

In search of the seismogenic source of the March 23rd 2018 earthquake (Mw 3.7) near Brindisi (Puglia, Southern Italy)

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Abstract

The portion of the southern Adriatic Sea, adjacent to the Murge area (Apulian Foreland, Southern Italy), is considered mainly aseismic. The recent March 23rd 2018 earthquake (Mw 3.7), occurred near Brindisi (Puglia Region), giving us occasion to reconsider data coming from different sources (instrumentally-recorded, historically-documented and palaeoseismologically-interpreted earthquakes), that suggest some moderate seismic shocks in this portion of the Adriatic Sea. The present study, based on the re-interpretation of public domain seismic profiles and exploration well logs available in the ViDEPI Project, has been focused on the recognition of faults with Quaternary activity in the epicentral area. A S-dipping fault, with a main dip-slip component of movement, is suggested to be the seismogenic source. Its geometry is consistent with the fault plane solution and the depth of the hypocenter calculated by the INGV (Istituto Nazionale di Geofisica e Vulcanologia).

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1. INTRODUCTION

The central part of the Apulian Foreland, including the Murge sector and its Adriatic offshore area (Southern Italy; Fig. 1a), have been generally considered practically free from significant levels of seismicity (Fig. 1b). However, this opinion is contradicted by several data, including historical documentation, instrumental observations (DEL GAUDIO et al., 2005; PIERRI et al., 2013; LOCATI et al., 2016; ROVIDA et al., 2016), seismically-induced soft-sediment deformation structures in Quaternary sediments (MORETTI, 2000; MORETTI et al., 2002), and large boulder accumulations resulting from tsunami events (MASTRONUZZI & SANSÒ, 2004; Fig. 1a). Such evidence of strong earthquakes suggest that the activity of local minor tectonic structures could have been “masked” by that of major seismogenic structures located in neighbouring regions (e.g., DEL GAUDIO et al., 2005, 2007). These include the Apennine and Dinarides-Albanides-Hellenides orogens (Figs. 1a-c), and the structures responsible for major historical earthquakes of the Northern Puglia Region (e.g., Mw 6.7 events of 1627 and 1646, and Mw 6.3 of 1731; ROVIDA et al., 2016), the exact location of which is still a matter for debate (e.g., DEL GAUDIO et al., 2007) and, in some studies, related to the Mattinata-Gondola Fault System (e.g., PATACCA & SCANDONE, 2004; TONDI et al., 2005; Figs. 1a,b). Additional support for this conjecture derives from the recent March 23rd 2018 earthquake, which occurred in the southeast Murge Adriatic offshore, at the transition between the Apulian Foreland and the Dinarides-Albanides foredeep domains.

According to the data reported for this event by INGV (Istituto Nazionale di Geofisica e Vulcanologia) on the Italian National Earthquake Centre website (<http://cnt.rm.ingv.it/>), this event (see <http://cnt.rm.ingv.it/event/18504011>) occurred at the hypocentral depth of 26–30 km, was characterized by an estimated moment magnitude of Mw 3.7, a scalar seismic moment M_0 of $4.74 \cdot 10^{14}$ N·m and a fault plane solution with two nodal

planes, one approximately E-W oriented, dipping towards the south (with strike, dip and rake of 81°, 87° and 124°, respectively) and the other approximately N-S oriented, dipping towards the west (with strike, dip and rake of 176°, 34° and 6°, respectively; Fig. 1d). This was the strongest shock recorded in the central Puglia Region since 1980, when local seismicity started to be more accurately monitored thanks to the integration of the National Seismic Network, managed by the INGV, with the regional instrumental network, managed by the University of Bari Seismological Observatory.

In order to identify the seismogenic source and resolve the fault plane ambiguity, the present study investigates the Quaternary activity of faults in the epicentral area (Fig. 1d) by the interpretation of public domain seismic profiles and exploration well logs available in the ViDEPI Project (ViDEPI, 2015).

The main results are discussed with data coming from different sources (e.g., palaeoseismicity, historical documentation, instrumentally recorded earthquakes). Therefore, the approach adopted in the present research study would be useful to analyze the seismicity of foreland/cratonic areas. Although these are generally considered to be practically aseismic, several studies suggest that tectonic stress can be transmitted far from the active plate boundaries, causing rare, although sometimes strong, seismic events (e.g., JOHNSTON & KANTER, 1990; CALAIS et al., 2016, and references therein).

2. GEOLOGICAL SETTING

The Apulian Foreland, which practically corresponds to the Puglia Region (Southern Italy), represents the Plio-Pleistocene foreland of the Apennine (westward) and the Dinarides-Albanides-Hellenide orogens (eastward); its Adriatic offshore almost coincides to the Dinarides-Albanides foredeep domain (e.g., RICCHETTI et al., 1988; Figs. 1a,c). The Apulian Foreland continen-

tal crust, showing a thickness of about 25–30 km (DEL GAUDIO et al., 2001; AMATO et al., 2014; de LORENZO et al., 2014), is characterized, in its uppermost part, by sedimentary cover about 7 km thick overlying a Variscan basement (Fig. 1c), the latter being exposed in the Calabrian massifs (FESTA et al., 2010). The sedimentary cover basically consists, from the bottom, of Permo-Triassic red beds (Verrucano Fm), a Triassic anhydrite-dolomite

succession (Burano Fm), and Jurassic – Cretaceous limestones belonging to the Apulia Platform (e.g., RICCHETTI et al., 1988; Fig. 1c). The latter extensively crops out in the Puglia Region, where a Middle Jurassic – Upper Cretaceous inner platform carbonate succession shows a thickness of about 4 km (CIARANFI et al., 1988; SPALLUTO et al., 2005). Locally, in the eastern Puglia Region, outcropping marginal pelagic carbonate sediments

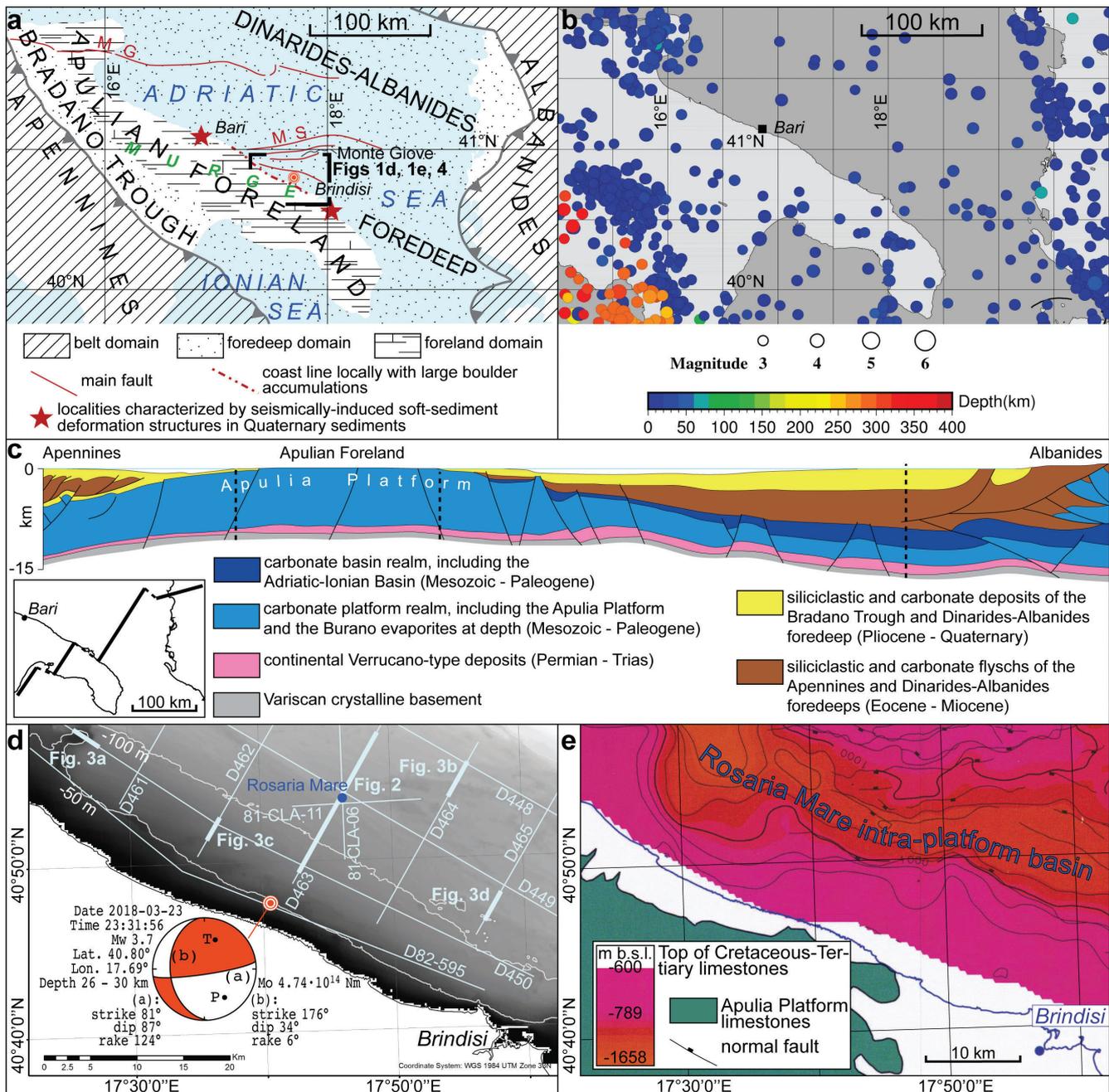


Figure 1. (a) Sketch to show major tectonic boundaries and fault systems of the southern Adriatic Sea and its adjacent areas (modified after RICCHETTI et al., 1988). The main fault systems, traced for the Apulian Foreland and its Adriatic offshore, are: MG – Mattinata-Gondola Fault System (after de ALTERIIS, 1995; CHILOVI et al., 2000); MS – Monopoli System (after MORELLI, 2002). Localities characterized by seismically-induced deformation structures in soft Quaternary sediments, from MORETTI (2000) and MORETTI et al. (2002). Coast line with local accumulations of large boulders, after MASTRONUZZI & SANSÒ (2004). (b) Geographical epicentral distribution of earthquakes of $M \geq 3.0$ located in the Apulian Foreland and surrounding regions, reported in CASTELLO et al. (2006), for the period 1981 – 2002, and in the Italian National Earthquake Centre website (<http://cnt.rm.ingv.it>), from 1981 to the date of the examined earthquake (2018.03.23); circle size is proportional to earthquake magnitude and colors indicate the hypocentral depths, according to the legend; the area of the panel is the same of that of Figure 1a. (c) Schematic geological cross section from the front of the Apennines to the front of the Albanides (redrawn and simplified after FANTONI & FRANCIOSI, 2010). (d) Map of the southeast Murge Adriatic offshore; the location of the Rosaria Mare exploration well and of the seismic profiles (from VIDEPI, 2015) is indicated; bathymetry after EMODnet (2017); coastline after puglia.com (2015). Epicenter location and earthquake parameters at side of the fault plane solution of the March 23rd 2018 seismic event, after INGV (<http://cnt.rm.ingv.it/event/18504011>). (e) Map of the top of Cretaceous-Tertiary limestones in the southeast Murge Adriatic offshore; the Upper Cretaceous Rosaria Mare intra-platform basin, delimited by extensional faults, can be appreciated (modified after NICOLAI & GAMBINI, 2007); the area of the panel is the same of that of Figure 1d.

record the lateral transition to the basinal domain (e.g., BORGOMANO, 2000; BRANDANO et al., 2010; MORSILLI et al., 2017), i.e., the Mesozoic – Paleogene Adriatic-Ionian Basin (Fig. 1c), which roughly occupied the position of the present-day Adriatic Sea (ZAPPATERRA, 1994). The top of this basin is dominated by pelagic carbonates belonging to the Cretaceous – Paleogene Scaglia-type deposits (NICOLAI & GAMBINI, 2007; FANTONI & FRANCIOSI, 2010); similar deposits, however, locally filled Upper Cretaceous intra-platform basins (de' DOMINICIS & MAZZOLDI, 1987; NICOLAI & GAMBINI, 2007; MASTROGIACOMO et al., 2012; FESTA et al., 2018) bounded by normal faults (e.g., NICOLAI & GAMBINI, 2007). In this regard, the margins of the Rosaria Mare intra-platform basin (located in the epicentral area) are geometrically controlled by Upper Cretaceous normal faults (NICOLAI & GAMBINI, 2007; Fig. 1e).

Neogene and Quaternary carbonate – terrigenous deposits locally and discordantly overlie the Mesozoic and Paleogene sediments (CIARANFI et al., 1988; TROPEANO & SABATO, 2000; TROPEANO et al., 2004). These deposits show an increasing thickness eastwards into the Dinarides-Albanides foredeep (Fig. 1c); here, they include the Miocene Bisciaro Fm, overlying the pelagic carbonates of the Adriatic-Ionian Basin (i.e. the Cretaceous – Paleogene Scaglia-type deposits; NICOLAI & GAMBINI, 2007; FANTONI & FRANCIOSI, 2010).

The major seismogenic structure dissecting the Apulian Foreland, as well as its adjacent Dinarides-Albanides foredeep, is the W-E striking Mattinata-Gondola Fault System (e.g., de ALTERIIS, 1995; CHILOVI et al., 2000; KASTELIC et al., 2013; Fig. 1a). It was able to produce seismic shocks larger than Mw 5 (see the Shallow Gondola Fault Zone, in DISS WORKING GROUP, 2018). South of this fault zone, the Murge area (Fig. 1a) is mainly affected by extensional faults striking NW-SE to W-E, towards the Adriatic coastline, and dipping from the NE to N, respectively (PIERI et al., 1997; TROPEANO et al., 1997). The low energy seismicity of the Murge area has been related to the activity of these faults (DEL GAUDIO et al., 2005), i.e., structures inherited since the Cretaceous (FESTA, 2003). Their possible continuation in the Adriatic offshore have been considered by MORELLI (2002), especially concerning the Monopoli System of faults, that were the origin of the Monte Giove structural high within the pre-Quaternary bedrock (Fig. 1a).

3. DATASET AND METHODS

To reach the objective of the present research paper, in addition to parameters of the March 23rd 2018 earthquake available on the institutional website of the INVG (<http://cnt.rm.ingv.it/event/18504011>; Figure 1d), the following public datasets, covering the epicentral area, were used:

- i) sea floor bathymetry (Fig. 1d; EMODnet, 2017);
- ii) Adriatic coastline of the southeast Murge (Fig. 1d; pugliacon, 2015);
- iii) seismic profiles (stack version) D82-595, 81-CLA-06, 81-CLA-11, D461, D462, D463, D464, D465, D448, D449 and D450 (Fig. 1d, for location; ViDEPI, 2015);
- iv) Rosaria Mare 1 well (Fig. 1d, for location; ViDEPI, 2015).

The georeferenced traces of the available seismic lines were uploaded in an ESRI ArcGis software project, and were interpreted to identify georeferenced faults affecting the Quaternary unit.

The mean interval velocity of 1800 m/sec (P-wave) for the drilled Quaternary deposits was used according to BALLY et al. (1986) and MORELLI (2002). XY geographic coordinates and

the depth Z, calculated in metres below sea level from two-way-time data, were obtained for a relevant number of points of the base of the Quaternary unit reflection; therefore, a .shp file containing XYZ values of each point was created in ESRI ArcMap software. To fill the gap of data missing between seismic profiles, the .shp file data were interpolated by “kriging” (a geostatistical “gridding” method), using the default linear variogram and smoothing interpolator (e.g., SARMA, 2009). Thus, an ESRI grid file was created to construct the contour map of the base of the Quaternary unit.

4. RESULTS

According to the 1850 m deep stratigraphic log of the Rosaria Mare 1 well (Fig. 2), the pre-Quaternary bedrock of the investigated area consists, from the bottom, of thick Cenomanian – Lower Senonian limestones, dolostones and marly limestones belonging to the Apulia Platform; they are topped by a thin lithostratigraphic unit represented by Upper Senonian – Oligocene basinal marly limestones, marls and limestones belonging to the Scaglia Fm; Aquitanian – Tortonian marls and limestones, belonging to the Bisciaro Fm, follow toward the top.

The Quaternary unit, dominated by clays and also consisting of sandy gravels, is characterized by continuous reflections generally prograding toward the NE (Fig. 2), namely into the deepest part of the Southern Adriatic Sea basin. The base of this unit exhibits a continuous high amplitude reflection, that has been recognized and traced with gentle dip angles in the whole investigated area (Figs. 2, 3a-d). However, in several seismic profiles, the base of the Quaternary unit is locally deformed by high-angle generally south- and north-dipping faults (dip-angle in the range of 60°–80°, obtained after time-to-depth conversion) having a normal component of movement (Figs. 2, 3a-d).

Tips of these faults are mostly interpreted within the Quaternary unit (left sector of Fig. 2, and Figs. 3a,c). Besides, fault terminations have been locally observed within the bedrock of the Quaternary unit, which is in this case gently folded due to the upward propagation of the underlying blind fault (right sector of Fig. 2, and Figs. 3b,d). Unfortunately, due to the general low resolution of the available unmigrated seismic profiles, it was not always possible to recognize whether the Quaternary unit succession is deformed by faulting also in its uppermost part, though locally it has been clearly observed that some faults deform the whole Quaternary unit (Fig. 3a).

The interpolation of fault data interpreted from available seismic sections allowed us to trace and delineate two main faults about 40 km long in map view (Fig. 4), which have been active during the Quaternary. The fault occupying the northern sector of the study area shows a gentle arcuate shape, with convexity towards the South, and a general W-E strike (Fig. 4). This high-angle, and S-dipping fault (right sector of Fig. 2, and Figs. 3a,b, 4) is the southern boundary fault of the Monte Giove structural high (Fig. 1a), i.e. the northern boundary fault of the Upper Cretaceous Rosaria Mare intra-platform basin (Fig. 1e). Southward, another high-angle fault generally strikes WNW-ESE and dips to the NNE (Fig. 4), as an antithetic to the S-dipping fault (left sector of Fig. 2, and Figs. 3c,d, 4). The vertical offset of the base of the Quaternary unit, estimated as 200 m maximum, is slightly greater along the S-dipping fault (Figs. 2, 3a-d).

As shown by the structure contour map of the base of the Quaternary unit in Figure 4, both faults give rise to a graben-type structure. Within this Quaternary graben-type structure, the high-amplitude reflection at the base of the Quaternary unit reaches a

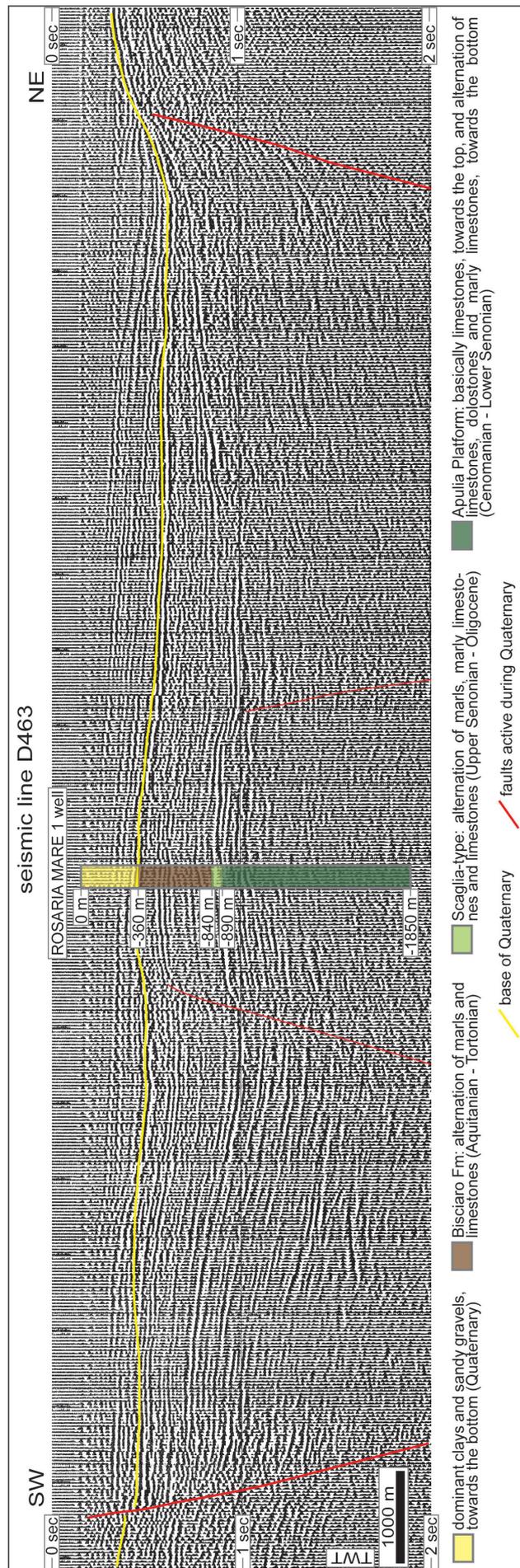


Figure 2. Seismic line D463 with interpretation of the base of Quaternary horizon and Quaternary active faults (see Fig. 1d for the line location).

maximum depth at about 0.8 sec (Two Way Times – TWT), or about 1000 m below sea level. On the graben shoulders, i.e. in the footwall of the two boundary faults, a minimum depth at about 0.3 sec (TWT), namely 200 m below sea level, has been calculated (Fig. 4). In the central part of the graben-type structure, the geometry of the base Quaternary structure contours indicates the presence of a NE-SW striking intra-basin high, culminating at about 450 m below sea level. This high is also bounded by two roughly E-W striking antithetic faults (Fig. 4) both showing a dip-slip displacement component, however, accommodating a minor offset of the base of the Quaternary horizon (central sector of Fig. 2).

5. DISCUSSION

According to the results obtained from the interpretation of seismic profiles used in this study, the S-dipping fault, located at the northern margin of the Rosaria Mare basin, is found as the only one geometrically coherent with the steeply (87°) S-dipping nodal plane in the fault plane solution of the March 23rd 2018 earthquake (Fig. 1d).

The rupture size of the March 23rd 2018 earthquake source cannot be reliably estimated through empirical relationships taking only into account the M_0 of $4.74 \cdot 10^{14}$ N·m of this event. In fact, such relations (e.g., WELLS & COPPERSMITH, 1994; WANG & OU, 1998; STOCK & SMITH, 2000) were calibrated for events with M_0 larger by orders of magnitude than the March 23rd 2018 earthquake, but it can be estimated that, in any case, the rupture of this earthquake source was sub-kilometric.

Although this fault clearly shows a dip-slip component of displacement of the base of the Quaternary stratigraphic horizon (Figs. 2, 3a-d), a combined reverse and dextral movement is indicated by the fault plane solution in Figure 1d. A right transtensional kinematic during the Quaternary, along the S-dipping fault may be invoked, suggested by the coeval prevalently SW-NE to SSW-NNE directed maximum horizontal extension both in the onshore vicinity of the fault (DI BUCCI et al., 2011) and on the regional scale (DI BUCCI et al., 2006; FRACASSI & VALENSISE, 2007). Since a relatively greater dip-slip component of Quaternary displacement can be observed on this S-dipping fault than on the NNE-dipping one (e.g., Figs. 2, 3a-d, 4), the graben-type structure bordered by these two faults (Fig. 4) could also be interpreted as a negative flower structure (Fig. 5), in which, according to the geometric features of flower structures (e.g., HARDING, 1985), the S-dipping fault would play the role of the main fault rooted at depth into a near-vertical fault plane, whereas the NNE-dipping one would be a subsidiary and antithetic fault (Fig. 5).

Regional geological literature revealed that the structural style of the Apulia Foreland and its adjacent foredeep domains is characterized by crustal-scale faults (e.g., DOGLIONI et al., 1994; PIERI et al., 1997; TROPEANO et al., 1997; MERLINI et al., 2000; ARGNANI et al., 2001; FINETTI & DEL BEN, 2005; BUTLER, 2009; SCISCIANI & CALAMITA, 2009; FANTONI & FRANCIOSI, 2010). Therefore, in the block-diagram of Figure 5, a deep geometric reconstruction of the S-dipping fault, as well as the NNE-dipping fault, has been attempted to a depth of 25–30 km, namely the depth of the hypocenter (Fig. 1d). Coherently with the geometry of the S-dipping fault, this reconstruction shows that the hypocenter roughly lies on the fault plane, which makes the association

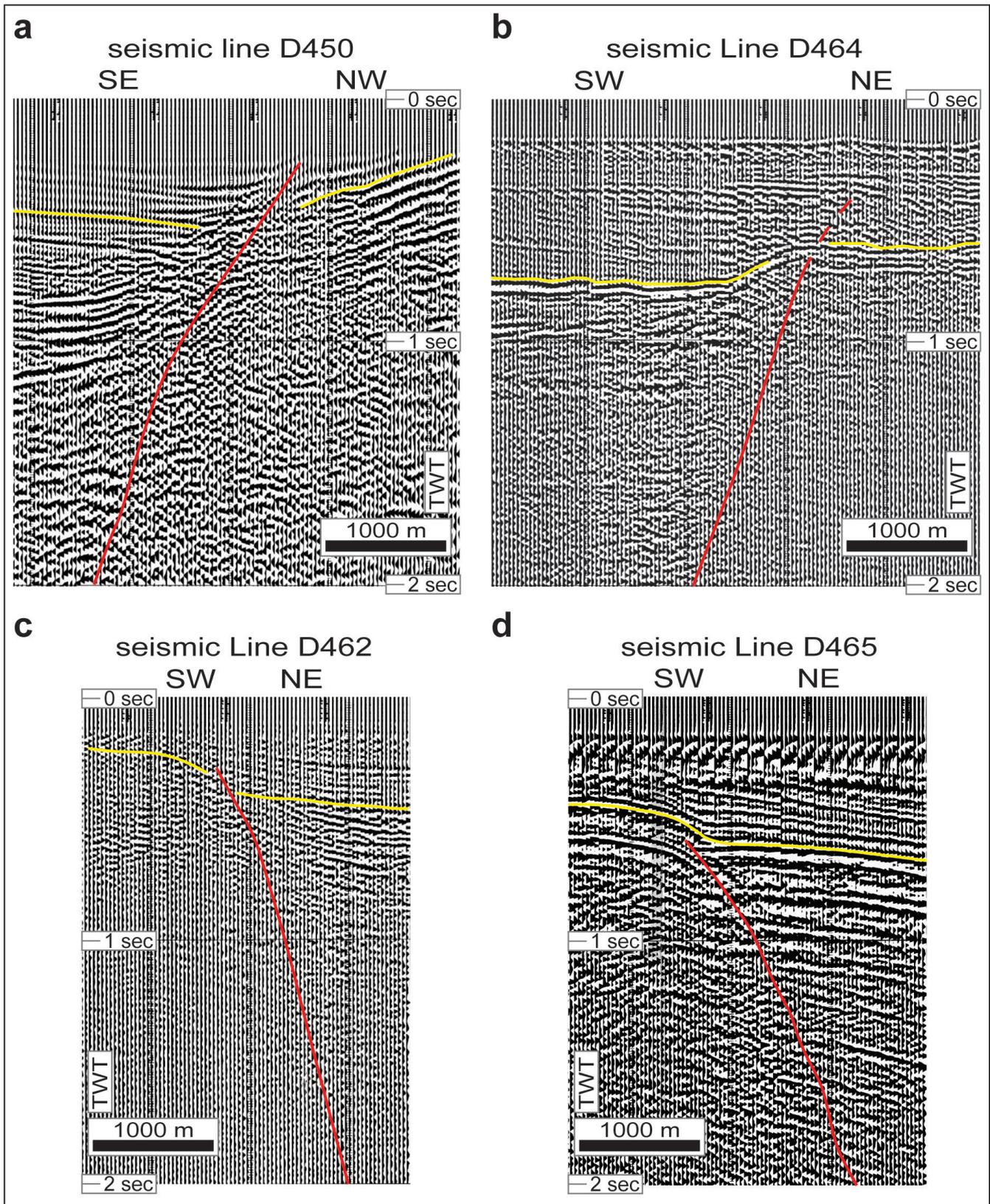


Figure 3. (a) and (b) Interpretation of the base of Quaternary unit, and of the S-dipping Quaternary fault on the seismic lines D450 and D464, respectively (legend as in Fig. 2; see Fig. 1d for their location). (c) and (d) Interpretation of the base of Quaternary unit, and of the NNE-dipping Quaternary fault on the seismic lines D462 and D465, respectively (legend as in Fig. 2; see Fig. 1d for their location).

of the earthquake to the activity of this fault plausible. In this regard, the reactivation at depth of a preexisting W-E striking fault, that geometrically controlled the northern margin of the Upper Cretaceous Rosaria Mare intra-platform basin (NICOLAI &

GAMBINI, 2007; Fig. 1e), and was also active during the Quaternary, can be considered to be in agreement with DI BUCCI et al. (2006). These authors interpreted the E-W striking, right-lateral seismogenic faults in the Apulian Foreland as inherited and

reactivated discontinuities. As a result, the epicenter occurred at a minimum distance of about 15 km South of the trace of the S-dipping fault (Figs. 1d, 4, 5).

The hypocenter depth is comparable to that of both the Moho beneath the Apulian Foreland (25–30 km; DEL GAUDIO et al., 2001; AMATO et al., 2014; de LORENZO et al., 2014) and the seismogenic layer locally identified below the northern Apulian Foreland (about 26 km; CHIARABBA et al., 2005). This indicates, for the study area, a relative high strength for the deeper lower crust, which is thus subject to brittle failure under tectonic stress.

From a palaeo-seismic point of view, seismically-induced deformation structures of soft-sediment have been reported in the youngest deposits cropping out along the Adriatic coastal sectors (Late Pleistocene marine terraced deposits). Liquefaction and/or fluidization effects have been analyzed in the Bari (MORETTI et al., 2002) and Brindisi areas (MORETTI, 2000; Fig. 1a). They involve deposits of back-shore and interdune environments containing sands with a high susceptibility to liquefaction (MORETTI et al., 2016). Despite the limitations of the actual palaeoseismic significance of seismites (MORETTI & van LOON, 2014), these traces of past earthquakes record seismic events with $M > 5$ that occurred within epicentral distances of about 100 km, as shown by empirical relationships for Southern Italy (GALLI, 2000) and in the adjacent Greek seismic zones (PAPADOPOULOS & LEFKOPOULOS, 1993). In other words, the known seismically-induced soft-sediment deformation structures in the Late Pleistocene deposits in the Brindisi and Bari areas, at 45 and 75 km from the epicenter, respectively (Fig. 1a), imply that some faults of the

central Apulian Foreland are able to produce seismic shocks with moderate- to high-magnitude.

Finally, the boulder accumulations that are reported along the coastline in the neighbourhood of the epicenter and which are interpreted as formed by tsunami events (MASTRONUZZI & SANSÒ, 2004; Fig. 1a) may be also the result of seismicity in the Adriatic offshore of the Murge area.

6. CONCLUDING REMARKS

In the epicentral area of the recent March 23rd 2018 earthquake (Mw 3.7) which occurred near Brindisi, in the Adriatic offshore of the southeastern Murge, interpretation of seismic profiles, available in the ViDEPI Project, supports the following conclusions:

- (i) two main high-angle faults, about 40 km in length, and active during the Quaternary, have been recognized on the margins of a graben-like structure, that corresponds with the Upper Cretaceous Rosaria Mare intra-platform basin: the northern one is the E-W to NW-SE striking and S-dipping fault; the southern one is a NW-SE striking and NNE-dipping fault;
- (ii) both faults mostly show dip-slip movement (even though a right transtensional kinematic cannot be excluded), and gave rise to a Quaternary negative flower structure: the S-dipping fault (showing vertical offset of the base of the Quaternary unit up to 200 m) and the NNE-dipping one (showing slightly lower offset) represent the main and the subsidiary faults, respectively;

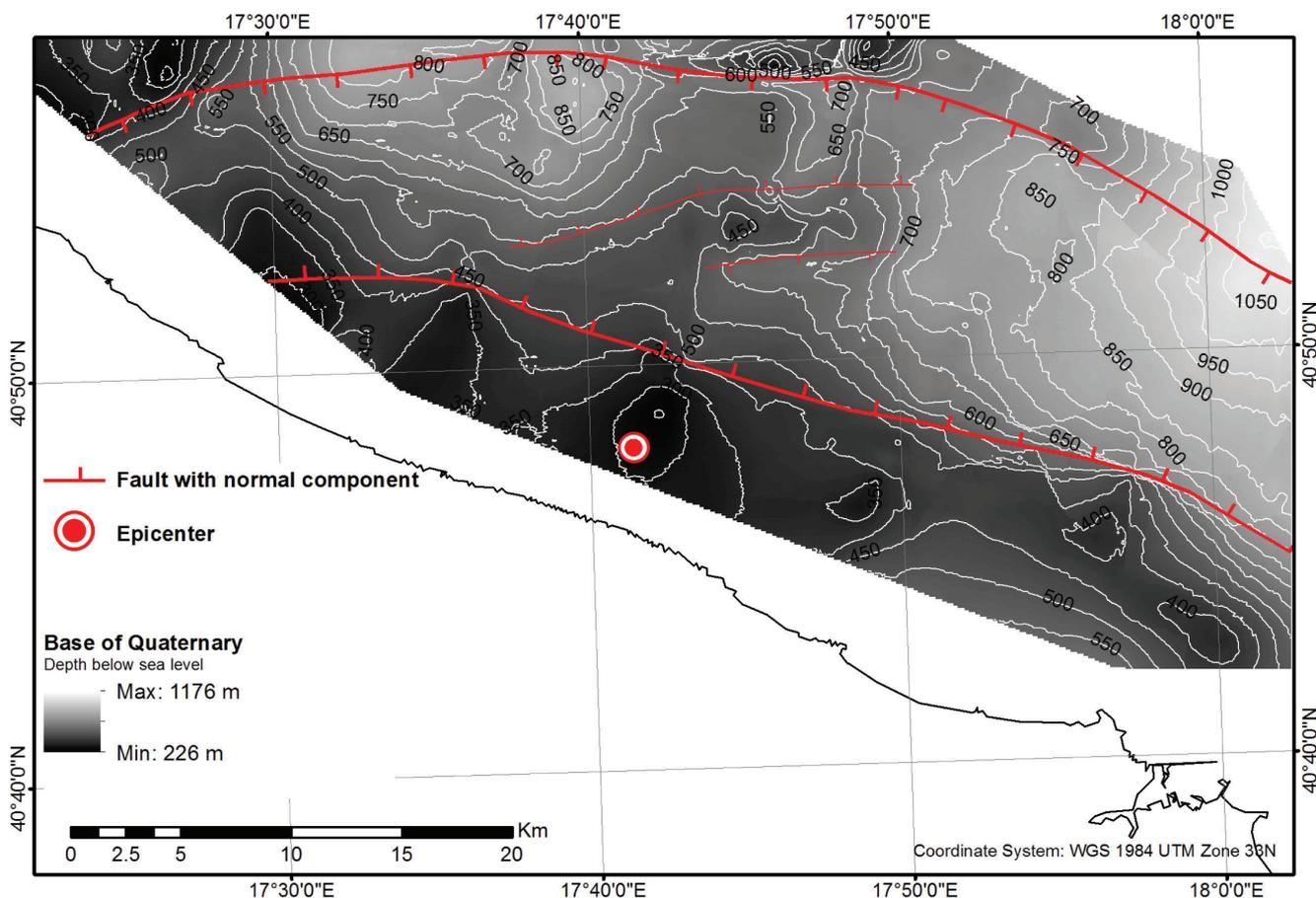


Figure 4. Structure contour map of the base Quaternary horizon of southeast Murge Adriatic offshore area (depth is expressed in metres below the sea level).

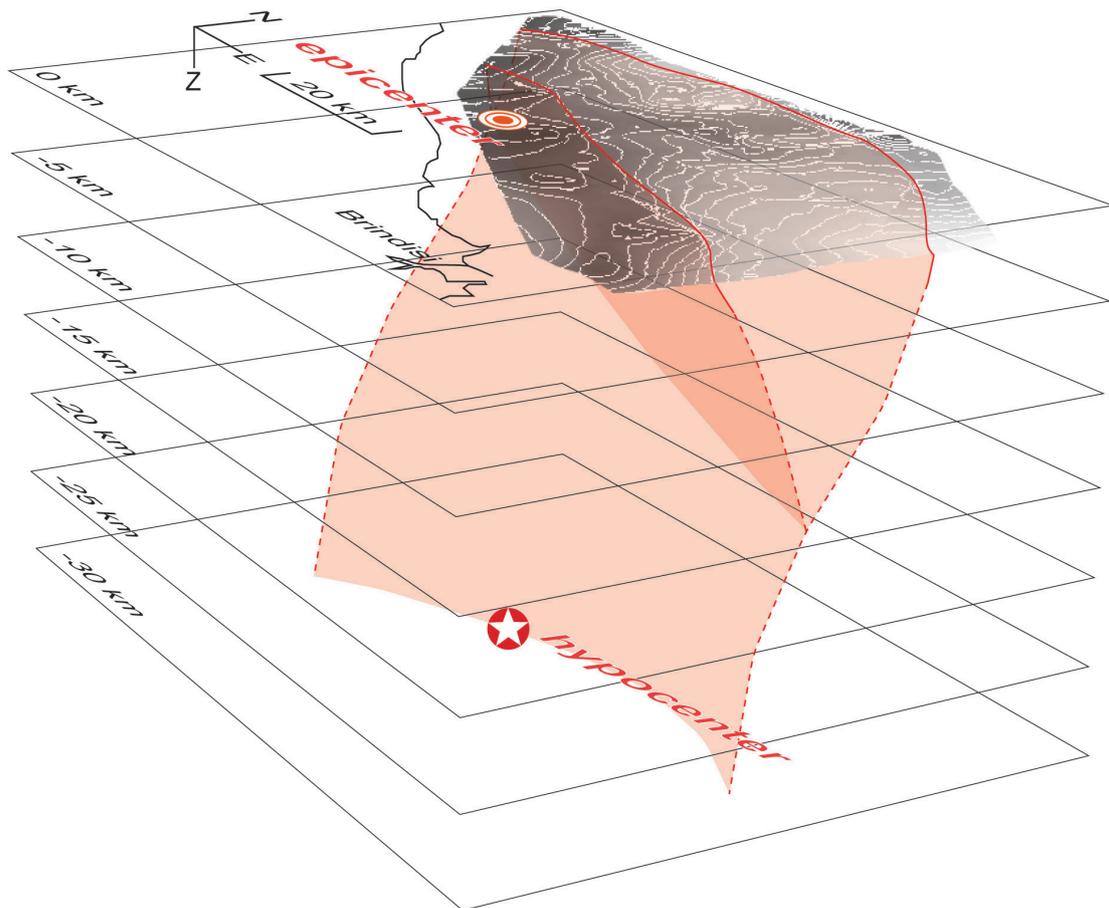


Figure 5. Block-diagram showing the deep geometric reconstruction of the faults detected in the study area (see Fig. 4). The hypocenter of the March 23rd 2018 earthquake is approximately lying on the S-dipping fault plane, making plausible the association of this seismic event to the deepest segment of this fault.

- (iii) the geometric coherence between the plane solution of the earthquake and the S-dipping fault, suggests that this structure, likely inherited from the late Cretaceous and active also during Quaternary, may represent the seismogenic source. The deep geometric reconstruction of the fault shows that the hypocenter, at a depth of 25–30 km, roughly lies on the fault plane, thus determining the epicenter at about 15 km southwards of the surface fault trace;
- (iv) in the central Apulian Foreland, seismites in the Late Pleistocene deposits, and recent large boulder accumulations caused by tsunami(s), may be the result of near field seismic shocks and not only the far field effects of distant seismogenic structures.

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