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WORKSHOP
GLOBAL GEOPHYSICAL INFORMATICS WITH APPLICATIONS TO RESEARCH IN EARTHQUAKE PREDICTIONS AND REDUCTION OF SEISMIC RISK

(15 November - 16 December 1988)

THE FORECAST OF THE MAGNITUDE 5.8, MAY 1984, EARTHQUAKE IN CENTRAL ITALY

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THE FORECAST OF THE MAGNITUDE 5.8, MAY 7TH 1984, EARTHQUAKE IN CENTRAL ITALY

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The 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 formed by 3 events in average, covering an average time window of 7 years. The average interarrival time between the 1st and 2nd event of each sequence being 5 years led to the tenative prediction of new earthquakes with moderately large magnitude to follow in a few years the event of November 20, 1980 (Caputo 1983). These earthquakes actually occurred on May 7th and May 11th, 1984 with magnitude 5.8 and 5.2. A more refined analysis reveals that the distribution of the interarrival times of the 15 sequences is exponential, while the the interarrival times of all the events and of the events within the sequences 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 foresee the occurrence of other earthquakes after few years, while it would be difficult to foresee the occurrence of a future sequence of earthquakes.

The data sets do not allow to foresee the occurrence of the third event of the sequence with a reliable confidence level, these occur with about 46% probability, in average they occur within 7 years from the first earthquake of each sequence and within 2 years from the second.

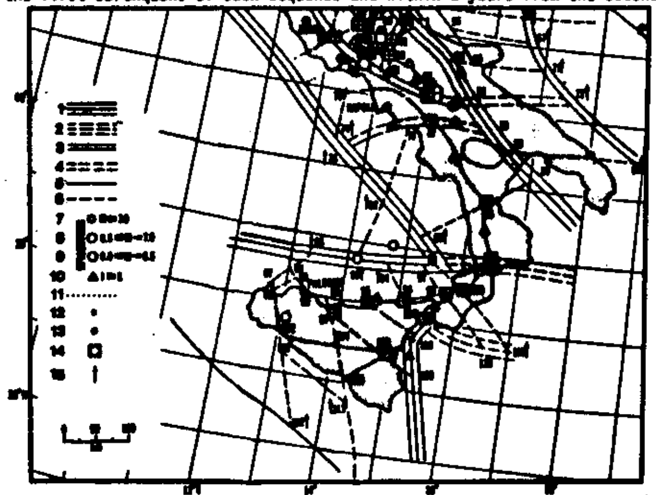

Figure 1 Map of the major lineaments of the Italian region, and of the intersections of the lineaments considered as potentially dangerous. Numbers in the key refer to the following classification of lineaments, epicenters, boundaries and intersections. Lineaments: 1,2 = first order; 3,4 = second order; 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.

Introduction

The statistical distribution of earthquake parameters has been studied since the beginning of modern seismology. It was 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 well known b value.

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

Caputo (1980a, 1982, 1981b) and Caputo Console (1980) studied the statistical distribution of the scaler moments M_0 of the linear size of the faults l and of the stress drops p and found that their density distributions $n_0(M_0)$, $n_1(l)$, $n_p(p)$ are power laws of M_0, l and p respectively, as he had predicted theoretically (Caputo 1976, 1980), and that some of the the exponents of the power laws are related.

$$\log n_0(M_0) = a_0 - b_0 \log M_0, \quad b_0 = \frac{\nu + 2}{3}$$

$$n_e(l) \propto l^{-\nu}, \quad \nu = \frac{3b}{c} + 1 \qquad (1)$$

$$n_p(p) \propto p^{-4+\alpha}, \qquad \alpha < 0 .$$

where b is obtained from the Ishimoto Iida (1939) empirical law, $c \approx 1.5$ 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 ENEL catalogue of Italian earthquakes, concluded that the catalogue seems complete in the time intervals given in Table 1 and in particular 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 tentative suggestion that other earthquakes of moderate magnitude may have occurred within several years; which 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 will examine the possibility of a fourth earthquake to occur the same area in a near future.

Will we have a fourth event in the sequence began in 1980?

The recent November 23, 1980 earthquake in Irpinia occurred in a location which was previously found to be seismically prone for events with $M \geq 6.5$ in the pattern recognition studies of Caputo et al. (1980) (see Fig. 1) 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, 1982) could be detected for lack of pertinent data.

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) tentatively indicates that the events with intensity larger or equal to IX which occurred since 1448 in that area may tend to cluster in time. The events are listed in Table 2. They have

intensities $I \geq IX$ in the ENEL (1978) catalogue; many of them are listed with intensity $I > IX$ in one of the two catalogues considered in this study.

In Table 1, the three earthquakes occurred in 1984 are listed without the intensity because we have not obtained an official report on it. Since the magnitude observed for the two events occurred in 1984 is larger than 5, and those of all the other events used Table 2 are 5 or more, it seemed acceptable to include the two events of May 7th and 11th 1984 in the Tables 2 and 3.

We shall call "sequence" a subset (of 2 or more events) of the set of 43 events listed in Table 2 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 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 minutes to 12 years. Two consecutive sequences are separated by 31 years in average. The total alarm time between the first and the second event of each sequence is 75 years or about 14% of the total time elapsed from the first event in the year 1448.

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

In 60% of the sequences of events (exceptions are those began in the years 1638, 1688, 1731, 1870, 1910, 1980) the first event of the sequence is not that with the largest intensity in the sequence. All sequences except those which began in 1755 and 1962 have an event with intensity larger than IX. The average interarrival time between the events with $I \geq IX\frac{1}{2}$ and the preceeding event is 11 years, the average interarrival time to the following event is 10 years. Comparing these averages with the interarrival time of all the events, 12.5, one may infer that there is no evidence for time or slip predictable models.

The earthquakes occurred 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 the sequence which began with the event of November 1980 will be formed by more than three events and which would be the time window in which we may expect a possible fourth event to occur.

We shall supplement here the analysis of Caputo (1983) with more studies trying to answer the questions above.

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

Since the density distribution of the scalar seismic momentum M_0, which represents energy, is a power law of M_0 (Caputo 1976, 1980b), assuming that the time t to accumulate the energy of large earthquake be proportional to the energy, we may tentatively assume that the density distribution n of the interarrival times of the events be a power law of the time. However, we know that the process, of accumulation of the energy for the next earthquake, began before last occurred. 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 last occurred earthquake. Then

$$\ln n = a + b \ln(t + c) \qquad (2)$$

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

Before discussing the result of the fits of the three sets of data to equation (2), we consider also the fits of the three sets to the function

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

where μ is the average number of events in each set, and also to the function

$$n_{e2} = A e^{-B t}, \qquad (4)$$

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

TABLE 4

SET	a	b	c	σ^2	μ	$-\ln\mu$	μ^{-1}	σ^2	lnA	-B	σ^2
I					31.02	-3.435	-0.032	0.047	-3.335	-0.032	0.042
II	-0.739	-1.132	0.75	0.010	3.76	-1.325	-0.265	0.211	-1.709	-0.173	0.035
III	4.653	-2.586	14.28	0.069	13.07	-2.570	-0.077	0.286			

In Figures 4, 5, and 6 one may 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 not significant to make a fit of n to set I because we 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.

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 almost the same order of magnitude.

One may also check that there is no correlation between the intensity of each earthquake and the interarrival time from the previous one for sets I and II; the same applies also to set III considering the correlation between the energy released in each sequence and the interarrival 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) has always the smallest σ^2 and is the closest to the data, which in turn seems to indicate that the process of release the elastic energy in this seismic 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 interarrival times of the sequences have nearly exponential distribution.

Certainly one may devise a multiparameter statistical law representing a random process which would fit the data better than n; however the random process mostly used for 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 a discussion. The laws n_{e1} and n_{e2} are mere statistical laws representing random processes; n_{e1} which is estimated using only the mean interarrival time 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 as the data make reasonable to assume). A better fit is obtained with n, which represents a tentative physical law; however n contains three arbitrary parameters to fit the data and therefore has a higher probability to give a smaller σ^2.

We may also add that the catalogues of earthquakes whose interarrival times were proved to be exponential (Gardner and Knopoff 1974), cover a large area where probably the processes of release of seismic energy are more than one and different. By selecting appropriate sets of events from an experimental distribution one may prove that an exponential distribution may be always considered the sum of non-exponential distributions. That could be the case of the catalogues of earthquakes of large regions: they may be the result of the sum of many different non-exponential processes.

Since in no case it was possible to prove that a catalogues of large events of a seismic region has an exponential distribution it seems therefore reasonable to consider that the sets I and II have a 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 interarrival time between the successive events in the sequences.

In Figure 7 we show the average interarrival time between the successive events of the sequence. It is clear that the events cluster towards the last one of each sequence.

In Figures 8 one may see the cumulative distribution of the interarrival times between first and second event of each sequence and between second and third event 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 ipocentral volume but concentrating it elsewhere until the number of asperities with a stress close to fracture 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 from the second.

We must add here that in the paper of Caputo (1983) the couple of events in 1962 was omitted for error, however this does not change significantly the results.

In Figure 9 we see the cumulative distribution of the time windows in which the sequences occur and one may note that 50% of them have duration less than 8.5 years.

The sequences with more than two events are now 47% of the total, 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 occur within 1.2 years from the third.

Table Captions

Table 1) Completeness of the ENEL Catalogue of Italian earthquakes occurred from the year 1000 through 1975.

Table 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) and Peronaci (1956). 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.

Table 3) 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.

Table 4) 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. σ^2 is the variance of the data with respect to the lines fitted.

TABLE 1

Completeness of the *ENEL* (1978) Catalogue of Italian Earthquakes

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

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	26				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
1664	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	6.7
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	6.9
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	16	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
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	6.3
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	56	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

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
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	5.24	7.00	31.01
		(3.07)	(5.63)	(8.35)	(32.59)

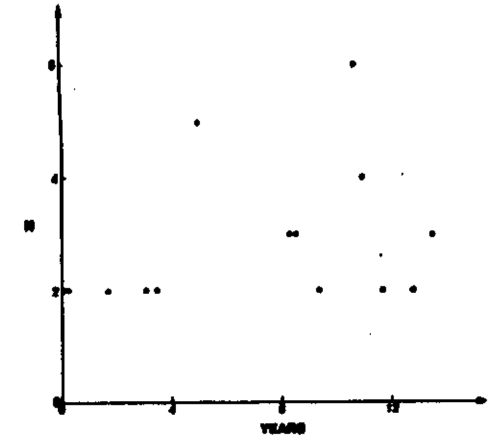

Figure 2 Number of events in each sequence as a function of the length of the sequence.

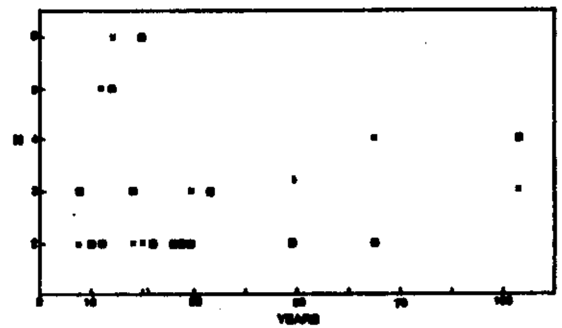

Figure 3 Number of events in each sequence as function of the interarrival time to previous sequence (squares) or to the following sequence (crosses).

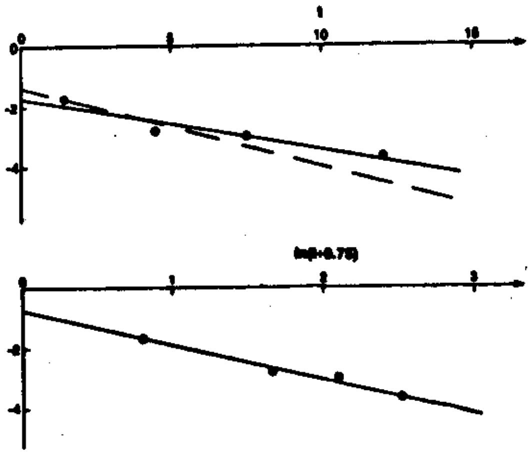

Figure 4 Best fit of (4) and (2) (continuous line top ln n_{e2} = -1.709 - 0.173t and bottom ln n = -0.739 - 1.13 ln (t + 0.75),) to the density distribution of the interarrival times of the events within the sequences. The dashed line is (3) with μ = 3.76 average interarrival time of events within sequences.

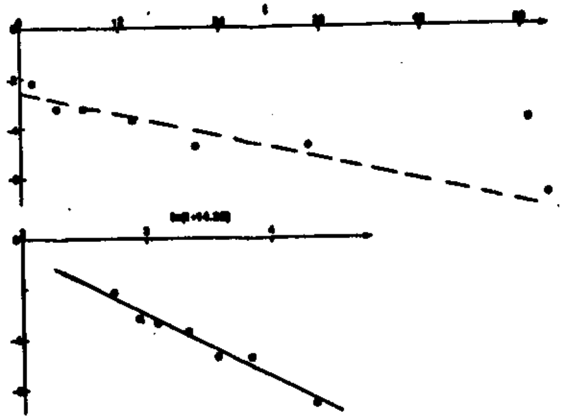

Figure 5 Best fit of (4) and (2) (continuous line bottom ln n = -4.65-2.58 ln (t + 14.25) to the density distribution of the interarrival times of all events. The dashed line is (3) with μ = 13.1 interarrival time of events.

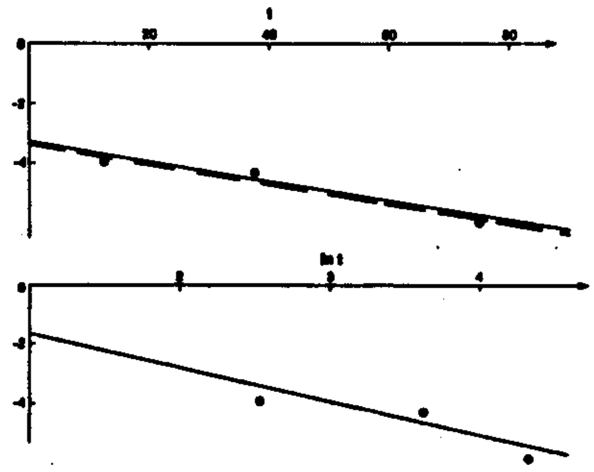

Figure 6 Best fit of (4) and (2) (continuous line top ln n_{e2} = -3.33-0.032t, and bottom ln n
-0.21-1.48 ln t, t > 10, c = 0) to the density distribution of the interarrival time
the sequences. The dashed line is (3) with μ = 31.0 interarrival times of the seque

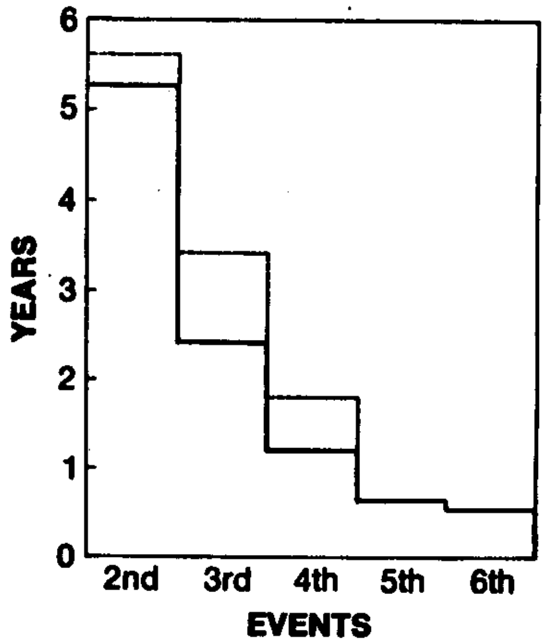

Figure 7 Average interarrival time between the nth and the (n + 1)th events of the sequences.
dashed lines give the values for the set of sequences of Table 5 in which the sequen
indicated in brackets substitutes the two sequences beginning on 1627 and 1638.

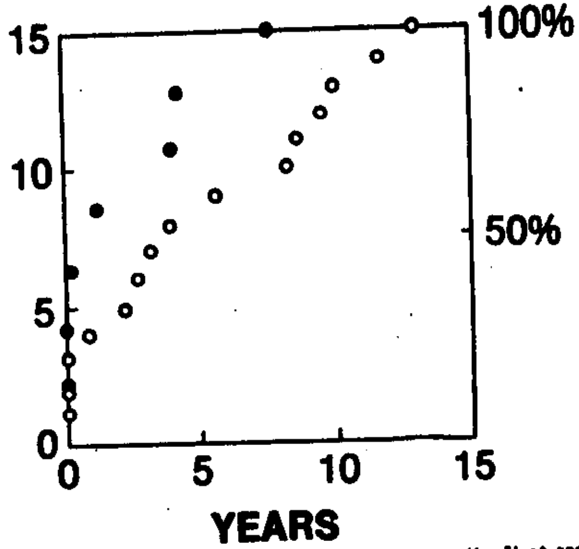

Figure 8 Cumulative distribution of the interarrival times between the first and the second event (open circles) and between the second and the third events (solid squares) in the sequences.

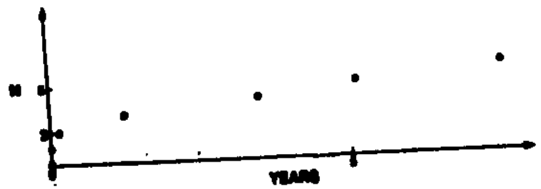

Figure 9 Cumulative distribution of the length of the time windows of the sequences.

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