

## CHAPTER 12

# Seismic strike-slip faults on a major boundary transverse to the Apenninic chain; the case of Molise (S. Italy) earthquake (31 October 2002).

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### Abstract

On 31 October 2002, a severe earthquake of  $M_w=5.9$  struck the Molise province in southern Italy. The earthquake occurred in an area which is characterized by both an absence of significant neotectonic faults and low seismicity, since no historical strong earthquakes have been reported. Neighbouring seismogenic areas are located westward along the NW–SE normal seismogenic belt of the central and southern Apenninic chain, as well as eastward along the Gargano promontory of the Apulian platform, which is mainly deformed by E–W strike-slip faults. The Molise earthquake seems to be directly related to the second seismogenic source because the epicentral area is located at the westward prolongation of the E–W strike-slip Mattinata Fault which bounds the southern part of the Gargano promontory. Moreover, the preliminary fault plane solution, the distribution of the aftershock sequence and the damage show that the seismogenic fault is also a strike-slip one in the same E–W direction. The only evidence of surface faulting was the presence of two small ruptures trending E–W and N–S, accompanied by strike-slip right-lateral and left-lateral movement respectively. The kinematic data are compatible with the fault plane solution.

### 1 Introduction

On 31 October 2002, a strong seismic event occurred in the Molise province in southern Italy (about 60 km WNW of Foggia or about 115 km NNE of Naples), followed by a second of similar magnitude the next day, resulting in 29 casualties and heavy damage in the epicentral area. Most of the victims were found in a collapsed school at the community of S. Giuliano di Puglia, where 26 children

(aged three to ten years old) and one teacher lost their lives. The earthquakes were felt all over the Molise province but they caused damage only in certain villages in the wider epicentral area.

The magnitude of the main shock was  $M_w=5.9$  (according to USGS) or  $M_w=5.7$  (according to INGV – Istituto Nazionale di Geofisica e Vulcanologia) and that of the strongest aftershock, which occurred the following day, was  $M_w=5.8$  (USGS) or  $M_w=5.7$  (INGV). The foci are shallow since the focal depth for both shocks was about 10 km (U.S.G.S.) or 20 km (INGV).

The Italian peninsula is characterized by strong catastrophic earthquakes, such as the 1977 Umbria, central Italy, earthquake ( $M_w=5.6$ , 11 casualties), the 1980 Eboli earthquake, south of Naples, ( $M_w=7.2$ , 2,735 casualties), the 1976 Friuli earthquake, north-east Italy, ( $M_w=6.5$ , 976 casualties), the 1915 Avezzano earthquake, southern Italy, (32,000 casualties), the 1908 Messina Strait earthquake (82,000 casualties), the 1905 and 1783 Calabria earthquakes (5,000 and 50,000 casualties respectively) and the 1693 southern Italy earthquake (60,000 casualties in Sicily and 93,000 in Naples).

The seismic event of 31 October 2002, occurred in an area that does not host high seismicity, since no major historical earthquakes have been reported.

The purpose of this paper is to correlate the neotectonic structure of the affected area to the seismotectonic regime of the earthquake, the distribution of the geotechnic effects and the damage.

## **2 Geodynamic frame of the Italian peninsula**

At the major area of the Italian peninsula several geodynamic units can be recognized, such as the "Alpine thrust system", the "Po plain", the "Apennine thrust system" and the "Calabrian arc" from north to south and the "Sardinia–Corsica block", the "Tyrrhenian extensional basin" and the "Adriatic block" from west to east (Figure 1).

The Apennines, which constitute the core of the Italian peninsula, south of the Po basin, belong to the southern branch of the alpine system of the Tethys which is characterized by tectonic movement and vergence of the large scale tectonic structures (folds, thrusts, etc.) towards the E-NE over the Apulian platform, which is considered as a part of the African plate (Aubouin [1], Disperati et al. [2], Elter & Scandone [3], Jolivet [4]). Southward, the Calabrian arc represents the boundary between the Apennine mountain range and the oceanic Mesozoic crust of the eastern Mediterranean (segment of the Tethys ocean). On the contrary, to the west of the boundary lies the oceanic basin of the Tyrrhenian Sea which represents a younger structure (Miocene – Upper Pliocene), (Jolivet [4], Meletti et al. [5]). Thus, a compressional geodynamic regime is recognized in the front of the Apennines towards the Adria plate (Apulian platform) and an extensional one to the west (Tyrrhenian basin).

The present seismotectonic regime of Italy is rather complex and bears important differences from the north to the south, as is obvious from the seismic and borehole breakout data (Mariucci & Muller [6]) as well as from the kinematic and dynamic data of the neotectonic faults. In particular, a more systematic

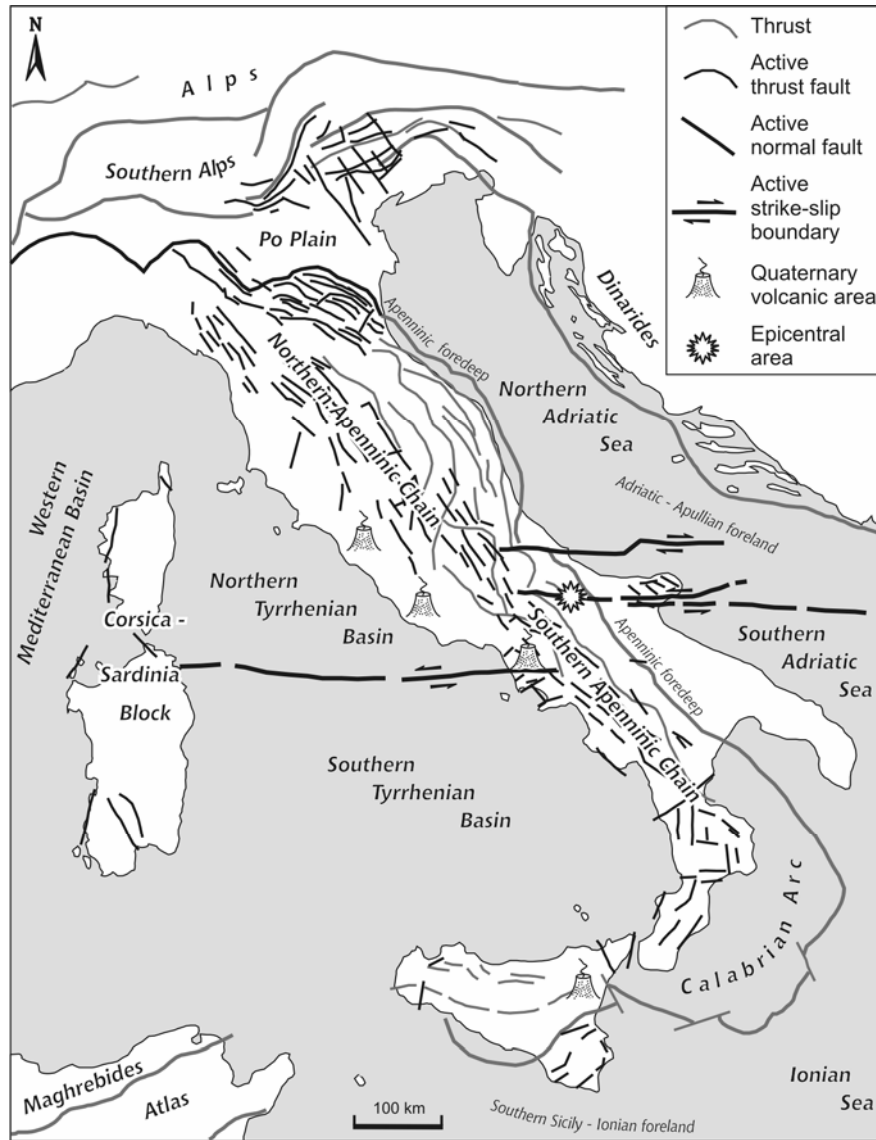


Figure 1: Schematic structural setting of Italy where the main geodynamic units and the E-W significant active strike-slip boundary (Favali et al. [8]) are presented.

variation of the tectonic regime is observed from SW to NE, as well as homogeneity in the central Apenninic belt and complexity to the north. Thus, at the northern Apennines (northern Adriatic foredeep), it seems that the Late Miocene uplift, and the following slab detachment and its southward migration along the

Apenninic chain, are accompanied by apparent normal or oblique-slip normal faults of NW–SE strike (NE–SW extension) in the upper crust (Figure 1). Deeper, however, where passive slab sinking occurs, strike-slip or thrust faults (NE–SW compression) dominate.

Along the Apenninic belt, the tectonic regime is mainly identified by NW–SE normal faults, resulting from the NE–SW extension that followed the upward flexure and the decompression of the Apennines (Mariucci & Muller [6], Meletti et al. [5]). In the southernmost Apenninic foredeep and in the Apulian foreland, the tectonic regime is expressed by both normal and strike-slip faults. In the Tyrrhenian coastal region the tectonic regime is characterized by normal or oblique-slip normal faults of basically NE–SW strike. In southern Italy, the tectonic regime is more complex in the wider area of the Calabrian arc because it is still controversial as to whether there is active subduction or persisting passive sinking of the Adria lithosphere. Both shallow and deep earthquakes occur in this area with focal mechanisms that show mainly strike-slip or transpressional zones rather than normal faulting.

These important changes of the seismotectonic characteristics along the Italian peninsula suggest a certain fragmentation of the foreland area through large-scale strike-slip zones that are developed across the Apenninic structure. These zones probably represent old transform faults such as those found in southern Sicily, in the Sicily channel, in the Gargano–Tremi region and in the Central Adriatic Sea (Mariucci & Muller. [6]).

### **3 Geological frame and seismotectonic regime of the wider affected area**

The wider affected area is located at the Gargano-Apulian peninsula, in southern Italy. The main alpine geological structure of this area is the thrust of the flysch-molasse type sediments of the external Apennines over the continental carbonate deposits of the Apulian platform (Aubouin [1], Jolivet [4]), (Figure 1). The latter corresponds to the main foreland of both the Apennines to the west and the Dinarides to the east.

The shallow Apulian platform (Gargano-Apulia), (Aubouin [1]) in the southeastern part of the Italian peninsula is characterized by the deposition of thick-bedded neritic limestones from Triassic to Tertiary, mainly representing reef phases, some thousands of meters thick. Typical outcrops of these carbonate deposits, which are almost horizontal without large scale deformation, can be observed along the road from Bari to Foggia. These sediments represent the relative autochthonous sequence (Figure 2).

The para-autochthonous sediments of the external Apennines, which are thrust over the Apulian platform to the east, represent a clastic sequence consisting of white-yellow and blue-grey marls with alternations of sandstones close to the front of the thrust. In the inner parts the alternations consist of white marls, sandstones, pelites and white marly limestones.

This clastic sequence represents syn-orogenic flysch-molasse type sediments, deposited at the Italian–Dinaric foredeep, which was developed around the

Apulian platform during the syn-orogenic stage of the Alpine orogen that followed the final collision between the Apulia (northern promontory of the African plate) and the European plate margins of the Apennines and Dinarides (Aubouin [1], Disperati et al. [2], Jolivet [4]).

This sequence is tectonised, folded and thrust (Figure 2) with tectonic transport from SW to NE during the Upper Miocene – Lower Pleistocene (Aubouin [1], Disperati et al. [2], Elter & Scandone [3]).

From a seismotectonic point of view, the affected area lacks important neotectonic structures or high seismicity. Active faults relating to strong earthquakes can only be found both to the west in the wider Isernia region (Apenninic chain) and to the east in the Gargano promontory (Apulian platform), bearing significant seismotectonic differences in each case (Figure 3).

The wider Isernia region is located on an important geological boundary representing the geometrical and structural discontinuity separating the northern from the southern Apennines with major morphological, tectonic differences as well as significant changes in seismicity and the geophysical data (Di Bucci et al. [7]). This boundary might be regarded as a persistent segment boundary, forming a long-term barrier to the propagation of rupture of active fault systems in this area (Figures 1 and 3).

The general neotectonic structure shows that all along the core of the Apennines a subsequent major phase of SW–NE extension has overprinted the compressional structures since the Middle Pleistocene. This tectonic regime is still active today, and therefore the youngest structures of the Apennines show a general NW–SE orientation and are responsible for the strongest earthquakes in this region. Well-known active fault zones (Figure 3) bearing significant differences on both sides of the boundary between the northern and southern Apennines are (Di Bucci et al. [7]):

- The Aremogna – Cinque Miglia – Mt. Rotella fault system (ACRFS), which is composed of NW–SE normal faults that cut Pleistocene and Holocene sediments.
- The Upper Sargano Valley fault system (USFS), which consists of normal and left-lateral strike-slip NW–SE faults.
- The Boiano Basin fault system (BBFS), which shows a complex extensional pattern and consists of a system of NW–SE synthetic and antithetic Quaternary normal faults linked with shallow pre-Quaternary E–W high angle faults reactivated by the SW–NE active extensional stress field.
- The Carpino and Le Piane fault system (CLPFS), consisting of NNW–SSE normal faults and where the most recent tectonic activity is consistent with the extensional regime which has acted since the Middle Pleistocene in this part of the Apennines chain.

Known earthquakes (Figure 3) relating to these active faults are (data from INGV): the 1984 Sangro River Valley earthquake ( $M_s=5.5$ ), the 1805 Boiano earthquake ( $M=6.6$ ) and the 1456 Gruppo di Lavoro earthquake ( $M=7.1$ ).



The active structures of the Gargano Promontory dominate to the east of the affected area, which represents a structurally high area where Mesozoic rocks rise about 1000 m above sea level. Two main tectonic zones, trending E–W, can be observed. The first of these, known as the Mattinata fault, is located on the southern margin of the Gargano peninsula and the second is located on the northern margin, in the wider region of the Tremiti Islands (Figure 3). These zones also extend for some tens of kilometers at the bottom of the Adriatic Sea separating the northern from the southern part of the area and exhibiting significant morphological and seismotectonic differences (Favali et al. [8]).

The kinematic and dynamic data along the above zones show strike-slip faults but the sense of shear is still controversial (Billi [9], Favali et al. [8], Salvini et al. [10]). The Tremiti Islands Fault has been interpreted as right-lateral but the Mattinata Fault as right-lateral, left-lateral, right to left lateral or left to right lateral inverted, undetermined strike-slip or reverse, although the prevalent interpretation agrees with a left-lateral strike-slip fault (Billi [9]). The tectonic data along the fault surface reveal complex kinematics and indicate (Favali et al. [8]): (i) E–W strike-slip left-lateral fault, partially transferred to NW–SE trending strike-slip left-lateral faults, (ii) minor reverse faulting (ENE–WSW compressional deformation), and (iii) pull-apart structures with E–W and NW–SE oblique-slip to dip-slip normal faults accompanied by second order left-lateral strike-slip E–W faults.

Although there are not enough seismological data for this region, the fault plane solutions of some recent earthquakes which occurred in the offshore area (three main shocks: 1986  $M_b=4.2$ , 1988  $M_b=5.3$  and 1989  $M_b=4.7$ ), (Favali et al. [8]) are in accordance with the tectonic data and display strike-slip faulting accompanied by a small thrust component. It should also be noted that the epicentres of earthquakes reported in the central Adriatic Sea are roughly aligned along an E–W direction parallel to these strike-slip zones. For this reason, some authors interpret the Adriatic block as a single, rigid, almost aseismic block (Favali et al. [8]). It is also mentioned that medium-magnitude shallow earthquakes, due to NE–SW normal fault reactivation as the fault plane solutions show, have been reported at the N-NE part of the Gargano promontory such as that of 30 September 1995 with  $M_w=5.2$ .

These E–W trending strike-slip zones are directly related to the evolution of the Gargano Promontory. This part of the Apulian platform has been uplifted by near vertical E–W or NW–SE faults since the Eocene. Most of these faults show evidence of early dip-slip movements compatible with uplift, and subordinate oblique to strike-slip motion due to younger reactivation. The structural analysis together with other geophysical and geological data reveal that the Gargano Promontory represents a push-up structure generated by the interaction of the E–W trending left-lateral strike-slip Mattinata fault system (MFS) southward and the E–W to NE–SW trending right-lateral strike-slip Tremiti Islands fault system (TIFS) northward (Favali et al. [8]).

It is underlined that this important tectonic zone, which is characterized by large-scale strike-slip faults and represents a seismically active deformation belt that cuts across the Adriatic basin, seems to be significant for the evolution not

only of the Adriatic block but also of the entire Italian peninsula as well as of the Tyrrhenian Sea (Favali et al. [8]). A possible westward prolongation of this tectonically active boundary up to the Tyrrhenian Sea, through the Apennines, is confirmed by important structures both in the Italian peninsula (boundary between the northern and the southern Apennines) as well as in the Tyrrhenian Sea (boundary between the northern and and southern Tyrrhenian Sea) and it has been interpreted as a transform fault (Figure 1).

Recent data from GPS velocities (Oldow et al. [11]) confirm this seismically active boundary and show that it is a quite complex structure. Therefore, it passes around the southern and eastern margins of the Tyrrhenian Basin, crosses Central Italy, extends into the Adriatic Sea and follows the western margin of the Dinaride tectonic belt. Along the Southern Apennines and the Adriatic coast the velocities of GPS measurements show movement towards the N, NNE and NW which are consistent with extension along the mountain belt and contraction across the foreland.

Submarine research and seismic profiles in the central Adriatic Sea reveal that E–W or NE–SW trending transpressional structures deform the sea floor, indicating recent activity, and together with the seismicity they provide a link between E–W trending faults of the Southern Dinaride belt and similarly oriented structures along the Adriatic margin of central Italy (De Alteriis [12]).

#### **4 The earthquake parameters**

The seismic sequence is emphasized by two main seismic events. The first and stronger of these (31 October) showed a magnitude of  $M_w=5.9$  on the Richter scale (USGS) or  $M_w=5.7$  (INGV), while the second one (1 November) bore a magnitude of  $M_w=5.8$  (USGS) or  $M_w=5.7$  (INGV). In both cases the earthquakes were shallow with a focal depth of the order of 10 km (USGS) or 20 km (INGV).

The two shocks and the aftershock sequence occurred in an area (a few km west of S. Giuliano di Puglia) that does not historically host major earthquakes and consequently is not classified in the current seismic codes.

The strongest historical and present-century earthquakes in the neighboring areas were (data from INGV): (i) the Apenninic sequence of December 1456,  $M=7.1$  (about 50-60 km to the S-SW of the recent seismogenic source), which caused heavy damage, (ii) the Gargano sequence of July–August 1627,  $M=6.8$  (about 40-50 km to the east of the recent seismogenic source), which caused damage estimated at 8-9 degree MCS, and (iii) the Matese earthquake of July 1805,  $M=6.6$  (about 50-60 km to the W-SW of the recent seismogenic source), with damage estimated at 6 MCS (Figure 3).

The 1456 and 1805 strong events, as well as a great number of strong or medium earthquakes, occurred along the main normal faulting seismogenic belt that runs along the crest of the central and southern Apennines. On the contrary, the epicenter of the 1627 catastrophic earthquake was located near the western margin of the Gargano promontory. Weaker earthquakes have also been reported, mainly to the east (about 60-100 km from the recent seismogenic source), such



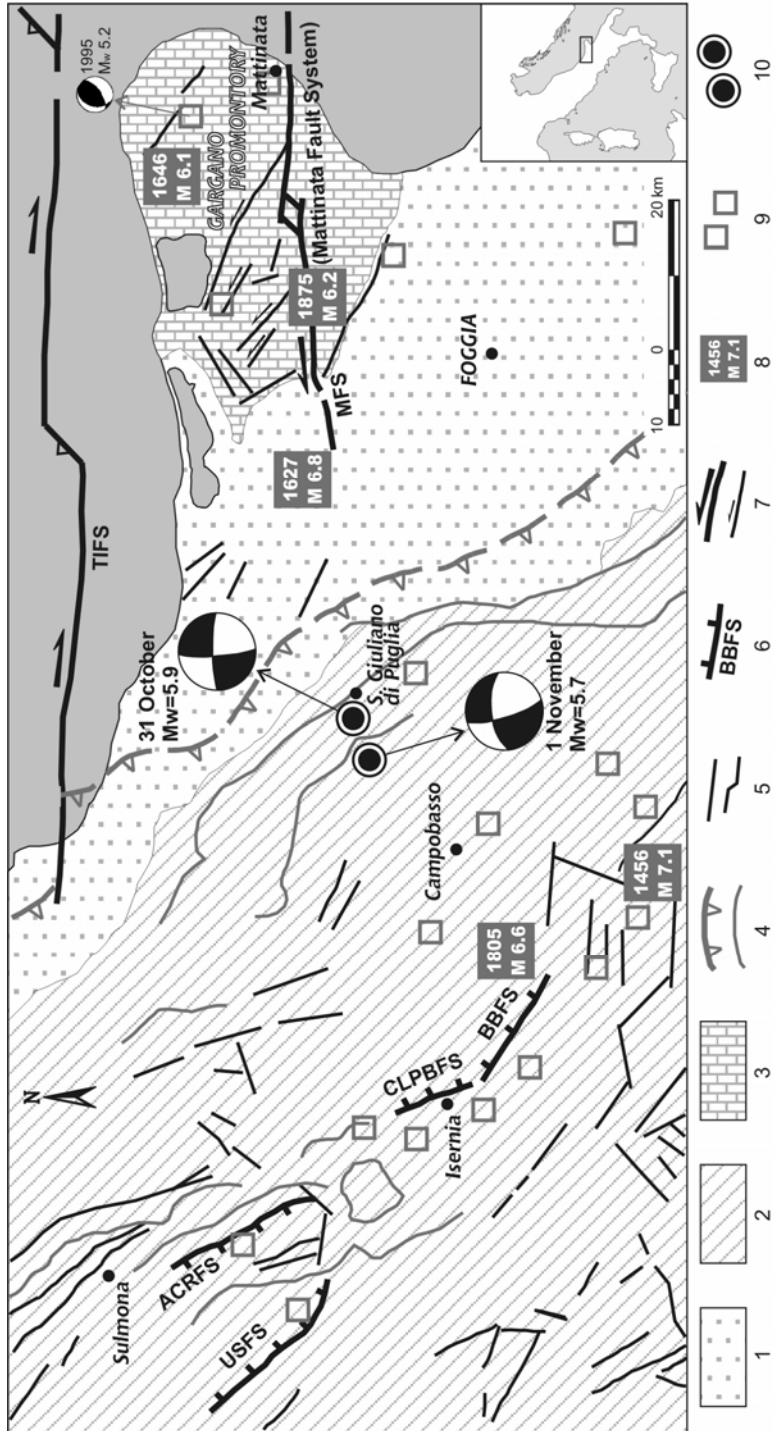


Figure 3: Seismotectonic regime of the wider affected area. [1. Marine and continental clastic deposits (Pliocene-Quaternary); 2. Parautochthonous elastic sediments of the ext. Apennines (Triassic-Tertiary); 3. Shallow neritic limestones of the Apulian platform (Triassic-Tertiary); 4. The main thrust of the Apennines over the Apulian platform and minor thrusts within the Apennines; 5. Active normal faults; 6. Significant active normal fault systems (see text); 7. Active strike-slip fault systems and faults; 8. The strongest catastrophic earthquakes; 9. Strong and medium earthquakes; 10. Main shock and strongest aftershock].

as the 1646 earthquake ( $M=6.1$ ) at the NE part of the Gargano promontory and the 1875 earthquake ( $M=6.2$ ) near the western part of the Mattinata Fault.

The moment-tensor solutions for both the main shock and the strongest aftershock (data from USGS and INGV) show that they occurred as the result of movement on a strike-slip fault with the two nodal planes trending N–S and E–W. Thus, according to the focal mechanism, the seismic fault would be either the N–S left-lateral fault or the E–W right-lateral one (Figure 4).

Elaboration of the aftershock sequence data, recorded by a local network (data from INGV), showed that the spatial distribution of the surface projection of the aftershocks follows an E–W narrow zone (about 30 km in length). This zone extends from the S. Giuliano region to the east up to the S. Angelo region to the west and represents the surface projection of the seismogenic source (Figure 4). The 3-D projection of the aftershock sequence shows that the depths of the aftershocks vary from about 10 to 23 km as well as that the seismogenic fault is almost vertical.

## **5 Tectonic structures, geotechnical effects and damage distribution**

As the fieldwork in the wider epicentral area showed, no neotectonic structures related to active faults, were observed. The hilly relief of the area results in distinctive morphological axes in the NW–SE direction which in most cases coincide with thrusts, reverse faults and folds, as a result of the deformation caused by the nappe emplacement of the Apennines over the Apulian foreland. Minor morphological axes or other morphological anomalies (scarps, drainage network asymmetries, etc.) are found in the NE–SW or E–W direction, and are probably a result of the neotectonic deformation but they cannot be directly related to active faults.

Most of the villages hit by the earthquake were founded on the parautochthonous clastic sequence that is thrust over the Apulian platform. This sequence consists of alternations of marls, sandstones and marly limestones that are folded and crossed by thrusts or other discontinuities (Figure 2). The steep relief in combination with the lithology and the geometry of rock discontinuities (thrusts, folds, bedding, etc.) forms slopes with high instability and susceptible to landslides. Many of these phenomena occurred during the earthquake, were detected in the wider epicentral area and were usually represented by small-scale landslides and rock-falls. Their spatial distribution, although scattered, shows a secondary E–W zonation (Figure 4).

A large number of open cracks and extensional ruptures, from one meter to several tens of meters long and with different orientations, were observed in the affected area. These ruptures usually exhibited openings of the order of some mm or cm and a vertical displacement of several cm. All of these ruptures were the result of geotechnical effects that occurred during the earthquake, such as slope failures, surficial sliding and landslides, usually along steep slopes, road cuts, and so on.

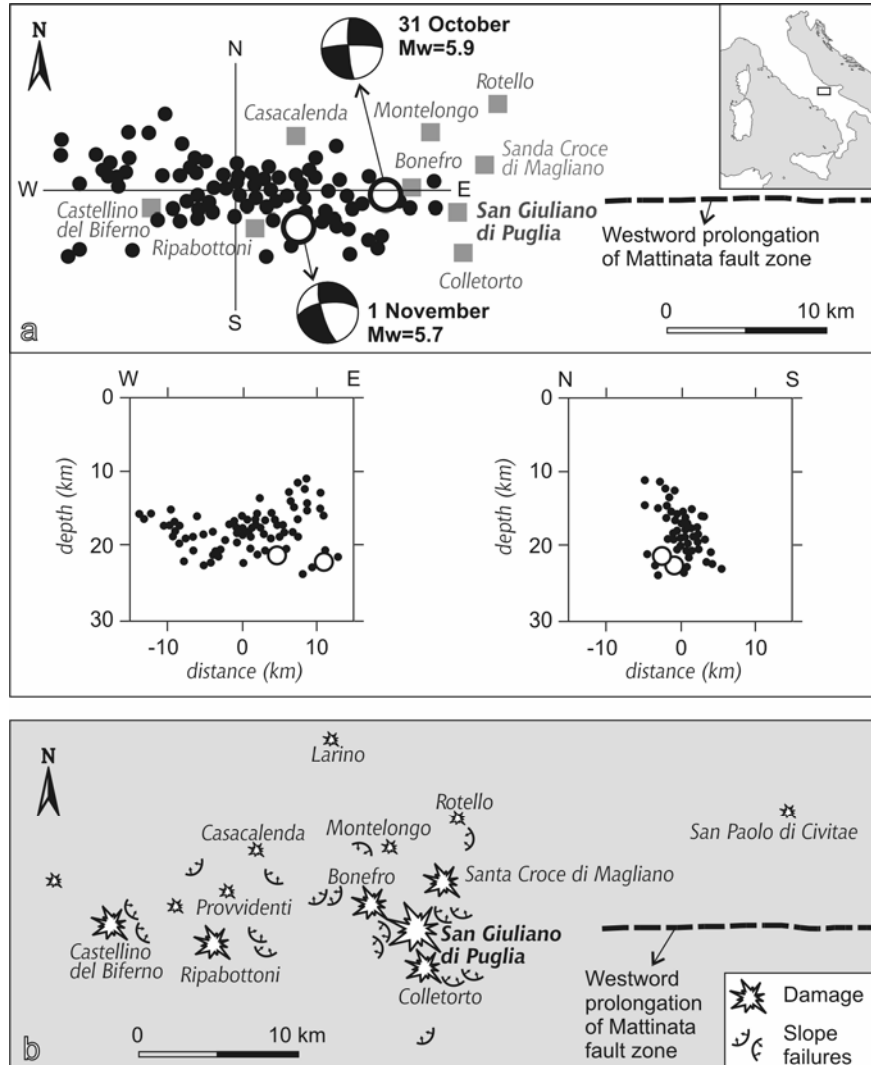


Figure 4: The spatial distribution of the aftershock sequence (a), as well as the distribution of the damage and the slope failures (b), are aligned along the same E-W direction, revealing the direction of the seismic fault.

In only two cases do the observed ruptures seem to be related to the seismic event. The first (Figures 5a,c) was located on the road that leads to S. Giuliano village, just before the entrance to the village (about 100 m from the houses of the eastern part of the village); it was approximately 20 m long and crosscut the road and the concrete retaining wall as well as the bedrock of clastic formations. The rupture bore a  $N80^{\circ}E$  strike and was accompanied by strike-slip right-lateral

offset of the order of only 1 cm. The second (Figures 5b,c) was located on the road from Colletorto village to S. Giuliano, with a N–S strike and a length of about 10 m. The kinematic data show a left-lateral strike-slip movement of the order of 3–5 mm. The geometric and kinematic features of these ruptures, and the fact that they don't seem to be related to landslides or other slope failures, lead to the conclusion that they probably represent seismic fractures, which coincide with the surface expression either of the seismic fault or of a secondary branch fault. On the other hand, the absence of similar ruptures shows that the mezo-seismal area is also characterized by the absence of significant surface faulting. This is probably due to the small magnitude of the earthquake, the geotechnical characteristics of the geological formations and the conditions of the fault propagation to the surface.

The damage distribution is another factor which usually gives us much information about the seismotectonic characteristics of an earthquake. In this case the buildings of the affected villages were mainly old structures and rarely modern ones, and as was expected the old buildings suffered most damage. Human intervention without previous technical studies created favorable conditions for the collapse of these buildings in most cases, such as that of the school in S. Giuliano with such tragic results.

Most of the damage occurred in S. Giuliano di Puglia rather than Colletorto, Bonefro or Santa Croce di Magliano. Serious damage occurred to the west of Castellino del Biferno and at Ripahottoni about 20 km from S. Giuliano. Minor damage was also observed in other villages in the wider area, while the earthquake was felt as far as Lucera to the south-east and the Termoli to the north.

The distribution of the damage and the macroseismic intensities follows the S. Giuliano – S. Angelo axis (Figure 4) and is clearly aligned along an E–W direction, an observation that was also made for the aftershock distribution as well as for the geotechnical effects.

## **6 Discussion – conclusions**

The Molise 31 October 2002,  $M_w=5.9$ , earthquake struck an area that is characterized by low seismicity, since no strong earthquakes have been reported. Moreover, as the fieldwork showed, there are no important neotectonic faults in the wider mezo-seismal area. No evidence of significant surficial expression of the seismogenic fault was found in the affected area, either in the form of a reactivated fault surface or in the form of a zone of surface ruptures. The open cracks and the extensional ruptures, which are observed mostly along the roads and the steep slopes, are associated mainly with landslides and slope failures (Figure 4). The only exception was the presence of two ruptures, some tens of meters long, between Colletorto and S. Giuliano, which showed an approximately N–W or E–W direction and a left-lateral or right-lateral strike-slip offset of the order of 5 mm or 1 cm (Figure 5).

The main problem of the Molise earthquake concerns the kinematic and dynamic regime of the seismogenic fault as well as the seismic source that is related to this seismic sequence. The narrow region, characterized by high seismic-

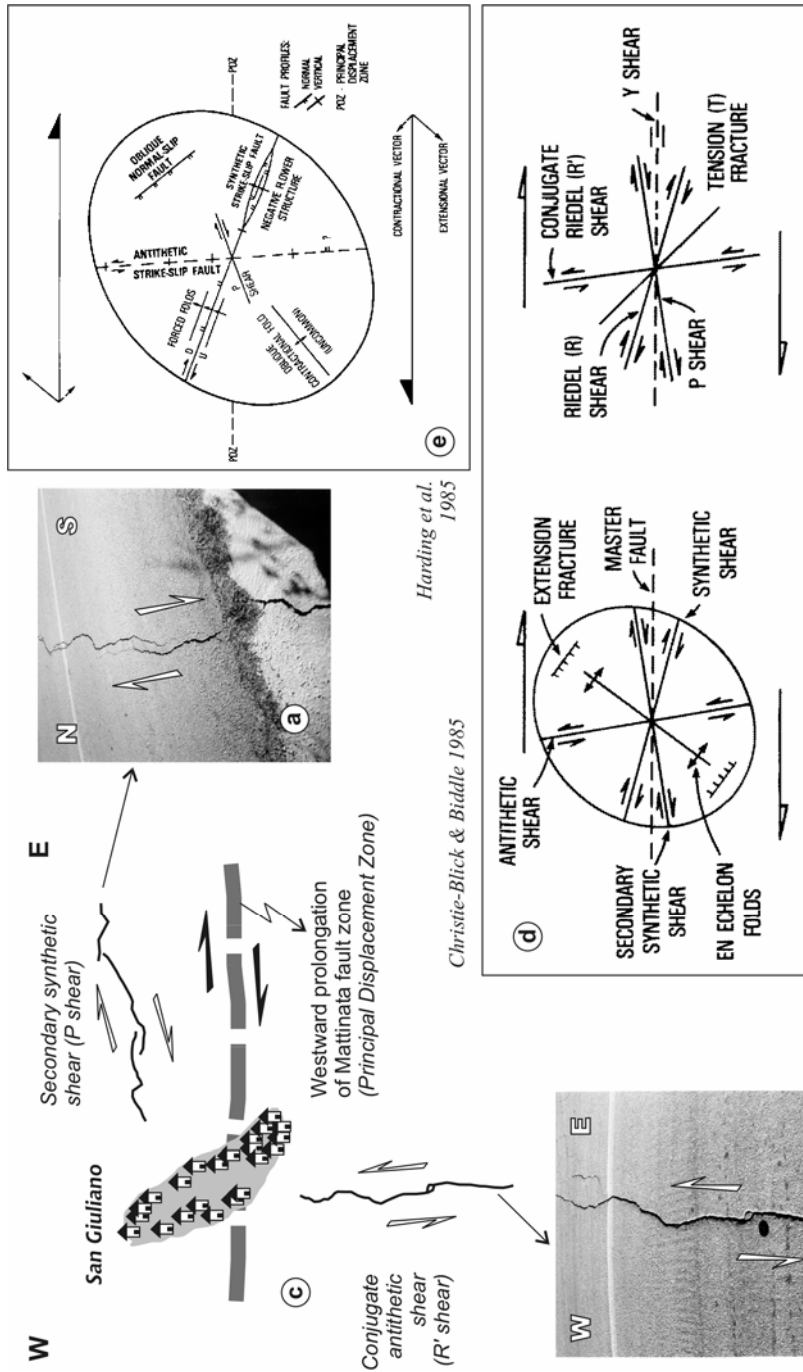


Figure 5: Kinematic interpretation of the two surface ruptures near San Giuliano village.

ity, is located about 60-70 km to the west (Figure 3) along the NW–SE normal seismogenic belt of the central and southern Apenninic chain (Di Bucci et al. [7]). Another seismogenic area (Figure 3), in a different geodynamic regime, however, lies about 80-100 km to the east, in the Gargano promontory. This area belongs to the Apulian platform and the Adriatic block and is characterized by E–W strike-slip faults (Favali et al. [8]). The prolongations of these faults to the west, to the Tyrrhenian Sea, form a zone which reveals an important geological boundary with fundamental lithospheric changes between the northern and southern parts (Figure 1).

The Molise earthquake seems to be directly connected to the eastern seismogenic area (Gargano promontory area) for the following reasons:

- The epicenters of the main shock and the aftershock sequence coincide with the westward prolongation of an E–W fault zone, which is the boundary between the southern margins of the Gargano promontory (known as the Mattinata fault system) and is characterized by left-lateral strike-slip movement (Figure 3).
- The focal mechanisms of the main shock and the strongest aftershock show a strike-slip fault that can be either N–S and left-lateral or E–W and right-lateral (Figure 4).
- The spatial distribution of the surface projection of the aftershock sequence depicts a distinctive E–W narrow zone and suggests that the seismogenic fault is the E–W one (Figure 4).
- The damage distribution and the macroseismic intensities follow the same E–W direction. Even the geotechnical effects, which present scattered distribution while they are controlled by high slope instability, show a secondary E–W zonation (Figure 4).
- From the two observed ruptures which seem to be related to the seismic event (Figure 5), the dominant was the N80°E one, with a right-lateral strike-slip offset that coincides with the fault-plane solution of the seismic fault. This rupture probably represents a secondary synthetic shear (P shear) due to the E–W strike-slip right-lateral shear along the seismic fault, which probably represents the principal displacement zone (PDZ), (Christie-Blick & Biddle [13], Harding et al. [14]), (Figure 5).
- From a kinematic point of view, the second N–S left-lateral strike-slip rupture is similar to the second of the nodal planes and probably represents the antithetic conjugate shear (R' shear) (Figure 5).

The correlation of the kinematics of the seismogenic fault to the kinematics of the Mattinata Fault zone is really obscure. The focal mechanism (as well as the observed E–W surface rupture) shows right-lateral movement for the E–W seismic fault, although the Mattinata Fault shows left-lateral movement. Because the Mattinata Fault System is a very complex fault zone, the fault segments could be interpreted as right- or left-lateral as well as right- to left-lateral or left- to right-lateral inverted (Billi [9], Favali et al. [8], Salvini et al. [10]).

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