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Investigating seismogenic faults in Central and Southern Apennines (Italy): modeling of fault-related landscape features

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Abstract
The direct identification of seismogenic structures in Southern Italy is often a difficult task, since finding seismogenic faults with clear surface expression associated is unlikely, even if they are the source of large magnitude earthquakes. A possible way to solve this problem is the investigation of a series of features of the surface landscape that could be attributed to repeated movements along a fault. In this paper we investigated the drainage, ancient coastlines, marine terraces and recent deposits of three different active tectonic basins in Central and Southern Italy. The combination of the modeling of these fault-related landscape features with historical and seismological data better constrained the geometry of the seismogenic faults responsible for three large magnitude historical events in the studied areas. The results show that in this section of the peninsula seismogenesis is often connected with blind almost pure dip-slip normal faults; the long-term activity of these faults produces intermontane basins or coastal plains that are sinking relative to the surrounding areas; the application of this methodology emphasizes the importance of geological and geomorphological studies for the recognition of seismogenic faults and for a complete assessment of the seismic hazard in Italy.

Key words *Apennines – historical earthquake – normal fault – drainage pattern – modeling of seismogenic faults*

1. The Central-Southern Apennines main seismogenic belt

The Italian Seismic Catalogue (Boschi *et al.*, 1995) shows that most of Italy is exposed to large earthquakes. This is especially true in the central-southern part of the Apennines chain, where most of the large magnitude historical seismicity has occurred within a seismogenic belt that is narrow but nearly continuous for several hundreds of kilometres between the latitudes of Rome and Reggio Calabria (Valensise *et al.*, 1993).

The Central-Southern Apennines main seismogenic belt (fig. 1) is not wider than a few tens of kilometres, and is composed of a number of 20 to 40 km-long neighbouring fault segments. The segments were directly observed in the field or inferred from the shape and extent of the mesoseismal areas of large historical earthquakes, from observations and modeling of the local geomorphology, from the inversion of coseismic elevation changes and from the study of the background seismicity. Along these faults almost pure dip-slip movement, evidenced by earthquake focal mechanisms, accommodates NE-SW to E-W extension perpendicular to the axis of the chain (Valensise *et al.*, 1993).

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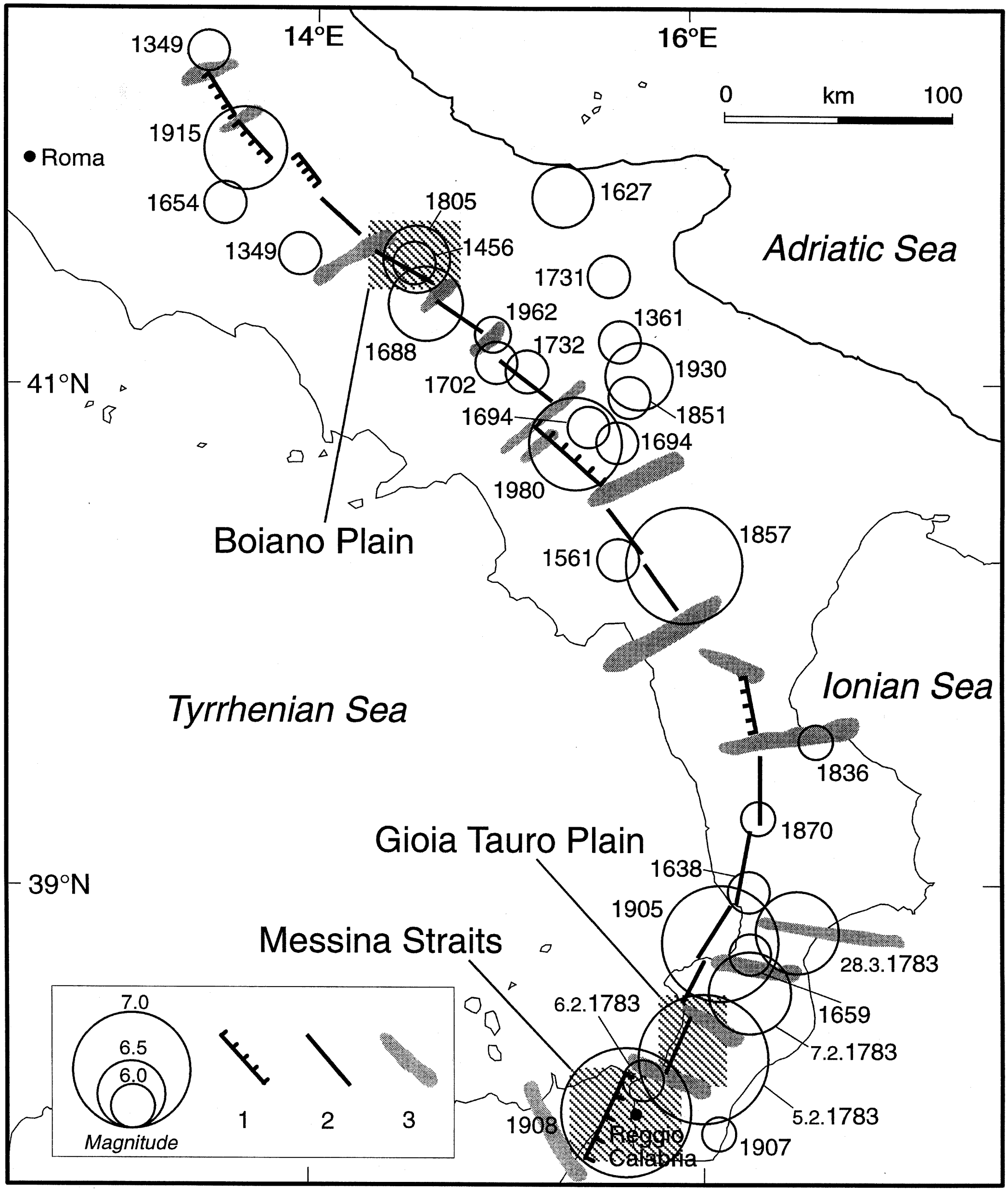

Fig. 1. The Central-Southern Apennines Seismogenic Belt (from Valensise *et al.*, 1993). The largest earthquakes since 1349 are shown (Boschi *et al.*, 1995). The studied areas are indicated in the shaded rectangles. Symbols: 1 = faults directly observed or inferred from instrumental data; 2 = faults inferred from geological or historical data; 3 = transverse seismogenic zones inferred from geological data. Although not yet completely understood, these transverse zones usually mark the boundaries of the main faults and generate intermediate magnitude earthquakes with mainly strike-slip focal mechanisms.

In spite of the length of these segments, and even though each of them is capable of producing earthquakes of magnitude ≥ 6.5 [Messina 1908 M_s = 7.5 (Gutenberg and Richter, 1954), Gioia Tauro 1783 M_S = 7.0, Val d'Agri 1857 M_s = 7.0 and Irpinia 1930 M_s = 6.7 (Boschi *et al.*, 1995)], such faults rarely exhibit a clear surface expression but in two cases during the instrumental era [Fucino 1915 M_w = 6.6 (Valensise, 1989), Irpinia 1980 M_s = 6.8 (Boschi *et al.*, 1981)] there have been surface ruptures associated with earthquakes.

2. Seismogenic faults and landscape modification

In the central-southern part of the Italian Peninsula the recognition and characterization of seismogenic structures through the traditional methods of palaeoseismology, like trenching across their surface expression, are often difficult or even impossible, because most of these faults are either hidden (with poor geomorphic expression associated) or blind (no surface ruptures at all) (Stein and Yeats, 1989). This particular situation is due to several causes:

– the propagation of the deformation is more difficult through a very thick, highly deformed, heterogeneous shallow crust (Jackson and White, 1989), in which the dominant lithologies may be insufficiently brittle to support surface faulting, as in the case of the Apennines (Westaway and Jackson, 1990);

– according to several Authors the active extensional phase in the Central and Southern Apennines is younger than 1 Ma (Pantosti and Valensise, 1990; Cinque *et al.*, 1993; Westaway, 1993; Hippolyte *et al.*, 1994), so that its geomorphic imprint is still hardly superposed on the inherited rugged topography largely dominated by Miocene-Pliocene thrust faults. For instance, the youthfulness of the extensional regime was suggested by a number of observations along the 38 km-long surface rupture related to the 1980 event: the presence of the rupture high on a mountain range, instead of at the base; the tendency to reverse the existing topography; the lack of Holocene activity along the main faults of the region (Pantosti and Valensise, 1990);

– as in the case of the 1980 earthquake, in some places the climatic processes are able to quickly obliterate the weak surface modifications produced by tectonic activity;

– the present deformation is slow, with slip rates generally < 1 mm/yr (Dumas *et al.*, 1987; Knott and Turco, 1991; Valensise and Pantosti, 1992; Pantosti *et al.*, 1993; Westaway, 1993; Michetti *et al.*, 1996; Pantosti *et al.*, 1996).

However, large magnitude normal faulting earthquakes ($M \geq 6.5$) produce significant vertical deformation of the topography within 10-20 km of the fault intersection with the surface; as a consequence the long-term activity of a seismogenic source alters the shape of geological bodies and twists the drainage pattern because uplifts and depressions are created.

The modifications to the ground surface that can be attributed to motions on pure dip-slip normal faults can produce:

1) deflections of the surface hydrography;

2) control upon the development of the drainage catchments;

3) sediments tilting toward the axis of the basin;

4) coastline displacement to different heights depending on their distance from the centre of sinking.

Our aim in this paper is to identify the seismogenic structures and to investigate their geometry, kinematics and seismic behaviour through the quantitative analysis of the accumulated regional deformation associated with their activity. The characteristics of deformed coastlines, marine terraces, marine and continental recent deposits, and the evolution of the drainage pattern are used to assess the long-term deformation patterns of a seismogenic fault. In this work we focused specific attention on the drainage pattern as it is one of the most significant features that could be influenced by tectonic activity; in fact, the study of some details of a fluvial network such as antecedence phenomena, rotation of rivers, shape of the catchments, sudden transitions from erosional to depositional behaviour and *vice versa*, can give us information on the position and type of the causative fault (Leeder and Jackson, 1993; Jackson and Leeder, 1994).

We present quantitative descriptions of the deformation induced by the movement on faults using verified simple elastic dislocation theory with modifications to account for interseismic non-elastic readjustments of the upper crust (Valensise and Ward, 1991). We present examples of our approach in three different areas: the Boiano Plain in the Central Apennines, the Gioia Tauro Plain and the Messina Straits in the Southern Apennines. Each area was struck in the past by large magnitude earthquakes evidenced by seismometric and/or macroseismic data, but no evidence of surface faulting was found.

3. Boiano Plain

The Boiano Plain (fig. 2) is a 30 km-long, NW-SE elongated basin, mainly filled with Neogene terrigenous deposits; to the South the plain is bounded by the Matese Mts., formed by Mesozoic carbonate sediments. The Rio River drains the northernmost part of the basin, joining the Biferno River to the SE. In 1805 a severe earthquake struck the area; the magnitude of this event was estimated in the range 6.5 to 7 on the basis of its intensity (I = X MCS; Boschi *et al.*, 1995) but no surface breaking was reported. Starting from the model proposed by Valensise *et al.* (1993), we calcu-

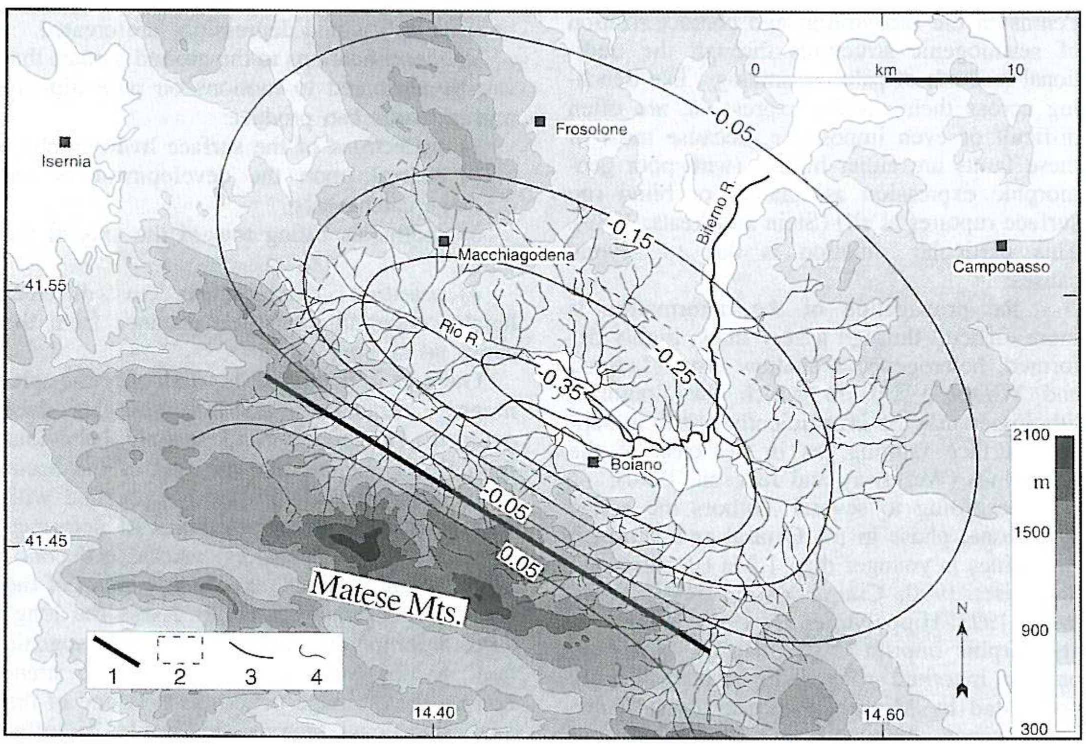

Fig. 2. Comparison between the predicted deformation field produced by the Boiano Fault and the topography in the Boiano Plain. The higher values of subsidence contour the most depressed part of the basin. It is also possible to observe that the spoon-shape of the topography matches the spoon-shape of the subsidence contours. Symbols: 1 = intersection of the predicted fault with the surface; 2 = surface projection of the fault plane; 3 = isolines of the vertical displacement. Contours are expressed in percent of the predicted slip on the fault (for 1 m of slip the contour interval is 10 cm); 4 = surface hydrography.

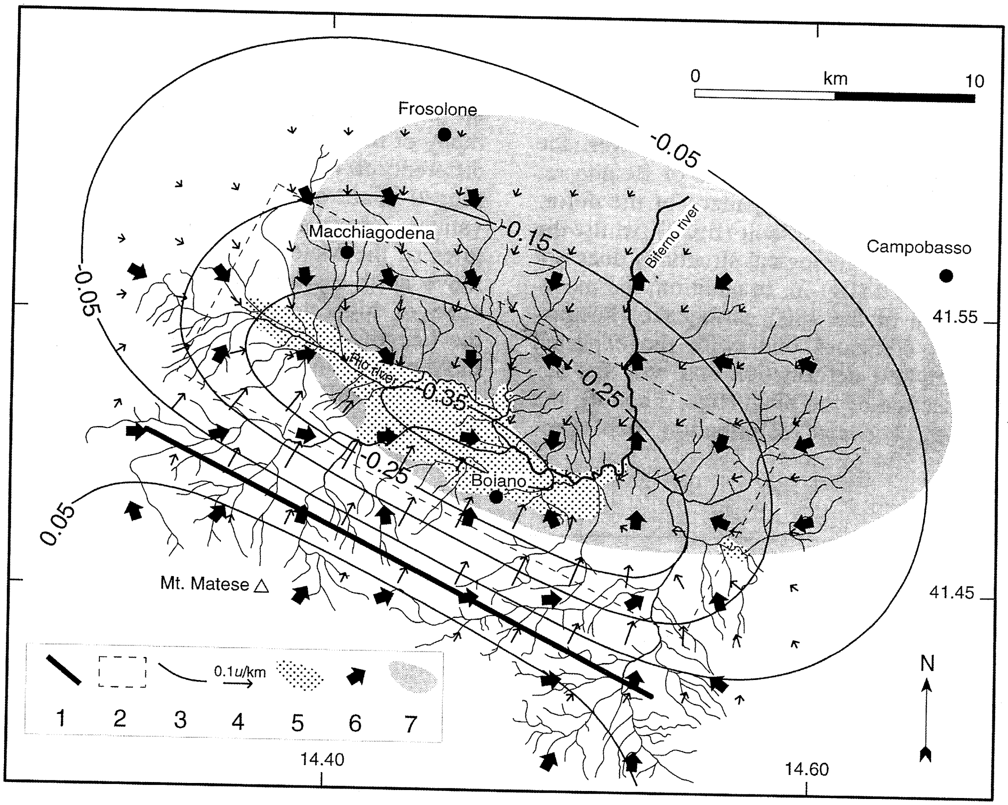

Fig. 3. Comparison between the deformation field produced by the Boiano Fault and the drainage pattern in the area of Boiano. The drainage distribution reflects the tilting field imposed by the fault. The expected zone of highest deformation coincides both with the aggrading section of the plain and with the mesoseismic area of the 1805-earthquake. Symbols: 1 = intersection of the Boiano Fault with the topography; 2 = surface projection of the fault plane; 3 = isolines of the vertical displacement. Contours are expressed in percent of the predicted slip on the fault (for 1 m of slip the contour interval is 10 cm); 4 = direction of the gradient of the vertical predicted deformation pattern. The length of the arrow in the key indicates that 1000 m of accumulated slip will produce 100 m/km tilting in that point (corresponding to a ~6° angle); 5 = flood plain associated with Rio and Biferno rivers; 6 = mean drainage direction at the vertices of 3 × 3 km cells; 7 = mesoseismic area of the 1805-earthquake (from Postpischl, 1985).

lated the pattern of surface modifications under the action of a fault with the following parameters:

- strike: 297°;
- dip: 60°NE;
- rake: 270° (normal fault);
- length: 20 km;
- down-dip width: 15 km;
- depth of top of the fault: 4 km.

In this case the position of the fault was mainly inferred from historical and seismological data but a careful study of the drainage pattern in the area confirmed the validity of this geometry. Figure 3 shows a comparison between expected elevation changes and tilting field produced by the postulated Boiano Fault, and the drainage pattern in the area. On the basis of the model, slip along the fault creates an elongated depression, with progressive deepening of the axial part. The drainage appears to be attracted toward this axial zone even in those areas where the topography suggests that the flow would be faster and more straightforward toward the NE (fig. 2). Moreover, the drainage distribution in the area of Boiano reflects quite faithfully the pattern of the deformation imposed by the fault (fig. 3), whilst the axis of the older geological structures does not coincide with it (fig. 2). In addition, the mesoseismic area of the 1805 earthquake (Postpischl, 1985) coincides both with the expected zone of highest deformation and with the aggrading section of the plain (figs. 3 and 4); the consistency between deformation field produced by the fault and the general shape of the Boiano basin suggests that the whole area reflects repeated 1805-type earthquakes along the same fault, as suggested also by the topography of the area, shown in fig. 2 by classes of different elevation. The topography is quite rugged in correspondence with the highest elevations, where the oldest E-W trending structures of the Matese Range are located. As we move north-eastward from the Range into the zone of highest deformation associated with the hanging-wall of the modelled fault plane, the topographic contours straighten out and rotate to NW-SE, sub-parallel to the strike of the fault.

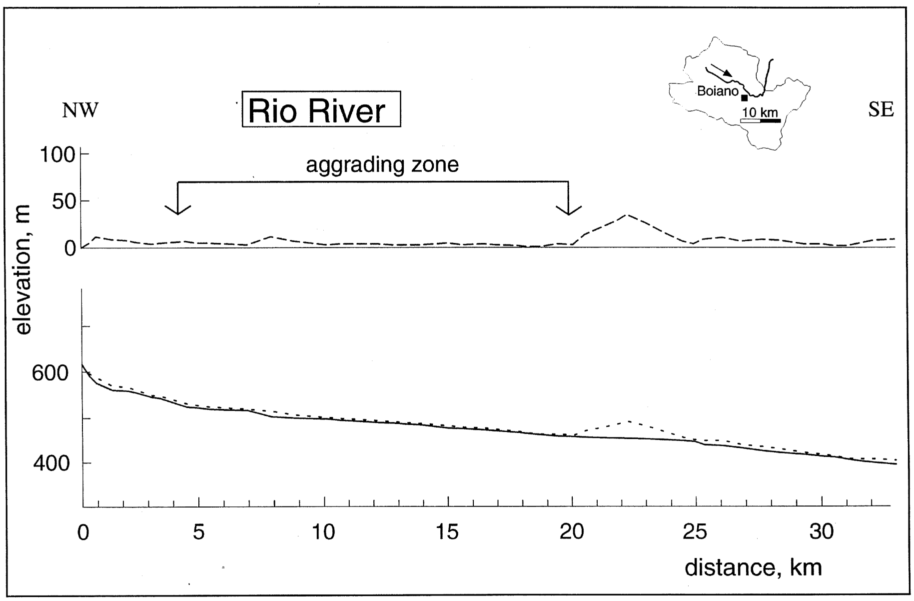

Fig. 4. The solid line shows the longitudinal profile of Rio River bed, *i.e.* the real profile of the stream. The dotted line indicates the topographic profile, that is the profile of the mean elevation of the river banks. The dashed line shows the differential profile, which is given by subtracting point by point the longitudinal profile from the topographic profile. The study of these profiles is often helpful in the identification of zones where a stream is aggrading (the longitudinal profile gets closer to the topographic profile and the differential profile remains steady or tapers to zero), or is undercutting (the differential profile rises): the former zone indicates negative vertical deformation, the latter positive vertical deformation. Out of the area influenced by the fault, the river only experiences the effects of the regional uplift and the fluctuations of sea level. In the case of the Rio River the flat central section of the differential profile corresponds to the zone where the stream flows along the plain in aggradation. The sharp rise in the differential profile marks the outlet of the river from the plain; from this point onward the river is no longer attracted by the fault and it starts undercutting.

Figure 4 shows the longitudinal profile of the Rio River that drains the plain in the axial direction; the flatness and steadiness for the plain zone in the differential profile (*i.e.*, the difference between the longitudinal profile and the topographic profile based on the elevation of the banks) suggest that the stream is aggrading in this area. The outlet from the plain is marked by a sharp rise of the differential profile, as the river starts cutting into a gorge since it is far away from the zone influenced by the fault.

4. Gioia Tauro Plain

The Gioia Tauro Plain (fig. 5) is a 30 km-long, NNE-SSW elongated basin, located between the Tyrrhenian Sea and the Aspromonte Ridge. The central part of the plain appears to be a continuous, flat, gently seaward dipping surface, while getting closer to the Aspromonte Ridge this surface becomes progressively steeper. The area was struck in 1783 by a tremendous earthquake ($M_s = 7.0$, $I =$ XI MCS; Boschi *et al.*, 1995). In spite of the large magnitude of the event no clear surface fault scarp formed; historical reports following the earthquake described only landslides, slumps, ground cracks and the formation of new lakes (De Dolemieu, 1784).

However, the area shows several geologic and geomorphologic elements such as marine terraces, recent marine deposits and drainage pattern, that appear tectonically controlled by the action of a blind normal fault; marine terraces in particular have been recognised in the area and generally in Southern Calabria since the beginning of the century (Cortese, 1909; Ricchetti and Ricchetti, 1991; Miyauchi *et al.*, 1994).

The study of the geological and geomorphologic markers in the area and of their deformation pattern allowed us to develop a model of a low angle blind fault with the following parameters (Valensise and D'Addezio, 1994):

- strike: 25°;
- dip: 35°ESE;
- rake: 270° (normal fault);
- length: 30 km;
- down-dip width: 17 km;
- depth of top of the fault: 3 km.

The geometry of this fault is consistent with the N110-N120 extensional stress field in the region defined by the structural analysis on faults and fractures in the area (Tortorici *et al.*, 1986), with the trend of the main geological structures (the crest of the Aspromonte Range, the axis of the plain, the coastline), and with the direction of maximum elongation of the macroseismic field of the 1783 earthquake (Postpischl, 1985) (fig. 5). Figure 5 shows the expected elevation changes and tilting field for unit slip on the Gioia Tauro Fault; for a slip of 1 km the fault should generate a quasi-symmetrical ~500 m deep depression, elongated parallel to the Aspromonte and remarkably coincident with the 1783 earthquake mesoseismic area.

A general model of the deformation field produced by a normal fault shows that the isolines straighten out above the superficial portion of the fault while they become more convex above its deep portion (figs. 3 and 5). In the Gioia Tauro Plain the modelled deformation pattern is consistent both with the dip of marine terraces in the area and with the course of the palaeoshorelines; it is possible to observe that the shape of the most recent of them (125-Kyr and Holocene) and of the present coastline is rather rectilinear, while the oldest show a remarkable convexity toward the East.

The deformation field of the Gioia Tauro Fault is also consistent when compared with the setting of the recent marine deposits in the plain. This sort of comparison is allowable only if the primary attitude of the deposits is known to be horizontal and if their actual geometry can completely be attributed to movements along the fault (*i.e.*, the sediments should not be older than the beginning of the fault activity). In the Gioia Tauro area, the sediments in the plain date from the Pleistocene and younger (Ogniben *et al.*, 1975) so they are not older than the beginning of the last tectonic regime (0.7-0.8 My) (Pantosti and Valensise, 1990; Cinque *et al.*, 1993; Westaway, 1993; Hippolyte *et al.*, 1994), while their original geometry is supposed to be almost horizontal or gently seaward dipping. The Pleistocene se-

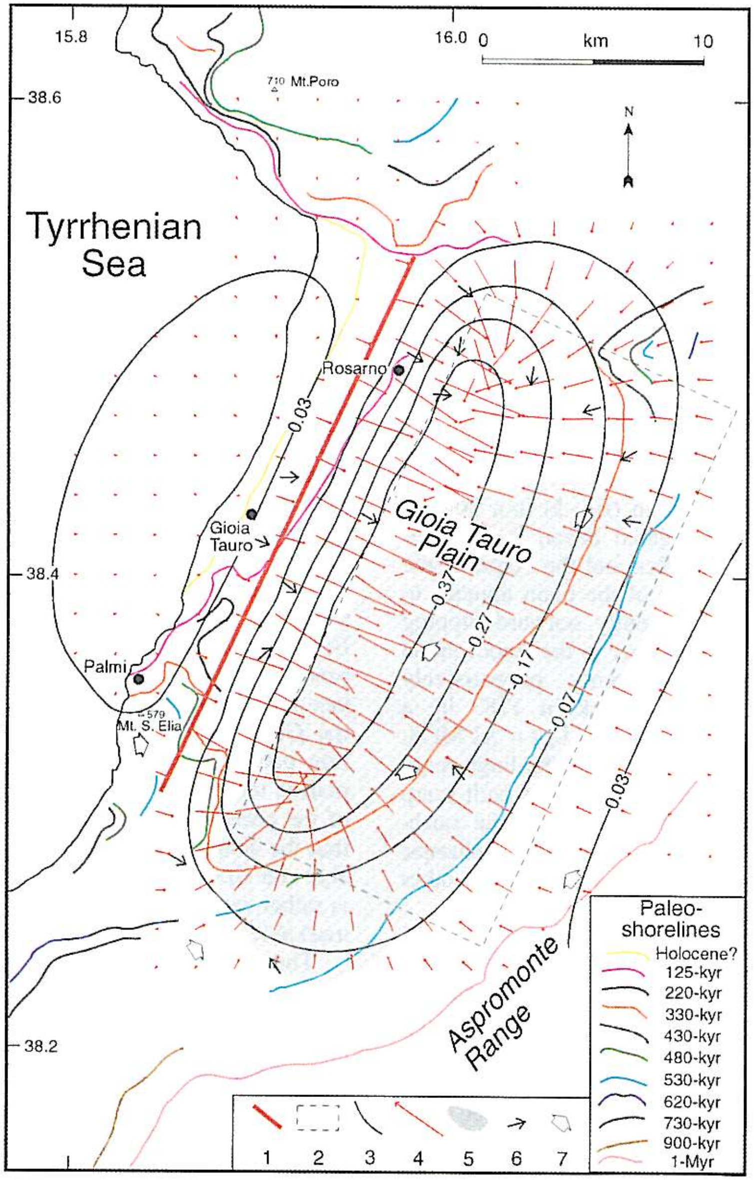

Fig. 5. The predicted deformation field produced by the Gioia Tauro Fault compared with the geological and geomorphological features in the Gioia Tauro Plain (modified from Valensise and D'Addezio, 1994). The predicted deformation field is consistent with the shape of the palaeoshorelines, the dip of the marine terraces and the attitude of the sediments in the plain; it also coincides with the mesoseismic area of the 1783-earthquake. Symbols: 1 = intersection of the Gioia Tauro Fault with the topography; 2 = surface projection of the fault plane; 3 = isolines of the vertical displacement. Contours are expressed in percent of the predicted slip on the fault (for 1 m of slip the contour interval is 10 cm); 4 = direction of the gradient of the vertical predicted deformation pattern. The length of the arrow in the key indicates that 1000 m of accumulated slip will produce 100 m/km tilting in that point (corresponding to a ~6° angle); 5 = mesoseismic area of the 1783-earthquake from Postpischl (1985); 6 = dip direction of recent marine deposits; 7 = dip direction of marine terraces.

quence has now a wide synclinal shape, with westward dipping strata at the foot of the Aspromonte Ridge and eastward dipping strata along the coast; the directions of the dip are generally converging toward the centre of the plain. The geometry of the sediments in the whole plain seems to fit well with the predicted deformation field for the Gioia Tauro Fault (fig. 5).

To better constrain the position of the seismogenic fault we also studied the local drainage pattern, that is another geomorphic element whose modifications can be related to the tectonic activity; the hydrography in the plain is quite simple, with three main watercourses (Mesima, Pelissa and Petrace rivers) generally flowing westward. As shown in fig. 6 the shape of the drainage pattern in the area fits quite faithfully with the direction of the vertical deformation gradient induced by the fault; from N to S the shape of the drainage pattern itself seems to be progressively rotating and converging toward two zones located ~10 km from the coast (fig. 6), and these two points of attraction of the drainage are placed inside the area of highest sinking produced by the fault. Further evidence comes from the behaviour of the Petrace River (and partly of the Pelissa River): it flows in a broad bed up to a few kilometres from the coast, then suddenly it becomes embanked by several meters. With this phenomenon of antecedence the stream maintains itself across a geological structure developing in its path; in the case of the Petrace River the movement along the fault back tilts the river profile uplifting its last part, that flows on the hanging-wall, with respect to the middle part (fig. 6).

Figure 7 shows the longitudinal profile of the Petrace River: the transition from crystalline to sedimentary bedrock corresponds to a sharp lowering in the differential profile. From this point onwards the difference between river-bed and topography keeps steady, showing that the river is entering a phase of aggradation. Near the river mouth the differential profile undergoes a slight yet visible rise; in this area the stream is antecedent as it is forced to cut into rocks that are uplifting and that tend to obstruct the river flow.

5. Messina Straits

The area of the Messina Straits and the 1908 catastrophic Messina earthquake have already been studied in the past ten years; Boschi *et al.* (1989) developed a seismogenic source model using a dataset of coseismic elevation changes following the 1908 main shock (Loperfido, 1909). According to this model the earthquake occurred along a ~15°-striking, 30°E-dipping blind normal fault (fig. 8). Starting from these data Valensise and Pantosti (1992) and D'Addezio *et al.* (1993) have already studied marine terraces and marine sedimentary units in the area, investigating the long-term deformation associated with the postulated fault; Cucci and Valensise (1995) highlighted some aspects of the drainage pattern along both sides of the Straits. In this paper we focused on all the characteristics of the drainage pattern in the area.

A summary of all the geological and geomorphologic observations available for the area is shown in fig. 8. Marine terraces bordering the Calabrian side of the Straits are probably the most outstanding tectonic-related geomorphologic feature in the area (Cortese, 1909; Dumas *et al.*, 1987; Ricchetti and Ricchetti, 1991; Miyauchi *et al.*, 1994). After study of aerial photos and field surveying, eleven different inner edges (palaeoshorelines) of the main terraces were reconstructed and mapped at an elevation varying between 50-60 and 1150-1200 m (D'Addezio *et al.*, 1993). As already seen in the case of the Gioia Tauro Plain, the most recent palaeoshorelines (especially the 125 Kyr one) exhibit a generally seaward concavity and dip directions toward the region of main coseismic deformation. Such a pattern is not found for the higher terraces, as they are beyond the region of largest influence of the 1908 fault; thus their convex and regular shape is only representative of the gradient of regional uplift. Moreover, the distribution of the Messina Gravels (Pleistocene), into which the lower terraces of both sides of the Straits are incised, follows the subsidence pattern associated with the 1908 earthquake (fig. 8), so that it is reasonable to suppose a genetic relationship with the seismogenic structure.

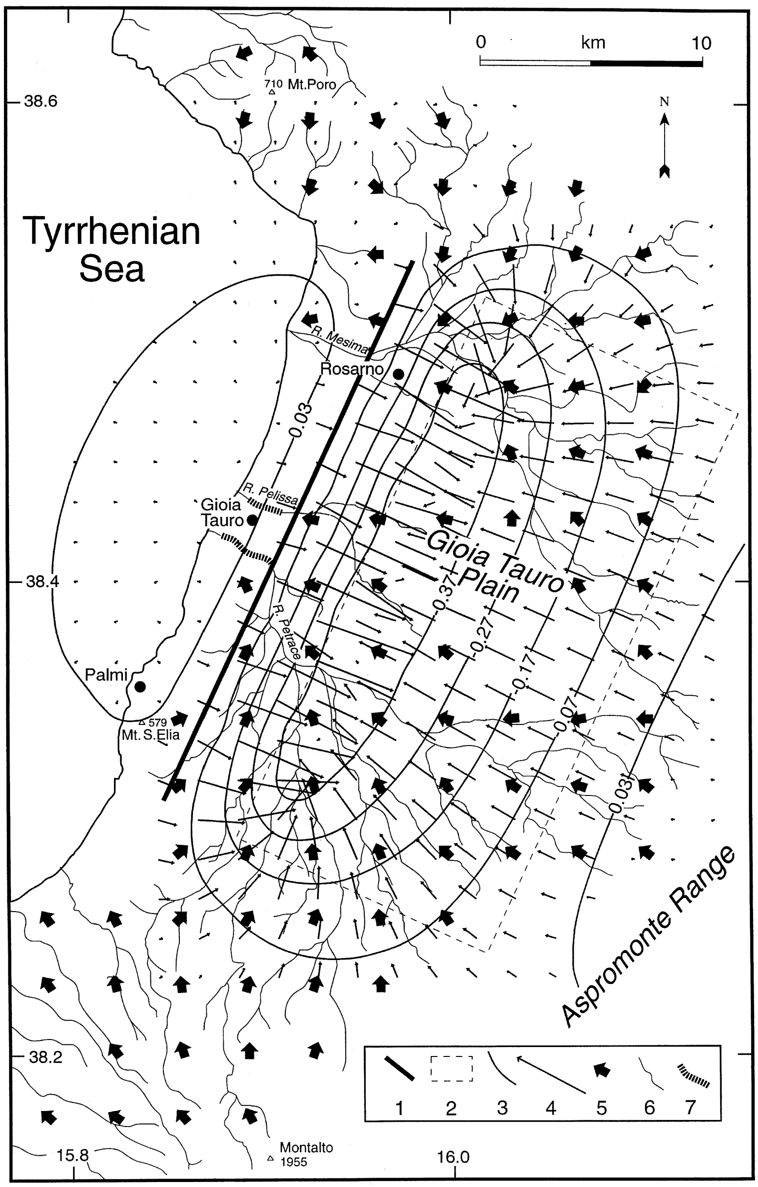

Fig. 6. Comparison between the deformation field produced by the Gioia Tauro Fault and the drainage pattern in the Gioia Tauro Plain (modified from Valensise and D'Addezio, 1994). The rivers in the plain rotate and converge toward the area of maximum subsidence. Symbols: 1 = intersection of the postulated fault with the topography; 2 = surface projection of the fault plane; 3 = isolines of the vertical displacement. Contours are expressed in percent of the predicted slip on the fault (for 1 m of slip the contour interval is 10 cm); 4 = direction of the gradient of the vertical predicted deformation pattern. The length of the arrow in the key indicates that 1000 m of accumulated slip will produce 100 m/km tilting in that point (corresponding to a ~6° angle); 5 = mean drainage direction at the vertices of 3 × 3 km cells; 6 = surface hydrography; 7 = sections of rivers showing antecedence.

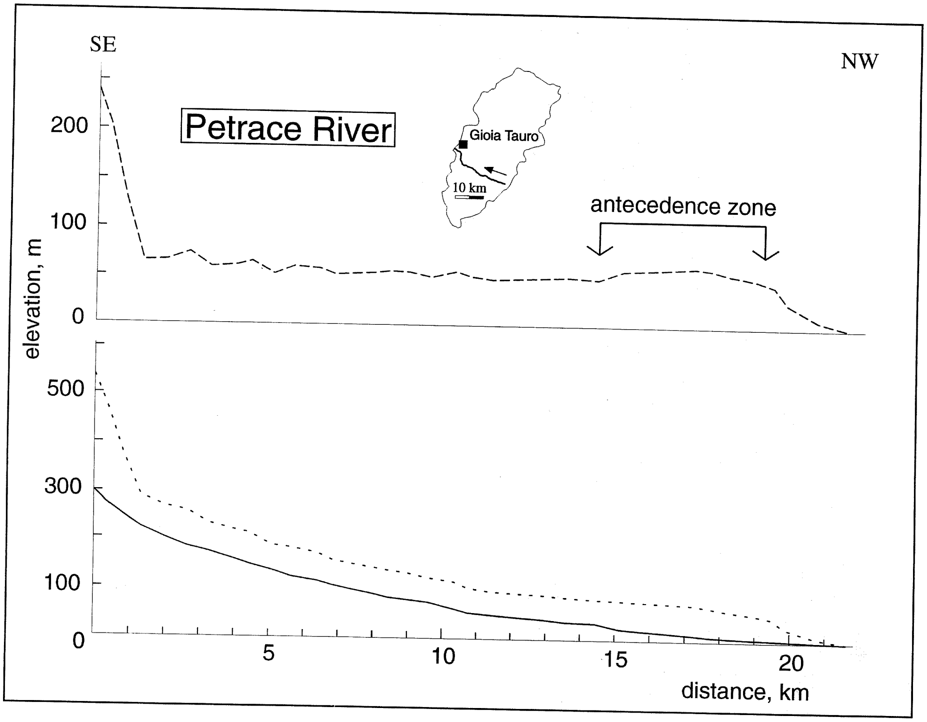

Fig. 7. Longitudinal, topographic and differential profiles along the Petrace river (see caption of fig. 4 for their definitions). The sharp lowering in the differential profile marks the transition from crystalline to sedimentary bedrock. The antecedence zone of the river, where the stream starts flowing in the footwall of the Gioia Tauro Fault, is clearly marked by a bulge in the differential profile.

To further constrain our model of fault we performed a quantitative analysis on drainage catchments of both sides of the Messina Straits. Leeder and Jackson (1993) show that in active tectonic basins the shape, length and slope of drainage catchments can be strictly related to their position with respect to the fault plane. In particular, they point out that if there is no substantial variation in the basement lithology, footwall catchments are smaller, steeper and shorter than those of the hanging wall. We considered the drainage area of both sides of the Messina Straits (fig. 9) and calculated the mean area, length and gradient for each catchment (table I). We suggest that these catchments are on different sides of the fault.

Data reported in table I are quite similar to those obtained by Leeder and Jackson (1993) for active extensional areas, like Dixie Valley in Nevada and the Gulf of Corinth in Greece. The use of this methodology can provide a general useful indication on the position and geometry of faults that do not produce surface ruptures; in our case it helped in locating a narrow area in which the projection of the fault plane is expected to intersect the surface. Moreover it allowed us to verify that the area contours a similar fault geometry to that proposed by Boschi *et al.* (1989).

Also the surface hydrography shows tectonic-related modifications: streams (called *fiumare*) flow perpendicular and straightforward to the coast along the central flanks of the Messina Straits, but at the northern end of the Straits they rotate southeastward in Sicily and southwestward in Calabria, as their course is

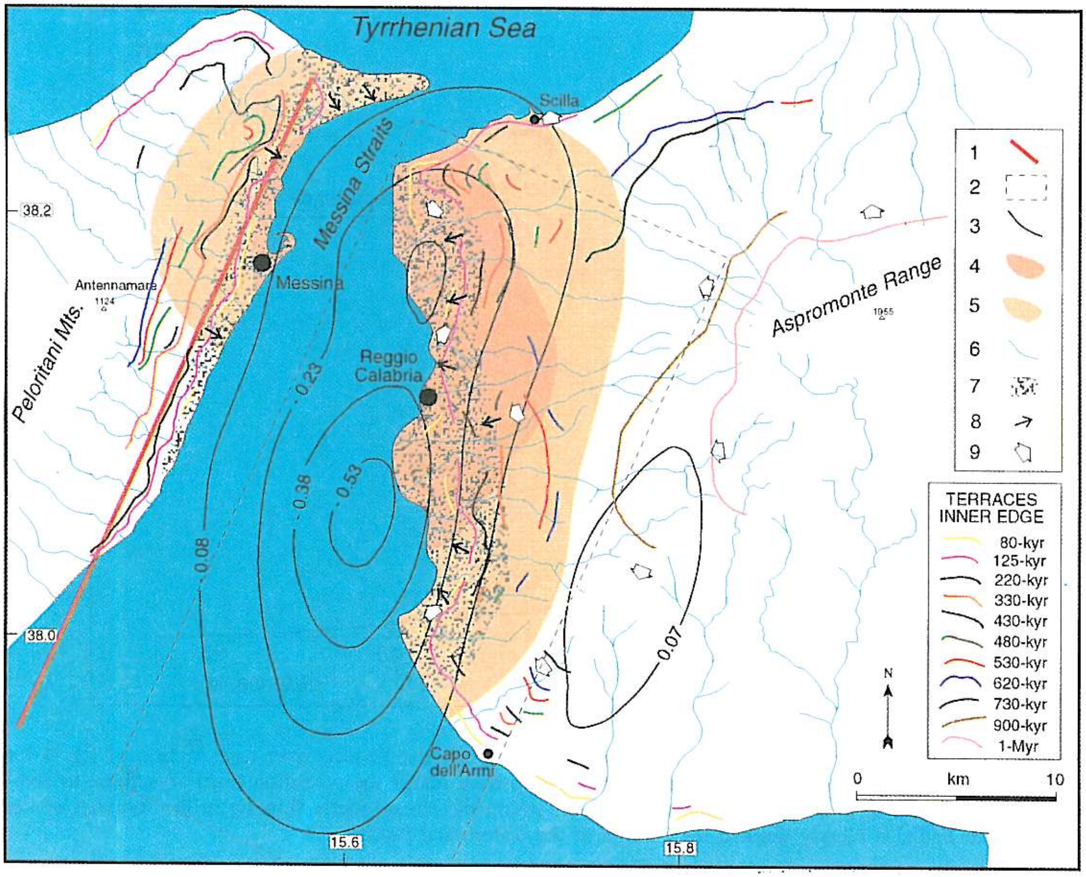

Fig. 8. Source model of the 1908-earthquake and predicted elevation changes produced by the Messina Fault, compared with the geological and geomorphological features in the Messina Straits (modified from Boschi *et al.*, 1989). Note the different shape and dip between the higher terraces (*i.e.*, the older terraces) which only experienced the effects of the regional uplift, and the most recent ones, which exhibit seaward concavity and dips toward the points of highest fault-related subsidence. It is also possible to observe the rotation of the rivers on both sides of the Straits toward the two points of maximum subsidence associated with the 1908-earthquake. Symbols: 1 = intersection of the Messina Fault with the surface; 2 = surface projection of the fault plane; 3 = predicted elevation changes (contours are in metres); 4 = *I* = XII MCS area; 5 = *I* = XI MCS area; 6 = drainage pattern; 7 = Messina Gravels distribution; 8 = dip direction of the Messina Gravels; 9 = dip direction of the marine terraces.

influenced by fault-related subsidence (fig. 8 and 9). The streams appear to be converging toward the two areas of maximum subsidence described by Boschi *et al.* (1989). Moving northward in the area between the Messina Straits and the Gioia Tauro Plain, where the rivers flow out of the area influenced by the fault and experience only the effects of regional uplift, they again align perpendicular to the coastline. Further north, the drainage pattern again rotates back toward the Gioia Tauro Plain, as already shown in fig. 6, because of a different local source of long-term tectonic deformation.

Table I. Geometric parameters of the drainage catchments in the Messina Straits area.

Footwall side	Hanging wall side
21 major catchments Drainage area: 130.3 km^2 Mean catchment area: 6.2 km^2 Mean catchment length: 4.8 km Mean catchment gradient: 0.178	17 major catchments Drainage area: 370.6 km^2 Mean catchment area: 21.8 km^2 Mean catchment length: 11.2 km Mean catchment gradient: 0.105

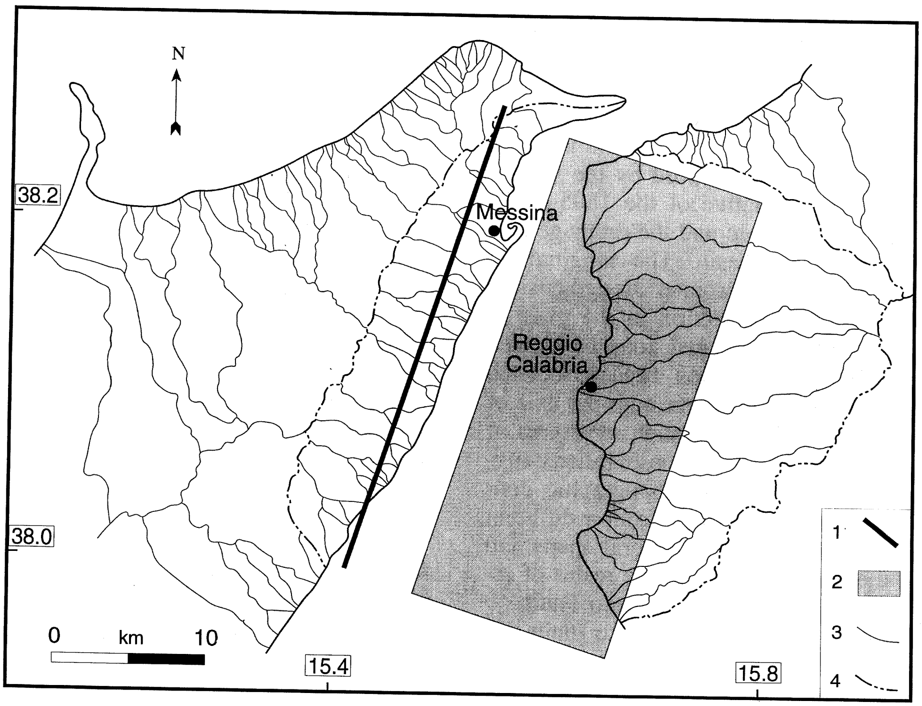

Fig. 9. Drainage catchments in the Messina Straits area. In the Sicilian side (footwall) the catchments are smaller, steeper and shorter than those of the Calabrian side (hanging wall). Symbols: 1 = intersection of the Messina Fault with the surface; 2 = surface projection of the fault plane; 3 = drainage catchment; 4 = drainage divide.

6. Discussion

The Italian seismic history of the past centuries shows a large number of moderate to large magnitude events: our aim is to locate potential seismogenic faults, so that each large earthquake can be assigned to its causative fault. This procedure may also identify new potential sources of future events. This effort is strongly hindered because the lack of clear surface ruptures connected with most past earthquakes suggests that blind faults are much more frequent than we could guess only a few years ago.

The first example of probable blind fault comes from the Boiano basin, where most of the geological structures are dominated by pre-Pleistocene compressional tectonics; in addition, no recent sediments or other geomorphological features that could have undergone only recent deformations were observed. Nevertheless, the historical record of the 1805-earthquake, with a mesoseismic area coincident with the shape of the plain, suggests that the Boiano zone could be an active intermontane basin. This suggestion is supported by the general observation that in the Apennines, active intermontane basins are sinking relative to a rising mountain chain, and often contain an aggrading drainage system (figs. 4 and 7).

In the Boiano area the present tectonic setting has already influenced the surface hydrography, as shown by the comparison between the deformation pattern induced by the slip on a blind fault representative of the 1805-earthquake macroseismic field and the drainage pattern over the active basin. The longitudinal profile of the main watercourse strengthens the fact that the aggrading section in the plain is connected with the postulated zone of highest subsidence. The deformation field associated with the fault is not coincident with the axis of the E-W trending Mesozoic main structures of the Matese Range. All these observations suggest that even if the major topographic contrasts in the area are inherited from a different previous tectonic phase, the general shape and extent of the basin are largely the result of repeated earthquakes along the Boiano Fault.

The situation for the Gioia Tauro Plain and the Messina Straits is different, because the surface landscape is characterized by recent geomorphological features, so that the geometry of their respective seismogenic sources can be more accurately constrained. In both cases the geological and geomorphological markers suggest similar patterns of the evolution of synclinal-shape structures, of about the same size and with the same direction; the axis of these folds coincides with the axis of the corresponding main feature of the surface landscape (alluvial plain or marine strait) we are investigating. Those folds can be considered the surface effect of movements along low angle blind normal faults (Valensise and Pantosti, 1992; Valensise and D'Addezio, 1994). The relatively low values of dip (30°-35°), although not frequent, have already been observed in other extensional terranes (Jackson *et al.*, 1988) and are in the range shown by most of the large seismogenic normal faults in the world (Jackson and White, 1989). Higher values of dip would have produced heavy inconsistencies with the coseismic elevation changes following the 1908-earthquake, in the case of the Messina Straits, and with the whole drainage system and the shape and position of the marine terraces in the Gioia Tauro Plain.

The geometry and seismic behaviour of the seismogenic sources described in this paper have been investigated using the pattern of marine terraces and the related coastlines, and the attitude of the recent marine deposits. The general shape and geomorphological features of the Messina Straits area reflect the pattern of expected elevation changes induced by a 1908-type earthquake, and the general shape and geomorphological features of the Gioia Tauro Plain are similar to the predicted deformation field produced by the Gioia Tauro Fault. These considerations suggest a close relationship of the two areas with the long-term activity of the causative faults.

A brief summary of the results achieved through the application of our methodology leads us to stress that:

1) earthquakes in the Central-Southern Apennines seismogenic belt occur along almost pure normal faults, and probably most of such faults are blind;

2) in an area undergoing rapid regional uplift, the repetition of these events produces intermontane basins or coastal plains that are sinking in relation to the surrounding area (*i.e.*, with lower uplift rate);

3) the identification and the quantitative description of potential seismogenic structures, where direct evidence is lacking, necessarily take place through indirect methods of investigation. Among these, number examination of the deformation of recent sedimentary units, the displacement of marine terraces or ancient coastlines and major importance must be given to the drainage pattern, which is the geomorphological most sensitive feature in the short term to tectonic stresses. In particular, the detailed analysis of the surface hydrography in the three studied areas clearly showed:

– in the Boiano basin, the good fit between the drainage pattern and the tilting field produced by the Boiano Fault, as well as the behaviour of the rivers that drain the plain through the examination of their longitudinal profiles;

– in the Gioia Tauro Plain, antecedence phenomena as well as the attraction of the watercourses and their consequent rotation toward points of maximum fault-related subsidence;

– in the Messina Straits, attraction and rotation of the *fiumare* toward the point of highest coseismic slip as well as the different characteristics of the drainage catchments on both sides of the fault.

As a final consideration, the study of some fault-related geological and geomorphologic features and the modeling of their deformation pattern represent a useful contribution for the recognition and the characterization of seismogenic faults and therefore for a more complete assessment of the seismic hazard in Italy.

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