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RESEARCH ARTICLE

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Integrated analysis of the Neogene–Quaternary Valdera-Volterra Basin (Northern Apennines). Evidence for composite development of hinterland basins

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Abstract

The Neogene and Quaternary hinterland basins of the Northern Apennine have been the subject of different tectonic interpretations. Several studies considered these basins as the result of polyphase normal faulting framed in a continuous crustal extensional regime since the middle Miocene. On the contrary, geophysical and geological studies provided evidence of the important role played by out-of-sequence thrusts and backthrusts in the evolution of these basins during a prolongated and intense period of shortening. Here we present an integrated analysis of 2D stacked seismic reflection profiles, stratigraphic and geophysical data from deep exploration wells, gravity data, and published geological and biostratigraphic data for the Valdera-Volterra basin (central Tuscany, Italy). The results support a polyphase and composite evolution of the basin, subdivided into three main phases. During the late Tortonian–Zanclean, the growth of major thrust-related anticlines controlled the evolution of the sedimentary basin. The growth of a syncline determined the creation of accommodation space for the sediments. This main compressional deformation occurred during the Messinian and ended during the Late Zanclean. NE migration of the depocentre during the Early Zanclean was identified, likely possibly due to a differential activity growth between the bordering anticlines. During the Piacenzian, an extensional phase has been recognised, superposed to the previous compressive phase. During the Latest Piacenzian–Early Pleistocene (?), a final compressional phase took place resulting in the positive inversion of the Piacenzian WSW dipping main border fault.

KEYWORDS

Hinterland basins, Northern Apennines, Polyphase tectono-sedimentary evolution, Seismic profiles

1 | INTRODUCTION

Hinterland basins, such as those of the Northern Apennines (NA), Andes, and Himalayas form on continental crust behind the front of foreland fold and thrust belts (Horton, 2012; McMillan et al., 2022; Roure, 2008; Yin et al., 2008, see Ingersoll, 2012 for a definition). These basins are often densely populated low-lying areas and cradle of civilizations for millennia. They are areas of great socio-economic importance and a deep understanding of their tectono-stratigraphic setting and evolution is crucial to assessing their potential subsurface resources and geohazards (Gong et al., 2023; Liu et al., 2021; Martelli et al., 2017; Molli et al., 2021; Zhi et al., 2022).

> **Highlights**
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> - Investigation of the Neogene-Quaternary evolution of the Valdera-Volterra Basin, central Tuscany.
> - Integration of seismic, gravity, well, surface geological and paleontological data.
> - Late Tortonian-Zanclean deposition controlled by major competing thrust-related anticlines.
> - Piacenzian extensional phase accommodated by border faults.
> - Latest Pliocene/early Pleistocene(?) tectonic mild positive inversion.

The NA (Figure 1a) are a NE-verging, arcuate fold, and thrust belt developed since the late Oligocene due to the closure of Tethys and subsequent collision of the Corso-Sardinian block and the Adria Plate (Boccaletti et al., 1971, 1980; Conti et al., 2020; Molli, 2008; Treves, 1994; Vai, 2001a). The NA is commonly subdivided into an outer (eastern) sector currently characterised by compressional tectonics and generalised uplift of orogenic terrains, and an inner (western) sector where marine and continental hinterland basins have formed since the middle/late Miocene to the Quaternary (e.g. Barchi, 2010; Boccaletti et al., 1995, 1999; Martini & Sagri, 1993; Vai, 2001a). The hinterland basins have also been defined in the last decades as *intermontane basins* in several studies (e.g. Conti et al., 2020; Ghinassi et al., 2021; Sani, Bonini, Piccardi, et al., 2009). The origin of the hinterland basins of the NA is strictly tied to the geodynamical model adopted to explain the formation of the chain. Different models have been proposed (see Bennett et al., 2012; Bonini et al., 2014 for a review), including (1) slab rollback and retreating that caused extension in the hinterland and active compression in the foreland associated with the W-dipping Adriatic lithospheric subduction, (2) slab detachment after continental collision, (3) retreat of the upper plate caused by contrasting westward motion of the lithosphere to the relative eastward flux of the asthenosphere, (4) orogenic (gravitational) collapse, of an over thickened orogenic wedge. As a matter of fact, the internal area of the NA basins formed since Middle–Late Miocene, roughly contemporaneously over an area wide about 120–150 km, that currently includes part of the Tyrrhenian Sea from the Pianosa—Montecristo ridge to the west, up to the Montalbano-M. del Chianti—M.Cetona ridge to the east (Figure 1). Later, since the Late Pliocene new continental basins formed eastward into two roughly parallel belts (Firenze-Valdarno-Val di Chiana and Mugello-Casentino, Figure 1). Although no specific studies investigated the possible origin of subsidence of the hinterland area of the NA favouring the development of the basins, the retreating slab of the Apennine subduction may have caused the dynamic subsidence of the whole hinterland area. On the other hand, we exclude the thermal subsidence considering the high heat flow still affecting the area, that on the contrary favoured the uplift (Mongelli et al., 1998). Moreover, flexural subsidence appears more appropriate for the external foredeep basin rather than the hinterland area, even if Horton et al. (2022) suggest that broken foreland basin formation may be associated with distant flexure loading, but specific studies about this topic should be addressed to investigate in more detail the problem of subsidence of the area.

Two contrasting hypotheses have been elaborated for the structural evolution of the basins occurring in the western sector of NA. One hypothesis proposes these basins as developed in an overall extensional tectonic regime related to the opening of the Tyrrhenian Sea either in a back-arc regime (Boccaletti et al., 1990; Patacca et al., 1990), or due to late orogenic gravity collapse of an overthickened accretionary prism, with the development of core complex structures associated with low-angle normal faults (Carmignani et al., 1994; Carmignani & Kligfield, 1990). In both these hypotheses, an extensional 'wave' followed the migration of the compressive front towards the east (Elter et al., 1975). In this setting, the Tuscan hinterland basins have been interpreted as graben (Lazzarotto & Mazzanti, 1976; Sestini, 1970; Trevisan, 1952) and half-graben (Martini & Sagri, 1993; Pascucci, 1997), or as bowl-shaped basins evolving into graben bounded by low- to high-angle normal faults (Brogi, 2011, 2020; Brogi et al., 2005; Carmignani et al., 1994; Martini et al., 2021; Pascucci et al., 1999, 2001).

An alternative hypothesis proposes that these basins formed during generalised compressional tectonics and that their evolution was controlled by generations of thrusts and backthrusts affecting their substratum

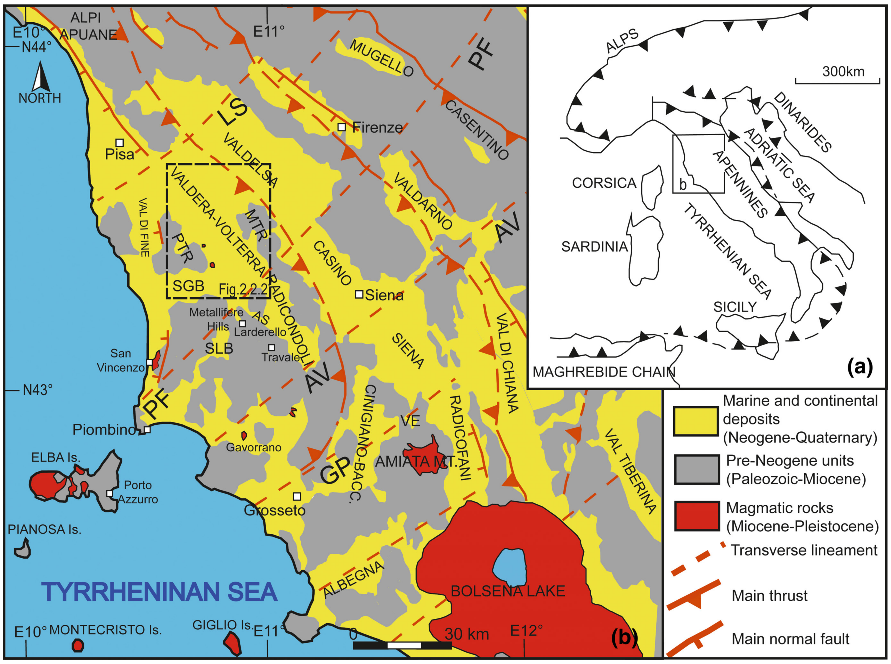


FIGURE 1 (a) Main mountain chains and features of Italy, (b) Schematic geological-structural map of the Inner Northern Apennines (Central Italy), with the location of the study area (modified from Sani et al., 2016). AS, Anqua sub-basin; AV, Arbia–Val Marecchia; GP, Grosseto–Pienza; LS, Livorno-Sillaro; MTR, Middle Tuscan Ridge; PF, Piombino–Faenza; PTR, Perityrrhenian Ridge; SGB, Sassa-Guardistallo Basin; VE, Velona Basin.

(e.g. Bonini & Sani, 2002; Bonini et al., 1999; Finetti et al., 2001, 2005; Sani et al., 2016). This hypothesis has been supported by field-based structural studies as well as detailed sedimentological-stratigraphic studies, and geophysical investigations, that evidenced the role of contractional structures in the evolution of these depocentres (e.g., Boccaletti et al., 1992, 1999; Bonini et al., 1999; Bonini & Moratti, 1995; Bonini & Sani, 2002; Finetti et al., 2001, 2005; Moratti & Bonini, 1998; Sani, Bonini, Cerrina, Feroni, et al., 2009; Sani, Bonini, Piccardi, et al., 2009; Sani et al., 2016). These studies generally identify common structural and stratigraphic features of the NA hinterland basins such as: (i) a general synformal shape located between thrust-related anticlines; (ii) the presence of strongly tilted basin-ward angular unconformities in the older sediments and gentler unconformities in the younger and sometimes growth strata at the basin margins indicating syndepositional margin uplift; (iii) the presence of compressional features at different scales, as thrust faults and mesoscale reverse faults and others, that often control the sedimentation; (iv) stress fields concordant with trajectories of the shortening direction orthogonal to the trend of the basins and the thrust-related anticlines at the basin margins that accommodated the uplift of the substratum; (v) the presence of more recent high-angle normal faults affecting the older compressive structures (e.g. Bonini & Sani, 2002; Bonini et al., 2013, 2014; Sani, Bonini, Piccardi, et al., 2009; Sani et al., 2016). Such a setting implies that the effects of extension driven by the Tyrrhenian Sea opening were confined in a more western position during the development of the hinterland basin, following later the compressive event (Sani, Bonini, Cerrina Feroni, et al., 2009).

In all the studied basins, we have detected extensional phases alternated to compressive phases that locally caused positive inversion of the previous structures (Bonini & Sani, 2002; Buttinelli et al., 2024; Sani et al., 2016). This process testifies that not a unique extensional regime affected the hinterland area, and one reason could be that the NA are a lateral chain in the broader context of the still active first-order Africa–Europe collision, with local factors that may act determining a more complex evolution.

Following these lines of evidence, the basins can be described as thrust-top basins or, following a recent definition, as broken foreland basins (Horton et al., 2022). The latter definition may be used because some of the proposed criteria for their identification are respected: the basement is involved in thrusting in the internal area of Tuscany; the area is affected by a high heat flow related to asthenosphere bulge (Finetti et al., 2001, 2005); the basins are confined into sectors delimited by thrust anticlines whose syn-depositional activity creates progressive unconformities along the basin margins (see Horton et al., 2022 for an exhaustive list of the main features). However, considering the debated origin and evolution of these basins, we maintain the more general definition of hinterland basins, based on their position with respect to the main chain.

This article investigates the tectono-stratigraphic evolution of the Neogene-Quaternary Valdera-Volterra Basin (Central Tuscany, Figure 1b), one of the largest hinterland basins in central-southern Tuscany, through the study of published and unpublished 2D seismic sections integrated with geophysical and stratigraphic data from deep boreholes and surface palaeontological samples (Data source: Regione Toscana n.d.—Micropaleontologia di superficie, BD_micro).

2 | GEOLOGICAL SETTING OF THE VALDERA-VOLTERRA BASIN

2.1 | Regional overview

The Neogene-Quaternary Valdera-Volterra Basin (VD-VR) is ~15 km wide and ~60 km long, (Figures 1 and 2) and is filled with an upper Serravallian–Pleistocene sedimentary succession up to ~2500 m thick (Bossio et al., 1996; Costantini et al., 2002; Lazzarotto et al., 2002; Martini et al., 2001; Figure 3b). The basin trends in an NNW direction and its NE and SW shoulders correspond with the Middle Tuscan Ridge (MTR) and the Perityrrhenian Ridge (PTR), respectively (Figures 1 and 2). The Pre-Serravallian substratum is highly deformed and consists mainly of Palaeozoic–early Cenozoic tectono-sedimentary units made of folded and thrusted limestones, sandstones, mudstones, ophiolites, and cherts (Bertini et al., 2000; Carmignani et al., 2001; Lazzarotto et al., 2002). These units represent adjacent palaeogeographical and tectonic domains established through the fragmentation of the Africa–Europe plates and the subsequent opening and spreading of the Ligurian-Piedmont Ocean (Molli, 2008 and reference therein). The oceanic basin is represented by the Jurassic-Paleogene Ligurian Units including remnants of the oceanic lithosphere (ophiolites) and its sedimentary cover of cherts and turbiditic mudstone and limestone (Bortolotti et al., 2001; Conti et al., 2020; Marroni et al., 2001; Pandeli et al., 2005 and reference therein; Figure 3a). The Sub-Ligurian units consist of Cretaceous–Oligocene turbiditic mudstone, limestone, and sandstone deposited in the transitional area between the Ligurian domain and the continental Tuscan domain (Conti et al., 2020 and reference therein; Figure 3a). The continental margin of Adria (a promontory of the African plate) (Adria) is represented by the Tuscan units. The Tuscan units are subdivided into the Tuscan Nappe and the Metamorphic Tuscan Nappe representing Internal and External Tuscan domains, respectively. The Tuscan Nappe mainly consists of upper Triassic-Cretaceous carbonates resting on thick evaporites (Burano Fm.), overlain by Cretaceous–Oligocene mixed carbonate-terrigenous deposits in turn capped by thick upper Oligocene–lower Miocene turbiditic sandstones and mudstones (Bortolotti et al., 1970; Carmignani et al., 2001; Conti et al., 2020; Fazzuoli et al., 1985 and reference therein; Figure 3a). The Metamorphic Tuscan Nappe consists of late Palaeozoic–Triassic quartzite (Verrucano Group, Auct.), late Triassic–Jurassic metacarbonates, Cretaceous–Oligocene calceschists, and Oligocene–lower Miocene metasandstones (Carmignani et al., 2001, and references therein). From the Late Cretaceous to the early Eocene, the Ligurian-Piedmont Ocean underwent a subduction followed from the Late Eocene to the Early(–Middle?) Miocene by a continental collision between the Corsica-Sardinia block (European plate) and the Adria Plate. This led to the progressive NE-verging stacking of the tectonic units resulting in a tectonic pile with the Ligurian Units occupying the topmost position overlying the Sub-Ligurian and the Tuscan units (Carmignani et al., 2001; Molli, 2008 and reference therein; Figure 3a), the last one lies unconformably over the Palaeozoic basement (Carella et al., 2000; Gianelli & Ruggieri, 2002; Musumeci et al., 2002; Pandeli, 2002; Vai, 2001a, 2001b).

In some portions of the NA hinterland, the direct superposition of the Ligurian Units over the Late Triassic Burano Formation was documented, a setting known as the Serie Ridotta (e.g. Bertini et al., 1991; Giannini et al., 1971; Signorini, 1949; Trevisan, 1955). The origin of the Serie Ridotta has been the subject of debate being ascribed to both early–middle Miocene regional extension accommodated by low-angle normal faults (Brogi et al., 2005; Carmignani et al., 1994; Lavecchia et al., 1984) and Early–Middle Miocene regional compression accommodated by out-of-sequence thrusting (e.g. Finetti et al., 2001; see Bonini et al., 2014 for a discussion). Regardless of its origin, field studies show that the Serie Ridotta has been affected by thrust and thrust-related-fold active after its formation (Carosi et al., 2004; Moretti, 1986; Pandeli et al., 2005).

2.2 | Structural architecture

The opening of the VD-VR, is referred to as the Middle–Late Miocene, though its tectono-sedimentary significance has been largely debated (e.g. Brogi & Liotta, 2008; Mazzanti, 1961; Pascucci et al., 1999; Sani et al., 2016).

Early studies referred the basin initiation to an extensional tectonic regime resulting in the formation of a graben (e.g., Giannini, 1962; Lazzarotto, 1967; Lazzarotto & Mazzanti, 1976). Successive studies updated this interpretation representing the basin as a half-graben (Martini & Sagri, 1993; Pascucci, 1997) or as a bowl-shaped depression that later evolved into an half-graben (Pascucci et al., 1999, 2001).

Geological mapping and structural studies, carried out in the southern and central portions of the basin, identified mesoscale reverse faults and asymmetric folds affecting the Neogene basin fill suggesting the presence of major compressive structures affected by normal faults activated during the later phase of basin evolution (Boccaletti et al., 1995; Boccaletti & Sani, 1998; Bonini & Moratti, 1995; Moratti & Bonini, 1998; Sani et al., 2016). These local-scale data suggest a complex structural evolution characterised by pulses of crustal shortening and

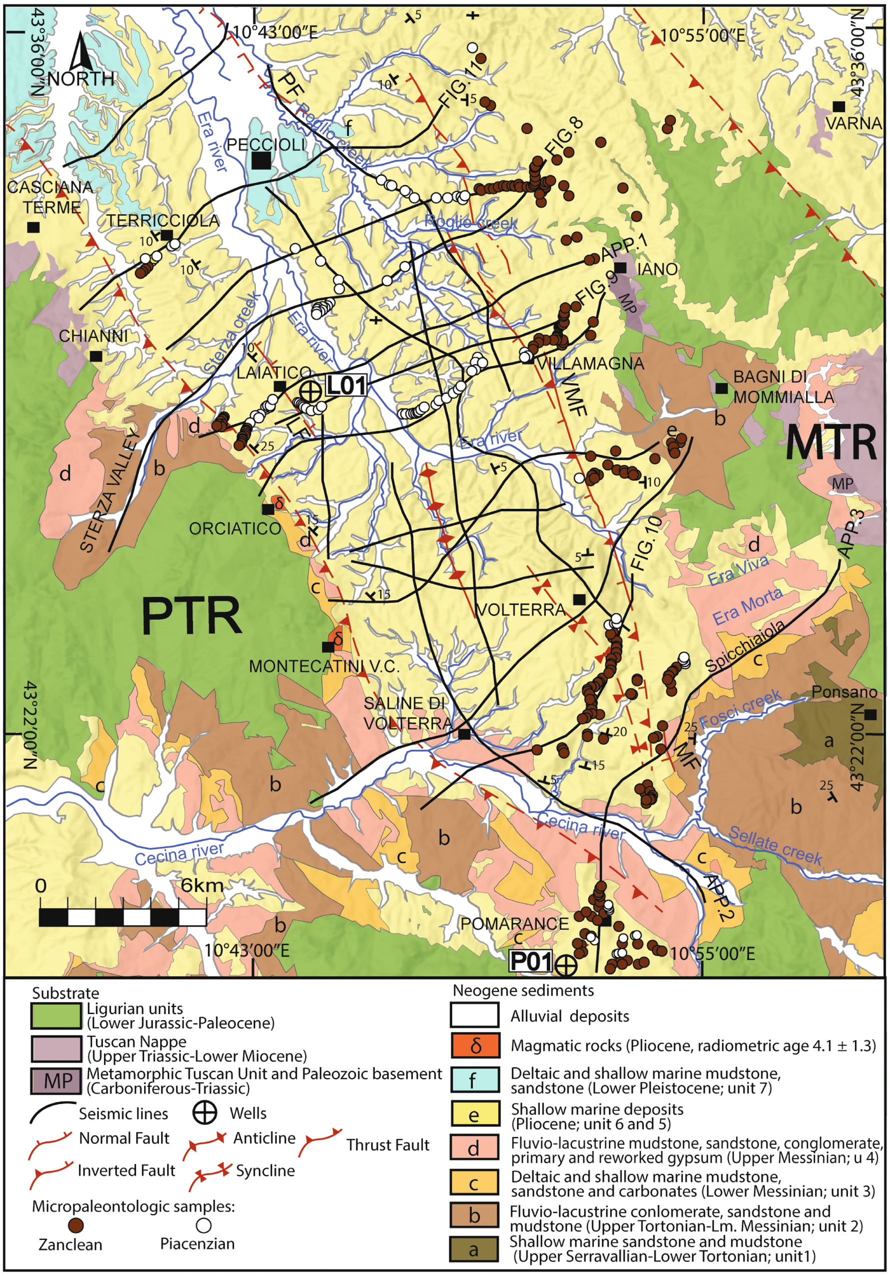


FIGURE 2 Schematic Geological map of the Valdera-Volterra Basin showing the major structures and the location of the seismic grid and the Laiatico01, Pomarance 01 wells (L01, P01) used in this study. LF, Laiatico fault; MF, Mazzolla fault; MTR, Middle Tuscan Ridge; PF, Peccioli fault; PTR, Perityrrhenian Ridge; VMF, Villamagna Fault.

they are consistent with the presence of major W-dipping crustal thrust involving the Tuscan metamorphic units of the Mid Tuscan Ridge (MTR, Figure 1) as also suggested by regional magnetic and Bouguer anomalies interpretations (Arisi Rota & Fichera, 1987; Cassano et al., 1998), seismic refraction data (Ponziani et al., 1995) and interpretations of seismic deep crustal reflection profiles (Italian CROP project. Bonini et al., 2014; Finetti et al., 2001, 2005). Furthermore, the interpretation of seismic profiles crossing the Sassa-Guardistallo Basin to the SW of the VD-VR (SGB, Figure 1) highlights the possible role of thrust faults reactivating the basement of the PTR (Figure 1; Cerrina Feroni et al., 2006). Finally, the combination of these lines of evidence supports an alternative hypothesis for the origin and Late Miocene development of the VD-VR as being due to a predominantly compressional tectonic regime (Boccaletti & Sani, 1998; Bonini & Moratti, 1995; Moratti & Bonini, 1998; Sani et al., 2016).

2.3 | Stratigraphy

The portion of the PTR bordering the basin to the southwest is characterised by Ligurian Units that in the northern portion of this ridge tectonically overlie the Tuscan Nappe, exposed around Chianni and Casciana Terme (Dallan, 1990, Marroni et al., 1990; Mazzanti, 2016; Squarci & Taffi, 1964 and reference therein; Figures 2 and 3c). S of the Sterza valley, the Ligurian Units rest directly over the Triassic Burano Formation, encountered

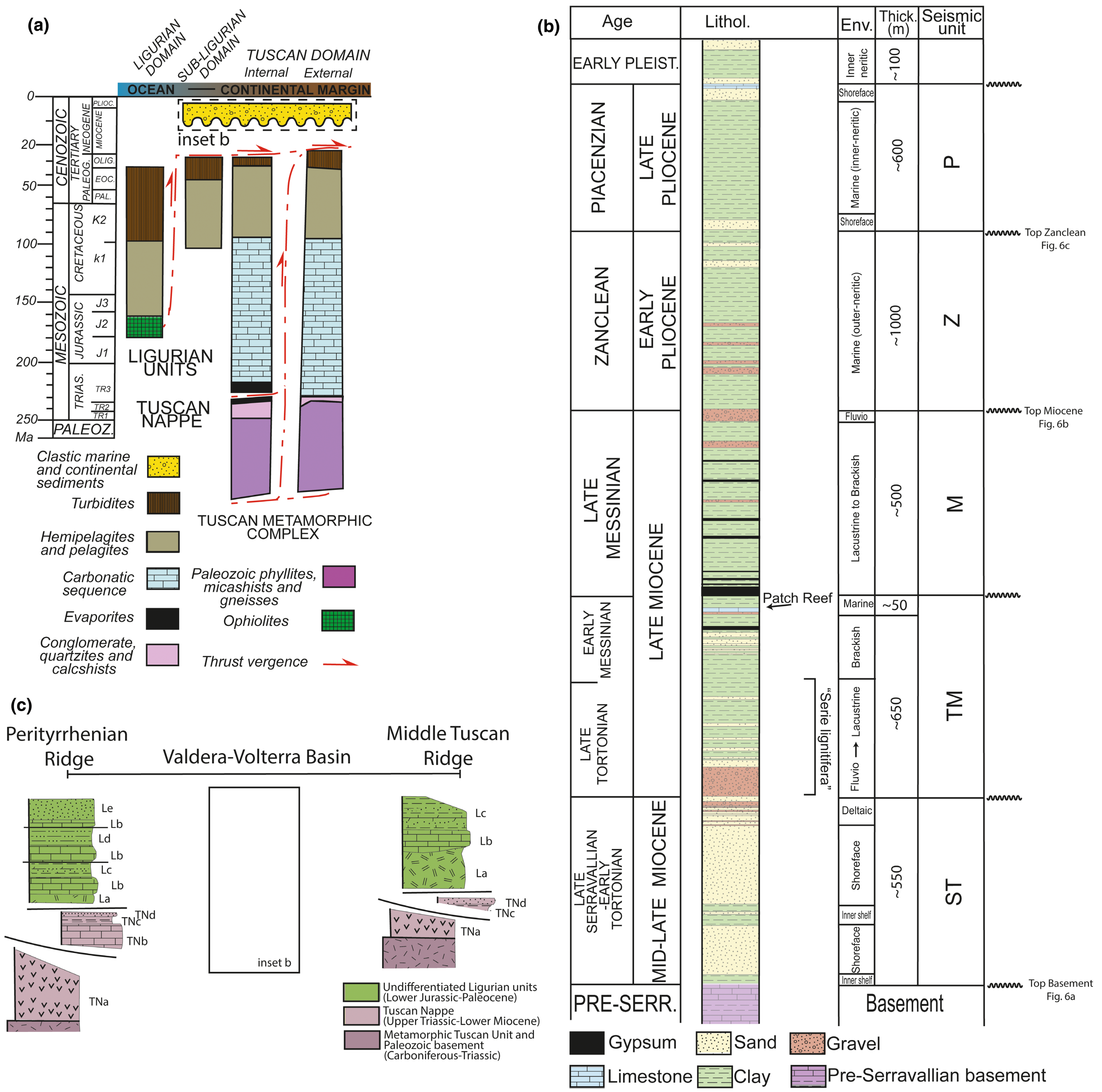


FIGURE 3 (a) Relationship between the stratigraphic and tectonic units of the Northern Apennines (modified after Carmignani et al., 1994). (b) Stratigraphic column of the Neogene fills of the Valdera-Volterra Basin (modified after Pascucci et al., 2007). (c) General stratigraphic scheme of the tectonic units of the inner Northern Apennines constituting the ridges bounding the VD-VR. TNa: Late Triassic evaporite; TNb: Jurassic-Cretaceous limestones and cherts; TNc: Palaeocene–Eocene mudstones and calcarenite; Td: Oligocene–lower Miocene sandstones; La: Jurassic oceanic crust consisting of peridotites, gabbros, and basalts; Lb: Sedimentary cover of the oceanic crust consisting Jurassic radiolarite and Cretaceous shale, clayey marl and limestone; Lc: Cretaceous turbiditic arenaceous, marly and calcareous succession; Ld: Eocene mudstone; Le: Upper Cretaceous-Palaeocene turbiditic arenaceous, marly and calcareous succession.

in deep wells (Bertini et al., 2000; Costantini et al., 2002; Franceschini, 1994; Lazzarotto et al., 2002), through a Serie Ridotta-type contact (Figures 2 and 3c). A Serie Ridotta style also characterises most of the MTR bordering the VD-VR Basin, where the Triassic formations rest unconformably over the Tuscan basement (the Permian–Triassic Monticiano Roccastrada Unit; Costantini et al., 1998, 2002 and references therein; Figure 2). Subordinately, in a few locations, the Ligurian Units are thrusted over the higher units of the Tuscan Nappe (i.e. N of Iano and SW of Varna; Costantini et al., 2002 and references therein; Figures 2 and 3c).

The upper Miocene–Pliocene succession was originally described on a lithostratigraphic base (Figure 3b; Bossio et al., 1996; Costantini et al., 2002; Lazzarotto et al., 2002; Martini et al., 2001) and later grossly subdivided into seven major depositional units separated by major unconformities (Pascucci et al., 1999). From the base, these units are:

1. Upper Serravallian–lower Tortonian deltaic-shallow marine sandstone and mudstone, topped by conglomerates, about 550 m thick ('Ponsano sandstones'; Bossio et al., 1997; Foresi et al., 1997; Mazzei et al., 1981; Mazzanti et al.,1981). These deposits lie unconformably on the Pre-Serallavallian substratum and they are interpreted alternatively as the infill of a late syn-collisional basin (Boccaletti et al., 1990; Decandia et al., 1993) or as the early deposition in an extensional basin (Elter & Sandrelli, 1995; Foresi et al., 1997). The unit crops out only in the area of Ponsano, in the southeastern portion of the basin (Figure 2).
2. Upper Tortonian–lowermost Messinian composite succession, up to 650 m thick, that in the lower part ('Serie Lignitifera'; Bossio et al., 1993; Lazzarotto & Mazzanti, 1976; Trevisan, 1952) consists of fluvio-lacustrine conglomerate, sandstone, and mudstone. The upper part of this unit consists of mudstones bearing a brackish ostracofauna indicating a progressive marine influence (Bossio et al., 1997). This unit lies unconformably both on the Upper Serravallian–Lower Tortonian unit as well as on the bedrock (Bossio et al., 1993). The unit crops out in the southern portion of the basin along the Cecina River, Fosci Creek, and Sellate Creek. The unit also crops out in the area of Bagni di Mommialla (eastern portion of the basin) and the Sterza Valley (western portion of the basin) (Figure 2).
3. Lower Messinian coastal and shallow marine mudstone, a few tens metres thick deposited in an inner shelf setting (*Pycnodonta* clay; Bossio et al., 1997) that towards the basin margins includes limited patches of reefal temperate carbonate (Castelnuovo limestone), conglomerate (Villa Mirabella conglomerate), and deltaic sandstone (Bossio, Cerri, et al., 1994; Bossio et al., 1996, 1997). The unit lies unconformably on the underlying units (Bossio et al., 1997) and crops out in the Spicchiaiola area and in the area along the Cecina River in the southern portion of the basin but also in the area of Montecatini V.C. and Orciatico along the western margin of the basin (Figure 2).
4. Upper Messinian primary (halite and selenitic gypsum), clastic (gypso-arenite, gypso-rudite) and diagenetic (anhydrite, alabaster) evaporites, interbedded with fluvio-deltaic sandstone, conglomerate, mudstone, and locally travertines, up to ~500 m thick (Bossio et al., 1993, Bossio, Cerri, et al., 1994, Bossio et al., 1996, 1997). Although not clearly recognised in the field, the unit is separated from the underlying ones by an unconformity (Bossio et al., 1997). The unit crops out in the area of Era Viva and Era Morta in the eastern portion of the basin, along the Cecina River in the southern portion of the basin but also in the area of Montecatini V.C. and Orciatico and in the Sterza Valley along the western margin of the basin (Figure 2).
5. Zanclean mudstone, sandstone, and subordinate conglomerate mainly deposited in the outer neritic marine zone. The unit is ~1000 m thick and lies unconformably on the Miocene units and the bedrock along the basin shoulders (Bossio et al., 1993, 1996; Bossio, Mazzanti, et al., 1994). The unit crops out in the axial portion of the basin (Figure 2).
6. Uppermost Zanclean–Piacenzian sandstone, biocalcarenites, and mudstone accumulated in the inner neritic marine zone and deltaic-shoreface settings (Bossio, Mazzanti, et al., 1994). This unit, about 600 m thick rests unconformably on the older units and the Pre-Serravallian bedrock. The unit crops out in the axial portion of the basin (Figure 2).
7. Lower Pleistocene mudstones and sandstones deposited in the inner neritic and deltaic zone (Bossio et al., 1993; Costantini et al., 2002) up to a few tens metres thick resting unconformably over the older clastic units and bedrock. This unit is limited to the northern portion of the basin (Figure 2).

Finally, in the western portion of the VD-VR, around Orciatico and Montecatini V.C. (Figure 2), lamproitic sub-intrusive bodies crop out. These magmatic bodies intruded Late Miocene–Early Pliocene succession during the Zanclean (radiometric age 4.1 ± 1.3; Borsi et al., 1967; Costantini et al., 2002; Ferrara & Tonarini, 1985; Peccerillo, 2005; Serri et al., 1993, 2001, and references therein).

3 | DATA AND METHODS

3.1 | Seismic and well data

This study is based on the interpretation of 18 2D stacked seismic reflection profiles (Table 1), provided in the SEG-Y format, acquired for hydrocarbon exploration purposes by AGIP (now ENI) in the 1980s.

A subset of the seismic lines was already published (e.g. Bossio et al., 1997; Brogi & Liotta, 2008; Del Campana, 1993; Mariani & Prato, 1988; Pascucci, 1997; Pascucci et al., 1999, 2001).

TABLE 1 Parameters and characteristics of 2D seismic profiles used in this study (in total approximately 258 km in length).

Line number	Length (km)	Shotpoint (SP) range
Dip lines		
PI-314-81	7.8	43-423
PI-368-85 (Figure 11)	15.4	8-644
PI-369-85 (Figure 8)	21.7	7-912
PI-370-85	14.6	5-774
PI-371-85	13.5	7-591
PI-372-85	18.7	540-1299
PI-373-85 (Appendix S3)	16.8	15-913
PI-376-87	14	5-706
PI-377-87 (Appendix S1)	15.8	5-784
PI-378-87	8.2	5-410
PI-379-87 (Figure 10)	10.7	34-613
PI-385-87	8.8	33-480
PI-386-88 (Figure 9)	10.9	33-566
Strike lines		
PI-374-85 (Appendix S2)	20.4	795-1869
PI-380-87	15.4	34-825
PI-381-87	21.4	295-1422
PI-383-87	5.7	33-313
PI-384-87	17.7	33-915

The lines were acquired longitudinal (NW–SE) and transversal (SW–NE) with respect to the trend of the VD-VR Basin (see Figure 2 for the location) using a vibroseis energy source. The data were recorded with usually 24 recording channels, group intervals of 40 m, and a fold coverage of generally 6000% (60 fold). The seismic datum is at the sea level.

Digital electrical logs (LAS format), including gamma ray log (GR), sonic (DT), and bulk density (RHOB) logs for two boreholes—Laiatico 01 (L01) and Pomarance 01 (P01)—were available for this study (Figure 4; PDF output for the Laiatico 01 well is available from the VIDEPI PROJECT database https://www.videpi.com/videpi/pozzi/consultabili.asp).

Well-to-seismic ties for L01 and P01 to the nearest seismic profiles (PI-377 and PI-373, respectively) were performed. A checkshots survey was available for the L01 well. Synthetic seismograms were generated using a Ricker wavelet of 25 Hz frequency and convolved with a reflectivity series derived from DT and RHOB logs. Uncertainties in the well-tie exist for the P01 due to the position of the well being at the southern end of line PI-373, where seismic imaging is poor.

Seismic stratigraphy has been interpreted considering the seismic facies and through the recognition of unconformities allowing the identification of six main seismic units (Figure 3b): basement; upper Serravallian-lower Tortonian (ST); late Serravallian–lower Messinian (TM); upper Messinian (M); Zanclean (Z); Piacenzian (P). Estimates of maximum thicknesses in metres were calculated using the interval velocity of the different units calculated from the checkshot survey. A mean velocity of ~3400, ~2900 m/s, and ~2300 m/s were calculated for the TM and M units, the Z unit and P unit, respectively. For the ST unit, which has not been drilled, an average velocity equal to the other Miocene units was assumed (~3400 m/s).

Seismic interpretation of the key horizons and faults proceeded from the well-imaged, well-constrained portions of the lines towards areas of poorer quality and constraints. The interpretation progressed outwards by loop-tie method.

Time structure maps (TSM) from the main interpreted horizons and isochores were generated for selected units (Figures 6 and 7) to establish a geological model over the area of study.

Using selected profiles (Figures 6c and 9c), measurements of thickness (TWT) of unit P along the main Villamagna fault system were generated to ascertain phases of fault growth and hence unravel the timing of fault activity.

3.2 | Integration of gravity, surface geologic and biostratigraphic data

Results from the seismic interpretation are integrated with Bouguer gravity anomaly data covering the area corresponding to the 2D seismic survey and with an assumed density of the surface rocks of the continental crust of 2.67 g/cm^3 (Figure 5). The gravity data have a sampling resolution of 1 station/4 km^2.

Surface geological data and biostratigraphic data (Data source: Regione Toscana n.d.—Micropaleontologia di superficie, BD_micro; https://www502.regione.toscana.it/geoscopio/geologia.html#) from surface micropaleontological sampling were also utilised to constrain the interpretation of the stratigraphic units along the seismic profiles.

Surface geological data include information from field studies (e.g. Bossio, Cerri, et al., 1994, Bossio, Mazzanti, et al., 1994; Bonini & Moratti, 1995; Sani et al., 2016; unpublished maps) and the CARG sheets of Pomarance (sheet 295, Lazzarotto et al., 2002), Volterra (sheet 285; Costantini et al., 2002) and the eastern portion of the Rosignano Marittimo (sheet 284; Mazzanti, 2016).

The biostratigraphic dataset utilised in this work is publicly available on the GEOscopio database of the Regione Toscana (Data source: Regione Toscana—Micropaleontologia di superficie, BD_micro) and was

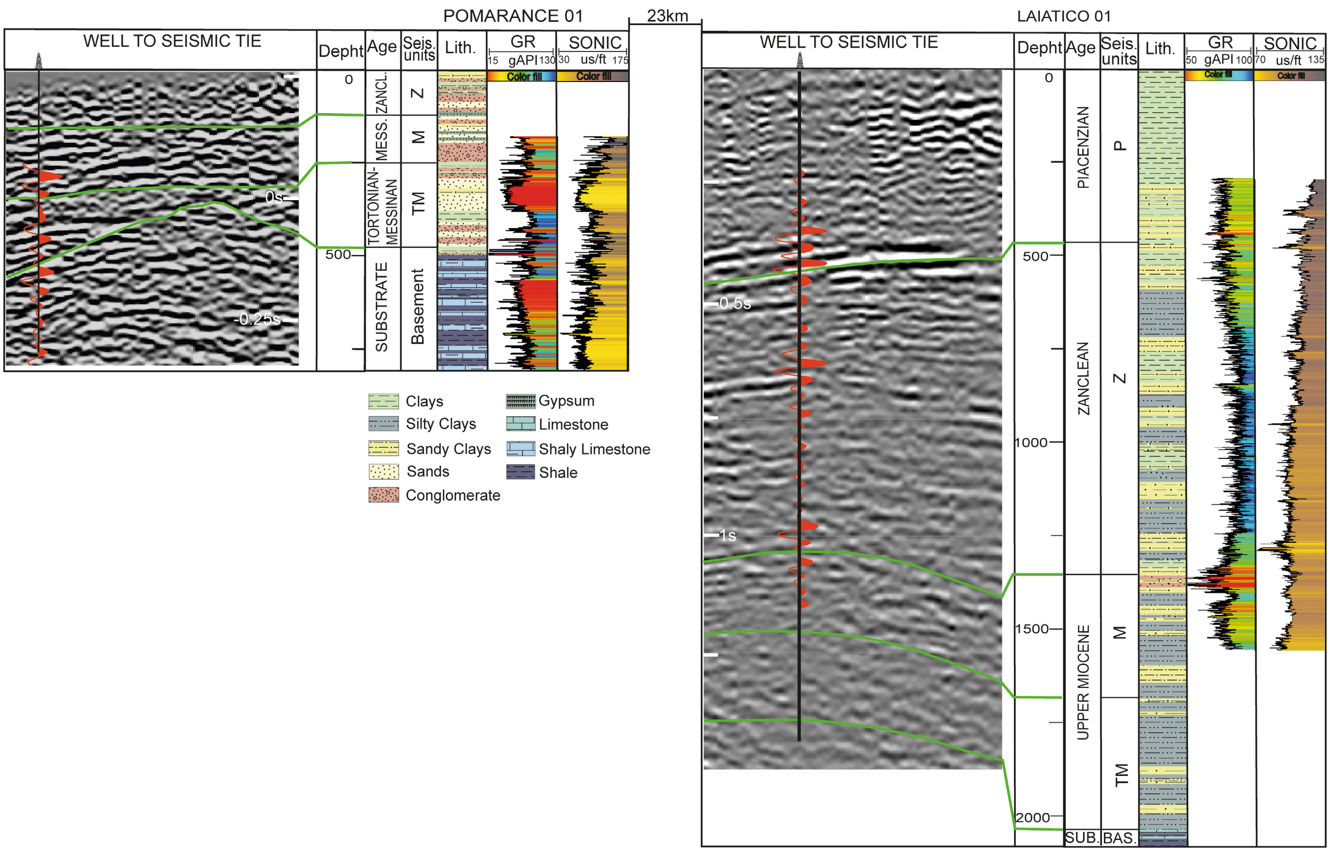


FIGURE 4 Synthetic column, gamma ray (GR), sonic logs, and synthetic seismograms of the Pomarance01 (P01) and Laiatico01 (L01) wells used in this research. The Pomarance 01 well reaches a depth of 1864 m, here represented the first 800 m. See Figure 2 for the location of the two wells.

acquired for the Pomarance and Volterra sheets of the CARG project. The location of the samples is shown in Figure 2.

3.3 | Limitations

The overall quality of seismic data varies across the lines and ranges from medium to poor. Clear reflections and faults are observed in the shallow parts of most sections, whereas quality decreases where artefacts, such as bow-tie and hyperbolic diffractions, noise, poor illumination and fault shadows are observed (Figures 8–11; Appendices S1–S3).

The basal unconformity separating the basin infill from the Pre-Serravallian substratum and the unconformities separating the Miocene units are more clearly recognisable in the southern sector of the VD-VR Basin, whereas in the central and northern sectors of the basin the presence of artefacts, attenuation due to the absorption of energy by the overlying unconsolidated sediments, and the seismic characteristics of the seismic units generate uncertainties in the interpretation. The unconformity separating the Miocene and the Pliocene units and the unconformity separating the Zanclean and Piacenzian units are clearly recognised along all the lines except at the ends of transversal lines, where the imaging is poor and the fault shadows are more evident, and at the top of the seismic lines where acquisition noise is evident.

4 | RESULTS

4.1 | Seismic stratigraphy

Based on their seismic characteristics (amplitude, lateral continuity, and stratal terminations), age, and presence of unconformities and correlative conformities, six main seismic-stratigraphic units are defined. The unconformities separating the units correspond to the main unconformities, recognisable in the field, separating the depositional units (e.g. Bossio et al., 1996; Bossio, Cerri, et al., 1994; Bossio, Mazzanti, et al., 1994); however, within some of the units, second-order unconformities can be distinguished.

The six main seismic-stratigraphic units are here described.

4.1.1 | Basement

This unit is generally characterised by chaotic to transparent seismic facies. In places, rare continuous reflections with high to medium amplitude are recognised (Figures 8–11; Appendices S1–S3). The GR and sonic logs in LAS format were available only for the P01 well. The sonic log of the L01 is available in the VIDEPI PROJECT database. The GR log shows variable values, whilst the sonic log shows generally low values (high velocity of the rock) with a spiky trend that increases upward (reducing rock velocity, Figure 4). The unit reaches the surface along some of the lines available in the dataset where it corresponds to the Pre-Serravallian substratum (including Ligurian Unit, Tuscan Units, and a portion of the Palaeozoic basement) forming the shoulders of the basin (see Section 2.2; Figure 2).

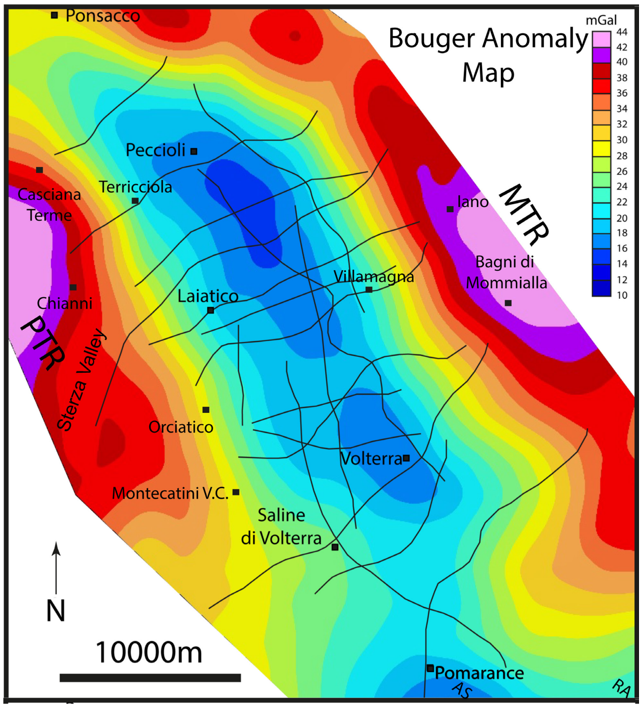


FIGURE 5 Gravity Bouguer Anomaly Map of the Valdera basin and surrounding area. AS: Anqua Sub-basin; RA: Radicondoli Basin.

4.1.2 | Unit ST (upper Serravallian–lower Tortonian)

The unit, correlated with Seq 1 of Pascucci (1997) and Pascucci et al. (1999), and V1 of Bossio et al. (1997; Table 2), is characterised by discontinuous to semicontinuous reflections. The unit is not drilled by any of the wells available for this study and it cannot be characterised with GR and sonic logs. The unit rests unconformably on the substratum. This contact is marked by a few reflections onlapping the underlying basement. The upper limit of the unit is an unconformity not easily recognisable because of the quality of the data. The unit is recognised only in the southernmost seismic profile available for this study where it reaches a maximum thickness of ~0.3 s (~500 m; SP 550–650; Appendix S3). The unit does

TABLE 2 Comparative seismo-stratigraphic table between the seismic units described in the literature and those used in the present paper.

		Seismic units				
Chronostr.	**Depos. units**	**Bossio et al. (1997)**	**Pascucci (1997)**	**Pascucci et al. (1999)**	**This work**	
Pleistocene	7			Seq6		
Piacenzian Lm.Zanclean	6		Seq4	Seq5	P	P3
						P2
						P1
Zanclean	5	V4		Seq4	Z	Z4
						Z3
						Z2
						Z1
Late Messinian	4	V3	Seq3	Seq3	M	
Early Messinian	3	V2	Seq2	Seq2	TM	
Early Messinian Late Tortonian	2					
Early Tortonian Late Serravallian	1	V1	Seq1	Seq1	ST	
Pre-Neogene bedrock						

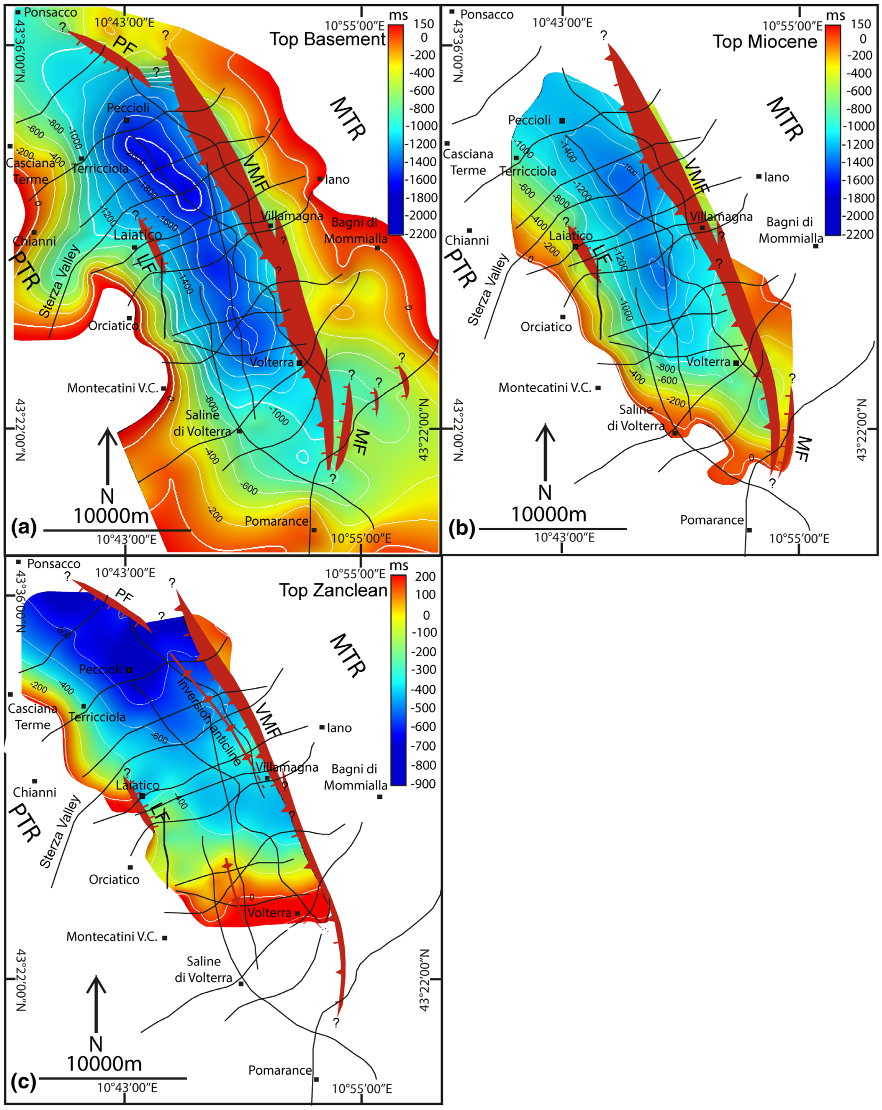


FIGURE 6 Time Structure Maps (TSM) of the: Top substrate (a); top Miocene (b); top Zanclean (c). All the TSM produced are derived from manually interpreted horizons. LF, Laiatico fault; MF, Mazzolla fault; PF, Peccioli fault; VMF, Villamagna fault.

not reach the surface and it is not directly correlatable with any of the major depositional units. Nevertheless, the presence farther S of the 'Ponsano sandstones' (Figure 2) and considering the average velocity of the Miocene succession (Section 3.1) it seems realistic to correlate the unit with this upper ST deposits.

4.1.3 | Unit TM (upper Tortonian–lower Messinian)

The unit, equated to Seq 2 of Pascucci (1997) and Pascucci et al. (1999), and V2 of Bossio et al. (1997; Table 2), consists of discontinuous to semicontinuous and chaotic reflections and less commonly of continuous to semicontinuous parallel and semi-parallel reflections with variable amplitude (Figures 8–11; Appendices S1 and S2). In the southernmost sector of the basin, transverse to the basin, continuous prograding reflections with a sigmoidal pattern are recognised (SP 150–300, Appendix S3), whilst parallel to the basin, a mounded pattern is recognised (SP 1550–1650, Appendix S2). The GR and sonic log in LAS format are recorded for this unit only in the P01 well. The sonic log of the L01 is available in the VIDEPI PROJECT database. The two logs show similar trends, with the lower part characterised by a saw tooth pattern due to the alternation of conglomerates, sand, and mudstone whilst the upper part is characterised by a blocky pattern dominated by sandy deposits and conglomerates at the top. The reflections onlap the underlying unit, whilst the top of the unit is bounded by an unconformity marked by truncation (Figures 8 and 11; Appendices S2 and S3). The unit reaches the surface mainly in the southern sector of the basin and in the Sterza valley, where it reaches the maximum thickness of ~0.7 s TWT (~1.2 km). The available seismic lines allow a good correlation between the seismic unit and the major depositional units and a good control of their age and lithological composition. This seismic unit corresponds to two of the major depositional units: the upper Tortonian–lowermost Messinian fluvial-lacustrine

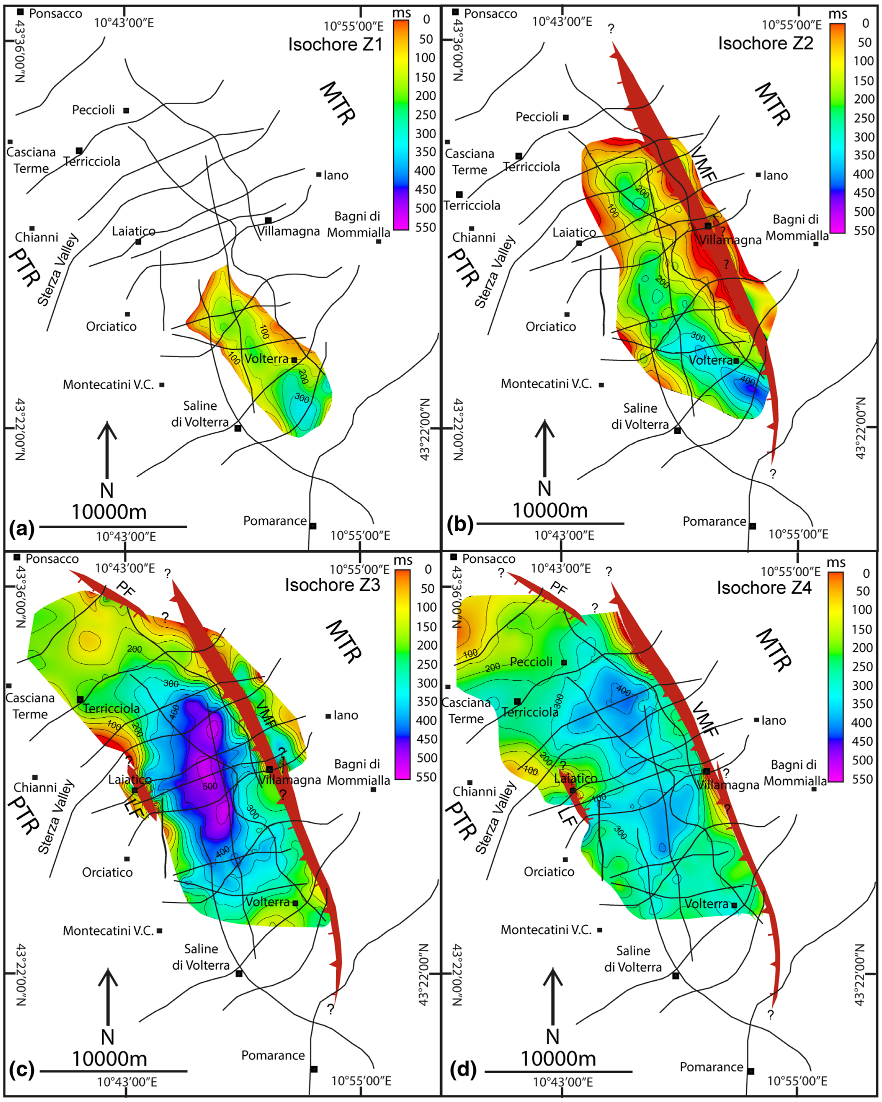


FIGURE 7 Isochore map of the subunit: Z1 (a); Z2 (b); Z3 (c); Z4 (d). LF, Laiatico fault; PF, Peccioli fault; VMF: Villamagna fault.

and brackish deposits and the lower Messinian coastal and shallow marine deposits.

4.1.4 | Unit M (upper Messinian)

The unit, which corresponds to Seq 3 of Pascucci (1997) and Pascucci et al. (1999), and V3 of Bossio et al. (1997; Table 2), is characterised by two main seismic facies, the first consists of continuous to semicontinuous parallel reflections with medium to high amplitude and the second consists of discontinuous reflections with variable amplitude (Figures 8–11; Appendices S1 and S2). The GR and sonic logs available for this unit are recorded for both wells, but they do not completely cover the unit. A complete sonic log of the L01 is available in the VIDEPI PROJECT database. The GR logs show mainly blocky trends related to mainly conglomerate and sand deposits in P01 and to muddy deposits interbedded with sand and rare conglomerate deposits in L01. The sonic log shows a trend of increasing values upward (reducing rock velocity) related to a decrease in sediment compaction (Figure 4). The unit rests unconformably on the TM unit and its top corresponds with an evident unconformity. The unit reaches a maximum thickness ~0.6 s TWT (~1.0 km, SP 1450–1550, Appendix S2) in the southern sector of the basin. It can be correlated with upper Messinian deposits exposed mainly in the southern part of the basin along several seismic profiles (Figure 2).

4.1.5 | Unit Z (Zanclean)

The unit, equivalent to the Seq 4 of Pascucci (1997) and Pascucci et al. (1999), V4 of Bossio et al. (1997; Table 2), is generally marked by layered parallel, continuous to semicontinuous reflections with medium to high amplitude (Figures 8–11; Appendices S1 and S2). Towards

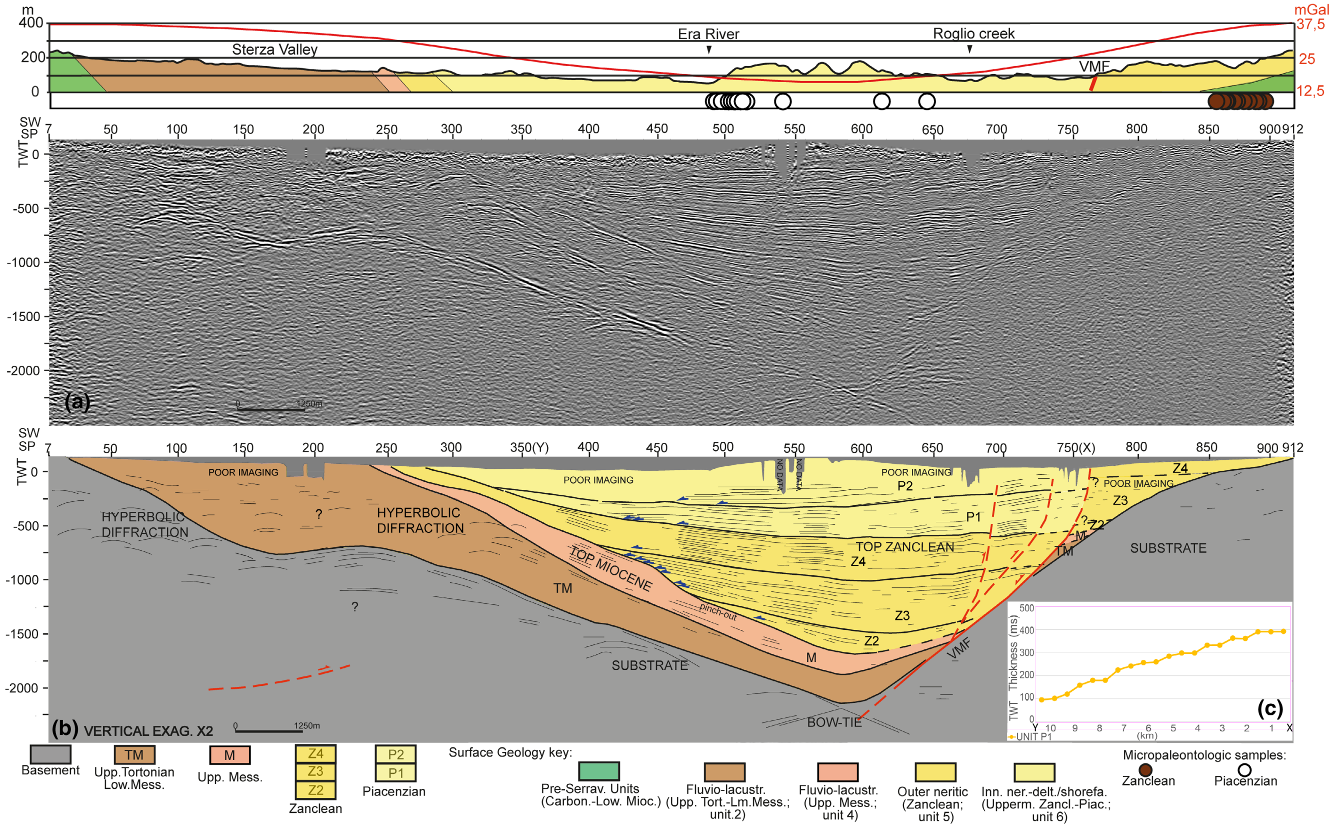


FIGURE 8 Uninterpreted (a) and interpreted (b) seismic reflection profile PI-369-85. (c) Graph representing the variation in the vertical thickness of the P1 subunits (TWT) with the distance from the Villamagna fault (VMF) measured along the section from x to y. At the top superficial cross-section.

the centre of the basin, the unit reaches the maximum thickness of ~1 s TWT (~1.4 km; SP 570–630, Figure 8; SP 250–330, Figure 9; SP 350–450, Appendix S1). The GR and sonic logs for this unit are recorded only in well L01. The GR log shows a general gradual increase and then a gradual decrease in the GR response, likely to be the result of retrogradation and progradation of a mainly muddy sedimentary system where the sand supply decreases and then increases. The GR trend is punctuated by frequent low peaks likely due to sandy turbiditic deposits interbedded with the muddy sedimentation. The sonic log shows a trend of increasing values upward (decreasing rock velocity, Figure 4) related to a decrease in sediment compaction. The sonic log trend is punctuated by low peaks, likely related to the turbidite events described above. The reflections of the unit onlap on the older units and the Pre-Serravallian substratum. The unit is correlated with the Zanclean outer neritic deposits crossed at the surface by several profiles in the southern portion of the basin (Figure 2). Based on the presence of three second-order unconformities four subunits are distinguished. The lower Z1 and Z2 subunits reach the maximum thickness in the southern portion of the basin (Figure 10) becoming thinner northward (Figures 8 and 9). The higher Z3 and the Z4 units reach their maximum thickness in the central part of the basin thinning out towards the N and S.

4.1.6 | Unit P (Piacenzian)

The unit, which corresponds to Seq 4 of Pascucci (1997) and to Seq 5 of Pascucci et al. (1999; Table 2), is generally marked by layered parallel, continuous to semi-continuous reflections with medium to high amplitude, showing clear onlapping on the older seismic units (Figures 8–11; Appendices S1 and S2). The GR and sonic log have been recorded in the well L01 only for a reduced portion in the lower part of the unit. The GR records a weak retrograding trend related to a decrease in the sand input in a mainly muddy sedimentary system. The sediment deposition, as for the Z unit, is punctuated by sandy turbiditic interbeds within the muddy sedimentation. The sonic log shows a trend of upward increasing values (decreasing rock velocity, Figure 4) related to a decrease in sediment compaction, with only a few peaks of low values. The unit reaches the maximum thickness of ~0.8 s TWT (~0.9 km; SP 380–430, Figure 11) in the

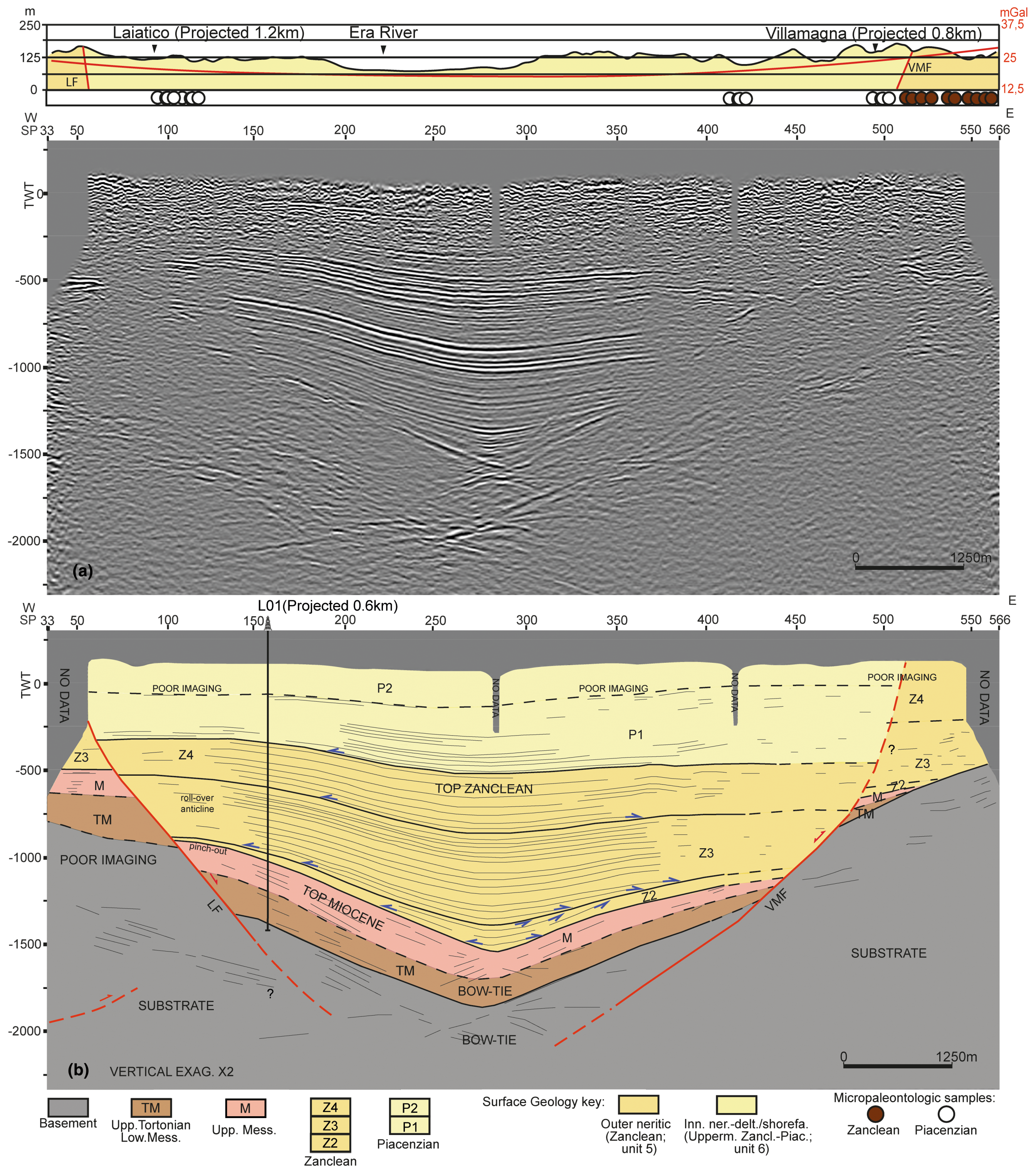


FIGURE 9 Uninterpreted (a) and interpreted (b) seismic reflection profile PI-386-88. LF, Laiatico fault; VMF: Villamagna fault. At the top superficial cross-section.

northern portion of the basin. It can be correlated with the Piacenzian deposits along many profiles (Figure 2). The recognition of two second-order unconformities allows the subdivision into three subunits thickening northward, though low-seismic resolution or lack of data at the top of the seismic profiles, particularly in the central portion of the basin, prevent reliable interpretation (Figure 9).

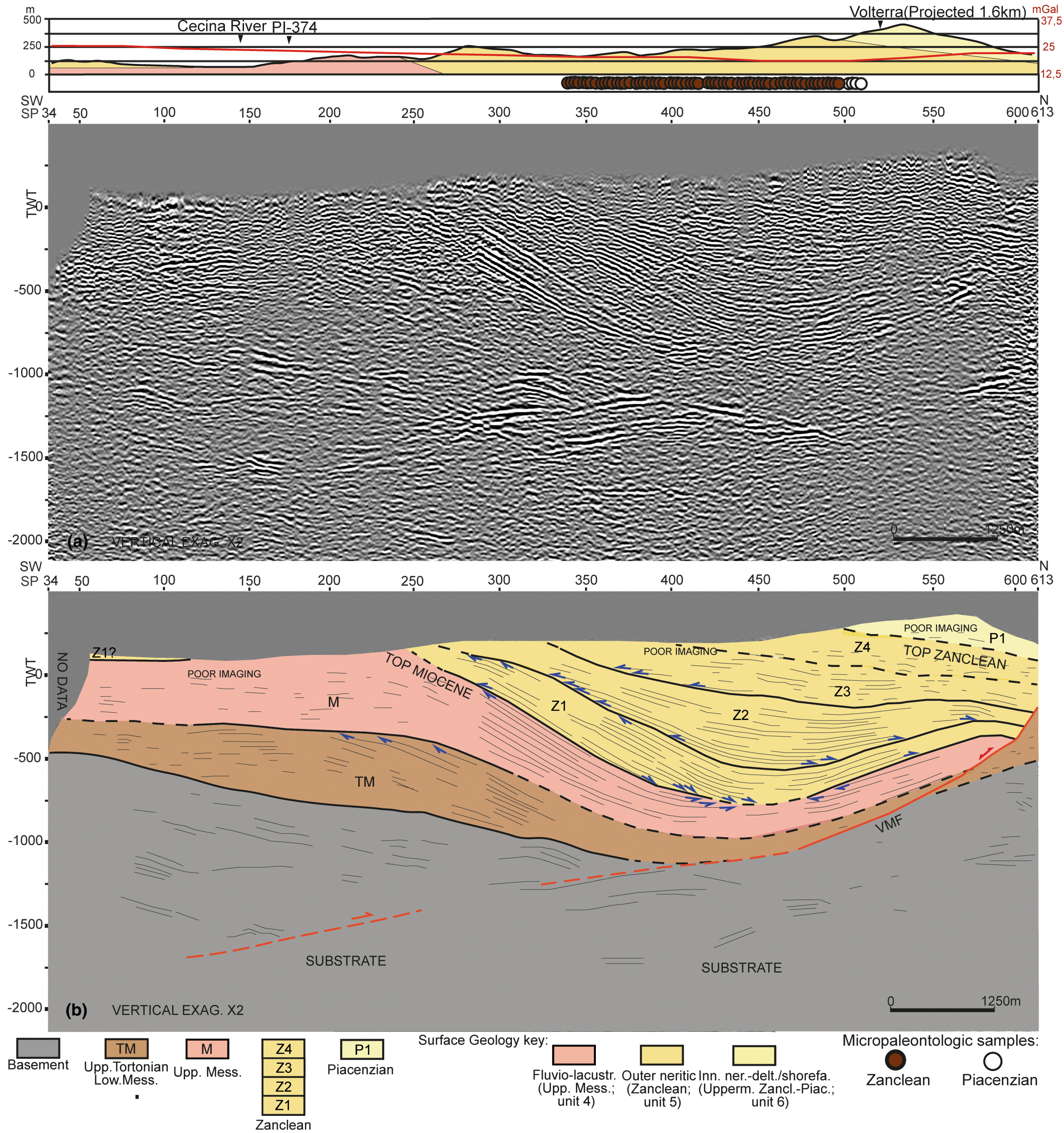


FIGURE 10 Uninterpreted (a) and interpreted (b) seismic reflection profile PI-379-87. VMF, Villamagna fault. At the top superficial cross-section.

4.2 | Stratigraphic and structural interpretation

4.2.1 | General basin structure

The Gravity Bouguer Anomaly Map (GBAM, Figure 5) shows an NNW–SSE trending asymmetric gravimetric low with the SW flank less steep than the NE flank. In the northern sector, the gravimetric low changes orientation slightly to a NW–SE trend. The basin is segmented with the presence of two minor lows separated by a NE–SW trending gravity high located in the centre of the basin, the northern low appears wider and with higher negative anomalies than the southern low. In the area of the Sterza valley, a minor gravimetric trending obliquely to the main low is recognisable.

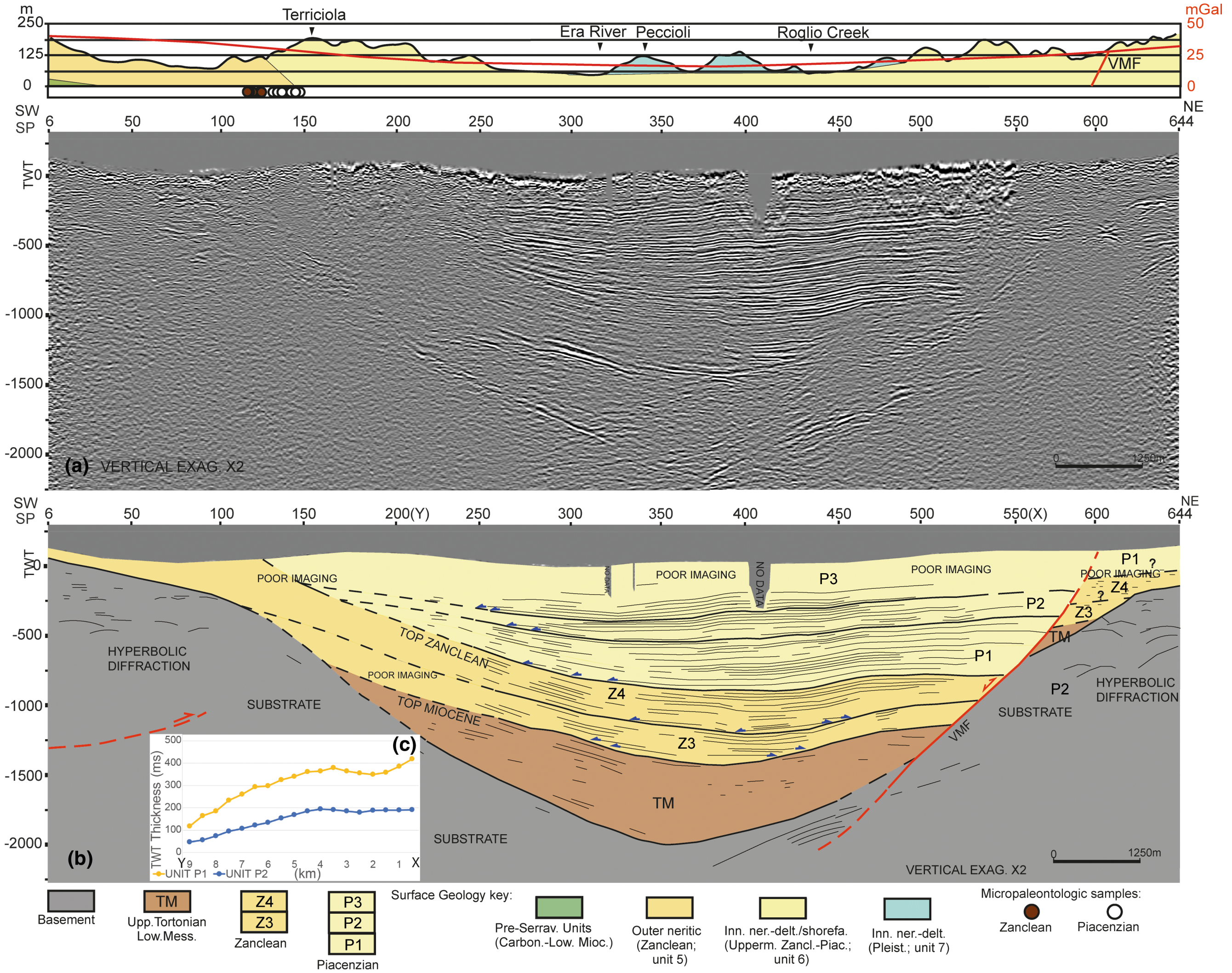


FIGURE 11 Uninterpreted (a) and interpreted (b) seismic reflection profile PI-368-85. (c) Graph representing the variation in the vertical thickness of the P1 and P2 subunits (TWT) with the distance from the Villamagna fault (VMF) measured along the section from x to y. At the top superficial cross-section.

The GBAM exhibits several similarities with the Top Basement time structure map (Figure 6a). This surface shows a structural low with a similar general trend delimited by two ridges (i.e. PTR and MTR), it also shows the presence in the central sector of the PTR a structural low near perpendicular to the main basin corresponding to the Sterza valley. The main difference between the GBAM and the Top Basement TSM is in the southernmost part of the basin (i.e. Pomarance area) where a gravimetric low indicates the occurrence of further depocentres (i.e. Anqua basin and Radicondoli basin; Figures 1 and 5) and the influence of the adjacent geothermal framework of the area of Larderello-Travale (Orlando, 2005).

Seismic data show that the overall structure of the VD-VR is NNW striking, structurally complex depocentre defined by a slightly asymmetric ~NNW trending syncline bordered by major N/NW trending border faults (Figures 6, 8, 9, 10 and 11). The syncline involves the upper Tortonian- Zanclean succession (Figures 6a,b, 8, 9, 10 and 11) and it is more open in the northern and central sector becoming tighter southward. The main border fault system is ~30 km long, bordering the NE shoulder of the basin. It trends NNW, dips towards WSW, and has an estimated offset of ~0.6 s (~870 m) at the top of the basement. This fault corresponds to the Villamagna Fault (VMF, Costantini et al., 2002 and reference therein). Although the low density of the seismic grid limits the interpretation of the spatial distribution of the faults, the VMF could be the result of the linkage of at least two main faults in the central portion of the basin, a few km SE of Villamagna. The linkage of the two branches is only partially recognisable in the seismic data (Figure 6) and a more detailed characterisation is not possible. In the southern portion of the basin, ~6 km SSE of Volterra, VMF overlaps and becomes synthetic to the Mazzolla Fault (MF; Bossio et al., 1996; Costantini et al., 2002; Lazzarotto et al., 2002; Appendix S3, SP 250–450). The MF is not recognised in the central part of the basin, but it is limited to the southern sector. Two other important faults bordering the basin can be identified. In the central sector, the SW basin shoulder is bordered by a ~4.5 km long NE dipping fault with an estimated offset of ~0.5 s (~475 m) at the top of the basement (Figure 9, SP 50–200; Appendix, SP 150–300). The estimated fault length is based on the seismic interpretation along a few available seismic lines in a relatively small area and it cannot be excluded that the fault may extend either farther N or farther S. This fault corresponds on the surface to the Laiatico Fault (LF in Figures 6, 7 and 9; Appendix S1; Costantini et al., 2002; Mazzanti, 1961). In the northernmost sector of the basin, a ~7 km long SW dipping fault, here called the Peccioli Fault (PF), with an estimated offset of ~0.5 s (~475 m, Figure 6a), at the top of the basement, is present bordering the VD-VR Basin. This fault corresponds to that one hypothesized by Marroni et al. (1990), which cannot be easily recognised in the field because it is covered by recent alluvial deposits. This fault oversteps the VMF probably forming a relay ramp, in an area not covered by the study dataset.

4.2.2 | Late Tortonian-Zanclean folding

Seismic data show that the units TM and M are folded forming a syncline (Figures 8–11; Appendix S1) with steep dipping reflections towards the centre of the basin. Along the Sterza valley (Figure 8, SP 15–250) and in the southern-easternmost sector of the VD-VR the TM reflections, where recognisable, are sub-horizontal (Appendix S3, SP 450–913). The two upper Miocene units are separated by an unconformity defined by truncation of the TM reflections (Figure 10, SP 200–270; Appendix S3, SP 200–270) and M onlapping reflections (Appendix S2, SP 950/1050; Appendix S3, SP 200–270) documenting a phase of strong erosion. The upper Miocene units are separated from the overlying units by an evident angular unconformity marked by clear onlapping recognisable in all the available seismic profiles. The Zanclean subunits, as the underlying Miocene units, are tilted to the NE due to a post-Zanclean activity of the VMF (Figures 8–11). Both the Z1 and Z2 subunits are involved in the general syncline. The two subunits thicken in the axial portion of the basin and they thin towards the borders, in the case of Z2 pinch-outs can be imaged (Figures 8 and 9; Appendix S1). The Z1 subunit is present in a NW–SE elongated limited area in the southern portion of the basin (Figure 7a) and it reaches the maximum thickness (~0.3 s) ~4.5 km S of Volterra. In the same area, the top of the subunit is characterised by truncated reflections attesting erosion (Figure 10, SP 250–400), this makes it possible to consider an even higher thickness. The thickness of the subunit reduces towards the N. The overlying subunit Z2 encompasses a NW–SE to N–S elongated wider area but the maximum thickness, similar to Z1, is reached in the southern sector (Figure 7b), ~2.5 km SSE of Volterra (NE with respect to the Z1 maximum thickness; Figure 7a,b). The thickness of the subunit reduces towards the north. Unlike the Z1, the top of the Z2 is not characterised at the top by clear truncated reflections in this area attesting the absence of strong erosion (Figure 10). The different location between the area of maximum thickness of two subunits suggests a migration of the depocentre related to differential uplift between the two margins of the basin. The Z3 covers a wide area going from the area S of Ponsacco to the area around Volterra and is gently folded. The subunit is thicker in the axial part of the basin, between Villamagna and Laiatico, where it is ~0.5 s thick, and becomes thinner towards the shoulder of the basins, where it becomes ~0.3 thick (Figure 7c). The thickness of the subunit reduces towards the N and S. The top of the subunit is not characterised by truncated reflections, so the thickness of the subunit is not clearly influenced by successive erosional phases. The reflections show growth strata on both the flanks consistent with the progressive syndepositional uplift of both the basin margins (Figures 8 and 9; Appendix S1). The Z4 subunit covers an area similar to the Z3 subunit and no important thickness variations are recognised (~0.4; Figure 7d). The maximum thickness of the unit is reached in a wide area range from Laitico to Villamagna and from Peccioli to Volterra. The thickness of the subunit reduces towards the N and S. Z4 does not show important folding except that related to the activity of the successive faults (Figures 8, 9 and 11; Appendix S1).

4.2.3 | Piacenzian normal faulting

The Piacenzian subunits are characterised by clear growth wedge thickening towards the NE where the VMF occurs. This is shown by: (1) the graph representing the variation of the thickness (TWT) of the P1 subunits (Piacenzian) with the distance from the VMF along the line PI-369-85 (Figure 8c); (2) the graph representing the variation of the thickness (TWT) of the P1 and P2 (Piacenzian) subunits with the distance from the VMF along the line PI-368-85 (Figure 11c).

The first graph shows the P1 thickening from ~0.1 to ~0.4 s towards NE, whilst the second graph shows the thickening of the P1 from ~0.1 to ~0.4 s and the P2 thickness from ~0.05 to ~0.2 s towards NE. Overall, the wedging of the Piacenzian subunits suggests that VMF controlled their development. Growth strata of the P1 and P2 subunits, related to the activity of the VMF, are evident in the northern sector of the basin (Figure 11, SP 200–400), whilst in the central sector of the basin, they are only partially recognisable (Figure 8, SP 350–550).

W/NW of the Volterra area, the Zanclean subunits are folded in a gentle large-scale NNW–SSE trending anticline (Figures 2 and 6c) here interpreted as further evidence of the Piacenzian activity of the VMF. The seismic data do not show clear evidence of syntectonic deposits related to the MF (Appendix S3, SP 300–450) but considering the geometrical relationship with the VMF a Piacenzian formation time is suggested.

Similarly in the north of the basin, the PF was active during the Piacenzian. On the SW flank of the central sector, the LF is associated with minor antithetic normal faults (Appendix S1). Slip along this fault was accompanied by the formation of a ~2.5 km wide roll-over anticline in the hangingwall of the structure involving both the Miocene and Zanclean units (Figure 9, SP 50–250; Appendix S1, SP 170–350), with the overlying Piacenzian deposit forming a small wedge thickening towards SW supporting an active tectonic control (Figure 9, SP 50–150; Appendix S1, SP 150–300). In the southernmost part of the basin, to the east of the MF, it is possible to recognise a group of faults with probably similar trends to the MF and VMF but with minor estimated offsets ~0.2 s (~190 m). These faults affect the Miocene units and the bedrock and were likely active in the same phase as the main border faults (Figure 6a; Appendix S3, SP 600–800).

4.2.4 | Latest Pliocene/early Pleistocene (?) tectonic inversion

The growth wedge associated with the VMF (Figure 8, SP 600–750; Figure 11, SP 300–600) shows reflections characterised by a mild tilting towards the SW. A gentle NE vergent asymmetrical anticline deforming the Piacenzian wedge can be recognised (Figures 6c and 11). The anticline is ~3 km wide and is located in the immediate hangingwall of VMF with a trend parallel to the strike of fault (Figure 6c). Folding is more evident in the north, whereas southward, it becomes more difficult to recognise. Furthermore, the Piacenzian succession and the underlying units are cut by minor SW dipping reverse faults with few ms of offset emanating from the VMF on the NE flank of the basin (Figure 8, SP 650–750; Appendix S1, SP 500–480). These observations suggest a weak tectonic inversion mainly involving the hangingwall of the VMF. Although a precise time constraint for the onset of inversion is not possible, the fact that the Piacenzian wedge is involved in the mild folding suggests that this compressional phase occurred during the latest Piacenzian/post-Piacenzian.

5 | DISCUSSION

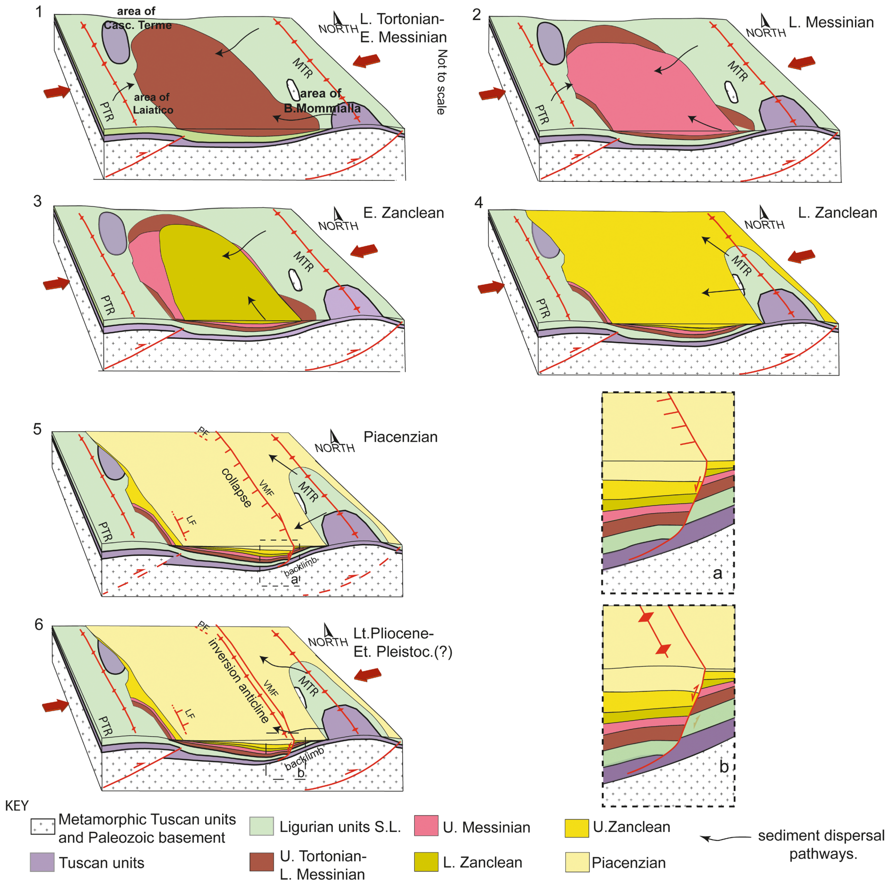
5.1 | Tectonic evolution of the Valdera-Volterra basin

The interpretation of the seismic data allowed determining a polyphasic evolution of the VD-VR Basin. Three main phases are proposed. During the first one, the development of the VD-VR Basin was controlled by two major E–NE-verging thrust-related anticlines bordering the basin (MTR and PTR; Figure 12). The major W/SW dipping, NNW–SSE striking, thrust faults, controlling the evolution of the anticlines, are rooted in the pre-Tortonian substratum and possibly within the Palaeozoic basement as suggested by many evidences for the MTR (see Section 2.1), and by the geophysical data available for the portion of PTR bordering the VD-VR Basin (Cerrina Feroni et al., 2006). Although the seismic profiles in our database only rarely offer insights into the substratum, the geometry of the sedimentary infill allows the kinematics of thrusting associated with the basin development itself to be determined. During the second phase, the basin evolution was controlled by the development of major normal faults that defined the basin's shoulders (VMF and LF) and offset the earlier thrust-related succession. As a matter of fact, similar evolution, characterised by polyphase alternance of extensional and compressional episodes with the presence of inverted structures, has been reconstructed also in other basins in the North Sea and in the external sectors of the NA (Scisciani et al., 2019, 2021).

5.1.1 | First phase: late Tortonian-Zanclean compression

The first compressive phase occurred between the Late Tortonian and Zanclean (Figure 12.1, 12.2, 12.3 and 12.4). During this phase, the basin is delimited by thrust faults. The growth of the thrust anticlines created accommodation space for the sediments between them. The deposits were gently folded forming the general NNW trending syncline characterising the basin and recognised in the field (Bonini & Moratti, 1995; Moratti & Bonini, 1998). A strong deformation occurred during the Messinian both at the transition between the Early Messinian (seismic unit TM) and Late Messinian (seismic unit M) and at the end of the Messinian (Figure 12.1 and 12.2). In both cases, unconformities marked by truncation and onlapping reflections were generated (Figure 10; Appendix S2). In the first interval, the unconformity is recognised by several authors in the field and through the analysis of seismic data (e.g. Bossio et al., 1997; Moratti & Bonini, 1998; Pascucci et al., 1999; Sani et al., 2016). At the end of the Messinian, the unconformity is even more evident with clear onlapping of the Pliocene units onto truncated underlying reflections (Figures 8–10; Appendices S1–S3). Minor thrusts, backthrusts, and thrust-related folding involving the basin infill probably elated to the activity of the main bordering thrusts are recognised at the outcrop scale by various

FIGURE 12 Evolutive model of the Valdera-Volterra basin. LF, Laiatico fault; MTR, Middle Tuscan Ridge; PF, Peccioli fault; PTR, Perityrrhenian Ridge; VMF, Villamagna fault.



authors in the fields. For instance, Sani et al. (2016) carried out a structural analysis documenting faults and folds compatible with the main E-verging structure (Sani et al., 2016). On the other side of the basin, around Bagni di Mommialla (Figure 2), mesostructural analysis evidenced reverse faults and associated folds (Bonini & Moratti, 1995; Moratti & Bonini, 1998). In the same area, Sani et al. (2016) recognised thrust faults superposing substratum units onto the upper Miocene units. Moreover Sani et al. (2016) report an isobaths contour map of the base of the salt layer from numerous wells drilled for the exploitation of Messinian salt levels (S to Montecatini V.C.). The map shows clearly roughly NNW–SSE trending anticlines and synclines related to thrusting associated with the main E-verging thrust fault in the western basin margin. They also provide evidence that the overlying Pliocene deposits are less deformed. Evidence of compression was recognised also in the Radicondoli basin (Figure 1) adjacent to the southern portion of the study area. Previous studies (Bonini & Moratti, 1995; Moratti & Bonini, 1998; Sani et al., 2016) show field data highlighting NNW trending backthrusts and WSW-verging thrust-related anticlines likely emanating from deeper W- and E-dipping thrusts in the pre-basin substratum. The field data were corroborated by the interpretation of seismic reflection sections and the presence in a deep well of the superposition of the Ligurian Units on the basin sedimentary rocks (Bonini et al., 2014). During the Early Zanclean (Figure 12), the compression phase continued. Although the overall deformation appears to have been weaker with respect to the earlier period, it is documented by the presence of subtle minor unconformities and by the fact that the subunits are gently folded. The migration of the depocentre towards NE shown by the isochore maps of the Z1, Z2, and Z3 units (Figure 7a–c) suggests a different uplift rate between the PTR and the MTR in this phase. Bonini et al. (1999) describe, in the Velona Basin (see Figure 1 for the location), the migration of the depocentre in basins located between two competing thrust-related anticlines with the same vergence as a function of the relative displacement rate along the competing thrust faults controlling the growth of the bordering anticlines. Although the model described by Bonini et al. (1999), to better fit their specific case of study, considers the presence of a thrust wedge structure for the hinterland thrust, which, in the case of the PTR, is recognised neither on the field nor in the seismic profiles, the concept can be still considered valid for the VD-VR Basin. The depocentre migration in the same sense of the thrusting direction is associated with a higher displacement rate along the hinterland thrust (i.e. PTR, type 3 of Bonini et al., 1999) or to a not active foreland thrust (i.e. MTR) and a simultaneous active hinterland thrust (type 5 of Bonini et al., 1999).

The reduction of thicknesses of the Z3 subunit from ~0.5 s in the axial part of the basin to ~0.3/0.2 s towards both the flanks of the basin (Figure 7c) and the fact that the reflections show growth strata on both the flanks are related to the uplift of both the ramp anticlines delimiting the basin. Upwards, the unit shows almost horizontal reflections (~0.4/0.3 s; Figures 7c, 8 and 9; Appendix S1) suggesting a decelerating uplift rate. The Z4 does not show important thickness variations (Figure 7d) documenting the deactivation of the thrust-related anticlines during the deposition of this subunit (Figure 12). During this deactivation phase, an increase in the sand supply is documented recorded by the GR log of the L01 well (Figure 4) showing a gradual decrease of gamma response indicating a phase of progradation of the sedimentary system. Noteworthy, Sandrelli et al. (2004) evidenced the presence of microfauna (in the upper portion of the G. punticulata zone) attesting a general bathymetric shallowing N of the Cecina River.

During this compressional phase, the emplacement of the lamproitic sub-intrusive bodies close to Orciatico and Montecatini V.C. occurred. Although the magmatic intrusion is usually associated with extensional settings, some studies described the emplacement of the magmatic bodies in contracting crust (e.g. Mohammad & Kazzaz, 2022; Papeschi et al., 2021). Sani et al. (2016) deeply discussed the emplacement of the lamproitic bodies of the VD-VR and other NA magmatic bodies in the compressional setting offering extensive literature from analogue modelling and field cases, to which the reader is invited to refer.

The prolonged compressional phase has been recognised in other NA hinterland basins, including the Fine and Sassa basins (Cerrina Feroni et al., 2006; Sani, Bonini, Cerrina Feroni, et al., 2009) and the Serrazzano-Lustignano Basin (Sani, Bonini, Cerrina Feroni, et al., 2009) to the west of the MTR and Valdelsa Basin (Benvenuti et al., 2014), Siena-Radicofani Basin (Bonini et al., 2014; Bonini & Sani, 2002), Cinigiano-Baccinello Basin (Bonini et al., 2014) to the east of the MTR. For the Valdelsa and Siena-Radicofani basins, the compressive deformation lasted up to the earliest Piacenzian (Bonini & Sani, 2002; Benvenuti et al., 2014; see Sani et al., 2016 for a discussion on the time of deformation of the NA hinterland basins).

As mentioned above (Section 2.2), for this interval of time several authors consider the basin as graben, half-graben, or a bowl-shaped depression that later evolved into a half-graben controlled by master faults active between the late Tortonian and the Zanclean (e.g. Martini & Sagri, 1993; Pascucci, 1997; Pascucci et al., 1999, 2001). As described above, wedge geometries thickening towards the border faults characterising the upper Miocene–lower Pliocene deposits are not recognised, making these hypotheses less compelling. Brogi and Liotta (2008), who worked in the adjacent Radicondoli area (Figure 1b) but offered an interpretation of a seismic line located north of Volterra and interpreted the basin as a hangingwall basin controlled during the Middle–Late Miocene by E-dipping low-angle normal faults. They interpreted the angular unconformities and erosional surfaces located in the Middle–upper Miocene deposits as markers of the substratum lateral segmentation. In this interpretation, the basin was successively dissected by high-angle normal faults during Pliocene time. Such an evolutionary model does not explain the general gentle syncline involving the upper Tortonian-Zanclean deposits documented in this study. Moreover, the presence of unconformities and growth strata in the Zanclean units and the migration of the depocentre recognised for this interval would not be explained by this model.

5.1.2 | Second phase: Piacenzian extension

With the deactivation of the thrusts faults the second phase of the basin evolution took place during the Piacenzian, with the onset of normal faulting (Figure 12). Such interpretation is based on the variation of thickness of the P subunits towards the border fault and the presence of growth strata, but also the presence of a roll-over anticline parallel to the LF affecting the underlying units. The faults created accommodation space for the Piacenzian succession, that thickens towards the faults reaching in some areas of the basin a thickness of ~0.9 km, and determined the tilting of the underlying units. We suggest that this normal faulting is related to the gravitational collapse of the overthickened crust leading to the activation of the NW/WNW faults roughly parallel to the basin margins. Few examples of clear gravitational collapse with the formation of normal fault-bounded basins in the hinterlands of fold-thrust belts are documented in other fold-thrust belts in the last decades (e.g. Giovanni et al., 2010). In VD-VR Basin, the faults affect the limbs of the thrust anticlines bordering the basin with a trend parallel or subparallel to the anticlines axis suggesting a passive control of the thrust anticlines as investigated by analogue modelling experiments (Corti et al., 2006; Del Ventisette et al., 2021; Faccenna et al., 1995). Although the available seismic dataset does not allow clear recognition of the detachment level at depth for these faults (Figures 8, 9 and 11; Appendix S1), we hypothesize that a possible level may be the Triassic evaporites, considering that they represent one of the most important and deep detachment level of the Apennine chain (e.g. Bonini & Sani, 2002; Barchi, 2010; Conti et al., 2020 and reference therein; Barchi & Tavarnelli, 2022).

The extensional phase here described has not been recognised by other studies, probably due to the low exposure of the outcrops and the evident limits of the seismic sections that create uncertainties on the presence, geometry, and role played by the bordering faults in the evolution allowing different interpretations (Bonini et al., 2014; Bonini & Moratti, 1995; Bossio et al., 1996, 1997; Brogi & Liotta, 2008; Costantini et al., 2002; Del Campana, 1993; Lazzarotto et al., 2002; Mariani & Prato, 1988; Moratti & Bonini, 1998; Pascucci, 1997; Pascucci et al., 1999, 2001; Sani et al., 2016). Furthermore, the previous studies have always focused on seismic lines located in the central and southern portion of the basin, not including the seismic lines in the northern sector of the basin, unlike this study, where the syn-kinematic Piacenzian deposits reach the maximum thickness and the geometry related to the VMF kinematic is more evident (Figure 11). In a regional view, the tectonic quiescence during the Piacenzian, which in the study area is expressed by the gravitational collapse and related normal faulting, has been recognised also in the adjacent Valdelsa basin (Benvenuti et al., 2014; Figure 1) possibly attesting to a general interruption of crustal shortening.

5.1.3 | Third phase: latest Pliocene/early Pleistocene(?) tectonic inversion

The last phase in the evolution of the VD-VR Basin is ascribed to a new slight shortening pulse that led to the mild positive inversion of the Villamagna Fault with the formation of the inversion anticline as well as the south-westward mild tilting of the Piacenzian subunits (Figure 12). As pointed out above, this phase probably occurred at the end of the Piacenzian-post-Piacenzian. Although a precise time constrains is not possible, the presence of fracture systems, stylolitic striae, and microfaults in conglomeratic levels, solution pits, and mesofaults recognised in the field and dated to the Early Pleistocene (Boccaletti et al., 1992) allows this phase to be assigned to the latest Pliocene/Early Pleistocene. The crustal shortening during the latest Pliocene/Early Pleistocene has been recognised also in other basins of the NA hinterland (e.g. Benvenuti et al., 2014; Bernini et al., 1990; Boccaletti et al., 1992, 1994; Finetti et al., 2001, 2005). The origin of this slight compressive phase is not fully understood, but it might be related to a new reactivation along the bordering thrust faults.

In fact, structural zones of weakness, often related to structural inheritance, play and represent a common element between different areas where polyphase history of reactivation and inversion occur (e.g. Scisciani et al., 2019, 2021).

Finally, the gentle anticline recognised in the Volterra area in the seismic sections (Figures 2 and 6c) is consistent with the surface geology (Costantini et al., 2002; Moratti & Bonini, 1998). This anticline has been interpreted as the result of Early Pleistocene compression (Moratti & Bonini, 1998), on the contrary, the present interpretation suggests to relate it to the Piacenzian extensional phase.

5.1.4 | Implication for alternative subsidence mechanisms

The results of this research provide the opportunity to discuss the mechanisms of subsidence that controlled the formation of the VD-VR Basin. The discussion might have relevance to better understand the development of hinterland basins of the Apennines and of other orogens elsewhere.

The mechanisms that may account for a generalised subsidence of the hinterland basins of the NA since Late Miocene were highlighted in the introduction. Our research has indicated that VD-VR Basin was affected by alternated phases of extension and prevailing compression involving activity of thrust affecting the substratum. Similar alternation of deformation phases has been described for surrounding basins of the NA such as Siena-Radicofani Basin (Bonini & Sani, 2002) and basins in the Tyrrhenian region (Buttinelli et al., 2024). This suggests that differing local factors determining accommodation acted during peculiar time spans. In the VD-VR Basin, during the main phases of compression, thrust activity determined the shifting of the depocentres and the creation of accommodation space at the rear or at the front of the thrust faults as suggested for the Velona Basin (Bonini et al., 1999). A valuable insight of our research is the occurrence of the Piacenzian extension which is ascribed to the gravitation collapse of elevated, early contractional structures (Figure 12). Our research suggests that gravitational collapse and creation of laterally extensive normal faults might have been an important drive for subsidence at the scale of the individual hangingwall of such structures (fault-induced subsidence).

Furthermore, although not quantified in this work, the compaction of the sediments and sea-level fluctuations could have also influenced the generation of accommodation during the whole basin evolution. The latter factor likely influenced the Pliocene succession in the VD-VR Basin as in the adjacent Valdelsa Basin (Benvenuti et al., 2014) where multiple relative sea-level fluctuations were recorded. In the Valdelsa Basin, the Piacenzian portion of the succession, for its seismic imaging and outcrop expression, outlines a dominant eustatic control.

In conclusion, the VD-VR Basin was likely affected by a composite range of subsidence factors acting at regional and local scales, during the same phases or at different times, offering possible parallelism with other hinterland basins either of the NA or other orogens.

5.2 | The development of the Valdera-Volterra basin in the regional tectonic and geodynamic setting

The proposed model of the Late Miocene–Early Pleistocene evolution of the VD-VR Basin does not fit with a hypothesis that the NA hinterland sector has been subject to almost uninterrupted extension since the Early–Middle Miocene (Carmignani et al., 1994; Carmignani & Kligfield, 1990; Jolivet et al., 1998, 2008; Jolivet & Faccenna, 2000). In fact, the VD-VR Basin seems to have developed as a composite basin where initial accommodation was created by folding related to a regional upper Miocene–Pliocene compressive regime in which crustal shortening played a major role and with subsequent Piacenzian growth of the depocentre driven by extension related to crustal collapse of early tectonic highs (Figure 12). The development of the VD-VR Basin can be framed in a sequence of events in the geodynamic evolution of the NA hinterland which, following Bonini et al. (2014), include: (1) a main collisional phase resulting in the formation of the NA, as a consequence of the W-directed subduction of the Adria Plate; (2) crustal stretching during the Early–Late Miocene (~16–9 Ma) due to the counter-clockwise rotation of the Corsica-Sardinia block (~16/15 Ma; Speranza et al., 2002) in turn related to the collapse of the Corsica-Apennine thrust wedge as the consequence of a slab retreat (Bonini et al., 2014 and references therein). The Serie Ridotta setting (Signorini, 1949) may have been produced during this stage by low-angle normal faulting (Brogi et al., 2005; Carmignani et al., 1994; Lavecchia et al., 1984); (3) a blocked subduction during the Late Miocene–Early Pliocene, possibly due to slab detachment, slab tear, subduction jump, stalled subduction, or alternatively to roll forward subduction which triggered a shortening phase (Bonini et al., 2014 and references therein). This phase corresponds to the prolongated Late Tortonian-Zanclean folding recognised in the VD-VR Basin; (4) an eastward shift of the compressive deformation during the Late Pliocene–Quaternary and crustal collapse accommodated by normal faults cross-cutting both the low-angle normal faults and the thrusts and folds affecting the basin fills attributed to several possible causes (Bonini et al., 2014 and references therein). The formation of the basin parallel bounding faults in the VD-VR Basin can be ascribed to this regional phase. Finally, A weak renewal of shortening following the Piacenzian normal-fault-driven collapse, recorded by fault inversion in the VD-VR Basin fills, points to new slight propagation of the Africa–Europe shortening documented at the front of the Appennines (Bertello et al., 2010; Fantoni & Franciosi, 2010 and reference therein) into internal sectors of the NA.

6 | CONCLUSIONS

An integrated approach based on the analysis of both geophysical and geological data has allowed the identification of the main structural features of the Valdera-Volterra Basin and the reconstruction of its Late Miocene to Early Pleistocene tectono-sedimentary evolution. This comprehensive dataset includes gravimetric data, 2D seismic profiles, stratigraphic and geophysical data from deep wells, and also published micropaleontological and surface geological data. The study has allowed the subdivision of the Neogene sedimentary succession into 5 main seismic units. The results reveal an articulated and composite basin development. They provide further evidence of the influence of compressive tectonics during the Late Tortonian-Zanclean, as proposed by some other authors to explain the basin evolution. The geometry of the seismic units and the unconformities document the crustal shortening resulting in a progressive formation of a basin parallel syncline controlled by the growth of thrust-related anticlines bordering the basin. Using isochore maps, a Zanclean migration of the depocentre, probably related to differential growth rate of the bordering anticlines, has been identified. The crustal shortening is presumably related to the cessation of the Adria Plate subduction or, alternatively, to roll forward subduction, as proposed by previous studies. The seismic sections, TSM, and distance vs. thickness graphs provide evidence of a Piacenzian extensional phase with the formation of a series of border faults cutting the upper Miocene–Lower Pliocene sedimentary succession and the underling Pre-Serravallian substratum and providing accommodation space for the Piacenzian sediments. This post-compressional collapse phase is common in some other NA hinterland basins. The origin of this collapse has been ascribed to several regional causes. The presence of fault parallel anticline involving the Piacenzian succession close to the main fault indicates mild positive inversion during the latest Piacenzian–Early Pleistocene. This latest phase of crustal shortening is a consequence of renewed propagation of the Africa–Europe shortening into internal sectors of the NA.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data, except those confidential provided by ENI, that support the findings of this study are available from the author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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