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Earthquake's swarms as forerunners of strong earthquakes in Italy

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RIASSUNTO - La maggior parte dei forti terremoti avvenuti in Italia sembra essere stata preceduta da anormali sciame di scosse più deboli. Fenomeni precursori simili a questi sono stati descritti nella nota di Prozorov et. al. (1972) relativa all'Asia Centrale. Molto spesso gli sciame avvengono in prossimità di uno stesso allineamento, come pure il forte terremoto che li segue.

SUMMARY - Most of strong earthquakes in Italy seem to be preceded by anomalous swarms of weaker shocks. Similiar precursor was described by Prozoroff and al (1972) for Central Asia. Most often the swarms occur near the same lineament, as the strong earthquake which follow them.

1. HYPOTHESIS.

Fig. 1, 2 show the major lineaments and epicenters. We considered separately the four regions shown in these figures. In each region (associated with a lineament of 1st rank) we find the years when the number of earthquakes is more than average. Then we consider the epicenters of these earthquakes. If most of them belong to a narrow cluster (comparative to the whole region) we call the corresponding group of earthquakes *a swarm*.

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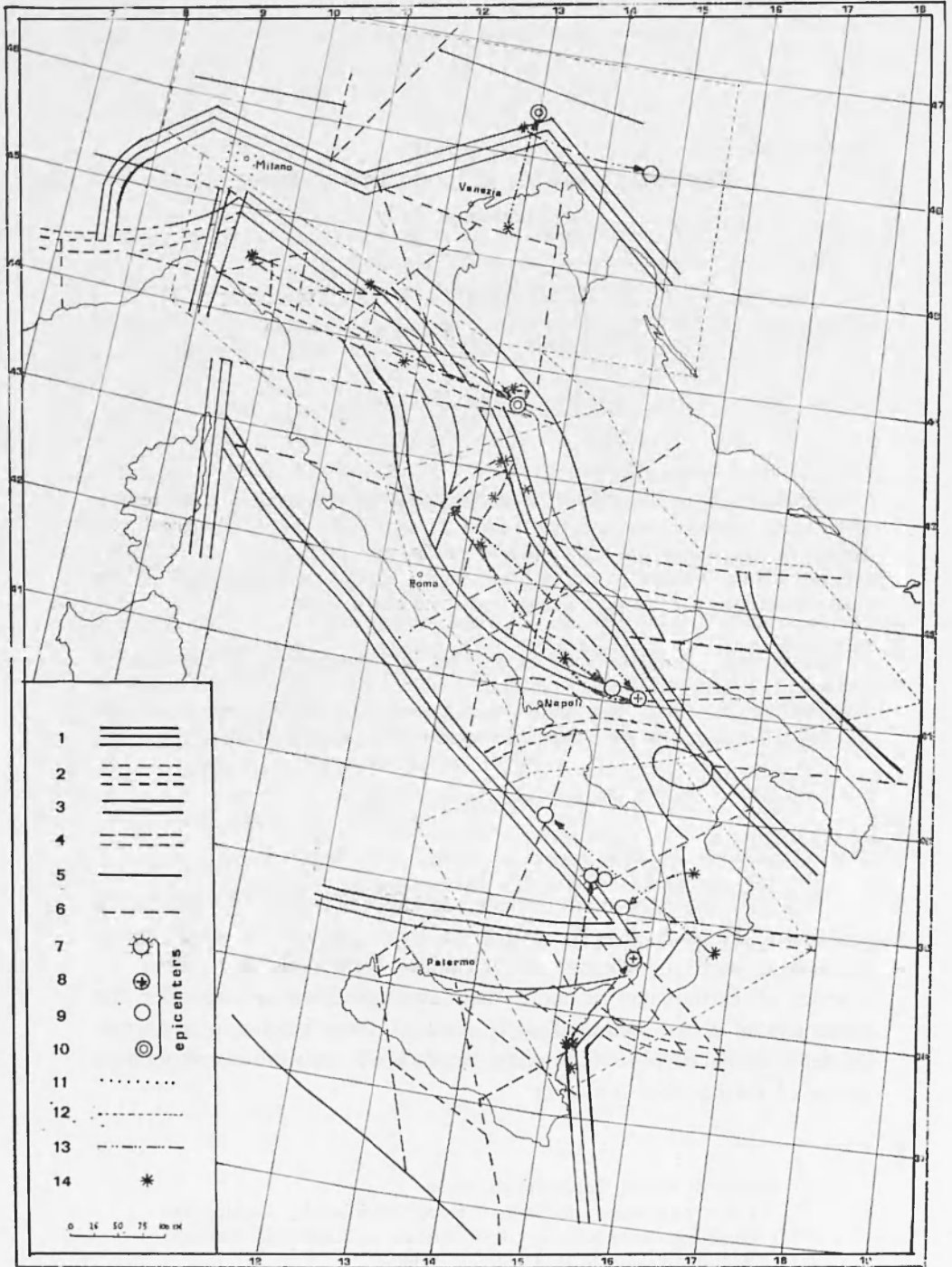


Fig. 1. Major lineaments and epicenters of strong earthquakes for the time interval 1904-1920 (after Caputo M., et al, in press); 1, 2 lineaments of I rank; 3, 4 lineaments of II rank; 5, 6 lineaments of III rank; 1, 3, 5 longitudinal lineaments; 2, 4, 6 transverse lineaments; 11 lineaments, not expressed in topography; 7—10 epicenters; 7 $M > 7.0$; 8 $6.5 \leq M < 7$; 9 $6.0 \leq M < 6.5$; 10 $5.8 \leq M < 6.0$; 12 boundaries of regions. From North to South: N 1 Northern frame of Po-walley; N 2 Northern Apennines; N 3 Central Apennines; N 4 So Italy and Sicily; 13 Swarms-forerunners and corresponding epicenters; 14 Swarms false alarms. The earthquakes of table 1 in region 4 are plotted only if $M \geq 6.1$.

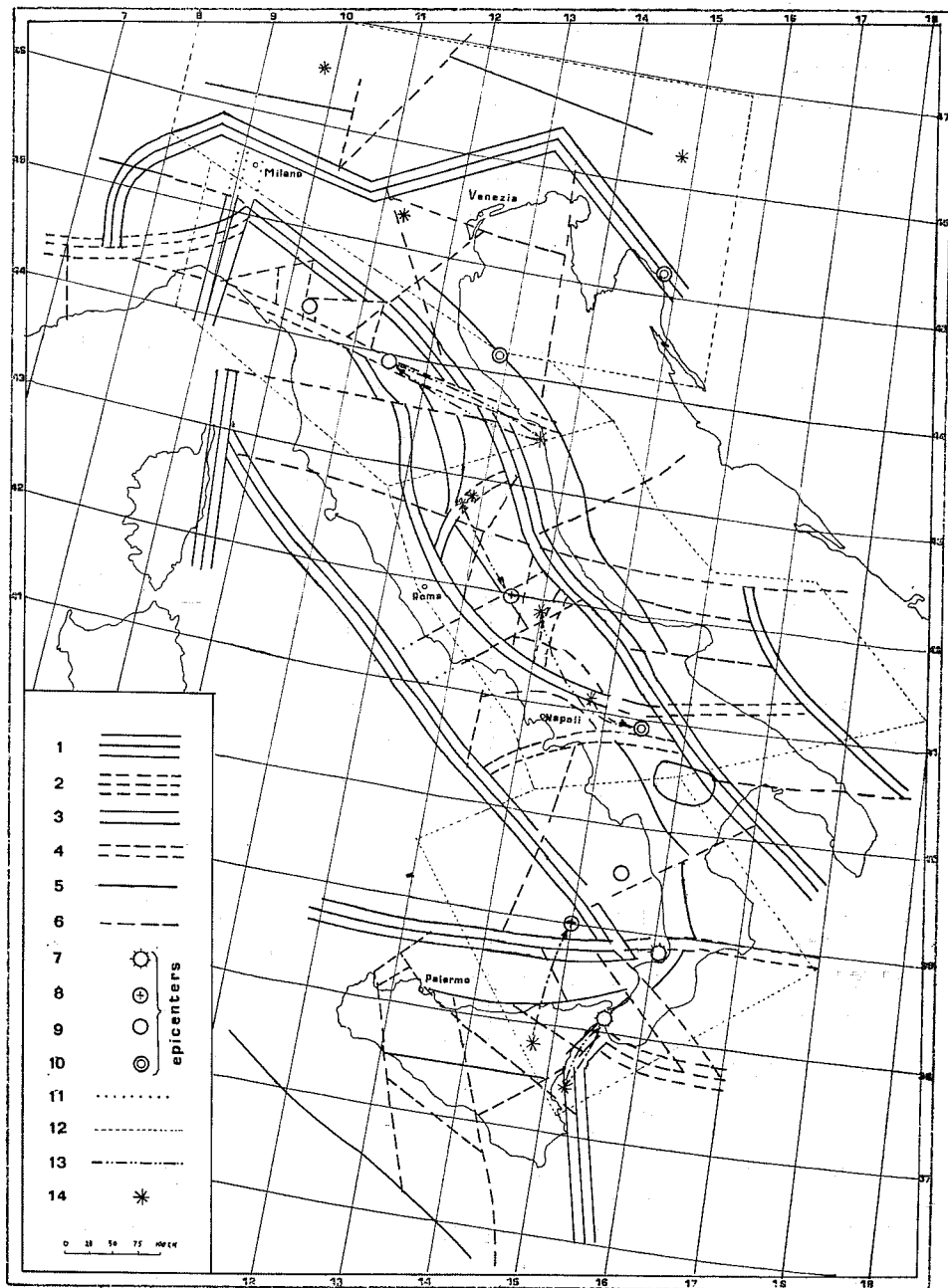


Fig. 2. Same, as Fig. 1, for the time interval 1921-1974.

The analysis of the catalogues (Caputo et al, 1974) and (Carrozzo et al. 1973) suggest the following hypothesis: during 6 years after the swarm a strong earthquake occurs in the same region.

To specify this hypothesis, we intrduce the following definitions.

$N(t)$ the number of all earthquakes in catalogues Caputo et al., Carrozzo et al. for the given region in the year t

$$n(t) = N(t) - n_a(t)$$

n_a the number of strong earthquakes

n_a is roughly estimated as follows: the territory is divided into rightangular cells 0.2° in latitudes and 0.4° in longitudes. Consider the cell where the strong earthquakes took place in year t and the four celles which have a side in common with that considered, n_a is number of carthquakes occurred in these five cells after the strong earthquakes in the years t and $t+1$.

$\bar{N}(t), \bar{n}(t)$ are the average values of $N(t), n(t)$ in the interval $1904 \div t$.

Strong earthquake in this paper is by definition an earthquake with magnitude $M \geq M_0$; $M_0 = 6.1$ for Southern Italy, and $M_0 = 5.8$ for Northern and Central Italy.

Swarm. Take the year when $\bar{n}(t) > \bar{N}(t)$. Find the double cell (0.4° in lat. \times 0.8° in long.) with maximal number of earthquakes $r(t)$, afer elimination of the aftershocks. If $r(t) > \frac{1}{2} n(t)$, the earthquakes occurred in this cell in the year t form a swarm.

The alarm is declared for six years after the swarm and determinates after these six year or after a strong earthquakes during them.

These definitions involve some arbitrary parameters, which will be varied. The definition of the number of the aftershocks and of the swarm are made deliberately rough to avoid more arbitrary parameters, in particular, n_a includes the foreshocks, which are usual but few.

2. PROCESSING OF EARTHQUAKE'S CATALOG.

In the time interval 1904-1972 we used the catalogues Caputo et al, Carrozzo et al., in the interval 1973-74 we used the less complete data obtained from USGS, 1974. The list of earthquakes with $M \geq 5.8$ is given in table 1. The earthquake's swarms determined, as defined above, are listed in Table 2 and shown on figs 3-6. We see, that our

TABLE 1. Earthquakes of Italy with $M \geq 5.8$.

NN.	Data	Epicenter		depth	Magni- tude	Region on Fig. 1
		φ	λ			
1.	8. 9. 1905	38.83	16.1	25	7.3	4
2.	23. 10. 1907	38.0	16.1	12	5.9	
3.	28. 12. 1908	38.17	15.58	10	7.0	4
4.	7. 6. 1910	40.9	15.45	25	5.9	3
5.	1. 8. 1910	39.0	15.0	200	6.8	4
6.	5. 4. 1911	39.5	15.5	200	6.3	4
7.	13. 1. 1915	41.98	13.6	10	6.8	3
8.	7. 7. 1915	39.0	15.0	250	5.9	
9.	12. 3. 1916	45.2	14.8	25	5.8	1
10.	17. 5. 1916	44.18	12.91	20	5.8	2
11.	29. 6. 1919	43.9	11.5	25	6.2	2
12.	7. 9. 1920	44.25	10.28	10	6.3	2
13.	17. 8. 1926	39.0	14.75	25	6.0	
14.	7. 3. 1928	38.6	15.8	100	6.6	4
15.	27. 3. 1928	46.4	13.0	25	5.8	1
16.	23. 7. 1930	41.05	15.42	7	6.5	3
17.	30. 10. 1930	43.73	13.33	4	5.9	2
18.	17. 10. 1937	39.3	15.2	300	5.8	4
19.	13. 4. 1938	39.3	15.2	275	7.1	4
20.	16. 3. 1941	38.3	12.2	100	6.9	
21.	25. 1. 1946	46.3	7.5	35	6.0	
22.	26. 12. 1952	39.8	14.5	275	6.2	4
23.	23. 11. 1954	38.5	15.0	225	5.8	4
24.	1. 2. 1956	39.07	15.58	235	6.1	4
25.	3. 1. 1960	39.27	15.31	281	6.1	4
26.	21. 8. 1962	41.1	15.1	34	6.1	3
27.	19. 5. 1963	46.0	14.6	32	6.0 5.6	1
28.	19. 7. 1963	43.3	8.2	33	6.0	
29.	15. 1. 1968	37.9	13.0	33	5.8	

(*) Earthquake Nr 27 is listed with magnitude 6; a revision of the data suggest that its magnitude should be $M=5.6$. This changes slightly some numerical results, but the changes in the conclusions are not relevant.

TABLE 2. Strong earthquakes and swarms.

N in table	Region Fig. 1	Strong earthquakes				Swarm - forerunner.				
		year	φ	λ	M	year	φ	λ	$n(t)$	$r(t)$
1	4	1905	38.83	16.1	7.3	—	—	—	—	—
3	4	1908	38.17	15.58	7.0	1906	37.5	15.2	12	8
						1907	37.5	15.2	7	5
4	3	1910	40.9	15.45	5.9	1905	41.1	14.8	28	15
						1907	41.9	14.0	25	15
5	4	1910	39.0	15.0	6.8	1908	37.7	14.8	21	6
6	4	1911	39.5	15.5	6.3	—	—	—	—	—
7	3	1915	41.98	13.6	6.8	1910	42.7	12.8	34	34
9	1	1916	45.2	14.8	5.8	—	—	—	—	—
10	2	1916	44.18	12.91	5.8	—	—	—	—	—
11	2	1919	43.9	11.5	6.2	1917	43.5	13.6	262	156
						1918	43.5	13.6	135	93
12	2	1920	44.25	10.28	6.3	—	—	—	—	—
13	4	1928	38.6	15.8	6.6	1923	37.7	15.2	28	20
15	1	1928	46.4	13.0	5.8	1922	45.3	12.8	14	12
16	3	1930	41.05	15.42	6.5	1924	42.5	12.8	82	59
						1927	41.3	14.4	59	36
17	2	1930	43.73	13.33	9.9	1924	43.7	13.2	66	42
						1927	44.5	9.6	178	162
						1928	44.5	9.6	246	216
						1929	44.5	11.2	120	76
19	4	1938	39.3	15.2	7.1	1935	37.7	15.2	20	13
22	4	1952	39.8	14.5	6.2	1947	38.7	16.8	75	56
24	4	1956	39.07	15.58	6.1	9155	39.5	16.4	22	14
25	4	1960	39.27	15.31	6.1	—	—	—	—	—
26	3	1962	41.1	15.1	6.1	1961	42.3	13.2	82	66
27	1	1963	46.0	14.6	6.0	1960	46.3	12.8	33	20

TABLE 2a. False alarms.

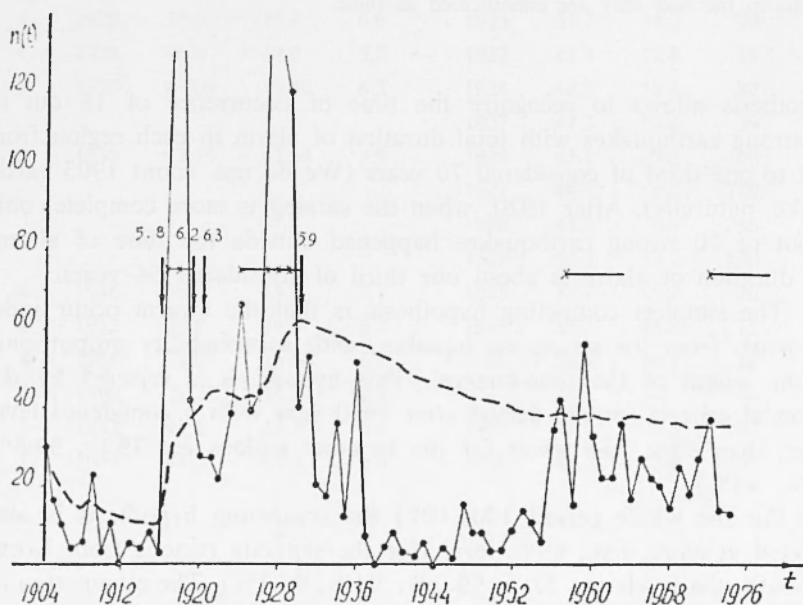
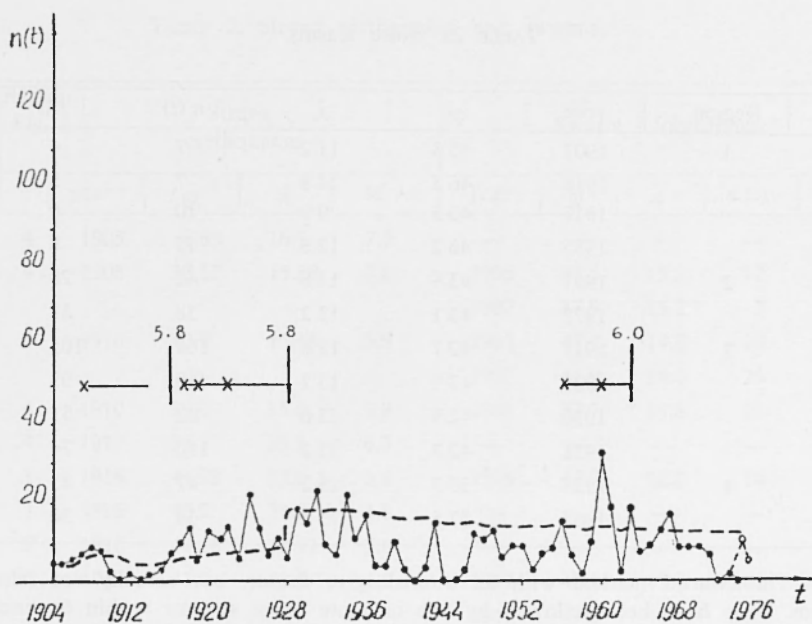
	Region	year	φ	λ	$n(t)$	$r(t)$
1	1	1907	45.3	11.2	7	4
2*		1916	46.3	14.8	7	5
3*		1917	46.5	9.9	10	6
4*		1955	46.3	12.8	15	8
5	2	1957	43.9	11.8	42	28
6		1972	43.1	13.2	38	33
7*	3	1917	42.7	12.8	164	105
8*		1921	43.1	13.2	119	95
9		1930	42.9	13.6	62	51
10		1951	42.7	13.2	110	74
11	4	1928	37.7	15.2	47	25
12		1963	37.5	15.2	34	30

The swarms marked with an asterisk give longer, but actually not false alarm. They have been followed by one or more other swarms within 6 years, and the last one has been followed by an earthquake within 6 years. In the counts in the text they are classified as false.

hypothesis allows to recognize the time of occurrence of 14 out of 19 strong earthquakes with total duration of alarm in each region from half to one third of considered 70 years (We do not count 1905 earthquake, naturally). After 1920, when the catalog is more complete, only 1 out of 10 strong earthquakes happened outside the time of alarm; the duration of alarm is about one third of considered 54 years.

The simplest competing hypothesis is that the swarm occur independently from the strong earthquakes, with a probability proportional to the length of the time-interval. This hypothesis is rejected by the binomial criteria for the period after 1920 year with a confidence level more, than 99% (the levels for the separate regions are 79%; 99.8% 88%; 94%).

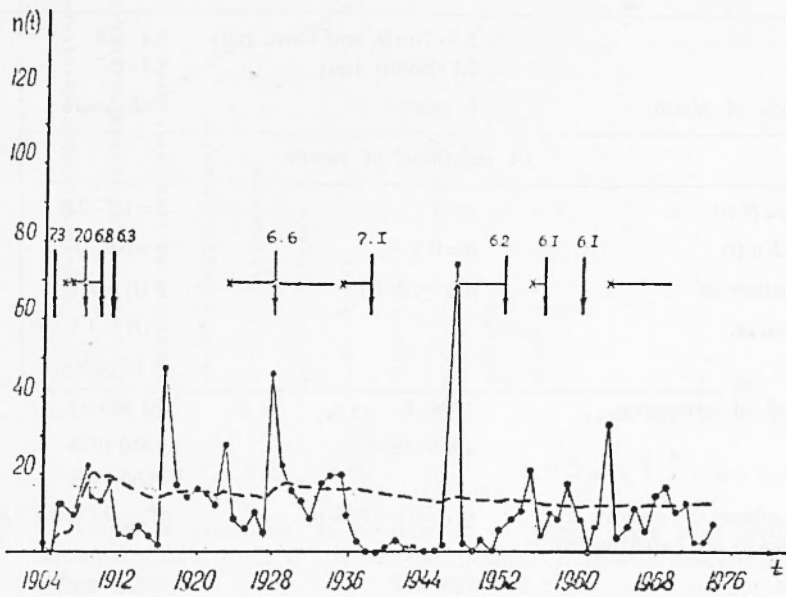
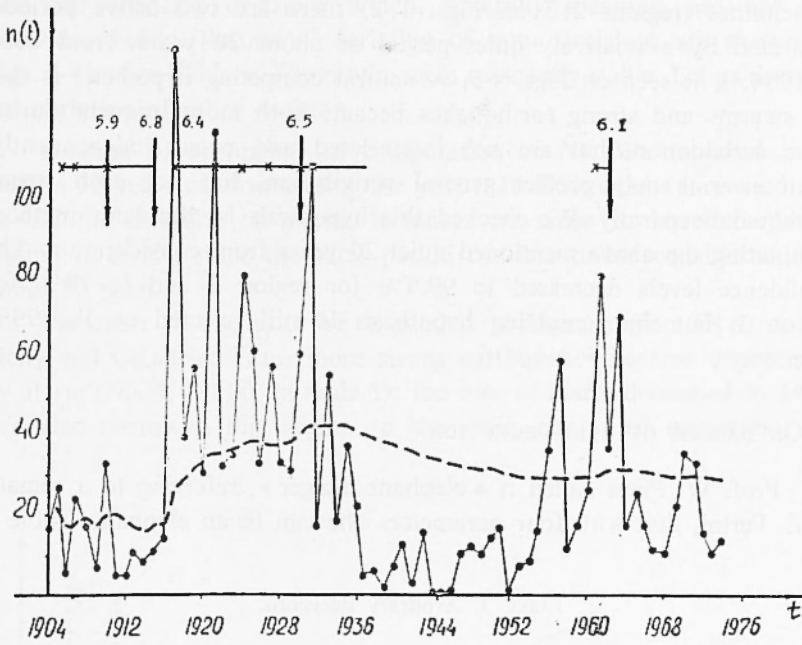
For the whole period 1904-1974 the competing hypothesis is also rejected at more then, 99% level (for the separate regions from North to South, the levels are 51%, 99.9%, 94%, 96.3%). The elimination of this simplest competing hypothesis does not prove ours, of course. One more competing hypothesis was tested. In the North and Central



Figs. 3-6. Strong earthquakes and swarms in regions 1-4.

— $n(t)$
 - - - $N(t)$

the arrow and number indicate the time and magnitude of the strong earthquake; the horizontal segment indicates an alarm x , is a swarm.



Appennines (regions 2, 3 on Figs. 1, 2) there are two active periods, separated by a relatively quiet period of about 20 years, from 1934 to 1954; it is seen on Figs. 4-5. A natural competing hypothesis is that the swarms and strong earthquakes became both more frequent during these activation, but are not interrelated and occur independently. Then swarms may predict general activation, but not each strong earthquake separately. We checked this hypothesis by the same method, eliminating the above mentioned quiet 20 years from consideration. The confidence levels decreased to 99.5% for region 2 and to 76% for region 3, but the competing hypothesis is still rejected on the 99% level.

3. ON DANGER OF SELF-DECEPTION.

Prof. W. Press called it « elephant danger », referring to a remark of E. Fermi, that with four parameters one can fit an elephant. Table 3

TABLE 3. Arbitrary decisions.

Decision	Main variant	Range
1. M_0	5.8 - North and Cent. Italy 6.1 - South Italy	5.4 - 6.4 5.7 - 6.7
2. Duration of alarm.	6 years	4 - 8 years
3.4 definition of swarm		
3. $n(t) > a \bar{N}(t)$	$a=1$	$a=1.2 - 2.0$
4. $r(t) > b n(t)$	$b=0.5$	$b=0.6 - 0.7$
5. Elimination of aftershocks.	$n(t) > \bar{N}(t)$	$n(t) > \bar{n}(t)$ $n(t) > 1.5 \bar{n}(t)$ $\bar{N}(t) > N(t)$
6. Interval of averaging.	1904 - t	30 years
7. T	1904 - 1974	1920-1974 1890-1974
8. Area, where the swarms and aftershocks are concentrated	$0,4^0 \text{ lat} \times 0,8^0 \text{ long}$	(*) $0,2^0 \text{ lat} \times 0,8^0 \text{ long}$
9. Region.	figs 1; 2	see pag. 5; 6

(*) Actually the swarms occupy much lesser region, to that this definition is taken for convenience and does not influence the results, much.

lists our arbitrary decisions which, generally speaking, are not free from data-fitting. Results of variation of same decisions are shown on Figs. 7-9 and in Table 4. The results seem reasonably stable. Let us describe the variation of other decision.

Interval of averaging (in computation of \bar{N}). We replaced it by using a 30 years window ending the year t . Its fluctuations increased and so did the duration of alarm. It makes no sense to introduce larger sliding intervals, since the total period of time under consideration is about 70 years.

Variation of regions. We expanded southern region (N 4) to all Sicily and Calabria. Three more strong earthquakes became unpreceded by alarm (NN 4, 19, 20, in table 1); the time of alarm decreased to 34%. We also narrowed this region to the main cluster of epicenters. No

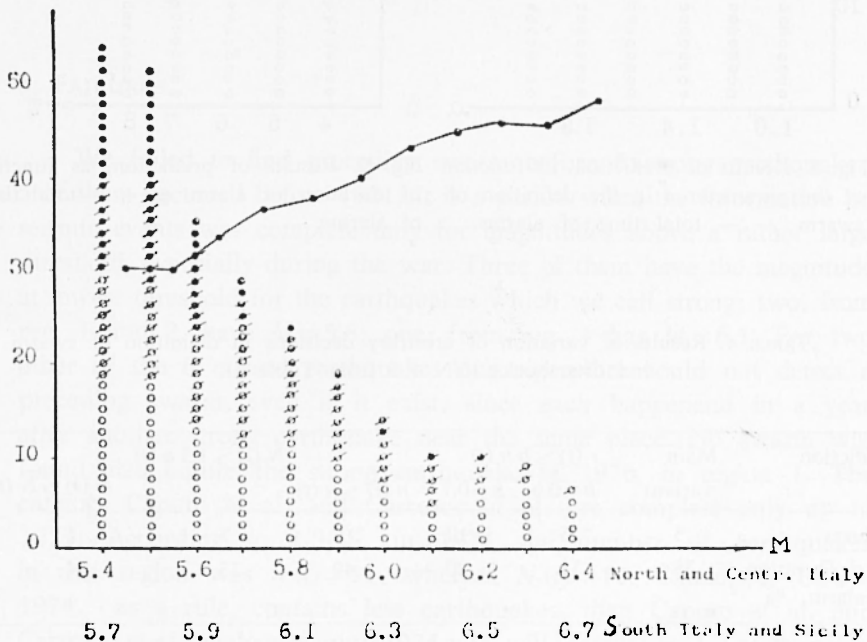


Fig. 7. Results of prediction, as function of M. Open circle is a predicted earthquake, solid circle is a missed earthquake. Circle with dash-earthquake before 1921. —.— total time of alarm in % of total time interval.

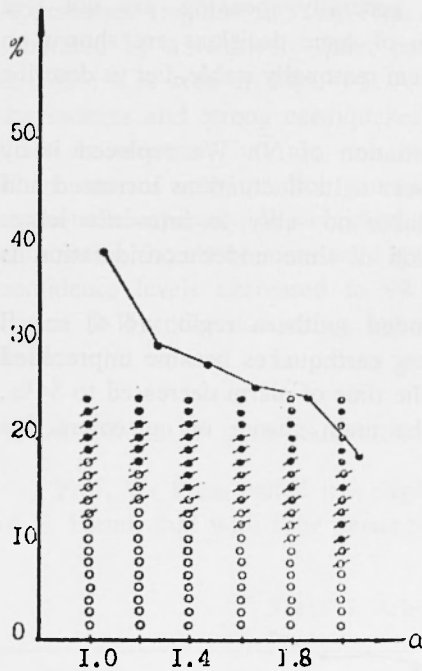


Fig. 8. Results of prediction, as function of the parameter a in the definition of swarm. —.— total time of swarm. —.— total time of alarms.

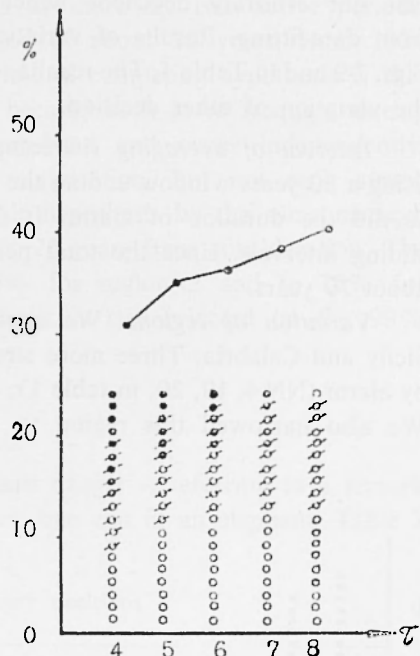


Fig. 9. Results of prediction, as function of duration of alarm τ . —.—total time of swarm. —.— total time of alarms.

TABLE 4. Results of variation of arbitrary decisions in definition of swarm and aftershocks (NN 4,5 from Table 3).

Prediction	Main variant	$r(t) > b n(t)$		$N(t) > 1.5 \bar{n}(t)$		
		$b=0.6$	$b=0.7$	$n(t) > \bar{n}(t)$	$N(t) > \bar{N}(t)$	
Failures	5	6	10	5	7	5
Total Duration of alarm, %	38	31	20	49	33	44

more strong earthquakes were missed and duration of alarm remained about the same. Ditto for expansion of central Appennines (reg. 3) westward, up to about 12° E.

Some of our strong earthquakes in Southern region (reg. 4) have an intermediate focal depth. It would seem natural to consider them separately. But the data do not suggest any reasons for this. In general the reasonable change of the regions affects our results not significantly. Still, it remains our main worry.

4. THE RELATIVE POSITION OF STRONG EARTHQUAKES AND PRECEDING WARMS.

Is shown on Figs. 1, 2. The distance between them is in average about 150 km, and in some cases more than 300 km. It seems not unnaturally large: the length of the sources of our strong earthquakes can reach at least tens of km, and the area of preparation should be several times larger. So the swarm does not indicate the place of the future earthquake inside the region.

5. FAILURES.

We failed to find preceding swarm before 6 strong earthquakes. 5 of them occurred before 1921; it is a period when the information on seismic events was complete only for magnitudes above a rather large threshold, especially during the war. Three of them have the magnitude at lowest threshold for the earthquakes which we call strong; two, from reg. 1 and 2, have $M=5.8$; one, from reg. 4 has $M=6.1$. For two other of the 6 missed earthquakes our algorithm could not detect a preceding swarm, even if it exist, since each happenend in a year after another strong earthquake near the same place. No swarm was found also before the strong earthquake of 1976, in region 1. The catalogs Caputo et al. and Carrozzo et al. are complete only up to 1973. According to USGS, in 1974 the number of earthquakes in this region was $n(t)=11$, whereas $N(t)=12$. Catalogue, USGS, 1974, as a rule, contains less earthquakes, than Caputo et al. and Carrozzo et al. catalogues up to 1974 $n(t)$ will increase by 1-2 earthquakes at last; then there will be a swarm in 1974, before 1976 strong earthquake.

In general, the failures do not seem discouraging although these comments are not intended to comment them away.

TABLE 5.

Region	Earthquakes predicted	False alarms	Earthquakes missed	Total earthquakes	
1	2	0	0	2	1921-1974
2	1	1	0	1	
3	2	1	0	2	
4	4	2	1	5	
	9	4	1	10	
1	2	2	1	3	1904-1974
2	2	1	2	4	
3	4	1	0	4	
4	6	2	2	8 (*)	
	14	5	5	19	

(*) 1905 not counted, since algorithm cant predict it by definition.

CONCLUSION.

Our results illustrate large potential possibilities of tracing the precursors of strong earthquakes in earthquake's catalogs. The use of neotectonics is essential.

It seems convincing, that the swarms precede strong earthquakes in Italy. To evaluate the importance of swarms, as practical precursors, we have to study other regions and wait for future strong earthquakes in Italy. An alarm in region 2 for 1972-78 deserves attention in this context. Our of 16 previous continuous alarms 12 were not false. Practically valuable long-term prediction to our opinion may be possible only with a complex of such precursors.

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REFERENCES

- BELOUSSOV V. V., SORSKY A. A. and BUNE B. I., 1967. - *Seismotectonic map of Europe*, Moscow, Nauka.
- CAPUTO M., POSTPICHL D., 1974. - *Catalog of the Earthquakes of Italy*.
- CAPUTO M., KEILS BOROK V. I., OFICEROVA E., RANZMAN E., ROTWAIN I. M., SOLOVJEFF A., In press. *Pattern recognition of earth quake-prone areas in Italy*, « Physics of the Earth and Planetary Interiors ».
- GELFAND I. M., GUBERMAN SH., KEILIS BOROK V. I., KNOPOFF L., PRESS F., RANZMAN E. IA., ROTWAIN I. M., SADOVSKY A. M., 1976. - *Pattern Recognition, applied to Earthquake Epicenters in California*. « Physics of the Earth and Planetary Interior. », 11, pp. 227-283.
- CARROZZO M. T., DE VISINTINI G., GIORGETTI F., IACCARINO E., 1973. - *General Catalogue of Italian Earthquakes*. Comit. Naz. En. Nucl. RT/PROT (73) 12.
- OGNIBEN L. (editor), 1973. - *Structural model of Italy scale 1:1.000.000*, CNR. NN. 1, 2 Roma.
- PROZOROFF A. G. and RANZMAN E. IA., 1972. - *Statistics of Earthquakes and Morphostructures of Central Asia (in Russian)*. Doklady Akademii Nauk SSSR, Geofizika, 207, 2.
- SHATSKY I. S. (editor), 1972. - *Tectonic map of Europe 1:2.500.000*, GUGT, Moscow.
- US GEOLOGICAL SURVEY, NATIONAL EARTHQUAKE INFORMATION SERVICE, 1974. - *Preliminary determination of epicenters*.
- YANSHIN A. L. (ed.), 1966. - *Tectonic map of Eurasia, 1:5.000.000*, Moscow, Nedra.