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Forecasting Where Larger Crustal Earthquakes Are Likely to Occur in Italy in the Near Future

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Abstract A forecast of future occurrences of larger ($M \geqq 5.9$) crustal earthquakes in Italy is made on the basis of historic and instrumental seismicity, and following a seismotectonic regionalization recently derived on the basis of geological evidence combined with earthquake epicenters and focal mechanisms. Completeness problems in the seismic catalog allow one to study only 20 regions out of 58. Large crustal seismicity within each seismogenic region is modeled as either a periodic Gauss process or a random Poisson process according to the experimental coefficient of variation of the series of past occurrences in each region. Return times are estimated directly from the series of ($M \geqq 4.5$) earthquakes if they are sufficient in number, or from the Gutenberg–Richter law applied to lower magnitude seismicity ($M \geqq 4.5$) otherwise. The immediate probability of an $M \geqq 5.9$ crustal seismic event is estimated to be very low in all regions except southeastern Sicily and Appennino Abruzzese. In the near future (next 20 yr), the estimated probability is high (above 65%) also in the Appennino Forlivese and Naso–Capo d'Orlando regions. In addition to detailed seismic risk reevaluations, these regions represent the best bet for a program of intensive monitoring to gather a record of the process of strain accumulation and seismic release.

Introduction

If the physics of seismic phenomena were simple, earthquake prediction would have been routine a long time ago. Unfortunately, this is not the case, and detailed modeling still appears infeasible. Practical alternatives are therefore mostly sought on semi-empirical grounds, hoping to achieve the capability of correctly describing the timing of earthquake occurrence in a given region. Unfortunately, even the most promising semi-empirical earthquake models presented so far, i.e., the *slip predictable* and *time predictable* models, have proven to be practically effective in very few cases (Bufe *et al.,* 1977; Shimazaki and Nakata, 1980; Sykes and Quittmeyer, 1981; Kiremidjan and Anagnos 1984; Anagnos and Kiremidjan, 1984; Nishenko, 1985; Papazachos, 1989) and appear generally inapplicable.

A strategy that is likely to allow a quantum leap in our knowledge of the physical processes leading to earthquakes, and eventually in our capability to predict them, is to use statistics to forecast where large earthquakes will next occur in the near future, closely monitor such regions, and record all possible information about the process of earthquake generation. A seismic forecast, i.e., an estimate of the probability of future earthquakes, is also one of the main ingredients required for evaluating the impact of earthquakes on a specific site. The other factors are attenuation, geologic structure beneath the site, and topography, and the whole lot combined with vulnerability yields the seismic risk. The present work will disregard all the latter aspects and will concentrate solely on attempting to forecast the sites, if any, on the Italian territory in which large crustal earthquakes are likely occur in the near future.

There are three main problems in reliably evaluating the probability of future earthquake occurrences. The first problem is represented by catalog incompleteness, i.e., by a recorded seismicity that is different from real seismicity. Incompleteness is a function of event size (large events are more difficult to miss or wrongly parameterize than small ones) and affects all catalogs because of the pointlike distribution of seismographs (or observers in noninstrumental studies). The problem of the incompleteness of seismic catalogs has already been studied in detail and a satisfactory solution has been obtained by efficient expressly tailored statistical procedures (Tinti and Mulargia, 1985a, 1985b; Mulargia and Tinti, 1985; Mulargia *et al.,* 1987).

The second problem is the statistical distribution ruling event occurrence. Several distributions have been used to model seismic activity. Poisson statistics has been undoubtedly the most extensively used, since, in many cases, for large events a simple discrete Poisson distribution provides a close fit. Most of the proposed alternative distributions, like Weibull and lognormal, are modifications of Poisson distribution, attempting to compensate for what appears to be the major drawback of a Poisson process: the independence of each event from the time elapsed since the previous occurrence. In other words, the latter implies an event probability that is independent of the time elapsed since the previous occurrence, rather than one increasing in time as required by any feasible physical reasoning based on strain accumulation. More recently, the picture has been found to be even more complex since earthquake occurrence is probably dominated by clustering at both short (foreshocks, aftershocks, swarms) and long time scales (Kagan and Jackson, 1991). This is exactly the opposite of a quasi-periodic occurrence timing, and would imply "the longer it has been since last earthquake, the longer the expected time till the next" (Davis *et al.,* 1989). The process must nevertheless break at some point if all seismic regions are not to ineluctably reach quiescence. Some inference on this crucial point can be made on the basis of the coefficient of variation C_v, defined as $C_v = \sigma_{\bar{T}}/\bar{T}$, where $\bar{T}$ is the average interoccurrence time and $\sigma_{\bar{T}}$ is its standard deviation (Kagan and Jackson, 1991). A perfectly periodic phenomenon would have a coefficient of variation equal to 0 and a completely random (Poisson) phenomenon equal to 1. Clustered occurrences would have C_v values larger than 1, ideally tending to infinity for fractal processes as the observation time increases. Rather than attempting to find an optimal distribution of gen-

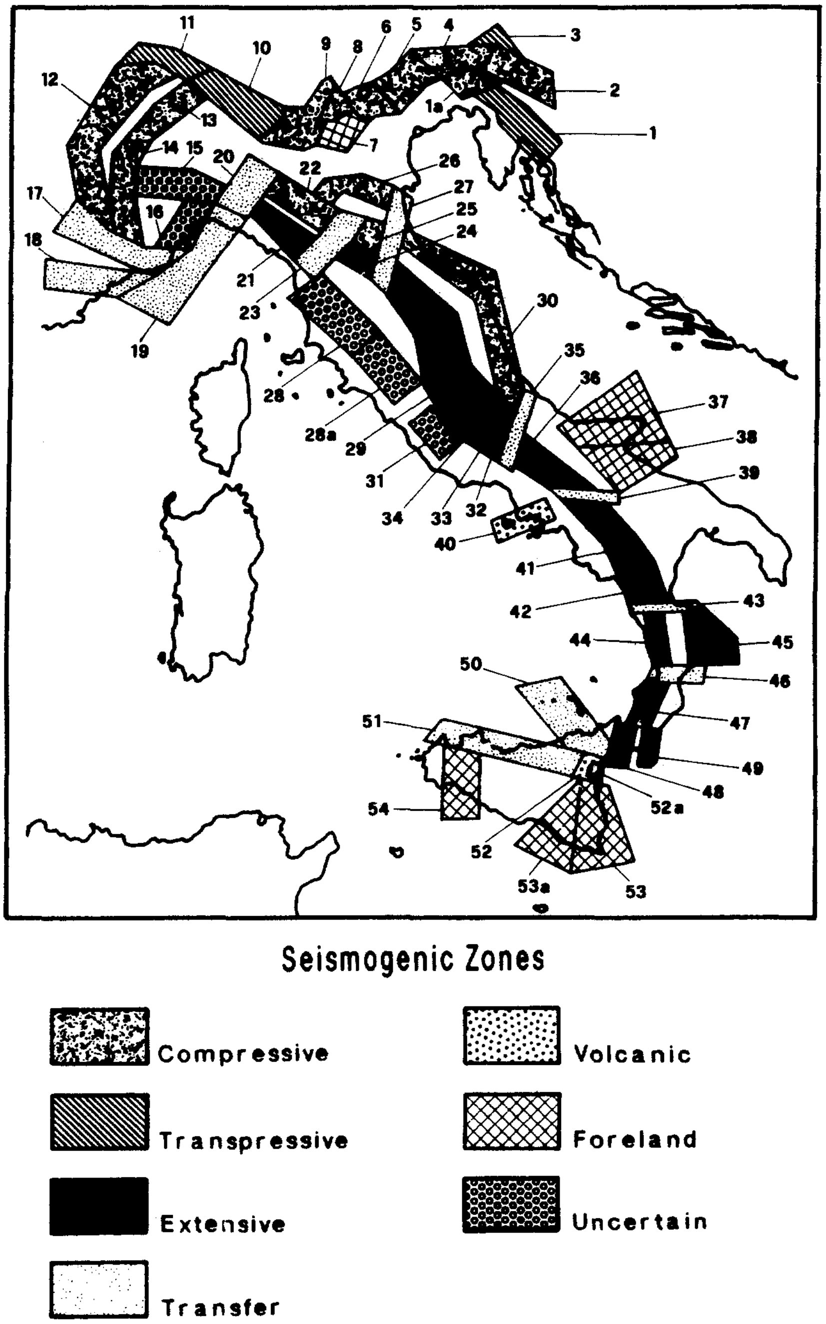

Figure 1. The seismotectonic regionalization of the Gruppo Nazionale Difesa dai Terremoti of the Consiglio Nazionale delle Ricerche (Scandone, 1992). The tectonic styles characterizing the 58 regions are indicated with different shading. Note that some regions (1, 28, 52, and 53) share the same seismotectonic character of a neighbor but are identified as separate units since they are disjointed by a major structural discontinuity.

eral validity, a much debated problem (see, e.g., Brillinger, 1982; Jacob, 1984; Nishenko, 1985; Nishenko and Buland, 1987), we describe earthquake occurrence on the basis of the coefficient of variation C_v. Namely, we take the radical approach of modeling quasi-periodic seismicity ($C_v \simeq 0$) with a stationary ideal Gauss process, i.e., a process that has $C_v \equiv 0$, and completely random seismicity ($C_v \simeq 1$) with a stationary Poisson process, which has a $C_v \equiv 1$. The conceptual scheme behind this reasoning takes its moves from physical modeling: a Gauss process would imply a strictly deterministic physical model, a Poisson process a purely stochastic model, and clustering a chaotic model. Note that for an ideal Gauss process we assume for interevent times a normal distribution with vanishing variance with respect to the mean, i.e., approaching a delta function. As is apparent in the following, we find little evidence of clustering ($C_v \gg 1$), so that cluster modeling appears unnecessary. Note that the choice of the cross-over point between Gauss and Poisson processes is not critical since the first tends to the second when dispersion becomes high. We use the following selection scheme: Gauss process in the regions where $0 < C_v \leqq 0.7$ and Poisson process in the regions where $0.7 < C_v$ (Fig. 1).

The third problem is represented by regionalization, since all parameterizations of seismicity operate on regions in which activity is assumed to be uniform. Each hazard study implies therefore a regionalization, which is performed on a more or less subjective basis. Usually, tectonic arguments are invoked. A regionalization of this type is reliable only in places characterized by simple tectonics. This is certainly not the case in Italy, where the tectonic picture is so complex that a commonly accepted interpretation is still lacking (Scandone, 1979, 1982; Mantovani, 1982; Mantovani *et al.,* 1985; Patacca *et al.,* 1992). Exposed tracks of active faults are scarce, and considerable uncertainty exists about the identification of the active tectonic structures. Defining seismogenic regions in such a complex context is very difficult. A way to minimize bias has been recently explored by the Gruppo Nazionale Difesa dai Terremoti of the Consiglio Nazionale delle Ricerche (Scandone, 1992), locating the active structures through the combination of neotectonic surveying with seismicity data regarding historic and instrumental epicenters and focal mechanisms. The result was the identification of 58 seismogenic regions, each one homogeneous in terms of tectonic character (compressive, tensile, *etc.*), which are shown in Figure 2. While this cannot be viewed as a definitive answer, and work is in progress to enhance resolution, it undoubtedly represents a first comprehensive reference, and a compulsory choice at the present moment.

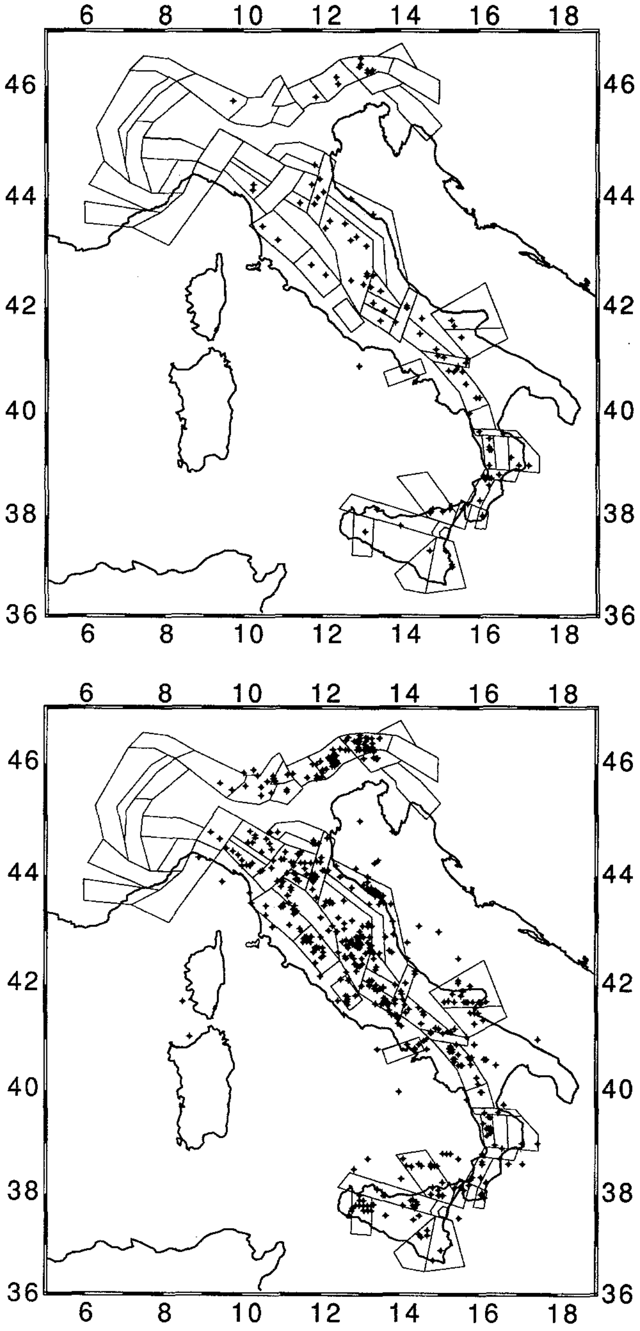

Figure 2. Epicenters of the earthquakes used in this work. (a) The areal distribution of the events with $M \geqq 5.9$; (b) events with $M \geqq 4.5$.

The Seismicity Data

The data on which the statistical estimates of the recurrence of earthquakes in a given region can be based are essentially of three types: palaeoseismic evidence, instrumental catalogs, and historical catalogs. Palaeoseismic data have been profitably used for some faults in California, both regarding Quaternary structures (Swan *et al.,* 1980) and more recent sediments (Sieh, 1978; Raleigh *et al.,* 1982), but no such data are available for the Italian territory. Instrumental seismicity is certainly the most complete set, but samples only a very small fraction of the repeat time of large events. On the other hand, historical seismicity is exceptionally well documented in Italy.

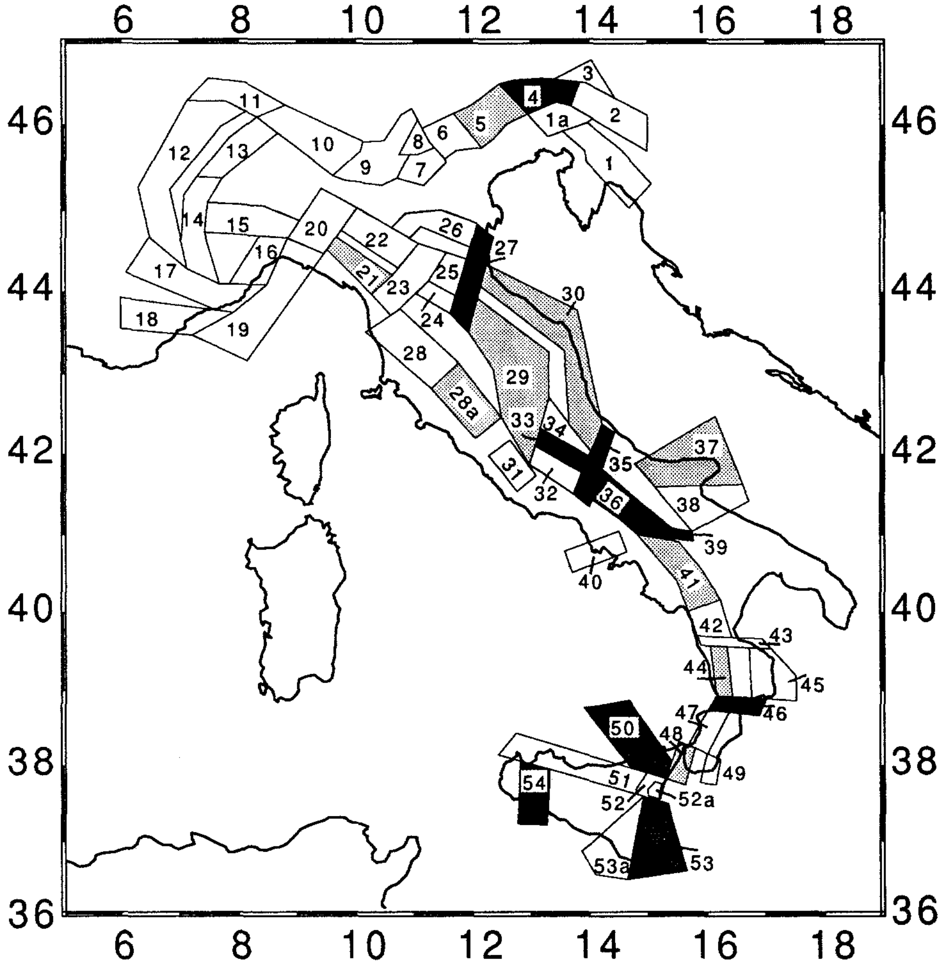

Figure 3. The 20 regions analyzed in the present study. The two distribution used to model event occurrence according to the coefficient of variation (see text), Gauss and Poisson, are shown, respectively, with a black and a shaded pattern.

The Istituto Nazionale di Geofisica (ING) Italian seismic catalog provides a large data base of over 50,000 events relative to the period 1500 B.C. to the present, and is continuously updated on the basis of the 72-station telemetered network that ING operates on Italian territory (Fig. 3). All events, except the ones in this century, are located and estimated in size on the sole basis of the macroseismic data compiled by reading historical reports. Considerable errors are thus possible due to both catalog incompleteness and parameter inhomogeneity.

In general, the importance of incompleteness is much greater in the noninstrumental parts of the catalog. The incompleteness of the Italian seismic catalog has been studied in detail through efficient statistical procedures (Mulargia and Tinti, 1985; Mulargia *et al.,* 1987), and the record has been found to be complete since the year 1600 for events with Mercalli intensity I ≧ IX and since the year 1860 for events with I ≧ VII.

Table 1

Maximum Macroseismic Intensity (above Degree VII) and Local Magnitude Data for the Earthquakes in Which Both Are Available (186 Events) in the Il Catalogo dei Terremoti, Istituto Nazionale di Geofisica (1993). The First Column Reports the Intensity, the Second One the Median Value for Local Magnitude, Which Is the Best Estimator (cf., Sibol *et al.,* 1987), and the Third and Fourth Columns, Respectively, Report the First- and Third-Quartile Local Magnitude Values

Int.	*M* Median	I Quart.	III Quart.
7.0	4.50	4.30	4.85
8.0	4.80	4.55	5.15
9.0	5.60	5.40	5.95
10.0	6.50	6.00	6.75
11.0	6.95	6.80	7.10

The inhomogeneity in the recorded parameters is linked to incompleteness. In the present work, it is particularly important to estimate the magnitude of historic events. This can be effectively achieved by converting the maximum Mercalli intensity to magnitude according to a tabular relation on the median values in each intensity class, tuning the conversion factor on a set for which both intensity and magnitude values are available (Sibol *et al.,* 1987). Table 1 reports these values for various intensity classes in the ING seismic catalog, based on the 186 events of the ING seismic catalog for which both instrumental and macroseismic data were available. On this basis, events with maximum intensity VII correspond to magnitude 4.5, events with maximum intensity VIII correspond to magnitude 4.8, events with maximum intensity IX correspond to magnitude 5.9, events with maximum intensity X correspond to magnitude 6.5, and events with maximum intensity XI correspond to magnitude 7.0. Note that the probable error, i.e., the difference between median and first and third interquartiles, is about 0.2. This means that, since intensity is known with an indetermination certainly smaller than 1°, magnitude can be inferred with an error comparable with instrumental estimates. We can thus be rather confident in the noninstrumental part of the ING catalog.

Analyzing Italian Seismicity

The aim of the present work is to evaluate the probability of occurrence for events with magnitude $\geqq 5.9$ on Italian territory. Seismic cycles with several occurrences relative to $M \geqq 5.9$ events are present only in a few regions. The lowest limit for any estimate is three events, i.e., two interevent times, which is satisfied in 11 regions. In the remaining regions, we attempt an estimate of the average return time and the related standard deviation of $M \geqq 5.9$ on the basis of an extrapolation of the Gutenberg–Richter relation $\log (N_c) = a - bM$ tuned on smaller events. Events with magnitude $M \geqq 4.5$ are used to this extent, since the relative completeness period of the catalog (after the year 1860) appears sufficiently long to caution against short-period fluctuations in seismicity (aftershocks are not removed). As regards the estimate of the parameters in the Gutenberg–Richter law, for which we assume a b value constant in time, several techniques have been suggested, based on the modification of linear regression and maximum likelihood. Each technique has advantages and disadvantages that have been extensively discussed in the literature (e.g., Weichert, 1980; Bender, 1983). Conceptually, maximum likelihood (ML) is the superior estimation technique: in practice, however, ML accords so little weight to the upper magnitude points that it is less suitable than least squares for estimating the recurrence intervals of high-magnitude infrequent earthquakes (Shi and Bolt, 1982). We therefore rely on a standard least-squares linear regression. Gutenberg–Richter parameters, the related errors, the number of events used in each regression, and the estimated return time for an $M = 5.9$ event are shown in Table 2. Finally, note that since the estimates of return times for $M = 5.9$ events are based on an extrapolation, a relatively large number of events with $M \geqq 4.5$ are required: we considered regions with at least 10 such occurrences. This allows us to study nine further regions.

Calculating the coefficient of variation C_v for each region yields values ranging from 0.03 to 1.41 for both real occurrences and Gutenberg–Richter estimates (Table 2), which indicates a seismicity varying from almost exact periodicity to slight clustering. The evidence of clustering is

Table 2

Region Number, Number of Events in the Complete Catalog with $M \geqq 5.9$, Return Time T_R, and Related Standard Deviation S_R of an Event with $M \geqq 5.9$ Directly Inferred from Real Previous Occurrences. For Regions with Less than Three Events, Gutenberg–Richter Coefficients a and b, Return Time T_{GR}, and Standard Deviation s_{GR} Calculated from Events with $M \geqq 4.5$ (Provided They Are More Than 10 in Number) According to Gutenberg–Richter Law. C_v Indicates the Coefficient of Variation, i.e., the Ratio of Standard Deviation to Return Time

Region	N ($M \geqq 5.9$)	T_R	s_R	N ($M \geqq 4.5$)	a	b	T_{GR}	s_{GR}	C_v
4	3	94	46						0.49
5	2			30	3.50 ± 0.76	0.53 ± 0.13	69	51	0.74
21	2			12	2.65 ± 1.46	0.45 ± 0.26	163	171	1.04
27	4	70	32						0.45
28a	2			26	5.14 ± 1.11	0.84 ± 0.20	108	81	0.75
29	9	27	36						1.33
30	2			35	5.73 ± 1.88	0.96 ± 0.33	150	219	1.46
33	2			12	2.20 ± 0.39	0.32 ± 0.06	78	35	0.45
34	3	61	2						0.03
35	2			23	5.55 ± 0.81	0.91 ± 0.14	113	60	0.53
36	2			12	4.06 ± 0.75	0.66 ± 0.13	109	53	0.48
37	3	133	114						0.86
39	3	75	44						0.59
41	6	57	43						0.76
44	5	64	70						1.09
46	5	80	43						0.53
48	2			43	2.59 ± 0.94	0.39 ± 0.15	87	106	1.22
50	5	56	29						0.51
53	3	77	12						0.16
54	1			22	4.70 ± 1.04	0.77 ± 0.19	109	76	0.70

Table 3

The Same as Table 2 but for Events with $M \geqq 6.5$

Region	N ($M \geqq 6.5$)	T_R	s_R	N ($M \geqq 4.5$)	a	b	T_{GR}	s_{GR}	C_v
5	1			30	3.50 ± 0.76	0.53 ± 0.13	141	108	0.77
29	3	107	29						0.27
33	1			12	2.20 ± 0.39	0.32 ± 0.06	119	54	0.45
36	1			12	4.06 ± 0.75	0.66 ± 0.13	267	153	0.57
37	1			24	5.26 ± 1.18	0,88 ± 0.21	450	436	0.97
39	3	75	44						0.59
41	2			21	4.37 ± 0.69	0.67 ± 0.12	163	86	0.52
44	2			15	2.65 ± 0.58	0.40 ± 0.10	135	76	0.57
46	3	123	0						0.00
48	2			43	2.59 ± 0.94	0.39 ± 0.15	148	182	1.23

Table 4

Estimated Probability of Occurrence of Earthquakes with $M \geqq 5.9$ in Each Region for the Next 5, 20, and 100 yr Assuming Either a Gauss or a Poisson Process for Event Occurrence Depending on the Coefficient of Variation (See Table 2 and Text). The 68% Confidence Limits Are Given

		Gauss Process			Poisson Process		
Zone	Last Event (m/d/yr)	5 yr	20 yr	100 yr	5 yr	20 yr	100 yr
4	05/06/1976	0.00–0.05	0.01–0.21	0.31–0.91			
5	10/18/1936				0.04–0.15	0.16–0.44	0.44–0.87
21	09/07/1920				0.02–0.07	0.07–0.23	0.28–0.66
27	10/30/1870	0.19–0.38	0.61–0.87	1.00–1.00			
28a	09/10/1919				0.03–0.10	0.11–0.33	0.35–0.77
29	04/26/1917				0.13–0.23	0.41–0.63	0.97–0.99
30	10/30/1930				0.02–0.08	0.08–0.25	0.30–0.68
33	01/13/1915	0.03–0.18	0.17–0.60	0.95–1.00			
34	10/06/1762	1.00–1.00	1.00–1.00	1.00–1.00			
35	09/26/1933	0.00–0.06	0.02–0.24	0.30–0.88			
36	08/21/1962	0.00–0.06	0.01–0.17	0.20–0.84			
37	08/10/1893				0.02–0.07	0.09–0.25	0.34–0.70
39	08/14/1851	0.13–0.28	0.45–0.75	0.99–1.00			
41	11/23/1980				0.06–0.13	0.22–0.41	0.64–0.88
44	12/03/1887				0.05–0.12	0.19–0.40	0.58–0.87
46	05/11/1947	0.01–0.11	0.06–0.40	0.69–0.99			
48	12/28/1908				0.04–0.12	0.13–0.38	0.39–0.81
50	03/05/1823	0.44–0.60	0.92–0.98	1.00–1.00			
53	08/07/1846	0.87–0.94	1.00–1.00	1.00–1.00			
54	01/15/1968	0.00–0.04	0.01–0.15	0.13–0.72			

weak since C_v is not much greater than 1, and this occurs in just a few regions; we therefore limit our modeling to the two extreme cases of exactly periodic (Gauss) and completely random (Poisson). According to the historic record, in most of the seismic areas analyzed, $M = 5.9$ practically coincides with the maximum possible magnitude. In the regions where larger earthquakes occurred in historical times, we also applied the same analysis as above using as a lower threshold $M \geqq 6.5$. Analysis was applied to all regions where at least one event of that size occurred. The distribution parameters for this case is given in Table 3. For the events with $M \geqq 6.5$, 10 regions could be studied, seven of which by fitting Gutenberg–Richter law.

Results and Discussion

First of all, a comparison between Figures 1 and 3 suggests no evident link between tectonic character and distribution type ruling event occurrence.

The probability of occurrence P of an event with $M \geqq 5.9$, evaluated in each of the 20 regions modeled as either a Gauss or Poisson process according to the coefficient of variation, is shown in Table 4 for the next 5, 20, and 100 yr. Note that, by definition, in a Gauss process, the conditional and unconditional probabilities are different, so that the probabilities increase with the time elapsed since the last event, while in the Poisson process the two probabilities are identical so that the values shown are the same in any 5-, 20-, or 100-yr period. The probability of occurrence in the

Table 5

The Same as Table 4 but Relative to Earthquakes with $M \geqq 6.5$

		Gauss Process			Poisson Process		
Zone	Last Event	5 yr	20 yr	100 yr	5 yr	20 yr	100 yr
5	06/29/1873				0.02–0.11	0.08–0.32	0.27–0.76
29	04/26/1917	0.01–0.13	0.06–0.49	0.91–1.00			
33	01/13/1915	0.01–0.08	0.03–0.29	0.44–0.94			
36	07/26/1805	0.00–0.03	0.01–0.12	0.10–0.54			
37	07/30/1627				0.00–0.04	0.08–0.14	0.12–0.47
39	08/14/1851	0.13–0.28	0.45–0.75	0.99–1.00			
41	12/16/1857	0.01–0.06	0.03–0.24	0.30–0.83			
44	10/04/1870	0.01–0.08	0.05–0.29	0.41–0.89			
46	09/08/1905	0.00–0.00	0.00–0.00	1.00–1.00			
48	12/28/1908				0.04–0.14	0.15–0.43	0.43–0.84

next 5 yr is low everywhere, except in regions 34 (Aquilano), which has a P virtually equal to unity, and 53 (southeastern Sicily), which has a $P = 0.87 \sim 0.94$. Note that the high probability of region 34 comes from the fact that after three almost exactly spaced earthquakes (61 ± 2 yr) no large magnitude activity occurred in the following 200 yr. While the small number of observed occurrences suggests prudence, one could also see this as an indirect evidence of clustering. In addition to the above regions, the occurrence probability in the next 20 yr is high in regions 27 (Forlivese), with a $P = 0.61 \sim 0.87$, and 50 (Naso–Capo d'Orlando), with $P = 0.92 \sim 0.98$. Within the next 100 yr, the probability of occurrence of an event with magnitude $\geqq 5.9$ is high (average $P \geqq 0.7$) in most regions. The only exceptions are regions 21 (Garfagnana), with $P = 0.57$, and 35 (Appennino Abruzzese), with $P = 0.08 \sim 0.63$. Region 4 (Friuli) is on the border, with $P = 0.31 \sim 0.91$.

The probabilities of occurrence for events with magnitude $M \geqq 6.5$ are given in Table 5. All values are low in the next 5 and 20 yr, and become high in the next 100 yr only in regions 39 (Ofanto) and 46 (Stretta di Catanzaro). The latter is worth noting: with three events almost exactly spaced by 123 yr (the standard deviation is practically 0), the estimated probability is thus almost exactly 0 up to year 2028 (123 yr after the last occurrence), when it becomes 1. Obviously, here also the observation is merely based on three events, just as in region 34, and this recommends caution in accepting this evidence.

Conclusions

The probability of occurrence of $M \geqq 5.9$ crustal earthquakes in Italy appears high in the near future only in just a few regions: southeastern Sicily, Aquilano, Naso–Capo d'Orlando, and Forlivese. In addition to detailed seismic risk reevaluations, all these regions should be objects of intensive monitoring toward a better comprehension of local tectonics and the physical processes related to earthquake generation. If the picture is extended to a time period of 100 yr, many other regions show a high probability of occurrence, and these will certainly have to be considered in seismic risk studies. Available data allowed the study of only one-third of the Italian seismic regions. Therefore, the above forecast is not exhaustive.

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