NEOGENE 3D-STRUCTURAL ARCHITECTURE OF THE NORTH-WEST APENNINES: THE ROLE OF THE LOW ANGLE NORMAL FAULTS AND BASEMENT THRUSTS

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ABSTRACT

The northern Apennines of Italy are a classical site for studying fundamental issues in tectonic studies, such as ophiolite formation and emplacement, kinematics of thrust wedges, role of in- and out-of-sequence thrusting, and of along strike segmentation, syn-orogenic versus post-orogenic extension, interplay between tectonics, erosion and sedimentation etc. Accordingly, the northern Apennines have been extensively studied since more than two centuries ago. Despite the huge amount of available data with different resolution, a 3D comprehensive regional view combining in a modern framework all available surface and subsurface information for contiguous sectors of the chain is still lacking. We performed such an attempt in the area framed between the Taro valley to the north and the northern termination of the Alpi Apuane to the south. The region includes the main morphostructural zones of the North-West Apennines from the Tyrrhenian coast (SSW of La Spezia), through the main topographic divide of the Apennines, up to the foothills range of the chain to the north. The area has been investigated through a multidisciplinary approach that integrated surface geological data, collected during the last two decades of structural and stratigraphic field works, and subsurface geological data. The construction of two regional NE-SW trending cross-sections (the Levanto-Pontremoli-Parma to the north and the La Spezia-Sarzana-North Apuane-Cerreto to the south), intersected by a NW-SE trending Taro-Lunigiana-Alpi Apuane composite section, allowed us to illustrate (i) the role of out-of-sequence blind thrusting in the basement, (ii) the presence of low-angle normal faulting and its relationships with recent to active high-angle normal faulting. Both extensional and contractional systems have relevant implications for the tectonics of the northern Apennines as well as the seismotectonics of the studied region.

Key words:

Low-angle normal faults, high-angle normal faults, basement thrusts, orogenic wedge kinematics, northern Apennines, Alpi Apuane, Lunigiana.

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Highlights:

We present 3D frame for surface and subsurface structures of the North-West Apennines

We supply a more precise definition of the deep Apenninic tectonic structures focusing on the role of “basement” units and their characterization

We present a new outline of the shallower portions of the nappe stack by definition of the geometries of Low-Angle Normal Faults (LANFs) and their relationships with the High-Angle Normal Faults (HANFs)

We emphasise the role of blind basement thrusts, the architecture of LANF-systems and overprint relationships with recent- to-active HANFs

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1. INTRODUCTION

The recognition of extensional structures and low angle normal faults (LANFs) in contractional orogens (Molnar & Tapponier, 1978; Burg et al., 1984; Platt, 1986; Malavieille, 1987; Selverstone, 1988; Ratschbacher et al., 1989; Carmignani & Kligfield, 1990; Wheeler & Butler, 1993; Ring et al., 1999) has opened new ways of interpretation and understanding of the orogenic processes and of mountain belt evolution. The association and the interplay between extensional and contractional structures have been connected to the different stages of orogen growth, from the early intrawedge evolution to the late- and post-collisional stages (e.g. Jolivet et al., 1990; Malavieille & Taboada, 1991; Burchfiel et al., 1992; Crespo Blanc et al., 1994; Doglioni, 1995; Vissers et al., 1995; Froitzheim et al., 1997; Ring et al., 1999; Xiapolias & Doutsos, 2000; Whitney et al., 2013). In the different tectonic frames, LANFs occurences have been heatedly debated for their role in the stretching of the continental crust, the exhumation of the metamorphic rocks, for their kinematics and related strain features as well as for their original geometric and seismotectonic characters (e.g. Wernicke, 1981; Lister & Davis, 1984; Jackson, 1987; Abers, 1991; Armjo et al., 1996; Jolivet et al., 2003; Collettini et al., 2004; Manatschal et al., 2007). In the circum-Mediterranean orogens extensional processes have been widely recognized as playing a major role in shaping the regional architecture and the kinematic history of different mountain belts (Dewey, 1988; Platt & Vissers, 1989; Durand et al. 1999; Oldow et al., 1993; Crespo Blanc et al., 1994; Lonergan & White, 1997; Jolivet et al., 1999; Faccenna et al., 2001; Papanikolaou & Royden, 2007; Rossetti et al., 2008; Mazzoli et al., 2008; Papanikolau et al., 2009; Handy et al., 2010; Ustaszewski et al., 2010; Tirel et al., 2013; Van Hinsbergen & Schmid, 2012; Jolivet et al., 2013). In this frame, since the seminal paper of Elter et al. (1975), the northern Apennines have represented a key orogen for analyzing the syn-convergence extensional processes and related structures (Malinverno and Ryan, 1986; Royden et al. 1987; Patacca et al., 1990; Doglioni, 1991; Carmignani et al., 1995; Jolivet et al., 1998; Barchi et al., 1998; Fellin et al., 2007; Thomson et al., 2010; Mirabella et al., 2011; Carminati, Doglioni, 2012; Le Breton et al., 2018 and references therein).

Nevertheless, in contrast to the northeast frontal reaches of the chain (Artoni et al., 2010, 2014; Bonini et al., 2014; Cuffaro et al., 2010; Fantoni et al., 2010; Mosca et al., 2010; Picotti and Pazzaglia, 2008; Scrocca et al., 2013; Turrini et al., 2016), the western inner northern Apennines although deeply investigated (Reutter et al., 1978; Carmignani and Kligfield, 1990; Decandia et al., 1998; Plesi et al., 1998; Baldacci et al., 2001; Vai and Castellarin,

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2001; Cerrina Feroni et al., 2002) still lack a 3D comprehensive regional view combining all available surface and subsurface information for the different sectors of the chain.

The general architecture of the northern segment of the mountain belt as figured since the early 60's by Elter (1960) and Zanzucchi (1963) represents a still valid first order regional sketch which, however, is basically cylindric in its conceptual view (Elter, 1960) and does not include or take into account structural features documented in more recent geological literature (e.g. Carmignani & Kligfield, 1990; Vescovi, 1993; Argnani et al., 1997; Cerrina Feroni et al., 2003; Vescovi, 2005; Picotti & Pazzaglia, 2008; Carlini et al., 2013; Clemenzi et al., 2015).

The geometries and 3D architecture of low angle normal faults shaping the present-day nappe stack, their activation timing and relationships with the recent to active tectonic structures are not, for instance, well documented yet. Moreover, the role of blind basement thrusts, their overall subsurface geometries, kinematics and timing is only roughly described and generally neglected (Artoni et al., 1992; Storti, 1995; Boccaletti & Sani, 1996; Argnani et al., 2003; Bonini et al. 2009; Molli et al., 2015; Bonini et al., 2016).

This work aims to constrain the role of crustal-scale thrust faults and low-angle normal faults of the North West portion of the northern Apennines. For this purpose, we developed three regional cross sections partially constrained by seismic lines: two NE-SW trending and one longitudinal NW-SE trending ending at the northern boundary of the Alpi Apuane (Figure 1).

The northern line (Figure 1) was first interpreted by Reutter et al., (1983) & Hill and Hayward (1990) and more recently revised by Bernini et al., (1991); Artoni et al. (1992); Argnani et al. (1997); Bernini et al. (1997); Bernini & Papani (2002); Carlini et al. (2013) among others. Moreover, the interpretation of this cross-section has been widely used as framework for seismotectonic interpretations of the region (Boncio et al., 2001; Eva et al. 2014; Boncio et al., 2007; Di Naccio et al., 2013; Pezzo et al. 2015; Bonini et al., 2016).

In the light of these seismotectonic implications as well as for a better knowledge of the western northern Apennines, this contribution aims to give a more comprehensive, regional 3D view of the shallow crustal architecture combining all available surface and subsurface information for the analysed sector of the chain.

2. GEOLOGICAL SETTING OF THE WESTERN NORTHERN APENNINES

The northern Apennines including their northwestern segment, are the result of the Neogene deformation of the Adria continental crust and the overlying remnants of the former

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intraoceanic accretionary wedge (Doglioni et al., 1998; Jolivet et al., 1998; Molli, 2008). The latter is represented by the so-called ophiolite-bearing Ligurian and subLigurian units, which may be observed superimposed (Figure 1b) to the Tuscan and Romagna-Umbria units formed by continental-derived sequence of the distal to proximal Adria margin (Elter, 1975; Principi & Treves, 1984; Zanzucchi 1994; Bernini et al, 1997; Vai & Castellarin, 2001; Bettelli & Vannucchi, 2011).

The tectonic history predating and partially tracking the involvement of the Adria continental margin in the underthrusting processes is recorded in the Ligurian and subLigurian units and in the overlying Epiligurian sedimentary basins and described by different contributions (e.g. Vescovi, 1993; Marroni & Pandolfi, 1996; Marroni & Treves, 1998; Daniele & Plesi, 2000; Marroni et al., 2002; Remitti et al. 2011; Vannucchi et al. 2012; Piazza et al., 2016 and references therein).

After the inception of the continental subduction during the Oligocene, parts of the Adria continental margin were imbricated and incorporated into the orogenic wedge at shallow crustal levels (e.g. the Tuscan Nappe), whereas other portions (exposed at regional scale in tectonic windows such as the Alpi Apuane, Figure 1) were underthrusted to greater depths and metamorphosed (Carmignani et al., 1990; Jolivet et al., 1998). Early syncontractional exhumation occurred within a sub-marine wedge during the Miocene retreating of the Adria plate (Molli et al., 2002; Fellin et al., 2007; Thomson et al., 2010). In a transect across the Alpi Apuane this first exhumation stage has been inferred to result from a combination of low-angle normal faulting in the upper parts of the prism, coupled with ductile thinning related to formation of an antiformal stack in the lower parts (Molli et al., 2002; Fellin et al., 2007; Molli, 2012). From 4-5 Ma onward, the final exhumation of the Alpi Apuane and the formation of the major sourrounding reliefs occurred thanks to the concurrent contribution of surface erosion and normal faulting (Balestrieri et al., 2003; Fellin et al., 2007; Thomson et al., 2010). These combined processes unroofed the antiformal stack of Alpi Apuane with its core of metamorphic units surrounded by two Neogene-basins (Figure 1), the eastern intramontane Garfagnana and the partially marine western lower Lunigiana–Versilia basins (Molli et al., 2016 and references therein).

North of the Alpi Apuane, during the same time span (4-5 Ma to present) the main morphology of the region has been also realized as formed by two grabens (Val di Vara and upper Lunigiana) and the interposed structural highs including the main topograhic divide of this segment of the Apennines (Figure 1).

The extensional tectonics related to the present day morphostructure has been the object of

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different contributions (e.g. Federici, 1973; Raggi, 1985; Bernini, 1991; Bernini et al., 1991; Moretti, 1992; Bernini & Papani, 2002; Argnani et al, 2003; Di Naccio et al., 2013 among the others), whereas the early stages of the exhumation and nappe excision have been only recently described for the eastern sector of the chain (Artoni et al., 1992; Artoni et al., 2006; Carlini et al., 2013), but never analyzed in detail in the western and uppermost part of the nappe stack in relationship with its subsurface structures (see Vescovi et al., 2014).

The main characters of the sedimentary and tectonic units discussed in the text, are briefly outlined below (Figure 1b). They are represented from top to bottom by:

- Continental deposits of Villafranchian age, forming the sedimentary filling of the intermontane basins of the high Taro valley (Compiano), upper Lunigiana (Pontremoli and Aulla-Olivola basins) and lower Lunigiana (Sarzana basin), this latter grading southward (Figure 1) to the partially marine Versilia basin (Federici, 1973; Raggi, 1985; Bernini et al., 1991; Abbate et al., 2002; Raggi, 2016). The deposits of the latter two basins show the same vertical sedimentary evolution with an initial stage of lacustrine and palustrine enviroment followed by fluviatile deposits (Bernini and Papani, 2002 and references therein). The base of the northernmost basin segment (Pontremoli) shows continental deposits being younger (middle Villafranchian land mammal age; i.e. early Pleistocene) with respect to the southernmost segment (Aulla-Olivola), whose base is early Pliocene (Federici, 1978; Raggi, 1985; Bernini et al., 1991; Bertoldi, 1995; Bernini & Papani, 2002). The Compiano basin, which similarly to the other Villafranchian basins, is composed by a fluvio-lacustrine stratigraphic sequence of latest Pliocene-Middle Pleistocene age shows a partially different and peculiar tectonic evolution (Boccaletti et al., 1990; Bernini et al., 1994; Argnani et al., 1997 and references therein) as described below:
- The Epiligurian sequence, which represents wedge-top basins characterized by middle Eocene-early Messinian successions made up of tectonically-controlled turbidites, shelf and slope deposits passing upward to shelfal and locally shallow water primary evaporites (Artoni et al., 2004; Amorosi et al., 1993; Mutti et al., 1995; Piazza et al., 2016 and references therein). These sequences are only exposed east of the main topographic divide of Mt. Orsaro-Mt. Acuto ridge (Figure 1);
- Ligurian units are traditionally considered as the remnants of an intraoceanic accretionary wedge developed during the closure of the Ligurian ocean, a segment of the Alpine Tethys (Principi & Treves, 1985; Vescovi, 1993; Remitti et al., 2011, Vescovi et al 1999; Molli, 2008; Malavieille et al 2016). Within the Ligurian units two main groups are traditionally distinguished (Elter, 1975):

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a) Internal Ligurian Units, characterized by the presence of Jurassic ophiolites and their upper Jurassic-Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with a Cretaceous-Paleocene siliciclastic turbiditic sequence (Lavagna slates, Gottero sandstones and Bocco/Colli-Tavarone shaly complex); b) External Ligurian units, characterized by the presence of Cretaceous-middle Eocene calcareous dominant flysch sequences (Helminthoid flysch) associated with complexes or pre-flysch formations called “basal complexes”.

The Ligurian units have been furthermore subdivided (Bernini et al., 1997) in lower Ligurides (directly overlying the Subligurian or the foredeep units) and upper Ligurides (always observed in the upper portion of the Ligurian nappe). The upper Ligurides overthrusted the lower ones during the middle Eocene and are unconformably overlain by the Epiligurian Succession (Piazza et al., 2016).

- SubLigurian units crop out geometrically below the composite Ligurian system and are characterized by a strong thickness variability at the regional scale. The subLigurian units are represented by Cretaceous–Eocene sequences mainly formed by sandstones and shaly-calcareous deposits (Ostia–Scabiazza and Canetolo Fm.s) followed by Oligocene–lower Miocene (Aquitanian) siliciclastic and marly deposits (Aveto–Petrignacola and Coli units) (Cerrina Feroni et al. 2002 and references therein). Within the Cretaceous–Paleogene sequence, unconformities and depositional hiatuses (Plesi, 1975; Vescovi 1993, 1998; Remitti et al., 2011) of Early, Middle and Late Eocene age are documented, and volcanoclastic deposits with calc-alkaline affinities (the Aveto–Petrignacola Fm.) are dated to the lower Oligocene (Elter et al., 1996; Boccaletti et al. 1971; Ruffini et al. 1995; Cibin et al. 1998);

- Tuscan Nappe and the underlaying Tuscan metamorphic units represent the former distal margin of the stretched Adria (called Tuscan Domain, Elter, 1975). The Tuscan Nappe consists of Mesozoic carbonates and Tertiary deep water and turbiditic sequences, usually detached from their original basement along the décollement level of the Norian anidrites and dolostones, the latter comparable with the Anidriti di Burano Fm. (Ciarapica & Passeri, 2002 and references therein). These anydrites and dolostones are transformed almost everywhere (with some relevant exceptions) into cataclastic breccias called Calcare Cavernoso or “cellular” limestone (Zaccagna, 1932; Vighi, 1958; Baldacci et al., 1967; Gandin et al., 2000). Locally (see below) the decollement level of the Tuscan Nappe is deeper and represented by Carnian pelites, quartzites, and carbonates comparable with the Tocchi Fm. in Southern Tuscany (Abbate et al., 2002; Aldinucci et al., 2008). The post-Norian sequence

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continues with Rhaetian to Hettangian shallow water limestones (Rhaetavicula Contorta and Calcare Massiccio), Lower Liassic to Cretaceous pelagic limestones, radiolarites and shales (Calcare selcifero, Marne a Posidonomya, Diaspri, Maiolica), grading to hemipelagic deposits of the Scaglia (Cretaceous-Oligocene), to end with the siliciclastic foredeep turbidites of the Macigno (upper Oligocene-lower Miocene). The entire sequence, with a thickness between 2000 and 4000 m shows a strong lateral and longitudinal variability in its Mesozoic part related with a paleogeographic heritage of block faulting and fragmentation of the former passive margin formed during the rifting and early inversion stages (Fazzuoli et al., 1986; Ciarapica & Passeri, 2002; Molli & Meccheri, 2012);

- Tuscan metamorphic units will be illustrated in some details in the following chapter 4.1 of the subsurface “basement” map and “basement” tectonic units.

3. MATERIALS AND METHODS

The study area, framed between the Taro valley to the north and the northern termination of the Alpi Apuane to the south, includes the main morphostructural zones of the North-West Apennines from the Tyrrhenian coast, West-Northwest of La Spezia city, to the external frontal part of the chain (Figure 1). The area has been investigated through a multidisciplinary approach which has taken into account:

- Compiled structural and stratigraphic data collected during the last two decades in the internal (i.e. SW) as well as external (i.e. NE) sectors of the chain integrated with available geological maps and cross sections (Elter and Schwab, 1957; Abbate, 1969; Raggi & Monteforti, 1975; Vescovi, 1991; Storti, 1995; Plesi et al 1998; Carmignani et al., 2002; Bernini & Papani, 2002; Cerrina Feroni et al., 2002; Abbate et al., 2002; Puccinelli et al., 2004; Clemenzi et al., 2015; Molli et al., 2015 and references therein).
- subsurface geology includes: a) interpreted seismic reflection profiles and b) analysis of boreholes stratigraphies. The subsurface geological data mainly consist of 39 deep boreholes stratigraphies and 47 commercial 2D seismic reflection profiles (for a total length of 1191 km), made available by ENI S.p.A (Figure 2). The analysis of seismic reflection profiles has been integrated with previously published and unpublished interpretations of subsurface data (Argnani et al., 2003; Camurri, 2000; Camurri et al., 2001; Molli et al., 2016). Stratigraphies of the boreholes were obtained from well logs freely available and downloadable from the ViDEPI Project database (http://unmig.sviluppoeconomico.gov.it/videpi/).

The subsurface structural geometries were constrained by a projection of reliable structural

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data at depth from the shallowest to the deepest portion of the nappe stack architecture in areas where multidisciplinary tectonic studies were recently performed (e.g. Carlini et al., 2013; Clemenzi et al., 2015; Molli et al., 2016).

The seismic lines used to build the regional cross-sections have been depth-converted using the interval velocity profiles calculated from the stacking velocities suggested by Barchi et al., (1998).

All available data sets including thermochronological contraints (Fellin et al., 2007; Thomson et al., 2010; Carlini et al., 2013) as well as seismotectonic features (references in Eva et al. 2014, Mantovani et al. 2009; Elter et al., 2012; Di Naccio et al., 2013; Mantovani et al., 2015; Molli et al., 2016) were also taken into account to better highlight, on one hand the long term evolution of the orogenic wedge and on the other hand the deep geometry of recent to active major faults.

All the geological data were georeferenced in a GIS database (ESRI ArcMap 10 software).

Particular attention was devoted to the structural interpretation aimed to give: 1) a more precise definition of the deep Apenninic tectonic structures, i.e. the involvement of the "basement" units and their structural characterization (see below); 2) a clearer outline of the shallower portions of the nappe stack, in particular the definition and geometries of Low Angle Normal Faults (LANFs) and their relationships with the High Angle Normal Faults (HANFs) including their cross-cutting relationships where present (Figure 2).

4. 3D SUBSURFACE STRUCTURES AS CONSTRAINED BY SEISMIC DATA

In the subsurface, different tectonics units could be distinguished on the base of distinct seismic facies as follows:

- the Epiligurian succession is often represented by quite reflective signals, especially the thick Epiligurian succession as observed. East of studied area where reflective horizons show good lateral continuity and consistency down to the lower contact of the Ligurian and SubLigurian Units (Carlini et al., 2013);
- the Ligurian and SubLigurian Units are locally characterized by strong reflective seismic signals with high amplitude and low frequency, which form clearly distinguishable portions displaying discrete lateral continuity (Figure 2);
- the foredeep Tuscan units together with their Mesozoic carbonate substratum are always characterized by poorly- to no-reflective seismic signature, which is distributed over large areas, preferentially in the external and central western portion of the seismic profiles; locally

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high amplitude reflectors appear, but they are extremely short and without lateral continuity and they might be associated to thrust/detachment zones.

- "seismic basement" is characterized by seismic velocity around of and higher than 5 km/sec, and shows high amplitudes and low frequency reflective horizons which are highly discontinuos and generally with low to steep dip (Figure 2). The latter likely correspond to basement fault zones.

The seismic reflectors have been calibrated, where possible, with the aid of stratigraphies of boreholes located close to the traces of the seismic lines, i.e. Pontremoli and Lama dei Cerri wells (Eni S.p.A). The seismic lines used to build the regional cross-sections have been depth-converted using the interval velocity profiles calculated from the stacking velocities suggested by Barchi et al. (1998). The "seismic basement" has been internally subdivided according to its geometry of superimposition and correlations with exposed metamorphic units known following most recent structural and metamorphic studies (e.g. Molli et al., 2000; Molli & Meccheri, 2012; Molli et al., 2015; Lo Pò et al., 2016; Lo Pò et al., 2018).

4.1 SUBSURFACE "BASEMENT" MAP AND "BASEMENT" TECTONIC UNITS

The geometry of the top surface of the seismic basement is expressed by a new isochron map (Figure 3) which integrates both previous published (Argnani et al., 1997, 2003) and unpublished works (Camurri, 2000; Camurri et al., 2001). Moreover a representative profile of the seismic basement is shown along the NW-SE trending cross-section composed by three different seismic reflection profiles (Figure 4).

The contour isochron map and seismic profiles allowed to recognize four main "seismic basement" culminations (i.e. Alpi Apuane, Punta Bianca-Bracco, Pontremoli and Gotra, Figure 3a).

The first order structure is represented (Figure 3) in the southeastern side of the map by the regional-scale "basement" culmination of the Alpi Apuane. The contour map shows the northward prolongation of the Alpi Apuane metamorphic units below the surface nappe stack as characterized by a N-dipping and NE-SW trending subsurface step zone (Figures 3,4). The contact between the metamorphic footwall and the non-metamorphic hangingwall units corresponds at the surface with a system of high angle faults, that are part of the North Apuane Fault system (Molli et al., 2015; Molli et al., 2016) cfr. Sarzana-Equi Terme lineament (Boccaletti & Napoleone, 1977); Marciaso-Tenerano Fault (Scandone, 1998); North Apuane Fault/Transfer Zone (Brozzetti et al., 2007a,b).

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Altogether with the Alpi Apuane culmination, the isobaths of the top of the basement show other regional scale “basement” culminations. The Punta Bianca-Bracco culmination is a nearly 20 Km long elongate antiform with a crest at 1.2 s TWT in the north-western part and an exposed basement sector in its south-eastern side around the Punta Bianca promontory (Figures 1, 3). This antiform underlies the regional scale La Spezia fold (Carter, 1992; Giammarino & Giglia, 1990; Carosi et al., 1998; Abbate et al., 2005; Molli et al., 2011) as seen in Figure 1 and cross-sections of Figures 6 and 10. This “basement” antiform has a steep NE/N-dipping and NW-SE trending north-easternmost limb (Figure 3). Similarly to the North Apuane Fault it may be considered the deep expression of a surface system of segmented high angle normal faults which have a dominant NW-SE trend and a subordinate NE-SW one (Figure 1).

The third structural culmination (Pontremoli), also elongated in the NW-SE direction, is centered below Pontremoli in Lunigiana, at a depth of c. 1,3 s TWT (Figures 2, 3, 4). This culmination has been reached at a depth of nearly 2900 m by the Pontremoli well of Eni Spa (Anelli et al., 1994). The Pontremoli well log (Figure 5) has been used to calibrate the interpretation of the seismic line of Figure 6 and will be discuss later.

The fourth culmination (Gotra), also well evident (Figures 3 and 4) shows a NE-SW transversal trend which defines a “basement” high at a depth of 1 s TWT. This “basement” high underlies the main orographic divide of the Apennines between the Mt. Gottero and Mt. Molinatico, that is associated at the surface with a transversal NE/SW striking system of faults (Figure 7), which may be related with the seismically active tectonic lineament, know as “Taro Line” (Elter, 1975; Monteforti & Raggi, 1980; Bernini & Papani, 1987; Vescovi, 1991; Argnani et al 1997; Eva et al., 1978; Eva et al., 2014).

To subdivide the subsurface “seismic basement” into tectonic units, a correlation between surface and subsurface has to be established. The proposed correlation (Figure 3b) derives from an interpretation of the geometries observed in the seismic line (Figures 4,6 and 10) and by taking into account tectonic signatures of the metamorphic units as constrained by the most recent structural and metamorphic data sets collected both at the surface and subsurface, e.g. in the Cerreto area, Alpi Apuane and Punta Bianca and in the Pontremoli well (Molli et al., 2002; Montanini & Molli, 2002; Molli, 2012; Lo Po’ et al., 2016a; Lo Po’ et al., 2016b, Lo Po’ et al., 2017).

The seismic basement of Camurri (2000); Camurri et al., (2001); Argnani et al., (2003) is here subdivided into the following main composite “basement” units:

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- Unit 1: supra-Apuane;
- Unit 2: Apuane metamorphic units and Apuane "equivalent";
- Unit 3: sub-Apuane;

Unit 1 - supra-Apuane - includes all the metamorphic units exposed in a westernmost and uppermost position relative to the metamorphic units outcropping in the Alpi Apuane. Unit 1 at surface includes two main tectonic units observable in the eastern Promontory of La Spezia, the lowermost Punta Bianca unit and the uppermost SanTerenzo unit.

The Punta Bianca unit (Storti, 1995) consists of a Paleozoic sequence made up of phyllites metasiltstones and quartzites affected by a greenschist facies Variscan overprint (Franceschelli et al., 1986; Storti, 1995; Conti et al., 1991; Lo Po' et al., 2016) and a Middle Triassic (Anisian to Carnian) metasedimentary sequence including metaconglomerates, metasandstones, and metasiltites, shallow to deep marine carbonates (metalimestones, calcschists and metapelites and marbles) associated with alkaline metabasites (Ricci, 1965; Stoppa, 1985) interpreted as submarine eruptions during continental rifting (Martini et al., 1986; Ciarapica & Passeri, 1985; Storti, 1996; Patacca et al., 2011). The Punta Bianca sequence ends with mature fluvial red beds (Verrucano s.s.) changing upward into shallow marine sands and carbonates comparable with the San Terenzo Schists (see below). The peak metamorphism during Apenninic history for Punta Bianca unit has been defined in the Mesozoic and Paleozoic sequences in the range of 300-400 °C and 5-7 Kb (Franceschelli et al., 1986; Lo Po' et al., 2016 and references therein).

The San Terenzo unit is mainly formed by the youngest part of the Verrucano sequence mainly quarzites and phyllites with subordinate metalimestones and metapelites (Abbate et al., 2002). Locally (e.g. on the coastal cliff close to San Terenzo village), a stratigraphic contact with dolomites-evaporites has been documented as an evidence for a continental to shallow marine transition of Carnian age. This stratigraphic setting fits what observed in southern Tuscany for the Tocchi Fm. (Ciarapica & Passeri, 1985; Abbate et al., 2005; Aldinucci et al., 2008; Patacca et al., 2011). Moreover, a stratigraphic connection between the San Terenzo schists and the overlying Carnian to Oligo-Miocene terms of the Tuscan Nappe sequence in the La Spezia promontory has been previously suggested (Ciarapica & Passeri, 1984; Passeri, 1984; Storti, 1995; Abbate et al., 2002). The San Terenzo schists record a peak temperature not higher than 300 °C (Leoni & Pertusati, 2003).

Unit 2 - Apuane metamorphic units and Apuane "equivalent" - is made-up by the metamorphic units exposed in the Alpi Apuane tectonic window (Carmignani et al., 1990;

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Molli et al., 2002; Molli, 2008 and references therein) where two major units, the Massa and the Apuane units, are traditionally distinguished on the stratigraphic grounds (Carmignani et al., 2004) and their different apenninic-age metamorphic imprint (Giglia et al., 1977; Molli et al., 2002; Molli, 2012).

The Massa unit, exposed in the south-west part of the Alpi Apuane, is characterized by a pre-Mesozoic basement and a Mid-Triassic cover sequence analogue to the one described at Punta Bianca and similarly including a Paleozoic basement with evidence of a pre-Alpine low grade greenschist-facies fabrics related to the Variscan orogeny (Conti et al. 1991 and references therein). The Mesozoic cover consists of an upper Permian/lower Triassic terrigenous sequence and a mid-upper Triassic metasediments (Elter et al., 1966; Martini et al., 1986; Patacca et al., 2011) formed by quartzose clast-supported metaconglomerates, metasandstones, metasiltstones and black phyllites overlain by marine deposits (Ladinian crynoidal marbles, carbonate metabreccias, calcschists and phyllites), intercalated with alkaline metabasics. Upwards the succession ends up with coarse-grained quarzitic metarudites, quarzites and phyllites.

The Alpine metamorphism (as constrained in the Mesozoic rocks) is characterized by kyanite+chloritoid+phengitic muscovite assemblages in metapelites. Orogenic peak conditions of metamorphism have been estimated in the range of 0,6-0,8GPa and 420-500°C (Franceschelli et al., 1986; Jolivet et al., 1998; Franceschelli & Memmi, 1999; Molli et al., 2000b).

The Apuane unit is made up of an Upper Triassic-Oligocene metasedimentary sequence unconformably overlying a Paleozoic basement. This latter is formed by the same rock-types described for the Massa and Punta Bianca units (Gattiglio & Meccheri, 1987; Conti et al., 1993) and similarly shows greenschist-facies metamorphism and pre-Alpine deformation (Conti et al., 1991b). The Mesozoic cover-rocks include thin Triassic continental to shallow water Verrucano-like deposits followed by Upper Triassic-Liassic carbonate platform metasediments consisting of dolostones, dolomitic marbles and marbles (the famous “Carrara marbles”), which are followed by Upper Liassic-Lower Cretaceous cherty metalimestone, cherts, calcschists. Lower Cretaceous to Lower Oligocene sericitic phyllites and calcschists, with marble interlayers, are related to deep- water sedimentation during drowning of the former carbonate platform. The Oligocene-early Miocene (?) sedimentation of turbiditic metasandstones (“Pseudomacigno”) closes the sedimentary sequence. The metamorphism is characterized by pyrophyllite + chloritoid + chlorite + phengitic muscovite in metapelites. Peak metamorphic conditions have been estimated in the range of 0.4-0.6 GPa and 350-450

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°C (Franceschelli et al., 1986; Di Pisa et al., 1987; Jolivet et al., 1998; Molli et al., 2000b; Molli, 2008; Cinquini, 2014). Geochronological data document metamorphic re-crystallization and deformation during mid-crustal involvement in the Apenninic wedge at early Miocene (27–20 Ma) and cooling below 250°C at c.11 Ma (Kligfield et al., 1986; Fellin et al., 2007).

Unit 3 - subApuane - includes a group of tectonic units, some of which have no direct equivalent in surface exposure.

The "basement" unit 3 has been drilled in the Pontremoli well of Eni S.p.A (Anelli et al., 1994; Montanini & Molli 2002; Lo Po' 2014; Lo Po' et al., 2016) from 3054 to 3520 m below a major fault zone (see chapter below and Figure 5a) separating cover from "seismic basement".

Unit 3 is formed by an upper portion (from 3054 to 3150 m) of mono-metamorphic schists and phyllites overlying garnet-bearing micaschists drilled between 3150 to 3520 m. The garnet-bearing micaschists which were investigated in details by Lo Po' (2014) and Lo Po' et al. (2016) represent the geometrically deepest known basement of the northern Apennines. For these micaschists two alternative PTt evolutions were proposed on the base of petrological and geochronological (U/Th Monazite) data (Lo Po' et al., 2016). Our geometric and structural frame (Figure 1b, 3b) supports the interpretation of micaschists as part of a polyorogenic basement unit, with ~~a~~ its main fabric of pre-Apenninic age (documented by the anticlockwise P–T path at c. 290 Ma) reworked at shallow crustal depth during the Apenninic contractional history (c. 19 Ma) during which fluid infiltrations and a weak overprinting of the main fabrics occurred.

Within the fault zone at the top of Unit 3 slices of black phyllites and schists were met at c.2900 m. These phyllites and black schists show similarities in microscopic fabrics with slates of the Apuane unit in particular to the Tertiary Pseudomacigno Fm. or the Silurian black schists of Paleozoic basement (Figure 5 b,c). We therefore consider these low grade rocks as a sliced segment of Unit 2 originally overlying west of present position, the Unit 3.

Although not represented in the "basement" map of Figures 2, 3 the metamorphic slices exposed in association with Triassic evaporites and quartzites around the Cerreto Pass (Figures 1 and 2) are also worth to be mentioned here the Cerreto basement rocks consist of lenses and plurimetric bodies of amphibolites included in a sequence of metapsammites, biotite and muscovite schists. Both metasediments and amphibolites underwent a retrograde evolution starting from an initial medium-pressure amphibolite stage (P ~ 0,8GPa, T ~650°C) down to greenschist condition (Molli et al., 2002; Lo Pò, 2014 and Lo Po' et al., 2017).
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^{40}Ar/^{39}Ar dating performed on two hornblende samples (312 and 328 Ma) indicates a Variscan age for the amphibolite-facies metamorphism (Molli et al., 2002), whereas the retrograde overprint may be related to the Post Variscan events including the Triassic-Jurassic Tethyan rifting (Lo Po', 2014; Lo Po' et al. 2017). The present tectonic setting of the Cerreto basement rocks, i.e. rootless slices within the cover unit, is related to the Apenninic thrusting (Figure 10), occurred at shallow crustal depth without development of pervasive syn-metamorphic structures. This tectonic record is well documented in the quartzites of the Cerreto area (Calzolari et al., 1993; Plesi et al. 2000, Molli et al., 2002; Leoni & Pertusati, 2003), which may therefore compared with the San Terenzo Schists. The "seismic basement" distinguished in Figure 3 includes, therefore, mono- or polyorogenic tectonic units (e.g. metasedimentary cover and/or Paleozoic basement), each of them characterized by a different Apenninic metamorphic record and/or a variable tectono-metamorphic pre-Apenninic (Variscan or Post Variscan) signature (Figure 1b).

5. REGIONAL CROSS-SECTION 1: THE LEVANTO-PONTREMOLI-PARMA TRANSECT

The regional cross-section Levanto-Pontremoli-Parma of Figure 6 outlines the main northern Apennines structures NW of the Alpi Apuane. At surface it cross-cuts the Ligurian units (both the Internal and External Ligurian units following Elter, 1975's nomenclature) along the Tyrrhenian coast line. It strikes toward NE within the Val di Vara and upper Lunigiana valley crossing northeastward the main Apenninic orographic divide close to the Cirone pass to reach the Po Plain near Felino (Parma). Close to Pontremoli the cross-section is constrained at depth thanks to an Eni S.p.A. deep borehole, "Pozzo Pontremoli" which reached the "seismic basement" as previously described.

In the cross section the youngest structures are represented by a system of high angle normal faults (Raggi, 1985; Bernini et al., 1991; Bernini & Papani, 2002). This fault system controlled the two NW-SE oriented tectonic depression of the Val di Vara and Upper Lunigiana separated by the horst of Mt.Picchiara and limited to the east by the main orographic divide of the Mt. Orsaro-Mt. Acuto ridge (Figure 1).

The major faults defining the system are the east-dipping La Spezia Fault in its northernmost segment and its conjugate west-dipping Mt. Vruga system for the Vara valley and the west-dipping Groppodalosio-Comano system with its antithetical northeast-dipping structures in

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the upper Magra valley (Figure 1). At surface, the La Spezia Fault is a NW-SE trending 20 Km long structure with a cumulative Plio-Quaternary displacement of c. 1000 m (Giglia, 1974; Bernini, 1991; Abbate et al., 2002). Along the profile of cross-section 1, the northwestern segment (Padivarma-Beverino) of the La Spezia Fault, reaches the basement at a depth of c.3000 m it downthrows basement's top surface of c. 1000 m (Figure 6a). The Mt. Vruga-Parana system (cfr. Bernini & Papani, 2002) is a c.16 km long, southwest-dipping group of dominantly normal faults bounding the Mt. Cornoviglio-Mt. Picchiara ridge and showing a cumulative vertical displacement larger than 600-700 m.

The Groppodalosio-Comano system is a major group of faults bounding the northeast side of the Magra valley. In the upper Lunigiana along the trace of cross-section 1, the Groppodalosio-Comano system is composed by two major segmented faults, the Arzengio-Mocrone and the Groppodalosio-Compione faults (Figure 1). The Groppodalosio-Comano system is striking almost NW-SE and dipping 60-70° to the SW. The cumulative vertical displacement may be quantified around 600 m for the Arzengio-Mocrone and in excess of 1 km for the Groppodalosio-Compione fault (Bernini et al., 1991; Bernini and Papani, 2002; Lucca et al., 2016). The main activity of the Arzengio fault is constrained following Bernini et al., (1991), as pre-Middle Pleistocene since Middle Pleistocene conglomerates seal the fault east of Bagnone whereas it is younger (i.e. post Middle Pleistocene) in the easternmost Groppodalosio fault (Bernini et al., 1991; Bernini & Papani, 2002).

The antitethic east-dipping fault system exposed in the South West side of the Magra valley includes the Codolo-Montereggio and the Mulazzo faults of Bernini & Papani (2002). As figured by Elter & Schwab (1959) and later on described by Bernini (1991) and Bernini et al. (1991) the east dipping faults have listric geometry.

The east-dipping faults of the west side of Magra valley have been interpreted in different ways in the literature. Boncio et al., (2000) and Argnani et al., (2003) consider them as part of regional scale system (the Etrurian Fault system) accomodating Pliocene to present-day active extension in the Apennines. On the other hand, Bernini et al., (1991) previously proposed to consider them as the shallow listric fan (Gibbs, 1984) related with the main high angle west-dipping Groppodalosio-Compione system, we will come back to this point later on in the discussion chapter.

The high angle faults of the Val di Vara-Val di Magra extensional system cross-cut and clearly postdate (Figure 2) an early generation of low-angle normal faults (LANF), here called Vara-Verde detachment (Vescovi et al., 2014). The Vara-Verde LANF system

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represents actually a complex structure consisting of multiple levels of detachment within the weaker layers of the Ligurian and Subligurian units (Figures 6 and 7).

In the Vara valley, the Vara-Verde LANF is composed by two major faults; the uppermost located at the base of Gottero unit and mainly developed within the Val Lavagna Schists and the second one at the base of Helmintoid Flysch (Lower Ligurides of Bernini et al., 1997). The Val Lavagna Schists may be observed in the footwall of the LANF with a thickness of at least 600 m (e.g. Monterosso area) whereas in the Vara Valley they are tectonically reduced to a total thickness in the range of c.150 to 0 meters. Further northeast in the Verde valley (Figures 1 and 6), the uppermost detachment cuts down-section merging in the lowermost fault zone (base of Helminthoid Flysch) resulting in the direct contact the Gottero unit (Mt.Gottero sandstone) and, locally, the underlying subLigurides and locally with the Macigno Fm. of the Tuscan nappe (Elter & Schwab, 1959; Vescovi, 1991). Considering the thickness of the Ligurian units exposed in the Vara valley (Monteforti & Raggi, 1975) and comparing them with those tectonically reduced on the Verde section, an excision accounting of at least of 3 km may be quantified. Toward west, along the coast line in the Punta Mesco promontory west of the Monterosso village, an hectometer-scale synthetic structure developed in the footwall of the Vara-Verde detachment is well exposed (Figures 1, 6 and 8).

The shallowest expression of the Vara-Verde detachment system may be searched NE of the main topographic divide at the base of the Epiligurian Succession (Figures 1, 6, 7 and 9), where low angle normal faults (called Epiligurian detachment) have been described (Artoni et al., 2006; Carlini et al., 2013). These structures bring the upper portion of the Ranzano sandstones (Late Eocene-Early Oligocene) in direct contact with the Ligurian units with an amount of tectonic excision of about 500 m of the underlying stratigraphic terms, and a horizontal displacement of c. 5 km towards NNE (Artoni et al., 2006, Figures 1 and 7). The kinematic compatibility (Figures 7 and 9), the overprinting relationships with later SE-NW oriented HANF systems and the sealing relationships with Compiano (Pliocene) deposits support the tectonic correlation between the Epiligurian and the Vara-Verde detachments as part of the same extensional system as further discussed later on.

The cross section in Figure 6 althogether with the LANF systems within the upper part of orogenic prism (within and at the bases of Ligurian and SubLigurian units i.e. the Vara-Verde detachment system) also shows other LANF’s developed within the lowermost Tuscan Nappe sequence. This lowermost LANFs detached the Macigno Fm. from the underlying carbonates along the pelites of the Scaglia Fm. and thinned out the Mesozoic carbonates from an original thickness observable in La Spezia area, c.3500 m, to less than 2500 m, below the Lunigiana.

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The previously described extensional systems of HANFs and LANFs, overprint a contractional nappe stack whose major structures are represented, from west to east, by:

1) the northern segment of the La Spezia backfold (Carosi et al., 2002; Giammarino & Giglia, 1990 and references therein). The structure, well imaged in the cross-section of Figure 6 in its normal limb, involves the complete nappe stack from the Ligurian units to the underlying Tuscan nappe which includes the complete stratigraphic sequence from the Macigno Fm. (Oligocene-early Miocene) down to the Triassic carbonates for a total thickness of c. 5000 m. The cross-section at depth envisaged some minor structures of the La Spezia fold to be considered either as southwest-verging back-thrusts (Argnani et al., 2003) or as folds involving the underlying "seismic basement" of Unit 1 (the geometrical solution proposed in Figure 6);

2) the Tuscan Nappe frontal overturned fold (Baldacci et al., 1967; Reutter et al., 1983; Calzolari et al., 1993; Fazzuoli et al., 1994; Plesi et al., 1998) is exposed in the cross-section of Figure 6 in its lateral forelimb (Bernini & Vescovi, 2002). This regional structure is related with a major "out-of sequence" thrust (Plesi et al., 1998; Vescovi, 2005; Plesi et al., 2000; Clemenzi et al., 2014) which shows in cross-section a flat of at least 18 km (Figure 6). The thrust doubled the thickness of Tuscan units as documented in the Pontremoli well, where Anelli et al (1994) described at the base of the Mesozoic carbonates of the Tuscan Nappe, part of the former Ligurian-subLigurian wedge (Tertiary Flysch and Canetolo Fms., called "Alberese" in Anelli et al., 1994). These units have a total thickness of c.500 m overlying a lowermost tectonic element (c. 800 m thick) which includes Oligocene-early Miocene turbiditic sandstones and their tectonically thinned Mesozoic sequence. Moreover, this lower unit can be directly related, from a seismic viewpoint, to the turbiditc sandstones (Pracchiola unit), observed towards NE in the Lama dei Cerri well (Figure 6). The original thrust contact between Tuscan Nappe and the Tuscan lower unit has been reactivated and inverted, along its footwall, by the west-dipping high angle normal fault of the M.Vruga system and partially reworked as a flat of the east dipping low-angle extensional detachement (LANF) along its hangingwall ramp as illustrated in the cross-section of Figure 6 and documented in the Pontremoli well (Anelli et al., 1994).

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6. REGIONAL CROSS-SECTION 2: THE LA SPEZIA-SARZANA-CERRETO TRANSECT

The regional La Spezia-Sarzana-north Apuane-Cerreto cross-section of Figure 10 outlines the main Northern Apennines structures north west of the Alpi Apuane, c. 20 km south of the previously illustrated transect of Figure 6. Along this cross-section the Alpi Apuane basement high is projected downplunge and constrained at depth with the Eni S.p.A Monti-Equi Terme line (Camurri, 2000; Molli et al., 2016), the southernmost segment of the composite transversal strike Taro-Pontremoli-Lunigiana profile of Figure 4. Moreover, the easternmost segment of the cross section is constrained at depth by the seismic lines Sassalbo-Castelnuovo Monti (Line 1 described in Chicchi et al., 2002, Figure 10a).

As in the regional cross-section 1 of Figure 6, the youngest structures are represented by a system of high angle normal faults constituting part of the southern portion of the Val di Vara-Val di Magra extensional system (Raggi, 1985; Bernini & Papani, 2002; Argnani et al., 2003). This fault system defines the main morphostructure of the area characterized by three NW-SE oriented tectonic depressions, the Brugnato-La Spezia Gulf, the lower Lunigiana-Sarzana and the upper Lunigiana and four related composite ridges such as: the western promontory of La Spezia ending southward with the Palmaria island; the eastern promontory of La Spezia ending southward in Punta Bianca, the Mt.Nebbione-Mt.Grosso ridge and the easternmost Mt. Orsaro-Mt. Acuto ridge that is the main Apenninic orographic divide along this transect (Figures 1, 10).

The La Spezia Fault in the regional cross section 2 (Figure 10) cuts through the top of the “seismic basement” Unit 1 and underlying units exposed in the hangingwall block inland of La Spezia. Similarly to the regional cross-section 1, also in the La Spezia-Sarzana-North Apuane-Cerreto transect, the high angle faults cross-cut and therefore postdates a system of low angle normal faults (LANF) firstly described in the area by Storti (1995) and recently re-analyzed and studied in detail by Clemenzi et al. (2015).

The uppermost structures of the LANFs system may be considered the southern prolongation of the Vara-Verde detachment, whereas the lowermost ones within and at the base of the Tuscan Nappe are the Pitelli and the Tellaro detachments of Storti (1995). The Vara-Verde detachment along this section consists of several low-angle normal faults outcropping in the highly anthropizated area east La Spezia city and therefore not well exposed. The uppermost fault system juxtaposes the Ligurian units, here represented by the uppermost Gottero unit, to the SubLigurian units with the total excision of the Helminthoid Flysch (lower Ligurides of

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Bernini et al., 1997). The degree of tectonic thinning reaches its maximum east of La Spezia city, where the vertical distance between the Gottero unit and the Macigno is less than ~500 m. The cumulative offset of the faults of the Vara-Verde detachment system in this southernmost portion can be roughly estimated to be ~c.5 km based on the assumption of a 15° average fault dip.

Eastward the displacement of lower detachments belonging to the Vara-Verde system are partially accomodated with contractional structures doubling the lower Ligurides (Helminthoid flysch) and Subligurian units (Figure10) as documented on the relief west of the Alpi Apuane-Mt.Grosso ridges (Monteforti & Raggi, 1975; Del Tredici & Robbiano, 1997; Abbate et al., 2002). Below the Vara-Verde detachment two major low angle normal faults may be defined: the uppermost Pitelli detachment and the lowermost Tellaro detachment after Storti, (1995) and Clemenzi et al. (2015). The Pitelli detachment affected the Macigno and the underlying Scaglia formations thinning the original thickness of the Macigno from c. 2500 m west of La Spezia to less than 500 m. The Tellaro detachment is ~30–50 m thick and includes major low-angle normal faults and subsidiary high-angle extensional faults well exposed in low-strain shear lenses (Storti, 1995; Clemenzi et al., 2015). The master detachment is located at the base of the Cretaceous-Tertiary shales of the Scaglia Toscana Fm. (Figures 10 and 11), but it is usually not well exposed except along the Tyrrhenian shoreline, where in the footwall damage zone of the master detachment, low-angle fault zones affect the Triassic to Jurassic Fms. (Figure 11). The tectonic transport direction of this fault system, determined along the coast side (Storti, 1995; Carosi et al., 1998; Clemenzi et al., 2015), is top-to the-NE, varying between N010E and N080E (Figure 2 and 10). The degree of tectonic thinning is quite variable along strike, reaching its maximum near Lerici village (Figure 1), where ~500 m of thinning is associated with the complete elision of the Jurassic Formations and the direct juxtaposition of the Upper Cretaceous-Tertiary shales of the Scaglia Toscana Fm. on the Upper Triassic limestones. The cumulative offset of the Tellaro detachment fault system can be roughly estimated to be ~1.3 km, based on the assumption of a 25° average fault dip and the offset between stratigraphic units (Clemenzi et al., 2015).

Similarly to the uppermost Vara-Verde detachments, the Pitelli and Tellaro detachments (Figure 10) accomodate their displacements with contractional bedding-parallel faults within the Tuscan Nappe respectively, at the base or within the Mesozoic carbonatic sequence, along the Cretaceous-Tertiary levels of the Scaglia Fm. and along the contact between Scaglia and Macigno Fm. (Figure 10).

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The previously described extensional structures overprint the contractional nappe stack whose major structures along this cross-section are:

- the La Spezia west-vergent backfold (Figure 1, 10) which, differently from the regional cross section 1, may be entirely reconstructed projecting up-plunge the younger Cretaceous-Tertiary terms exposed north of La Spezia and the Triassic-Jurassic carbonatic sequence exposed in the La Spezia area. The La Spezia fold is characterized by a 2 Km long overturned limb formed in the Triassic carbonates well exposed along the coast from north of Portovenere village to the Palmaria island (Federici & Raggi, 1975; Giammarino & Giglia, 1991; Carter, 1992; Carosi et al. 1996; Molli et al., 2011). Moreover, based on ~~of~~ the structural geometries observable in the hinge zone and overturned limb, we support the reconstruction of the megafold as a west facing asymmetric S-fold connected in subsurface and below the sea level with a west-dipping monoclinal normal limb (Figure 10). This supports the early interpretations of Elter, (1960); Roeder, (1984); Giammarino & Giglia (1991); Carmignani et al., (1996); Leoni & Pertusati, (2003) and disclaim the model reproposed by Abbate et al. (2004) who instead envisaged the overturned limb of La Spezia fold truncated at the base by a flat west-vergent backthrust.
- the Tuscan Nappe east-vergent frontal overturned fold, visible in the Cerreto pass area (Baldacci et al., 1967; Reutter et al., 1980; Calzolari et al.,1993; Plesi et al., 2000). This structure is part of a regional structure which can be traced along whole northern Apennines, from the Mt. Orsaro (regional section 1) until Monte Cetona in southern Tuscany (Baldacci et al., 1967; Baldacci et al., 1992; Fazzuoli et al., 1998; Brogi & Liotta, 2002; Brogi, 2008; Piscopo et al, 2009). This structure may be associated with a fault-propagation fold related to a major "out-of sequence" thrust-(Plesi et al., 1998; Boccaletti & Sani, 1998; Vescovi, 2005; Plesi et al., 2000; Clemenzi et al., 2014), whose flat is observable in sub-surface below the Lunigiana (Figure 6) and cross-cutted in the Pontremoli well (Anelli et al., 1994). The Tuscan Nappe and the lower Tuscan Unit as defined in cross-section 1 are also present in the cross-section 2 (Figure 10), with the lower Tuscan Unit being represented by the Cervarola sandstone cropping out in the Cerreto tectonic window (Figure 1).

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7. DISCUSSION

7.1 ESTIMATE OF MAGNITUDE OF UPPER CRUSTAL EXTENSION AND ITS TIMING

The retrodeformation (Figure 12) of the youngest structures in the two presented regional cross-sections allowed us to estimate of the extension accomodated by the high angle normal faults to less than 10% in agreement with Bernini & Papani, (2002). This extension started in the late Miocene ?-early Pliocene as documented by the sedimentary record of intermontane to marine Aulla-Olivola and Sarzana basins (Federici, 1973; Raggi, 1985; Abbate et al., 2002; Boccaletti et al., 1991; Raggi, 2016) and it is still active today, as suggested by historical and instrumental seismicity (Frepoli & Amato, 1997; Boccaletti et al., 2004; Eva et al., 2005; Eva et al. 2014; Di Naccio et al., 2014; Molli et al., 2016 and references therein). The average displacement rate for this recent stage of deformation by HANFs may be calculated at c. 0,6 mm/y a value comparable to the rate defined by Bennett et al. (2012). This extensional activity, however, was not constant in time (Bernini & Papani, 2002; Boccaletti et al., 1991; Argnani et al., 2003). In the studied area (Lunigiana and Sarzana basins), the major changes in the extensional rates are documented by the two regional unconformities recorded in the fluvio-lacustrine deposits toward the end of the middle-late Pliocene and Middle Pleistocene (Bernini et alii, 1990; Patacca et al., 1990; Bernini & Papani, 2002; Abbate et al., 2002; Argnani et al., 2003; Scrocca et al., 2013), respectively.

Moreover, by comparing the cross-sections of Figure 6 and Figure10, restored by the system of HANFs, the 3D architecture of low angle normal faults affecting the studied portion of the northwestern Apennines may be reconstructed (Figure 12). The system of low angle detachments shows an evident along strike southeastward increase in tectonic thinning. In more details, considering the total thickness of the nappe system between the base of Gottero sandstone and the top of Tuscan metamorphic unit (e.g the “undeformed pre-LANFs” frame) of c.6 km (see H in Figure12) this appear to be reduced at c. 3 km (h’ in Figure12a) by the LANFs system in cross-section 1 and at less than 1 km (h’’ in Figure 12b) in cross-section 2 with a thinning of the H nappe stack thickness respectively of 50% in cross-section 1 and of 86% in cross-section 2. The Tuscan Nappe is thinned from its complete thickness of c.3000-3200 m (pre-LANFs frame) to 2300 m in cross-section 1 and less than 800 m in cross-section 2 (15% cross-section 1 vs. 75% cross-section 2).

On the base of overprint relationships with the HANFs, the timing of activation of the low angle normal faults (Tellaro-Pitelli, Vara-Verde and Epiligurian detachments) may be

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inferred to predate and therefore older than 4-5 Ma. This time constraint is consistent with the exhumation history and LANF activity in the Alpi Apuane as documented by the structural and thermochronological data (Molli et al., 2002; Balestrieri et al., 2003; Fellin et al., 2007; Molli, 2012) and those of the Epiligurian succession remnants (Figure 7) (Artoni et al., 2006, Carlini et al., 2013). The lack of data on the beginning of the activity of the LANFs structures preclude any displacement rate estimate for the detachment-stage history, which could be started during the thicknening of the crust and continued during the switching to the crustal thinning tectonic regime until to c.5 Ma when the HANFs stage started.

7.2 THE ROLE OF BASEMENT THRUST

The analysis of the two regional cross sections (Figures 6 and 10) combined with the NW-SE trending strike one (Figure 4) allowed to make some considerations about the role of basement thrust and relationships with shallower extensional structures. In particular, overprint relationships put constraints on the tectonic significance and timing of the surface faults part of the Taro System (Bernini & Papani, 2007) in its westernmost segment which may be associated with the lateral ramp of basement thrust accomodating NE-SW crustal shortening (Figures 4 and 7). This basement lateral ramp, here named Taro Lateral Ramp (TLR), would results to be younger than the LANF system, since the Vara-Verde detachment, its northernmost prolongation and the shallower Epiligurian detachment are deformed above the crest of the basement stack, forming a complex antiformal structure (Figures 3, 4 and 10b). Moreover, the Epiligurian detachment is eroded below the Compiano basin (Figures 1, 4, 7 and 8) documenting its pre-Pliocene age confirming what envisaged by Artoni et al. (2006).

The development of the TLR in the present day geometry occurred, therefore, since late Miocene and continued during middle-late Pliocene as documented by the unconformity at the base and within the Compiano sedimentary sequence and by the internal deformation recorded in its deposits (Bernini et al., 1994; Argnani et al., 2003). Deformation along the Taro Line is still continuing today, as documented by the historical and instrumental seismicity (Eva et al., 1978; Monteforti and Raggi, 1980; Cattaneo et al., 1986; Elter et al., 2012).

The second major transversal trending basement high is the northern boundary of the Alpi Apuane (Figure 3). As previously illustrated (§ 4.1), this lineament may be considered the subsurface expression of a regional high angle extensional fault system (North Apuane Fault)

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whose activity started during Pliocene and it is still ongoing (Molli et al., 2015 and references therein).

The correlation firstly underlined by Molli et al., (2016) between nappe stack units at surface (Alpi Apuane and sourroundings) and subsurface (Figures 4 and 11a) i.e. between footwall and hangingwall blocks of a the HANF system, document an along strike variation of the thrust sheets architecture, with an extra thrust sheet (lower Tuscan unit) underlying the Tuscan Nappe in Lunigiana.

For the pre-HANF configuration of the contractional nappe-stack three geometric-kinematic reconstructions may be suggested (Figure 13). The first solution envisiged the simple restauration of the Lunigiana and Apuane "basement" units at the same datum plane (Figure 13b). In this interpretation, and using constraints deriving from the composite strike section (Figure 4) and data of the Pontremoli well, the Apuane southern segment appear to be lacking of the XX cover unit (lower Tuscan elements of Figure 6), i.e the Oligocene-Early Miocene turbiditic sandstones (to be compared with the exposed Cerreto Sandstone and the turbiditic sandstones in the Lama dei Cerri) and their Mesozoic and Tertiary sequence. This unit may have been thinned by extensional tectonics and displaced eastward of the Alpi Apuane. This excision of the lower Tuscan unit has to be connected with the sopra-Apuane LANF system and may be dated as older than 4-5 Ma, fitting the structural constraints and the exhumation history documented in the Alpi Apuane metamorphic complex (Molli et al., 2002; Fellin et al., 2007; Molli, 2012). This solution, however, is not in line with data of the exposed units eastward of the Alpi Apuane, which do not show any evidence of relicts equivalent of the XX unit neither of those within or around the Alpi Apuane. The units originally interposed between Tuscan nappe and the Apuane metamorphic core were made, indeed, of low grade metamorphic sequences (Molli et al., 2000; Cinquini, 2015) and not of unmetamorphic ones similar to the XX cover unit (or lower Tuscan unit) (Anelli et al., 1994).

A second solution (Figure 13c) implies the prolongation toward south of the unit underlying the Tuscan Nappe in Lunigiana and therefore the occurence of the metamorphic units of the Alpi Apuane above a thrust on the non-metamorphic XX cover unit. This solution follows the proposition by Storti, (1995), who based his inference on the regional scale gravimetric and magnetic data (CNR, 1992), in particular the distribution of Bouguer's anomalies (CNR, 1992), which do not show any maximum in correspondence of the Alpi Apuane metamorphic core. This solution, however, does not fit the map of "basement" of Figure 2 which shows, east of the Alpi Apuane, an eastward-dipping monocline of "seismic basement", without any lower velocity "cover-unit" inserted in between. Moreover, the

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gravimetric data (CNR, 1992) originally used by Storti (1995) were not designed to show local scale gravimetric anomalies.

A third solution (our preferred) implies the retrodeformation at the same datum level of the basal contact of the Tuscan nappe (Figure 13d). Following this option the metamorphic units of the Alpi Apuane are juxstaposed laterally on the non-metamorphic XX-cover unit. This solution requires the presence of a lateral blind basement ramp, analogue to the previously described Taro ramp (Figure 4). The blind lateral ramp may have been activated post deposition of the youngest terms (siliciclastic turbidites) part of XX-unit (i.e. during Middle Miocene) and later overprinted by transtensional kinematic, since the early Pliocene (Molli et al., 2015).

7.2 HANFs AND LANFs: THE ROLE OF STRUCTURAL INHERITANCE AND THE SEISMOTECTONIC IMPLICATIONS

The two regional cross sections show how inherited heterogeneities in the upper crust play a major role in localizing extensional deformation structures.

The first kind of control may be observed for the HANFs (Figures 6, 10, 12) which cross-cut the shallow crustal nappes and thrusts stacking of the cover units in the upper 3-4 Km of depth, whereas reworked and reactived previous contractional structures, i.e. "basement" crustal ramps, (Figures 12, 13) downward in the crust below 4-5 Km of depth.

A second type of control may be observed for the LANFs which are developed along the major stacking-related thrusts and nappe-contacts as two main regional faults system. The Vara-Verde LANFs system plays the role of uppermost detachment within and at the base of the Ligurian units. This LANFs system has an overall eastward cut down-section as testified, by its localization at the base of Gottero sandstone in the west and at the base of Helminthoid Flysch toward east. Minor splays of the uppermost detachement may be observed at the base of subLigurian units, and at the base of Epiligurian system (Epiligurian detachment). Similarly, the former thrusts at the base of Tuscan nappe and/or of the lower Tuscan unit (in upper Lunigiana), has been reactivated in extension to become the lowermost regional detachment of the Pitelli and Tellaro LANFs system. This lowermost LANFs system defines a major detachment separating, along its flat, cover- from "basement"-units. Minor splays of the system may be localized with the shaly levels of the Tuscan units in the Cretaceous Scaglia Fm. as well as in the Jurassic marly limestone (Posidonomia marls Fm) (Figure 1b).

Weak heterogeneities within the stratigraphic units and major discontinuities represented by thrusts and nappe contacts strongly controls, therefore, the localization of the strain. In the

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studied area, these weak layers are mainly formed by carbonatic cataclasites derived from former evaporite-rich protoliths (base of Tuscan nappe) and/or shaly fault rocks (in the Ligurian and SubLigurian units as well in Tuscan shaly and marly formations). This kind of localization of extensional structures, has been reported in other segments of the Apennines (Carmignani et al., 1995; Brogi & Liotta, 2008) as well as in other circum-Mediterranean orogens (Booth-Rea et al., 2004; Ring et al., 2010; Jolivet et al., 2013) where it has been also investigated by numerical models (Le Pourhiet et al., 2004; Huet et al., 2011a,b).

The description of HANFs and LANFs in the studied area has also some major seismotectonic implications as hereafter suggested. Following an original working hypothesis of Boncio et al. (2000), different authors (e.g. Meletti et al., 2008; Di Naccio et al., 2013; Stramondo et al., 2014; Pezzo et al., 2014; DISS 3.2.0) support a regional seismotectonic model of two low angle normal faults called the Lunigiana and Garfagnana LANFs. These LANFs are considered part of the Etrurian Fault System, a major active east-dipping extensional fault system which extends over- more than 350 km along strike controlling the distribution of seismicity in northern-central Italy (Barchi et al., 1998; Boncio et al., 1998; Lavecchia et al., 2009; Lavecchia et al., 2016).

The Lunigiana LANF, northernmost structure of this fault system, has been described by using the geosismic line Levanto-Parma (Argnani et al., 2003; Boncio et al. 2010) with a flat at a depth of c.2900 m along the cover-“basement” contact (Anelli et al., 1994) below the Lunigiana. Considering that (i) in our revision of Levanto-Parma seismic line (Figure 6) the HANFs cross-cut the cover-“basement” detachment and that (ii) the distribution of seismicity supposed to mark the trace of the detachment below the Lunigiana is c.5 km deeper of the fault trace (Eva et al., 2014), we argue against the major role of Lunigiana fault as a relevant seismogenic LANF structure of the inner North West Apennines. On the contrary we suggest that the fault systems relevant for seismotectonic interpretation and hazards issue in the region are the high-angle, west-dipping faults e.g. the Compione-Comano System as well as the transversal North Apuane Fault which both cut into the “basement” deeper then 4-5 Km in agreement with the current sismicity of the area and the Lunigiana 2013 EQ’s ipocenter (Eva et al., 2014; Stramondo et al., 2014; Pezzo et al., 2014; Molli et al., 2015).

8. SUMMARY OF RESULTS AND CONCLUDING REMARKS

On the basis of the presented shallow crustal cross-sections extending from the Tyrrhenian to the frontal part of the western northern Apennines and with a full use of the regional

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geological knowledge, we summarize hereafter the results and the first order points of our contribution:

1) The LANF system, as documented in our cross-sections, affected all tectonic units from the lowermost Tuscan ones to the Epiligurian system and produced the observed variable thickness and architectural frame of the entire cover-nappe stack. An increase of the amount of tectonic excision along strike from northwest to southeast is estimated to vary from respectively (c. 46% to c.86%). The maximum thinning is reached around La Spezia and south-eastward toward the Alpi Apuane, i.e toward the metamorphic core culmination of the north-west Apennines. This architectural character, associated with different degrees of structural omission of the cover nappe-stack trough low-angle normal fault systems, appears to be present at the scale of the entire Northern Apennines, from north of Lunigiana toward the southern Tuscany, where it is classicaly recognized and described as “Serie Ridotta” (Carmignani et al., 1995; Brogi & Liotta, 2006 and references therein).

The LANF system, within in the studied area, is clearly older than 5-4 Ma as constrained by intermontane to marine basin deposits of Villafranchian age (Compiano, Lunigiana, Garfagnana and Versilia basins) and by cross-cutting structural relationships with the HANFs system, which shaped the morphostructural grain of the area since the deactivation time of the LANFs i.e. from 5-4 Ma to the present. This temporal and kinematic evolution is consistent with those documented in the southern Tuscany where two stages of activity of extensional faulting related to LANFs and later HANFs have also been recognized (Brogi & Liotta, 2008; Brogi, 2008; Bonini et al., 2014);

2) Two main “basement” thrust shaped the structural architecture of the studied area:

The northern “basement” thrust is represented by a subsurface basement lateral ramp of the TLR, related at the surface with the mainly SW-NE trending faults of the Taro System (Bernini & Papani, 2007) forming the south-western portion of the Taro line (Figures 3,4 and 7). The activation of this lateral ramp may be dated as pre- Pliocene and its ongoing activity is documented by the present-day seismicity (Eva et al., 2014 and references). The documented activity of the TLR, in turn, witnesses for the activity of the kinematically linked “out of sequence” “basement” thrust represented in Figure 3 in the sub-Apuane (Unit 3) “basement” sheets.

The southernmost “basement” transversal structure may be envisaged at the northern termination of the Alpi Apuane where our geometric-kinematic reconstructions (Figure 13) support a tectonic inheritence of a Late Miocene “basement” lateral ramp reactivated in transtension since the early Pliocene (Molli et al., 2016). Therefore, in contrast to the TLR,

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the current kinematics of the North Apuane Fault is opposite (dextral-normal) to that related with its original tectonic frame (sinistral-reverse);

3) The along strike non-cylindricity of the regional architecture, connected with the thrust-stack architectures and crustal "basement" contraction but also related with the amount of excision in the shallowest unmetamorphic nappe stack. This challenges the traditional cylindrical interpretation originally proposed and rarely put under discussion (but see Cerrina Feroni et al., 2002);

4) Finally, our new presented data may have implications for the seismotectonic model and interpretations of the studied region. In contrast with the currently accepted model (Boncio et al. 2000; Meletti et al., 2008; Di Naccio et al., 2013; Stramondo et al., 2014; Pezzo et al., 2014, DISS 3.2.0) we argue against the major role of Lunigiana fault as a relevant seismogenic LANF structure of the inner North West Apennine. On the contrary we suggest that the fault systems seismically active and cause of hazards issues in the region are the high-angle, west-dipping faults, e.g. the Compione-Comano System as well as the transversal North Apuane Fault. This latter fault, is possibly kinematically linked with the west-dipping border faults at the western side of the Alpi Apuane an highly inhabited region.

5) Finally we note that both development and activity of the basement ramp and the Low-Angle Normal Fault systems, with their architecture, kinematic characters (north to south increase in thinning) and timing (pre 5-4 Ma) is consistent with the rototranslational kinematics (Figure 14) of the northern Apennines (Elter & Pertusati, 1973; Royden et al. 1987; Boccaletti et al. 1990; Vai & Castellarin, 2001; Faccenna et al., 2001; Molli, 2008; Caricchi et al., 2014; Le Breton et al., 2018). This tectonic framework also fits the present day tectonics (Bennett et al., 2012; Doglioni and Carminati, 2012; Faccenna et al., 2004) and the seismic activity of the system of both High-Angle Normal to Transtensive structures as well as crustal basement thrusts (Eva et al., 2014; Molli et al., 2016; Bonini et al., 2016 and references therein). All these faults systems characterize and are actively shaping the studied sector of the northen Apennines (Figure 14d). The transition from LANFs to HANFs stage documented in this study, and also reported for the Southern Tuscany (e.g. Brogi, Liotta 2008 and references), occurred at c. 5-4 Ma. Consequently, this change in style of deformation at regional-scale has to be fully included in the geodynamic framework of the northern Apennines.

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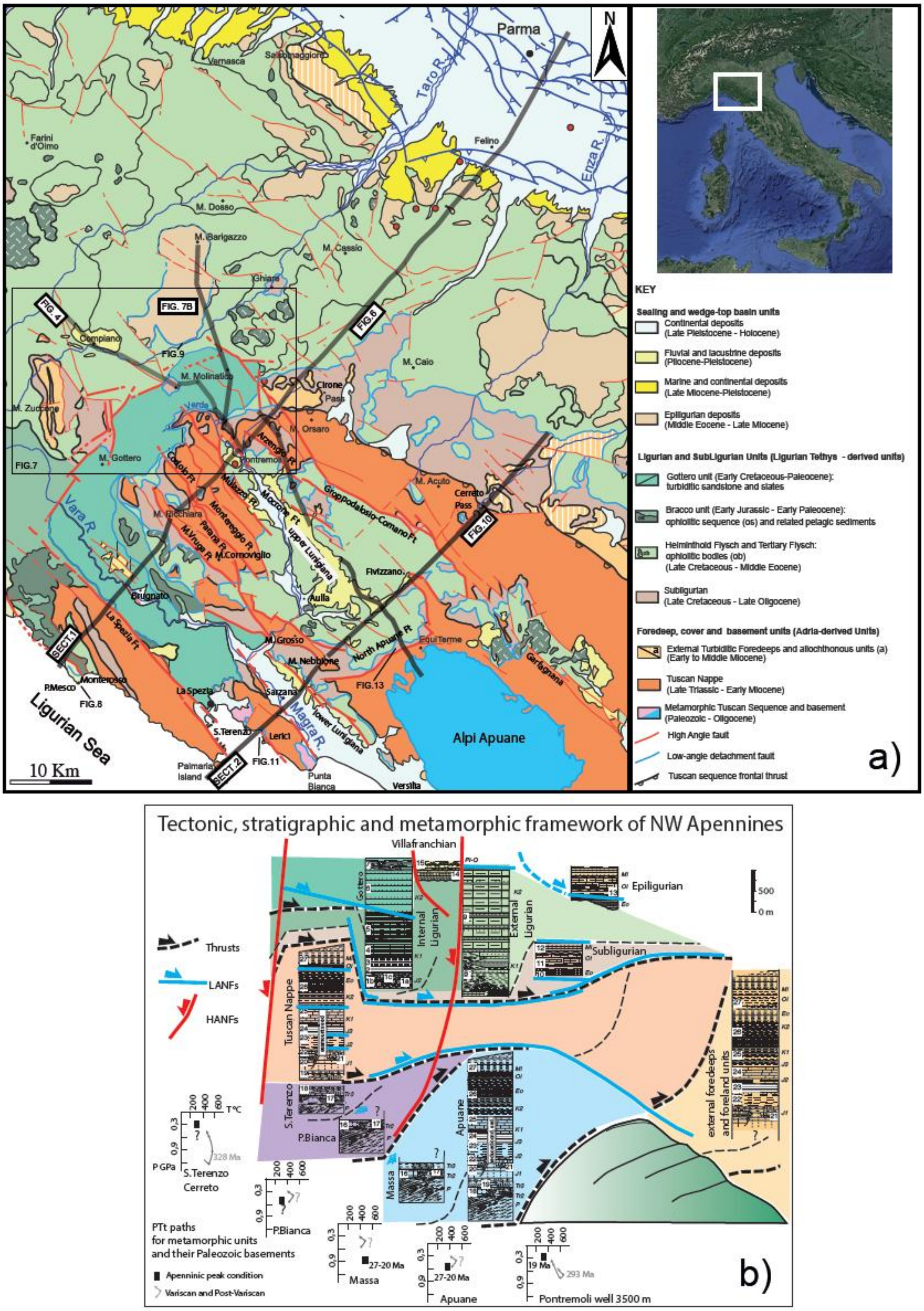

Figure 1: a) Geological setting of the North-West Apennines with indicated the geological cross-sections described in the paper and the main discussed structures (modified after

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Bernini et al., 1997); b) tectonic, stratigraphic and metamorphic framework of studied area (modified after Molli, 2008). For the schematic stratigraphic sequences: (1) ophiolitic basement: (1a) mantle serpentinites, (1b) gabbros, (1c) basalts; (2) cherts; (3) Calpionella limestones; (4) Palombini shales; (5) Val Lavagna schists; (6) Gottero sandstones; (7) Bocco/Colli Tavarone Paleocene shaly complexes; (8) Basal complexes: ophiolitic melanges and sandstones; (9) Helminthoid Flysch (10) Ostia-Scabiazza sandstones; (11) Canetolo fm. (limestones and shales) and Tertiary Flysch; (12) Aveto/Petrignacola sandstones; 13) Ranzano sandstones (within the Epiligurian sequences); (14,15) Villafranchian continental deposits mainly shales and conglomerates; (16) Metaconglomerates, metasandstones, shallow to deep marine carbonates and alkaline metavolcanics transgressive on Variscan and post-Variscan units (P); (17) continental ‘Verrucano’ and marine transgressive deposits on Variscan and post-Variscan units (P); (18) evaporites and dolomites; (19) Rhaetavicula contorta limestone and marls; (20) Massiccio limestone; (21) Rosso Ammonitico; (22) cherty limestone; (23) Posidonia marls; (24) Cherts; (25) Maiolica; (26) Scaglia Toscana, Scisti a Fucoidi; (27) siliciclastic turbidites (Macigno, PseudoMacigno, Cervarola, Marnoso–Arenacea). Also indicated: the approximate scale of thickness (0-500 m) for the stratigraphic sequences and the PTt paths for the metamorphic units and their Paleozoic basements. In black Apenninic age PT peak conditions, in gray Variscan or Post-Variscan PTt paths (references in the text).

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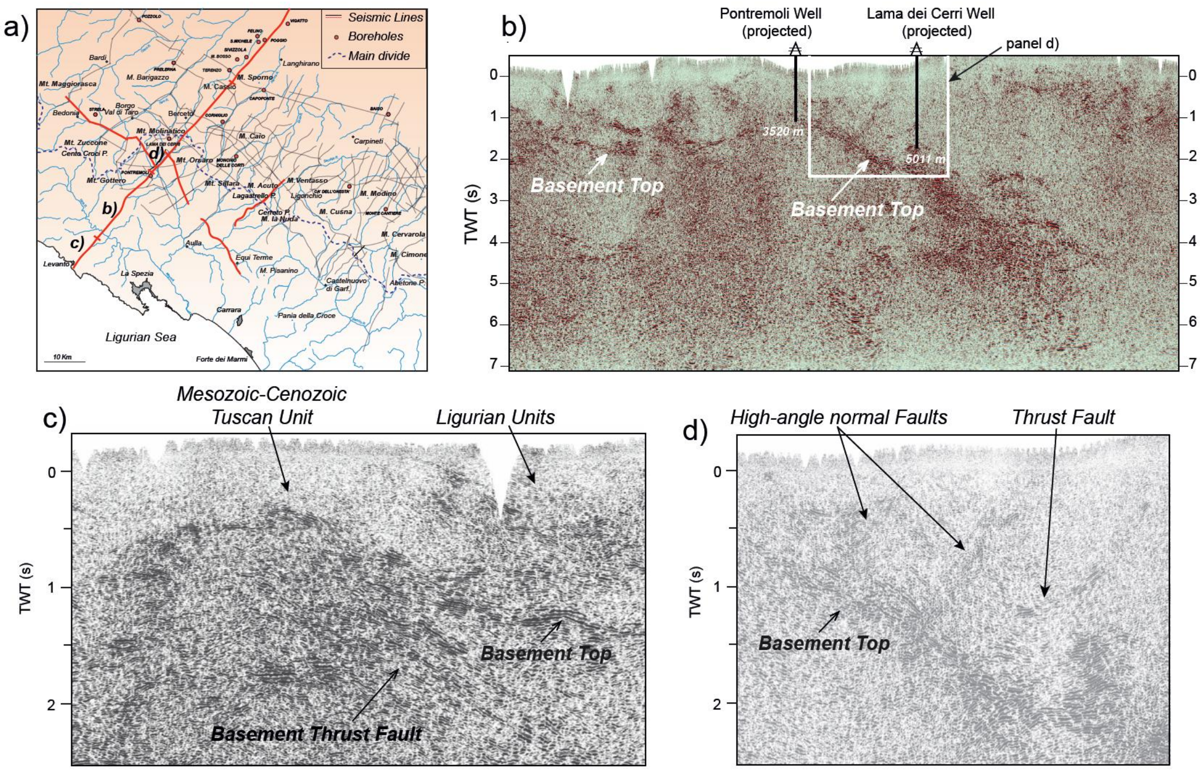

Figure 2: a) Subsurface geological data made available by ENI S.p.A. and ViDEPI Project database, with indications of seismic lines and boreholes location used in this work; b) portion of the Levanto-Pontremoli-Parma seismic line (sect.1/Fig.6) showing in some details the seismic signature characterizing the North-West Apennines as illustrated in the paper; c) westernmost portion of section 1 with seismic characters of "basament" and "cover" units and their internal structures; d) central part of seismic line (sect.1/Figure 6) showing high angle normal faults and cross-cut relationships with "seismic basement" in Lunigiana.

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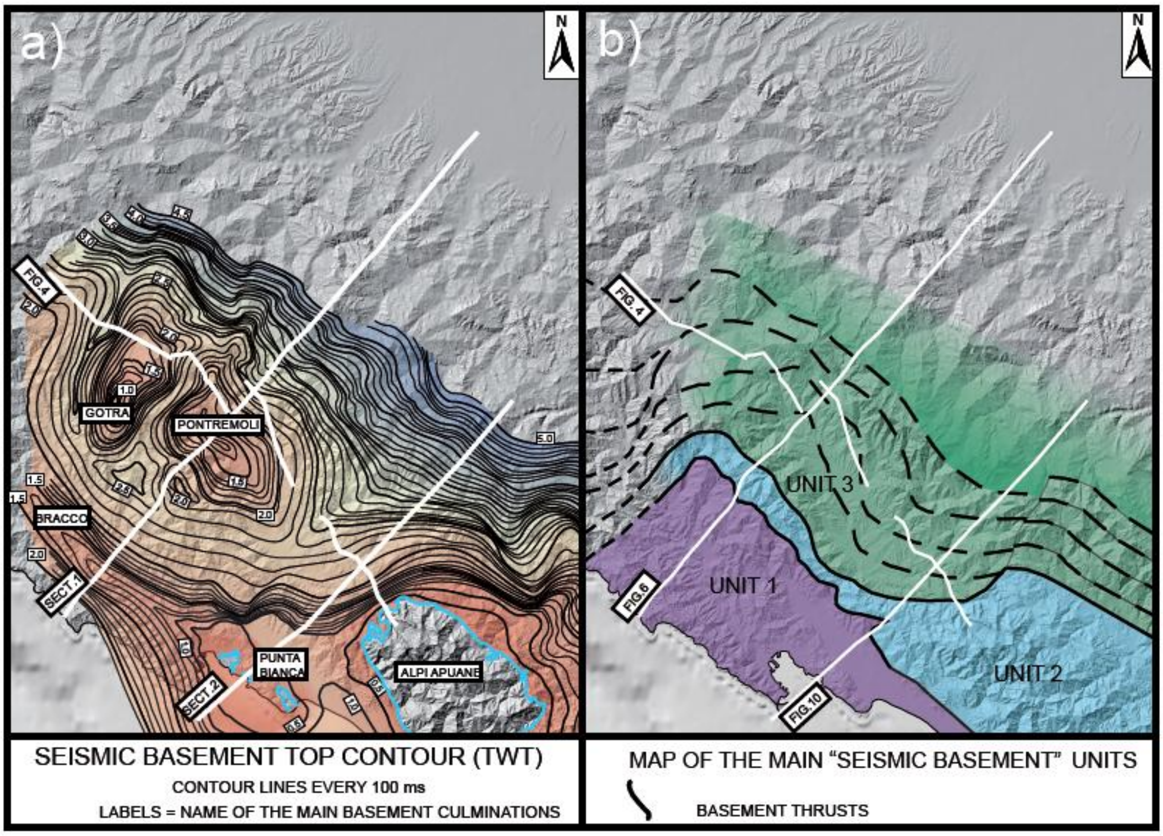

Figure 3: a) Contour of seismic basement top (in sec Twt); 3b) Map of "seismic basement" subdivided in the main composite "basement" tectonic units correlated with the exposed Tuscan metamorphic units.

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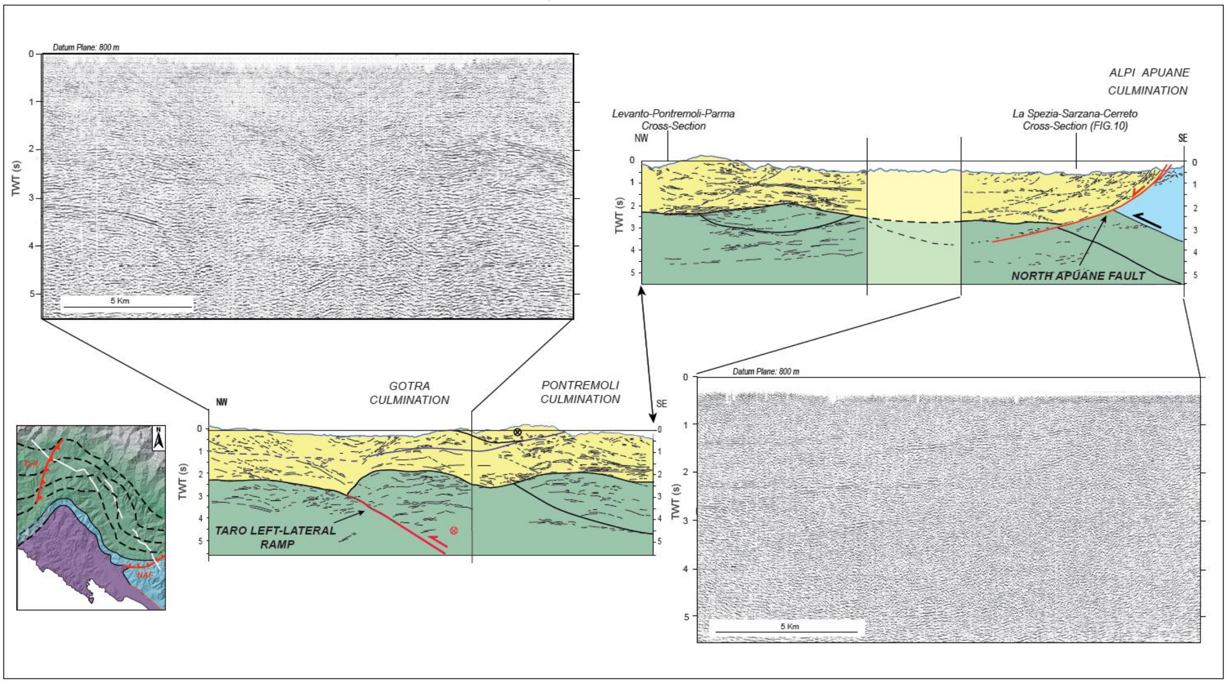

Figure 4: Crustal Taro-Pontremoli-Lunigiana-Apuane strike section with details of seismic lines and related line drawing (inset: white traces are the locations of the seismic reflection profiles projected onto the seismic basement units).

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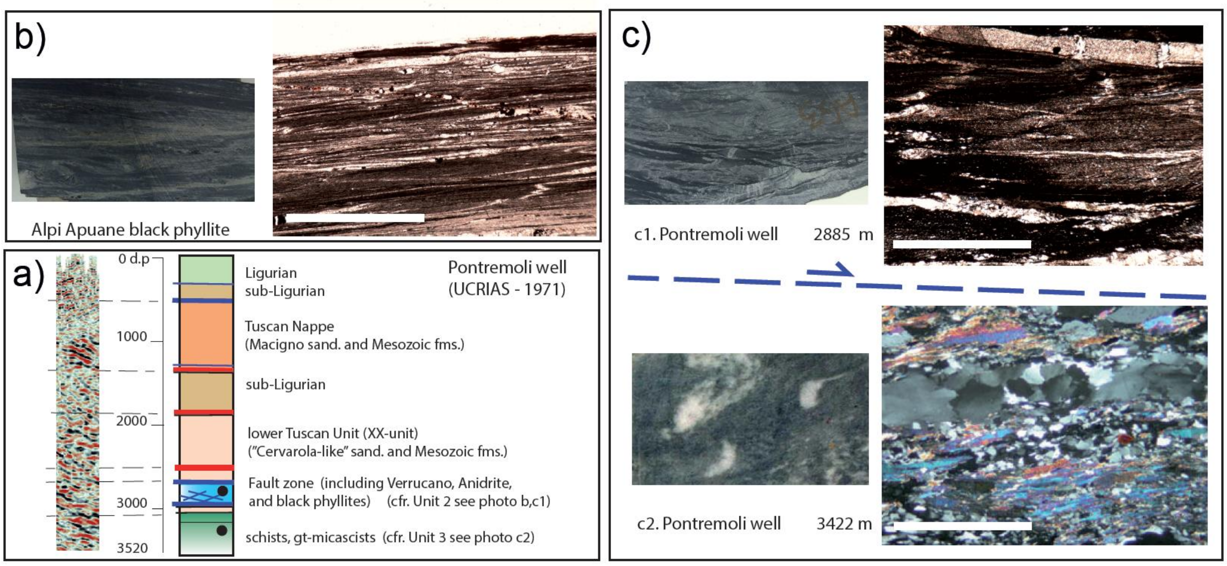

Figure 5: a) Comparison of seismic signals and tectono-stratigraphic log of Pontremoli well; b) rock-slice and representative thin section (natural polarized light, scale bar 1,5 mm) of black phyllites from the Alpi Apuane (Unit 2); c) rock-slices and representative thin sections from basal portion of Pontremoli well (Unit 3), black phyllites at a depth of 2885 m vs. micaschists at a depth of 3422 m (natural polarized light, scale bar 1,5 mm).

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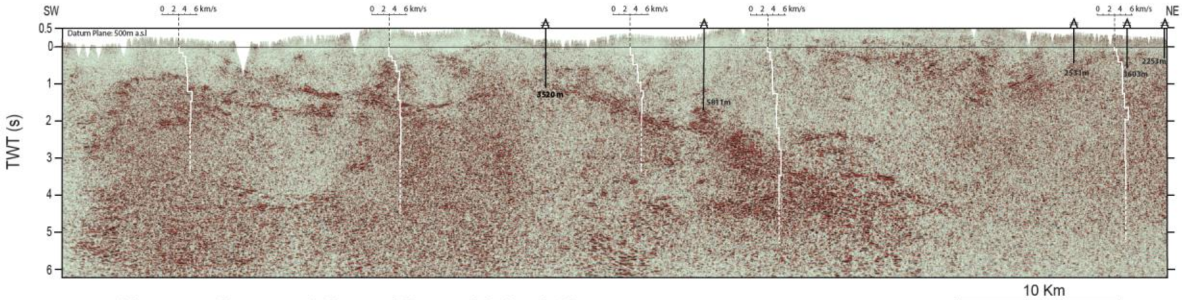
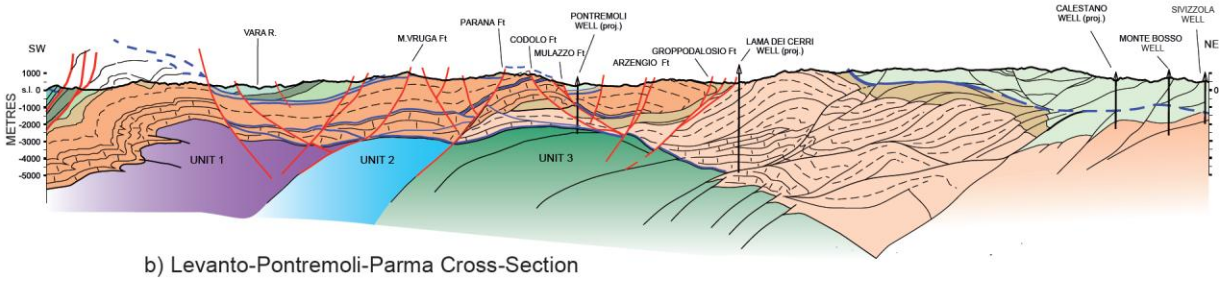


a) Levanto-Pontremoli-Parma Migrated Seismic Line



b) Levanto-Pontremoli-Parma Cross-Section

Figure 6: Levanto-Pontremoli-Felino cross-section 1 with comparison of a) migrated seismic line and b) related geological depth cross-section.

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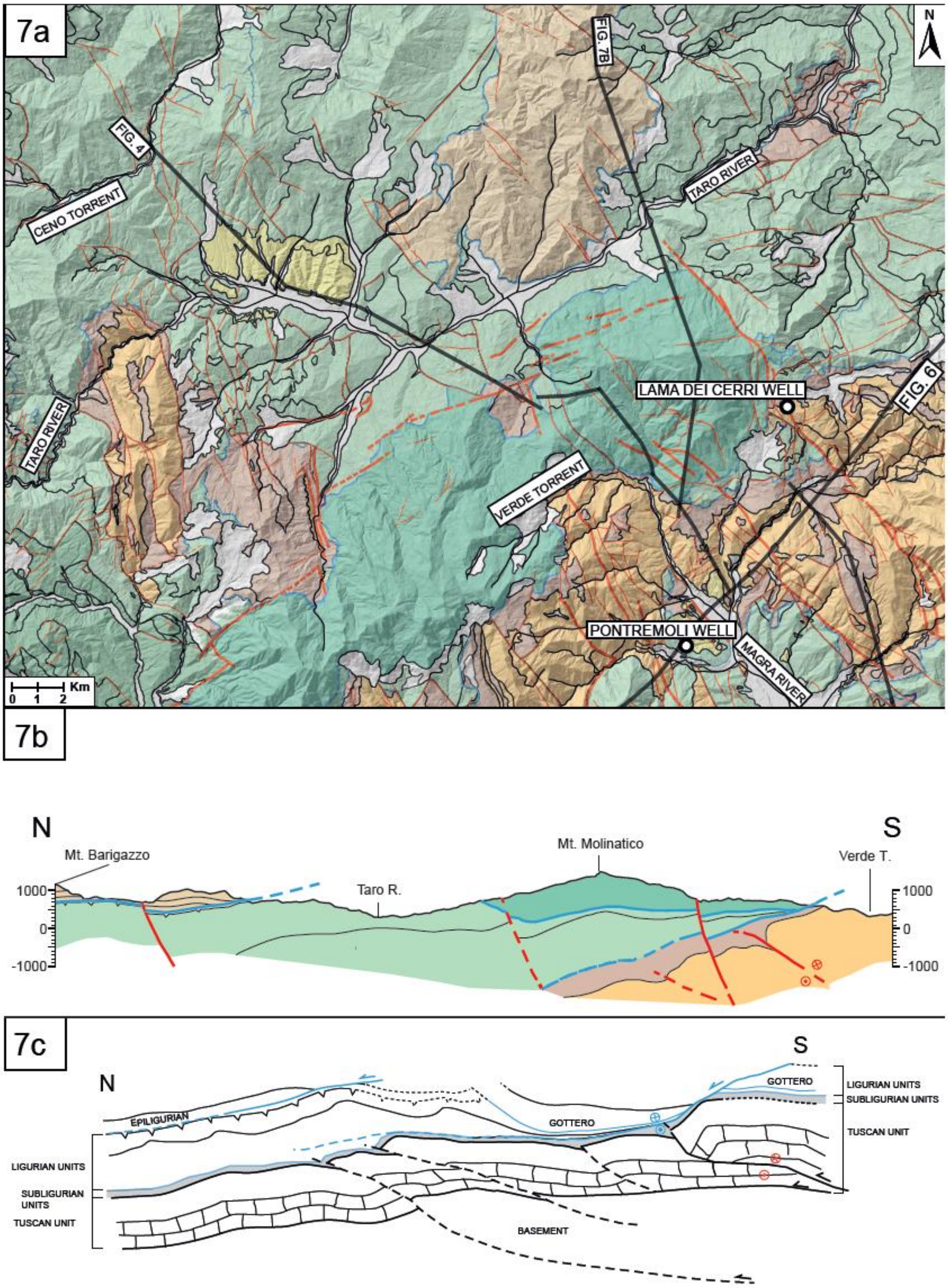

Figure 7: a) Geological map between upper Lunigiana and Taro region with b) geological cross section and c) deep tectonic interpretation (see Figure 4) illustrating the Vara-Verde and Epiligurian detachments across the TLR (Taro Lateral Ramp).

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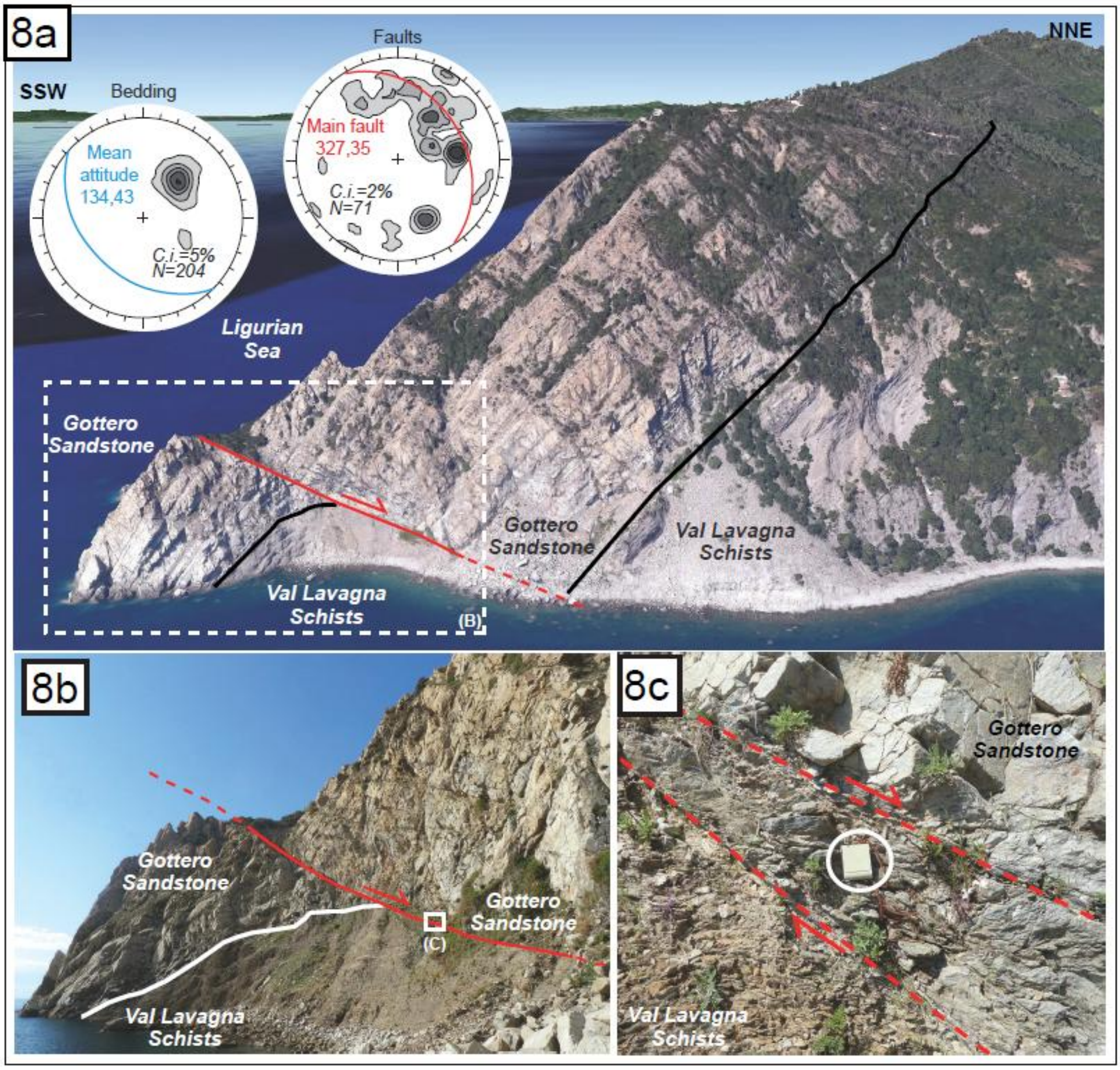

Figure 8 Lower splay of the Vara-Verde detachment in the P.Mesco area west of Monterosso with kinematic data. The top-to-the east low angle normal fault affects the stratigraphic contact between Gottero Sandstone and Val Lavagna Schists with a) large scale view in Google Earth oblique image; b) field view and c) mesoscopic characters of the fault rock.

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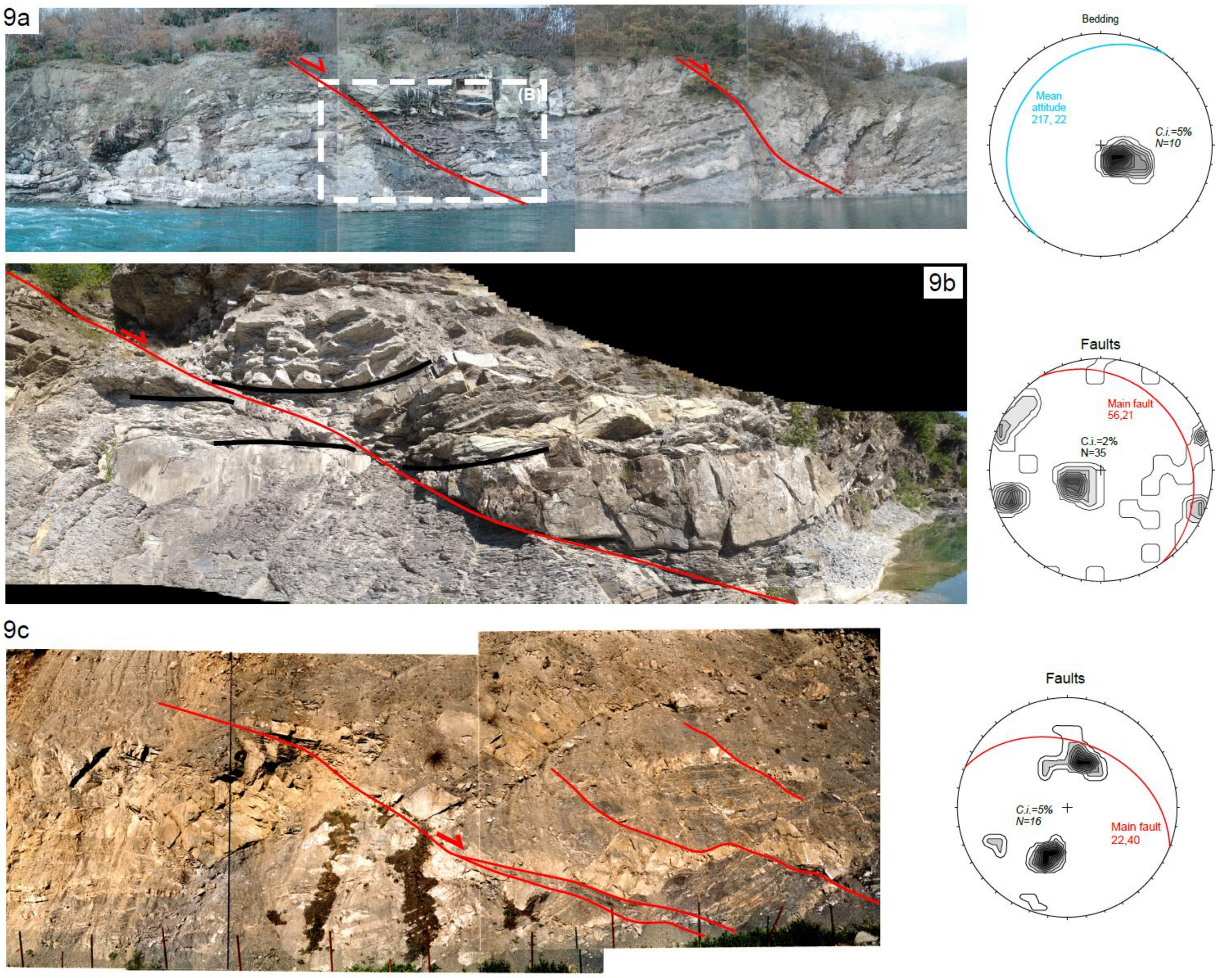

Figure 9: Vara-Verde and Epiligurian detachment along the Taro river with kinematic data: a) large scale view of an arrays of decameter-scale low angle normal faults affecting Helmintohoid Flysch b) close up of one of the low-angle normal faults; c) Epiligurian detachment affecting shale-marls units of Ranzano Fm. at the contact with the underlying Ligurian units to show structural details and fault rocks.

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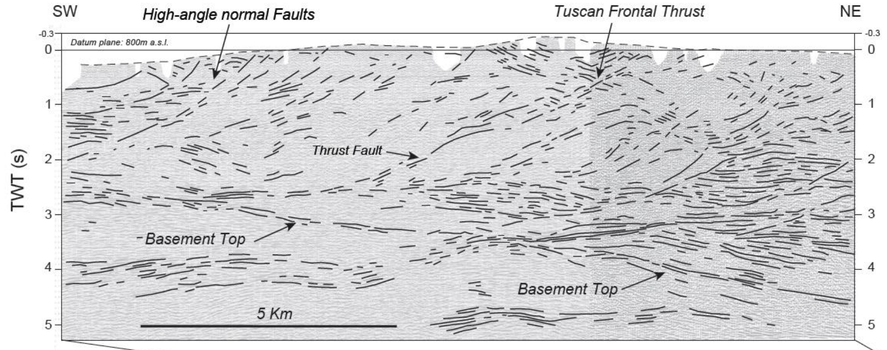
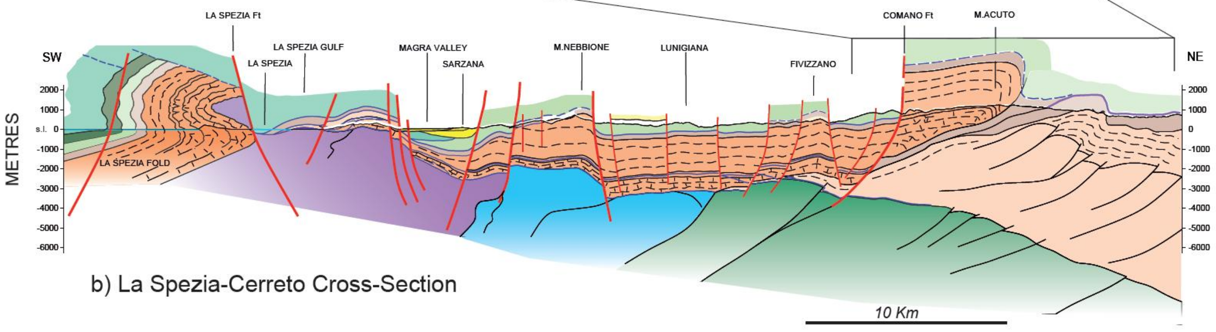


a) Interpreted Nearest Seismic Line



b) La Spezia-Cerreto Cross-Section

Figure10: La Spezia-Sarzana-Cerreto cross-section 2 with line-drawing of the interpreted nearest seismic line. In the geological cross-section within the Tuscan Nappe (Triassic-Late Jurassic carbonates, Cretaceous-Tertiary shales – Scaglia Fm. and Tertiary Macigno sandstone are respectively represented with brick pattern, continuous double lines and dashed lines);

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Figure 11: Tellaro detachment with kinematic data in the type-area (coast-line near Tellaro village): a) large scale view with outlined the excision of Tuscan Nappe stratigraphy with direct justaxposition of Cretaceous-Tertiary Fms. with Triassic-Jurassic carbonates; b), c) close up and internal structures of Tellaro detachment (details in Clemenzi et al., 2015; Storti, 1995).

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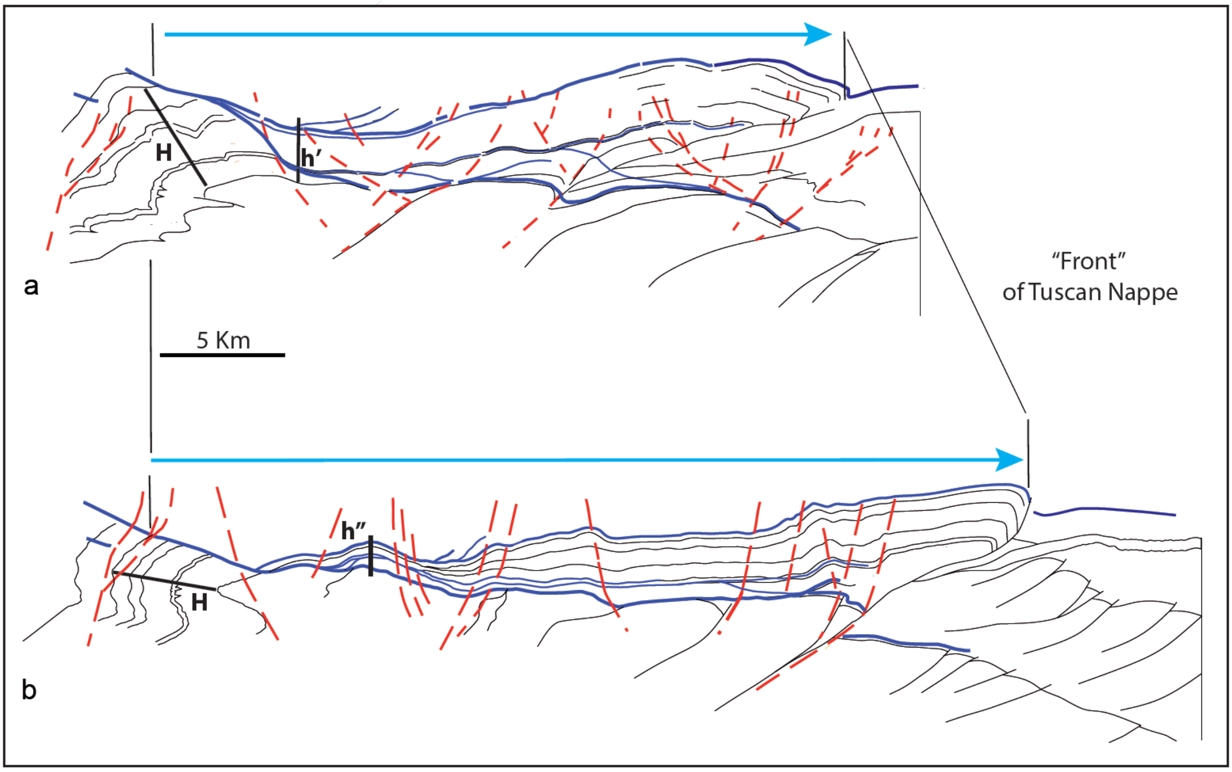

Figure 12: Regional cross-sections 1 and 2 restored by the HANFs. The comparison between the two cross-sections, separated by distance of c. 20 Km, allowed to highlight the along-strike variability of the nappe stack and architectures of the LANF System together with cross-cut relationships between post-stacking fold structures (La Spezia Fold) and the detachment systems. An along along strike, north to south, increase in tectonic excision is evident by comparison of the “undeformed” pre-LANFs frame (H) which accounts the total thickness of tectonic units from the base of Tuscan Nappe to base of Gottero Unit with h and h’ (“deformed state”) using the same datum references.

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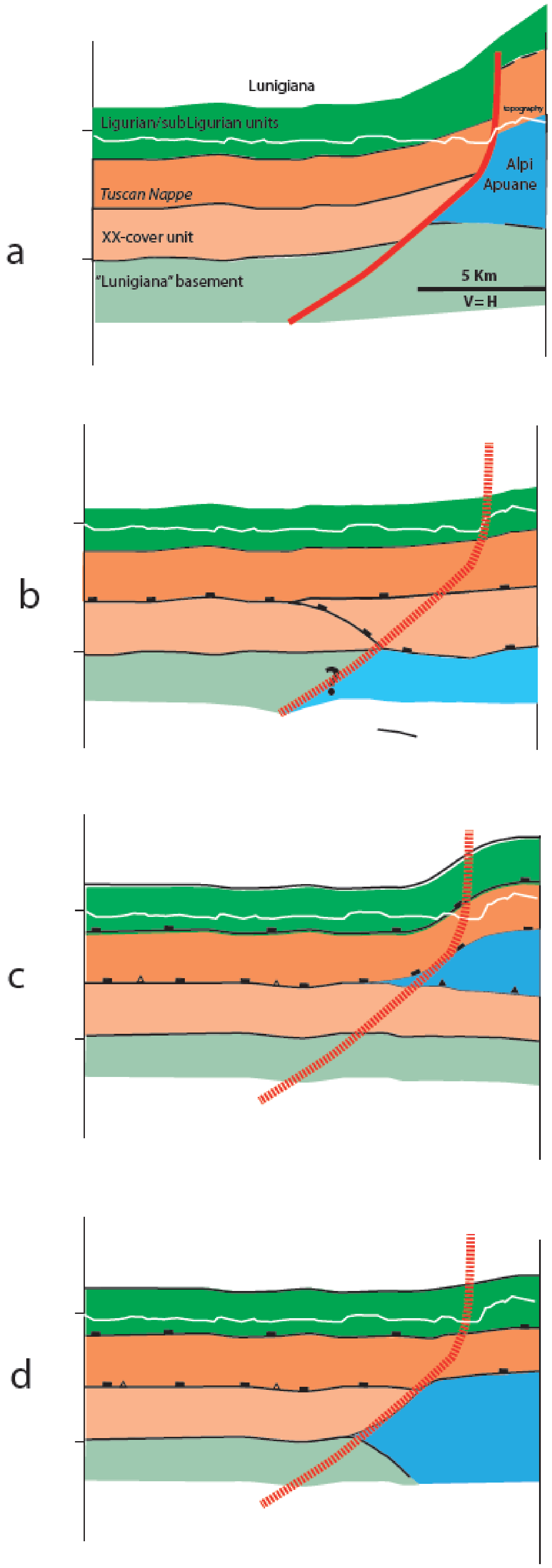
a
Lunigiana
Ligurian/subLigurian units
topography
Alpi Apuane
Tuscan Nappe
XX-cover unit
"Lunigiana" basement
5 Km
V= H
b
?
c
d

Figure 13: Structural interpretations for the Apuane/Lunigiana relationships across the North Apuane Fault: a) present day structural frame; b) XX unit (lower Tuscan unit in Lunigiana) in supra-Apuane position; c) XX unit (lower Tuscan unit in Lunigiana) in sub-Apuane position; d) XX unit (lower Tuscan unit in Lunigiana) in lateral juxtaposition as a result of basement thrusting. This kinematic solution found a direct analogue in the tectonic setting of Taro lateral ramp.

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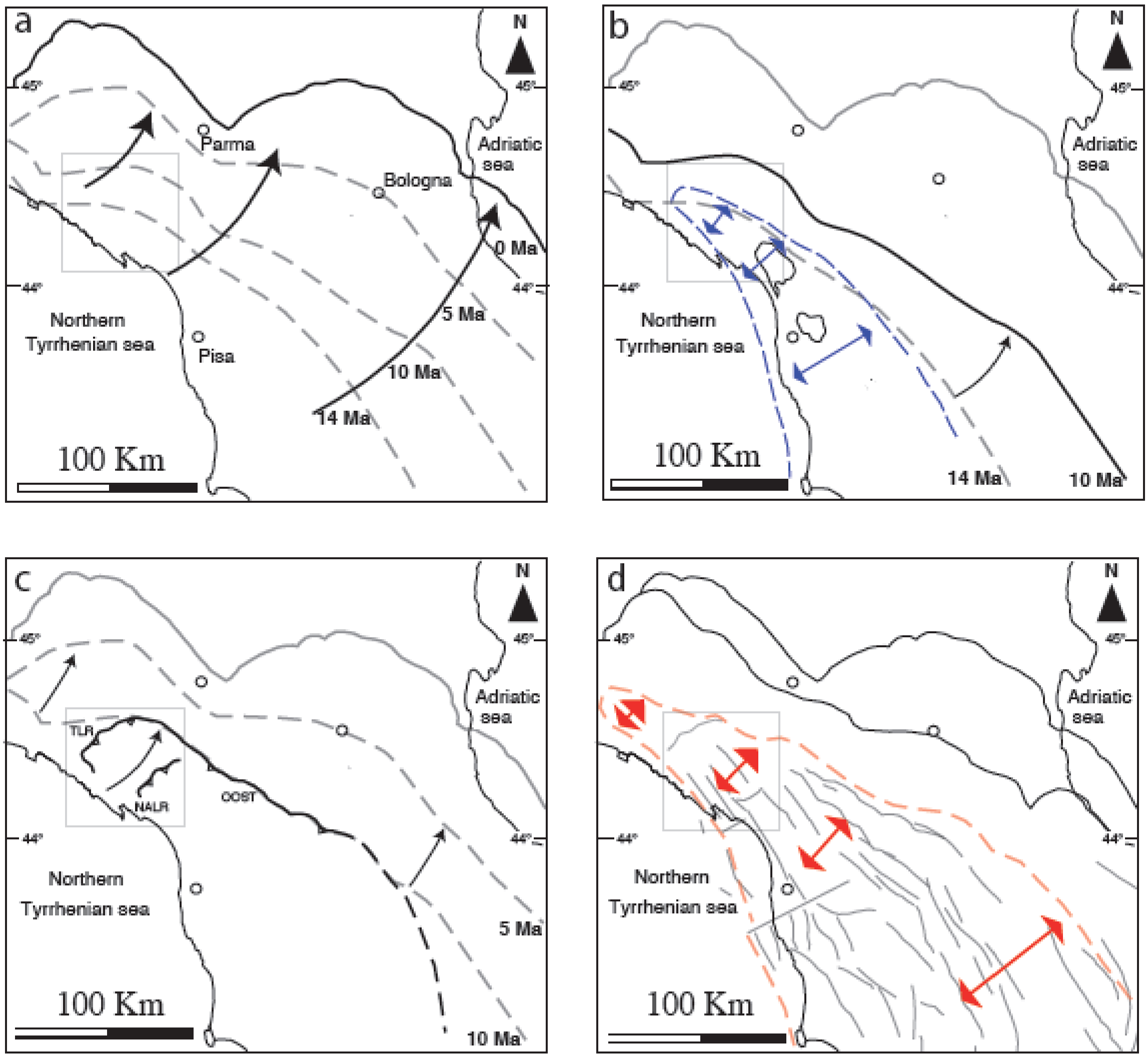

Figure 14: Geometric-kinematic frame for the Neogene low-angle normal faulting, basement thrusting and recent-to-present day high angle normal faulting in the studied area (framed with the rectangle). The template of the documented structures, their architecture and evolution may be related with the rototranslational kinematics of the growing Apennines orogenic wedge with time (see recent recostruction in Le Breton et al., 2018): a) kinematics of the deformation front of the northern Apennines orogenic wedge in 4 key steps at 14 Ma, 10 Ma, 5 Ma and present day (0 Ma) (based on Le Breton et al., 2018); b) development of the LANF stage ending between 10 to 5 Ma with indication of the inner extensional domain (blue dashed lines) and the coheval contractional front (continuous black line), in dashed grey the position of contractional front at 14 Ma; c) kinematics of the deformation front during the development of out-of-sequence thrusts (OOST) in the internal part of wedge and development of the North Apuane Lateral Ramp (NALR) and then the Taro Lateral Ramp

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(TLR) in the time interval between 10 and 5 Ma. With dashed lines position of the deformation fronts during the 10 to 5 Ma time interval; d) present day setting with thick and thin black lines indicating the buried active deformation front and the out-of-sequence frontal thrusts of the Apennines wedge. In red dashed lines, the inner extensional domain is represented with the red double arrowed lines to indicate the present day along strike differential extension as documented by geodetic data (Bennett et al., 2012). In gray the high angle normal faults and the active transversal lines are represented.

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