INTERNATIONAL ATOMIC ENERGY AGENCY
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WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

(15 November - 16 December 1988)

THE PHYSICS OF EARTHQUAKE PREDICTION

Part II

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THE PHYSICS OF EARTHQUAKE PREDICTION

L. Knopoff

1. PHYSICS vs. PHENOMENOLOGY
2. GEOPHYSICAL CONSTRAINTS
   STATISTICS, GEOMETRY, TRIGGERING
3. LABORATORY EXPERIMENTS
4. PHYSICS of FRACTURE
5. CRACK FUSION MODELS
6. CRACK GROWTH MODELS
7. (Renormalization Group)
8. DYNAMICAL SYSTEMS
9. CHAOS, etc.
10. "THERMODYNAMICS"
11. SEISMIC RISK from PHYSICAL MODELS (Engineering)
12. TIME-DELAY DESTABILIZATION
13. (Triangle Billiard)
14. EFFECTS of LOWER THRESHOLDS of STRENGTH
15. MECHANISMS OF ATTENUATION in the FOCAL ZONE

METHODS OF EARTHQUAKE PREDICTION

1. ASTROLOGY/ESP

   The oldest of the methods, but the least tested statistically.

2. SERENDIPITY

   Notice if an event occurs before an earthquake and assume they are correlated.

   Difficult to test statistically

   Little or no theory for the relationship

   Heaviest investment of $ at present.

   Examples: Anomalous tilts, seismicity, radon, water levels, animal behavior, etc.

3. STATISTICS

   NOT ENOUGH LARGE EARTHQUAKES. To improve statistics assume small earthquakes are scaled-down versions of large earthquakes and practice statistics on the small ones

4. PHYSICS

   CONSTRUCT a model with a small number of parameters and use it to extrapolate from a small number of (large) earthquake occurrences.

   CAN SUCH MODELS BE CONSTRUCTED?

ASSUMPTION:

EARTHQUAKE PREDICTION IS POSSIBLE.

IF ASSUMPTION IS CORRECT, THEN EARTHQUAKES ARE NOT INDEPENDENTLY OCCURRING EVENTS.

MEDICINE

EPIDEMIOLOGY

- ATOMIC BOMBS
- JAYWALKING
- X-RAYS
- SMOKING
- FATTY FOODS
- POLLUTED WATER
- SHELLFISH (out of season)

etc.

ETIOLOGY

- DNA
- VIRUSES
- MICROBIOLOGY
- BIOCHEMISTRY
  - Proteins
  - Chromosomes
  - etc.

PHYSICAL THEORY

$\Longrightarrow$ QUANTITATIVE MODELING

WHAT CAN IT DO FOR US?

- UNDERSTANDING PHENOMENOLOGY
- TESTING PHENOMENOLOGICAL ASSUMPTIONS
- NEW (or better) PHENOMENOLOGY
- ON-LINE PREDICTION (ENGINEERING)

EARTHQUAKE PREDICTION

PHENOMENOLOGY

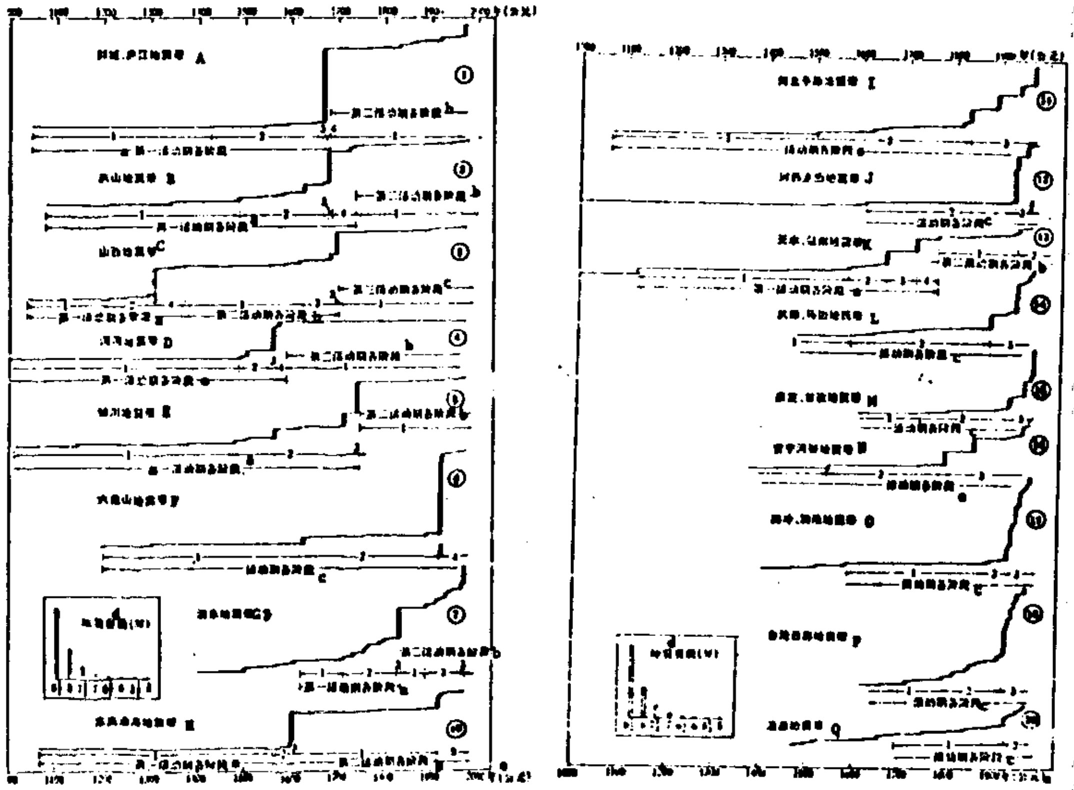
- EARTHQUAKE CLUSTERING
- ELECTRICAL CONDUCTIVITY
- WATER LEVEL
- RADON
- TILT
- SEISMIC WAVE VELOCITY
- ANIMAL BEHAVIOR

etc.

PHYSICS

- FRACTURING
- PLATE TECTONICS
- STRESS REDISTRIBUTION
- RHEOLOGY
  creep
  friction
- GEOMETRY

CLUSTERING ⟺ PATTERNS

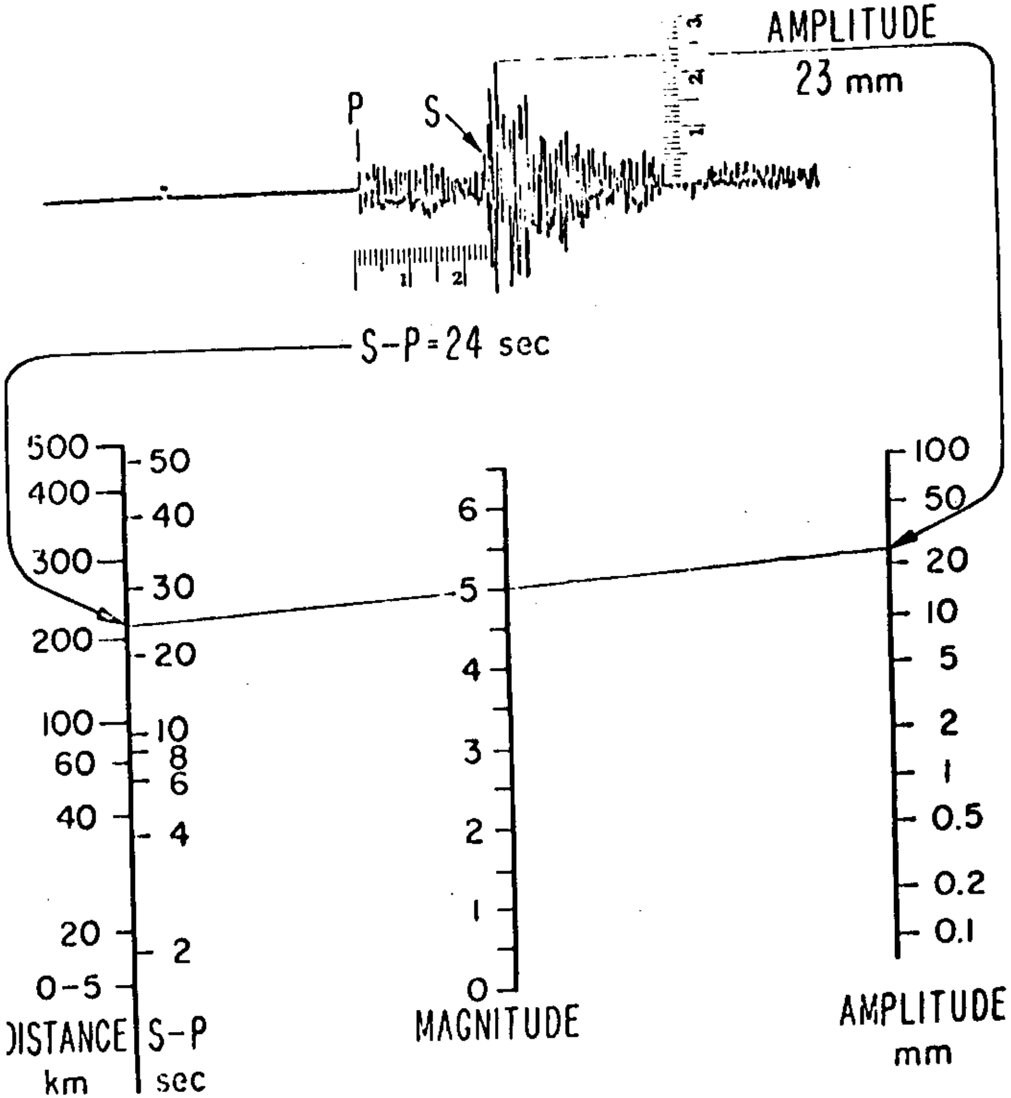


strain release curves for the seismic zones of China.

a. Stages of the first seismic period.
b. Stages of the second seismic period.
c. Stages of the third seismic period.
d. Magnitude.
e. Year (AD).

A. Tancheng-Lujiang seismic zone.
B. Yanshan seismic zone.
C. Shansi seismic zone.
D. Weihe seismic zone.
E. Yinchan seismic zone.
F. Liupanshan seismic zone.
G. Eastern Yunnan seismic zone.
H. Southeast coast seismic zone.

I. Hopei plain seismic zone.
J. Hoxi corridor seismic zone.
K. Tienshu-Lanzhou seismic zone.
L. Wudu-Mabian seismic zone.
M. Kangding-Ganzi seismic zone.
N. Anning valley seismic zone.
O. Tengcong-Langcong seismic zone.
P. Western Taiwan seismic zone.
Q. Western Yunnan seismic zone.

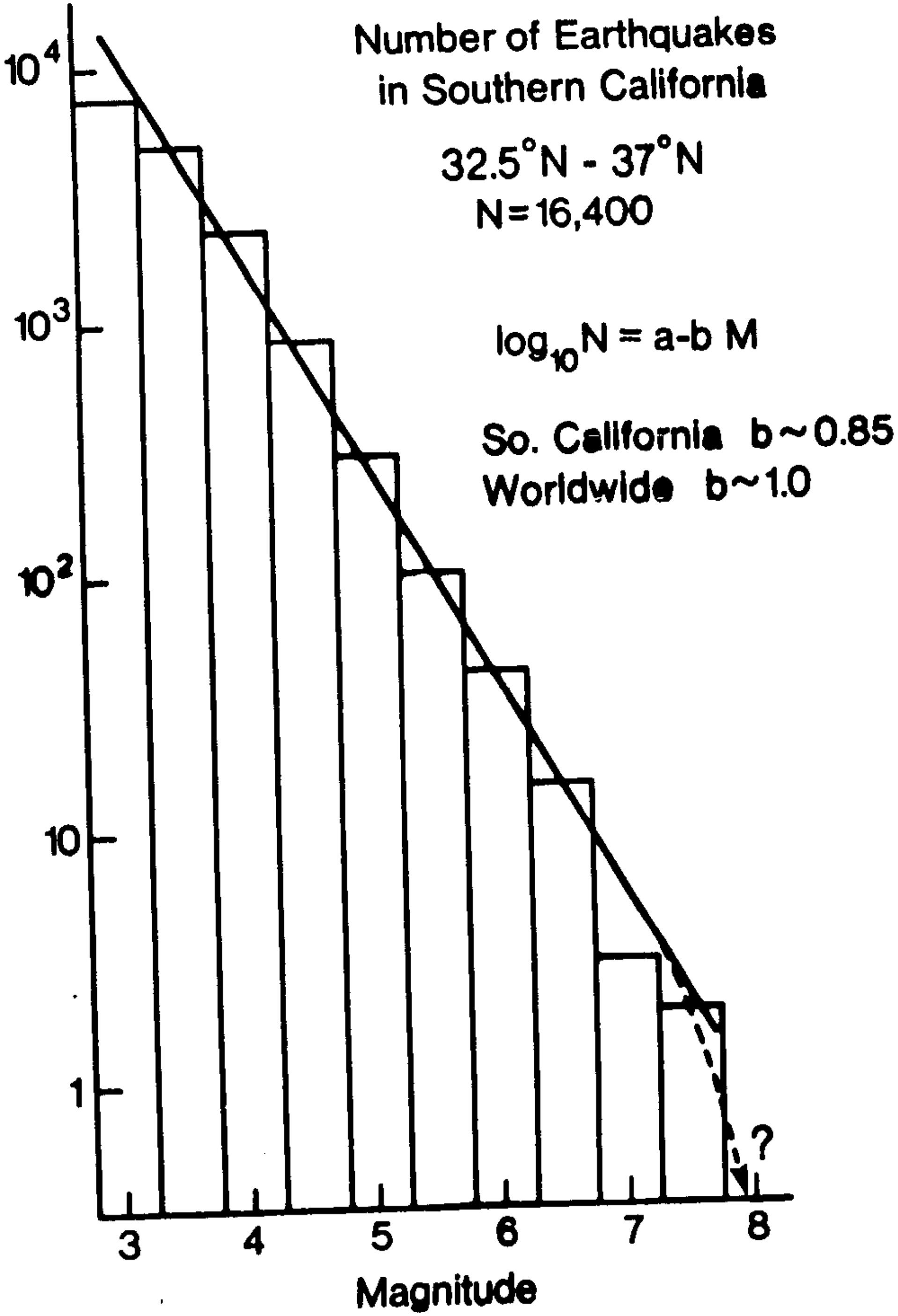


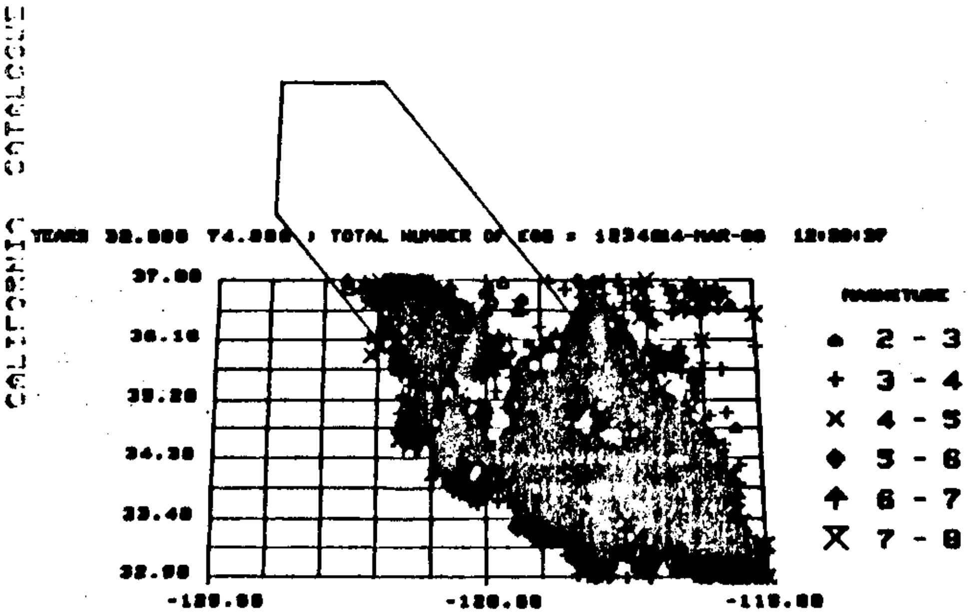
TO DETERMINE THE MAGNITUDE OF AN EARTHQUAKE WE CONNECT ON THE CHART

A. THE MAXIMUM AMPLITUDE RECORDED BY A STANDARD SEISMOMETER, AND

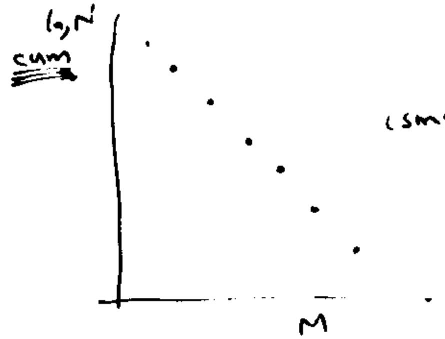
B. THE DISTANCE OF THAT SEISMOMETER FROM THE EPICENTER OF THE EARTHQUAKE (OR THE DIFFERENCE IN TIMES OF ARRIVAL OF THE P AND S WAVES)

BY A STRAIGHT LINE, WHICH CROSSES THE CENTER SCALE AT THE MAGNITUDE





STATISTICAL ANALYSIS (determination of a, b) and variances



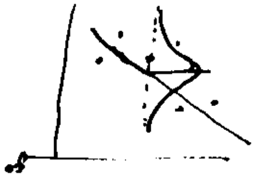
[redacted] Goals

determine a, b AND VARIANCES !!!

(smoothing!)

$\log_{10} N = a - bM$

(ordinary) Least squares?



Assume
1. Normal distr. of errors
2. statistical independence of each measurement
3. equal weights

I

$$\Delta N = \frac{b \Delta M}{\log_{10} e} \, e^{\left(\frac{a - bM}{\log_{10} e}\right)}$$

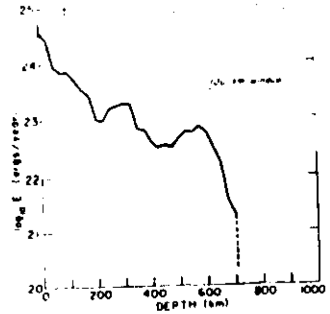
$\log_{10} \Delta N = \log (b \Delta M) + a - bM$

Least squares? Assumpt. 1 & 2. But 3?

III

Di.ffl

Theory of earthquakes?



World-wide earthquake energy rate-depth function

(most eqs occur in upper 15km of earth).

(rad. of earth = 6371km)

IV. Maximum likelihood

If $\log_{10} N_{cum} = a - bM$

$$\Delta N_i = N_{cum_i} \frac{b\Delta M}{\log_{10} e}$$

normalizing factor

Prob of 1 eq. in ith interval = $\frac{b\Delta M}{\log_{10} e} e^{\frac{a-bM_i}{\log_{10} e}} \left\{\frac{1}{N.F.}\right\}$

Prob of observing n_i eqs. in ith mag. interval

$$P = \prod_{i=1}^{I} \left\{\frac{b\Delta M}{\log_{10} e} e^{\frac{a-bM_i}{\log_{10} e}} \frac{1}{N.F.}\right\}^{n_i}$$

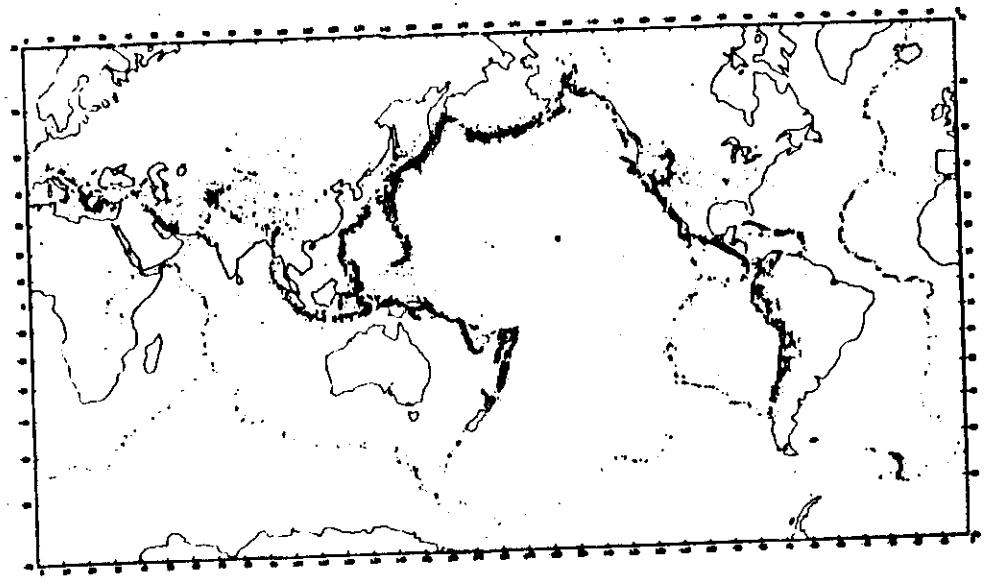
$$N.F. = \sum \Delta N_i = \sum \frac{b\Delta M}{\log_{10} e} e^{a-bM_i}$$

Take $\log_e P = \left[\frac{a}{\log_{10} e} - \log_e N.F. + \log_e b\Delta M - \log_e \log_{10} e\right] \sum n_i - \frac{b \sum M_i n_i}{\log_{10} e}$

$$\left.-\sum_i^I (b\Delta M)\, 10^{a-bM_i}\right\}$$

Thus $\mathrm{Max} \left\{(a + \log b\Delta M) \sum_i^I n_i - b \sum_i^I n_i M_i \right.$

see Kantorovich, Molchan, Keilis-Borok - Computational Seismology, vol. 5, pp 80-128, 1971



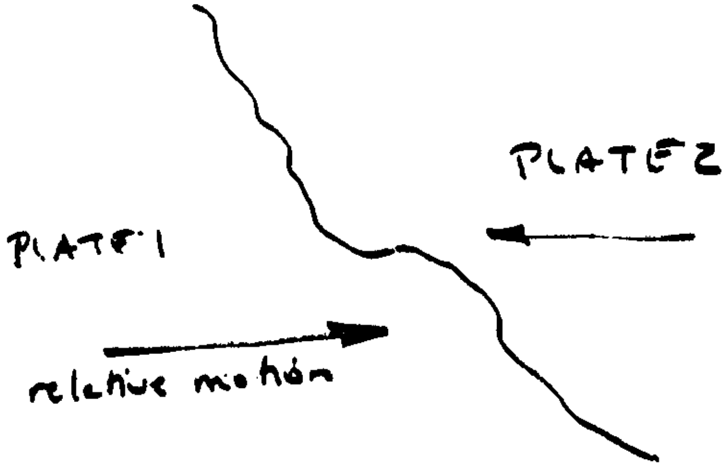
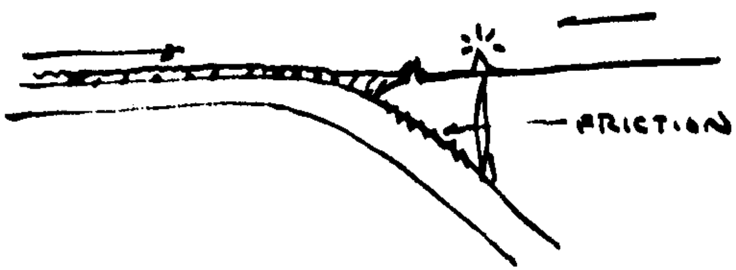


PLATE 2
PLATE 1
relative motion


FRICTION

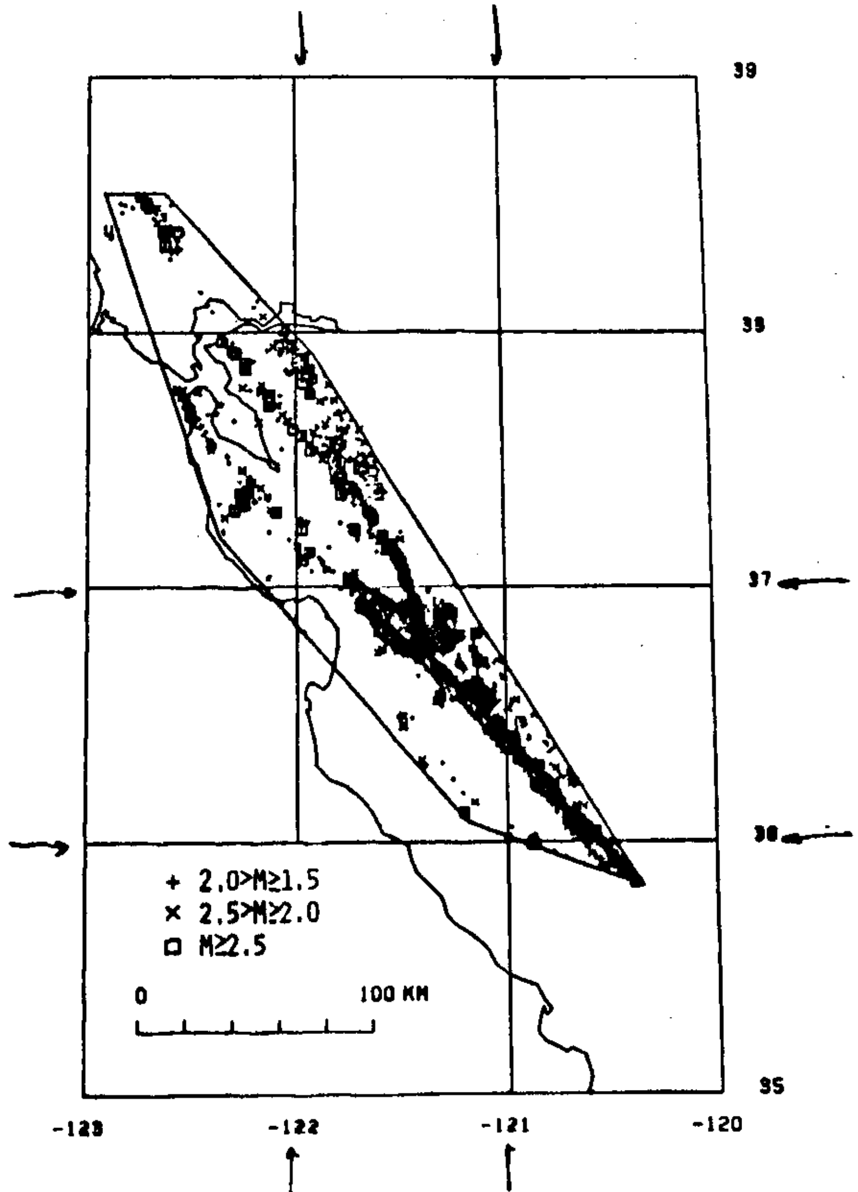

39
38
37
36
35
+ 2.0>M≥1.5
× 2.5>M≥2.0
□ M≥2.5
0
100 KM
-123
-122
-121
-120

Fig. 2a

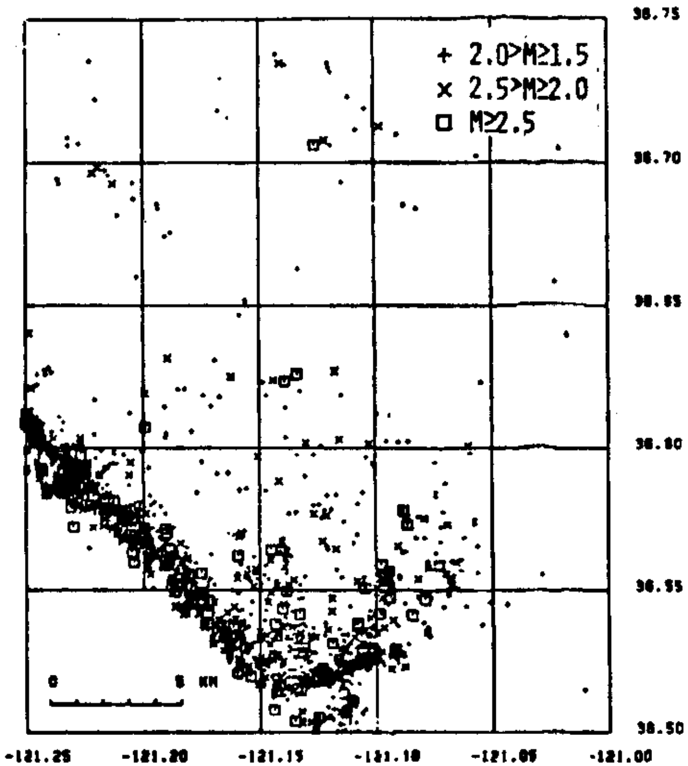

+ 2.0>M≥1.5
× 2.5>M≥2.0
□ M≥2.5
0 5 KM
36.75
36.70
36.65
36.60
36.55
36.50
-121.25
-121.20
-121.15
-121.10
-121.05
-121.00

Fig. 2c

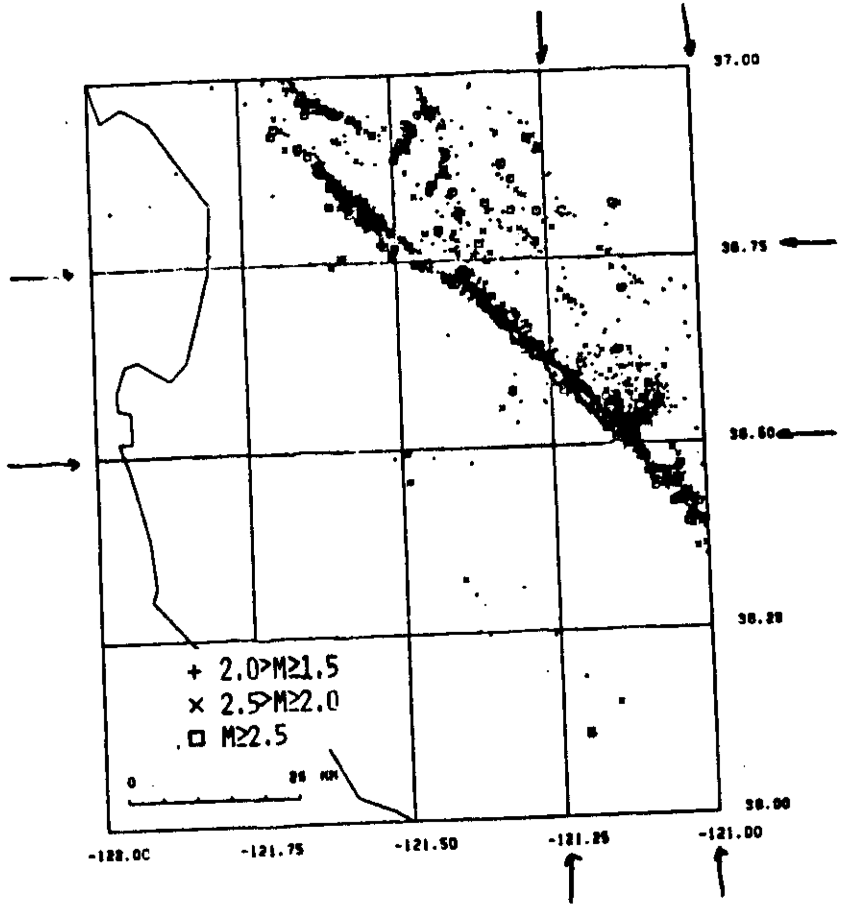
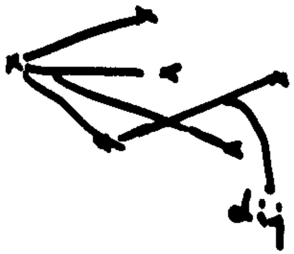
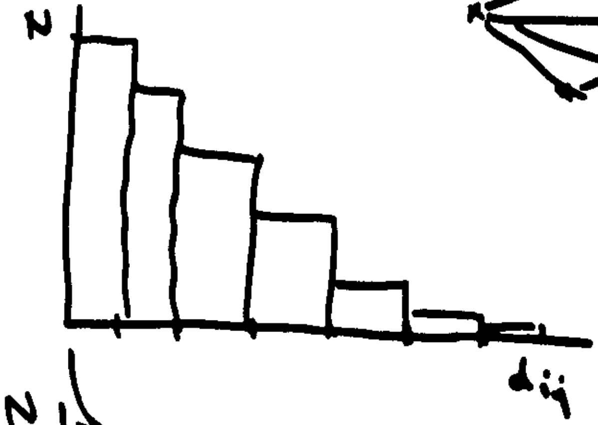

37.00
36.75
36.50
36.25
36.00
+ 2.0>M≥1.5
× 2.5>M≥2.0
□ M≥2.5
0 25 KM
-122.00
-121.75
-121.50
-121.25
-121.00

Fig. 2b

2-point distribution

$$\frac{N(N-1)}{2} \sim \frac{N^2}{2}$$





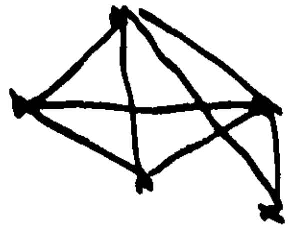
$$N \sim d^{-1}$$

4-point distrib.

$$\frac{N(N-1)(N-2)(N-3)}{4\cdot 3\cdot 2\cdot 1} \sim \frac{N^4}{24}$$

Calc. Vol of tetrahedron

(if eqs. lie on plane, distrib. = $\delta(V)$)



$$\frac{N(N-1)(N-2)}{3\cdot 2\cdot 1} \sim N^3/6$$

4. GEOMETRICAL CONSTRAINTS

Spatial Distribution

2-point correlation function:

$e^{-\lambda x}$ Distribution $\sim \frac{1}{x}$ FRACTAL

self-similar

3-point correlation fn.:   Dist. $\sim 1/A$ SCALE 2km $\leftrightarrow$ 2000km

$\boxed{\text{ua}^{+}}$

4-point correlation fn.:   Dist. $\sim 1/V$

(Kagan & Knopoff, 1980; Kagan, 1982a,b)

If faults are planes Dist $\sim \delta(V)$ Hence faults are not planes

On shorter distance scales → roughness (elevation) studies

Temporal Distribution

2-point correlation fn.:   Dist. $\sim 1/t$ scale 2hrs $\leftrightarrow$ 10yrs

(Omori, 1892)

(Kagan & Knopoff, 1986)

Hence earthquakes not Poisson Independent

(if P. Ind. Dist $\sim e^{-\lambda t}$)

Conclusion:

Fractal spatial & Temporal Relations dominate geometry & time rel^ns of earthquake faults.

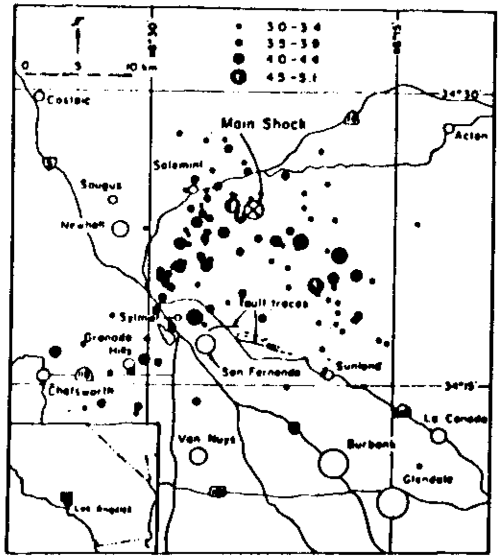
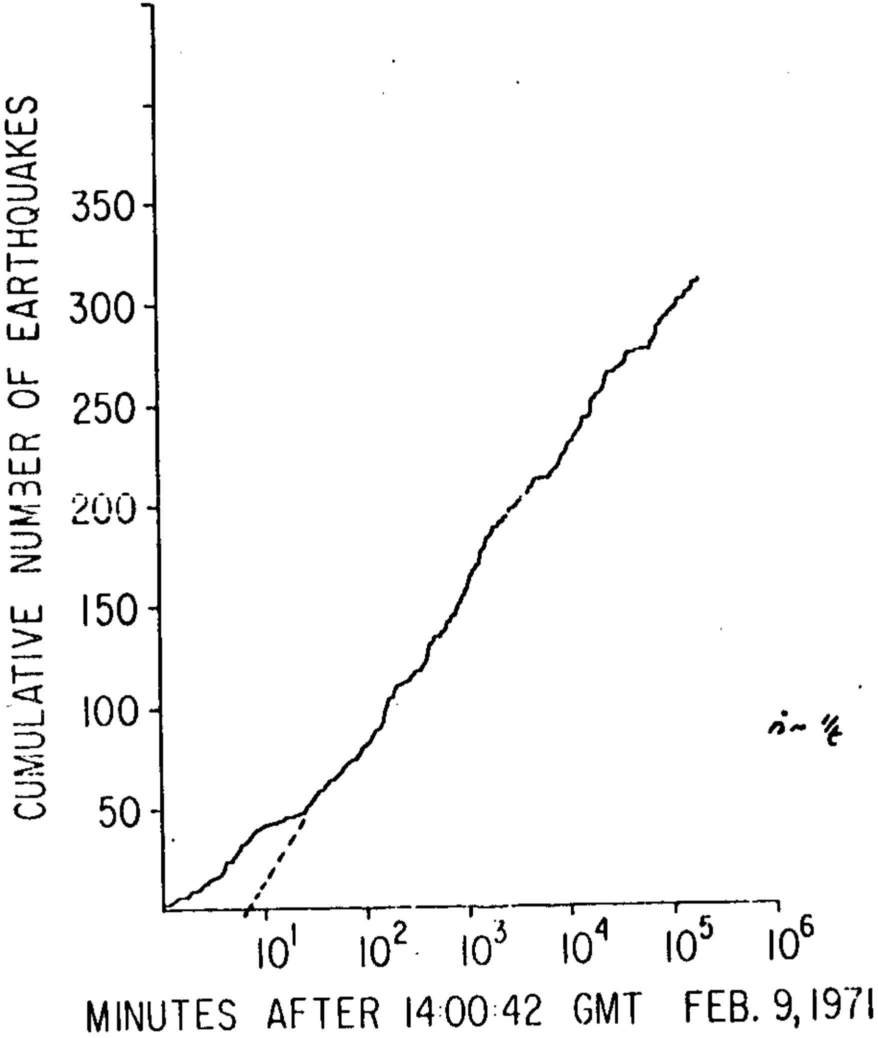
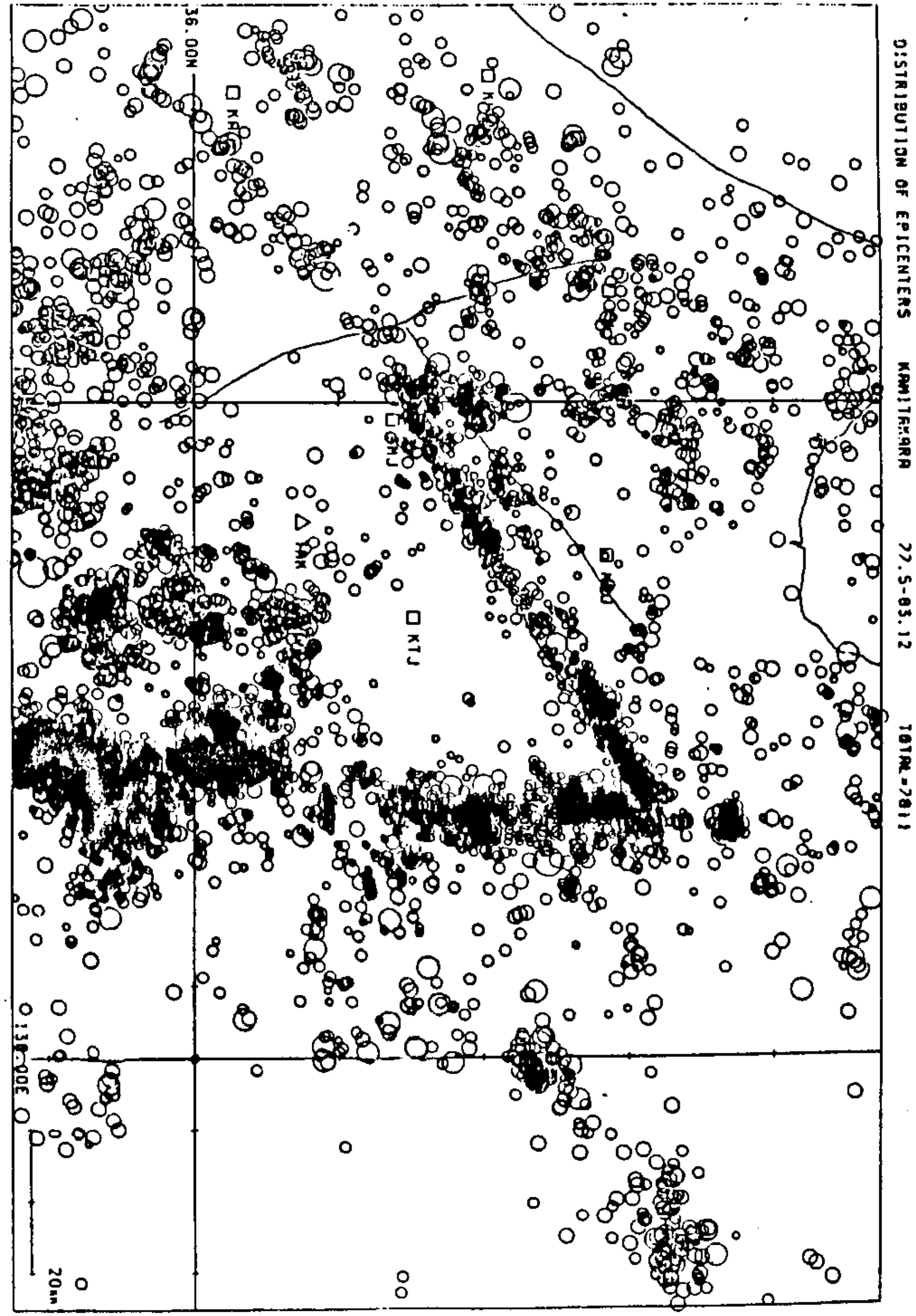


FIGURE 1.—Index map of study area, showing epicenters of the main shock and aftershocks of magnitude 3.0 and greater of the San Fernando earthquake for the first 3 weeks of activity, February 9 through March 1, 1971.


CUMULATIVE NUMBER OF EARTHQUAKES
50
100
150
200
250
300
350
10^1 10^2 10^3 10^4 10^5 10^6
MINUTES AFTER 14:00:42 GMT FEB. 9, 1971

$n \sim 1/t$


DISTRIBUTION OF EPICENTERS KAMITAKARA 77.5-83.12 TOTAL=7811
36.00N
KTJ
20km

$L \propto s^n$

Sayles + Thomas

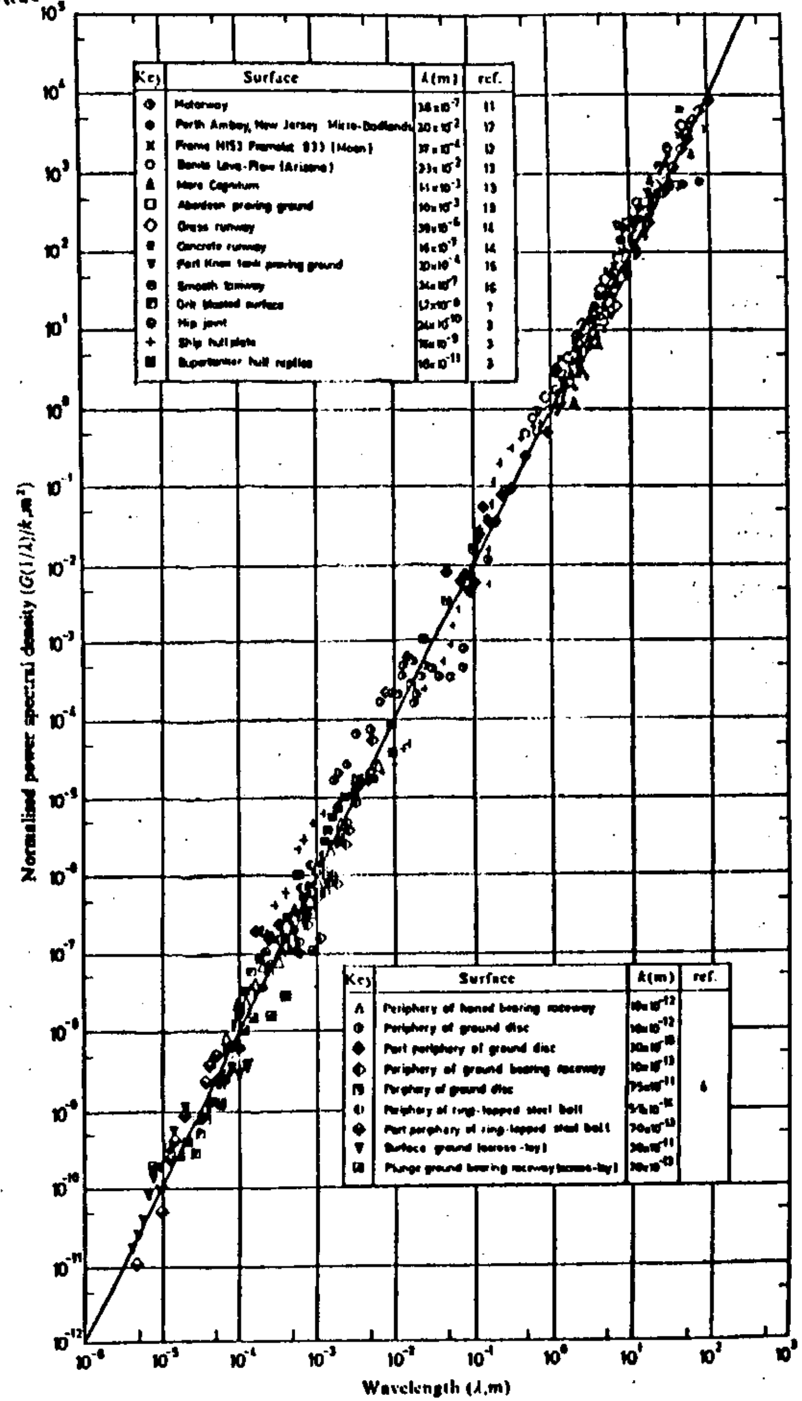


Fig. 2 Variation of normalised power spectral density ($G(1/\lambda)/k$, m^3) with wavelength (λ, m). The graph shows that many different surface topographies existing in the physical universe have a similar form of power spectrum. Note that the spectra available cover almost eight decades of surface wavelength and throughout this range the r.m.s. power increases, to a good approximation, as the square of the wavelength (solid line, equation (2)).

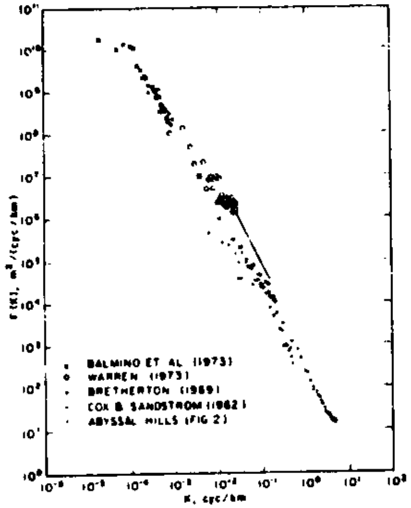


Fig. 8. Composite of estimates of the spectrum of the elevation of the Earth's surface.

ridges for mathematical simplicity, the work required to raise a hill is given by

$$W = \int_{-\infty}^{\infty} \int_{0}^{\zeta(x)} \rho g z \, dz \, dx,$$

where ρ is the effective density of rock (relative to water or air), g is the acceleration of gravity, and $\zeta(x)$ defines the hill cross-section. For the models considered previously, we have

$$W = \tfrac{1}{2}\rho g H^2 L \int_{-\infty}^{\infty} \eta^2(x/L)\, d(x/L).$$

The integral in this expression is a constant, so that the mechanical energy of formation is proportional to H^2L. The statistical distribution of mechanical energy of formation is then determined by the expression

$$L\overline{H^2}p(L) = L \int_0^\infty H^2 p(H, L)\, dH,$$

where again, $p(H, L)$ is the joint probability density of hill heights and widths. The expression $L\overline{H^2}p(L)$ specifies how the energy of formation is distributed among the various hill sizes: $L\overline{H^2}$ is proportional to the energy of formation of a typical hill of characteristic width L, while $p(L)$ specifies the relative frequency of occurrence of such hills. If the energy is distributed uniformly over hill sizes, then we may set $L\overline{H^2}p(L)$ = constant, and the power spectrum is of the form

$$F(k) = B \int_0^\infty L\,|\hat{\eta}(kL)|^2 dL,$$

where B is a constant, and we may then express

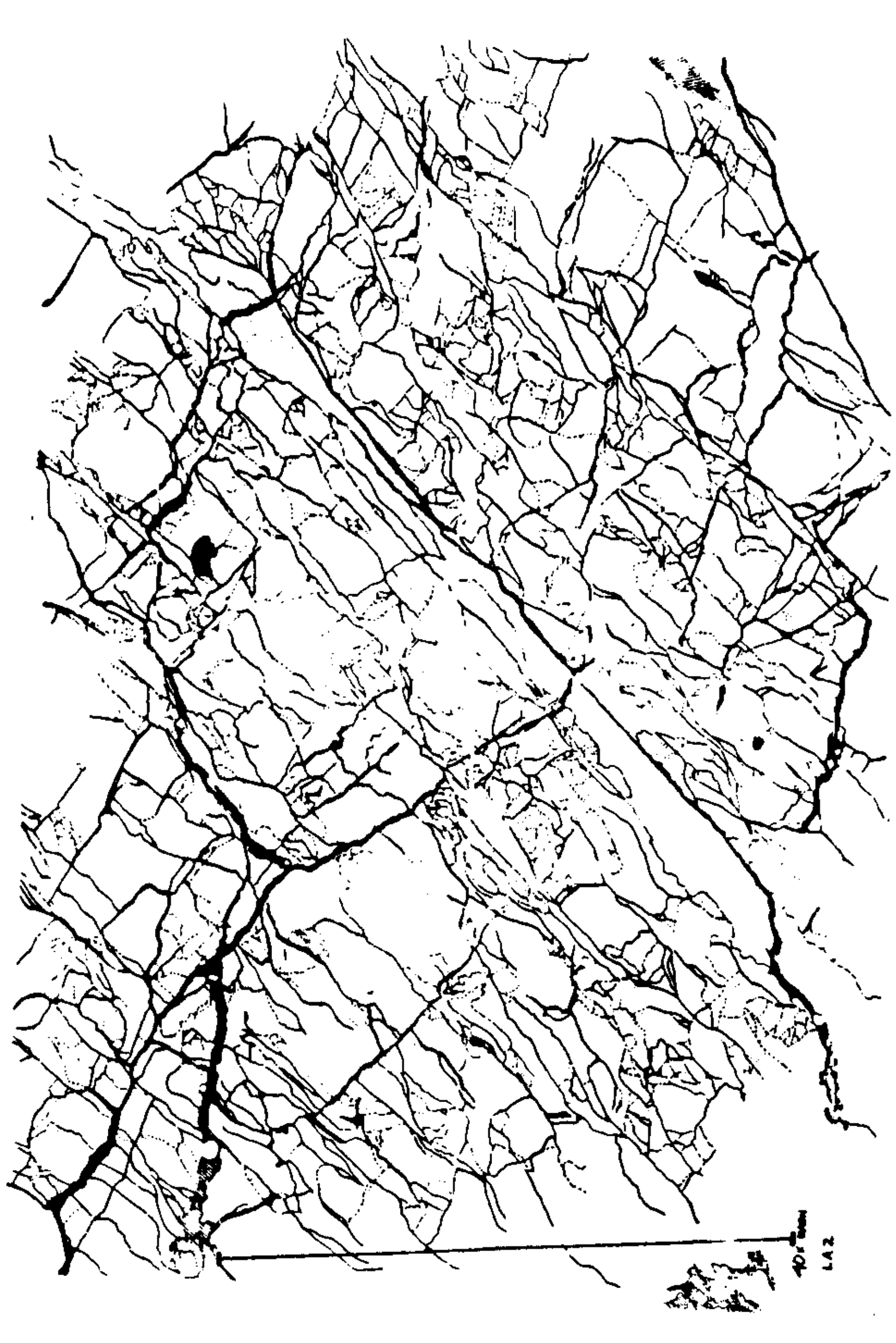
$$F(k) = Bk^{-2} \int_0^\infty x\,|\hat{\eta}(x)|^2 dx.$$

The integral is a constant, independent of k, so that the spectrum behaves as k^{-2}.

Thus, the observed overall inverse square law dependence on wavenumber of the topographic power spectrum is consistent with an interpretation of the topography as a random distribution of hills or ridges in which the energy of formation is distributed uniformly over hill sizes. The smaller hills may require less energy of formation, but are sufficiently more numerous than the larger hills so as to insure this equipartition of energy.

DISCUSSION

We have considered in some detail the power spectrum of the Earth's topography. On a global scale, the spectrum exhibits an overall inverse square law dependence on wave number. This particular spectral form admits a rather simple, yet appealing, interpretation. If the topography is modelled as a random distribution of independent hills or ridges, then the observed shape of the spectrum implies an equilibrium state of maximum disorder in which energy of formation is distributed uniformly over all hill sizes. Smaller hills or features may be less energetic than the larger



Southern California

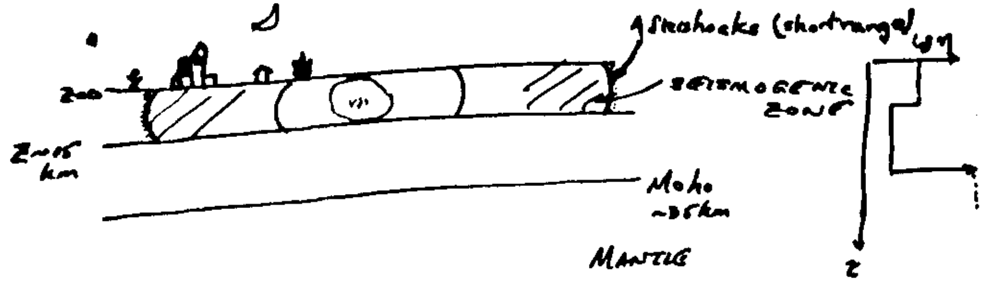
M ≥ 3,	1 eq. per	2.2 days
4		16 "
5		110 "
6		2.1 years
7		15 years
8		110 years
		±?

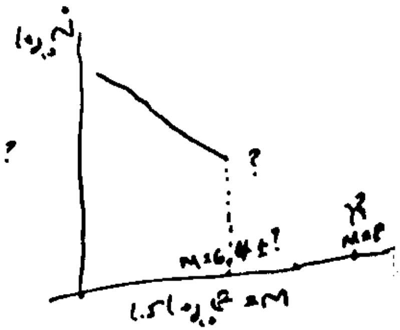
The standard deviation of a Poisson independent model is equal to the mean.

GEOMETRICAL CONSTRAINTS

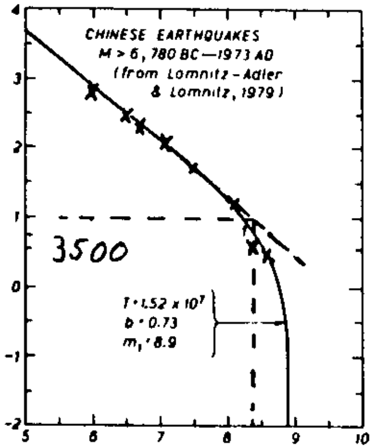
Magnitude	Characteristic (Fault) Length
8	500 km
7	70
6	10
5	1.5 ?

Cross-section of earth for shallow focus earthquakes:





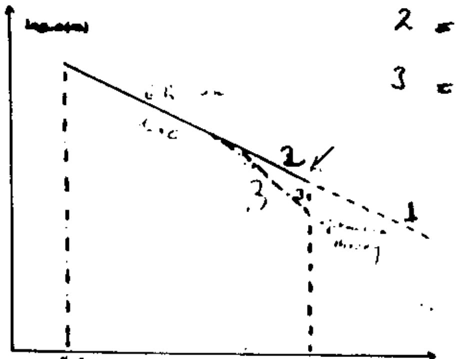
$\log E = \alpha + \beta M$



Mmax

M →

Aantal events met magnitude M >, in 2700 jaar.



m →

1 = GR-verdeling
2 = Afgebr GR "
3 = Afgebr GR + extra informatie

9

... in cm². This result is essentially the same as earlier results obtained by Tocher (1958) and Iida (1959, 1965). The uncertainties in (6) are large but not surprising in view of the differences in location and type among the faults.

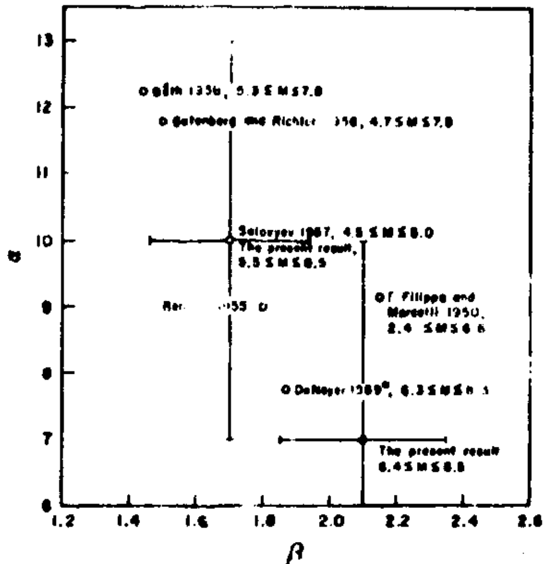


FIG. 2. Coefficients in the magnitude energy relation. Bars indicate uncertainties in the present results. We arbitrarily take the uncertainty in α to be 2 units. *See Tocher (1958).

Comparing (5) and (6), we obtain

$$\beta = 1.70 \pm 0.24$$

$$\alpha = \log[\eta k\mu(D_i + D_f)] - (3.47 \pm 2.04). \tag{7}$$

This value of β agrees approximately with other estimates (Figure 2).

We note that, if the two smallest shocks are omitted from the above calculation, then

$$\beta = 2.11 \pm 0.25$$

$$\alpha = \log[\eta k\mu(D_i + D_f)] - (6.77 \pm 2.11)$$

The value of α can, in principle, be determined from (7). However, because of the lack of knowledge of the parameters in (7) and particularly of $(D_i + D_f)$ and η, α can at best be estimated only very roughly at the present time. In the laboratory model study referred to above, we observed the fractional stress drop $\delta = D/D_i$ for the

$\log N_{cum} = a - bM$

N_{cum} = no of eqs. per time (usually 1 year) with mags > M.

for	So. Calif.	$a = 4.77$	$b = 0.85$
	New Zealand	$a = 5.2$	$b = 0.90$
	Japan	$a = 7.2$	$b = 1.00$
	Worldwide	$a = 8.56$	$b = 1.0$

± ?

Richter p. 359

Magnitude-energy

$\log E = \alpha + \beta M$

$\alpha = 11.8$	$\beta = 1.5$	Gutenberg & Richter 1956
$= 10.0$	$1.7 \pm .2$ to $.3$	King & Knopoff (BSSA, 59, 1969, 269)

correlated?

Magnitude-fault length

$M = c_0 + d_0 \log L$

$c_0 = .75$	$d_0 = .98$	L = cm Tocher (1958)
2.27	$.76$	Iida (1955)

± (large!)

Seismic Moment

$M_0 = \mu \cdot$ average slip $\cdot$ fault area (energy)

(Aki, 1962)(Niigata)

$M_0 \cong 10^{30}$ dyn cm. 1960 Chile, 1964 Alaska

10^{12} microearthquakes

10^{8} microfractures in lab

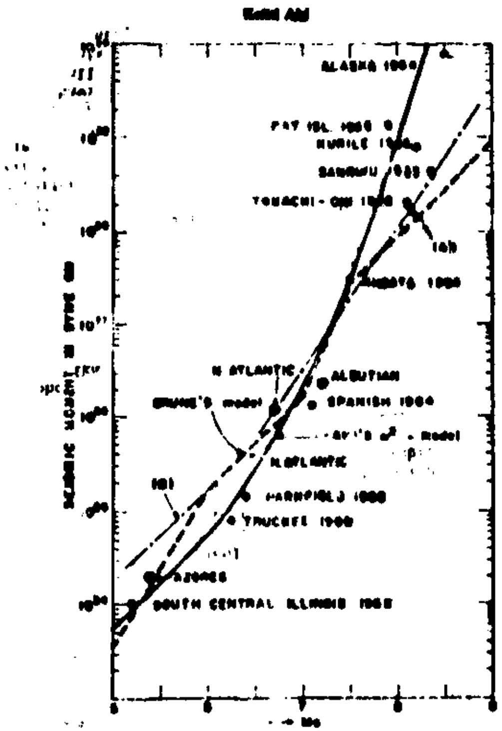
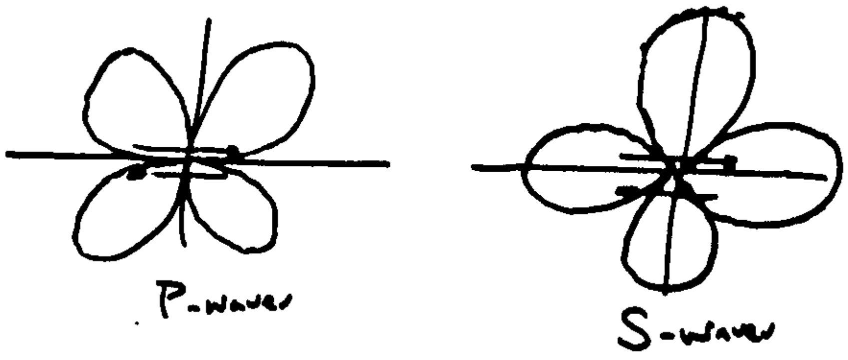
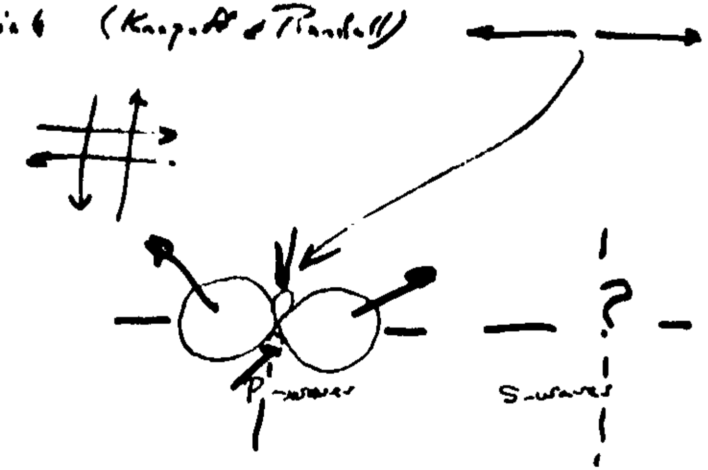


FIG. 4. Seismic moment as a function of magnitude reproduced from Aki (1972) with additional lines (A') and (B) for the ω-model of Brune & King (1967) as described in text.

If a fault is not a plane, what does this do to all of our preconceptions about fault-plane solutions?



(compl.) linear vector dipole (Knopoff & Randall)
double couple



CONSTRAINTS ON MODELS

SELF-SIMILARITY

- WIDE RANGE OF SCALES

  cum $N \sim E^{-\beta}$? $\beta \sim 1.5$

- MAGNITUDE $M \sim \beta \log E/E_0$

  $M=8 \Rightarrow E \sim 10^{22-24}$ erg.

- SIZE OF FRACTURE

  $M=8 \Rightarrow L \sim 500$ km ±

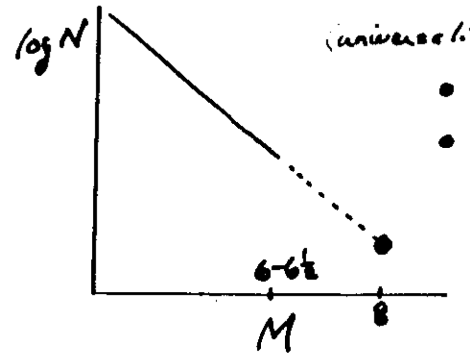
  7 70 ±

  6 10 ±

  ⋮

- TRUNCATED DISTRIBUTION

  $M_{MAX} \Rightarrow E_{MAX} \Rightarrow L_{MAX}$



(universality of b-value)

- GEOMETRY non-planarity anisotropy?
- TIME Omori law

TRIGGERING? MIGRATION?

TABLE III

Space–time–magnitude moment, $M_1 \geq 8.0$ (shallow), $M_2 \geq 8.0$ (shallow), $\Delta R = 250$ km, $\Delta T = 1$ year

$0 \longrightarrow n\Delta T$ / $m\Delta R$	$n = 1$	2	3	4	5	6	7	8	9	10	S	$P < 5\%$
$m = 1$	7	5	1	2	1	.	1	.	1	.	78	≥4
2	3	1	.	1	3	3	2	1	1	.	114	≥5
3	1	1	2	2	6	1	2	2	2	1	130	≥5
4	5	2	3	3	2	.	.	2	.	1	146	≥5
5	.	5	1	.	5	1	.	2	.	.	110	≥4
6	1	3	7	.	.	1	.	.	3	2	102	≥4
7	2	.	4	.	2	2	1	4	1	2	122	≥5
8	1	1	5	4	2	2	7	4	2	1	148	≥5
9	1	2	3	4	2	3	.	4	.	1	148	≥5
10	.	3	2	3	2	3	2	1	1	1	148	≥5

Table 2

Strong Earthquakes and Pattern B

in Southern California

N	Date	Epicenter λ (°W)	ϕ (°N)	M	b_i (2 days)
	3-11-33	118.0	33.6	6.3	103
1*	12-31-34	114.8	32.0	7.1	
2	5-19-40	115.5	32.7	6.7	
	7- 1-41	119.6	34.4	5.9	11
3†	10-21-42	116.0	33.0	6.5	
	3-15-46	118.1	35.7	6.3	14
	4-10-47	116.6	35.0	6.2	14
	7-24-47	116.5	34.0	5.5	15
4	12- 4-48	116.4	33.9	6.5	
	7-28-50	115.6	33.1	5.4	18[a]
5	7-21-52	119.0	35.0	7.7	
	3-19-54	116.2	33.3	6.2	19
	11-12-54	116.0	31.5	6.3	19
6	2- 9-56	115.9	31.8	6.8	
	12- 1-58	115.8	32.3	5.8	11
7	4- 9-68	116.1	33.2	6.4	13
	3-21-69	114.2	31.2	5.8	42[b]
8	2- 9-71	118.4	34.4	6.4	69

* Preceded by strong foreshock:
12-30-34 115.5 32.3 6.5

† Aftershock of 2

[a] 26 shocks in 2 day interval straddling this event including foreshoc
and M = 5.5 aftershock

[b] 49 shocks in 2 day interval straddling this event, including foresho

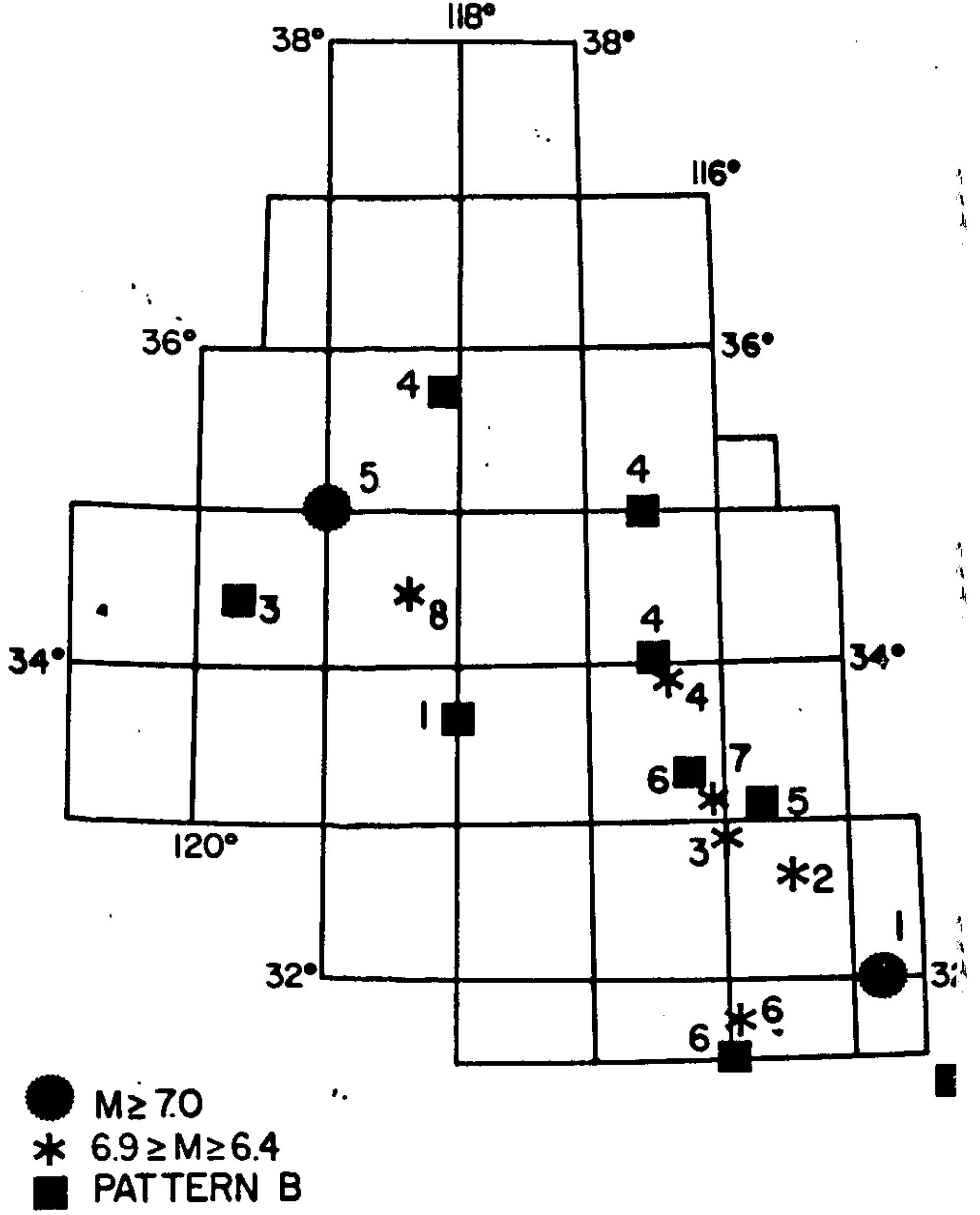
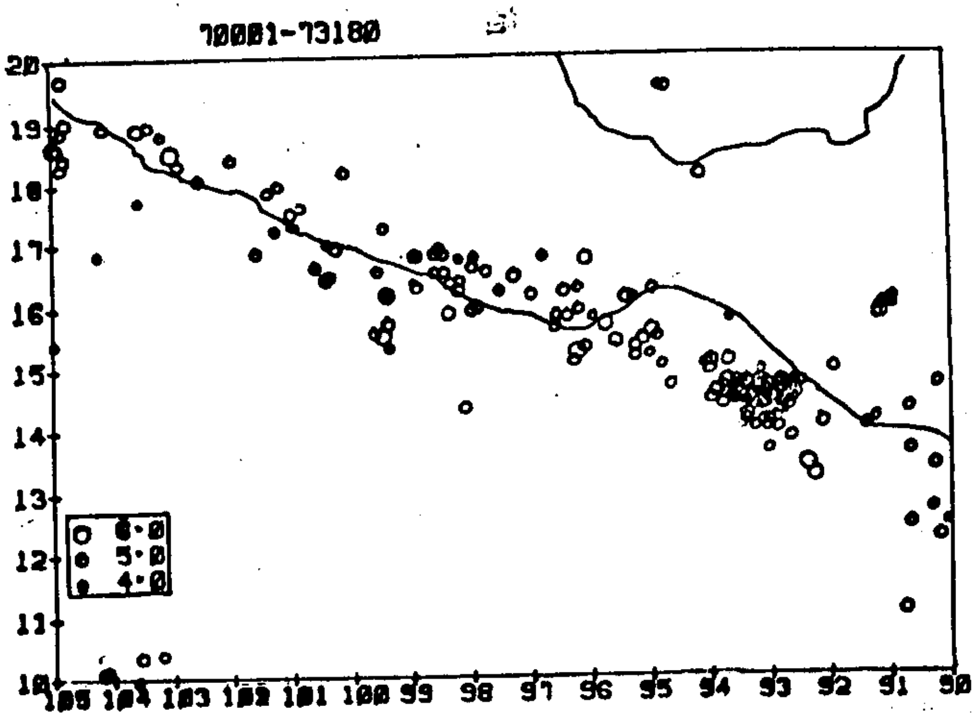
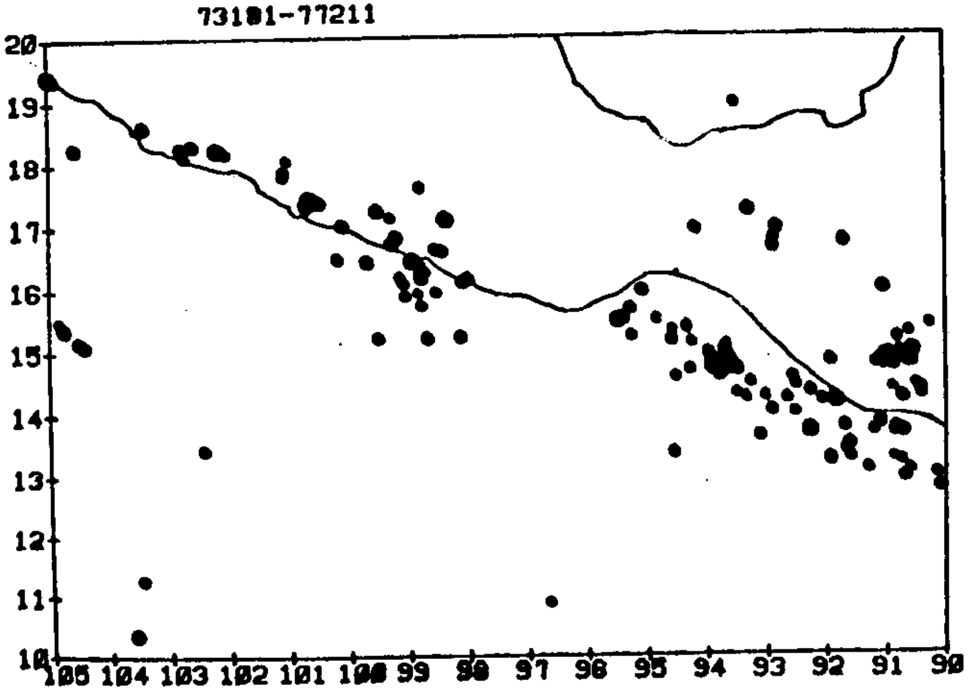
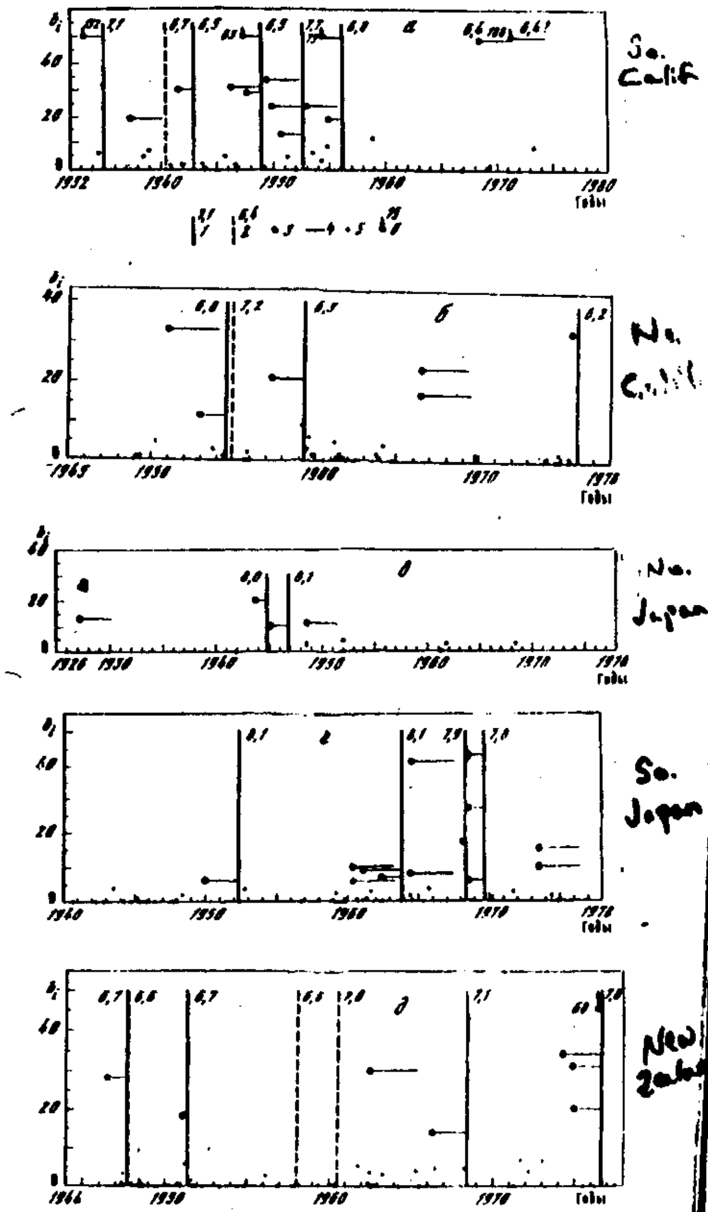


Fig. 2







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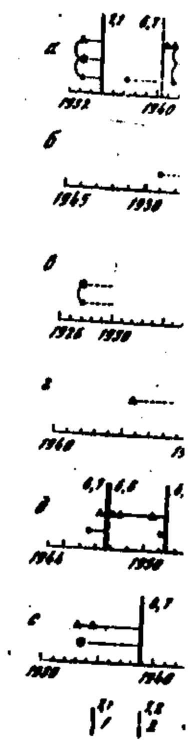
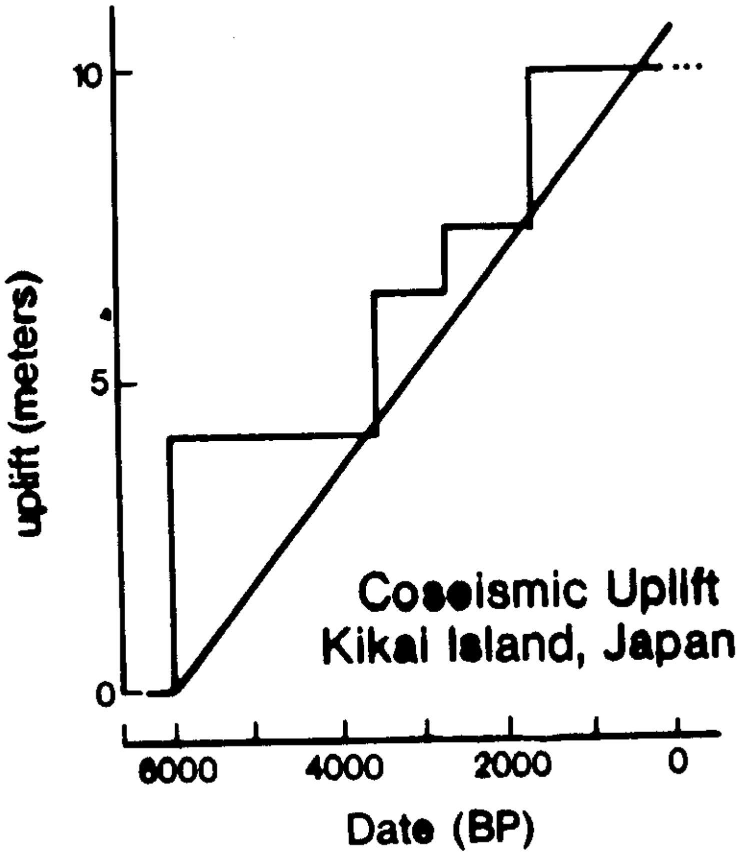


Рис. 2. Сводка результатов
а — Южная Калифорния (В, …
в — Северная Япония (В, Σ); …
предвестники удалось выделить …
вестники: 3 — В; 4 — Θ; 5 — Σ …
одного и того же главного толчка …
ной, 9 — не осмысленной

яляют сформулировать р…
надежность разных реди…
постей каталогов вылетр…

В целом наш опыт сот…
размерам регионах с густ…
В, а в больших регионах…
вестники Σ. Два примера…
даны на рис. 3.

Рис. 4. Взрывы афтершоков …
ной Калифорнии (б), Южной …
1, 2 — сильные землетрясения и ф…
афтершоков; 4 — период тревог…
сигналу



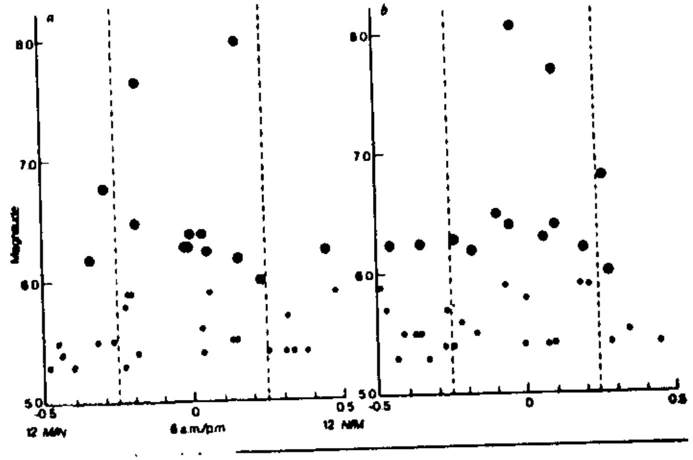


Fig. 3 a, Times of occurrence of southern California earthquakes on a scale of period 12 h; 6 a.m./p.m. is at the centre of the diagram. Large earthquakes cluster in the central half of the diagram. b, Times of occurrence of southern California earthquakes on a scale of period 18.613 yr. The zero of phase is 12 January 1932. Large earthquakes cluster in the central half of the diagram.

Summary of Lect. 1.

1. Seismicity is pervaded by self-similarity
   a. Power law Energy-frequency relation
   b. Power law rate of occurrence of aftershock
   c. Power law higher order spatial moments
2. Earthquake symmetries (power laws) are broken by Max Magnitude (size)
3. Earthquake occurrence does not depend on local geology
   a. What does it depend on?
4. Clustering (non-Poissonian character) gives hope for prediction
5. Faults are not planar
   a. 3-dimensionality
6. Small seismicity probably does not occur <u>on</u> sites of large earthquakes
7. Phenomenology of seismic gaps and doughnuts.
   a. Temporary (temporal) reduction in seismicity in the neighborhood of a future large shock.
8. Foreshocks?
9. We must study the fracture of damaged material. If the damage increases as we approach a (geological) fault, why is the geological fault very strong?