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Stability of Premonitory Seismicity Pattern in Italy and Feasibility of Intermediate-Term Earthquake Prediction

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Stability of premonitory seismicity pattern in Italy and feasibility of intermediate-term earthquake prediction

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ABSTRACT: The algorithm CN makes use of normalized functions therefore the original algorithm, developed for the Californian-Nevada region, can be directly applied without any adjustment of the parameters also to the determination of the Time of Increased Probability (TIPs) of strong earthquakes for Central Italy. The prediction is applied to the events with magnitude $M \geq M_0 = 5.6$, which, in Central Italy, have a return period of about 6 years, the same as the California-Nevada region. The availability of the digital earthquake bulletins of the Istituto Nazionale di Geofisica (ING) permits to extend to May 1991 the study made by Keilis-Borok et al. (1990).

The analysis of seismicity and seismotectonic considerations allowes to formulate a new regionalization. The use of this regionalization permits to reduce the total alarm time, the failures to predict and to narrow the spatial uncertainty of the prediction with respect to the results of Keilis-Borok et al. (1990).

A stable premonitory pattern is obtained even when the key parameters of the CN algorithm and the duration of the learning period are changed and different earthquake catalogues are used.

The extension of the analysis to the period 1904-1940, for which $M_0=6$, allows us to identify self-similar properties between the two periods in spite of the much higher seismicity level of the early period compared with the recent one.

1 INTRODUCTION

The algorithm CN is described in full detail by Gabrielov et al. (1986) and Keilis-Borok, et al. (1990), and an application of this algorithm to Central Italy is given by Keilis-Borok et al. (1990). The algorithm CN is designed to define the Time of Increased Probability of strong earthquakes (TIP). For this purpose the traits considered are the level of seismic activity, its variation in time, clustering of the earthquakes in space and time, and their concentration in space.

The functions which describe the traits for a given territory are defined in table 1. These functions are normalized so that they can be applied to different territories, with different seismicity, without any change. The normalization is obtained by choosing three magnitude ranges, m_1, m_2 and m_3, satisfying the condition that, in the territory under study, the average annual number of events with $M \geq m_i$ is equal to the costants, a_i, common to all seismically active territories.

The flow of the earthquakes is represented, at each time t, by the vector formed by the values of the different functions at the time t. The value of the minimum magnitude of the events to be predicted (strong events), M_0, satisfies in general two simultaneous conditions: 1) to correspond to events with a return period of about 6 years; 2) to be as close as possible to a minimum in the histogram Number of events-Magnitude (fig. 1). Condition 1) is justified by the attempt to preserve the value used for the California-Nevada region; condition 2) is suggested by the necessity of minimizing the effect of the threshold introduced by the choice of M_0.

In the CN analysis of the flow of earthquakes, the time axis is divided into three intervals: *D* (dangerous), *N* (non-dangerous) and *X* (undetermined). The *D* intervals extend for two years before each strong event ($M \geq M_0$). Intervals *X* extend for three years after each strong event; if a strong earthquake occurs within three years the *X* period becomes a *D* period. The remaining time intervals are *N* intervals.

The functions, defined in table 1, are discretized by defining the thresholds small, medium and large, on the basis of the quantiles levels 1/3 and 2/3. We then estimate the combinations of the different discretized functions which are more typical for intervals *D*, and for intervals *N*. Following the procedure of pattern recognition, features *D* are defined by the condition that, in general, they occur during the intervals *D* and not during the intervals *N*. Features *N* are definited by the reverse condition. Each feature corresponds to a discretized value of the function, or to a combination of such values, for 2 or 3 functions.

A TIP is declared at the time *t* for one year if:

$$n_{D(t)} - n_{N(t)} \geq V = 5$$

$$\sigma(t) = 10^{-\beta(M_0-\alpha)} \Sigma 10^{\beta(M_i-\alpha)} < E = 4.9 \qquad (1)$$

where

$$\beta = 1; \ \alpha = 4.5$$

$n_{D(t)}$ is the number of characteristic features *D* that the flow of earthquakes has at the time t;

$n_{N(t)}$ is the number of features *N*;

$\sigma(t)$ is a function proportional to the total number of ruptures in each main shocks area contained in the studied region within a period of 3 years before the time t.

Consecutive TIPs may overlap and give an alarm period longer than one year. The TIP can be interrupted if $\sigma(t) > E$, then the TIP can be shorter than one year. If, during a TIP, we have not a strong event we have a 'false alarm'; if we have a strong event outside the TIP we have a 'failure to predict'.

All the constants and the definition of *D* and *N* features appearing in the algorithm CN are determined from the retrospective analysis of the California-Nevada seismicity (Keilis-Borok et al., 1990).

2 REGIONALIZATION

The regionalization is a very important factor to produce a useful prediction, minimizing the spatial uncertainty. The area where a strong earthquake has to be predicted must be the smallest possible, but there are some limitations to its minimum dimensions: 1) the borders of the area must not cross continuous seismotectonic zones and, 2) the annual number of earthquakes has to be ≥3 for the magnitude for which the catalogue is complete.

The regionalization used by Keilis-Borok et al.(1990) (fig. 2), based only on the boundaries and completeness of ENEL catalogue covers an area of about 6.3×10^5 km^2 allows to obtain overall satisfactory results, but with not negligible false alarms and failures to predict (fig. 3).

Some events, in the area analyzed, can be easily correlated with the seismicity of the eastern border of the Adriatic microplate (compare fig. 2 and fig. 4). Furthermore, the analysis of the occurrence, just before the TIPs, of the events with magnitude greater than the minimum magnitude, m_1, used in the definition of the functions in the CN algorithm, shows that, in all the three-years time intervals which immediately precede the TIPs, it is possible to identify three distinct seismically active areas: the Apennines, the Ancona zone and the Gargano region (compare fig. 4 with fig. 5-8). The seismicity along the Apennines is present during all TIPs, while the events in the Ancona zone and in the Gargano region occur only before the false alarms (fig. 6 and fig. 7). This may be taken as a strong indicator that the events in Ancona zone and Gargano region are associated with dynamic processes of the lithospheric blocks which are different from those characterizing the Apennines and that the earthquakes along the Apennines are independent from the seismicity of the other two areas (Ancona zone and Gargano region).

Furthermore, the map of the main shocks in Italy shows that there are two maxima in number of events in the Apennines (Umbria and Lazio) and, in general, a very large number of events along the Apennines from Liguria to Campania (fig. 9); this area can be separated from the other seismic regions in Italy. The map of the events with $M \geq m_1 = 4.4$, shown in fig. 10, indicates that the events in the Ancona and Gargano regions can be separated in space with respect to the events located in the Apennines.

The tectonic map by Patacca et al. (1990), shows that in the Central Apennines (Toscana, Umbria, Marche) there are two almost parallel NW-SE elongated active areas (fig. 11). The alignment near to the Adriatic Sea is in a compressive state, while the other, more to the west, has an extensional character. The Gargano region has, on the other hand, a tectonic behavior characterized by the coexistence of mechanisms of dip-slip, oblique slip, and strike slip type (Patacca et al., 1990).

On the basis of these seismotectonic considerations, a new regionalization is proposed. The new regionalization (e.g. see fig. 9) includes the seismicity maxima present in the Apennines and the extensional areas oriented NW-SE, and excludes the Ancona zone and the Gargano region. The Ligurian Sea, Tyrrhenian Sea and the coasts of Toscana are also not included, since the very low seismicity in these areas does not occur in the periods just before the TIPs (fig. 5-8), and therefore does not influence the functions used by the CN algorithm.

In a first step the analysis of Keilis-Borok et al. (1990) has been repeated with the new regionalization, using the catalogue ENEL-CSEM-ING. In this case there are 4 strong events, all predicted (no failures to predict), and the total alarm period is about 32% of the total time (fig. 12).

In a second step a new catalogue has been prepared. For the period 1900-1979, the new catalogue is formed by the catalogue PFG, which is the revised version of the ENEL catalogue. From 1930, the catalogue ING has been used. The magnitude M_l (local magnitude) has been considered whenever available; if M_l is not available, the values M_I (magnitude from intensity), in PFG catalogue, and M_d (duration magnitude), in ING catalogue, have been used.

In the new catalogue the event of 7/5/1984 has a magnitude, 5.4, less than M_0=5.6, thus there are only 3 strong earthquakes. All of them have been predicted and the total alarm occupies about the 23% of the total time. This percentage is significantly less than the one determined from the analysis done with the ENEL-CSEM-ING catalogue (fig. 13).

The area considered with the new regionalization is only about the 15% of the one used by Keilis-Borok et al. (1990), therefore, the number of earthquakes is significantly reduced. The histogram Number of events-Magnitude has a minimum for M just less than 5.4. Events with such a magnitude have a return period of about 6 years. Therefore the analysis has been made using the value of M_0=5.4. In this case there are 5 strong events, 4 of which are predicted and the alarm occupies about 30% of the total time (fig. 14).

3 STABILITY

The test of the stability of the premonitory seismicity pattern and of the feasibility of the prediction has been carried out with respect to changes:
1) in the length of the learning period, 2) in catalogues, and 3) in the thresholds for the rules to declare a TIP.

The learning period, which must be at least 20 years long, is the period in which the catalogue is analyzed in order to define the values of the thresholds m_1, m_2, m_3 and the values of the functions in the periods immediately before a strong earthquake (*D* periods) and in the periods without strong earthquakes (*N* periods). The stability of the premonitory pattern has been successfully tested using two different learning periods, 1954-1980 and 1954-1986. Since in the time interval 1980-1986 there is only one *D* period the stability of the results is mainly relevant with respect to changes of m_1, m_2, m_3.

The differences which are present in the available catalogues are quite significant, has can be seem from fig. 15; for example, in the catalogue ENEL-CSEM-ING there are 4 strong earthquakes with $M \geq 5.6$, while in the PFG-ING catalogue the earthquakes with $M \geq 5.6$ are only 3. The results of the processing of both catalogues, for the two different regionalizations, and for two different values of M_0 are reported in table 2. The results are satisfactory and stable, mainly when the regionalization based also on seismotectonic considerations is used. In general, the number of failures to predict is 0 or 1, and the total alarm time is less than 35% of the total time. Only in two cases (variants 4 and 5 in table 2) there is a large number of failures to predict. In these two cases the catalogue used is the PFG-ING and the regionalization is the one based only on catalogue boundaries and completeness.

The thresholds for the rules to declare a TIP are given by equations (1). The value normally used (Keilis-Borok et al. 1990) for the parameter *E* is 4.9 and for the parameter *V* is 5, as shown in table 2. To test the stability of the premonitory pattern, the values of *E* and *V* have been changed with respect to the default values. The results obtained changing these two values, for all the variants given in table 2, are show in figure 16. The results are very stable even for variation of *E* and *V* in a rather large range. Only for extreme values of the two parameters the stability is lost.

4 PERIOD 1904-1940

The analysis of the PFG catalogue shows that information, sufficiently complete for the use of the algorithm CN, is contained also in the period 1904-1940, the incompleteness of the catalogue in the period 1941-1953 being strongly correlated with World war 2. Therefore the algorithm CN has been applied also to the period 1904-1940. The seismicity in this time interval is higher than in the period 1954-1991 and the magnitude, M_0, corresponding to events with a return period of about 6 years and to a minimum in the histogram Number of events-Magnitude, is around 6.0 (fig. 17).

In table 3, variant 1, are reported the results obtained for M_0=6.0. The number of strong events is 3, 2 of them are predicted, and the alarm occupies about 38.0% of the total time (fig. 18). If the value of M_0 is decreased to 5.6 the number of strong events becomes 7, 3 of them are predicted, and the alarm duration is equal to 22.3% of the total time (variant 4, table 3). In both cases the learning period used goes from 1904 to 1940.

Even if the level of seismicity in the earlier time interval is much higher than in the later one, the good results of the diagnosis of TIPs for each item separately indicate that self-similarity seems to characterize the two periods.

5 CONCLUSION

A significant reduction of the spatial uncertainty in the identification of a TIP has been obtained using a regionalization based not only on catalogue completeness but also on seismotectonic evidences. The use of such regionalization, in general, increases also the stability of the premonitory pattern.

All the stability tests made changing the learning period for the definition of the thresholds m_1, m_2, and m_3, the catalogue, the thresholds for the rules to declare a TIP, and the regionalization, show that the CN algorithm in central Italy gives very stable results.

The analysis of the period 1904-1940 shows that even when the catalogue completeness threshold corresponds to a magnitude as high as 4.0 the CN algorithm gives still useful information. The comparison of the results obtained in the period 1904-1940 and in the period 1954-1991 supplies a further evidence in favour of the existence of self-similarity in the occurrence of earthquakes (e.g. Kagan and Knopoff, 1981).

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PFG, Catalogo dei terremoti italiani dall'anno 1000 al 1980 (ed. Postpischl, D.)(CNR-P.F. Geodinamica, 1985).

Table 1. Functions used in the algorithm CN.

Table 2. Results of the stability tests of the premonitory seismicity pattern. The old regionalization is the one proposed by Keilis-Borok et al. (1990) and the new is the regionalization proposed in this paper. The old catalogue is the ENEL-CSEM-ING and the new catalogue is the PFG-ING. A is the number of events to be predicted, B is the number of failure to predict, C is the percent of total time occupied by alarms.

Table 3. Results obtained from the analysis of two different periods, 1904-1940 and 1954-1990, characterized by different seismicity levels. A is the number of events to be predicted, B is the number of failure to predict, C is the percent of total time occupied by alarms.

Figure 1. Diagram Number of events-Magnitude, with step of 0.2 in magnitude, in the years 1950-1990 for the new regionalization proposed in this paper. Catalogue PFG-ING.

Figure 2. Epicenters recorded in the period 1950-1990; small dots indicate events with magnitude $M \geq 4.4$; large dots indicate events with magnitude $M \geq M_0 = 5.6$; the poligon indicates the boundaries of the regionalization proposed by Keilis-Borok et al. (1990).

Figure 3. Results of the diagnosis of TIPs, for the regionalization of fig. 2, as deduced from the catalogue ENEL-CSEM-ING; $M_0=5.6$. The time of occurence of a strong earthquake is indicated by an arrow and the number above it gives the magnitude; TIPs are indicated by block rectangles (Keilis-Borok et al., 1990).

Figure 4. Map showing the boundaries of the Adriatic microplate after Horvath and Channel (1976) and other geographycal regions mentionated in the text.

Figure 5. Main shocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP, and strong earthquake (large dot). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

Figure 6. Main shocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP. No strong earthquake occurred during the TIP (false alarm). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

Figure 7. Main shocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP. No strong earthquake occurred during the TIP (false alarm). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

Figure 8. Main shocks (small dots) with $M \geq m_1 = 4.4$ for three years before the TIP, and strong earthquakes (large dots). The polygon indicates the boundaries of the regionalization. Only the events inside the PFG polygon are considered.

Figure 9. New regionalization for the diagnosis of TIPs superimposed to the map of seismicity. In the map is represented the total number of earthquakes smoothed within a 0.6° diameter circle. Each smoothing circle is centered on the knots of a grid of 0.2°x0.2°. Different shading correspond to the ranges of the number of the events shown in the scale. The main shocks catalogue from 1000 to 1990 has been used.

Figure 10. New regionalization for the diagnosis of TIPs and main events with magnitude $M \geq 4.4$. Catalogue ENEL-CSEM-ING.

Figure 11. New regionalization superimposed to the seismotectonic map of Patacca et al. (1990): 1) extensional areas, 2) compressional areas, 3) transition areas and 4) areas of fracture in foreland zone.

Figure 12. Results, based on catalogues ENEL-CSEM-ING, of the diagnosis of TIPs for the new regionalization; M_0=5.6. The time of occurence of a strong earthquake is indicated by an arrow and the number above it gives the magnitude; TIPs are indicates by block rectangles.

Figure 13. Results, based on catalogues PFG-ING, of the diagnosis of TIPs for the new regionalization; M_0=5.6. The time of occurence of a strong earthquake is indicated by an arrow and the number above it gives the magnitude; TIPs are indicated by block rectangles.

Figure 14. Results, based on catalogues PFG-ING, of the diagnosis of TIPs for the new regionalization; M_0=5.4. The time of occurence of a strong earthquake is indicated by an arrow and the number above it gives the magnitude; TIPs are indicates by block rectangles.

Figure 15. Diagram Number of events-Magnitude, with step of 0.5 in magnitude, for catalogues ENEL-CSEM-ING (grey bars) and PFG-ING (black bars).

Figure 16. Diagrams Percent of failures to predict-Percent of TIPs duration obtained varying the parameters V and E in the tests of Table 5. Between brackets the values of V and E are given in the order.

Figure 17. Diagram Number of events-Magnitude, with step of 0.2 in magnitude, in the years 1900-1940 for the new regionalization proposed in this paper. Catalogue PFG-ING.

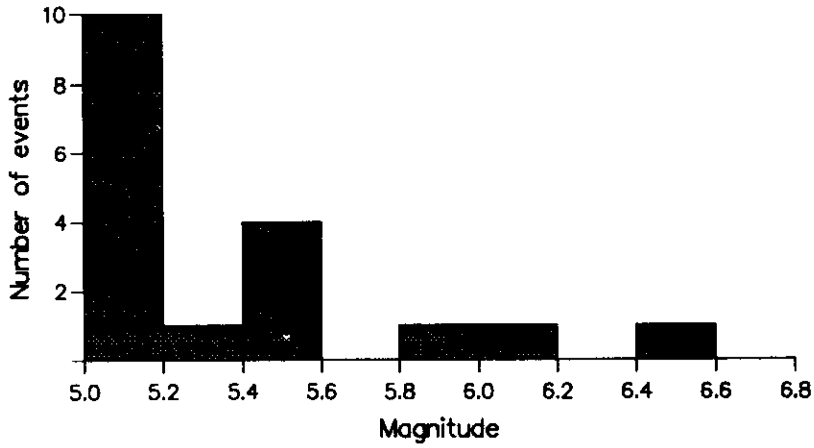
Figure 18. Results, based on catalogues PFG-ING, of the diagnosis of TIPs for the new regionalization; and for two different thresholds M_0. The time of occurence of a strong earthquake is indicated by an arrow and the number above it gives the magnitude; TIPs are indicates by block rectangles.

SIGMA(t)	SIGMA(t)=$\Sigma 10^{\beta(M_i-\alpha)}$; the main shocks with $m_i \le M_i \le M_0$-0.1 and origin time (t-3 years)$\le t_i \le$t are included in the summation; α=4.5, β=1.00.
S_{max}(t)	S_{max}(t)=max{S_1/N_1, S_2/N_2, S_3/N_3} where S_j is calculated as SIGMA(t) for the events with the origin time (t-j years)$\le t_i \le$t-(j-1) years), and N_j is the number of earthquakes in the sum.
Z_{max}(t)	Z_{max}(t)=max{$Z_1/N_1^{2/3}$, $Z_2/N_2^{2/3}$, $Z_3/N_3^{2/3}$} where Z_j is calculated as S_j, but with β=0.5 and N_j is the number of earthquakes in the sum.
N_2(t)	Number of main shocks with M$\ge m_3$, which occurred in the time interval (t-3 years, t).
N_3(t)	Number of main shocks with M$\ge m_2$, which occurred in the time interval (t-10 years, t-7 years)
K(t)	K(t) =K_1-K_2, where K_i is the number of main shocks with $M_i \ge m_2$ and origin time (t-2·j years)$\le t_i \le$(t-2·(j-1) years).
B_{max}(t)	Maximum number of aftershocks for each main shock, counted within a radius of 50 km for the first 2 days after the main shock and for M>M_0-3.6.
G(t)	G(t)=1-P, where P is the ratio of the number of the main shocks with $M_j \ge m_2$ ($m_2 > m_1$) to the number of the main shocks with $M_j \ge m_1$. Only main shocks with origin time (t-1 year)$\le t_j \le$t are considered.
q(t)	q(t)=$\Sigma^{6}_{j=1}$ max{0,6a_2-n_j}, where a_2 is the average annual number of main shocks with $M_i \ge m_2$, n_j is the number of main shocks with $M_j \ge m_2$ and origin time (t-(8+j) years)$\le t_j \le$(t-(2+j) years).

N°	M_0		Regionalization		Learning period		Catalog used for learning		Catalog used for analysis		Threshold Parameters		Results		
	5.4	5.6	old	new	1954 1980	1954 1986	old	new	old	new	V	E	A	B	C
1		X	X			X	X		X		5	4.9	6	1	26
2		X	X			X		X	X		5	4.9	6	1	33.3
3		X	X			X	X			X	5	4.9	4	1	29.6
4		X	X			X		X		X	5	4.9	4	3	27.4
5	X		X		X			X		X	5	4.9	8	4	26.9
6	X			X	X			X		X	5	4.9	5	1	37.4
7	X			X		X		X		X	5	4.9	5	1	31.9
8		X		X	X			X		X	5	4.9	3	0	23.7
9		X		X		X		X	X		5	4.9	4	0	31.5
10		X		X		X		X		X	5	4.9	3	0	23.3

Table 2

N°	M_0		Learning period		Analysis period		Threshold parameters		Results		
	5.6	6.0	1904 1940	1954 1980	1904 1940	1954 1990	V	E	A	B	C
1		**X**	**X**		**X**		5	4.7	3	1	38.0
2		**X**	**X**			**X**	5	4.7	2	1	33.6
3	**X**			**X**		**X**	5	4.9	3	0	23.7
4	**X**		**X**		**X**		5	3.1	7	4	22.3
5	**X**			**X**	**X**		5	3.1	7	3	40.0
6	**X**		**X**			**X**	5	4.9	3	2	16.1



10
8
6
4
2
Number of events
5.0
5.2
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6.0
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6.8
Magnitude

ENEL-CSEM-ING, 1950-1990.

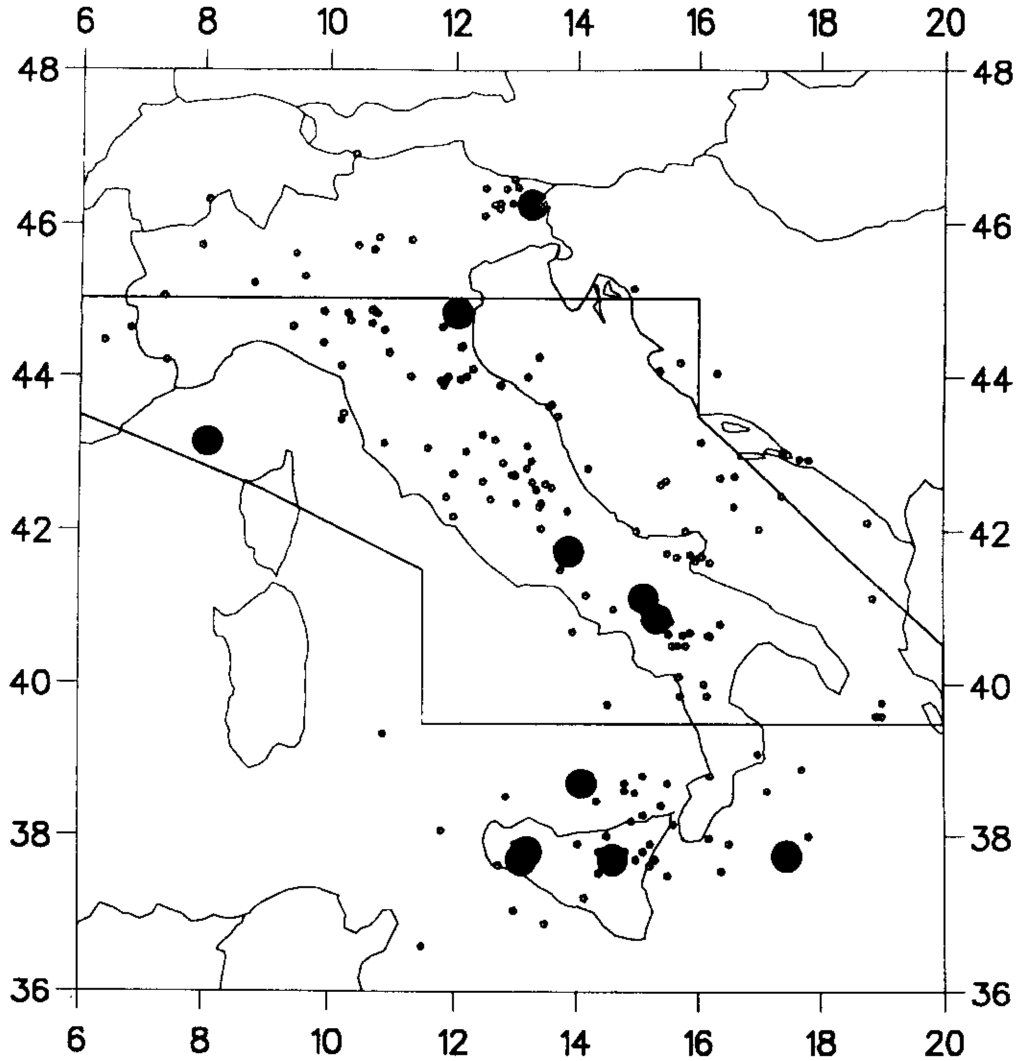
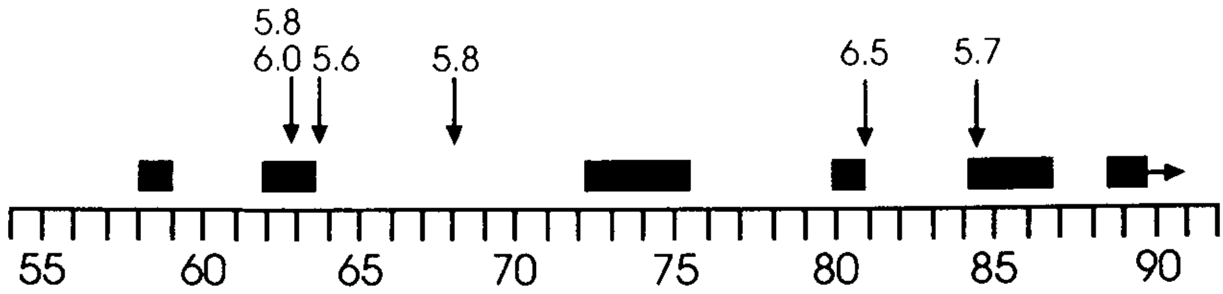


FIG 2

ENEL-CSEM-ING (1954-1989)



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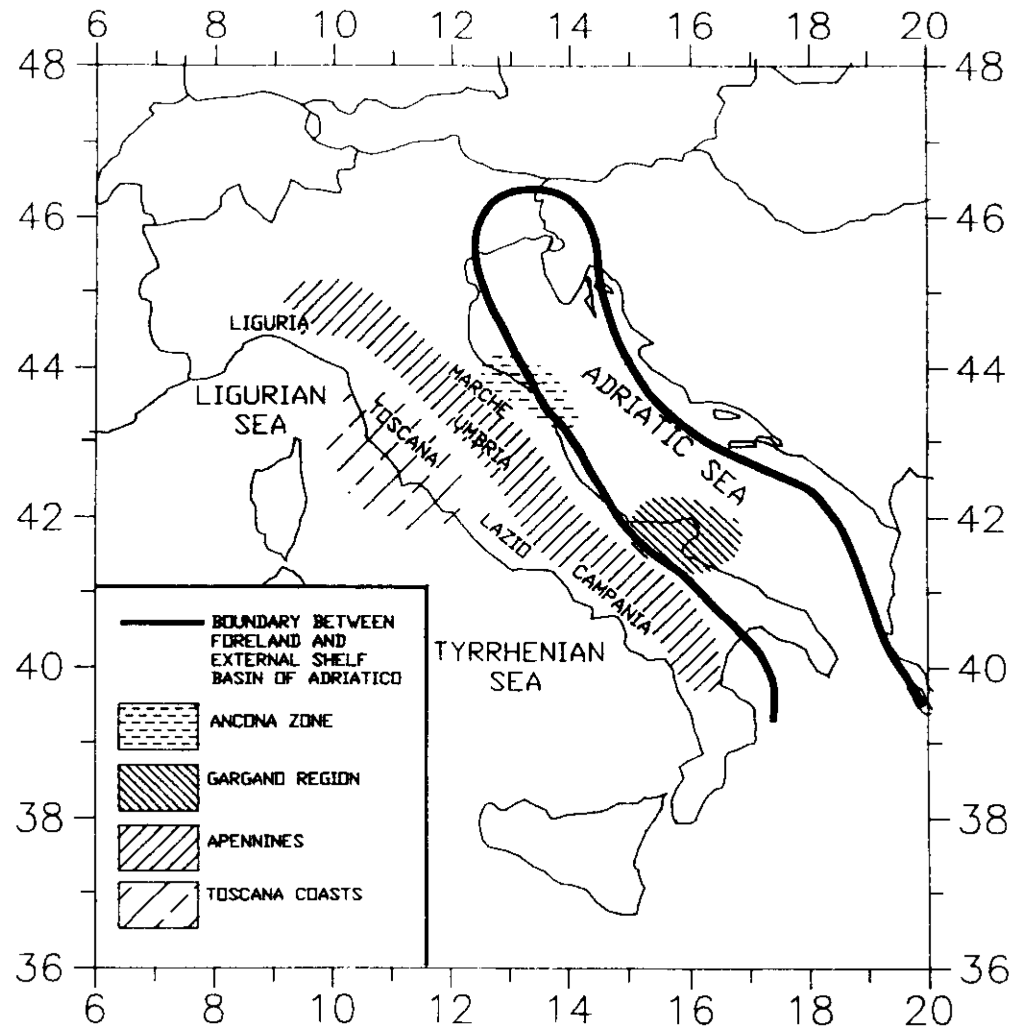
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6 8 10 12 14 16 18 20
48 46 44 42 40 38 36

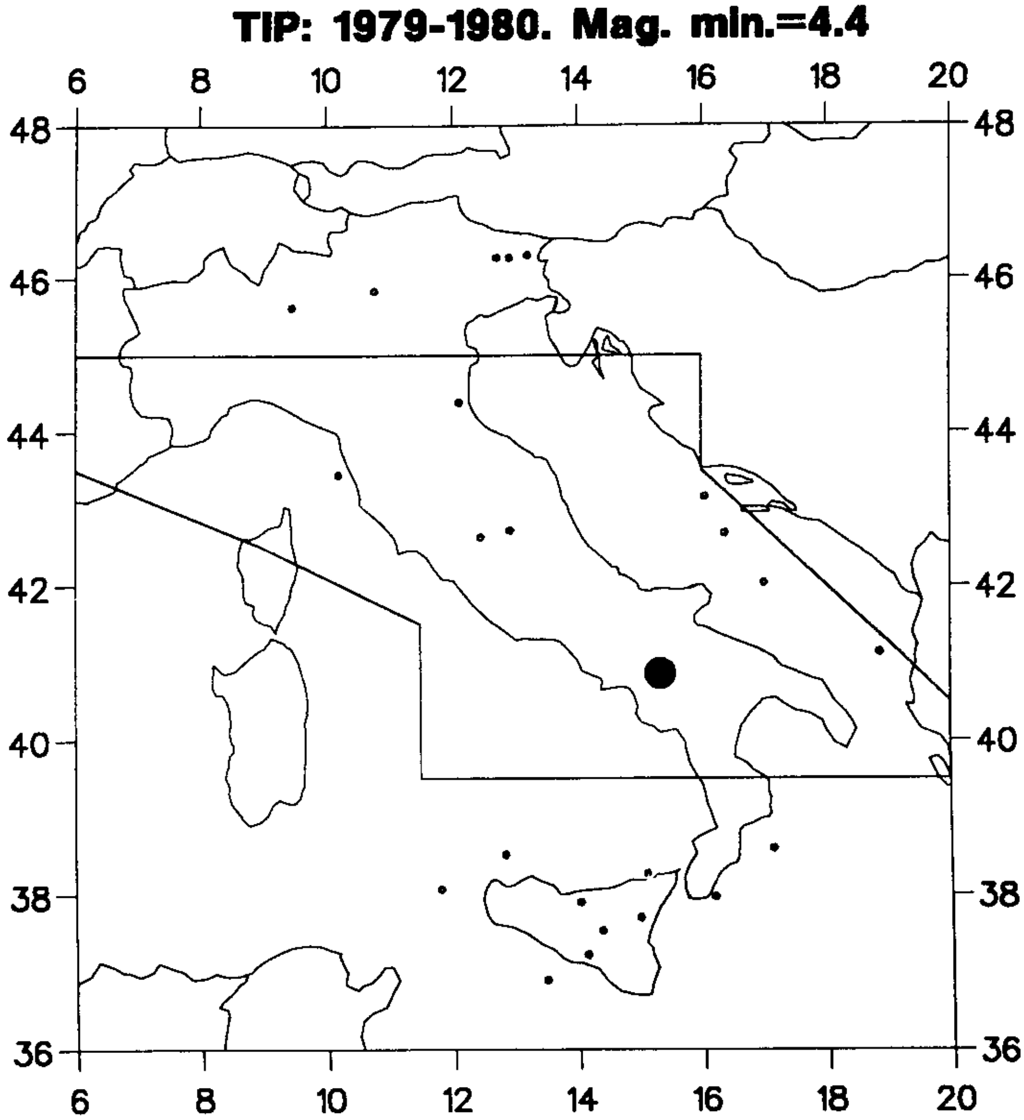


FIG.5

TIP: 1958-1959. Mag. min.=4.4

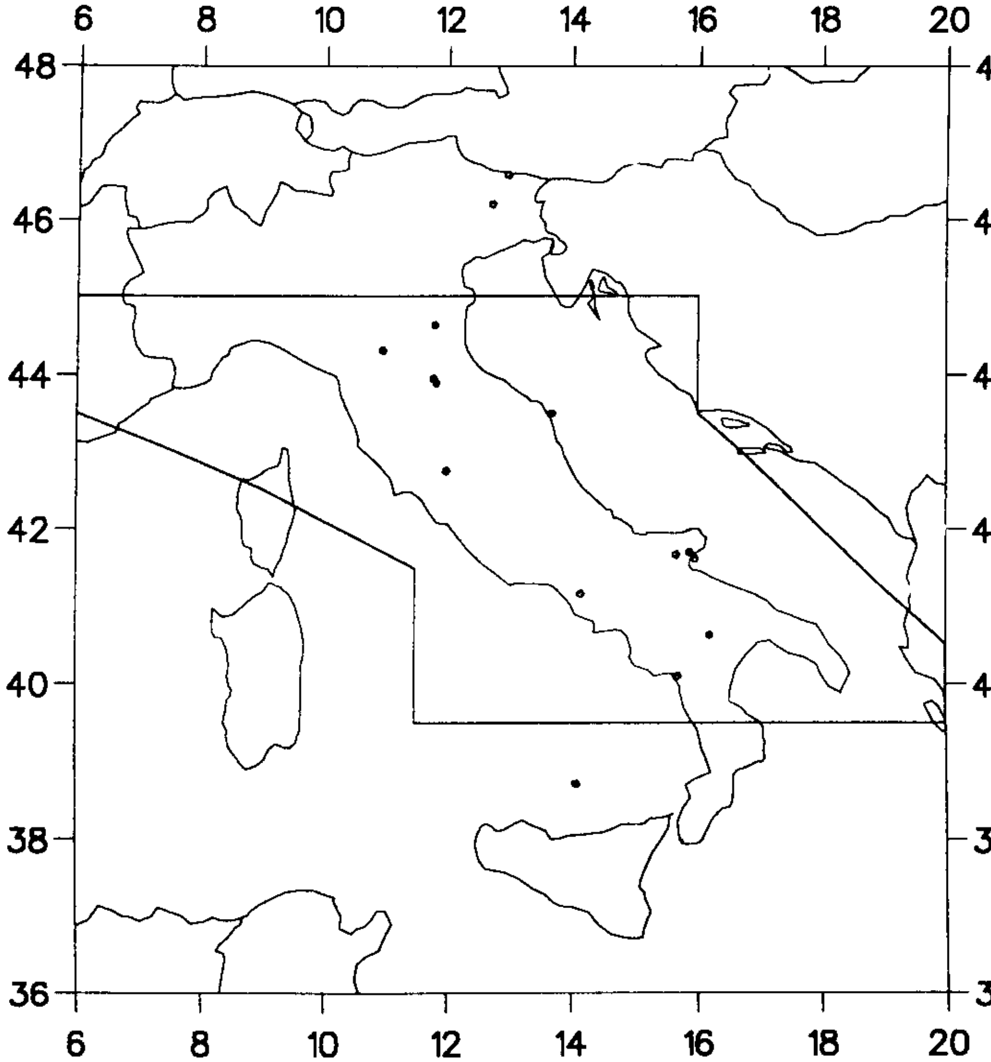


FIG 6

TIP: 1972-1975. Mag. min.=4.4

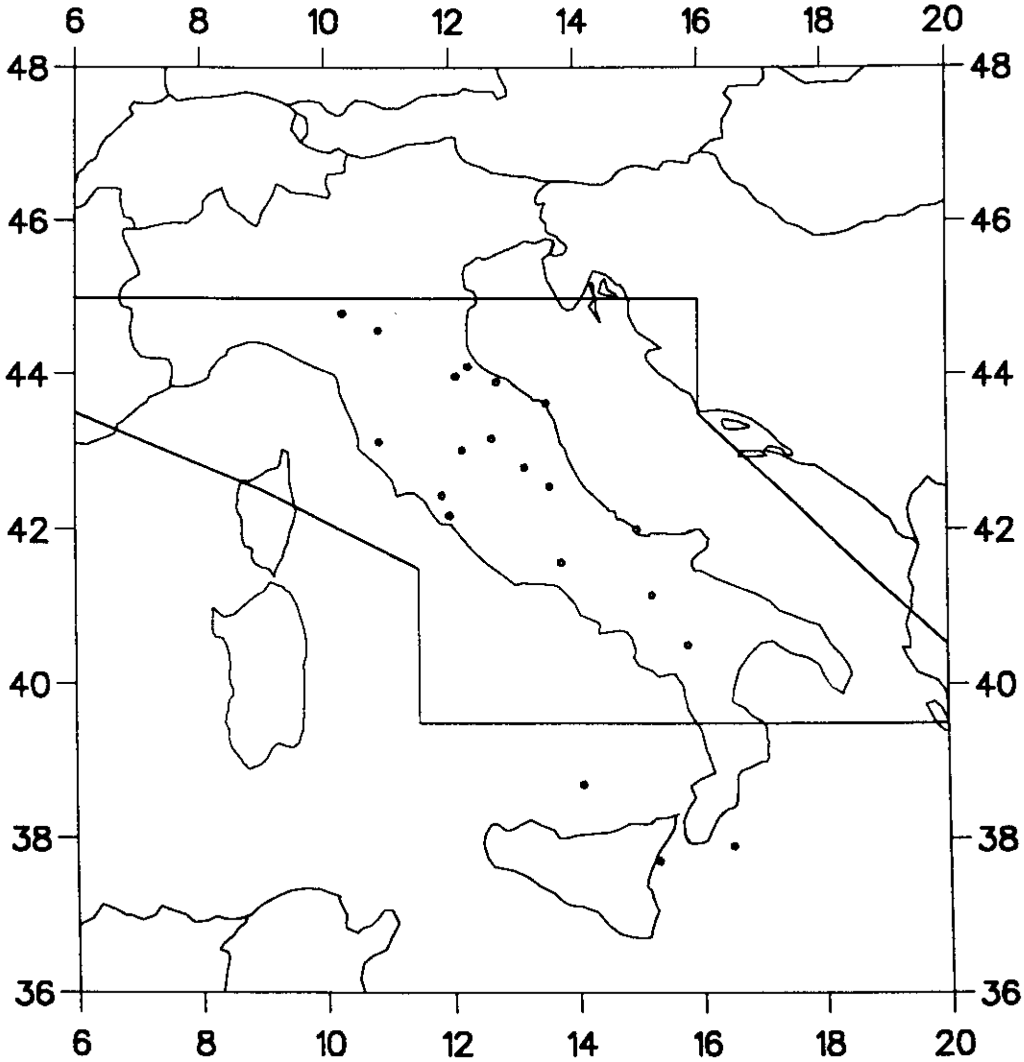


FIG 7

TIP: 1961-1963. Mag. min.=4.4.

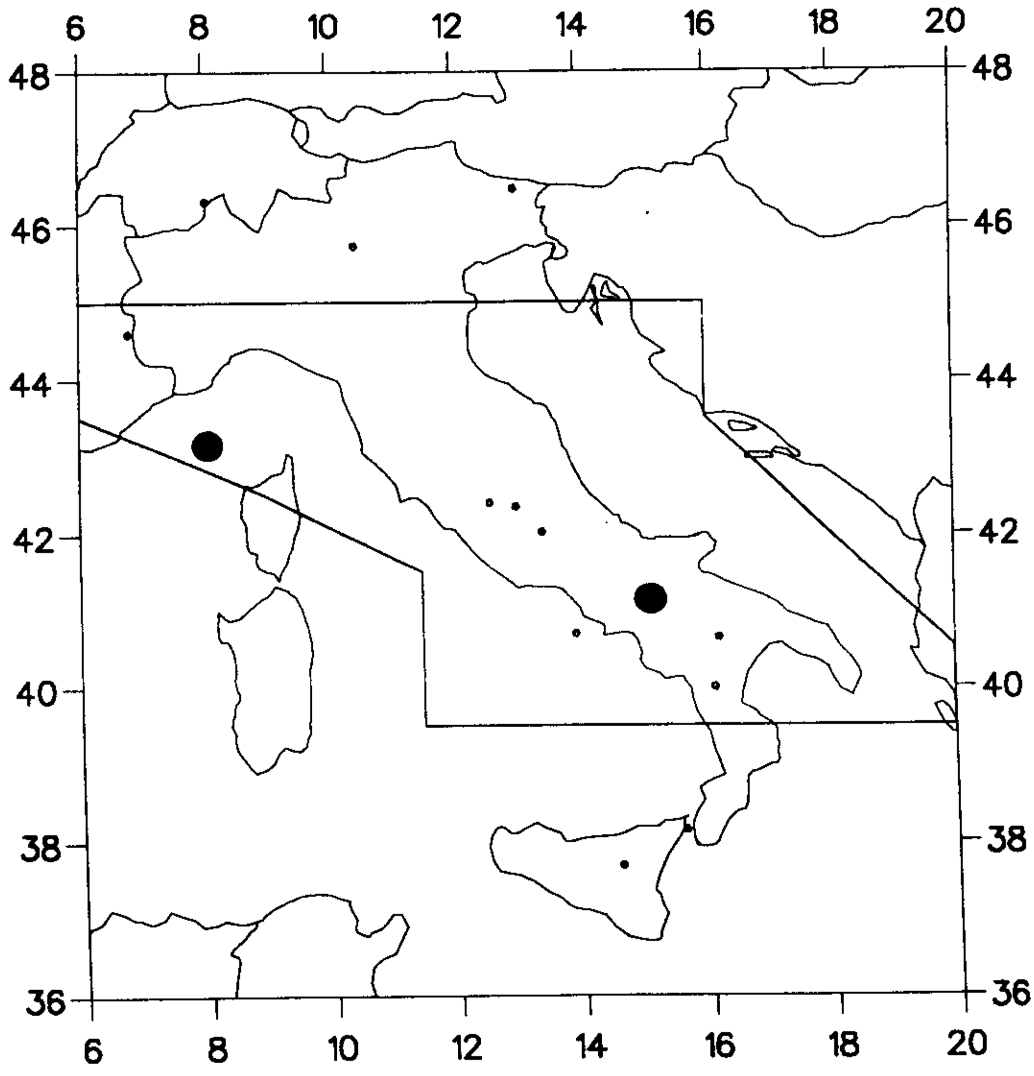


FIG 3

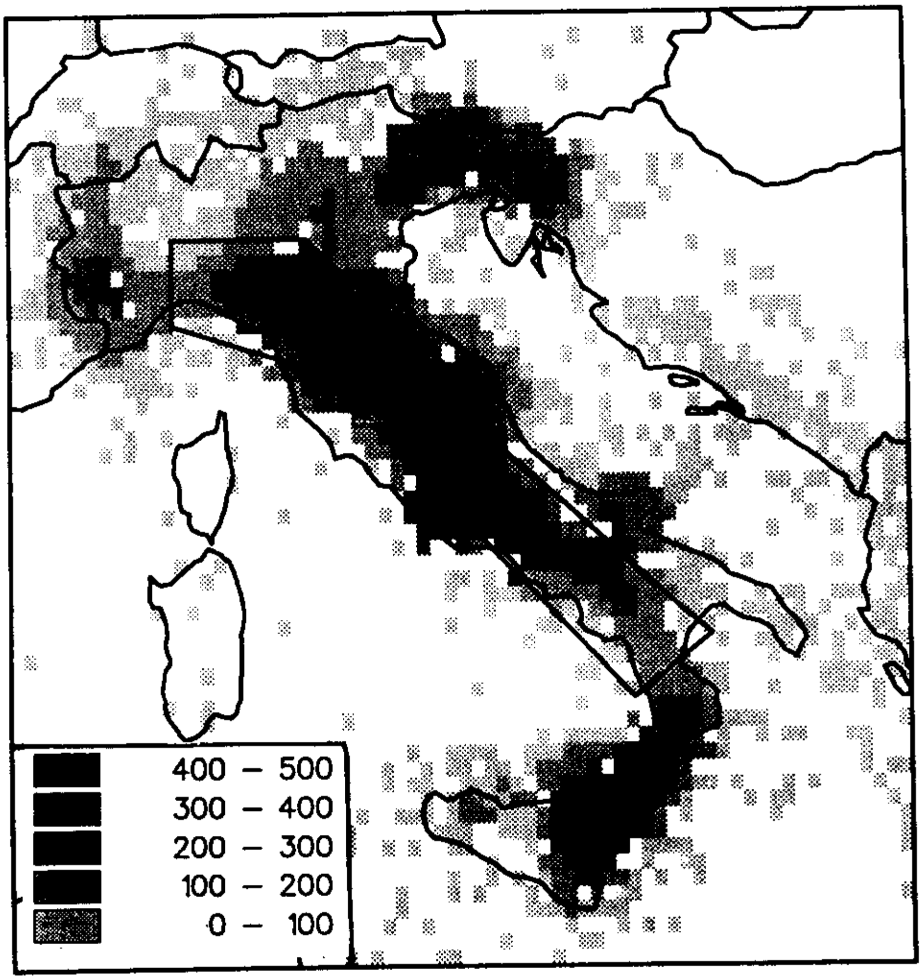


FIG 4

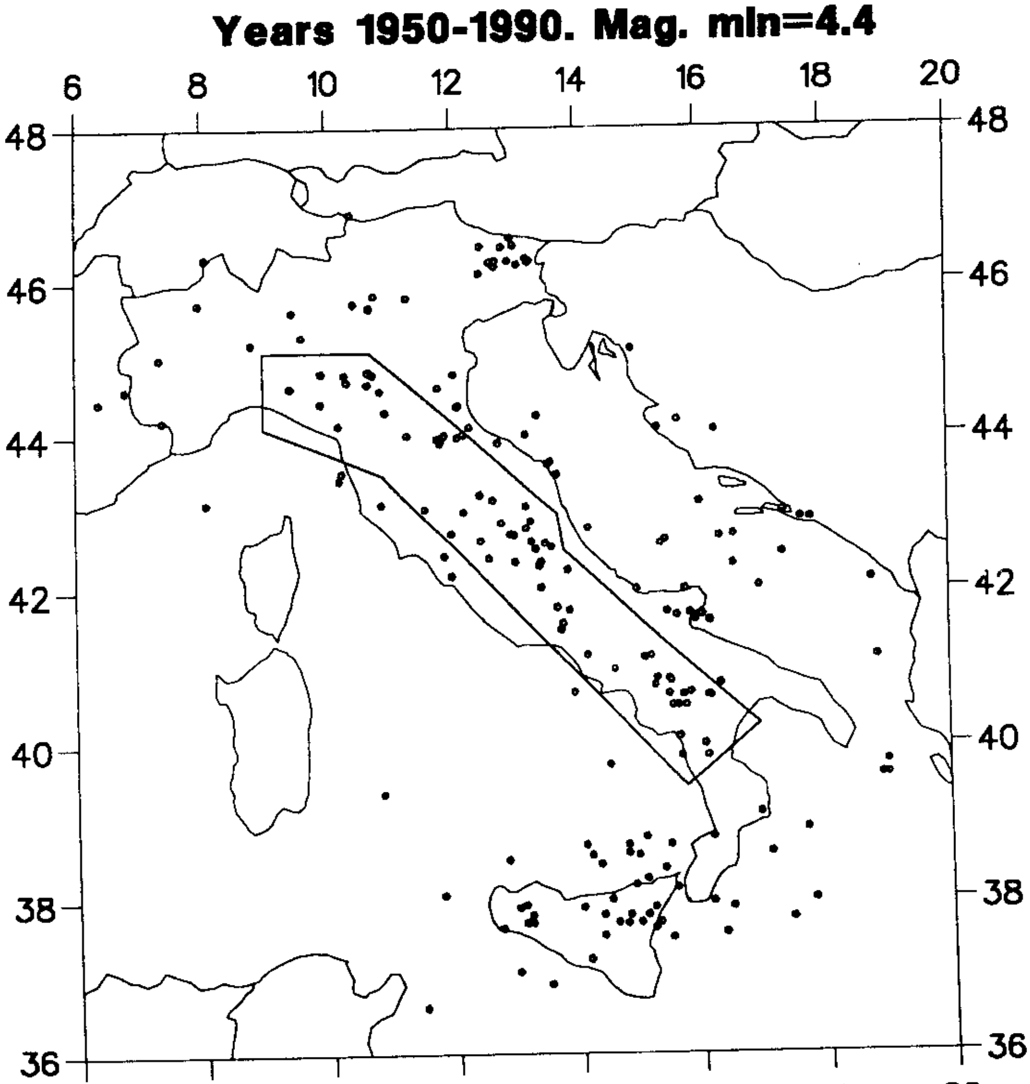


FIG 10

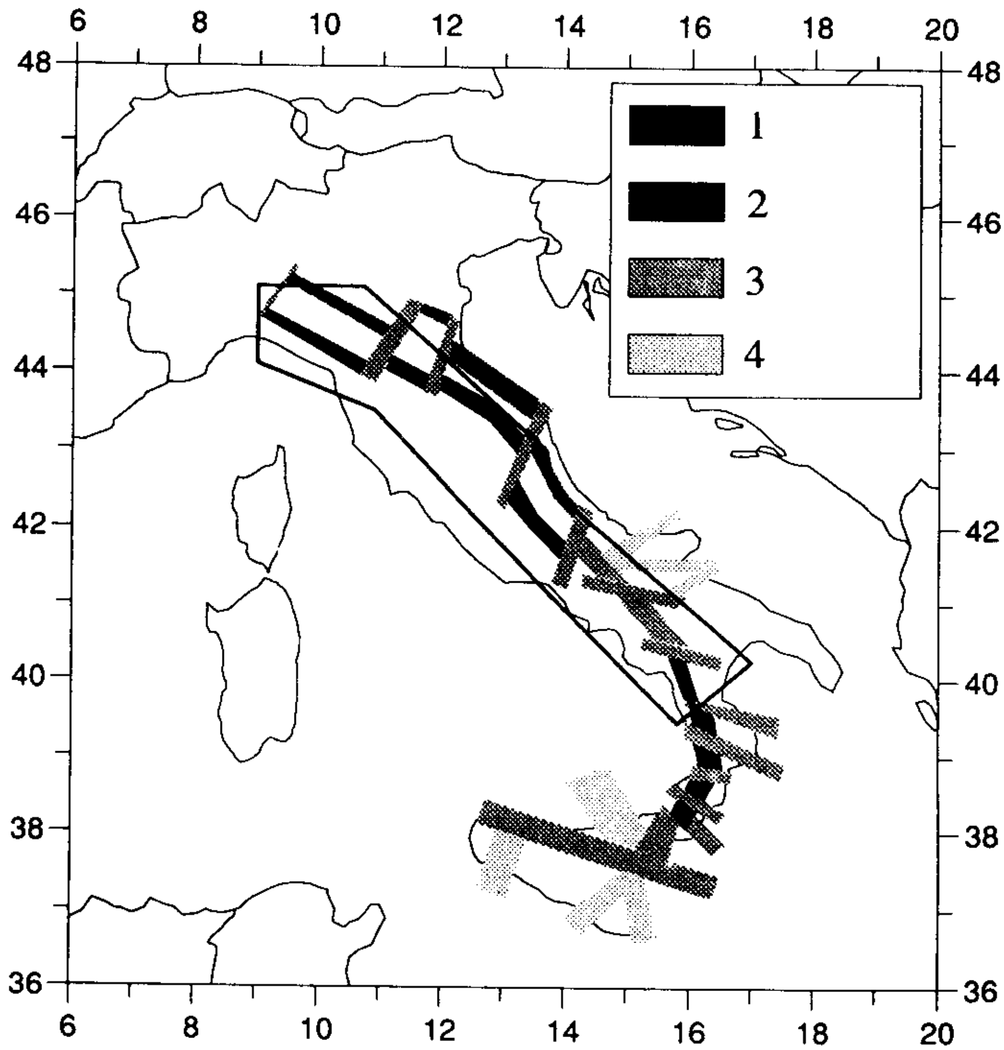


FIG 11

ENEL-CSEM-ING (1954-1991)

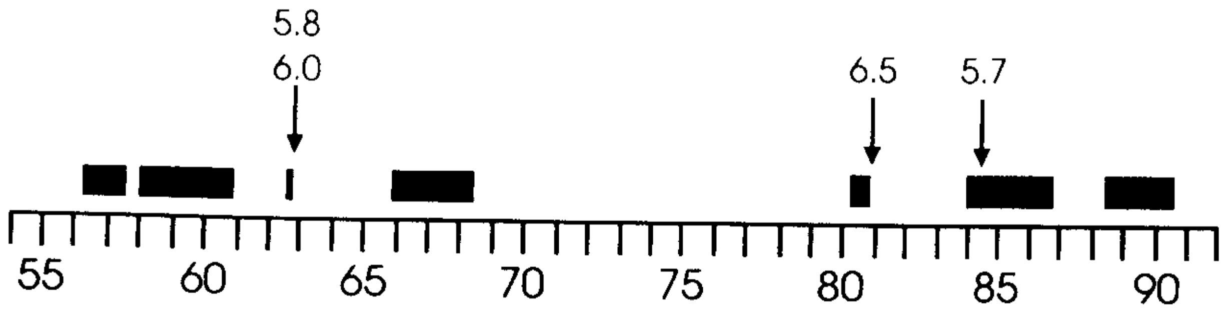


Fig 12

PFG-ING (1954-1991)

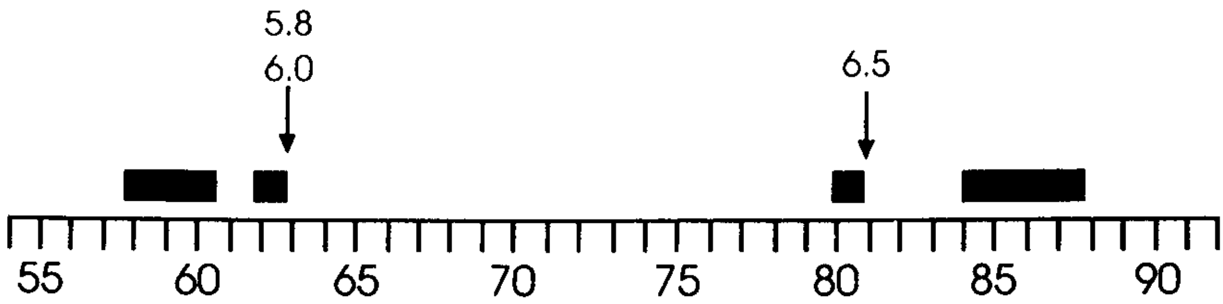


Fig. 12

PFG-ING (1954-1991)

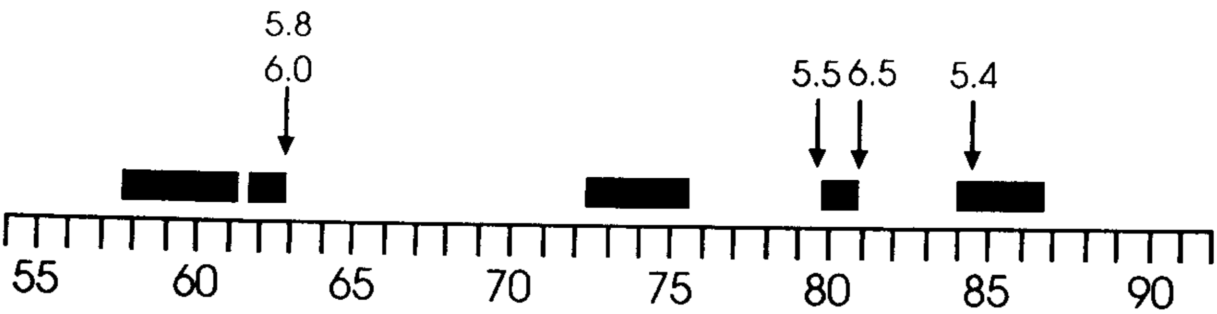
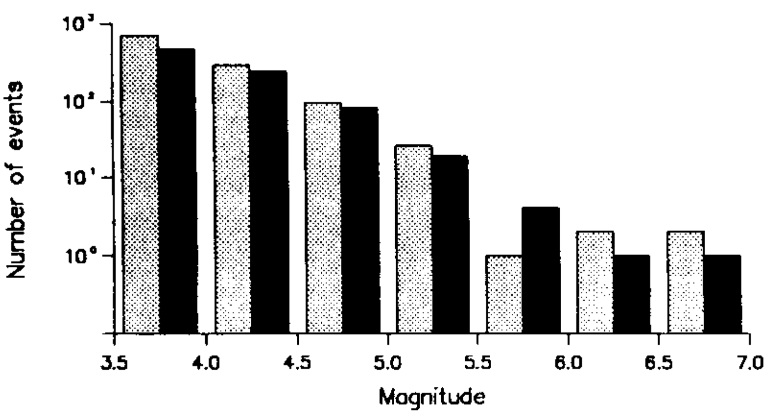


Fig. 4

Fig 15



10³
10²
10¹
10⁰
Number of events
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
Magnitude

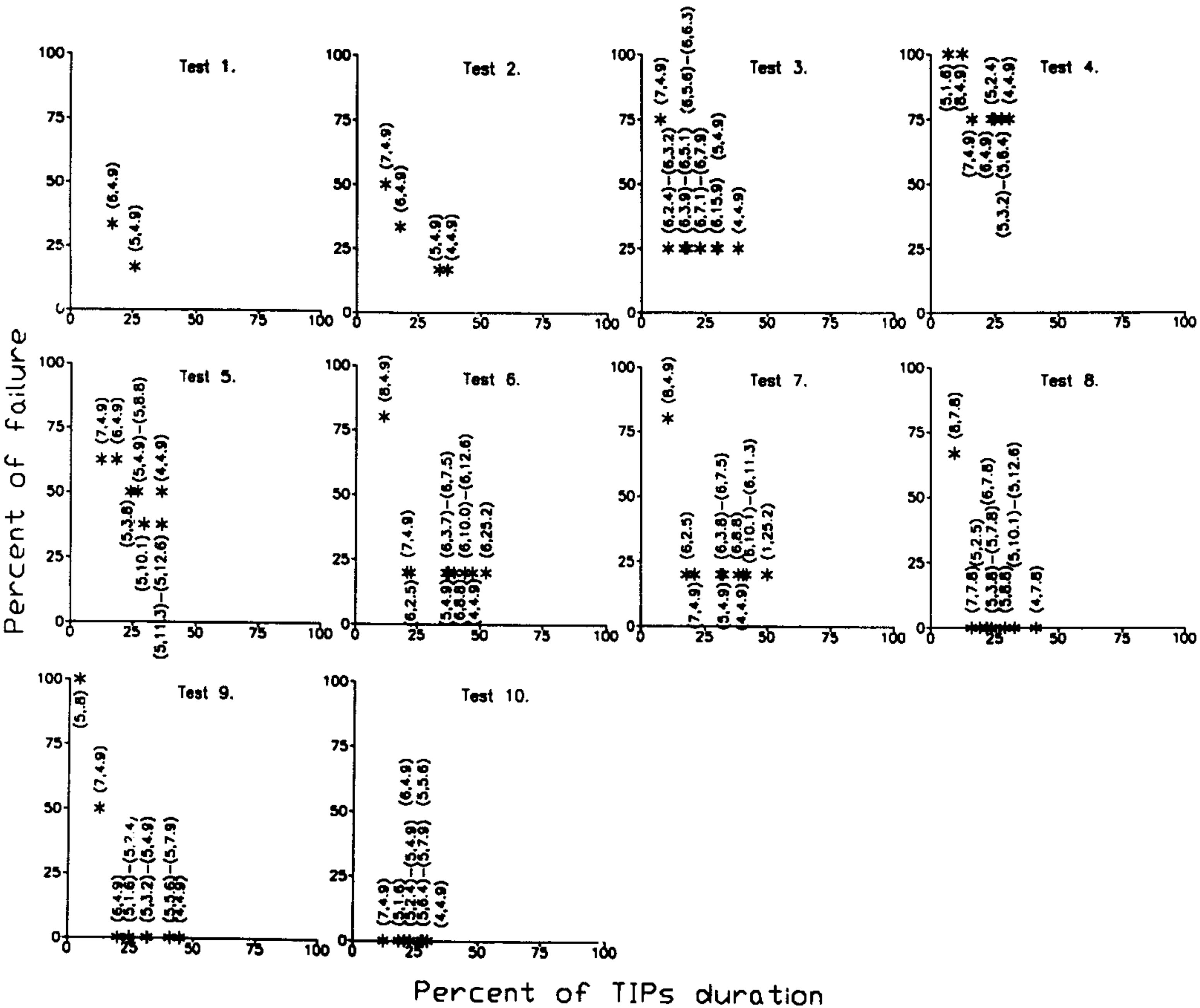
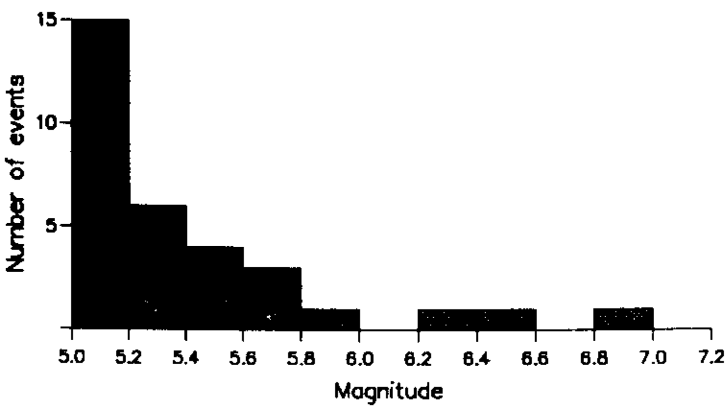
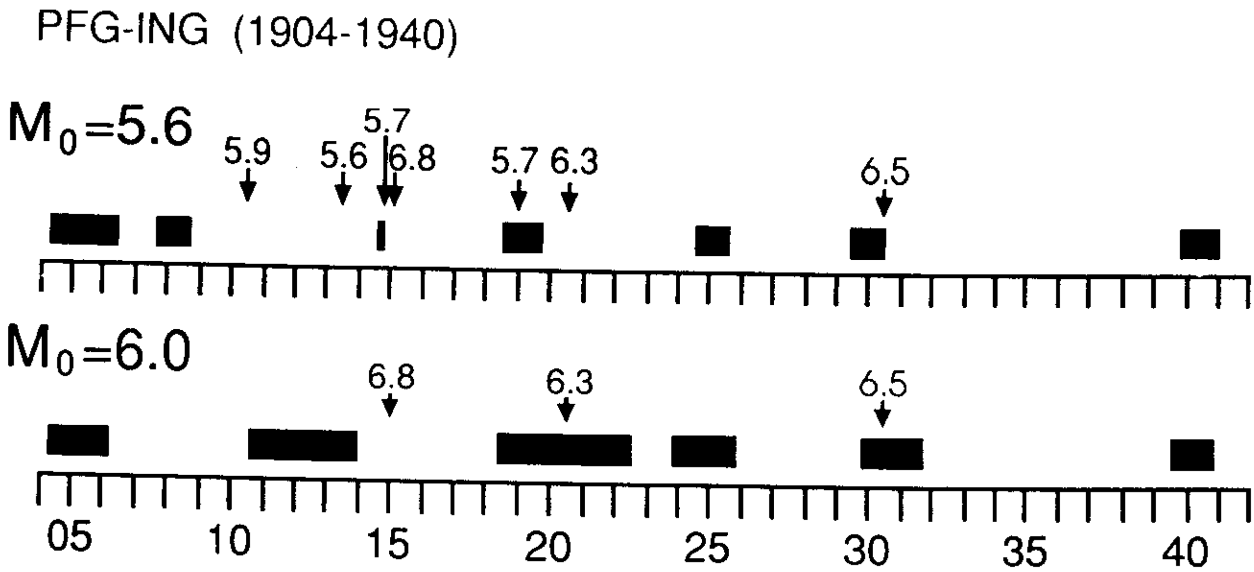

Percent of failure
Percent of TIPs duration
Test 1.
Test 2.
Test 3.
Test 4.
Test 5.
Test 6.
Test 7.
Test 8.
Test 9.
Test 10.

Fig. 4



15
10
5
Number of events
5.0
5.2
5.4
5.6
5.8
6.0
6.2
6.4
6.6
6.8
7.0
7.2
Magnitude



PFG-ING (1904-1940)
M0=5.6
5.9
5.6
5.7
6.8
5.7
6.3
6.5
M0=6.0
6.8
6.3
6.5
05
10
15
20
25
30
35
40