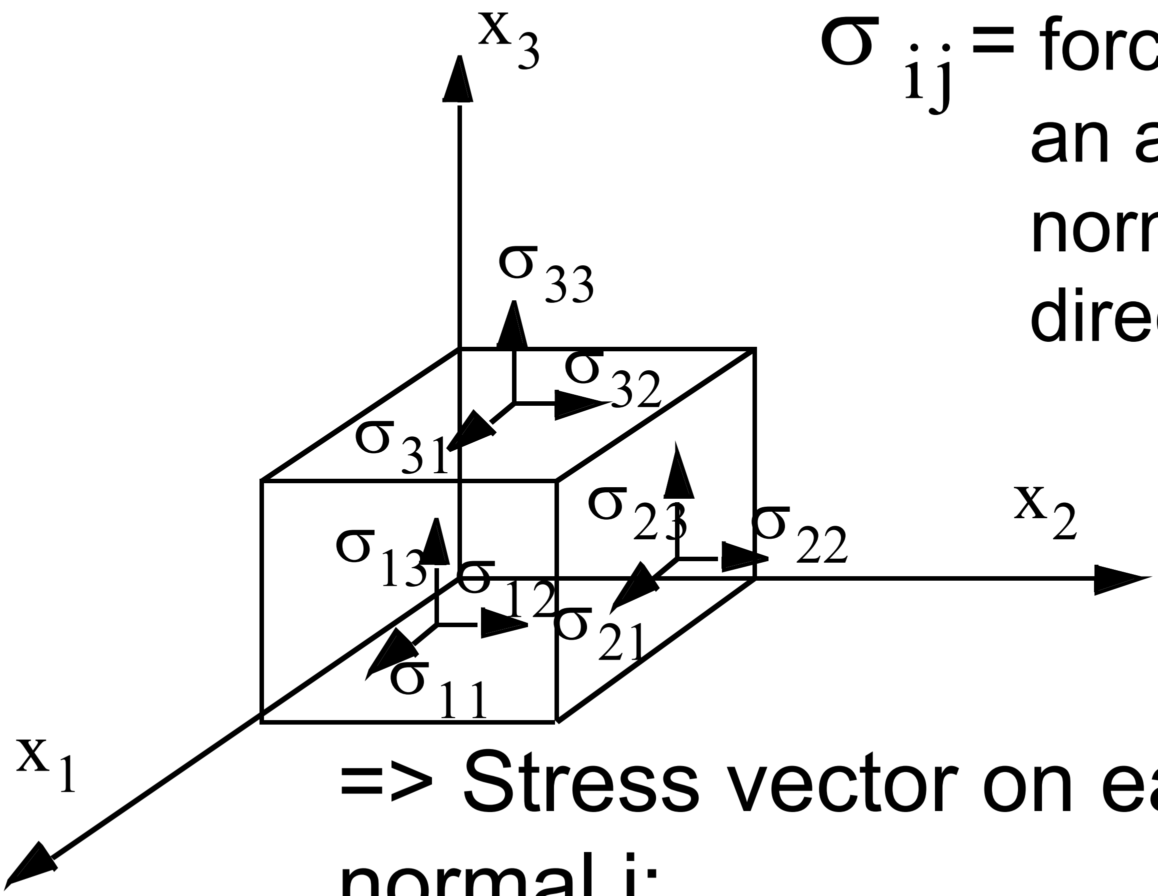
Definition of stress: Force per area

=> What unit? Which area?

=> Complete description of stress state requires specification of forces acting on an arbitrary area

=> Stress tensor σ_{ij}

Meaning of σ_{ij}:



σ_{ij} = force in j direction on an area whose normal points to i direction

=> Stress vector on each area with normal i:

$$\vec{T}^{(i)} = (T_1^{(i)}, T_2^{(i)}, T_3^{(i)}) = (\sigma_{i1}, \sigma_{i2}, \sigma_{i3})$$

Stress vector on an arbitrary area with normal vector $\vec{n}$:

$$\vec{T}(\vec{n}) = \lim_{ds \to 0} \frac{\vec{F}}{ds}$$

with $\vec{F}$ = force acting on the area ds .

If stress tensor known:

=> Forces parallel to coordinate axes known

=> Easy calculation of stress vector $\vec{T}(\vec{n})$ on any area normal to $\vec{n}$:

$$\vec{T}(\vec{n}) = \underline{\sigma} \cdot \vec{n}$$

Characteristics of Stress tensor

- Stress and strain are related through elastic material properties (small deformations)

Stress-strain relations (Hooke‘s Law):

$$\sigma_{ij} = c_{ijkl}\tau_{kl}$$

τ_{kl} : strain

c_{ijkl} : general elastic tensor

anisotropy: up to 27 independent components

isotropy: 2 independent components (Lamé parameter λ and μ)

Characteristics of Stress tensor

Number of quantities needed to determine $\underline{\sigma}$:

- Most general case: 9
- In practice: symmetrical stress tensor, i.e. $\sigma_{ij} = \sigma_{ji}$

$\Rightarrow$Rotation to **principal axes system**

(eigenvectors and eigenvalues)

In principal axes system:

$$\underline{\sigma} = \begin{pmatrix} \sigma_1 & 0 & 0 \\ 0 & \sigma_2 & 0 \\ 0 & 0 & \sigma_3 \end{pmatrix} \quad \sigma_1, \sigma_2, \sigma_3 \text{ principal stresses}$$

$$\text{convention: } \sigma_1 > \sigma_2 > \sigma_3$$

σ_1 maximum compression

σ_3 minimum compression (maximum dilatation)

$\sigma_1, \sigma_2, \sigma_3$ fully describe stress state

Decomposition of the stress vector

Normal stress $\vec{\sigma}_n$ = perpendicular to area (parallel to $\vec{n}$)

Shear stress $\vec{\tau}$ = tangential to area (perpendicular to $\vec{n}$)

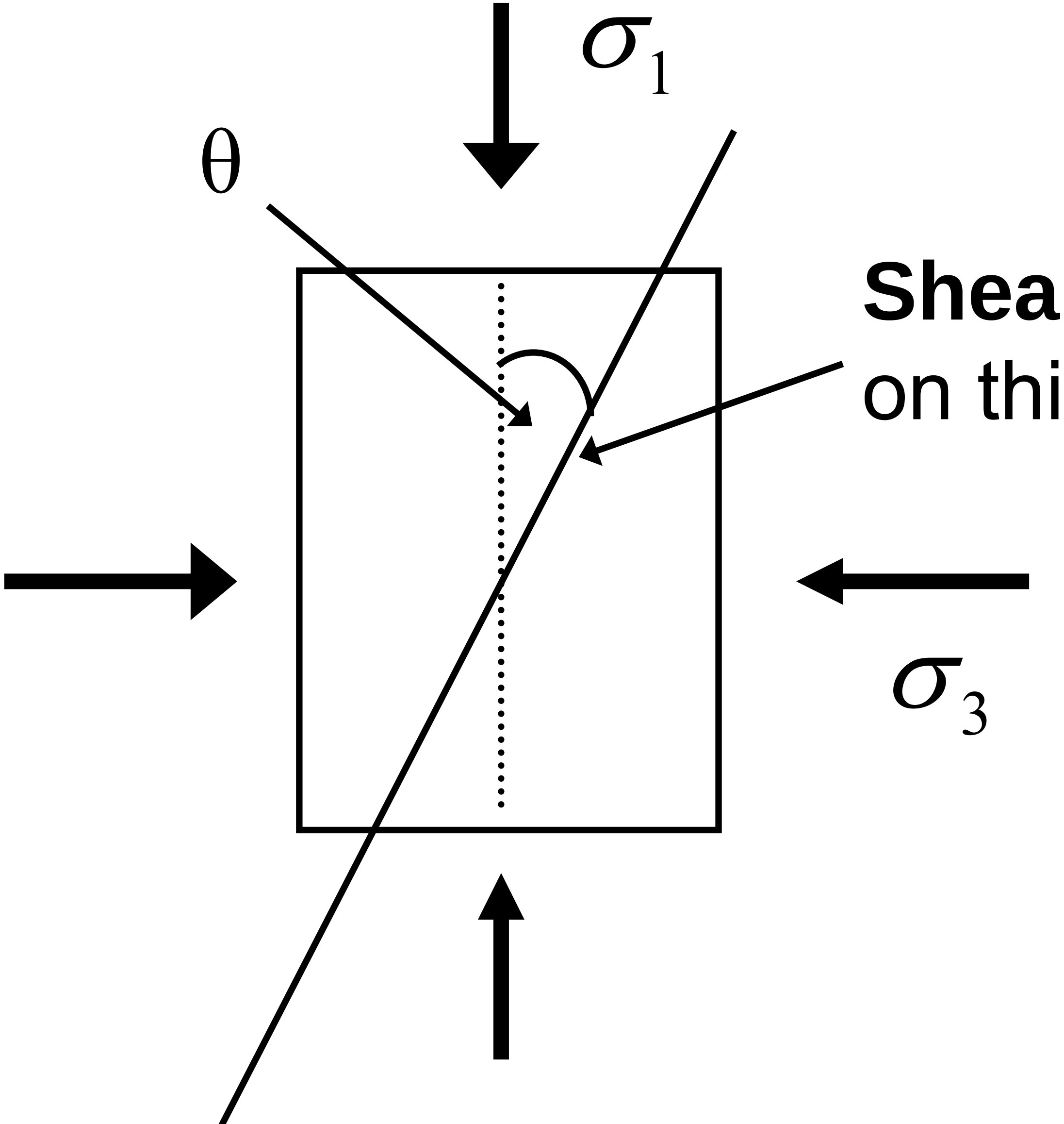
a) Pre-existing fault:

Direction of $\vec{\tau}$ determines direction of motion, $\vec{\sigma}_n$ acts against motion

b) Homogeneous rock:

rupture along the area where shear stress exceeds rigidity

Shear stress τ on arbitray plane?



Shear Stress τ
on this plane?

Numerical determination of τ

a) determine $\underline{\sigma}$ and $\vec{n}$

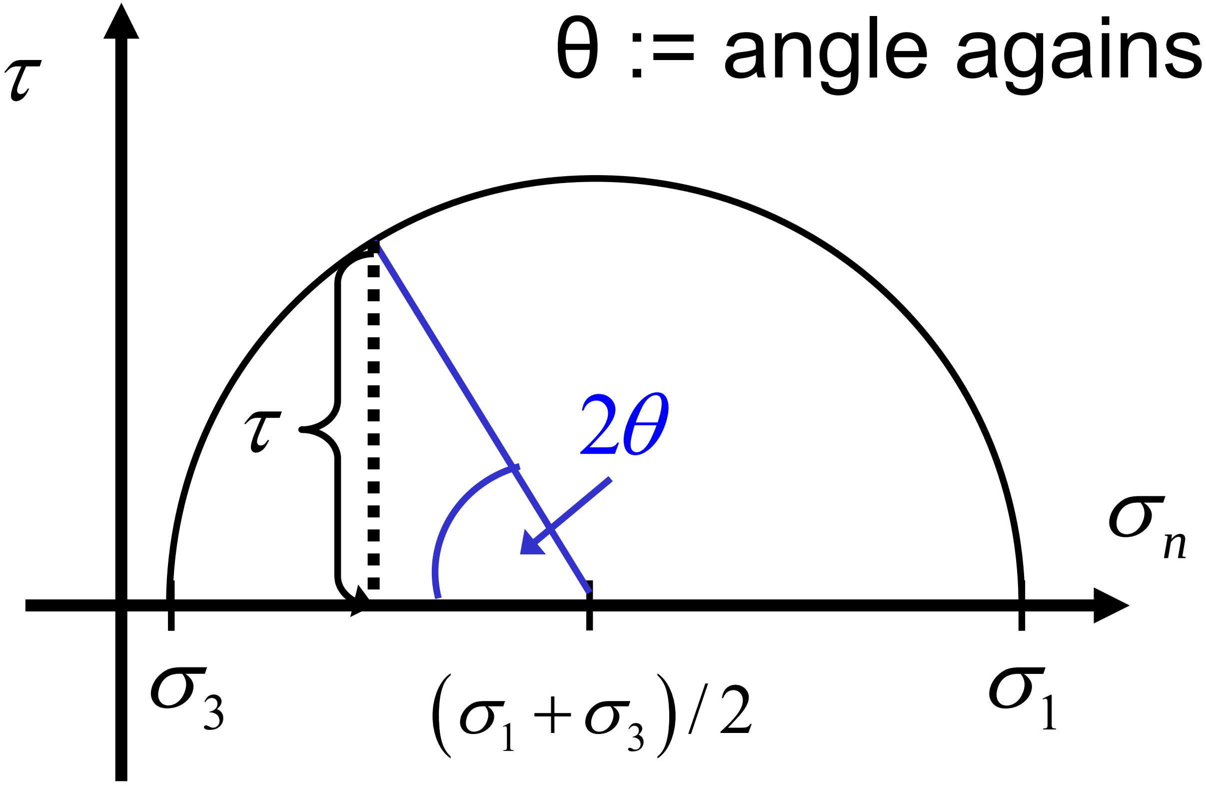
b) determine $\vec{T}\left(\vec{n}\right)$ as $\underline{\sigma} \cdot \vec{n}$

c) decompose $\vec{T}\left(\vec{n}\right)$ into σ_n and τ

Interpretation Mohr Circle

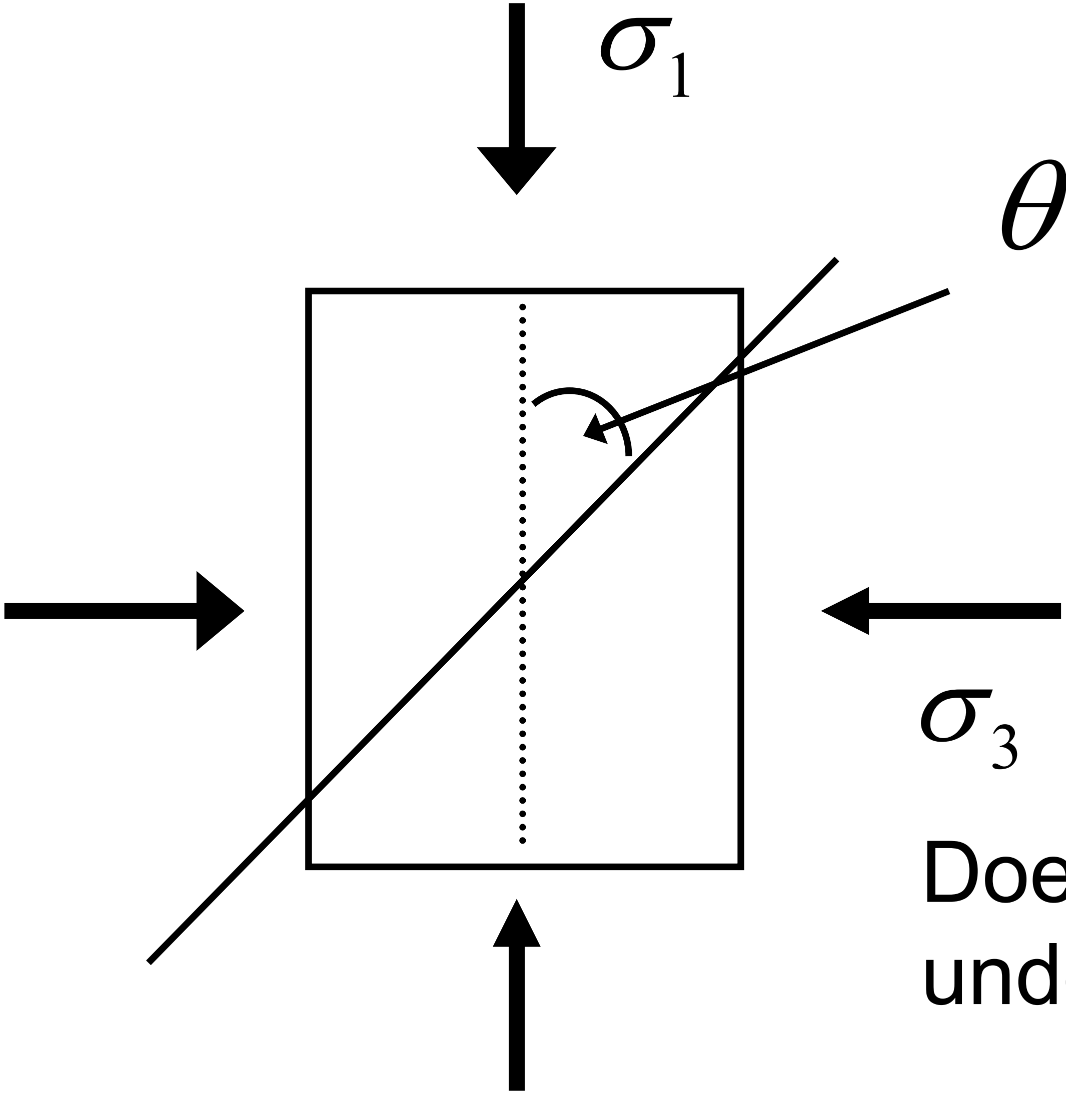
Radius: $(\sigma_1 - \sigma_3) / 2$

θ := angle against σ_1



- The shear stress τ at maximum at $\theta=45°$ direction.

Maximum shear stress τ condition?



Does fracture appear under 45˚?

Coulomb fracture criterium

$$\tau_{crit} = \tau_0 + \mu \cdot \sigma_n$$

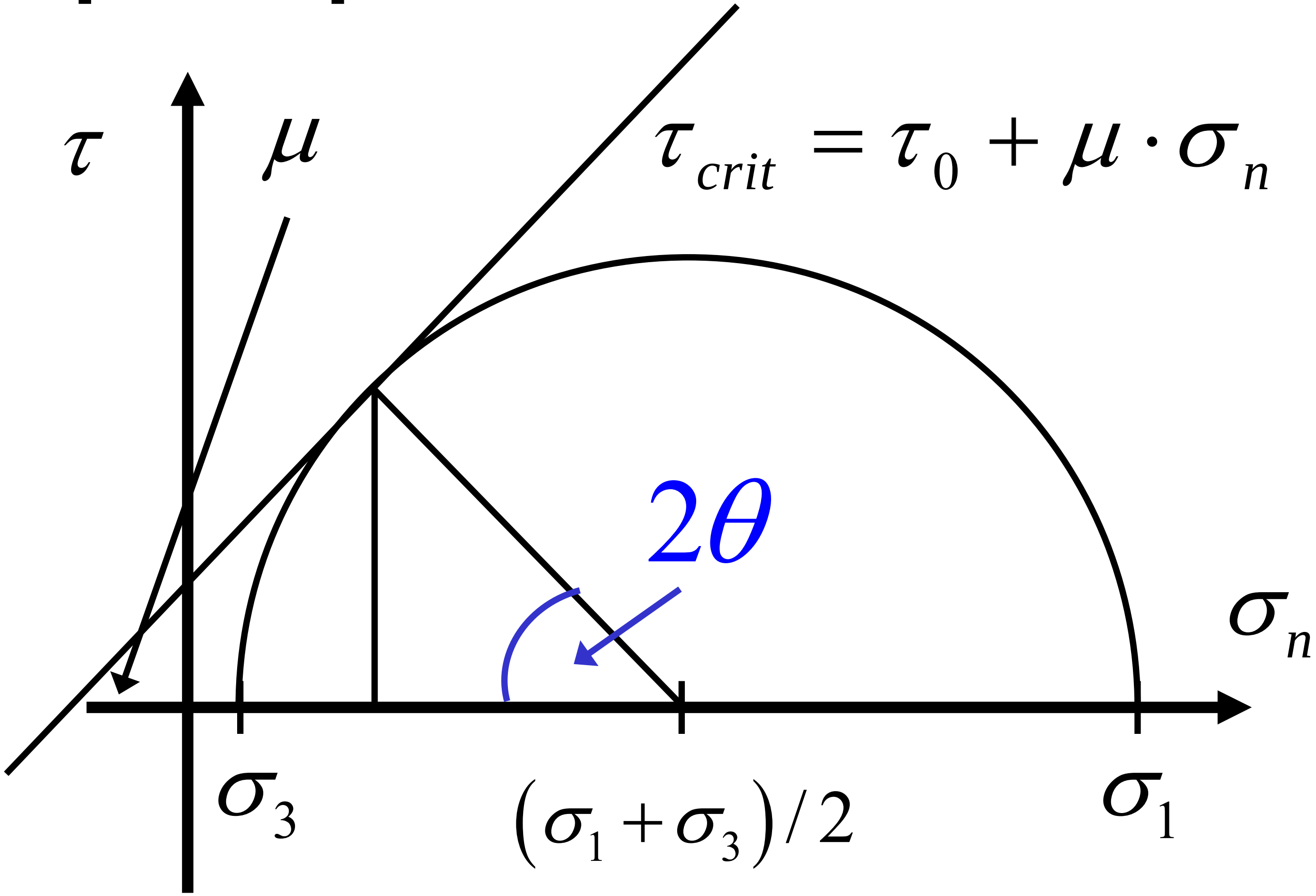
τ_{crit} = critical shear strength

τ_0 = cohesion

μ = coefficient of internal friction

σ_n = normal stress

Rupture plane and Mohr circle



Real materials do **not** rupture under 45° to σ_1!

Θ depends on μ, normally θ≈30°

In nature:

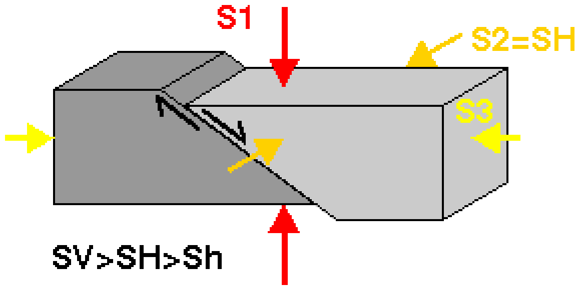
- Orientation of principal stress axes approx. horizontal or vertical

$$\text{Vertical stress} = \begin{cases} \text{maximum} \\ \text{medium} \\ \text{minimum principal stress} \end{cases}$$

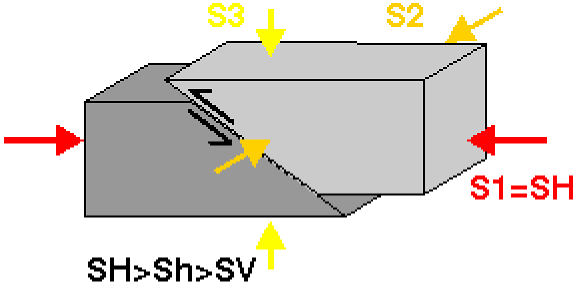
=> different stress regimes

=> different tectonic structures (stress regime)

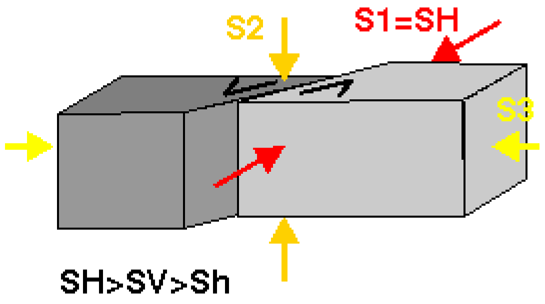
Fault types & stress regimes



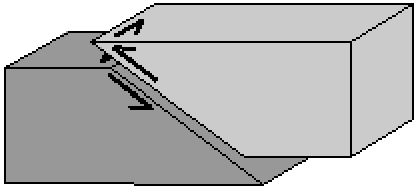
NF: Normal faulting



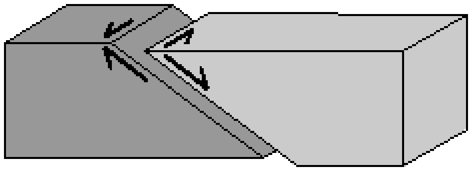
TF: Thrust faulting



SS: Strike-slip faulting (includes minor normal or thrust component)



TS: Predominately thrust with strike-slip component



NS: Predominately normal with strike-slip component

If Coulomb criterium applies: first estimate stress field from fault-plane solution dependent on coefficient of internal friction.

Determination of the stress state

1. Analysis of harnesses on faults (Striemung)
2. Fault-plane solutions
3. Borehole breakouts
4. Hydraulic fracturing
5. Overcoring
6. Volcano alignment
7. Mineral alignment after recrystalization

1. Analysis of harnesses on faults (Striemung)

Assumptions:

a) fault at ca. 30° to σ_1

b) motion parallel to τ_{max} in fault plane

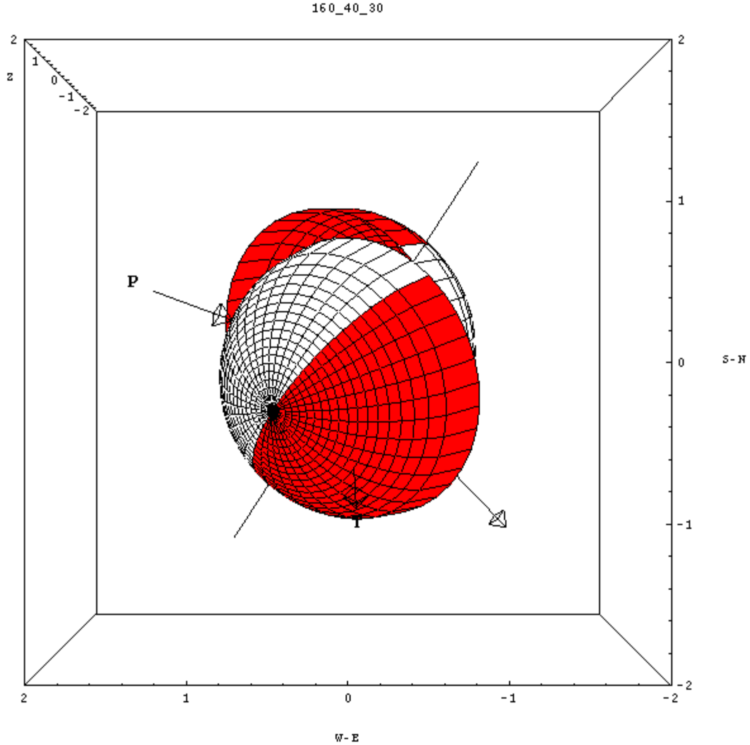
=>Information about paleo stress field

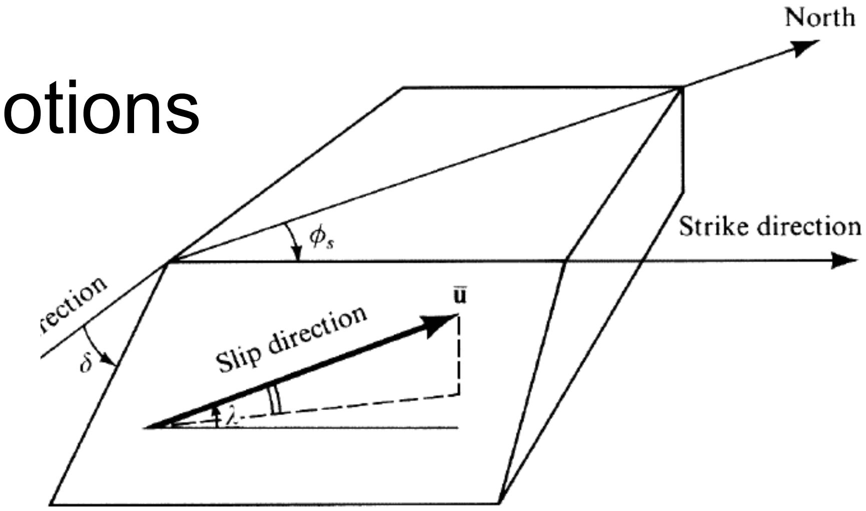
For recent stress field: **fault plane solutions**

2. Fault plane solutions

Principle:

- Reconstruction of fault kinematics from observations of seismic waves
- Mainly P-wave first motions





$$0 \le \Phi < 360^\circ$$

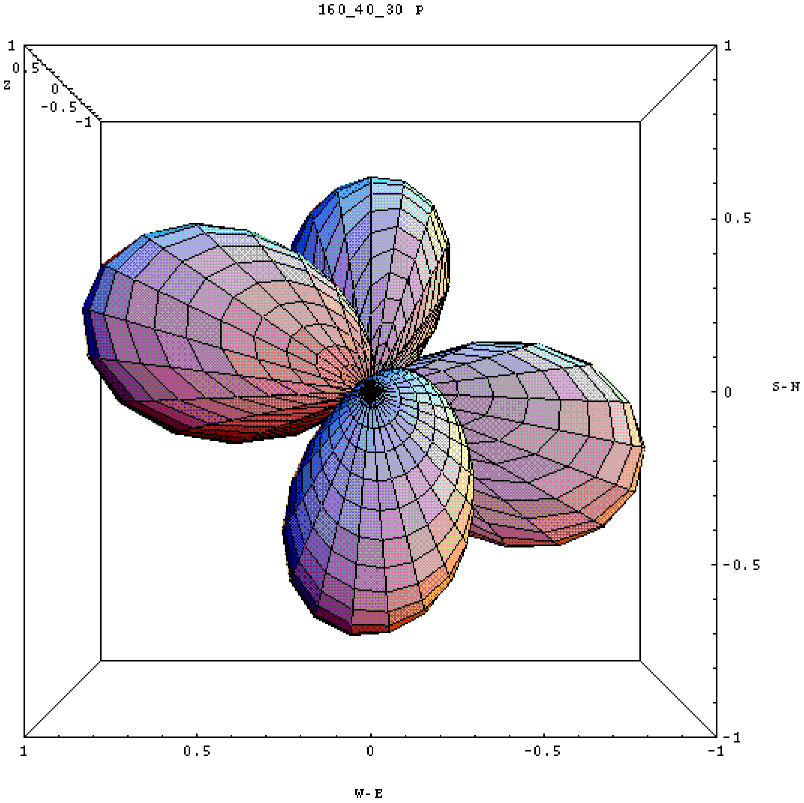
$$0 \le \delta \le 90^\circ$$

$$-180^\circ < \lambda \le 180^\circ$$

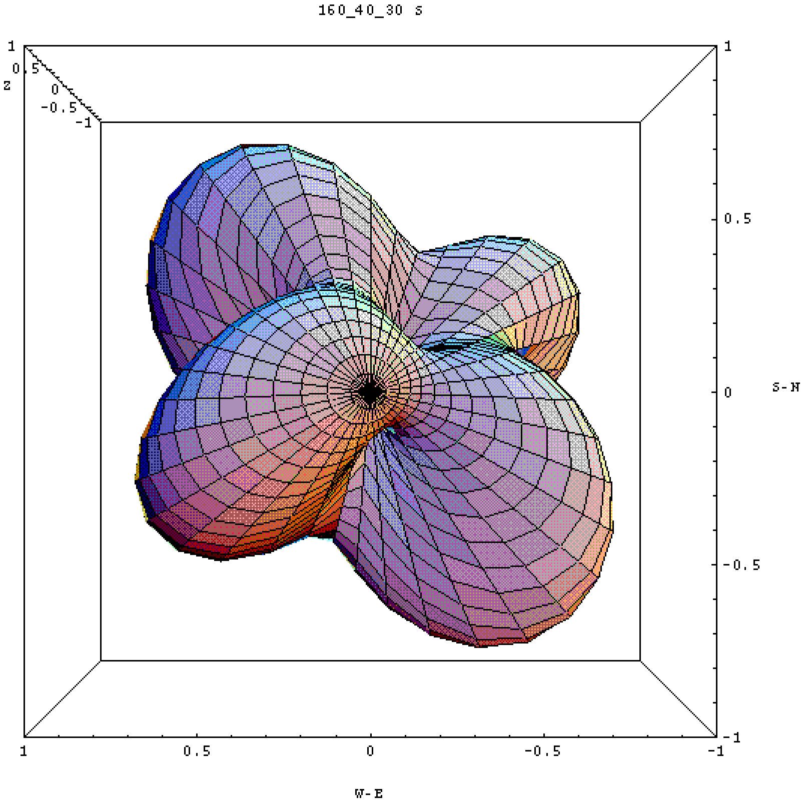
2. Fault plane solutions

P-, T-axes:

Directions of maximal compression / extension, explain radiation pattern of seismic waves



P-wave radiation pattern



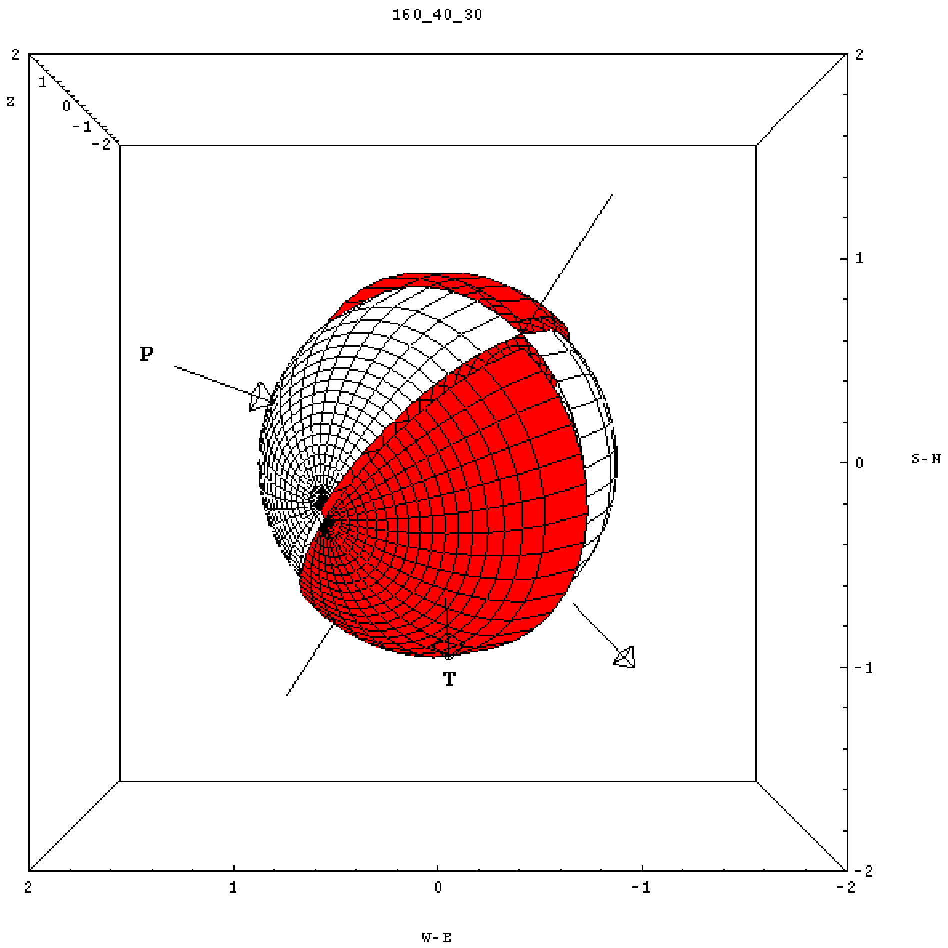
S-wave radiation pattern

$$\left.\begin{array}{l} P = \sigma_1 \\ T = \sigma_3 \end{array}\right\} \text{ if } \textbf{45° hypothesis} \text{ applies}$$

- In reality:

  internal friction => σ_1 at appr. 30° to fault
- Angles up to 0° possible

In both cases 4 quadrants of different deformation:



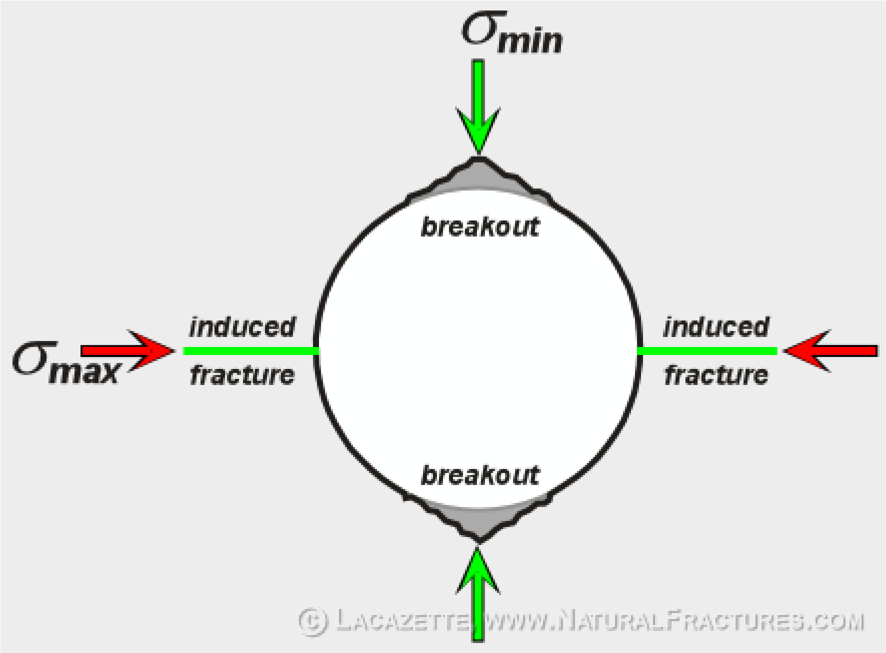
=>Ambiguity has no effect on P- and T-axes

Summary

=>**Dynamic** interpretation of single FPS questionable, only **P-, T-axes** can be derived

=>Principle stress axes σ_1, σ_3 from simultaneous **stress tensor inversion** of several FPS

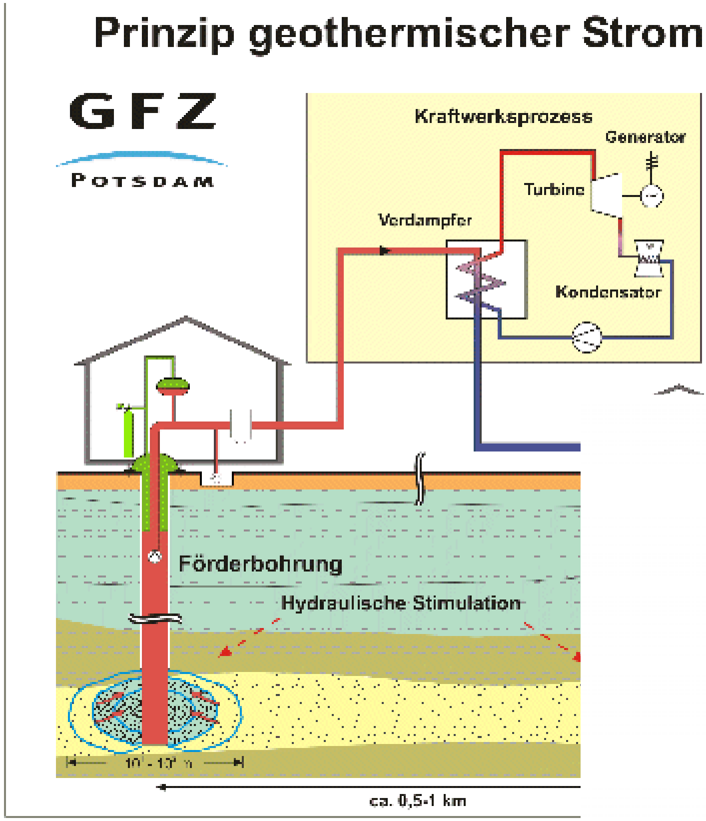
3. Borehole breakouts



- At borehole in tectonically stressed material **concentration of stress**

- Breakouts at azimuth corresponding to minimum horizontal stress s_{hmin} =>conclusion to s_{hmin}, s_{Hmax}
- Observation with televiewers

4. Hydraulic fracturing



Injection of liquid into borehole
=> Extensional fracture
parallel to s_{Hmax}

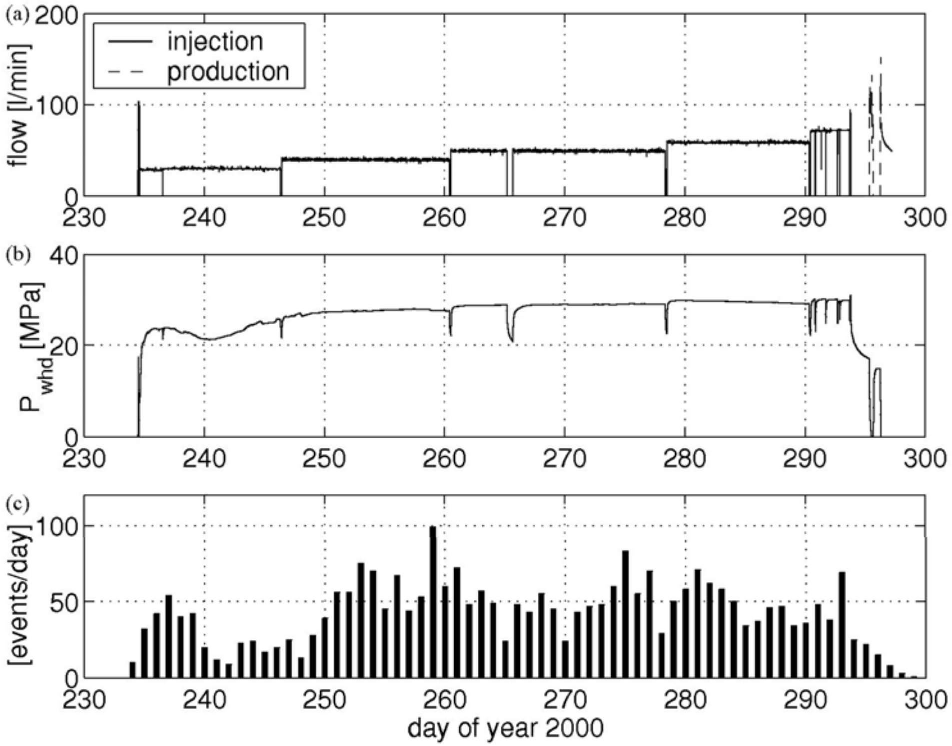
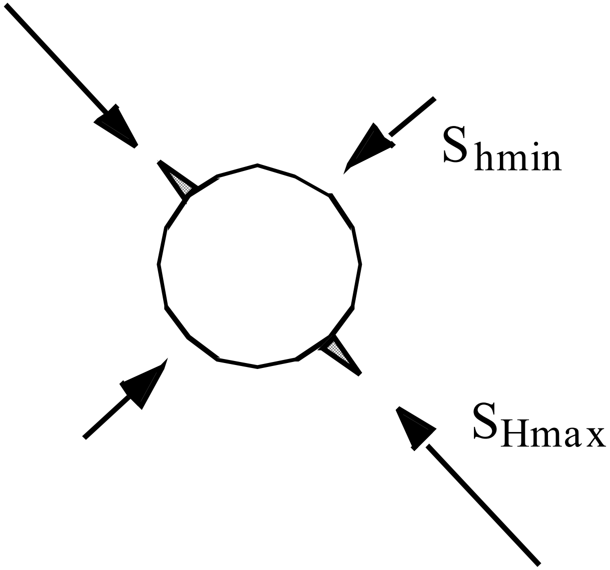


Figure 1. Injection rate (top), well head pressure (middle) and rate of induced events (bottom) as a function of time for the KTB fluid-injection experiment in 2000.

Baisch & Harjes, GJI, 2003

4. Hydraulic fracturing



- Injection of liquid into borehole
  => Extensional fracture parallel to s_{Hmax}

- Pumping curves => exact value for s_{hmin}
  => estimate of limits for s_{Hmax}
- Practical difficulty: detection of induced fracture
- Also hydraulic tests on preexisting fractures

5. Overcoring

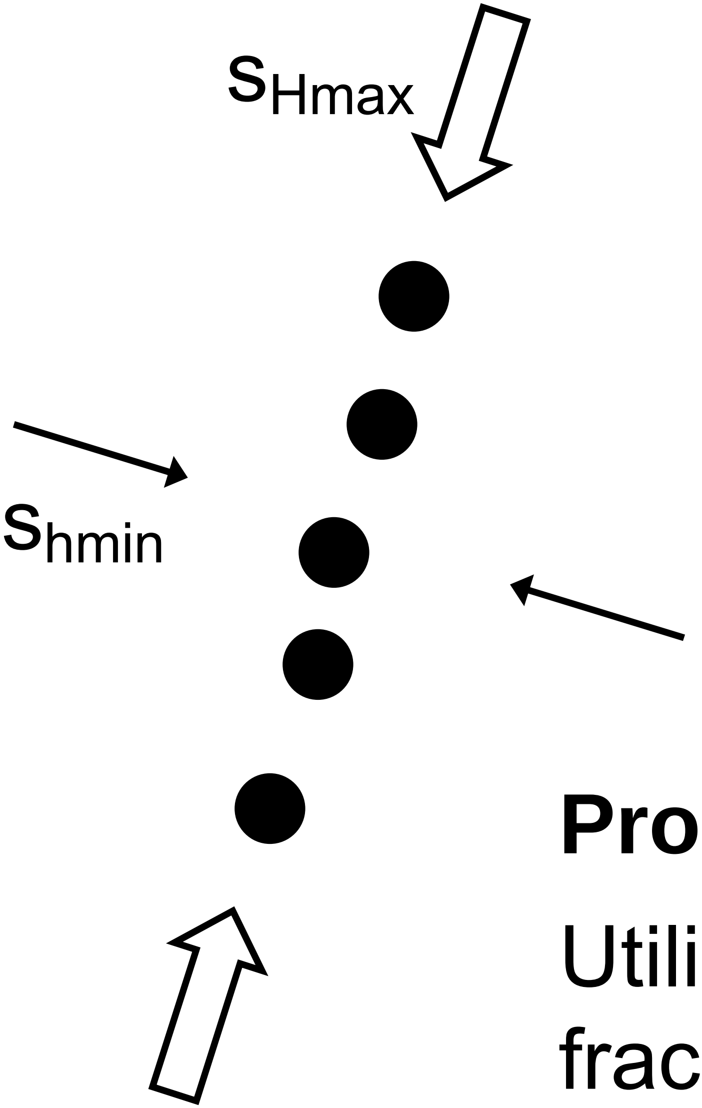
- Measurement of core relaxation immediately after extraction
- Requires exact knowledge of material tensor

Problems:

- Measurement on very small area => inexact
- Only near-surface samples => topographic effect on deformation can be large

=> correlation with tectonic stress problematic

6. Volcano alignment and dikes



- Analogous to hydro-fracturing
- Liquid = magma
- In young volcanic regions

Problem:

Utilisation of pre-existing old fractures possible

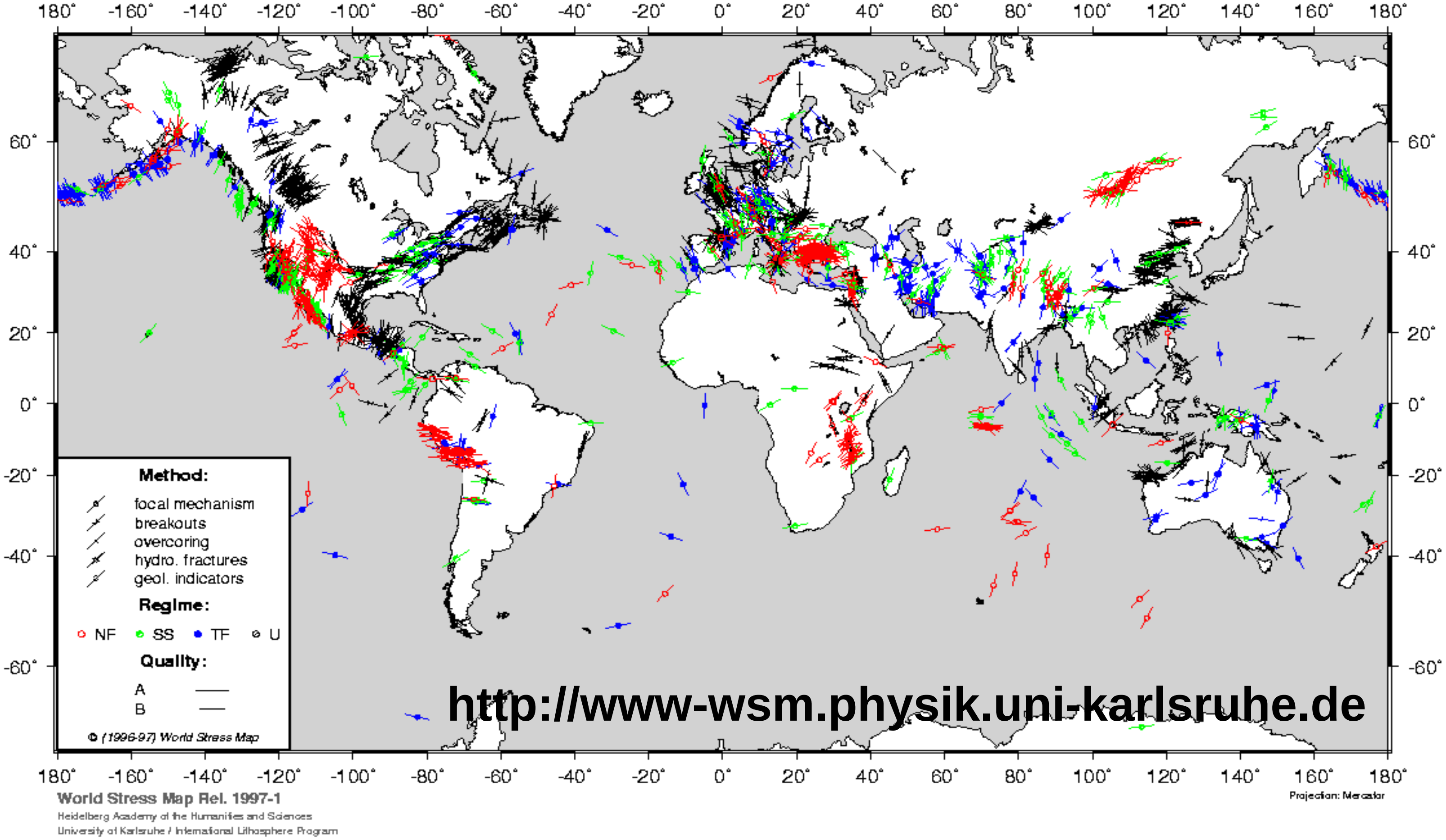
7. Pressure solution, quartz twinning

- Recristallization in direction of minimal pressure

Summary

- Many stress indicators exist
- Different information, from paleo stress directions to complete in situ stress tensor
- Since 1986 systematic global lithosphere stress field investigation

B World Stress Map Projekt



http://www-wsm.physik.uni-karlsruhe.de

World Stress Map Rel. 1997-1
Heidelberg Academy of the Humanities and Sciences
University of Karlsruhe / International Lithosphere Program

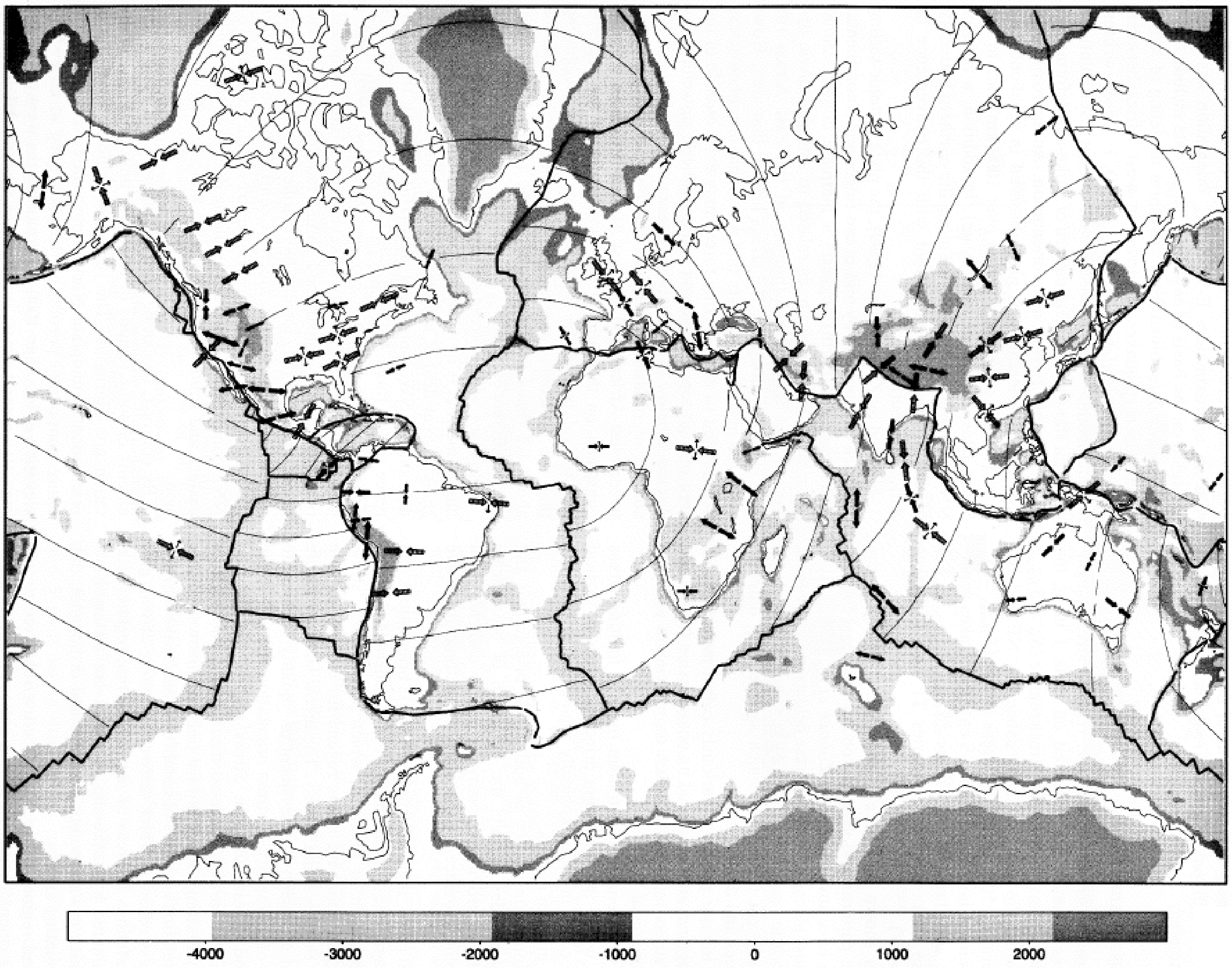
Compilation of the global stress field, S_{Hmax} directions

30 groups, > 18 countries, 54% FPS, 28% borehole, breakouts, 4.5% hydrofracs, 3.4% overcoring, 4.1% volcano alignment

Global results, first order effects

- In brittle crust almost everywhere consistent stress field
- Intraplate areas: horizontal s_1 => strike slip, thrust
- Extension often in areas of high topography
- Stress provinces with consistent s_1, s_3

Generalized stress map

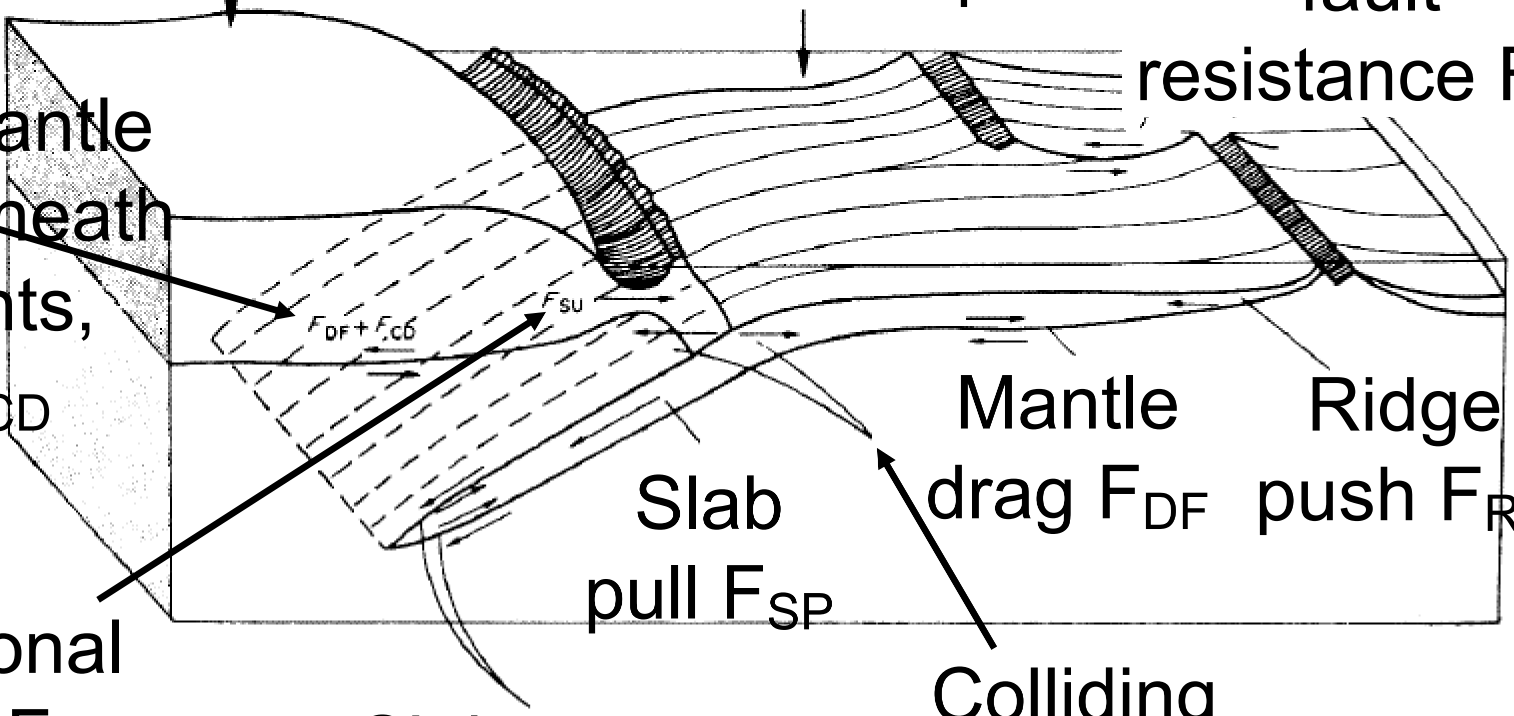


→← thrust

←→ normal fault

→↕← strike slip

Forces acting on a plate



Continental plate

Oceanic plate

Transform fault resistance F_{TF}

Extra mantle drag beneath continents, $F_{DF} + F_{CD}$

Mantle drag F_{DF}

Ridge push F_{RP}

Slab pull F_{SP}

Suctional force F_{SU}

Slab resistance F_{SR}

Colliding resistance F_{CR}

Bild: Fowler S. 368 (Fig. 8.20)

First order global stress patterns

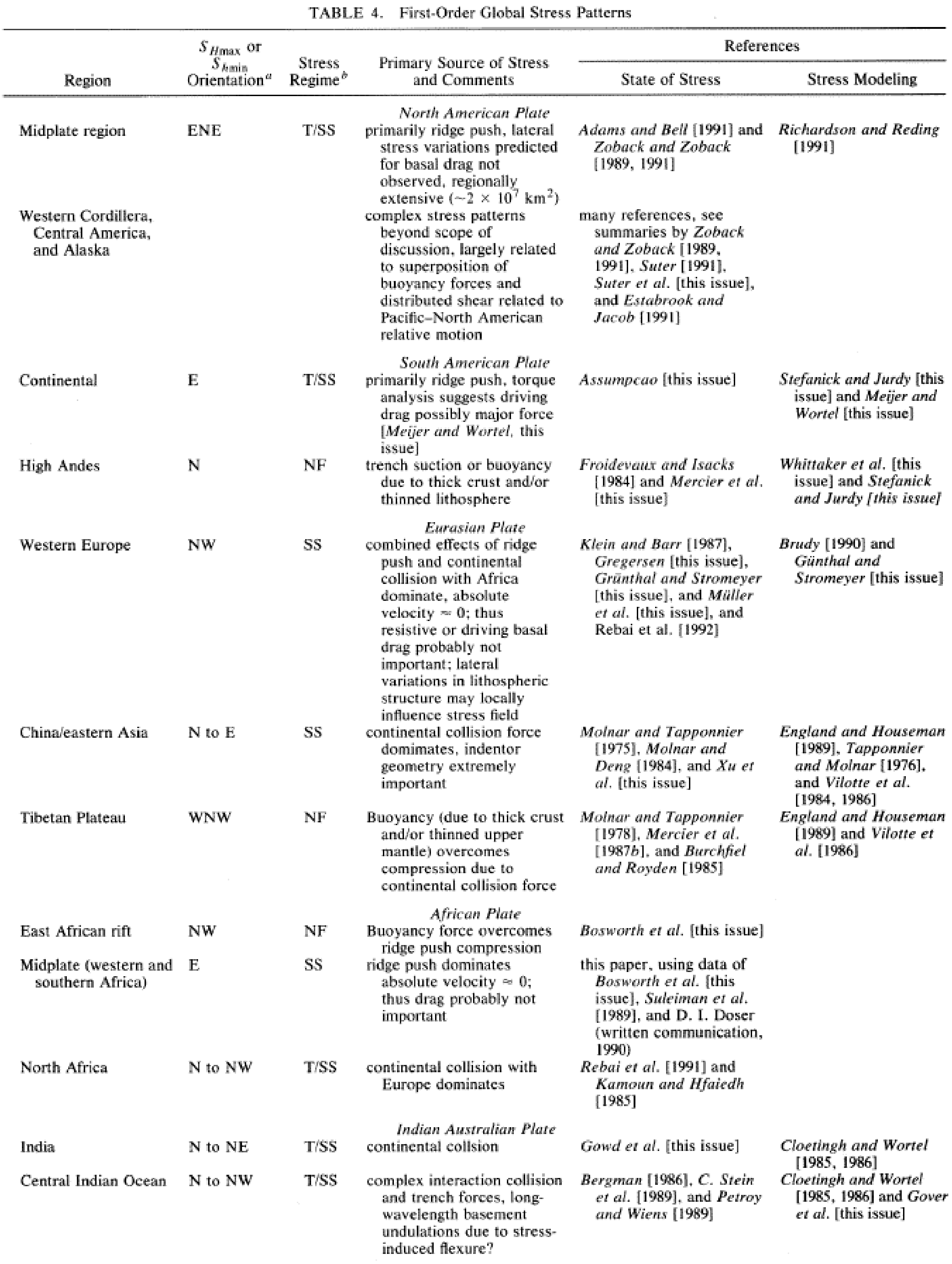


TABLE 4. First-Order Global Stress Patterns

Region	$S_{H\max}$ or $S_{h\min}$ Orientation[a]	Stress Regime[b]	Primary Source of Stress and Comments	References	
				State of Stress	Stress Modeling
			North American Plate		
Midplate region	ENE	T/SS	primarily ridge push, lateral stress variations predicted for basal drag not observed, regionally extensive (~2 × 10^7 km^2)	*Adams and Bell* [1991] and *Zoback and Zoback* [1989, 1991]	*Richardson and Reding* [1991]
Western Cordillera, Central America, and Alaska			complex stress patterns beyond scope of discussion, largely related to superposition of buoyancy forces and distributed shear related to Pacific–North American relative motion	many references, see summaries by *Zoback and Zoback* [1989, 1991], *Suter* [1991], *Suter et al.* [this issue], and *Estabrook and Jacob* [1991]	
			South American Plate		
Continental	E	T/SS	primarily ridge push, torque analysis suggests driving drag possibly major force [*Meijer and Wortel*, this issue]	*Assumpcao* [this issue]	*Stefanick and Jurdy* [this issue] and *Meijer and Wortel* [this issue]
High Andes	N	NF	trench suction or buoyancy due to thick crust and/or thinned lithosphere	*Froidevaux and Isacks* [1984] and *Mercier et al.* [this issue]	*Whittaker et al.* [this issue] and *Stefanick and Jurdy [this issue]*
			Eurasian Plate		
Western Europe	NW	SS	combined effects of ridge push and continental collision with Africa dominate, absolute velocity ≈ 0; thus resistive or driving basal drag probably not important; lateral variations in lithospheric structure may locally influence stress field	*Klein and Barr* [1987], *Gregersen* [this issue], *Grünthal and Stromeyer* [this issue], and *Müller et al.* [this issue], and Rebai et al. [1992]	*Brudy* [1990] and *Günthal and Stromeyer* [this issue]
China/eastern Asia	N to E	SS	continental collision force domimates, indentor geometry extremely important	*Molnar and Tapponnier* [1975], *Molnar and Deng* [1984], and *Xu et al.* [this issue]	*England and Houseman* [1989], *Tapponnier and Molnar* [1976], and *Vilotte et al.* [1984, 1986]
Tibetan Plateau	WNW	NF	Buoyancy (due to thick crust and/or thinned upper mantle) overcomes compression due to continental collision force	*Molnar and Tapponnier* [1978], *Mercier et al.* [1987*b*], and *Burchfiel and Royden* [1985]	*England and Houseman* [1989] and *Vilotte et al.* [1986]
			African Plate		
East African rift	NW	NF	Buoyancy force overcomes ridge push compression	*Bosworth et al.* [this issue]	
Midplate (western and southern Africa)	E	SS	ridge push dominates absolute velocity ≈ 0; thus drag probably not important	this paper, using data of *Bosworth et al.* [this issue], *Suleiman et al.* [1989], and D. I. Doser (written communication, 1990)	
North Africa	N to NW	T/SS	continental collision with Europe dominates	*Rebai et al.* [1991] and *Kamoun and Hfaiedh* [1985]	
			Indian Australian Plate		
India	N to NE	T/SS	continental collsion	*Gowd et al.* [this issue]	*Cloetingh and Wortel* [1985, 1986]
Central Indian Ocean	N to NW	T/SS	complex interaction collision and trench forces, long-wavelength basement undulations due to stress-induced flexure?	*Bergman* [1986], *C. Stein et al.* [1989], and *Petroy and Wiens* [1989]	*Cloetingh and Wortel* [1985, 1986] and *Gover et al.* [this issue]

First order global stress patterns (2)

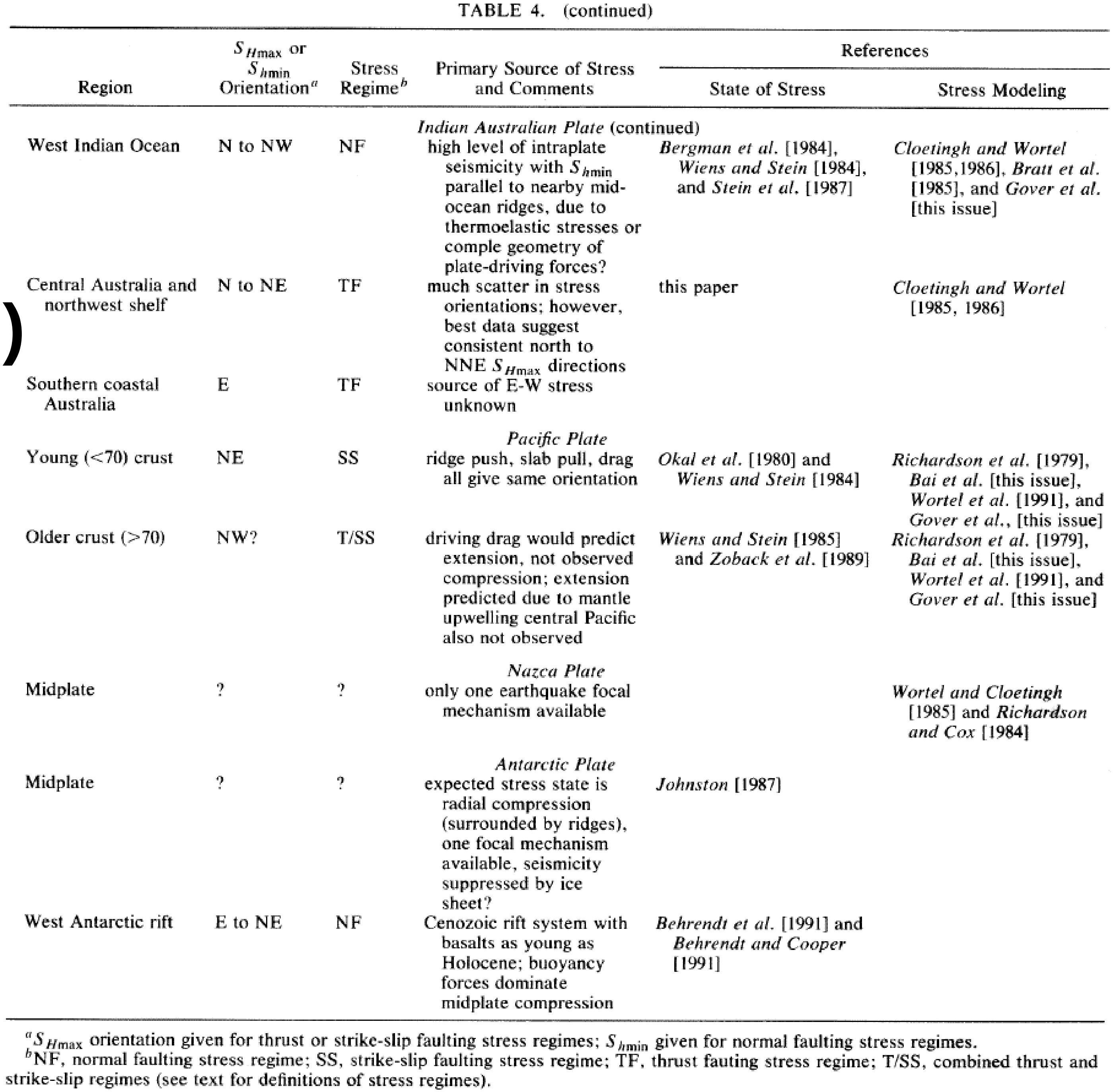


TABLE 4. (continued)

Region	$S_{H\max}$ or $S_{h\min}$ Orientation[a]	Stress Regime[b]	Primary Source of Stress and Comments	References: State of Stress	References: Stress Modeling
			Indian Australian Plate (continued)		
West Indian Ocean	N to NW	NF	high level of intraplate seismicity with $S_{h\min}$ parallel to nearby mid-ocean ridges, due to thermoelastic stresses or comple geometry of plate-driving forces?	*Bergman et al.* [1984], *Wiens and Stein* [1984], and *Stein et al.* [1987]	*Cloetingh and Wortel* [1985,1986], *Bratt et al.* [1985], and *Gover et al.* [this issue]
Central Australia and northwest shelf	N to NE	TF	much scatter in stress orientations; however, best data suggest consistent north to NNE $S_{H\max}$ directions	this paper	*Cloetingh and Wortel* [1985, 1986]
Southern coastal Australia	E	TF	source of E-W stress unknown		
			Pacific Plate		
Young (<70) crust	NE	SS	ridge push, slab pull, drag all give same orientation	*Okal et al.* [1980] and *Wiens and Stein* [1984]	*Richardson et al.* [1979], *Bai et al.* [this issue], *Wortel et al.* [1991], and *Gover et al.*, [this issue]
Older crust (>70)	NW?	T/SS	driving drag would predict extension, not observed compression; extension predicted due to mantle upwelling central Pacific also not observed	*Wiens and Stein* [1985] and *Zoback et al.* [1989]	*Richardson et al.* [1979], *Bai et al.* [this issue], *Wortel et al.* [1991], and *Gover et al.* [this issue]
			Nazca Plate		
Midplate	?	?	only one earthquake focal mechanism available		*Wortel and Cloetingh* [1985] and *Richardson and Cox* [1984]
			Antarctic Plate		
Midplate	?	?	expected stress state is radial compression (surrounded by ridges), one focal mechanism available, seismicity suppressed by ice sheet?	*Johnston* [1987]	
West Antarctic rift	E to NE	NF	Cenozoic rift system with basalts as young as Holocene; buoyancy forces dominate midplate compression	*Behrendt et al.* [1991] and *Behrendt and Cooper* [1991]	

[a] $S_{H\max}$ orientation given for thrust or strike-slip faulting stress regimes; $S_{h\min}$ given for normal faulting stress regimes.

[b] NF, normal faulting stress regime; SS, strike-slip faulting stress regime; TF, thrust fauting stress regime; T/SS, combined thrust and strike-slip regimes (see text for definitions of stress regimes).

Interpretation of first order stress patterns

1. Compression within plates due to compressive forces acting on plate margins (ridge push, continental collision)
2. Buoyancy in regions of high elevation (Tibet) can locally compensate intra plate compression
3. Basal drag difficult to estimate

Higher order stress patterns

Variety of effects:

- Deflection due to load (ice, sediments, sea mounts), at subduction zones (outer arc bulge)
- Lateral density contrasts (intrusions, isostatically uncompensated orogens)
- Lithosphere thinning (East African Rift) => intra plate extension
- Lithosphere thickening (Colorado Plateau, Western Alps) => rotation of S_1