Earthquake’s swarms as forerunners of strong earthquakes in Italy

M. CAPUTO (*), P. GASPERINI (**), V. KEILIS-BOROK (**), L. MARCELLI (***) , I. ROTWAIN (****)

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Riassunto - La maggior parte dei forti terremoti avvenuti in Italia sembra essere stata preceduta da anormali sciami 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 sciami 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. Similar 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.

(*) Istituto di Fisica, Università di Roma.
(**) Centro elettronico dell’Italia Centro Meridionale, Casalecchio.
(***) Accademia delle Scienze URSS, Istituto di Sismologia, Mosca.
(****) Istituto Nazionale di Geofisica, Roma.
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; 7—10 epicenters; 7—: M > 7.0; 8 6.5 ≤ M < 7.0; 9 6.0 ≤ M < 6.5; 10 5.8 ≤ M < 6.0; 11 boundaries of regions. From North to South: N1 Northern frame of Po-valley; N2 Northern Apennines; N3 Central Apennines; N4 So Italy and Sicily; 14 Swarms-forerunners and corresponding epicenters; 15 Swarms-false alarms. The earthquakes of table 1 in region 4 are plotted only if M > 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 introduce 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 right angular cells $0.2^\circ$ in latitudes and $0.4^\circ$ in longitudes. Consider the cell where the strong earthquakes took place in year $t$ and the four cells which have a side in common with that considered, $n_a$ is number of earthquakes occurred in these five cells after the strong earthquakes in the years $t$ and $(t+1).

$N(t)$, $n(t)$ are the average values of $N(t)$, $n(t)$ in the interval 1904-72.

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

**Swarm.** Take the year when $n(t) > N(t)$. Find the double cell $(0.4^\circ$ in lat. $x 0.8^\circ$ in long.) with maximal number of earthquakes $r(t)$, after 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 determines 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 $M > 5.8$.

| NN  | Data   | Epicenter $\phi$ | $\lambda$ | depth | Magnitude | Region on Fig. 1 |
|-----|--------|------------------|-----------|-------|-----------|-----------------|
| 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             | 13.0      | 250   | 5.9       |                 |
| 9.  | 12. 5. 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    | 45.9             | 11.5      | 25    | 6.2       | 2               |
| 12. | 7. 9. 1920     | 44.25            | 10.28     | 10    | 6.3       | 2               |
| 13. | 17. 8. 1926    | 39.0             | 14.73     | 23    | 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. | 21. 7. 1930    | 41.0            | 15.42     | 7     | 6.5       | 5               |
| 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            | 15.38     | 225   | 6.1       | 4               |
| 25. | 5. 3. 1960     | 39.27            | 13.51     | 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 $\pm$ 5.6 | 1          |
| 28. | 19. 7. 1965    | 45.3             | 8.2       | 35    | 6.0       |                 |
| 29. | 15. 1. 1968    | 37.9             | 13.0      | 33    | 5.8       |                 |

(*) Earthquake No. 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 Region I table | Fig. 1 | Strong earthquakes | Swarm - forerunner. |
|---------------------|--------|---------------------|---------------------|
|                     | year   | ρ | λ | M | year | ρ | λ | π(t) | r(t) |
| 1                   | 4      | 1905 | 38.83 | 16.1 | 7.3 | — | — | — | — |
| 2                   | 4      | 1906 | 38.17 | 15.58 | 7.0 | 1907 | 37.5 | 15.2 | 7 | 5 |
| 3                   | 3      | 1910 | 40.0 | 15.45 | 5.9 | 1905 | 41.1 | 14.9 | 28 | 15 |
| 4                   | 4      | 1910 | 39.0 | 15.0 | 6.8 | 1906 | 37.7 | 14.8 | 21 | 6 |
| 5                   | 4      | 1911 | 39.5 | 15.5 | 6.3 | — | — | — | — |
| 6                   | 3      | 1913 | 41.9 | 13.6 | 6.8 | 1910 | 42.7 | 12.8 | 34 | 34 |
| 7                   | 1      | 1916 | 45.2 | 14.8 | 5.8 | — | — | — | — |
| 8                   | 2      | 1916 | 31.4 | 12.9 | 5.8 | — | — | — | — |
| 9                   | 2      | 1919 | 39.9 | 11.5 | 6.2 | 1917 | 43.5 | 13.6 | 262 | 156 |
| 10                  | 2      | 1920 | 44.25 | 10.28 | 6.3 | — | — | — | — |
| 11                  | 2      | 1921 | 45.15 | 11.53 | 6.9 | 1920 | 43.5 | 13.6 | 135 | 93 |
| 12                  | 4      | 1928 | 38.6 | 15.8 | 6.6 | 1923 | 37.7 | 15.2 | 28 | 20 |
| 13                  | 1      | 1928 | 46.4 | 13.0 | 5.8 | 1922 | 45.5 | 12.8 | 14 | 12 |
| 14                  | 3      | 1930 | 41.05 | 15.42 | 6.5 | 1924 | 42.5 | 12.8 | 82 | 59 |
| 15                  | 2      | 1930 | 43.75 | 13.33 | 9.9 | 1924 | 43.7 | 13.2 | 66 | 42 |
| 16                  | 2      | 1930 | 44.5 | 9.6 | 178 | 162 |
| 17                  | 4      | 1938 | 39.3 | 15.2 | 7.1 | 1935 | 37.7 | 15.2 | 20 | 13 |
| 18                  | 4      | 1952 | 39.8 | 14.5 | 6.2 | 1947 | 38.7 | 16.8 | 75 | 56 |
| 19                  | 4      | 1956 | 39.07 | 15.58 | 6.1 | 1955 | 39.3 | 16.4 | 22 | 14 |
| 20                  | 4      | 1960 | 39.27 | 15.31 | 6.1 | — | — | — | — |
| 21                  | 3      | 1962 | 41.1 | 15.1 | 6.1 | 1961 | 42.3 | 13.2 | 82 | 66 |
| 22                  | 1      | 1963 | 40.0 | 14.6 | 6.0 | 1960 | 40.3 | 12.8 | 35 | 20 |
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. 

The 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 than 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

| Region | year | p | \( \lambda \) | \( n(\lambda) \) | \( \varepsilon(\lambda) \) |
|--------|------|---|------------|------------|----------------|
| 1      | 1907 | 45.5 | 11.2 | 7 | 4 |
| 2*     | 1916 | 46.5 | 14.8 | 7 | 5 |
| 3*     | 1917 | 46.5 | 9.9  | 10 | 6 |
| 4*     | 1915 | 46.5 | 12.8 | 15 | 8 |
| 5      | 2    | 1917 | 43.9 | 11.8 | 42 | 28 |
| 6      | 1972 | 43.1 | 13.3 | 38 | 33 |
| 7*     | 3    | 1917 | 42.7 | 12.8 | 104 | 105 |
| 8*     | 1921 | 43.1 | 13.2 | 119 | 95 |
| 9      | 1930 | 42.9 | 13.6 | 62 | 51 |
| 10     | 1931 | 42.7 | 13.2 | 110 | 74 |
| 11     | 4    | 1928 | 37.7 | 15.2 | 47 | 25 |
| 12     | 1965 | 37.5 | 15.2 | 34 | 30 |
Figs. 3-6. Strong earthquakes and swarms in regions 1-4.

The arrow and number indicate the time and magnitude of the strong earthquake; the horizontal segment indicates an alarm that a swarm.
EARTHQUAKE'S SWARMS AS FORERUNNERS OF STRONG ETC.
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 activations, 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 | 5.4 - 6.4 |
| 2. Duration of alarm. | 6 years | 4 - 8 years |
| 3. $n(t) > a \cdot N(t)$ | $a = 1$ | $a = 1.2 - 2.0$ |
| 4. $r(t) > b \cdot n(t)$ | $b = 0.5$ | $b = 0.6 - 0.7$ |
| 5. Elimination of aftershocks. | $n(0) > N(t)$ | $n(t) > n(t)$ |
| 6. Interval of averaging. | 1904 - 1974 | 30 years |
| 7. $T$ | 1904 - 1974 | 1920-1974 |
| 8. Area, where the swarms and aftershocks are concentrated | 0.4° lat $\times$ 0.8° long | (*) 0.2° lat $\times$ 0.8° long |
| 9. Region. | Figs 1; 2 | sec pag. 5; 6 |

(*) Actually the swarms occupy much lesser region, so 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 unprecedeed by alarm (NN 4, 19, 20, in table 1); the time of alarm decreased to 54%. We also narrowed this region to the main cluster of epicenters. No

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**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. $\cdots \cdots$ total time of alarm in % of total time interval.
Fig. 8. Results of prediction, as function of the parameter $\alpha$ in the definition of swarm. $-.-.$ total time of alarms.

Fig. 9. Results of prediction, as function of duration of alarm $\tau$. $-.-.$ 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 | $r(t) > b \pi(t)$ | $N(t) > 13 \pi(t)$ | $N(t) > N(t)$ |
|------------|--------------|-------------------|---------------------|---------------|
| Failures   | 5            | 0                 | 5                   | 5             |
| Duration   | 58           | 51                | 49                  | 49            |
| Alarm, %   |              |                   |                     |               |

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 happened 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 Carrozzi 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 Carrozzi 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                |
| 2      | 1                     | 1            | 0                 | 1                |
| 3      | 2                     | 1            | 0                 | 2                |
| 4      | 4                     | 2            | 1                 | 5                |
|        | 9                     | 4            | 1                 | 10               |
| 1      | 2                     | 2            | 1                 | 3                |
| 2      | 2                     | 1            | 2                 | 4                |
| 3      | 4                     | 1            | 0                 | 4                |
| 4      | 6                     | 2            | 2                 | 8 (*)            |
|        | 14                    | 5            | 5                 | 19               |

(*) 1905 not counted, since algorithm can't 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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