- From one earthquake parameter one can deduce the others (self-similarity)
- Not all earthquakes result in surface rupture
- Basis on Tsunami. Was the 2011 tsunami expected ?
- Use of normal distribution

Warm-up discussion

What are the different effects of earthquakes ?

- Magnitude, size and energy of earthquakes
  - Style of faulting
  - Size
  - Scaling laws
  - Stress drops and energy
- Effects of earthquakes
  - Surface rupture
  - Tsunami
  - Landslide
  - Liquefactions

References

Stein and Wysession. 2003. Chapter 4.

Kanamori and Brodsky. 2004. The physics of earthquakes. Rep. Prog. Phys. 67. pp 1429-1496.

Wells and Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seismol. Soc. Am., 84, 974–1002.

Suggested papers (lecture 2)

- Wells and Coppersmith, 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, Bull. Seismol. Soc. Am., 84, 974–1002.

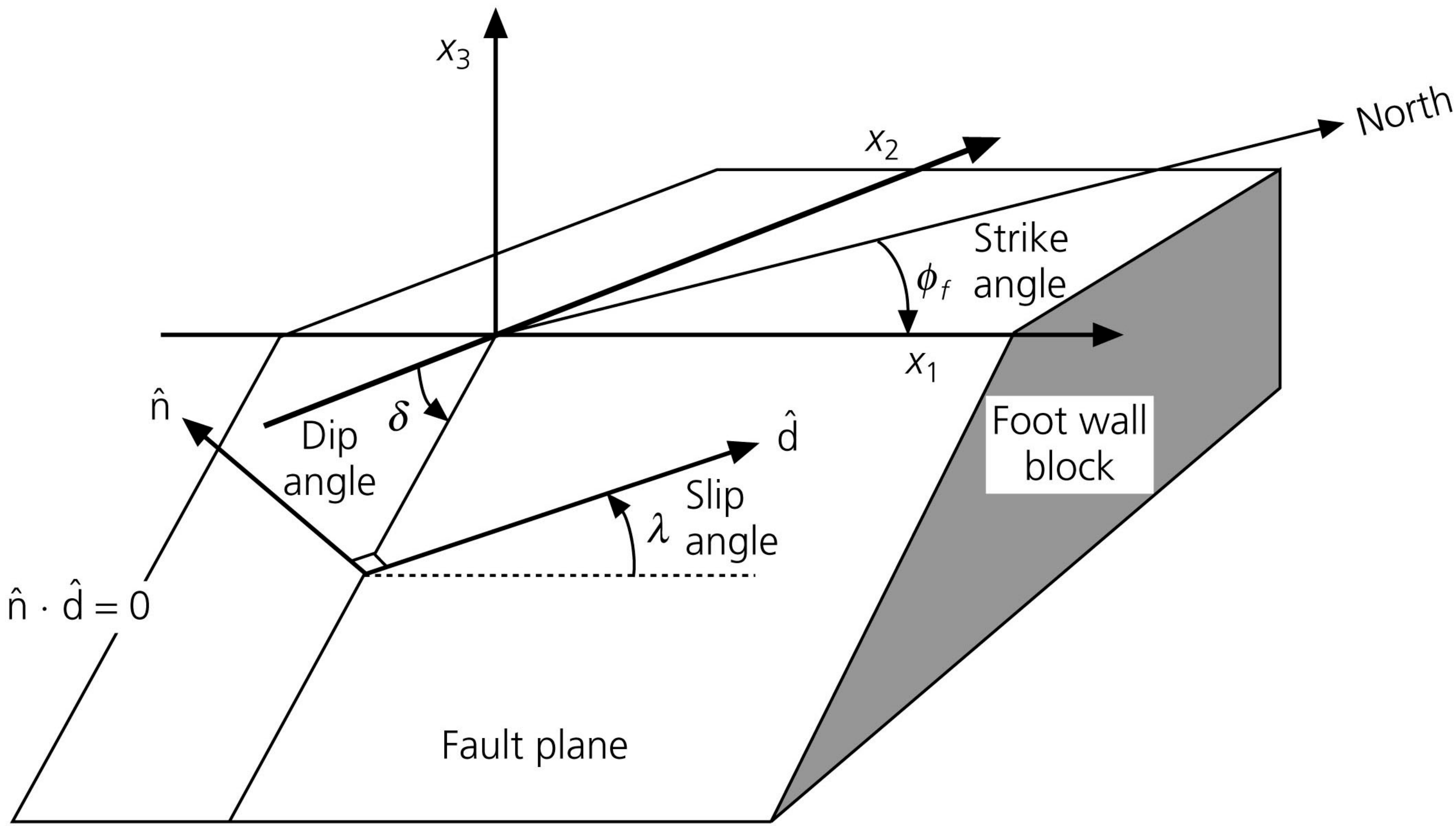
- IAEA SAFETY STANDARDS SERIES. Evaluation of Seismic Hazards for Nuclear Power Plants SAFETY GUIDE No. NS-G-3.3 INTERNATIONAL ATOMIC ENERGY AGENCY VIENNA

- Kameda, 2012. Proceedings of the International Symposium on Engineering Lessons learned from the 2011 Great East Japan Earthquake, March 1-4, 2012 Tokyo

Fault movement and fault geometry

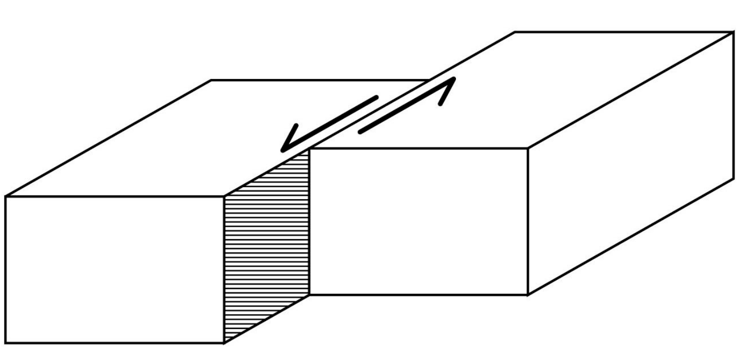
- The slip vector indicates the direction in which the upper side of the fault (hanging wall block) moved with respect to the lower side (the footwall block)

Figure 4.2-2: Fault geometry used in earthquake studies.

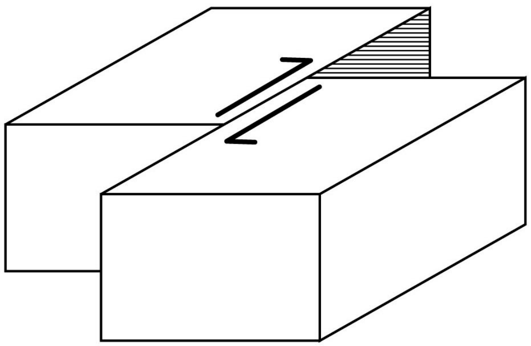


Sources: Stein et Wysession

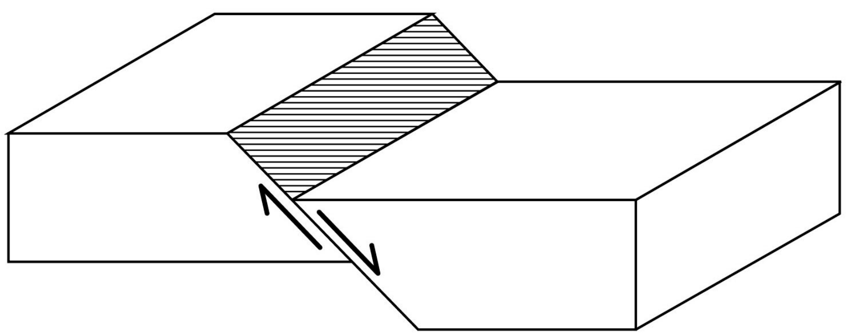
Figure 4.2-3: Basic types of faulting.



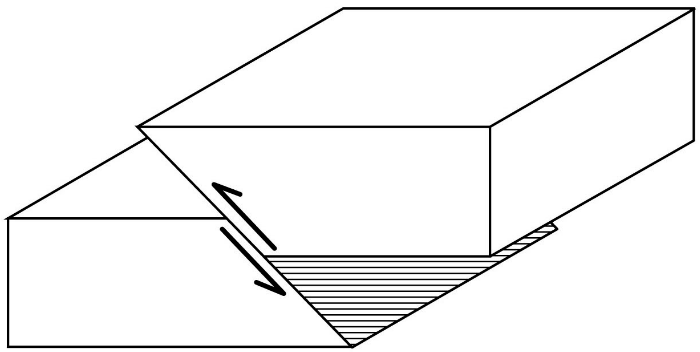
Left-lateral strike-slip fault
($\lambda = 0°$)



Right-lateral strike-slip fault
($\lambda = 180°$)



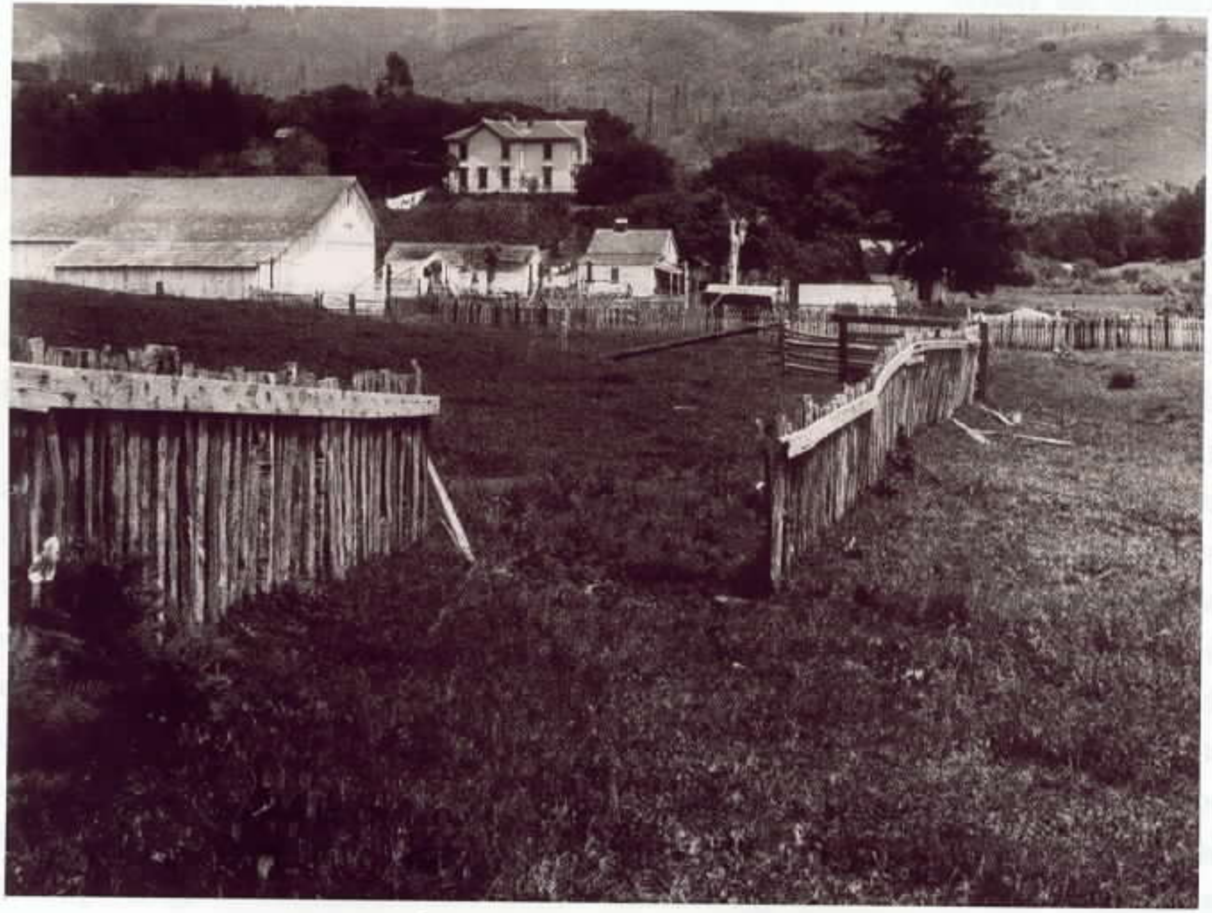
Normal dip-slip fault
($\lambda = -90°$)



Reverse dip-slip fault
($\lambda = 90°$)

Sources: Stein et Wysession

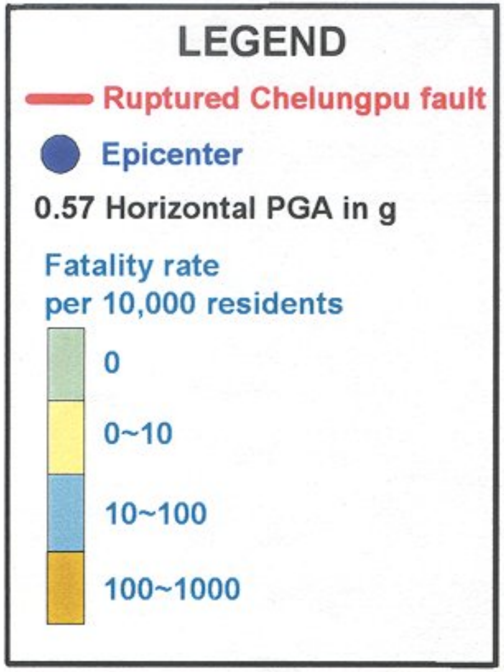
Style of faulting
Surface traces

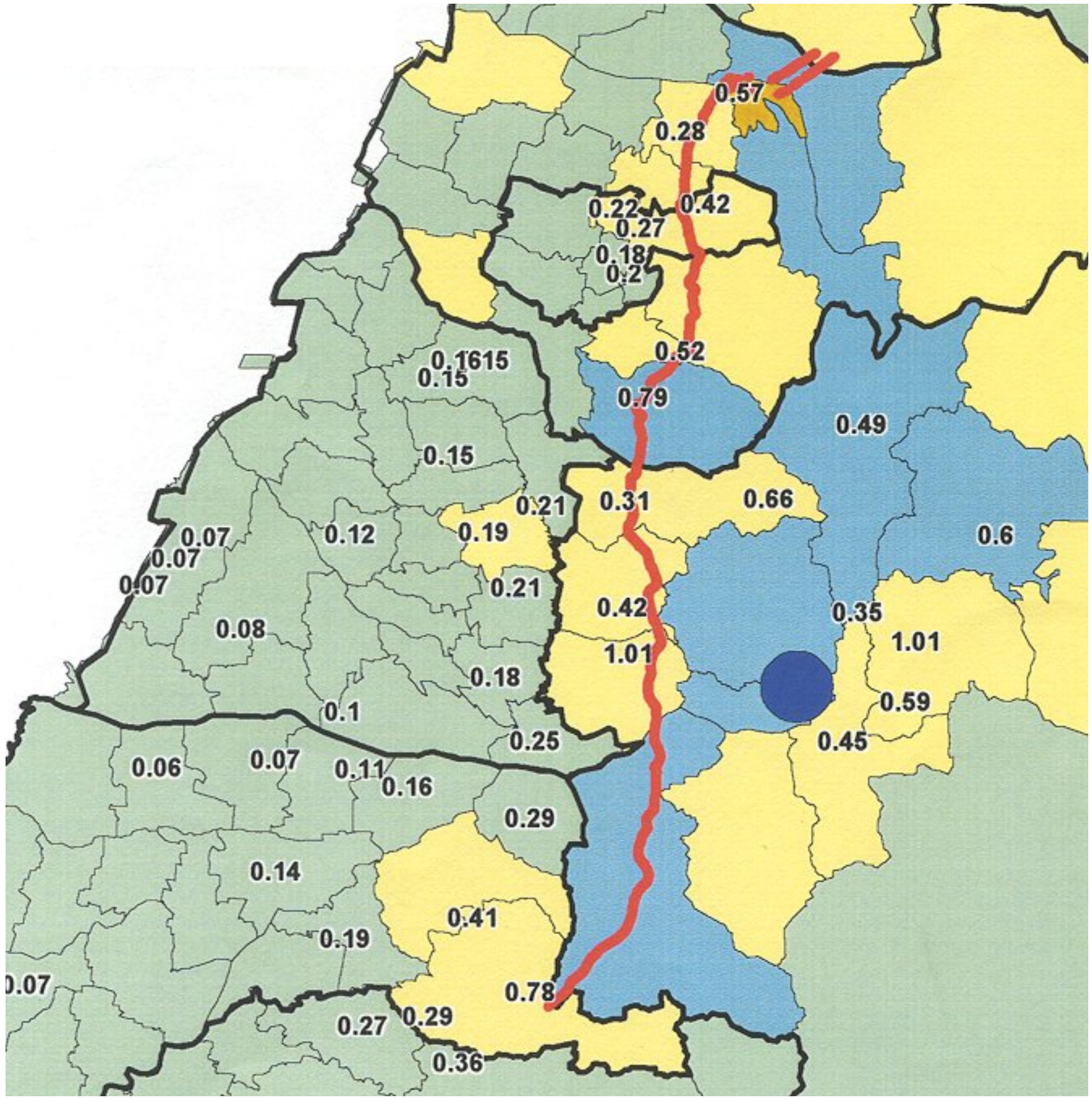


This fence running across the San Andreas fault in Marin County was offset 8.5 ft in the 1906 San Francisco earthquake as the land on the far side of the fault moved to the right.

Type of faulting ? Displacement ?

Length ?

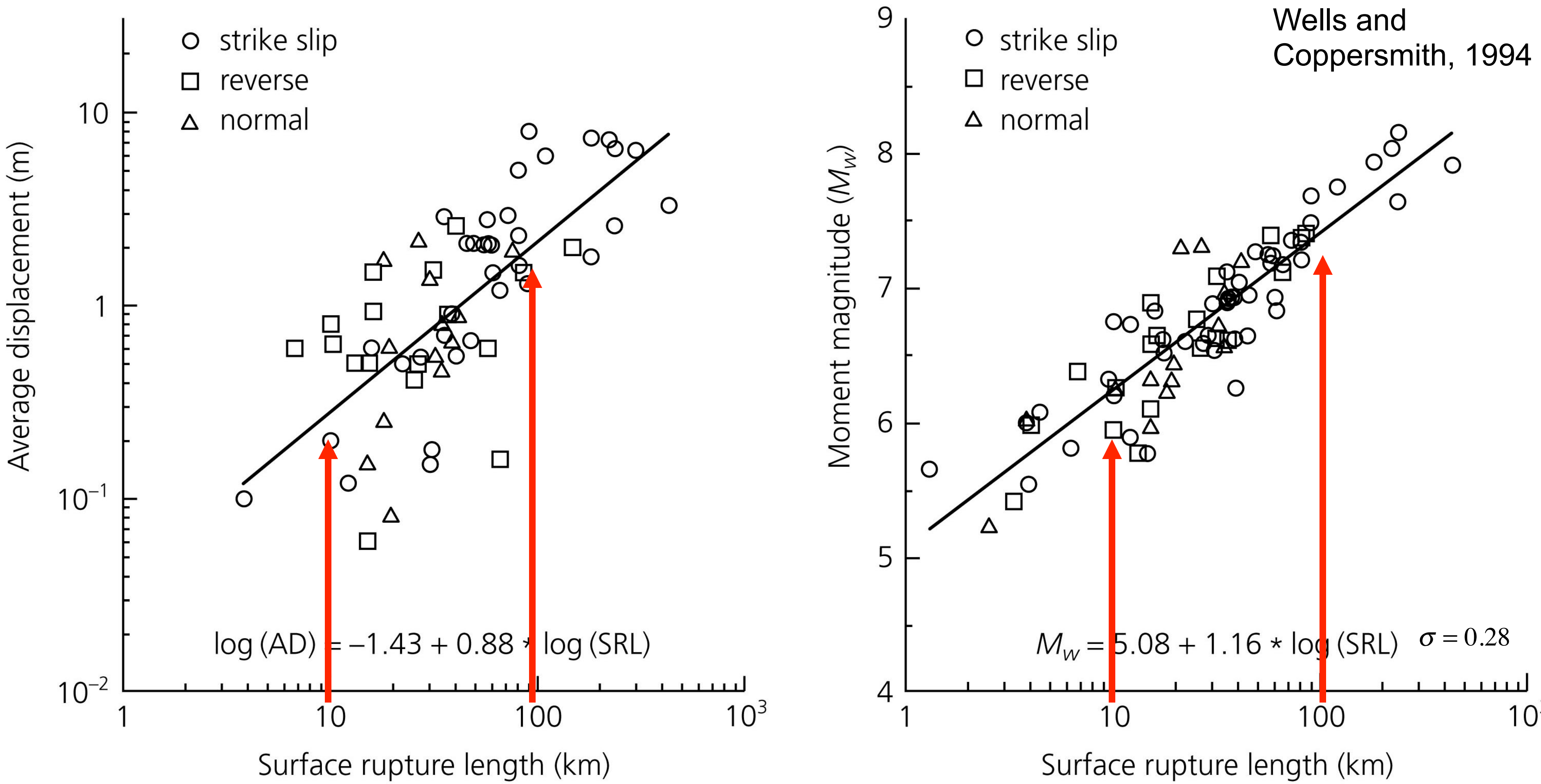




Yi Ben Tsai, 1999

LARGER EARTHQUAKES GENERALLY HAVE LONGER FAULTS AND LARGER SLIP

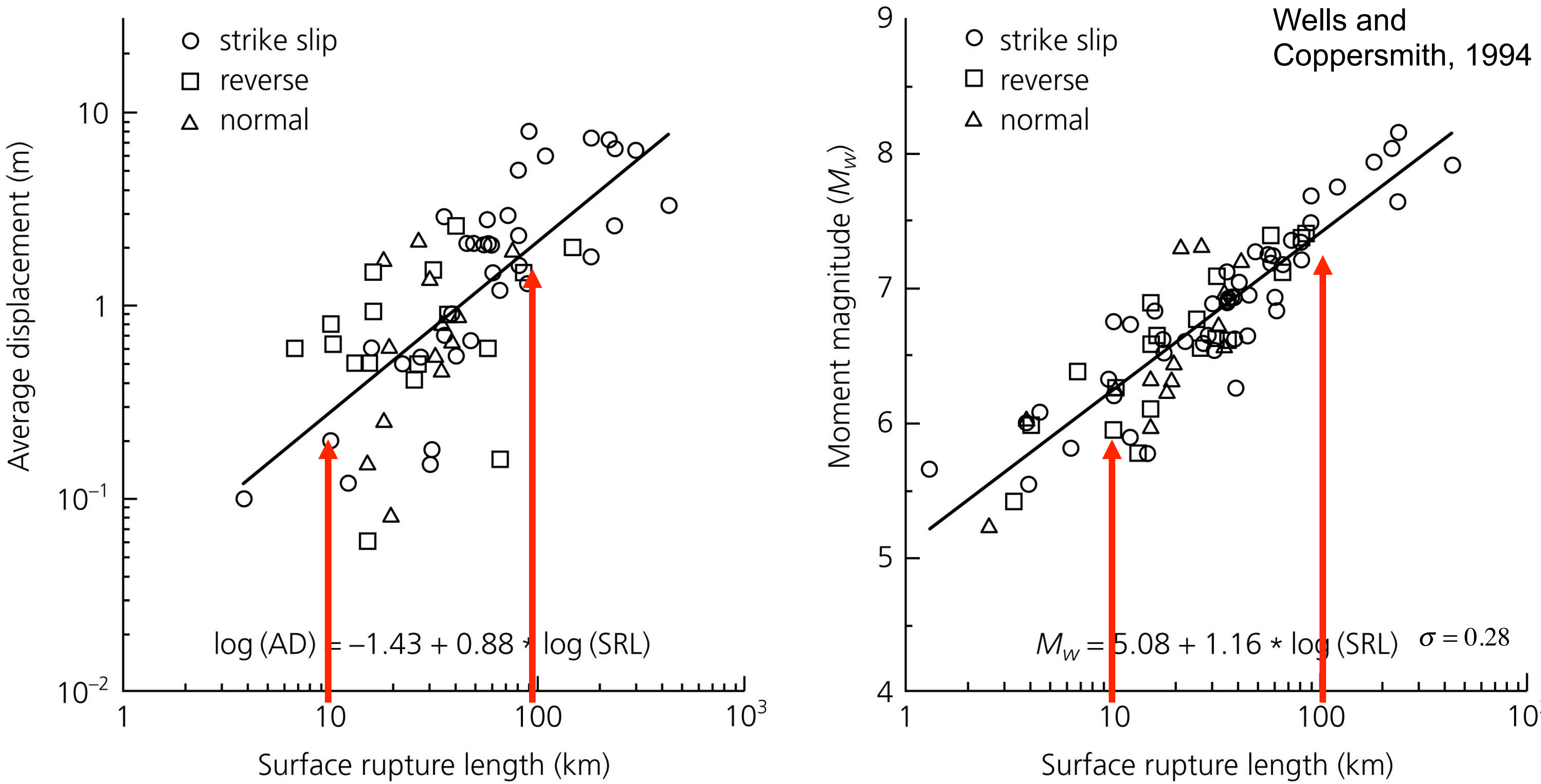
Figure 4.6-7: Empirical relations between slip, fault length, and moment.



M7, ~ 100 km long, 1 m slip; M6, ~ 10 km long, ~ 20 cm slip
Important for tectonics, earthquake source physics, hazard estimation

LARGER EARTHQUAKES GENERALLY HAVE LONGER FAULTS AND LARGER SLIP

Figure 4.6-7: Empirical relations between slip, fault length, and moment.



Why can we, from one earthquake parameter deduce the others (self-similarity) ?

Table 4-1 Empirical Relationships between Moment Magnitude, M_w, Surface Rupture Length, L (km), Rupture Area, A (km^2), and Maximum Surface Displacement, $D(m)$

Fault Movement	Number of Events	Relationship	σ_{M_w}	Relationship	$\sigma_{\log L, A, D}$
Strike slip	43	$M_w = 5.16 + 1.12 \log L$	0.28	$\log L = 0.74M_w - 3.55$	0.23
Reverse	19	$M_w = 5.00 + 1.22 \log L$	0.28	$\log L = 0.63M_w - 2.86$	0.20
Normal	15	$M_w = 4.86 + 1.32 \log L$	0.34	$\log L = 0.50M_w - 2.01$	0.21
All	77	$M_w = 5.08 + 1.16 \log L$	0.28	$\log L = 0.69M_w - 3.22$	0.22
Strike Slip	83	$M_w = 3.98 + 1.02 \log A$	0.23	$\log A = 0.90M_w - 3.42$	0.22
Reverse	43	$M_w = 4.33 + 0.90 \log A$	0.25	$\log A = 0.98M_w - 3.99$	0.26
Normal	22	$M_w = 3.93 + 1.02 \log A$	0.25	$\log A = 0.82M_w - 2.87$	0.22
All	148	$M_w = 4.07 + 0.98 \log A$	0.24	$\log A = 0.91M_w - 3.49$	0.24
Strike slip	43	$M_w = 6.81 + 0.78 \log D$	0.29	$\log D = 1.03M_w - 7.03$	0.34
Reverse[a]	21	$M_w = 6.52 + 0.44 \log D$	0.52	$\log D = 0.29M_w - 1.84$	0.42
Normal	16	$M_w = 6.61 + 0.71 \log D$	0.34	$\log D = 0.89M_w - 5.90$	0.38
All	80	$M_w = 6.69 + 0.74 \log D$	0.40	$\log D = 0.82M_w - 5.46$	0.42

Source: Wells and Coppersmith (1994).

[a] Regression relationships are not statistically significant at a 95% probability level (note inconsistency of regression coefficients and standard deviations).

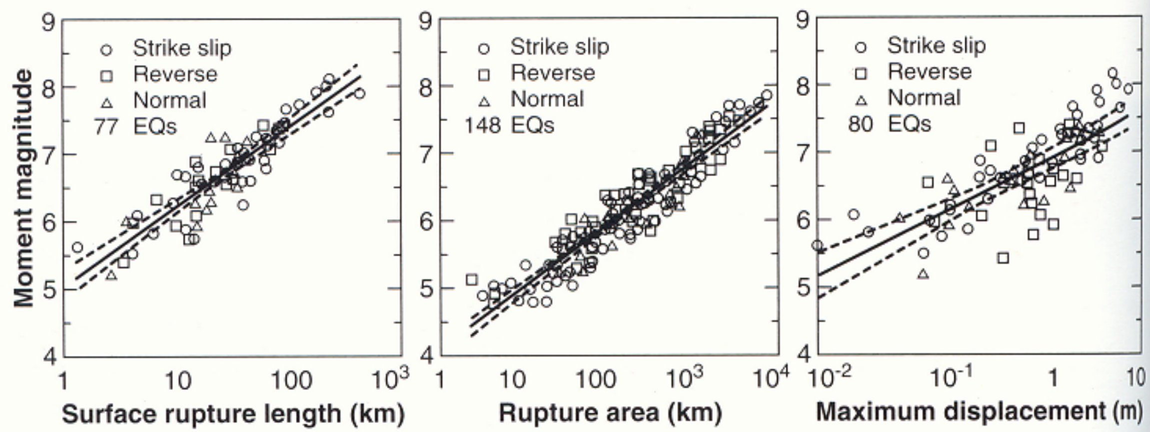


Figure 4.3 Scatter inherent in databases from which correlations of Table 4-1 were developed. (After Wells and Coppersmith, 1994. Used by permission of the Seismological Society of America.)

Variability : Log normal statistics

C.7.2 Normal Distribution

The most commonly used probability distribution in statistics is the *normal distribution* (or *Gaussian distribution*). Its PDF, which plots as the familiar bell-shaped curve of Figure C.6a, describes sets of data produced by a wide variety of physical processes. The normal distribution is completely defined by two parameters: the mean and standard deviation. Mathematically, the PDF of a normally distributed random variable X with mean $\bar{x}$ and standard deviation σ_x is given by

$$f_X(x) = \frac{1}{\sqrt{2\pi}\sigma_x} \exp\left[-\frac{1}{2}\left(\frac{x-\bar{x}}{\sigma_x}\right)^2\right] \qquad \text{(C.18)}$$

The PDF and CDF for a normal distribution are illustrated in Figure C.6. Examples of normal pdf's for random variables with different means and standard deviations are shown in Figure C.7.

Integration of the PDF of the normal distribution does not produce a simple expression for the CDF, so values of the normal CDF are usually expressed in tabular form. The

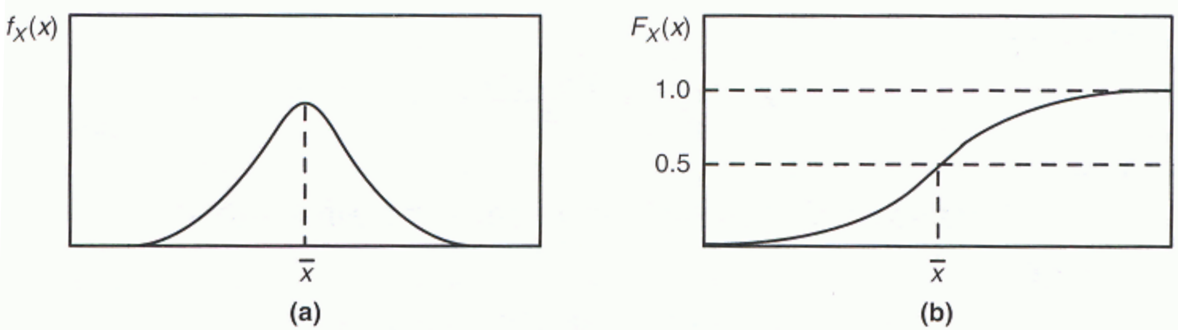


Figure C.6 Normal distribution: (a) probability density function; (b) cumulative distribution function.

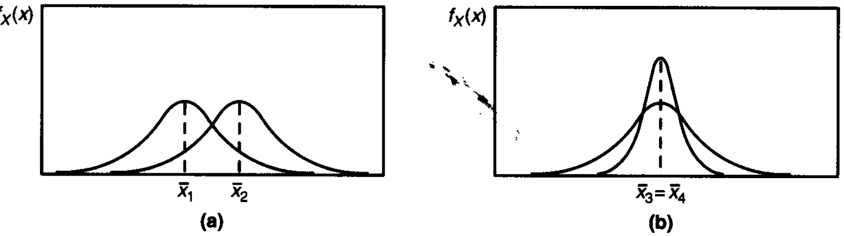


Figure C.7 Normal distributions for (a) two random variables, X_1 and X_2, with different means but the same standard deviation, and (b) two random variables, X_3 and X_4, with the same mean but different standard deviations.

normal CDF is most efficiently expressed in terms of the *standard normal variable*, Z, which can be computed for any random variable, X, using the transformation

$$Z = \frac{X - \bar{x}}{\sigma_x} \qquad \text{(C.19)}$$

Whenever X has a value, x, the corresponding value of Z is $z = (x - \bar{x})/\sigma_x$. Thus, the mean value of Z is $\bar{z} = 0$ and the standard deviation is $\sigma_z = 1$. Tabulated values of the standard normal CDF are presented in Table C-1.

Example C.5

Given a normally distributed random variable, X, with $\bar{x} = 270$ and $\sigma_x = 40$, compute the probability that (a) $X < 300$, (b) $X > 350$, and (c) $200 < X < 240$.

Solution (a) For $X = 300$,

$$Z = \frac{X - \bar{x}}{\sigma_x} = \frac{300 - 270}{40} = 0.75$$

Then

$$P[X < 300] = P[Z < 0.75] = F_z(0.75) = 1 - F_z(-0.75) = 1 - 0.2266 = 0.7734$$

(b) For $X = 350$,

$$Z = \frac{X - \bar{x}}{\sigma_x} = \frac{350 - 270}{40} = 2.0$$

Then

$$P[X > 350] = P[Z > 2.0] = 1 - F_z(2.0) = F_z(-2.0) = 0.0228$$

(c) For $X = 200$,

$$Z = \frac{X - \bar{x}}{\sigma_x} = \frac{200 - 270}{40} = -1.75$$

For $X = 240$,

$$Z = \frac{X - \bar{x}}{\sigma_x} = \frac{240 - 270}{40} = -0.75$$

Then

$$P[200 < X < 240] = P[-1.75 < Z < -0.75] = F_z(-0.75) - F_z(-1.75)$$
$$= 0.2266 - 0.0401 = 0.1865$$

TABLE C-1 Values of the CDF of the standard normal distribution, $F_Z(z) = 1 - F_Z(-z)$

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
−3.4	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002
−3.3	0.0005	0.0005	0.0005	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003
−3.2	0.0007	0.0007	0.0006	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0005
−3.1	0.0010	0.0009	0.0009	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007
−3.0	0.0013	0.0013	0.0013	0.0012	0.0012	0.0011	0.0011	0.0011	0.0010	0.0010
−2.9	0.0019	0.0018	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014
−2.8	0.0026	0.0025	0.0024	0.0023	0.0023	0.0022	0.0021	0.0021	0.0020	0.0019
−2.7	0.0035	0.0034	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026
−2.6	0.0047	0.0045	0.0044	0.0043	0.0041	0.0040	0.0039	0.0038	0.0037	0.0036
−2.5	0.0062	0.0060	0.0059	0.0057	0.0055	0.0054	0.0052	0.0051	0.0049	0.0048
−2.4	0.0082	0.0080	0.0078	0.0075	0.0073	0.0071	0.0069	0.0068	0.0066	0.0064
−2.3	0.0107	0.0104	0.0102	0.0099	0.0096	0.0094	0.0091	0.0089	0.0087	0.0084
−2.2	0.0139	0.0136	0.0132	0.0129	0.0125	0.0122	0.0119	0.0116	0.0113	0.0110
−2.1	0.0179	0.0174	0.0170	0.0166	0.0162	0.0158	0.0154	0.0150	0.0146	0.0143
−2.0	0.0228	0.0222	0.0217	0.0212	0.0207	0.0202	0.0197	0.0192	0.0188	0.0183
−1.9	0.0287	0.0281	0.0274	0.0268	0.0262	0.0256	0.0250	0.0244	0.0239	0.0233
−1.8	0.0359	0.0352	0.0344	0.0336	0.0329	0.0322	0.0314	0.0304	0.0301	0.0294
−1.7	0.0446	0.0436	0.0427	0.0418	0.0409	0.0401	0.0392	0.0384	0.0375	0.0367
−1.6	0.0548	0.0537	0.0526	0.0516	0.0505	0.0495	0.0485	0.0475	0.0465	0.0455
−1.5	0.0668	0.0655	0.0643	0.0630	0.0618	0.0606	0.0594	0.0582	0.0571	0.0559
−1.4	0.0808	0.0793	0.0778	0.0764	0.0749	0.0735	0.0722	0.0708	0.0694	0.0681
−1.3	0.0968	0.0951	0.0934	0.0918	0.0901	0.0885	0.0859	0.0853	0.0838	0.0823
−1.2	0.1151	0.1131	0.1112	0.1093	0.1075	0.1056	0.1038	0.1020	0.1003	0.0985
−1.1	0.1357	0.1335	0.1314	0.1292	0.1271	0.1251	0.1230	0.1210	0.1190	0.1170
−1.0	0.1587	0.1562	0.1539	0.1515	0.1492	0.1469	0.1446	0.1423	0.1401	0.1379
−0.9	0.1841	0.1814	0.1788	0.1762	0.1736	0.1711	0.1685	0.1660	0.1635	0.1611
−0.8	0.2119	0.2090	0.2061	0.2033	0.2005	0.1977	0.1949	0.1922	0.1894	0.1867
−0.7	0.2420	0.2389	0.2358	0.2327	0.2296	0.2266	0.2236	0.2206	0.2177	0.2148
−0.6	0.2743	0.2709	0.2676	0.2643	0.2611	0.2578	0.2546	0.2514	0.2483	0.2451
−0.5	0.3085	0.3050	0.3015	0.2981	0.2946	0.2912	0.2877	0.2843	0.2810	0.2776
−0.4	0.3446	0.3409	0.3372	0.3336	0.3300	0.3264	0.3228	0.3192	0.3156	0.3121
−0.3	0.3821	0.3783	0.3745	0.3707	0.3669	0.3632	0.3594	0.3557	0.3520	0.3483
−0.2	0.4207	0.4168	0.4129	0.4090	0.4052	0.4013	0.3974	0.3936	0.3897	0.3859
−0.1	0.4602	0.4562	0.4522	0.4483	0.4443	0.4404	0.4365	0.4325	0.4286	0.4247
−0.0	0.5000	0.4960	0.4920	0.4880	0.4840	0.4801	0.4761	0.4721	0.4681	0.4641

Kramer, 1996

Application

Regression over log L:

$\sigma = 0.3$

Probability of 68% to find log L between log $L_{theo}-\sigma$ and log $L_{theo}+\sigma$

That is L between $L_{theo}/2$ and 2 L_{theo} !!

A physical model for earthquake scaling

A finite shear crack of radius a with uniform stress drop $\Delta\sigma$: static solution (Eshelby, 1957):

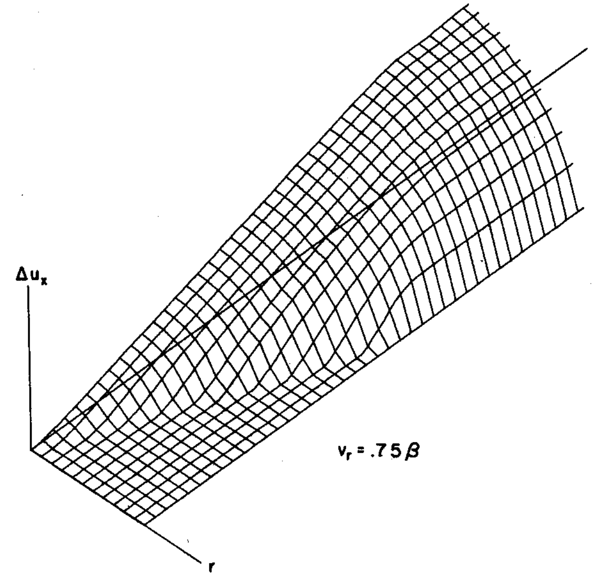
$$\Delta u(\xi) = \frac{7\pi}{12}\frac{\Delta\sigma}{\mu}a\sqrt{1-\frac{\xi^2}{a^2}}$$

$\Rightarrow [u]_{max}$ or $[\bar{u}] \sim a$ at constant $\Delta\sigma$

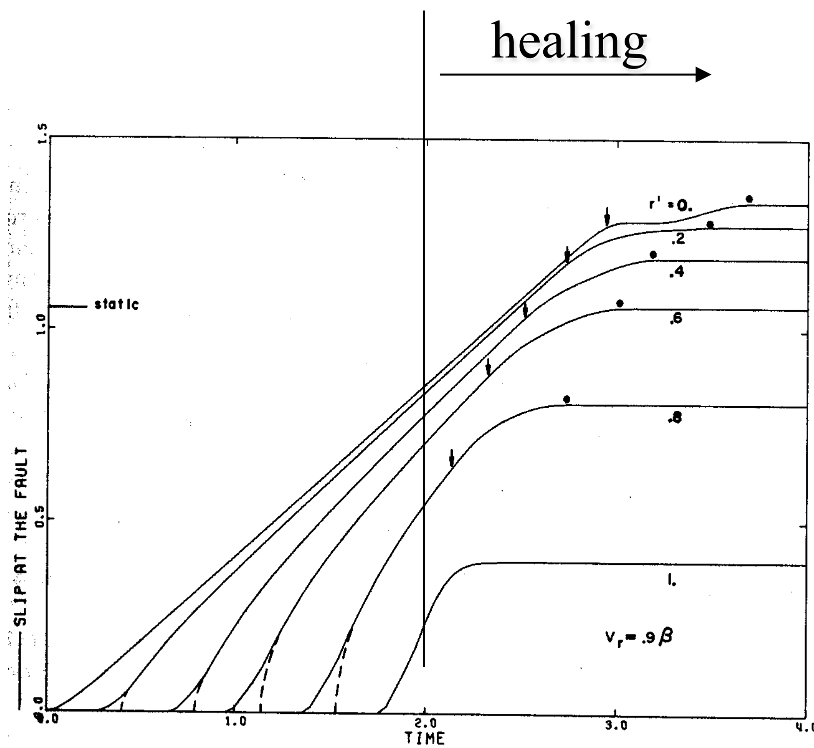
$$M_0 = \mu[\bar{u}]\pi a^2 = \frac{16}{7}\Delta\sigma a^3$$

Kostrov's self similar propagating crack: elliptical slip distribution

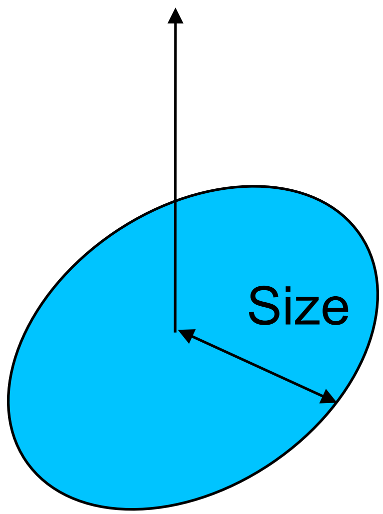
Madariaga (1976):
Numerical solution for a circular crack of finite size propagating at constant velocity.

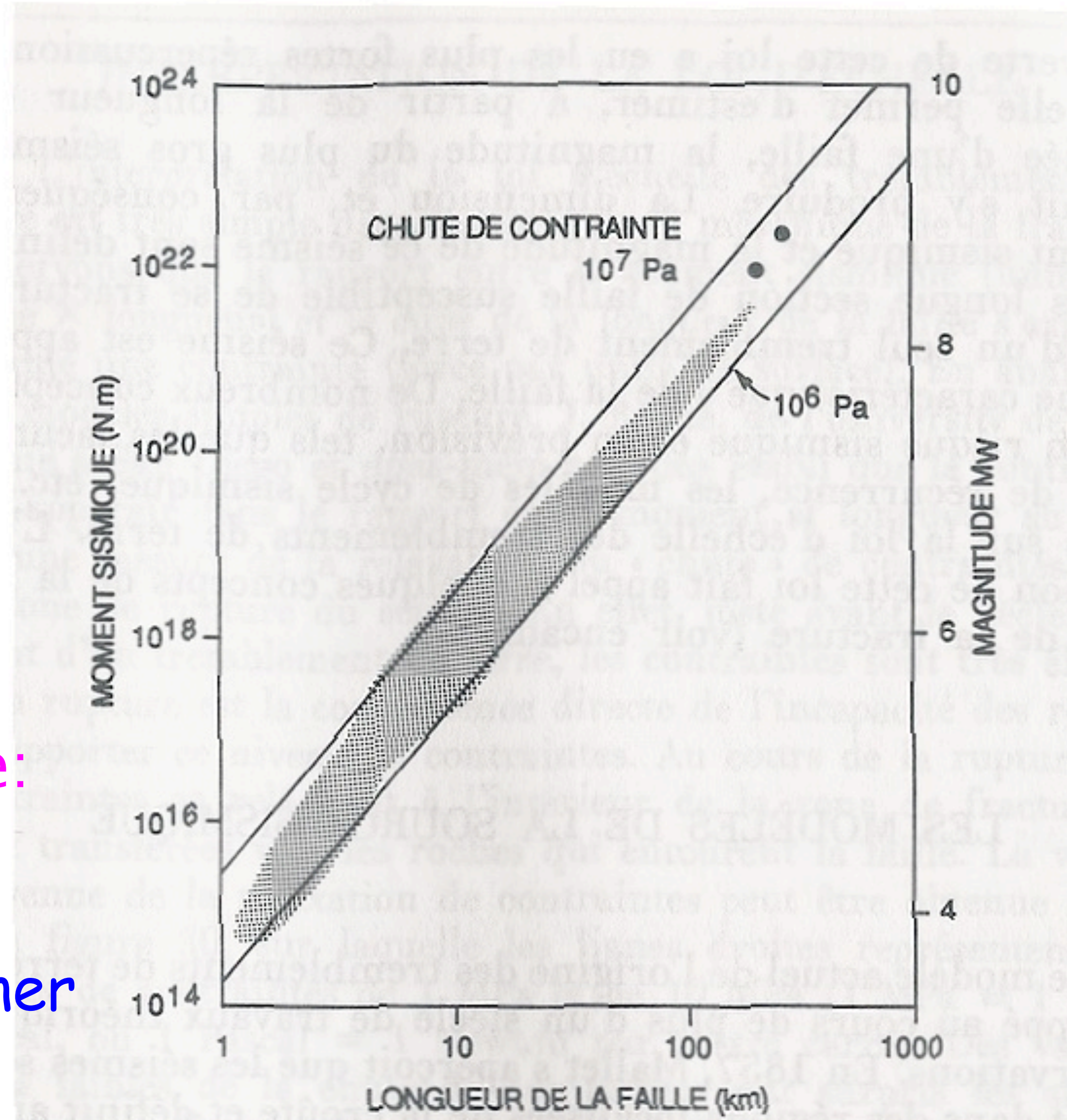


healing



Earthquake scaling law





There is a single scale:

Earthquake size L
Given by duration or corner frequency

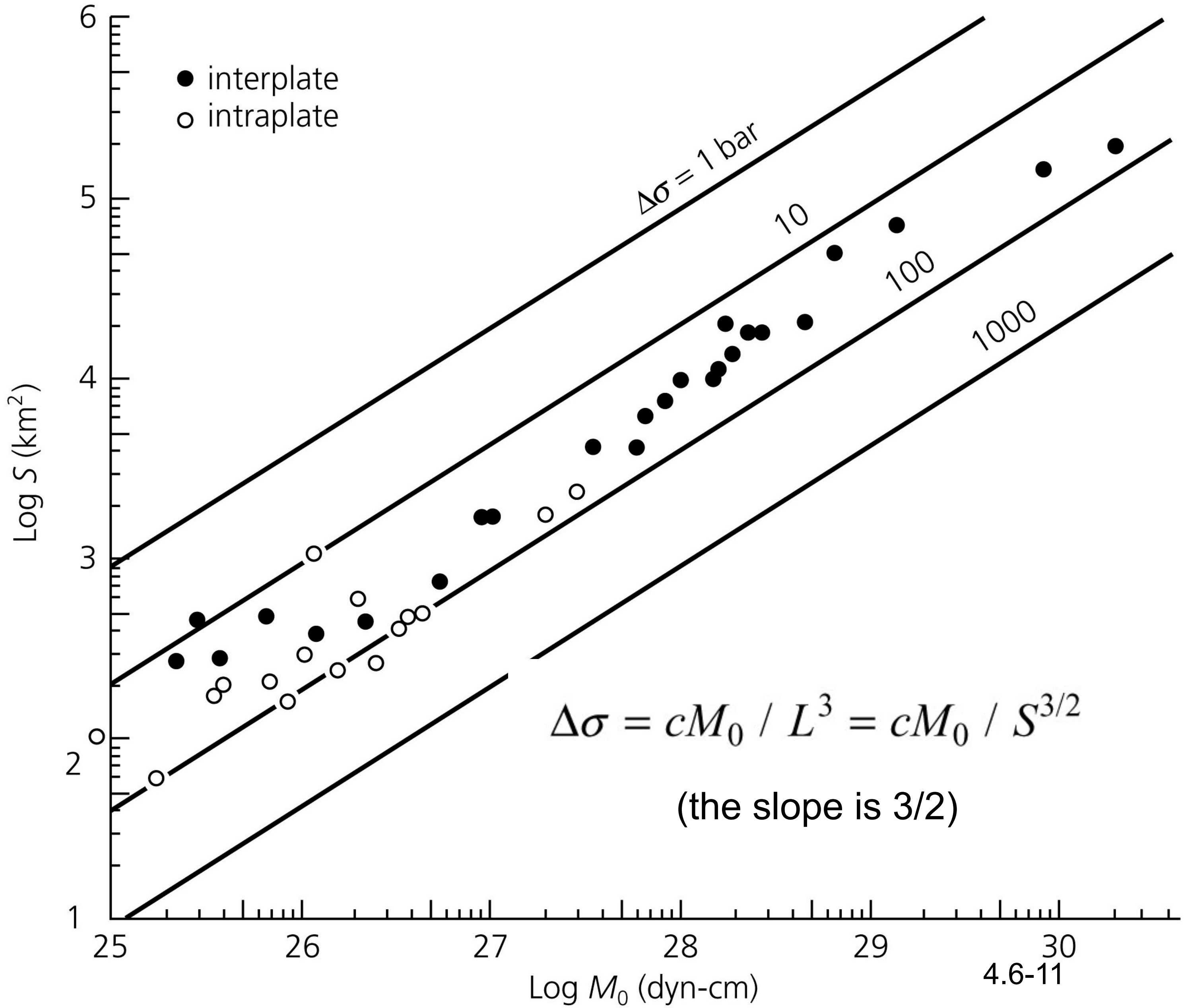
Stress drop

- In general, there is no way to measure the absolute stress in the Earth at depths of earthquakes.
- Seismologists do measure a static stress drop, commonly written as $\Delta\tau s$.
- The static stress drop is estimated from the slip in the earthquake.

$$\Delta \tau_s = C\mu \frac{D}{W}$$

- In general, C is a dimensionless constant. W is the small dimension of the fault. This is called a "*W*-model", since for constant stress drop slip is proportional to *W*.

Earthquake of different size have (almost) the same stress drop…

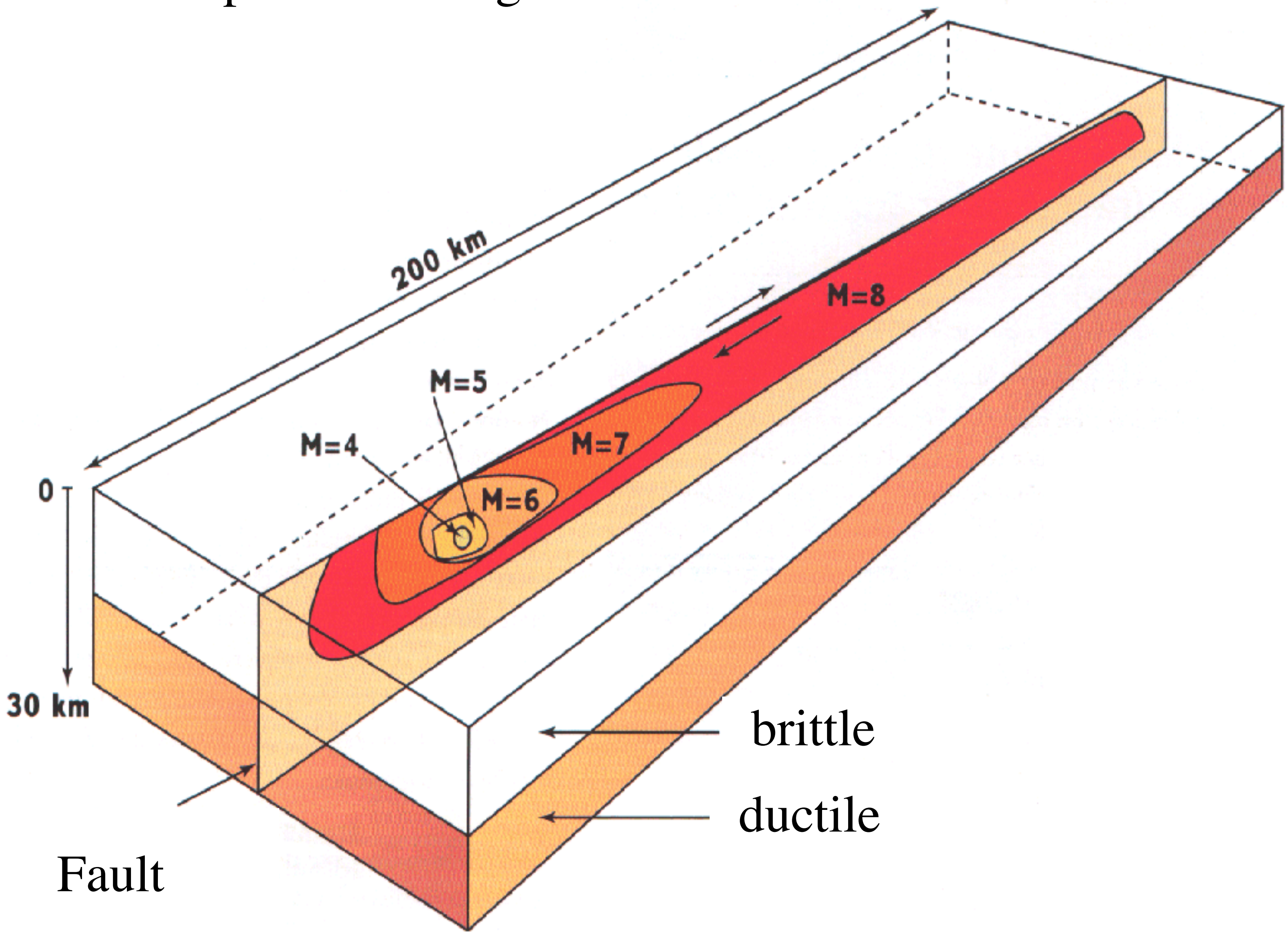


$$\Delta\sigma = cM_0 / L^3 = cM_0 / S^{3/2}$$

(the slope is 3/2)

4.6-11

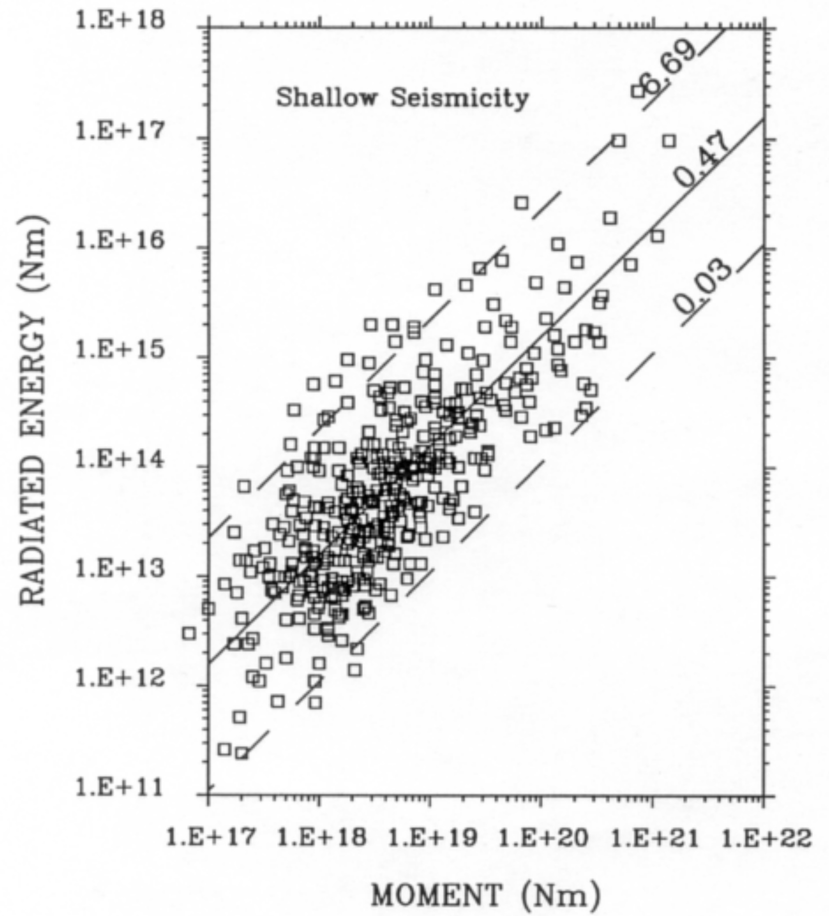
Surface rupture and magnitude



Source : les tremblements de terre en France; 1997

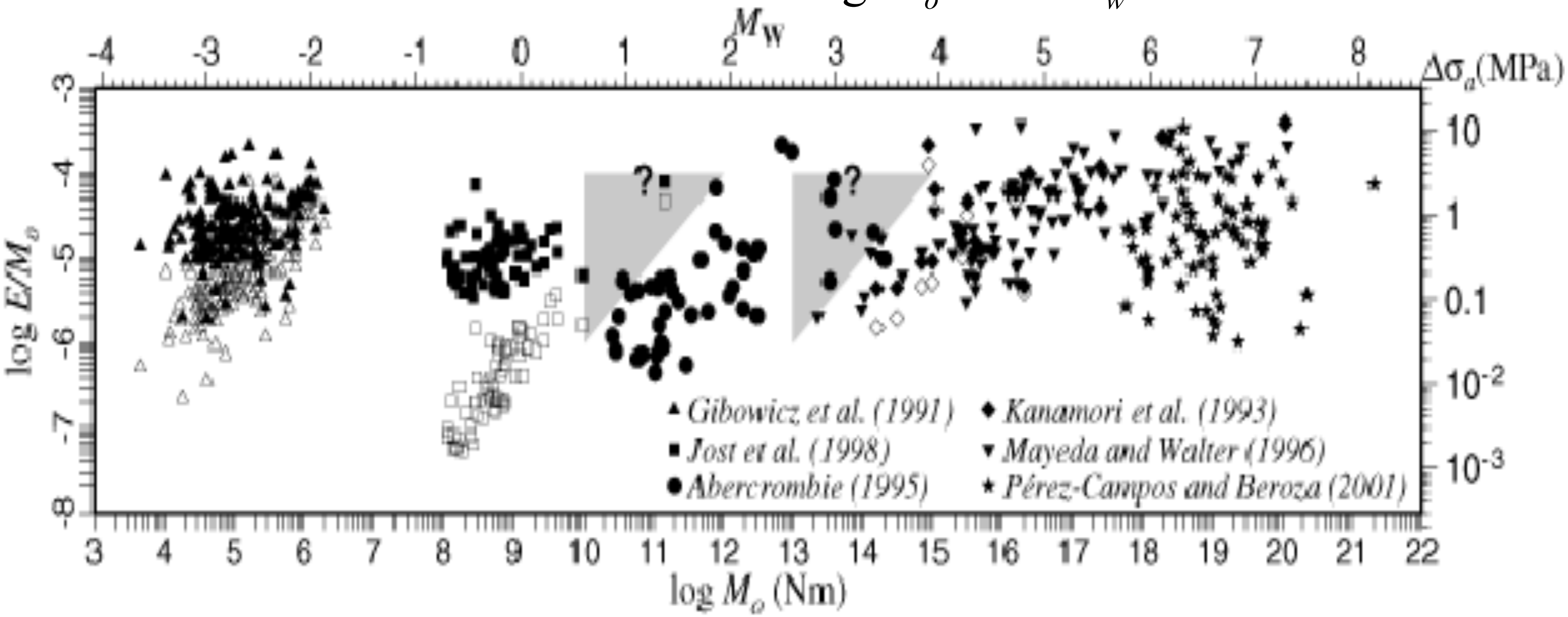
Another measure of stress drop : Radiated energy vs Moment

$$E_S = \frac{1}{2}\Delta\sigma < D > S = \frac{1}{2\mu}\Delta\sigma M_0$$



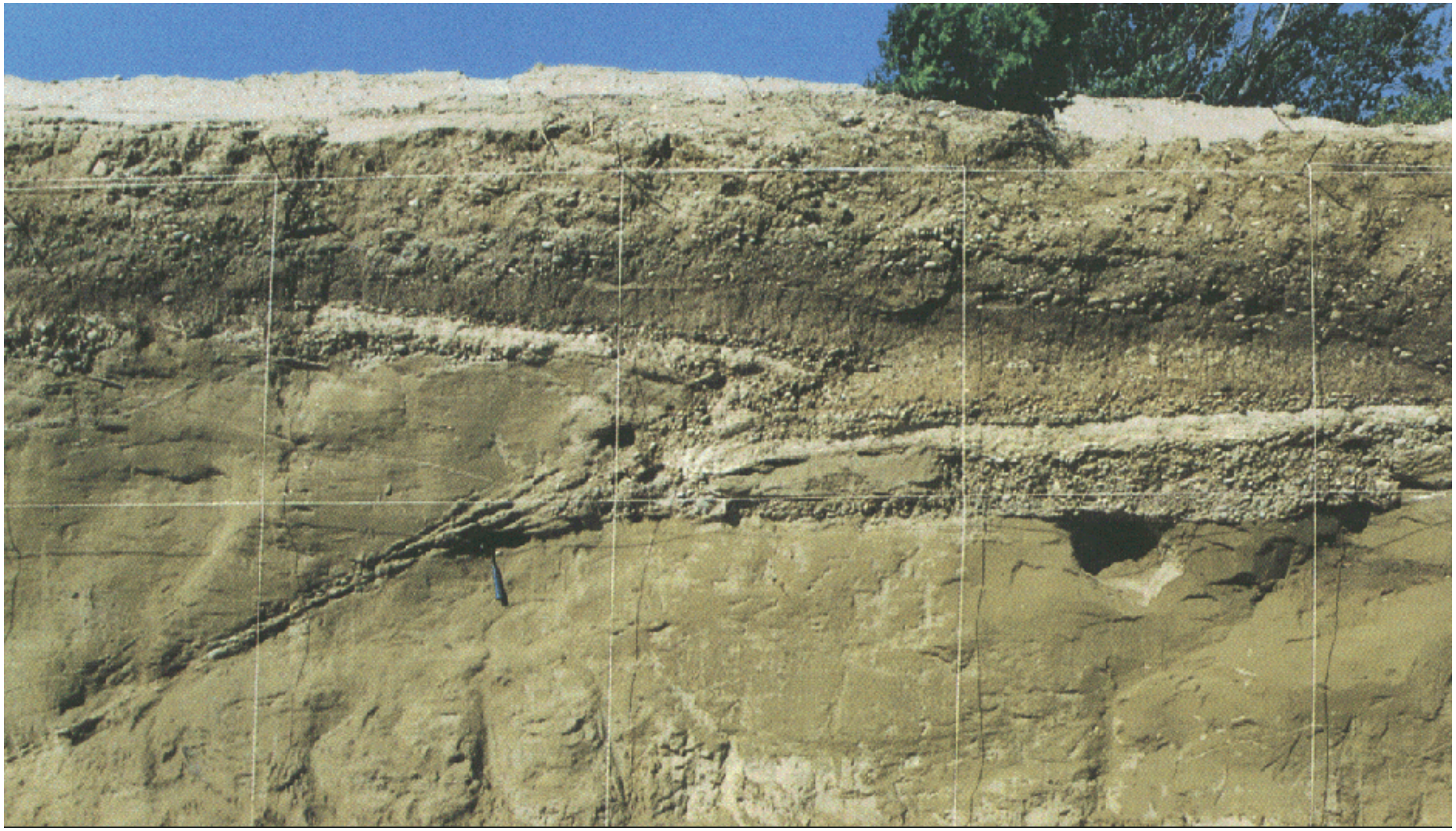
Summary of Observed Radiated Energy vs Moment

$$\log M_o = 1.5\,M_w + 9.6$$



Beroza et al, 2001

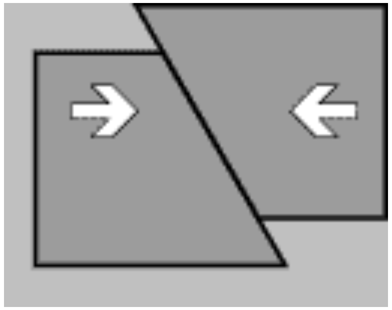
Exercice : earhquake magnitude associated to the trench-observation (AD=0.9 m)?

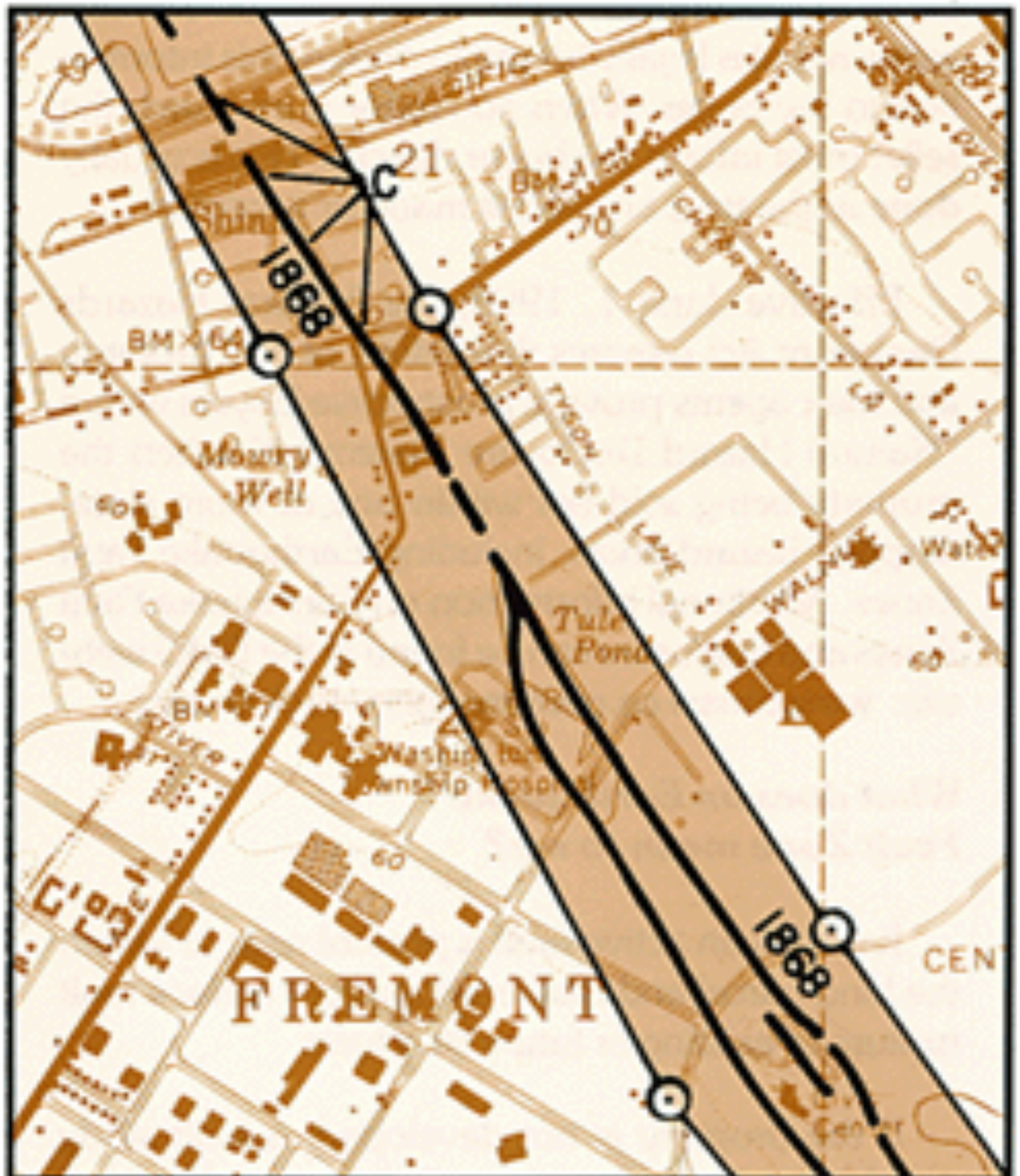


Sources : Kramer, Geotechnical Earthquake Engineering, 1997 (droite)
Rapport de mission AFPS, 2000 (gauche, haut), Grellet et al., 1993 (gauche, bas),

Paléoséisme de Courthézon, vallée du Rh

Chi-Chi, EQ, 1999





CALIFORNIA
CONSERVATION

La source et le spectre du mouvement sismique : le spectre en ω^2

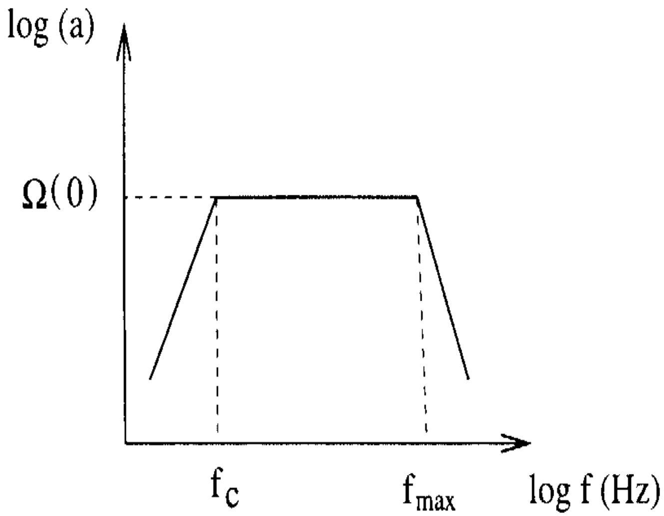


FIG. 3.3 – *Allure caractéristique d'un spectre d'accélération en "ω^2".*

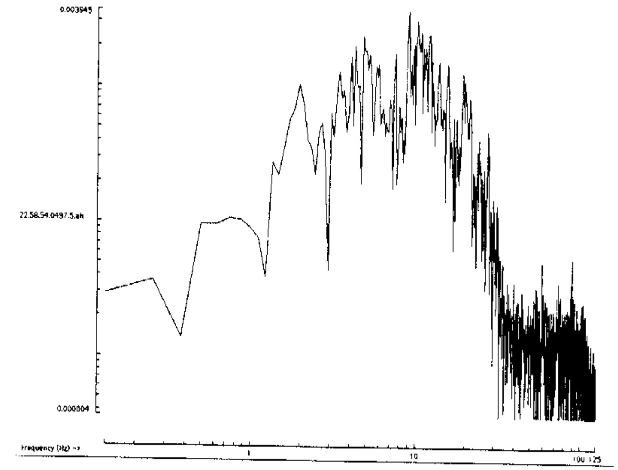


FIG. 3.4 – *Allure d'un spectre d'accélération réel (donnée de Turquie, réplique du séi d'Erzincan 1992: magnitude de moment environ 4, enregistré à 5 km de l'épicentre, "ω^2".*

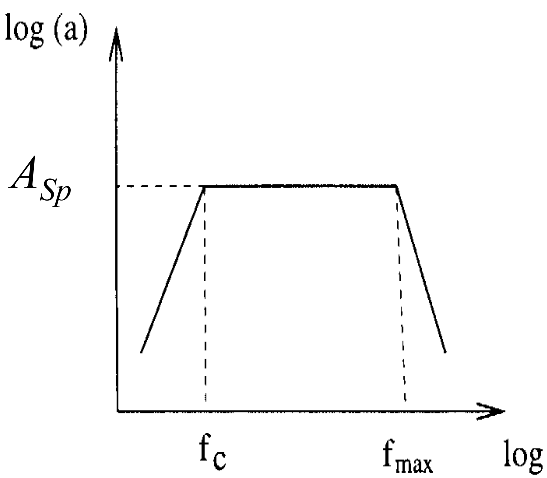
Le spectre en accélération en source proche est schématiquement représenté par 3 tendances : des très basses fréquences jusqu'à fc une croissance en f^2, une stabilisation (« plateau des fréquences intermédiaires »), puis à partir d'une fréquence fmax (liée aux conditions d'atténuation) une décroissance brutale des hautes fréquences. Cette forme dépend des propriétés de la source sismique. Le niveau du plateau intermédiaire est lié au moment sismique M_0 du séisme ($=\mu Ad$). La fréquence coin est inversement proportionnelle à la taille du séisme.

$$a(f) = C\frac{f^2}{1+\left(\frac{f}{f_c}\right)^2}$$

La forme du spectre en accélération (ou en déplacement) permet de trouver les ordres de grandeur de la taille du séisme, de son moment et donc du glissement moyen.

Berge, 1996

Niveau plat du spectre d'accélération:



$$A_{Sp} \sim f_c^2 M$$

$$M \sim L^3$$

$$f_c \sim 1/L$$

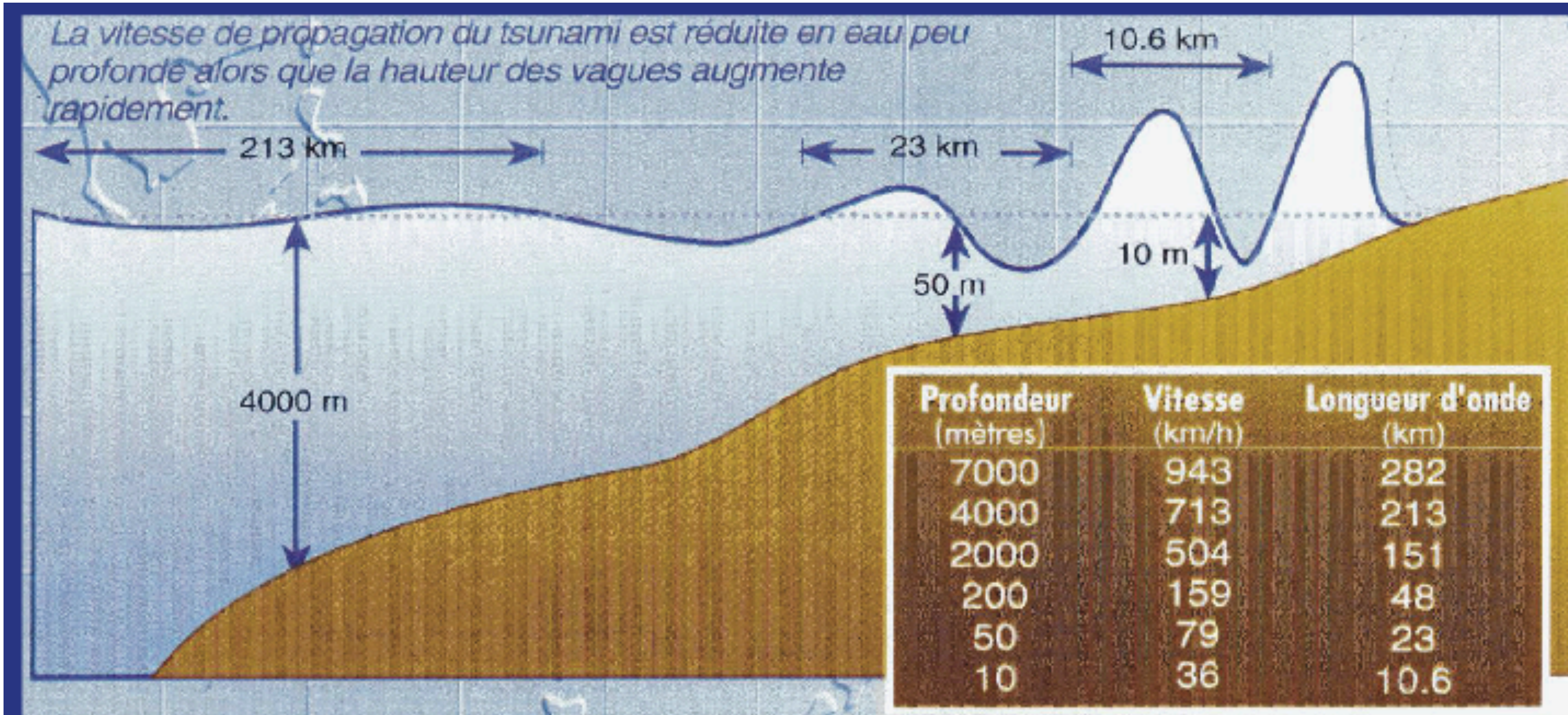
$$\Rightarrow A_{Sp} \sim L$$

On peut donc attendre des accélérations maximales du sol très dispersées en fonction du moment.

Tsunami velocity?

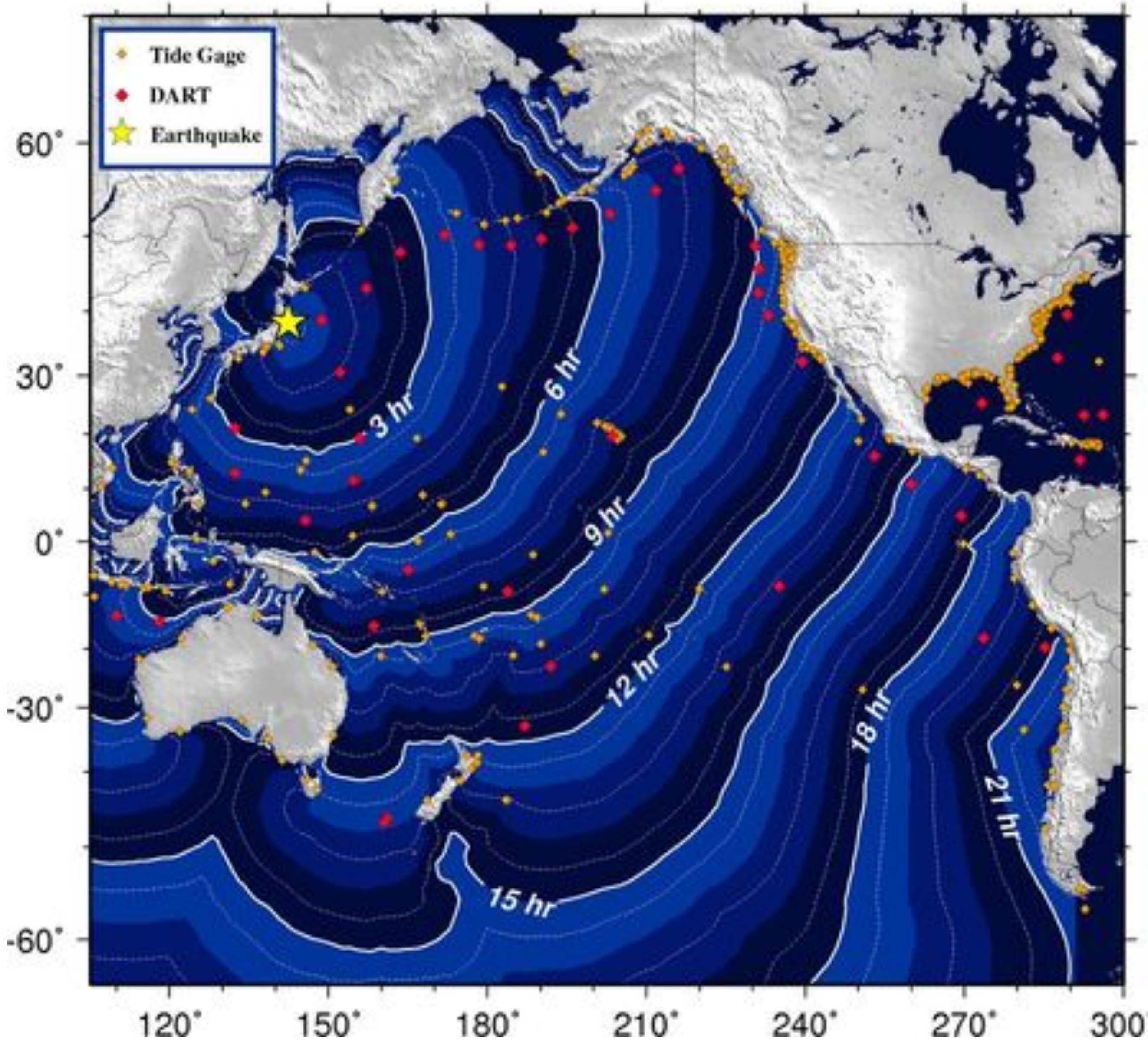
$V = (g*h)^{0.5}$=200m/s=3600x200/1000=720 km/hour

h=4000m/s
g=10m/s



Profondeur (mètres)	Vitesse (km/h)	Longueur d'onde (km)
7000	943	282
4000	713	213
2000	504	151
200	159	48
50	79	23
10	36	10.6

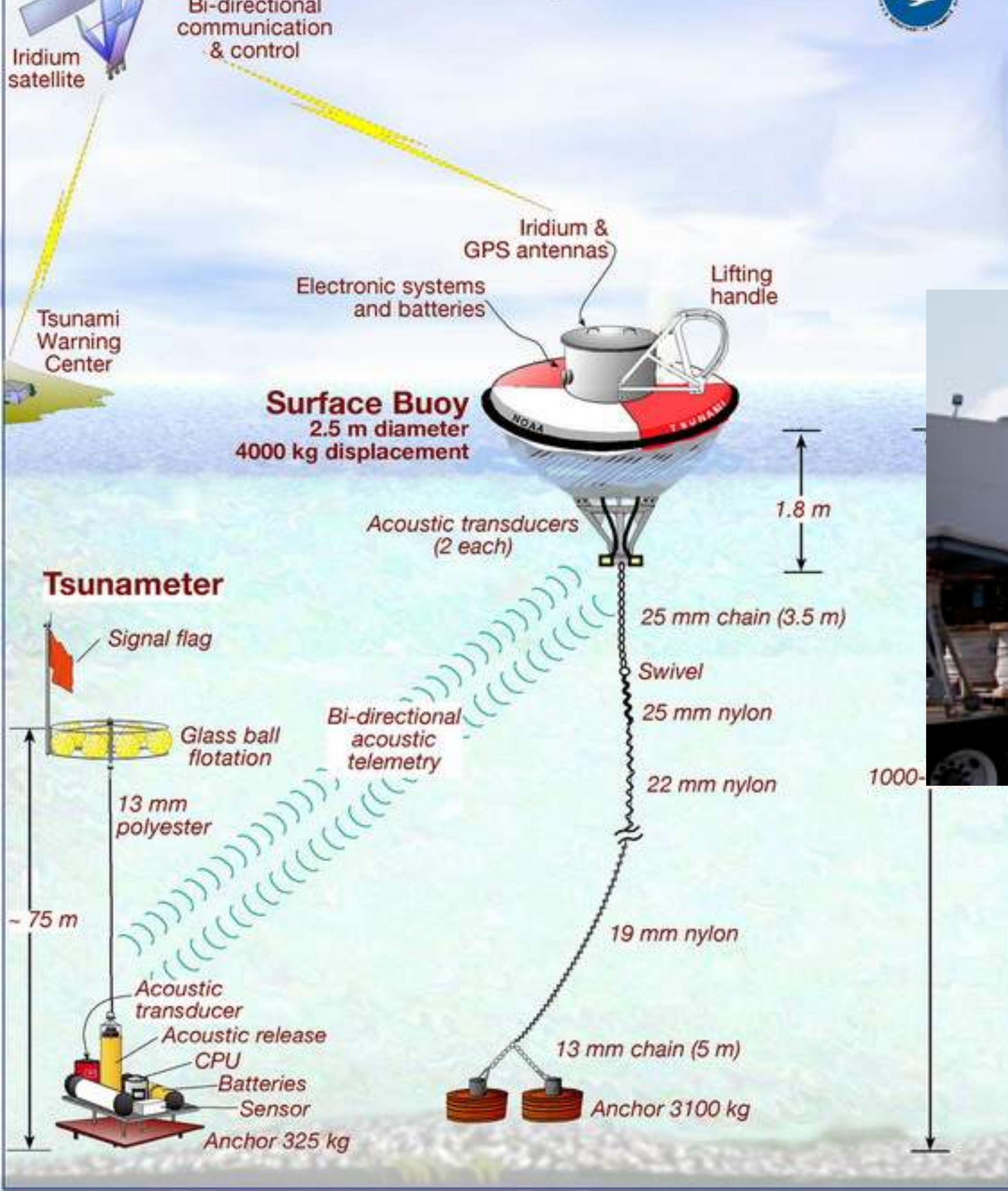
Tsunami Travel Times

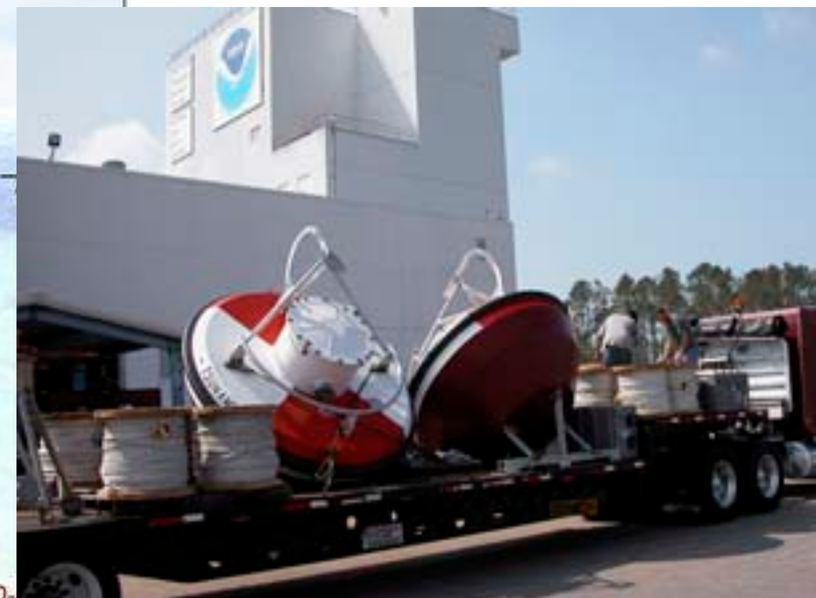


1957, arrivée à Hawai

A quoi ne ressemble pas un tsunami

Hokusai, ~1831


Bi-directional communication & control
Iridium satellite
Iridium & GPS antennas
Lifting handle
Electronic systems and batteries
Tsunami Warning Center
Surface Buoy
2.5 m diameter
4000 kg displacement
1.8 m
Acoustic transducers (2 each)
Tsunameter
25 mm chain (3.5 m)
Signal flag
Swivel
25 mm nylon
Bi-directional acoustic telemetry
Glass ball flotation
22 mm nylon
1000-
13 mm polyester
~ 75 m
19 mm nylon
Acoustic transducer
Acoustic release
CPU
Batteries
Sensor
Anchor 325 kg
13 mm chain (5 m)
Anchor 3100 kg



Tsunami

- Magnitude 8 : 3-5 m
- Magnitude 9 : 9-15 m