Insights on the seismotectonics of the western part of northern Calabria (southern Italy) by integrated geological and geophysical data: Coexistence of shallow extensional and deep strike-slip kinematics

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ABSTRACT

We assess the seismotectonics of the western part of the border area between the Southern Apennines and Calabrian Arc, centered on the Mercure extensional basin, by integrating recent seismicity with a reconstruction of the structural frame from surface to deep crust. The analysis of low-magnitude ($M_\text{L} \leq 3.5$) events occurred in the area during 2013–2017, when evaluated in the context of the structural model, has revealed an unexpected complexity of seismotectonics processes. Hypocentral distribution and kinematics allow separating these events into three groups. Focal mechanisms of the shallower ($< 9$ km) set of events show extensional kinematics. These results are consistent with the last kinematic event recorded on outcropping faults, and with the typical depth and kinematics of normal faulting earthquakes in the axial part of southern Italy. By contrast, intermediate ($\sim 9$–$17$ km) and deep ($\sim 17$–$23$ km) events have fault plane solutions characterized by strike- to reverse-oblique slip, but they differ from each other in the orientation of the principal axes. The intermediate events have P axes with a NE-SW trend, which is at odds with the NW-SE trend recorded by strike-slip earthquakes affecting the Apulia foreland plate in the eastern part of southern Italy. The intermediate events are interpreted to reflect reactivation of faults in the Apulia unit involved in thrust uplift, and appears aligned along an ~WNW-ESE trending deep crustal, possibly lithospheric boundary. Instead, deep events beneath the basin, which have P-axis with a NW-SE trend, hint to the activity of a deep overthrust of the Tyrrhenian back-arc basin crust over the continental crust of the Apulia margin, or alternatively, to a tear fault in the underthrust Apulia plate. Results of this work suggest that extensional faulting, as believed so far, does not solely characterize the seismotectonics of the axial part of the Southern Apennines.

1. Introduction

The Apennines of Italy are characterized by different seismotectonic regimes that affect adjoining regions. For instance, active foreland contraction and hinterland extension tightly juxtaposes in the northern part of the Apennines (Montone et al., 2012). Differently, strike-slip and extensional seismicity are currently found in the eastern and western part, respectively, of southern Italy (Fig. 1a). In this region, the boundary between extension and strike-slip deformation is ill-defined, and broadly runs east of the main mountain belt, where large historical and instrumental extensional earthquakes occur. Strike-slip earthquakes in the east have typically deeper ($\sim 15$–$35$ km depth) focal depths than extensional earthquakes in the west, the latter being located in the upper $\sim 12$–$15$ km of the crust (Boncio et al., 2007).

Until recent years, it was acknowledged that the two deformation regimes in southern Italy are laterally adjacent, but it was unknown whether and to what extent they were intertwined and/or vertically superposed (e.g. Di Bucci et al., 2006; Boncio et al., 2007). Recent works have shown that strike-slip earthquakes occur also in the axial part of the Campania-Molise Apennines (Fig. 1a), rightly beneath the active extensional compartment (e.g. Adinolfi et al., 2015; Vannoli et al., 2016). In a wide sector to the south, the Calabria-Lucania border region (Fig. 1a, b), and specifically in the area centered around the Mercure Basin, only few moderate-sized extensional earthquakes were so far recorded (Fig. 2). Thus, it is believed that the seismotectonics of the Calabria-Lucania border sector is solely characterized by extension (DISS Working Group, 2015, and references therein; Totaro et al., 2015; Brozzetti et al., 2017).

Instrumentally recorded earthquakes in the Mercure Basin area include the September 9, 1998 ($M_\text{W} = 5.5$) Mercure earthquake, and the
2010–2013 Pollino sequence (maximum magnitude $M_L = 5.0$; Totaro et al., 2015). This latter sequence affected the area southeast of the basin (Fig. 2), with extensional earthquakes distributed between 5 and 10 km depth. After the October 25, 2012 $M_L = 5.0$ event (Fig. 2), seismicity in the epicentral area abruptly decreased and the sequence could be considered ended in spring 2013.

In order to assess the seismotectonics of the studied region, we use a combination of geological and geophysical data, both original and published, integrating an analysis of recent seismicity with an assessment of the geological-structural frame of the region from surface to deep crust. Specifically, we analyzed the low-magnitude seismicity recorded by the National Seismic Network of the Istituto Nazionale di Geofisica e Vulcanologia (INGV) during June 2013–March 2017, and following the significant slowdown of the Pollino sequence. Geological data derives from observations on outcropping faults. The new seismological and geological data were integrated with existing subsurface geological and with geophysical data in order to build a crustal model for the seismotectonics of the area.

The analysis presented here evidences different styles of seismic deformation at diverse crustal depths and in spatially conterminous tectonic domains. We document for the first time in the Calabria-Lucania border region the co-existence of normal faulting in the shallow crust, and strike-slip faulting in the intermediate and lower crust. The finding that the two deformation styles interact in this area offers a chance to investigate how different geodynamic processes control the seismotectonics of this sector of southern Italy.

2. Background setting

2.1. Regional tectonic and geodynamic frame

Southern Italy is floored by the Southern Apennines fold-and-thrust belt in the western and central part, by the Apulia foreland in the eastern part, and by the Calabrian Arc in the south (Fig. 1b). The Southern Apennines and Calabrian Arc formed in response to north-west-directed subduction and delamination of the Adriatic-Ionian slab (Fig. 1b), a small continental to oceanic lithospheric fragment trapped within the articulated collision boundary between Africa and Europe (Malinverno and Ryan, 1986; Patacca et al., 1990; Faccenna et al., 2001). In the Apennines, orogenic growth was characterized by Miocene to Pliocene east-to northeast directed imbrication of detached thrust sheets made of Mesozoic and Cenozoic sedimentary rocks over the Apulia part of the Adriatic foreland (Menardi Noguera and Rea, 2000). During the late contractional stage (Late Pliocene to Early Pleistocene), the thick Apulia crust was involved in the thrust system, and duplexes of Apulian rocks were underplated at the base of the orogenic belt (Menardi Noguera and Rea, 2000). Regional appraisal of oil-exploration data has documented that the buried
imbribates of the Apulia platform are bound by high-angle reverse faults with dominant NW-SE strike (Menardi Noguera and Rea, 2000; Shiner et al., 2004; Nicolai and Gambini, 2007).

In the hinterland side of the orogen, contraction was followed by extension, which resulted in stretching of continental crust and local emplacement of oceanic crust beneath the Tyrrhenian back-arc basin (Fig. 1b; Malinverno and Ryan, 1986). Following hinterland stretching and uplift of a Tyrrhenian mantle wedge beneath the southern Italy continental margin (Doglioni et al., 1996), Late Pliocene-Quaternary extensional faults crosscut the thrust structures and formed coastal and intermountain basins west of and along the Apennines axis (Hippolyte et al., 1995). Extension progressed from west to east, and since the Middle Pleistocene, an array of normal faults established along the ~30 km wide axial part of the chain, where it includes major re-recognized seismogenic structures (Fig. 1a). Within the active extensional belt, moderate to large (Mmax ~ 7) earthquakes occur at focal depths of ~10–13 km and exhibit focal mechanisms with primarily normal faulting features and tensile axis roughly orthogonal to the chain (Fig. 1a). Seismological observations are consistent with fault-slip data from Quaternary rocks (Maschio et al., 2005; Papanikolaou and Roberts, 2007; Brozzetti et al., 2009; Faure Walker et al., 2012), and with GPS geodetic velocities (Ferranti et al., 2014a).

In the eastern sector of southern Italy, some of the high-angle faults that cut the Apulian rocks exposed in the foreland or imbricated beneath the Apennines are seismically active with strike-slip kinematics. Focal depths (~15–35 km) are deeper than those that characterize the extensional earthquakes in the west (Pondrelli et al., 2006; Boncio et al., 2007). Seismogenic deformation is expressed by sequences, characterized by a sparse seismicity, by events with moderate magnitude, and by general east-west alignments that outline the subsequence location of broad systems of right-lateral faults (e.g. Ariano Irpino 1962, Potenza 1990–91, and San Giuliano 2002 sequences, Fig. 1a). Unlike the normal faults in the west, the location, geometry and seismic potential of active transcurrent faults in the eastern domain is not well understood, because most of the faults are buried. These faults are thought to be Mesozoic or older extensional structures that controlled the sedimentary evolution of the Apulia platform and were reactivated with reverse or transpressional motion during the Pliocene-Early Pleistocene collision stage (Shiner et al., 2004), and in strike-slip motion since then (Di Bucci et al., 2006).

The two active kinematics domains, extension in the west and strike-slip in the east, are separated by a rather ill-defined boundary that runs just east of the mountain chain, and broadly follow a deep limit between the Tyrrhenian and Adriatic crust (Fig. 1a; Scarascia et al., 1994; Di Stefano et al., 2011). However, a thorough comprehension of the transition between extension and strike-slip is not yet available, and current seismotectonic models hold the two deformation regimes are segregated in spatially distinct domains (Boncio et al., 2007).

An additional limit of regional significance separates the Southern Apennines in the north and the Calabrian Arc in the south. This boundary has an ~WNW-ENE trend and stretches from the Tyrrhenian to the Ionian margin of southern Italy (Fig. 1a). The surface expression of this limit broadly coincides with the Pollino Line, a transcurrent shear zone with associated tensional and compressional features (Ghietsi and Vezzani, 1982; Van Dijk et al., 2000). Investigators proposed a main left-lateral kinematics (Ghietsi and Vezzani, 1982) for the Pollino Line, and some suggested it was reactivated as normal since the Middle Pleistocene, at least in its western sector (Schiattarella, 1998). In the east, the boundary continues offshore the Ionian Sea (Fig. 1a), where recent left-transpressional activity is suggested by marine geophysical studies (Ferranti et al., 2014b). In the west, the boundary encompasses the Mercure Basin area (Fig. 2).

The surface limit spatially overlaps a deep boundary that separates lower crustal and lithospheric domains characterized by low- and high-Vp values in the Southern Apennines and in the Calabrian Arc, respectively (Totaro et al., 2013; Chiarabba et al., 2016). The active role of this boundary is documented by sharp changes in the seismicity...
epicentral distribution, in the style of seismic faulting (Totaro et al., 2013; Presti et al., 2013), and in geodetic velocity epicentral distribution, in the style of seismic faulting (Totaro et al., 2013). The deep discontinuity overlies the northern lateral edge of the Ionian slab subducted underneath the Tyrrhenian Sea, which has been developed through tearing at the expenses of the northern continental margin of the Ionian Mesozoic ocean basin (Fig. 1b; Faccenna et al., 2011). According to many investigators, tearing may have evolved to a STEP (Subduction-Transform Edge Propagator) fault during subduction roll-back which would drive southeast tearing may have evolved to a STEP (Subduction-Transform Edge Propagator) fault during subduction roll-back which would drive southeast
displacement, including co-seismic deformation effects of the 1998 earthquake, on the Serra Sardina fault (SSF), a NNW-striking secondary fault at the northwestern termination of the CaF (Fig. 2a). Papanikolaou and Roberts (2007) argued that a 32 km long fault system, which runs through the central part of the basin, mostly encompassing the traces of the CaF and the RF, has controlled the basin evolution since Late Pliocene. Based on post-glacial fault scarp analysis, they suggested that the CaF slipped during the Holocene. Instead, Brozzetti et al. (2009) proposed that the 18 km long CPST fault focuses current deformation including the 1998 seismic sequence.

The transtensional and extensional faults and associated basin deposits terminate slightly to the northeast of the Mercure Basin and the Pollino Ridge (Fig. 2a). Further to the northeast, where the Quaternary geology is characterized by shallow-marine to continental deposits filling in the S. Arcangelo basin (Fig. 2b), extensional structures are lacking or only locally developed. This latter basin evolved from a proximal foredeep to a piggy-back basin during the last (Late Pliocene-Middle Pleistocene) contractual stage of the Apennine orogeny (Patacca and Scandone, 2007).

Seismicity and GPS velocities document current extension beneath the Mercure Basin. Based on geodetic velocities residuals, Ferranti et al. (2014a) argued that an integrated ~1.5 ± 0.3 mm/yr extension occurs, along an ~NE-SW direction across a modeled ~NNW-ESE striking structure which limits the basin to the north and mostly encompasses currently recognized faults (Fig. 2a).

Only moderate earthquakes have struck the Mercure Basin and surroundings in historical time (Fig. 2a and Table 1; Rovida et al., 2016; Tertulliani anducci, 2014). On September 9, 1998, a MW = 5.6 earthquake started a 14 month long sequence in the Mercure Basin (Guerra et al., 2005). Estimates of the mainshock depth vary greatly from 10 km (Brozzetti et al., 2009), to 14–16 km (Guerra et al., 2005; Arrigo et al., 2006), and to 20–25 km (Galli et al., 2001). According to Arrigo et al. (2006) and the CMT catalogue (http://www.globalcmt.org/), the mainshock focal mechanism had an extensional kinematics with NW-SE striking nodal planes. Differently, Gervasi and Moretti (1999) proposed a strike-slip solution with NNW- SSE and ENE-WSW striking planes (Fig. 2a). Brozzetti et al. (2009) proposed a normal faulting event, with a rupture nucleated on the NW portion of the CPST fault at 8–10 km depth that propagated upward to 4 km depth. A small percentage of aftershocks (10%) were by them located at depths between 10 and 12 km, where the CPST seismogenic fault was supposed to detach at the brittle-ductile transition. Conversely, based on macroseismic data, Galli et al. (2001) proposed that a regional, E-W trending seismogenic zone with a left-lateral kinematics, stretching from the Tyrrhenian margin to the eastern side of the Mercure Basin, was the source of the 1998 and other historical (1708, 1894)

### Table 1

Historical earthquakes with magnitude > 4.0 in the Mercure Basin region. (Derived from the CPTI15 database; Rovida et al., 2016).

<table>
<thead>
<tr>
<th>N</th>
<th>Data</th>
<th>HIL.MM.SS (UTC)</th>
<th>Epicentral area</th>
<th>LAT N</th>
<th>LON E</th>
<th>Depth</th>
<th>I0</th>
<th>MW</th>
<th>Me</th>
</tr>
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<tr>
<td>1</td>
<td>1559/04/27</td>
<td>12</td>
<td>Pollino</td>
<td>39.844</td>
<td>16.136</td>
<td>–</td>
<td>6-7</td>
<td>4.9</td>
<td>4.9</td>
</tr>
<tr>
<td>2</td>
<td>1693/01/08</td>
<td>Pollino</td>
<td>39.973</td>
<td>16.105</td>
<td>–</td>
<td>8</td>
<td>5.6</td>
<td>5.6</td>
<td></td>
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<tr>
<td>3</td>
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<td>Pollino</td>
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<td>App. Lucano</td>
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<td>15.786</td>
<td>–</td>
<td>8</td>
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<td>4</td>
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<td>8</td>
<td>5.9</td>
<td>5.9</td>
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<td>Pollino</td>
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<td>–</td>
<td>7</td>
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<td>5.0</td>
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<td>6</td>
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<td>19.29,58,00</td>
<td>Basilicata mer.</td>
<td>40.086</td>
<td>15.871</td>
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<td>5</td>
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<td>7</td>
<td>1968/03/22</td>
<td>12.03,90,00</td>
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<td>40.019</td>
<td>16.053</td>
<td>–</td>
<td>5-6</td>
<td>4.7</td>
<td>4.6</td>
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<tr>
<td>8</td>
<td>1980/03/09</td>
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<td>Pollino</td>
<td>40.011</td>
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<td>7</td>
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<td>11.28,00,34</td>
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<td>6-7</td>
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<td>10</td>
<td>1998/11/08</td>
<td>22.33,41,99</td>
<td>App. Lucano</td>
<td>40.049</td>
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<td>5-6</td>
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<td>11</td>
<td>1999/04/11</td>
<td>09.49,22,75</td>
<td>App. Lucano</td>
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<td>23.05,24,73</td>
<td>Pollino</td>
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<td>16.015</td>
<td>9.7</td>
<td>6</td>
<td>5.3</td>
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</table>

I0 = Epicentral intensity; Me = Moment magnitude: instrumental determination; MW = Moment magnitude: macroseismic determination.
During 2010–2013, the area immediately southeast of the Mercure Basin has experienced a seismic crisis (known as the Pollino seismic sequence) involving > 5000 earthquakes of $M_L \leq 5.0$ distributed between 5 and 10 km depth (Totaro et al., 2013, 2015). The strongest earthquake in the sequence occurred on 25 October 2012 and had a local magnitude $M_L = 5.0$. A $M_L = 4.3$ earthquake that occurred on 28 May 2012 ~ 5 km east of the $M_L = 5.0$ event (Fig. 2a) preceded this event. The more energetic events had extensional kinematics and NNW-SSE striking nodal planes. The events distributed into two main clusters, western and eastern (Fig. 2a). Seismic activity started in the western cluster, but afterwards it activated both clusters together (Totaro et al., 2015). Totaro et al. (2015) proposed that the western cluster was generated by ~10 km long, NNW-SSE striking, WSW dipping normal faults located southeast of the basin (MF1 and MF2, Fig. 2a). They further suggested that these faults root beneath 10 km depth into shallow-dipping detachments inherited from the pre-existing Apennine thrust tectonics. Brozzetti et al. (2017) extended the analysis to year 2014 and identified the sources of the western and eastern clusters with faults coinciding with MF1 and MF2, and with additional faults to the east, respectively.

3. Methods

In this study, we use a combination of geological-structural, seismicity and geophysical data. We first assessed the geometry and kinematics of the major exposed extensional faults (CaF, MSF, CPST, Figs. 3, 4). These faults were characterized in terms of their slip history, integrating original and published (Brozzetti et al., 2009) data. We collected fault-slip data along the main fault surfaces or on footwall synthetic and antithetic faults in close proximity of the main fault. Care was exercised in detecting consistent superposition relations between different striation sets on fault surfaces, which could reveal the existence of temporally discrete episodes of deformation under different displacement fields. For each lineation set, we made a statistical analysis of the fault-slip data on individual faults by means of the inversion technique of Marrett and Allmendinger (1990) in order to compute the orientation of kinematic axes and determine the tectonic regime.

To assess the latest background seismicity of the Mercure Basin and surroundings, we analyzed the seismicity during June 2013–March 2017, immediately following the significant slowdown of the Pollino sequence. We utilized data recorded by the seismic stations belonging to the Italian National Seismic Network of the INGV (Fig. 5). Following the beginning of the Pollino sequence, the permanent seismic network existing in the area was implemented with temporary stations installed by the University of Calabria (since October 2010) and INGV (since November 2011; Margheriti et al., 2013). Thanks to the network densification, resulting in a better azimuthal coverage of seismic stations in the area, we were able to locate also very low magnitude seismic events.

The waveforms of the events occurred in the area between Latitude 39.300–40.140 and Longitude 15.800–16.200 were collected to perform a manual re-picking of P- and S-phases. To estimate the reliability of earthquake location we performed several trials taking into consideration the number of P and S pickings, the azimuthal coverage of the seismic stations in and around the study area and the velocity model adopted. The dependence of earthquake location from the velocity model was estimated through location trials on events with variable number of recordings, utilizing both the recent P-wave velocity model along the main fault surfaces or on footwall synthetic and antithetic faults in close proximity of the main fault.
Fig. 4. Outcrop view of the major transtensional and normal faults in the Mercure Basin. a) the Castelluccio fault just north of Castelluccio Inferiore village (site a, Fig. 3), showing well-developed oblique tectogrooves (arrows pointing to hanging-wall block) documenting D1 transtension. b) synthetic minor fault associated to the tip of the Madonna del Soccorso fault (site c, Fig. 3), and displacing with left-oblique sense (arrows parallel to pencil pointing to hanging-wall block) the (Lower?) Pleistocene coarse Castelluccio fanglomerate during D1. c) two sets of striations incised on the Castelluccio fault (site a, Fig. 3), with the dip-slip (D2) superposed onto the oblique-slip (D1) lineations (arrows pointing to hanging-wall block). d) the Mt. Misciarolara normal fault cutting through Upper Pliocene?-Lower Pleistocene slope breccias on the footwall block of the Mercure Basin during D0; arrows pointing to hanging-wall block.

Fig. 5. Map of the Mercure Basin and surroundings showing the June 2013–March 2017 seismicity. Epicenters are coloured according to hypocentral depth and scaled according to magnitude. The dotted ellipse surrounds the August 2013 swarm. Triangles are seismic stations (T-numbered labels are temporary stations). AA’ and BB’ are traces of seismicity section distribution (Fig. 6) and of the crustal sections (Figs. 10, 11).
of the crust and upper lithosphere for the Calabrian Arc region proposed by Orecchio et al. (2011), and the local velocity model realized to locate seismic events occurred in the same area of the present study by Guerra et al. (2005). The results obtained using the Guerra et al. (2005) velocity model show the highest stability of earthquake location parameters because it minimizes both the residuals and the relative errors, particularly for the depth of the events. Therefore, we adopted it for this study (Table 2).

Based on results of the trials, for location purposes we selected events recorded by a minimum of five stations and with at least five P- and four S-phase readings. The selected seismic events have been located by means of the HYPOELLIPSE algorithm (Lahr, 1999) with a Vp/Vs ratio, obtained by trial-and-error procedure, resulting in a value of 1.78. Scarcely 80% of the relocated earthquakes are of quality A and about 10% are of quality B. This means that horizontal and vertical 68% confidence interval is < 1.34 km for quality A and < 2.67 km for quality B. Earthquakes with quality C and D, about 10%, have not been considered for this study.

Re-picking the seismic events led to obtain a P-wave polarity dataset that we used to compute focal mechanisms by means of the standard FPFIT grid-search algorithm (Reasenberg and Oppenheimer, 1985). The number of polarity data used (>10) and the good azimuthal coverage of the seismic stations at short epicentral distance (< 70 km) led to stable solutions, with average errors on the maximum likelihood solutions < 15° for strike, dip and rake.

Finally, in order to disentangle the various structures responsible for the observed seismicity, we constructed a crustal model beneath the Mercure Basin area using a blend of geological and seismological data. Specifically, we employed field observations and published oil exploration data (Nicolai and Gambini, 2007), which provide a re-construction of the top of the Apulia platform, to model the thickness of the shallower structural units and the position and geometry of tectonic horizons down to ~6 km depth. Deeper horizons were traced from exploration data (Nicolai and Gambini, 2007), which provide a re-construction of the top of the Apulia platform, to model the thickness of the shallower structural units and the position and geometry of tectonic horizons down to ~6 km depth. Deeper horizons were traced from extrapolation of regional stratigraphy and structural data calibrated against Deep Seismic Soundings (DSS) and magnetic data, and rheological modeling (Speranza and Chiappini, 2002; Boncio et al., 2007).

<table>
<thead>
<tr>
<th>Vp (km/s)</th>
<th>Depth (km)</th>
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</table>

4. Results

4.1. Fault-kinematic analysis

We observed superposition of two sets of slip lineations (D1 and D2) on the major fault surfaces (striae superposition stereonet, Fig. 3). An additional set of slip lineation was observed on some minor faults north of the basin, and, although its chronological relation with the other two sets has not been established, it is thought to be older (D0).

The D1 slip lineations (Fig. 3) have a moderate (~45° to SE) rake angle and indicate left-translational motion on the NW- to WNW striking faults. This slip-lineation set has been observed on both the CaF and on the MSF where these faults cut the Mesozoic limestone bedrock (Fig. 4a) and locally Pleistocene conglomerates (Fig. 4b). This lineation inversion on aggregated data from both faults (sites a to c, Fig. 3) allowed computing an ~N-S trending tensile axes for this slip episode (D1 stereonet, Fig. 3; Table 3). It is important to note that slip indicators (tectogrooves, rock striations) related to this deformation event have a well-developed morphology and decorate exposed fault surfaces for up to tens of meters and with cm- to dm-scale wavelength (Fig. 4a).

Conversely, kinematic indicators referred to a superposed slip event D2 have a minor morphological appearance and were not capable to erase the trace of the earlier slip event Fig. 4c). The D2 slip lineations were observed at the base of the CaF fault scarp and have shorter wavelength than those of D1. These second lineations are almost dip-slip (~85° to SE; Fig. 4c), and their inversion yields a ~NE-SW trending tensile axis (D2 stereonet, Fig. 3; Table 3).

The above observations indicate that the left-translational slip has left the major imprint on the fault slip history in terms of displacement magnitude, whereas the normal slip has contributed less to fault displacement. These results are consistent with previous models of basin formation (Schiattarella et al., 1994), and with published fault-slip analysis (Brozzetti et al., 2009), although the latter authors did not single out a relative chronology of slip. Conversely, results presented here are not consistent with the work of Marra (1998), who proposed only a trans-tensional motion on the Mercure Basin faults. Although we documented that these faults have accommodated a major trans-tension displacement, on the CaF it was clearly superposed by a dip-slip motion.

We did not carry observations on the CPST fault. Brozzetti et al. (2009) found that this fault has a subdue morphostructural expression and is only characterized by the dip-slip that we relate to a second kinematic regime (Fig. 3). On this basis, they argued that the CPST fault is a young, active structure when compared to the CaF and MSF.

An additional slip episode, characterized by ~E-W extensional displacement (D0 in Fig. 3) has been observed on minor (1 km scale length), N- to NNE-striking faults in the footwall of the main basin faults (stations d and e in Fig. 3); a similar trend of the slip vector is reported on the Serra Sardina fault (Brozzetti et al., 2009). This deformation event is recorded on an inverted thrust fault carrying deep basinal rocks onto carbonate platform rocks (site d, Fig. 3), and on newly formed faults that cut Lower Pleistocene alluvial conglomerate and slope breccias (Fig. 4d) correlative of the Castelluccio conglomerate. The chronological relation of this extension with the previously described deformations has not been established, but geological and geomorphological criteria suggest it is older. Faults active during D0 are located in the up-thrown block flanking the Mercure Basin to the north and are not related to the topography created by slip on the NW-SE trending master basin faults during D1 and D2. These observations indicate that the ~N-S striking faults were active during a previous slip episode. These faults were studied by Mazzoli et al. (2014), who attributed them a Late Pliocene-Early Pleistocene age, and proposed they formed during extensional collapse of the uppermost thrust sheets triggered by thrust uplift of Apulian rocks at depth. Conversely, based on the control on basin evolution (e.g. Schiattarella et al., 1994;
slip events D1 and D2 can be aged to the late Early Pleistocene and late Middle Pleistocene-Holocene, respectively.

4.2. Seismicity distribution

The epicentral distribution of ~330 best-located events, with 1.0 ≤ ML ≤ 3.0, roughly aligns along the NW-SE direction, i.e. the axis of the Apennine chain. A concentration of events that occurred prevalently in the period 2014–2015 is found southeast of the Mercure Basin and spatially overlaps with the epicentral area of the Pollino sequence (Figs. 2a, 5). Almost all relocated events are single events except about 10 of them, with similar hypocenter coordinates, that occurred in 2 h on August 28, 2013, whose epicenters lie just to the west of the basin (Fig. 5).

The hypocenters distribution show that about 80% of the events are confined between ~5–9 km depth, whereas the remaining ones are distributed at two depth intervals, namely between 9–17 km and 17–23 km, respectively (Fig. 6). In the following, we will refer to these three groups of earthquakes as shallow, intermediate and deep events. The events occurred on August 28, 2013 are located in the deeper group, and are characterized by two events with ML ~ 2.4 (Fig. 6). Conversely, the magnitude of the remaining deep and intermediate events is around 1.5.

4.3. Kinematic characterization of the shallow seismic events

Almost all the fault plane solutions of the shallow events (depth between 5 and 11 km) show extensional or transtensional focal mechanisms (Fig. 7; Appendices A1 to A3) with the trend of the T-axes ranging from ENE-WSW in the east to NW-SE in the west (Fig. 9).

A first subsection of those shallow focal mechanisms, which has ~NNW-SSE trend of nodal planes and ~ENE-WSW trend of tensile axis, is found southeast of the Mercure Basin (Figs. 7, 9a). They include the most energetic (ML = 3.3) event of the period (event B7, Appendix A2). This group of events spatially coincides with, and has an extensional kinematic comparable to, the focal mechanisms computed for the 2010–2013 Pollino sequence (Totaro et al., 2015). Our results indicate that the Pollino sequence is ongoing, albeit at a very low seismicity rate. These extensional events have hypocenters at 5–6, occasionally 7–8 km depth, and we assign it to the eastern cluster defined by Totaro et al. (2015). An upward linear projection of the preferred nodal plane of the most energetic events of this group fall close to the southeastern segment of the CPST, Gallizzi and Viggianello-Piano di Pollino faults (Fig. 9a). The NE-SW to ENE-WSW trend of tensile axes is consistent with the extension recorded on these faults (Fig. 9).

Geodetic observations (Fig. 2a) are consistent with seismicity results. A small E-W divergence (< 1 mm/yr) is recorded between ACRI and TIMP GPS site velocities during 2000–2010 (Ferranti et al., 2014a). A more significant ~NE-SW divergence (at ~1.5 mm/yr) is documented between TIMP and CUCC GPS site velocities, which spans the 2006–2011 time interval (Palano et al., 2011; Ferranti et al., 2014a).

Within and northwest of the Mercure Basin, upper crustal seismicity shows a more complex kinematics. A significant number of isolated or locally grouped epicenters are found in the southern part of the Mercure Basin and spatially overlap with the northern part of the western cluster of the 2010–2013 Pollino sequence (Figs. 2a, 5). Inspection of focal mechanisms in this area reveals that only a couple of them (e.g. A1, C8; Fig. 7) have a kinematic consistent with the earthquakes of the Pollino seismic sequence, characterized by almost pure extension on NNW-SSE trending nodal planes. Instead, most of them have different trend of nodal planes (e.g. A7, which has nodal planes striking ~NE-SW; Fig. 7), or show transcurrent kinematics (e.g. A10). The upward projection of the south- to south-western dipping nodal planes for this group of
events falls very close to the southeastern buried prosecution of the CaF fault (Fig. 9a). However, the tensile axis of these events, that trends ~E-W to ~ESE-WNW, is not comparable to the geological extension axis of event D2 for the CaF (Fig. 3), suggesting the activation of ~NE-striking segments at the lateral termination of main faults (e.g. B15, A7, Fig. 9a).

The three shallow events grouped west of the basin show a strike-slip (events A4, A8) or oblique-extensional (event A3) kinematics, respectively (Fig. 7). The northeast projection of the NNW to NW striking planes fall close to the Serra Sardina Fault (Fig. 9a), whose reactivation during the 1998 earthquake was proposed by Michetti et al. (2000). However, both the strike-slip kinematics and the NW-SE to E-W trend of the tensile axes of these events are not compatible with the most recent geological slip on the Serra Sardina Fault (Figs. 3, 7, 9a). Rather, based also on a slight alignment of epicenters in this sector (Fig. 5), we prefer the northwest projection of the NE-striking nodal planes, which could highlight the activity at 5–6 km depth of a mapped ~NE-SW trending fault zone (Fig. 9a).

4.4. Kinematic characterization of the intermediate and deep seismic events

Intermediate depth (9–17 km) events are confined immediately to the north and northwest of the Mercure Basin (Fig. 5). Three of these events have transcurrent to transpressional kinematics with NE-SW trending P axes (B3, C1, C4, Fig. 8).

The slight ~ESE-WNW alignment of events at 9–17 km between B3 and C1 (Figs. 5, 8) could highlight a similar strike of the rupture planes for B3, C4 and for the slightly deeper (17 km) C1 events located in between them. These events have a P axis with a similar NE-SW trend, and spatially fall within an ~ESE-trending belt of buried faults that displace the top of the Apulia platform north of the Mercure Basin (Fig. 9b). By selecting the ~E-W striking nodal planes for the three events, this fault zone is characterized by left-reverse motion.

Deeper (~20 km) events A5 and A6, which are similarly characterized by a strike-slip kinematics with about E-W and N-S nodal planes (Fig 8), belongs to a little swarm composed of nearly 10 events that occurred in 2 h on August 28, 2013. The swarm epicenters forms a small ~NNE-SSW trending alignment just west of the Mercure Basin, at a marked northward bend of the contour lines of the top of the Apulian platform (Fig. 5). Because of their depth, these faults are located 8–10 km beneath the Apulia sedimentary succession, suggesting that the bend continues in the Apulia middle crust. Remarkably, the P-axes of these events are rotated of ~90° with respect to the P-axes of the ESE-WNW band of intermediate-deep events north of the basin (Fig. 9b).

4.5. Crustal model

We show our crustal model reconstruction for the seismotectonics of the studied region by drawing two structural profiles, which are oriented NW-SE and NE-SW, respectively (Figs. 10, 11; traces in Figs. 2b, 5). Our SW-NE profile is nearly parallel and is located ~40 and ~20 km to the southeast of Boncio et al. (2007) and Speranza and Chiappini (2002) profiles, respectively (Fig. 2b). A qualitative spatial correspondence between those two and our NE-SW profile was achieved by broadly matching the position of the Apulia antiform involved in thrusting beneath the Apennines. By doing this, we were able to import relevant information from the two profiles into our reconstruction.

The uppermost tectonic horizon in the model is represented by the thrust surface flooring a wedge composed of thin thrust sheets of
Mesozoic-Cenozoic basinal and platform rocks of the Apennines allochthonous belt (Iannace et al., 2007). In this region, the wedge has a limited (up to ~7 km) and uneven thickness, and a relatively low Vp velocity (average 4.5 km/s), indicating it behaves as a ductile layer.

The allochthonous wedge lies above the thicker, relatively less-displaced Apulian thrust-fold belt that formed at the expenses of Mesozoic-Cenozoic platform carbonates correlative of the Apulian foreland rocks (Fig. 1b) and underthrust beneath the Apennines. These
fast (Vp = 6.0 km/s) sedimentary rocks have a stiff behavior when compared to the overlaying wedge, and represent the main brittle layer in the current seismotectonic setting of the Apennines (Bisio et al., 2004; Ferranti et al., 2015).

Oil-exploratory data provide isobaths of the top of the Apulian platform (Nicolai and Gambini, 2007), which are used as control points through which this horizon is interpolated (Figs. 8, 10, 11). Notice that the published map does not provide information to reconstruct the architecture of the Apulian antiformal belt southwest of the Mercure Basin. A prominent culmination (at up to ~1 km b.s.l.) of the Apulian belt is found between the Mercure and S. Arcangelo basins (Fig. 10), and corresponds to a N-S to NW-SE trending central ridge that culminates at ~2 km at Mt. Alpi and at ~0 km beneath Mt. Pollino (Fig. 8). This subsurface central ridge steeply dips to the northeast and to the southwest underneath the S. Arcangelo and Mercure basins, respectively (Fig. 8). The buried structural highs and lows are associated to ~N-S, NW-SE and E-W striking high-angle reverse or transpressive faults (Figs. 8, 10, and 11). The synclinal low north of the antiform hosts the Late Pliocene to Middle Pleistocene sediments filling the S. Arcangelo contractional basin. Instead, the structural low south of the antiform is reworked by transtensional and extensional faults, and hosts the Mercure Basin (Fig. 10).

The thickness of the Apulian platform as recorded by deep wells (Improtta et al., 2000) and by teleseismic receiver function analysis (Amato et al., 2014) in the Apulia foreland is ~7 km on average, and includes Mesozoic-Cenozoic carbonate and Triassic evaporites. We assume a similar thickness underneath the study area, and place the base of the Apulia platform at a depth variable from 8 to 11 km b.s.l.

The subjacent crust is formed by a layer of Permian-Triassic continental to transitional siliciclastic deposits, which were penetrated by the Puglia 1 well in the Apulian foreland for about ~1 km (Improtta et al., 2000). This layer, known as Verrucano s. l., has a thickness range estimated from 0 to 4 km (Amato et al., 2014); we choose a mean 2 km model thickness (Figs. 10, 11). The relatively slower (Vp = 5.0) Verrucano layer is thought to have a ductile behavior (Boncio et al., 2007), and separates the two brittle layers of the Apulian sedimentary succession above from the Paleozoic and older crystalline basement of the Apulian middle crust below, respectively.

The structure of the middle crust underlying the region is reconstructed through DSS data (Scarascia et al., 1994), as well as receiver functions and controlled source seismology analysis (Di Stefano et al., 2011). A doubling of the Apulian middle crust (Vp = 6.3 km/s; Scarascia et al., 1994) underlies the uplifted Apulian antiform beneath the high crest of the Apennines (Fig. 10). Deep seismic sounding data suggest, for the area southwest of the Mercure Basin, a thinned and slower (Vp = 6.0 km/s) middle crust, which rests above a high-velocity (Vp = 6.8 km/s) body interpreted as Tyrrenhian lower crust (Fig. 10). The Tyrrenhian lower crust together with the underlying mantle,
which results from back-arc stretching in the hinterland of the Apennines, is thought to be wedged onto the Apulian crust (Figs. 1b, 10). The position of the overthrust and of the Tyrrenian wedge is not adequately resolved at the scale of the present study, but DSS and receiver function data indicate it underlies the extension domain just west of the Mercure Basin (Fig. 2b). We have positioned the tip of the overriding plate beneath the more easterly-located extensional fault (CPST, Fig. 10). The top of the Tyrrenian crust in the hanging-wall of the deep overthrust lies at depths decreasing from ~20 km to ~15 km moving from east to west (Fig. 10). Forward modeling of regional magnetic anomalies performed by Speranza and Chiappini (2002) along a NE-SW profile striking ~15 km NW of the Mercure Basin (Fig. 2b) places the 600 °C isotherm, which marks a geothermal rise related to the Tyrrenian crust inflow, at a comparable depth range (Fig. 10).

Quaternary normal faults are traced in the profiles across and around the Mercure Basin, as observed in surface exposures, where they have a 65°–70° dip (Fig. 10). These faults cut through the Apennines imbricate wedge (+1 to ~5 km depth) and the Apulia sedimentary crust (~3 to ~10 km depth), where they progressively flatten down-dip (dotted in Figs. 10, 11). These faults detach either along the ductile Verrucano layer, or along east-dipping detachments whose surface breakaway zone is mapped just west of the study area (Brozzetti et al., 2017). The offset caused by the extensional faults does not match the broad bulge of the Apulia unit, supporting the acknowledged contention that the bulge results from earlier shortening (Mazzoli et al., 2014).

5. Discussion

5.1. Seismotectonic interpretation

Intriguing relations between crustal structure and current seismicity in the Mercure Basin region emerge when the seismic events are plotted on the constructed crustal model (Figs. 10, 11). Several seismic events fall in the extensional domain, where they are associated to the 2010–2013 Pollino seismic sequence and its post-2013 continuation. The focal volume containing such seismicity is largely confined within the stiff sedimentary crust of Apulia, with only sparse events falling in the overlying, ductile-behaving Apennines imbricate wedge (Figs. 10, 11).

Extensional focal mechanisms are only located beneath the southeast sector of the Mercure Basin (Fig. 7), and are likely associated to the activity of the deep (5–8 km depth) part of the CPST, GaF and VPP faults (Fig. 9a). As regards the CaF, low-moderate seismicity and related focal mechanisms analyzed here indicate that its deep (5–7 km) part may be currently in transtension, with activity possibly concentrated at the N-S to NE-SW lateral boundary segments (Figs. 5, 7). The extensional and transtensional seismicity, as suggested by focal mechanisms, terminate at ~9 km depth near the base of the Apulia platform where faults possibly detach on the Verrucano layer (Fig. 10). We note, however, that the relocated hypocentral volumes are compatible with an eastward dip of the base of the upper crust seismogenic volume. This occurrence would support the model of northeast-dipping, low-angle detachment faults that limit downwards the shallow extensional seismicity as proposed for the Mercure-Pollino region by Brozzetti et al. (2017). An east-dipping discontinuity representing the basal detachment of the major west-dipping intra-Apennine seismogenic faults has been also been proposed for the hypocentral areas of the L’Aquila 2009 and the Central Italy 2016 seismic sequence (Lavecchia et al., 2017). In the NW-SE profile, shallow seismicity slightly deepens to the northwest following the uneven geometry of the uplifted Apulia platform (Fig. 11). Results shown here confirm previous inferences (Bisio et al., 2004; Ferranti et al., 2015) on the major role played by the brittle Apulia carbonates in the seismotectonic setting of the Apennines upper crust.

Strike- and reverse-oblique slip focal mechanisms are found to the northeast of the basin at a depth range of 9–17 km, and have P axes striking ~NE-SW (Fig. 9b). We suggest these events are related to reactivation of high-angle reverse faults that cut through the Apulia platform and crystalline crust involved in previous thrust uplift. Notably, these events are located in the Apulia antiformal stack in the hanging-wall to the deep overthrust of the Tyrrenian crust (Fig. 10).

Earthquakes are not observed at the 7–17 km depth range southwest of the basin (Figs. 5, 10). This is consistent with results of rheological (Boncio et al., 2007) and magnetic (Speranza and Chiappini, 2002) modeling, supporting the notion that the low-velocity middle crust in this sector is characterized by high heat flow (Della Vedova et al., 2001), likely related to eastward wedging of the Tyrrenian crust, which suppresses brittle fracturing.
Deeper events (17–23 km) are found beneath the extensional domain and are represented by the August 2013 short seismic swarm occurred west of the Mercure Basin (Figs. 5, 8). Focal mechanisms show strike-slip kinematics, but, unlike the strike-reverse slip earthquakes in the Apulia middle crust found to the northeast, their P axes have a NW-SE trend. In our model, these events are located in the Tyrrhenian crust above its overthrust above the Apulian crust (Fig. 10). However, given the uncertainty in the depth position of the reconstructed interface between the Tyrrhenian and the Apulian crusts, and subordinately in the hypocenter location (up to ~1.3 and ~2.7 km for quality A and B events, respectively), we cannot exclude that the deep seismicity studied here falls within the footwall of the overthrust. As argued above, this swarm is nearly parallel and spatially coincides with a bend in the Apulia platform (Fig. 5), which could hint to a control exerted on seismicity by the inherited deformation pattern of the Apulian crust.

The segregation of events within specific depth intervals and laterally adjacent structural domains is not reflected in geodetic data, which only record the surface displacement field. Specifically, the divergence between GPS site velocities reflects the extensional deformation observed in the first ~9 km depth or even shallower. This geodetic divergence may be related to strain accumulation that has only partially released during the 2010–2013 seismic sequence, and during the part of the shallow 2013–2017 seismic activity analyzed here. The detachment of the extensional seismicity on the Verrucano layer or on low-angle faults, and the ductile behavior of the thinned Apulia middle crust conspire to prevent geodetic detection of the deeper strike-slip events at ~9–17 km depth in the SW part of the investigated area.

5.2. Geodynamic implications

At a regional scale, the Apulia middle crust underthrust beneath the Apennines hosts the moderate seismic sequences (Potenza 1990–91, San Giuliano 2002) that have occurred during the last decades in the strike-slip domain that characterizes the eastern part of southern Italy (Fig. 1a). These sequences are characterized by strike-slip events typically recorded at depth > 15 km in the footwall of the orogenic detachment (Boncio et al., 2007). The kinematics and the trend of the principal stress axes (NW-SE and NE-SW directions for the P and T axes, respectively) of focal mechanisms belonging to these sequences agree with the regional stress field, which is driven by the interaction between the Adriatic and European plates (Montone et al., 2012).

In contrast, the kinematics of strike-oblique slip events found in the Apulia crust at 9–17 km depth northeast of the Mercure Basin do not conform to the regional stress field, insofar they are located in the hanging-wall and not in the footwall of the deep overthrust (Fig. 10). However, recent work elsewhere in the Apennines has shown that strike-slip events may also occur in the Apulia hanging-wall involved in thick-skinned thrusting in close proximity of the extensional belt of the high Apennines (e.g. the 1962 Ariano Irpino sequence, Fig. 1a, where the first shock (Mw = 6.1) is placed at 9 km depth; Vannoli et al., 2016). This occurrence could also hold true for some moderate strike-slip earthquakes under the axial and western part of the belt (the 1981 Baiano earthquake, which is placed at ~10 km depth (http://csi.rm.ingv.it/); the 1971 Val d’Agri earthquake; the 2012 Mt. 4.1 Benevento event, Adinolfi et al., 2015; Fig. 1a).

In addition, differently from other strike-slip earthquakes in southern Italy (Fig. 1a), the P-axes of intermediate depth events in our study area have a NE-SW trend (Fig. 9b), which is rotated of ~90° with respect to the regional stress field. These events appear aligned along a ~ESE-WNW deformation zone that characterizes the sector immediately north of the Mercure Basin. We propose that this deformation zone which controls the different kinematic behavior results from a local, strong mechanical heterogeneity ensuing from the Pliocene-Quaternary interaction between the Apennines-Calabrian Arc and underlying Adriatic-Apulian and Ionian crust (Fig. 1b). Specifically, the deformation zone may be part of the regional tectonic boundary that separates the Apennines from the Calabrian Arc (Fig. 1a, b; Totaro et al., 2013; Presti et al., 2013; Ferranti et al., 2014b). Such boundary does not limit the uppermost structural levels, but rather ensues from Late Neogene decoupling of the fast SE-retreating Ionian oceanic slab from the stalling Apulia continental lithosphere (Faccenna et al., 2011). Under the above scenario, the hypothesis that the 1998 earthquake, as suggested by its macroseismic field (Fig. 2b), as well as other historical events, were generated along the same deformation zone (Galli et al., 2001), should be deemed further consideration.

On the other hand, the kinematics that characterizes the > 17 km depth events found in the study area does conform to the regional stress field. In our reconstruction, these events are associated to the inflow of the young Tyrrhenian back-arc crust within the flexed Apulian continental crust (Figs. 10, 11). However, as outlined in the previous section, uncertainty in the crustal model reconstruction allows arguing that the deep earthquakes fall within the Apulian middle crust in the footwall of the overthrust. Under this alternative scenario, the deep strike-slip seismicity could highlight the presence of tear faults within the subducted plate. This fault may represent the deep crustal counterpart of the regional lithospheric boundary that separates the Ionian-Calabrian from the Apennines-Adriatic domains, and that controls the intermediate-depth seismicity (Fig. 1a, b; Totaro et al., 2013; Presti et al., 2013).

This alternative interpretation however faces the difficulty that the shear boundary that has decoupled the Ionian oceanic slab from the Adriatic-Apulian continental crust now lies at very high depths in this sector of the Tyrrhenian Sea margin (Fig. 1b), and its sinking should be accompanied in the shallow crust by extensional and not strike-slip deformation. Possibly, the polylaplace slip history recorded on some of the studied faults (e.g. CaF and MSF) marks stages in the evolution of the deep boundary. The Early Pleistocene transgression recorded on these faults could be related to tearing of the slab, whereas the Middle Pleistocene switch to extension could indicate the STEP-like sinking of the boundary and accompanying inflow of the Tyrrhenian young lithosphere. The deep strike-slip events studied here, which are conceivably located in this latter layer, would thus indicate that Ionian and Adriatic plate kinematics are now decoupled, and that the deep crustal seismicity is controlled by the larger plate interaction.

6. Conclusions

Integration of geological and geophysical data has allowed to characterize the seismotectonic frame of the western part of the Calabria-Lucania border region centered around the Mercure Basin from surface to deep crust. Low-energy seismicity analysis, although limited to a short time period (2013–2017) shows that seismic deformation is complex and a variety of different tectonic processes may be at work in this region. This result is partly surprising because existing seismotectonic models hold that the axial part of the Southern Apennines experiences solely extension, which is released during moderate and large earthquakes. Instead, low-energy events testify that extensional faulting with ENE-WSW tensile axes is segregated in the upper crust (above 9 km depth) and, as published geodetic data show, is detached from laterally and vertically adjacent crustal domains which are characterized by strike-slip earthquakes.

Extensional earthquakes are located in the Apulian platform and probably reactivate existing faults that had an earlier (Early Pleistocene) and more significant history of transtension. Thus, as documented elsewhere in the Apennines, active extension may be a young feature.

Strikingly, extensional seismicity abruptly ends where the normal faulting documented in the geological record terminate at the north-eastern border of the Mercure Basin and is replaced by reverse and transpressional tectonics. In this latter area, intermediate (9–17 km) depth strike-slip and locally reverse-oblique seismicity are observed prevalently in the Apulia middle crust. These earthquakes distribute...
along an ~ESE-WNW trending band and are characterized by NE-SW trending P-axes. Because these observations are at odds with the regional kinematics of strike-slip earthquakes in the eastern part of southern Italy, which have NW-SE trending P-axes (Fig. 1a), we argue that seismicity here is controlled by inherited mechanical anisotropies. These latter are represented by high-angle faults which acted as reverse during the contractual uplift of the Apulian unit beneath the Southern Apennines (Fig. 10). Unlike other strike-slip earthquakes in the eastern part of southern Italy (Fig. 1a), which are located in the Apulian unit underthrusting the Apennines orogen, the intermediate events studied here are found in the Apulia unit involved in contractual uplift. We propose that this departure from the regional pattern is controlled by the local anisotropy represented by an ~ESE-WNW trending deformation belt. This belt could be part of a regional deep crustal to lithospheric boundary stretching from the Tyrrhenian to the Ionian coast and separating the Southern Apennines from the Calabrian Arc.

Deeper (~17–23 km) strike-slip earthquakes are found beneath and west of the extensional domain. These events are conceivably located in the Tyrrhenian lower crust wedged beneath the Apennines and underlying Apulia foreland, or, alternatively, in the latter domain, where they would document tearing of the subducted Ionian-Adriatic plate. The deep strike-slip events conform to the regional kinematics, suggesting that they are controlled by the large-scale plate interaction.

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