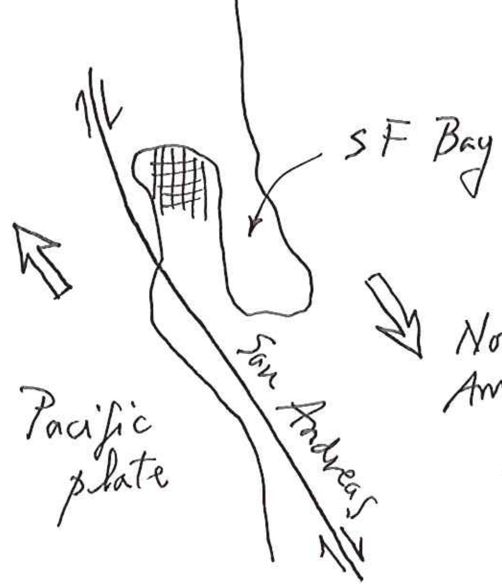
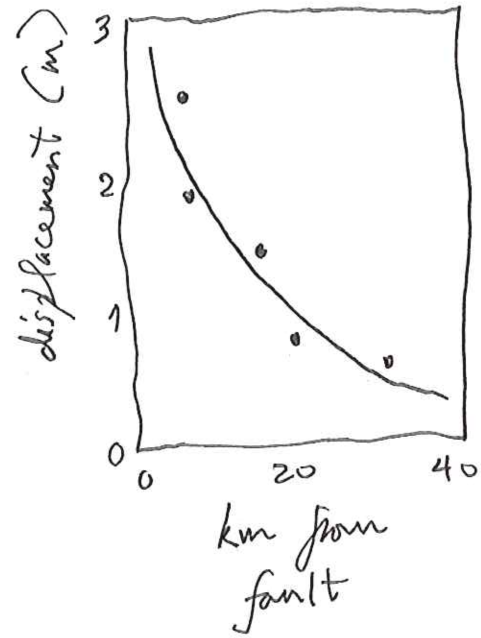
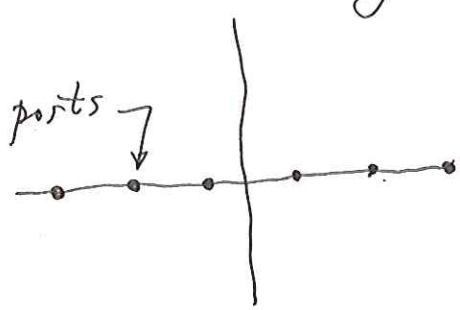
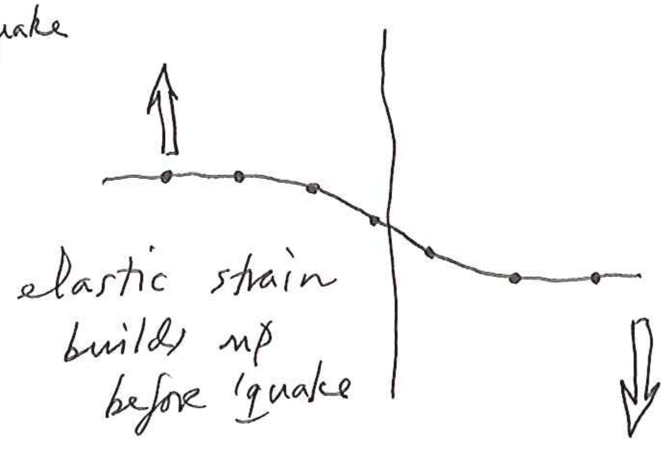
1906 San Francisco earthquake
H.F. Reid — elastic rebound hypothesis



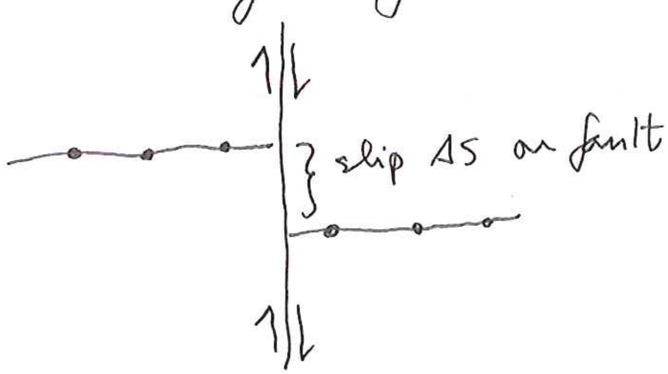


Imaginary fence across
SAn Andreas long before 'quake



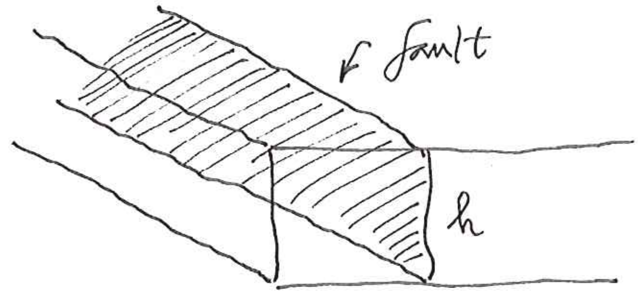


Catastrophic failure when
the strength of the fault is exceeded



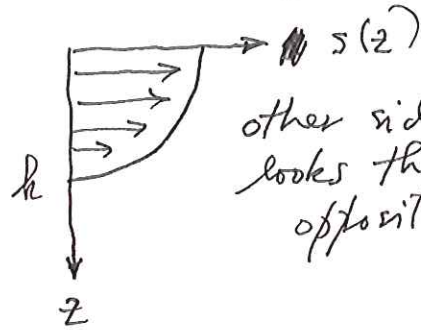
A fence straight just
before 'quake would look
like this

Mathematical model — the quake relieves the stress by an amount $\Delta\sigma$ down to a depth h on an infinitely long fault



The slip of each side (as a function of depth z)

$$s(z) = \frac{\Delta\sigma}{\mu}\sqrt{h^2 - z^2}$$



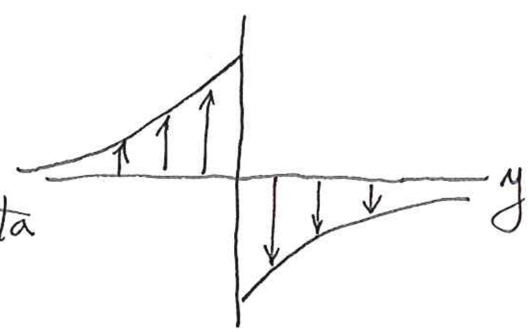
other side looks the opposite

The total slip on the ⊕'s surface ($z=0$) is

$$\boxed{\Delta s = 2\left(\frac{\Delta\sigma}{\mu}\right)h}$$

As a function of distance x away from the fault, on the surface of the ⊕, the slip is

$$s(y) = \frac{\Delta\sigma}{\mu}\left[\sqrt{h^2+y^2} - y\right]$$



A fit to Reid's SF quake data gives

$\Delta s = 5$ m

$h \approx 6$ km — depth of strike-slip faulting

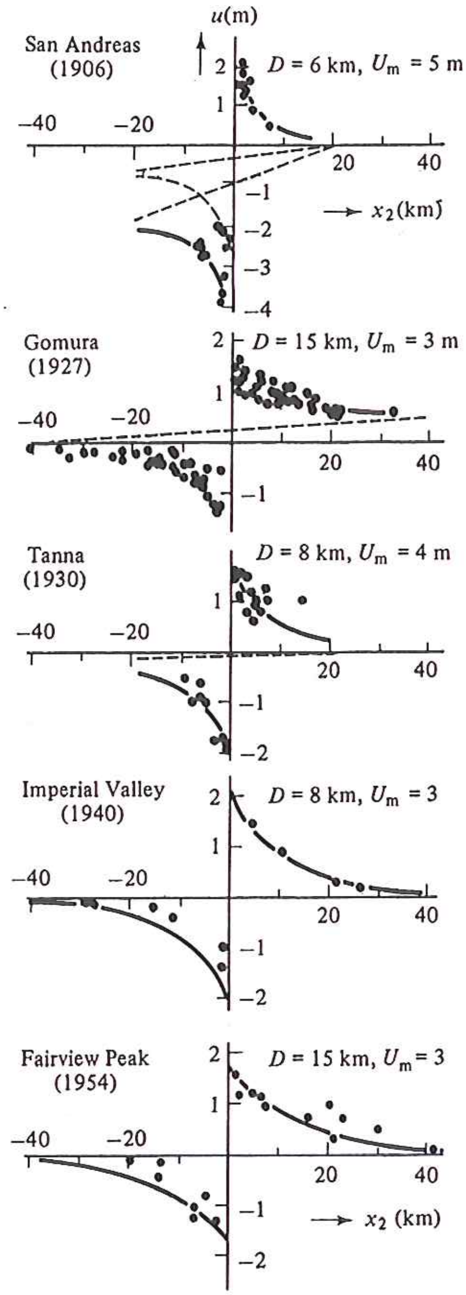


Fig. 4.9. Surface displacements (parallel to the fault strike) associated with several representative strike-slip faults for comparison with the predictions of the vertical strike-slip model (fig. 4.7). Broken lines show corrections for the hypothetical strain accumulation during the period between pre- and post-earthquake surveys. (After Kasahara, 1960.)

$1 \text{ Nm} = 10^7$ dyne cm

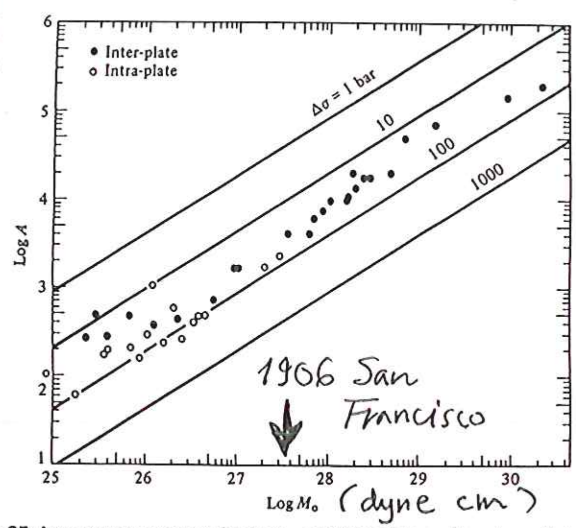


FIGURE 9.25 Area versus moment for inter- and intraplate earthquakes. Note that the interplate earthquakes show little scatter about a stress drop of 30 bars. The intraplate earthquakes have stress drops of ~100 bars. (Modified from Kanamori and Anderson, 1975.)

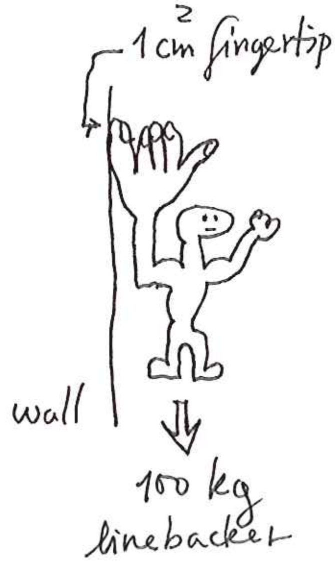
Stress drop:

crustal rigidity

$$\Delta\sigma = \frac{\mu\,\Delta s}{2h} = \frac{3\cdot 10^{10}\ \text{Pa} \times 5\ \text{m}}{2\cdot 6\cdot 10^{3}\ \text{m}}$$

$$\boxed{\Delta\sigma \approx 10\ \text{MPa} = 100\ \text{bars}}$$

shear strength of San Andreas fault



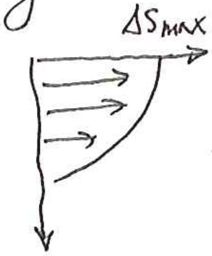
Earthquake moment:

Best measure of the size of an earthquake

$$M_0 = \mu\, A\, \overline{\Delta s}$$

fault area

average slip



$$\overline{\Delta s} = \frac{\pi}{4}\,\Delta s_{max}$$

$$M_0 = (3\cdot 10^{10})\,(6\cdot 500)\cdot 10^{6}\cdot \frac{\pi}{4}\cdot 5 = \underline{4\cdot 10^{20}\ \text{Nm}}$$

500 km length of rupture

1906 SF 'quake

Radiated elastic energy

$$E = \frac{1}{2}\,\Delta\sigma\, A\, \overline{\Delta s} = \underline{6\cdot 10^{16}\ \text{Joules}} \quad (1906\ \text{SF 'quake})$$

For comparison:

daily US electrical energy consumption : $11\cdot 10^{16}$ J

Hiroshima nuclear explosion : 14 kT = $6\cdot 10^{13}$ J

Mt. Pinatubo eruption : 10^{20} J

same units (1 J = 1 Nm)

$$E = \left(\frac{\Delta\sigma}{2\mu}\right) M_0$$

Typical quake stress drops are in range
$\Delta\sigma = 1 - 10$ MPa (say average 3 MPa)

Then $$\boxed{E \approx \frac{M_0}{2\cdot 10^4}}$$ *

Circular fault patch model:

$$\boxed{\overline{\Delta s} = \frac{16}{7\pi}\left(\frac{\Delta\sigma}{\mu}\right) a}$$

stress drops $\Delta\sigma$ on a circular patch of radius a

Bigger patches have bigger slip

$$M_0 = \mu \overset{\pi a^2}{A}\, \overline{\Delta s} = \frac{16}{7} \Delta\sigma\, a^3$$

$$= \frac{16}{7\sqrt{\pi^3}} \Delta\sigma\, A^{3/2}$$

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

or on a log-log plot:

$$\boxed{\log M_0 = \underbrace{\log(0.4\,\Delta\sigma)}_{\approx \text{ constant}} + \underbrace{\frac{3}{2}}_{\text{slope } 3/2} \log A}$$

Earthquake magnitude

An older empirical measure of earthquake size. For large earthquakes, now defined in terms of moment $\bar{M}_0$ by

$$\boxed{M = \frac{2}{3}\log_{10} M_0 - 6.1 \quad \star\star}$$ — so-called moment magnitude

1906 SF quake : $M = 7.7$

Combining $\star$ and $\star\star$ gives energy-magnitude relation:

$$\boxed{\log_{10} E\,(\text{Joules}) = 1.5M + 4.8}$$

magnitude M	moment M_0 (Nm)	energy E (J)
6	$1 \cdot 10^{18}$	$6.3 \cdot 10^{13}$
7	$4 \cdot 10^{19}$	$2 \cdot 10^{15}$
8	$1 \cdot 10^{21}$	$6.3 \cdot 10^{16}$
9	$4 \cdot 10^{22}$	$2 \cdot 10^{18}$

An increase in magnitude $\Delta M = 1$: $10^{1.5} =$ <u>31.6 times as energetic</u>

An increase by $\Delta M = 2$: $10^{3} =$ <u>1000 times as energetic</u>

Earthquake statistics:

Gutenburg – Richter frequency–magnitude law

N = number of quakes of magnitude $\geq M$
(in a given region and a given time interval)

$$\boxed{\log_{10} N = a - bM \qquad b \approx 1}$$

a decrease by $\Delta M = 1 \Rightarrow$ 10 times as many quakes

The constant a depends on size of region and time interval

Corresponding moment – frequency law

$$\log_{10} N = a - b\left(\tfrac{2}{3}\log_{10} M_0 - 6.1\right)$$

or with $b = 1$

$$\boxed{\log_{10} N + \tfrac{2}{3}\log_{10} M_0 = a + 6.1}$$

$$N M_0^{2/3} = 10^{a+6.1}$$

$$\boxed{N = \underbrace{10^{a+6.1}}_{\text{const}} M_0^{-2/3}}$$

$-2/3$ slope on a log – log plot

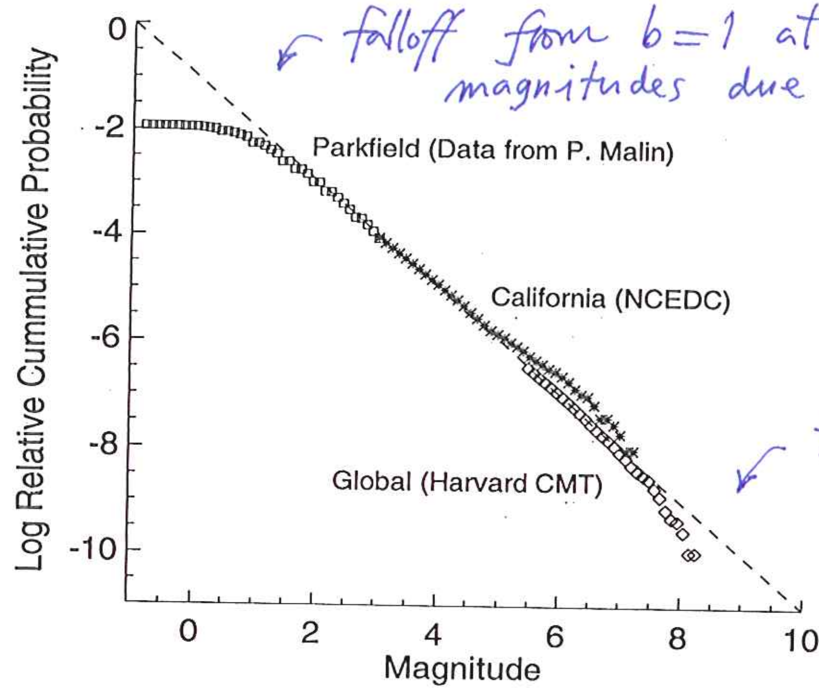
Shallow quakes worldwide:

M	M_0 (Nm)	N (# per year)
9	$4\cdot10^{22}$	0.16
8	$1\cdot10^{21}$	1.6
7	$4\cdot10^{19}$	16
6	$1\cdot10^{18}$	160
5	$4\cdot10^{16}$	1600
4	$1\cdot10^{15}$	16,000

M_0 in Nm

$$\boxed{\begin{aligned} \log_{10} N &= 8.2 - M \\ N &= 2\cdot10^{14} M_0^{-2/3} \end{aligned}}$$

about 40 quakes/day worldwide $M \geq 4$.



falloff from $b=1$ at small magnitudes due to detection capability of seismic network

falloff from $b=1$ at large magnitude due to insufficiently long data base

Total energy released by earthquakes per year

note: this now the interval number rather than the cumulative number

M	$N(M+1 \leq$ magnitude $\leq M)$	E (Joules/yr)
8	1.4	10^{17}
7	14	$3 \cdot 10^{16}$
6	140	10^{16}
5	1400	$3 \cdot 10^{15}$
4	14,000	10^{15}
		⋮

$\boxed{\text{total} \approx 2 \cdot 10^{17}\ \text{J/yr}}$

Earthquake energy release is dominated by the occasional large earthquake

or $6 \cdot 10^9$ W

$\approx \frac{1}{5000} \times$ total heat flow

This a measure of the thermal efficiency of the $\oplus$ as a heat engine.

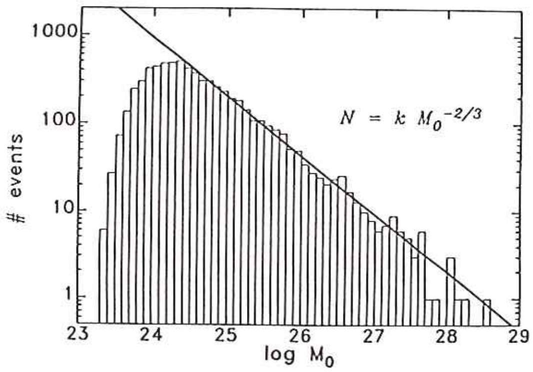


FIGURE 9.30 Number of earthquakes as a function of seismic moment. This is a global data set for shallow events since 1977. (Courtesy of Göran Ekström.)

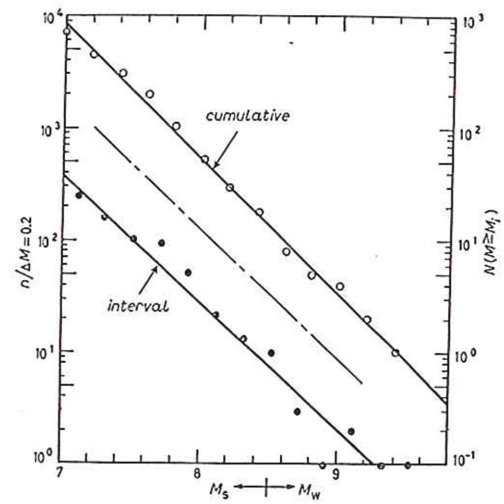


Fig. 1. – The magnitude-frequency relation for the earthquakes in the world during the period from 1904 to 1980. The surface wave magnitude M_S listed in [1] is used for all the events except those with $M_w > 8.5$ for which M_w is used. The ordinate on the left is for the interval frequency ($\log n = (10.42 \pm 0.57) - (1.13 \pm 0.7)\,M$) ($n_2$ in table II, the number of events per 0.2 magnitude unit for the period 1904 to 1980), and that on the right is for the cumulative frequency ($\log N = (11.41 \pm 0.19) - (1.21 \pm 0.02)\,M$)

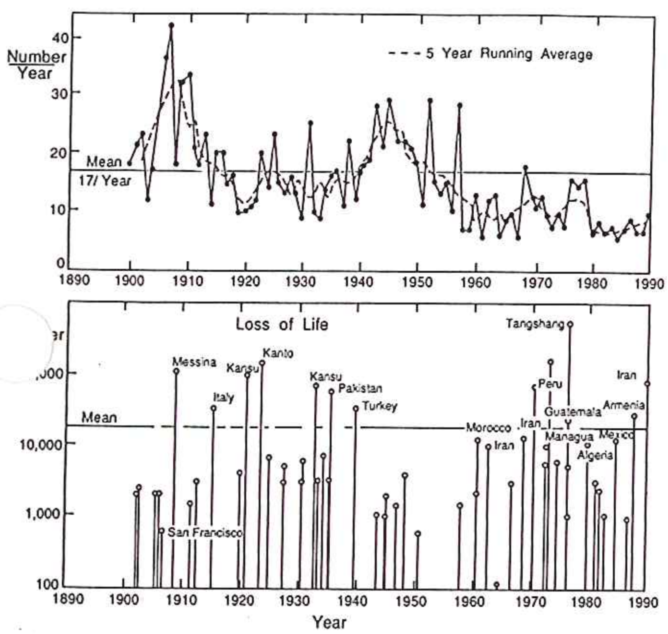
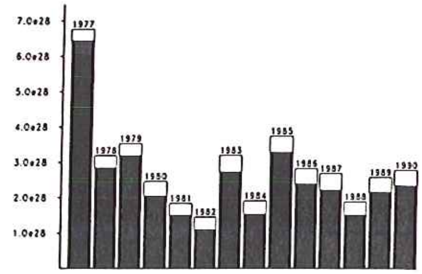


FIGURE 1.10 (Top) The annual number of large ($M_S \geq 7.0$) shallow earthquakes around the world. There are about 17 events of this size annually. (Bottom) The history of earthquake-induced fatalities in this century, with the locations of major events being indicated. Note the poor correlation with the top trace. Even small earthquakes can cause extensive loss of life in regions with poor building construction, or if secondary hazards such as fires or landslides enhance the damage. (Modified from Kanamori, 1977, 1978.)



The annual cumulative seismic moment release from all significant seismic events, which is about 800 events per year. The darker portion of each bar indicates the contribution from just the $M_W \geq 6.5$ events, demonstrating that the small number of large events (about 20/yr) dominates. (From Dziewonski *et al.*, 1990, 1991.)

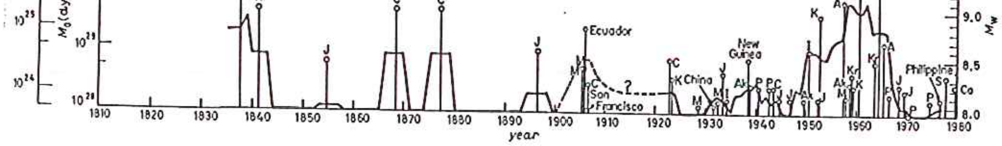
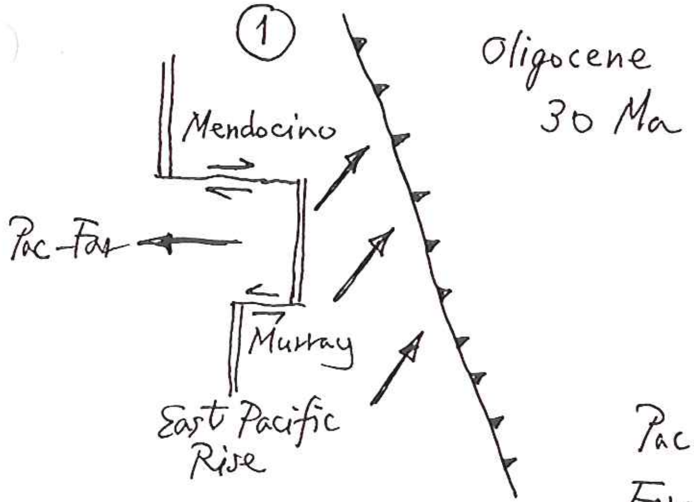
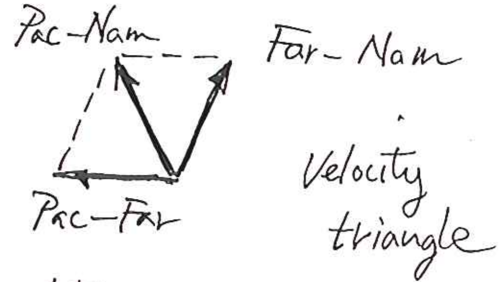


Fig. 4. – The seismic moment M_0, the seismic energy E and the magnitude M_w of great and large earthquakes as a function of time (A, Aleutian; Ak, Alaska; C, Chile; Co, Colombia; I, India; J, Japan; K, Kamchatka; Kr, Kurile; M, Mongolia; P, Peru; S, Sumbawa). The solid curve shows unlagged 5-year running average (in erg per year) taken at the center of the interval (modified from [2]). For the period from 1835 to 1900, tsunami magnitude M_t [1] is used to estimate M_0, E and M_w.

Evolution of the California Margin





Pac : Pacific plate
Far : Farallon plate
Nam : North American plate