Journal of Theoretical Physics

Founded and Edited by M. Apostol **121** (2005)

ISSN 1453-4428

Principles of Earthquake Forecasting
Short-Term Prediction
Application to Vrancea

apoma Laboratory
Magurele-Bucharest, August 2005

Special day:

Yesterday $M = 3$, Vrancea (one in $5 - 6$ days)
(Institute for Earth's Physics Daily Report)

Prediction: Today an $M > 4.8$ (that can be felt in Bucharest), most likely

Probability $\sim 2\%$

Theory validated on the spot!

What means 2% **a probability?**

Live 50 times the same situation, then you have almost surely one such event!

This means about one $M > 4.8$ **surely in one year (**50 **times** $5 - 6$ **days), in the next day following one of** $M > 3$**!**

Summary

Principles of Earthquake Forecasting

-Statistical approach

$$P(M,t,\mathbf{r},...)=d^3N/dMdtd\mathbf{r}$$

-A priori knowledge (conditioned probabilities, Bayesian theory)

-Analysis of a statistically significant data set

-Prediction: "what happened will happens again"

-"Shaking" map (effects rate, Mercalli intensity, peak ground acceleration)

$$I(t,\mathbf{r})=\int dMd\mathbf{r}'I(M,\mathbf{r}-\mathbf{r}')P(M,t,\mathbf{r}')$$

Regular Earthquakes. Mean Recurrence Time. Long-Term Forecasting

(apoLab, 2004-2005)

-Mean recurrence time t_r

-Probability $\sim 1/t_r^2$

-Accumulating seismic energy $t_r\sim E^{1/r}$; geometric exponent $r=1/3$ (point-like focus)

$r=1/2$ (two-dimensional fault)

-Gutenberg-Richter $\ln(E/E_0)=bM \quad (b=3.5)$

Gutenberg-Richter Magnitude Distribution

$$P(M)=\beta e^{-\beta M} \ \ , \ \ \beta=br$$

-well documented

$$log\ distr \quad \ln(N/T)=\ln(\beta\Delta M/t_0)-\beta M$$

$$exced\ rate \quad \ln(N_{ex}/T)=-\ln(t_0)-\beta M$$

-seismicity rate $1/t_0=N_0/T$

Statistical Analysis

-Overall, worldwide data (Bullen, 1963) $(5.8 < M < 7.3, \ \Delta M = 0.1)$

$$\beta = 1.38 \ , \ (r = 0.39 \ , \ b = 3.5), \ 1/t_0 = 10^{5.5} \ per \ year$$

-Point-like focus model: $\beta = 1.17 \ , \ (r = 1/3 \ , \ b = 3.5)$

-California: $\beta = 2.3, \ r = 0.66, \ 1/t_0 = 10^{7.5} \ per \ year$

-Vrancea (**apoLab, 2005**): $\beta = 1.89 \ , \ (r = 0.54 \ , \ fault), \ 1/t_0 = 10^{4.21} \ per \ year$

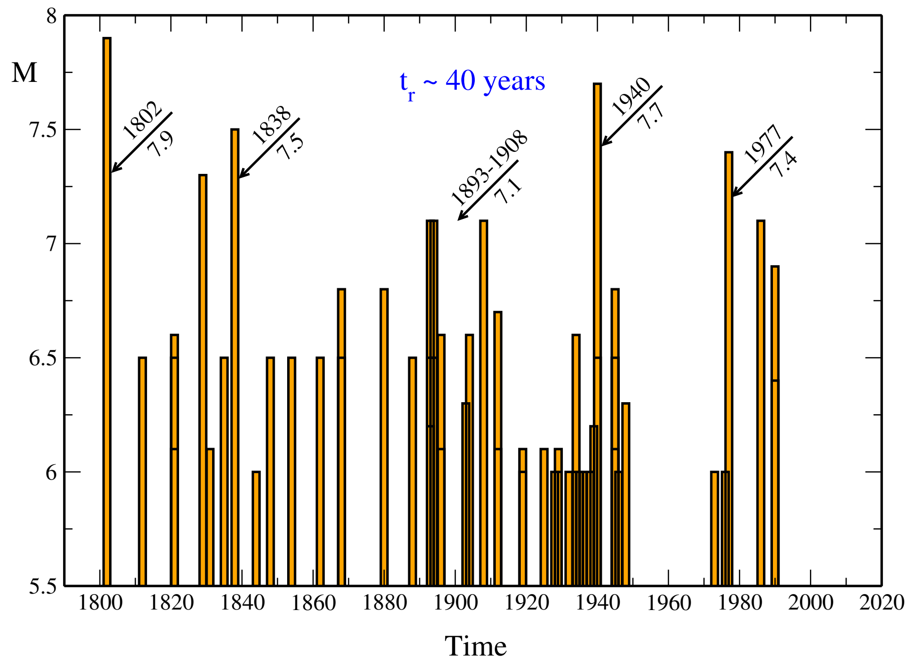
Mean Recurrence Time

$$t_r = (t_0/\beta\Delta M)e^{\beta M} \ \ , \ \ t_{ex} = t_0 e^{\beta M}$$

-Vrancea: $t_r = 34.9$ years $(M > 7)$

-Statistical character, randomness, Poisson assumption $p(t) = t_r e^{-t/t_r}$

-Deviation $(\bar{t^2})^{1/2} - t_r = 0.41 t_r$; $\quad t_r = 34.9 \pm 14.3$ years; little practical use



Vrancea earthquakes with (moment) magnitude $M > 6$ in the last two centuries (Romanian Earthquakes Catalogue, 2005)

Summary

Accompanying Seismic Activity. Omori's Law

(apoLab, 2005)

-Omori's law $dn/d\tau \sim 1/\tau$, aftershocks, or foreshocks

-originating in the self-replication of a generating exponential $\sim e^{-\alpha\tau} = e^{-2\tau/t_r}$

-abrupt fall, long tail

-similar for $m = M_0 - M$; $\sim e^{-\beta|m|}$; $\bar{m} = 0$, $(\bar{m}^2)^{1/2} = \sqrt{2}/\beta = 1.2$ ($\beta = 1.17$); Bath's law

-similar for $1/E$; $dE/d\tau \sim 1/\tau^2$ (emp evidence) ($E \sim 1/\tau$, released energy)

Short-Term Seismic Activity is More Complex

-Omori's law - a particular short-term pattern

$$M = M_0 - \alpha\tau/\beta \quad (\alpha(M_0))$$

-Scarcity of data (poor statistics), little practical use

-Disentangling accompanying events from the regular ones (especially for long time)

-Any aftershock or foreshock: a "main" shock in turn; multi-branch activity

-M and t independent statistical variables

California Short-Term Prediction Model

$$P(M,t,r) = const \cdot e^{-\beta M} \cdot \frac{1}{t+t_c} \cdot \frac{1}{(r+r_c)^2}$$

-cutoff t_c, cutoff r_c; ($t \sim r$; area variables$\rightarrow 1/r^2$); isotropy; spatial grid 5 km

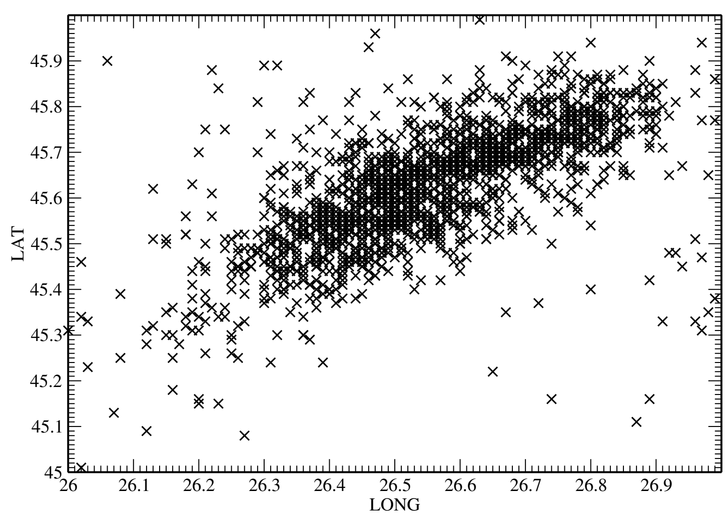
-time-descending sequences, over a few months, within $M \pm 0.5$

-fit; ongoing sequence; prediction; null hypothesis (former half predicts the later half)

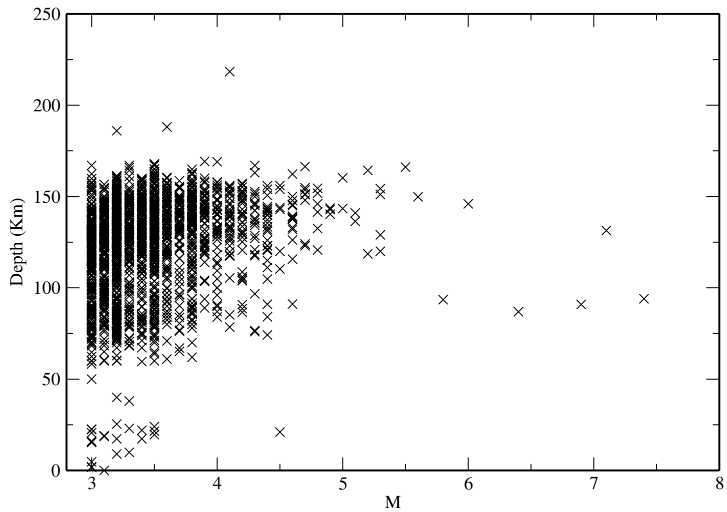
-real-time "shaking" map

Summary

Vrancea Focus (Fault)



Geographical distribution of 1999 Vrancea earthquakes with (moment) magnitude $M > 3$ recorded between 1974 and 2004 (30 years) within $45° - 46°$N latitude and $26° - 27°$E longitude (Romanian Earthquake Catalogue)



Depth distribution of 1999 Vrancea earthquakes with (moment) magnitude $M > 3$ recorded between 1974 and 2004 (30 years) within $45° - 46°$N latitude and $26° - 27°$E longitude (Romanian Earthquake Catalogue)

Vrancea Earthquakes

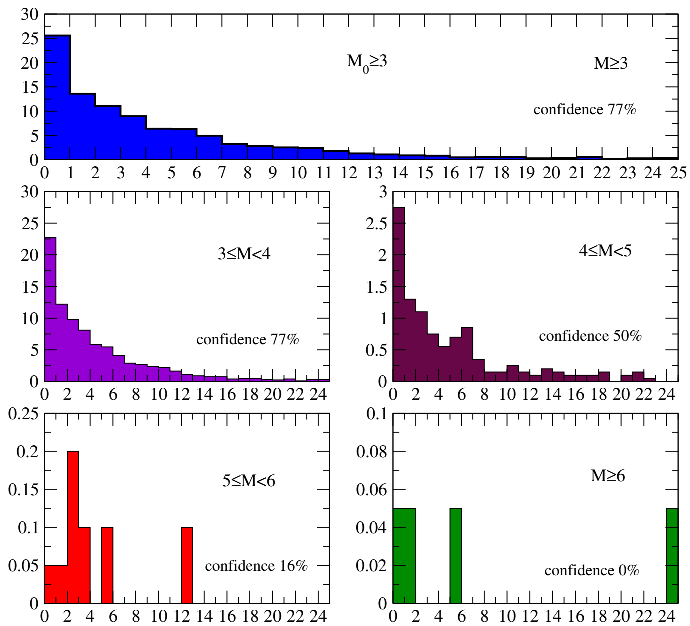
day	N=1998	P(t)%	N(3<M<4)=1769	P(3<M<4,t)%
0	511	25.58	454	22.72
1	272	13.61	244	12.21
2	221	11.06	195	9.76
3	179	8.96	162	8.11
4	128	6.41	117	5.86

N(4<M<5)=211	P(4<M<5,t) %
55	2.75
26	1.30
22	1.10
15	0.75
11	0.55

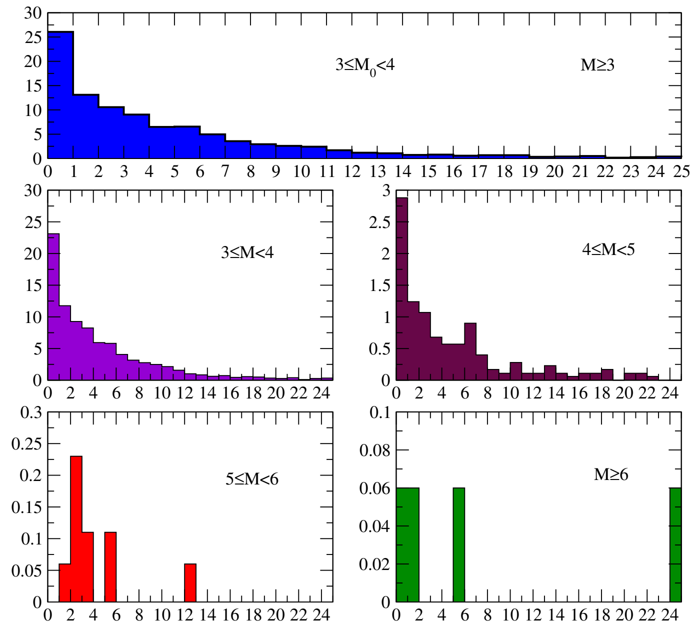
N(5<M<6)=13	P(5<M<6,t)%	N(6<M<8)=5	P(6<M<8,t)%
1	0.05	1	0.05
1	0.05	1	0.05
4	0.20	0	0.00
2	0.10	0	0.00
0	0.00	0	0.00

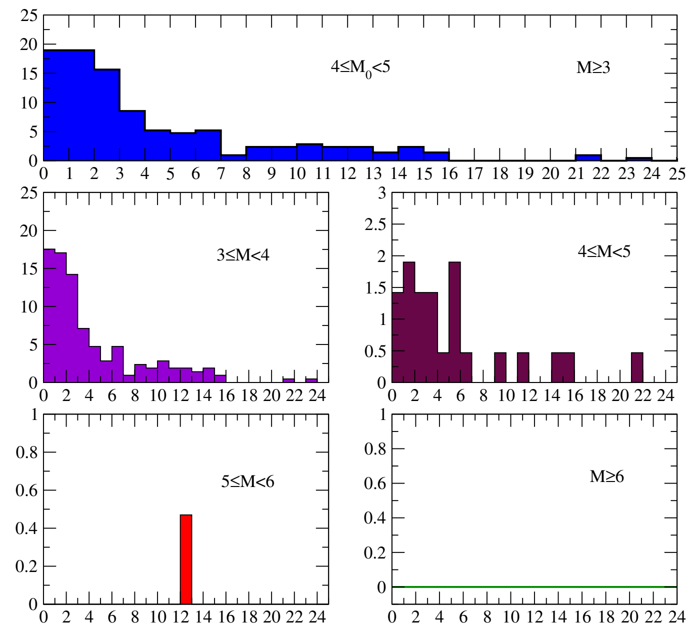
Event distribution for Vrancea next-earthquake (1999 Vrancea earthquakes with (moment) magnitude $M > 3$, recorded between 1974 and 2004 (30 years) within $45° - 46°$N latitude and $26° - 27°$E longitude (Romanian Earthquake Catalogue)

Next-Earthquake Probability $P(t)$, $P(M,t)$

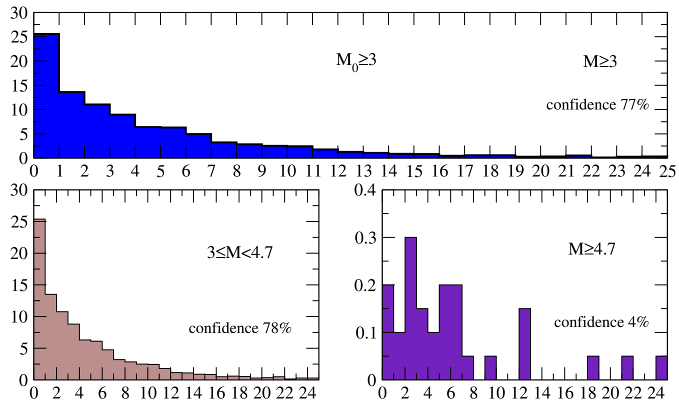


Time-Magnitude Distribution for the Next-Earthquake $P(t/M_0)$, $P(M, t/M_0)$





Next-Earthquake Time-Magnitude Distribution for Threshold Magnitude $M = 4.7$



Conclusions

-Decrease in time; Omori- type power laws

-Correlation time $\sim 20-25$ days, correlation size $M < 4-5$

-Poor statistics for $M > 5$

-Null hypothesis: first half of data to predict the second half of data; confidence level

Summary

1 Pair Distribution

2 Scaling Time

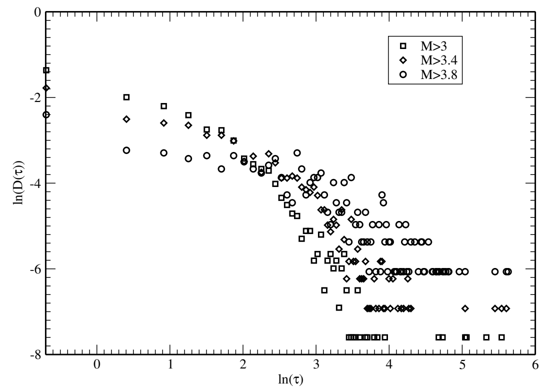
3 Universal Function

4 Prediction for Vrancea $M > 5$

5 Conclusions

Pair Distribution

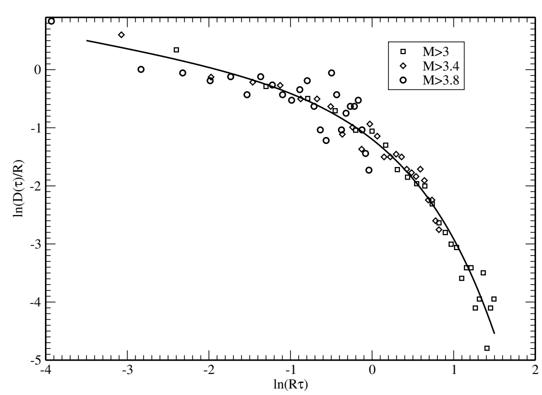
$$D(\tau) = dN/Nd\tau = \frac{1}{N}\sum_i \delta(t_{i+1} - t_i - \tau)$$



Pair distribution vs time (days) for 1999 earthquakes recorded in Vrancea 1974-2004 ($M > 3$)

Scaling Time

$$N = N_{ex}\ ,\ R = N_{ex}/T = t_0^{-1}e^{-\beta M_c}\ ,\ \ D(\tau) = Rf(R\tau)$$



Rescaled pair distributions and the fit (solid curve, $r = 0.25$, $B = 1.17$, $C = 0.71$) for 1999 earthquakes recorded in Vrancea between 1974 and 2004 ($M > 3$)

Universal Function

(apoLab 2005)

-$D(\tau) \sim t \sim E^r \sim 1/\tau^r$; $D(\tau) \sim R/(R\tau)^r$: $R\tau \to 0$; $r = 0.54$, Vrancea

-$R\tau \gg 1$, exponential, uncorrelated, $D(\tau) \sim e^{-R\tau/B}$

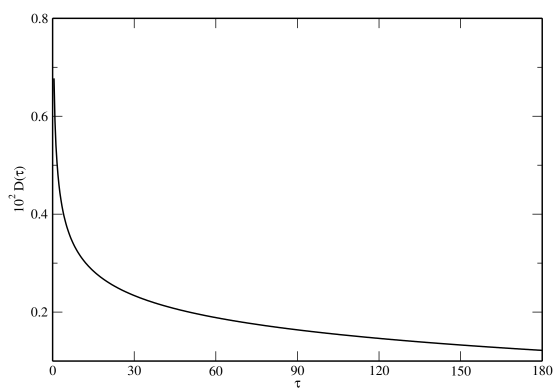
-correction factor $B = R'/R = (1 + e^{bM})^r / e^{brM} \sim 2^r$

-Euler's Gamma class of functions: fitting exponent r

$$D(\tau) = CR \cdot \frac{1}{(R\tau)^r} \cdot e^{-R\tau/B}$$

Prediction for Vrancea $M > 5$

$r = 0.25$, $B = 1.17$, $C = 0.71$ $R = t_0^{-1} e^{-\beta M}$ (fit to recurrence law $\beta = 1.76$, $-\ln t_0 = 8.99$; actually 18 seisms $M > 5$ out of 1999 in 30 years).



Next-earthquake time (days) distribution for Vrancea $M > 5$

For instance, 0.8% to have two $M > 5$ in the same day

Conclusions

-Main feature of earthquakes: seismicity rate $N_{ex}/T = t_0^{-1}e^{-\beta M}$ (their own rhythm)

-Clustering for small τ; inverse-power law (both self-replication and Omori's law and regular seismicity); by accumulating energy spatially and releasing it temporaly!

-Randomness for rare events, Poisson-like