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Analysis of the seismicity of Southeastern Sicily: a proposed tectonic interpretation

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Abstract
Southeastern Sicily is one of the Italian regions with high seismic risk and is characterised by the occurrence in the past of large destructive events (M_s = 6.4-7.3) over a territory which is densely urbanised today. The main earthquakes were analysed and some minor damaging shocks reviewed to investigate the main seismogenic features of the region. The comparison between the pattern of seismicity and evidence of Quaternary tectonics allowed us to propose a first tentative, tectonic interpretation of the earthquakes. On the whole, the seismicity of SE Sicily seems distributed along regional fault systems which have had a role in the recent geodynamic evolution of the area. The Malta escarpment, the only structure whose late Quaternary-recent activity is currently known, appears the most probable source for earthquakes with about 7 magnitude. Although no evidence of tectonics subsequent to the middle Pleistocene is available for them, the Scicli line and the NE-SW fault system delimiting the northern sector of the Hyblean plateau seem seismically active with events with maximum magnitude of 5.2 and 6.4, respectively.

Key words *historical seismicity – macroseismics – source parameters – Quaternary tectonics – seismogenic faults – Hyblean plateau - SE Sicily*

1. Introduction

Eastern Sicily is one of the most seismically active regions of Italy. In general, earthquakes which severely affect the area are explained in the frame of the post-collision processes between the African plate margin and the Calabrian arc (fig. 1). On a local scale however, the tectonic framework resulting from regional master faults and associated second order structures is so complicated in terms of geometry, dynamics and kinematics that no interpretation has been unequivocally accepted so far.

A few large earthquakes in NE Sicily have been associated with specific faults (Barbano *et al.*, 1979; Ghisetti, 1992; Valensise and Pantosti, 1992), but similar investigations in the Hyblean area are limited (D'Addezio and Valensise, 1991; Monaco and Tortorici, 1995). This is probably because of the low number of large instrumentally recorded earthquakes, the interpretative problems of macroseismic historical data, the lack of reported surface faulting evidence as well as the poor knowledge of late Quaternary-Holocene tectonics. Some preliminary analyses on the seismotectonic features of SE Sicily were made by Barbano *et al.* (1978) and Carbone *et al.* (1982), but no specific association between earthquakes and faults has been suggested. On a larger scale Scandone *et al.* (1992) proposed, in the framework of the Italian territory hazard

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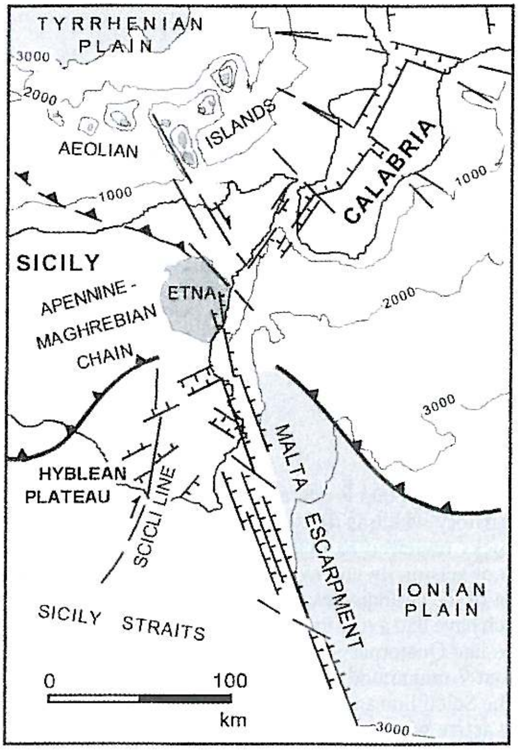


Fig. 1. Sketch map of the regional geological setting of Eastern Sicily and location of the Hyblean plateau.

assessment, two wide seismogenic zones in SE Sicily: the ZS 78, which encompasses the NE-SW fault system occurring along the northwestern margin of the Hyblean plateau (the Scicli line is not considered active); the ZS 79, which encloses the Malta escarpment and other associated structures developing along the Ionian coast.

In recent years, many studies have been carried out on the historical seismicity of this area. In particular two main groups have worked on this topic: Boschi *et al.* (1995, 1997) restudied the strongest earthquakes (intensity $I >$ VIII); Barbano *et al.* (1996) and Monachesi and Stucchi (1998) revised most of the events with VI $\leq I \leq$ VIII of the Italian catalogue (Postpischl, 1985). Some other less damaging earthquakes, which were not recently revised, have been analysed by us on the basis of original historical information and for most of them intensity maps have been compiled and new source parameters estimated. On the other hand most of the geological literature on the region takes a very broad-scale approach and is altogether generic about active tectonics, providing only very little evidence for late Pleistocene to recent activity, and reflects the poor attention devoted to the tectonic problem.

This paper tries to give a first tentative tectonic interpretation of the earthquakes using, as a starting-point, epicentres and intensity datapoint distribution of the damaging events and searching faults which for location, Quaternary activity, size, and kinematics may represent consistent sources.

2. Long-term seismicity

SE Sicily was hit in the pre-instrumental period by two earthquakes with estimated magnitude about 7: the February 4, 1169 and January 11, 1693 shocks. Since 1000 to date, just four other earthquakes in the area have exceeded magnitude 5.8: the July 7, 1125, the December 10, 1542, the January 9, 1693 and the February 20, 1818 events. In the same period six shocks had a magnitude between 5.0 and 5.8 (table I); earthquakes below this magnitude threshold are not frequent (Camassi and Stucchi, 1997). As shown by Azzaro *et al.* (1999) from the historical point of view there should be no gaps of information in the last 1000 years for destructive events ($M_s \geq 5.2$) and the catalogue may be considered complete with reference to the earthquakes above the damage threshold (fig. 2). Long-term seismicity is mainly distributed in two sectors: along the Ionian coast, where the events have also reached $M_s \geq 6.0$; in the inner area with earthquakes with $M_s \leq 5.5$ (fig. 3). Although short-term seismicity may not be representative of seismicity as a whole, 1986-1995 instrumental data (Salvi *et al.*, 1996) also show events more frequently occurring along the eastern coastal sector, where the 1990 earthquake $M_s = 5.3$ also took place (Amato *et al.*, 1995).

A summary of earthquakes analysed in this study is reported in table I. The source parame-

Table I. Main damaging earthquakes in SE Sicily and related source parameters. Epicentres are retrieved from Camassi and Stucchi (1997), those marked with an asterisk from Boschi *et al.* (1997). In italics parameters revised in this study, in bold instrumental observations. See text for further explanations. Other sources used for the revision: [1] *Corriere di Catania* (1903); *Giornale di Catania* (1903); Agamennone (1905); Arcidiacono (1905); [2] Martinelli (1912); [3] Caloi (1942); [4] Azzaro *et al.* (1992); *Bollettino Macrosismico* (1990); *La Sicilia* (1990). Sz = seismogenic zone according to Scandone *et al.* (1992).

Year	Month	Day	Epicentral area	I_0 (MCS)	Lat.	Long.	Sz	M_S	M_r	M_E	M_0 (dyne·cm)	References
1125	6	7	Siracusa	VIII-IX	37.061	15.296*	79	*5.9*	5.9		8.9E + 24	Boschi *et al.* (1997)
1169	2	4	Sicilia Orientale	XI	37.333	15.200	79	7.3	5.6	8.3	1.1E + 27	Lombardo (1985)
1542	12	10	Sortino	X	37.214	14.944*	79	6.4	6.6	6.3	5.0E + 25	Boschi *et al.* (1995)
1624	10	3	Mineo	VIII	37.267	14.733	78	5.5	5.6		2.2E + 24	Barbano *et al.* (1996)
1693	1	9	Sicilia Orientale	VIII-IX	37.185	15.015*	79	*5.9*	6.1		8.9E + 24	Boschi *et al.* (1995)
1693	1	11	Sicilia Orientale	X-XI	37.443	15.192	79	7.0	7.4	7.0	4.0E + 26	Boschi *et al.* (1995)
1698	4	12	Vizzini	VII	37.217	14.767	78	5.0			4.0E + 23	Barbano *et al.* (1996)
1717	4	4	Vittoria	VI-VII	36.950	14.533	78	4.7			1.4E + 23	Barbano *et al.* (1996)
1727	1	7	Noto	VII-VIII	36.883	15.067	79	5.2			7.9E + 23	Barbano *et al.* (1996)
1818	2	20	Catanese	IX	37.616	15.099	79	6.2	6.2	5.8	2.5E + 25	Boschi *et al.* (1995)
1818	3	1	Monti Iblei	VII-VIII	37.173	14.803*	78	5.2	5.9		7.9E + 23	Boschi *et al.* (1995)
1846	4	22	Catania	V-VI	37.500	15.083	79	4.2			2.5E + 22	Barbano *et al.* (1996)
1848	1	11	Augusta	VIII	37.217	15.233	79	5.5			2.2E + 24	Barbano *et al.* (1996)
1878	10	4	Mineo	*VI-VII*	*37.266*	*14.691*	78	*4.7*			1.4E + 23	This study
1895	4	13	Vizzini	*VI-VII*	*37.095*	*14.677*	78	*4.7*			1.4E + 23	This study
1898	11	3	Caltagirone	*V-VI*	*37.172*	*14.542*	78	*4.2*			2.5E + 22	This study
1903	2	10	Noto	VI	36.850	15.000	79	4.4			5.0E + 22	Monachesi and Stucchi (1998)
1903	7	13	Niscemi	V-VI	*37.142*	*14.566*	78	4.2			2.5E + 22	This study [1]
1909	1	2	Caltagirone	VI	*37.231*	*14.520*	78	4.4			5.0E + 22	This study [2]
1937	3	6	Vittoria	V-VI	*36.904*	*14.750*	78	4.2			2.5E + 22	This study [3]
1949	10	8	Modica	VI-VII	36.867	14.983	78	4.8			2.0E + 23	This study
1959	12	23	Piana di Catania	VI-VII	*37.428*	*14.890*	78	4.7			1.4E + 23	This study
1980	1	23	Modica	V-VI	36.880	14.740	78	**4.0**			1.3E + 22	Patanè and Imposa (1987)
1990	10	29	Canale di Malta	*V-VI*	*36.402*	*14.774*	78	**4.0**			1.3E + 22	This study [4]
1990	12	13	Sicilia Sud-Orientale	VII-VIII	37.270	15.070	79	**5.3**			1.1E + 24	Boschi *et al.* (1997)
1990	12	16	Carlentini	VI-VII	*37.258*	*15.375*	79	**4.2**			2.5E + 22	*Bollettino Macrosismico* (1990)

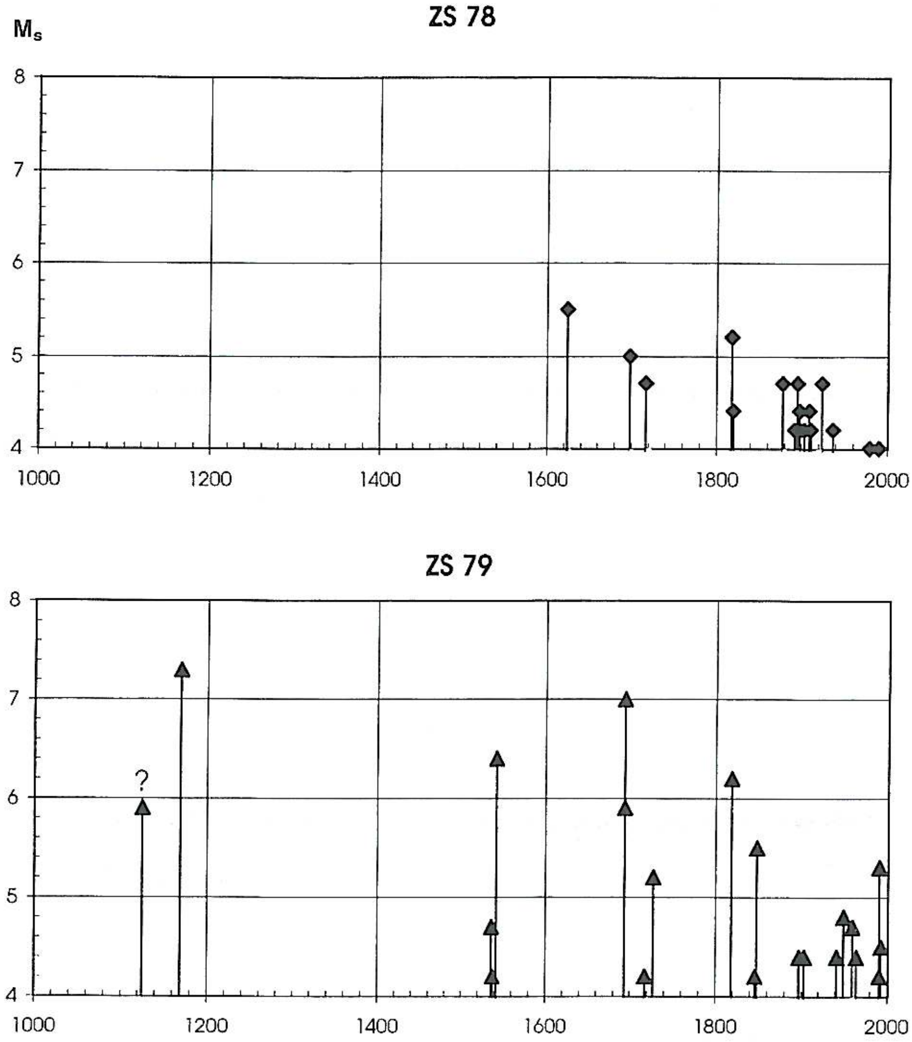


Fig. 2. Time distribution of seismicity ($M_S \geq 4.0$) in western (ZS 78) and eastern (ZS 79) Hyblean region. The incompleteness of the catalogue for moderate ($M_S < 5.9$) events before 1600 is evident.

ters are retrieved from Camassi and Stucchi (1997) and Boschi *et al.* (1997). For the minor events revised by us the epicentres were determined, according to Camassi and Stucchi (1997), as the barycentre of the data points with intensity $I = I_s, I_{s-1}$; the equivalent surface wave magnitudes M_S were calculated from the tabular relationship by Rebez and Stucchi (1997), obtained through correlation of the instrumental values with the epicentral intensities of the database of the Italian earthquakes (Monachesi and Stucchi, 1998). The equivalent magnitudes M_e were derived by Boschi *et al.* (1997) from the extent of the areas with the same intensity; the magnitudes M_R were estimated by Westaway (1992) from the radii of the intensity isoseismals. For the $M \geq 5$ earthquakes the only instrumental source parameters available refer to the 1990 earthquake (Giardini *et al.*, 1995); few other instrumental magnitudes are available. Comparison between different types of magnitude shows similar values, except for the 1169 event for which magnitude varies considerably between 5.6 to 8.3 depending on the adopted estimation method, but a value $M_s \approx 7.0$ seems the most likely. The seismic moments M_0 of the largest events such as the 1169 and 1693 ones, computed by the Hanks and Kanamori (1979) relationship using the M_s values, are comparable to that of the $M_s = 7.3$ 1908 Messina earthquake ($M_0 = 4.9E + 26$ in Capuano *et al.*, 1988), which was inferred by levelling data inversion.

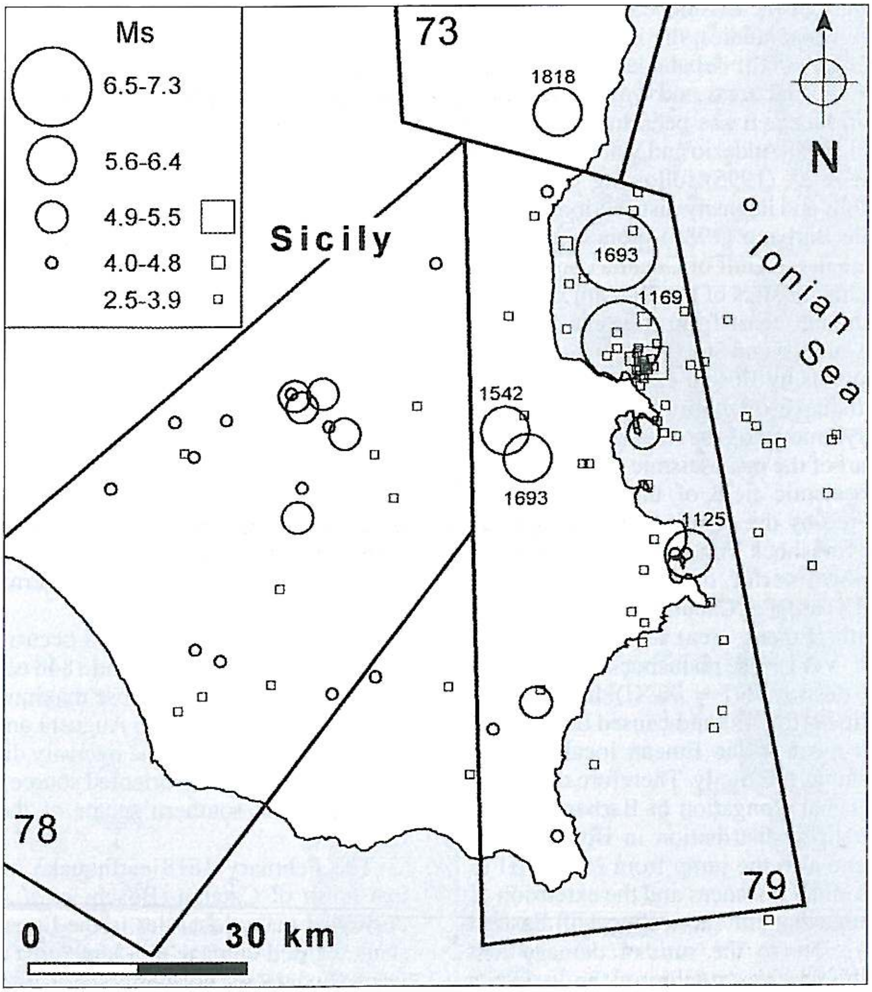


Fig. 3. Location of earthquakes in SE Sicily from 1000 to date. Circles represent macroseismic epicentres according to table I; squares indicate 1986-1995 instrumental locations by ING seismic network (Amato *et al.*, 1995; Salvi *et al.*, 1996). The boxes show the extension of the seismogenic zones proposed by Scandone *et al.* (1992).

Likewise, moment estimations of moderate historical events ($M_s \approx 5.2$-5.5) are consistent with the instrumental value of the 1990 earthquake ($M_0 = 3.7E + 24$ in Giardini *et al.*, 1995).

2.1. *Ionian coast*

The January 11, 1693 earthquake is the best known among the largest events occurring in SE Sicily. In spite of the existence of many coeval reports and recent studies, the interpretation of this earthquake is still debatable because it affected large coastal areas and was preceded by a strong foreshock. It has been located inland, near Lentini, by D'Addezio and Valensise (1991) and Boschi *et al.* (1995) following geological considerations and intensity distribution, respectively, while Barbano (1985) proposed a location offshore in the Gulf of Catania considering also the characteristics of the tsunami observed along the Ionian coast from Messina to Syracuse. Also Camassi and Stucchi (1997), although using datapoints by Boschi *et al.* (1995), located the earthquake offshore since they considered the asymmetry of the macroseismic field, showing part of the mesoseismic area in the sea. The macroseismic field of the mainshock is indeed altered by the damage provoked by the January 9 foreshock (fig. 4a), which heavily damaged the interior of the Syracuse area (I = VIII-IX) as far as Catania (I = VIII), while further north (Etnean area) it produced lower effects (I = V-VI). The mainshock (January 11) completely destroyed (I = X-XI) the previously hit localities (fig. 4b) and caused devastation (I = X) in most of the Etnean localities and damage as far as NE Sicily. Therefore the NNE-SSW isoseismal elongation of Barbano (1985) and the intensity distribution in Boschi *et al.* (1995) – note also the jump from I = X-XI to I = VII on small distances and the extension of the $I >$ IX area that embraces almost all Eastern Sicily – are due to the sum of damage that provoked the total destruction of the localities inland of Syracuse. The intensity distribution of the foreshock suggests a source inland, northwest of Syracuse, but it is strongly biased by the lack of data in the Ragusa area, whereas the datapoint distribution of the mainshock may be explained by a source located northward, where damage was stronger than previously. The large number of shocks felt at the coastal localities between Catania and Syracuse before the January 9 and after the January 11 events (Boccone, 1697) is indeed consistent with a source area close to the sea.

The 1169 earthquake has been studied by Lombardo (1985) and recently revised by Boschi *et al.* (1995). The little available information refers to some towns in SE Sicily (Aci Castello, Catania, Lentini, Modica, Sortino with I = XI in Lombardo, 1985, and I = X in Boschi *et al.*, 1995). Syracuse was also heavily damaged (I = X in Lombardo, 1985, and I = IX in Boschi *et al.*, 1995). Destruction and permanent effects on the ground extended as far as Piazza Armerina in the middle of Sicily and Messina and Reggio Calabria to the north. Tsunami effects along the coast are reported for Messina, Catania and the Simeto river. Despite the uncertainty of historical data, the analogies shown by the 1169 and 1693 earthquakes suggest a similar location and magnitude for both events.

The 1125 earthquake (Boschi *et al.*, 1997) is a scantily defined earthquake that was cited in most previous catalogues with different dates; Barbano *et al.* (1996) considered it a doubtful event. Since the only intensity datapoint is Syracuse (I = IX), we cannot estimate how reliable the parameters are either in terms of magnitude or source location.

Among other minor events occurring in the coastal sector are the 1846 and 1848 earthquakes (Barbano *et al.*, 1996), whose maximum effects affected the area between Augusta and Catania (fig. 4c). In these cases the intensity distribution suggests a NNW-SSE oriented source, probably located in the southern sector of the Gulf of Catania.

The February 1818 earthquake hit an area just north of Catania (Boschi *et al.*, 1995). It destroyed many localities in the Etnean eastern flank, caused damage in a large area extending from Catania to Northern Sicily and was felt almost throughout the island as far as Malta and Calabria (fig. 4d). This pattern is totally different from those of the typical low magnitude-shallow depth Etnean events, producing very narrow damage zones and felt areas of tens of

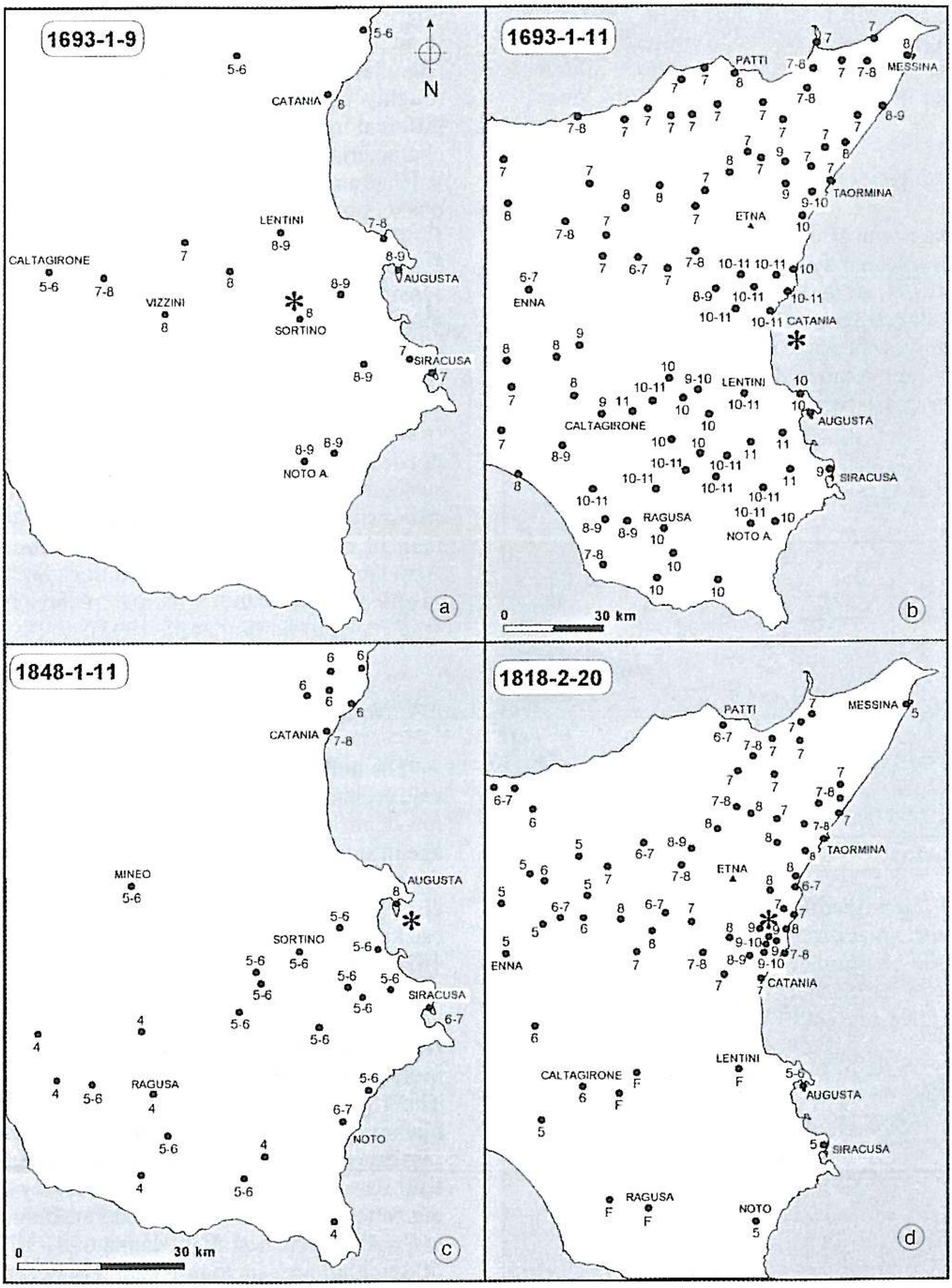


Fig. 4a-d. Intensity maps: a-b) foreshock (January 9) and mainshock (January 11) of the 1693 (simplified from Boschi *et al.*, 1995); c) 1848 Augusta earthquake (from Barbano *et al.*, 1996); d) 1818 Etnean area earthquake (simplified from Boschi *et al.*, 1995).

kilometers (Lo Giudice and Rasà, 1992). Thus the 1818 shock must be considered a typical crustal regional earthquake, whose source is located in the eastern side of the Etna area.

2.2. *Northeastern sector*

The northeastern border of the Hyblean plateau is affected by seismic activity whose greatest effects are related to the 1542 and 1990 earthquakes (Boschi *et al.*, 1995, 1997). The former was one of the strongest events (M_S = 6.4) of the region since damage extended from the Ionian coast zone as far as Caltagirone in the interior. Destruction mainly affected a large area located between Lentini and Grammichele (fig. 5a). The intensity distribution shows a roughly E-W direction of energy propagation different from the NNW-SSE to NNE-SSW ones characteristic of the coastal events. This should indicate another type of source for the 1542 earthquake, probably located inland west of Lentini.

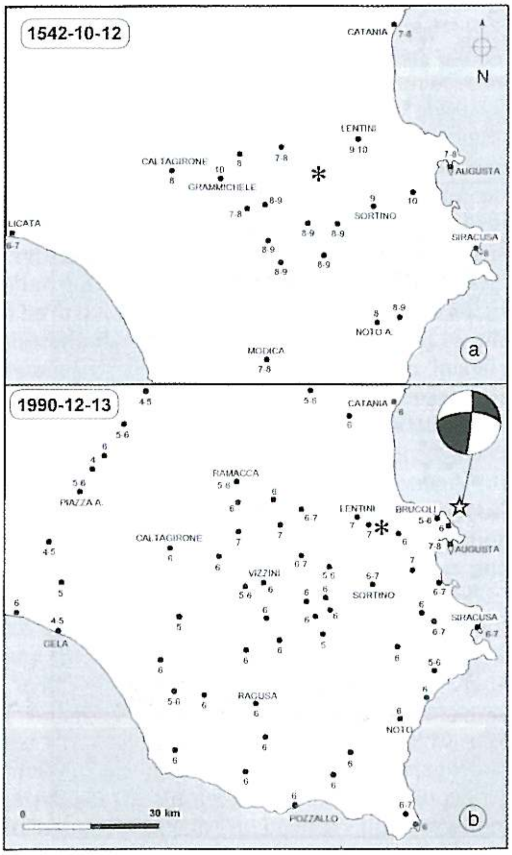


Fig. 5a,b. Intensity maps: a) 1542 Sortino earthquake (from Boschi *et al.*, 1995); b) 1990 Lentini earthquake (simplified from Boschi *et al.*, 1997).

The 1990 earthquake is the only significant event of the Hyblean region for which recent seismological data are available. Although of moderate magnitude (M_S = 5.3) it caused deaths and widespread damage in the Lentini area (fig. 5b); the epicentre was instrumentally located in the Ionian sea a few kilometres offshore from Brucoli. However, instrumental data are not decisive for the definition of the seismogenic structure since the fault plane solution indicates strike-slip, either left-lateral on a N-S striking fault or right-lateral on an E-W striking fault. Also the aftershock distribution does not definitively constrain the principal plane (Amato *et al.*, 1995; Giardini *et al.* 1995).

2.3. *Northwestern sector*

The northwestern border of the Hyblean plateau is characterised by moderate intensity-shallow depth earthquakes typically producing damage in small areas. Major effects are observed in the Mineo area where frequent minor shocks were also locally felt (Postpischl, 1985). The strongest known event (M_S = 5.5) in the area is the 1624 one (Barbano *et al.*, 1996) (fig. 6a). The 1878 shock caused slight damage in Mineo and was felt in a few surrounding localities (fig. 6b). Other earthquakes with similar features took place some tens of kilometers westward. The 1898 (fig. 6c), 1903 and 1909 seismic sequences affected the Caltagirone-Niscemi area, just beyond the external limit of the Hyblean plateau. The 1959 earthquake showed a very different pattern since, albeit of a moderate magnitude (M_S = 4.7), it caused slight damage in a NE-SW, 60 km long area including Caltagirone, Mineo, Militello, Scordia and some localities on the southern flank of Etna (fig. 6d); moreover it was also felt throughout Sicily. These features suggest a deep source located in the Catania plain.

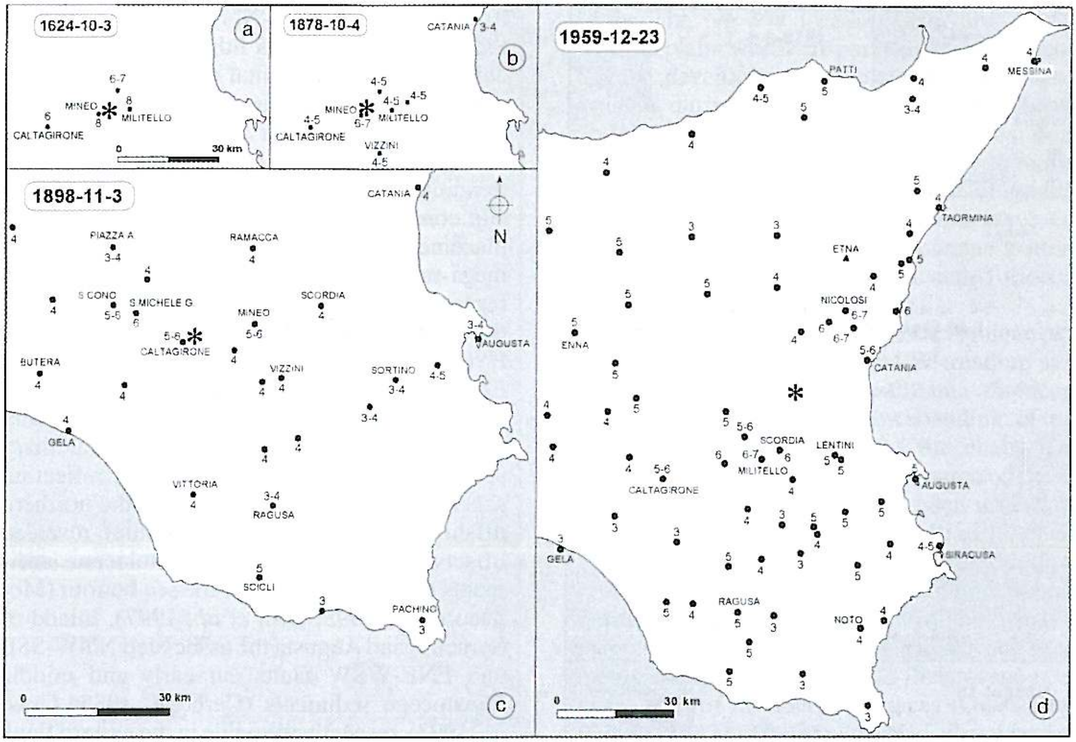


Fig. 6a-d. Intensity maps of (a) 1624 (from Barbano *et al.*, 1996) and (b) 1878 Mineo earthquakes (revised on the basis of Silvestri, 1879); c) 1898 Caltagirone mainshock (revised on the basis of Agamennone, 1900; Eredia, 1905); d) 1959 Piana di Catania earthquake (revised on the basis of *Bollettino Sismico*, 1959; *La Sicilia*, 1959).

2.4. *Central sector*

The inner Hyblean zone is characterised by low to moderate magnitude earthquakes. The strongest events are the 1698 (Barbano *et al.*, 1996), March 1818 (Boschi *et al.*, 1995) and 1895 shocks located in the Vizzini-Licodia area. Distribution of intensity data points (fig. 7a-c) suggests, at least in the better documented cases, a *ca.* N-S oriented source. The southernmost area shows a lower seismic release. The 1949, 1980 (Patanè and Imposa, 1987) and October 1990 shocks had maximum effects in Modica, Ragusa and Scicli respectively (fig. 8a,b) and intensity distributions are consistent with a source with N-S trend.

The southern coastal sector is characterised by other damaging earthquakes. In the Vittoria plain are located the 1717 (Barbano *et al.*, 1996) and 1937 events, whose macroseismic features indicate very shallow-low magnitude sources, while in the southeastern-most corner of Sicily the 1727 (Barbano *et al.*, 1996) and 1903 Noto earthquakes occurred (fig. 8c,d).

3. Evidence of Quaternary activity

A problem that arises when trying to define the active faults of the area, which are those potentially seismogenic, is that tectonic activity is generically related to the Quaternary age, given that no evidence of late Pleistocene-Holocene displacements is available except for a very few cases.

The Malta escarpment is one of the master faults in the Central Mediterranean developing

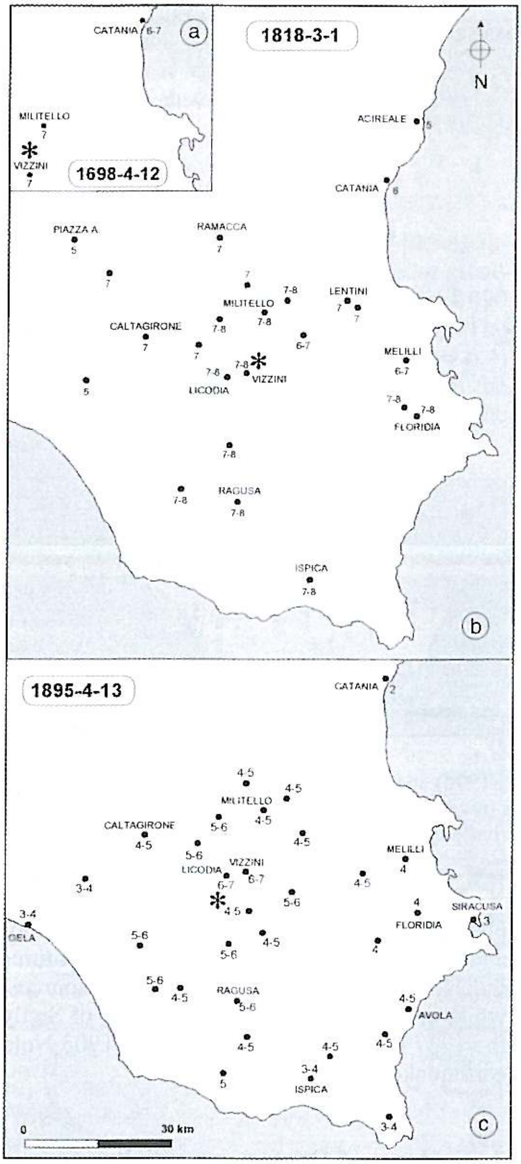
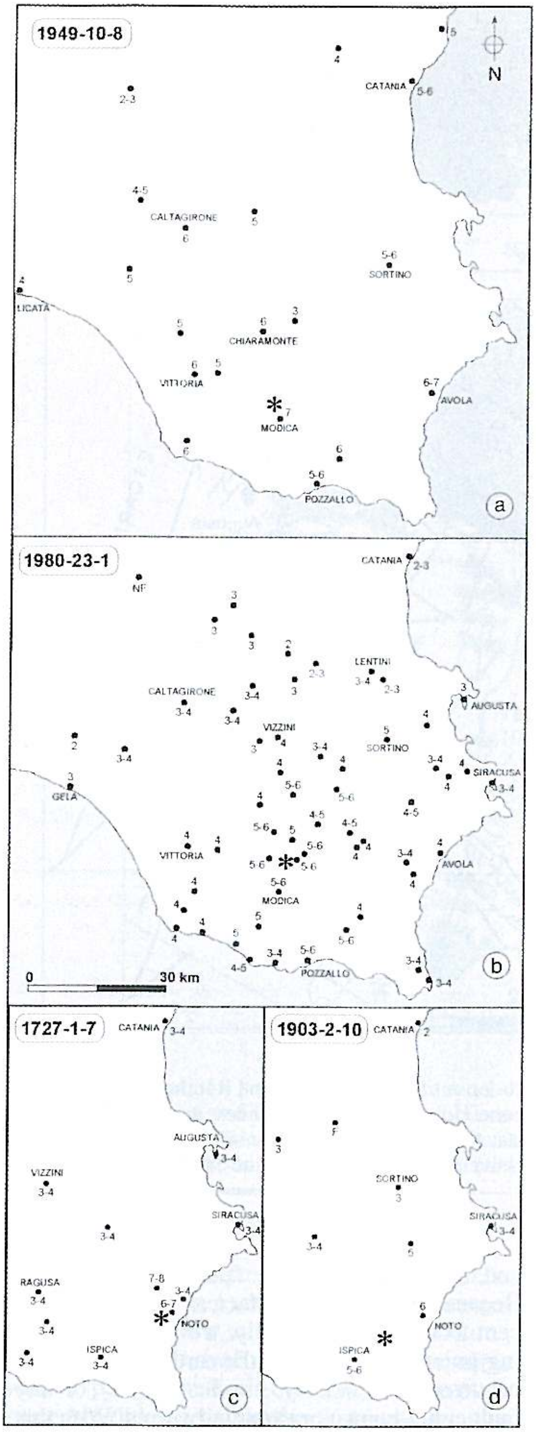


Fig. 7a-c. Intensity maps: a) 1698 Vizzini earthquake (from Barbano *et al.*, 1996); b) 1818 Monti Iblei earthquake (from Boschi *et al.*, 1995); c) 1895 Vizzini shock (revised on the basis of *Corriere di Catania*, 1895; Baratta, 1895; Arcidiacono, 1896).

for over 200 km from North Africa to Eastern Sicily, and represents a lithospheric fault zone delimiting the continental crust of the African platform from the Ionian Sea domain with oceanic crust (Scandone *et al.*, 1981; Casero *et al.*, 1984). It consists of an east-dipping, NNW-SSE trending normal fault belt, with minor strike-slip component, and a cumulative vertical displacement of 3000 m (figs. 1 and 9). Such a mega-structure is offset by WNW and ENE transfer faults which divide it into different segments, the northernmost ones bordering the Eastern Hyblean coast and extending inland as far as the Etnean area (Lo Giudice *et al.*, 1982; Continisio *et al.*, 1997). The Malta escarpment is the only structure in SE Sicily whose late Quaternary activity is presently known. In fact, reflection seismic profiles carried out across the northern offshore segment (Gulf of Catania) revealed offsets of middle Pleistocene-Holocene sediments and displacement of the sea bottom (Monaco *et al.*, 1995; Hirn *et al.*, 1997). Inland of Syracuse and Augusta the associated NNW-SSE and ENE-WSW faults cut early and middle Pleistocene sediments (Carbone, 1985; Grasso, 1993), respectively, while in the eastern flank of Etna the NNW-SSE fault zone (Timpe) offsets Holocene volcanics and historical lavas (Monaco *et al.*, 1997) and is also characterised by coseismic surface faulting (Azzaro, 1999).

The inner sector of the Hyblean plateau is crossed by the Scicli line (fig. 9), a first order strike-slip fault zone developing for a length of about 100 km from the Sicily Straits as far as the northern margin of the plateau (Grasso and Reuther, 1988). Such a system consists of three main, right-lateral fault segments, striking N-S, and of second order structures with NE-SW, *en-échelon* arrangement which accommodate, on both sides of the fault zone, the shear deformation (Ghisetti and Vezzani, 1980). Evidence of Quaternary activity is reported only for the northern segment in the Vizzini-Licodia area, where compressional tectonics (strike-slip faults, thrusts) affect the Plio-early Quaternary deposits, and for the southern one near Cava d'Aliga, as drag folding of middle Pleistocene sediments (Grasso and Reuther, 1988). Also some splay faults of the Scicli system show Quaternary ac-



tivity. The NE-SW trending structures in the Vittoria plain, which are partially blind, controlled the development of small scale pull-apart grabens during the middle Pleistocene (Grasso and Reuther, 1988). Along the Ispica fault dextral movement produced drag folds of the lower Pleistocene sediments, uplift of middle Pleistocene-Holocene beaches and wave-cut platforms, anomalies in the drainage pattern (Grasso *et al.*, 1992; Monaco and Tortorici, 1995).

The northwestern margin of the Hyblean plateau is downfaulted by a NE-SW trending system which forms the Gela-Catania foredeep, representing the flexural downbending of the foreland beneath the front of the chain. The externalmost unit, the Gela nappe, overrode early Pleistocene sediments and has been in its turn sutured by Quaternary terrains (Bianchi *et al.*, 1987). One of the main extensional structures bordering the foreland is the Mineo fault, whose Quaternary activity is testified by the synsedimentary deformation of early Pleistocene sediments and by the post-middle Pleistocene relevant uplift of the marine terraces (Grasso and Pedley, 1990). The area is also characterised by structural depressions such as the Scordia-Lentini graben, which offset lower Pleistocene deposits (Carbone *et al.*, 1987); the tilting of faulted formations and of the lower-middle Pleistocene marine terraces was also observed on both sides of the graben (D'Addezio and Valensise, 1991). The above outlined picture shows that the state of knowledge is generic probably since no investigation has been specifically devoted to a systematic search for clues of active tectonics. At present it is not clear if this is due to the poor attention devoted to the problem or to the real lack of field evidence.

Fig. 8a-d. Intensity maps: a) 1949 (revised on the basis of *Bollettino Sismico Mensile*, 1949) and (b) 1980 Modica earthquakes (simplified from Patanè and Imposa, 1987); c) 1727 (from Barbano *et al.*, 1996) and (d) 1903 Noto earthquakes (from Monachesi and Stucchi, 1998).

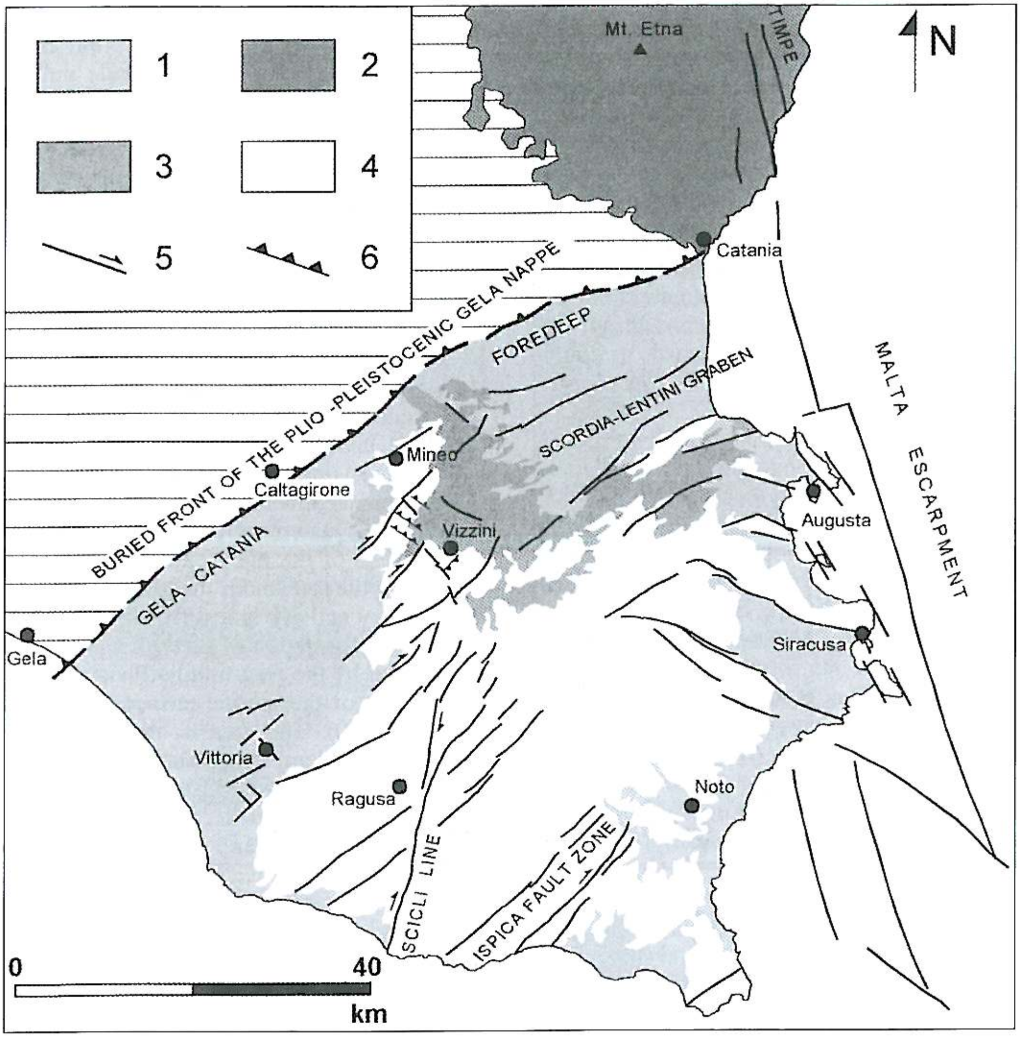


Fig. 9. Simplified geologic map of SE Sicily (based on Carbone *et al.*, 1987; Grasso and Reuther, 1988, Lentini *et al.*, 1996). 1 = Recent-Quaternary deposits; 2 = late Pleistocene-Holocene Etnean volcanics; 3 = Plio-Pleistocene Hyblean volcanics; 4 = Meso-Cainozoic carbonate sediments; 5 = normal faults (strike-slip components shown by arrows); 6 = thrusts. Horizontal bars indicate the compressive domain of the Apennine-Maghrebian chain.

4. Possible relationship between earthquakes and tectonics

Preliminary hypotheses on the link between earthquakes and active or presumed active faults were made by comparing intensity data patterns and Quaternary tectonic framework (fig. 10). Because of the poor characterisation of the recent tectonics in SE Sicily, we used as a starting-point in our analysis the earthquakes whose occurrence, obviously, implies activity of any fault either known or eventually blind. With this

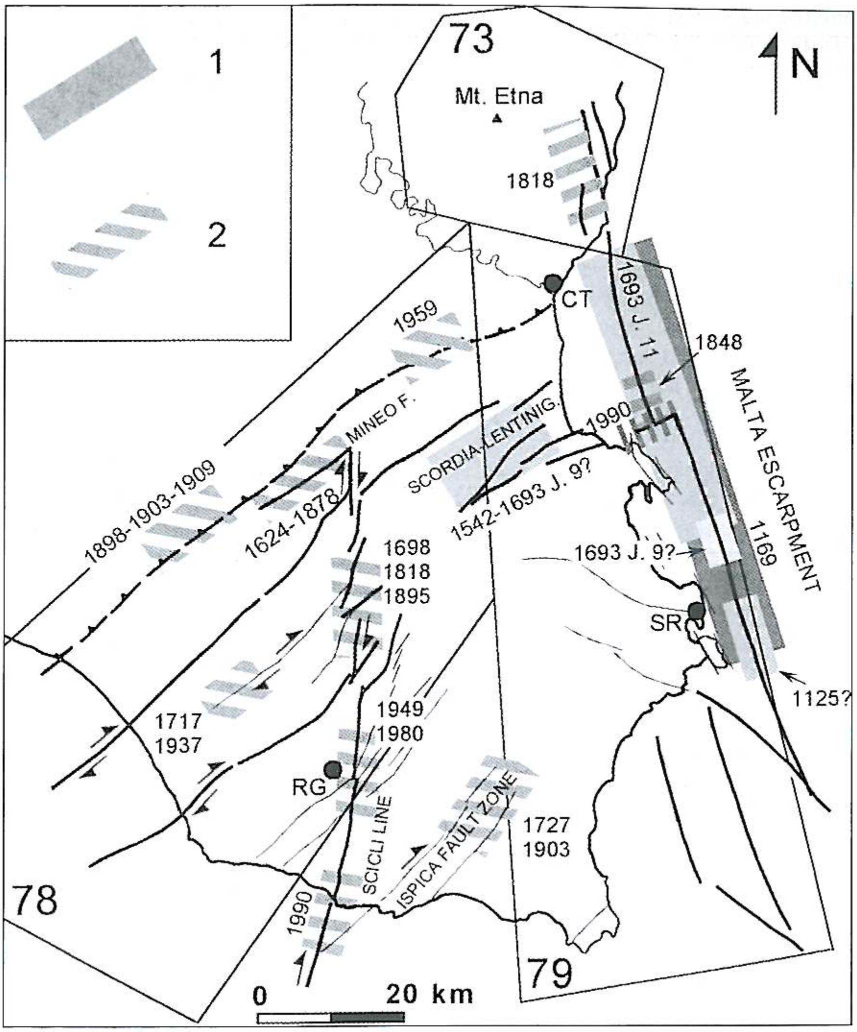


Fig. 10. Proposal of a seismogenic sketch model of SE Sicily (main structural elements from Bianchi *et al.*, 1987; Ben-Avraham and Grasso, 1991). 1 = Location and computed length (in scale) of ruptures of the largest events; 2 = ruptures with length lesser than 7 km. Question marks indicate very doubtful correlations. For geological symbols see fig. 9; the boxes show the seismogenic zones by Scandone *et al.* (1992).

assumption, we adopted the following criteria for the association: 1) the proximity of the macroseismic epicentre to a Quaternary structure; 2) the distribution of the intensity datapoints with respect to the fault orientation. Moreover, since we did not tackle the problem quantitatively, we assumed for simplicity that intensities are symmetrical with respect to the source. For the 1169 and 1693 earthquakes, due to their complexity, different considerations were also taken into account. Finally, in order to verify compatibility with the dimension of the associ-

Table II. Inferred seismogenic faults of SE Sicily. Length of fault segments are derived from geological maps reported in literature. Rupture lengths are computed only for $M_s \geq 5.2$ earthquakes using the relationship by Wells and Coppersmith (1994).

Fault	Prevailing slip type	Fault segment	Maximum length (km)	Associated earthquakes	Rupture length (km)
Malta escarpment	Normal	Etna (Timpe)	15	20.02.1818	11
		Gulf of Catania	28	04.02.1169	66
				11.01.1693	41
				22.04.1846	
				11.01.1848	3.8
		Augusta - Siracusa	53	07.06.1125?	7
				09.01.1693?	7
Scicli line	Strike	Vizzini	18	12.04.1698	
				01.03.1818	2.3
				13.04.1895	
		Ragusa	12	08.10.1949	
				23.01.1980	
		Scicli	18	29.10.1990	
Scordia-Lentini graben	Normal	Inland	17	10.12.1542	16
	Strike?	Offshore extension?	11	13.12.1990	2.7
Mineo	Normal		10	03.10.1624	3.8
				04.10.1878	
Piana di Catania	Normal	Blind	?	23.12.1959	
Caltagirone	Normal	Blind	?	03.11.1898	
				13.07.1903	
				02.01.1909	
Ispica	Strike		20	07.01.1727	2.3
				10.02.1903	
Vittoria	Strike		10	04.04.1717	
				06.03.1937	

ated fault, we also calculated the rupture lengths using the M_s values in the relationship by Wells and Coppersmith (1994) (table II).

As previously discussed, there is no consensus on the 1693 earthquake sources, so various authors have suggested different seismogenic structures on the basis of different approaches. D'Addezio and Valensise (1991) proposed a ENE-WSW blind normal fault with a 30° SSE dip, vertical extension of 10 km and top near the northern border of the Scordia-Lentini graben. Since the structural setting of the area is ruled by the northwest dipping, stepwise downfaulting of the foreland underneath the chain front (Bianchi *et al.*, 1987; Carbone *et al.*, 1987), the proposed structure should represent an antithetic structure of the NE-SW system (and also of the Scordia-Lentini graben). This model does not seem likely because a low-angle fault with a depth of 10 km does not fit the 3D geometry of the Scordia-Lentini graben, whose width ranges from 2 to 10 km. It follows that if the 30° dip is correct, the fault bottom must be shallower or, alternatively, if the depth of the fault is correct, the dip must be higher than 30°.

Sirovich and Pettenati (1999), applying a computer algorithm to invert macroseismic data, found that a hypothetical blind strike-slip fault, parallel and east of the Scicli line, is the source best fitting the observed intensity pattern while the synthetic pseudo-intensities obtained using the Malta escarpment are unable to reproduce the southwestern part of the macroseismic field. The authors concluded that both the faults may be candidate sources of the 1693 earthquakes. In our opinion the first source does not take into account that the macroseismic field is the result of two shocks and that a strike-slip fault is unable to generate tsunami. Furthermore, it is not likely that a 80 km long fault which affects a stiff plateau such as the Hyblean one, consisting of more than 7 km of brittle carbonatic rocks, does not give any surface morphological evidence.

By simulating tsunami from different possible sources such as the structure proposed by D'Addezio and Valensise (1991), the northern section of the Scicli line (but assuming a vertical displacement), and the Malta escarpment, Piatanesi and Tinti (1998) showed that a source in the Malta escarpment offshore of Augusta best fits the initial withdrawal of the sea observed along the Ionian coast after the January 11 earthquake.

On the basis of the tsunami modelling, the observations on the damage pattern of the January 9 and 11 events, the distribution of the felt fore- and aftershocks, the evidence of Holocene displacements and the lack of surface faulting that should have been present considering the magnitude of the largest event, we deem the Malta escarpment fault system the most likely source for the 1693 earthquakes. Taking into account the possible epicentre shift from south to north suggested by the intensity distribution, we propose that the foreshock might be located offshore of Augusta, while the mainshock was in the Gulf of Catania (fig. 10). As a possible alternative, we cannot exclude that the Scordia-Lentini graben may have been the January 9 causative fault. Data available for the 1169 event make it difficult to associate it with a fault, even if the analogies with the 1693 earthquake suggest the activation of a portion of the same structure. Minor earthquakes such as the 1125?, 1846 and 1848 events may be due to minor ruptures along the Malta escarpment. As regards the 1818 earthquake, secondary faulting observed in the eastern flank of Etna along the NNW-SSE trending fault zone (Azzaro, 1999) as well as the tsunami occurring along the Ionian coast, support the hypothesis of the activation of the deeper, buried part of the northernmost segment of the Malta escarpment (Continisio *et al.*, 1997).

The 1542 and 1990 events had greatest effects in the northern sector of the Hyblean area. No clear evidence of late Pleistocene-Holocene activity is available for this area but high rates of crustal deformation have been detected by geodetic surveys carried out across the coastal sector of the Scordia-Lentini graben. By inverting data from precise levelling measured during 1972-1989, Mulargia *et al.* (1985, 1991) found vertical movements with rates up to 1.5 cm/yr on a fault system arranged in a graben-like structure. The displacement is essentially due to aseismic slip, local effects of instability or subsidence on a large scale being ruled out. Such geodetical information, unlike geological data, may provide evidence for the present activity of the Scordia-Lentini graben. Considering also the *ca.* E-W trending intensity distribution, we suppose that the 1542 event may have resulted from the activation of this fault system. As concerns the 1990 earthquake, both the N-S striking Malta escarpment and the E-W transfer fault, which offsets and separates it into the Syracuse and Gulf of Catania segments, are present close to the instrumental epicentre. Considering that the strike-slip motion of the focal mechanism is neither consistent with the prevalent normal component of the Malta escarpment nor with the mainly E-W trending intensity distribution, we retain that the E-W right-lateral strike-slip fault occurring offshore, east of the Scordia-Lentini graben, to be the most probable source of the 1990 earthquake.

Seismicity located along the northwestern margin of the Hyblean plateau may be associated with the NE-SW trending normal structures which downfault the foreland under the most external units of the chain. The distribution of intensity data suggests that the earthquake sources may be related to the activation of the Mineo fault (1624, 1878 events), for which the latest activity dates to post-middle Pleistocene, and of the NE-SW blind normal structures which occur, under the thrust-belt front (here thick 1-2 km, in Bianchi *et al.*, 1987), in the Caltagirone area (1898, 1903, 1909 shocks) and in the Catania plain (1959 earthquake).

Although no evidence of post-early Pleistocene activity is available for the Scicli line, intensity datapoints fill in the areas of Vizzini (1698, 1818 March and 1895 events) and Modica (1949, 1980), suggesting the activation of two different sectors of this fault system. Finally, macroseismic data of the 1717-1937 and 1727-1903 events may be consistent with sources in some splay faults of the Scicli system, such as those in the Vittoria plain and the Ispica fault zone, showing activity until middle Pleistocene and Holocene, respectively.

5. Conclusions

Earthquakes in SE Sicily seem distributed along regional faults which have played a role in the recent geodynamic evolution of the area. In spite of the very little evidence of late Quaternary tectonics reported in literature, the comparison between long-term seismicity and lower-middle Pleistocene faults led us to propose a possible association between earthquakes and faults (even blind) whose present activity seems revealed so far, mostly if not only, by the seismicity itself (fig. 10). As regards low-moderate magnitude earthquakes, damaging small areas in the inner sector of the Hyblean plateau, data are reliable and suggest associations with minor structures or single fault segments such as the Mineo fault, responsible for moderate ($M_s \approx 5$) shallow seismicity, or the Scicli line, characterised by $M_s \leq 4.8$ events in the southern part and $M_s = 4.8\text{-}5.2$ shocks in the northern one. The estimated values of rupture length are dimensionally compatible with the size of the faults (table II). Major problems arise when trying to associate the stronger earthquakes located along the coastal sector. Geodetical and macroseismic evidence seems consistent with the activation of the Scordia-Lentini graben (or its offshore extension) for $M_s \approx 6.4$ earthquakes. The Malta escarpment appears the only structure with Holocene-recent activity, location, size and kinematics (prevailingly dip-slip) suitable for generating large tsunamigenic earthquakes ($M_s \approx 7.0$). In the case of 1693 events we hypothesise the activation of two fault segments, part of the Augusta one for the foreshock on January 9 and the Gulf of Catania segment during the mainshock on January 11. The rupture length computed for the January 11, 1693 earthquake using $M_s = 7.0$ is 41 km, but the associated fault segment of the Gulf of Catania is 28 km long. This implies two possible alternatives: 1) the rupture involved not only the Gulf of Catania segment but also part of the Augusta one, perhaps enucleating from the end-point rupture of the January 9 foreshock; 2) the magnitude of the mainshock (7.0 to 7.4 according to different authors) is overestimated – consider the cumulative effects of the two shocks – and a value of 6.8, calculated using the length (28 km) of the Gulf of Catania segment, may be likely.

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