Pliocene-Quaternary seismogenic faults in the inner Northern Apennines (Valdelsa Basin, southern Tuscany) and their role in controlling the local seismicity

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Abstract

Pliocene-Quaternary faults are relevant structures to constrain the seismotectonic context and contribute to the evaluation of the seismic hazard of a region. Many of these faults, however, do not show clear surface evidence even when releasing earthquakes. For these reasons they can be extremely dangerous as they receive less attention and are more difficult to identify. Among the various surface geology studies and/or paleoseismological investigations, we focus our attention on the integration of different data-sets like seismic reflection profiles, surface kinematic data and the relocation of seismological data, which allow to identify and characterize active faults whose dimension and earthquake potential would otherwise be not large enough to make them identifiable. We take as an example the Montespertoli NE-trending fault in southern Tuscany (central Italy) to which we associate the 2016 M=3.9 Castelfiorentino earthquake. This structure

is part of a wider (in the order of 15-20 km) crustal scale shear zone, which may be responsible for strong historical earthquakes of the area.

Keywords: *active faults, seismic profiles, earthquakes, strike-slip faults, inner Northern Apennines*

1 Introduction

Active faults capable of generating earthquakes may be blind, not reaching the ground surface, and or be masked by continuous burial/erosion processes at the surface (e.g. Lettis et al., 1997). Nevertheless, depending on their dimensions and depths, such structures may provide relevant surface or co-seismic effects, when activated. In some cases, faults can be relevant and capable to produce damaging earthquakes also generating surface primary ruptures. In some other cases, fault segments are too small for producing large magnitude events and co-seismic surface effects, but are large enough to cause significant ground shaking and be clearly felt by the population. In both cases, these elusive faults represent structures that may result very dangerous in populated areas, especially those with high vulnerability due to the presence of historical buildings. Several examples exist of damaging earthquakes occurred in the recent past, which are interpreted as generated by blind faults (Whittier Narrows 1987 Los Angeles California (USA) M=5.9 - Hauksson et al., 1988; Haiti 2010 M=7.0 - Hayes et al., 2010; Christchurch 2010 New Zealand M=7.1 - Li et al., 2014; Van 2011 Turkey M=7.1 - Dogan and Karakas, 2013; Po Plain 2012 Italy M=5.8 - Burrato et al., 2012). In some cases, such faults never ruptured the surface but bear evidences of activity at the surface like evidence of folding (e.g., Ventura anticline in California, Sahw and Suppe, 1994; Montello anticline in Italy, Benedetti et al., 1998). In many cases, for such structures no detailed information on their potential was given prior to the seismic events.

Other faults, though potentially active and seismogenic, are called “hidden”, their recent geological and morphological evidences being little and hence difficult to identify or to infer. This is, for example, the case of the M=4.9 earthquake in 2019 in France, which occurred on a reactivated Oligocene thrust fault with absence of geomorphic evidence of cumulative compressional deformation along the fault for several thousand or tens of thousands of years. Such hidden structures can have important consequences for the society because they are hard to find due to their subdue geological or morphological evidences. This implies the existence of active faults, not yet identified but that, at least in historical times, gave rise to considerable seismic events. These faults, not showing clear surface evidence of activity remain mostly unidentified, most studies being focused on indirect surface evidence of their existence and activity.

In order to characterize the earthquake potential of these faults, different approached are available which span from morphotectonic evidence, to paleoseismological investigations (e.g. Hancock et al., 1999; Piccardi et al., 1999; Burrato et al., 2012; Brogi et al., 2017; Piccardi et al., 2017; Nirta et al., 2021).

Other approaches were also developed aiming at the integration of both surface and subsurface data-sets including seismic interpretation, boreholes data, compared with seismological data to infer faults geometry and slip rates. In fact, the increasing availability of subsurface geological and geophysical information has given the opportunity to identify and map faults in the subsurface in great detail (e.g.,Armijo et al., 1996; Pratt et al., 1998; Di Bucci et al., 2006; Bell et al., 2009; Toscani et al., 2009; Mirabella et al., 2008; Brogi et al., 2014). In some cases, the comparison of both geomorphic anomalies mapping with subsurface reconstructions, results in an effective identification of potentially active faults (e.g. Toscani et al., 2009 and therein references).

In this paper we focus on a fault system, active since the Neogene, affecting a sector of southern Tuscany (Valdelsa Basin, Fig.1a), generating low-magnitude earthquakes in 2014 and 2016 (Castelfiorentino and Certaldo earthquakes, M=3.9 (2016-10-25) and M=3.4 (2014-08-09) (Fig.1b) in an area where the occurrence of active faults has never been documented before.

Though the low magnitude of the events and the absence of important damage, these earthquakes occurred in an area where historically stronger events are documented (equivalent magnitude Me=5.5) and which show high vulnerability due to the presence of both high population density and historical and art buildings.

After an introduction of the geological and tectonic setting, we present a new interpretation of seismic reflection profiles, acquired for hydrocarbons exploration by AGIP during the 80's, calibrated with borehole logs, surface fault kinematic data and integrate them with an accurate relocation of the seismological data. We conclude that the Castelfiorentino and Certaldo earthquakes and their minor sequences, are associated with a NE-trending fault system, which belong to a much wider crustal scale structure, orthogonal to the main trend of the Valdelsa Basin. We discuss the role of these faults in controlling earthquakes, their detection by means of subsurface data and the possible correlation with geomorphological observations and we frame their evolution in the Neogene-Quaternary tectonic setting of the inner Northern Apennines.

2. Geological and seismotectonic setting

The Northern Apennines originated from the convergence and collision (late Cretaceous–early Miocene) between the Adria promontory and the European plate, represented by the Sardinia–Corsica massif (Molli, 2008 with references therein). In the inner zone of the Northern Apennines this process gave rise to the stacking of several tectonic units deriving from different paleogeographic domains (Vai and Martini, 2001), which are, from top to bottom (Carmignani et al., 1994): (a) Ligurian Units, derived from the Ligurian-Piedmont Domain, and consisting of remnants of Jurassic oceanic crust and its late Jurassic-Cretaceous, mainly clayey, sedimentary cover; (b) Sub-Ligurian Units (Sub-Ligurian Domain), made up of Cretaceous-Oligocene turbidites; (c) Tuscan Units forming a duplex system and composed by HP metamorphic and sedimentary units ranging from the Palaeozoic to the Early Miocene (Pandeli et al., 1991; Carmignani et al., 1994; Rossetti et al., 2002; Brogi and Giorgetti, 2012; Bianco et al., 2015) (Fig.2a). The Ligurian and Sub-Ligurian units were thrusted eastward over the Tuscan Nappe during late Oligocene–early Miocene. After nappe stacking, eastward migrating extension affected the inner Northern Apennines (i.e., northern Tyrrhenian Basin and Tuscany - e.g. Barchi, 2010; Carmignani et al., 1995; Doglioni, 1991; Lavecchia, 1988; Molli, 2008; Patacca et al., 1990; Rossetti et al., 2015) since Miocene (Carmignani et al., 1995; Dallmayer and Liotta, 1998; Liotta et al., 1998; Brogi and Liotta, 2008; Brogi, 2011) and determined the development of mainly eastward dipping normal faults, which produced: (a) the lateral segmentation of the more competent levels within the previously stacked tectonic units (Decandia et al., 1993); (b) the consequent westward rotation of their hanging walls (Brogi, 2004); (c) the direct superimposition of the Ligurian Units on the late Triassic evaporite and/or on the Palaeozoic phyllites, both representing regional detachment levels (Brogi and Liotta, 2008); and (d) an extension of at least 120% (Carmignani et al., 1994; Brogi, 2006). The youngest extensional event (Barchi, 2010; Dallmayer and Liotta, 1998), active since early Zanclean (Martini et al., 2021), is characterized by NW-trending normal faults crosscutting the previously developed structures (Calamai et al., 1970; Lazzarotto and Mazzanti, 1978; Mazzanti, 1966) and defining tectonic depressions where Pliocene to Quaternary marine to continental sediments were deposited (Bossio et al., 1993a; Martini and

Sagri, 1993). The amount of extension associated with this event is estimated in the order of 6–7% (Carmignani et al., 1994).

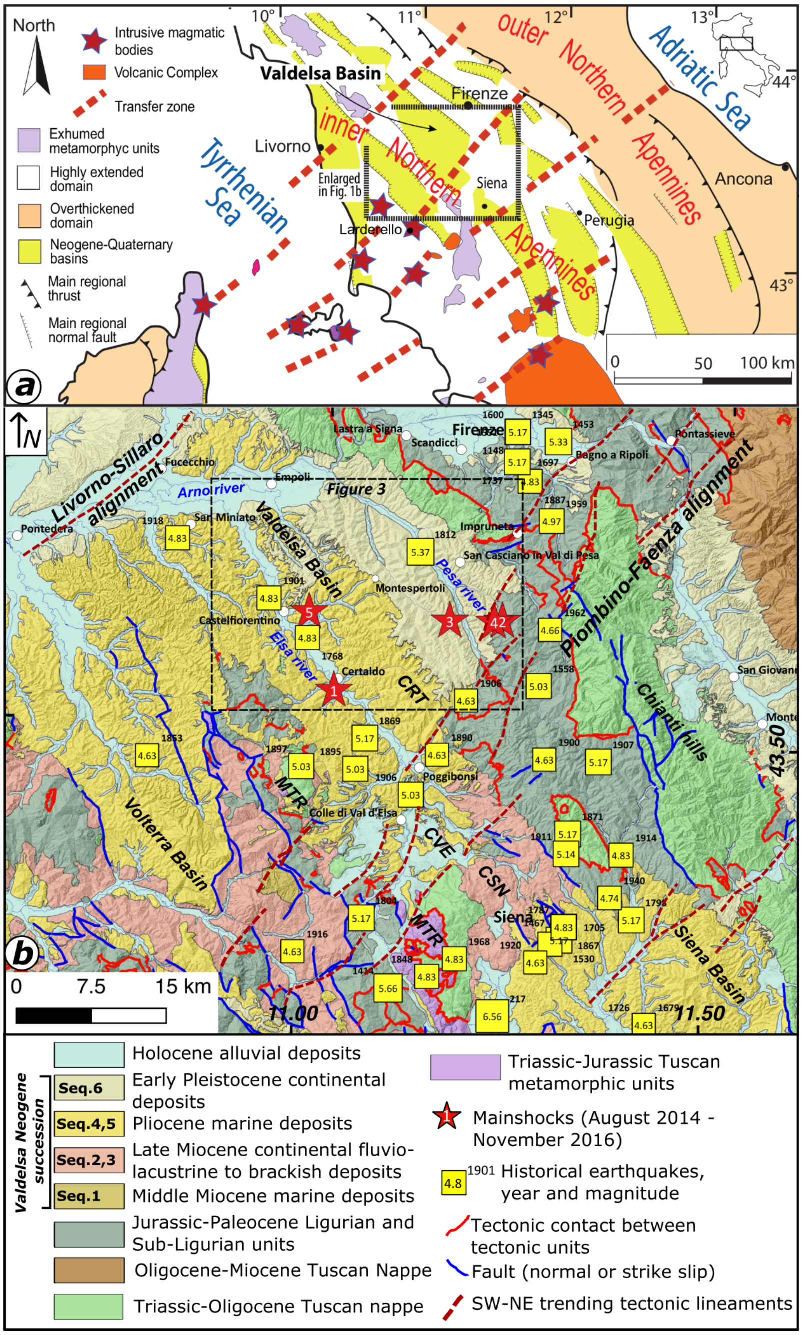

Fig. 1. (a) Tectonic sketch of the Inner Northern Apennines (Central Italy) showing the relationships between the SW–NE lineaments, the Neogene–Quaternary basins and the intrusive magmatic bodies. (b) Geological map of the Valdelsa Basin with the main SW–NE-trending lineaments, the historical seismicity (equivalent magnitude Me > 4.5), and the 2014–16 mainshocks relocated and discussed in this work. Within the map, the Valdelsa Neogene deposits are numbered from Sequence 1 to Sequence 6 for further reference in the text. MTR: Middle Tuscan Ridge; CRT: Certaldo Sub-Basin; CVE: Colle Val d'Elsa Sub-Basin; CSN: Casino Basin.

These depressions are coeval with NE-trending faults zones (Liotta, 1991) that controlled the volcanism and the emplacement of magmatic bodies at shallow crustal levels (Fig.1a) (Acocella and Funiciello, 2006; Dini et al., 2008; Farina et al., 2010; Brogi et al., 2010; Liotta et al., 2015). These SW-NE trending faults zones (as the Livorno-Sillaro Line - Fig.1b), recognized by many authors since the 60's through satellite images analyses (Ambrosetti et al., 1978; Boccaletti et al., 1985), are characterized by strike-to oblique-slip kinematics and associated horizontal displacements (see Basili and Valensise, 2001; Brogi et al., 2013; Liotta and Brogi, 2020). The origin and role of these structures is not well established, and they are interpreted alternatively as transfer zones, lateral ramps of thrusts, segmenting features of the NW-SE trending extensional systems (Ghelardoni 1965; Boccaletti and Dainelli 1982; Fazzini and Gelmini 1982; Rosenbaum and Piana Agostinetti 2015). One of these main fault zones (named as the "Piombino-Faenza Line") crosses the study area (Fig.1b) and interrupts the continuity of the Valdelsa Basin and of other basins (Firenze, Casino -CSN and Volterra basins in Fig.1b) (Canuti et al., 1966; Bossio et al., 2002).

The Neogene extensional setting and evolution, confirmed by many field and laboratory studies (among the others: Lavecchia, 1988; Jolivet et al., 1990; Carmignani et al., 1994; Liotta et al., 1998; Barchi et al., 1998; Gualtieri et al., 1998; Negredo et al., 1999; Rossetti et al., 1999; Di Bucci and Mazzoli, 2002; Pera et al., 2003; Bartole, 1995; Collettini et al., 2006; Brogi, 2008) has been challenged by alternative interpretations (e.g. Finetti et al., 2001; Finetti, 2006; Bonini and Moratti, 1995; Bonini and Sani, 2002; Bonini et al., 2014). A discussion about the reasons why an extensional setting better explains the regional geological features of Tuscany, is given in Brogi et al. (2005), Brogi and Liotta (2008) and Brogi (2011, 2020) to which we address the reader for further information.

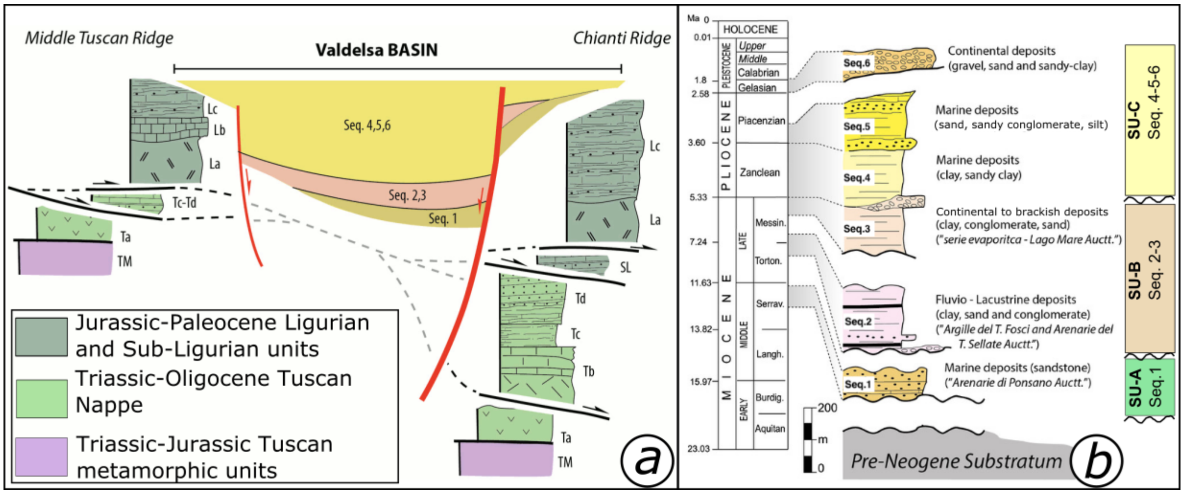

Fig. 2. a) Sketch of the tectonic units of the inner Northern Apennines and of their relationship with the Valdelsa Basin infill.TM:Triassic Verrucanosiliciclastics Group and Jurassic–Eocene metasedimentary cover; Ta: Late Triassic evaporite; Tc-Td: Cretaceous – early Miocene clayey and arenaceous succession; La: Jurassic oceanic crust (peridotites, gabbros and basalts); Lb: sedimentary cover made of Jurassic radiolarite and Cretaceous shale, clayey marl and limestone; Lc: S. Fiora unit composed of Cretaceous– Eocene clayey–marly and arenaceous succession. (b) Sequence-stratigraphic subdivision of the Neogene succession present in Valdelsa Basin and based on the distinctions proposed by Pascucci et al. (2007). Results composed by the superposition of marine (Seq. 1, 4, 5) and continental (Seq. 2, 3, 6) sequences characterized by variable thickness and lithological composition. To the right the sequences are grouped in relation to the seismic units (SU) shown later in the paper. Sequences are locally divided by unconformities (thicker undulated lines).

The inner zone of the Northern Apennines is characterized by low magnitude seismic events (M<4.5) mainly confined to the shallow crust, at depths ranging between 3 and 10 km (Batini et al., 1995; Cameli et al., 1993; Di Bucci and Mazzoli, 2002; Selvaggi and Amato, 1992; Braun et al., 2018a). The majority of earthquakes are concentrated in the geothermal areas of Tuscany, South of the study area (Larderello-Travale and Mount Amiata) and Northern Latium (Batini et al., 1985; Buonasorte et al., 1987; Cameli et al., 1998; Console and Rosini, 1998; Albarello et al., 2005; Braun et al., 2018a; 2018b; Lisi et al., 2019), where some of them could be probably ascribed to the extraction and reinjection of geothermal fluids. Relatively low seismicity characterizes the other areas of Tuscany.

In terms of seismic hazard, southern Tuscany, as well as the inner Northern Apennines, was considered of modest interest and seismogenically less energetic, in contrast with outer zones (e.g., the Umbria-Marche and Abruzzo Regions and the Adriatic Sea), where earthquakes recorded in the last century reached magnitudes up to 6.8 (Avezzano earthquake, 1915, 32,000 victims - Console et al., 1993; De Luca et al., 1999; Galadini and Galli, 2000; Alessandrini et al., 2001; Chiarabba et al., 2005; Pace et al., 2006; Faenza and Pierdominici, 2007).

Nevertheless, the available information concerning the historical seismicity of both Valdelsa and Chianti areas in southern Tuscany (i.e., DBMI15, Locati et al., 2016) highlights a different scenario where damaging seismic events were documented (Boschi et al., 1997; Camassi et al., 2011) (Fig.1b).

3. The Valdelsa Basin

The Valdelsa Basin (Fig.3, location in Fig.1b) is part of a broad Neogene NNW–SSE oriented tectonic depression, crossing southern Tuscany from the Arno River (to the North) to the Bolsena lake (to the South) and comprehending the Siena and the Casino basins (Fig.1b). The 70 km long extending Valdelsa Basin shows an articulated width, ranging from 30 km in its northern portion (Certaldo sub-Basin) to less than 15 km in its southern sector (Colle Val d'Elsa sub-Basin), with the threshold located in correspondence of NE-SW oriented tectonic lineament, known as the Piombino-Faenza Line (Fig.1b) (Ambrosetti et al., 1978; Boccaletti et al., 1985; Liotta, 1991).

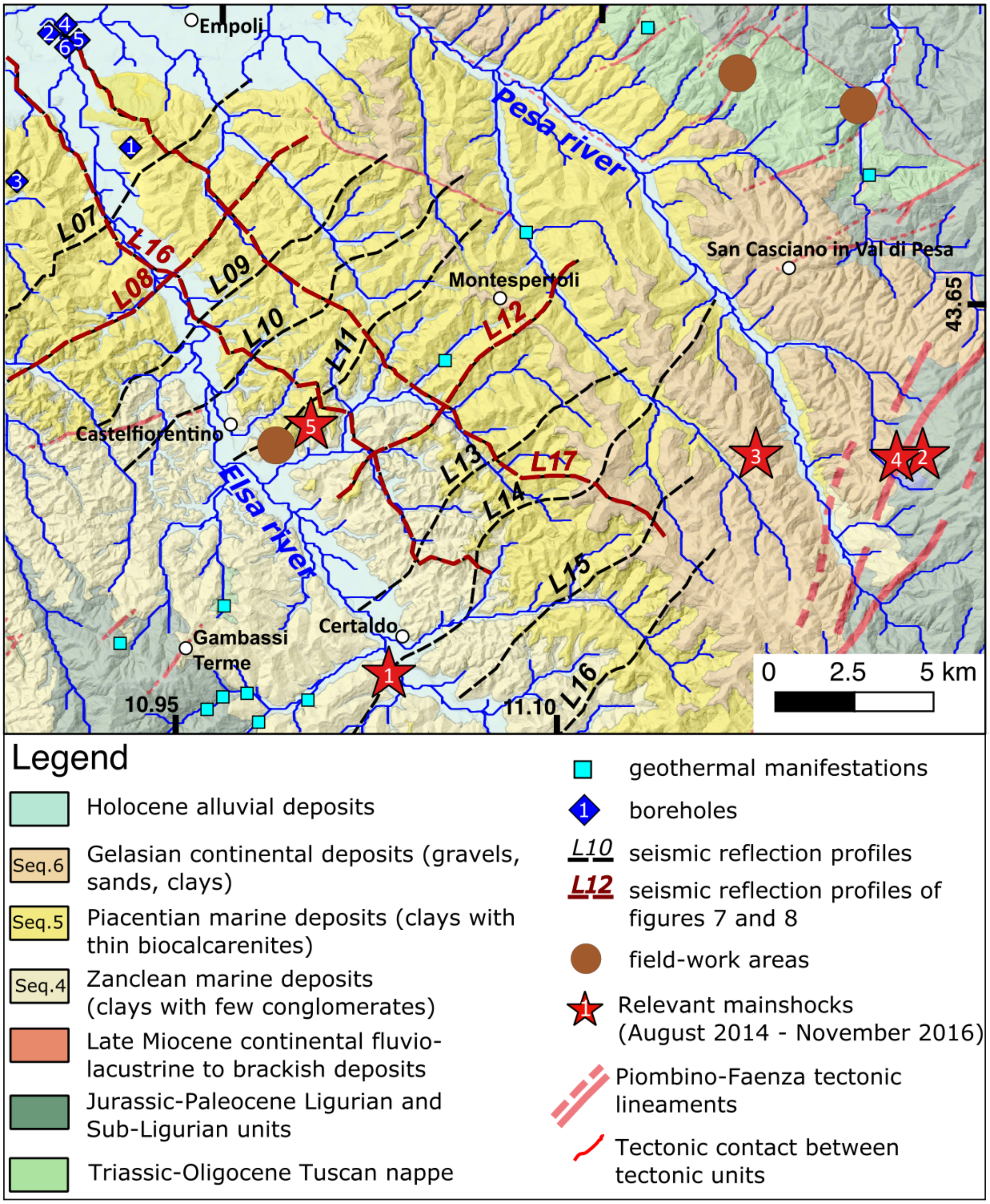

Fig. 3. Geological map of the study area (location in Fig. 1b) showing the distribution of the Neogene deposits, the position of the 2014–16 mainshocks, and the position of the subsurface data used for the subsurface reconstruction (boreholes and seismic reflection profiles). Key to borehole numbers: 1 = Monterappoli1; 2 = Certaldo2; 3 = Certaldo3; 4 = Certaldo4; 5 = Certaldo1; 6 = CertaldoSud1.

The basin is delimited by the Middle-Tuscan Range and Chianti hills to the SW and NE, respectively (Fig.1b), where metamorphic and non-metamorphic units, forming the remnants of the Northern Apennines tectonic pile, are exposed. These units are, from the top (Fig.2a): a) the Ophiolitic Unit (the uppermost tectonic unit belonging to the Ligurian Complex) consisting of remnants of the Jurassic oceanic crust (serpentinized harzburgite, gabbro and basalt; La in Fig.2a), and the sedimentary cover, mainly composed of Jurassic radiolarite and Cretaceous shale, clayey marl and limestone (Lb in Fig.2a); b) the S. Fiora Unit composed of Cretaceous–Eocene clayey-marly and arenaceous succession deposited on the oceanic crust of the Neo-Tethys (Lc in Fig.2a); c) the Canetolo Unit (Argille e calcari Auct.) composed of Eocene clayey-carbonate succession deposited in a transition crustal sector passing from the oceanic crust to the Adria continental margin (SL in Fig.2a); d) the Tuscan Nappe representing the deepest non-metamorphic tectonic units of the Northern Apennines, composed of Late Triassic evaporite (Ta in Fig.2a), Jurassic–Cretaceous carbonate-siliceous (Tb in Fig.2a) and Cretaceous–Early Miocene clayey (Tc in Fig.2a) and arenaceous (Td in Fig.2a) succession; e) the Tuscan Metamorphic Unit consisting of a metamorphic succession composed of the Palaeozoic phyllite-quarzitic Group, the Triassic Verrucano metasiliciclastics Group and Jurassic– Eocene metasedimentary cover (marble, calcschist and phyllite; TM in Fig.2a).

Boreholes and indirect subsurface data analyses in the basin highlight buried structural highs, both longitudinal and transversal to the basin (Mariani and Prato, 1988; Pascucci et al., 2007; Benvenuti et al., 2014), separating the depocenter, infilled with more than 1 km of sediments and located in a narrow sector comprised between the western basin shoulder and the valley of the Elsa river (Pascucci et al., 2007).

The whole study area is affected by both NW- and NE-striking faults of regional relevance (Fig.1b). A mostly continuous SW-dipping normal fault system occurs in the eastern border of the Basin. The fault segments separating the Neogene deposits from the pre-Neogene Units are mostly buried, but parallel segments can be recognized within the substratum units (Fig.1b). Nevertheless, the prolongation of this fault system, as well as of the basin itself toward the SE, is interrupted in correspondence of the NE-striking Piombino-Faenza tectonic lineament.

The Valdelsa Basin is characterized by heat flow values locally reaching 100 mW/m^2 (Mongelli and Zito, 1991), in the range of the average value of the southern Tuscany geothermal anomaly (Della Vedova et al., 2001). The whole Valdelsa Basin is therefore characterized by geothermal manifestations, consisting of tectonically controlled thermal springs and gas vents (Bencini et al., 1979; Fazzuoli et al., 1983; Minissale, 2004) mainly concentrated in the Gambassi Terme-Certaldo area and Montespertoli-Firenze area (Fig.3) and located along a dominant SW-NE trend. The physico-chemical characters of the thermal waters allow to recognize some different compositional groups. According to several authors (Bencini et al., 1979, Fazzuoli et al., 1993, Celati et al., 1990; Minissale, 2004), the most homogeneous group consists of alkaline-chloride type waters that seem mainly controlled by evaporitic processes possibly related with Triassic Burano Fm. Other types of waters, as e.g. alkaline-bicarbonate type, may reflect the interaction with different rocks from carbonate successions (Ligurian and/or Tuscan Units) to Neogene clays.

3.a. Stratigraphy of the Neogene deposits

The sediments cropping out in the Valdelsa Basin consist of Plio-Pleistocene marine and continental deposits. The marine Pliocene sediments, mostly made of clay, marl, sand, gravel and conglomerate, are unconformably overlaid by fluvio-lacustrine Pleistocene gravel, sand, clay and locally by Middle–Late Pleistocene continental carbonate (Capezzuoli & Sandrelli, 2004;

Capezzuoli et al., 2009). The stratigraphic setting of the Valdelsa Basin was classically described through informal lithostratigraphy of an overall regressive trend (Lotti, 1900; Lotti et al., 1908; Canuti et al., 1966; Merla & Bortolotti, 1967; Merla et al., 1967) and biostratigraphically constrained by markers among which planktonic foraminifera, nannofossils (Bossio et al., 1993b; Capezzuoli et al., 2005) and continental micromammals (Abbazzi et al., 2008; Benvenuti et al., 1995).

A detailed revision of the tectono-stratigraphic setting was performed by Benvenuti & Degl'Innocenti (2001) and Benvenuti et al. (2014), who divided the upper Messinian-Pliocene infilling succession in seven unconformities-bounded stratigraphic units (S1-S7).

We refer to the subdivision of the units proposed by Pascucci et al. (2007) schematized in figure 2b as more directly connected to the seismic units described later in the text. According to Pascucci et al. (2007), the basin results infilled with up to 1000 m of Late Miocene and 1000 m of Pliocene deposits (Seq.2 to Seq.5). A deeper Late Serravallian succession (Seq.1) formed by continental to shallow marine sandstone and conglomerate (Ponsano Sandstone Fm; Foresi et al., 2003 and references therein), unconformably resting on the basin substratum represented by Ligurian Units, was described in discontinuous exposures in the SE portion of the basin (Lazzarotto and Sandrelli, 1977; Pasini and Sandrelli, 1977).

The Late Miocene continental succession unconformably overlies the Seq.1 and encompasses Late Tortonian–Messinian fluvial-lacustrine sediments (Seq.2), mainly consisting of clayey-sandy levels and conglomerate with interbedded lignite level beds ("Serie Lignitifera"), and late Messinian lacustrine clays (Seq.3; S1 of Benvenuti et al., 2014) with layers of sandstone and conglomerates occurring mainly in the SE area (Casino Basin; Lazzarotto and Sandrelli, 1977).

Seq.3 is overlain by the Zanclean Seq.4 (S2, S3 of Benvenuti et al., 2014) mostly composed of marine clays with a few interstratified conglomeratic layers. Clay dominates the centre of the basin, with the coarser clastic deposits occurring on the margins. The Piacenzian Seq.5 (S4, S5, S6 of Benvenuti et al., 2014) is composed of marine clays; thin sandstone units occur at its base and top, where there are also local, thin biocalcarenites.

The above units are overlain by an Early Pleistocene (Gelasian) deposition (S7 of Benvenuti et al., 2014) of fluvial drainages deriving from the Chianti Hills.

3.b. Historical and instrumental seismicity

Widespread low-magnitude seismicity characterizes the whole inner zone of the Northern Apennines. The seismic events are mainly confined to the upper crust, at depths ranging from 3 to 10 km (Cameli et al., 1993; Di Bucci and Mazzoli, 2002; Selvaggi and Amato, 1992). The INGV earthquake catalogues CPTI-15 (Rovida et al., 2016) and DBMI15 (Locati et al., 2016) indicate that the historical seismicity in the area was characterized by several moderate earthquakes, with magnitudes in the Valdelsa Basin up to Me=5.1 (Fig.1b).

The strongest seismic event ever reported in the area between Chianti and Valdelsa occurred on 18 May 1895 and had a magnitude of Me 5.5. The intensity reached VIII (MCS and caused 4 casualties. As one of the aftermaths, the small locality Sant'Andrea changed its name to Sant'Andrea in Percussina (name derived from "percussion" to testify ground shaking). However, recent seismic events with epicentres inside the study area (Castelfiorentino – Certaldo) never exceed M 4.7. Recently, 4 relevant seismic sequences ($3.4<M<4.1$) occurred in the area between Valdelsa and Chianti areas (Tab.1).

4. Methods

We integrate available surface structural and kinematic data in the substrate, the interpretation of a set of seismic reflection profiles calibrated with boreholes and the re-location of seismicity to identify possible surface and subsurface evidence of the faults responsible for the recent-most seismic sequences. We performed fieldwork along bedrock-hosted fault segments in order to get information on the fault geometry and kinematics. Fieldwork data were gathered at three main structural sites located in figure 3.

Basing on a detailed revision of the Neogene deposits stratigraphy we interpreted a set of seismic reflection profiles, which cross the Valdelsa basin and which were calibrated with both surface geology and the Monterappoli1 borehole, which is the closest and most relevant in the area (Fig.3). The seismic profiles interpretation allowed us to draw a subsurface image of the relevant tectonic structures and to identify and map the Neogene basin depocenter throughout the area.

We re-located the Certaldo (2014) and Castelfiorentino (2016) main shocks of the seismic sequences and plotted the events onto two cross-sections obtained from the depth converted seismic reflection profiles.

We compared the above mentioned data-sets and interpreted the results into a comprehensive picture of the elusive active faults of the area.

5. Data

5.a. Structural and kinematic data

Considering that the epicentral distribution of the earthquakes is mostly concentrated along a SW-NE trending tectonic lineament, detailed structural analyses were carried out on a wide area comprehending the central-eastern part of the Valdelsa Basin and its eastern shoulder. Here, structural and kinematic data were collected in few (due to the scarcity of significant outcrops), but noteworthy exposures (see location in Fig.3). The clay and silt filling the basin, in fact, are not suitable for the development and preservation of fault scarps, as well as the related kinematic indicators. Although this limitation, mesoscopic faults were analysed in few exposures made up of unconsolidated clayey deposits, belonging to the Piacenzian marine succession and on the pre-Neogene units (i.e., Tuscan Nappe and Ligurian Units) of the basin substratum, in order to obtain more exhaustive geometric and kinematic pieces of information. The collection of these data was mostly in the substratum and few in the basin infill and was aimed at reasonably avoiding kinematic data deriving from pre-Neogene deformational events. By this approach, independently by the deformed lithotypes, rock age and kinematic indicators, the orientation of the analysed mesoscopic faults follow the main trend of the regional-scale structures (Fig.1b), thus displaying both NW- and NE-striking fault systems.

Kinematics was analysed overall for the NE-trending structures, being these latter the most recurring structures in the study area. Exposures suitable for kinematic analyses are rare, due to the lithological composition of the Ligurian Units mainly formed by shale with interbedded limestone beds. Nevertheless, continuous exposures of sandstone and marl levels were found on fresh-cuts along the main roads or within river incisions. More than 50 kinematic data points were collected from 3 structural stations in three field-work areas (see location in Fig.3).

In the sandstone and marly rocks of the Tuscan Nappe and Ligurian Units, respectively, the bulk of the mesoscale faults are characterized by a core zone up to 40 cm size, derived from the comminution of the damaged lithotypes (Fig.4). The fault damage zone is characterized by well-organized fracture networks defining meter sized domains, with different amount of deformation that decreases with distance from the core zone. Kinematic indicators are given by slicken-lines, calcite fibre steps and chatter marks (Fig.4), arrays of extensional jogs and T-fractures. Kinematic indicators on the NE-striking fault system show at least three superposed movements, in few structural stations (Fig.5). Movements range from strike-slip to oblique-slip even if dominant oblique- to normal components were recognized. In the basin-fill, fault slip surfaces are not so widespread due to the dominant clayey and sandy composition of the Neogene sediments. Fault surfaces with clear kinematic indicators were not recognized but clear NE-striking fault segments were analysed in an abandoned quarry nearby Castelfiorentino (Fig.6). Here, the bulk of the meso-faults affecting the unconsolidated sediments is characterized by apparent offsets of few decimetres and by a thin core (about 1 cm). Data on fault geometry and kinematics are reported in the diagram of figure 5.

Kinematic data from the measured fault surfaces can be used for paleo-stress analysis, graphically represented by double-couple fault-plane solution diagrams (Angelier, 1979).

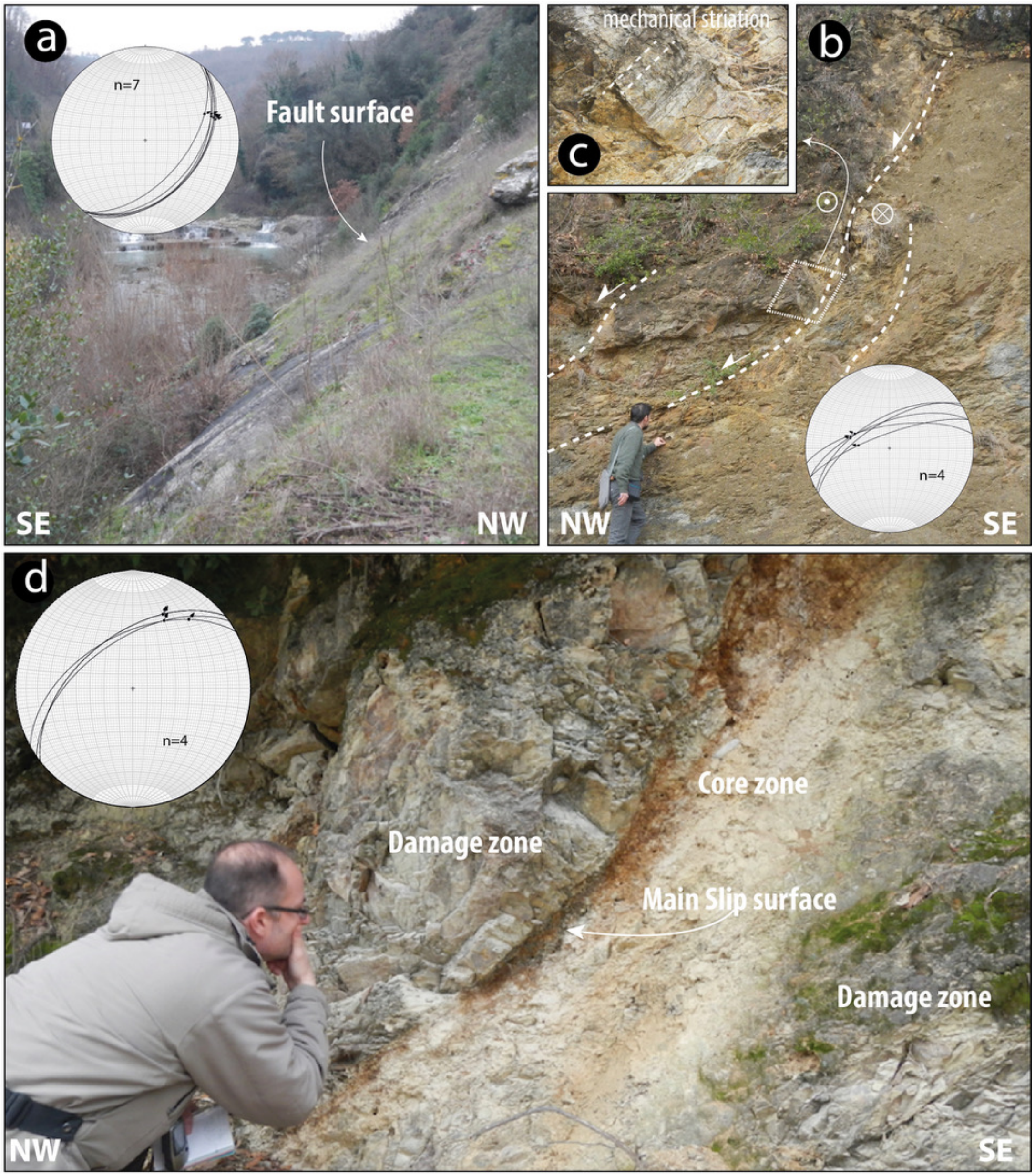

Fig. 4. Examples of mesoscopic-scale fault analysed north of San Casciano Val di Pesa (see Fig. 3 for location): (a) SE-dipping transtensional left-lateral fault affecting late Oligocene sandstone of the Tuscan Succession; (b) outcrop-scale transtensional left-lateral NW-dipping fault affecting alternated limestone beds and shale of the Ligurian units; (c) detail of the kinematic indicators in (b) showing transtensional left-lateral kinematics; (d) NW-dipping right-lateral oblique-slip fault zone showing a core c. 50 cm thick surrounded by metres-thick damage zone affecting marly limestone of the Ligurian units. Stereographic diagrams (lower hemisphere, equal area) indicate fault and striae measured in the fault surfaces shown in the photographs.

In figure 5 NE-striking oblique-slip faults with right- and left-lateral movements were analysed separately. Right-lateral faults display a maximum compressional axis about E-W trending. The minimum compressional axis is always almost sub-horizontal and about N-S trending. Left-lateral faults display a maximum compressional axis about N-S trending and a minimum compressional axis almost sub-horizontal and about W-E trending.

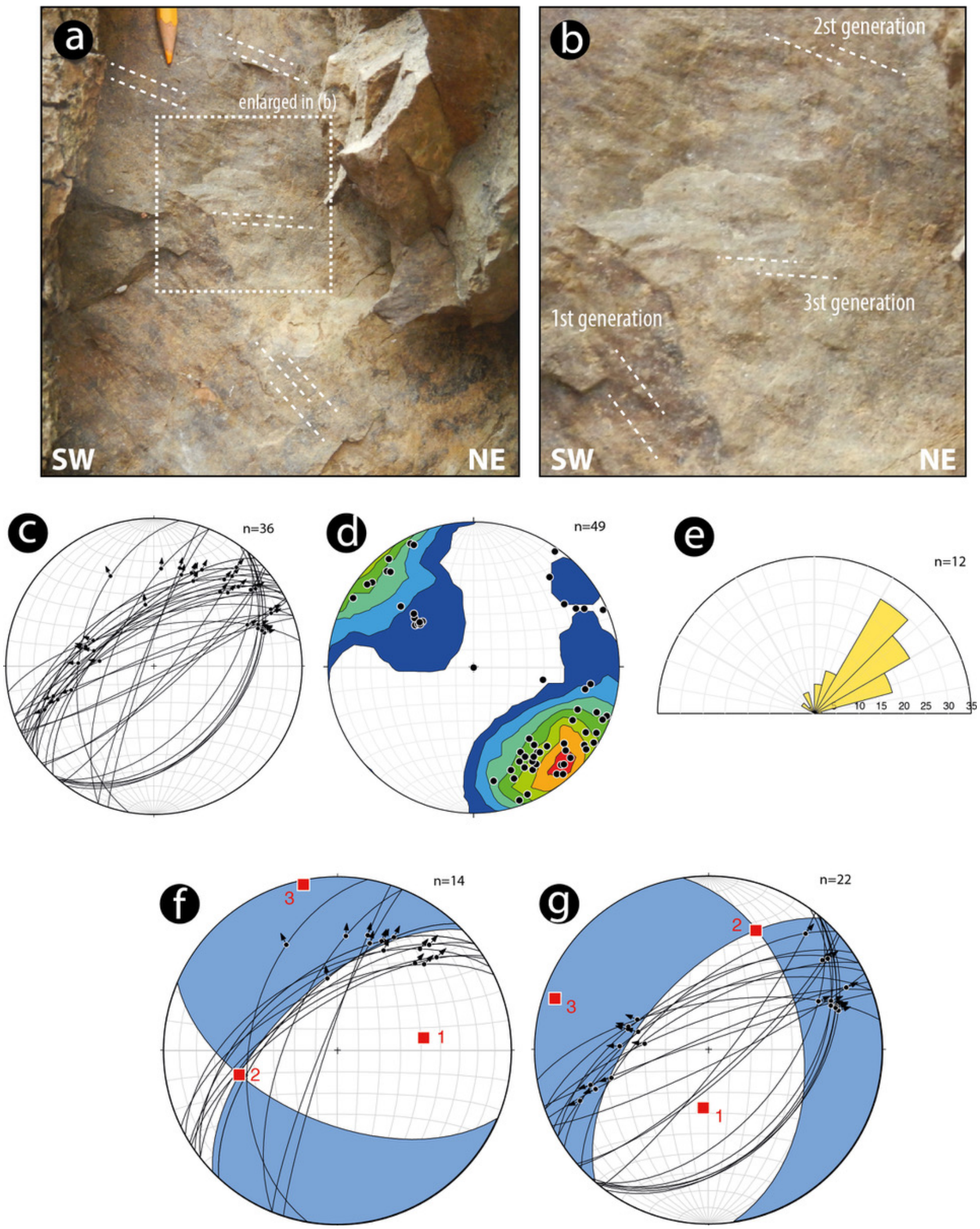

Fig. 5. a) Superposed kinematics indicators on a fault surface in late Oligocene sandstone north of San Casciano ValdiPesa(see Fig.3 for location);(b)detail of three generations of movements; (c) stereographic diagrams (lower hemisphere, equal area) indicating the representative fault and striae measured in the measured fault; (d) density contours of fault poles; (e) fault strikes rose diagrams; (f, g) palaeo-strain analysis using the right-diedra method (Angelier, 1979) obtained with Faultkin application (Marrett and Allmendinger, 1990; Allmendinger et al. 2012) showing fault-plane solutions and main kinematic axes.

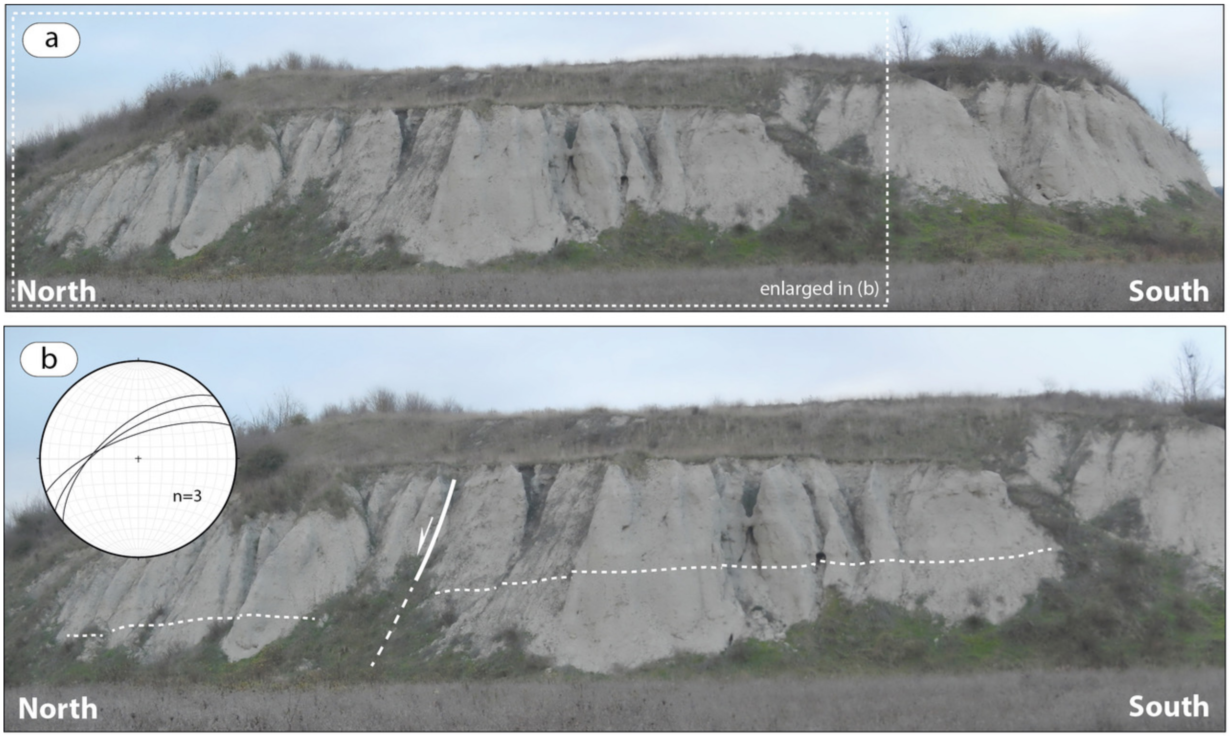

Fig. 6. NE-striking fault segments in an abandoned quarry near Castelfiorentino(see Fig.3 for location).The apparent offsets in the unconsolidated sediments are of a few decimetres and from a c. 1 cm thin core.

5.b. Interpretation of seismic lines and basin architecture

We considered a data-set of about 150 km of seismic data made of 12 seismic reflection profiles, acquired in the ’80 by Agip oil company (presently ENI) and 6 boreholes (see location in Fig.3). Some of these seismic profiles were interpreted in the past and some of them are already published (Pascucci et al., 2007; Benvenuti et al., 2014). The seismic lines are both longitudinal (NW-SE) and transversal (SW-NE) with respect to the trend of the basin and main geological structures and reach about 4 seconds TWT corresponding to about 6 km on the basis of the average subsurface velocities.

The quality of the seismic lines is very good in the upper 2s TWT due to the good penetration of the seismic signal and to the lithological characteristics of the basins infill being mostly made of both marine and continental sandy and clayey successions.

We interpreted the complete dataset and present four most representative seismic profiles, which image the subsurface geological setting of the area (Fig. 7 and Fig. 8).

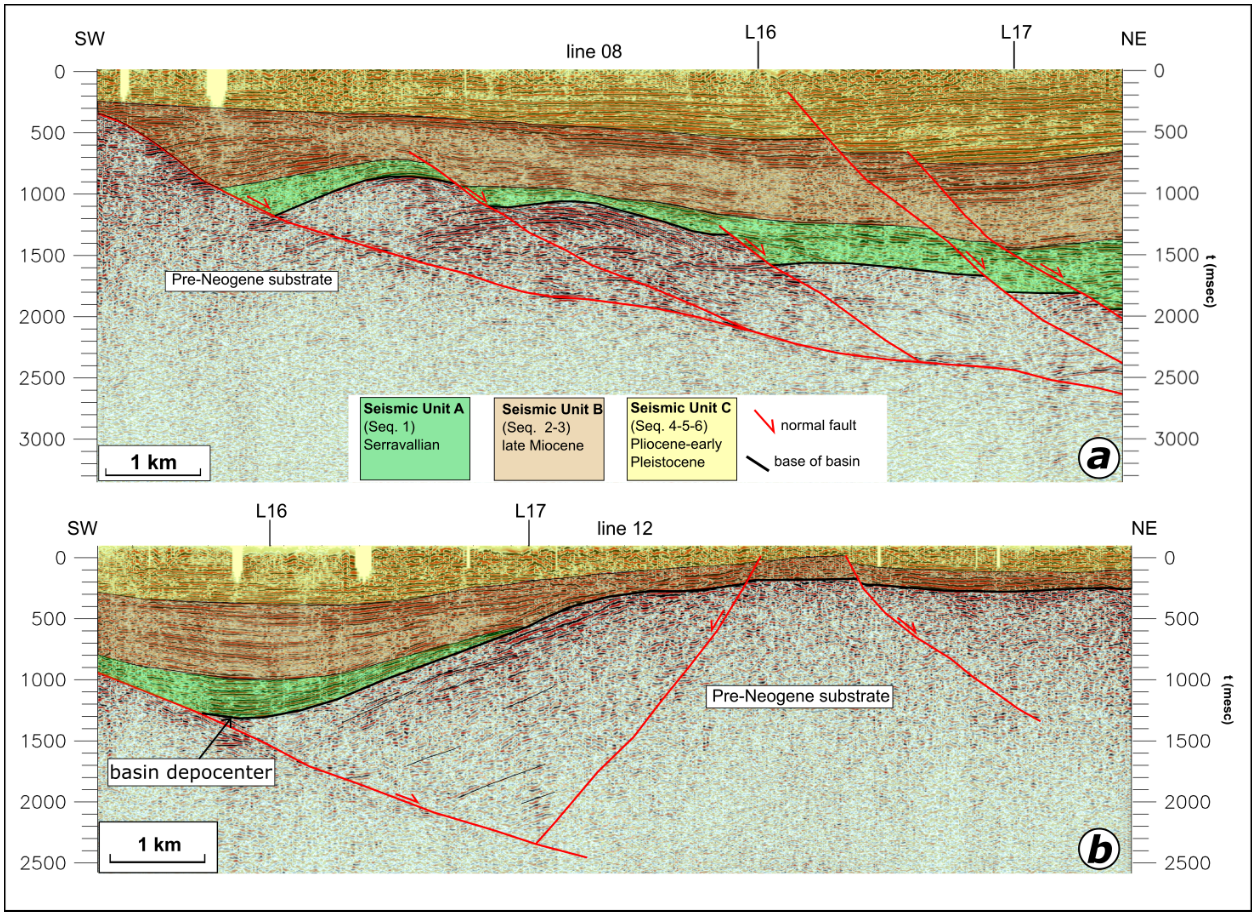

Fig. 7. Geological interpretation of seismic lines L8(a) and L12(b) (see Fig.3 for location) showing the deep geometry of the Valdelsa Neogene deposits and their relationships with the main extensional structures of the area.

The interpretation of the seismic data was calibrated with Monterappoli1-well, which is the closest to the study area (location in Fig.3). Also, the most representative wells of the area (Certaldo1, Certaldo2, Certaldo3, CertaldoSud1 and Certaldo4) were considered in order to have a better control on the later continuity of the drilled successions. The Monterappoli1 borehole (publicly available in the VIDEPI PROJECT database – https://www.videpi.com/videpi/pozzi/consultabili.asp) was projected onto the closest seismic profile (L17 in Fig.3) and the main lithological boundaries were associated to the corresponding reflectors. The association between the contacts encountered in the borehole and the seismic profile was made by using the stacking interval velocities, which were compared with the available data for these units (Bally et al., 1986; Buonasorte et al., 1988; Barchi et al., 1998). On these bases we consider two main velocity bodies, the Pliocene (Vp~2.6 km/s) and the Miocene (Vp~3.5 km/s). So, we make use of these interval velocities to estimate the depth and thickness of the sedimentary infill of the basin.

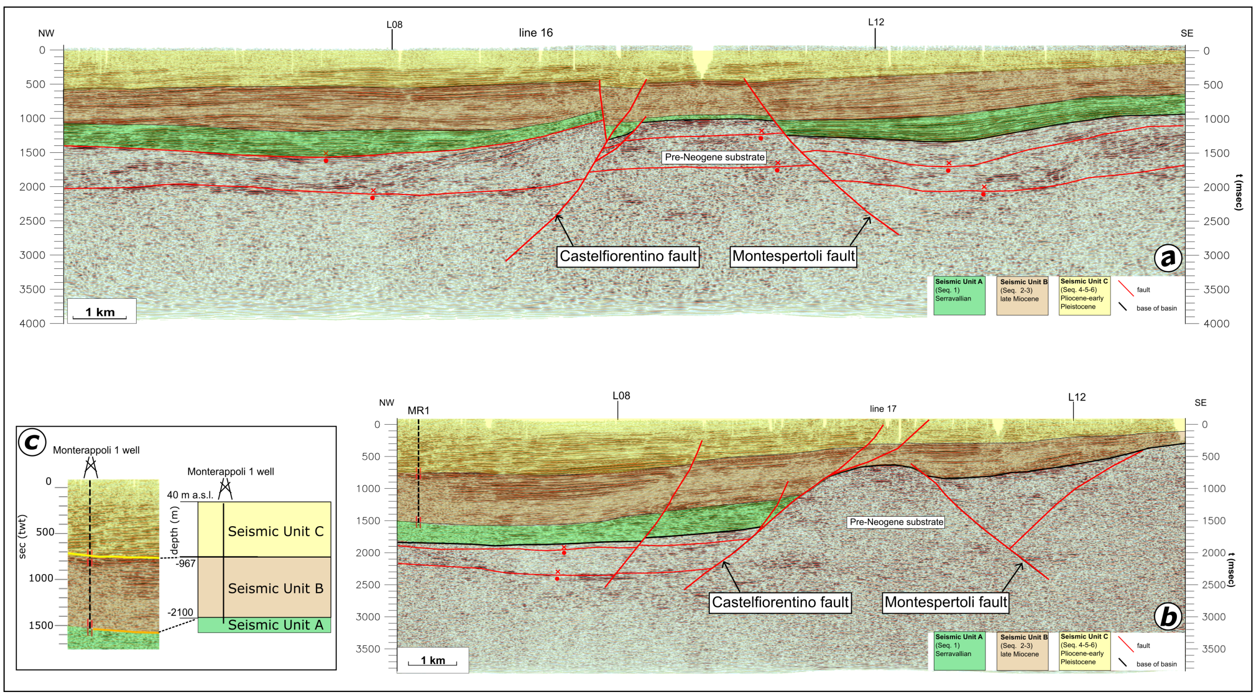

Fig. 8. Geological interpretation of seismic lines L16 (a) and L17 (b) (see Fig. 3 for location) showing the longitudinal deep geometry of the Valdelsa Neogene deposits and their relationships with two main faults (Castelfiorentino and Montespertoli), which controlled the most recent thickness of the Valdelsa infill. The position of the intersections with seismic lines L8 and L12 (Fig. 6) is also reported. The Castelfiorentino and Montespertoli faults interrupt the depth trace of the main normal faults of seismic lines L8 and L12 post-dating them. (c) Seismic stratigraphy of the Monterappoli-1 well and association with the seismic units (SU).

We identify three main seismic units of the Valdelsa Basin (Fig.2b), which are well identifiable in the seismic profiles and which we relate to the stratigraphic sequences described above and represented in figure 2b. From top to bottom, these are: i) Seismic Unit A (SU-A, Fig.2b) corresponds to the late Serravallian, continental to shallow marine Seq.1 sequence (Ponsano Fm); ii) Seismic Unit B (SU-B, Fig.2b) comprehends the Seq.2 and Seq.3 Tortonian-Messinian continental succession; iii) Seismic Unit C (SU-C, Fig.2b) includes Seq.4, 5, 6 and corresponds to the Pliocene marine deposits and the Gelasian continental ones.

On the basis of the extrapolation of the boundaries between the seismic units along the seismic profiles and the corresponding seismic profile intersections, we were able to draw a consistent interpretation of the subsurface geological setting of the area, synthetized in two transversal SW-NE trending seismic reflection profiles (line 8 and line 12, Fig.7a and Fig.7b) and two longitudinal NW-SE trending profiles (line 16 and line 17, Fig.8a and Fig.8b).

The oldest seismic unit is Seismic Unit A (SU-A), which in the seismic profiles is represented by light seismic facies with a series of well recognizable and continuous reflectors and few higher amplitude horizons (Fig.8c).

The intermediate seismic unit (Seismic Unit B, SU-B) is represented by a less light and transparent seismic facies and an upper part characterized by a set of well bedded and higher amplitude reflectors (Fig.8c) possibly representative of the more clayey upper Miocene lacustrine unit (Seq.3 in Fig.2b). The uppermost seismic unit (Seismic Unit C, SU-C) is represented by an alternation of continuous high amplitude layers and still continuous but lighter than the underlying deposits (Fig.8c).

The transversal profiles provide an image of the architecture of the extensional basins showing the presence of an ENE-dipping extensional detachment with associated synthetic splays and subordinate antithetic faults. The oldest unit at the normal faults hanging-wall is represented by the Serravallian Seq.1, which unconformably overlies the pre-Neogene substrate (Fig.7a). This sequence is not always present in the subsurface as shown by line 12 (Fig.7b) where in the central part of the section the substrate is overlaid directly by SU-B (probably only the upper Miocene lacustrine Seq.3).

The Neogene sediments reach a thickness in the order of 2 km progressively diminishing to few hundreds of meters.

The longitudinal seismic sections (Fig.8) provide an excellent image of the lateral continuity of the Neogene deposits from NW to SE. The seismic line 16 (Fig.8a), running SW of the line 17 (Fig.8b) and hence closer to the present-day Elsa river valley is the longest and shows the thinning of the sequences, especially of SU-A in correspondence of a pre-Neogene structural high bounded by two sub-vertical faults. The substrate structural high in the central part of the section is responsible for the thinning of the sequences, especially of SU-A and is bounded by a NW dipping and a SE dipping fault here named Castelfiorentino and Montespertoli faults, respectively. The Neogene deposits are much thicker SE of the substrate high and reach a maximum thickness in the order of 2 km.

The seismic line 17 (Fig.8b) shows that the same pre-Neogene structural high here is higher and causes all the seismic units and especially SU-A, to thin abruptly towards the SE. The maximum thickness of all the Neogene sediments is about 1.8s TWT, which corresponds to about 2 km on the basis of the available information on the seismic velocities. The thickness reduces to few hundreds of meters in the south-eastern part of the sections.

5.c. Seismological data

We relocated the two recent-most moderate earthquakes, which struck the area in 2014 and 2016, the Certaldo (2014) and the Castelfiorentino (2016) earthquakes.

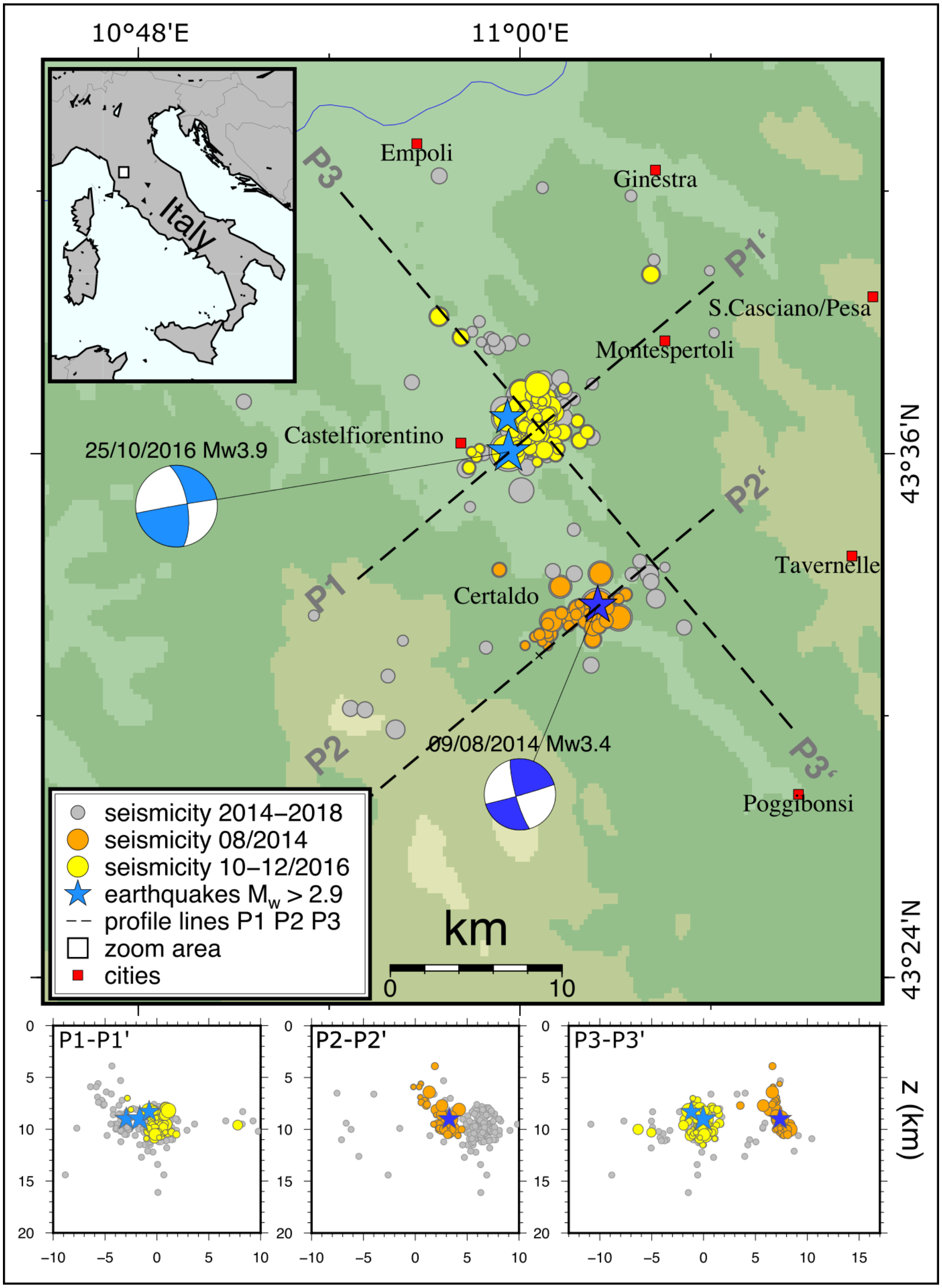

Fig. 9. Distribution of the 2014 Certaldo and 2016 Castelfiorentino seismic sequences relocated in this work, and the mainshock focal mechanisms showing either a dextral SW–NE-trending or a sinistral NW–SE-trending kinematics. The seismicity distribution at depth is imaged by the P1, P2 and P3 cross-sections.

5.c.1.The Certaldo seismic sequence (M 3.4 - 2014-08-09)

After a short foreshock sequence of eight hours, a seismic event of M 3.4 occurred in the central part of the Valdelsa Basin (near Certaldo, Fig.3 and Table 1) on 09/08/2014 at 13:47 UTC. The main shock was located at a depth of 9 km and was followed by a short-lived aftershock sequence of about 40 events, which ceased after less than one week. Due to the shallow hypocentral depths of 5-10 km, about a dozen earthquakes were felt by the population. The seismic source mechanism was calculated by first motion polarities, as well as Moment Tensor Inversion (MTI) and resulted as a pure double couple with the following parameters: strike 74°/slip 88°/rake 170° (Fig.9).

5.c.2. The Castelfiorentino earthquake (M=3.9 - 2016-10-25)

Two years later, a further seismic sequence of 160 events circa shattered the NW shoulder of the Valdelsa Basin (Fig.3). After isolated and sporadic events since January, during October 2016 the seismic activity increased significantly, culminating in the M 3.9 main shock 25/10/2016 at 16:53 UTC. The epicentre of the main shock was localized at Castelfiorentino, 10 km NNW with respect to the Certaldo sequence, at a hypocentral depth of 9 km. The calculation of the source mechanism, both, by the inversion of first motion polarities, as well as by MTI, led to a similar result as for the Certaldo main shock: strike 260°, dip 89, slip 158.

Both seismic sequences show striking similarities: the hypocentres of the main shock are located at about 9 km and also the fore- and aftershocks are confined in the upper crust. The source mechanisms of the main shocks are pure double-couples, with a predominant strike slip mechanism: nearly N-S (left lateral, P3) or rather E-W striking (right lateral P1, P2 in Fig.3), whose active fault plane cannot be irreproachably determined (Fig.9).

6. Results

By using the seismic velocities of the deposits, we converted to depth the two longitudinal sections and we drew two integrated geological cross-sections extrapolated down to about 5 km of depth in order to compare the subsurface geometries with the earthquake locations (Fig.10).

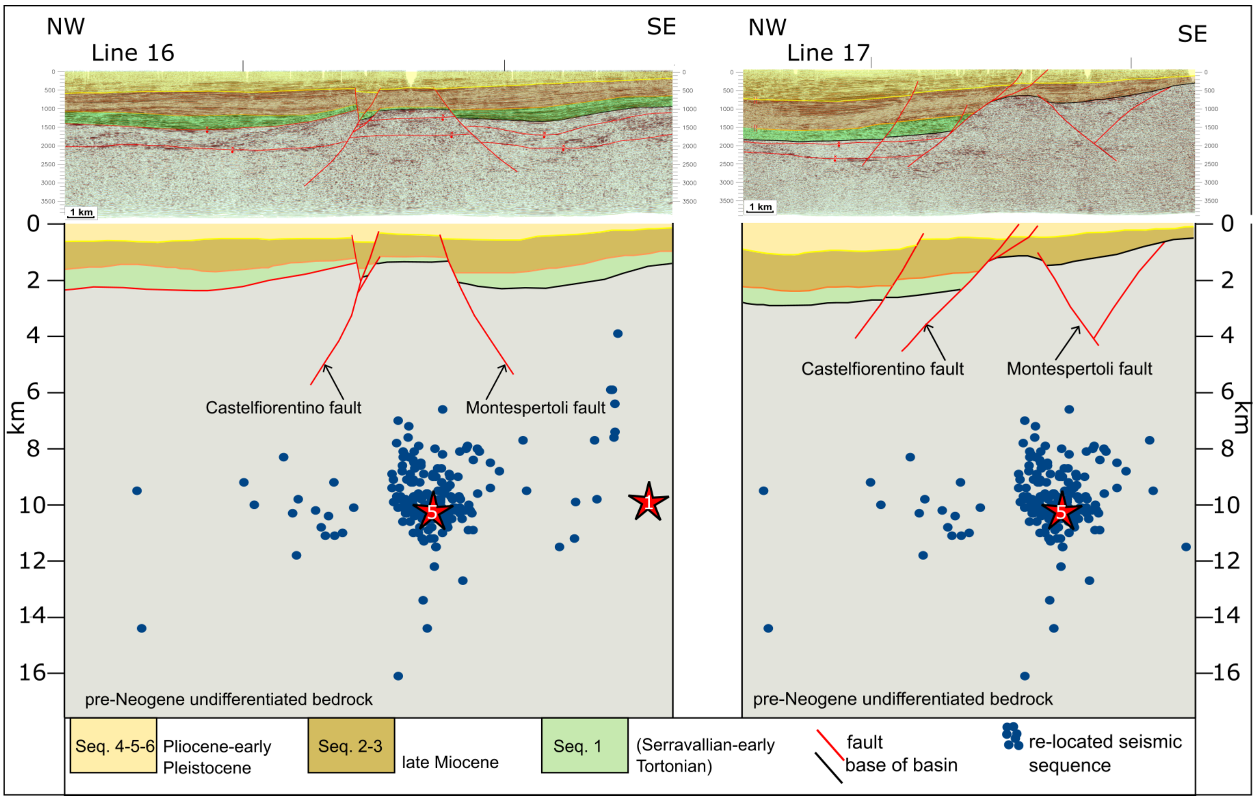

Fig. 10. (Colour online) Depth conversion of seismic lines L16 and L17 and projection of the relocated seismicity and mainshocks onto the depth-converted cross-sections. See text for details and data discussion.

The earthquakes are distributed at around 10 km of depth and do not show a clear planar geometry mostly as a consequence of their small intensity and of the fact that they are not associated to a moderate or a strong event during which a set of hundreds or thousands of aftershocks develop and are often aligned along planes, which are associable to the main fault rupture (for example, see Latorre et al., 2016; Valoroso et al., 2017; Michele et al., 2020 among others). Nevertheless, the relocated earthquakes plotted onto the geological section show that seismicity is located below the Castelfiorentino and Montespertoli faults at similar depth for both sequences (Certaldo 2014, M=3.4 and Castelfiorentino 2016, M=3.9), even if slightly shifted below the Montespertoli fault (Fig.10).

The resolution of the seismic reflection profiles does not allow to see offsets younger than the early Pliocene, so order to verify the possible role of the SW-NE striking Castelfiorentino and Montespertoli faults in controlling the Neogene basin dimension or in displacing its position, we mapped both the Neogene depocenter throughout the whole seismic lines data-set and the surface projection of the SW-NE striking Castelfiorentino and Montespertoli faults foot-wall cut-offs (see Fig.8a and 8b) with the substrate (the base of basin deposits).

The results are illustrated in figure11. The map shows the seismic lines dataset and the position of the surface projection of these two key-elements. It can be observed that the faults cut-offs projection at surface depicts the Castelfiorentino and Montespertoli faults strike, which is SW-NE, about N40°.

The Castelfiorentino and Montespertoli faults border a structural high (Castelfiorentino High of Benvenuti et al., 2014) constituted by the pre-Neogene substrate with a steep to sub-vertical geometry in cross-section (Fig.10). At surface, the Certaldo and Montespertoli faults show a trend of about N40° similar to the strikes of the focal mechanisms of both the Certaldo and Castelfiorentino earthquakes (Fig.9).

The position of the Neogene depocenter provides interesting points of discussion. The first thing to observe is that the present-day Elsa River is systematically shifted to the west with respect to the Neogene depocenter (Fig.11). A similar situation was previously observed for the northeastern Quaternary basins of the Tiber River (Pucci et al., 2014) and interpreted as due to the continuous activity of the basin-bounding normal faults and in particular to the NE-dipping normal faults. The second observation is that the alignment of points corresponding to the position on the Neogene depocenter in the seismic profiles is not continuous along a NW-SE direction but is divided into two parts and shifted right-laterally in correspondence with the valley connecting the Elsa River and the village of Montespertoli, between seismic lines L11 and L12 (Fig.11). This shift also corresponds to the foot-wall cut offs alignment of the Montespertoli fault.

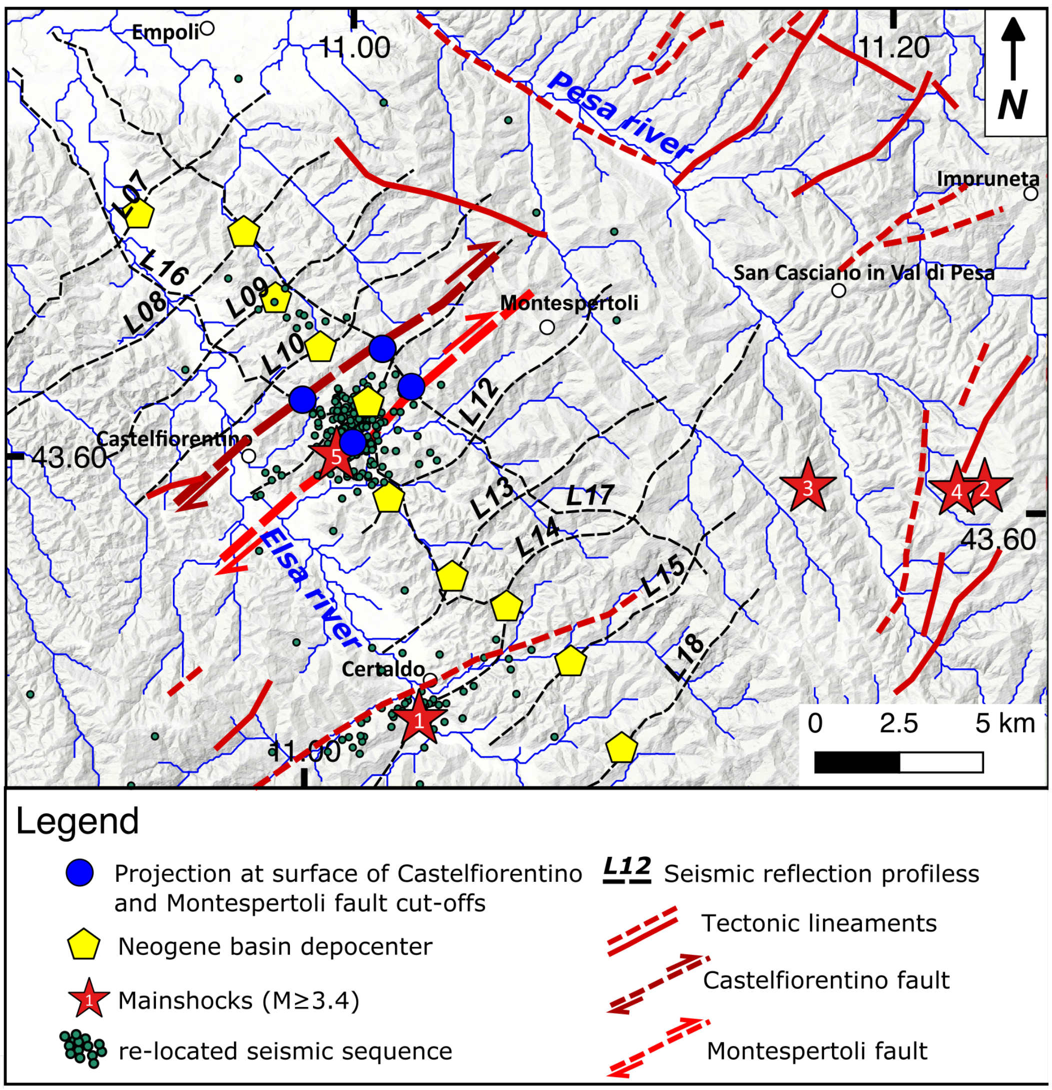

Fig. 11. Surface projection of the pre-Neogene substrate fault footwall cut-offs (blue circles), of the Neogene basin depocentre and the relocated seismicity. The figure shows the relationship between the distribution of seismicity, the Castelfiorentino earthquake position and dextral shift of the Neogene basin depocentre suggesting that the Montespertoli fault (thick red dotted dextral fault) was responsible for the 2016 seismic sequence. Both the Castelfiorentino and the Montespertoli fault trends agree with the other SW–NE trending of the region.

These observations indicate that: i) the Valdelsa Basin Neogene deposition is controlled by the NW-SE trending normal faults clearly visible in the seismic reflection profiles (Fig.7); ii) extension was accommodated mostly by the NE-dipping faults, which were able to progressively drag the depocenter to the NE and at the same time to maintain the Elsa River at its position, at the normal fault hanging-wall; iii) there occurred a later deformation ascribable to a SW-NE trending fault, which displaced the Neogene depocenter original trend. According to the above-mentioned points we suggest that the SW-NE striking Montespertoli fault is mostly capable of shifting the depocenter of the basin horizontally by about 1.2 km with right-lateral kinematics (Fig.11). Given the fault geometry, which dips to the SE, the resulting movement would be right-lateral or slightly transtensional.

The observation of the drainage pattern distribution of the study area seems in agreement with a fault control on the river network. The drainage pattern is mostly oriented SE-NW and associated to the Elsa and Pesa rivers (Fig.11). Few areas, where the rivers show a significant deviation from the dominant SE-NW trend, differ in terms of drainage orientation and display tight curves along a SW-NE direction of flow. The three most evident SW-NE alignments in the study area are along the previously mentioned Piombino-Faenza Line to the south, along the Certaldo-S. Casciano in Vall di Pesa area and along the Castelfiorentino area (Fig.11).

According to the seismic sequence relocation and the 2016 Castelfiorentino focal mechanism solution we suggest that the fault, which ruptured in 2016 strikes SW-NE with a right-lateral kinematics corresponds to the Montespertoli fault. Similarly, we propose that 2014 Mw=3.4 earthquake could have activated another SW-NE trending fault belonging to the same fault segments pertaining to the Piombino-Faenza lineament. The same fault and/or fault segments may be responsible for the other earthquakes in the area, especially for the 2015 Tavarnelle in Val di Pesa, Mw=3.7 event.

At surface, these faults are parallel to the fault segments analysed in the eastern shoulder of the basin, in the Impruneta – San Casciano in Val di Pesa surroundings (Fig.11). Similarly, the identified faults are parallel to the "Piombino-Faenza" shear zone, therefore implying their reasonable genetic relation.

7. Discussion

The widespread seismicity recorded in the SE sector of the Valdelsa Basin, with hypocentral distribution ranging from focal depths from 8 to 12 km (Fig.10), supports for the existence of active NE-striking fault segments in the central-southern sector of the basin. Faults related to the seismic events were identified in the presented seismic profiles (Fig.7, 8) and delimit a NE-trending structural high buried underneath the Pliocene sediments. These faults did not directly rupture the topographic surface indicating that the fault segments are characterized by small offsets, as also supported by the low-magnitude seismicity. The analysed fault segments in the basin shoulder, in fact, highlight meters or decametres off-sets and show mineralization on the fault planes (e.g., calcite slickenfibers, Figs.4-6). This evidence supports for a fault activity occurred at deeper structural levels, implying that the studied fault zones were progressively uplifted and exhumed after their development, hence testifying their long-living activity. Nevertheless, these structures although indicating a variable kinematics through-time, show dominant NE-striking strike- to oblique-slip movements, comparable with the focal mechanisms of the seismic events (Fig.9). This supports the fact that the Certaldo and Castelfiorentino faults, along which the 2014-2016 hypocentres are localized, are part of a long-living fault system inherent to the “Piombino-Faenza” shear zone. In this view, a Neogene-Quaternary activity under the same regional stress field can be envisaged to promote exhumation of the basin shoulders and the segmentation of the basin. In fact, both the NE- and NW- striking faults controlled the development of the Valdelsa Basin (Pascucci et al., 1999) as well as the whole Neogene structural depressions of the inner Northern Apennines (Martini and Sagri, 1993). NW-striking faults controlled the development of the structural depression while the NE-striking ones accommodated the different amount of extension (i.e. transfer zones).

The age and role of transversal lineaments in the Northern Apennines have long been discussed (e.g., Fazzini and Gelmini, 1982; Bemporad et al., 1986; Liotta, 1991; Pascucci et al., 2007) and their impact in controlling low-magnitude earthquakes has also been highlighted for the northern Tuscany (e.g., Molli et al., 2021). Many of these “lineaments” are ascribed to the presence of lithotypes, which react differently to erosion as it could be the case of the “Piombino-Faenza line”. Nevertheless, the here documented Certaldo-S. Casciano in Val di Pesa and Castelfiorentino lineaments do not show any direct connection with lithology or bedding attitude and could be only related to the presence of SW-NE trending tectonic structures, as also supported by the seismicity concentrated along their traces.

On the other hand, both NE- and NW-striking faults seem to have controlled the orientation of the main river/stream valleys in the whole basin (Fig.3). In our case, the two NE-trending lineaments correspond to relevant NE-SW river alignments, along which geothermal manifestations are present (see Fig.3), supporting their connection with both a tectonic origin and a crustal relevance also in controlling the geothermal fluids circulation. Interestingly, a tectonic control on the river network of the same area was early recognized by Canuti et al. (1975), though not framed into an active tectonic significance of the river anomalies.

The collected kinematics coupled with information from the focal mechanisms related to the local seismicity indicate that the two orthogonal faults acted mainly as normal faults (NW-striking) and strike-slip/oblique-slip faults (NE-striking) and this interplay accounts for an extensional evolution of the basin (Martini and Sagri, 1993; Pascucci et al., 1999). A different scenario was proposed by Benvenuti et al. (2014) that, although similarly depicting the occurrence of “basin-transverse lineaments” separating the Valdelsa Basin in two sub-basins, suggest that the whole basin was strictly controlled by NW-trending regional thrusts that controlled the depocentres location as well as the sedimentation. The interplay between compressional tectonics and eustatic sea-level fluctuations are invoked as dominant factors forcing the deposition of sedimentary cycles at the basin scale. In this scenario, the Valdelsa Basin is not considered an extensional basin but a thrust-top basin developed during compressional tectonics since the Late Miocene. This hypothesis is in line with those sustained by some authors (e.g. Boccaletti et al., 1999; Bonini and Sani, 2002; Finetti, 2006), who refer the Neogene-Quaternary tectonic evolution of the Tuscany strictly controlled by unceasing compressional tectonics active since Late Cretaceous and giving rise to different generations of thrusts and back-thrusts and associated thrust-top basins (e.g. Bonini et al., 2001; Finetti et al., 2001).

Our data are in contrast with the hypothesis of Benvenuti et al. (2014) and support a different structural and kinematic scenario. The fault kinematics in the exhumed basin shoulder accounts for Neogene-Quaternary normal and strike-/oblique-slip faults. Thrusts occurrence is only suggested by the stacked units forming the orogenic pile, but these tectonic contacts, interpreted as low-angle normal faults by other authors (Carmignani et al., 1994; Liotta et al., 1998), are dissected by both NE- and NW-trending faults occurring at the basin scale and documented in this paper. So, in our point of view, a Neogene-Quaternary extensional evolution can better explain the setting of the Valdelsa Basin and therefore its seismotectonic framework and the overall thinned crust well documented by geophysical data-sets (e.g. Pauselli et al., 2006). Along the same line, the reasons why the geological evolution of the Valdelsa Basin and the whole inner Northern Apennines is better framed in an extensional setting instead of a compressional one is reported in some papers (Brogi et al., 2005; Brogi and Liotta, 2008; Barchi, 2010; Liotta and Brogi, 2020; Brogi, 2011, 2020) to which the readers are addressed for a more exhaustive discussion.

The NE-striking faults, both exposed and inferred by seismological analyses (Fig.9) are parallel to the Piombino-Faenza Line regional structure (Fig.1b), a first-order structure crossing the whole Northern Apennines (Ambrosetti et al., 1978; Boccaletti et al., 1985) and interpreted, in the inner zone, as a kilometre-wide, crustal-scale transfer-zone accommodating extension since Late Miocene (Liotta, 1991; Dini et al., 2008; Liotta et al., 2015). The geometry and kinematics of the fault segments forming this transfer zone were constrained in the Larderello geothermal area, to the south-west of the study area (Fig.1a), where such structure is playing a fundamental role in controlling fluid-flow, heat flux and magma emplacement at depth (Gola et al. 2017; Liotta and Brogi, 2020). Similarly, to the study area, in the Larderello geothermal area the fault segments were active during the Neogene and are still active (Liotta and Brogi, 2020 for a review), as indicated by the localized low-magnitude seismicity (Batini et al., 1985; Albarello et al., 2005; Bagagli et al., 2020).

The kinematics of these transfer zone is the result of superimposed movements though the Neogene-Quaternary, as a consequence of the role of this structure in separating crustal sectors with different amount of extension and differentiated uplift (Liotta and Brogi, 2020). It derives that the fault segments forming the transfer zone are characterized by multiple kinematics, ranging from strike-slip to normal, also with intermediate kinematics. Similar evidences were documented for several transfer zones in the whole inner Northern Apennines (e.g., Brogi et al., 2013; Liotta et al., 2015), producing seismicity (Buonasorte et al., 1991; Brogi and Fabbrini, 2009; Brogi et al., 2012; Piccardi et al., 2017; Brogi et al., 2020). This is also the same evidence we observe for the NE-striking faults exposed in the study area.

This work, even though regarding relatively small magnitude events, evidences the importance of integrating different datasets and approaches to identify active or potentially active faults. Their recognition is fundamental in particular for those areas characterized by historical earthquakes, but without recent events. In these areas, characterized by high vulnerability, which show great exposure of both human lives, infrastructures and historical heritage, the definition of such potentially active faults plays a fundamental role in the definition of the seismic hazard and the prevention and conservation of the historical and artistic heritage. Italian examples are represented by important cultural artistic centres as Assisi and Norcia in Northern Apennine, that are located close to recognized seismogenic faults and historically suffered of repeated damages due to strong earthquakes (see, for instance the seismic sequences of Colfiorito 1997-98, L'Aquila 2009; Ferrara 2012, Norcia 2016).

In the study area the city of Florence and its surroundings, a worldwide know UNESCO site was characterized by a M=5.4 event (18/05/1895), which though being of a moderate magnitude, caused important damage (Cioppi, 1995; Guidoboni e Ferrari, 1995) and to which no causative fault is still mapped.

Our study suggests that the recognized faults could be related to NE-SW alignments potentially connected to the 1895 event, which damage maps indicate a possible SW-NE alignment (Cioppi, 1995). However, detailed and modern studies would be needed in order to understand the active tectonics indicators, which must be hidden in both surface and subsurface geological evidence of the area.

8. Conclusions

We identify a long-living Miocene-Holocene SW-NE trending fault system in southern Tuscany, which affects the Neogene Valdelsa Basin developed at the hanging-wall of NW-SE trending normal faults. The SW-NE trending fault system played the role of transfer zone since Miocene and consists of both exhumed and blind, still active, fault segments. Through a multidisciplinary approach, integrating surface kinematic data, subsurface geophysical and geological data and the relocation of seismological data we identify a previously unknown active fault (Montespertoli faults) not reaching the topographic surface, which we interpret as responsible for the 2016 Castelfiorentino (M=3.9) earthquake (western Northern Apennines of Italy). Despite the relatively small magnitude of the event, the Montespertoli fault is part of the much wider SW-NE striking crustal shear zones developed across the western part of the Italian peninsula (the Livorno-Sillaro and Piombino-Faenza tectonic lineaments, Fig.1b) that have also controlled the tectono-sedimentary evolution of the Neogene-Quaternary basins since Middle-Upper Miocene (Bossio et al., 1993a). This crustal shear zone controlled also the emplacement of felsic magmatic intrusion since the Pliocene (Farina et al., 2010) and still controls the seismicity and geothermal circulation in the Larderello area (Liotta and Brogi, 2020), therefore revealing its seismotectonic relevance.
We suggest that the earthquake that stroke the historical town of Firenze in 1895 (M=5.4) and which caused severe damage to both building and art may have been linked to the same NE-striking crustal shear zone.

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Figure captions:

Figure 1. a) Tectonic sketch of the Inner Northern Apennines (Central Italy) showing the relationships between the SW-NE lineaments, the Neogene-Quaternary basins and the intrusive magmatic bodies;

b) Geological map of the Valdelsa Basin with the main SW-NE trending lineaments, the historical seismicity (equivalent magnitude Me>4.5), and the 2014-2016 mainshocks relocated and discussed in this work. Within the map, the Valdelsa Neogene deposits are numbered from Sequence 1 to Sequence 6 for further reference in the text. MTR: Middle

Tuscan Ridge; CRT: Certaldo Sub-Basin; CVE: Colle Val d'Elsa Sub-Basin; CSN: Casino Basin.

Figure 2. a) Sketch of the tectonic units of the inner Northern Apennines and of their relationship with the Valdelsa basin infill; TM - Triassic Verrucano siliciclastics Group and Jurassic– Eocene metasedimentary cover; Ta - Late Triassic evaporite; Tc-Td - Cretaceous–Early Miocene clayey and arenaceous succession; La - Jurassic oceanic crust (peridotites, gabbros and basalts); Lb - sedimentary cover made of Jurassic radiolarite and Cretaceous shale, clayey marl and limestone; Lc - S. Fiora Unit composed of Cretaceous–Eocene clayey-marly and arenaceous succession

b) Sequence stratigraphic subdivision of the Neogene succession present in Valdelsa Basin and based on the distinctions proposed by Pascucci et al. (2007). It results composed by the superposition of marine (Seq. 1, 4, 5) and continental (Seq. 2, 3, 6) sequences characterized by variable thickness and lithological composition. To the right the sequences are grouped in relation to the Seismic Units (SU) shown later in the article, Sequences are locally divided by unconformities (thicker undulated lines). More details are discussed in the text.

Figure 3. Geological map of the study area (location in figure 1b) showing the distribution of the Neogene deposits, the position of the 2014-2016 mainshocks, the position of the subsurface data used for the subsurface reconstruction (boreholes and seismic reflection profiles). Key to borehole numbers: 1 = Monterappoli1; 2 = Certaldo2; 3 = Certaldo3; 4 = Certaldo4; 5 = Certaldo1; 6 = CertaldoSud1.

Figure 4. Examples of mesoscopic scale fault analysed north to San Casciano Val di Pesa (see Fig.3 or location): a) SE-dipping transtensional left-lateral fault affecting late Oligocene sandstone of the Tuscan Succession; b) outcrop-scale transtensional left-lateral NW-dipping fault affecting alternated limestone beds and shale of the Ligurian Units; c) detail of the kinematic indicators in b) showing transtensional left-lateral kinematics; d) NW-dipping right-lateral oblique-slip fault zone showing a core about 50 cm thick surrounded by meters thick damage zone affecting marly limestone of the Ligurian Units. Stereographic diagrams (lower hemisphere, equal area) indicate fault and striae measured in the fault surfaces shown in the photographs.

Figure 5. a) Superposed kinematics indicators on a fault surface in late Oligocene sandstone north to the San Casciano Val di Pesa, see Fig.3 for location and the text for more details; b) detail of three generations of movements; c) stereographic diagrams (lower hemisphere, equal area) indicating the representative fault and striae measured in the measured fault; d) density contours of fault poles; e) fault strikes rose diagrams; f), g) paleo-strain analysis using the right-diedra method (Angelier, 1979) obtained with Faultkin application (Marrett and Allmendinger, 1990; Allmendinger et al., 2012) showing fault-plane solutions and main kinematic axes.

Figure 6. NE-striking fault segments in an abandoned quarry nearby Castelfiorentino (see location in Fig.3). The apparent offsets in the unconsolidated sediments are of few decimetres and by a about 1 cm thin core.

Figure 7. Geological interpretation of seismic lines L8 (a) and L12 (b) (see figure 3 for location) showing the deep geometry of the Valdelsa Neogene deposits and their relationships with the main extensional structures of the area.

Figure 8. Geological interpretation of seismic lines L16 (a) and L17 (b) (see figure 3 for location) showing the longitudinal deep geometry of the Valdelsa Neogene deposits and their relationships with two main faults (Castelfiorentino and Montespertoli), which controlled the recentmost thickness of the Valdelsa infill. The position of the intersections with seismic lines L8 and L12 (figure 6) is also reported. The Castelfiorentino and Montespertoli faults interrupt the depth trace of the main normal faults of seismic lines L8 and L12 post-dating them. c) Seismic stratigraphy of the Monterappoli-1 well and association with the Seismic Units (SU).

Figure 9. Distribution of the 2014 Certaldo and 2016 Castelfiorentino seismic sequences relocated in this work and the mainshock focal mechanisms showing either a dextral SW-NE trending or a sinistral NW-SE trending kinematics. The seismicity distribution at depth is imaged by the P1, P2 and P3 cross-sections.

Figure 10. Depth conversion of seismic lines L16 and L17 and projection of the relocated seismicity and mainshocks onto the depth-converted cross-sections. See text for details and data discussion.

Figure 11. Surface projection of the pre-Neogene substrate fault foot-wall cut-offs (blue circles), of the Neogene basin depocenter and the relocated seismicity. The figure shows the relationship between the distribution of seismicity, the Castelfiorentino earthquake position and dextral shift of the Neogene basin depocenter suggesting that the Montespertoli fault (thick red dotted dextral fault) was responsible for the 2016 seismic sequence. Both the Castelfiorentino and the Montespertoli fault trends agree with the other SW-NE trending of the region.

Table 1 Mainshocks within the study area

Date	Time	Lat [°N]	Lon [°E]	Dep [km]	Magnitude		location
09/08/2014	13:47:49	43.5367	11.0358	9.9	Mw	3.4	1. Certaldo
19/12/2014	10:36:31	43.6058	11.2405	8.6	Mw	4.1	2. Greve in Chianti
04/03/2015	00:00:04	43.6038	11.1753	9.2	Mw	3.7	3. Tavarnelle Val di Pesa
13/09/2015	01:04:35	43.6047	11.2303	8.9	ML	3.8	4. Tavarnelle Val di Pesa
25/10/2016	16:53:01	43.6063	11.0007	10.2	Mw	3.9	5. Castelfiorentino

Tab.1: Relevant mainshocks occurring in the period August 2014 to November 2016 in the study area (after http:/terremoti.ingv.it). The "Certaldo" (1) and "Castelfiorentino" (5) event are discussed in more detail on the text and their focal solution is shown in figure 9.