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Seismotectonic outline of South-Eastern Sicily: an evaluation of available options for the earthquake fault rupture scenario

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Abstract

Seismotectonic information and interpretations available for SE Sicily suggest three groups of possible sources for the $M = 7.1 - 7.5$ mainshock of 1693 and its strong foreshock: (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. We use a new kinematic model to invert the data sets of macroseismic intensities of the two earthquakes to retrieve information on their sources. For this, we invert point observations, or intensities tessellated with the Voronoi polygons technique, and treat residuals of inversion in the matrix of points, or in the tessellated plane. Our inversions of the regional intensity patterns using this technique show that family N° 3 is a good candidate for the foreshock of 9 January 1693. For the mainshock of 11 January 1693, an almost perfect synthesis of its intensity IX area was obtained with our model and a source belonging to family N° 3. However, all information considered (tsunami included), this earthquake 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.

Introduction

We present (i) a summary of the seismotectonic information and interpretations available for SE Sicily, and (ii) the results of macroseismic data inversions of the two main 1693 earthquakes. Point (i) provides geometrical and kinematic data for quantitative seismological modelling. Point (ii) might, itself, stimulate new geological surveys to search for eventual traces of the causative faults of these earthquakes of the XVII Century, and consequently new seismotectonic interpretations.

Regarding the inversions, we note that drawing isoseismal maps by hand or automatically, starting from irregularly spaced point observations, is a widespread practice. Contoured isoseismals are often conceived as an attempt to generate a global picture of earthquake effects in a region, which will somehow overcome the paucity of available point observations. We have argued that this is an ill-posed problem (Pettenati et al., 1998). In fact, it is often forgotten that (1) the regional intensity field of an earthquake is the result of the summing of continuous components (such as radiation and attenuation) with discontinuous components (such as the effects of crustal and site geology); (2) the Nyquist principle also holds when tracing isoseismals; thus, details (spatial high-frequencies) can be observed only in areas with many observation points; (3) the combined process of the procedures of sampling plus contouring constitutes a two-dimensional filter. For these reasons, traditional isoseismals are hardly usable for automatic inversions. Here, therefore, we treat the macroseismic intensity data observed in the field directly. We do this quantitatively and objectively by minimizing by trial-and-error the calculated-minus-observed intensity residuals of the inversion in the matrix of intensity points, or in the tessellated plane. Our tessellated geographical representation of intensity data, together with the subsequent objective and quantitative treatment, has already made possible to invert the observed intensity data set of the December 13 1990, $M = 5.4$ earthquake in SE Sicily (Sirovich and Pettenati, 1998). In this case, our inversion of intensity was able to retrieve kinematic information about the source that is in reasonable agreement with the information derived by Giardini et al. (1995) from seismographic observations.

Available information

From a general seismotectonic point of view, some workers think that the Apenninic seismic belt of the Italian mainland continues into Sicily, bordered by normal faults along the northern shores of the island (e.g. Pantosti and Valensise, 1995). Starting from the early study by Omori (1909) other workers argue that the seismic belt continues southward as the ‘Siculo-Calabrian rift zone’ (Monaco et al., 1997), bounding the coast of Sicily and extending offshore as the Ibleo-Maltese Escarpment (Westaway, 1993; Tortorici et al., 1986, 1995).

We refer to Figure 1 which shows a large-scale tectonic/neotectonic sketch of southeastern Sicily. This sketch summarizes proposals by Ghisetti and Vezzani (1980), and by ‘The Structural Model of Italy’ by Bigi et al. (1990). The Ibleo-Maltese faults F3 and F4, which have been recently traced by Hirn et al. (1997) using new deep seismic profiles, have been added.

Almost all authors consider the Hyblean foreland as part of the northern margin of the African continental crust, which is bounded to the north by the thrust front of the Apennine allocthonous units. The latter is part of the orocline thrust belt, which extends from Tunisia to the Southern Apennines and marks the convergence between Europe and Africa. According to Ghisetti and Vezzani (1980), two principal extensional structures can be identified in the African domain of southern Sicily: (i) the two adjacent Simeto and Scordia-Lentini grabens, and (ii) the Pantelleria rift system in the Sicily Strait (Reuther et al., 1993), which are thought to be linked by the NNE-SSW trending Scicli-Ragusa-Monte Lauro fault system. Note that, according to the more recent studies by Grasso (1993) and Gardiner et al. (1995), the Simeto structure is a foredeep.

The most prominent physiographical and structural feature of the area is found offshore, south-east of Sicily, however, and is the well known Ibleo-Maltese Escarpment. In the literature, both the terms ≪Malta Escarpment≫ and ≪Ibleo-Maltese Escarpment≫ are used. This fault system separates the shelf zone (west) from the deep Ionian basin (east). It is one of the most evident structures in the Mediterranean Basin, and is found here approximately 10 to 50 km offshore, from 200 to 1,200 m depth. Regionally, the escarpment extends for more than 300 km, its steep slope descending to more than 3000 m below sea level (with a corresponding composite vertical offset of 3 km south of Cape Passero; see Figure 1).

The Ibleo-Maltese Escarpment is composed of a system of normal faults NNW-SSE trending, ENE dipping, with second-order strike components (Grasso, 1993). These components would be dextral according to Ghisetti and Vezzani (1982; their Figure 8(c)), and Monaco and Tortorici (1995); sinistral in recent times following Ben-Avraham and Grasso (1990), and Reuther et al. (1993). The age and origin of the escarpment are still a matter of debate. In the schematic structural map of Scandone et al. (1981), the Scicli-Ragusa-Monte Lauro fault and the Ibleo-Maltese Escarpment merge off-shore Mount Etna.

In greater detail, the Hyblean plateau was lightly deformed by the Alpine orogenesis, and has been subjected to moderate uplift and overall extensional tectonics. It is characterized by a NE-SW trending horst, which is delimited to the NW, from the transition zone to the Gela-Catania foredeep, by a normal fault system oriented NE-SW. On the other side, NNW-SSE trending normal-transcurrent faults are found along the coast from Augusta to Siracusa, and are the ‘natural’ inland extension of the Ibleo-Maltese Escarpment (Carbone et al., 1982, 1989). According to Grasso (1993) these horsts and grabens, which occur in a 50 km long and 20 km wide belt from Siracusa to Augusta, are transtensional 2nd order structures superimposed over the dominant vertical displacement along the escarpment, and they also underwent left-lateral movements.

Regarding the present status of the Ibleo-Maltese Escarpment, according to Carbone et al. (1982), there is clear evidence that its northern, inland prolongation in the Acireale fault system (the so-called ‘Timpe’), close to the SE and E of Mt. Etna, is active. In fact some of these faults produced lava flows in historical times. Azzaro and Barbano (1996) also observe that the causative fault of the anomalous ‘Etnean’ earthquake of 20 February 1818, 18:20, $M_e = 6.2$ was deeper than usual in this volcanic zone, and argue that the source possibly was an inland extension of

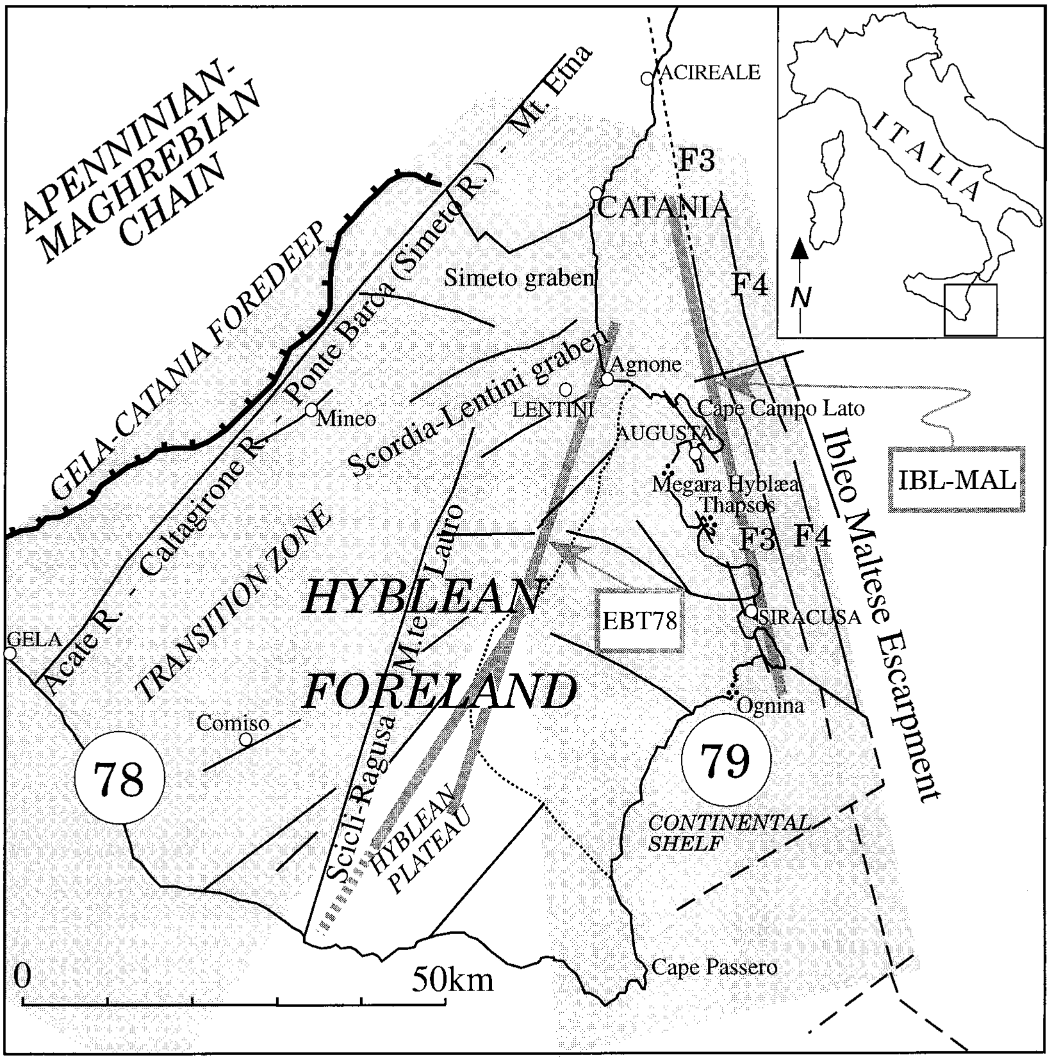

Figure 1. Tectonic sketch of SE Sicily, and localities cited in the text. All kinds of faults, more (continuous) or less (dashed) reliable, are indicated with simple lines; with the exception of the limit of the Gela-Catania Foredeep (hatched line). EBT78 and IBL-MAL (heavy segments) are the tentative sources for the 9 January and 11 January 1693 earthquakes obtained in this study (see the text and Tables 5 and 6). N. 78 and 79 indicate seismogenic areas (patterned) adopted by GNDT (1996).

the Ibleo-Maltese Escarpment (see the definition of M_e in Boschi et al. 1995a; page 94). Recent data (Hirn et al., 1997) confirm the continuity between the Ibleo-Maltese Escarpment normal faults system and the Timpe system. Lentini et al. (1994) think that the escarpment perhaps originated during Mesozoic times, and was reactivated by prevalently normal movements during the Plio-Pleistocene; early reflection seismics (MS26 Line in Finetti, 1982; MS20 Line in Jongsma et al., 1985) revealed its impressive system of faults, and new crustal seismic surveys, achieved on normal-incidence reflection profiles in the eastern Sicily offshore (Hirn et al., 1997), recently confirmed this.

Recent tectonics and postulated seismogenic faults

By 1980, three systems of inland active faults have been described associated with the geodynamic evolution of south-eastern Sicily in Plio-Quaternary (Di Geronimo et al., 1980); namely, (1) those trending NE-SW which were interpreted to be responsible for the stepwise lowering of the Hyblean succession beneath the Catania-Gela foredeep; (2) the NNW-SSE and NW-SE trending faults, which truncate the Hyblean

Plateau along its Ionian margin, being related to the inland extension of the Ibleo-Maltese Escarpment; (3) those trending from E-W to NE-SW which flank the graben of Scordia-Lentini, and the horsts in between. In this complicated picture, Di Geronimo et al. (1980) attribute a Middle Pliocene age to the principal inland transcurrent movements in the region, and postulate that at present mainly normal movements are still active.

A slightly different picture is given by the Neotectonic Map of Italy (Ambrosetti et al., 1983). There, the SE-verging thrust system is active during Quaternary times. According to Ghisetti and Vezzani (1980), the Scicli-Ragusa-Monte Lauro is a right-lateral fault system, active in the Pliocene-Quaternary and/or Quaternary. Evidence of right-lateral neotectonic activity of the Scicli fault during the latest Miocene to the Pleistocene, from the coast to approximately 15 km inland was given by Grasso and Reuther (1988; see their Figure 5); they measured the mechanism in two sites where the fault transects the Miocene carbonates or marls (see also: Pedley and Grasso, 1992), and derived a right-lateral mechanism from a 'well developed drag anticline' in a sea-shore outcrop of Middle Pleistocene sands. Note that these authors assume a regional geodynamic interpretative model different from that of Ghisetti and Vezzani (1980). Several normal faults should also be active during the same period: the inland normal-transcurrent faults, sub-parallel to the Ibleo-Maltese Escarpment, and the tectonic line which is found along the coast from Messina to Taormina (the so-called 'Taormina Line' going WNW-ESE). Ambrosetti et al. (1983) attribute dominant normal movements to the Taormina Line; in more detail, Ciaranfi et al. (1983) postulate that normal movements have taken place along this line since the Middle Pliocene up to the present time, while early strike-slip movements (sinistral) acted in the Lower Pliocene. On the other hand, following Ciaranfi et al. (1983), the Taormina Line doesn't represent a transform structure, but is rather a sub-horizontal thrust surface (consequently, nonseismogenic).

The Quaternary activity of the system of NE-SW-trending faults along the eastern coast of Sicily was recognized also by Grasso et al. (1979). Carbone et al. (1982) evidenced an important tectonic phase during the Middle and Upper Pliocene along the whole NE-SW-trending system from Comiso to Agnone (northernmost sector of the Hyblean area; see Figure 1), with basaltic flows clearly cut by NE-SW-striking faults.

Regarding off-shore structures, the recent seismic time sections presented by Hirn et al. (1997) clearly show a series of high-angle ENE-verging normal faults immediately offshore the Ibleo-Maltese Escarpment (up to 30 km offshore of both Catania and Augusta). These faults cut the sea-floor and penetrate the upper crust, cutting the continental margin of Sicily on the Ionian side. Hirn et al. (1997; their Figure 9) connect the intersections between the observed faults F3 to F7 and the available seismic sections with straight dashed lines striking NNW. Thus, in contrast with previous interpretations, they suggest that the normal faults in the area are not cut by east-west-trending transfer faults with predominant strike slip movements. For example, the occurrence of strike slip faults offshore Cape Campolato (Augusta) is supported by Finetti (1982) and Bigi et al. (1990).

Hirn et al. (1997) suggest that the dip of these high-angle ENE-verging normal faults decrease at depth. The approximate dip of the upper part of faults F3 to F7 in the migrated sections is $65^\circ - 70^\circ$ (Cernobori, private communication, 1997).

Evidence of down-dip movements of the coast south of Augusta in historical times comes from comparing the work by Schmiedt (1972) with the recent data of Stewart et al. (1997). Mulargia et al. (1991) have already used the work by Schmiedt (1972), who measured the subsidence of the Roman ports of Megara Hyblæa, Thapsos, and Ognina over the last 2,000 years (see Figure 1). An apparent 1–1.5 m subsidence was estimated at all these ports. This has two implications: firstly, the absence of vertical relative movements between these Roman ports indicates that the NNW-SSE-trending normal-transcurrent faults in the area have not experienced relative updip movements, or were quiescent, over the last 2,000 years. The second implication is that the Megara Hyblaea-Thapsos-Ognina area subsided considerably with respect to the more northern coast of Sicily and to the Calabrian coast. We know, in fact, that regional uplift continued there and in the southern Italian Peninsula during this period (Westaway, 1993).

Then, Stewart et al. (1997) give evidence (C^{14} assay of biota of notch levels) of upward movements of the northern part of the coast of eastern Sicily, near Taormina (43 km NNE of Catania). They conclude that coastal uplift near Taormina involved two principal abrupt crustal movements, possibly strong earthquakes, in the last 3,500 yr. However, ≪the elevations of raised Holocene shorelines along the Taormina coast are broadly consistent with equivalent features reported from the opposing Calabrian margin of the Straits of Messina≫ (Stewart et al., 1997, p. 45) and with regional uplift of the southern Italian Peninsula (Westaway, 1993).

For the last millennia, the data by Schmiedt (1972), and by Stewart et al. (1997) suggest down-dip movements of the coast south of Augusta (possibly along a blind fault belonging to the Ibleo-Maltese Escarpment fault system), and viceversa up-dip movements of the coast NE of Mt. Etna (possibly along the Taormina Line sensu Ambrosetti et al., 1983).

Regarding the postulated seismogenic faults, we would like to stress that attributing earthquakes of the past to a fault or structure is difficult where quantitative paleoseismological data, other empirical evidence, or any back-prediction based on modelling, are unavailable, as in the study area. In these conditions, any attribution runs the risk of being subjective. Nevertheless, it is worth to summarize at least the most recent opinions of workers who have dealt with this matter.

Patanè and Imposa (1989) note that the mezoseismal area ($I = \mathrm{V}$ and VI degrees) of the small earthquake of 23 January 1980, 22:21 local time, was elongated parallel and east of the Scicli-Ragusa-Giarratana-M.te Lauro fault system (see Figure 2(d)). This would prove the area east of this fault system to be seismically active in recent times as well.

A general interpretation of the positions of seismogenic areas throughout the Italian territory has been carried out by experts under the National Group for Defence against Earthquakes (GNDT, 1996). In this study two seismogenic areas are identified in south-eastern Sicily: areas N° 78, and 79 (see Figure 1). In short, the former area includes the series of NNE-SSW-trending faults whose clearest surficial expression is the Scicli-Ragusa-Monte Lauro line, the latter surrounds the well-known Ibleo-Maltese Escarpment (see Figure 1). This seismogenetic interpretation agrees with the structural sketch by Reuther et al. (1993).

Note that Bianca et al. (1997) suggest that the ruptures of the 9 January and 11 January 1693 earthquakes might have occurred along the normal faults detected offshore the Ibleo-Maltese Escarpment.

Source-inferences derived from macroseismic information

Barbano and Cosentino (1981) calculated the focal depth of the 1693 mainshock using the Sponheuer (1960) approach; the result was approximately 20 km. Values from 7.0 ± 0.3 (Westaway, 1992) to 7.7–7.8 (Schick, 1977) were proposed for its magnitude. However, in the case under study, this kind of results is questionable due to the proximity of the sea (and consequently the absence of a large part of the intensity field), and the combination of the effects of the two strong shocks of 9 and 11 January 1693. Many papers have also used the shape of isoseismals to formulate hypotheses for epicentral locations; thus, some authors placed the epicentre inland, while others argued that it was offshore. We consider it impossible to constrain the epicentre using damage evidence only qualitatively. We think, however, that most often there is a relation between the position and extension of the highest degree isoseismal and the approximate surface projection of the source. From this point of view, the intensities observed in 1693 at six sites close to the SE Sicilian coast (see Table 1, Figures 4 and 6) are crucial for deriving a rough location of the main shock rupture plane, and it will be seen that they are crucial also for inversions.

If the responses at these sites could be proved to have been misinterpreted, or to have been systematically lowered by true local deamplification, the result would be an area of XI degree completely open toward the sea. In turn, this would allow for a seismic source totally, or in part, offshore. For this reason, the geology of these sites, and their behaviour during other earthquakes in the past were checked (see Figure 2 and Tables 1–2). Table 2 gives the geological nature of these sites modified and shortened from that of the 1 to 100.000 geological map by Carbone et al. (1989); their locations are in Figure 4.

As shown in Table 2, all sites are generally stiff. None of them is on sound rock, which might cause deamplification; rather, some amplification could perhaps occur at Siracusa and at Augusta due to the relatively less stiff local soils and the presence of flat promontories downtown. A special study has been conducted on the seismic effects of 1693 in the Siracusa area; at Ortigia (the promontory of old Siracusa) the revised intensity given to the overall effects of the earthquake is IX (Boschi et al., 1995b).

Statistical tests (Sirovich et al., 1998) show that, at the scale of this study (one I value per inhabited centre), site conditions do not systematically bias the ‘local’ seismic responses of the sites. Therefore, regarding the site geology, we are confident enough that the six intensity data coming from these crucial sites are not due to anomalous deamplification. Note that the sites of Augusta (8–9 degree), Catania (7–8), and

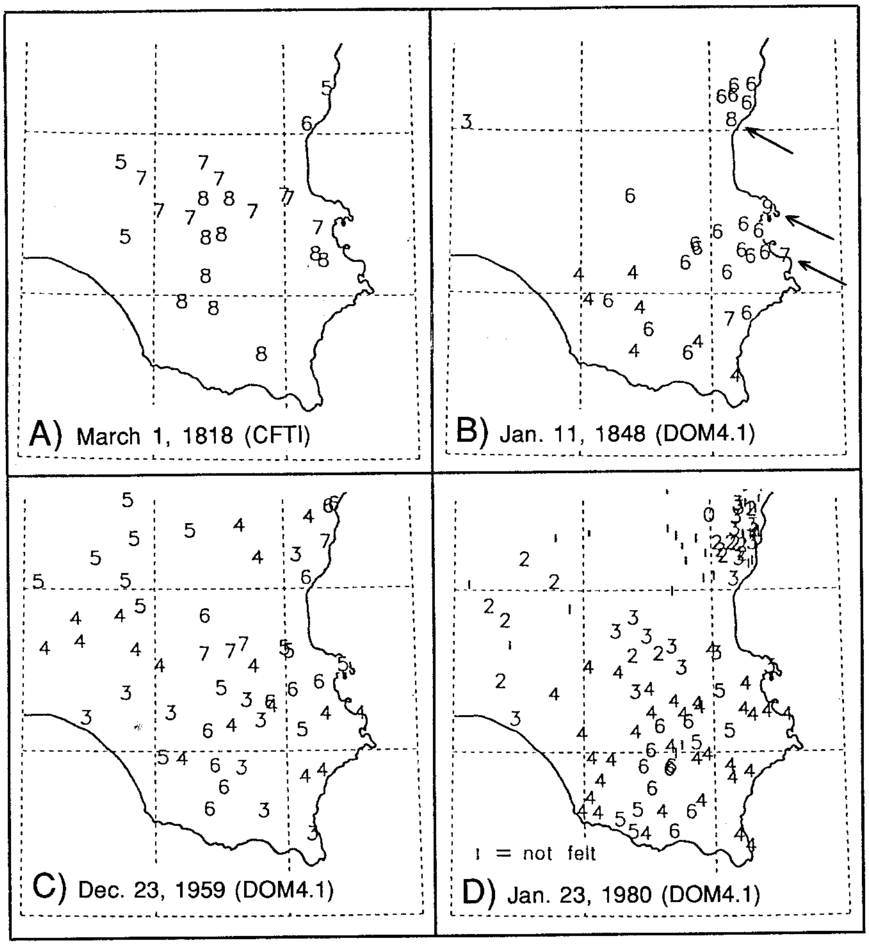

Figure 2. *I* 'point' values of the March 1, 1818 (Figure 2(a)), January 11, 1848 (Figure 2(b)), December 23, 1959 (Figure 2(c)), and January 23, 1980 (Figure 2(d)) earthquakes in SE Sicily. See the references in Table 3.

Table 1. The intensities observed in 1693 at six sites close to the SE Sicilian coast, which are crucial for discriminating between offshore and inland sources

site / earthquake	Brucoli	Augusta	Belvedere	Siracusa	Floridia	Avola Vecchia
01/09/1693*	8	8	7	7	9	9
01/11/1693	10*	10* – 10^	8*	9* – 10^	11* – 10^	10* – 10^

* data from Boschi et al. (1995a).
^ from Barbano and Cosentino (1981).

Siracusa (6–7) experienced the highest damage during the 11 January 1848, earthquake (see arrows in Figure 2b; only the upper values are shown).

We also examined all *I* data sets available for other earthquakes in the area. Table 3 shows all *I* distributions that could give qualitative evidence on the approximate locations of the seismic sources in the region south of Mount Etna; Figure 2 presents the more complete data sets. Regarding the 13 December 1990, earthquake, see the syntheses in Sirovich and Pettenati (1998) giving a nucleation point offshore and a strike-slip EW mechanism.

We believe, however, that the concepts of the centre of gravity of *I* 'points' coinciding with the epicentre, and even of macroseismic epicentre, are highly questionable. Also, we stress that none of the events

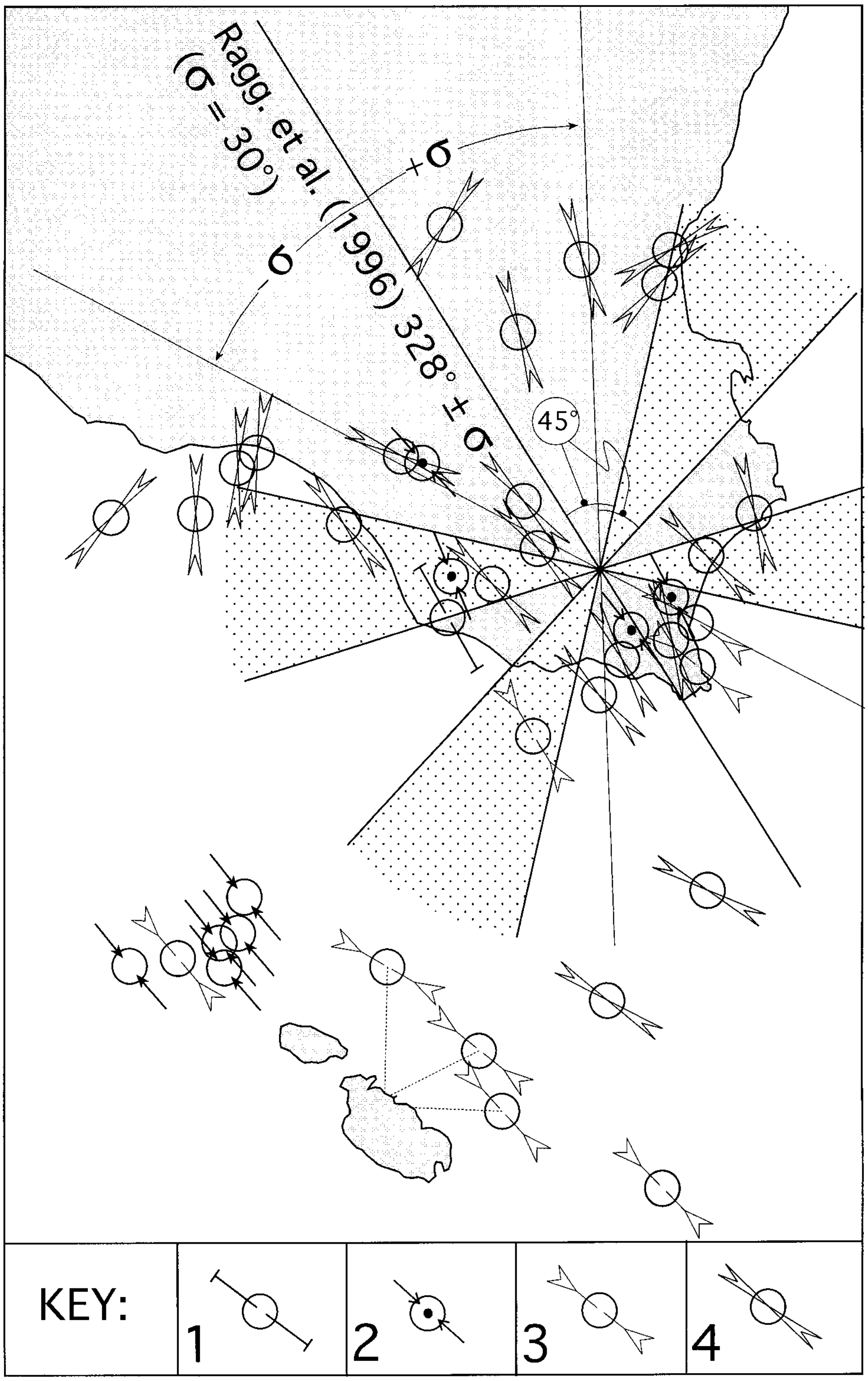

Figure 3. Principal $S_{H\max}$ stress directions inferred in the study area. (1) Müller et al. (1992; S_H overcoring method); (2) Grasso et al. (1995); (3) Gardiner et al. (1995); (4) Montone et al. (1996). (2) to (4) summarize borehole breakout data from various workers.

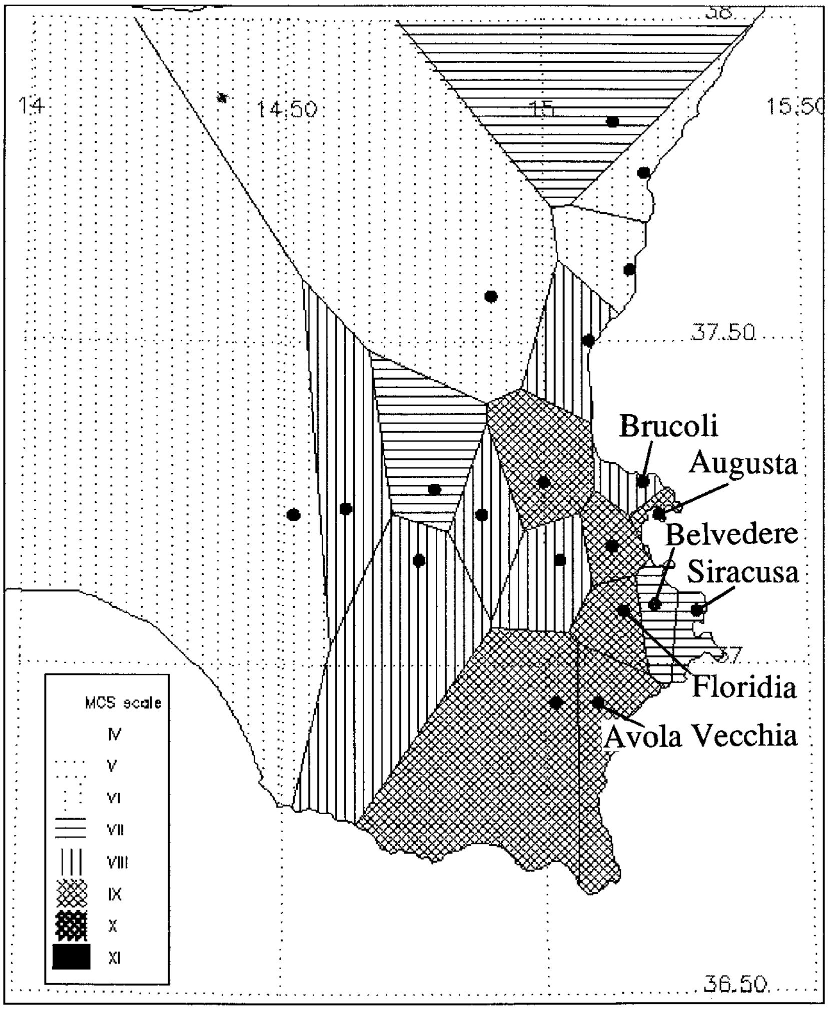

Figure 4. 9 January 1693 earthquake. Tessellated observed macroseismic intensities in SE Sicily. The dots are the 'surveyed' sites (I data from Boschi et al., 1995a).

Table 2. Summarized geological nature of the sites of Table 1

Site	Geology (from Carbone et al., 1989)
Brucoli, Belvedere, Floridia, Avola Vecchia	'Monti Climiti' Formation (massive and stratified calcarenites; Upper Oligocene-Middle Miocene)
Augusta	in part, sands, calcarenites and gravels with various degrees of cementation, and conglomerates, of the Middle-Upper Pleistocene; in part highly overconsolidated clay, and marly clay of the Lower Pleistocene
Siracusa (old town)	on the flat Ortigia promontory ('Monte Carrubba' Formation – stratified friable-to-well-cemented calcarenites; Upper Miocene)

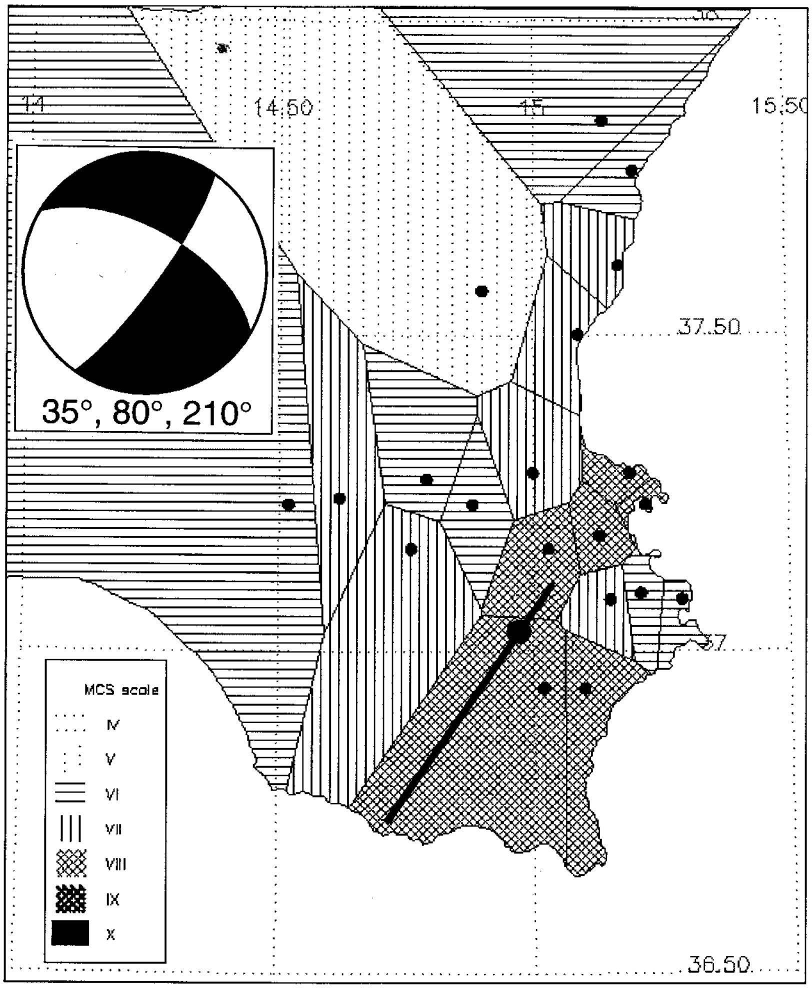

Figure 5. Synthetic bestfit of the tessellated observed macroseismic intensities for the 9 January 1693 earthquake (see Figure 4). The black segment, and large dot, are the source used (SW segment of EBT 78) and the nucleation, respectively (see Table 5).

listed in Table 3 has a density of *I* 'points' per unit area high enough (according to the Nyquist principle) to constrain adequately the shapes of the mezoseismal areas, nor to understand for example if those of 1169, 1542, 1693, 1727, 1848, 1949, and 1980 open toward the sea, or tend to close near the coast. The bases for these criticisms are more thoroughly given elsewhere (Pettenati et al., 1998).

It seems reasonable, however, that, if the entire source is offshore, damage generally decreases from the coast inland (although particular focalizations of energy due to reflection/refraction within the crust could provide an exception; see for example Priolo, 1999).

In conclusion, a qualitative overview of the available *I* fields suggests the existence of the following principal sources of varying potentials (the years of the correlated events are in parentheses):

– two sources inland: (1) possibly 'small', in inner Sicily (Mineo area; 1542, 1624); (2) possibly 'large' striking approximately NE and crossing the Hyblean Mountains from coast to coast (1169; and 1959 and 1980 [Figures 2(c), 2(d)]);
– one source offshore, perhaps associated with the Ibleo-Maltese fault system (1848 in Figure 2(b), 1169[?]);
– other sparce sources inland, possibly 'small', sometimes with offshore extension (1624, 1727, 1818 in Figure 2(a), 1949)

If the distribution of the *I* 'points' of the 9 January and 11 January 1693 earthquakes are overviewed in the same way, the max. *I* 'points' (9 and 11, re-

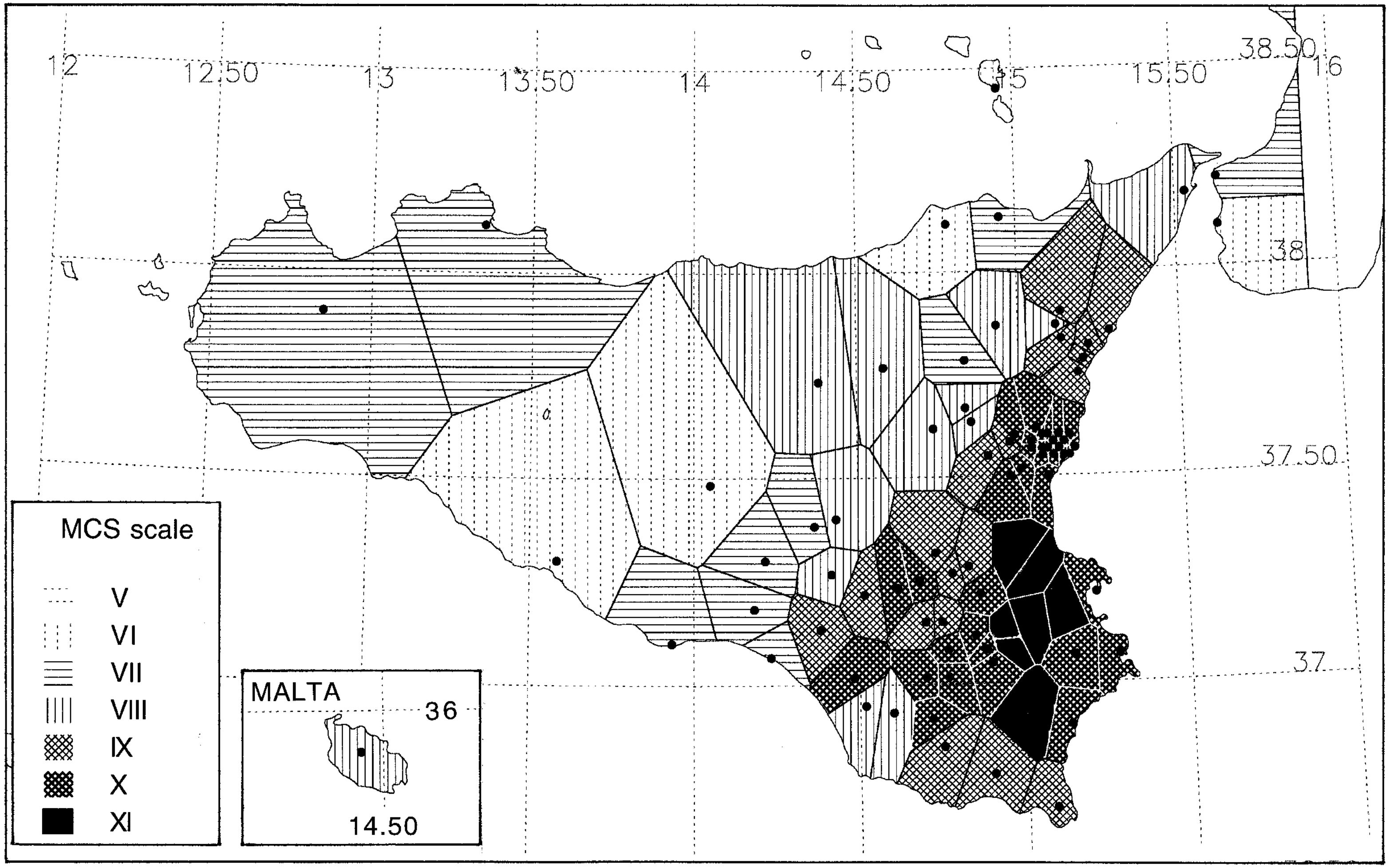

Figure 6. Tessellated observed macroseismic intensities for the 11 January 1693 earthquake in SE Sicily. The dots are the 'surveyed' sites (*I* data from Barbano and Cosentino, 1981).

Table 3. *I* data sets available in the study area, and qualitative hypotheses on the approximate locations of the related seismic sources

Date	Max. *I* (MCS)	Catalogue used (*)	tentative position of the source (qualitative)
Feb. 04, 1169	X	CFTI	very few data; (1) in part inland from the SW coast to Catania; or (2) offshore Mount Etna with strong radiation toward SW (?)
Dec. 10, 1542	X	CFTI	perhaps inland (see the degrees 8 along the East coast)
Oct. 03, 1624	IX	CFTI	very few data; inland (surficial?)
Jan. 07, 1727	VIII	DOM4.1	perhaps inland, close to the SE coast (surficial?)
Mar. 01, 1818	VIII	CFTI	inland (Hyblean Mountains), or offshore the southern coast (see Figure 2(a))
Jan. 11, 1848	IX	DOM4.1	offshore (Ibleo-Maltese Escarpment [?]) (see Figure 2(b))
Oct. 08, 1949	VII	DOM4.1	sparce data; inland and/or offshore the East coast
Dic. 23, 1959	VII	DOM4.1	in great part inland; points 7 and 6 trace approximately a NE striking stripe from the SW coast to the area of Catania (see Figure 2(c))
Jan. 23, 1980	VI	DOM4.1	in great part inland; points 6 and 5 trace a stripe from the SW coast towards NE, approximately 25km long (see Figure 2(d))

(*) Catalogues' key: CFTI = Boschi et al. (1995a); DOM4.1 = Camassi and Stucchi (1997)

spectively) line up approximately in a strip trending NNE-SSW from the coast south of Catania into area of the Hyblean Mountains (see Figures 4 and 6).

Tsunami

The 11 January 1693 event caused a tsunami which was described by some coeval authors. The sea retreated before the earthquake and then its level temporarily increased by 30 '*cubits*' (15 m) in the harbour of Augusta (Boschi et al., 1995a). After retreating, at Catania the sea level reached S. Filippo Square, downtown (Barbano, 1997, written communication). Barbano and Cosentino (1981) speculate that this could imply a normal fault mechanism for the 11 January earthquake; and Carbone et al. (1982) add that the sea retreating before the earthquake could suggest collapse of the Ionian sector along the Ibleo-Maltese Escarpment fault system. Quantitative modelling was done recently by Piatanesi and Tinti (1998) with the finite element method and adopting four tentative faults inland and offshore. The experimental control points for this modelling where six harbours in eastern Sicily for which historical documents report initial sea withdrawal followed by flooding. According to these authors, only a fault striking NNW (called S3), parallel to the Ibleo-Maltese Escarpment and tangent to the promontories close to Augusta and Siracusa, satisfies the experimental constraints. Note that a fault further offshore, where the main submarine morphological expression of the Escarpment is found, gives instead initial flooding at Augusta and Siracusa.

It is worth noting that no tsunami is reported for the strong foreshock of 9 January 1693 ($M_e = 6.0$; Boschi et al., 1995a).

It is reported that also the event of 1169 would have caused a strong tsunami, with a 6 km transgression of sea water along the Simeto River valley (D'Addezio and Valensise, 1991). Then, according to Azzaro and Barbano (1996), the earthquake of 20 February 1818, 18:20 ($M_e = 6.2$; Boschi et al., 1995a) also caused evidences of a tsunami along the Ionian coast of Sicily. The area most heavily stricken in 1818 (intensity IX–X) is on the SE flank of Mount Etna. On the other hand, some speculations reported in the XVII Century regarding a tsunami associated with an earthquake in 177 A.D. are probably unreliable (Tinti, 1997, written communication).

Quantitative information

A rough estimation of the scalar moment from the empirical relationship between seismic moment and the area of isoseismal curves from many Italian earthquakes gives a value in the order of 10^{20} $N{\cdot}m$ for the main shock of 11 January 1693; and the expected magnitude for a characteristic earthquake occurring in this area is larger than about 7 (Amato et al., 1995). This scalar moment may be overestimated, however, because the damage patterns of the two shocks of 1693 superimpose.

Seismological information and hypotheses derived from quantitative modelling of pre-1990 earthquakes in the area are scarse. It is worth quoting the simultaneous inversion of earthquake data prior 1980 and of velocity models in the Hyblean region by Del Pezzo et al. (1981); their study indicated events occurring within the first 10–15 km in the crust, and fault plane solutions where left-lateral strike-slip mechanisms along approximately N-S oriented faults predominate.

70 km north of our study area, Valensise and Pantosti (1992) studied the zone of the Messina and Reggio earthquake of 1908. This earthquake had a magnitude $M_s = 7.5$ (Gutenberg and Richter, 1954), and a 10 m-high tsunami-wave developed on that occasion. It probably had a normal mechanism on a blind fault, striking NNE.

The stress field

An important constraint for seismological modelling is the present stress regime in the area. Apart from the extensional (with subordinated strike-slip) movements hypothesized for the coastal and west Ionian area, no quantitative evidence is available for offshore SE Sicily.

According to Cristofolini et al. (1985), for the inland region the general trend of the external compressive structures in Sicily indicates a N-S and NNW-SSE oriented axis of maximum horizontal compressive stress $S_{H\max}$.

Ragg et al. (1995, 1996) inferred the orientation of in-situ tectonic stress in Sicily from borehole breakouts from 22 wells in Sicily (see also Montone et al., 1996). Borehole breakouts consist of couples of spalled volumes which develop around a boring, and they are caused by conjugate shear fractures that form when a well is drilled in rocks subjected to an anisotropic stress field. The two opposite spalled zones are aligned along the direction of the minimum horizontal stress.

For SE Sicily, in the area of the Hyblean Plateau, Ragg et al. (1996) deduce from breakouts a nearly NNW orientation (148° ± 30° at one standard deviation level; 328°±30° under the convention adopted in the present paper) for the present maximum horizontal compressive stress $S_{H\max}$. However, the principal tectonic stresses rotate anti-clockwise in the vicinity of the surface front of the Gela Nappe. More recent breakout data confirm these orientations in the area (Amato, 1996, written communication), which had also been obtained in previous regional analyses using different techniques (see Müller et al., 1992; their Figure 3). See a summary of the available data in Figure 3.

When constraining the hypothetic rupture planes used in modelling, in this paper, we refer to the direction 328° $\pm\,\sigma$ ($\sigma = 30°$) obtained by Ragg et al. (1996) on the Hyblean Plateau.

Note that it is generally accepted that brittle fracture takes place in the crust at high normal stresses, with failure envelopes in the Mohr diagram becoming parallel to the axis of normal stress. This regime implies a 45°-angle between the failure plane and the direction of the principal normal stress, and causes the planes on which the maximum shearing stress acts to coincide with the failure. The same occurs with the friction angle $\phi = 0$ concept in the Coulomb rupture criterion. Obviously, when one or more planes of weakness pre-exist in the stressed region, the pattern of tectonic work done complicates. Given the aforementioned $S_{H\max}$ orientations by Ragg et al. (1996), the simplest models which could account for the expenditure of positive tectonic work in the area would be:

(1) two (sub-)vertical rupture planes oriented +45° or −45° with respect to the cited NNW orientation of $S_{H\max}$. One σ considered, this gives two possible ranges for the strike of the hypothetical sub-vertical rupture planes: 13° to 43°, and 253° to 283° (see the patterned sectors in Figure 3).

(2) a reverse fault striking 58° ± 30° (dipping 45° towards SSE), or 238° ± 30° (dipping 45° towards NNW).

Inversion of intensity patterns

Geophysical inversion of I patterns involves many problems regarding the I data themselves such as: their intrinsic nature; the questionable practice of treating I as a real number in regression analyses; the unclear influence of source-, path-, and site-effects. We discussed elsewhere the widespread practice (manual or automatic) of drawing isoseismals, and showed that often it does not take care of the space- frequency-incompleteness of data according to the Nyquist principle (Pettenati et al., 1998).

Before inverting the I data, we searched for site amplifications or deamplifications. Analysis of the distributions of the D logarithms, gave no outliers; we found only a slight tendency for loose-soil sites to amplify I beyond 120 km from the source (Sirovich et al., 1998).

The dimension and geological heterogeneity of the surveyed 'points' may explain why intensity is less sensitive to very local geological conditions than other, quantitative, strong motion parameters.

Since macroseismic scales have a descriptive nature, the use of a numerical axis to treat intensity by regressions or syntheses suggests using the term 'pseudo-intensity' (see also Peruzza, 1996). We will call 'I' the macroseismic intensity referred to its proper scale; and 'i' – 'pseudo-intensity' – the macroseismic intensity forced into a numerical, integer or real, scale.

In this paper we use the maximum values reported for each site. This choice has only minor consequences on the general results of the inversion, however.

Our kinematic model, and related graphic convention, are illustrated elsewhere (Sirovich 1996a, 1997) and are not repeated here. The algorithm has been improved by analysing 1720 'point' I data for five earthquakes in the Los Angeles, California, area: San Fernando (9 February 1971), Whittier Narrows (10 January 1987), Upland (28 February 1990), Sierra Madre (28 June 1991), Northridge (17 January 1994), with Seismic Moment approximately from $2.7 \cdot 10^{17}$ to $2.2 \cdot 10^{19}$ $N \cdot m$. The reason for choosing these events was that they are all from the same region and were well recorded; thus, path- and site-effects are hopefully minimized, and we had the opportunity to compare the results of our inversions with the kinematic characteristics determined by other authors who used modern techniques and seismograms (Sirovich, 1996a, b). The 1720 I data come from the computer files of the U. S. Geological Survey at Denver (James W. Dewey, 1994 written communication). Soil classifications for the California sites were based on a proprietary database developed by Risk Management Solutions, Inc. of Menlo Park, California (Fouad Bendimerad, 1997 written communication).

The values of log KF showed a linear relation to the corresponding pseudo-intensities at the sites, but the data of the strongest shocks (San Fernando, and Northridge) were clearly detached from those of the smallest ones (Upland, and Sierra Madre), and the data of the intermediate M_o earthquake of Whittier Narrows lay approximately in between. This suggested to include more variables in the (log KF; i) regressions to take into account, above all, the 'size' of the shocks. For this purpose, we tested the length, width and surface of the fault, mean slip, stress drop, seismic moment, hypocentral depth of the earthquakes, and found that the inclusion of a selected combination of seismic moments M_o was resolutive. The statistical analyses gave the linear multiregression (1) which is used to calculate 'point' pseudo-intensities i at location (x, y).

$$i(x, y) = 9.241 + 3.358 \cdot \log_{10} KF(x, y) + \\ + (8.04 \cdot 10^{-20}) \cdot M_0, \qquad (1)$$

where (± 0.152) is the standard error of the intercept, and (± 0.124) and ($\pm 0.54^{-20}$) are the standard errors of the coefficients. *KF(x,y)* are nondimensional values calculated at location (x, y) by our formula (Sirovich, 1996a), M_0 is Seismic Moment $(N \cdot m)$. Unexpectedly, the log M_0 fit was slightly worse; log M_0 might prevail by treating data belonging to earthquakes spanning over a wider M_0 range. We stress that Equation (1) can be used only within the range in which it was calculated $(2.7 \cdot 10^{17} - 2.2 \cdot 10^{19}\ N \cdot m)$, however.

The I data of the five earthquakes in the greater Los Angeles region are in the Modified Mercalli, MM, scale of 1931, while those of Sicily are in the MSK-64, and the MCS scales. Fortunately, in the range of values used here, there is a substantial equivalence between the three scales (Murphy and O'Brien, 1977; Monachesi and Stucchi, 1996); thus, we treat information from Sicily without adjustments.

As said, before inverting the I data from the two earthquakes of 1693 in SE Sicily, we tested our procedure on the $M_L = 5.4$ earthquake of 13 December 1990 in the same region successfully (Pettenati et al., 1998; Sirovich and Pettenati, 1998). After this encouraging test, the following results represent the first quantitative hypotheses on the possible sources of one of the most historically destructive earthquakes of the Central Mediterranean area.

To find the synthetic i patterns that best fit the observations, we tessellate both the observed I patterns, and the synthetic i by Voronoi polygons (Preparata and Shamos, 1985). As known, this technique of spatial representation of data is particularly suitable for qualitative or discrete-valued variables such as I. Note that the Voronoi tessellation honours the data, and it associates to them information regarding spatial density and contiguity of observations in the plane. Within each polygon, the reliability of information decreases with the distance from the point which generated the polygon. The union of all polygons with their values gives the tessellated intensity field of an earthquake. The most trivial use of this approach could be in decision-making during the drawing of traditional isoseismals (but we do not encourage this), and in discriminating eventual anomalous responses of groups of sites. Then, the tessellated observed intensities (see Figures 4 and 6) are easy-to-grasp pictures, and they are objective, which is essential when used in inversions.

For this, we perform statistical tests on the residuals (i) directly at all I 'points', and also (ii) over the whole area (V-V and C-V tests in Tables 5–6). In the V-V test the fields of both observed I and synthetic pseudo-intensity were tessellated, and the weighted sum of the squares of the residuals was calculated over the whole territory. In the C-V test the tessellated observed I field is compared directly with the whole synthetic field (which is a continuous function). See the details of the choice of the weights in Sirovich et al. (1998).

Starting structures for the inversions

Using all the previously described seismotectonic information, we adopted the following families of sources for constraining the inversions of the I data (see Figure 1):

(1) IBL-MAL: normal faults, steeply dipping towards ENE (with 0 to 50% sinistral, or dextral, strike-slip components), belonging *latu sensu* to the Ibleo-Maltese Escarpment fault system. Both offshore and inland faults in the coastal area were considered;

(2) SCO-LEN: normal faults associated with the Scordia-Lentini grabens, dipping N and NNW and trending from E-W to NE-SW;

(3) SCICLI-EBT78: strike-slip faults, in part associated with the Scicli-Ragusa-Monte Lauro fault system; sub-vertical, trending from N to NNE, with left- or right-lateral movements. In particular, EBT78 is a proposed strike-slip sub-vertical transfer structure, striking approximately NNE. It would lie on the eastern flank of the promontory formed by the Bouguer gravity, and magnetic anomalies in the area of the Hyblean Plateau. This promontory strikes $20° - 30°$ (Ben-Avraham and Grasso, 1990; see their Figure 8) as does EBT78. The acronym indicates that the upward vertical projection of this rupture plane almost coincides with the eastern edge of the transfer seismogenic zone N°78, one of the seismogenic zones recently adopted by the experts of the National Group for Defence against Earthquakes (GNDT) for calculating the seismic hazard of Italy (GNDT 1996). The seismotectonic interpretation of GNDT agrees with the aforementioned proposals by Ghisetti and Vezzani (1980); in fact, zone N°78 works as a transfer zone between the two adjacent Simeto and Scordia-Lentini structures, on the one side, and the Pantelleria rift system in the Sicily Strait, on the other.

Table 4 summarizes the principal qualities and deficiencies of the possible seismogenic sources.

Results of inversions

Figure 4 shows the tessellated observed I of the 9 January 1693 earthquake. The dots are the surveyed sites (Boschi et al., 1995a). Figure 5 shows the best tessellated synthetic i patterns, calculated adopting the SW segment of the source that we called EBT78.

The kinematic characteristics of the best selected sources for each family of rupture planes are in Table 5. Due to their similarity, families 3 and 4 of Table 4 now are called Scicli-EBT78. The residuals of a pure strike-slip mechanism on the Scicli-EBT78 source are in square brackets. Worse statistics are obtained if a traditional circular 'attenuation law' is used to back-predict the I patterns (see the used law and its scores in Sirovich et al., 1998). We quantified the errors (in parentheses in Table 5, positive and negative) of the principal parameters obtained. The same was done in Table 6; note that in both tables, considering the errors, pure strike-slip mechanisms for the two earthquakes are not precluded. In fact, for example, $\ll$rake angle = 210° (+34° − −43°)$\gg$ for the Scicli-EBT78 source in Table 5 means that the value of the calculated rake angle can span from 167° to 244°.

To quantify these errors, we started from a reasonable assumption: one degree uncertainty in the I estimate is common in the field (and from the seismological interpretation of historical documents), whilst an error of two degrees is unlikely. Thus, regarding M_0, we ascertained its error (more precisely: sensitivity) until reaching a change of two degrees of i in Equation (1); we did this both by studying the theoretical propagation of errors in the equation, and, empirically, by trial-and-error in the matrix of the sites. The latter type of test started from the best fitted solutions shown in Table 5 (and 6); it consisted in increasing (and decreasing) progressively the M_0 value till these increments (and decrements) caused the first change of two degrees in the calculated i values of the sites' matrix.

The theoretical propagation of errors in Equation (1) gave the M_0 error at $\pm 1.25 \cdot 10^{19}\ N \cdot m$. In the case of the January 9 event, the empirical

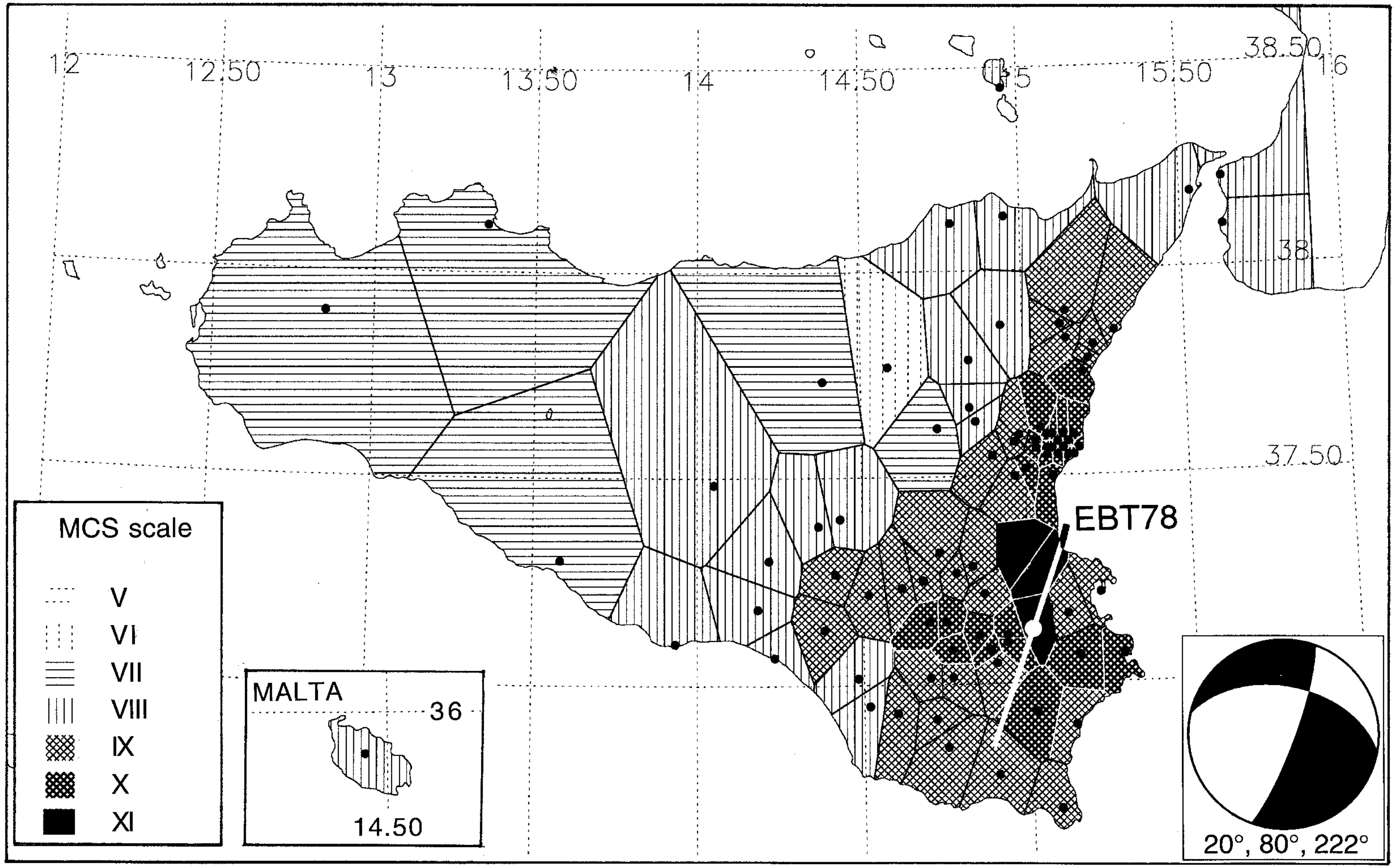

Figure 7. Synthetic bestfit of the tessellated observed macroseismic intensities for the 11 January 1693 earthquake. The white segment is the source used (NE segment of EBT 78) with its nucleation (white dot) (see Table 6).

Table 4. Principal qualities and deficiencies of the considered families of seismogenic sources

family / info. match	Regional tectonic role	Neotectonic evidence	Seismological evidence	Tsunamigenic (qualitative)	Historical earthquakes (qualitative)	Stress orientation compatible
(1) IBL-MAL	YES	YES	*	YES (?)$	PROBABLE	(?)
(2) SCO-LEN	YES	YES	/	(?)	(?)	*NO*
(3) SCICLI	YES	YES	/	*NO*	PROBABLE	YES
(4) EBT78	YES	/	?¶	(?)	PROBABLE	YES

* The epicenter of the $M_L = 5.4$ earthquake of 13 December 1990 is offshore in the area of the Ibleo Maltese Escarpment, but on an EW dextral transcurrent fault (or NS sinistral).
$ According to the modeling by Piatanesi and Tinti (1998), this requisite is satisfied only if a *vertical* rupture plane *tangential* to the Augusta and Siracusa promontories is chosen.
¶ Elongation of the mezoseismal area (I = V and VI degrees) of the earthquake of 23 January 1980 (Patanè and Imposa, 1989).

Table 5. 9 January 1693, earthquake. Kinematic characteristics of the best selected sources for each family of rupture planes of Table 4 (see text)

9 Jan. 1693 Best Source	Ibleo-Maltese Escarpment	Scordia-Lentini Graben	Scicli-EBT78	'Attenuation law', equation*
Parameter				
Latitude (°)	37.10	37.28	37.03	/
Longitude (°)	15.37	15.05	14.97	/
Depth (km)	10 (+20 − 10)	10 (+10 − 6)	10 (+15 − 10)	/
Length (km)	30 + 30	30 + 10	10 + 40	/
Strike angle (°)	350 (+16 − 9)	250 (+13 − 8)	35 (+5 − 17)	/
Dip angle (°)	80 (+10 − 44)	60 (+14 − 33)	80 (+10 − 50)	/
Rake angle¶ (°)	300 (+22 − 16)	300 (+20 − 25)	210 (+34 − 43)	/
Mach number	0.7	0.7	0.65	/
V_S (km s^{-1})	3.5	3.5	3.5	/
M_0 (10^{19} $N \cdot m$)	2.95 (+1.25 − 1.30)	2.60 (+1.28 − 1.36)	2.35 (+1.26 − 1.38)	/
Residuals			[pure strike]	
At the I 'points'	29	33	11 [13]†	25
V-V test	5.75	8.11	2.66 [1.92]†	6.09
C-V test	152,578	156,814	108,699 [111,036]†	333,212

* We employed the formula used by the Working Group of GNDT (GNDT, 1996) for their seismogenic area N° 79 (SE Sicily); it derives from the model by Grandori et al. (1987); the epicentre is from Boschi et al. (1995a).
¶ ±180° ambiguity, given the adopted procedure.
† with rake angle equal to 0° or 180°.

technique which uses the matrix of sites gave an asymmetric sensitivity ($+1.26$ and $-1.38 \cdot 10^{19}$ $N \cdot m$; see Table 5; sensitivities in Tables 5 and 6 are written in parentheses close to their respective parametres). Alternatively, the sensitivity calculated empirically for the main shock of January 11 coincides exactly with the theoretical sensitivity ($\pm 1.25 \cdot 10^{19}$ $N \cdot m$). The sensitivities of the best fitted strike, dip, and rake angles, and of the best fitted depth, were calculated only empirically using the matrix of sites. To do so, the value of each best fitted parametre was increased (and decreased) progressively, and a series of syntheses produced; the first change of two degrees of the calculated i values in the matrix picked out the error (sensitivity) of the parametre in question (see the Discussion). Figure 6 shows the tessellated observed I of the 11 January 1693 earthquake (from Barbano and Cosentino, 1981). Figure 7 shows the best tessel-

Table 6. As in Table 5, but for the 11 January 1693 earthquake. (The data of a pure strike-slip mechanism on the Scicli-EBT78 source are in square brackets)

Jan. 11, 1693 Best Source	Ibleo-Maltese Escarpment	Scordia-Lentini Graben	Scicli-EBT78	'Attenuation law' as in Table 5
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^{-1})	3.5	3.5	3.5	/
Seismic Moment (10^{19} $N \cdot m$)	4.35 (±1.25)	4.80 (±1.25)	4.57 (±1.25)	/
Residuals			[pure strike]	
At the I 'points'	192	105	60 [82]*	290
V-V test	934.37	960.08	373.24 [158.59]*	1116.77
C-V test	50,997	56,536	37,600 [51,385]*	81,522

¶ ±180° ambiguity, given the adopted procedure.
* with rake angle equal to 0° or 180°.

lated synthetic i patterns. These were also calculated adopting the EBT78 source, NE segment. The kinematic characteristics of the main shock are in Table 6. According to formula $M = 2/3(\log M_0) - 10.7$ in Hanks and Kanamori (1979), the value of M_0 reported in the table corresponds approximately to a Moment Magnitude $M = 7.1 \pm 0.1$.

The less satisfactory, or unsuccesfull, syntheses obtained are not shown here. We inverted also the I data of Boschi et al. (1995a) for the 11 January main shock. The resulting bestfitting source is close to that shown in Figure 7, Table 6, but it scores slightly worse residuals (see Sirovich et al., 1998).

Discussion and concluding remarks

We want to state beforehand that we had to use deep tectonic data of different reliabilities: large-scale regional tectonic models (mostly inland), and detailed data coming from seismic prospecting (mostly offshore). Unfortunately, this was unavoidable.

The new offshore seismic profiles by Hirn et al. (1997) stop approximately 5 to 15 km from the coast. Thus, one cannot check either the continuity between the offshore Ibleo-Maltese faults and the on shore subparallel faults, or the existence of the hypothesized EBT78 blind fault.

The fact that the offshore Ibleo-Maltese normal faults cut and offset the sea floor (Hirn et al., 1997) is not a final proof of their more or less recent geological activity, nor of their seismic activity. As a matter of fact: (1) it is well known that energetic submarine environments may show faults displacing old strata not covered by younger sediments; (2) the age of the truncated sediments is not known, and (3) there is an uncertainty in the estimate of the thickness of Recent and present day sediments covering the faulted areas investigated by Hirn et al. (1997), if any. Regarding this, the Ionian sector under study is characterized by high space-variability of the bottom current regime. Thus, on the one hand, Miocene sediments of Messinian age are found at 1 m depth, 50 km off Siracusa, south of profile N° 5 in the area of fault F6 of Hirn et al. (1997) (see logs N° J89-10 and overall J89-11 in Sartori et al., 1991). On the other hand, Recent sediments are found closer to the coast (Rossi and Sartori, 1981). Consider also that the high-energy low-frequency source (Avedik et al., 1995) used by Hirn et al. (1997) probably allows a resolution no finer than 50 m or so, and this reflects in the dating of the fault movements based on sedimentation rates.

Next, our inversions are partly constrained by two weak experimental evidences: (i) the intensity at Malta, and (ii) at some coastal sites between Siracusa and Catania.

The Malta datum in Figure 6 is questionable because of the difficulty of classifying the partial collapse of St. Paul's cathedral, and because it could be due either to radiation from the source, or to preferential transmission of seismic energy from Sicily to Malta (the Hyblean Plateau links southeastern Sicily with the Malta island; Grasso, 1993).

Regarding the contradictory epicentral locations of the 11 January 1693 earthquake, which were derived from the macroseismic data, we stress that the density of surveyed sites inside the mezoseismal area is not sufficient, according to the Nyquist principle, to constrain the shape of the isoseismal of XI degree to a closed or open form. (According to traditional practice, the former would imply a source mostly inland, and the latter a source mostly offshore.)

As for the results of our syntheses, one deficiency of our KF procedure is that, given a certain rupture mechanism (and rake angle r), and adopting $r \pm 180°$, it produces the same radiation but with reversed polarities. Thus, figures identical to Figures 5 and 7 are obtained with rake angles equal to $210° \pm 180°$, and $222° \pm 180°$, respectively. The same holds for the other rake angles shown in Tables 5 and 6. This ambiguity may be solved only with additional tectonic/geodynamic information.

Then, we note that the length of EBT78 toward the S, which presumably activated on 9 January 1693, is weakly constrained due to the paucity of I 'points' toward that direction. For this earthquake, the synthetics produced by EBT78 are far better than those given by any other source considered. In particular, our inversions exclude the possibility of an offshore source east of Siracusa-Augusta. Due to the lack of both I data in the southern area of the Hyblean Mountains, and of seismotectonically plausible offshore sources in those directions, we did not explore the possibility of an offshore source for this earthquake south or SSE of Cape Passero (see Figure 1).

Regarding the synthetics of the 11 January earthquake, compare Figures 6 and 7, and note the almost perfect fit of the intensity IX area. This is a striking result.

Then, it is worth commenting that the M_0 sensitivity calculated empirically for the main shock of 11 January coincides exactly with the theoretical sensitivity, whilst it is larger and asymmetric for the foreshock (compare Tables 5 and 6; the theoretical sensitivity for the foreshock is also $1.25 \cdot 10^{19}\ N \cdot m$). This occurs because the intensities produced by the main shock are sampled through the study of historical documents in a sufficient number of sites, whilst the matrix of sites available for the foreshock is scarce. We recall that we used 90 sites for the main shock (from Barbano and Cosentino, 1981), and 26 sites for the foreshock (Boschi et al., 1995a). As a consequence, Tables 5 and 6 indicate that the sensitivities of the parameters of the 9 January event, calculated empirically, are generally larger and more asymmetric than those of the main event of 11 January. Then, given the half-space medium adopted in the present paper, hypocentral depth is not a crucial point, and its sensitivity less significant. Finally, the positive and negative limits of the sensitivities shown in Tables 5 and 6 are conservative because each one, alone, allows at least one site of the matrix of the synthesized values to change by the maximum assumed possible variation (two intensity degrees).

The two proposed EBT78 segments overlap in part, giving a total seismogenic structure approximately 80 km long, with strike angle $20° - 35°$. This transcurrent structure cuts SE Sicily from the Sicily Channel coast to a point some kilometres offshore the Ionian coast, 10 km south of the city of Catania. However, no continuous surface faulting corresponding to the intersection of our source EBT78 with the topographical surface is known. Is this sufficient to rule out our result? On the one hand, a possible explanation is the obliteration by erosion or sedimentation (or perhaps the insufficient geological knowledge of the area); on the other hand, ≪numerous large earthquakes of this century have made it increasingly clear that *blind faulting* is a common feature of high-potential faults in widely different tectonic settings≫ (Valensise and Pantosti; 1992, p. 472; from their introduction to the hypothesis on the causative fault of the Messina-Reggio Calabria, $M_S = 7.5$, earthquake in 1908).

Figures 5 and 7 show that both nucleation points are best placed inland. However, for the nucleation of the 11 January 1693 main shock, a location slightly offshore, more NNE-wards along the EBT78 line source, gives almost the same statistical scores as those shown in Table 6. For this earthquake, intriguing results are also obtained with an extensional source, and a relevant strike-slip component, along the Ibleo-Maltese Escarpment. No Ibleo-Maltese sources are able, however, to give strong i in the Hyblean Mountains area, and, simultaneously, relatively lower *i* along the SE coast.

Then, one important factor is that the strong foreshock of 9 January modified the vulnerability of buildings in the area, and a possible overestimation of damage related to the subsequent main shock might need to be taken into account. Regarding this, note that the *I* data presented by Barbano and Cosentino (1981) cumulate the effects of the two events; but also those by Boschi et al. (1995a) are perhaps in part cumulative, notwithstanding their great efforts in dividing the effects of the two shocks. In fact, the two intensity data sets are not very different. Thus, the inversion of the mainshock data by Boschi et al. (1995a) still points toward an inland EBT78 source (Sirovich et al., 1998). If the overestimation is true, an Ibleo-Maltese source could regain credence.

Then, we refer to Zollo et al. (1999, this issue) for the ground accelerations back-predicted for the 11 January 1693 earthquake, in the 0.5–20 Hz frequency range. They use a more complete model but based upon the so-called high-frequency approximation, or asymptotic approach, as is ours; and adopt an offshore segmented source compatible with the Ibleo-Maltese composite structure. Note their synthetic maxima in the coastal area immediately north of Catania; high values of acceleration are calculated also along the coast from south of Siracusa to north of Augusta. But the acceleration values rapidly decrease from 200 cm s^{-2}, near the coast, to less than 24 cm s^{-2} inland toward the Hyblean area, where, instead, a high level of damage is present (Figure 6).

We calculated the synthetic regional patterns of pseudo-intensity (not shown here) using Ibleo-Maltese Escarpment sources, and obtained results in agreement with those of Zollo et al. (1999). But also our best Ibleo-Maltese source (see Table 6) is unable to fit the high *I* values in the inland Hyblean area, SW of the source.

It is interesting, however, that the coefficient of variation calculated by Zollo et al. (1999) reaches its highest values just SW of the source, i.e., toward the area where agreement between synthetics and observations is worse, and where damage is more cumulative.

The study by Piatanesi et al. (1998) on the tsunami caused by the mainshock of 11 January 1693 is interesting but unconclusive. Firstly, because the tsunami could have been produced by a submarine slide instead; secondly, due to the incompleteness of the historical evidence, and to the resolutive limits of the model used. For example, no control points are available south of Siracusa, where modelling gives positive edge wave polarities. Then, Piatanesi et al. (1998) smoothed the coastline, and this produced important changes in the shape of the coast between Siracusa and Augusta. Also, the dip angle assumed for the Ibleo-Maltese faults (vertical, with purely vertical movements) contradicts the value ($65° - 70°$; decreasing at depth) obtained from reflection seismics by Hirn et al. (1997).

Unfortunately, *I* data are the only quantitative seismological data available for the sources of destructive earthquakes in the area. Their inversions indicate EBT78 as a plausible source for the strong foreshock of 9 January 1693 (compare Figures 4 and 5), and also of the mainshock of 11 January (see degree IX in Figures 6 and 7, and Tables 5 and 6).

We consider EBT78 to be compatible with inland seismotectonics. In fact, the geodynamic model of the area of the Strait of Sicily rift zone, the Malta Platform, and of SE Sicily involves one major 'transfer zone' which links the eastern end of the Strait of Sicily rift zone to the front of the thrust in Sicily, and it goes N-NE like our source EBT78. EBT78 is also compatible with the stress orientation in the area.

On the other hand, from our inversions and the results by Zollo et al. (1999), and considering also that the intensity data of the mainshock are likely to be corrupted by the preceding event, an Ibleo-Maltese fault remains a 'natural' candidate for the source of the 11 January 1693 earthquake. This Ibleo-Maltese source ought to be approximately tangential to the Augusta and Siracusa promontories, however (as is our source in Figure 1 and Table 6), because only a fault close to the coast 1) minimizes *I*-fitting errors, and 2) is likely (see Piatanesi and Tinti, 1998) to produce the right tsunami polarities.

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