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Research paper

Influence of structural inheritance on foreland-foredeep system evolution: An example from the Po valley region (northern Italy)

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ABSTRACT

Understanding the development of foreland-foredeep systems and the influence exerted by pre-existing structures on their evolution is an important step for defining the key factors that control long-term basin and lithosphere dynamics, comprehending the associated seismic hazard and assessing their economic potential in the domain of hydrocarbon exploration.

The Po Valley is a rather unique foreland basin for two major reasons: a) it developed intermittently at the front of two different mountain chains, the Northern Apennines and the Southern Alps, progressively converging one towards the other; b) the inherited structures, mainly derived from the Mesozoic extensional tectonics, are oriented at high angle to the advancing belts. The coexistence of these two factors and their various implications make the Po Valley basin a complex case study that deserves attention.

Taking advantage of the recent building of a 3D structural model across the region, we reconstructed the possible geometry and migration pattern of the Tertiary basins that developed at the front of the Northern Apennines and the Southern Alps, as part of the Po Valley tectonic evolution. In addition, a number of sections sliced from the 3D model across selected domains have then been used to restore the present-day structural units to their pre-compressional setting, while highlighting the key stages of their geological history.

Results from the model analysis show that the Mesozoic extension-related tectonics and the associated carbonate facies geometry and distribution localized and constrained the Alpine structures inside/around the basin. Their control on the Cenozoic deformation and sedimentation is evident during the Paleogene and the Miocene whereas it becomes more subtle during the Plio-Pleistocene when lithospheric-scale mechanisms need to be invoked.

Notwithstanding the model uncertainties and its explicit regional significance, our results may be taken as reference for any foreland-foredeep setting worldwide, especially in complex systems where tectono-sedimentary inhomogeneity is spatially and temporally dominant.

1. Introduction and aim of the study

A foreland basin is a structural basin that forms at the front of a mountain belt basically by bending of the lithosphere as a function of its flexural rigidity and the associated loading from the belt itself (De Celles and Giles, 1996). The consequent foreland width and depth define the accommodation space for the sediments that fill the basin, thus developing the derived foredeep sedimentary successions (Beaumont et al., 1999). According to the polarity of the subduction system that controls the evolution of an orogenic belt, foreland basins are normally separated into two different categories: peripheral or pro-wedge and retro-arc or retro-wedge (De Celles and Giles, 1996; Ziegler et al., 2002; Naylor and Sinclair, 2008). During development of foreland-foredeep domains, the inherited crustal structural fabric as well as the thermal state of the lithosphere may impact the progressive deformation history

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depending (among the many factors) on the pre-existing mechanical stratigraphy (horizontal and vertical), the distribution/geometry of structures (notably, their orientation with respect to the evolving regional stress field) and at a larger scale on the flexural rigidity of the foreland lithosphere.

The Po Valley (Fig. 1a,b) is a foreland basin (Bello and Fantoni, 2002; Fantoni et al., 2004; Turrini et al., 2014, 2015; Rossi et al., 2015) where the above cited factors have interacted through time and space to give birth to the present-day tectonic system. This system was formed as a result of a rather complex geodynamics, which controlled deformation and sedimentation, respectively of and onto the northern segment of the Adria micro-plate (Carminati and Doglioni, 2012; see also references hereinafter in Section 2). The long-lasting convergence process created opposite verging belts, namely the Northern Apennines and Southern Alps. From Paleogene to present times, the amplification and propagation of those mountain chains controlled the differential flexure of the Po Valley-Adria lithosphere, the associated tilting and bulging of the foreland domain, the rapid sedimentation of thick foredeep-type deposits and their successive involvement within the developing tectonic wedges (e.g., Carminati and Doglioni, 2012 and references therein). Remarkably, part of the described tectonic evolution caused non-homogeneous deformation of the common foreland region, where mainly extension-related Mesozoic structures have been reactivated and/or overprinted by the Cenozoic folds and thrusts.

The influence of the inherited Mesozoic extensional structures on the Alpine tectonics in and around the Po Valley region has been already discussed by various authors in the literature (Castellarin et al., 1985; Doglioni and Bosellini, 1987; Zanchi et al., 1990; Schonborn, 1992; Fantoni et al., 2004; Ravaglia et al., 2006, Castellarin and Cantelli, 2010; Cuffaro et al., 2010; Carminati and Doglioni, 2012; Vannoli et al., 2015; Pfiffner, 2014; Turrini et al., 2014). Key message from those studies is that the extension-related structures which formed the Adria plate margin during the Mesozoic have strongly controlled the progressive Alpine tectonics in the region. The derived interference between late-Triassic to early Jurassic, mainly N-S-oriented, extension-related structures and Cenozoic, generically WNW-ESE-oriented compression-related structures can be tracked at different scales of observation, especially across the Southern Alps outcrops and by the exploration wells drilled inside the Po Valley basin (Cassano et al., 1986; Bertotti et al., 1993; Schonborn, 1992; Fantoni et al., 2004).

As a follow-up to the 3D structural and seismo-tectonic models that have been recently built and analyzed across the Po Valley region (Turrini et al., 2014, 2015), this study aims at providing new evidences of the long-term influence that the distribution and geometry of pre-Alpine Mesozoic structures have had on the evolution of the Po Valley foreland-foredeep system since the Paleogene.

With respect to the previous works (Turrini et al., 2014, 2015) the main achievement of the study was certainly the integration of the structural-kinematic component with the 3D model geometries across the entire basin. In particular during this modeling phase, the 4D (space + time) interplay among distribution of the Tertiary-Mesozoic-basement units and lithospheric phenomena (flexure, belt progression) from Paleogene to present could be illustrated and demonstrated with new questions for discussion. Remarkably, given the available literature, the performed 2D restorations represent the first attempt to analyse the basin evolution systematically and across a geometrically consistent regional framework.

Despite the region uniqueness and beyond the derived regional implications, this study also intends at providing an interesting and solid term of comparison for other complex foreland basin systems worldwide, where large-scale structures and sediment distribution are highly variable both in time and space owing to structural inheritance.

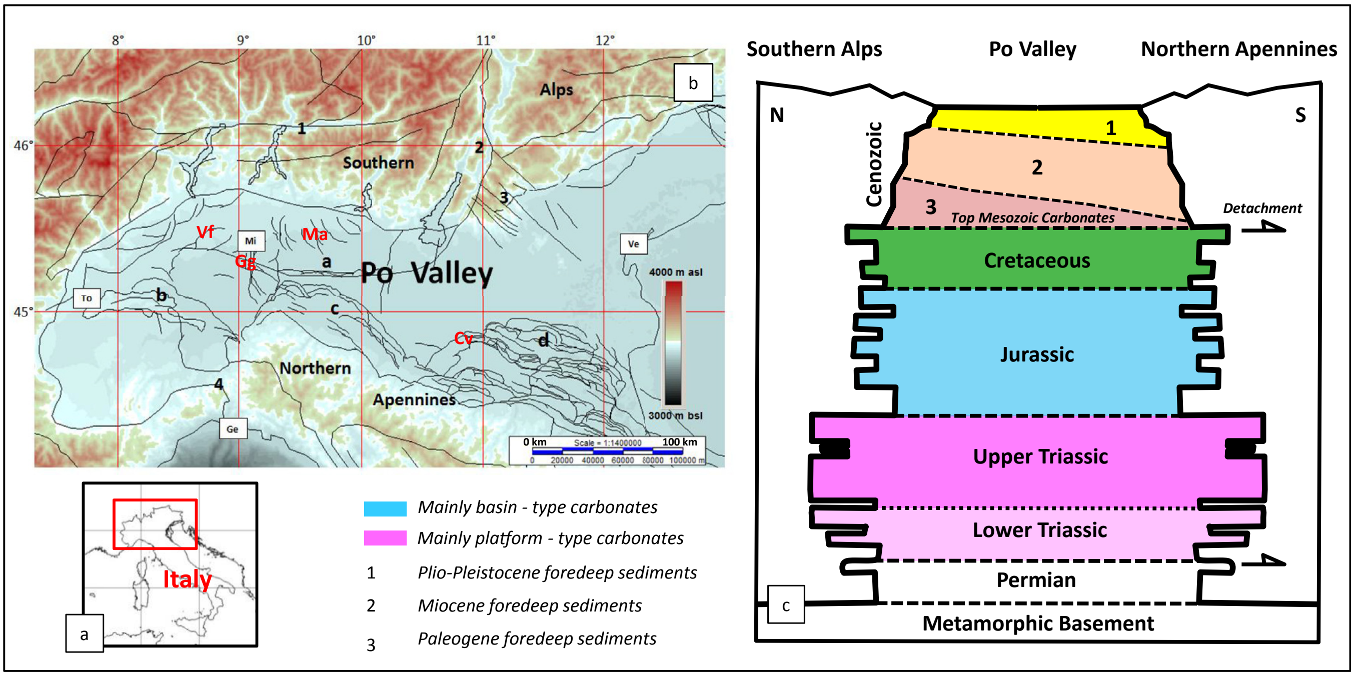


Fig. 1. a) - Location map. b) Digital topography and tectonic framework (modified from Turrini et al., 2014) around the Po Valley region. (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Sestri-Voltaggio-Villavernia Lines; (a–e) buried thrust fronts (modified after Bigi et al., 1990): a = Milano Thrust Front; b = Monferrato Thrust Front; c = Emilian Thrust Front; d = Ferrara-Romagna Thrust Front. Main cities are indicated: Mi = Milano, To = Torino, Ge = Genova, Ve = Venezia. c) Simplified stratigraphy of the Po Valley. 1, 2 and 3 in the Cenozoic units indicate respectively the foredeep deposits of Fig. 5c, b and a,.

2. The Po valley

2.1. Regional framework

The interaction between Eurasia and Africa plates drove the geodynamic evolution of the Alps and Apennines belts. The Adria microplate is commonly known as the African promontory involved in the collision with Eurasia (Dercourt et al., 1986). The convergence of the two plates caused indentation between the Northern Alps metamorphic belt and the Insubric domain, active since the Cretaceous up to the present (Coward et al., 1989; Dewey et al., 1989; Dal Piaz et al., 2003; Carminati and Doglioni, 2012). The development of the Southern Alps, and the growth of the Northern Apennines (Boccaletti et al., 1990; Cibin et al., 2004; Di Giulio et al., 2013) led to the formation of the Neogene Po Plain foreland basin, interposed between the two opposite verging chains (Fig. 1b).

The Southern Alps derive from the deformation of a passive continental margin, progressively involved into a collision (e.g., Castellarin et al., 1992; Bertotti et al., 1993; Di Giulio et al., 2001; Barbieri et al., 2004). The outermost buried fronts of that belt are formed by S-verging thrust systems, trending WNW-ESE partly outcropping in the foothill zone and partly buried under Neogene-Quaternary sediments of the Po Plain (Castellarin and Vai, 1986; Castellarin et al., 1992; Fantoni et al., 2004; Ravaglia et al., 2006). The Apennine sector facing the Po Valley consists of buried compressional structures bounded to the south by the Pedeapenninic Thrust Front (PTF) (Pieri and Groppi, 1981; Boccaletti et al., 1985; Castellarin et al., 1985; Cassano et al., 1986; Bigi et al., 1990; Fantoni and Franciosi, 2010; Ghielmi et al., 2010, 2013). These structures mainly refer to N to NE-verging blind thrusts and folds which controlled the rapid deposition of up to 7–8 km thick Neogene-Quaternary syntectonic sediments. Three main buried structural arcs were formed in different times and are associated with different amounts of shortening. From west to east they are (Fig. 1b): 1) the Monferrato arc (an allochthonous tectonic wedge with undefined shortening - Mosca, 2013 - successively re-folded and thrusted between Messinian and Pleistocene); 2) the Emilia arc (20–25% of shortening – Castellarin et al., 1985; Perotti, 1991; Toscani et al., 2014 - mainly active during Pliocene) and 3) the Ferrara-Romagna arc (more than 30–35% of shortening – Castellarin et al., 1985 - tectonically active at present time – Maesano et al., 2015a). The eastward increase in shortening is consistent with the Northern Apennine counter clockwise rotation during its emplacement within an oblique collisional framework (Bally et al., 1986; Vanossi et al., 1994; Cibin et al., 2003; Carminati et al., 2012; Maino et al., 2013).

The Po Valley units separate the Southern Alps and the Northern Apennines and they constitute the common foreland-foredeep system of these two diachronous and opposite verging chains since the Paleogene (see recent synthesis by Turrini et al., 2014, 2015 and references therein). The ancient foreland units, as part of the Mesozoic passive margin, currently form thrust imbricates variably dipping and hidden below thick Cenozoic clastic sediments (Pieri and Groppi, 1981; Cassano et al., 1986; Mariotti and Doglioni, 2000; Fantoni and Franciosi, 2010; Turrini et al., 2014). The ancient foredeep units, derived from the erosion of the Southern Alps (e.g. Carrapa and Di Giulio, 2001; Di Giulio et al., 2001) and of the Northern Apennines (Rizzini and Dondi, 1978; Dondi and D'Andrea, 1986; Ravaglia et al., 2004; Mancin et al., 2009) form a thick sedimentary wedge that, as a whole, can exceed 9 km in total thickness.

The Mesozoic succession is formed by Upper Triassic carbonate platform rocks and by Jurassic to Cretaceous pelagic carbonates resting on top of metamorphic basement rocks (Cassano et al., 1986) (Fig. 1c). The overlying Tertiary sediments (Fig. 1c) consists of Paleogene marls, some Messinian evaporites, sand-shale Pliocene turbidites, Early Pleistocene marine sands and Late Pleistocene alluvial deposits. From the mechanical point of view, the Po Plain stratigraphy includes two major décollement levels (Fig. 1c) which strongly impact the structural style in the basin (Fantoni et al., 2004; Ravaglia et al., 2006, Turrini et al., 2014, 2015): the deeper detachment corresponds to the evaporites at the bottom of the Mesozoic carbonate units; the shallower detachment occurs on top of the carbonate series, in correspondence of Late Eocene-Early Oligocene marls.

The Po Valley tectono-stratigraphic units and sedimentary infill provide a quite complete record of the compressional tectonic phases that affected, from Cretaceous onwards, the Triassic-Jurassic passive margin and giving rise to the formation of a Neogene-Quaternary foredeep basin (Dondi and D'Andrea, 1986; Argnani and Ricci Lucchi, 2001; Ghielmi et al., 2010, 2013). Timing of the related tectonic events is provided by the age of syntectonic deposits and the associated growth strata geometries (Ghielmi et al., 2010, 2013; Rossi et al., 2015).

During the Late Oligocene the Adria plate ended its rotation (Carminati et al., 2012; Malusà et al., 2016) yet continued to move NNW-ward and collided with the Eurasian plate. At the same time, the Apennine fronts rotated counter-clockwise while the Southern Alps fronts were translated southwards, both belts thrusting onto the common Po Valley foreland (Carminati et al., 2012). During the Middle Miocene, due to the progressive advance of the Apennine belt (Carminati et al., 2012), the Southern Alps and the Northern Apennine fronts were closer. The foredeep space was further reduced at early Pliocene times when the Southern Alps fronts (almost no longer tectonically active) and the active Northern Apennine became parallel and faced each other. From early Pliocene onwards only the Northern Apennine fronts remained tectonically active, deforming the buried geometries to their present configuration. GPS measurements and slip rates calculations describe the present (last 20–30 years) and recent (last 1.8My) deformations, respectively. GPS velocities show a general NNE trend with decreasing values going from the outcropping Northern Apennines to the Po Valley region (Bennett et al., 2012; Serpelloni et al., 2005, 2007). Tectonic motion along the Plio-Pleistocene thrust segments is essentially concentrated on the Northern Apennine buried fronts (particularly the Ferrara region). Slip rate values calculated for the last 1.8My are higher (Maesano et al., 2013, 2015a) with respect to the rest of the Po Valley as they occur in regions where major earthquakes have been reported (Basili et al., 2008; DISS Working Group, 2015; Turrini et al., 2015; Bonini et al., 2014). Being a flat alluvial plain, outcrops or field evidences of neotectonic activities are lacking in the Po Valley. Hence, the most recent tectonic events are evidenced by drainage anomalies (Burrato et al., 2003) and, locally, anticline hinges outcrop creating isolated reliefs. Examples of these are the San Colombano hill, belonging to the buried fronts of the Northern Apennines (Toscani et al., 2014), the Capriano del Colle hill, in the Southern Alps (Livio et al., 2009b) and the Montello hill, in the Eastern Southern Alps (Burrato et al., 2008; Caputo et al., 2010).

3. Data & methodology

The 3D model building workflow has been already presented and discussed in terms of the associated data, methodology and uncertainty by previous papers (Turrini et al., 2014, 2015). Nevertheless, because of the continuous refining and updating of the model structural geometries it is worth to briefly review the entire process while describing the new features and operations.

3.1. Model building phase 1

The base framework of the model has been performed by integrating most of the public data available for the region, i.e., cross-sections, contour maps and wells (Turrini et al., 2014, 2015 and reference therein) and they are all measured in depth (Fig. 2). Noteworthy, no seismic data have been used during the entire building workflow, this being due to two particular reasons: a) seismic lines in the Po Valley region are exclusive property of ENI (previously Agip S.p.a., the national oil company) and the few available for public access cannot provide an homogeneous distribution of information for the aimed model building; b) the use of depth data allows any problem derived from time-to-depth conversion and the related velocity distribution to be circumvented. Noticeably, the initial model framework was based on a net of widely used cross-sections published by Agip and built from seismic, wells, geophysical maps (gravity and magnetic) and full knowledge of the region (Pieri and Groppi, 1981; Cassano et al., 1986) (Fig. 3a). The above mentioned set of depth data was geo-referenced, digitized and cross-checked for geometrical compatibility in 3D. Once the different interpretations have been transformed into their digital 2D format (xyz lines), they have been gridded to form the surfaces which constitute the model elements. The primary aim was to construct a number of key surfaces that define the model 'stratigraphy', i.e. from top to bottom, topography, base Pliocene, top Mesozoic carbonates, near top Triassic, top basement and Moho. A preliminary, crustal scale 3D geo-volume was then obtained and was used to illustrate (Turrini et al., 2014): a) the regional setting across the basin and b) the possible link among the very deep (Moho), deep (basement and Mesozoic carbonates) and shallow (base Pliocene and outcrops and major tectonic trends from the surrounding Southern Alps and Northern Apennines belts) structures. The entire model building process was performed by the MOVE structural package.

3.2. Model building phase 2

Phase 2 of the model building workflow was particularly devoted to the fault reconstruction, essentially across the Mesozoic layers (Fig. 3b) and subordinately across the Tertiary deposits. The model was then integrated with the earthquake events taken from the INGV web site (Turrini et al., 2015).

As part of phase 2-workflow, still performed using the MOVE software, all key fault maps selected from the literature (Pieri and Groppi, 1981; Casero et al., 1990; Fantoni et al., 2004, Cimolino et al., 2010; Rogledi, 2010) were a) digitized as lines, b) draped onto the specific model layer, c) the composing fault segments projected to depth as planes, accordingly to the most valuable dip angle, d) the reconstructed surfaces sliced for 3D consistency inside the final model. The process was rigorously performed across the main oil field in the region (Fig. 3c). An original technique was used to review and refine both the model stratigraphic layers and the 3D faults: all model surfaces were exported from the MOVE software and imported into the 2D/3D Kingdom package (normally used for seismic interpretation) where, once transformed to gridded layers, they could be re-picked and tied to the well data on a regular and dense net of blank pseudo-SEGY panels (Fig. 3d) created inside the software. With such a technique, all structural features were

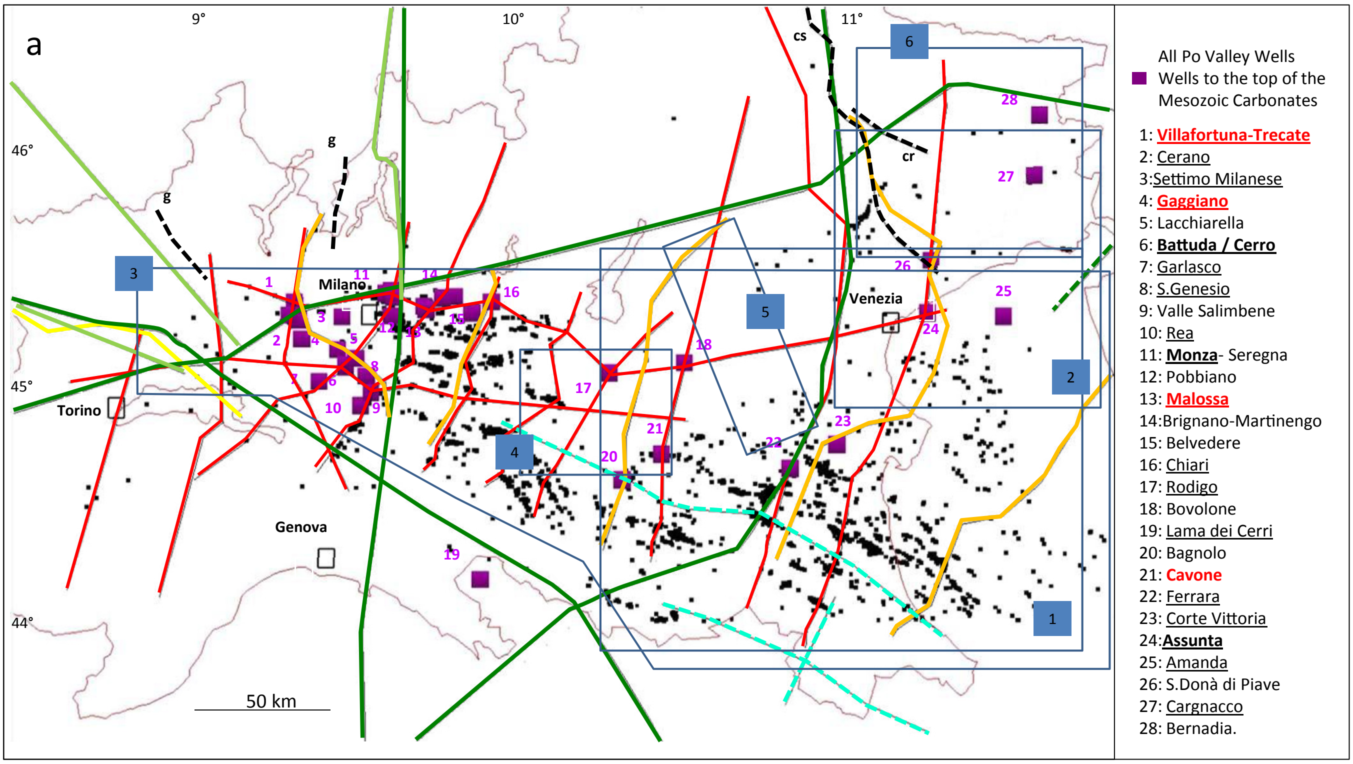


Fig. 2. (a) Data distribution: maps, cross-sections and wells available from the public domain. In the well list: red = fields; bold black = wells drilling down to the Po Valley basement; underlined = wells drilling down to the Triassic succession. Cross-sections: red set from Cassano et al., 1986; orange set from Fantoni et al., 2004 and Fantoni and Franciosi, 2010; dark-green set from Roeder, 1991; light-green set from Schmid and Kissling (2000; yellow is CROP-ECORS from Roure et al. (1990); light-blue set from Boccaletti et al. (2010); black set from (cs) Castellarin et al., 2005, (cr) Casero et al., 1990 and (g) Greber et al., 1997. Box 1 = top Mesozoic Carbonates depth contour map area, from Casero et al., 1990; box 2 = top Mesozoic Carbonates depth contour map area, from Cimolino et al., 2010; box 3 = top Mesozoic depth map area, from Nicolai and Gambini (2007); box 4 = depth maps from GEOMOL project, 2015; box 5 = serial depth sections from Pola et al., 2014; box 6 = serial depth sections from Ponton, 2010. Latitude and Longitude values are North and East of Greenwich. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

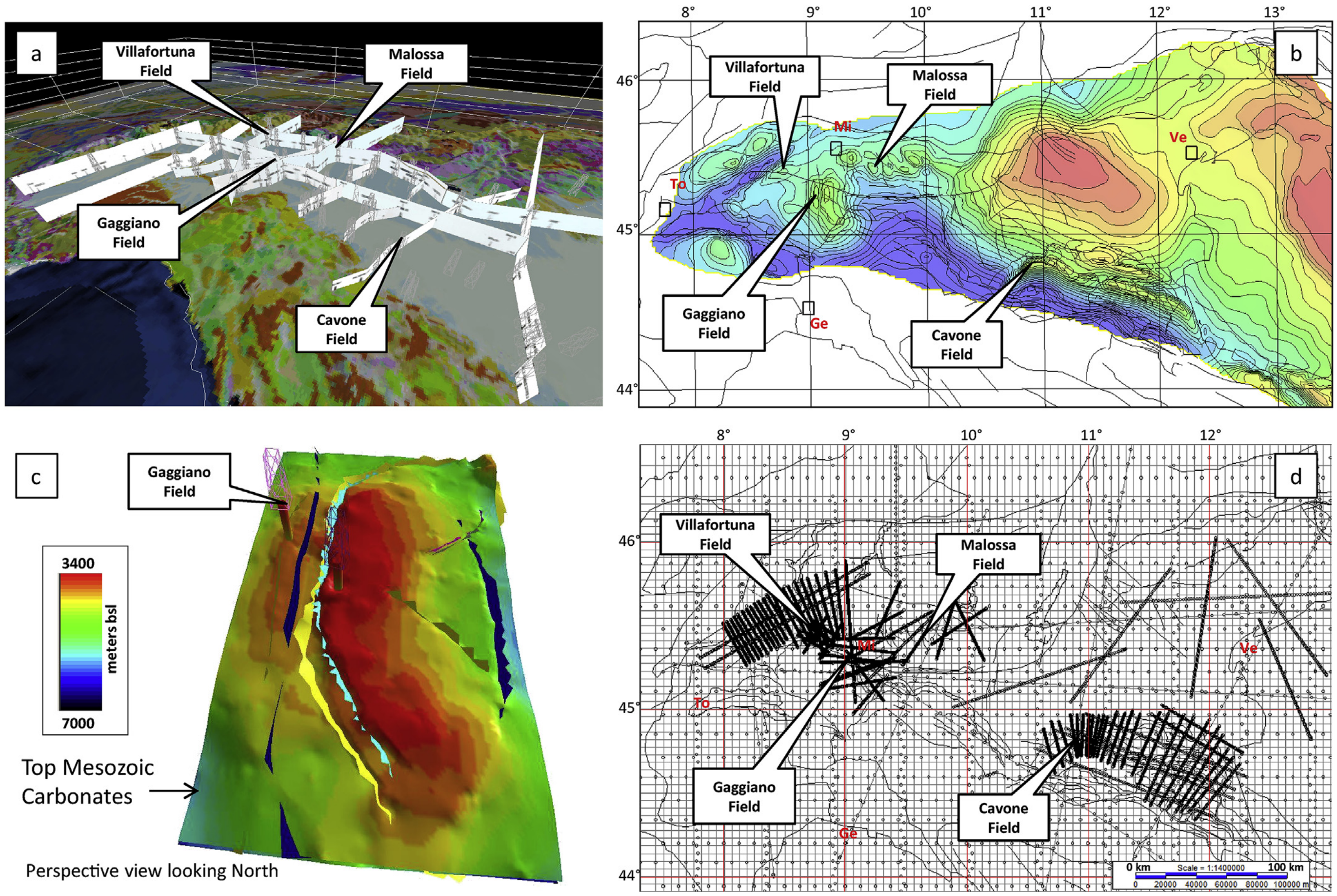


Fig. 3. Different images and views taken from the 3D model. a) DEM of the Po Valley (view from SE) with simplified geological map on the surface and cross sections from Cassano et al. (1986); b) depth structure contour map of the top of Mesozoic carbonates; c) 3d view of the Gaggiano field and the Lacchiarella inversion basin; d) Pseudo-sgy panels imported into the Kingdom project across the Po Valley basin (see text for explanation).

systematically analyzed every 5 km and the model structures were progressively validated along those sections much like in-lines and dip-lines inside a crustal scale pseudo-3D seismic survey. To be mentioned, the fault-surface building tool available in the Kingdom software was particularly useful for revisiting existing faults as well as building new ones when necessary.

3.3. *Model building phase 3*

The last phase of the 3D structural model reconstruction essentially consisted of infilling the Tertiary stratigraphy between the base Pliocene and the top Mesozoic layers. The exercise was entirely performed with the Kingdom software along the same pseudo-SEGY panels and by the same technique described for the model building phase 2. Noteworthy, some further integration of structural data/interpretation from the public literature was performed (Pola et al., 2014; GEOMOL project). Phase-1 cross-sections from Cassano et al. (1986) were again used as references to the work because they provide a real homogeneous set of data, seismic derived and tied to the key wells in the region. However, given the sparse distribution of those data and the tectono-stratigraphic complexity of the Po Valley Tertiary section, we acknowledge that the modeled top Oligocene, mid-early and mid-late Miocene grids a) represent, at present, a first approximation of the possible geological surfaces, b) would need further refining in order to interpret in detail the associated faults. Despite such an approximation, the new Tertiary layering can be considered a valid representation of the regional framework at the selected geological times. Hence the modeled layers were used to build isopach maps that do eventually describe the paleogeographic context of the different major foredeep basins (Fig. 5). In particular: a) the Paleogene as a whole (Paleocene-Eocene-Oligocene undifferentiated section), Miocene and Plio-Pleistocene foredeep wedges can now be identified in terms of specific geometry and dimension, b) because a clear-cut separation between the early-mid Miocene and the mid-late Miocene wedges remains problematic at the scale of the model, only the total Miocene isopach is presented in this paper whereas specific annotations have been added to that map to suggest the possible prevalence and extension of the different Miocene basins and the associated overlap zones. To be ultimately noted, the current results can be biased by local deviations from the average thickness, being related either to local tectonic overthickening within the different Miocene units and/or to erosional events (Pieri and Groppi, 1981; Ricci Lucchi, 1986; Rossi et al., 2015; Ghielmi et al., 2013; Di Giulio et al., 2013). Nevertheless, at the scale of the entire Po Valley region, the reconstructed Tertiary geometries are geologically sound and are consistent with the available public data and interpretations.

3.4. *Restoration*

2D restoration of selected cross-sections sliced from the model has been performed by the Structural Solver software (Nunns & Logan LLC). Key principles and assumptions behind the restoration algorithm (Nunns, 1991) are that length is conserved along the reference horizon and that the deformed units are restored using vertical shear.

The purpose of the 2D restoration exercise is to validate the modeled 3D geometries in the respect of the standard balancing/restoration criteria (Dahlstrom, 1969; Hossack, 1979; Gibbs, 1983; Moretti and Raoult, 1990; Moretti et al., 1990), while attempting to define the key timing of the structure evolution (see Section 4.3). Also, the methodology is specifically used for the recognition of the Mesozoic framework in the central Po Valley foreland after vertical slicing of a number of serial cross-sections that were drawn in order to intersect the major oil fields in the region (see Section 4.3).

Important notes to the performed restorations are:

1. All of the structures cut from the 3D model had to be slightly edited to correct obvious geometrical inconsistencies derived from the model building and the related surface gridding. As such, those structures could be reasonably balanced before proceeding with the 2D restoration;
2. Given the available data, the model crustal-scale and the difficulty in choosing the required dip-direction due to the various structure orientations and the possible oblique movements along the faults (see discussion Section 5.2), the restored configurations should be considered as schematic and over-simplified solutions to the present-day structure complexity;
3. Provided the above consideration, the performed restorations were particularly devoted to unraveling the first-order crustal-scale tectono-sedimentary framework in terms of successive foredeeps, rather than to restoring the single structures in detail;
4. Results from restoration of the selected cross-sections in terms of structure timing, together with the kinematics information from the available literature (Castellarin et al., 1985; Doglioni and Bosellini, 1987; Nardon et al.,1991; Roure et al., 1990; Schonborn, 1992; Greber et al., 1997; Bello and Fantoni, 2002; Benedetti et al., 2003; Fantoni et al., 2003, 2004; Toscani et al., 2006, 2009; Livio et al., 2009a,b; Boccaletti et al., 2010; Mosca et al., 2010; Ponton, 2010; Masetti et al., 2012; Bresciani and Perotti, 2014; Pola et al., 2014), have been used to compile a deformation-time map that helps visualize the deformation progression across the Po Valley basin (see Fig. 15): in this sense, the derived deformation ages have been posted as punctual values across the basin and successively gridded into a continuous map representation of the regional tectonic evolution.

4. Structural geometries and kinematics in the Po Valley foreland basin

While few and isolated cross-sections have been built and restored in the past to gain information about selected areas of the Po Valley (Castellarin et al., 1985; Toscani et al., 2014), we use hereinafter the 3D model elements to provide a regional view of the basin tectonic kinematics from the Paleogene to the present. The derived structural evolution was defined by two different approaches. The first one relies upon the spatial definition of the successive foredeep basin geometries and dimensions: this allowed the recognition of the migration through time of the foredeep while considering the possible sediment contribution from the South Alpine and the Northern Apennines belts. The second approach refers to the restoration of the model structural units, which will expectedly improve recognition of the main stages of development of structures with reference to the associated syntectonic deposits. The restoration also further allows the pre-alpine paleogeography and the influence of the inherited structural pattern on the present-day regional structural fabric to be demonstrated.

4.1. *Geometry of the present-day foreland at top Mesozoic level*

The 3D structural model performed across the Po Valley basin has fully described the present-day deformation geometries in the region (Turrini et al., 2014, 2015). In particular, the top Mesozoic surface provided an outstanding picture of the deep foreland structures where two major domains can be observed caught in between the Southern Alps and the Northern Apennines belt (Fig. 4a). The western domain is deformed into a basin-and-dome pattern where variably oriented, thick-skinned structures occur. The eastern domain is essentially dominated by a large foreland high onto which the thin-skinned (mainly) Ferrara tectonic arc is thrust and displaced as part of the Apennines external front.

The current tectonic architecture of the carbonates essentially results from interference among a) Cenozoic, compression-related structures, b) pre-existing, Mesozoic (late Triassic-Early Jurassic) extension-related geometries, c) Mesozoic tectono-stratigraphic domains/facies (Fig. 4b) (Castellarin et al., 1985; Doglioni and Bosellini, 1987; Zanchi et al., 1990; Schonborn, 1992; Fantoni et al., 2004; Ravaglia et al., 2006, Castellarin and Cantelli, 2010; Cuffaro et al., 2010; Carminati and Doglioni, 2012; Vannoli et al., 2015; Pfiffner, 2014; Turrini et al., 2014). Within such a framework the foreland units are buried below Tertiary clastic sediments, these being deposited coevally with the progressive tectonic advancement of the Southern Alps and Northern Apennines belts towards the common foreland domain. Structures in the Tertiary deposits refer to folds and thrusts essentially oriented WNW-ESE (Pieri and Groppi, 1981; Bigi et al., 1990; Turrini et al., 2014 and references therein).

For the scope of this work it is important to stress that facies and geometry of the Triassic and Liassic carbonate formations are particularly discontinuous across the Po Valley basin (Fig. 4b) (Fantoni and Franciosi, 2010; Masetti et al., 2012; Turrini et al., 2016). Here, the derived syn-rift pelagic deposits and intra-pelagic ridges and plateaus, highly variable in terms of both thickness and rheology, likely constitute a non-homogeneous mechanical framework to the Alpine tectonic evolution of the basin.

4.2. *Geometry and migration of the Tertiary foredeeps*

4.2.1. *The Paleogene foredeep*

The Paleogene foredeep is shown in Fig. 5a by the isopach map which has been computed between the top of the Mesozoic Carbonates and the top Oligocene 3D grids. The map mainly considers the interpreted, undifferentiated, Paleogene section and aims at reproducing the possible paleogeography at top Oligocene time. As such, the derived thickness map of the foredeep deposits delineates the regional geometry of the basin which consists of two different zones at the front of the Southern Alps. The western zone (west of the Giudicarie trend; Giudicarie FZ in Fig. 5a) reaches a maximum thickness of 6–8 km and can be separated into two sub-zones, west and east of Milano, at the front of the western and central sectors of the Southern Alps, respectively. The eastern zone (east of the Giudicarie trend) shows a maximum thickness of 2 km at the front of the eastern sector of the Southern Alps.

The Paleogene foredeep map also shows two important anomalies which, due to their thickness, stand out from the regional basin fabric (Fig. 5a, A and B). The A anomaly is defined by a reduced thickness of the Paleogene deposits (approximately 1.5 km) as also indicated by a number of deep wells in the area: Seregna 1, Malossa 1, Chiari 1, Belvedere 1 (see Fig. 2 for well location) (Videpi database (http://unmig.sviluppoeconomico.gov.it/videpi/en/; Cassano et al., 1986). The structural restoration performed in Section 4.3 suggests the presence of a pre-existing structural high which corresponds to the Malossa oil field area. Conversely, the B anomaly is

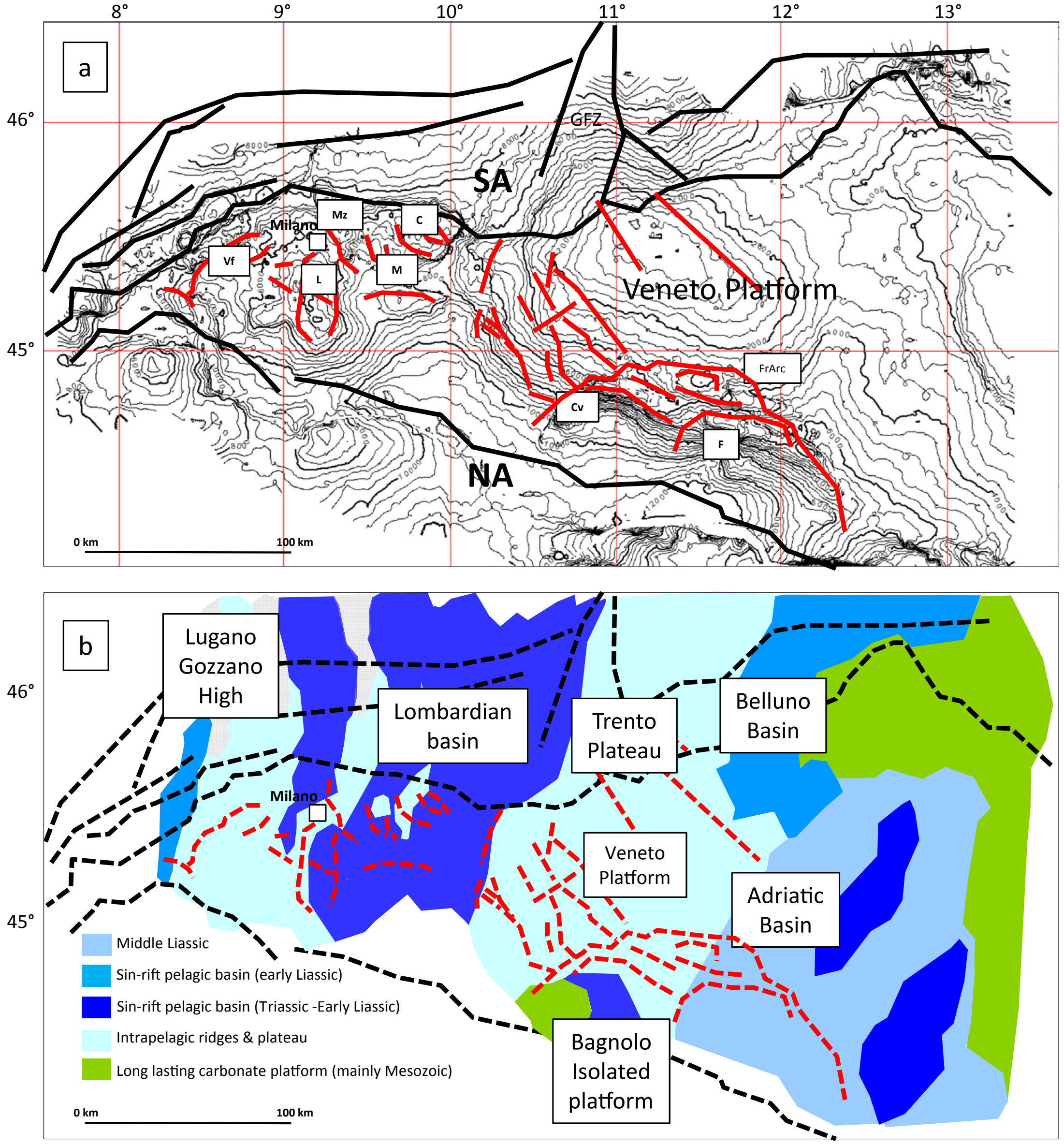


Fig. 4. a) Structure contour map (contour lines every 400 m) of the present day top Mesozoic Carbonates as derived from the Po Valley 3D structural model (Turrini et al., 2014): red and black lines are main buried faults and outcropping tectonic trends, respectively. Labels in the map are referred to hydrocarbon fields and/or geological structures described in the text (Vf = Villafortuna; L = Lacchiarella; M = Malossa; C = Chiari; Mz = Monza; Cv = Cavone; F = Ferrara; FrArc = Ferrara Arc). b) Tectono-stratigraphic unit distribution and facies (modified from Fantoni and Franciosi, 2010). Main structural elements (from Fig.4a) as dotted thick red and black lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

defined by an important thickness of the Paleogene sediments (approximately 2–3 km). Although some local tectonic overthickening is evident from the available data (Cassano et al., 1986) and confirmed by the structural restoration, the B zone might represent the northern termination of a Paleogene basin, which cannot be associated to the Southern Alp belt progression (see Discussion).

4.2.2. The Miocene foredeep

The 3D model Miocene isopach map (Fig. 5b) looks more complex than the one obtained for the Paleogene period. This complexity seemingly results from the interference between the Southern Alps and the Northern Apennines contributions to sedimentary input and tectonics.

At the scale of the Po Valley basin, two major zones can again be defined east and west of the Giudicarie trend (i.e. like for the Paleogene foredeep basin map, Fig. 5a). In the eastern part of the basin, the Miocene units are thin to nearly absent. Nevertheless, the isopach map shows differential thickening inside the Ferrara tectonic arc region with values between 1 km and 4 km. Here, the maximum thickness of Miocene sediments can be correlated with the B anomaly zone already recognized in the Paleogene foredeep map. In the western part of the basin, the thickness of the Miocene sediments varies between 1 km and 5 km on average. Inside this region, a N-S and a WSW-ENE oriented culminations (minimum sediment thickness) separate three different sub-zones:

1. East of Milano, the Miocene sedimentary wedge thickness gently increases towards the Northern Apennines. The 3D model reveals the present-day overlap between the early-mid

Miocene wedge and the late-mid Miocene which can be positioned at the mid-distance between the Southern Alps and the Northern Apennines outcrops. In this context, the early-mid Miocene basin has its depocenter to the north of the overlap zone and is possibly related to the Southern Alps foredeep accumulation (emM in Fig. 5b). Conversely, the mid-late Miocene basin and associated depocenter can be located to the south of the overlap zone and related to the Northern Apennines foredeep (mlM in Fig. 5b);

2. North-west of Milano the 3D shape of the early-mid Miocene deposits indicates the presence of a foredeep basin (emM in Fig. 5b) related to the western Southern Alps segment;
3. South-west of Milano, the modeled mid-late Miocene deposits thickness (mlM in Fig. 5b) defines the foredeep depocenter at the front of the Monferrato tectonic arc.

4.2.3. The Plio-Pleistocene foredeep

The Plio-Pleistocene foredeep geometry and dimension are illustrated in Fig. 5c which also is the representation of the current setting in the Po Valley region. Notwithstanding the intense tectonics, the map shows that the thickness of the present sedimentary wedge increases southwards and eastwards, as it reaches some maximum values (7–9 km) at the front of the Northern Apennines outcrops, inside and NW of the Ferrara tectonic arc. These geometries are in agreement with previous works (Pieri and Groppi, 1981; Cassano et al., 1986, Ghielmi et al., 2013; Turrini et al., 2014).

4.3. 2D restoration across the Po valley foreland basin

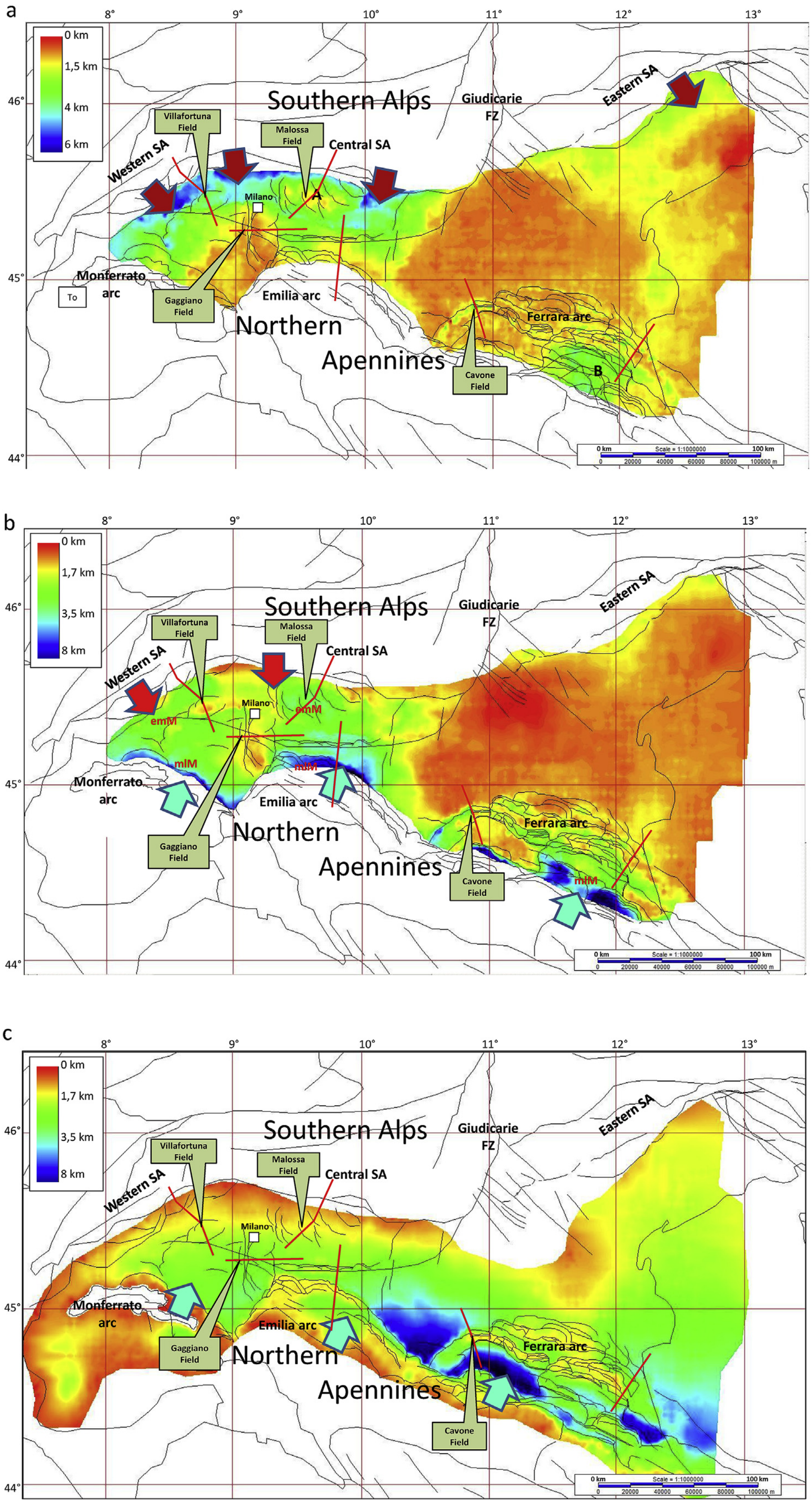
A number of selected cross-sections representative of the major Po Valley domains has been sliced from the 3D model and restored into their possible pre-compressional geometry. While checking the three-dimensional consistency of the modeled structures, 2D restoration helps in identifying the timing of their formation with respect to the larger-scale foredeep migration and reconstructing the pre-Alpine, Mesozoic extensional pattern.

Cross-section 1 cuts through the western Southern Alps foothills and the adjacent foreland domain (the Gattinara and the Villafortuna units respectively) (Fig. 6a). The present-day structures show a classic tectonic wedge configuration across the Southern Alps foothills domain. The north-dipping faults (arising from the belt) cut across the metamorphic basement and the Mesozoic units; they are flat at the base of the Tertiary sedimentary section and ramp again onto the Villafortuna foreland structure. The latter is deformed by south-dipping and antithetic north-dipping thrusts, which involve both the basement and the overlying Mesozoic thin cover. Well data in the region (Turbigo 1, Videpi database) indicate that the Paleogene section on top of the Villafortuna structure is faulted and tectonically over-thickened. The early-mid Miocene sediments are folded according to the thrust propagation and eroded at the crest culmination. Ultimately, the base of Pliocene deposits is tilted towards the south (i.e. towards the Northern Apennines). The restoration exercise (Fig. 6b) allows reconstruction of the foredeep and foreland units back into their pre-compressional configuration: a) the Paleogene sedimentary wedge is revealed with a possible maximum thickness of 4 km in between the Southern Alps and the foreland; b) the Jurassic-Cretaceous section is thinning southwards with a minimum thickness to the south of the Villafortuna location; c) here Triassic-Liassic faults should be invoked to justify the well-stratigraphy where a regional Jurassic high is interpreted (Cassano et al., 1986; Fantoni et al., 2004). From the comparison of the present geometries and their restoration, the mid-late Miocene appears to be the key moment in the structural timing of the foreland units due to folding and thrusting across the entire basement-Mesozoic-Tertiary rock package. Interestingly, the reconstructed geometry of the Paleogene wedge suggests the possible existence of early compressional structures (Oligocene?) inside the Southern Alps tectonic stack, in agreement with earlier works (Cassano et al., 1986; Schonborn, 1992).

Cross-section 2 (Fig. 7a) has been sliced across the units which form the foreland-foredeep domain at the front of the central Southern Alps, between Milano and the Giudicarie trend. The section shows: a) Plio-Pleistocene foredeep sedimentary wedge thinning northwards (i.e. towards the Southern Alps outcrops); b) a variable thickness of mainly early-mid Miocene sediments; c) evidence for a Paleogene wedge, involved in the compressional deformation; d) folds and faults that deform the Mesozoic section and the underlying basement. Despite the possible presence of thrusts across the Tertiary sedimentary package (Pieri and Groppi, 1981; Cassano et al., 1986, Fantoni et al., 2004) and the consequent over-estimate of the original sediment thickness, the presence of a Paleogene foredeep wedge, with a depocenter at the front of the Southern Alps belt, is supported by the restored sections at top Paleogene time (Fig. 7b). The resulting configuration highlights the regional dip of the Mesozoic carbonates towards the front of the advancing Southern Alps located north.

Cross-section 3 cuts through the western Po Valley (south of Milano) with a west-east orientation (Fig. 8a). The section essentially focuses on the structural geometries below the top of the Mesozoic carbonates, namely the Lacchiarella inverted Jurassic extensional graben and the adjacent Gaggiano high. The Tertiary deposits on top of those structures consist of thin mid-Miocene to nearly absent Paleogene clastics, below a thick Plio-Pleistocene package. Restoration of the cross-section to top Oligocene (Fig. 8b) allows the early basin inversion of the Lacchiarella Jurassic-Cretaceous graben to be highlighted (Fantoni et al., 2004) (see Fig. 12 for a pseudo-3D representation of the Mesozoic pre-compressional setting). The comparison with the present-day structure (Fig. 8a) suggests weak reactivation of the Lacchiarella fault system during the Miocene. To the west of the Lacchiarella basin, the Tertiary evolution of the Gaggiano units is revealed: a) since Triassic time (Fig. 8a–b) the Gaggiano structures constitute the footwall faulted blocks of the Lacchiarella fault as the Lacchiarella basin formed by extension and was subsequently inverted by compression; b) since the Paleogene and during the whole Neogene (Fig. 8 a–b), the Gaggiano structures were progressively buried and tilted westwards in response to lithospheric flexure of the Po Valley foreland.

The structures which form the zone of interaction between the buried fronts of the Northern Apennines (Emilia arc) and the Southern Alps (Milano arc) are represented in cross-section 4 (Fig. 9a). Along this section, the Tertiary sediments are deformed by folding and thrusting (Pieri and Groppi, 1981; Cassano et al., 1986) detached close to the top of the Mesozoic carbonates. At depth (6 km bsl), the carbonates are modeled to be eventually deformed by compression and tectonically displaced northwards below the Tertiary section, as suggested by Bello and Fantoni (2002). The restoration of the structures at the base Pliocene time (Fig. 9b) reveals that the Miocene sedimentary wedges are thinning northwards, over the south-dipping Mesozoic carbonates. Conversely, the Paleogene foredeep basin is thickening northwards (Fig. 9c), thus suggesting a regional dip of the associated Po Valley foreland towards the Southern Alps, as already shown by cross-sections 1 and 2 (Figs. 6 and 7). Timing of development of the shallow structures is clearly Plio-Pleistocene whereas, given the available constraints (Bello and Fantoni, 2002), the deep thrust-anticline in the Mesozoic carbonates could have developed at any moment from the top Oligocene to the present.


a
0 km
1,5 km
4 km
6 km
Southern Alps
Giudicarie FZ
Eastern SA
Western SA
Central SA
Villafortuna Field
Malossa Field
Milano
A
Gaggiano Field
Monferrato arc
To
Emilia arc
Northern Apennines
Ferrara arc
Cavone Field
B
8°
9°
10°
11°
12°
13°
46°
45°
44°
0 km Scale = 1:1000000 100 km
0 20000 40000 60000 80000 100000 m
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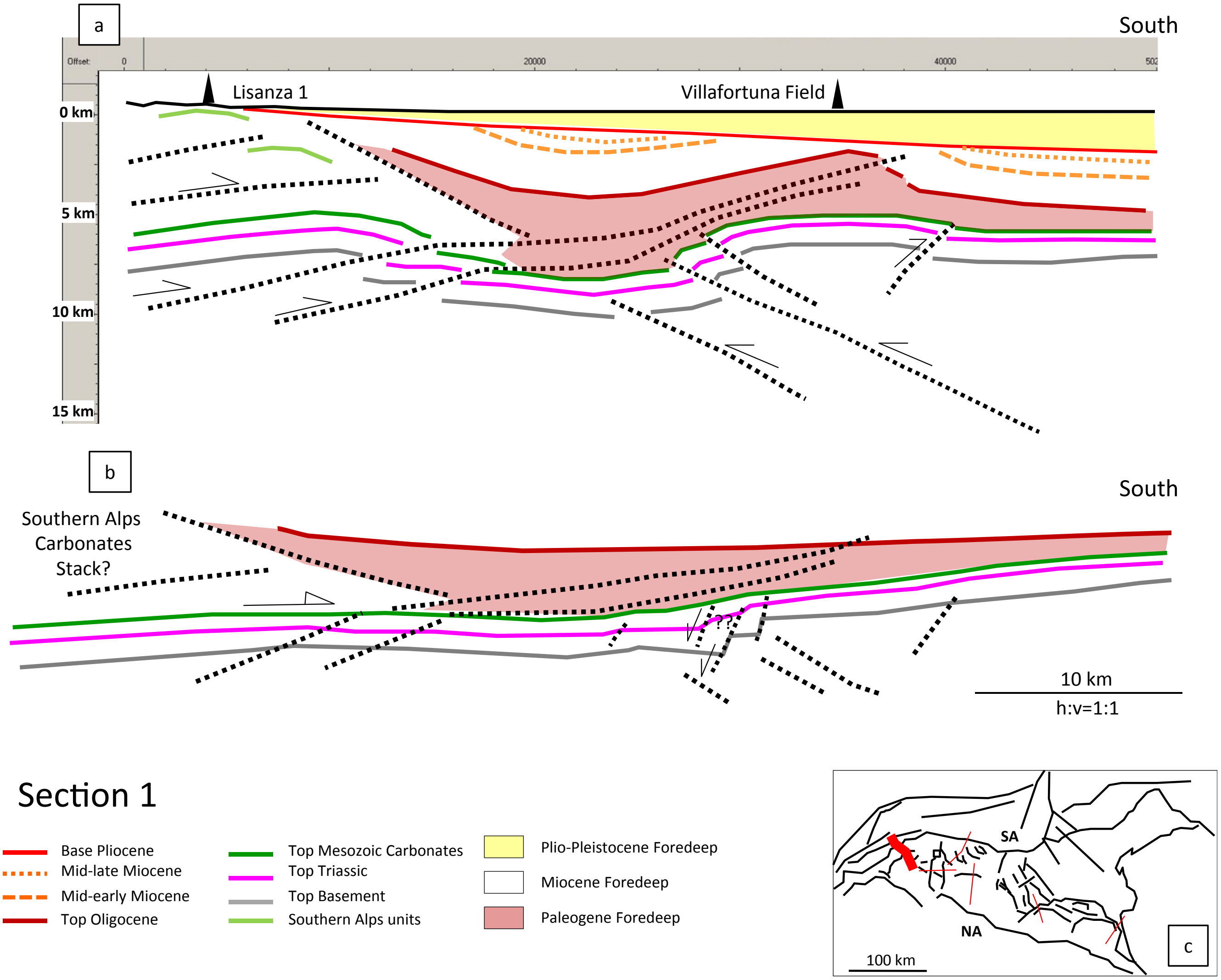

Fig. 6. Section 1: a) present-day structures in the Southern Alps-Villafortuna field region; b) structures restored at top mid-early Miocene time; c) cross-section location and tectonic elements from Fig. 4a.

Cross-section 5 and 6 (Figs. 10 and 11) show the structure-types forming the Ferrara arc, where the external front of the Northern Apennines is thrusting onto the Po Valley foreland (Pieri and Groppi, 1981; Castellarin et al., 1985; Cassano et al., 1986; Turrini et al., 2014 and references therein). Along section 5 (Fig. 10a), i.e., across the western lateral ramp of the Ferrara arc, the Cavone culmination results from strong tectonic imbrication of the Pre-Pliocene rocks detached along the top Triassic and the top of the crystalline basement. All across the thrusted fold, the Paleogene-Miocene sediments are relatively thin (Cassano et al., 1986) and nearly absent on the footwall-foreland side of the faulted anticline. The shape of the Plio-Pleistocene sedimentary wedge clearly indicates a regional southward dip of the foreland domain. The restoration (Fig. 10b) confirms the presence of a variable thickness Tertiary section, which becomes very thin northwards, and is possibly controlled by the presence of Paleogene-Miocene normal faults. The onset of the compressional structure is essentially Plio-Pleistocene in age as indicated by: a) folding and thrusting of the entire Meso-Cenozoic stratigraphic package, b) faults cutting through the base Pliocene surface, c) regional tilting of the foreland (and the faults within it) southwards (i.e. towards the Northern Apennines belt).

Cross-section 6 cuts through the eastern sector of the Ferrara tectonic arc (Fig. 11a) and shows NE verging faulted anticlines detached at multiple levels, with shallow pop-up structures involving post-Mesozoic deposits. At depth, faulting appears to deform also the basement, ahead and below the external, main thrust front. The pre-compressional configuration (Fig. 11b) highlights that Tertiary

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Fig. 5. a - Isopach map of the Paleogene deposits, built from the 3D model. Thickness variations highlight foredeep geometry across the Po Valley. Red lines represent the traces of the cross-sections selected for restoration and discussed in the text. Red arrows indicate prevalent foredeep sediment sources (Pfiffner, 2014). b) - Isopach map of the Miocene deposits, built from the 3D model. Thickness variations allow imaging of the foredeep basin geometry across the Po Valley region: emM = area for prevalent early-mid Miocene foredeep deposition; mlM = area for prevalent mid-late Miocene foredeep deposition. Red lines are location of the cross-sections selected for restoration. Red arrows and blue arrows indicates the prevalent foredeep sediment sources from the Southern Alps and Apennines belts, respectively. c) - Isopach map of the Plio-Pleistocene deposits, built from the 3D model. Thickness variations highlight foredeep geometry across the Po Valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

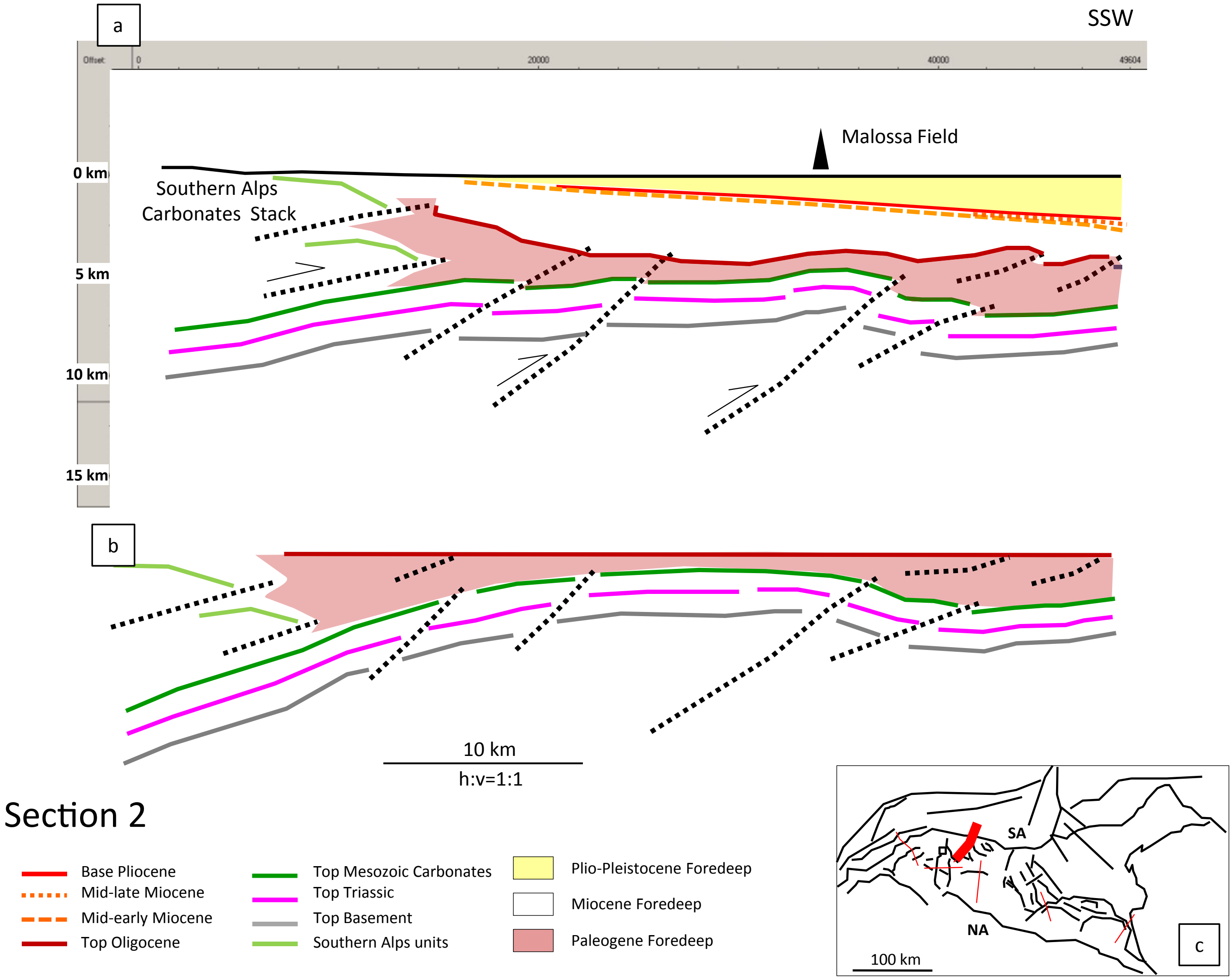

Fig. 7. Section 2: a) present-day structures in the Southern Alps-Malossa field region; b) structures restored at top Oligocene time; c) cross-section location and tectonic elements from Fig. 4a.

sediments, possibly Paleogene and Miocene in age (Cassano et al., 1986), become thinner northwards. The presence of some possible Paleogene-Miocene faults can again be speculated to control the Tertiary sediment variation, like for cross-section 5 (Fig. 10b). Also in this case, timing of main deformation is Plio-Pleistocene.

Cross-sections 7 to 12 (Figs. 12 and 13) have been sliced from the 3D model with the aim to intersect the deep units which form the Mesozoic foreland in the most suitable orientation for restoration. Due to the nearly N-S direction of the Mesozoic paleogeographic elements (Turrini et al., 2014 and reference therein), the sections are oriented approximately east-west and they extend from the central to the westernmost Po Valley. For all of the chosen cross-sections, the overlying Tertiary sediments and tectonics are excluded from the exercise, provided their main sense of displacement along the north-south direction (i.e. perpendicular to the section planes). The present-day structures in the area (Fig. 12) show faulting and folding of the Mesozoic carbonates and their basement (Cassano et al., 1986; Fantoni et al., 2004; Ravaglia et al., 2006; Turrini et al., 2014). The final tectono-stratigraphic setting suggests basin inversion as the dominant deformation process with a) vertical expulsion of the Jurassic-Cretaceous basins, b) limited displacement along the single faults, c) localized thrust-related stacking and possible short-cutting of the pre-Alpine extensional hinge blocks (Fig. 12: below the Monza 1 location and structures to the west of the Malossa field).

Restoration of the structures (Fig. 13) allows the possible Mesozoic, extensional geometries to be reconstructed back to their pre-compressional configuration (this latter essentially referring to the early Liassic episode of extensional deformation, the late Triassic episode being nearly impossible to be distinguished around the basin). Diffuse faulted blocks-forming horsts and deep grabens are revealed together with their possible original dimensions (30 km long and 15 km wide, maximum thickness of the Mesozoic package of 4 km). Basins show lozenge-shape geometry and curved fault traces with relay zones at the transition between the different basins (Fig. 13a). Thickening of the Jurassic-Cretaceous sediments is also revealed (Fig. 13: the Belvedere and the Lacchiarella basins).

In details, all of the mentioned extension-related features are confirmed. In the northernmost region (cross-sections 11 and 12 in Fig. 13) the major boundary fault is west dipping yet east-dipping faults are developed as well. The two fault sets control the thickness increase of both the Jurassic and Triassic sediments from west

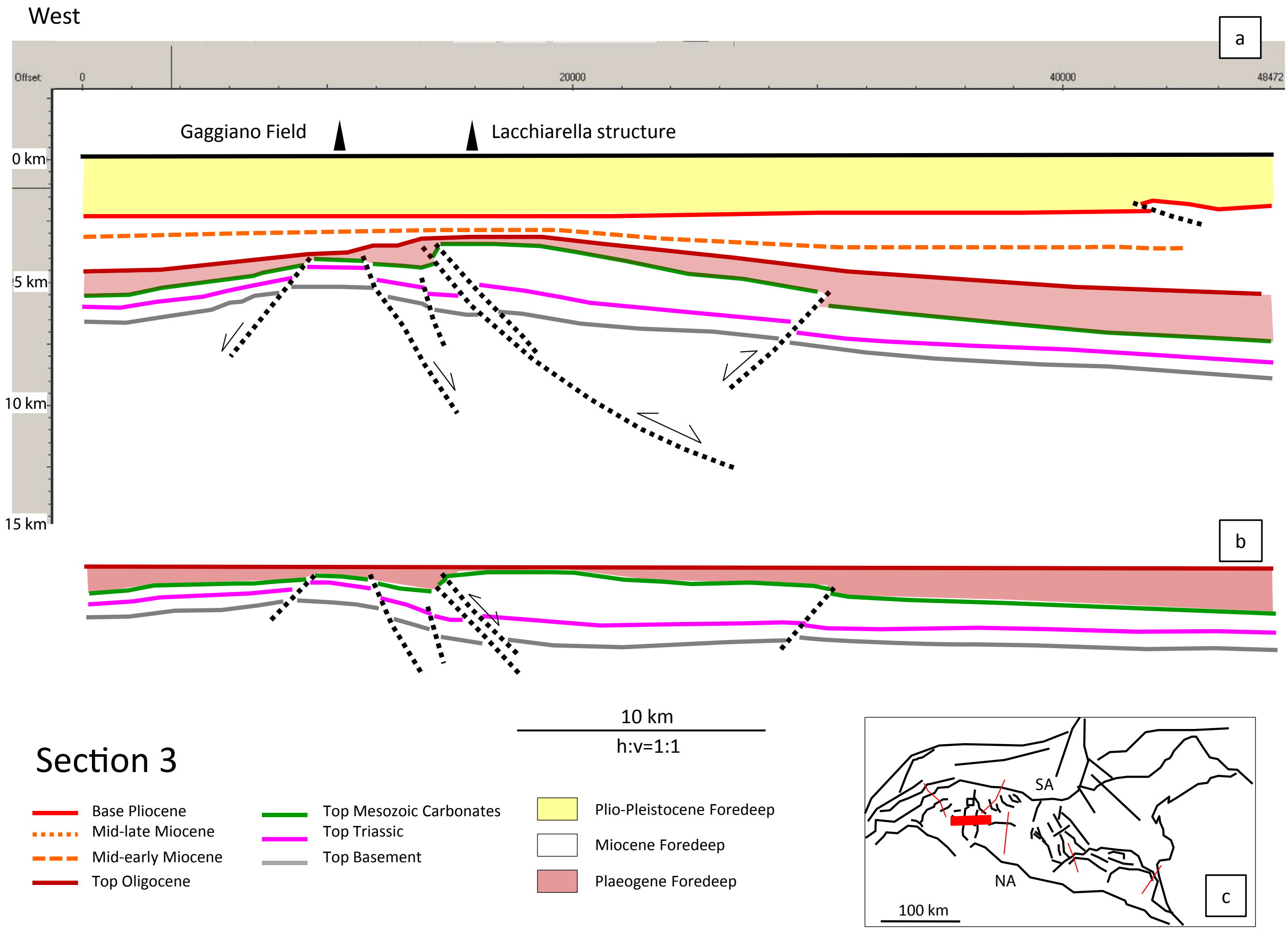

Fig. 8. Section 3: a) present-day structures in the Gaggiano field-Lacchiarella structure region; b) structures restored at top Oligocene time; c) cross-section location and tectonic elements from Fig.4a.

to east. In the southernmost region (cross-sections 13-16 in Fig. 13) the master fault dips towards the east so that the west dipping faults are mainly minor antithetic faults. Nevertheless and once again, thickness of the Mesozoic deposits appears to increase towards the east of the region. The pseudo-3D perspective observation of the serial cross-sections clearly reveals the possible correlation across the modeled faults.

The comparison between Figs. 12 and 13 helps to recognize those faults which could have been re-activated during the Alpine inversion tectonics. At the same time it is also possible to define which of the present faults have been newly created under compression (see fault legend Fig. 13).

The restoration of the various cross-sections indicates an average shortening between 10% and 15% with a minimum value (5%) measured in the Lacchiarella inversion basin (Fig. 8) and a maximum value (28%) across the Cavone structure (Fig. 10). The shortening values correspond to a cumulative displacement along the faults which have been modeled along the various cross-sections in the range of 2–5 km in the western Po Valley and 10–12 km across the Ferrara arc in the eastern Po Valley.

5. Discussion

Worldwide examples available from the literature (e.g. Beydoun et al., 1992; Uliana et al., 1995; Maţenco et al., 1997; Muñoz-Jiménez and Casas-Sainz, 1997; Garfunkel and Greiling, 2002; Ziegler et al., 2002; Lacombe al., 2003; Norman Kent and Dasgupta, 2004; McQuarrie et al., 2005; Mann et al., 2006; Naylor and Sinclair, 2008; Oszczypko, 2006; Fantoni and Franciosi, 2010; Toscani et al., 2014) allows the Po Valley to be considered as a rather unique foreland basin. This is essentially because of the occurrence of two key-characteristics: a) it developed intermittently at the front of two different mountain chains, the Northern Apennines and the Southern Alps, progressively converging one towards the other; b) the inherited structures, mainly derived from the Mesozoic extensional tectonics, are oriented at high angle to the advancing belts.

Starting from such considerations, in the following discussion we use the outcomes of this study to argue about the Oligocene-Neogene Po Valley foreland evolution under a new, basin scale and quantitative perspective. In particular, a) the reconstructed Tertiary basins' geometry/migration (section 4.2) is used to substantiate the foreland development as a function of the Mesozoic tectonics and carbonate facies distribution during the Alpine structural history; b) the performed 2D restorations (section 4.3) are used to suggest the Cenozoic tectonics in terms of structures' timing and structural mechanics across the basin; c) the overall results are used to focus on the Po Valley lithosphere geodynamics while comparing them to some foreland-foredeep configurations taken from the available literature.

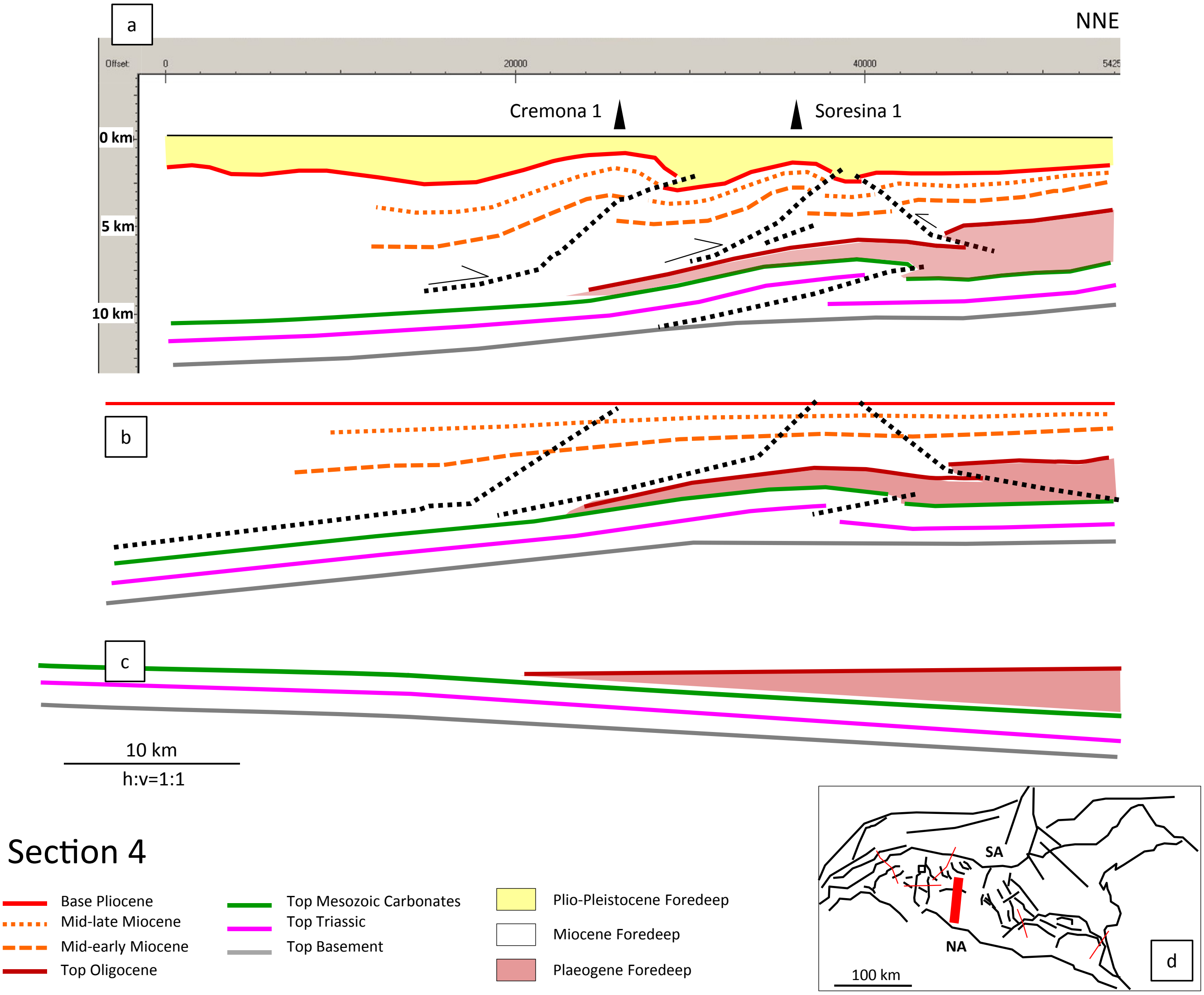

Fig. 9. Section 4: a) present-day structures in the Cremona-Soresina structure region; b) structures restored at near top Miocene time; c) cross-section location and tectonic elements from Fig. 4a.

5.1. *Influence of the Mesozoic inherited structures on the foreland tectonics*

5.1.1. *Foredeep migration-geometry versus Mesozoic tectono-stratigraphic grain*

Deposition of the Paleogene foredeep sediments (Fig. 14a) appears to have taken place predominantly in the northern sector of the western Po Valley region. Here the sedimentary wedge of the Gonfolite formation (Bernoulli et al., 1993; Di Capua et al., 2015) was deposited along and deformed by the Southern Alps external front (Figs. 14a, 6–7 km of sediment thickness). Over the eastern Po Valley, the deposition of the Paleogene successions (1–2 km) was largely impeached by the foreland architecture. In that area, the Mesozoic carbonates and their underlying basement provide a crustal-scale structural high and an obstacle to the belt propagation (i.e. the Veneto Platform in Fig. 14a; Masetti et al., 2012; Turrini et al., 2014; Toscani et al., 2016 and references therein). The deformation-time map of the basin (Fig. 15) shows that the western Po Valley was strongly affected by the Alpine compression, which resulted in some early-stage thrusting inside the Southern Alps (Fig. 6) (Schonborn, 1992; Greber et al., 1997) and local inversion of pre-existing extensional basins at the front of the advancing belt (Fig. 8) (Fantoni et al., 2004).

In Miocene times, compression was particularly concentrated all along the front of the Southern Alps (Fig. 15) and, through time, it progressively migrated eastwards (Castellarin et al., 1985; Doglioni and Bosellini, 1987; Ponton, 2010). Both the foredeep geometry and the foreland deformation inside the Po Valley basin appear to have been strongly influenced by the pre-Alpine configuration (Fig. 14b). The modeled geometry of the Miocene basins suggests a setting similar to the Paleogene one: the foreland backbone controlled the distribution of the foredeep sediments whose major depocenters occurred in the western Po Valley (1–4 km), likely responding to both the Southern Alps and the Northern Apennines tectonic pulses and sedimentary input (Fig. 16b). On the other hand and again, the eastern Po Valley foreland domain was an area of reduced sedimentation (1–2 km) and still stood as a barrier to the progression of the buried Southern Alps and Northern Apennines deformation fronts (Figs. 14b and 16b).

Ultimately, during Plio-Pleistocene times, deformation was essentially occurring at the front of the Apenninic belt and along the eastern sector of the Southern Alps (Figs. 14c and 15) (Turrini

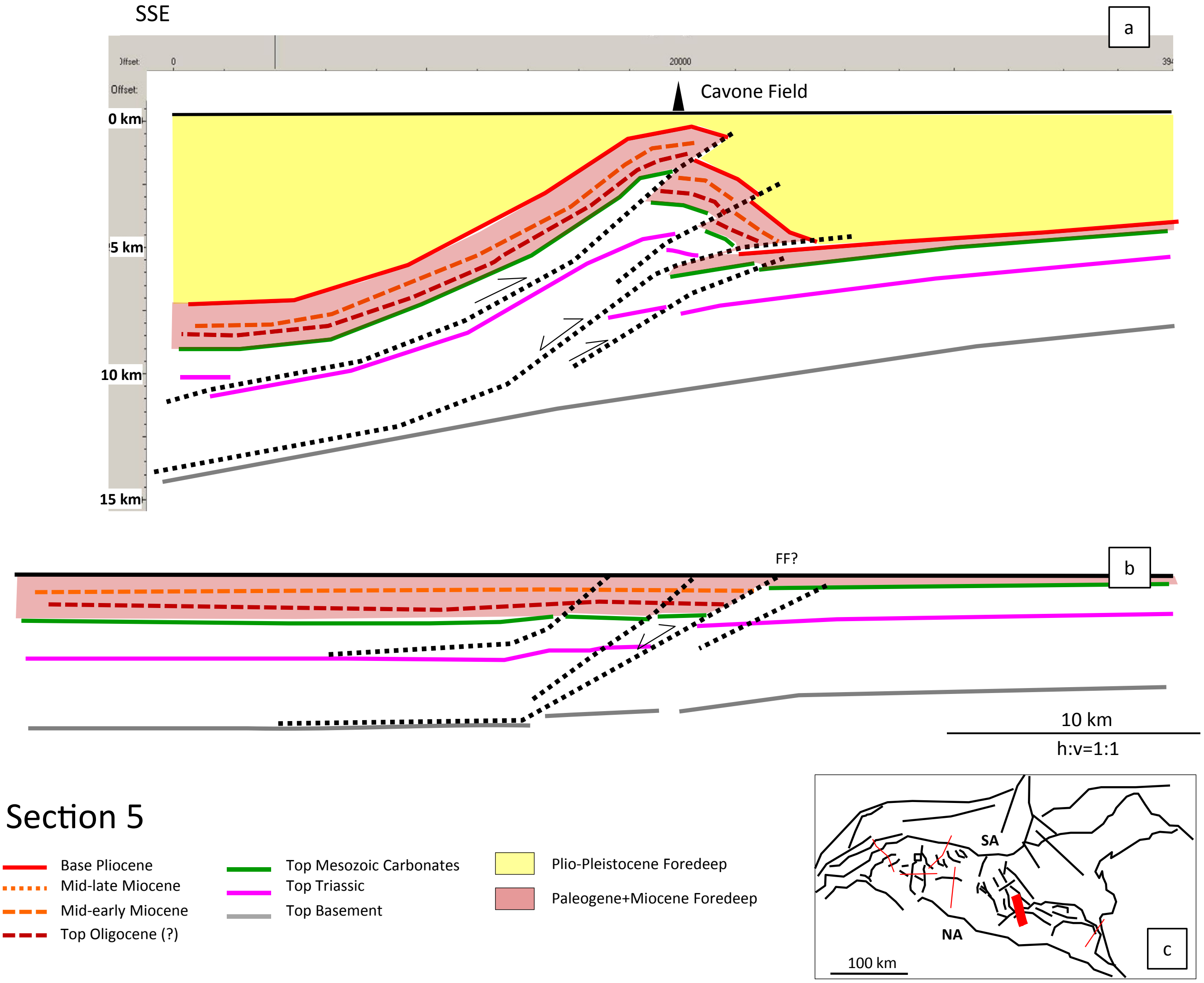

Fig. 10. Section 5: a) present-day structures in the Cavone field region, across the western Ferrara arc (Northern Apennines buried external front); b) structures restored at near top Miocene time; FF = possible flexure related fault c) cross-section location and tectonic elements from Fig. 4a.

et al., 2015 and references therein). The reconstructed Plio-Pleistocene basin geometry confirms that the crustal scale configuration has dramatically changed during that period. Indeed, the related isopach map indicates progressive thinning of the associated sedimentary wedge towards the Southern Alps and the development of some major depocenters (4–8 km) along the Northern Apennines (Fig. 16c). Due to the ongoing processes (subduction, lithosphere flexuring; see below) the influence of the Apenninic orogeny on the Po Valley tectonics became dominant while the inheritance from the Mesozoic fabric appears more subtle: a) the Apennines external front cuts across the foreland domain in the eastern Po Valley foreland while forming the Ferrara arc; b) here, the pre-compressional boundary between the Trento platform and the Adriatic basins (Fantoni and Franciosi, 2010; Masetti et al., 2012) was displaced towards the NE, c) the derived transfer zone (Pieri and Groppi, 1981; Bigi et al., 1990; Turrini et al., 2014, 2015 and references therein) that can be observed to separate the Ferrara arc into two different structural units (see Figs. 4b and 14c) may represent the ultimate indicator of the Mesozoic structural inheritance.

5.1.2. *Alpine tectonics versus Mesozoic tectono-stratigraphic grain*

It is noticeable that during the entire Cenozoic, the foreland tectono-stratigraphic elements inherited from the Mesozoic extensional phases remained oriented at high angle with respect to the advancing belt fronts (see and compare Figs. 14 and 16). Such faults are the only ones which localize important thickness variations of the Mesozoic deposits (Fig. 13: the Belvedere and Lacchiarella basins). Considering the general NNW motion of the Adria plate (Carminati et al., 2012; Pfiffner, 2014, Fig. 16a) and the nearly N-S orientation of the pre-Alpine faults, an important component of wrenching (i.e. oblique compression) along these faults can be likely speculated during the inversion process. Further, 3D model geometries shows that only part of the extension-related faults were reactivated by compression while others were not (see and compare Figs. 12 and 13). At the same time, newly formed thrusts cut through the Mesozoic stratigraphic succession and the underlying basement.

Following the examples and studies from Letouzey (1990), Lowell (1995) and Ziegler (1989) while considering the structure kinematics and the geodynamic time-steps illustrated in Figs. 15 and 16, it is then possible to suggest that:

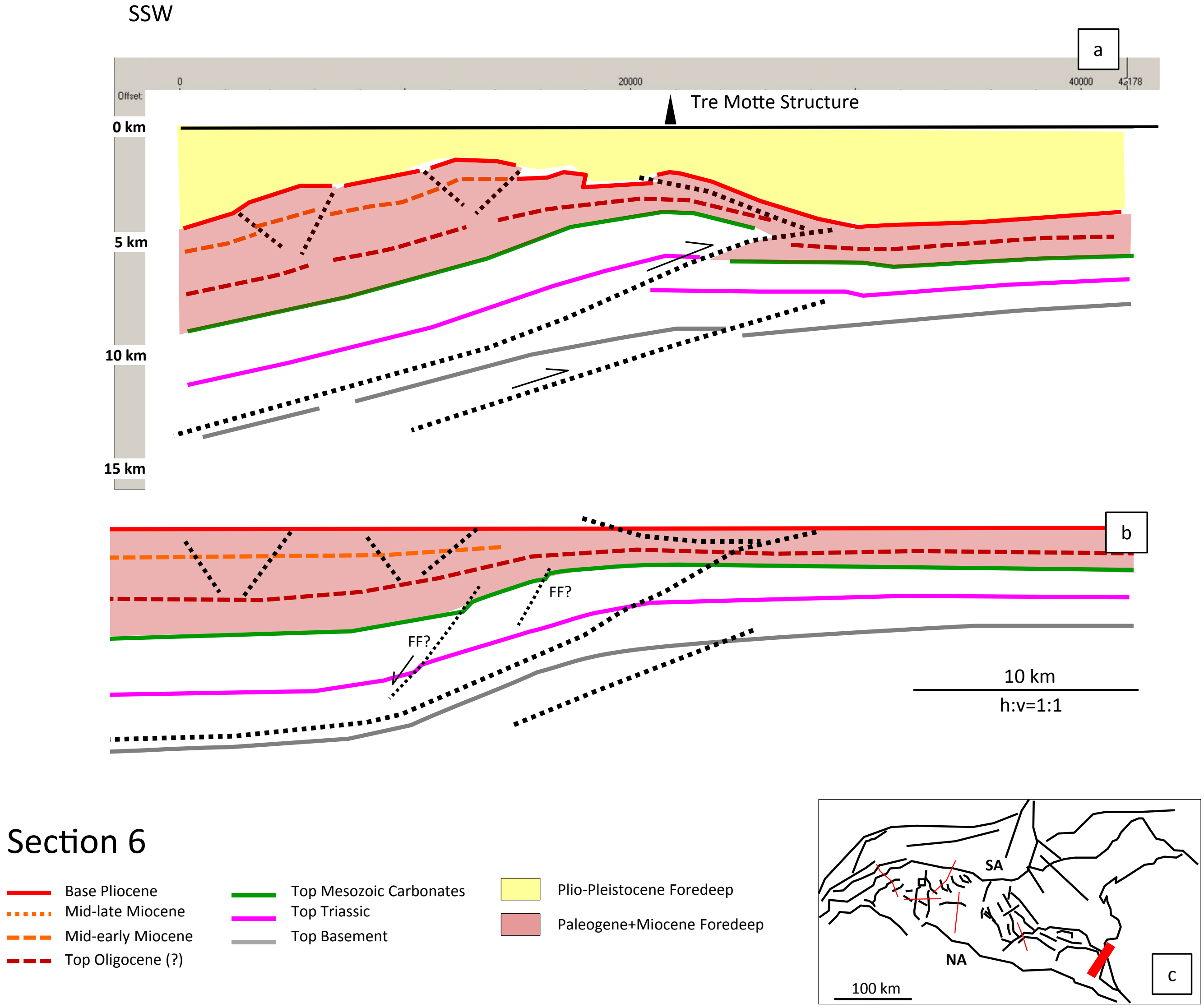

Fig. 11. Section 6: a) present-day structures in the Tre Motte well region, across the eastern Ferrara arc (Northern Apennines buried external front); b) structures restored at near top Miocene time; FF = possible flexure related fault c) cross-section location and tectonic elements from Fig. 4a.

1. Inherited Mesozoic faults that were reactivated across the Po Valley foreland (see and compare Figs. 12 and 13) must have undergone an important strike-slip deformation component due to their obliquity with respect to the direction of tectonic transport of the Alpine fronts. As an extreme case, those faults oriented parallel to the maximum compressional direction possibly did not suffer any strike-slip deformation at all (Lowell, 1995). However, the final, variable oblique component would be difficult to assess by the current crustal-scale 3D model. Further specific analysis based on fault slip tendency (Maesano et al., 2015b), sedimentation rates (Maesano and D'Ambrogi, 2016) and high resolution 3D seismic data would serve that objective. Similar structural configuration are rare yet the Ceara Piaui basin in northeast Brazil and the Salta Province in northern Argentina (Lowell, 1995 and reference therein) might be considered as possible analogs to the deep setting in the Po Valley;
2. the newly formed Alpine faults likely account for generic oblique deformation with a dominant reverse component. These thrusts eventually decapitate pre-existing hinge zones (short-cut structures; e.g. the Monza structure: see and compare Figs. 12 and 13) or they passively displace old normal faults (e.g. the Villafortuna and Malossa field structures: see and compare Figs. 12 and 13) (Errico et al., 1980; Fantoni et al., 2004). In such a case, the strike-slip component is subordinate to the compressional one. Similar configurations are widely known from the North Sea region (see examples from Buchanan and Buchanan, 1995), the Atlas foreland (Letouzey, 1990; Lowell, 1995), the western and central Argentina (Uliana et al., 1995) and the Pyrenees foreland (Bond and McClay, 1995; Guimera et al., 1995);
3. the interaction among pre-orogenic (approximately N-S oriented, extension-related) and orogenic (approximately ESE-WNW oriented, compression-related) faults could eventually play a key role in controlling the localization of arc-shaped fronts in the Mesozoic-basement rock package, namely the Ferrara arc (Fig. 4a). In this case, together with the carbonate facies distribution (Fig. 4a–b), fault interference would control the development of lateral ramps, tear-transfer zones and some possible differential displacement inside the thrust-related

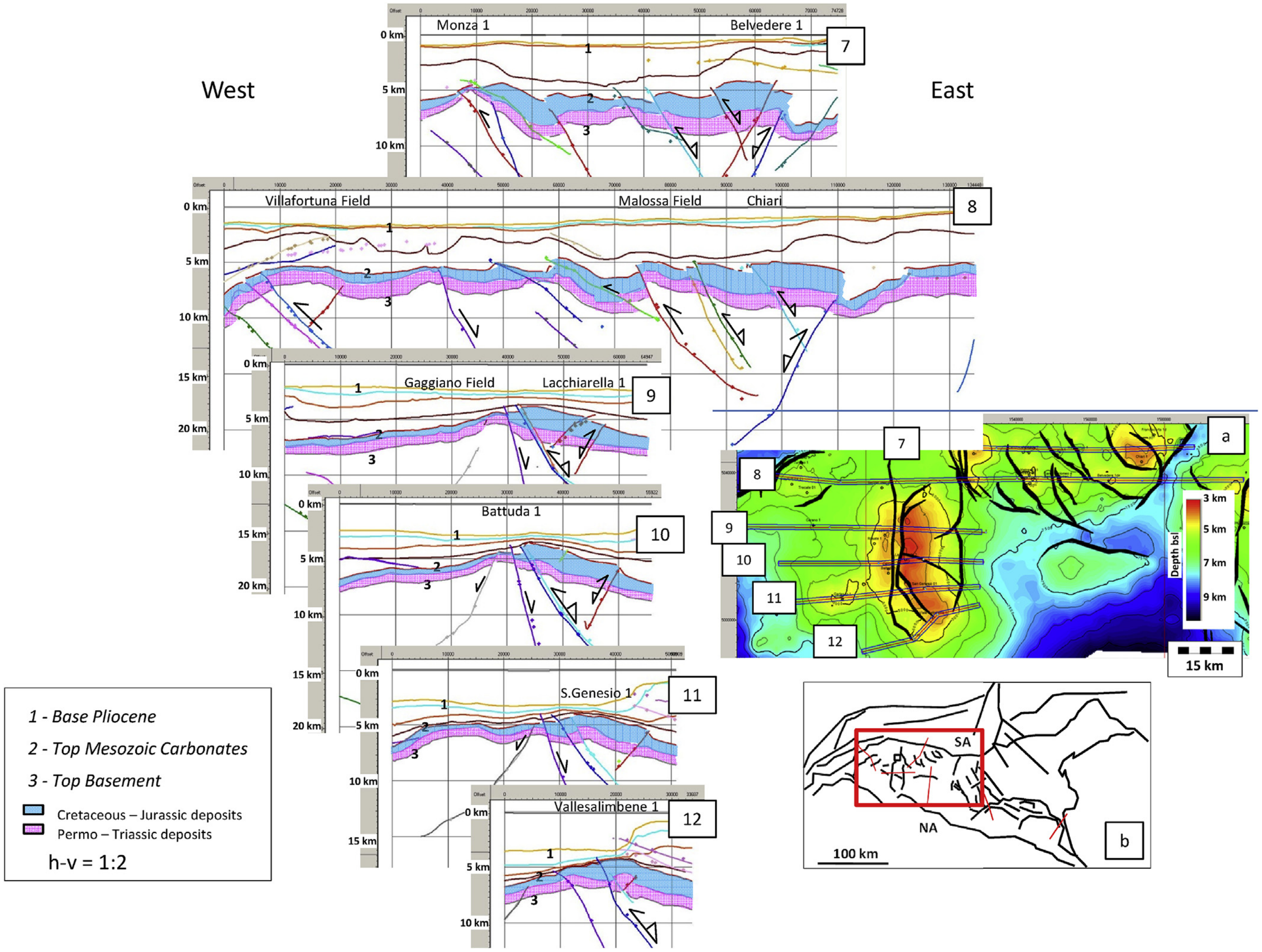

Fig. 12. Serial cross-sections illustrating the present-day structures in the western and central Po Valley: fault colour-code derives from correlation criteria only, during interpretation in the Kingdom software (see arrows for main fault kinematics: normal, reverse, inverted); a) Cross-section location on the top Mesozoic carbonate depth map (black polygons are faults); b) study area location in the Po Valley region. The structure and the cross sections are discussed in Section 4.3.

units of the structural arc (Ravaglia et al., 2006; Doglioni and Carminati, 2008; Bonini et al., 2014; Vannoli et al., 2015 and references therein), similar to what has been reported for instance in the Taiwan foreland (Lacombe et al., 2003);

4. bends in the extensional fault patterns, on map view, might have localized releasing-restraining deformation zones (Figs. 4 and 15) (Letouzey, 1990; Lowell, 1995);
5. during the Paleogene, given the distance of the Po Valley foreland from the Alpine orogeny (Fig. 16a: more than 100 km?), localized fault reactivation and basin inversion (Bernoulli et al., 1990, Bertotti et al., 1998, Fantoni et al., 2004, Cuffaro et al., 2010) were likely responding to some intra-plate deformation in response to far-field stress transmission. Such a situation is similar to a multitude of positive inverted features that can be mapped 100-to-1000 km away from the Alpine suture (Ziegler, 1989 and various examples from Buchanan and Buchanan, 1995);
6. in Miocene times, thrusting and pre-compressional fault reactivation might have equally contributed to the Po Valley regional basin inversion because of a relative proximity of the foreland to the Southern Alps and the Northern Apennines chains (Fig. 16b);
7. since the Pliocene, thrusting is the primary deformation mechanism across the foreland units (Castellarin et al., 1985). This is especially striking along the southern sectors of the basin where the foreland domain becomes the regional footwall of the Northern Apennines front (Fig. 16c), as suggested by the earthquake occurrence across the Ferrara tectonic arc (Bonini et al., 2014; Carannante et al., 2015; Turrini et al., 2015 and references therein). During this period, post-Mesozoic, likely flexure-related faults (Fig. 10) were reactivated (WNW-ESE oriented, parallel to the Apennines mountain front?), short-cut geometries developed (Figs. 10 and 11) and inherited pre-Alpine faults were possibly re-used to form lateral ramps/tear-transfer zones inside the tectonic arcs (see discussion above).

5.1.3. - *Po valley tectonics and kinematics versus inherited lithospheric weakness*

As already mentioned, basin inversion inside the Po Valley region (and the associated foredeep migration) was locally enhanced or impeached by the facies and geometry distribution of the Mesozoic carbonate deposits across the foreland domains (Fig. 4b).

The whole process was eventually influenced by the strength and thermal state of the Po Valley/Adria lithosphere at the time of orogenic shortening as inherited from lithospheric stretching and heating during the Triassic-Liassic rift evolution. Such a generic

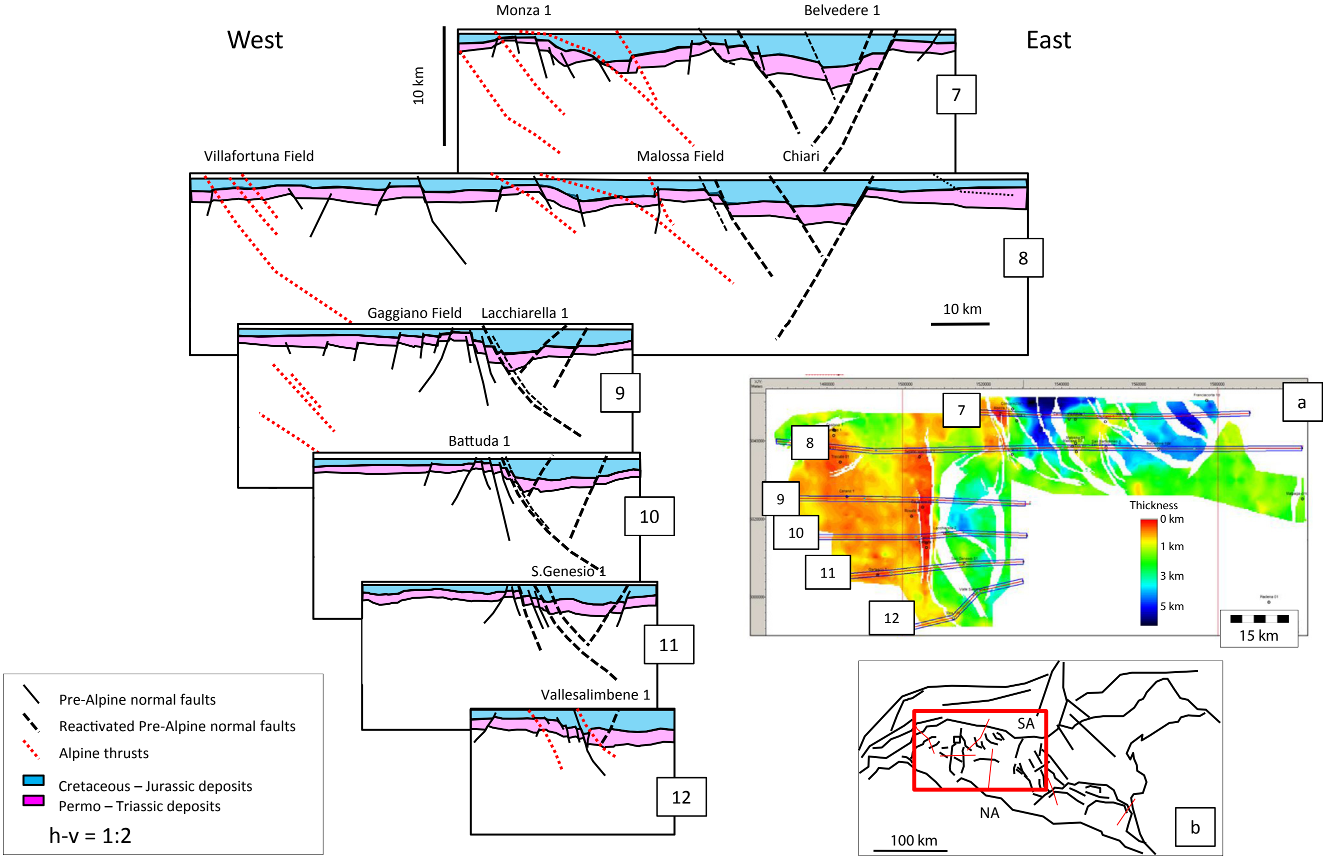

Fig. 13. Serial cross section of Fig. 11 after restoration of the structures at the top of Mesozoic. Pre-alpine normal faults, reactivated normal faults and Alpine thrusts have been distinguished in order to highlight the effect of the Alpine tectonic activity on a pre-existing inherited paleogeography; a) Cross-section location on the Jurassic-Cretaceous isopach map and fault polygons (in white); b) study area location in the Po Valley region. The structure and the cross sections are discussed in Section 4.3.

consideration is supported by theory (Cloetingh et al., 2005) and examples worldwide (e.g. Desegaulx et al., 1990; Mouthereau et al., 2013). Nevertheless, once the weak stretching of the crust during the Mesozoic events is considered (30-25 km of crustal thickness soon after the rifting? Fantoni and Scotti, 2003) together with the progressive thermal re-equilibration from Paleogene to present (e.g. heat flow values went back to a 'normal' 60 mW/m2 by the beginning of Cretaceous: Fantoni and Scotti, 2003 and references therein), we would speculate that both inherited crustal stretching and heating did not act as primary elements in controlling the Alpine structural evolution and the flexural response of the lithosphere within the Po Valley foreland-foredeep system.

5.2. *Considerations about the Po valley as a retro/pro wedge foreland basin*

Although foreland basins can be found all over the world in association with the development of ancient (pre-Cenozoic) and modern (Cenozoic) mountain ranges, rare are the situations that can be fully compared with the Po Valley foreland-foredeep tectonic system, in terms of interaction between the contributing belts and the derived tectono-stratigraphic complexity.

Indeed, from Cretaceous to present-day the Po Valley region was

1. the retro-wedge foreland basin to the Southern Alps; examples of similar setting include the Andean basins, the Pyrenees-Aquitaine basin, the late Mesozoic to Cenozoic Rocky Mountain basins of North America, the Appalachian basin (e.g., Garfunkel and Greiling, 2002; Ziegler et al., 2002; McQuarrie et al., 2005; Naylor and Sinclair, 2008),
2. possibly the simultaneous retro/pro-wedge foreland basin to the Southern Alps and the Northern Apennines, respectively. This complex setting of a flexural basin trapped in between two convergent orogenic fronts would compare with the Roja through (northern Spain), that is the common foreland of western Pyrenees and Cameros-Demanda Massif, the Adriatic sea (between Apennines et Dinarides-Albanides), the Assam basin (northeastern India) between SE verging Himalaya thrust and NW verging fronts of the Assam-Arakan belt, and the Maracaibo basin between Caribbean belt, Andes de Merida and Sierra de Perija (e.g., Muñoz-Jiménez and Casas-Sainz, 1997; Norman Kent and Dasgupta, 2004; Mann et al., 2006; Fantoni and Franciosi, 2010).
3. the pro-wedge foreland basin to the Northern Apennines, a setting to be compared to the Atlas basin, the Uralian basin, the Ebro basin of the South Pyrenees, the Carpathian basin and the coastal Plain of Taiwan: Maţenco et al., 1997, 2003; Ziegler et al., 2002; Lin and Watts, 2002; Tensi et al., 2006; Oszczypko, 2006; Naylor and Sinclair, 2008).

As the various basin-type systems progressively developed through the Tertiary, the related depozones (De Celles and Giles, 1996) were formed mainly in response to the surrounding geodynamics (Fig. 16).

The Paleogene, Southern Alps-related retro-wedge foreland basin was likely (exclusively?) controlled (Ziegler et al., 2002) by the topographic load of the orogenic wedge and a moderate flexure

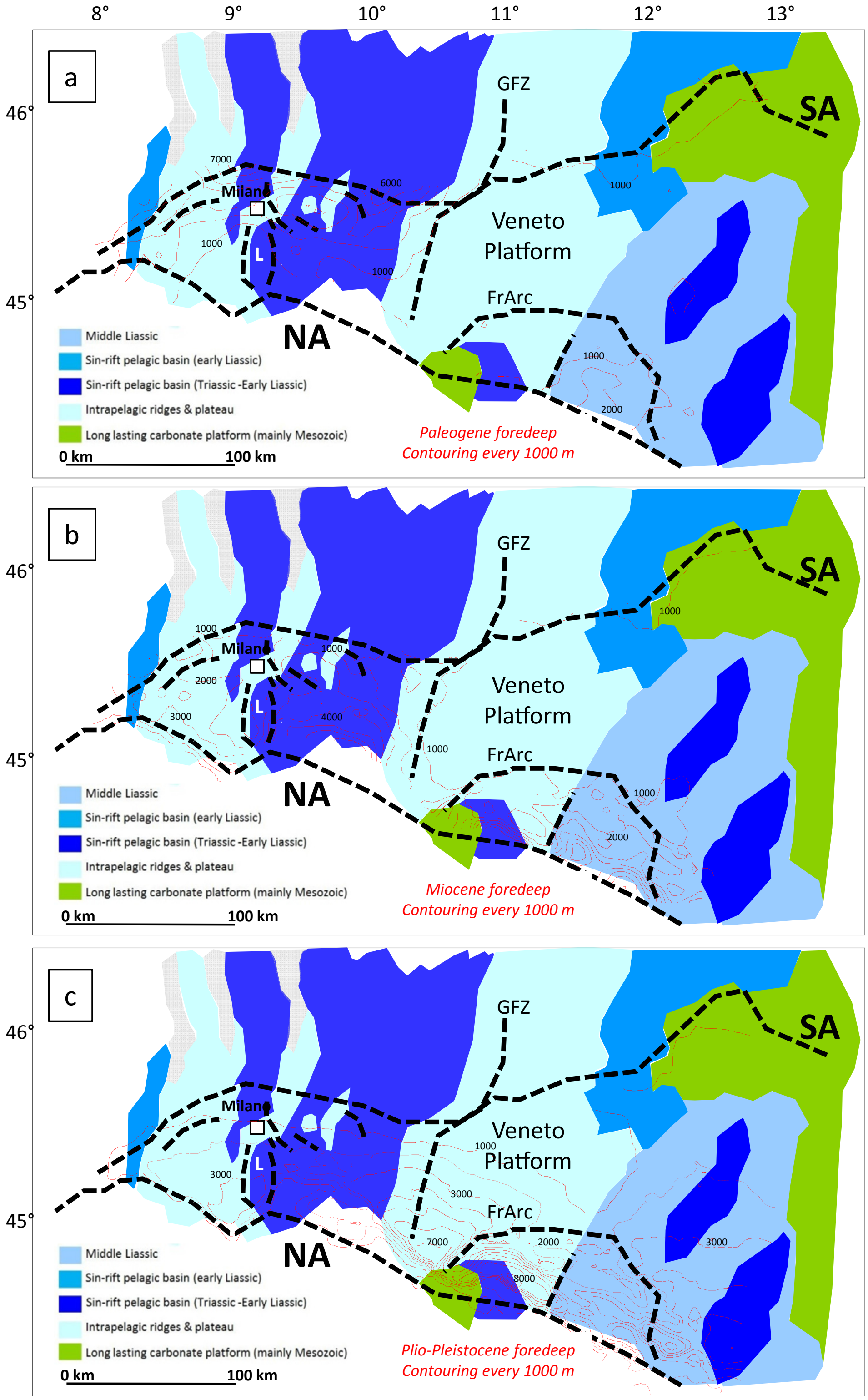

Fig. 14. Foredeep geometry against the simplified present-day, top Mesozoic tectonics (black dashed lines; see Fig. 3a for the complete fault pattern) and the main tectono-stratigraphic unit distribution (from Fig. 4b). Contour lines of the foredeep are represented in red (every 1000 m) respectively for Paleogene (a), Miocene (b) and Plio-Pleistocene (c) times. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of the Adria lithosphere. From the performed model, the associated foredeep could fill a variable accommodation space 30–50 km wide and 1–6 km thick along the segmented belt (Figs. 5a and 15a). Also clearly illustrated by the modeled top Oligocene foreland-foredeep map, the Mesozoic carbonates units provided a differentiated forebulge depozone (region of potential flexure uplift with possible reduced sedimentation; DeCelles and Giles, 1996), by abrupt, W-to-E lateral changes in the carbonate mechanical stratigraphy and inherited geometry of the pre-Alpine structures (see section 5.1). The anomaly B already described SE of the basin (Figs. 5a and 16a)

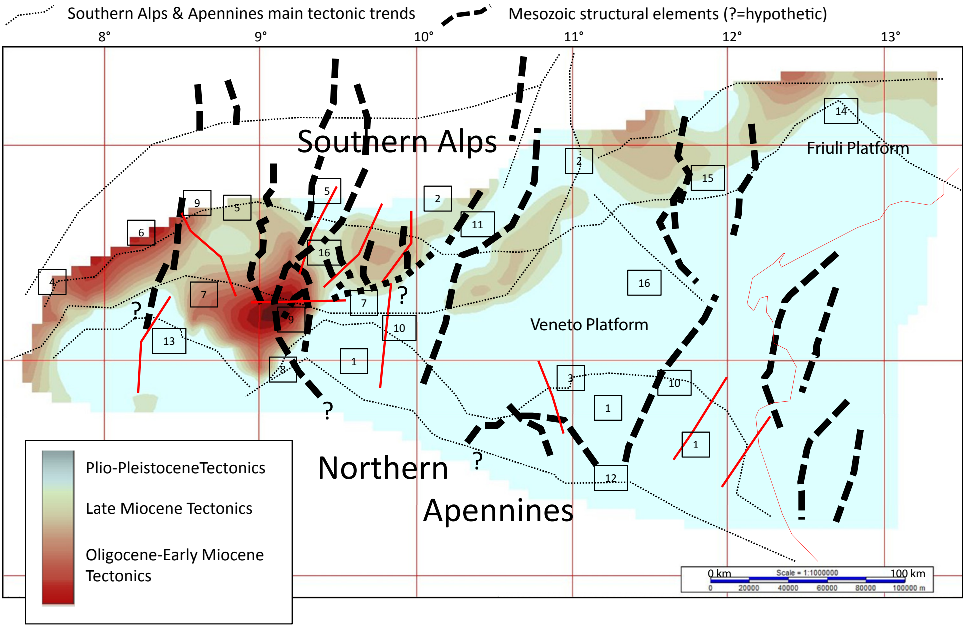

Fig. 15. Deformation-time map illustrating the timing of the main stages of the tectonic evolution of the Po Valley (red Oligocene-Early Miocene to grey Plio-Pleistocene): black thick dashed lines are main pre-Alpine Mesozoic lineaments; black thin dashed lines are main Alpine-Apennine lineaments. Cross-sections traces described in previous pictures and in the text are also indicated by thin red solid lines. Numbers refer to key papers which have been used for adding deformation timing-points for final gridding: 1) Castellarin et al., 1985; 2) Doglioni and Bosellini, 1987; 3) Nardon et al., 1991; 4) Roure et al., 1990; 5) Schonborn, 1992; 6) Greber et al., 1997; 7) Bello and Fantoni, 2002; 8) Benedetti et al., 2003; 9) Fantoni et al., 2003, 2004; 10) Toscani et al., 2006, 2009; 11) Livio et al., 2009a; 12) Boccaletti et al., 2010; 13) Mosca et al., 2010; Ponton, 2010; 14) Masetti et al., 2012; 15) Bresciani and Perotti, 2014; 16) Pola et al., 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

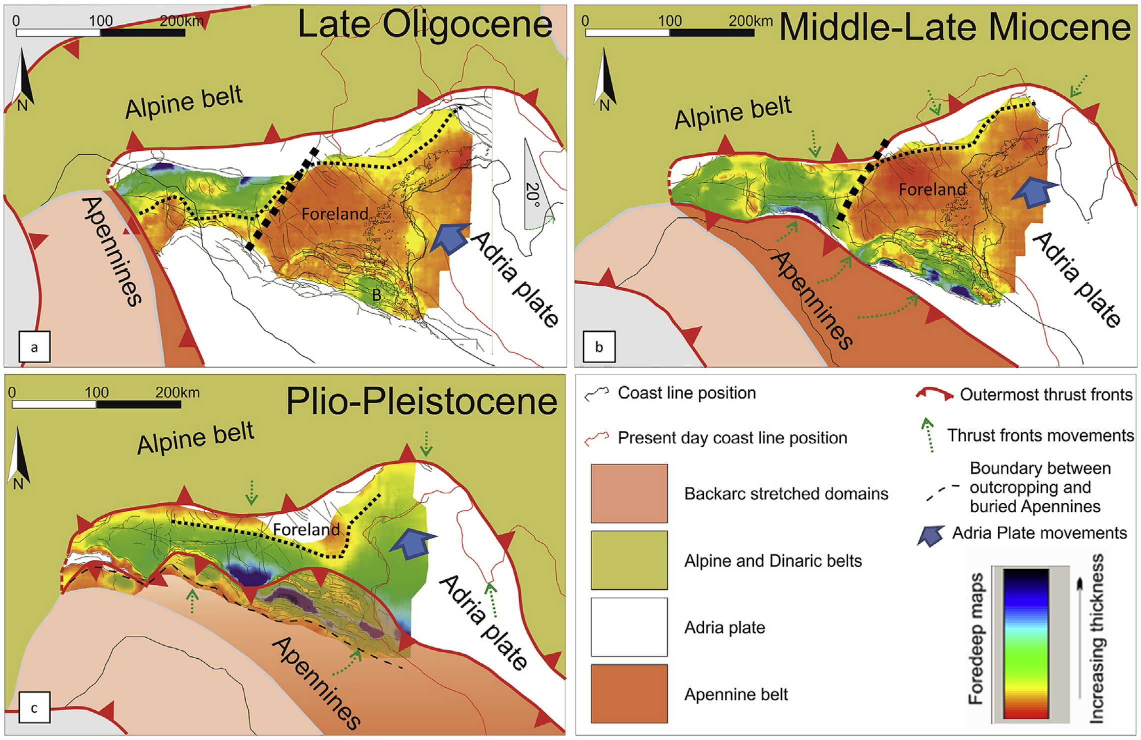

Fig. 16. —Po Valley foredeep geometry and basin migration (see maps in Fig. 5) against the Alps-Apennines geodynamic framework at a) Oligocene, b) upper Miocene and c) base Pliocene time (geodynamic framework modified after Carminati et al., 2012).

could eventually represent part of backbulge domain of the Paleogene foreland basin (could it be, alternatively, the backbulge of the Dinarides foredeep?). Mechanical coupling at crustal level (Ziegler et al., 2002) of the Southern Alps orogenic wedge with its retro-wedge foreland basin can be speculated during the Paleogene when the far-field inversion of the extension-related structures (Fig. 8) are considered.

The Southern Alps retro-wedge and the Northern Apennines pro-wedge foreland basins interfered with each other during the Miocene period (Fig. 16b). The progressive flexure and bending of the Po Valley-Adria plate below the Northern Apennines have possibly controlled the asymmetry of the overall foredeep sedimentary wedge which became thicker towards the south of the region. The associated wedge-top sediments deposited at the front of both the Southern Alps (on top of the Paleogene foredeep) and the Northern Apennines (Di Giulio et al., 2013; Rossi et al., 2015). The forebulge depozone is difficult to be defined yet it may be represented by the thin sediments which cover the east Po Valley foreland unit (Figs. 5b and 16b). No backbulge depositional areas can be recognized from the Miocene foreland-foredeep map (Figs. 5b and 16b). The thrust-related imbricates by low-angle detachments at the front of the Southern Alps (i.e. below the Lisanza structure on cross-section 1, Fig. 6) suggest mechanical coupling at upper-crustal levels (Ziegler et al., 2002) between the Southern Alps and the northern sectors of the foreland (i.e. the regional footwall to the belt). At the same time involvement of the basement by high angle thrusts (see the Villafortuna structure on cross-section 1, Fig. 6 and the Malossa structures on cross-section 2, Fig. 7) also indicate crustal mechanical coupling between the belts and the far-field foreland domain (Ziegler et al., 2002). The entire thrust-belt-foreland structure associations and the related deformation mechanisms suggest thick skinned tectonics (Lacombe and Bellahsen, 2016).

The Plio-Pleistocene configuration described in Figs. 5c and 16c represents the Northern Apennines pro-wedge foreland basin. The Adria lithosphere flexure controlled the basin geometry (Kruse and Royden, 1994; Doglioni, 1995; Carminati et al., 2003; Carminati and Doglioni, 2012) which is narrow and deep (50 km wide, max 7–9 km deep) (Fig. 16c; see also Fig. 5c). The associated equivalent elastic thickness would be in the order of 20 km (Watts, 1992; Mouthereau et al., 2013). The Pliocene sediments represent the main wedge-top depozone at the front of the Apennine belt. At the same time, the Plio-Pleistocene deposits constitute the foredeep deposits, these being thinning northwards. The forebulge depozone is definitively absent because of the short distance between the Southern Alps and the Northern Apennines mountain belts (Toscani et al., 2014). During this geological period mechanical coupling of the orogenic wedge with the foreland appears mainly restricted to upper crustal levels (Ziegler et al., 2002). In fact, all across the Northern Apennines tectonic arcs, folds and thrusts were mainly controlled by rheologically weak sedimentary layers, such as evaporites (Burano formation in the Ferrara arc; Cassano et al., 1986; Turrini et al., 2014, 2015 and references therein) and overpressured sandstones-shales intervals (Bosica and Shiner, 2013), these acting as stress guides and activated as detachment horizons. Subordinately, crustal mechanical coupling between the belt and the far-field foreland, hence involvement of the basement, may be loosely inferred from the deep earthquakes distribution in the eastern domain of the Po Valley exclusively (Vannoli et al., 2015; Carannante et al., 2015; Turrini et al., 2015).

6. Conclusions

The Po Valley developed as the nearly simultaneous pro/retro-wedge foreland basin to the Southern Alps and the Northern Apennines, respectively.

By implementing the available 3D structural model with some new grid horizons within the Tertiary succession we have provided the possible geometry and migration of the related foreland-foredeep tectonic system from Oligocene to present-day.

The final 3D model reconstruction and the 2D restoration across selected structural domains illustrate the following conclusions:

1. the Mesozoic, extension-related tectonics and the associated carbonate facies geometry and distribution have strongly controlled the Alpine structures inside/around the basin;
2. their control on the Cenozoic deformation and sedimentation is evident during the Paleogene and the Miocene whereas it becomes more subtle during the Plio-Pleistocene;
3. indeed, basin inversion and reactivation (with undefined strike-slip component) of pre-Alpine faults (approximately N-S oriented) intermittently occurred during the Paleogene and Miocene, when crustal mechanical coupling between the belts and the foreland enhanced intra-plate deformation, far from the advancing orogens: thick skinned tectonics was then dominant across the belt-foreland system;
4. in this period, flexure of the Po Valley/Adria plate was responding initially (Paleogene) to the Southern Alps growth and lately (Miocene) to the Northern Apennines development also, leaving room for the associated foredeep basin deposition;
5. in Plio-Pleistocene times the presence of a narrow and deep foredeep at the front of the Northern Apennines refers to a clear asymmetry of the Po Valley/Adria flexure;
6. Plio-Pleistocene deformation of the foreland mainly occurs at the external front of the Northern Apennines by thrusting, with local inversion-reactivation of both flexure-related faults (approximately WNW-ESE oriented) and pre-Alpine discontinuities (approximately N-S oriented): a) the two fault families compete to form tectonic arcs in the Mesozoic section, b) thin-skinned tectonics prevails across the eastern Po Valley foreland domain, c) involvement of the basement in that region is possible yet still debatable;
7. the narrow and deep Plio-Pleistocene foredeep basin all along the front of the Northern Apennines suggests that a) the foreland flexure is rather homogeneous below the belt, b) the N-S oriented lithospheric weaknesses derived from the Triassic-Liassic extensional tectonics do not exert a major control on the crustal deformation of the subducting Po Valley-Adria plate (possibly due to a weak amount of pre-orogenic extension together with a re-gained thermal equilibrium since the Triassic-Liassic rifting).

Once all elements are considered (differential bending of the Po Valley-Adria lithosphere below the two belts, intermittent and variable rate and direction of shortening ahead of the belts, highly differentiated mechanical stratigraphy and non-homogeneous geometry/dimension of the pre-compressional foreland units, variable sedimentation rates along the belts), the geological complexity of the region stands out as a real challenge for integration of all available data and interpretations.

As a follow-up to the 3D structural model (Turrini et al., 2014) and the 3D seismo-tectonic model of the basin (Turrini et al., 2015), this study provides a quantitative, kinematically and geometrically consistent picture of the Po Valley foreland-foredeep evolution at the basin scale: this represents a true novelty, so far missing in the regional literature.

Beyond the explicit regional implications, despite the necessary simplifications of the model and notwithstanding the related uncertainties, this case study can serve as a source of inspiration in terms of both scientific thinking and working methodology for other complex foreland basins worldwide, especially those where tectono-sedimentary inhomogeneity is spatially and temporally dominant and lateral structure correlation is complex and debatable owing to the lack of clear seismic data.

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