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The 2021–2022 Genoa seismic sequences reveal distributed strike-slip deformation in the Alps-Apennines transition zone, NW Italy

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ABSTRACT

The complex tectonic evolution of the Alps-Apennines transition zone in NW Italy is still a matter of debate. In this work, we analyze the 2021–2022 seismic sequences around Genoa to understand how convergence between Africa and Europe is presently accommodated across the Alps-Apennines transition zone. The map-view distribution of HypoDD-relocated seismic events reveals a NE-SW alignment for the Savignone seismic sequence, and NNW-SSE alignments for the Borzonasca and Bargagli sequences. The Borzonasca seismic sequence plots in correspondence of the Villalvernia-Varzi-Ottone Fault, which is often considered as the boundary between the Alps and the Apennines, whereas no seismicity is documented along the Sestri-Voltaggio Fault. The main-shock focal solutions are invariably strike-slip, with near-vertical NNW-SSE and NE-SW to ENE-WSW nodal planes. The evident earthquake alignments in the study area mark active, km-scale fault planes in the upper crust, pointing to a scenario of distributed strike-slip deformation in the transition zone between the Alps and the Apennines. The NE-SW faults are inherited structures that underwent major Neogene rotations and are no longer suitably oriented to accommodate the northward motion of Adria relative to Europe. The Bargagli seismic sequence may reflect the formation of new NNW-SSE strike-slip faults in the upper crust that are more suitably oriented to accommodate the present-day stress field, consistent with the seismotectonic framework outlined by recent works in the nearby regions of the Adria-Europe plate-boundary zone. Our results highlight the important role of strike-slip faulting in the Adria-Europe plate boundary zone not only in the past, but also during its present-day evolution.

1. Introduction

The Alps-Apennines transition zone represents one of the most complex segments of the Cenozoic Adria-Europe plate boundary (Jolivet and Faccenna, 2000; Handy et al., 2010; Malusà et al., 2015). It is located in northwestern Italy, above the opposite-dipping and partly interacting Alpine and Apenninic slabs (e.g., Vignaroli et al., 2008; Zhao et al., 2016; Eva et al., 2020; Paffrath et al., 2021) (Fig. 1). Several studies have long discussed the relationships between the Alps and the Apennines within the framework of Central Mediterranean tectonics (e.g., Alvarez et al., 1974; Dewey et al., 1989; Laubscher et al., 1992; Castellarin, 2001; Rosenbaum and Lister, 2004; Schettino and Turco, 2006; Argnani, 2009; Molli et al., 2010; Carminati and Doglioni, 2012; Malusà et al., 2016a). Great emphasis was generally placed on the location of the Alps-Apennines boundary, which was often envisaged as a discrete fault boundary, either represented by the Sestri-Voltaggio Fault or the Villalvernia-Varzi-Ottone Fault, with contrasting interpretations depending on the different working hypotheses and data sets used (e.g., Elter and Pertusati, 1973; Cortesogno et al., 1979; Cortesogno and Haccard, 1984; Hoogerduijn Strating, 1991; Crispini and Capponi, 2001; Cerrina Feroni et al., 2004; Malusà and Balestrieri, 2012; Schmid et al., 2017). However, the occurrence of monotonous successions of mainly fine-grained turbidites to the east of the Sestri-Voltaggio Fault (Elter and Marroni, 2006; Capponi, 2008) has so far precluded a shared interpretation of the complex tectonic evolution and ongoing tectonic activity of the Alps-Apennines transition zone.

Useful pinpoints for the analysis of complex, partly understood plate-boundary zones are potentially provided by seismotectonics. According to both instrumental and historical seismic catalogues, earthquakes in the area in between the Sestri-Voltaggio Fault and the Villalvernia-Varzi-Ottone Fault are neither frequent nor strong. However, from September to December 2022, the area east of Genoa was shaken by 25

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seismic events of local magnitude M_l ranging from 1.3 to 4. The strongest events of the sequence, referred to as the Bargagli seismic sequence hereafter, were on September 22 ($M_l = 4.0$) and October 5 ($M_l = 3.3$). Both events had hypocentral depth of ~6.7 km. They were felt in a wide area, and some damage was reported after the M_l 4.0 main shock. The Bargagli seismic sequence was preceded by other two sequences: one in the NW near Savignone, recorded from August to October 2021, and another one in the east near Borzonasca, recorded from February to March 2022. After this unexpected seismicity, Solarino and Eva (2023) re-analyzed the historical seismograms stored by the Sismos project (www.sismos.rm.ingv.it) and proposed that at least one other earthquake of comparable magnitude previously occurred near Bargagli in the last century (September 21, 1924).

In this work, we take advantage of the 2021–2022 seismic sequences around Genoa to discuss how convergence between Africa and Europe (Calais et al., 2002; Nocquet, 2012) is presently accommodated across the Alps-Apennines transition zone. Our data set includes all the seismic events recorded between the Sestri-Voltaggio Fault and the Villalvernia-Varzi-Ottone Fault since 1989 and, based on a careful relocation, provides an improved seismotectonic picture that integrates the conceptual seismotectonic model recently proposed by Eva et al. (2020) and shed new light on the tectonic evolution of this complex segment of the Adria-Europe plate-boundary zone.

2. Tectonic setting

The Alps-Apennines transition zone is located above the SE-dipping Alpine slab, in the north, and the SW-dipping Apenninic slab, in the south (Piromallo and Morelli, 2003; Giacomuzzi et al., 2011; Zhao et al., 2016; Malusà et al., 2021) (Fig. 1c). It acquired its complex present-day configuration during Cretaceous-to-Present convergence between Africa and Eurasia (Dewey et al., 1989; Jolivet et al., 2003; Handy et al., 2010). Plate convergence in this region was initially accommodated, since the Late Cretaceous, by Alpine subduction and progressive consumption of the Alpine Tethys and adjoined European paleomargin beneath Adria, a microplate located at the northern tip of Africa (Zhao et al., 2015; Paul et al., 2022). A NW-dipping Apenninic subduction zone started developing along the western boundary of the Adriatic microplate during the Paleogene, and progressively involved the southernmost segments of the Alpine subduction wedge (e.g., Malusà et al., 2015, 2016a). During the Neogene, the onset of Apenninic slab retreat determined the opening of the Ligurian-Provençal and Tyrrhenian basins in the Apenninic backarc

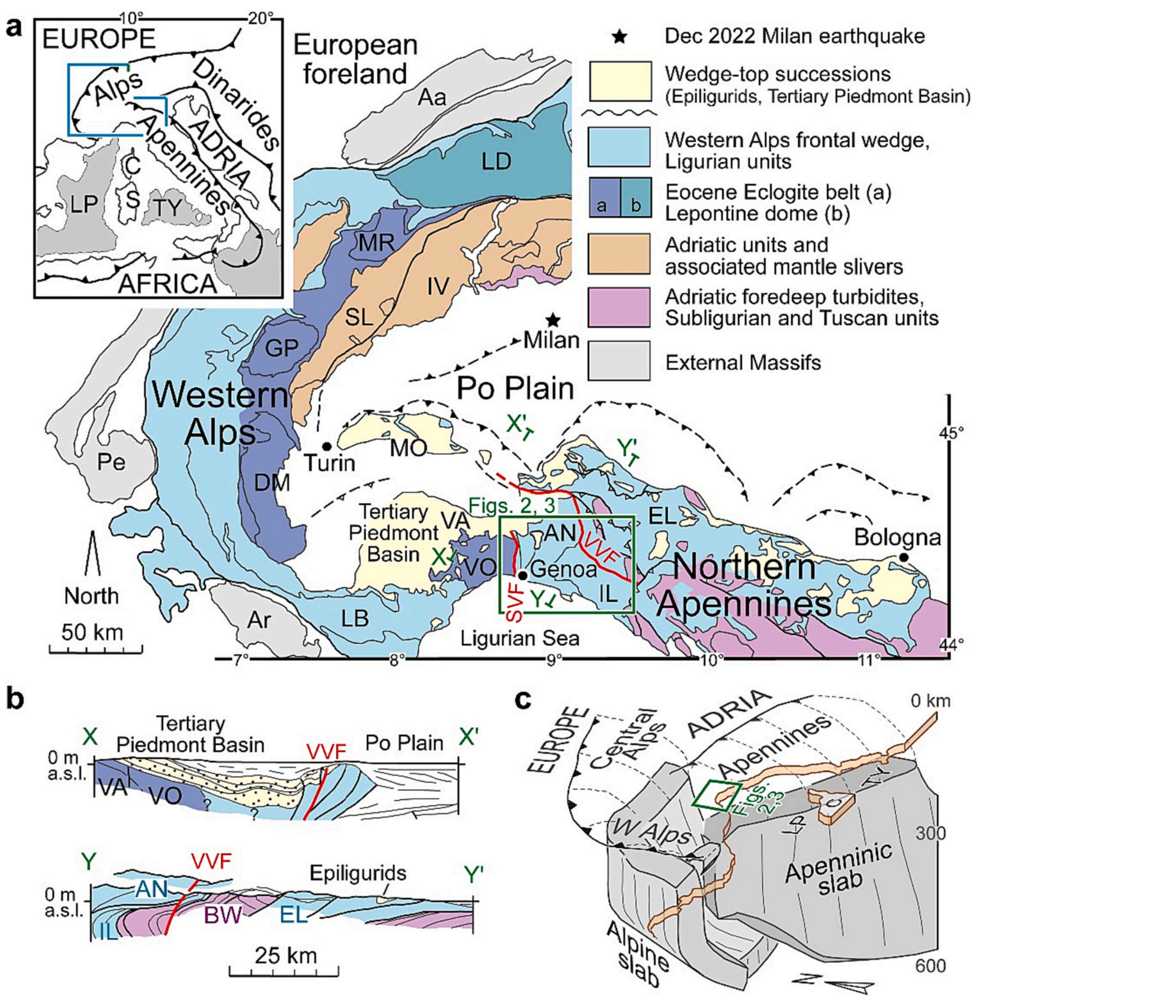

Fig. 1. Tectonic setting. a) Sketch map of the Western Alps and the Northern Apennines within the framework of the Adria-Europe plate boundary zone (inset) (after Malusà et al., 2015). The thick red lines indicate the major tectonic structures classically referred to as the boundary between the Alps and the Apennines (SVF: Sestri-Voltaggio Fault; VVF = Villalvernia-Varzi-Ottone Fault). The green box indicates the area of the Alps-Apennines transition zone analyzed in this study. Black star = location of the December 2022 Milan earthquake (Malusà et al., 2022). b) Representative cross sections (after Malusà and Balestrieri, 2012). c) Slab structure beneath the Alps-Apennines transition zone (after Zhao et al., 2016; Eva et al., 2020). Acronyms: Aa, Aar; AN, Antola; Ar, Argentera; BW, Bobbio tectonic window; C, Corsica; DM, Dora-Maira; EL, External Ligurids; GP, Gran Paradiso; IL, Internal Ligurids; IV, Ivrea-Verbano; LB, Ligurian Briançonnais; LD, Lepontine dome; LP, Ligurian-Provençal basin; MO, Monferrato; MR, Monte Rosa; Pe, Pelvoux; S, Sardinia; SL, Sesia-Lanzo; TY, Tyrrhenian basin; VA, Valosio; VO, Voltri. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and the coeval counterclockwise rotation of Corsica-Sardinia (Gattacceca et al., 2007; Faccenna et al., 2014; Malusà et al., 2016b).

The Alpine subduction wedge includes in the study area two major tectonic domains: an Eocene Eclogite belt (dark blue in Fig. 1a) and a lower-pressure Frontal wedge (light blue in Fig. 1a) (Malusà et al., 2011). The Eocene Eclogite belt consists of eclogitized continental crust units (VA in Fig. 1a,b) overlain by the eclogitic meta-ophiolites of the Voltri Unit (VO in Fig. 1a,b). The Frontal wedge includes low-grade Ligurian units (Cerrina Feroni et al., 2004; Schmid et al., 2017) that were deformed and metamorphosed before the middle Eocene (Ellero et al., 2001; Marroni et al., 2001) and were subsequently unconformably covered by Epiligurian sedimentary successions (Catanzariti et al., 2002). The underlying Subligurian and Tuscan units (purple in Fig. 1a,b) were accreted at a later stage of the orogeny within the framework of Apenninic subduction and coeval northward motion of the retreating Adriatic microplate. They consist of Meso-Cenozoic successions and Oligocene-Miocene turbidites exposed in tectonic windows carved in the Ligurian units (e.g., the Bobbio window, BW in Fig. 1b) (Elter, 1997; Anfinson et al., 2016; Malusà et al., 2016b). In the northern part of the study area, the Alpine subduction wedge is unconformably overlain by north-dipping sedimentary successions of the Oligocene-Miocene Tertiary Piedmont Basin (Pieri and Groppi, 1981; Mutti et al., 1995; Marroni, 2006; Mosca et al., 2010).

The Sestri-Voltaggio and Villalvernia-Varzi-Ottone faults (in red in Fig. 1a,b) are the major tectonic structures classically recognized in the Alps-Apennines transition zone (e.g., Elter and Pertusati, 1973; Laubscher, 1988; Castellarin, 2001; Crispini and Capponi, 2001; Capponi et al., 2007; Molli et al., 2010; Malusà and Balestrieri, 2012). The Sestri-Voltaggio Fault (SVF in Fig. 1a) is located in the western part of the study area in front of the Polcevera Canyon, a major morphologic feature offshore Genoa. It separates the eclogitic metaophiolites of the Voltri Unit from the lower-pressure rocks of the Sestri-Voltaggio Zone, Internal Ligurian units and overlying Antola flysch sequences farther east (IL and AN in Fig. 1) (e.g., Capponi et al., 2016). Based on the metamorphic gap between the tectonic units exposed on either side of the fault, the Sestri-Voltaggio Fault has been sometimes interpreted as the metamorphic boundary between the Alps and the Apennines (Rovereto, 1939; Laubscher, 1988; Castellarin, 2001; Crispini and Capponi, 2001; Pasquale et al., 2001; Capponi et al., 2007; Bosellini, 2017). However, this fault is apparently not associated with major seismicity (Eva et al., 2020) and displaces only to a lesser extent the overlying Oligocene-Miocene strata of the Tertiary Piedmont Basin, which suggests that it has been poorly active after the Eocene (Elter and Pertusati, 1973; Molli et al., 2010).

The Villalvernia-Varzi-Ottone Fault (VVF in Fig. 1) is exposed on the northeastern side of the study area. It is part of a Miocene-Pliocene transpressional system that cuts obliquely across the southern part of the Alpine orogenic wedge (Elter and Pertusati, 1973; Malusà et al., 2015). It shows contrasting features along strike. To the east (cross-section Y-Y′ in Fig. 1), it juxtaposes the Antola and Internal Ligurian units against the External Ligurian units (EL in Fig. 1), cutting across the Subligurian and Tuscan units exposed in the Bobbio tectonic window (BW in Fig. 1). To the west (cross-section X-X’ in Fig. 1), it juxtaposes the north-dipping successions of the Tertiary Piedmont Basin against uplifted External Ligurian Units (Cerrina Feroni et al., 2004; Malusà and Balestrieri, 2012).

Most of the region located between the Sestri-Voltaggio Fault and the Villalvernia-Varzi-Ottone Fault has been recently mapped within the

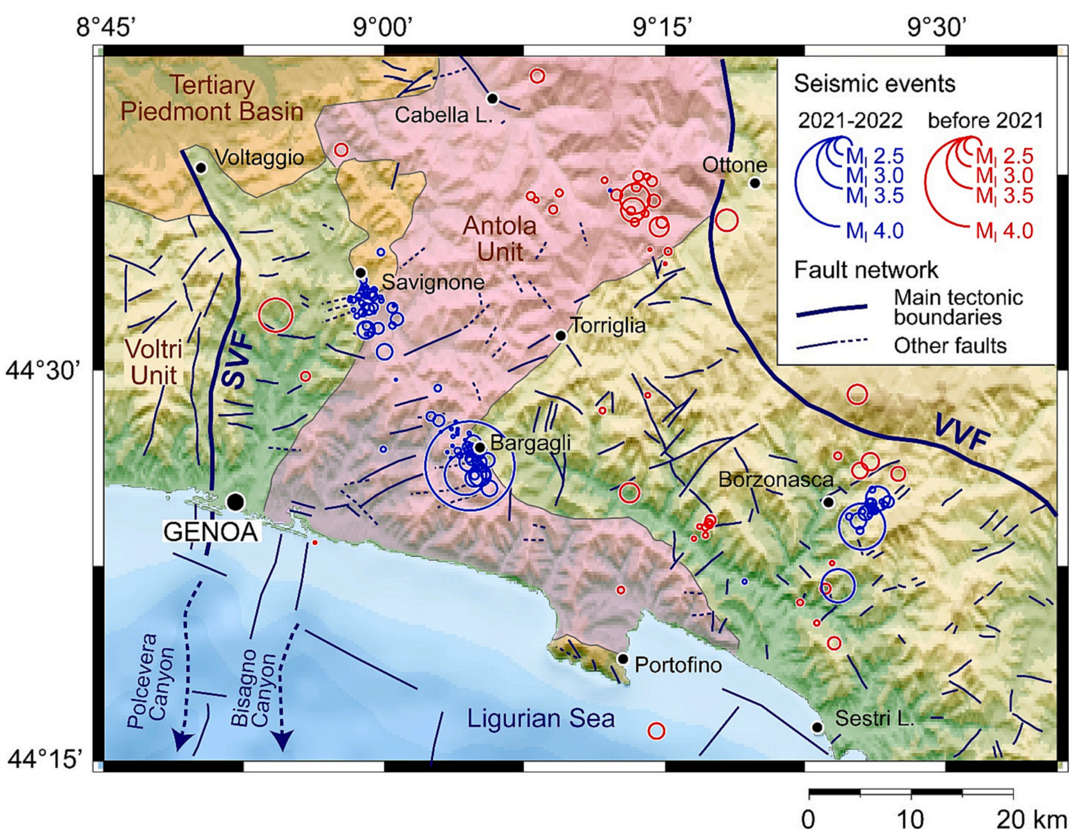

Fig. 2. Spatial distribution of seismic events recorded in the study area before 2021 (in red) and in 2021–2022 (in blue). SVF = Sestri-Voltaggio Fault; VVF = Villalvernia-Varzi-Ottone Fault. The thin blue lines are major faults mapped during the CARG mapping project (Bortolotti, 2011; Capponi, 2008; Elter and Marroni, 2006; Elter and Zanzucchi, 2005; Marroni, 2006) and the Regione Liguria mapping projects (http://srvcarto.regione.liguria.it/; Morelli et al., 2022). The dashed lines indicate faults that do not displace any major lithological boundaries. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

framework of national (CARG) and other associated mapping projects (e.g., Bortolotti, 2011; Capponi, 2008; Elter and Marroni, 2006; Elter and Zanzucchi, 2005; Marroni, 2006; Morelli et al., 2022). A tectonic synthesis of these maps is presented in Fig. 2, where the continuous lines indicate the major faults displacing major geological boundaries, and the dashed lines indicate other faults mapped in the field that do not displace any major lithological boundaries. It is evident that the fault network is best defined in the region around the Sestri-Voltaggio Fault and in the Internal Ligurian Units, whereas it is less clearly defined in the Antola Unit, likely due to the monotonous successions of mainly fine-grained turbidites that makes faults less evident in the field. Around the Sestri-Voltaggio Fault, the orientation of mapped faults is N-S, ENE-WSW, and WNW-ESE in the Voltri Unit to the west of the fault, and mainly WNW-ESE to the east of the fault. In the Internal Ligurian Units, NNW-SSE to NNE-SSW faults are systematically cut by dominant ENE-WSW and WNW-ESE faults. In the Antola Unit, most of the faults have a ENE-WSW strike. NNW-SSE faults are also present in the Antola Unit, but they do not displace any major lithological boundaries (Fig. 2).

3. Methods

We selected seismic events occurred in the period 1989–2022 in the quadrangle of latitude 44°15′-44°41′ and longitude 8°45′-9°35′ between the Sestri-Voltaggio and Villalvernia-Varzi-Ottone faults, for a total of 160 earthquakes (Fig. 2). Waveforms for 50 seismic broadband stations within ~100 km from the center of the study area were downloaded from the EIDA database (Strollo et al., 2021). Because the accuracy of phase readings is crucial for obtaining high quality seismic locations, we performed manual picking of P and S phases, which ensured high quality detections with estimated pick errors on the order of a few hundreds of milliseconds. We exclusively considered data with high signal-to-noise ratios to avoid false detections in the light of the low magnitude of analyzed earthquakes. Earthquake data were processed by a single operator (E.E.) to avoid any bias due to the application of different weighting schemes. We thus obtained an initial dataset of 3076 P and 2420 S phase picks.

Seismic events were preliminary located with Hypoellipse (Lahr, 1999), a software for routine earthquake location that ensures a good compromise between location accuracy, time needed for hypocenter determination and computational burden. Because locations based on Hypoellipse may be inadequate for advanced seismotectonic applications (see, e.g., Eva et al., 2020), more accurate locations were provided by the HypoDD algorithm (Waldhauser and Ellsworth, 2000), which utilizes the double difference solve technique for spatially related events recorded at common stations.

For nearby events, the ray paths of different events to each common station should be nearly identical, and the differences between observed and expected travel times should exclusively reflect the relative difference in the location of the events. Based on this principle, HypoDD iteratively minimizes the arrival time residuals by using input data either derived from bulletin and phase picks or from waveform cross-correlation. HypoDD either uses a weighted least squares approach, a singular value decomposition approach, or a conjugate gradient approach. The conjugate gradient approach is more suitable for large data sets, whereas the singular value decomposition approach works better for smaller data sets (hundreds of events) and produces more accurate error estimates.

In this study, the pairing of events was performed from phase picking using the PH2DT routine, which is included in the HypoDD software, coupled with a rather wide mesh. Data were cut between 10 s before the origin time and 50 s after the origin time. Waveforms were bandpass filtered [1–9 Hz] and processed for similarities in the time domain for all possible event pairs using samples of 2 s for P waves and 3 s for S waves (Schaff, 2004). The cross-correlation threshold was set to 70%.

Although the locations of closely spaced events are generally poorly dependent on the velocity model, using an incorrect velocity model may affect the results of the HypoDD runs (Wolfe, 2002; Michelini and Lomax, 2004). We computed a reference 1-D model using the program VELEST (Kissling, 1988). Phase selections were pre-processed to select data from connected events. We built a network of links between events to form a chain of linked event pairs. We calculated travel time differences between events after choosing a maximum of 10 neighbors per event within a distance of 10 km. Event pairs with at least 8 observations were retained, since the number of unknowns for an event pair is 8, and a maximum number of observations in each event pair was set equal to 15. An important factor to be considered when applying HypoDD is that travel time errors increase with increasing distance between analyzed events, which is mainly due to heterogeneities in the velocity structure (Waldhauser and Ellsworth, 2000; Waldhauser and Schaff, 2008). Therefore, we tested several values of maximum separation distance. We also removed delay outliers that are much larger than the expected value for the respective event pair during preprocessing. The HypoDD code refines clustering according to a selected maximum distance between connected pairs. In each run, we progressively decreased the maximum distance between connected pairs from 10 km to 4 km for phase data, and from 9 km to 2 km for cross-correlation data. We assigned a greater weight to cross-correlation data because they are less prone to manual errors and applied the singular value decomposition solving method to compute the location errors. Finally, we used the locations from HypoDD to compute focal mechanisms for the main shock of the three sequences, based on first onset polarities (Reasenberg and Oppenheimer, 1985) and high-quality location parameters.

4. Results

Fig. 2 shows the spatial distribution of seismic events, as located with Hypoellipse, recorded in the study area before 2021 (in red) and in 2021–2022 (in blue). Most of the events in the period 1989–2021 (~50, red circles in Fig. 2) are in the northern and eastern sectors of the study area, far away from the city of Genoa, and have magnitude $M_l < 3$. Only a few events occurred before July 2021 at the same sites of the 2021–2022 seismic sequences. The 2021–2022 seismic sequences are located near the villages of Savignone, Borzonasca and Bargagli. They are apparently far away from the Sestri-Voltaggio and Villalvernia-Varzi-Ottone faults. After Hypoellipse location, they do not show any obvious linear trend.

Fig. 3 shows the spatial distribution of seismic events after HypoDD relocation. Only 85 events out of the initial 160 could be successfully relocated. Most of the successfully relocated events (78 out of 85) belong to the 2021–2022 seismic sequences. Most of the earthquakes in the northern sector of the study area were recognized by HypoDD as isolated events and were not relocated. The relocated seismicity shows very small horizontal and vertical errors, <100 m for the Savignone and Borzonasca sequences, and <300 m for the Bargagli sequence.

The clusters of the 2021–2022 seismic sequences are very tight, with seismic events located <5 km apart from each other. Two of these clusters are located immediately to the east of Savignone and to the north of Bargagli. The third cluster, previously referred to the village of Borzonasca, after HypoDD relocation plots right in correspondence of the Villalvernia-Varzi-Ottone Fault.

Fig. 3 also shows the focal mechanism for the main shock of each sequence, as determined by the first onset polarities using HypoDD relocations. All focal mechanisms are well constrained by 58 to 141 polarities with fair to good azimuthal distributions, despite the presence of the Ligurian Sea in the south where permanent seismic stations are not present. All the focal solutions are strike-slip, with near-vertical NNW-SSE and NE-SW to ENE-WSW nodal planes.

Due to the tight clustering of seismic events, zoomed maps are necessary to assess the spatial distribution of events for each cluster. These maps are shown in the upper frames of Fig. 4, where the map-view distribution of relocated events reveals a NE-SW alignment for the Savignone sequence, and NNW-SSE alignments for the Borzonasca and

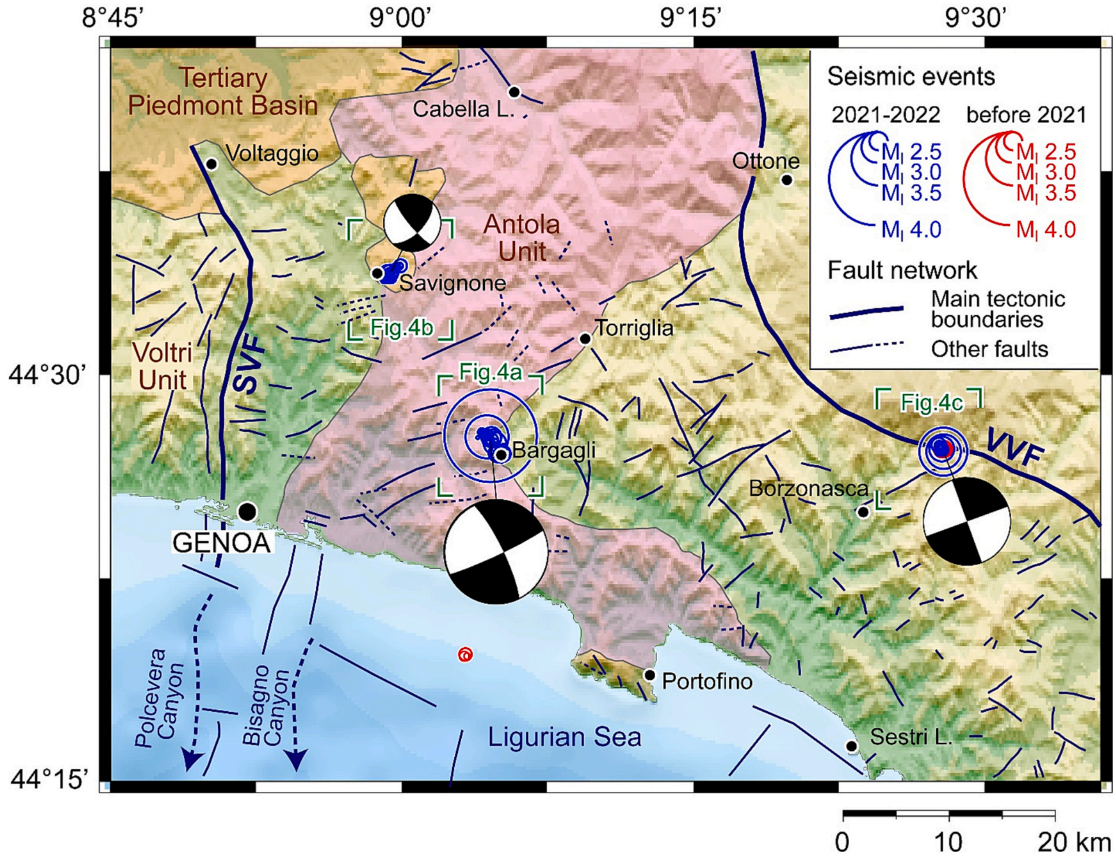

Fig. 3. Spatial distribution of seismic events shown in Fig. 2 after HypoDD relocation. The beach balls show the focal mechanisms for the Bargagli, Savignone and Borzonasca main seismic events in 2021–2022.

Bargagli sequences (Fig. 4a-c). These alignments are near-parallel to the main-shock nodal planes determined by the analysis of the first onset polarities (see Fig. 3). Relocated seismic events are also plotted in cross section in Fig. 4d-f. The chosen cross sections are perpendicular to the strike of the nodal planes that best mimic the distribution of earthquakes for each sequence. The Savignone sequence defines a near-vertical distribution of events in the 8–9 km depth range (Fig. 4e). Events are distributed in the 7–7.5 km depth range for the Borzonasca sequence (Fig. 4f), and in the 6.5–7.5 km depth range for the Bargagli sequence, where the strongest event ($M_l = 4.0$) was located at 6.8 km depth (Fig. 4d).

5. Discussion

The 2021–2022 Genoa seismic sequences show evident alignments that are supportive of km-scale faults in the upper crust in between the Sestri-Voltaggio and Villalvernia-Varzi-Ottone faults. The Borzonasca cluster plots right in correspondence of the Villalvernia-Varzi-Ottone Fault and may simply mark the sinistral strike-slip activity of a splay of this long-recognized major structure. No activity is documented, after HypoDD relocation, along the Sestri-Voltaggio Fault, as already shown by other recent seismotectonic studies (e.g., Eva et al., 2020). Based on our analysis, strike-slip deformation in the Alps-Apennines transition zone appears to be distributed in the upper crust along fault segments of different orientation, which partly share the same orientation with faults now exposed at the Earth's surface (Fig. 4). These findings may be supportive of a scenario of local strike-slip faulting associated with thrusting and folding, as proposed for example by Tibaldi et al. (2023) for the frontal part of the Northern Apennines. However, such a scenario would require these strike-slip events to be associated with other larger magnitude earthquakes with reverse focal mechanisms. This is not the case. The strike-slip earthquakes analyzed in this work are in fact the only seismic events recorded so far between the Sestri-Voltaggio Fault and the Villalvernia-Varzi-Ottone Fault.

The alignment defined by the earthquakes of the 2022 Bargagli seismic sequence is about 3.5 to 4 km long. It is oriented NNW-SSE and is located in an area where no major fault has been recognized during recent geological surveys (e.g., Elter and Marroni, 2006) (Fig. 4a). Most of the faults detected in the nearby areas have a ENE-WSW strike, but a NNW-SSE fault, labelled as Passo del Fuoco Fault (PFF) in Fig. 4a, was however recognized a few kilometers farther north. Because this fault does not displace any major lithological boundaries in the study area, we should be aware that faults with NNW-SSE orientation recognized by seismotectonics might be difficult to detect by field geologists even if they can reach the Earth's surface. Our data indicate that these faults are documented in the upper crust as deep as 6.5–7.5 km and that they may be more widespread than previously thought. The map-view distribution of the Bargagli seismic events is consistent with the orientation of one of the main-shock nodal planes (Fig. 3), which is thus interpreted as a steeply dipping, left-lateral NNW-SSE fault plane.

Magnitude versus rupture length scales in seismotectonic studies are generally computed for magnitudes higher than $M_w > 5.0$. However, some authors speculate that self-similar scaling may occur even for smaller magnitude events (e.g., Trippetta et al., 2019). If this assumption is correct, the rupture length scale of 3.5–4 km inferred for the Bargagli main shock would be consistent with its $M_l = 4.0$ magnitude. We may thus ascribe the Bargagli seismic sequences to a rupture due to the development of a newly-formed strike-slip fault in the upper crust. Any events recording the reactivation of pre-existing faults with the same length would in fact be smaller magnitude.

Further north, the NE-SW alignment defined by the 2021 Savignone seismic sequence is about 2.5 km long in map view (Fig. 4b). Its NE-SW

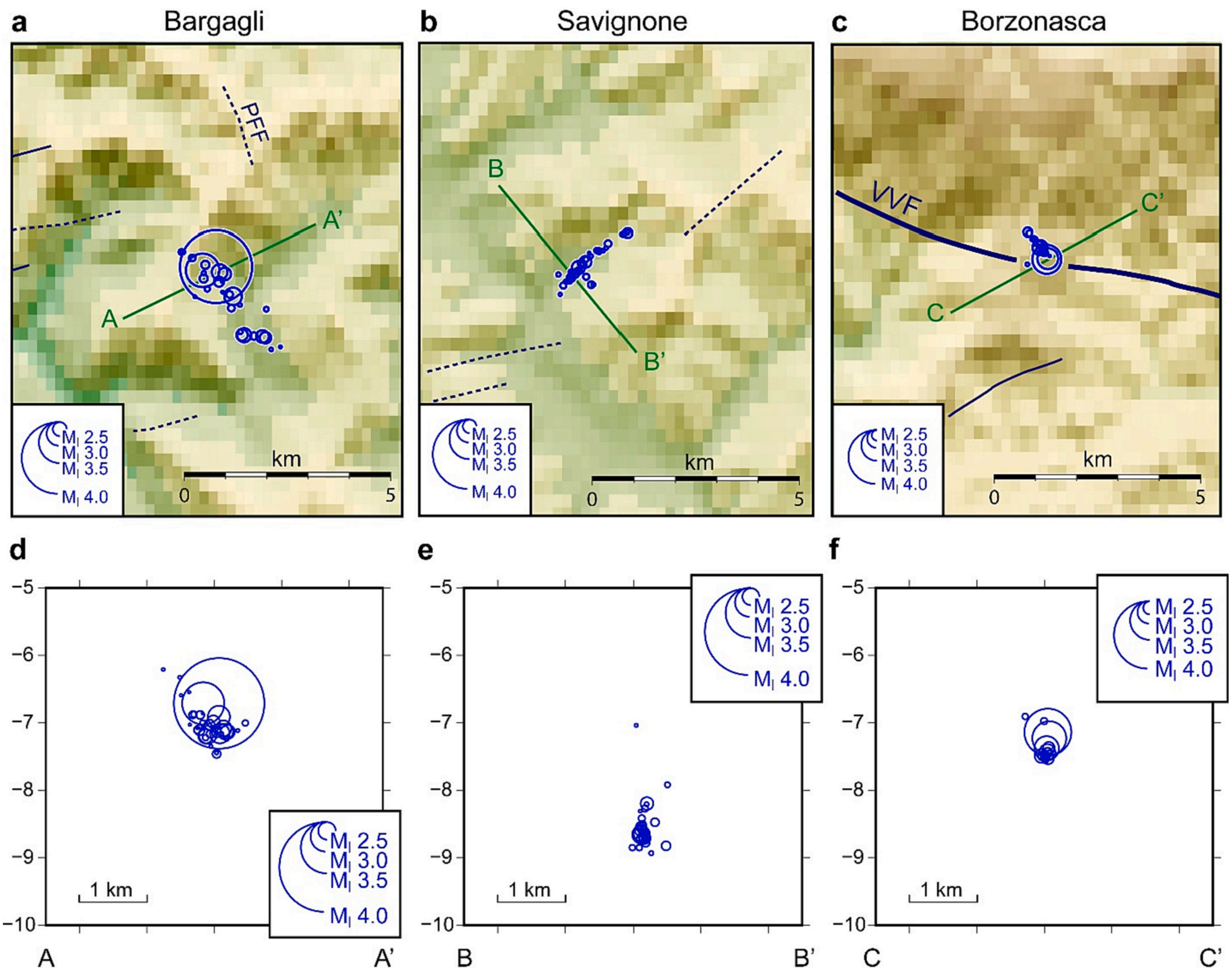

Fig. 4. Detailed distribution of seismic events in the Bargagli, Savignone and Borzonasca areas in map view (a-c) and cross section (d-f). See map locations in Fig. 3. The thin blue lines are major faults mapped during the CARG mapping project; the dashed lines indicate faults that do not displace any major lithological boundaries. VVF = Villalvernia-Varzi-Ottone Fault. PFF = Passo del Fuoco Fault. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

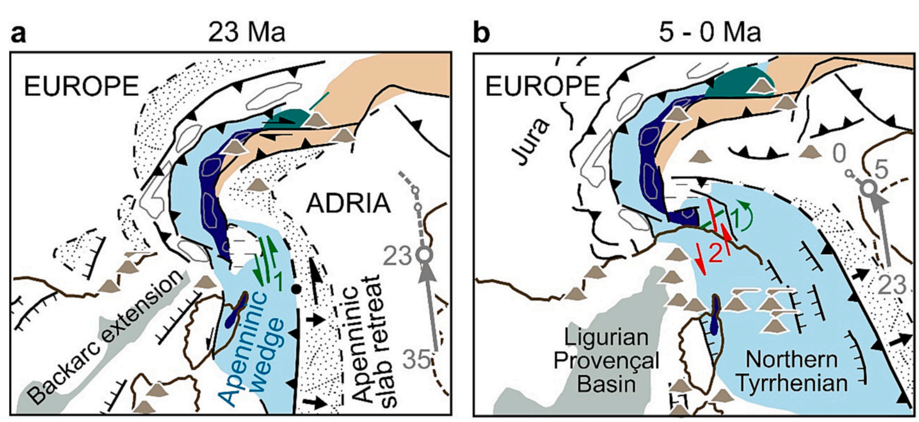

Fig. 5. Conceptual scheme showing the progressive accommodation of Adria-Europe convergence in the Alps-Apennines transition zone before (a) and after (b) slab retreat and Ligurian-Provençal and Tyrrhenian basin opening (based on Malusà et al., 2015). After counterclockwise block rotation, older strike-slip faults (1, in green) are no longer suitably oriented to accommodate Adria-Europe convergence (grey arrow, numbers = age in Ma), and new NNW-SSE left-lateral faults may form through new ruptures as revealed by the Bargagli earthquake (2, in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

orientation is consistent with the orientation of many faults mapped in the Antola Unit (Elter and Marroni, 2006; Capponi, 2008). Faults with similar orientation, but not displacing any major lithological boundaries, were indeed detected to the east of Savignone not far from the site of the 2021 seismic events (Fig. 4b). Based on our data, we can conclude that these NE-SW faults are thus more widespread in the Antola Unit than previously thought based on geological maps. However, unlike the case of the Bargagli sequence, the 2.5 km length scale defined by the distribution of the Savignone seismic events is evidently too long for the associated magnitudes. We can thus safely ascribe the Savignone seismic sequence to the reactivation of a pre-existing fault according to a strike-slip kinematics with a reverse component (Fig. 3). Such fault likely cuts across the upper crust down to 8–9 km depth (Fig. 4e).

Our results shed new light on the way Africa-Europe convergence is accommodated across the Alps-Apennines transition zone (Fig. 5), and suggests a scenario of ongoing distributed strike-slip deformation in the region to the east of the Sestri-Voltaggio Fault. In that region, part of the deformation related to the northward motion of Adria relative to Europe, albeit minor, is presently accommodated by strike-slip motion along inherited NE-SW faults, as documented by the 2021 Savignone seismic sequence. We propose that these NE-SW faults were originally oriented NNW-SSE. They likely enucleated within a left-lateral deformation corridor at the boundary between the Alps and the Apennines, prior to the opening of the Ligurian-Provençal and Tyrrhenian basins (1, in green in Fig. 5a) (e.g., Malusà et al., 2015). Their present-day orientation was acquired after a major counterclockwise rotation of crustal blocks in the Alps-Apennines transition zone, which is constrained to the Neogene by available paleomagnetic data (Muttoni et al., 1998, 2000; Maffione et al., 2008).

After such counterclockwise rotation, these faults were no longer suitably oriented to accommodate the northward motion of Adria relative to Europe (grey arrow in Fig. 5a,b). The new ruptures revealed by the Bargagli seismic sequence may therefore simply reflect the formation of new strike-slip faults in the upper crust that are more suitably oriented to accommodate the present-day motion of Adria (2, in red in Fig. 5b). This would explain why the magnitude of the Bargagli main shock is much greater than the magnitude of the seismic events delineating the NE-SW fault near Savignone.

Notably, a seismotectonic framework dominated by left-lateral motion along steeply dipping NNW-SSE faults was recently documented by Eva et al. (2020) in the region encompassing the western Po Plain, the Ligurian Alps, and the adjoining offshore regions, and at different depth ranges from the uppermost crust to the lithospheric mantle (Eva et al., 2015; Malusà et al., 2017). The earthquakes located along the Rivoli-Marene deep fault, to the west of the study area, are dominantly strike-slip (Eva et al., 2015). The April 2003 Valle Scrivia earthquake (Ml 4.7), just north of the study area, shows a strike-slip focal mechanism (Pondrelli et al., 2006). The 4.6 ± 0.3 moment magnitude earthquake occurred in December 2020 beneath Milan (see location in Fig. 1) is supportive of active left-lateral slip in the Adriatic mantle even farther north, which may trigger outgassing of deeply recycled carbon (Malusà et al., 2022). However, a strike-slip seismotectonic scenario cannot be exported farther east to the frontal part of the Northern Apennines, where seismicity is mainly controlled by active thrust faults along the edge of the Po Plain (e.g., Benedetti et al., 2003).

6. Conclusion

Accurate relocation of the 2021–2022 Genoa seismic sequences using the HypoDD algorithm provides new insights on the way Adria-Europe convergence is accommodated across the Alps-Apennines transition zone. No seismic activity is documented along the Sestri-Voltaggio Fault, which is often considered as the boundary between the Alps and the Apennines. The Borzonasca seismic sequence plots right in correspondence of the Villalvernia-Varzi-Ottone Fault, despite it was preliminarily located by Hypoellipse ca 10 km to the south. This underlines the importance of an accurate relocation of seismic events before attempting any seismotectonic interpretations. In the study area, evident earthquake alignments mark active, km-scale fault planes in the upper crust that share the same orientation with faults at the Earth's surface, pointing to a scenario of distributed strike-slip deformation in the transition zone between the Alps and the Apennines. In this area, inherited faults that underwent major Neogene rotation are no longer suitably oriented to accommodate the northward motion of Adria relative to Europe. We propose that the Bargagli seismic sequence may reflect the formation of new NNW-SSE strike-slip faults in the upper crust that are more suitably oriented to accommodate the present-day stress field in this complex segment of the Adria-Europe plate-boundary zone.

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CRediT authorship contribution statement

E. Eva: Writing – review & editing, Software, Investigation, Formal analysis, Conceptualization. **M.G. Malusà:** Conceptualization, Writing – original draft, Visualization. **S. Solarino:** Writing – review & editing, Supervision, Resources, Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Seismic data used in this work can be downloaded from the EIDA database at the link http://www.orfeus-eu.org/data/eida/.

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