1. SEISMOTECTONIC FRAMEWORK AND SCENARIO EARTHQUAKES

1.1 Introduction

(R. Azzaro, M.S. Barbano, L. Sirovich, F. Pettenati and M. Bobbio)

One of the main problems encountered in seismic hazard and earthquake scenario studies is related to the definition of the seismic sources. In fact, a deterministic approach, such as that adopted in the Catania project, requires knowledge about the location, geometry and rupture mechanism of the seismogenic fault. In the present case, these tasks are made difficult by the following factors:

1) the area of SE Sicily, and more specifically the city of Catania itself, were hit by strong earthquakes before the XVIII Century (see Fig.1.1);
2) the post-1693 seismic quiescence is still poorly understood;
3) no large earthquakes were instrumentally recorded in the region;
4) the regional tectonic, geodynamical and kinematic framework is complex and no comprehensive seismotectonic interpretation has been accepted so far by the scientific community;
5) the lack of surface faulting evidence together with the poor knowledge of late Quaternary - Holocene tectonics. In addition, one cannot neglect the ongoing debate on the use of macroseismic data for seismotectonic purposes; this is crucial in an area, like SE Sicily, where quantitative information on the connection between faults and seismic sources is scarce. This situation also reflects on the different approaches followed by the authors of the sub-sections.

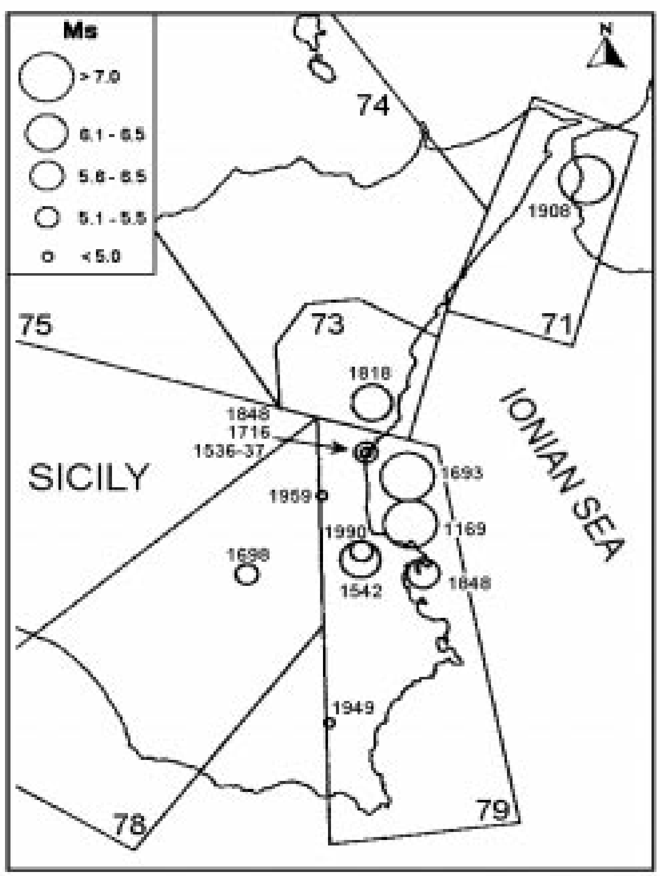

Fig.1.1 - Historical earthquakes that caused damage in Catania (Azzaro et al, 1999)

Sub-section 1.2 outlines the results of the analyses based on a comparison between long-term seismicity patterns and evidence of Quaternary tectonics. The aim is to provide a tentative tectonic interpretation of the seismic activity and to formulate the scenario events as possible repetitions of strong past earthquakes (January 11, 1693 and February 20, 1818 earthquakes). In the seismogenic model of SE Sicily proposed here and adopted in the Project, the most probable source for earthquakes heavily damaging Catania appears to be the Malta Escarpment.

Sub-section 1.3, on the other hand, presents the results of an alternative quantitative approach which treats macroseismic intensity data by tessellation, and uses observed intensities for source parameter inversion. The geometrical and kinematic source characteristics of the Dec. 13, 1990 earthquake, retrieved by inversion, are close to those determined instrumentally, in other independent studies. Regarding preinstrumental events, two groups of possible sources are suggested for the mainshock of Jan. 11, 1693 (one inland, and one offshore), and one (inland) for its strong foreshock of Jan. 9.

1.2 Seismogenic features of SE Sicily and scenario earthquakes for Catania

(R. Azzaro and M.S. Barbano)

1.2.1 *Introduction*

The seismicity patterns and the evidence of Quaternary tectonics have been analysed in order to investigate the main seismogenic features of SE Sicily, and to formulate scenario earthquakes for Catania. Because of the poor characterisation of the recent tectonics in the region, we have used as a starting point in our analysis the earthquakes whose occurrence, obviously, implies activity of any fault, known or blind. In short, we have adopted the following criteria for the association between earthquakes and faults: (i) the proximity of the macroseismic epicentre to a Quaternary fault; (ii) the distribution of the intensity datapoints with respect to the fault orientation. An extensive discussion on adopted rules and on the analysis of different seismogenic structures, suggested by various authors on the basis of different approaches, is given in Azzaro and Barbano (1999).

In the following, a first, tentative tectonic interpretation of the earthquakes in SE Sicily is proposed with particular regard to the seismic sources of the 1693 and 1818 earthquakes, selected as scenario events for Catania.

1.2.2 *Seismotectonic outline*

SE Sicily was hit in the pre-instrumental period by two major earthquakes, with estimated magnitude about 7: the Feb. 4 1169 and Jan. 11 1693 shocks (see Fig.1.2). From 1000 a.d. to date, just four other earthquakes in the area have exceeded an estimated magnitude 5.8: the Jul. 7 1125, the Dec. 10 1542, the Jan. 9 1693 and the Feb. 20 1818 events. In the same period six shocks have had a magnitude between 5.0 and 5.8; earthquakes below this magnitude threshold are also infrequent. Seismicity is mainly distributed in two sectors: along the coast, where the events have also reached $M_S \geq 7.0$, and inland with earthquakes with $M_S \leq 5.5$ (see Fig.1.1). A problem that arises when trying to define the active faults of the area, which are potentially seismogenic, is that tectonic activity is generically related to the Quaternary, because no evidence of late Pleistocene-Holocene displacements is available except for a very few cases.

The Malta Escarpment, the only structure with presently known late Quaternary activity, appears to be the most probable source for the largest earthquakes which hit the region. It is one of the master faults in the central Mediterranean, developing for over 200 km as a NNW-SSE normal fault belt, with minor strike-slip component and a cumulative vertical displacement of 3000 m. This structure appears to be subdivided into different segments, the northernmost ones bordering the eastern Hyblean coast and extending inland as far as the Mt. Etna area (Continisio *et al.*, 1997) (see Fig.1.3). Evidence of activity includes offset of middle Pleistocene-Holocene sediments revealed by seismic profiles in the Gulf of Catania (Hirn *et al.*, 1997), and displacement of Holocene-historical volcanics with coseismic surface faulting on the eastern flank of Etna (so-called Timpe) (Monaco *et al.*, 1997; Azzaro, 1999); in the Siracusa-Augusta area the associated faults cut middle-Pleistocene sediments (Carbone, 1985). The inner sector of the Hyblean Plateau is crossed by the Scicli Line, 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). The latter is downfaulted by a NE-SW trending system beneath the front of the outermost unit of the Apennine-Maghrebian chain (AMC) and it is characterised by wide Quaternary structural depressions such as the Scordia-Lentini graben. Although no evidence of tectonics subsequent to the middle Pleistocene is available for the Scicli Line, and for the NE-SW fault system affecting the northern sector of the Hyblean Plateau, the earthquake distribution may be related with minor seismogenic structures, responsible for events with maximum estimated magnitude of 5.2 and 6.4, respectively (Azzaro and Barbano, 1999).

1.2.3 *The scenario seismic events*

Based on the historical seismicity, as a maximum expected earthquake in Catania it is reasonable to assume the repetition of a destructive earthquake such as the 1169 or 1693 events, with intensity X-XI MCS and estimated magnitude between 7.0 and 7.4. Based on the evidence of a large amount of coeval reports and recent studies (see also section 8), the 1693 earthquake may reliably be selected as a first-level scenario event. In addition, the 1818 event (M_S=6.2), which caused damage (I = VII MCS) in Catania has been selected as second-level scenario earthquake. This event is of interest for the Project because it affected a relatively modern city, whose historical centre, rebuilt after the destruction of the 1693, is quite similar to the present one. Furthermore, this event was generated by a fault not far from the city. The return periods estimated for the Catania site range from 250 to 500 years for an event like 1693, and from 40 to 90 years for an event such as 1818 (Azzaro et al., 1999).

The January 11, 1693 earthquake

The interpretation of this earthquake is still subject to debate because it affected large coastal areas and was preceded by a strong foreshock on Jan. 9th, which heavily damaged the interior of the Siracusa area (I=VIII-IX) as far as Catania (I=VIII), while further north (Etnean area) it produced lower effects (I=V-VI). The mainshock (Jan. 11) completely destroyed (I=X-XI) the previously hit centers (Fig. 1.2a) and caused devastation (I=X) in most of the localities around Mt.Etna, producing damage as far as NE Sicily. In Catania alone it caused about 11900 victims, or about 3/4 of the population. The intensity distribution of the foreshock suggests a source inland, northwest of Siracusa, but it is strongly biased by the lack of data in the Ragusa area. On the other hand, the intensity distribution of the mainshock may be explained by a source located further to the north, where damage was stronger than in the foreshock. On the basis of the tsunami modelling (Piatanesi and Tinti, 1998), the distribution of the felt fore- and aftershocks, and the lack of surface faulting that should have been present considering the magnitude of the mainshock, Azzaro and Barbano (1999) consider the Malta Escarpment fault system as the most probable source for the 1693 earthquakes. Taking into account the possible epicentre shift from south to north, they suggested that the foreshock might be located offshore of Augusta, where a tsunami was also observed during this earthquake (Campis, 1694), while the mainshock should have ruptured the Malta Escarpment in the Gulf of Catania.

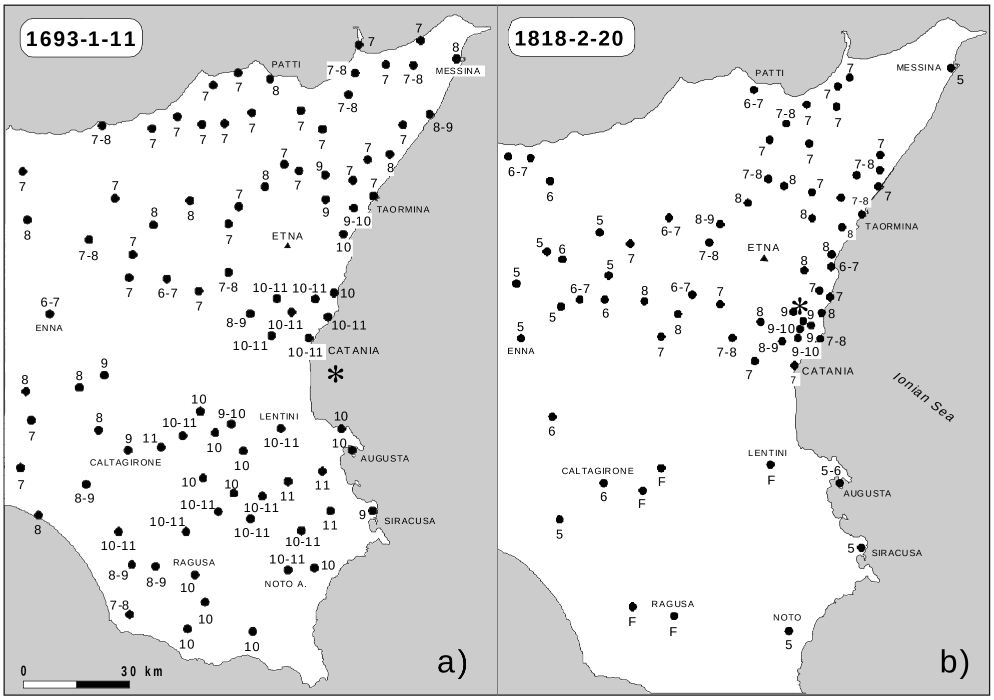

Figure 1.2 - Intensity maps (simplified from Boschi et al., 1995): a) mainshock (Jan. 11) of the 1693; b) 1818 Etnean area earthquake. Asterisks indicate the macroseismic epicentres according to Camassi and Stucchi (1997).

The February 20, 1818 earthquake

The Feb. 1818 earthquake had its epicentre just north of Catania. It destroyed many villages in the eastern flank of Mt. Etna, caused damage in a large area extending from Catania to Northern Sicily and was felt in almost all the island as far as Malta and Calabria (Fig. 1.2b). This pattern is totally different compared with those of the typical low magnitude-shallow depth volcanic Etnean events, which produce very narrow damage zones and felt areas of tens of kilometres. Thus, the 1818 shock must be indeed considered as a typical crustal regional earthquake. Secondary faulting observed in the eastern flank of Mt. 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 a deeper, blind segment of the Malta Escarpment below the eastern side of Etna.

1.2.4 *Proposed association between earthquakes and active faults*

Earthquakes in SE Sicily seem to be 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 Pleistocene-Holocene faults led us to propose a possible association between earthquakes and faults, even blind ones, whose present activity seems revealed so far, mostly if not only, by the seismicity itself (Fig. 1.3).

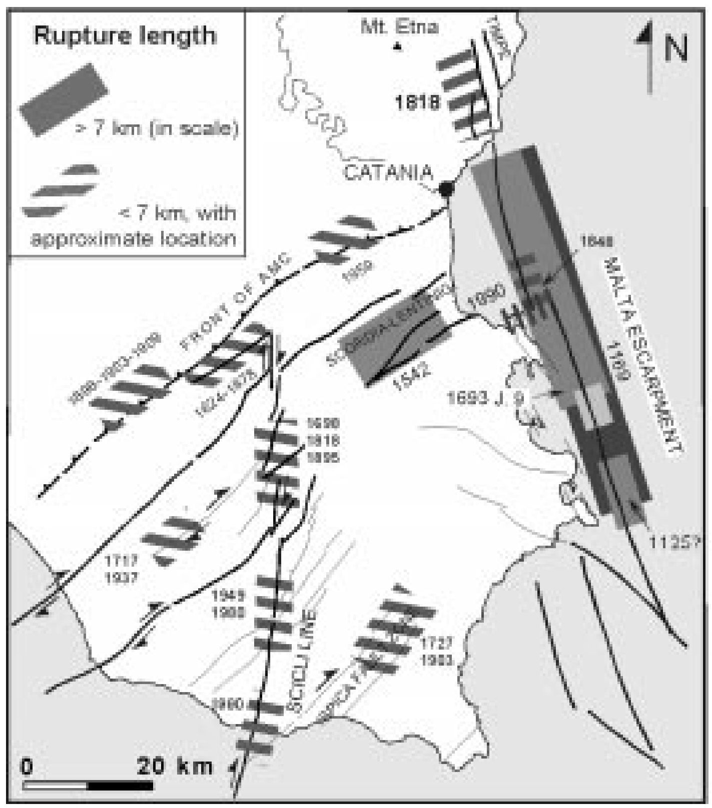

Fig. 1.3 - Seismogenic sketch model of SE Sicily (modified from Azzaro and Barbano, 1999). Question marks indicate very doubtful correlations.

The Malta Escarpment appears the most probable source for earthquakes heavily damaging Catania. The rupture length estimated by the relation of Wells and Coppersmith (1994) for the Jan. 11, 1693 earthquake using M_S = 7.0 is 41 km. However, the associated fault segment in the Gulf of Catania is only 28 km long (Table 1.1). This implies two possible alternatives: (i) the rupture involved not only the Gulf of Catania segment of the Malta Escarpment but also part of the Augusta segment, perhaps enucleating from the end-point rupture of the Jan. 9 foreshock; (ii) the magnitude of the mainshock (7.0 to 7.4 according to different authors) is overestimated, as a result of considering the cumulative effects of the two shocks., and a value of 6.8, based on the length (28 km) of the Gulf of Catania segment alone, may be more likely. As regards the 1818 source, the estimated rupture length, 11 km, is compatible with the size of the surface faults (Table 1.1). However, since the hatched area labelled 1818 in Fig.1.3 indicates the approximate location of a deep structure, errors in fault location are about 5 km.

Table 1.1: Description of the faults used in the earthquake scenarios

<table>
<tr><th>Fault</th><th>Prevailing slip type</th><th>Fault segment</th><th>Maximum length (km)</th><th>Associated earthquakes</th><th>M_S</th><th colspan="2">Rupture length (km)</th></tr>
<tr><td rowspan="4">Malta Escarpment</td><td rowspan="4">Normal</td><td>Etna (Timpe)</td><td>15</td><td>20.02.1818</td><td>6.2</td><td colspan="2">11</td></tr>
<tr><td>Gulf of Catania</td><td>28</td><td rowspan="2">11.01.1693</td><td rowspan="2">7.0</td><td rowspan="2">41</td><td>28</td></tr>
<tr><td rowspan="2">Augusta-Siracusa</td><td rowspan="2">53</td><td>13</td></tr>
<tr><td>09.01.1693</td><td>5.9</td><td colspan="2">7</td></tr>
</table>

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1.3 Evaluation of available options for the earthquake fault rupture scenario through source parameter inversion of intensity data

(L.Sirovich, F. Pettenati, M. Bobbio)

1.3.1 *Introduction*

We examined three groups of possible sources for the mainshock of Jan. 11, 1693 and its strong foreshock of Jan. 9, see also Figure 1.3, in 1.2, namely: 1) normal faults belonging to the Ibleo-Maltese Escarpment (also: Malta Escarpment); 2) normal faults associated with the two adjacent Simeto and Scordia-Lentini structures; 3) a transfer structure between the Sicily Straits rift system and the two grabens to the north (see a seismotectonic discussion in Sirovich and Pettenati, 1999). Given the *inland* regional orientation of the maximum horizontal compressive stress by Ragg et al. (1996), the simplest models which could account for the expense of positive tectonic work in the inland area would belong to families 2) and 3)

We consider it very difficult to constrain the epicentre (or the source parametres) using damage evidence only qualitatively. Also, we stress that none of the events of 1169, 1542, 1624, 1693, 1727, 1818, 1848, 1949, 1959 and 1980 has a density of intensity points per unit area high enough (according to the Nyquist principle) to adequately constrain the shapes of the mezoseismal areas, nor to understand, for example, if such areas are open toward the sea, or tend to close near the coast. The bases for this criticism are given more thoroughly elsewhere (Pettenati et al., 1998; Sirovich and Pettenati, 1999). The following results represent, we believe, the first quantitative hypotheses on the possible sources of one of the most destructive earthquakes of the Central Mediterranean area.

1.3.2 *The method*

We used a new kinematic model to invert the data sets of macroseismic intensities, *I*, of the two earthquakes of 1693 to retrieve information on their sources (see the presentation of the model in Sirovich, 1997; and the inversion technique in Pettenati et al., 1999). For this, we inverted point observations, or intensities tessellated with the Voronoi polygons technique, and treated residuals of inversion in the matrix of points, or in the tessellated plane. The application of the Voronoi technique of spatial representation of macroseismic intensity data is pretty new. This kind of partition is particularly suitable for qualitative or discrete-valued variables such as intensity; it solves the problem of proximity in the plane so that all points inside each polygon are unequivocally closer to the surveyed site generating that polygon, than to any other surveyed site. The union of all polygons with their values gives the tessellated intensity map of an earthquake. See the Voronoi Web Site (1999) for other properties and geophysical applications. Before inverting the historical data, we analysed the influence of the site responses and discarded a few statistical outliers (there is only a slight tendency for loose soil sites to amplify intensity beyond 120 km from the source; Sirovich et al., 1998). Then, we validated our technique by analysing the earthquake of Dec. 13, 1990; in this case, we obtained from the inversion source parametres (an offshore W-E trending strike-slip fault) which agree with the estimates by other authors, who used instrumental measurements.

1.3.3 *Results*

Figure 1.4 shows the tessellated observed intensity (MCS) of the January 9, 1693 earthquake. The dots are the surveyed sites (Boschi et al., 1995). Figure 1.5 shows the best tessellated synthetic intensity patterns, calculated adopting the SW segment of the source that we called EBT78 (family 3). Figure 1.6 shows the tessellated observed intensity of the January 11, 1693 earthquake (from Barbano and Cosentino, 1981). Figure 1.7 shows the best tessellated synthetic intensity patterns. These were also calculated adopting the NE segment of the EBT78 source. The kinematic characteristics of the main shock are in Table 1.2.

Table 1.2: Source parametres of the January 11, 1693, earthquake.

Jan. 11, 1693 Best sources	family (1) Ibleo-Malt. Escarp.	family (2) Scordia-Lentini	family (3) Scicli-EBT78
PARAMETER			
Latitude (°)	37.33	37.28	37.13
Longitude (°)	15.24	15.05	15.01
Depth (km)	10 (+10-6)	10 (+7-5)	10 (+15-5)
Length (km)	20+40	30+10	27+33
Strike angle (°)	350 (+7-13)	250 (+8-7)	20 (±10)
Dip angle (°)	75 (+18-36)	60 (+13-20)	80 (+10-32)
Rake angle¦ (°)	300 (+23-7)	300 (+19-16)	222 (+21-41)
Mach number	0.7	0.7	0.6
V_S (km/s)	3.5	3.5	3.5
Seismic Moment (10^{19}N×m)	4.35 (±1.25)	4.80 (±1.25)	4.57 (±1.25)

¦ ±180° ambiguity, given the adopted procedure.

Our inversions of the regional intensity patterns show that family no.(3) in Table 1.2 is a good candidate for the foreshock of January 9, 1693. For the mainshock of January 11, 1693, an almost perfect synthesis of its intensity IX area was obtained with our model and a source belonging to family no. (3). In both cases, the source EBT78 (fam. 3) scores the minimum residuals (see Sirovich and Pettenati, 1999). However, all information considered (tsunami included), the main shock could have been produced either by (3) or by a fault located along the Ibleo-Maltese Escarpment, and tangential to the Augusta and Siracusa promontories (fam. 1).

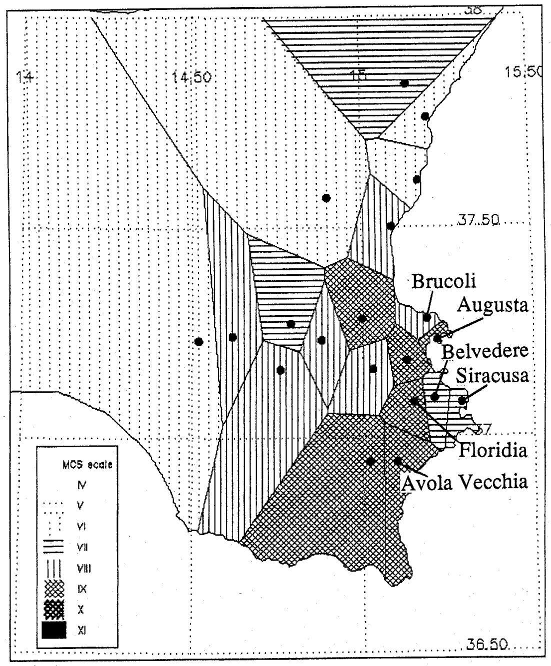

Fig.1.4 - January 9, 1693, earthquake. Tessellated observed macroseismic intensities in SE Sicily. The dots are the "surveyed" sites (intensity data from Boschi et al. *1995).*

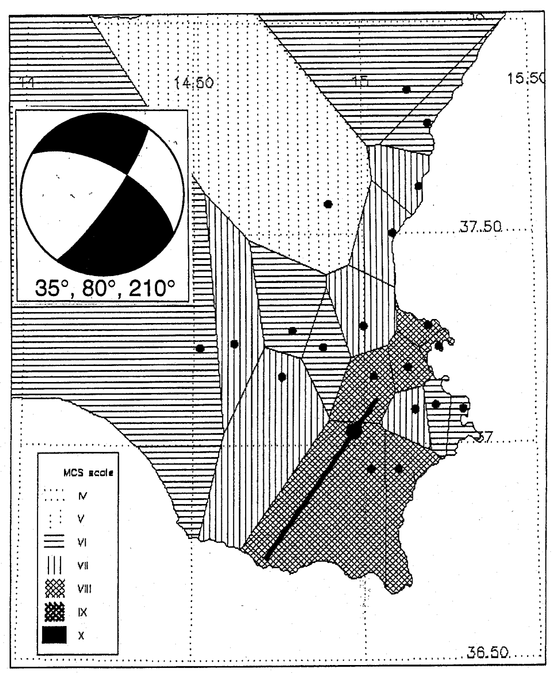

Fig.1.5 - Synthetic best fit of the tessellated observed macroseismic intensities for the January 9, 1693 earthquake (see Fig.1.4). The black segment and the large dot are the source used (SW segment of EBT78) and the nucleation, respectively.

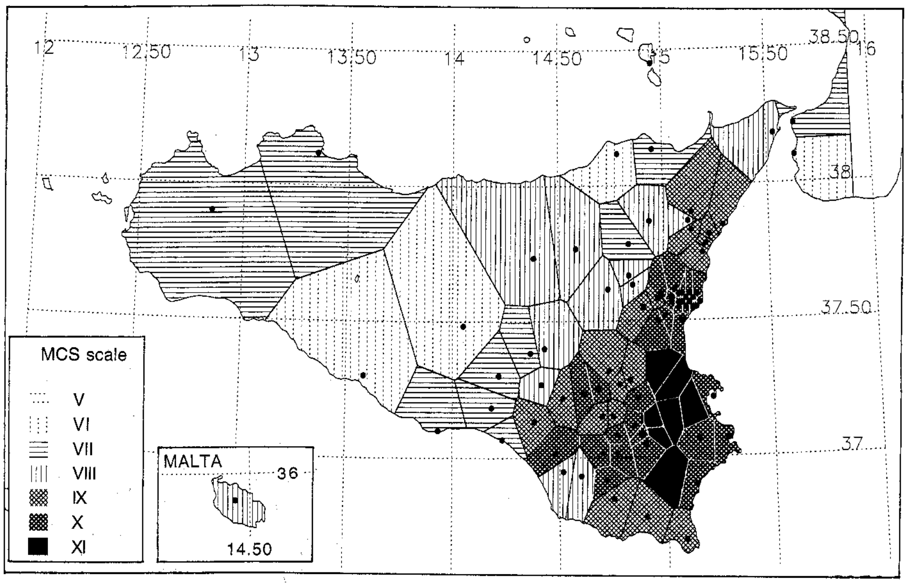

Fig.1.6 - *Tessellated observed macroseismic intensities for the January 11, 1693 earthquake in SE Sicily. The dots are the "surveyed" sites (intensity data from Barbano e Cosentino, 1981).*

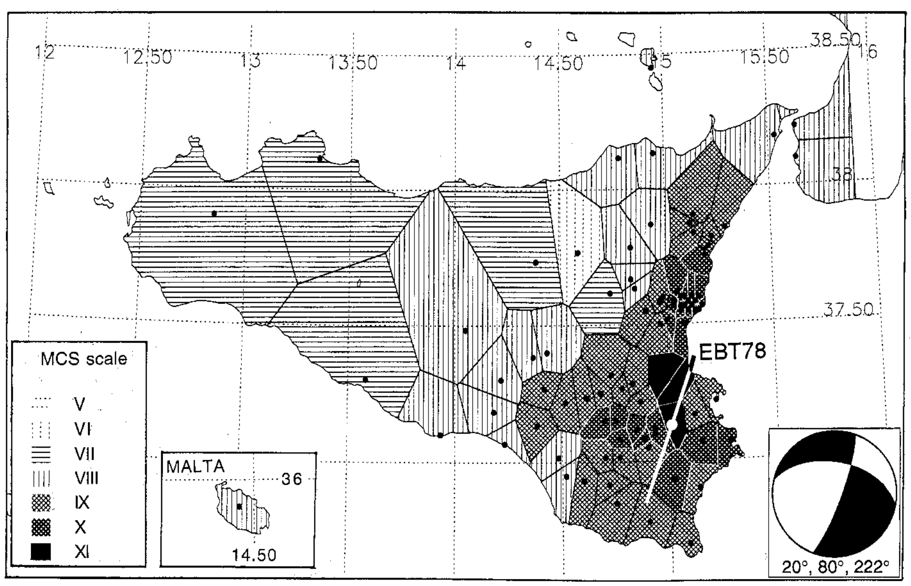

Fig.1.7 - *Synthetic bestfit of the tessellated observed macroseismic intensities for the January 11, 1693 earthquake. The white segment is the source used (NE segment of EBT78) with its nucleation (white dot) (see Table 1.2).*

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