Journal of Seismology **8:** 259–273, 2004.

The 1627 Gargano earthquake (Southern Italy): Identification and characterization of the causative fault

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Received 21 January 2003; accepted in revised form 18 November 2003

Key words: 1627 earthquake, Apricena Fault, Basso Molise, Gargano, Northern Capitanata, seismic source, seismotectonics, Southern Italy

Abstract

We present the results of a study of the subsurface tectonic features of the Basso Molise, Western Gargano and Northern Capitanata regions (Southern Italy) aimed at the identification of the source of the disastrous 1627 Gargano earthquake. In the maximum-damage area of this earthquake we have recognised a normal fault, here called the Apricena Fault, which has been identified as the fault that caused the seismic event. The Apricena Fault, striking WNW-ESE and dipping towards SSW, extends in the subsurface for about 30 kilometres from Serracapriola to Santa Maria di Stignano cutting through the whole Quaternary sequence. Other important tectonic structures trending WNW-ESE recognized in the area belong to an inactive Pleistocene strike-slip-fault system that is linked to the Mattinata Fault and to its offshore continuation in the Gondola-Grifone structural high. The Mattinata Fault and the Gondola-Grifone High form a quite complex structural feature whose kinematic behaviour is still matter of debate in the regional geological literature. NW-SE structural features recognized in the area are extensional faults whose activity was probably related to the late flexure-hinge retreat of the Adria plate margin during the Late Pliocene-Early Pleistocene eastward migration of the thrust belt-foredeep-foreland system.

Introduction

On 30 July 1627 a severe earthquake in Southern Italy struck the Basso Molise, Western Gargano and Northern Capitanata regions producing widespread destruction and causing more than 5000 victims, 4500 of which in the villages of Apricena, Lesina, San Paolo di Civitate, San Severo, Serracapriola and Torremaggiore (Molin and Margottini, 1985; Boschi et al., 1995). The seismic event was also responsible for a tsunami whose effects were particularly significant along the northern coast of the Gargano Promontory (Guidoboni and Tinti, 1988). Figure 1 is the intensity map of the maximum-damage area. Tentative isoseismal lines delimiting areas with intensities $\geq$ VIII-IX MCS have also been traced.

The 1627 earthquake is the largest historical event in the Basso Molise, Gargano and Capitanata regions, with a macroseismic magnitude=6.73 according to the new parametric catalogue of Italian earthquakes (CPTI catalogue, Gruppo di Lavoro CPTI, 1999). Despite the remarkable strength of this earthquake, the causative geological structure has not been identified as yet (see Galadini et al., 2000; Meletti et al., 2000; Valensise and Pantosti, 2001). Basing their evidence merely on the tsunami occurrence, Mele et al. (1990), Argnani et al. (1993) and Console et al. (1993) have proposed an offshore location of the seismic source, possibly in correspondence to the Tremiti Islands, notwithstanding the low intensity (VII MCS) experienced in this area and the devastation (IX and X MCS) suffered by several villages in Basso Molise, Western Gargano and Northern Capitanata. Numerical simulations carried out by Tinti and Piatanesi (1996) on the earthquake-induced tsunami show that the best matched source for the observed data corresponds to a fault located onshore south of Lesina, characterized by dip-slip motion, that caused uplift of the sea block facing the

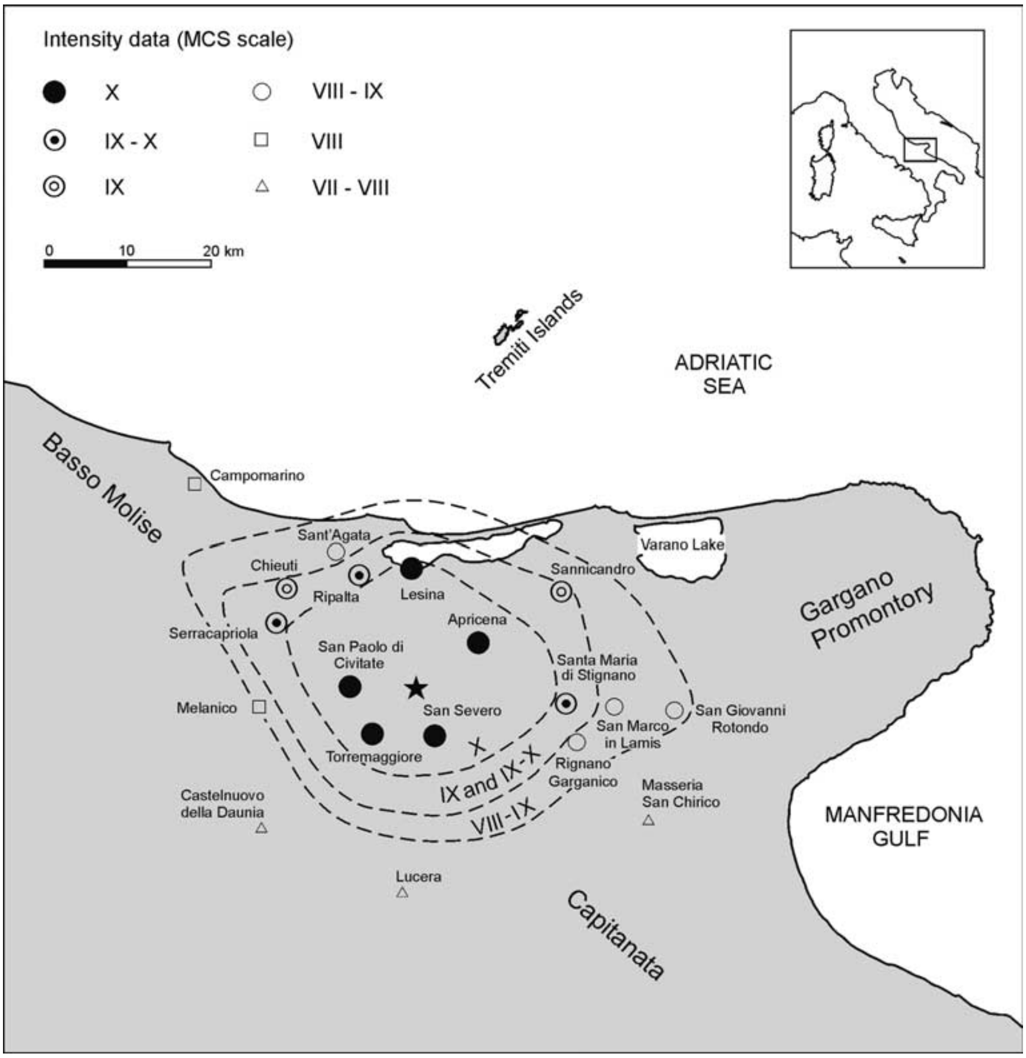

Figure 1. Intensity map of the 1627 Gargano earthquake showing sites with I ≥ VII-VIII MCS (intensities from Boschi et al., 1995). The star indicates the epicenter location according to the CPTI catalogue, Gruppo di Lavoro CPTI, 1999). Tentative isoseismal lines delimiting areas with a damage degree ≥ VIII-IX MCS have also been traced. The insert shows the location of the damaged area.

Lesina Lake. The CPTI catalogue places the epicenter of the 1627 earthquake onshore, about halfway between Apricena and Torremaggiore. A seismogenic fault striking N111°± 37 with a length of 32.6 kilometres was computed by Gasperini et al. (1999) using exclusively the macroseismic data contained in the 'Catalogo dei Forti Terremoti in Italia dal 461 a. C. al 1980' (CFTI catalogue, Boschi et al., 1995). A seismogenic fault trending N130° and dipping 45° with a rake of 90° had been previously computed by Panza et al. (1991) starting from synthetic isoseismals derived from Molin and Margottini (1985). The parameters computed by Gasperini et al. (1999), with small variations in the strike value (N113°±33), are reported in the Database of Potential Sources for Earthquakes Larger than M 5.5 in Italy (Valensise and Pantosti 2001). Recently, Salvi et al. (2000) have indicated as probable source of the 1627 earthquake a WSW-ENE trending fault the existence of which would be suggested by a morphotectonic structure 26 kilometres long, identified on satellite images and digital topography, developed between Apricena and Sannicandro.

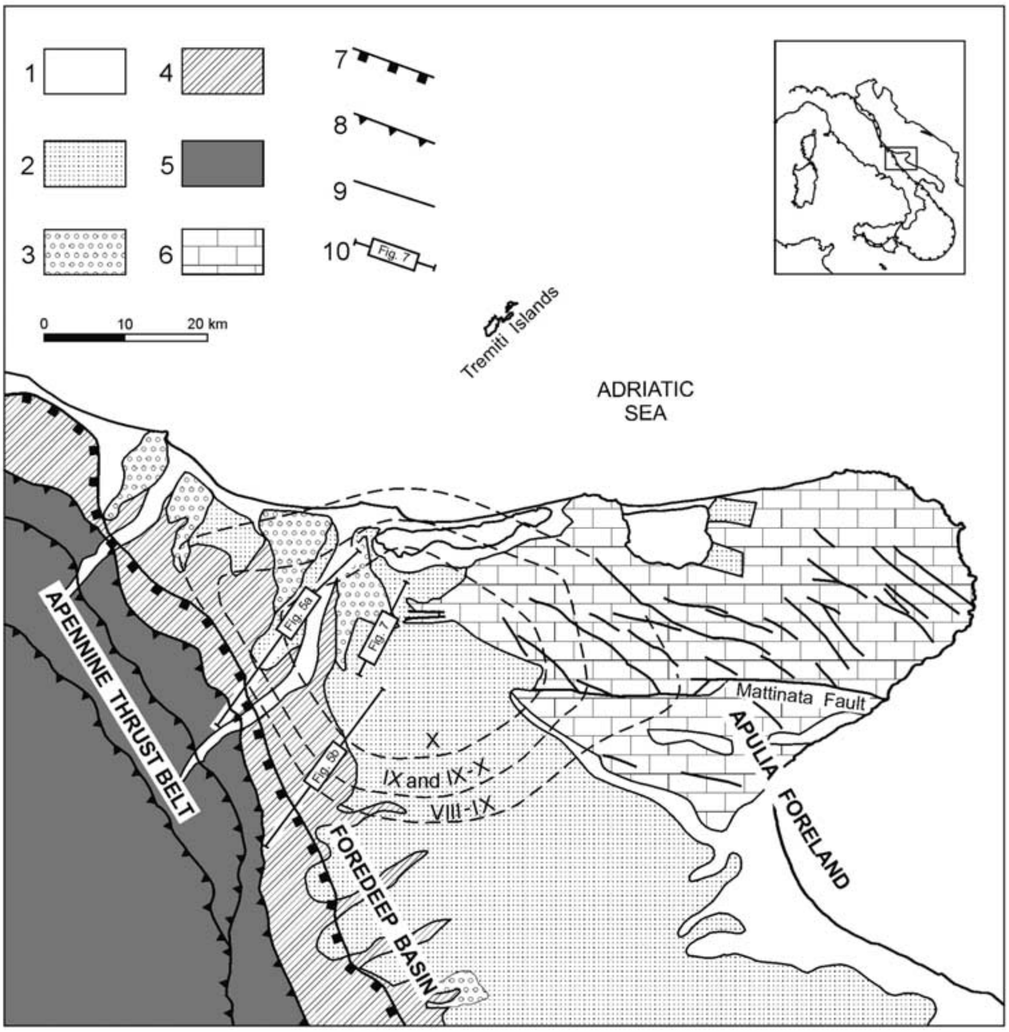

Figure 2. Schematic geological map of the Basso Molise, Gargano and Northern Capitanata regions. The isoseismal lines of the 1627 earthquake given in Figure 1 have been also traced in order to underline the area of maximum damage. The insert shows the location of the study area together with the buried front of the Apenninic nappes. 1 Holocene continental and subordinate shallow-marine deposits. 2 Middle and Upper Pleistocene continental deposits. 3 Regressive marine sands and continental conglomerates dubitatively attributed to the Middle Pleistocene. 4 Lower Pleistocene open-marine clays. 5 Apenninic nappes and Miocene-Pliocene thrust-sheet-top deposits involved in the orogenic transport. 6 Mesozoic-Tertiary carbonates of the Apulia foreland. 7 Buried front of the Apenninic nappes. 8 Emergence of frontal and oblique ramps in the Apennine thrust belt. 9 Faults, including normal faults and strike-slip faults. 10 Traces of the sections of figures 5a,b and 7.

Geological framework

The epicentral area of the 1627 earthquake is positioned a few kilometres to the east of the Apennine front (see Figure 2) and occupies a large portion of the foredeep basin in the Basso Molise and Northern Capitanata regions, as well as the inner margin of the Apulia foreland in the Western Gargano region. Mesozoic-Tertiary platform-to-basin carbonates belonging to the Apulia foreland are widely exposed in the Gargano Promontory (see, among others, Masse and Luperto Sinni, 1987; Ricchetti et al., 1988; Luperto Sinni and Borgomano, 1994; Morsilli and Bosellini, 1997; Bosellini et al., 1999; Borgomano, 2000). In the subsurface, these carbonates lie upon Triassic evaporites that in turn stratigraphically overlie terrigenous paralic deposits attributed to the Permian and to the Early Triassic (see Gargano 1 well and, south of the study region, Puglia 1 well that reaches a depth of 7070 metres). The Mesozoic-Tertiary Apulia carbonates cropping out in Western Gargano make up in Basso Molise and Capitanata the rigid substratum of the foredeep basin (Casnedi et al., 1981; Balduzzi et al., 1982; Casnedi, 1988; Patacca and Scandone, 2001). The foredeep basin is filled with a thick pile of Plio-Pleistocene terrigenous deposits exceeding 3000 metres in the inner part of the basin. In Figure 2, the Lower Pleistocene open-marine clays grading upwards into sands and conglomerates dubitably attributed to the Middle Pleistocene represent the uppermost part of the Plio-Pleistocene foredeep sequence. These regressive deposits are disconformably overlain by Middle-Upper Pleistocene continental conglomerates and subordinate sands.

Referring to Figure 1, the isoseismal lines of maximum damage of the 1627 Gargano earthquake indicate that the seismic source has to be located somewhere between Serracapriola, San Marco in Lamis, Lesina and Torremaggiore. Taking into account the magnitude of the earthquake, we would expect on the surface a fault segment 20–25 kilometres long (see Wells and Coppersmith 1994), unless the seismic source is represented by a blind fault. Actually, no fault has been recognised on the surface in this area, with the exception of two W-E trending small fault segments located west of Apricena. The lack of faults in the epicentral area of the 1627 earthquake apparently contrasts with the widespread occurrence of faults in the Gargano Promontory, the latter representing itself a seismogenic area. However, we must consider that the rigid basement, made up of Mesozoic-Tertiary limestones and dolomites, is exposed only in the Gargano Promontory whilst in Basso Molise and Northern Capitanata these carbonates are covered by a stack of Plio-Pleistocene soft sediments. The structural map of Figure 3, reproduced with slight modifications from Sella et al. (1988), shows the top-carbonate isobaths in the foredeep basin together with the faults that have dissected the Apulia platform. The map does not entirely cover the epicentral area of the 1627 earthquake, but however represents a reliable, though partial document of the subsurface tectonic structures in the Basso Molise and Northern Capitanata regions. On the basis of merely the azimuth distribution, the faults given in Figure 3 can be divided into two major groups:

1. NW-SE trending faults, widely developed in the western part of the study area, with strike values of the single fault segments ranging between N130° and N150°;
2. WNW-ESE trending faults, developed over the whole area, with strike values of the single fault segments ranging between N100° and N110°.

In both groups, some faults exceeding 20 kilometres in length appear to be adequate to produce destructive earthquakes comparable with the 1627 event in case of their reactivation.

Until now, no information has been available on the timing of the fault activity in the region damaged by the 1627 earthquake. Consequently, the kinematic behaviour of the aforementioned fault systems was poorly known. This paper provides new data on this topic. Our investigation is based on the interpretation of several hundred kilometres of reflection seismic lines, most of which not in the public domain, and on the stratigraphic analysis of several commercial boreholes. Figure 4 shows the location of the analysed wells and seismic lines. The distribution of the latter allowed us to fill the gap of information on the subsurface features in the epicentral area present in the map of Sella et al. (1988). The principal result of our study is the identification of a WNW-ESE active fault extending for about 30 kilometres from Serra Capriola to Santa Maria di Stignano, which represents the source of the disastrous 1627 Gargano earthquake.

Architecture of the Plio-Pleistocene deposits in the area affected by the 1627 earthquake

Figure 5 shows two dip-oriented regional profiles across the outer margin of the Apennines and the adjacent foredeep basin in the Basso Molise and Daunia-Northern Capitanata regions (see location in Figures 2 and 6). These geological profiles, schematically showing the overall geometry of the Plio-Pleistocene foredeep deposits together with the essential basin-fill architecture, are based on interpreted seismic profiles tied to several wells. In these profiles, the top of the Apulia carbonates is everywhere seismically expressed by a high-amplitude strong reflector. Locally, Triassic evaporites and Permian-Triassic terrigenous deposits representing the base of the Apulia platform are also recognisable, outlined by a package of high-amplitude/high frequency reflectors that sharply contrasts with the overlying reflection-free Mesozoic-Tertiary carbonates. An evident thrust ramp dipping about 30° towards SW or WSW characterises the outer margin of the Apennine mountain chain in the whole study area. In some places, Pliocene thrust-top deposits deeply involved in the late orogenic transport unconformably overlie the Apenninic nappes (e.g. Figure 5a).

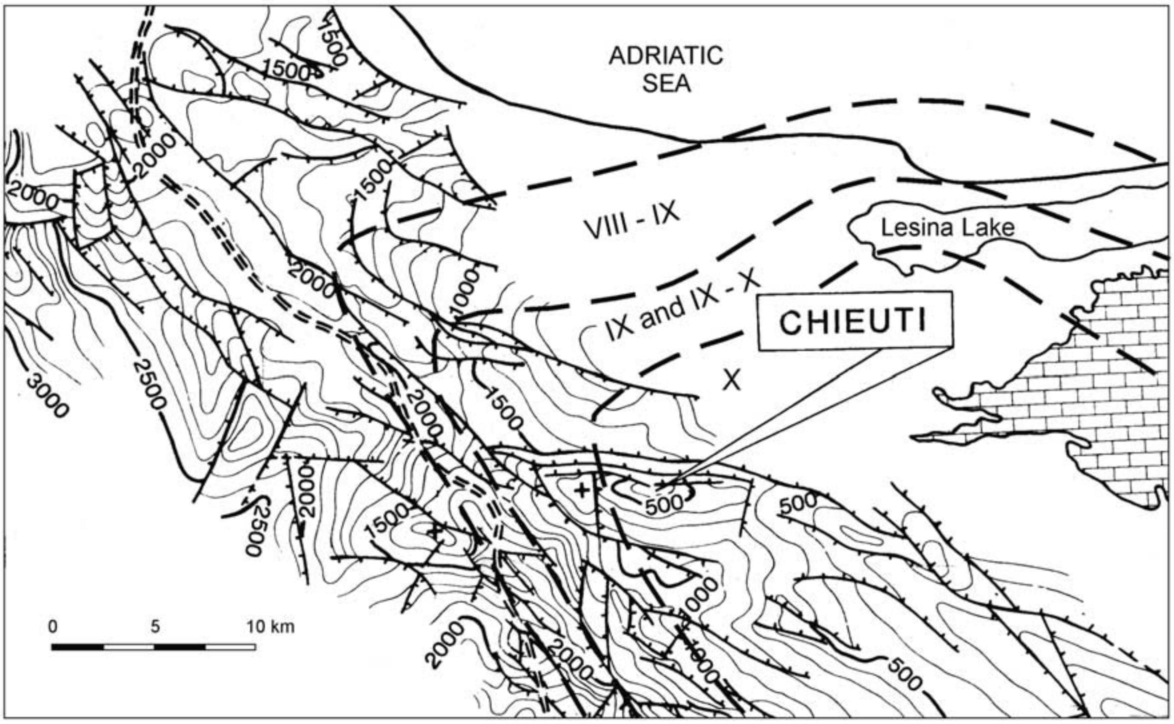

Figure 3. Structural map of the Apuliaplatform (after Sella et al., 1988) showing isobaths (in metres) of the top of the Mesozoic-Tertiary carbonates. Barbed lines indicate normal faults. The hatched double line marks the buried front of the Apenninic nappes. The location of the Chieuti High is also shown.

The Plio-Pleistocene sediments filling the foredeep basin have been divided into four intervals according to their position with respect to the Apennine frontal ramp and according to their internal seismostratigraphic signatures. The first tree intervals, broadly corresponding to foredeep systems tracts of the thrust-related depositional sequences described by Patacca and Scandone (2001) just south of the study area, have been entirely controlled by compressional tectonics. The fourth interval, on the contrary, is related to the end of the Apulia flexure-hinge retreat and to the beginning of a generalized uplift in the Southern Apennines accompanied by a regional tilting towards NE. We have distinguished:

1. Pre-ramp clastic wedge (prograding basin-floor lobes and condensed section in Patacca and Scandone 2001) deposited before and during the last orogenic transport of the allochthonous sheets. These deposits consist of a stack of well-bedded turbiditic sandstones that accumulated during the Late Pliocene (3.30–1.83 Ma) in a foredeep basin presently buried under the Apenninic nappes. A condensed section of Lower Pleistocene mudstones (Santernian p.p., 1.83 to about 1.57 Ma) separates the sandy turbidites from the overlying deposits of the syn-ramp wedge;
2. Syn-ramp clastic wedge (active-frontal-ramp systems tract in Patacca and Scandone 2001) represented by a thick body of prograding slope-fan deposits landward truncated by the Apennine frontal ramp attributed to the Santernian p.p. and to the Emilian p.p., that is to the lower-middle part of the Early Pleistocene (1.57–1.50 Ma). Towards the foreland, these deposits onlap against the Apulia carbonates that constitute the outer (eastern) flank of the foredeep basin. Widespread olistostromes deriving from the rising nappe front characterize the inner portion of the syn-ramp wedge;
3. Post-ramp deposits represented in the lower half portion by Lower Pleistocene siliciclastic deposits (Emilian p.p., 1.50–1.25 Ma) onlapping the Apennine frontal ramp, as well as by transgressive open-marine mudstones of Emilian p.p.-Sicilian p.p. age (1.25–0.92 Ma). This part of the post-ramp deposits corresponds to the backward-thrust-migration systems tract of Patacca and Scandone (2001).

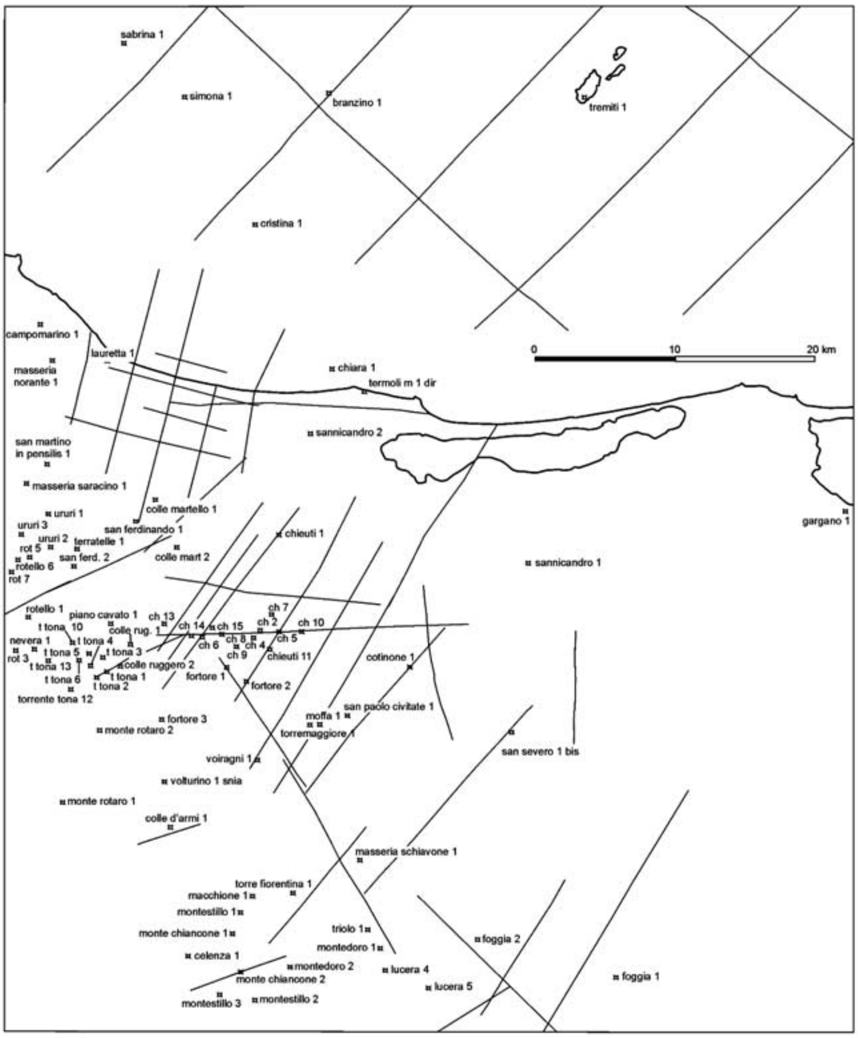

Figure 4. Base map of the study area showing the location of the seismic lines and wells analysed in the present study.

The upper half portion of the post-ramp deposits is represented by a Lower-Middle Pleistocene (0.92–0.66 Ma) prograding shelf system ending with shallow-water sands. This part of the post-ramp deposits corresponds to the forward-thrust-migration systems tract of Patacca and Scandone (2001);

4. Middle Pleistocene regressive shallow-marine sands and continental conglomerates.

Due to the well-defined geometry and to the characteristic stratigraphic signatures, the described intervals have been easily recognized in all the analysed profiles and have been mapped in the subsurface over the whole study area. This 3D reconstruction of the Plio-Pleistocene deposits allowed us to establish a detailed stratigraphic framework that we used for classifying the faults recognized in the subsurface not only according to the typology and strike but also according to the relative age of activity. It is important to underline that the compressional tectonics, together with the flexural subsidence controlling the sedimentary characteristics of the Plio-Pleistocene deposits in the foredeep basin, ceased in the Southern Apennines around 0.65 Ma, that is near the base of the regressive sands of interval 4, because of a sudden change of the geodynamic regime (Cinque et al., 1993; Hippolyte et al., 1994). Consequently, structural features pre-dating 0.65 Ma, related to an ancient and presently inactive stress field, are usually dead and are presumed to have no influence on the present-day

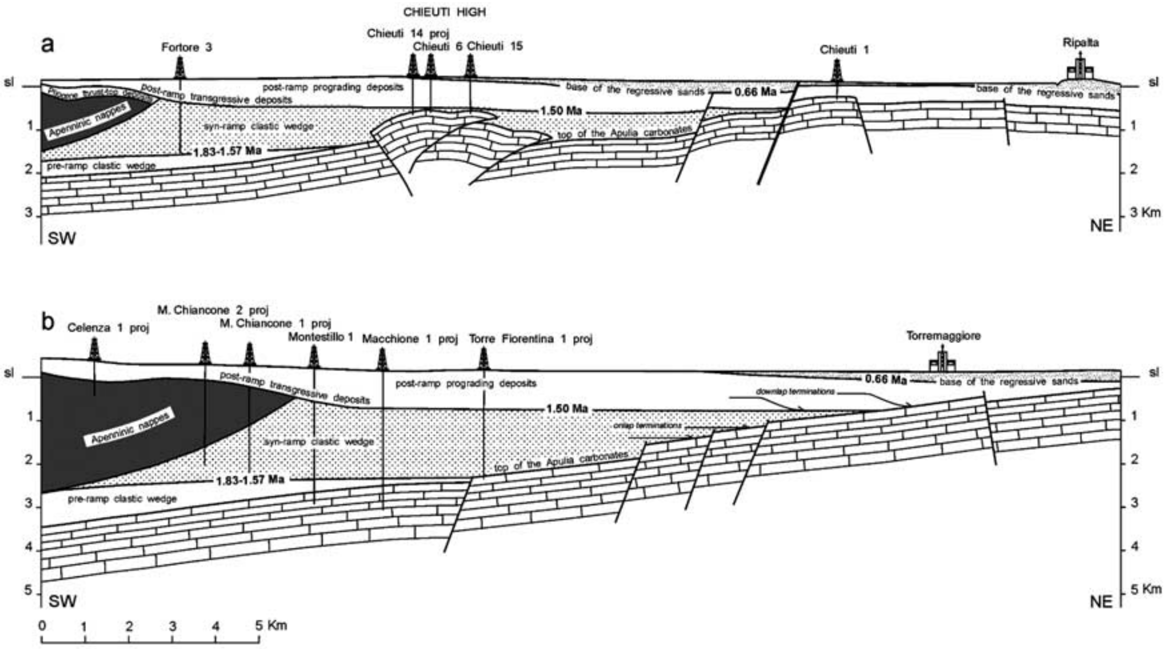

Figure 5. Geological profiles across the Apenninic margin and the foredeep basin in the Basso Molise area (5a) and in the Daunia-Northern Capitanata region (5b). See location in Figure 2.

seismicity. Figures 5a and 5b (see location in Figures 2 an 6) provide clear examples of fault chronology. Figure 5b shows some faults that dissected the carbonate basement before and during the deposition of the syn-ramp clastic wedge and do not show any sign of reactivation in late Early Pleistocene times with the exception of a NE-dipping fault located near Torremaggiore, which however pre-dates the base of the regressive sands (0.66 Ma). In Figure 5a, the stratal geometry of the Plio-Pleistocene deposits shows that the faults responsible for the growth of the Chieuti High ceased their activity before the sedimentation of the post-ramp deposits. In the same figure, two normal faults deforming the post-ramp prograding deposits give evidence of a younger extensional activity north of the Chieuti High. The southern fault may be considered currently inactive because it appears to have been sealed by the base of the regressive sands. Conversely, the northern fault (highlighted in the picture) displaces the base of the regressive sands, testifying to a persisting younger activity.

Fault analysis and identification of the potential seismic sources

The structural map of Figure 6 is an updated contour map at the top of the Apulia carbonates that integrates the previous information, mostly derived from Sella et al. (1998), with the additional data collected during our seismic investigation. This map provides a basis for fault characterization in terms of geometry and kinematics. The methodology adopted led us to recognize in the area damaged by the 1627 earthquake five fault systems showing different directions and/or different ages of activity:

1. NW-SE normal-fault system, active during the Late Pliocene and Early Pleistocene;
2. NE-SW vertical-fault system, active during the Early Pleistocene;
3. WNW-ESE high-angle-fault transpressive system, active during the Early Pleistocene up to the base of the post-ramp prograding deposits;
4. WNW-ESE normal-fault system active during the Early Pleistocene up to the base of the regressive sands, with no evidence of activity in recent times;
5. WNW-ESE normal-fault system active in recent times.

The NW-SE normal-fault system is developed only in the western part of the study area. The faults, most

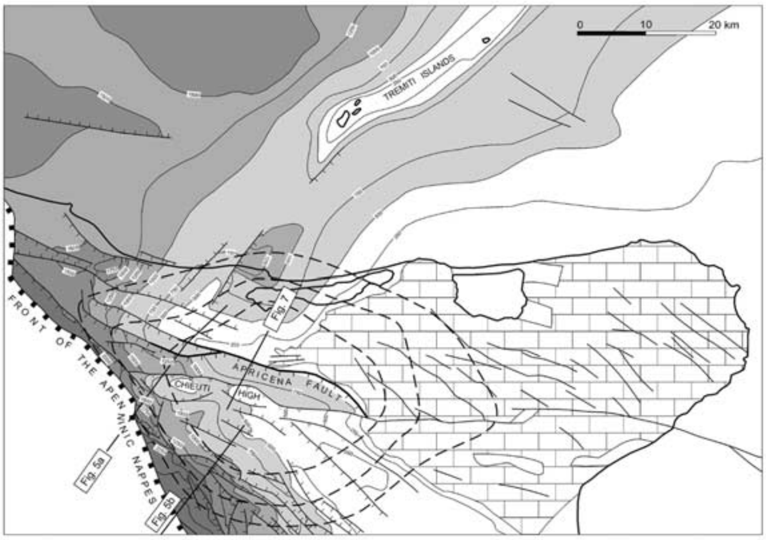

Figure 6. Structural map of the Apulia platform showing isobaths (in metres) of the top of the Mesozoic-Tertiary carbonates in the Basso Molise-Northern Capitanata region and in the Tremiti area. Barbed lines indicate normal faults; lines with triangles indicate reverse faults. The heavier barbed line marks the Apricena Fault. See discussion in the text.

of which are SW dipping, have dissected the Apulia carbonates and have been systematically sealed by the base of the syn-ramp deposits. In a few cases, also the lower portion of the syn-ramp deposits appears to have been affected by gentle deformation. However, this deformation did not propagate upwards in the upper portion of the syn-ramp wedge. We interpret the NW-SE normal faults, active during Late Pliocene-Early Pleistocene times, as a response of the brittle Apulia carbonates to the flexure-hinge retreat of the Apulia plate margin.

The NE-SW vertical-fault system, probably representing the southern termination of the Tremiti structural high, has been recognized onshore only in the Sant'Agata region, west of the Lesina Lake. The system is represented in this area by two short fault segments sealed by deposits correlatable with the post-ramp prograding deposits of Figure 5 attributed to the late Early Pleistocene.

The WNW-ESE high-angle-fault transpressive system is well represented in the Chieuti High. We have interpreted this tectonic structure as a push-up feature limited by south-dipping and north-dipping high-angle faults with oblique slip. As shown in Figure 5a, the growth of the Chieuti structural high took place partly before and partly during the deposition of the syn-ramp clastic wedge. The overlying post-ramp deposits, showing no trace of deformation, fix the upper boundary of the fault activity.

WNW-ESE normal faults are widespread in the area damaged by the 1627 earthquake. We have recognized two systems having the same orientation but different ages and geological significance.

The older, inactive WNW-ESE normal-fault system is represented by prevailing south-dipping faults south of the Chieuti 1 well and by prevailing north-dipping faults north of this borehole. The faults belonging to this system appear to have been sealed partly by the syn-ramp deposits and partly by the post-ramp prograding deposits. We think that the fault activity was related in this case to the late steps of the Apulia flexure-hinge retreat and to consequent bulging effects in the foreland area. If this interpretation is correct, also this system was active in a tectonic regime preceding the 0.65 Ma geodynamic change and is at present dead like the other above-described fault systems.

The younger WNW-ESE normal-fault system is represented by a south-dipping major fault, here called the Apricena Fault, and by associated minor branches giving evidence of activity during and after the sedimentation of the post-ramp deposits (see Figure 5). As shown in Figure 5a, also the regressive sands forming the upper part of the post-ramp deposits have been dissected by this fault. Figure 7 is a line drawing of a SW-NE oriented seismic profile that intersects the Apricena Fault about 10 kilometres west of Apricena village. The picture shows a top-carbonate throw of

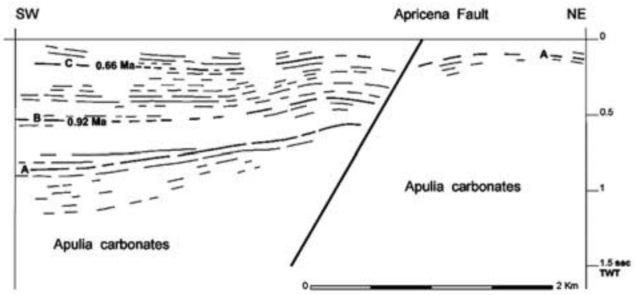

Figure 7. Line drawing of a seismic profile cutting across the Apricena Fault (location in figures 2, 6 and 8). The base of the regressive sands has been displaced by the fault and a rollover anticline has developed in the hangingwall block. A top of the Apulia carbonates; B base of the post-ramp prograding deposits; C base of the regressive sands.

about 0.4 sec TWT that corresponds to a vertical displacement slightly exceeding 500 metres. The fault cuts across the entire pile of Plio-Pleistocene deposits, including the regressive sands. Although the rake angle is unknown, a rollover anticline developed in the hangingwall block shows an important component of dip-slip motion in the cumulative displacement. The fact that in the hangingwall block the 0.92–0.66 Ma interval is quite isopachous and the fact that the 0.66 Ma horizon is involved in the rollover anticline demonstrate that the bulk of the activity of the Apricena Fault took place when the sedimentation of the regressive sands had already started. Since the Apricena Fault is characterised by an important dip-slip displacement, growth strata would be expected in the hangingwall block above the regressive Pleistocene deposits. On the contrary, no growth strata have been observed. As a matter of fact, we must say that no seismic response is present in the uppermost part of the analysed line, so that no information on the shallow deposits is available down to a depth of 150–200 metres. Two kilometres east of the profile shown in Figure 7, the Mesozoic-Tertiary carbonates of the footwall block crop out in a W-E oriented ridge representing the emergence of a structural high that includes the Chieuti 1 well site and extends westwards in the subsurface as far as the Fortore River (see Figure 8). In the area crossed by the section of Figure 7, the top of the hangingwall block of the Apricena fault is occupied by Upper Pleistocene-Holocene alluvial deposits that appear to have been incised by streams flowing towards the south and southeast. Figure 8 shows the ridge delimited southwards by the Apricena fault, together with the overall drainage pattern in the area, characterised by water discharge towards the north and towards the south in correspondence to the northern flank and to the southern flank of the structural high respectively. The picture also shows the ‘seismogenic box’ obtained with the procedure by Gasperini et al. (1999).

Comparison between the macroseismic field of the 1627 Gargano earthquake and the pattern of the faults identified in the subsurface

We have seen that among the several faults active during the Pleistocene in the area damaged by the 1627 earthquake the WNW-ESE Apricena Fault is the only tectonic structure showing evidence of activity in recent times. This observation obviously makes the Apricena Fault the best candidate for the source of the 1627 earthquake. The causal relationships between the Apricena Fault and the 1627 earthquake become very clear if we superimpose the isoseismal lines on the structural features reconstructed by the subsurface analysis (see Figure 6). We know that the main shock of the 1627 earthquake (July, 30) was followed by strong aftershocks that possibly influenced the general damage scenario but we do not believe that these aftershocks were able to significantly change the overall shape of the macroseismic field. Considering the fault location, as well as the length and the strike of the single fault segments, only two faults could represent the source of the 1627 disastrous earthquake: the high-angle strike-slip fault responsible for the Chieuti High and the Apricena Fault. The results of the investigation concerning the timing of the fault activity throughout the study region allow us to exclude the faults limiting the Chieuti High and to consider the Apricena Fault the only possible source of the 1627 earthquake. It is noteworthy that the source of the earthquake obtained from the macroseismic data according to the procedure of Gasperini et al. (1999) fits surprisingly well with the observed Apricena Fault, so well that

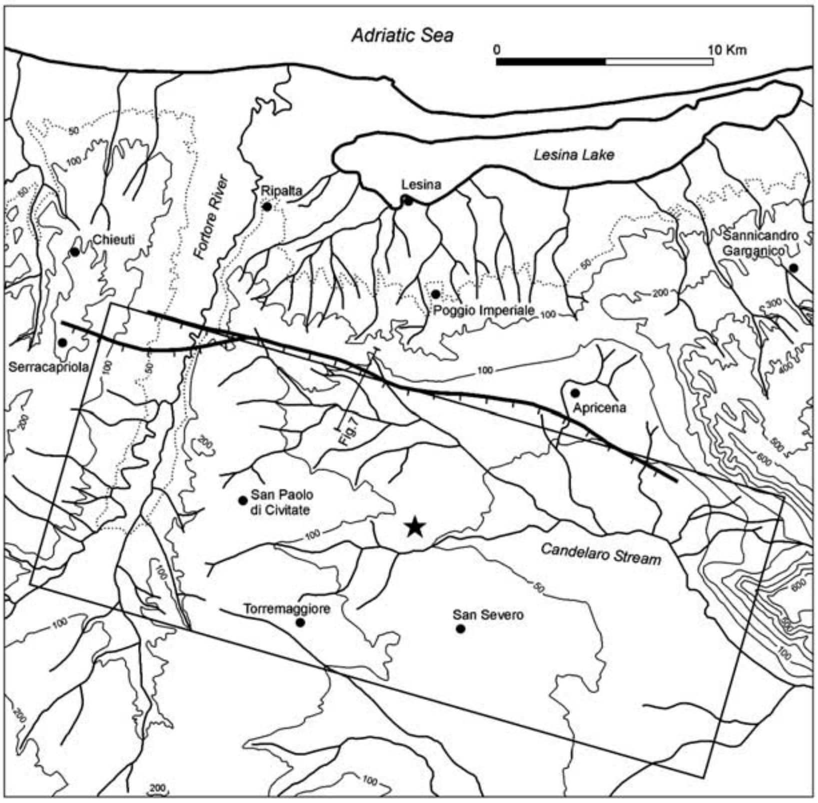

Figure 8. Principal morphologic features in the area crossed by the Apricena Fault. The rectangle represents the 'seismogenic box' of the 1627 earthquake obtained from the intensity data by using the procedure of Gasperini at al. (1999). The star indicates the epicenter location according to the CPTI catalogue.

the northern long side of the computed 'seismogenic box' almost coincides with the surface projection of the fault recognised in the subsurface (see Figure 8).

Eastern and western termination of the Apricena Fault

In the Western Gargano region, the Apricena Fault and the high-angle fault system delimiting the Chieuti High join an important W-E fault system known in the geological literature as the Mattinata Fault.The latter, in turn, joins in the Adriatic offshore area another important fault system, called the Gondola-Grifone structure that extends with a W-E direction for about 130 kilometres (see Figure 9). The Mattinata Fault, exposed from San Marco in Lamis to the Adriatic coast for more than 40 kilometres, has been recognised by Piccardi (1998) as the most important seismogenic structure of the Gargano region. We must remember that the Gargano Promontory is an earthquake-prone area which has undergone in historical times two destructive events with magnitude $\geq$ 6 (1223 Eastern Gargano earthquake with IX MCS at Santa Tecla and Sfilzi and with VIII-IX at Vico del Gargano; 1646 Eastern Gargano earthquake with IX-X MCS at Ischitella and Carpino and with IX at Vico del Gargano, Vieste and Monte Sant'Angelo, according to Boschi et al., 1995). In the current geological literature, different and often conflicting interpretations exist on the Mattinata Fault and on the Gondola-Grifone structure.

As regards the Mattinata fault, at least five different interpretations are reported in the geological literature:

1. Reverse fault according to Ortolani and Pagliuca (1987, 1988);
2. Dextral strike-slip fault according to Finetti (1982), Guerricchio (1983,1986), Finetti et al. (1987), Guerricchio and Wasowski (1988);
3. Sinistral strike-slip fault according to Funiciello et al. (1988, 1991), Favali et al. (1992, 1993a, 1993b), Console et al. (1993), Salvini and Funi-

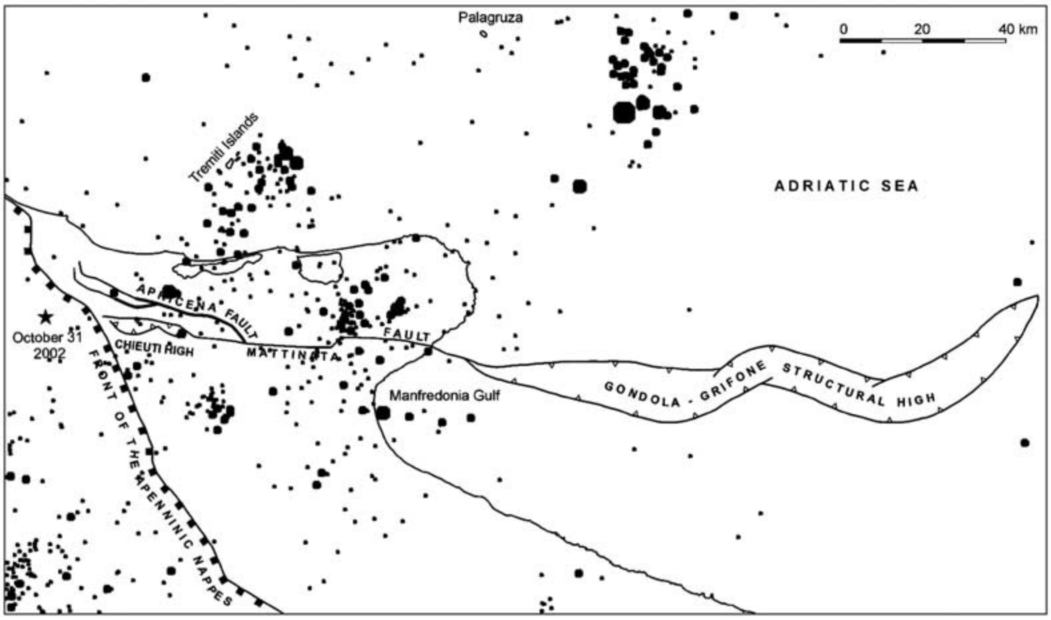

Figure 9. Recent (1981–1996) instrumental seismicity of the Gargano Promontory and surrounding areas (from Gasperini and Monachesi, 2000) together with some major structural features discussed in the text. The strongest earthquake in the area (M_B = 5.1 according to Gasperini and Monachesi, 2000) took place on 26 April 1988 about 40 kilometres SE of Palagruza. The map also shows the epicenter of the October 31, 2002 Molise earthquake (location and M_l magnitude=5.4 according to INGV).

ciello (1994), Salvini et al. (1999), Billi (2000), Billi and Salvini (2000);

4. Strike-slip fault with sinistral lateral motion during the Late Miocene-Early Pliocene and dextral lateral motion starting from Late Pliocene times according to Chilovi et al. (2000);
5. Dip-slip fault with a component of dextral strike-slip motion according to Piccardi (1998).

As regards the Gondola-Grifone structure, four different interpretations exist:

1. Dextral strike-slip fault according to Finetti (1982), Finetti et al. (1987), De Dominicis and Mazzoldi (1987), Colantoni et al. (1990), Aiello and De Alteriis (1991), De Alteriis and Aiello (1993), Tramontana et al. (1995);
2. Sinistral strike-slip fault according to Favali et al. (1992, 1993a, 1993b) and Console et al. (1993);
3. Strike-slip fault with dextral lateral motion changing in recent times into a sinistral lateral motion according to De Alteriis (1995);
4. Fold generated by inversion tectonics according to Argnani et al. (1993, 1994, 1996).

It is beyond the scope of this paper to make an exhaustive critical examination of all the aforementioned interpretations. We simply observe that the contradictions existing in the geological literature about the kinematic behaviour of the Mattinata Fault may be explained, at least in part, by taking into consideration its complex polyphasic history. A polyphasic history of this structure through Tertiary and Quaternary times, on the other hand, had already been recognised by Chilovi et al. (2000).

In the Basso Molise region, the fault system delimiting the Chieuti High joins the Mattinata Fault West of Santa Maria di Stignano. The Mattinata Fault, in turn, joins the Goldola-Grifone structural high in the Manfredonia Gulf. We have seen that the Chieuti High was active in Early Pleistocene times before the deposition of the post-ramp prograding deposits. Public seismic lines in the Adriatic offshore area (D 435–438, D 442, D 445–450, F76 001–017, F76 019, F76 021) show that also the Gondola-Grifone structure was active in the Early Pleistocene and probably moved as a dextral transpressive feature, as suggested by the en-echelon arrangement of second-order internal features and by the occurrence of push-up structures in correspondence to restraining bends. The same lines show that the tectonic activity in the Gondola-Grifone structure ceased at all, as in the Chieuti structure, during the upper part of the Early Pleistocene. Therefore, it is reasonable to suppose that during the Early Pleistocene before the deposition of the post-ramp prograding deposits, the Chieuti High, the Mattinata Fault and the Gondola-Grifone structure acted as a single transpressive system which extended for about 200 kilometres from the Basso Molise region to the eastern termination of the Gondola-Grifone structure. West of Santa Maria di Stignano, also the Apricena Fault joins the Mattinata Fault. The Apricena Fault has been identified in this paper as the causative fault of the 1627 earthquake; the Mattinata Fault has been indicated by Piccardi (1998) as the source of the most important seismic events in the Gargano Promontory. These observations suggest that in the upper part of the Early Pleistocene the Mattinata Fault disengaged from the Chieuti High, which remained inactive, and began to move in a new stress field, together with the Apricena Fault, as an extensional feature with a component of right-lateral motion as recognised by Piccardi (1988). At present, the seismic activity appears to be concentrated in the Gargano Promontory and in the Northern Capitanata region, as well as in the Adriatic area north and northeast of Gargano (see Figure 9). No seismicity, on the contrary, seems to be associated with the Gondola-Grifone structure. The lack of seismicity and the absence of recent tectonic deformation associated with this important structural feature suggest the existence of a dextral transfer system extending from the Manfredonia Gulf to the seismic area SE of Palagruza, which delimits to the east the Gargano Promontory and separates active and non-active foreland areas. A parallel SW-NE strike-slip fault system transferring with left-lateral motion the seismic activity from the Apricena Fault to other structural features located in the Adriatic offshore is also suggested by the present-day seismicity pattern, which shows a concentration of epicenters roughly aligned with the Tremiti structural high.

On 31 October 2002 an earthquake of $M_l = 5.4$ with epicenter located in the Apennine thrust belt about 20 kilometres W of the Chieuti High struck the Basso Molise region with maximum damage in San Giuliano di Puglia (I = VIII-IX MCS). The earthquake was followed by numerous aftershocks the most energetic of which ($M_l = 5.3$) occurred the day after the main shock. The focal solutions of the two major events show strike-slip-fault mechanisms with sinistral N-S and dextral W-E nodal planes. The aftershock distribution strongly suggests the activation of a W-E directed tectonic structure. More exhaustive information on the October 31 and November 1, 2002 earthquakes, as well as on the entire seismic sequence, is available on the home page of the National Institute of Geophysics and Volcanology (http: //www.ingv.it). The epicenters of the October 31 and November 1, 2002 earthquakes lie in an area where no previous event had been reported in the Italian catalogues. However, the occurrence of earthquakes with moderate energy in that area may have a logical explanation that accounts for the focal mechanism of the events and for the W-E trend of the causative geological structure. Right-lateral faults having W-E or WSW-ENE trend, in fact, may play the role of transfer faults able to accommodate sinistral offsets between NW-SE or WNW-ESE master faults in the Apennines and NW-SE or WNW-ESE master faults in the Apulia foreland, all these faults being active in the same regional stress field. We must remember here that both the Southern Apennines and Northern Capitanata-Gargano are characterised by a regional stress field with T axis oriented SW-NE (Montone et al., 1999; Frepoli and Amato, 2000a, b).

An exhaustive interpretation of the regional seismicity of Basso Molise, Northern Capitanata, Gargano, Southern Capitanata and surrounding offshore areas goes beyond our scope. The surface and subsurface investigation carried out in the area affected by the 1627 earthquake, in fact, should be extended to the entire seismic region. Our interest here was only to focus attention on the potential of a kinematic approach in seismotectonic studies.

Results and general remarks

Stratigraphic and structural investigations carried out on the subsurface geological structures of the Basso Molise and Northern Capitanata regions have enabled us to identify a WNW-ESE trending and SSW dipping fault about 30 kilometres long which cuts across the entire pile of Plio-Pleistocene deposits displaying evidence of activity in recent times. The top-carbonate throw exceeding 500 metres and a rollover anticline developed in the Quaternary deposits of the hanging-wall block indicate a prevailing dip-slip displacement. This fault, here called the Apricena Fault, has been recognised as the source of the disastrous 1627 Gargano earthquake (see Figure 8). Other faults active in recent times which are large enough to produce earthquakes comparable with the 1627 event do not exist in the study region, neither in the Adriatic Sea north of the Lesina Lake nor in the Apulia mainland. Previous locations of the seismic source in correspondence to the NE-SW trending Tremiti structural high (Mele et al., 1990; Argnani et al., 1993; Console et al., 1993) or in correspondence to a WSW-ENE morphotectonic structure developed between Apricena and Sannicandro (Salvi et al., 2000) do not fit the available data. A south-dipping normal fault located somewhere south of Lesina causing uplift of the sea-facing footwall block was already expected by Tinti and Piatanesi (1996) on the base of numerical simulations of the tsunami that followed the main shock. A dip-slip motion without important strike-slip components was also expected by Panza et al. (1991) who modelled the 1627 seismic source starting from synthetic isoseismals. We wish to remark, here, that the length and the strike of the Apricena Fault mapped in our study have a very good fit with the 1627 seismic source computed by Gasperini et al. (1999) starting from macroseismic data. This coincidence enhances once more the important role played in seismotectonic analyses by reliable reconstructions of historical earthquakes.

The identification of the seismic source of the disastrous 1627 earthquake, as well as the understanding of the kinematic relationships between the Apricena Fault and other tectonic structures active during Quaternary times in the Basso Molise, Gargano and Adriatic offshore areas, has been made possible by a close integration of stratigraphic and structural investigations. We believe that this integrated approach, in which we try to extend the basic concepts of the 2D/3D structural balance and palinspastic restoration to the kinematic analysis of an earthquake-prone region, may represent a powerful tool in seismotectonic investigations, mostly in regions where important tectonic changes in the tectonic behaviour have occurred in relatively recent times and where short-lived fault systems have followed one after the other in very short time intervals. Of course, there are intrinsic limits to our approach and additional investigations based on different methods (high-resolution seismic profiles, radar, trenching etc.) will be needed to fully understand the activity of an important seismogenic fault such as the Apricena Fault.

Acknowledgements

This research has been financially supported by ENEA-RAD. The analysed seismic lines not in the public domain were kindly provided by ENI-AGIP and by SOGIN. Loading of the borehole stratigraphic information in the database was carried out by Tiziana Ciomei. Graphics were prepared by Barbara Taccini. We are grateful to the anonymous Referee2 whose constructive criticism contributed to improve the quality of the paper.

References

Aiello, G. and De Alteriis, G., 1991, Il margine adriatico della Puglia: fisiografia ed evoluzione terziaria, *Mem. Soc. geol. ital.* **47**, 197–212.

Argnani, A., Bonazzi, C., Evangelisti, D., Favali, P., Frugoni, F., Gasperini, M., Ligi, M., Marani, M. and Mele, G., 1996, Tettonica dell'Adriatico meridionale, *Mem. Soc. geol. ital.* **51**, 227–237.

Argnani, A., Bortoluzzi, G., Favali, P., Frugoni, F., Gasperini, M., Ligi, M., Marani, M., Mattietti, G. and Mele, G., 1994, Foreland tectonics in the Southern Adriatic Sea, *Mem. Soc. geol. ital.* **48**, 573–578.

Argnani, A., Favali, P., Frugoni, F., Gasperini, M., Ligi, M., Marani, M., Mattietti, G. and Mele, G., 1993, Foreland deformational pattern in the Southern Adriatic Sea, *Ann. Geofis*. **36**, 229–247.

Balduzzi, A., Casnedi, R., Crescenti, U. and Tonna, M., 1982, Il Plio-Pleistocene del sottosuolo del Bacino Pugliese (Avanfossa Appenninica), *Geologica rom.* **21**, 1–28.

Billi, A., 2000, Stili e processi deformativi nell'Avampaese Apulo. *Univ. degli Studi di Roma 3*, *Dottorato di Ricerca in Geodinamica, Dissertazione Finale*, 173 pp.

Billi, A. and Salvini, F., 2000, Sistemi di fratture associati a faglie in rocce carbonatiche: nuovi dati sull'evoluzione tettonica del Promontorio del Gargano, *Boll. Soc. geol. ital.* **119**, 237–250.

Borgomano, J.R.F., 2000, The upper Cretaceous carbonates of the Gargano-Murge region, southern Italy: A model of platform-to-basin transition, *Bull. amer. Assoc. Petroleum Geol.* **84**(10), 1561–1588.

Boschi, E., Ferrari, G., Gasperini, P., Guidoboni, E., Smriglio, G. and Valensise, G., 1995, Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980, *ING-SGA*, Bologna, 973 pp.

Bosellini, A., Morsilli, M. and Neri, C., 1999, Long-term event stratigraphy of the Apulia platform margin (upper Jurassic to Eocene, Gargano, Southern Italy), *J. sediment. Res.* **69**(6), 1241–1252.

Casnedi, R., 1988, La fossa bradanica: origine, sedimentazione e migrazione, *Mem. Soc. geol. ital.* **41**, 439–448.

Casnedi, R., Crescenti, U., D'Amato, C., Moscardini, F. and Rossi, U., 1981, Il Plio-Pleistocene del sottosuolo molisano, *Geologica rom.* **20**, 1–42.

Chilovi, C., De Feyter, A.J. and Pompucci, A., 2000, Wrench zone reactivation in the Adriatic Block: the example of the Mattinata Fault System (SE Italy), *Boll. Soc. geol. ital.* **119**, 3–8.

Cinque, A., Patacca, E., Scandone, P. and Tozzi, M., 1993, Quaternary kinematic evolution of the Southern Apennines. Relationships between surface geological features and deep lithospheric structures. Spec. Issue on the Workshop: *Modes of crustal deformation: from the brittle upper crust through detachments to the ductile lower crust*, (Erice, November 18–24, 1991), *Ann. Geofis.* **36**, 249–260.

Colantoni, P., Tramontana, M. and Tedeschi, R., 1990, Contributo alla conoscenza dell'avampaese apulo: struttura del Golfo di Manfredonia (Adriatico Meridionale), *G. Geol.* **52**, 19–32.

Console, R., Di Giovambattista, P., Favali, P., Presgrave, B.W., Mattietti, G. and Smriglio, G., 1993, Seismicity of the Adriatic microplate, *Tectonophysics*, **218**, 343–354.

De Alteriis, G., 1995, Different foreland basins in Italy: examples from the central and southern Adriatic Sea, *Tectonophysics* **252**, 349–373.

De Alteriis, G. and Aiello, G., 1993, Stratigraphy and tectonics offshore of Puglia (Italy, southern Adriatic Sea), *Marine Geol.* **113**, 233–253.

De Dominicis, A. and Mazzoldi, G., 1987, Interpretazione geologico-strutturale del margine orientale della piattaforma apula, *Mem. Soc. geol. ital.* **38**, 163–176.

Favali, P., Funiciello, R., Mattietti, G., Mele, G., Montone, P., Salvini, F. and Tozzi M., 1992, Seismotectonic identity of the southern Adriatic area. In: Carmignani, L. and Sassi, F.P. (eds.), *Contributions to the Geology of Italy with special regards to the Paleozoic basements. A volume dedicated to Tommaso Cocozza,* IGCP No. 276, *Newsletter*, **5**, 339–343.

Favali, P., Funiciello, R., Mattietti, G., Mele, G. and Salvini F., 1993,. An active margin across the Adriatic Sea (central Mediterranean Sea), *Tectonophysics* **219**, 109–117.

Favali, P., Funiciello, R. and Salvini, F., 1993b, Geological and seismological evidence of strike-slip displacement along the E-W Adriatic-Central Apennines belt. In: Boschi, E., Mantovani, E. and Morelli, A., (eds.), *Recent Evolution and Seismicity of the Mediterranean Region*, NATO ASI Series, C**402**, 333–346.

Finetti, I., 1982, Structure, stratigraphy and evolution of central Mediterranean, *Boll. Geofis. teor. appl.* **24**, 247–315.

Finetti, I., Bricchi, G., Del Ben, A., Pipan, M. and Xuan, Z., 1987, Geophysical study of the Adria plate, *Mem. Soc. geol. ital.* **40**, 335–344.

Frepoli, A. and Amato, A., 2000a, Fault plane solutions of crustal earthquakes in Southern Italy (1988–1995): seismotectonic implications, *Ann. Geofis.* **43**, 437–467.

Frepoli, A. and Amato, A., 2000b, Spatial variation in stresses in peninsular Italy and Sicily from background seismicity, *Tectonophysics*, **317**, 109–124.

Funiciello, R., Montone, P., Parotto, M., Salvini, F. and Tozzi, M., 1991, Geodynamical evolution of an intra-orogenic foreland: the Apulia case history (Italy), *Boll. Soc. geol. ital.* **110**, 419–425.

Funiciello, R., Montone, P., Salvini, F. and Tozzi, M., 1988, Caratteri strutturali del promontorio del Gargano, *Mem. Soc. geol. ital.* **41**, 1235–1243.

Galadini, F., Meletti, C. and Vittori, E., 2000, Stato delle conoscenze sulle faglie attive in Italia: elementi geologici di superficie. Risultati del progetto 5.1.2. 'Inventario delle faglie attive e dei terremoti ad esse associabili'. In: Galadini, F., Meletti, C. and Rebez, A. (eds.), *Le ricerche del GNDT sul campo della pericolosità sismica (1996–1999),* CNR-Gruppo Nazionale per la Difesa dai Terremoti-Roma, pp. 107–136.

Gasperini, P., Bernardini, F., Valensise, G. and Boschi, E., 1999, Defining Seismogenic Sources from Historical Earthquake Felt Reports, *Bull. of the Seismol. Soc. of Amer.* **89**(1), 94–110.

Gasperini, P. and Monachesi, G., (a cura di), 2000, Catalogo Strumentale dei Terremoti 1981–1996. http://ibogfs.df.unibo.it/user2/paolo/www/gndt.html

Gruppo Di Lavoro CPTI, 1999, Catalogo Parametrico dei Terremoti Italiani, *ING, GNDT, GSA, SSN*, Bologna, 92 pp.

Guerricchio, A., 1983, Strutture tettoniche di compressione nel Gargano di elevato interesse applicativo evidenziate da immagine da satellite, *Geol. Appl. Idrogeol.* **18**, 491–506.

Guerricchio, A., 1986, Esempi di bacini pull apart nel Gargano (Puglia settentrionale), *Geol. Appl. Idrogeol.* **21**, 25–36.

Guerricchio, A. and Wasowski, J.J., 1988, Some remarks on the tectonic significance of the paleomagnetic data from Gargano, Southern Italy, *Mem. Soc. geol. ital.* **41**, 1263–1269.

Guidoboni, E. and Tinti, S., 1988, A review of the historical 1627 tsunami in the southern Adriatic, *Science of Tsunami Hazards* **6**, 11–16.

Hippolyte, J.C., Angelier, J. and Roure, F., 1994, A major geodynamic change revealed by Quaternary stress patterns in the Southern Apennines (Italy), *Tectonophysics* **230**, 199–210.

Luperto Sinni, E. and Borgomano, S., 1994, Stratigrafia del Cretaceo superiore in facies di scarpata di Monte Sant'Angelo (Promontorio del Gargano, Italia Meridionale), *Boll. Soc. geol. ital.* **113**, 355–382.

Masse, J.P. and Luperto Sinni, E., 1987, A platform to basin transition model: the lower Cretaceous carbonates of the Gargano massif (Southern Italy), *Mem. Soc. geol. ital.* **40**, 99–108.

Mele, G., Mattietti, G. and Favali, P., 1990, Sismotettonica dell'area adriatica: interpretazione di dati sismologici recenti, *Mem. Soc. geol. ital.* **45**, 233–241.

Meletti, C., Patacca, E. and Scandone P., 2000, Construction of a seismotectonic model: the case of Italy, *Pageoph* **157**, 11–35.

Molin, D. and Margottino, C., 1985, The earthquake of July 1627 in the Northern Capitanata. In: Postpischl, D. (ed.), Atlas of isoseismal maps of Italian earthquakes. CNR-P.F. Geodinamica, Bologna, pp. 36–37.

Montone, P., Amato, A. and Pondrelli, S., 1999, Active stress map of Italy, *J. geophys. Res.* **104**, 25,595–25,610.

Morsilli, M. and Borsellini, A., 1997, Carbonate facies zonation of the upper Jurassic-lower Cretaceous Apulia platform margin (Gargano Promontory, Southern Italy), *Riv. ital. Paleont. (Stratigr.)* **103**(2), 193–206.

Ortolani, F. and Pagliuca, S., 1987, Tettonica transpressiva nel Gargano e rapporti con le catene appenninica e dinarica, *Mem. Soc. geol. ital.* **38**, 205–224.

Ortolani, F. and Pagliuca, S., 1988, Il Gargano (Italia meridionale): un settore di 'avampaese' deformato tra la catena appenninica e dinarica, *Mem. Soc. geol. ital.* **41**, 1245–1252.

Panza, G.F., Craglietto, A. and Suhadolc, P., 1991, Source geometry of historical events retrieved by synthetic isoseismals. In: Stucchi, M., Postpischl, D. and Slejko, D. (eds.), Investigation of Historical Earthquakes in Europe, *Tectonophysics* **193**, 173–184.

Patacca, E. and Scandone, P., 2001, Late thrust propagation and sedimentary response in the thrust belt-foredeep system of the Southern Apennines (Pliocene-Pleistocene), In: Vai, G.B. and Martini, I.P. (eds.), Anatomy of an Orogen: The Apennines and Adjacent Mediterranean Basins. Kluwer Academic Publ., pp. 401–440.

Piccardi, L., 1998, Cinematica attuale, comportamento sismico e sismologia storica della faglia di Monte sant'Angelo (Gargano, Italia): la possibile rottura superficiale del 'leggendario' terremoto del 493 D.C. *Geogr. Fis. Dinam. Quat.* **21**, 155–166.

Ricchetti, G., Ciaranfi, N., Luperto Sinni, E., Monelli, F. and Pieri, P., 1988, Geodinamica ed evoluzione stratigrafico tettonica dell'Avampaese Apulo, *Mem. Soc. geol. ital.* **41**, 57–82.

Salvi, S., Quattrocchi, F., Brunori, C.A., Doumaz, F., Angelone, M., Billi, A., Buongiorno, F., Funiciello, R., Guerra, M., Mele, G., Pizzino, L. and Salvini, F., 1999, A multidisciplinary approach to earthquake research: implementation of a Geochemical Geographic Information System for the Gargano site, southern Italy. *Nat. Hazards* **20**, 255–278.

Salvini F., Billi A., Wise, D. U., 1999, Strike-slip fault-propagation cleavage in carbonate rocks: the Mattinata fault Zone, Southern Apennines, Italy, *J. Struct. Geol.* **21**, 1731–1749.

Salvini, F. and Funiciello, R., 1994, Rigetti stratigrafici e rigetti reali: il paradosso apparente della faglia di Mattinata (Gargano). *Soc. Geol. Ital.*, 77° Riunione estiva-Congr. Naz. 'Geologia delle aree di avampaese', (Bari, 26–28 sett., 1994), Riassunti, pp. 29–31.

Sella, M., Turci, C., Riva, A., 1988, Petroleum geology of the 'Fossa Bradanica' (Foredeep of the Southern Apennine thrust belt). *Mem. Soc. geol. ital.* **41**, 87–107.

Tinti, S. and Piatanesi, A., 1996, Numerical simulations of the tsunami induced by the 1627 earthquake affecting Gargano, Southern Italy, *J. Geodyn*. **21**, 141–160.

Tramontana, M., Morelli, D. and Colantoni, P., 1995, Tettonica plio-quaternaria del sistema sud-garganico (settore orientale) nel quadro evolutivo dell'Adriatico centro-meridionale, *Stud. geol. Camerti* vol. spec., 1995/2, 467–473.

Valensise, G. and Pantosti, D. (eds.), 2001, Database of potential sources for earthquakes larger than M 5.5 in Italy. Version 2.0–2001. *Ann. Geofis.* Suppl. **44**(4), 797–964, with CD-Rom.

Wells, D.L. and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement, *Bull. of the Seismol. Soc. of Amer.* **84**, 974–1002.