

Geospatial 3D model of active normal faults offshore the Salento Peninsula (Ionian Sea, Italy): implications for hazard evaluation

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Abstract – The development of dedicated software has opened a new frontier in Earth Sciences, leading to a more accurate spatial analysis of geological structures and to 3D geospatial models. We studied the offshore of the Salento Peninsula (Italy) that is part of the stable Apulian foreland of the Southern Apennines thrust belt. We interpreted a seismic grid, calibrated by borehole data, using seismic stratigraphy and structural geology approaches in a dedicated GIS environment. We built 2-D models of relevant geological surfaces and 3-D digital models of the subsurface showing NW-SE and NNW-SSE normal faults. Some of these structures are active faults displacing the seafloor and are associated with historical and recorded earthquakes. Hence, the identification of these active faults implies a potential seismogenetic source in the Salento Peninsula offshore that should be considered in the earthquake and tsunami hazard evaluation of the coasts of southern Italy, Albania and Greece.

The analysis of the crustal deformation of the offshore of the Salento Peninsula, coupled with its historical and recorded earthquakes provided a means to identify an area of active deformation (normal faulting) of the Apulian foreland. In this study, we construct a detailed geospatial 3-D geological model of the subsurface. The results obtained by integrating multi-source data (seismic reflection profiles, boreholes and seismicity), greatly improved our understanding of the geometry of the active normal faults located off Salento Peninsula that likely represent significant earthquake and tsunami hazards to the coasts of southern Italy, Albania and Greece.

I. INTRODUCTION

Active faulting in submarine environment is a geologic hazard with a causative relation to earthquakes and associated strong ground motion, tectonic deformation, landslides and rockfalls, and tsunamis. The natural hazards that are secondary with respect to earthquakes may considerably increase the damage and the casualties and enhance the risk associated with the seismic impact.

Even if faults are three-dimensional geological structures, yet they are typically represented and interpreted into two dimensions (outcrop geological maps and structure contour maps). Maps associated with serial sections provide a closer approach to three dimensionality. However, computer technology nowadays permits geological interpretation in a three-dimensional environment from the beginning. Fully 3-D geological models allow for significantly more accurate interpretations that can be much easily shared with other geologists and with the public.

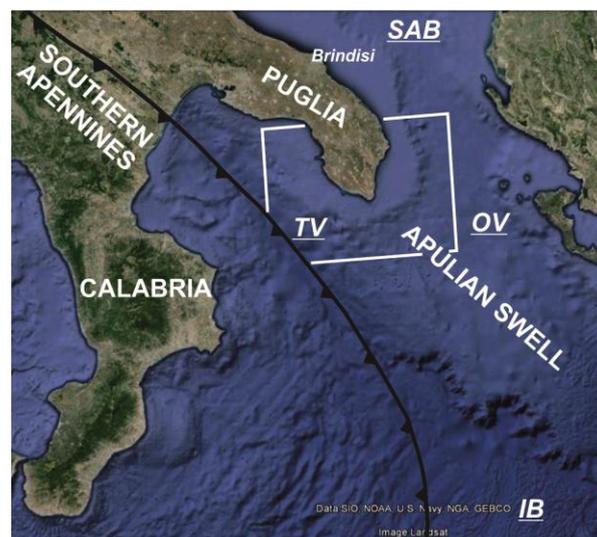


Fig. 1. Index map of Italy and location of the study area (white box). SAB= Southern Adriatic basin, IB= Ionian basin, OV= Otranto Valley, TV= Taranto Valley.

II. GEOLOGICAL SETTING AND SEISMICITY

The Apulia foreland, a part of the Apulian (or Adriatic) plate, is an autochthonous region eastwards of the southern Apennine thrust belt. The Apulia foreland is weakly deformed, and corresponds to a large NW-SE

crustal antiform displaced by normal faults. It consists of an emerged area (Puglia) and a corresponding submerged sector (Apulian swell; sensu [1]) that separates the southern Adriatic Basin at the southern edge of the Otranto channel from the deeper Ionian Sea along the Taranto trench (Fig. 1). The Apulia foreland, drilled by exploratory wells (Fig. 2), shows a rather uniform structure with a Variscan crystalline basement and a 6 km-thick Mesozoic carbonatic cover [2] overlain by thin discontinuous Cenozoic deposits [3]. The Puglia foreland began to uplift since the Middle Pleistocene [3, 4, 5, 6]. It is segmented into three main blocks with different degrees of uplift: from the higher Gargano and Murge to the Salento lowland toward the southeast [3, 7]. NW-SE and NNW-SSE trending normal faults have been reported in the Apulian swell south of Salento [8, 9, 10].

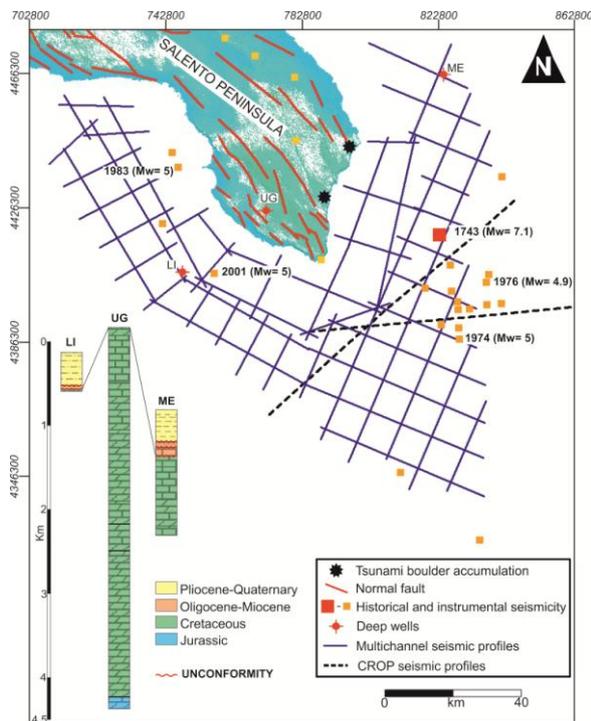


Fig. 2. Index map of seismic grid, stratigraphic successions of onshore and offshore deep wells and historical and instrumental seismicity [11, 12, 13]. UG= Ugento 1 well, LI= Lieta 1 well, ME= Merlo 1 well. Faults are from [14].

Several low-energy and a few high-energy earthquakes have hit the Salento Peninsula over the last centuries. The strongest historical earthquake of the last 1000 years occurred on February 20, 1743 (Ionian Sea, I=IX MCS, $M_w=7.1$; [11]; Fig. 2). It caused the most severe damage in Puglia, killing about 180 people, and was distinctly felt as far as the western coast of Greece, Malta, in Southern Italy and in some localities of Central and Northern Italy. This event, associated to coseismic deformation of the seafloor, triggered a tsunami that accumulated boulders until to 70 tons along the coastline [15, 16, 17, 18]. A historical source from

Brindisi [19] also reported that the sea level withdrew locally.

III. MATERIALS AND METHODS

The Salento Peninsula offshore was investigated using two sets of multi-channel seismic profiles with different resolution and penetration, calibrated by well logs (Fig. 2). The first seismic grid was acquired by the Western Geophysical Company in 1968, following the commitment of Italy's Minister of Industry to carry out a regional survey of the entire Italian continental shelf [20]. Seismic data were acquired using an Aquapulse energy source with a 24-trace, 1600 m-long streamer, a sampling rate of 2 ms, 68 m shot and group interval, 10–80 Hz filter, and a recorded length of 5 s. The processing sequence included deconvolution before stack, normal move out stack 1200%, time variant filter, playback unfiltered. The second seismic data set was obtained within the frame of the CROP Project (joint cooperation between the Italian Research Council, CNR, the national oil company, ENI-Divisione AGIP, and the national electric company, ENEL), an attempt of a comprehensive study of the crustal structure of Italy and surrounding seas. The CROP seismic profiles were acquired and processed in the 1980s and 1990s and an atlas of the seismic profiles was successively published by CNR [21]. The CROP data differ from commercial multichannel profiles, as they are Near Vertical Reflection seismic profiles characterized by deep penetration (17 s, two-way travel-time) and relatively low resolution. Our study uses two CROP offshore seismic sections (M5 and M38) of the Ionian Sea (Fig. 2).

The raster images of seismic profiles were converted into segy format and then imported in a geographic information system (GIS) environment. Line drawing, interpretation of profiles and modeling of geological surfaces were performed using Kingdom® software (copyright HIS Inc.). Gridding and contouring were performed on geologic horizons in order to generate 2-D models and the isochron map of the succession. An iterative testing was adopted to select the best algorithm and processing parameters. Faults were interpreted on seismic reflection profiles (the most important data that provide locations and structures of active faults), mapped in a GIS environment, and displayed as lines on structure contour maps and isochron map. Due to the relatively dense spacing of the 2-D seismic lines, it was possible to recognize and link the major faults based on their geometry, dip direction and amount of offset. The final step was the construction of the 3D digital models using the Vu-PACK module that permits accurate interpretation and the control of opacity, color, and lighting of represented objects (e.g. volumes, horizons and faults). Seismic interpretation was made according to the seismic stratigraphic method where individual seismic units are recognized based on groups of seismic reflections sharing similar characters (e.g. configuration, amplitude, continuity and frequency). Stratigraphic

units were traced based on their boundaries and internal and external configurations [22]. Seismic units were calibrated using the lithostratigraphic data from deep offshore and onshore boreholes [20].

IV. RESULTS

Seismic-stratigraphic interpretation permitted the recognition of an acoustic substrate (AS), marked by reflection-free seismic facies characterized by high-amplitude and good to moderate continuity of reflectors at the top. Unit AS is overlain by an unconformity-bounded unit (PQ) mainly characterized by parallel and/or subparallel reflectors with good to moderate amplitude, variable frequency and good continuity (Fig. 3). The well-defined layering of unit PQ helps the identification of small-scale normal faults. Its upper boundary corresponding to the present-day seafloor of the study area is locally deformed (Fig. 3), thus suggesting recent and active faulting.

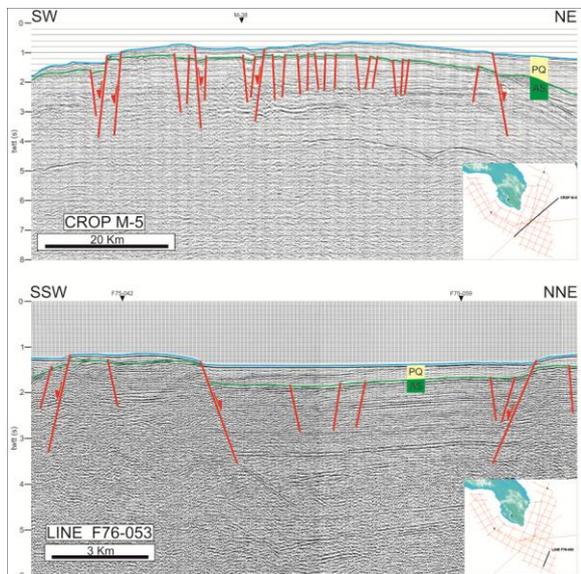


Fig. 3. Interpreted seismic sections showing units PQ and AS displaced by the active extensional structures.

The offshore seismic data set based on the stratigraphic successions of the 590 m-deep Lieta 1 well and 2307 m-deep Merlo 1 well. The Lieta 1 well (Fig. 2) displays a thin Plio-Quaternary succession (400 m-thick) represented by calcareous breccia, marls and clays overlying Cretaceous carbonates. The Merlo 1 well (Fig. 2) is characterized instead, from base to top by: a) Cretaceous carbonates; b) Upper Oligocene calcarenitic deposits; c) Clays and marls with some levels of limestones Tortonian-Messinian in age; d) Plio-Quaternary succession (400 m-thick) made up of clays. Thus, based on subsurface and outcrop data we correlated the acoustic substrate (AS) to the Mesozoic-Early Cenozoic carbonates-Upper Miocene deposits and unit PQ to the Pliocene-Quaternary deposits, respectively.

The structure contour map and the geospatial 3-D

model of the acoustic substrate (Figs. 4, 5) basically show a large, NW-SE trending antiform. The structure is displaced by a series of NW-SE and NNW-SSE up-to 40 km-long normal fault segments characterized by a maximum throw of 0.4 km (assuming a V_p of 2 km/s in the depth conversion of the Pliocene-Pleistocene seismic unit). These offshore structures display the same trend of the Salento Peninsula faults. The acoustic substrate, very shallow near the coast, reaches its maximum depth (>2.6 s, twtt) southwest and northeast of the antiformal hinge (Fig. 4).

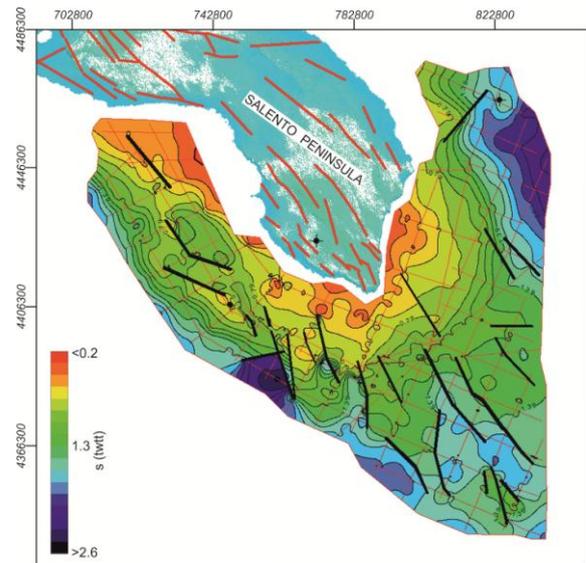


Fig. 4. Structure contour map of the acoustic substrate. Bold black lines = normal faults. Contour interval is 0.15 s. Map coordinate system: UTM, WGS84.

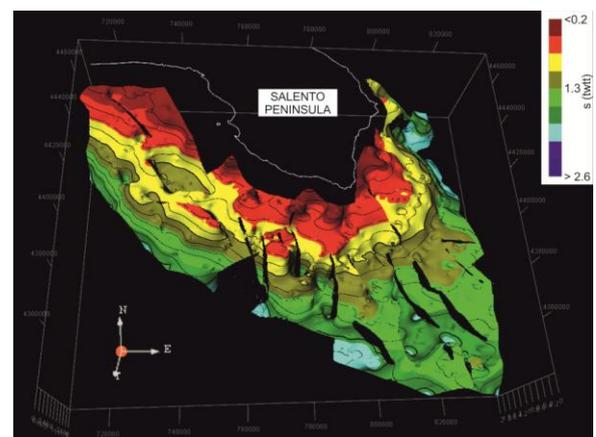


Fig. 5. 3-D digital model inserted into the spatial-oriented grid of the acoustic substrate of the Salento Peninsula offshore; view from south, vertical scale in seconds. Coordinate system: UTM, WGS84.

The structure contour map and the 3-D model of the seafloor display NW-SE and NNW-SSE active normal faults in the outermost offshore of the study area (Figs. 6,7). These faults form up to 300 m-high submarine scarps (CROP M5 profile, Fig. 3).

The Plio-Quaternary sedimentary unit display symmetrical depressions and highs (Figs. 3,8). Its isochron map (Fig. 8) features two main fault-bounded thickness maxima: a southern depocenter, >1.3 s-thick (twtt), located in the southwestern sector of the Salento Peninsula offshore, roughly parallel to the coastline; and a northern depocenter, 1.2 s-thick (twtt), in the area south of Merlo 1 well.

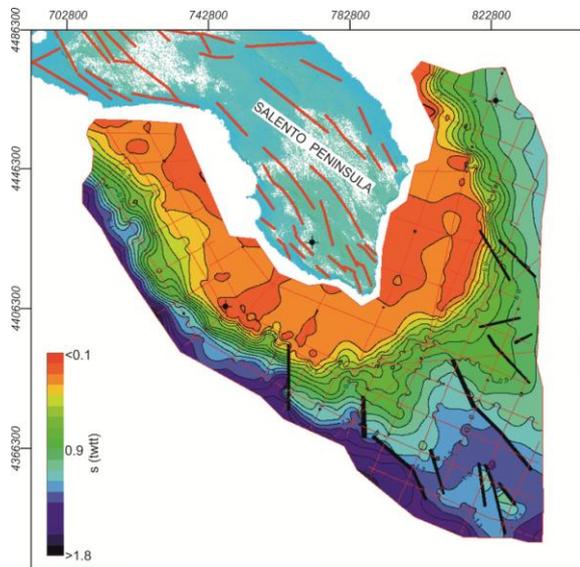


Fig. 6. Structure contour map of the seafloor. Bold black lines = normal faults. Contour interval is 0.10 s. Map coordinate system: UTM, WGS84.

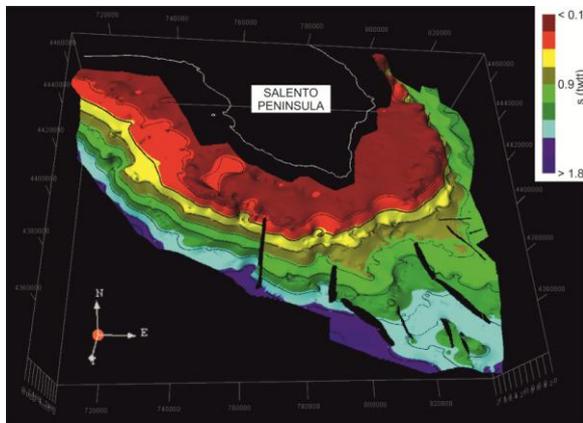


Fig. 7. 3-D digital model inserted into the spatial-oriented grid of the seafloor of the Salento Peninsula offshore; view from south, vertical scale in seconds. Coordinate system: UTM, WGS84.

V. DISCUSSION AND CONCLUSION

The stratigraphic and structural interpretation of a multichannel seismic data set, calibrated by wells, using a GIS dedicated software produced 2-D and 3-D geospatial models of stratigraphic and structural surfaces of the Salento Peninsula offshore.

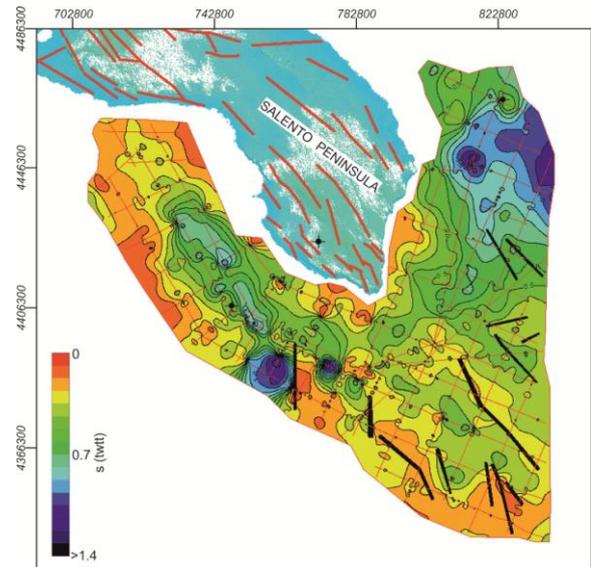


Fig. 8. Isochron map of the Plio-Quaternary sedimentary succession. Bold black lines = active normal faults. Contour interval is 0.10 s. Map coordinate system: UTM, WGS84.

The following multi-stage normal faulting was recognized in the study area: 1) older faults, buried by Pliocene-Quaternary deposits, that displace the acoustic substrate; 2) younger faults that affect the seafloor. The persistent fault pattern trend (NW-SE and NNW-SSE) of both stages likely indicates a constant direction of extension throughout the Pliocene-Quaternary. The areal distribution and timing of these structures suggest a progressive south-eastwards propagation of extension.

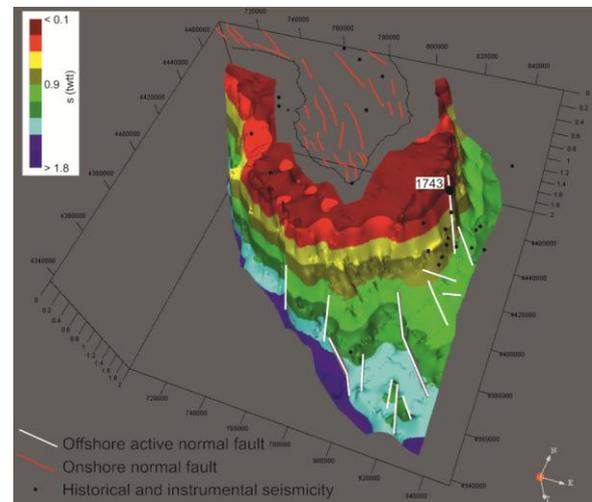


Fig. 9. 3-D digital model of the seafloor of the Salento Peninsula offshore showing the active normal faults and spatial distribution of historical and recorded earthquakes [11, 12, 13]; view from southeast, vertical scale in seconds. Coordinate system: UTM, WGS84.

The link between active faults and earthquakes in the Salento area remains controversial and only a few data on focal mechanism are available. According to [8], the

structures that could be responsible for both the 1743 event and other smaller earthquakes of Salento are several active or recent normal faults that displace the seafloor. On the contrary, [9] interpreted the Apulian foreland as a crustal-scale open antiform due to the orthogonal flexure mechanism associated with the bending of the Adriatic-Apulian lithosphere due to the double load of the Hellenides and Apennines thrust belts. Accordingly [9, 23] suggest that shallower active normal faults record extension of the outer arc as deeper seismicity of the area is linked to inner arc shortening.

In summary, following [8], our hypothesis is that the source of the 1743 earthquake corresponds to an active normal fault that displaced the sea floor of the Apulian swell. This hypothesis is confirmed by the tsunami record of this earthquake [15, 16, 19], implying a significant coseismic deformation of the seafloor, and supported by our identification of a NNW-SSE normal fault near the hypothetical source (Fig. 9).

This study highlights the seismogenetic and tsunamigenic potential of active faults located offshore the Salento Peninsula that should be considered in the hazard evaluation of the coasts of southern Italy, Albania and Greece.

It is noteworthy that previous studies reported only 2-D views (seismic sections and maps) of active faults in the Salento Peninsula offshore. Instead our fully 3-D geospatial model of the Salento Peninsula offshore provides a significantly improved interpretation of these potential seismogenetic sources, much easier to share with other geologists and with the public.

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