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Long-term premonitory seismicity patterns in Italy

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Summary. The clustering of earthquakes as a premonition to a strong earthquake in the same region is defined as pattern BG, which is a generalization of patterns B ('burst of aftershocks') and S ('swarm'), described previously (Caputo *et al.*; Keilis-Borok *et al.*); five out of the seven strongest earthquakes in Italy ($M \geqslant 6.3$, 1900–1980) are preceded by pattern BG within 5 yr; and eight out of 11 patterns BG are followed by a strong earthquake within 5 yr; the last pattern BG (1979 November 11) was diagnosed in advance of the Irpinia earthquake of 1980 November 23 ($M = 6.5$). The statistical significance of pattern BG cannot be tested with the data on Italy alone.

Introduction

Abnormally large clustering of the earthquakes in time and space was described in Caputo *et al.* (1977), Keilis-Borok, Knopoff & Rotwain (1980a) and Keilis-Borok *et al.* (1980b) as being premonitory to a strong earthquake in the same region. Two non-contradictory diagnostics of such premonitory clustering were suggested in Caputo *et al.* (1977), Keilis-Borok *et al.* (1980a, b). One diagnostic was named 'burst of aftershocks', or 'pattern B'. It is a main shock with an abnormally large number of aftershocks during the first few days. Another diagnostic was named 'swarm' or 'pattern S'. It is a group of earthquakes which includes a large part of the earthquakes of the whole region during the same time interval; an additional condition is that the activity of the whole region during this interval is sufficiently large. Formal definitions of patterns B and S can be found in Keilis-Borok *et al.* (1980a, b). According to these definitions, all earthquakes (pattern S), mainshocks and aftershocks (pattern B) are considered in certain ranges of magnitude.

The present paper describes an attempt to define premonitory clustering independently of the magnitudes of the earthquakes in a cluster. Such a definition, if found, will be more robust than the definitions of patterns B and S; it will neglect a possibly important feature of the clusters (namely the upper and lower limits of the magnitude), but at this price a smaller number of parameters will be data-fitted. The search for such a definition was enter-

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tained in order to analyse the most complete catalogue of the Italian earthquakes – the catalogue ENEL (Caputo 1981) with earthquakes from the year 1000 until 1975, where the magnitude is indicated only for about 10 per cent of the events of the twentieth century. After we had analysed this catalogue and data-fitted all parameters, the catalogue CC (Caputo & Console 1980, private communication) for 1975–1979 became available. Its analysis showed pattern BG. It was followed by the earthquake of 1980 November 23. This is one of the not too numerous cases when the precursor could be formally diagnosed in advance.

Regretably, pattern BG, like many other long-term precursors, does not indicate the place of the coming earthquake within the region.

Algorithm

Let us denote by i, the sequence number of the earthquake in the catalogue; t_i, the time of the ith earthquake; h_i, the focal depth; M_i, the magnitude; R_{ij}, the distance between the epicentres of ith and jth earthquakes.

A strong earthquake, for which we are searching the premonitory pattern, is defined by two conditions: (1) $M_i \geqslant M_0$, (2) it is not an aftershock of a strong earthquake. Aftershocks are defined, as described in Keilis-Borok *et al.* (1980a, b) and Gardner & Knopoff (1974).

Pattern BG is diagnosed as follows:

(1) We eliminate from the catalogue the strong earthquakes, their aftershocks and all earthquakes with $h_i \geqslant H$ (H will be defined below).

(2) For each of the remaining earthquakes we count the number $b_i(e)$; this is the number of the earthquakes with $0 \leqslant t_j - t_i \leqslant e$, $R_{ij} < R$.

Pattern BG is defined by condition $b_i > \bar{B}$. It may be diagnosed at the moment, when the count of b_i reached the threshold B, i.e. before the period e (of the pattern B of the 'burst of aftershocks', Keilis-Borok *et al.* 1980a), expired. At this moment we declare an 'alarm', i.e. the time of increased probability of the strong earthquake (the acronym TIP could be less alarming). The TIP lasts until the strong earthquake, but no longer than τ yr. If a strong earthquake does not occur within τ yr, the pattern is called off (a false alarm). Each pattern BG starts a period of alarm; these periods may overlap. An earthquake may be counted in several patterns BG (contrary to pattern B).

Pattern BG is in a way a generalization of patterns B and S. With identical parameters pattern BG will be diagnosed when either pattern B or pattern S occur (but not vice versa), because patterns B and S are more constrained.

Data processing

PARAMETERS

We assumed $M_0 = 6.3$; $H = 60$ km; $e = 1$ yr; $R = 50$ km; $B = 125$; $\tau = 5$ yr. The values of H_0 and R are the same as in previous studies of premonitory clustering; r, B and M_0 were data-fitted on retrospective analysis for 1900–1975. To test the stability of results, we varied the parameters as described below.

Strong earthquakes. To identify them (and for this purpose only) we need to know the magnitudes. If the magnitude of an earthquake is not indicated in the catalogue ENEL we assumed for such an earthquake the maximal value of magnitudes from other catalogues: USGS (1980), Carrozzo *et al.* (1973), Karnik (1971), ISC (1976). The strong earthquakes, identified in this way, are listed in Table 1, where they are underlined.

Table 1. Pattern BG and strong earthquakes. Strong earthquakes are underlined. For the patterns BG, ϕ, λ are the average values in the cluster and M is the maximal value (for the clusters of 1906 and 1910 the values of M are not known), r is the distance between the average point of the cluster and the epicentre of subsequent strong earthquake. * indicates a false alarm; † indicates a probable false alarm; ‡ indicates Sicily and Calabria.

Date	ϕ	λ	M	b_i	Lead time (yr)	r (km)
8.9.1905‡	38.83	16.10	7.3			
10.12.1906‡	37.98	13.69		172	2.05	166
28.12.1908‡	38.17	15.58	7.0			
28.II.1910	42.68	12.90		131	4.12	97
13.I.1915	41.98	13.60	6.8			
24.5.1917	42.82	12.77	5.0	142	3.29	256
5.6.1917	43.76	12.65	5.5	125	3.26	198
17.4.1918	43.52	13.63	4.4	142	2.39	281
7.9.1920	44.25	10.28	6.3			
14.I.1928	44.45	9.62	4.8	257†	2.52	606
13.7.1928	46.39	12.99	4.2	168†	2.02	625
23.7.1930	41.05	15.42	6.5			
24.6.1941	42.89	12.56	4.3	133*		
2.2.1968‡	37.87	13.06	6.0	166*		
5.8.1971	41.43	13.99	4.0	144	4.75	542
6.2.1972	43.64	13.46	4.7	205	4.25	293
6.5.1976	46.27	13.25	6.5			
8.II.1979	42.75	13.00	5.5	158	1.04	254
23.II.1980	40.90	14.80	6.5			

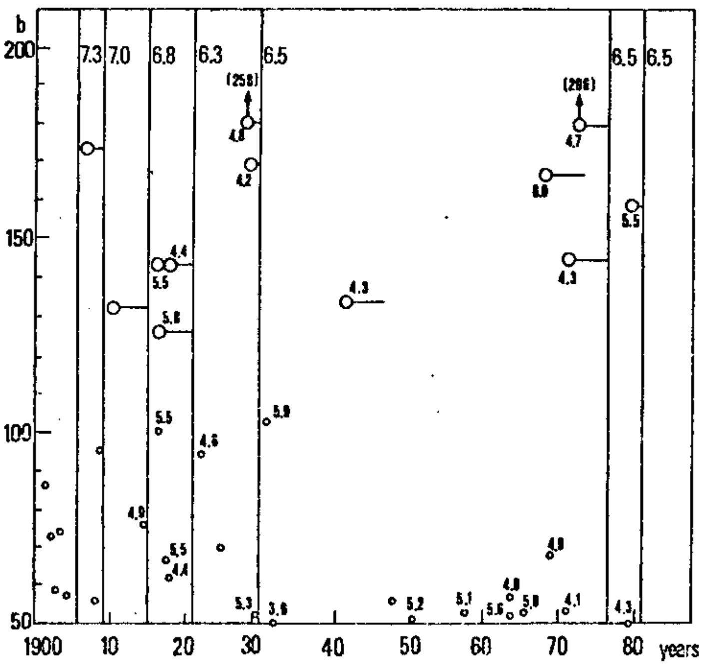

Figure 1. Patterns BG and strong earthquakes. Strong earthquakes ($M \geq 6.3$) are indicated by vertical lines; magnitudes are indicated at the top. Circles show the values of b_i; the largest magnitude of the earthquakes counted in b is indicated. The large circles show the pattern BG ($b \geq 125$). The last pattern BG is diagnosed from the catalogue CC, all others are from the catalogue ENEL.

Patterns BG, identified by the analysis of the catalogue ENEL, 1900–1975, are shown in Table 1 and Fig. 1. Out of 11 patterns, nine are followed by a strong earthquake within 5 yr. However, two patterns in 1928 may be not associated with the subsequent strong earthquake $M = 6.5$ since its distance r from the centre of pattern BG is greater than the empirical limit for reported long-term precursors $10^{0.43M}$ km.

The stability of results was tested by the following variation of parameters: M_0, from 6 to 6.5; R, from 25 to 100 km; B, from 100 to 150 (for $R = 25$ and 50 km) and from 120 to 170 (for $R = 100$ km); $e = 1/2$ yr (for B from 75 to 125). The stability seems acceptable: most unfavourable combination of parameters gives not more than two additional errors.

It has been found that varying the parameters in the above-mentioned ranges does not change the result significantly; in fact the most unfavourable combination of parameters gives only two more errors than Table 1, which is considered very satisfactory.

Forward prediction. Parameters of the algorithm were fitted to the catalogue ENEL for 1900–75. Then the catalogue CC (Caputo & Console 1980) for 1975–79 was received. The processing of the catalogue CC with the same parameters shows the pattern BG with $b_i = 310$, which is far above the threshold $\bar{B} = 125$ (256 out of the 310 events in this pattern are the aftershocks of the earthquake of 1979 September 19, $M = 5.5$). However, application of the same threshold B to the catalogue CC could lead to a false alarm, since the catalogue CC is more complete: the average annual number of events, $\bar{N}$, in the catalogue CC is 2.5 larger than in the catalogue ENEL (3 times larger before elimination of the aftershocks). To confirm the existence of the last pattern BG we levelled the completeness of the catalogue ENEL and CC by eliminating from CC the earthquakes with $M < 3$. Then $\bar{N}$ in the catalogue CC became even smaller than in the catalogue ENEL by 10 per cent. However, pattern BG remains: $b_i = 158$ for $M_i > 3$. A natural suspicion could arise that this pattern is diagnosed because in its vicinity N is larger than for the whole catalogue. This suspicion can also be rejected, as $\bar{N}$ is even smaller in this vicinity. For example, in the rectangle $41° \leq \phi \leq 44°$; $12° \leq \lambda \leq 15°$, $\bar{N}$ is smaller by 20 per cent. An earthquake with $M = 6.5$ (last line in Table 1) actually occurred about 1 yr after the last pattern BG.

Conclusions

The pattern BG apparently deserves attention in connection with the problem of the prediction of the strongest earthquakes of Italy. The relative position of patterns BG and strong earthquakes suggest that continental Italy and Sicily – Calabria could be probably considered separately. Our data do not exclude the hypothesis that pattern BG indicates an increase of the frequency of occurrence of strong earthquakes, without direct association of each pattern with a particular strong earthquake. In other words we cannot exclude that seismic activity has increased in the period considered and that the correlation which we found is a natural consequence of this increase.

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