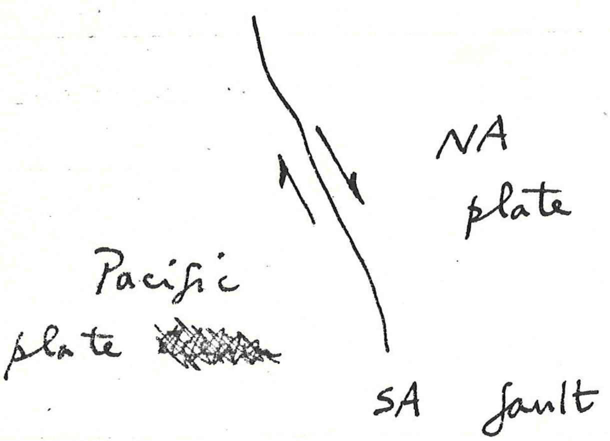
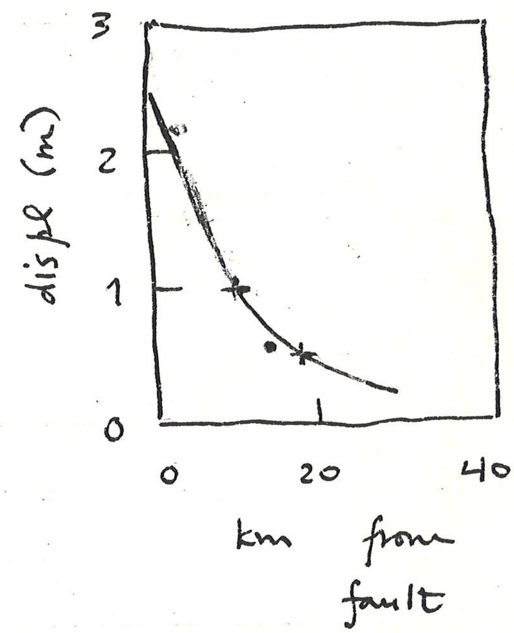
Lecture on mechanics of faulting for John Suppe's 316 Structural Geology course Wednesday 9 April 1980.

Seismologists view: what can earthquakes tell us about faulting?

H. F. Reid 1911 formulated elastic rebound theory. 1906 SF quake Strike-slip motion on SA fault

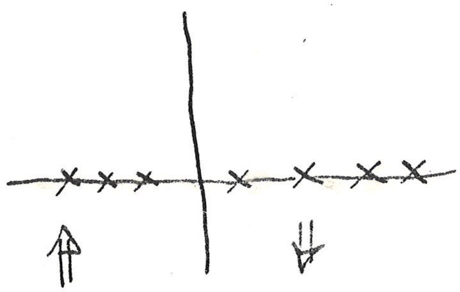
Surveying: triangulation nets resurved after earthquake



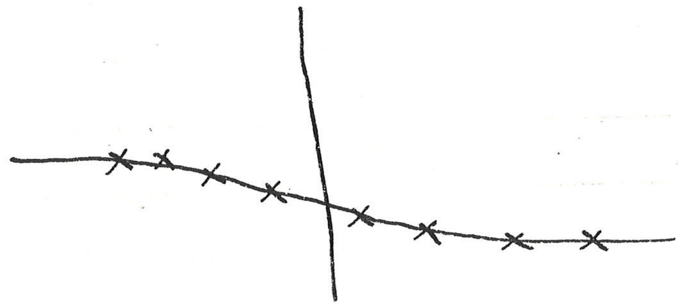


This an inverse picture of elastic strain released by quake.
Quake = slip on fault, on otherwise elastic medium.

Consider an imaginary fence long before earthquake

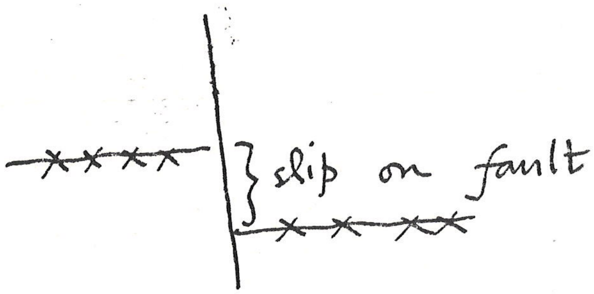


plates are moving

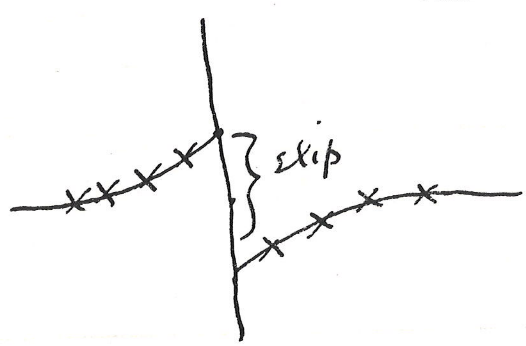


strain builds up

Finally friction on pre-existing fault no longer sufficient to hold two plates together. Catastrophic slip occurs



If fence was straight at t=0- one would see



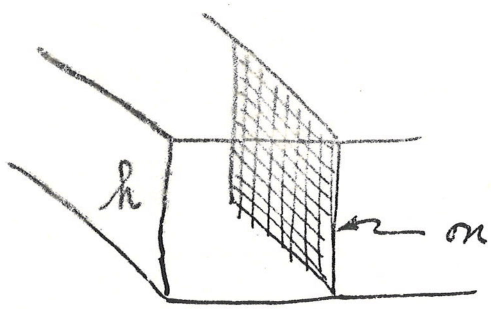
This slippage relieves the shear stress on the fault.

Say before it was σ_1 dyne/cm^2

After it drops to σ_2 dyne/cm^2.

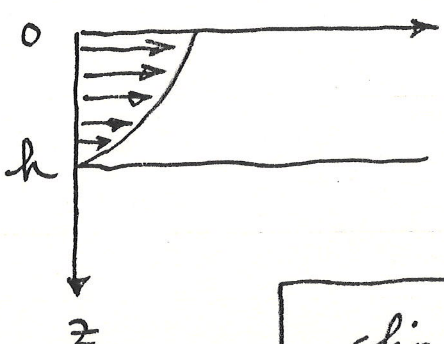
The stress drop $\Delta\sigma = \sigma_1 - \sigma_2$. This is one of the quantities seismologists seek to measure — the amount by which the stress is relieved.

Mathematical problem:
half space initially has shear stress σ_1 everywhere



on any plane shear stress of σ_1 dyne cm^{-2}
rock on west pulling rock on east to the north.

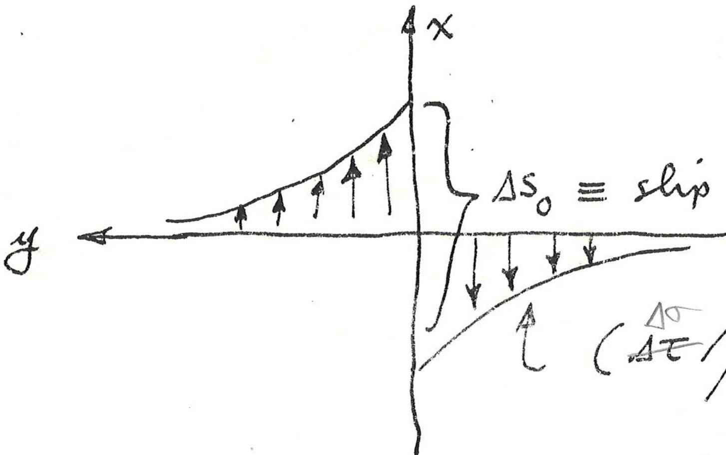
Now say stress drops by $\Delta\sigma$ down to a depth h. What is displacement everywhere. This an elastic b.v. problem easily solved. Answer: displacement on fault surface



each side slips by an amount $(\overset{\Delta\sigma}{\cancel{\Delta\tau}}/\mu)(h^2 - z^2)^{1/2}$

$$\boxed{\text{slip } \Delta s = (2\overset{\Delta\sigma}{\cancel{\Delta\tau}}/\mu)(h^2 - z^2)^{1/2}}$$

Away from fault : map view



$(\overset{\Delta\sigma}{\cancel{\Delta\tau}}/\mu)\,[(h^2+y^2)^{1/2} - y]$

note: for $y = 0 \to (\Delta\tau/\mu)\,h$
for $y \to \infty \to 0$.

One can fit a function of form

$$(\Delta s_0/2)\,[\,(h^2+y^2)^{1/2} - y\,]$$ to survey data.

This done for 1906 event by Leon Knopoff.
Found $h = 5-10$ km <u>very shallow</u>
Length of faulting ~ 435 km.
This consistent however with distribution of <u>seismicity</u> in California. All smaller earthquakes < 20-30 km depth.

What is <u>stress drop</u>?

$$\overset{\Delta\sigma}{\Delta\tau}/\mu = \Delta s_0/2h \qquad 0.25-0.5\cdot 10^{-3}$$
$$= 5/2\,(5-10\cdot 10^3) \sim$$

μ for typical crustal rocks $\sim 3 \cdot 10^{-11}$ dyne/cm^2

$$\Delta\tau = 6\text{-}12 \cdot 10^{7} \text{ dyne/cm}^2$$

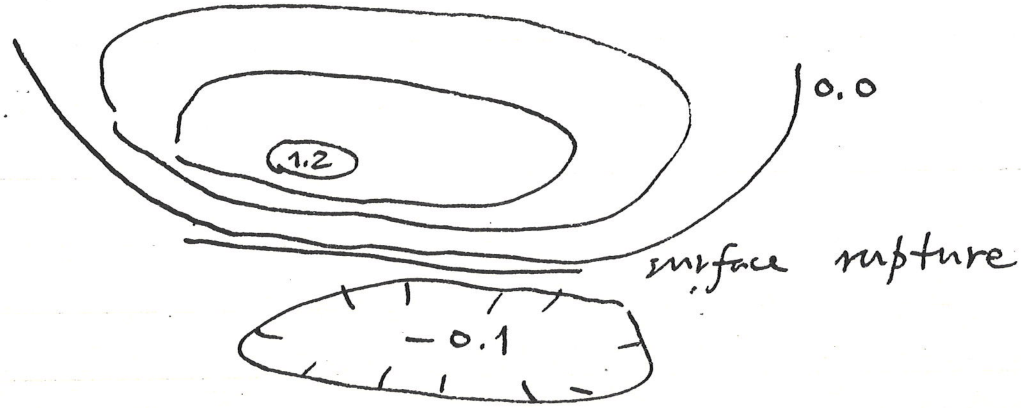
$$\boxed{\overset{\Delta\sigma}{\Delta\tau} \sim 60-120 \text{ bars}}$$

This a typical value always found for crustal quakes $\overset{\Delta\sigma}{\Delta\tau} = 10 - 100$ bars.

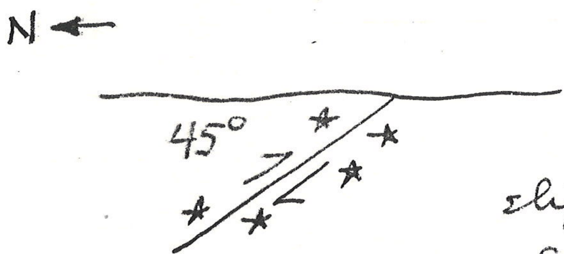
Note that the displacements only depend on $\Delta\tau$, not σ_1 or σ_2. Thus only $\Delta\sigma$ can be measured.

There are only a few quakes for which this kind of near-field static deformation data is available.

One other example – the most thoroughly studied earthquake ever. The San Fernando quake of 197



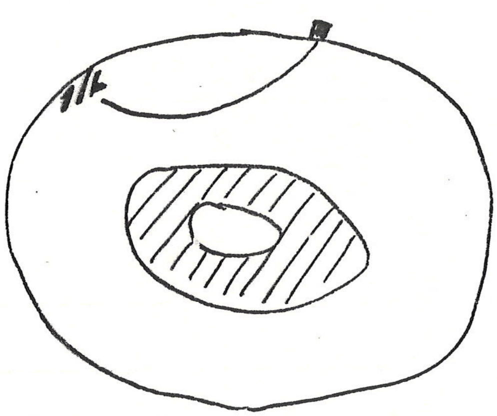
Contour map of vertical displacement in meters. This a thrust event on a ~ 45° dipping fault

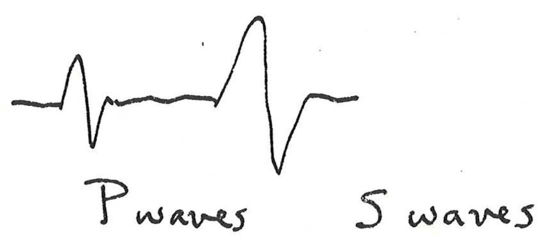


slip about 1 m on fault at ~ 45° down to ~ 15-20 km depth.

Fault delineated fairly well by aftershock distribution.

In absence of this type of data can use seismograms to determine fault parameters associated with quakes



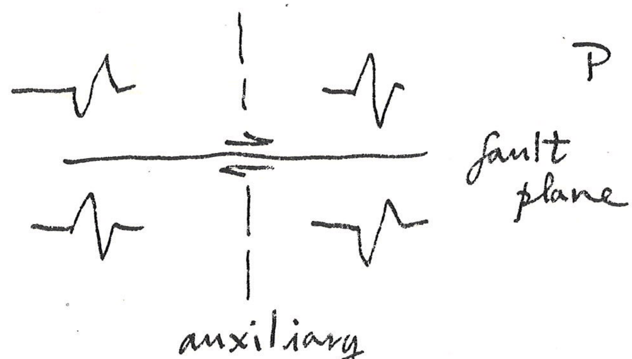


What properties can be measured from P and S waves?

First <u>radiation pattern</u> can tell one the orientation. Example:

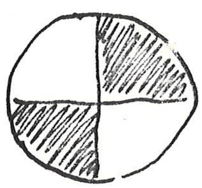
Strike slip fault

P wave first motion



(normal is direction of slip on fault)

Generally one plots sterographic projection of lower focal hemisphere + or −.



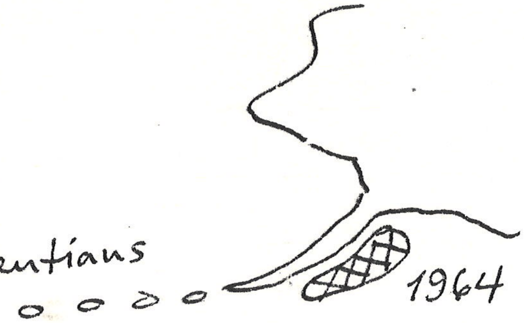
Note ambiguity — can't tell fault plane from auxiliary plane.

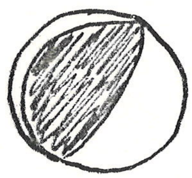
Could be

instead.

An example: the Alaskan <u>quake</u> of 1964.

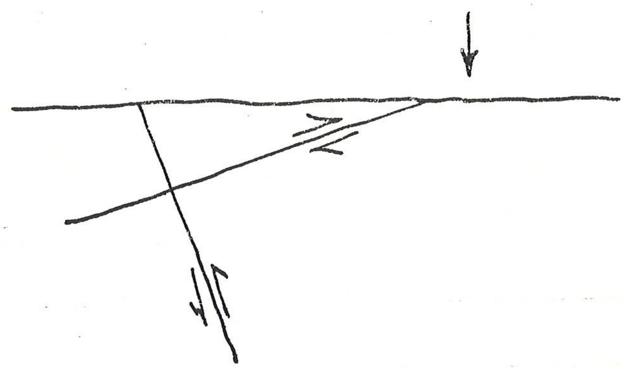
Study of focal mechanisms not yet highly developed — plate tectonics not yet developed.





Stauder and Bollinger
focal mechanism solution.

Two possibilities



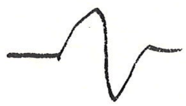
Clearly shallow angle rather than steeply dipping thrust is preferred.

→ TRANSFORM 'QUAKES a la SYKES

The best measure of the size of an earthquake is the so-called <u>seismic</u> <u>moment</u> (dyne - cm)

$$\boxed{M_0 = \mu \, \overline{\Delta s} \, \underbrace{A}_{\text{fault area}}}$$

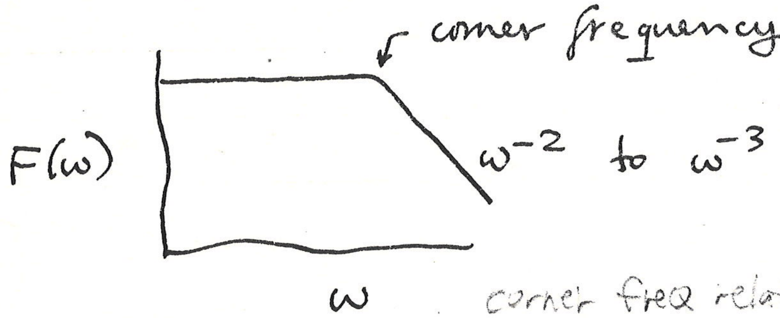
How is it measured?

 P wave. Take Fourier transform of P waveform.

Find it looks like for low frequencies

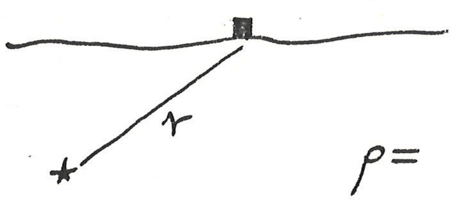
$$F(\omega) = [4\pi\rho\alpha^3 r]^{-1} \, \mathcal{R} \, M_0$$

$\uparrow$ radiation pattern find from focal mechanism



corner freq related to fault length

Low-frequency level of P wave spectrum $\propto$ to moment M_0



Small crustal quakes

ρ = density
α = P wave speed

Largest moment ever measured
$2\text{-}3 \cdot 10^{30}$ dyne-cm for Chilean quake of 1960

$\Delta S \sim 10$ m or 10^3 cm $\qquad \mu \sim 10^{12}$

$A = 1000 \times 2\text{-}\cancel{3}00$ km $\sim 2\text{-}3 \cdot 10^{15}$ cm^2
surface length × down dip length.

How can $\Delta\sigma$ thus be measured?
Need to determine A also.

Another math problem

Say stress $\overset{\Delta\sigma}{\cancel{\Delta\tau}}$ is released on a <u>circular</u> fault radius a in an ∞ medium
What is resulting slip on fault

$$\Delta s(r) = \frac{2\,\overset{\Delta\sigma}{\cancel{\Delta\tau}}}{\mu C}\left(a^2 - r^2\right)^{1/2}$$

max at center
falls to zero at edge

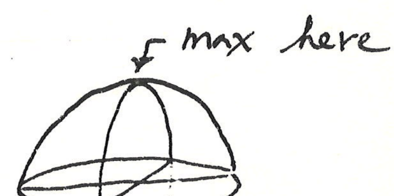
$$C = \frac{\pi}{4}(2-\nu)/(1-\nu) \qquad \nu = \text{Poisson's ratio}$$

$\nu \sim 1/4$ for crustal rocks

$$C = \frac{7\pi}{12}$$

$$\boxed{\Delta s(r) = \frac{24}{7\pi}\,\frac{\overset{\Delta\sigma}{\cancel{\Delta\tau}}}{\mu}\left(a^2 - r^2\right)^{1/2}}$$

nearly 1.



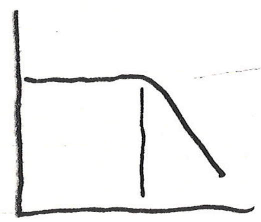
$$M_0 = \mu \int_0^a \Delta s(r)\, r\, dr \, .$$

Find $\boxed{\Delta\sigma = \frac{7}{16}\frac{M_0}{a^3}}$

Thus if know M_0 and $A = \pi a^2$ can find $\Delta\sigma$.

Can find A approximately by aftershock distribution.

Also ω_{corner} depends on a. In fact



ω_{corner}

$$a = \text{const}\,\frac{\alpha}{\omega_{corner}}$$

different models use different constants here but all $O(1)$.

Can also write as $M_0 = \text{const}\ \Delta\sigma\ A^{3/2}$

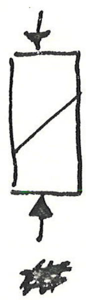
$$\text{const} = \frac{16}{7}\,\pi^{-3/2} \sim 0.4$$

$$\boxed{M_0 \sim 0.4\ \Delta\sigma\,.\,A^{3/2}}$$

$$\boxed{\log A = \frac{2}{3}\log M_0 - \frac{2}{3}\log(0.4\,\Delta\sigma)}$$

If $\Delta\sigma$ = const, $\log A \propto \frac{2}{3}\log M_0$. This appears to be quite accurately true. $\Delta\sigma \sim 10 - 100$ bars.

There is a real problem here. Friction experiments in lab



saw cut

shear stress on saw cut required to cause sliding

$$\boxed{\sigma_f = 0.85\,\sigma_n \quad \text{below 2 kbar}}$$

$$\boxed{\sigma_f \sim 0.5 + 0.6\,\sigma_n \quad \text{above 2 kbar}}$$

coeff. of friction = 0.6

Byerlee's "law"

At mid crustal depths $\sigma_n \sim \rho g h$

$\rho \sim 3 \quad g \sim 10^3 \quad h = 10^5$ cm/km

$\sigma_n \sim 300\,h$ bars. (h in km)

mid-crustal $\sigma_n = \cancel{2-5}$ 1-3 kbar. (~~3-15 km~~ 3-10 km)

so $\sigma_f \sim 1-3$ kbars expected
at ~~3–15~~ 3–10 km depth.

This discrepancy not understood. One of the outstanding tectonic problems.
Stress drops of <u>quakes</u> $\ll$ frictional stresses measured in lab — and $\Delta\sigma$ is very nearly const $\rightarrow$ suggests stress drop is $\sim$ complete.

<u>Possibilities</u> : 1. pore pressure decreases σ_n $\quad \tau = \tau_0 + \eta\,\sigma_n(1-\lambda) \quad \lambda = \frac{P_{pore}}{P_{confining}}$

2. ~~η 0.6~~ 0.85 decreased in fault gouge

3. lab results on cm-sized samples simply not relevant

4. Fault asperities : $\Delta\sigma$ Kb at asperities, but average is less.

These are <u>low</u> <u>stress</u> possibilities.

<u>High stress</u> favored by some —
requires $\Delta\sigma$ be a small fraction of ambient stress σ_1. If this so how do faults stop when just a tad of their stress is released?

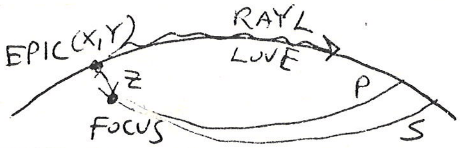
Lack of <u>heat flow anomaly</u> over SA favors <u>low stress</u>.
Work done per cm^2 by slippage along SA

$$\dot{E} = \sigma_f\,\Delta\dot{s} \leftarrow \text{slip rate}$$

Bound on $\sigma_1 \approx$ 200–300 bars. 1 depends on σ_f.

Earthquakes

lectures for GEO 319, 8, 10, 12, 16 DEC 1980



characterize event:

1). Location
Epicenter (X, Y, 0)
Focal Depth Z

2) Origin time
as part of (X, Y, Z, t), determined from travel times

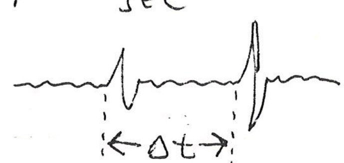
with 3 P-arrivals → (X, Y, t) determined ; Z assumed
> 3 least square solution for (X, Y, Z, t)
as done by ISC teleseismically

local events: get local P & S velocities

S ⊗ —— 12:00:00 —— quarry blasts —— 12:00:01
R=1 R= 6 km

$V_p = \frac{5\ km}{sec}$

then have record:



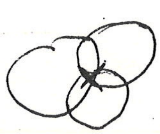
~~$V_p t = V_s(t) + \Delta t$~~

epicentral distance $R = V_p t_p = V_s(t_p + \Delta t)$

t_p = ~~arr~~ time of P − origin time

for $V_p = 6$ km/sec
$V_s = 4$
Δt = [illegible] sec get $6\ t_p \frac{km}{sec} = 4\ t_p + 4$ km

$t_p = 2$ sec ⇒ $R = V_p t_p = 12$ km



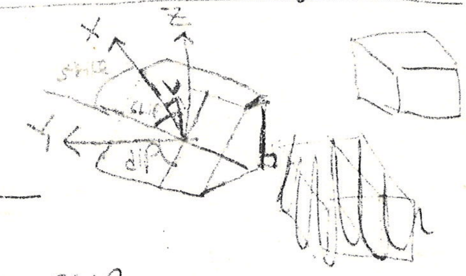
use several stations

[illegible] to get depth e.g. (P − pP times)

epicenters constrained to 10s of meters
depth z is most poorly constrained parameter owing to near-surface inhomogeneities

3) Source

a) fault orientation



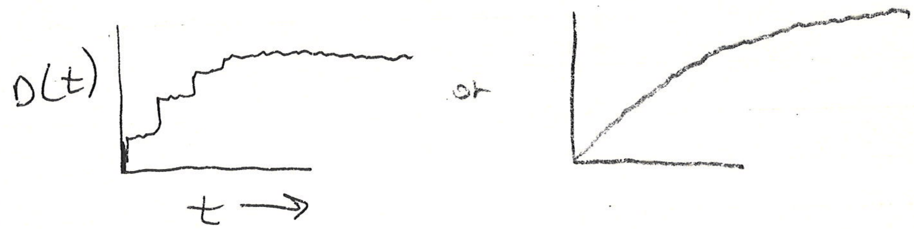
from body waves - fault plane solution using first motions
surface waves - use amplitude and phase

b) fault dimension
length L, width W from aftershocks

c) fault dislocation D
measure displacement offset in field

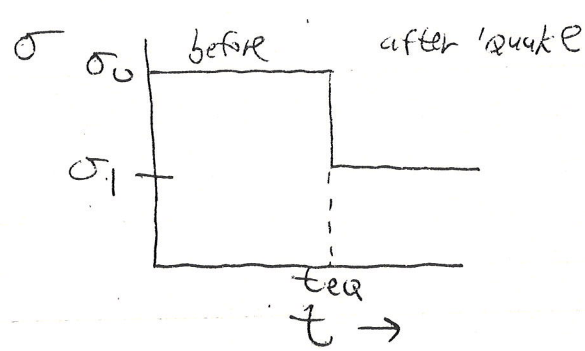
d) rupture velocity V
source as propagating stick-slip jumps

e) rise time



f) stress drop

$\Delta\sigma = \sigma_0 - \sigma_1$



g) Magnitude, energy

Richter Magnitude Scale M_b body wave magnitude
$M_b \propto \log E$

Intensity : Modified Mercali Scale ; subjective

Moment - ~~[illegible]~~

$M_b = \log_{10}(\text{Amplitude})$

amplitude in microns on a short period instrument w/a magnification of 2800 at ~~a~~ a distance of 100 km from the source

typically to $\pm$ 0.2
mainly via WWSSN – ~ 130 stations

modified Mercalli Intensity Scale
based on subjective rating of shaking at a given location
I → XII
barely felt — total destruction

historically important

energy $\propto$ (displacement)^2

$\log_{10} E = 11.3 + 1.8\ M_b$ (ergs)

$E = 10^{11.3} \cdot 10^{1.8 M_b}$

$E \tilde{\propto} 10^{2 M_b}$

one step increase in M_b ⇒ 10 x displacement, 100 x energy

	M_b	#/year	
	≥ 8	1.1	← releases most of Σ energy
destructive	7–7.9	18	
damaging	6–6.9	120	
	5–5.9	800	
	4–4.9	6200	wwssn limit
felt	3–3.9	49,000	
	2–2.9	300,000	

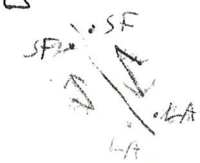
m_b	event	fault dimensions (km)	fault displacement (m)
8.5	Alaska '64	500 x 300	7
7.9	Rat Island '65	450 x 150	3
8.2	Kurile Is '63	250 x 150	3

observed 'Quake locations

~~[illegible]~~
concentrated in belts along plate margins
a look at seismicity map shows quakes define plate bdry's well

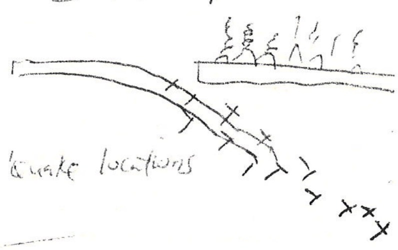
only 10% of quakes are deeper than 30 km
deepest quakes at ~ 700 km in subduction zones

shallow, normal faulting events characterize ridges
strike-slip on transform faults
S.A. – strike-slip fault



neighbors in 100 my

Benioff zone:



slab defined by 'quake locations

seismic moment

$$M_o = \mu \cdot \text{Area} \cdot \overline{\text{displacement}}$$

units of torque
$F \times d$

$$= \mu \cdot (WL) \cdot \bar{D}$$

more on this later + how to measure it

preferred measure of 'quake size

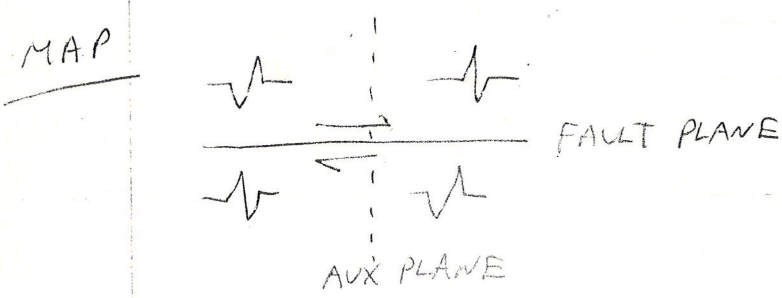
stress system causes radiation field
seismogram not a direct measure of displacement but rather displacement on fault

due to radiated stress field

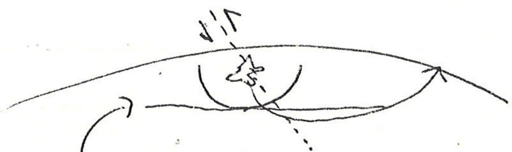
more appropriate to characterize 'quake according to force at focus, not displacement.

San Andreas

focal mechanism 1st motion study (when near-field static def unavailable i.e. usually)

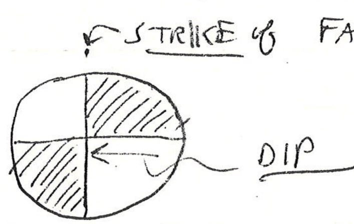


For spherical ⊕, must use projection to plot stations at teleseismic distances:



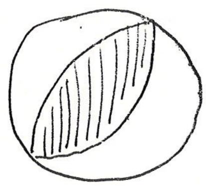
stereographic projection onto this plane – plot C or D

STRIKE SLIP

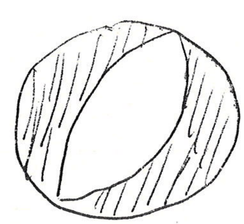


NOTE AMBIGUITY – could be ⇂|↾ motion instead.

THRUST

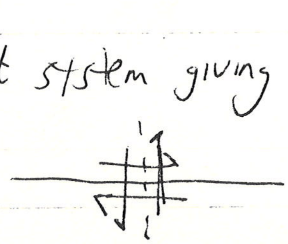


NORMAL



~~gta~~ 1964 Honda questioned the 'single couple' fault model as it leads to net torque in ⊕, not an equilibrium situation.

Simplest system giving no net torque: double couple



~~since shown mathematically that double couple is preferred mechanism.~~

<u>single couple</u> radiation pattern vs. <u>double couple</u>

P

S:

dipole

quadrupole

- but S polarization studies inconclusive
- since shown mathematically that double couple is preferred

~~examples~~
~~Alaska '64 – but significance not understood yet~~

<u>SEISMIC MOMENT</u> $M_0 = \mu \overline{\Delta S} A$ is magnitude of one of the couples

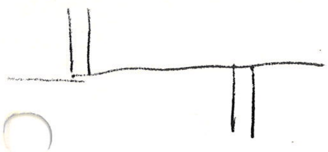
<u>examples</u>

Alaska '64 – but significance not yet understood

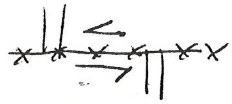
<u>Transform Quakes</u> Sykes '67

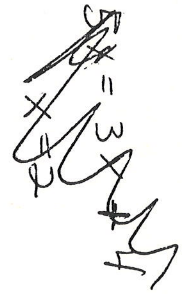
lent credence to mech. sol'ns & a step in plate tectonic history

Transform 'Quakes

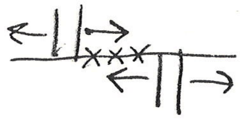


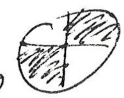
OLD VIEW mountain chain offset by ocean floor stresses. Mountains passive

would expect:  quakes all along rift with mechanism 

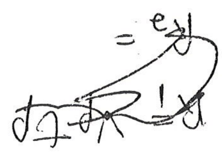


Sykes: ridges are active spreading centers

expect  seismicity only between ridge segments where opposing motion is occuring

mechanism 

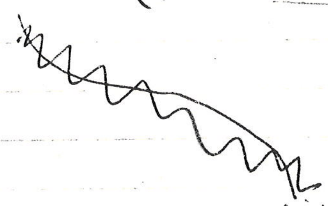
in fact observed,
lent credence to focal mech. solutions
+ part of develop. of plate tectonics



Earthquake Prediction

Seismic gap - motion, seismicity, expected but not seen

possible 'quake zone: "locked" by stresses
(continents move aseismically via plate creep)

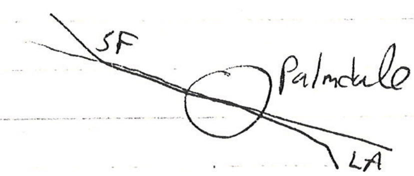


Alaskan Gap
Peru Gap - Andes latest prediction

what processes are active here ?

DILATANCY at about 1/2 its fracture strength, rock swells (+ ΔV) due to opening of small cracks (more pore volume).

Palmdale bulge was thought to show this dilatancy



Lab Experiments (Mid '60s)
brought rock to state of dilatancy (wet rocks)
measured
1) changes in electr. resistivity - (water leaves, resis. up)
2) change in V_p/V_s

Results: 1) resistivity up
2) V_p/V_s drops - mostly V_p decrease

1969 - Garm USSR
monitored
a) V_p/V_s
b) Resis.
c) radon content of water → radon unstable, cracks allow to leave, enter ground H_2O

other possible precursors:
d) looked for calm periods before 'quakes
e) Δ in local $\vec{B}$ field, rock's magnetism & stress

to explain these changes

Dilatancy-Fluid Diffusion Model

Nur, 1972; Scholz, Sykes, Aggarwal 1973

stage I. Buildup of Tectonic stress (locked fault, seismic gap)

II Dilatancy starts - cracks open - rock undersaturated
1) Vp/Vs drops
2) resistivity up
3) $+\Delta V$ in focal region (bulge)
4) # of small background tremors decrease - DILATANCY HARDENING

$$\tau = \tau_0 + n\sigma_N \rightarrow \tau = \tau_0 + n\,\sigma_N(1-\lambda)$$

5) radon content of H_2O in area increases

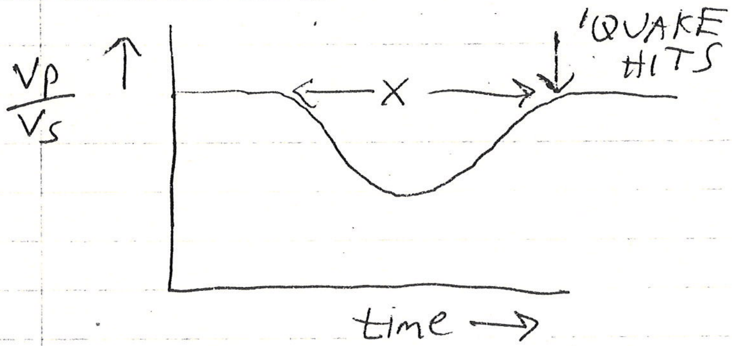
$$\lambda = \frac{P_{pore}}{P_{confining}}$$

III water diffuses into focal region
· pore pressure increases
1) Vp/Vs increases
2) rock weakened
3) # of small 'quakes increases

IV rapid movement before 'quake: foreshocks

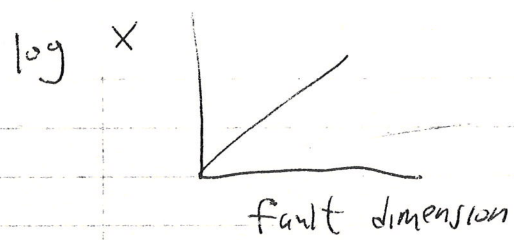
V stress released by main shock
crust returns to original properties.

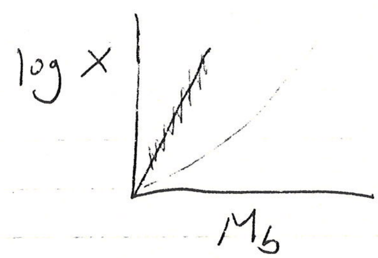
larger magnitude → larger volume → longer time for water to diffuse into area



$X \propto$ quake magnitude

to see whole precursor interval May 7 ~ 13 yrs.
8 ~ 83 yrs.





Denver Earthquakes
importance of P_{pore}

Rocky Mt. Arsenal — forced injection
3-4000 ft.

Rangeley, Co.
injection in oil wells