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Irregular Regularities in Regional Seismicity

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THE OCCURRENCE OF LARGE EARTHQUAKES IN SOUTH ITALY

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ABSTRACT

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An analysis of the data in the catalogues of Italian earthquakes indicates that large earthquakes which occur in the area of radius of about 140 km centered in the Straits of Messina occur in sequences. Each sequence is generally formed by two events and covers an average time window of 10 years.

The last four sequences occurred in the time windows 1783–1891, 1818–1823, 1865–1870, 1905–1908 and are separated by about 40 years indicating that in that area there is now a gap in the time domain.

The analysis of the data in the Catalogue for the region between the latitudes 39°N and 41°50′N indicates that in that region the large earthquakes occurred in 13 sequences. Each sequence is formed by 3 events in average and covers an average time window of 7 years. This indicates that, after the earthquake of Nov. 1980, which occurred after a gap of 67 years, other moderately large earthquakes may be expected in that area in the next few years.

INTRODUCTION

The seismicity of the Southern Apennines and Sicily is well described in the catalogues of the Italian earthquakes (Baratta, 1901; Carrozzo et al., 1973; ENEL, 1978). The most recent and complete of them is the ENEL catalogue which contains 20,568 events occurred in Italy between the years 1000 and 1975.

Considering reasonably long time intervals one may verify in all catalogues of earthquakes that the number $n(I, \Delta, t)$ of events with the same intensity recorded in the time interval Δ (centered in t) is generally increasing with t. Since smaller events have smaller probability to be recorded it is generally considered that the increase of $n(I, \Delta, t)$ with time is due to the incompleteness of the information although one may not rule out that the number of earthquakes $n(I, \Delta, t)$ which really occurred in a region may vary in time.

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The catalogue of Carrozzo et al. (1973) lists about 10.000 events from the year 0 until 1970 (however, only 94 of them occurred prior to the year 1000). The Baratta (1901) catalogue was compiled at the end of the 19th Century, although it is an important document, it is not as complete as the others, mostly for the smaller events; it does not give intensities nor coordinates of the events but important detailed description of the locations and the damages which occurred there. In the ENEL catalogue (1978) the epicentral coordinates of the events which were recorded instrumentally have been recomputed using the most updated models of the Italian territory, where this was not possible the epicenters were estimated from the isoseismals or assuming it where the largest damage was recorded or, in case of the smaller events, where the event was felt. In most cases we may assume the accuracy of the epicentral coordinates is less than 10 km.

A comparison of the two catalogues made by Caputo (1981) shows that the most frequent disagreement between the catalogues of ENEL (1978) and Carrozzo et al. (1973) concerns the intensity of historic earthquakes which had to be inferred from the description of the events in very old books or cronicles; the disagreements between the intensities of the events of the areas considered in this study is limited to at most one degree of intensity; in all Italian earthquakes with $I \geqslant$ IX, for 38 events I is larger in the Carrozzo et al. (1973) catalogue, for 5 events I is larger in the ENEL catalogues. The ENEL catalogue is not only the most complete but apparently it is also more accurate in the epicentral coordinates and intensity of the events. For this study we therefore used the ENEL catalogue.

Assuming that the statistical density distribution of the number of earthquakes does not change with time in 1000 years and provided reasonably long time intervals for the statistics are considered, we obtain for the completeness of the ENEL catalogue the time windows listed in Table I; as in most catalogues of earthquakes, the completeness is increasing with time. Table I was obtained by considering time windows at 10 and 25 years which gave the same results. The distribution of events in time windows of 25 years is shown in Table II.

The time T_I, after which the catalogue was tentatively considered complete for the intensity I, was estimated assuming that the average number of events $n(I, \Delta, t)$ in

TABLE I

Completeness of the ENEL (1978) Catalogue of Italian Earthquakes

Intensity, I	Completeness of the catalogue
$\geqslant$ VI	1885–1975
$\geqslant$ VII	1775–1975
$\geqslant$ VIII	1700–1975
$\geqslant$ IX	1600–1975
$\geqslant$ X	1550–1975
$\geqslant$ XI	1000–1975

TABLE II

Number of earthquakes of the ENEL Catalogue of Italian earthquakes in different time windows

Years	Intensity: VI	VII	VIII	IX	X	XI
1000–1024	2	2	1	0	0	0
1025–1049	0	0	0	0	0	0
1050–1074	0	1	1	0	0	0
1075–1099	0	3	0	1	0	0
1100–1124	1	2	4	0	1	0
1125–1149	1	5	1	0	1	0
1150–1174	1	4	2	0	0	1
1175–1199	0	3	1	1	2	0
1200–1224	0	4	0	1	1	0
1225–1249	5	8	2	0	0	0
1250–1274	1	1	3	2	0	0
1275–1299	2	11	14	3	2	0
1300–1324	6	13	8	0	0	0
1325–1349	2	4	3	1	2	1
1350–1374	3	10	6	1	0	0
1375–1399	10	12	4	0	0	0
1400–1424	6	9	4	3	0	0
1425–1449	8	8	2	2	0	0
1450–1474	11	18	7	4	1	1
1475–1499	7	15	6	1	0	0
1500–1524	10	15	5	4	1	0
1525–1549	8	15	7	2	1	0
1550–1574	5	18	5	6	1	0
1575–1599	8	12	6	1	0	0
1600–1624	12	15	9	3	1	0
1625–1649	12	19	7	7	1	0
1650–1674	7	8	5	5	2	0
1675–1699	34	17	7	5	3	0
1700–1724	26	32	16	4	3	0
1725–1749	36	50	16	6	1	0
1750–1474	54	30	7	8	0	0
1775–1799	55	94	20	13	1	2
1800–1824	31	49	14	2	3	0
1825–1849	82	70	16	7	3	0
1850–1874	99	73	16	5	4	0
1875–1899	192	109	26	4	0	0
1900–1924	369	129	27	5	3	3
1925–1949	168	60	15	5	1	0
1950–1974	234	72	28	4	0	0

contiguous successive time windows Δ_I are distributed according to a Gaussian distribution with mean value $\langle n_{\Delta I} \rangle$ and standard deviation $\sigma_{\Delta I}$; $\langle n_{\Delta I} \rangle$ and $\sigma_{\Delta I}$ are estimated in time windows (obviously much larger than Δ_I) in which the Italian seismic network and/or the macroseismic service were such to secure the completeness of the catalogue. For instance, one may assume that from the beginning of the century the seismic network and macroseismic service would detect all events of intensity VII or larger, or that all events with intensity XI and XII were reported in the cronicles from year 1000.

Given a Δ_I which secure $n(I, \Delta, t) \geqslant 10$ (note that for all Δ_I considered and $I <$ IX there is one exception, namely for $I =$ VIII and $\Delta_{\mathrm{VIII}} = 1774{-}1750$) one compares $|\langle n_{\Delta I}\rangle - n(I, \Delta, t)|$ with $\sigma_{\Delta I}$; the catalogue is then considered complete after the year T_I if $|\langle n_{\Delta I}|\rangle - n(I, \Delta, t)| < \sigma_{\Delta I}$ for $t \geqslant T_I$. It has always been verified that for time windows prior to T_I one finds $|\langle n_{\Delta I}\rangle - n(I, \Delta, t)| > \sigma_{\Delta I}$. For $I =$ VI we used $\Delta_I = 10$ years, for VI $< I <$ IX we used $\Delta_I = 25$ years; for $I =$ IX we used $\Delta_I = 50$ years; in this case $n(I, \Delta, t) \geqslant 9$.

It has also been verified that for $I =$ VII the windowings with $\Delta_I = 10$ years and $\Delta_I = 25$ give the same results, taking into account the lower resolution of $\Delta_I = 25$; and also that for $I =$ VIII, the windowing with $\Delta_I = 25$ and $\Delta_I = 50$ give the same results. Moreover the initial time of the windowing with $\Delta_I = 10$ has been shifted by 2 years, that with $\Delta_I = 25$ has been shifted by 5 years, and that with $\Delta_I = 50$ has been shifted by 25 years verifying that one obtains for T_I the same results.

The $I =$ X deserves special attention because the number of events per century in the last five centuries in general is less than 10, for instance the number of events in the interval 1875–1975 is 4; considering the historic conditions of Italy prior to 1500 and that between 1400 and 1500 only one event was recorded, after applying the above mentioned criterion we tentatively assumed $T_x = 1500$ verifying that $\sigma_{\Delta x} > |\langle n_{\Delta x}\rangle - n(x, \Delta, t)|$ for $t < T_x$. However, we cannot rule out that the large fluctuation prior to 1500 be real.

Another test of completeness has been done by comparing the a_1 and b_1 values of the law:

$$\log n = a_1 - b_1 I$$

for time windows beginning at different times in the past. The results of this test are in agreement with those of the previous tests.

In this study we consider two areas: the circle of 140 km radius centered in the Messina Strait (area B) (see Fig. 1) and the portion of the Southern Apennines between latitudes 39°N, 41.8°N (area A) (see Fig. 2). Both areas have been very seismic in the past. For the area A, the ENEL (1978) catalogue lists 38 earthquakes with intensity IX or more occurring after 1448. For the area B, the ENEL (1978) catalogue lists 16 events with intensity X or more occurred after the year 1100. It is worth noting that both areas include a large or complete portion of the D (dangerous) areas defined in southern Italy by a pattern recognition study of earthquake-prone areas of Italy (Caputo et al., 1980). Area A includes the epicenter of the November 23rd 1980 earthquake ($M_s = 6.9$) which coincides with intersection 77 of Fig. 2.

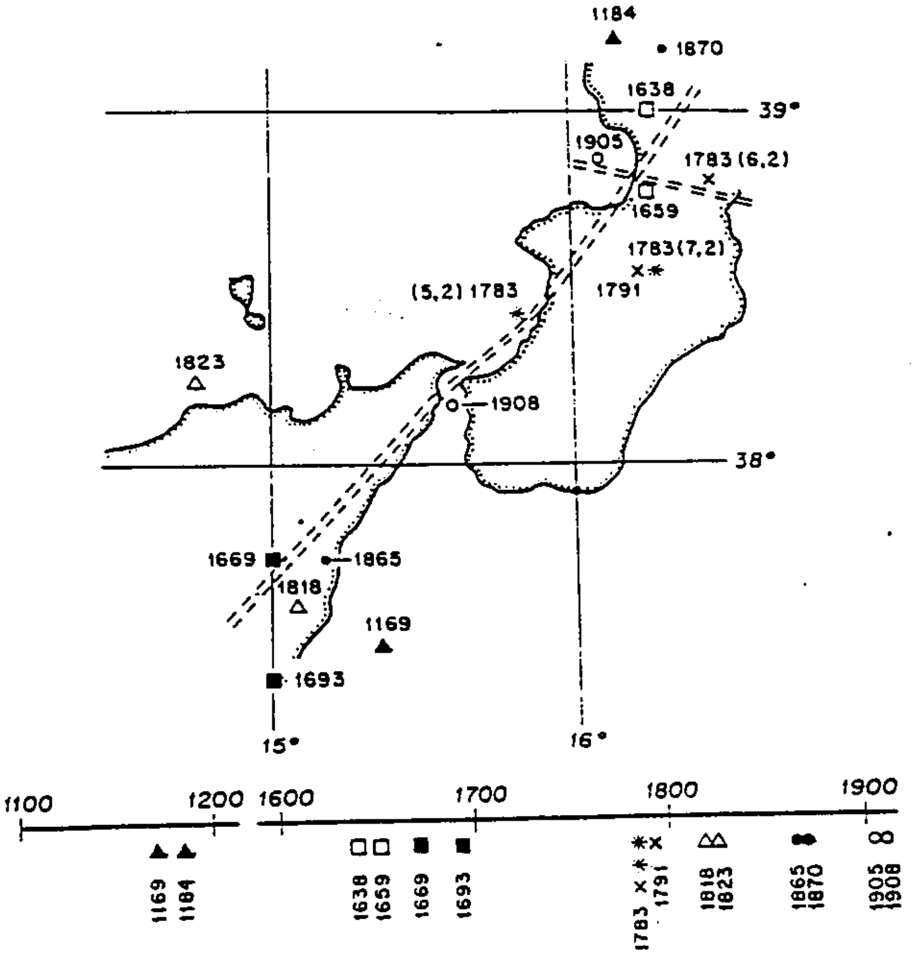

Fig. 1. Earthquakes of intensity $I \geq X$ within a radius of 140 km from Messina. As can be seen in the time scale, the earthquakes seem to occur in pairs in the time domain. The time elapsed since the last pair suggests that another pair is due soon. The two events of each pair are separated by the geologic lineaments marked by the double dashed lines. The epicenters of the three events in 1783 are marked also with the day and the month.

The number of events recorded in the last decades in both areas suggests that there has been continuity of the seismic activity for the small and moderate size earthquake: we shall assume here that this seismicity will continue in the future with the same statistical distribution over a reasonably long time window and also for the large earthquakes. With this assumption, a systematic analysis was made of the ENEL (1978) catalogue to search for periodicities and for gaps in the occurrence of large earthquakes in the areas A and B.

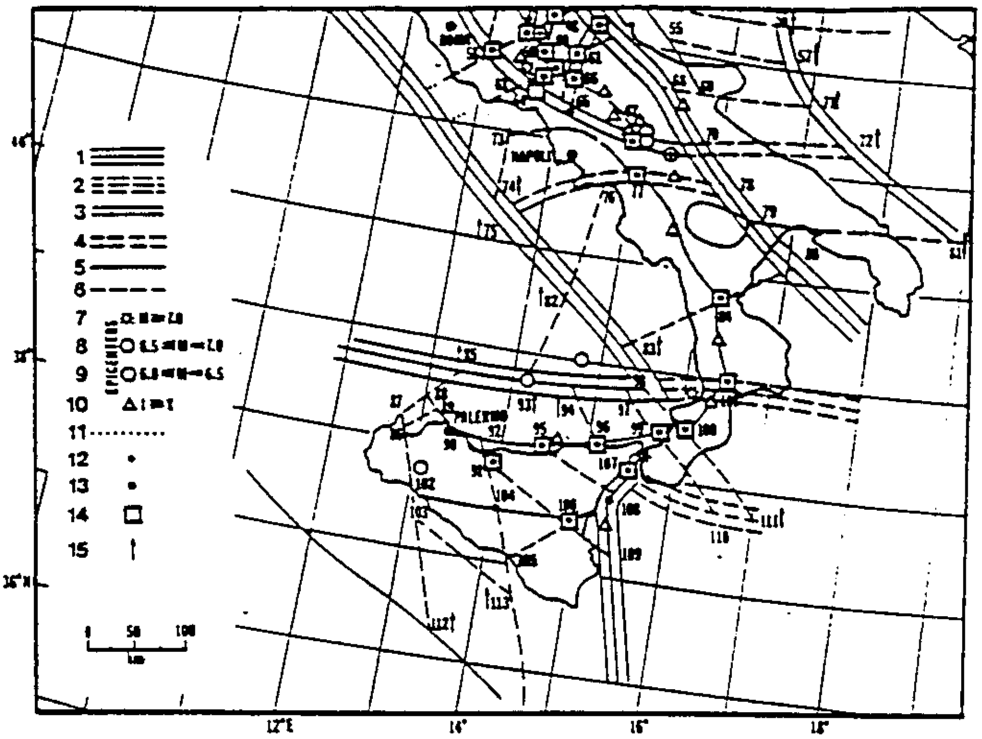

Fig. 2. Map of the major lineaments of the Italian region, and of the intersections of the lineaments considered as potentially dangerous. Numbers in the key refer to the following classification of lineaments, epicenters, boundaries and intersections. Lineaments: *1*, *2* = first order; *3*, *4* = second order; *5*, *6* = third order; *1*, *3* and *5* longitudinal, *2*, *4* and *6* are not expressed in topography. *7*, *8*, *9*, *10* = epicenters, *11* = uncertain lineaments (covered by sediments or sea). Intersections: *12* = recognized as D in the basic variant; *13* = recognized as uncertain in the basic variant; *14* = recognized as D in the earthquake future experiment; *15* = not used because the intersections are on the outer boundaries of the regions.

THE MESSINA STRAIT AREA

The 16 earthquakes shown in Fig. 2 have intensity X or more in one of the catalogues of Carrozzo et al. (1973) and ENEL (1978). The probability that 16 events distributed over 980 years are agregated in 8 pairs, and that the two events of each pair are separated by at most 25 years, is less than $7 \cdot 10^{-5}$.

Let E_i be the earthquake that occurred at time t_i ($t_{i+1} > t_i$; $i = 1,16$). We shall consider a pair of two earthquakes E_{2j}, E_{2j-1} ($j = 1,8$); the time ($t_{2j} - t_{2j-1}$) separating the two elements of each pair (see Fig. 1) is less than 23 years, $\langle t_{2j} - t_{2j-1} \rangle = 10$ years. The time separating two successive pairs, $t_{2j+1} - t_{2j}$, has an average value of about 100 years.

We call $t_{2j+1} - t_{2j}$ the alarm period for the event E_{2j+1} after the event E_{2j} has occurred, and see that the total alarm time is 81 years or 10% of the total time for 8 pairs. Also from the year 1791 three pairs occurred at regular time intervals of about 40 years: since 73 years have already elapsed since the last pair, another pair of the earthquakes of intensity X or more may be expected in that area in the near future. But if we consider the preceding period, we may see that larger gaps have occurred prior to 1783 and the present gap is significant only if the seismic regime after 1783 will be continued. One may also note in Fig. 2 that the two events of each pair are separated by the double lines which are first order (long one) and second order (the short one) lineaments of the pattern recognition study of the earthquake-prone areas of Italy (Caputo et al., 1980; Benvenuti and Caputo, 1982); this gives an indication on where the second of the two events may occur.

The earthquakes of 1905 and 1908 have been preceded by swarms in Sicily in the years 1905 and 1906 in agreement with the theory of Caputo et al. (1977); the fact that no precursors have been found for the pairs of earthquakes occurring prior to 1905 is not surprising and is probably due to the incompleteness of the catalogue.

We may therefore infer that a future couple of events in that area may be preceded by a swarm (Caputo et al., 1977). Also, since the events expected should have intensity $I \geqslant X$, which correspond to magnitudes 6.5 or more, the future event may occur in one of the points anticipated by the pattern recognition study.

THE SOUTHERN APENNINES AREA

The recent November 23, 1980 earthquake in Irpinia occurred in a location which was found previously to be seismically prone for events with $M \geqslant 6.5$ in the pattern recognition studies of Caputo et al. (1980) and Benvenuti and Caputo (1982), and was preceded by a swarm precursor (Caputo et al., 1983). For a detailed discussion of the precursors of this event see Del Pezzo et al. (1983); however, no reddening of the spectral lines of the earthquake parameters (Caputo, 1983) could be detected for lack of pertinent data. A detailed analysis of the catalogues of earthquakes of the portion of the Apennines between latitudes 39°N and 42°N from the year 1448 to the present indicates that the 38 events with intensity larger or equal to IX which occurred since 1448 in that area tend to cluster for this region. The occurrence of these earthquakes is listed in Table III. These events are those with intensities $I \geqslant IX$ of ENEL (1978) catalogue; many of them are listed with intensity $I > IX$ in one of the two catalogues considered in this study.

We shall call sequence a subset (of 2 or more events) of this set of 38 events when the events of the subset occur in a time interval of 13 years or less. The 38 events can be divided in sequences in many ways, we chose that indicated in Table III. There are 13 sequences of events, the average number of events in each sequence is about 3, the average time between first and last events of each sequence is about 7 years and ranges from a few months to 13 years. Two consecutive sequences are separated by

TABLE III

Sequences of large earthquakes in the Southern Apennines (between the latitudes 39°N and 41° 50'N)

Time window	Events (intensity, year)	Number of events	Time to second event of sequence (years)	Length of time window of each sequence (years)	Gap between successive sequences (years)
1448–1456	IX, 1448; XI, 1456; IX, 1456	3	8	8	94
1550–1561	IX, 1550; IX, 1560; IX, 1561; X, 1561	4	10	11	66
1627–1627	IX, 1627; X$\frac{1}{2}$, 1627;	2	0	0	11
1638–1638	X, 1638; IX, 1638	2	0	0	8
1646–1654	IX, 1646; X, 1654; IX, 1654	3	8	8	34
1688–1702	X, 1688; X, 1694; IX, 1702	3	6	14	29
1731–1732	X, 1731; IX, 1732	2	1	1	23
1755–1767	IX, 1755; IX, 1767	2	12	12	29
1796–1805	IX, 1796; X$\frac{1}{2}$, 1805	2	9	9	21
1826–1836	IX, 1826; IX, 1828; X, 1832 IX, 1835; IX, 1836; IX, 1836	6	2	10	15
1851–1858	IX, 1851; IX, 1854; IX, 1857; X, 1857; X, 1858	5	3	7	12
1870–1883	X, 1870; IX, 1883	2	13	13	27
1910–1913	IX$\frac{1}{2}$, 1910; IX, 1913	2	3	3	67
1980–?	X, 1980	?	?	?	
Average		3	5.7	7.4	33

33 years in average. The total alarm time between the first and the second event of each sequence is 75 years or about 16% of the total time for 13 pairs from the first event of the first pair.

In all of these sequences of events except those after the years 1550, 1646, 1796, 1851, the first event of the sequence has the largest intensity.

The statistical distribution of earthquakes was studied since the beginning of seismology; some early studies (AKi, 1956; Knopoff, 1964) concluded that the main sequence events were non-Poissonian. However, it has been noted (Gardner and Knopoff, 1974) that the California earthquakes with $M \geqslant 3.8$ between 1952 and 1971, after properly removing the aftershocks have a Poissonian distribution, that the same property is valid also for $M \geqslant 4.3$, $M \geqslant 4.8$, $M \geqslant 5.3$, but for $M \geqslant 5.8$ the number of events is not sufficient to draw any conclusion. Also the number of events considered in Table III is insufficient to draw any conclusions as to their statistical distribution law; however, assuming tentatively that their distribution is Poissonian, we find that the probability that 38 events distributed over 532 years are aggregated in 13 sequences, such that in each sequence there are at least two events and the time difference between the first and last event of each sequence is less then 3 years, is less than 10^{-10}.

From these considerations it is inferred that the intensity X earthquake which occurred in Irpinia on November 23, 1980, may be followed by other earthquakes in that region. It is of great interest to know when will occur the second event of sequence which began with the earthquake of November 23rd 1980. Assuming again that the distribution is Poissonian the probability that 26 events distributed over 532 years are aggregated in pairs, such that time separation of the two events if each pair is less than 10 years, is less than 10^{-5}. The observed cumulative distribution of the time difference between the first and the second event of each sequence is presented in Fig. 3, where one may verify that in 84% of the cases the second event occurs within 10 years after the first. From Table III one may see that in 52% of the cases the sequence of events is formed by two events only.

The density distribution of the inter-arrival time in each sequence is non-Poissonian, this suggests that it may be possible to foresee the arrival time of the events which suppositevely arrives after the first of the sequence.

The density distribution of the inter-arrival times of the first and the second event of each sequence is very close to that of the length of each sequence, this seems to imply that in each sequence the events cluster near the last event; in fact the average successive inter-arrival time in each sequence is decreasing as shown in Table IV.

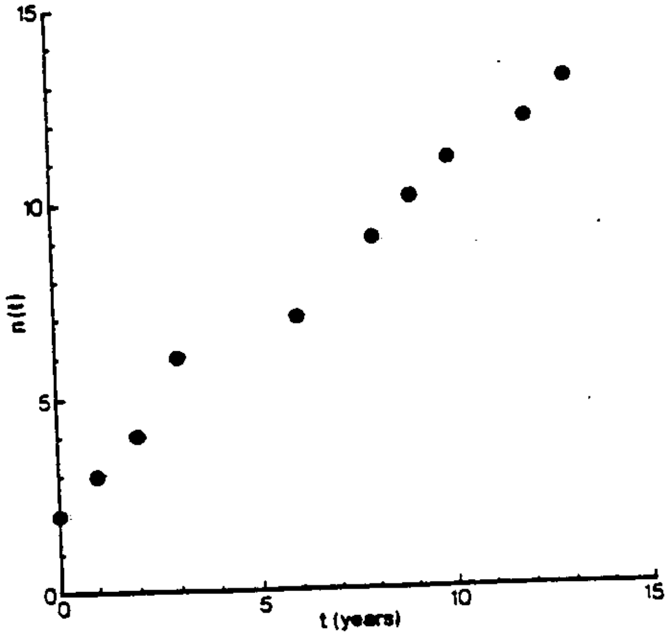

Fig. 3. $n(t)$ is the number of cases in which the second event of each sequence of Table III occurred within the time t measured from the first event of the sequence.

TABLE IV

Average successive inter-arrival time in each sequence of Table III

	1st–2nd	2nd–3rd	3rd–4th	4th–5th	5th–6th
Inter-arrival time in years	5.9	2.8	1.2	0.63	0.57
Number of cases	13	6	3	2	1

The pattern recognition study of the earthquake prone areas in Italy does not necessarily forecast the location of the expected earthquakes in area B because the intensity of these events is anticipated to be IX or more which in turn could imply a magnitude less than 6.5 which escapes the possibilities of the pattern recognition study aiming to magnitudes $M \geqslant 6.5$. The same reasoning applies to the swarm precursors which generally aim at magnitudes $M \geqslant 6.5$. However, other precursors such as variation of radon content in subterranean waters of tilts or deformations of the ground, may indicate the time and location of the future epicenters; the presence of these signals prior to some earthquakes has been already proven possible in the Apennines (Alessio et al., 1980).

CONCLUSIONS

According to this study the two areas considered may experience a large earthquake in the near future.

Concerning the area around the Strait of Messina the earthquake may occur in one of the points of that area indicated as D in the pattern recognition study of the Italian region made by Caputo et al. (1980) shown in Fig. 2.

If we focus our analysis to the period after 1783 we see that the groups of earthquakes are regularly separated by about 40 years and the present gap of 73 years is very significant. But if we consider also the preceding period, we see that larger gaps have occurred and the present gap would be significant only if the seismic regime after 1783 will be continued. Also we must consider that we cannot firmly exclude that some large earthquakes which occurred prior to the year 1500, are not listed in the catalogue.

In the Southern Apennines the earthquake expected may not occur in one of the points indicated as D in the pattern recognition study of Caputo et al. (1980) because this aims to earthquakes with magnitudes $M \geqslant 6.5$ while the earthquake expected here may have a smaller magnitude.

The catalogue used in this study (ENEL, 1978) should be complete for intensities $I \geqslant$ IX only after the year 1550. Therefore the incompleteness could affect only the first sequence of Table III. The gap of 67 years recorded before the last event is then very significant. If the past experience is repeated, the earthquakes which will probably occur after that of November 1980 may occur in a time window of 13 years or shorter. There is a 46% probability that the next event will occur within 3 years.

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The forecast of the magnitude 5.8, May 7th 1984, earthquake in Central Italy

Michele Caputo*

Resumen

El 23 de noviembre de 1980 un terremoto de magnitud M=6.5 ocurrió en la parte sur de los Apeninos a la latitud 40°55' y longitud 15°22'. Siguiendo la tradición del análisis estadístico del catálogo italiano de terremotos que condujo en el pasado al desarrollo de algunos métodos de predicción a largo plazo de grandes terremotos (Caputo et al., 1977; Caputo et al., 1983), aquel catálogo fue examinado a efectos de investigar modelos de sismicidad con los cuales fuera posible estimar la probabilidad, a su vez, de una fuerte réplica. El análisis del catálogo de terremotos italiano con intensidades mayores de VIII desde el año 1448 reveló que, entre las latitudes 39°N y 41°57'N (excluyendo Apulia), los sismos ocurrieron en 15 secuencias, cada una compuesta promedialmente de tres eventos dentro de un período de siete años. A su vez, dentro de cada secuencia, el tiempo promedio entre el primer y segundo evento, es de cinco años.

Este modelo de secuencias de grandes terremotos condujo a una tentativa de predicción de nuevos terremotos con una magnitud moderada, a seguir unos pocos años después al evento del 20 de noviembre de 1980 (Caputo, 1983). Estos terremotos realmente ocurrieron en mayo 7 y en mayo 11 de 1984 con magnitudes 5.8 y 5.2, respectivamente.

Los últimos sismos mencionados indicaron que la predicción era correcta y que, por lo tanto, era apropiado estudiar con mayor detalle el conjunto de secuencias de terremotos, así como las secuencias de todos los eventos y la distribución de eventos dentro de aquellas secuencias, a efectos de encontrar posibles leyes físicas que pudieran regular el comportamiento de los terremotos dentro de las secuencias y la agregación de los mismos para formar aquellas. Un análisis más refinado reveló que la distribución de los tiempos entre las secuencias era exponencial, lo que implica que no es posible prever

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a partir del análisis numérico la ocurrencia del primer evento de cada secuencia. Por lo tanto, fue dejado para estudios posteriores la viabilidad de una predicción de una segunda o una tercera fuerte réplica después que el primer evento tuvo lugar. El análisis estadístico indicaba que los tiempos entre todos los eventos, o entre los eventos de una secuencia aislada tienen una distribución no exponencial. Esto implica que después del primer sismo de una secuencia (como es el caso del terremoto de 1980 mencionado), se puede prever la ocurrencia de otro sismo moderado o grande, en el término de pocos años.

Asimismo fue encontrado que en el 50% de los casos el segundo evento en las secuencias ocurre dentro de los cuatro años contados desde el primero; en el 50% de los casos el tercer evento tuvo lugar dentro del año y medio después del segundo. Las secuencias con más de dos eventos son el 47% y las secuencias con más de tres eventos son solamente el 20% del total, lo que indica que la probabilidad de un cuarto evento después de aquel de noviembre de 1980 es bastante baja. Por otra parte, los datos existentes no permiten preveer la ocurrencia de un tercer evento de la secuencia señalada, con aceptable confianza.

Parece que las secuencias ocurren de acuerdo a una distribución de Poisson, mientras que el conjunto de eventos dentro de las secuencias pueden tener una distribución exponencial generalizada. Sin embargo, puede ser más probable que estos eventos ocurran de acuerdo a una ley exponencial del tiempo. Esta distribución sugiere que cada shock altera la distribución de tensiones, liberándola en el volumen epicentral y concentrándola en otro lado hasta que un número de asperezas sujetas a una tensión cercana a su punto de ruptura, son fracturadas. Parece, por lo tanto, que estas asperezas están generalmente presentes pero en un número limitado.

El conjunto de todos los eventos no tiene una significativa probabilidad de seguir una distribución de Poisson o una distribución exponencial. La ley de distribución exponencial de los eventos dentro de las secuencias queda enmascarada por la adición de la distribución incierta de las secuencias mismas.

La región sísmica considerada en este trabajo es de una extensión aproximadamente un tercio de la totalidad de la zona de los Apeninos. El catálogo de los terremotos de la porción norte de los Apeninos ha sido también estudiado, pero no hay evidencia de una posible concentración tal como ha sido determinada para las regiones sur y central.

Asimismo ha sido hallado (Caputo, 1983) que en un círculo de 140 Km. de radio alrededor de Mesina, que incluye la mayoría de los terremotos con intensidad X o mayores, están concentrados como muestra la Tabla 5. Aunque un par de sismos está separado por 24 años; la concentración parece remarcable, principalmente en los últimos 200 años; el máximo tiempo entre los eventos en las concentraciones en los últimos dos siglos es de ocho años y la separación entre estos grupos es de alrededor de 35 años. El número de eventos y grupos no es suficiente para permitir un análisis estadístico con aceptable confianza; sin embargo, esta aparente concentración merece aten-

ción porque han pasado 80 años desde la última concentración en el intervalo 1905-1908.

Abstract

Analysis of the catalogue of Italian earthquakes with intensities larger than VIII from the year 1448 reveals that, between the latitudes 39°N and 41°57'N (excluding Apulia), the earthquakes occurred in 15 sequences, each composed of an average of 3 events within an average time of 7 years. The average time between the 1st and 2nd events of each sequence is 5 years, which led to the tentative prediction of new earthquakes with moderately large magnitude to follow a few years after the event of November 20, 1980 (Caputo 1983). These earthquakes actually occurred on May 7th and May 11th, 1984 with magnitudes 5.8 and 5.2. A more refined analysis reveals that the distribution of the times between the 15 sequences is exponential; while the times between all the events, or between the events of one sequence have a non-exponential distribution. This implies that after the first earthquake of a sequence, as in the case of the 1980 earthquake, one may foresse the occurrence of other earthquakes after few years, while it would be difficult to foresse the occurrence of a future sequence of earthquakes.

The data do not allow us to foresse the occurrence of the third event of the sequence with acceptable confidence. These occur with about 46% probability. On average, they occur within 7 years from the first earthquake of their sequence and within 2 years from the second.

Introduction

The statistical distribution of earthquake parameters has been studied since the beginning of modern seismology. Work by Ishimoto and Iida (1939), who discovered that the log of the density distribution of the magnitude M is a linear function of M, which led to the definition of the now well-known b value.

Aki (1956) and Knopoff (1964) studied sequences of events in catalogues of earthquakes and concluded that they are not Poissonian; however Gardner and Knopoff (1974) found that California earthquakes with $M > 3.8$ between 1952 and 1971, after proper removal of aftershocks, have a Poissonian distribution. The same is true also for $M > 4.3$, $M > 4.8$, and $M > 5.3$; but for $M > 5.8$ the number of events is not sufficiently large to draw any reliable conclusion.

Caputo (1980a, 1982, 1981b) and Caputo and Console (1980) studied the statistical distribution of the scalar moments M_o as a function of the length of the fault l and of the stress drop p and found that their density distributions $n_o(M_o)$, $n_l(l)$, and $n_p(p)$ are powers of M_o, l and p respectively, as predicted theoretically (Caputo 1976, 1980), and that some of the exponents of power laws are related.

$$\log n_o(M_o) = e_o - b_o \log M_o, \; b_o = \frac{\nu+2}{3}$$

$$n^{(I)} \alpha_I I^{-\nu}, \; \nu = 3b + \frac{1}{c} \qquad (1)$$

$$n_p(P) \alpha p^{1+\alpha}, \; \alpha < 0$$

where b is obtained from the empirical law of Ishimoto and Iida (1939), $c \cong 1.5$ is the slope of the empirical log (moment)/magnitude relation (e.g. Hanks and Kanamori; 1979) and α as well as ν have been estimated by Caputo (1980a, 1980b, 1981c, 1981b, 1982, 1985) for several seismic regions or earthquakes sequences.

Other examples of statistical analysis pertinent to the present note are given by Caputo (1981a) who studied the Ente Nazionale Energia Elettrica (ENEL) catalogue of Italian earthquakes, and concluded that the catalogue seems complete in the time intervals given in Table 1. He also studied the seismicity of the Southern Appennines after the November 23, 1980 Irpinia earthquake in order to establish the possibility of occurrence of another earthquake in the same area in the near future. This led to the suggestion that other earthquakes of moderate magnitude should occur within several years. This was proved correct by the May 7th 1984 magnitude $M_s = 5.8$ earthquake and the May 11th 1984 magnitude $M_s = 5.2$ earthquake which occurred in the South-Central Appennines. The present paper examines the possibility of a fourth earthquake in the same area in the near future.

Table 1
Completeness of the ENEL (1978) Catalogue of Italian Earthquakes

Intensity, I	Completeness of catalogue
≥ VI	1885-1975
≥ VII	1775-1975
≥ VIII	1700-1975
≥ IX	1600-1975
≥ X	1550-1975
≥ XI	1000-1975

Completeness of the ENEL Catalogue of Italian earthquakes occurred from the year 1000 through 1975.

When was due a fourth event in the sequence which began in 1980?

The November 23, 1980 earthquake in Irpinia occurred in a location which was found in the pattern recognition studies of Caputo et al, (1980) and

Benvenuti and Caputo (1982), to be prone to events with M ≥ 6.5 (see Fig. 1). It was preceded by a swarm precursor (Caputo et al, 1983); for a detailed discussion of the precursors of this event see Del Pezzo et al, (1983).

A detailed analysis of the catalogues of earthquakes (ENEL 1978, Carrozzo et al, 1973) of the portion of the Appennines between latitudes 39°N and 42°N, from the year 1448 through 1964 (Caputo 1983), indicates that the events with intensity larger than or equal to IX tend to cluster in time. These events are listed in Table 2.

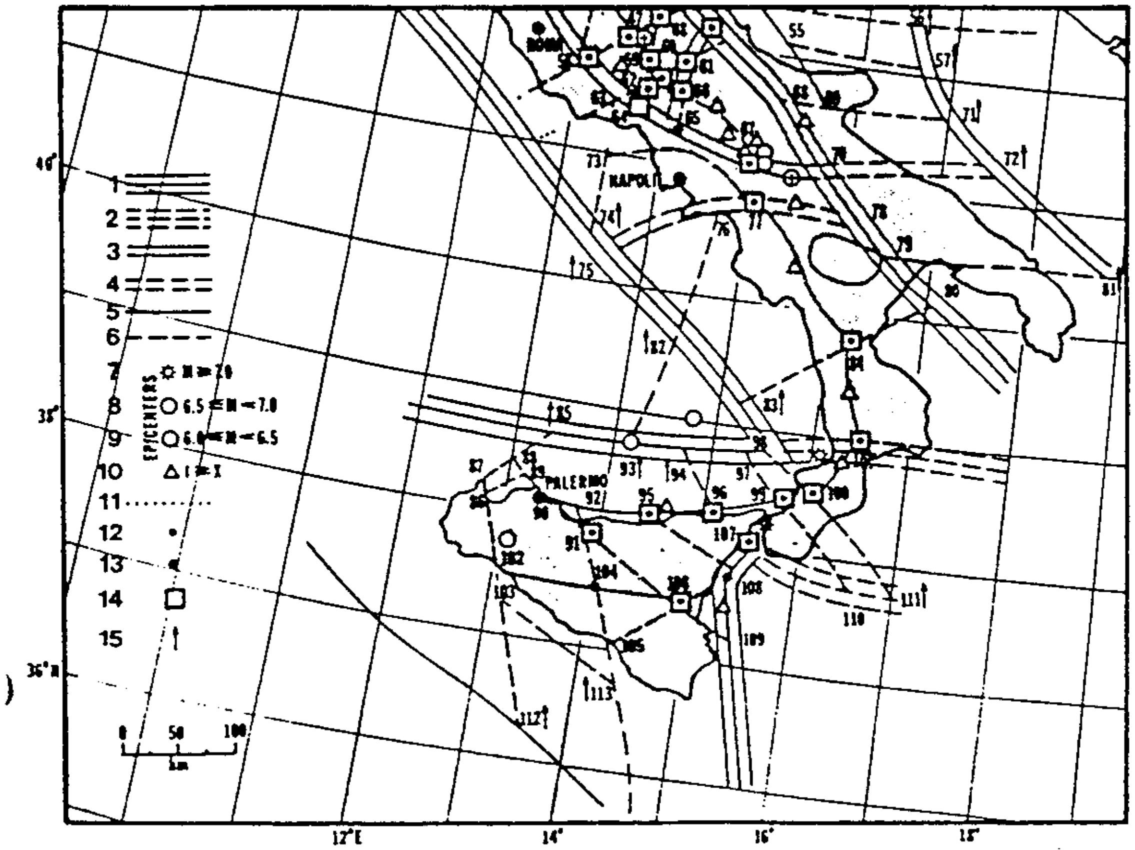

Figure 1. Map of the major lineaments of the Italian region, and of the intersections of the lineaments considered as potentially dangerous. Numbers in the key refer to the following classification of lineaments, epicenters, boundaries and intersections. Lineaments: 1,2 = first order; 3,4 = second order; 5,6 = third order; 1, 3 and 5 longitudinal, 2, 4 and 6 are not expressed in topography. 7, 8, 9 and 10 = epicenters, 11 = uncertain lineaments (covered by sediments or sea). Intersections: 12 = recognized as D in the basic variant: 13 = recognized as uncertain in the basic variant; 14 = recognized as D in the earthquake future experiment; 15 = not used because the intersections are on the outer boundaries of the regions.

In Table 1, the three earthquakes which occurred in 1984 are listed without their intensities because we have not obtained an official report on them. Since the magnitudes of the two events which occurred in 1984 is larger than 5, as are the magnitudes of all the other events in Table 2, it seemed acceptable to include the two events of May 7th and 11th 1984 in Tables 2 and 3.

We shall call a subset (of 2 or more events) of the set of 43 events listed in Table 2 a "sequence" when the events of the subset occur in a time interval of 14 years or less. The first sequence begins in 1448. The events can be divided in sequences in many ways; we chose that indicated in Table 2. There are 15 sequences; the average number of events in each sequence is about 3; the average time between first and last events of each sequence is about 7 years, and ranges from a few minutes to 12 years. Two consecutive sequences are separated by an average of 31 years. The total of the times between the

Table 2

YEAR	MON	DA	HO	MI	SE	LONG	LAT	INT	MAG	MAG
1448						40 45	14 15	9.0	5.6	5.0
1456	12	5	22			41 18	14 42	11.0	6.6	6.1
1456	12	30	8			41 15	14 45	9.0	5.6	5.3
1550	8	25				40 20	15 35	9.0	5.6	5.3
1560	5	11				41 20	16 30	9.0	5.6	5.4
1561	7	31	23			40 20	15 35	9.0	5.6	5.3
1561	8	19	19			40 20	15 35	10.0	6.1	5.7
1627	7	30	15	30		41 50	15 20	9.0	5.6	5.4
1627	8	9				41 50	15 20	9.5	5.8	5.4
1638	3	27	19	30		39 0	16 15	10.0	6.1	5.8
1638	6	9	4			39 0	17 15	9.0	5.6	5.4
1646	5	31	1	30		41 50	15 50	9.0	5.6	5.4
1654	7	23	24			41 45	13 30	10.0	6.1	5.7
1654	9	8				40 50	15 40	9.0	5.6	5.3
1688	6	5	13	15		41 12	14 54	10.0	6.1	5.7
1694	9	8	16	45		40 48	15 35	10.0	6.1	5.7
1702	3	14	4	23		40 57	14 50	9.0	5.6	5.3
1731	3	20	8	30		41 30	15 30	10.0	6.1	5.9
1732	11	29	12	30		41 10	15 4	9.0	5.6	5.8
1755	11	1	9			41 0	13 0	9.0	5.6	
1767	7	14				39 40	15 0	9.0	5.6	5.4
1796	3	18	16	30		40 45	13 50	9.0	5.6	5.0
1805	7	26	21	1	40	41 31	14 34	10.5	6.3	5.9
1826	2	1	4			40 35	15 40	9.0	5.6	5.3
1828	2	2	9	15		40 54	13 45	9.0	5.6	5.0
1832	3	8	18	15		39 0	17 0	10.0	5.6	5.4

Table 2
(continued)

YEAR	MON	DA	HO	MI	SE	LONG	LAT	INT	MAG	MAG
1835	10	12	12			39 25	16 15	9.0	5.6	5.4
1836	4	24	23	15		39 40	16 45	9.0	5.6	5.4
1836	11	20	7	30		40 0	15 45	9.0	5.6	5.3
1851	8	14	13	22	35	41 0	15 40	10.0	6.1	5.7
1854	2	12	17	30		39 20	16 10	9.0	5.6	5.4
1857	12	16	21	15		40 37	15 17	9.0	5.6	5.3
1857	12	16	21	18		40 17	15 55	10.0	6.1	5.7
1858	8	6	10	30		40 37	15 17	9.0	5.6	5.5
1870	10	4	16	55		39 17	16 17	10.0	6.1	5.8
1883	7	28	20	25		40 45	13 54	9.0	5.6	5.0
1910	6	7	2	4		40 54	15 27	9.5	5.8	5.3
1913	6	28	8	53	2	39 37	16 9	9.0	5.6	5.3
1962	8	21	18	10	30	41 8	15 7	9.0	5.6	5.8
1962	8	21	18	19	30	41 8	15 7	9.0	5.6	5.8
									M_L	M_s
1980	11	23	18	34	54	40 55	15 22		6.5	6.9
1984	5	7	17	49	42	41 46	13 54		6.0	5.8
1984	5	11	10	41	50	41 50	13 58		5.4	5.2

Coordinates, time of occurrence, intensities and magnitudes of the events considered in the region between latitudes of 30°N and 41°50'N in Italy (Apulia excluded). The intensities are those reported in the ENEL Catalogue. The magnitudes of the events until 1968 are those listed in the ENEL catalogue and estimated from the intensities according to empirical formulae of Karnik (1969). The events occurred after 1962 have M_L computed at Observatorio Geofisico of Trieste, while M_s is taken from Preliminary Determination of Epicenters Bulletin of U.S. Geological Survey lists.

first and the second event of all sequences is 75 years, or about 14% of the total time since 1448; these periods will be called "alarm times".

In Figure 2 one may see that there is no correlation between the number of events in the sequence and their duration. One may also see in Figure 3 that there is no correlation between the number of events in a sequence and the time to the preceeding or following sequence.

In 60% of the sequences (exceptions are those which began in the years 1638, 1688, 1731, 1870, 1910, 1980) the first event of the sequence is not that with the largest intensity. All sequences except those which began in 1755 and 1962 include an event with intensity larger than IX. The average time between the events with I ≥ IX½ and the preceeding event is 11 years; the average time to the following event is 10 years. Comparing these averages with the average interval time of all the events, 12.5 years, one may infer that there is no evidence for either the time- or slip-predictable models.

Table 3

Sequences of large earthquakes in the Southern Apennines (between the latitudes 39°N and 41°50'N)

Time window	Events (intensity, year)	Number of events	Time to second event of sequence (years)	Length of time window of each sequence (years)	Gap between successive sequences (years)
1448.496-1456.997	IX,1448.496; XI,1456.928; IX,1456.997	3	8.432	8.501	93.652
1550.649-1561.636	IX,1550.649; IX,1560.359; IX,1561.581; X,1561.636	4	9.710	10.987	65.942
1627.578-1627.606	IX,1627.578; X½,1627.606;	2	0.028	0.028	10.630
1638.236-1638.438	X,1638.236; IX,1638.438;	2	0.202	0.202	7.876
(1627.578-1638.438)	(IX,1627.578; X½,1627.606; X,1638.236; IX, 1638.438)	(4)	(0.028)	(10.860)	(7.977)
1646.414-1654.688	IX,1646.404; X,1654.562; IX,1654.688	3	8.148	8.284	33.739
1688.427-1702.200	X,1688.427; X,1694.688; IX,1702.200	3	6.261	13.573	29.016
1731.216-1732.912	X,1731.216; IX,1732.912;	2	1.696	1.696	22.924
1755.836-1767.534	IX,1755.836; IX,1767.534;	2	11.698	11.698	28.677

Table 3
(Continued)

Time window	Events (intensity, year)	Number of events	Time to second event of sequence (years)	Length of time window of each sequence (years)	Gap between successive sequences (years)
1796.211-1805.570	IX,1796.211; X½,1805.570	2	9.359	9.359	20.518
1826.088-1836.888	IX,1826.088; IX,1828.090 X,1832.186; IX,1835.781; IX,1836.315; IX,1836.888	6	2.002	10.800	14.731
1851.619-1858.597	IX,1851.619; IX,1854.021; IX,1857.962; X,1857.962; X,1858.597	5	2.511	6.978	12.165
1870.762-1883.575	X,1870.762; IX,1883.575	2	12.813	12.813	26.858
1910.433-1913.490	IX½,1910.443; IX,1913.480	2	3.057	3.057	49.148
1962.638-1962.638	IX,1962.638; IX,1962.638	2	0.000	0.000	18.258
1980.896-?	X,1980.896; 1984.351; 1984.359	3	3.455	?	?
Average		2.87 (3.07)	5.24 (5.63)	7.00 (8.35)	31.01 (32.59)

Sequences of earthquakes formed with the events of Table 2 and discussed in the paper. In brackets is also indicated the sequence substituting the two sequences beginning on 1627 and 1638 respectively; the discussion of this new set of sequences does not alter the conclusion of the paper, only the average interarrival times of Fig. 7 change slightly, those pertinent to this new set of sequences are indicated by a dashed line. Time is in years.

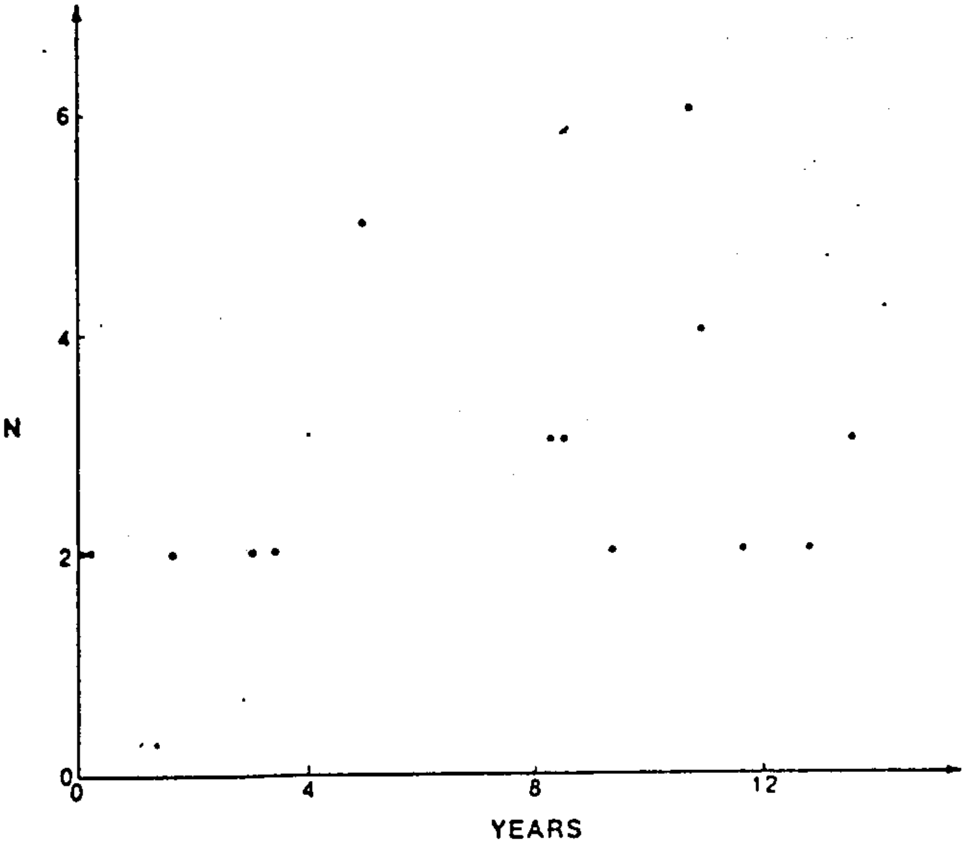

Figure 2. Number of events in each sequence as a function of the length of the sequence.

The earthquakes which occurred in May 7th 1984 and May 11th 1984 in that area proved that the tentative suggestion of Caputo (1983) "that another earthquake could possibly follow that of November 1980 in that area" was correct. Considering that the suggestion was based on the fact that the earthquakes in that area occur in sequences it seems reasonable to investigate whether this sequence will include more than three events, and when we might expect a fourth event to occur. We shall supplement here the analysis of Caputo (1983) with more studies trying to answer these questions.

For this purpose we studied the statistical distribution of three sets of interarrival times: of the sequences themselves (Set I), of the events within the sequences (Set II) and of all the events (Set III).

Since the density distribution of the seismic energy radiated W, is a power of W (Caputo 1976, 1980b), and assuming that the time t to accumulate the energy of large earthquake should be proportional to the elastic energy released and that this is proportional to W, we may tentatively propose that

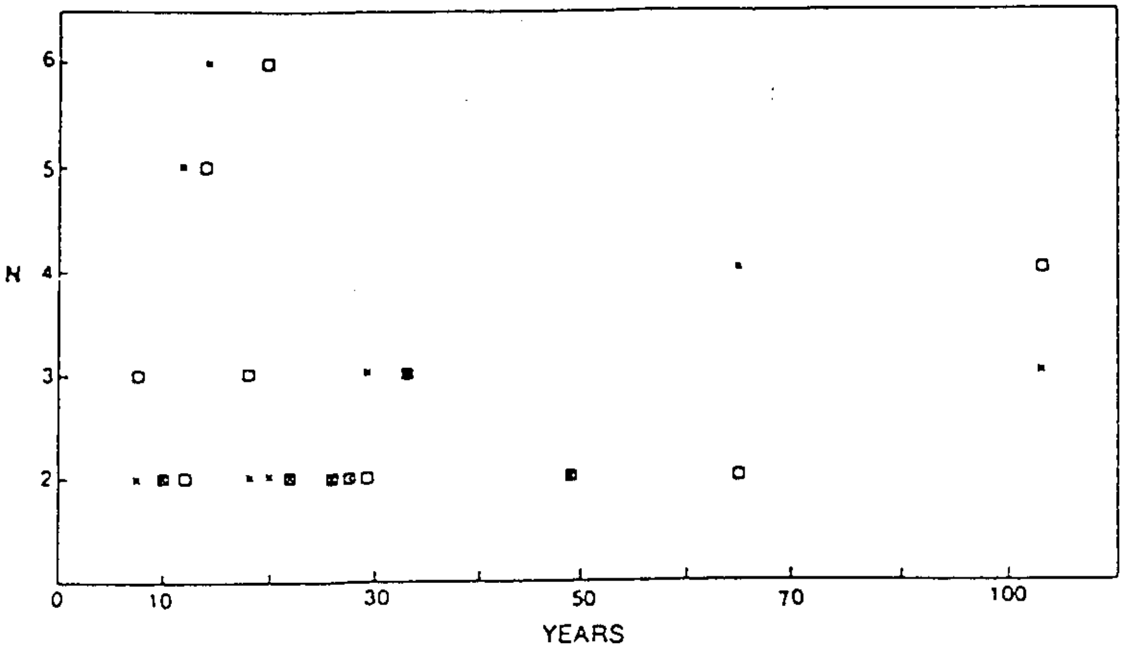

Figure 3. Number of events in each sequence as function of the interarrival time to previous sequence (squares) or to the following sequence (crosses).

the density distribution n of the interarrival times of the events should be a power law of the time. However, we know that the process of accumulation of the energy for the next earthquake, begins before last occurrs. To take into account both phenomena, we will tentatively add a constant c, to the time t, to represent an average time elapsed from the beginning of the accumulation of the stress until the new regime installed at the previous earthquake. Then

$$\ln(n) = a + b \ln(t + c) \tag{2}$$

which implies that after each large earthquake, time has a new role depending on the local geologic environment, (particularly the asperities), on the mechanism of the earthquake which triggered the new energy accumulation regime, as well as on the mechanism of the earthquake to be released.

The same could also be tentatively applied to the sequences of events, considering them as bursts of earthquakes preparing for a successive burst, although the mechanism involved would probably be different from that triggering the single earthquakes.

Before discussing the fit of the three sets of data to equation (2), in order to test the randomness of the data, we consider also the fit of the three sets to the function representing the Poisson distribution

$P_\alpha = \frac{\mu^\alpha}{\alpha!} e^{-\mu}$

$$n_{e1} = \mu^{-1}e^{\cancel{-\mu-\pi}} \qquad (3)$$

$= \mu^{-1} e^{-\mu^{-1} t}$

where μ is the average number of events in each set. To test the randomness of the data, we also considered the fit to the function representing a generalized Poisson distribution

$$n_{e2} = Ae^{-Bt} \qquad (4)$$

where $A > 0$, $B > 0$, $A \geq B$ for normalization. Obviously, the comparision of the σ^2 of the fits to the three functions is a measure of the nonrandomness of the data.

In Figures 4, 5, and 6 one may compare the fits of n, n_{e1}, and n_{e2} to sets II and III and the fits of n_{e1}, and n_{e2} to set I. It is not significant to make a fit of n to set I because it was possible to obtain only three points from the data available and the parameters to fit are three (a, b, c) which would give $\sigma^2 = 0$. Also the fit of set III to n_{e2} is not consistent because it gives $A < B$ and therefore is not listed in Table 4.

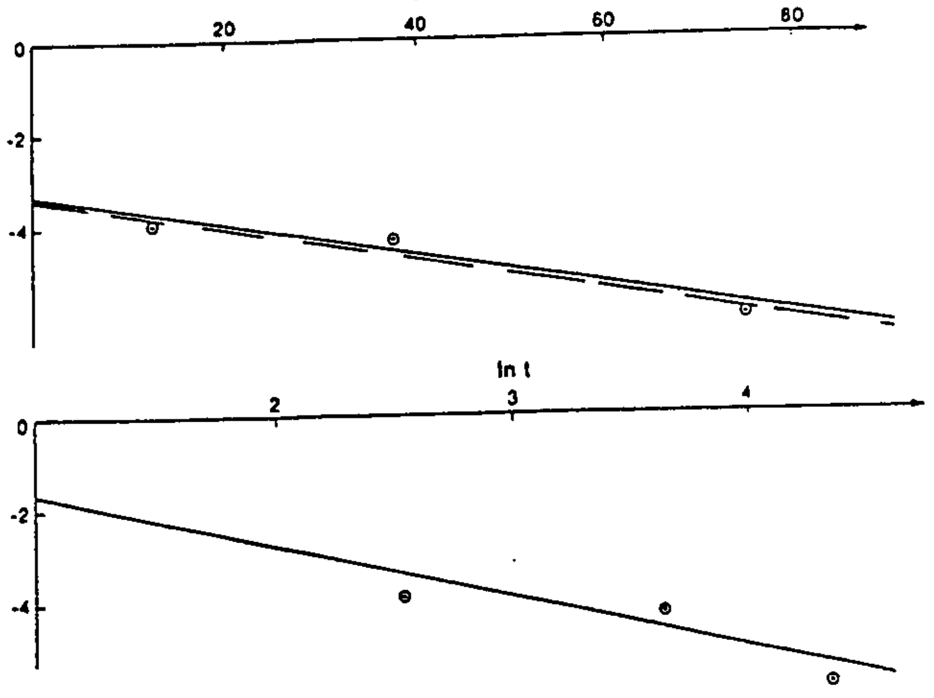

Figure 4. Best fit of (4) and (2) (continuous line top $\ln n_{e2} = -1.709 - 0.173t$ and bottom $\ln n = -0.739 - 1.13 \ln (t + 0.75)$, to the density distribution of the interarrival times of the events within the sequences. The dashed line is (3) with $\mu = 3.76$ average interarrival time of events within sequences.

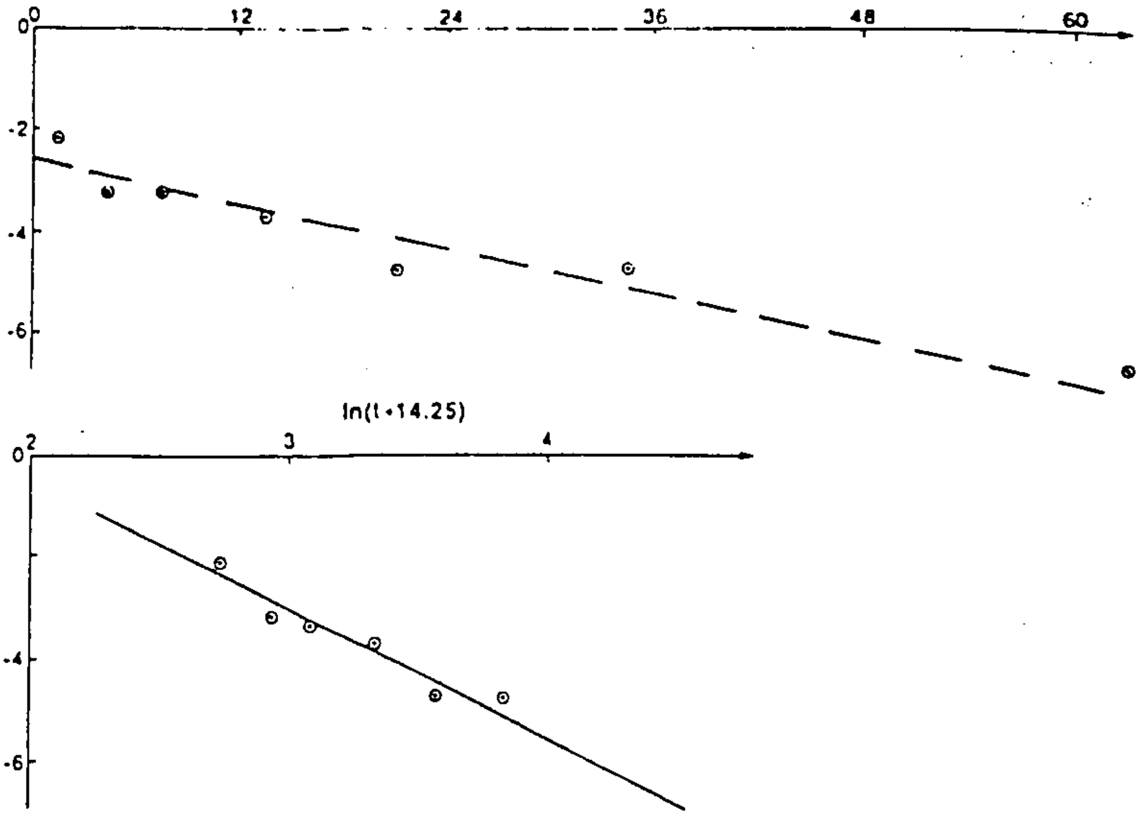

Figure 5. Best fit of (2) (continuous line bottom ln n = −4.65−2.58 ln (t + 14.25)) to the density distribution of the interarrival times of all events. The dashed line is (3) with μ = 13.1 interarrival time of events.

Since the average of the magnitudes estimated for each event considered differ from 5.9 by at most 0.6, we may tentatively consider that the earthquakes of the set have released energies of the same order of magnitude.

One may also check that there is no correlation between the intensity of each earthquake and the time from the previous one in sets I and II; te same applies to set III, considering the correlation between the energy released in each sequence and the time to the sequence preceeding it.

The results of the fit of the three sets of data to the three density distributions laws, shown in Table 4 and Fig. 4, 5, and 6 indicates that the law (2) always has the smallest σ^2 and is the closest to the data, which in turn seems to indicate that the process of release of the elastic energy in this region, through earthquakes of comparable order of magnitudes, is not random. The σ^2 of the fit of n_{e1} and n_{e2} to set I is relatively small and we could also infer that the interval times of the sequences have a nearly exponential distribution.

We should note however that if the earthquakes of the region were a random, stationary, uncorrelated process, the probability that clustering as the observed one arises by chance, is about 3%.

Certainly one may devise a multiparameter statistical law representing a random process which would fit the data better than n; however the random processes most used to represent earthquake catalogues are n_{e1}, and n_{e2} which we may tentatively rule out for sets II and III on the basis of the smaller σ^2.

The density distribution laws considered need discussion. The laws n_{e1} and n_{e2} are mere statistical laws representing random processes; n_{e1} is estimated using only the mean interval time and does not fit the data well, as one may see from σ^2. An improvement is obtained with n_{e2} because of one additional parameter (which would imply a normalization to a finite time (since $A > B$) as the data make reasonable to assume). A better fit is obtained with n,

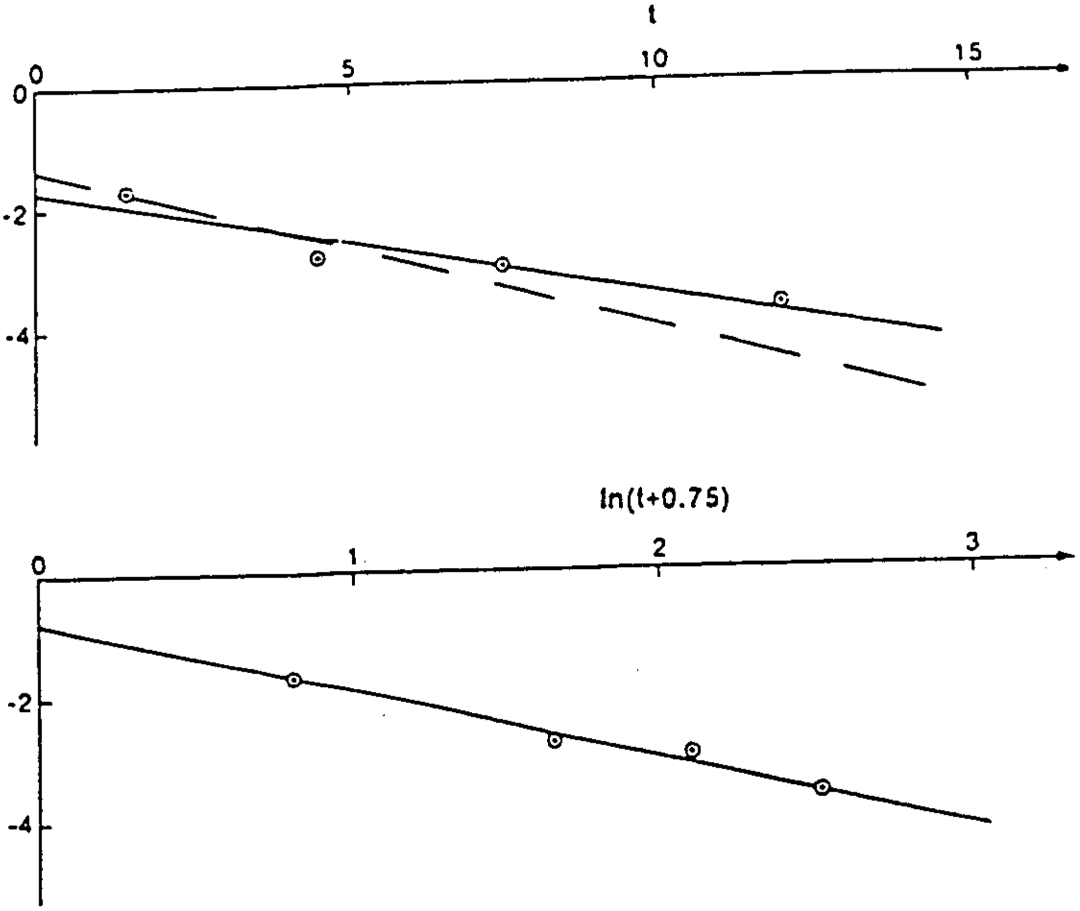

Figure 6. Best fit of (4) and (2) (continuous line top $\ln n_{e2} = -3.33-0.032t$, and bottom $\ln n = -0.21-1.48 \ln t$, t 10, c = 0) to the density distribution of the interarrival times of the sequences. The dashed line is (3) with $\mu = 31.0$ interarrival times of the sequences.

which represents a tentative physical model; however [illegible] three arbitrary parameters to fit the data and therefore [illegible] higher [illegible] of giving a smaller σ².

The catalogues of earth[illegible] (Gardner and Knopoff, 19[illegible] of seismic energy may be [illegible] from an experimental di[illegible] distribution may always b[illegible] necessarily all exponenti[illegible]

$\ln n(t_1) = \ln A + B\frac{1}{B}\ln\frac{A}{A-B} = 2\ln A - \ln(A-B) = \ln\frac{A^2}{A-B}$

$\ln n = a + b\ln(t+c)$

$\int_0^\infty n = \int_0^\infty e^a (t+c)^b dt = 1$; $e^a \frac{(t+c)^{b+1}}{b+1}\Big|_0^\infty$ se $b<-1$ ho $e^a\frac{c^{b+1}}{b+1} = 1$ cioè $\boxed{a + (b+1)\ln c - \ln(b+1) = 0}$ [illegible] se $b+1<0$

fino a $\left[e^a\frac{(t+c)^{b+1}}{b+1}\right]_0^{t_1} = \frac{e^a}{b+1}\left[(t_1+c)^{b+1} - c^{b+1}\right] = 1 \to e^a\left[(t_1+c)^{b+1} - c^{b+1}\right] = b+1$

Table 4

$t_1(A,B)$	SET	a	b	c	σ²	lnA	−B	σ²	μ	−lnμ	−μ⁻¹	σ²
71.5	I					−3.335	−0.032	0.042	31.02	−3.435	−0.032	0.047
42.3	II	−0.739	−1.132	0.75	0.010	−1.709	−0.173	0.035	3.76	−1.325	−0.265	0.211
	III	4.653	−2.585	14.25	0.069				13.07	−2.570	−0.077	0.285

Numerical values of the parameters of the density distributions n, n_{e1}, n_{e2} defined by (2), (3) and (4), obtained with least square method fit to the data sets I, II and III. σ² is the variance of the data with respect to the lines fitted.

$n(t)dt$ = probabilità [illegible] $n(t)$ ha dim. [illegible]

$A = B/(1-e^{-Bt_1})$

[illegible] $t_1 = t_{max}$

$\frac{B}{A} = 1 - e^{-Bt_1}$, $e^{-Bt_1} = 1 - \frac{B}{A}$

$t_1 = -\frac{1}{B}\ln\left(1-\frac{B}{A}\right)$

$= \frac{1}{B}\ln\frac{A}{A-B} = t_1 = \begin{cases}71.5 & \text{I}\\ 42.3 & \text{II}\end{cases}$

[illegible] media $A\,t\,e^{-Bt}$ [illegible]

$= A\{[illegible]\}$

$= \frac{1}{B}\left\{-t_1 e^{-Bt_1} + \frac{e^{-Bt}}{-B}[illegible]\right\}$

$= \frac{A}{B}\left\{-t_1 e^{-Bt_1} + \frac{1-e^{-Bt_1}}{B}\right\}$

$= \frac{A}{B^2}\left\{-(1+Bt_1)e^{-Bt_1} + 1\right\}$

se Bt_1 piccolo $\frac{A}{B^2}\left\{-(1+Bt_1)\left(1-Bt_1+\frac{B^2t_1^2}{2}\right)+1\right\} = \frac{A}{B^2}\frac{B^2t_1^2}{2} = A\frac{t_1^2}{2}$ indip. da B which represents a tentative physical model; however n contains three arbitrary parameters to fit the data and therefore has a higher probability of giving a smaller σ^2.

The catalogues of earthquakes whose interval times proved to be exponential (Gardner and Knopoff, 1974), cover a large area where the process of release of seismic energy may be severe. By selecting appropriates sets of events from an experimental distribution, one may "prove" that an exponential distribution may always be considered the sum of distribution which are not necessarily all exponentials. That could be the case of the catalogues of

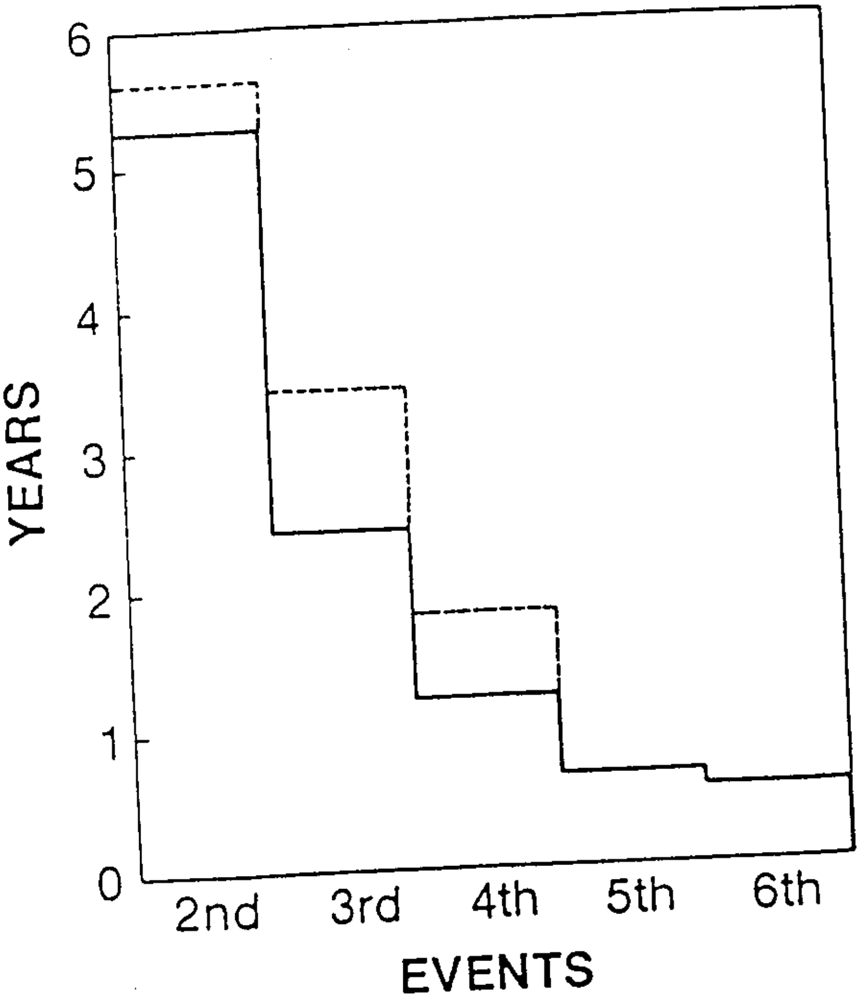

Figure 7. Average interarrival time between the nth and the (n + 1)th events of the sequences. The dashed lines give the values for the set of sequences of Table 5 in which the sequence indicated in brackets substitutes the two sequences beginning on 1627 and 1638.

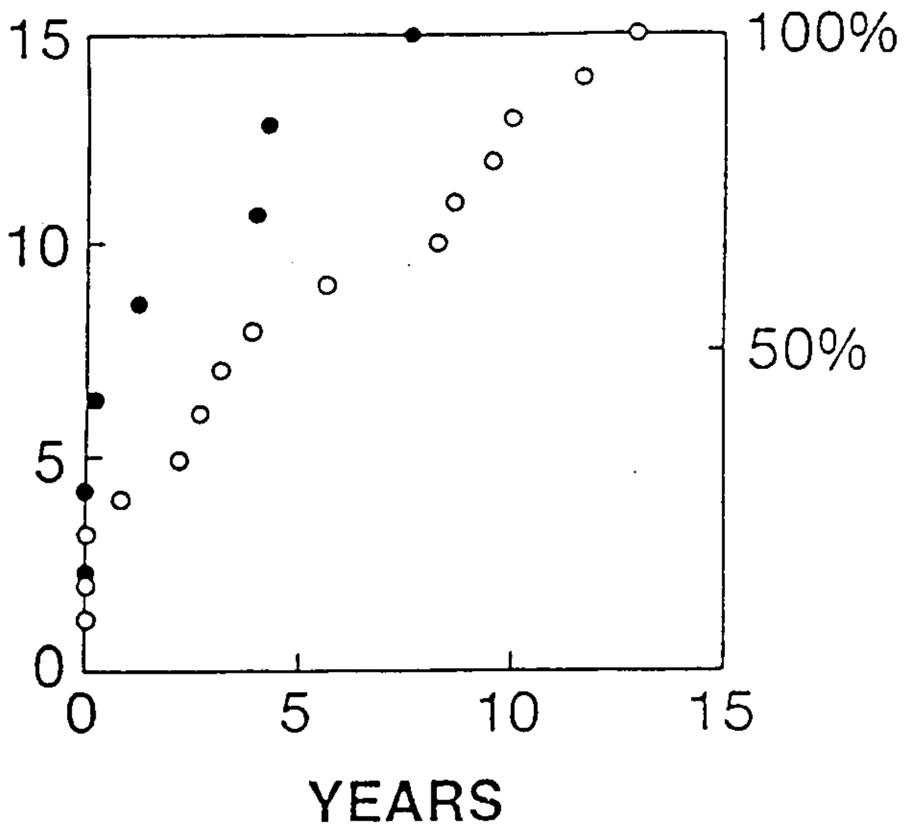

Figure 8. Cumulative distribution of the interarrival times between the first and the second event (open circles) and between the second and the third events (solid circles) in the sequences.

earthquakes of large regions: they may be the result of the sum of several different non-exponential processes.

Since in no case was it possible to prove that a regional catalogue of large events has an exponential distribution, it seems reasonable to consider that sets I and II have density distribution represented by n, rather n_{e1} or n_{e2}, on the basis of their σ^2.

We may thus suggest that it should be possible to predict the interval time between the successive events in the sequences.

Figure 7 shows the average interval time between the successive events of the sequence. It is clear that the events cluster towards the last one of each sequence.

Figure 8 shows the cumulative distribution of the interval times between the first and second events of each sequence and between the second and third events of each sequence, which reflects a property of Fig. 7. This may imply that each shock alters the distribution of stress, releasing it in the epicentral volume and concentrating it elsewhere, until a number of asperities with stress close to their fracture stress are ruptured. In 50% of the cases the second event occurs within four years from the first; in 50% of the cases the third event arrives within 1.5 years of the second.

In the paper of Caputo (1983) the two events in 1962 were omitted accidentally. Howeverm this does not change the results significantly.

Figure 9 shows the cumulative distribution of the time windows in which the sequence occur, and one may note that 50% of them have duration less than 8.5 years.

The sequences with more than two events are 47% of the total, and the sequences with more than three events are only 20%. It seems therefore that the probability of a fourth event in the sequence which began in 1980 is rather low; according to the data of Figure 7 we may say that a possible fourth event should have occurred within 1.2 years from the third, that is by June 1985. At present, the summer of 1987, the fourth event did not yet occur. This would indicate that the sequence of earthquakes which began in November 1980 actually ended in May 1984.

The seismic region considered in this paper is about one third of the Apennines; the catalogue of earthquakes of a northern portion of the Apennines has also been studied but no evidence has been found of a possible clustering such as that found in the south central portion. The study of the seismic region around the Messina Straits brought different results. It was found (Caputo, 1983) that in a circle of 140 km radius around Messina, which includes most earthquakes with intensity X or larger, are clustered as shown in Table 5. The clustering here seems to occur mostly in couples of events. Although one couple of events is separated by 24 years, the clustering seems remarkable, mostly in the last 200 years; the maximum time window of the events in the clusters of the last two centuries is 8 years. The number of events and clusters is not sufficient to allow a statistical analysis with acceptable confidence, however this apparent clustering deserves attention.

Table 5

	Number of events	Time window (years)
1169-1184	2	15
1638-1659	2	21
1669-1693	2	24
1783-1791	4	8
1818-1823	2	5
1865-1870	2	5
1905-1908	2	3

Earthquakes with intensity I > X in a circle with 140 km radius centered in the Messina Straits.

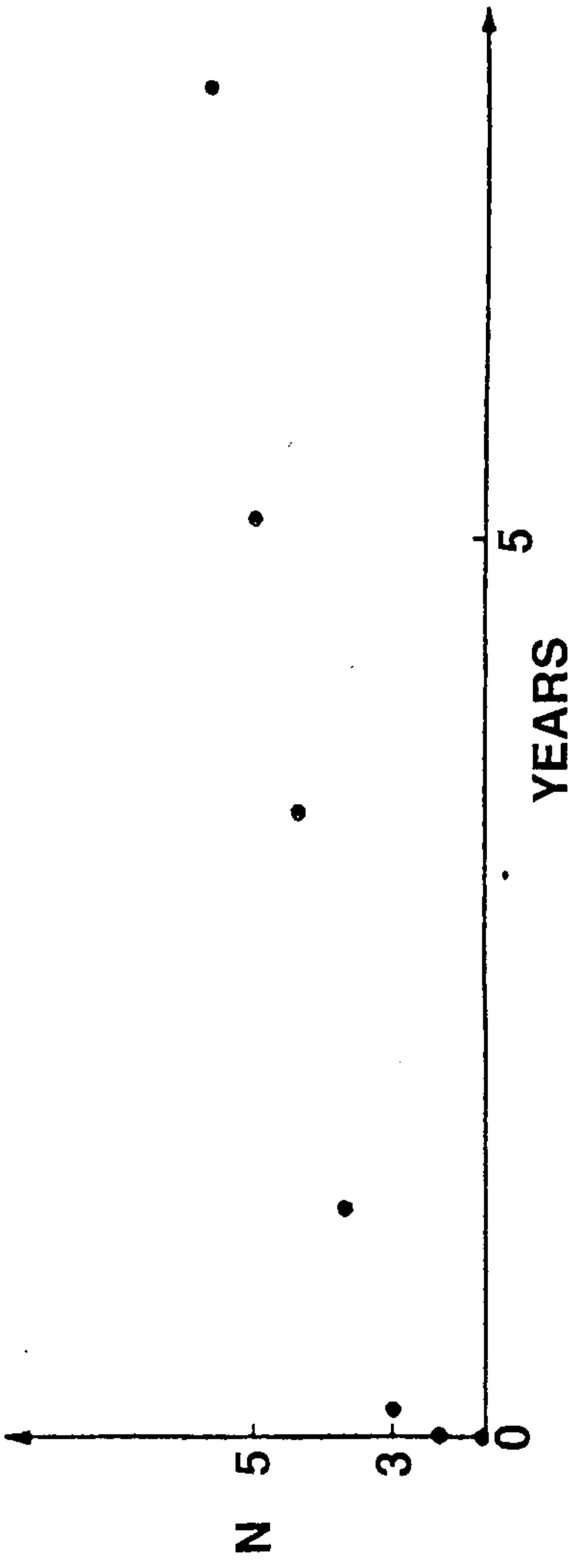

Figure 9. Cumulative distribution of the length of the time windows of the sequences.

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THE HYPOTHESES OF THE PREDICTION OF THE PARKFIELD EARTHQUAKE

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Great attention has been recently given to the moderate (M > 6) earthquakes sequence which occurred at Parkfield, namely in the years 1857, 1881, 1901, 1922, 1933, 1966, or about one avery 20 years (BAKUN and MCEVILLY 1984; BAKUN and LINDH 1985; SHEAVER 1985 *a* and *b*; WYSS *et al.* 1990 *a* and *b*; SAVAGE 1993).

It was rightly noted that the regularity of that sequence of events implied that a moderate earthquake should occur no later than March 1992 (WYSS *et al.* 1992 *a* and *b*) or pryor to January 1993 (SHEAVER 1985 *a* and *b*).

The earthquakes of the sequence occur at very regular time intervals with the exception of the 1934 event which, to keep strictly the regularity, should have occurred in 1944; the predictions mentioned above were made shifting the 1934 event to 1944 (hypothesis Q_0).

Savage (1993) noted that the prediction did not consider the following alternative hypotheses which he calls Q_1 and Q_2; in Q_1 the hypothesis Q_0 is considered false and it is assumed that the time intervals between the earthquakes are a random distribution with mean 21.9 yr and a standard deviation of 7.2 yr implying a 28% probability that the next event occurs after 1993.0 but only 5% probability that it occurs after 2003.65.

The hypothesis Q_2 considers the time of the earthquake occurrence as function of the events numerical order in the sequence and also that the events are predictable to an accuracy given by the random variable describing the scatter about linearity.

With Q_2 Savage (1993) estimates that there is a 9% probability that the next event occurs after 1993.0 and 5% probability that it occurs after 1996.0.

However there is also the hypothesis, not fully considered by Savage (1993), that the regularity of the sequence of 6 earthquakes is limited in time. To discuss this hypothesis we present here a sequence of earthquakes with in-

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tensity I ≥ X, which has some similarity with that of the Parkfield area, and occurred in an area A of 140 km radius around the Messina Straits.

Concerning the intensisties I ≥ X the catalogues of Italian earthquakes are considered complete since 1550. Between 1550 and 1783, in the area A around the Messina Straits there are 4earthquakes which seem randomly distributed in time and the last occurred in 1693.

However beginning in 1783 there seems to be an almost regular pattern of occurrence in which the events occur in sets of two or more in a limited time interval T_1, each set being separated from the following by a time interval T_2 much larger than the duration of the set as shown in figure 1.

The average value of T_1 is 5 yr with a standard deviation of 2.2 years and that of T_2 is 35 yr with standard deviation of 7.5 yr.

The cumulative distribution with mean 1905 + 35 = 1940 and standard deviation 7.5 is given by the t distribution with two degrees of freedom and implies that the following sequence had 3.2% probability to occur after the years 1993 and 3.0% probability to occur after the year 2000.

Since no earthquake with intensity I ≥ IX occurred in the area A until 1993, it is reasonable to assume that the regularity presumed between 1783 and 1908 has ceased and that another regime of energy release may have begun.

The same hypothesis may be considered also for the Parkfield sequence. The tectonic energy which accumulates in that area will eventually be released, howe~~r~~ver it is difficult to estimate when a new pattern of regularity will possibly be established because at the moment have been studied only the sequence of Parkfield and that of the Messina Strait and the latter indicates that the setting of a new pattern of events occurring at regular intervals may take more than 230 yeras as was the length of the quiesence before the pattern begun in 1783.

Abstract. Great attention has been given to the 6 moderate (M > 6) earthquakes sequence which occured at Parkfield (California) about one every 20 years. It was noted that this regularity implied that a moderate earthquake should occur no later than March 1992. With a new hypothesis Savage (1993) estimates that there is a 9% probability that the next event occurs after 1993.0 and 5% probability that it occurs after 1996.0. However there is also the hypothesis that the regularity of the sequence of 6 earthquakes is limited in time. We present here a set of 4 sequences of earthquakes with intensity I ≥ X, similar to that of the Pakfield area, occurred around the Messina Straits, began in 1783 and ended in 1908. It is estimated that the following

sequence had 3.2% probability to occur after the year 1993. Since no earthquake with intensity I ≥ IX occurred in the area untill 1993, it is reasonable to assume that the regularity has ceased. The same hypothesis may be considered also for the Parkfield sequence.

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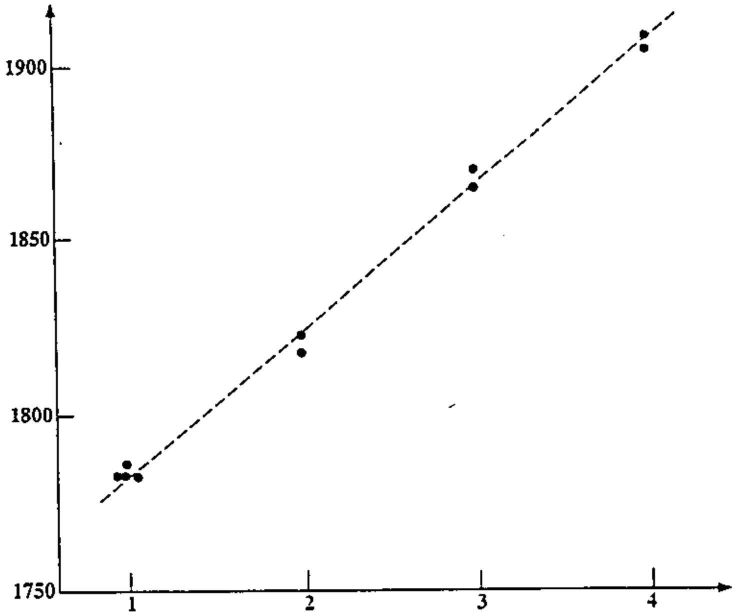

Figure 1 - Time of occurrence of earthquakes, in the area of 140 km radius around the Messina Straits, as function of the number in the sequence. The dashed line is a linear fit to the times of occurrence of the events.