The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1864-42

Ninth Workshop on Non-linear Dynamics and Earthquake Predictions

1 - 13 October 2007

Premonitory Seismicity Patterns for Moderate Size Earthquakes at Mt. Vesuvius

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ICTP

9th Workshop on Non-linear Dynamics and Earthquake predictions

Trieste - Italy, 1 - 13 October 2007

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Seismic activity at Mt. Vesuvius

- **The seismic activity at Mt. Vesuvius, instrumentally recorded at the OVO station since 1972, involves earthquakes with maximum magnitude M_d= 3.6.**
- **Though earthquakes in this area are not particularly strong, due to their shallow depths and to the high urbanization of the area, they can cause significant concern and damages.**

The precursory seismic activation preceding moderate size earthquakes occurring at Mt. Vesuvius is investigated.

Seismic activity at Mt. Vesuvius

The time characteristics of seismic activity at Mt. Vesuvius are investigated considering:

- **the time changes in the b-value**
- **the seismic energy release;**
- **the set of formally defined seismicity patterns identified by the algorithm CN**

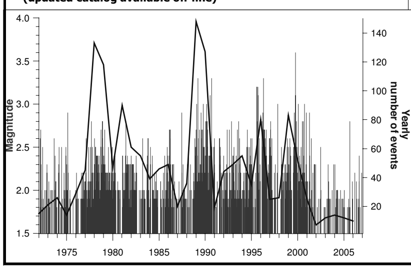
The features observed in seismic energy release are verified considering two independent data sets (OVO and BKE catalogs).

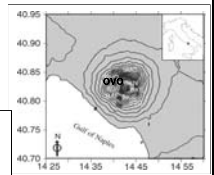
The OVO earthquake catalog

Data used: catalog of volcanic earthquakes recorded at the station OVO (Osservatorio Vesuviano – INGV, Naples)

Time period: 1972-2007

(updated catalog available on-line)





Time sequence of the events M(t) and yearly number of earthquakes with M≥M_c=1.8 reported in the OVO catalog

Seismic energy release

The seismic energy release is studied considering the quantity *E, computed from magnitude according to the formula:**

$$E^* = 10^{d(M-M_{\min})} \qquad d = \text{const}$$

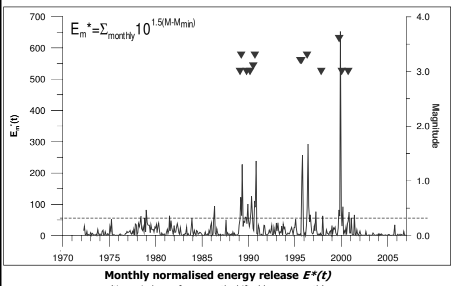
***E** represents the energy release normalised to the energy of the minimum magnitude event considered in the analysis, M_{min}=M_C=1.8:**

$$E^* = \frac{E}{E_{\min}} = \frac{10^{c+dM}}{10^{c+dM_{\min}}} \qquad c,d = \text{const}$$

Seismic energy release

Data used: catalog of volcanic earthquakes recorded at the station OVO (Osservatorio Vesuviano – INGV, Naples)

Time period: 1972-2007 (updated catalog available on-line)



Monthly normalised energy release *E*(t)*

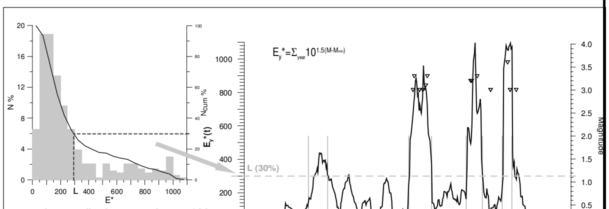
(time windows of one month shifted by one month)

- **The curve of monthly energy release *E*(t)* exhibits an almost constant background rate (*E^*_{montly}*≤50 during about 90% of the period of observation), with sporadic periods of strongly increased rates**

Seismic energy release

Formal definitions of the periods of quiescence, q and of the periods of activity, a.

- Periods of high seismic activity are characterised by energy rates with an increasing trend in time. An high number of earthquakes is not necessarily associated with high magnitudes.

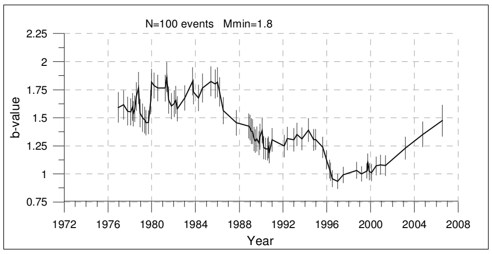


Yearly normalised energy release *E*(t)*

(time windows of one year shifted by one month)

Time changes of the *b-value*

- **An updated estimation of the time variations of the b-value in the Gutenberg-Richter (GR) law, shows that it decreases progressively from 1.8, before 1986, to about 1.0 in 1996. The b-value appears progressively increasing since 2001.**



(Maximum likelihood estimation by Wiemer & Zuniga, ZMAP software)

Time changes of the *b-value*

Updated estimation of the parameter b of the GR law for the formally identified periods of activity and quiescence (*Molchan et al., 1997*).

Interval	Time window	b-value		N
		a-intervals	q-intervals	
q1	1972.02.23-1977.10.31		1.59	143
a1	1977.11.01-1979.05.31	1.56		190
q2	1979.06.01-1988.07.31		1.72	482
a2	1988.08.01-1991.02.28	1.32		307
q3	1991.03.02-1995.01.31		1.29	167
a3	1995.02.01-1996.12.01	0.90		107
q4	1996.12.02-1999.02.28		1.08	62
a4	1999.03.01-2000.06.01	1.03		99
q5	2000.06.02-2007.05.01		1.53	112

Time changes of the *b-value*

Updated comparison of the *b-value* for the formally identified periods of activity and quiescence, as well as for some groups of them (*Molchan et al., 1997*).

Individual intervals

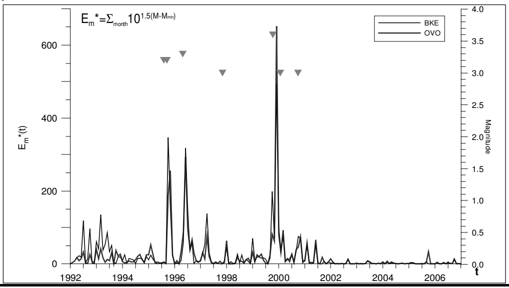
Intervals compared	π%	Conclusion of the comparison
a1, a2, a3, a4	>99.9%	b-values are different
a1, a2	92.6%	the differences in b-values is not significant
a3, a4	61.0%	the differences in b-values is not significant
q1, q2, q3, q4, q5	>99.9%	b-values are different
q1, q2	55.0%	the differences in b-values is not significant
q3, q4, q5	90.6%	the differences in b-values is not significant

Composite intervals

Intervals compared	N	b	b_{min}	b_{max}	Conclusion
a1+a2	497	1.37	1.26	1.49	b-values are different
a3+a4	190	0.96	0.81	1.12	
q1+q2	625	1.69	1.55	1.84	b-values are different
q3+q4+q5	343	1.31	1.17	1.46	
a1+a2+q1+q2	1122	1.51	1.42	1.61	b-values are different
a3+a4+q3+q4+q5	543	1.16	1.06	1.26	

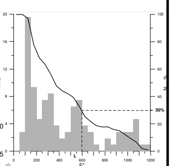
Time changes in seismic activity: the BKE catalog

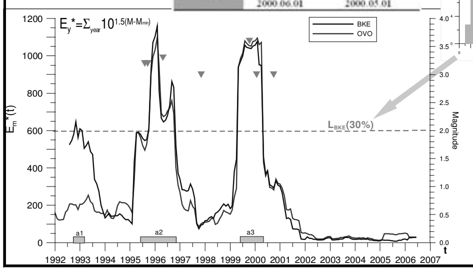
The time variations of the b-value and seismic energy release, observed for the OVO catalog, are verified performing a similar analysis with a different catalog of Vesuvian earthquakes, as compiled from the records at the BKE station during the period 1992-2007.



Time changes in seismic activity: the BKE catalog

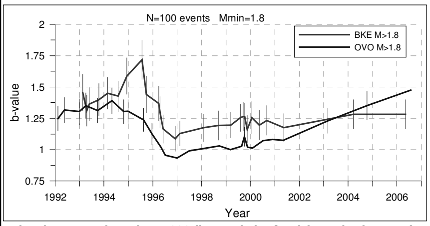
Periods of Activity	OVO	BKE
a1	=	1992.10.01
	=	1993.03.01
a2	1995.02.01	1995.06.01
	1996.11.01	1996.11.01
a3	1999.03.01	1999.06.01
	2000.06.01	2000.05.01





The analysis performed using the catalog compiled for the BKE stations confirms the identification of the periods of quiescence and activity, since 1994.

Time changes in seismic activity: the BKE catalog



- The analysis performed using the catalog compiled for the BKE station confirms the *b-value* decrement till 2000.
- The raise of the b-value, starting approximately in 2001, currently is statistically significant only for the OVO catalog.

b-value comparison since 1999 (last periods of activity and quiescence)

catalogs	π%	Time interval	N	b ± Δb	Conclusion
OVO	**99.5%**	**1999.3.1-2000.6.1**	99	**1.03±0.22**	Difference is significant
		2000.6.2-2007.5.1	112	**1.53±0.28**	
BKE	**94.1%**	**1999.6.1-2000.5.1**	103	**1.10±0.24**	Difference is NOT significant
		2000.5.2-2007.6.1	94	**1.47±0.29**	

CN algorithm at Mt. Vesuvius

CN algorithm applied at Mt. Vesuvius

- **The possibility of intermediate-term prediction of earthquakes with *M≥3.0* has been examined by retrospective and real-time application of CN algorithm (*Gabrielov et al., 1986; Rotwain and Novikova, 1999*) to the catalog of volcanic earthquakes recorded at the station OVO (Osservatorio Vesuviano – INGV, Naples) during the period: 1972-2007**
- **The predictive capability of single premonitory seismicity patterns (individual CN functions of the seismic flow) has been evaluated, to better understand the precursory activation characterising vesuvian micro-earthquakes.**
- **The evidenced properties of vesuvian seismicity, including the application of CN algorithm, have been verified considering the BKE catalog of earthquakes, available for the period 1992-2007**

CN algorithm applied at Mt. Vesuvius

The magnitude threshold M_0, selecting the events to be predicted, is varied within the range: 3.0 - 3.3.

By retrospective analysis, when a time scaling by a factor ϑ : 2.5 – 3 is introduced, more than 90% of the events with $M \geq M_0$ are predicted, with TIPs occupying about 30% of the total time considered.

M_0	ϑ	n/N	η	τ	k/K	κ	η+τ
3.0	3	12/13	0.08	0.31	7/19	0.37	0.39
3.1	2.5	7/7	0.0	0.31	7/14	0.50	0.31
3.2	2.5	6/6	0.0	0.32	7/13	0.53	0.32
3.3	3	4/4	0.0	0.33	7/11	0.64	0.33

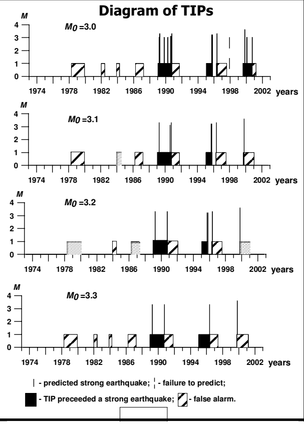
n =number of predicted earthquakes with $M \geq M_0$; *N* = total number of main shocks with $M \geq M_0$; $\eta = n/N$ statistic of failures to predict; $\tau = \tau_\Sigma/T$ statistic of alarm time; *k* = number of false alarms; *K* = total number of alarms; $\kappa = k/K$ statistic of false alarms

CN algorithm applied at Mt. Vesuvius

N°	Date	Magnitude
1	29.01.1989	3.0
2	19.03.1989	3.3
3	21.10.1989	3.0
4	4.03.1990	3.0
5	8.07.1990	3.1
6	10.09.1990	3.3
7	2.08.1995	3.2
8	16.09.1995	3.2
9	25.04.1996	3.3
10	5.11.1997	3.0
11	9.10.1999	3.6
12	22. 01.2000	3.0
13	27.09.2000	3.0

List of main shocks with M_d≥3.0

Diagram of TIPs



"Seismic History" Experiment

The "Seismic History" experiment is a simulation of the forward prediction of strong earthquakes. The time period (TSP) considered for automatic setting of the algorithm thresholds, is progressively reduced.

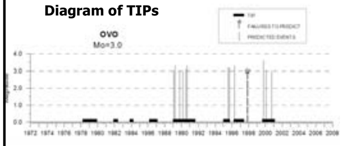
The results of the experiment for M_0 = 3.0 and ϑ =3 show that the (η+τ) is in the range: 0.39 to 0.43, well below the value (η+τ)=1 corresponding to the results of a random guess.

End of TSP	n/N	η	τ	k/K	κ	η+τ	n_f/N_f
2000.1.1	12/13	0.08	0.31	7/19	0.37	0.39	2/2
1998.2.22	12/13	0.08	0.31	9/21	0.43	0.39	3/3
1996.6.24	11/13	0.15	0.24	6/17	0.35	0.4	3/4
1995.10.24	11/13	0.15	0.26	5/16	0.31	0.41	3/5
1990.10.24	11/13	0.15	0.27	6/17	0.35	0.43	5/7
1989.10.24	12/13	0.08	0.35	7/19	0.37	0.43	9/10

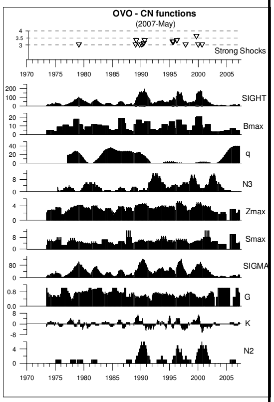
n = number of predicted earthquakes with M ≥3;
N = total number of main shocks with M ≥ 3
η = n/N statistic of failures to predict
τ = τ_Σ /T statistic of alarm time
k= number of false alarms
K = total number of alarms
κ= k/K statistic of false alarms
n_f/N_f= statistic of successful predictions outside TSP

Diagnosis of TIPs at Mt. Vesuvius

Diagram of TIPs



Routine updating of TIPs diagnosis for the occurrence of earthquakes with $M_d \geq 3.0$
(analysis updated to September 17 2007)

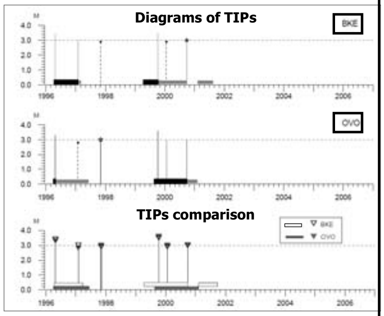


Analysis of the time behaviour of CN functions

Diagnosis of TIPs at Mt. Vesuvius: the BKE catalog

ORIGIN TIME		M_{BKE}	M_{OVO}
1992-08-05	4.29	**3.1**	2.7
1995-08-02	2.07	**3.4**	**3.2**
1995-09-16	9.03	2.8	**3.2**
1995-09-24	2.26	**3.1**	3.1 (aft)
1996-04-25	20.55	**3.4**	**3.3**
1997-02-01	6.56	**3.0**	2.8
1997-11-05	11.28	2.9	**3.0**
1999-10-09	5.41	**3.5**	**3.6**
2000-01-22	3.34	2.9	**3.0**
2000-09-27	7.01	**3.0**	**3.0**

List of main shocks with reported in BKE and their correspondent in OVO .
Main shocks with Md≥3.0 are marked in bold.



CN algorithm applied at Mt. Vesuvius

- **The experiments performed by means of CN algorithm application to the OVO catalog, show that satisfactory prediction results can be obtained when a time scaling is introduced.**
- **The quality of these predictions appears quite stable with respect to variations of M_0 and is similar to the quality of CN application in regions of tectonic seismic activity.**
- **The control experiment "Seismic History" demonstrates the stability of the obtained results and indicates that the algorithm CN can be applied to monitor the preparation of impending earthquakes with M≥3.0 at Mt. Vesuvius.**

Rotwain I., De Natale G., Kuznetzov I., Peresan A., Panza G. F. , (2006) Pure and Applied Geophysics. 163 (1), 19-39.

Test in real-time diagnosis of TIPs at Mt. Vesuvius

CN algorithm (*Keilis-Borok et al., 1990*)

General features:

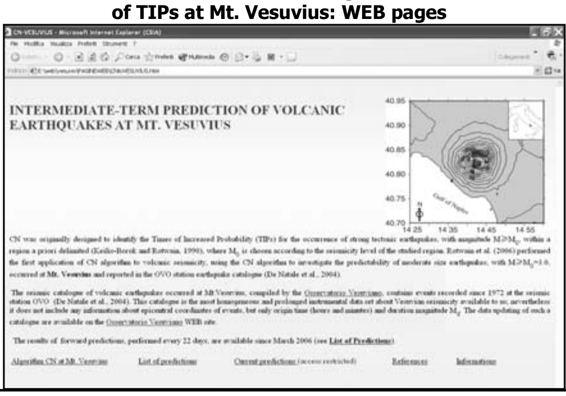
- **Fully formalized algorithm and computer codes available for independent testing;**
- **Use of published & routine catalogs of earthquakes;**
- **Tests ongoing in more than 20 regions worldwide to assess the significance of the issued predictions** (*e.g. Rotwain and Novikova, 1999*)

Mt. Vesuvius:

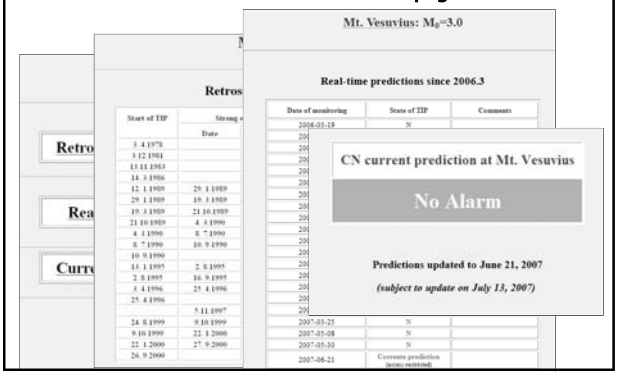
- **Test of CN application for the analysis of micro-earthquakes at Mt. Vesuvius, based on retrospective identification of TIPs;**
- **Stability tests with respect to the free parameters of the algorithm** ***(Rotwain I., De Natale G., Kuznetzov I., Peresan A., Panza G. F. , (2006) Pure and Applied Geophysics. 163 (1), 19-39).***
- **Stability tests with respect to the input data.**
- **CN predictions updated every 22 days since March 2006.**

Real time prediction test

Test in real-time diagnosis of TIPs at Mt. Vesuvius: WEB pages



Test in real-time diagnosis of TIPs at Mt. Vesuvius: WEB pages



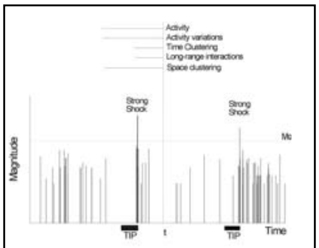
Analysis of the predictive capability of CN functions of seismic flow

Functions of seismic flow: integrals over seismic sequences

CN algorithm makes use of a set of empirical functions of time to quantify the seismicity patterns that characterize the seismic flow within a delimited region

Functions are normalized by minimal magnitude cutoff M_{min}, defined by one of the two conditions:

- **$M_{min} = M_0 - C$, C: constant**
- **M_{min} such as $N(M_{min}) = A$, A: constant rate of activity**



Magnitude cutoff for normalization of functions, based on rate of activity:
m1(a=3.0) m2(b=1.4) m3(c=0.4)

	N2	N3	K	G	Sigma	Smax	Zmax	q	Bmax
Mmin	m3	m2	m2	m2	m1	m1	m1	m2	-
Mmax	-	-	-	-	Mo-1	Mo-1	Mo-1	-	-

Analysis of the predictive capability of CN functions of seismic flow

- **The predictive capability of the each function of the seismic flow, which is used to quantify the premonitory seismicity patterns in CN algorithm application, is evaluated as a single precursor, considering earthquakes as reported in the OVO catalog.**
- **Each CN function is retrospectively analysed in order to find out a relationship between the occurrence of the M⩾3.0 events and the values assumed by the considered function.**
- **Prediction rule: an alarm is declared at the time t for the period [t;t+T] whenever the function value falls within a predefined range (e.g. $f(t) > f_0$).**

Functions of the seismic flow

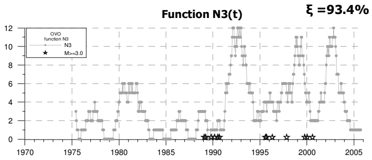
Seismic Activity Rate

I.

$$N3\left(t \middle| \underline{M}, s\right)$$

Number of main shocks with $M \geq \underline{M} = m2$, occurred in the time interval (t-3s, t-2s-1)

Function N3(t) **ξ =93.4%**

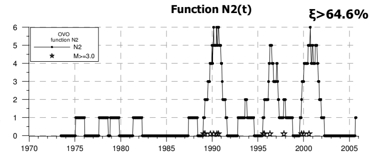


II.

$$N2\left(t \middle| \underline{M}, s\right)$$

Number of main shocks with $M \geq \underline{M} = m1$, occurred in the time interval (t-s,t)

Function N2(t) **ξ>64.6%**



Functions of the seismic flow

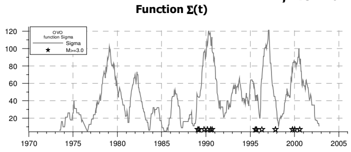
III. **Energy function Σ**

$$\Sigma\left(t \middle| \underline{M}, \overline{M}, s, \alpha, \beta\right) = \sum 10^{\beta(M_i - \alpha)}$$

with b=B=1.5

This function estimates the total energy of earthquakes with *Mo-0.1* $\geq M_i \geq$ *m*1

Function Σ(t) **ξ=48.2%**



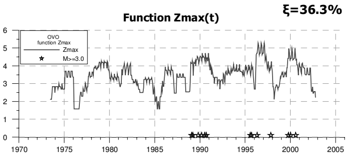
IV. **Space concentration of events**

$$Z_{max}(t) = \max_j \left[\frac{\sum\left(t_j \middle| \underline{M}, \overline{M}, s, \alpha, \beta\right)}{\left(N\left(t_j \middle| \underline{M}, s\right) - N\left(t_j \middle| \overline{M}, s\right)\right)^{\frac{2}{3}}} \right]$$

with j=1,2,3 $\beta \approx \frac{B}{3} = 0.5$

It is proportional to the ratio between the average linear dimension of sources and their average distance

Function Zmax(t) **ξ=36.3%**



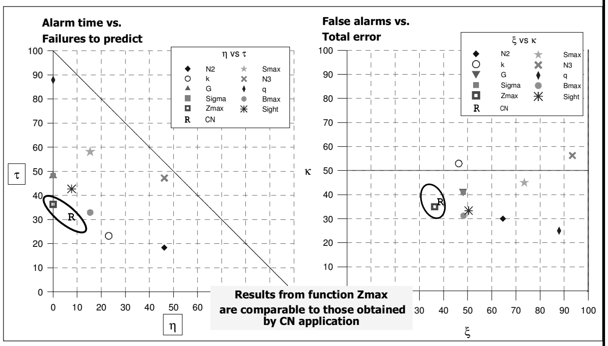
Predictions based on a single function: comparison of results

T=4 months						
Function	**τ%**	**η%**	**ξ%**	**K**	**k**	**κ%**
N2	18.4	46.2	**64.6**	10	3	**30.0**
K	23.2	23.1	**46.3**	17	9	**52.9**
G	48.1	0.0	**48.1**	22	9	**40.9**
Sigma	48.2	0.0	**48.2**	22	9	**40.9**
Smax	58.1	15.4	**73.5**	20	9	**45.0**
Zmax	36.3	0.0	**36.3**	20	7	**35.0**
N3	47.2	46.2	**93.4**	16	9	**56.3**
q	87.9	0.0	**87.9**	16	4	**25.0**
Bmax	32.9	15.4	**48.3**	16	5	**31.3**
Sight	42.7	7.7	**50.4**	18	6	**33.3**
CN	31.1	7.7	**38.8**	19	7	**36.8**

Comparison of the prediction results provided by the different functions of the seismic flow

η = percentage of failures to predict
τ= percentage of alarm time
ξ = total prediction error η+τ
k= number of false alarms
K= total number of alarms
κ= k/K statistic of false alarms

Predictions based on a single function: comparison of results



Results from function Zmax are comparable to those obtained by CN application

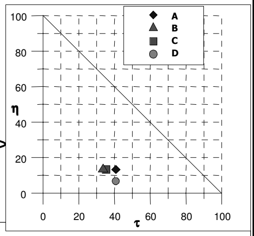
Analysis of inter-event times premonitory pattern

- The predictability of moderate size events (M≥3.0) occurred at Mt. Vesuvius, is investigated based on the inter-event times.
- The time elapsed between subsequent events (***inter-events days***) with magnitude $M \geq M_T$ is analysed for the OVO catalog.
- Different experiments are performed depending on the threshold M_T and on the length of the time windows used to estimate the average values of inter-events days.

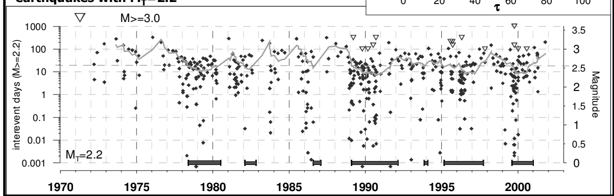
Prediction rule: an alarm is declared at the time t for the period [t;t+T] whenever the average value of inter-event days is below a predefined value: id(t)< id_0.

Analysis of inter-event times premonitory pattern

Test	Number of events in each window	Length of time window	Shift	id_0	ξ	κ
A	V	1 year	1 month	19.8	54.1%	35.0%
B	V	1 year	1 event	19.8	46.9%	31.6%
C	V	1 year	20 days	16.7	48.6%	38.1%
D	20	V	1 event	23.0	47.4%	33.3%



Time distribution of the inter-event times for earthquakes with M_T=2.2



Analysis of the predictive capability of CN functions of seismic flow – The BKE catalog

Function	Thresholds	τ %	η %	ξ %	K	k	κ %
N2	1	45.9	0	45.9	6	2	33.3
K	-2, 4	40.9	25	65.9	7	4	57.1
G	0.44,0.57	44.5	0	44.5	10	6	60.0
Sigma	39	50.0	0	50.0	6	2	33.3
Smax	5.01	54.3	0	55.0	6	2	33.3
Zmax	3.36	57.1	0	57.1	5	1	20.0
Bmax	22	56.6	0	56.6	7	3	42.9
Sight	79	33.3	0	33.3	6	2	33.3
CN	-	26.2	25	51.2	6	3	50.0

Comparison of the prediction results provided by the different functions of the seismic flow

η = percentage of failures to predict
τ= percentage of alarm time
ξ = total prediction error η+τ
k= number of false alarms
K= total number of alarms
κ= k/K statistic of false alarms

$Sight(t|\underline{M}, s, \alpha, \beta) = \sum_i 10^{\beta(M_i-\alpha)}$

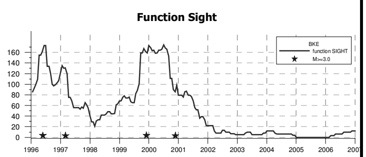
Analysis of the functions of seismic flow The BKE catalog

I. $$Sight(t|\underline{M}, s, \alpha, \beta) = \sum_i 10^{\beta(M_i-\alpha)}$$

With b=B=1.5

Main shocks with magnitude Mi≥M and the origin time between *t-s* to *t are considered*

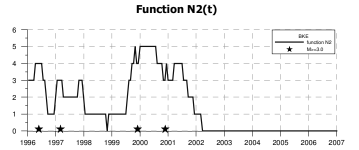
ξ=33.3%



II. N2(t|M, s)

The number of main shocks with M ≥M

ξ=45.9%



$Sight(t|\underline{M}, s, \alpha, \beta) = \sum_i 10^{\beta(M_i-\alpha)}$

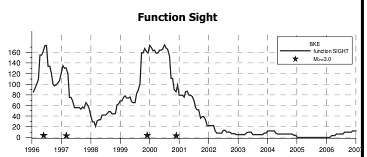
Analysis of the functions of seismic flow The BKE catalog

I. $$Sight(t|\underline{M}, s, \alpha, \beta) = \sum_i 10^{\beta(M_i-\alpha)}$$

With b=B=1.5

Main shocks with magnitude Mi≥M and the origin time between *t-s* to *t are considered*

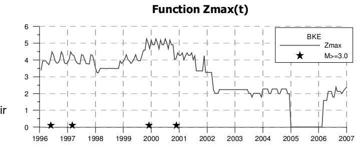
ξ=33.3%



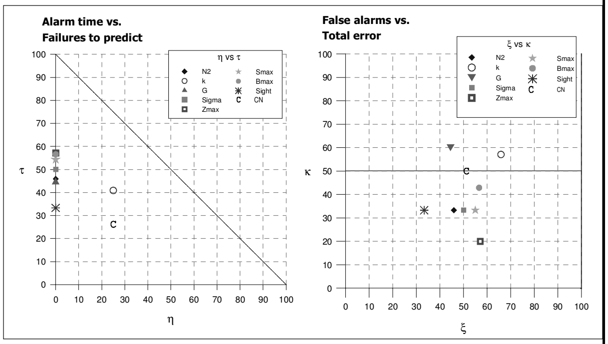
II. $$Z_{max}(t) = \max_j \left[\frac{\sum (t_j|\underline{M}, \overline{M}, s, \alpha, \beta)}{\left(N(t_j|\underline{M}, s) - N(t_j|\overline{M}, s)\right)^{\frac{2}{3}}} \right]$$

It is proportional to the ratio between the average linear dimension of sources and their average distance

ξ=57.1%



Analysis of the predictive capability of CN functions of seismic flow – The BKE catalog



Predictive capability of single premonitory seismicity patterns

- **The analysis in retrospective prediction based on some single premonitory seismicity patterns (CN functions and inter-event times) provide results that are rather stable and comparable with those obtained by CN algorithm.**
- **The best prediction results are obtained by functions Zmax, which is related to space-time clustering of earthquakes, Sight, that is related to energy release, and inter-event times.**
- **Experiments performed with the BKE catalog confirm the stability and significance of the results provided by CN and as well as by individual functions.**

Conclusions

- **The satisfactory results of CN application at Mt. Vesuvius seem to substantiate the similarity of the premonitory seismicity patterns characterising the seismic flow in tectonic and volcanic areas.**
- **The prediction experiments based on individual CN functions show that a certain predictability of moderate size earthquakes (M≥3.0) at Mt. Vesuvius can be attained by means of some single seismicity patterns.**
- **CN algorithm, which is based on multiple seismicity patterns, is generally more stable and outperforms single premonitory patterns either in terms of total error and rate of false alarms.**
- **Experiments performed with the BKE catalog confirm the stability and significance of the obtained results.**

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