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Present-day 3D structural model of the Po Valley basin, Northern Italy

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A B S T R A C T

A 3D structural model of the Po Valley basin (Northern Italy) was built by integrating the dataset available from the public domain (DEM, wells, isobath-maps, cross-sections, outcrop-trends).

The model shows the complex foredeep-foreland architecture across the basin, from the Moho level to the topography while illustrating the top Basement, top Triassic, top Mesozoic and base-Pliocene surface-grid structures.

The results, by model slicing and isopach-map reconstruction, suggest that the deep Moho architecture and the original tectonics of the ancient Adria-Po Valley passive continental margin are key factors in controlling the current structures type, orientation and distribution, at any of the shallowest levels across the basin. In particular, the analysis of the final 3D Mesozoic geometries against the pre and post-Alpine trends confirms the structural interference between the mutually perpendicular Triassic–Jurassic extensional structures and the Tertiary compressional ones, this being evident from the regional to the oil-field scale.

Despite the model uncertainty, mainly related to its dimension versus the original non-homogeneous dataset quality and distribution, the final geo-volume offers, for the first time in the region, a continuous three-dimensional visualization of the Po Valley tectonic architecture. It provides, simultaneously, a powerful tool for the reviewing of the basin structures and the potential support to future applications for both industry and academia.

1. Introduction and aims to the study

3D models bring fundamental constraints to the analysis of geological structures. Indeed, a 3D structural model is made of geological interfaces such as horizons and faults honouring available observation data. Anatomical visualisation, model building, model slicing and block-restoration are only a few among the functions that can be performed once a 3D volume is obtained. As software dedicated to 3D structural modelling have spread out on the market (http://www.3d-geology.de/software/geology_and_mining), the technique has become a standard procedure inside the geological community, with main applications to oil and gas fields (Mitra and Leslie, 2003; Turrini and Rennison, 2004; Dischinger and Mitra, 2006; Mitra et al., 2005, 2007; Valcarce et al., 2006; Turrini et al., 2009; Lindsay et al., 2012; Vouillamoz et al., 2012; Shao et al., 2012 and reference therein), groundwater aquifers (Berg et al., 2004 and references therein) and ore deposits (Han et al., 2011 and references therein). Although a complete review of the literature on the subject is beyond the scope of this paper it could be worthy to mention some major references with respect to selected geological domains of research.

a) 3D model building of geological structures: Caumon et al. (2009) present general procedures and guidelines to effectively build a structural model made of faults and horizons from sparse data;
b) Outcrop Geology: the British Geological Survey (Leslie et al., 2012) recently published an astonishing and interactive three-dimensional reconstruction of the Assynt Culmination, in the Moine Thrust Belt of NW Scotland (http://www.bgs.ac.uk/research/ukgeology/assyntCulmination.html);
c) Hydrocarbon Exploration: Mitra and Leslie (2003), Dischinger and Mitra (2006), Mitra et al. (2005, 2007) used 3D structural models to review and validate different oil fields in Algeria, the USA and Mexico;

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d) Sand-box models reconstruction: Guglielmo et al. (1997), McClay and Bonora (2001), built 3D structural models from sand-box (and silicone) geometries about salt tectonics and strike-slip tectonics, respectively;
e) The Alps: Vouillamoz et al. (2012) built a 3D model of the Western Alps, from the Jura to the Northwest, up to the Bergell granite intrusion and the Lepontine Dome to the East and limited to the South by the Ligurian basin;
f) Italian 3D geology: The Geological Survey of Italy, in collaboration with the Institute of Environmental Geology and Geoengineering and the Department of Earth Sciences of Sapienza University–Rome (D'Ambrogi et al., 2010), promoted the development of a three-dimensional environment where selected crustal and subcrustal-scale structures for the Italian region can be displayed, modelled and retrieved.

Despite the abundance of public data, mainly derived from the hydrocarbon exploration, and certainly because of their great inhomogeneity in terms of quality and distribution, the three-dimensional reconstruction of the Po Valley basin is still a task that has never been tackled so far.

Given such a unique technical challenge, this paper presents for the first time a 3D model of the Po Valley structural and hydrocarbon province from the Moho surface, 30 km deep on average below the mean sea-level, to the topographic level, while especially focussing on the top Mesozoic geometries. Major aims of the study, as part of an in-progress PhD research, are: a) to integrate the available non-homogeneous dataset into a homogeneous and geometrically coherent 3D geo-volume, b) to visualize and validate the three-dimensional crustal architecture of the area, c) to analyse the resulting structures by comparing the deep geometries with the shallow ones, d) to demonstrate how the inherited Triassic–Lower Jurassic tectonics likely controlled the present-day structural architecture (Mariotti and Doglioni, 2000; Ravaglia et al., 2006; Cuffaro et al., 2010; Fantoni et al., 2004) e) to provide a solid and geometrically consistent framework for future industry and academia applications.

2. Geological setting

The Italian peninsula is defined as the result of complex geodynamics where both pre-alpine (Mesozoic and pre-Mesozoic) and alpine (mainly Cenozoic) tectonics have interacted through time to create the current, high-complex structural and stratigraphic puzzle (Elter and Pertusati, 1973; Laubscher, 1996; Castellarin, 2001; Castellarin and Cantelli, 2010; Cuffaro et al., 2010; Mosca et al., 2010; Carminati and Doglioni, 2012 and reference therein). Within the derived geological setting (Fig. 1), the Po Valley represents the north-westernmost buried sector of the Apulian indenter (or Adria plate: Channell et al., 1979; Dewey et al., 1973; Dercourt

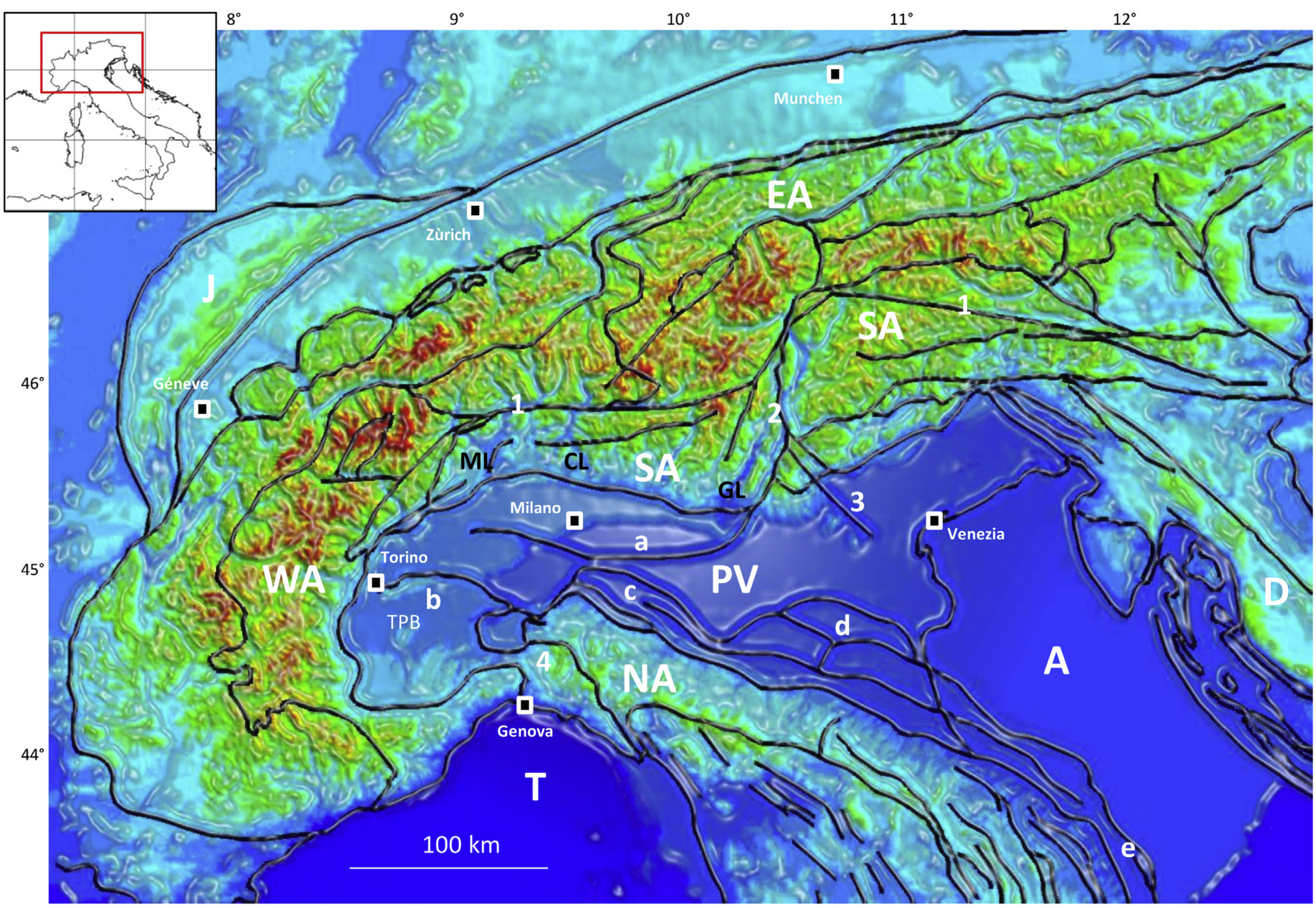

Figure 1. Digital topography and tectonic framework (from Nicolich, 2010) around the Po Valley region. (PV) Po Valley; (SA) Southern Alps; (NA) Northern Apennines; (WA) Western Alps; (EA) Eastern Alps; (D) Dinarides; (J) Jura Mountains; (A) Adriatic; (T) Tyrrhenian; (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line; (a–e) buried thrust fronts: a = Milano Thrust Front; b = Monferrato Thrust Front; c = Emilian Thrust Front; d = Ferrara-Romagna Thrust Front; e = Ancona Thrust Front. Tpb = Tertiary Piedmont Basin. ML = Maggiore Lake; CL=Como Lake; GL = Garda Lake. Latitude and Longitude values are North and East of Greenwich. Grid in the insert map is 500 km.

et al., 1986), the foreland-foredeep domain to the Alpine and Northern Apenninic belts and one of the major hydrocarbon provinces of continental Europe. The basin covers an area of approximately 50,000 km^2, it is geologically caught between the Alps, to the west and the north, and the Northern Apennines, to the south. Towards the east, the Po Valley sedimentary formations and structures gradually sink into the Adriatic domain as the topographic surface passes below the sea level.

Across the region, the structural geometries mainly refer to the external domains of the Southern Alps and the Northern Apennines (see Fig. 1) and intervening foreland, those belts creating outstanding tectonic arches while controlling the sediment infilling of the respective foredeep-basins (Pieri and Groppi, 1981; Cassano et al., 1986; Castellarin et al., 1985; Carminati and Doglioni, 2012; Argnani and Ricci Lucchi, 2001; Bartolini et al., 1996; Bertotti et al., 1997; Castellarin and Vai, 1986; Perotti, 1991; Perotti and Vercesi, 1991; Ricci Lucchi, 1986). Sedimentary successions (Fig. 2) encompass broadly Mesozoic carbonates through and dominantly clastic Cenozoic deposits, the whole sedimentary pile sitting on a crystalline basement essentially made of metamorphic rocks of Hercynian age. Most of the tectonic features were initially related to Upper Triassic–Lower Jurassic extension, with local evidence for Cretaceous to Paleogene structural inversion, followed by later Miocene–Pliocene compression affecting the foreland and the surrounding orogenic belts. Indeed, the tectonic history of the region likely started at the end of the Paleozoic and is still going on as accounted by recent studies and the latest earthquake-activity in the central and eastern parts of the basin (Burrato et al., 2003; Carminati et al., 2003, 2010; Toscani et al., 2006, 2009; Picotti and Pazzaglia, 2008; Livio et al., 2009; Di Bucci and Angeloni, 2012; Michetti et al., 2012; Maesano et al., 2013). In Triassic times (Jadoul et al., 1992), extension took place so that the Adria microplate, as part of the northern Africa carbonate-platform realm (Channell et al., 1979), was deformed by a rifting phase characterized by broad NS and EW trending faults generating horsts and grabens. During the Lower Jurassic (Bertotti et al., 1993; Fantoni et al., 2004), a renewed phase of crustal extension led to a structural fabric made up of half-grabens and ridges, mainly elongated along the NE–SW direction. Sedimentation of the carbonates kept pace with such tectonics so that shelf, marginal and basin type

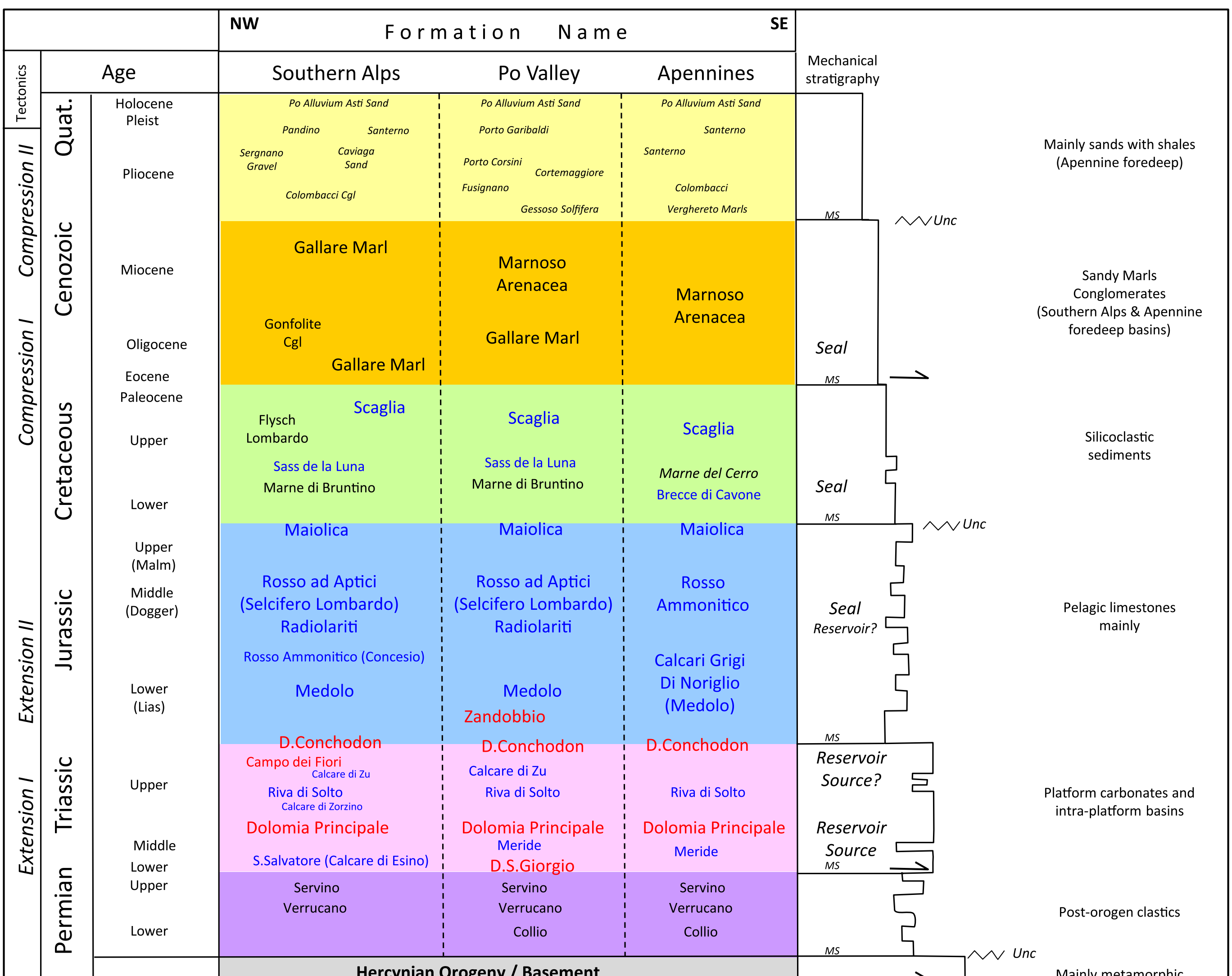

Figure 2. Schematic stratigraphic column of the Po Valley basin (modified from Lindquist, 1999; Casero, 2004). MS = major seismic event; unc = major unconformity. Only the hydrocarbon system related to the Mesozoic oils is described. Major detachment levels are suggested across the mechanical stratigraphy. Formations in blue are mostly limestones. Formations in red are mostly dolostones. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

deposits developed all through the region. Contraction of the Triassic–Lower Jurassic rift related structures was produced by late Cretaceous inversion tectonics with reactivation of some of the existing normal faults (Dal Piaz et al., 2004; Schmid et al., 2004). Later on, during the Miocene and Pliocene, the basin architecture evolved to become the foreland of the advancing fold-and-thrust belts from the Alps and the Apennines, while the Mesozoic rocks became deeply buried beneath Neogene clastics in the related foredeeps (Trumpy, 1973; Fantoni et al., 2004).

Since the end of the 19th century (Pieri, 1984) both gas and oil have been locally produced from a number of fields in the Po Valley, of which the Villafortuna-Trecate field (discovered in 1984 by ENI, 30 km west of Milan) has been, by far, the most successful (with 240 MMbbls from a Triassic carbonate reservoir). Hydrocarbons are trapped at different stratigraphic levels, with the deep Mesozoic carbonates (3000–6000 mbsl) representing the preferential target for oil exploration. Instead, the arenaceous intervals, of Miocene, Pliocene and Pleistocene age, are principally drilled for shallow (1000–3000 mbsl) gas accumulations, thermogenic and biogenic in origin. Remarkably, a large part of the geological knowledge in the region is related, directly or indirectly, to the oil business (Errico et al., 1980; Pieri and Groppi, 1981; Pieri, 1984; Bongiorni, 1987; Cassano et al., 1986; Mattavelli and Novelli, 1987; Mattavelli and Margarucci, 1992; Casero et al., 1990; Nardon et al., 1991; Lindquist, 1999; Bello and Fantoni, 2002; Fantoni et al., 2004). In particular, thanks to the extensive exploration activity performed in the period between 1960 and 2000, namely several exploration wells drilled to a total depth in the range of 3000–7000 m (e.g. Villafortuna-Trecate, Gaggiano, Malossa, Cavone, Assunta; see Fig. 3a for deep wells' name and distribution) and new modern 2d–3d reflection surveys, the buried structures of the Po Valley and the related hydrocarbon systems have been eventually described and

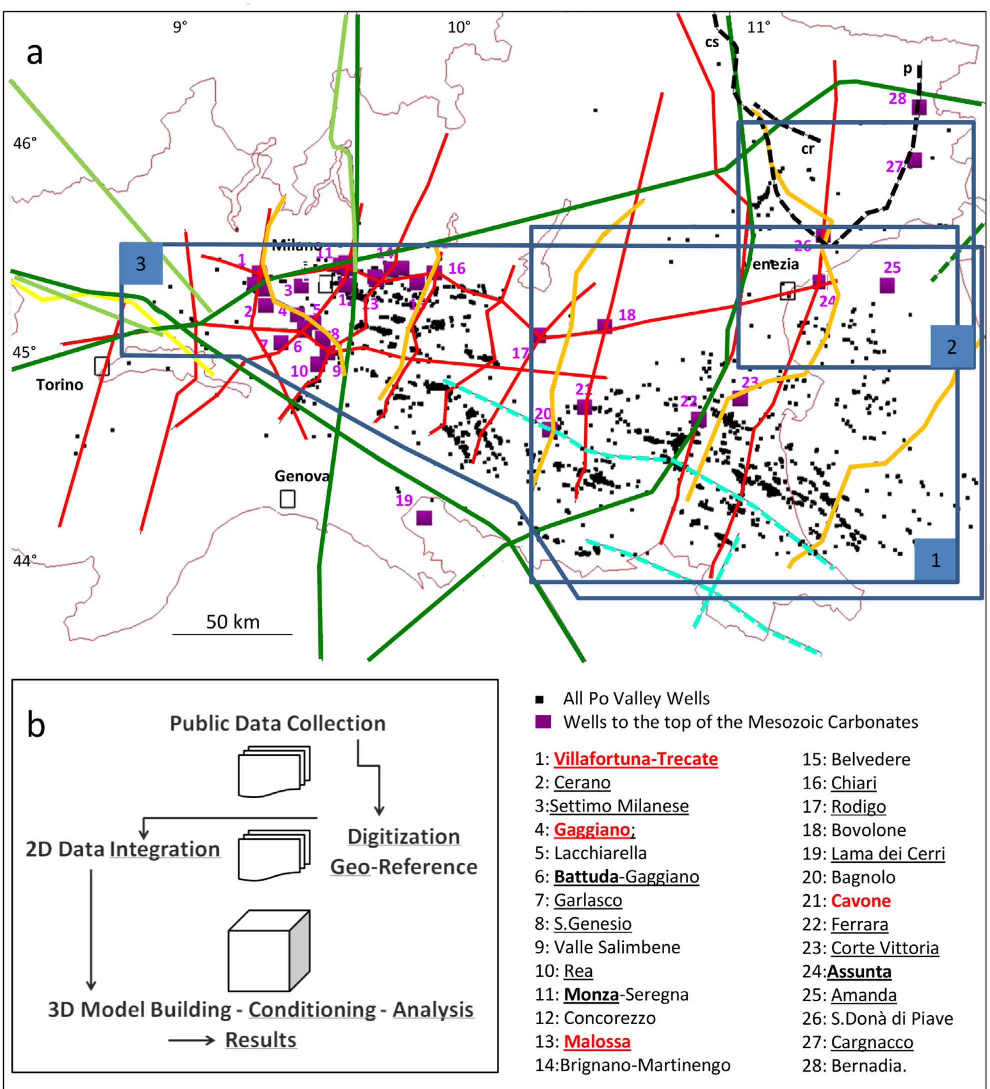

Figure 3. (a) Data distribution: cross-sections available from the public literature and wells (http://unmig.sviluppoeconomico.gov.it/unmig/pozzi/completo.asp; http://unmig.sviluppoeconomico.gov.it/videpi/kml/webgis.asp). In the well list: red = fields; bold black = wells drilling down to the Po Valley 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., 1991; light-blue set from Boccaletti et al., 2010; black set from (cs) Castellarin et al., 2005, (cr) Casero et al., 1990 and (p) Ponton, 2010. 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. Latitude and Longitude values are North and East of Greenwich. (b) Workflow for the 3D model building process and analysis. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

revealed to the scientific community. Through recent times, academia has provided a conspicuous literature on various subjects about the geology of the region. Livio et al. (2009) analysed the active structures of the Central Po Valley (east of Milan) by integration of seismic and seismicity. Boccaletti et al. (2010) published their results about the Quaternary morpho-tectonics of the central-eastern Po Valley, all along the external zone of the Northern Apennines. Mosca et al. (2010) discussed the structures and the kinematics of Western Po Valley with particular reference to the Tertiary Piedmont Basin region (SE of Torino). Cimolino et al. (2010) produced a top Mesozoic Carbonate depth map of the eastern Po Valley (south of Grado) while describing the interaction between the Dinaric deformation front and the offshore extension of the Po Valley foreland domain. Among the different papers and provided the dimension of the performed 3D modelling, the latest reviewing of the Adria Moho architecture presented by Nicolich (2010) is an important reference to this study. In fact, the related images and interpretative models reveal the crustal characteristics of the different units by their geophysical prospecting signatures (gravity, receiver functions, wide-angle seismic and vertical reflections). Such a review follows and updates a number of works dealing with the crustal anatomy of the Po Valley as part of the Alps–Apennines system: Roeder (1991) is likely the only author who attempted, so far, to build some contour maps of the tectonic units which model the Po Valley Moho and the neighbouring regions. Those maps are supported by key crustal-scale cross-sections which show the complexity and variability of the present crustal architecture. Roure et al. (1990) reported and used the results from the ECORS-CROP deep seismic profile to provide constraints on the post-collisional Alpine evolution and the associated early Miocene deformation beneath the western Po Valley. Schumacher and Laubscher (1996) discussed the possible 3D crustal architecture of the Alps–Apennines junction by reviewing selected seismic images and cross-sections presented by Pieri and Groppi (1981) and (Cassano et al. 1986). Compilations about the Moho crustal anatomy are also presented by Dézes and Ziegler (2004), Dézes et al. (2004) and Tesauro et al. (2008). Noteworthy, Schreiber et al. (2008) discussed a 3D geometrical model of the Moho topography in the south-western Alps by combining gravity, seismic and seismological constraints. At a larger scale, Vignaroli et al. (2008) and Larroque (2009) discussed the role of the Adria micro-plate as part of the Alps–Apennines tectonic system while presenting some former 3D block-diagram about the derived tectonic junction and the related subduction puzzle. More recently Maino et al. (2013) addressed the Alps–Apennines tectonic junction issue, by field-based structural and stratigraphic investigations at the transition between the Tertiary Piedmont Basin (Tpb in Fig. 1) and the Ligurian Alps, approximately 40 year after the review of Vanossi et al. (1986).

Although the buried structural setting of the Po Valley is rather well described by the available literature, the studies about the structural kinematics remains vaguely regional (Castellarin and Cantelli, 2010) or they refer to selected areas (Castellarin et al., 1985; Zoetemeijer et al., 1992; Fantoni et al., 2004). At the same time, although a possible stratigraphic template of the basin has been proposed by Lindquist (1999) and recently reviewed by Casero (2004), the current knowledge about the distribution of sedimentary formations is mainly related to the information coming from the outcrops (Castellarin and Vai, 1982; Jadoul and Rossi, 1982; Bertotti et al., 1993; Fantoni et al., 2003; Doglioni and Carminati, 2008; Berra et al., 2009) and the exploration industry data and reporting (Pieri and Groppi, 1981; Cassano et al., 1986; Fantoni et al., 2004; Ghielmi et al., 2010, 2012). Finally, in terms of geochemical and thermal modelling across the basin, the works from Mattavelli and Novelli (1987, 1990), Mattavelli and Margarucci (1992), Fantoni and Scotti (2003) and Viganò et al. (2011) are so far the key references that can be quoted on the subject.

3. Data and methodology

The data used to build the performed 3D model (Fig. 3a) are strictly derived from the public literature and the archives of the Italian Ministry of Energy (http://unmig.sviluppoeconomico.gov.it, namely the ViDEPI project) (Table 1). As such they mainly refer to geophysical and geological maps, cross-sections, well composite logs and stratigraphic columns. No seismic or confidential data have been used so far. In order to achieve the integration of such heterogeneous type of data-sets, these have been geo-referenced to a common geographical system (Transverse Mercator) and systematically digitized to transform any selected image into its numerical CAD-type format. During the process, images had often to be graphically and spatially re-arranged to correct for a) the image data quality, b) some local distortion, c) errors in the original scale definition. Lines from cross-sections and contours from maps were made ready for gridding into meshes whereas the well-stratigraphic cuts were locally input as control-points. In case the integration of various sources was necessary, the preliminary surfaces, obtained by gridding of the original xyz source points, were cut by serial, vertical slices and the resulting intersection lines were reviewed and averaged into one single line solution before re-gridding of the definitive surface. Continuous iteration between the progressive 2D and 3D models allowed the final structures to be built, validated in terms of geometrical consistency and analysed.

The overall workflow (Fig. 3b), from data collection and integration, to model-building and the final model validation/analysis, has been performed using the MOVE commercial package (2d/3d MOVE by Midland Valley).

4. Model uncertainty

Provided the current model results and the available data source distribution (see Figure 3a) and quality, the following vertical and horizontal uncertainty has been defined for the various 3D model layers.

a) Moho: the surface-grid is essentially averaging the results from Roeder (1991) and CROP (2004). Vertical uncertainty is in the range of 5–10 km, increasing towards the western Po Valley domain and close to the front of the Southern Alps and the Apennines. The final model layer seems reliable at the crustal scale and it has been validated by comparison with a number of crustal sections from the literature (Roure et al., 1990; Roeder, 1991; Schmid and Kissling, 2000; Castellarin et al., 2005) (location in Fig. 3a);
b) Top Basement: the surface grid exclusively refers to the result from Cassano et al. (1986) which used seismic, wells (Monza, Battuda and Assunta; see location in Figure 3a) and grav-mag maps to tie their data interpretation. Our model layer mainly derives from contouring of their basement map which, however and for some unknown reasons, locally deviates from the cross-sections basement geometry. It follows that depth uncertainty in the final 3D model layer ranges between 500 and >2000 m (extreme western sector of the west Po Valley domain, below the Monferrato belt, and at the front of the Appennines to the SW of the Ferrara-Romagna arch) so that it appears strongly reliable at the crustal scale and moderate to low reliable at the structure-scale, away from the reference wells;
c) Top Triassic: the surface grid mainly relates to the cross-sections from Cassano et al. (1986; location in Figure 3a)

Table 1
Data used to perform the 3D model building and validation of the Po Valley basin.

3D model	Data source	Data type	Modelling phase
MOHO	Roeder, 1991	Contour maps	Model building
	Roeder, 1991	Cross-sections	Model validation
	CROP, 2004	Contour map	Model building
	Roure et al., 1990	Cross-section	Model validation
	Schmid and Kissling, 2000	Cross-sections	Model validation
	Castellarin et al., 2005	Cross-section	Model validation
	Nicolich, 2010	Contour map	Model validation
Top Basement	Cassano et al., 1986	Contour map	Model building
	Cassano et al., 1986	Cross-sections	Model building
	Cassano et al., 1986	Well Tops	Model building
	Fantoni et al., 2004	Cross-sections	Model validation
	Fantoni and Franciosi, 2010	Cross-sections	Model validation
Top Trias	Cassano et al., 1986	Cross-sections	Model building
	Cassano et al., 1986	Well Tops	Model building
	Fantoni et al., 2004	Cross-sections	Model validation
	Fantoni and Franciosi, 2010	Cross-sections	Model validation
	ViDEPI Project	Wells locations & Tops	Model validation
Top Mesozoic Carbonates	Cassano et al., 1986	Cross-sections	Model building
	Cassano et al., 1986	Well Tops	Model building
	Bigi et al., 1989	Fault Map	Model validation
	Casero et al., 1990	Contour Map & Fault Map	Model building
	Bello and Fantoni, 2002	Cross-section	Model validation
	Fantoni et al., 2004	Cross-section & Fault Map	Model validation
	Nicolai and Gambini, 2007	Depth Map	Model validation
	Boccaletti et al., 2010	Cross-sections	Model validation
	Cimolino et al., 2010	Contour Map	Model building
	Fantoni and Franciosi, 2010	Cross-sections	Model validation
	Ponton, 2010	Cross-sections	Model validation
	ViDEPI Project	Wells locations & Tops	Model validation
Base Pliocene	Pieri and Groppi, 1981	Contour Map & Fault Map	Model building
	Pieri and Groppi, 1981	Well tops	Model building
	Cassano et al., 1986	Cross-sections	Model validation
	Cassano et al., 1986	Well tops	Model validation
Outcrops	Bigi et al., 1989	Outcrops & Fault trends	Model building
Digital Topography	http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp	Grid	Model building

which have been originally tied to nearly all of the wells that have drilled the possible top Triassic in the Po Valley basin (see these well location in Fig. 3). Major uncertainty relates to lack of interpretation of the top Triassic in part of the original cross-sections. Within such blank areas (i.e. western sector of the western Po Valley, southern sector of the Emilia arch) the most-likely top Triassic has been drawn by 3D model building and consistency check with the top Mesozoic and Basement geometries, above and below it. The related structures have been further validated by comparison with cross sections from Fantoni et al. (2004), Fantoni and Franciosi (2010) and 2 recent wells available from the ViDEPI web-site (Rea 1 and S. Genesio 1; location in Figure 3a). The final model grid is fairly reliable at the crustal scale and moderate to low reliable at the structure-scale, away from the reference wells;

d) Top Mesozoic: data source to the 3D model layer have been (Fig. 3a), a) the cross-sections from Cassano et al. (1986), those being tie to wells, seismic and grav-mag maps, b) the depth contour map from Casero et al. (1990 – from the Adriatic to the Ferrara-Romagna arch included), c) the depth contour map from Cimolino et al. (2010) (in the Friuli onshore-offshore – NE of Venezia), d) cross-sections from Boccaletti et al. (2010). The resulting 3D model layer and the structure distribution have been locally validated by comparison with a) the maps of Fantoni et al. (2004 – fault trends) and Nicolai and Gambini (2007 – regional depth map of the possible Mesozoic Carbonates) and b) cross sections from Casero et al. (1990), Bello and Fantoni (2002), Fantoni et al. (2004), Boccaletti et al. (2010), Fantoni and Franciosi (2010), Ponton (2010). The final surface-grid seems reliable at both crustal and structure scale. Provided the source data robustness (the authors of the reference papers are often coming from the industry thus driving their interpretation by seismic and well information) and their distribution, the 3D model vertical uncertainty is generally in the order 100–500 m with increasing ambiguity towards the Southern Alps and Northern Apennines fronts;

e) Base Pliocene: the 3D layer is exclusively drawn from the base Pliocene depth map, published by Pieri and Groppi (1981) and tied to massive seismic and well data. The related 3D model surface has been then validated by comparison with a) the Cassano et al. (1986) cross-sections and well tops and b) contours and fault trends from the structural model of Italy by Bigi et al. (1989). Wells from the ViDEPI web-site have not been reviewed during the base Pliocene Layer 3D model building thanks to the very weak uncertainty in the data published by the above mentioned authors. The final 3D surface can be considered reliable at both the basin and structure scale. The possible ambiguity in the model geometries and depth could eventually relate to the grid-surface smoothing which had to be run for graphical needs;

f) Isopach-maps: uncertainty about such maps is a natural consequence of the uncertainty described for each of the model layers. Therefore the final sediment thickness distribution and variation illustrated by the model are generically to be considered as crustal scale information rather than detail description of the Mesozoic, pre-compression, basin paleogeography.

Conclusively, uncertainty in the performed 3D model is certainly scale dependent: being essentially a crustal-scale model, the more we go into the details, the larger the uncertainty. To such extent, a) cross-sections obtained from vertical slicing of the model volume have been conditioned by integrating results from the literature (see references in the related figures), b) smaller and more refined models of some selected structures have been built at the occurrence (e.g. see structures versus hydrocarbons case study at the end of chapter 7.7).

5. The Po Valley 3D structural model

The performed 3D model covers an area of 700 by 400 km (with a core area of approximately 10,000 km^2). It extends at depth to integrate the Moho discontinuity separating the crust from the lithospheric mantle (30–50 km bsl). From top to bottom, the model "layers" are the digital topography, the base of the Pliocene sediments, the top of the Mesozoic Carbonate succession, the "near" top of the Triassic succession, the top of the so called "magnetic basement" (Cassano et al., 1986) and the top of the mantle, (Moho). Given the dimension of the final model, faults and syn-tectonic sediments discontinuously occurring within the Oligo-Miocene units at the front of the Northern Apennines and Southern Alps have only been reviewed locally during the model vertical slicing and the related cross-sections building.

6. Model analysis

The geometrical analysis of the model has been mainly performed by a) visualization and rendering of the model structural layers, b) vertical-horizontal slicing to create key-geological sections and depth-slices and c) isopach-map building between some of the model layers. Those three operations enhanced the general understanding and analysis of the geological 3D framework and they allowed the final grids and structures to be checked for errors and inconsistencies, therefore validated.

The different structural maps have been coloured by depth, and, at the occurrence, put against the outcrops, the shallow buried faults and the well location. As such the comparison and the possible link between all of the geometries (deep and shallow) can be, hopefully, straightforward. At the same time the rationale of the past exploration strategy in the region can also be quickly inferred.

6.1. Model visualization

6.1.1. Structural geometries at the Moho grid-surface

The Moho grid-surface (Fig. 4) is the deepest level in the model. Regionally, the Po Valley Moho, or Adria Moho, appears to be domed in the axial-central domain. It is flexured towards the north, below the Alps, and the south, below the Apennines, and nearly exposed at the surface in the west, north of Torino. Across the derived crustal unit, clearly over-thrusting the European Moho towards the north, deformation increases from east to west so that two separate domains can be defined: the gently deformed Eastern domain and the highly deformed Western domain. Indeed, in contrast with the uniform Moho geometry of the Eastern Po Valley-Adriatic domain, the Western Po Valley Moho architecture shows a complex structural setting at the Alps–Apennines junction (circle area AAJ in Fig. 4). Here we observe the interference between a) the southern termination of some NE–SW oriented, NW verging, thrust-related-imbricates (see also cross-sections in Figs. 11b, 15b, 16b) and b) the north-western segment of a WNW–ESE oriented sub-Apennines anticline feature, verging towards the NE (see also cross-sections in Figs. 12b, 13b, 14b). Within such a framework, a possible NNE–SSW oriented, sinistral transfer zone should accommodate the relative displacement between those two derived structural sectors.

It is relevant to note that the Moho flexure at the front of the Apennines leaves room for the shallow structures (white fault

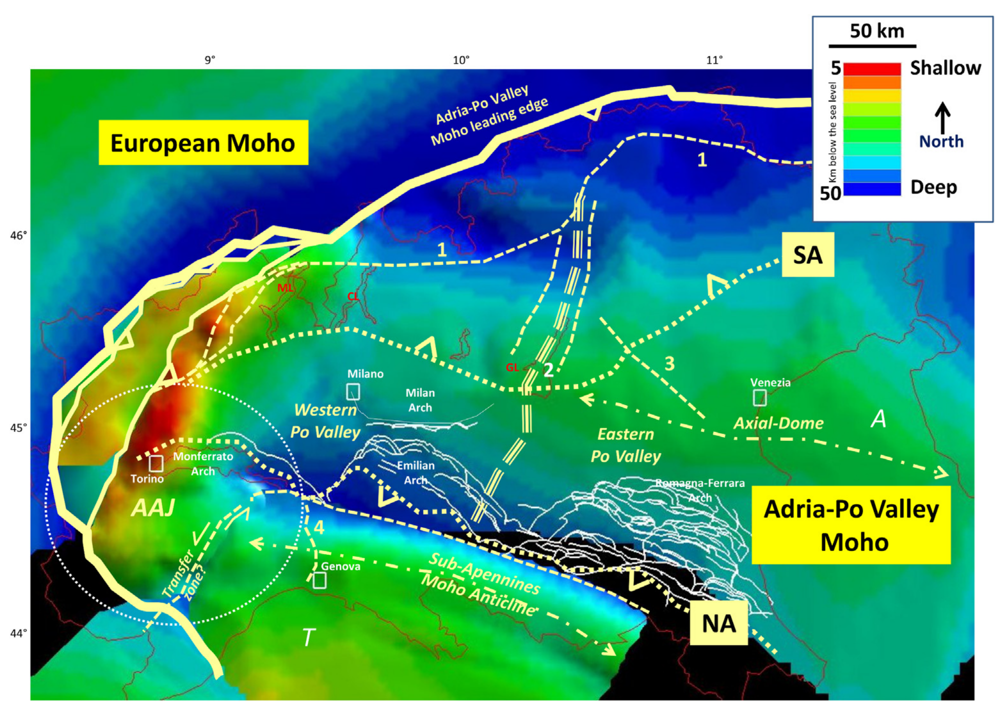

Figure 4. Structural geometries at the Moho grid-surface. Coast-line & northern Italy state boundaries in red. Large dashed segment is possible separation between western and eastern Po Valley domains. White lines are faults at base Pliocene level (Bigi et al., 1989). (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front; AAJ = Alps–Apennines Tectonic Junction (circle area). (A) Adriatic; (T) Tyrrhenian. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. ML = Maggiore Lake; CL = Como Lake; GL = Garda Lake. 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.)

pattern in Fig. 4). Conversely, no flexure of the Moho is shown at the South Alpine front.

Accordingly to the described structures, the depth of the final grid varies from 50 km to nearly 0 km below the mean sea level.

6.1.2. Structural geometries at the basement grid-surface

The top of the magnetic basement shows a generic structural conformity with the Moho geometry, as illustrated by Figure 5. As such, two major structural domains can be again defined: a) the western domain, deformed into a patchy, low-amplitude, high-and-low fabric and b) the eastern domain, mainly deformed by a large-amplitude crustal scale dome. Across the Po Valley, the basement depth increases from north to southwest reaching a maximum value of 17 km below the Apennine Chain. From the model, two large basement-related units appear to be part of the Northern Apennines arches (see Fig. 5, AB structural elements). Despite their evidence at the grid scale, no wells have drilled those units to prove their existence and constrain their tectonic significance.

6.1.3. Structural geometries at the "near" top Triassic grid-surface

The top Triassic surface-grid (Fig. 6) confirms the western and eastern Po Valley domains existence. At the local scale, the geometries of the western domain can be only guessed so that small highs and lows features appear, which could partly correspond to artifacts due to the data distribution (see Fig. 3a). In the eastern Po Valley, a regional anticlinal feature occurs on top of the basement dome (see Fig. 5) and it largely coincides with the Veneto Platform building. Such a structural element nearly comes to surface at the front of the Southern Alps, to the SE of the Garda Lake and it is recognized at depth by the Rodigo 1 well (well 17 in Fig. 3).

According to the depth model grid, the final Top Triassic unit (i.e. the main reservoir of the Po Valley deep play) is found at 3–15 km bsl, with regional dip towards the South, below the Apennines.

6.1.4. Structural geometries at the top of the Mesozoic carbonate grid-surface

The top of the Mesozoic carbonates (Fig. 7) is an extremely important surface. Infact, it is the top of the deep play for the hydrocarbon exploration in the region and the major seismic marker for the related structure interpretation (see Fig. 2). Depth values for the grid range from 0 to 11 km below the sea level according to the recognized structural architecture.

Once again, the western and eastern Po Valley domains can be immediately recognized also at this level. This confirms the tectonic pattern already observed at the Moho, at the basement and at Triassic level, as well as the geometrical conformity among the four model layers. In the detail, the Mesozoic carbonates of the western Po Valley (Fig. 8b) show dome-and-basin-types features, oriented parallel, oblique and perpendicular to both the Southern Alps and the Apennines mountain fronts. In the eastern Po Valley (see Fig. 7), the Mesozoic top surface is essentially modelled into a large dome, gently elongated in the NW–SE direction. To the south of such a regional feature, some thusted folds, oriented parallel to the Apennines, are shown. Those geometries can be enveloped into an arch where lateral-ramp, frontal-ramp and transfer structural elements can be recognized (Fig. 8c). In the NE corner of the Po Valley (i.e. the Veneto and Friuli domains) the interference between the Alpine and Dinaric tectonics is confirmed by the intersection of the related structural trends, WSW–ENE and NNW–SSE oriented, respectively.

6.1.5. Structural geometries at the base Pliocene grid-surface

This is the shallowest level of the 3D model below the topography and by far the most refined and structurally complex (Fig. 9). In reality, however, the final surface-grid defines a major unconformity across the entire Po Valley basin (bottom of the Pliocene–Quaternary sequence in Pieri and Groppi (1981); that is likely the Messinian unconformity). Therefore a) it properly illustrates the

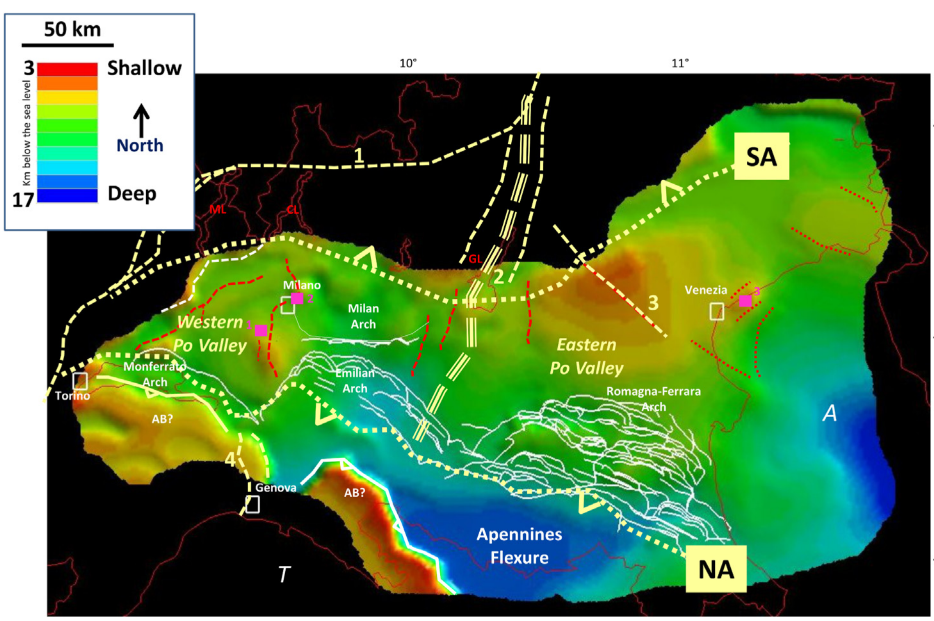

Figure 5. Structural geometries at the Basement grid-surface. Coast-line & northern Italy state boundaries in red. Large dashed segment is possible separation between western and eastern Po Valley domains. White lines are faults at base Pliocene level (Bigi et al., 1989). Purple squares = « basement » wells (1 = Battuda1; 2 = Monza1; 3 = Assunta1). Red stippled lines are possible major basement faults. AB = possible Allochthonous "Basement" units. (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front; (A) Adriatic; (T) Tyrrhenian. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. ML = Maggiore Lake; CL = Como Lake; GL = Garda Lake. 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.)

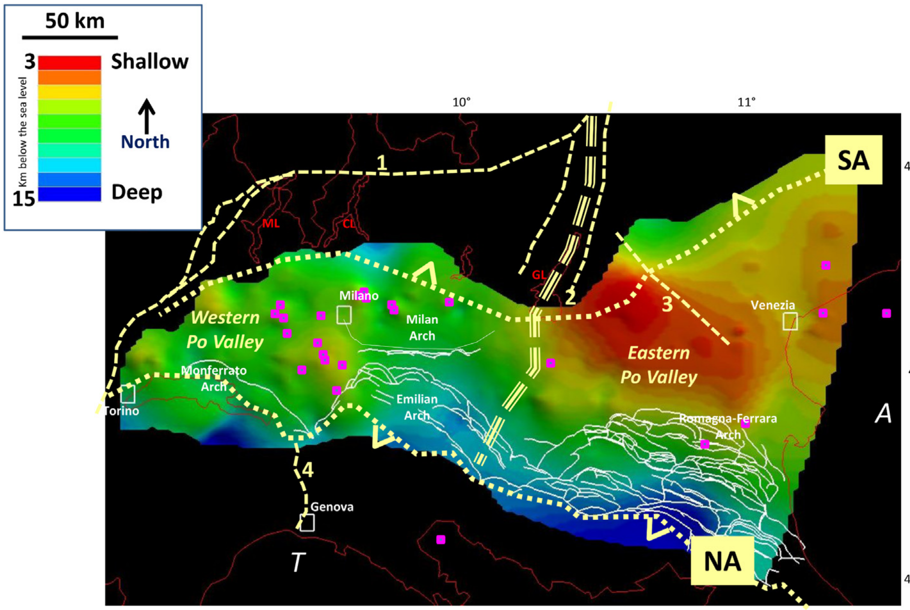

Figure 6. Structural geometries at the top Triassic grid-surface. Coast-line & northern Italy state boundaries in red. Large dashed segment is possible separation between western and eastern Po Valley domains. White lines are faults at base Pliocene level (Bigi et al., 1989). Purple squares = tie-wells to the top of the Mesozoic Carbonates (see Fig. 3 for well name). (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front; (A) Adriatic; (T) Tyrrhenian. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. ML = Maggiore Lake; CL = Como Lake; GL = Garda Lake. 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.)

Plio-Pleistocene structures, but b) it masks the details of the buried Oligocene and Miocene ones.

At the basin scale, a regional monocline can be observed at the base of the Pliocene, as it goes from 0 km at the front of the Southern Alps, to a maximum of 7 km in the eastern part of the Po Valley, close to the outcropping front of the Apenninic belt (see Fig. 9). Such a monocline is then modelled by 3 major tectonic arches (Monferrato Arch, Emilian Arch, Ferrara-Romagna Arch), their presence implying fold-and-thrusts tectonics and displacement of the related units towards the NE mainly. In details (Fig. 10), the folds seem to show segmented anticline axes and narrow synclines, locally anastomosed and sometimes arranged into an en-echelon pattern. Folds and thrusts within each of the arches are systematically NW–SE oriented and they deviate into the NE–SW direction when they pass to the western sides (i.e. the lateral-ramp domains) of the major arches.

At the front of the Southern Alps only the Milano arch (see Fig. 9) gently deforms the base Pliocene surface, most compressional

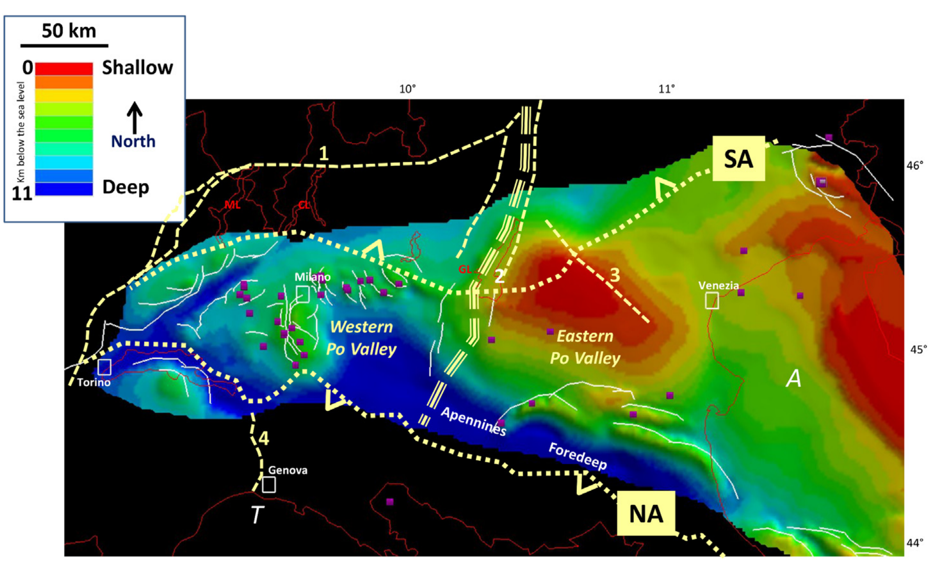

Figure 7. Structural geometries at the top of the Mesozoic Carbonate grid-surface. Coast-line & northern Italy state boundaries in red. Large dashed segment is possible separation between western and eastern Po Valley domains. White lines are faults at Top Mesozoic level. Purple squares = tie-wells to the top of the Mesozoic Carbonates (see Fig. 3 for well name). (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front; (A) Adriatic; (T) Tyrrenhian. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. ML = Maggiore Lake; CL = Como Lake; GL = Garda Lake. 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.)

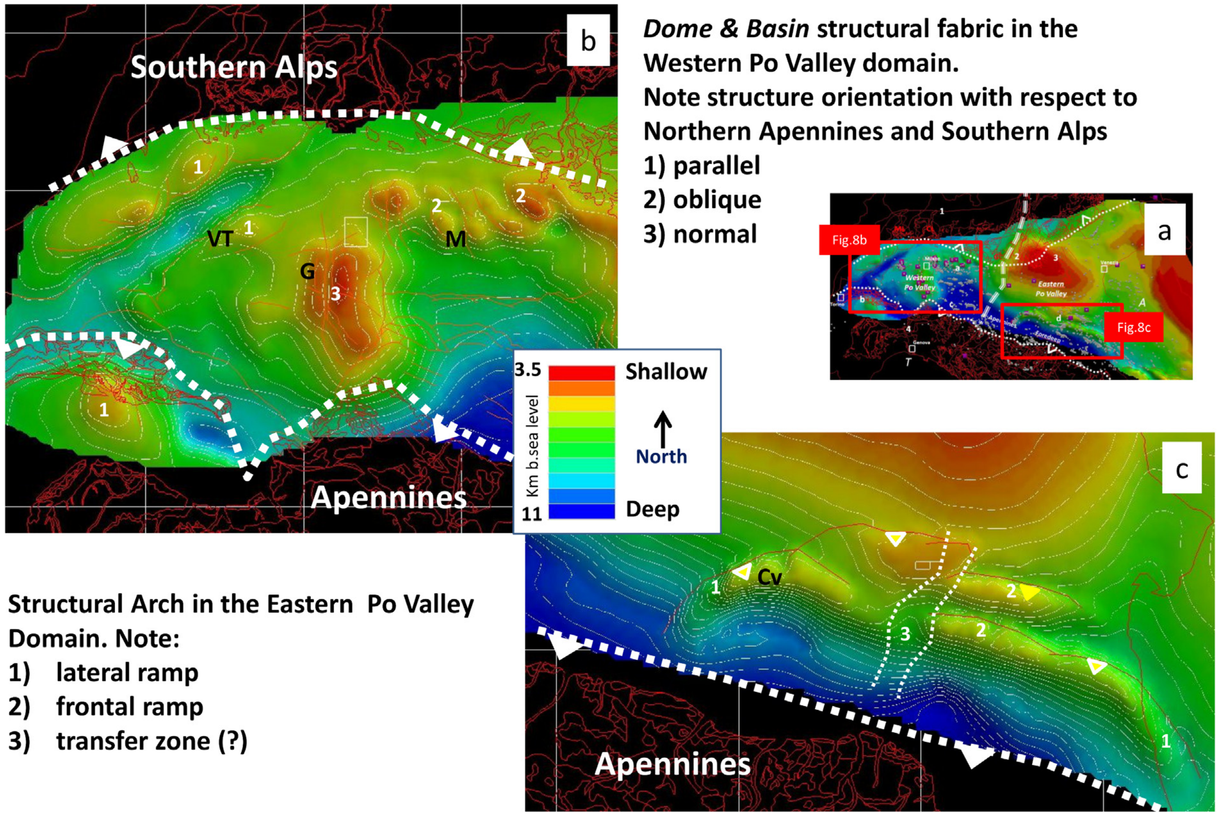

Figure 8. Detail structural geometries from the Top Mesozoic Carbonate grid-surface: (a) Location map for details in figures b and c; (b) Western Po Valley structures. VT = Villafortuna-Trecate field; G = Gaggiano field; M = Malossa field; (c) Eastern Po Valley structures. Cv = Cavone field. Red lines are outcrops. Grid in both figures is 50 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

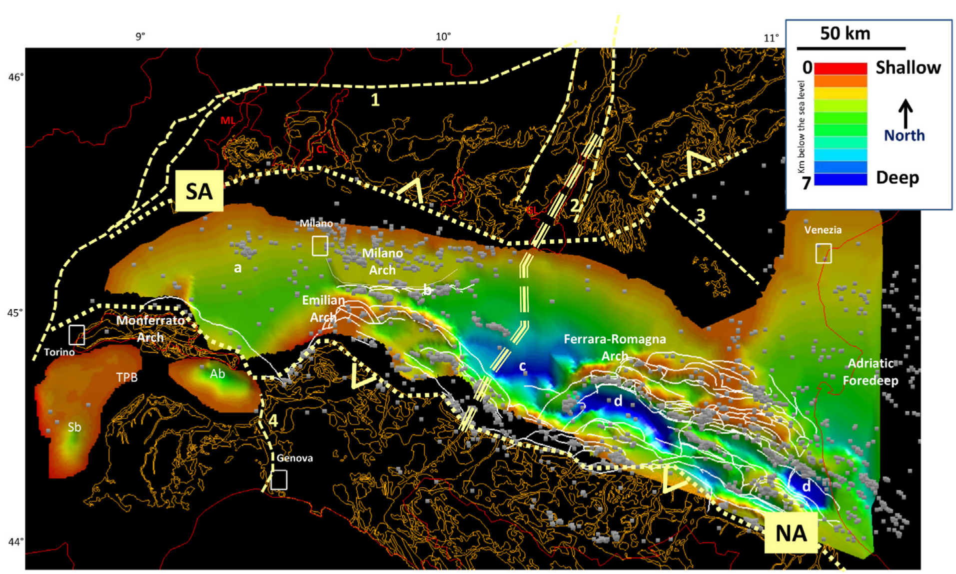

Figure 9. Structural geometries at the Base Pliocene grid-surface. Coast-line & northern Italy state boundaries in red. Southern Alps and Northern Apennines outcrops in orange. (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front. Large dashed segment is possible separation between western and eastern Po Valley domains. White lines are faults at base Pliocene level (Bigi et al., 1989). White dots are all the Po Valley wells. a) Regional monocline, b) SA versus NA thrust front clash-zone, c) major Pliocene foredeep depocenter, d) piggy-back basins within the Ferrara-Romagna tectonic arch. TPB = Tertiary Piedmont basin; Sb = Savigliano basin; Ab = Alessandria basin. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. ML = Maggiore Lake; CL = Como Lake; GL = Garda Lake. 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.)

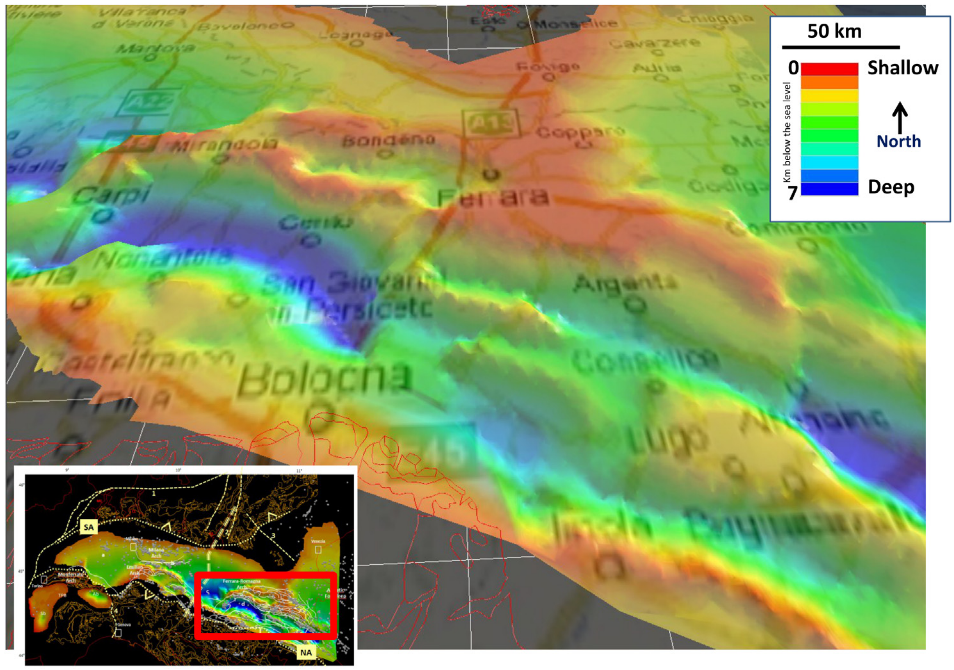

Figure 10. Detail of the Base Pliocene grid-surface structures from the Ferrara-Romagna arch (insert map for location): perspective view looking NNW. Geographic map draped on top of structure map for further references. See text for discussion. Grid is 100 km.

features there being instead sealed by the Pliocene unconformity. The interference between the Milano and the Emilian thrusts and folds define the clash zone between the buried domains of the Alps and the Apennines (b in Fig. 9), as described by Pieri and Groppi (1981).

At the rear of the Monerrato arch, within the Piedmont Tertiary Basin (TPB in Fig. 9), the Savigliano and Alessandria Pliocene basins are clearly illustrated by the 3D model grid-surface. The drastic rotation of the related basin axis, NS (Savigliano) to WNW–ESE (Alessandria), allows the structural interference between Alps and Apennines to be inferred and some change in the deep crustal fabric to be suggested (see paragraph 6.2.8).

In order to confirm and support the 3D model structural pattern, the fault trends from the structural model of Italy (Bigi et al., 1989) have been draped on the final grid surface (white lines in Fig. 9). The positive correlation among grid structures and fault lines is obvious, those latter essentially being the more recent updating by ENI of the original Pieri and Groppi (1981) seismic interpretation.

6.1.6. *Dip-map & fault pattern at top Mesozoic*

The faults that are shown on top of the 3D model grid-surfaces (see Figs. 6–9) refer to a) crustal scale discontinuities, b) regional trends, c) seismic scale faults and d) outcropping faults) (Pieri and Groppi, 1981; Bigi et al., 1989; Casero et al., 1990; Bertotti et al., 1993; Fantoni et al., 2003, 2004; Cimolino et al., 2010; Ponton, 2010). Hence, they represent the whole spectrum of discontinuities that is expected to cut across the entire 3D geo-volume. Given the main objective of this paper, only the faults that intersect the Mesozoic grid have been systematically reviewed by the model and they will be discussed hereafter with respect to the related top Mesozoic dip-map (Fig. 11).

The top Mesozoic fault sets that occur across the Po Valley basin (white lines in Fig. 11) show NE–SW and NW–SE dominant orientations with local deviations. Indeed, from Figure 11, a NW-trending fault system is present in the eastern part of the Po Valley while in the western part three fault systems can be recognised: NE–SW (the main system?), N–S and NW–SE. Among the various sets it is interesting to note that the NE–SW one appears to replicate the orientation of some major, crustal scale fault zones that can be recognized at the scale of the whole Alpine and Apennines thrust belts (i.e. the western segment of the Insubric line, the Giudicarie fault zone). In general terms of structural definition, the NE–SW and N–S oriented faults mainly refer to both Triassic and lower Jurassic extensional events (Bongiorni, 1987; Bertotti et al., 1993; Fantoni et al., 2004; Franciosi and Vignolo, 2002; Fantoni and Franciosi, 2010) while a large part of the NW–SE ones clearly show a geometrical correlation with the Alps and Apennines thrust front orientations. In details the tectonic origin of each single fault segment can be simple-to-very complex due to the deformation history of the basin structures: in that respect, some of the faults can be normal faults or thrusts exclusively, whereas others can be normal faults lately reactivated by thrusting with a large degree of possible variations in the final anatomy due to fault orientation and stress direction progression (Castellarin and Cantelli, 2010, and references therein). Irrespective of their tectonic origin, those dominant fault families bound and deform, with different degree of density, both the western and eastern domains. Given the available data, the fault spacing within the derived regional compartments can vary from 10 to 100 km.

The dip-map of Figure 11 shows the variation in dip of the top Mesozoic grid-surface across the Po-Valley. The spatial variation of dip on a surface can help locate fault zones that have been gridded during initial surface creation. The derived display that can be automatically generated by a computer is commonly used in structural geology analysis and, by successive mathematical elaborations, during seismic interpretation of faulted and fractured regions (Roberts, 2001; Klein et al., 2008; Resor, 2008). Such rendering tool can a) either confirm the presence of a major discontinuity for steep dip value localization or b) suggest the existence of subtle, minor discontinuities where gentle dip variations show geometrical consistency with the tectonic directions that can be defined in-around the study area. It follows that steep dip

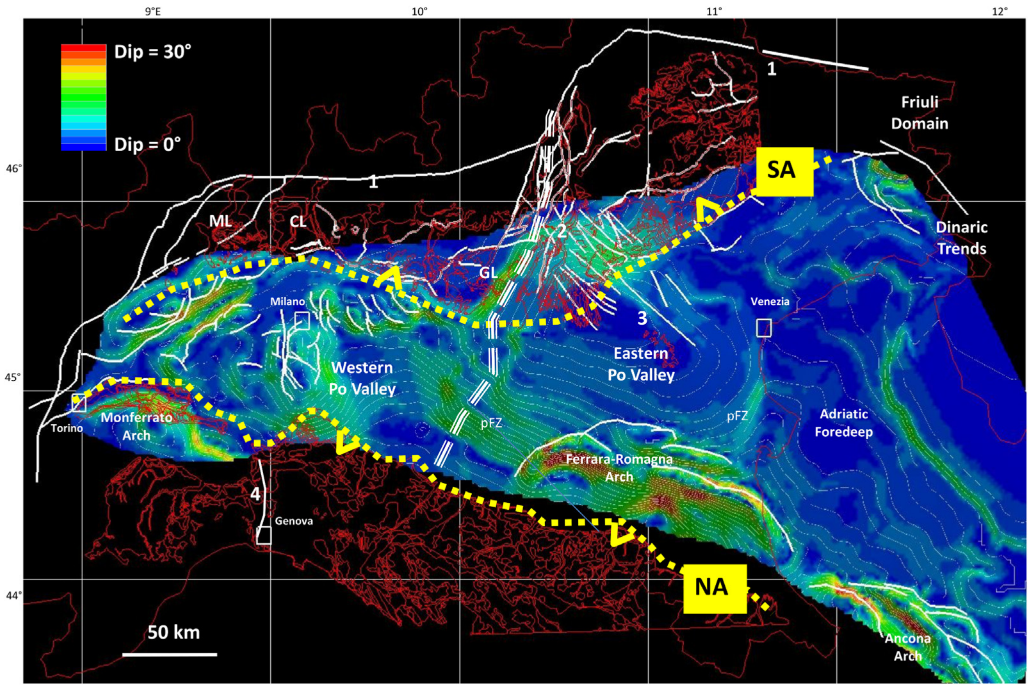

Figure 11. Top Mesozoic major faults from available literature (white lines) against 3D Model top Mesozoic dip-map (contouring is every 500 m). pFZ = possible fault zone (see text for discussion). Outcrops, coast-line & northern Italy state boundaries in red. (SA) Southern Alps outcropping thrust front; (NA) Northern Apennines outcropping thrust front. Main regional tectonic lineaments: (1) Insubric Line; (2) Giudicarie Line; (3) Schio-Vicenza Line; (4) Villavernia Line. Latitude and Longitude values are North and East of Greenwich. Grid is 100 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

alignments in the vicinity of already known tectonic features will likely validate the presence of important faults, whereas subtle dip-variation on a gentle monocline can allow some small faults, hidden to interpretation, to be suspected. It should be noted that the methodology cannot suggest by any means the kinematic nature of the discontinuity (i.e. normal, reverse, transcurrent) if the map is not coupled with the surrounding tectonic framework analysis.

The dip-map of Figure 11 seems to supports the regional scale compartments (east and west Po Valley), as well as the local scale structural complexity already shown by the top Mesozoic depth map (Figs. 7 and 8). Particularly outstanding are the Ferrara-Romagna tectonic arch and the dome-and-basin structural pattern in the western Po Valley. The performed rendering a) suggests the Po Valley fault density as it increases from east-to-west, b) confirms the structural interference between NE–SW and WNW–ESE fault sets, c) indicates some possible fault zones which have not been recognized so far around the eastern Po Valley regional scale dome features (i.e. pFZ green trends not overlaid by faults in Fig. 11).

6.2. Slicing the model

Slicing of the geo-volume at any chosen orientation is an important result from the performed 3D model. Observation of the resulting geometries along key directions or selected depths allows the structural uncertainty to be identified while improving the geological understanding across the entire Po Valley basin, from the crustal to the field scale. The final cross-sections are eventually used to refine the original 3D model.

6.2.1. Cross-section 1 (Fig. 12)

The section, SSE–NNW oriented, slices the western domain of the Po Valley foreland-foredeep system, this being tightly caught in between the Southern Alps and the Ligurian Alps (Fig. 12b). Folding and thrusting of the Moho discontinuity at depth seem to control the shallow deformation. As such, the relatively thin Po Valley Mesozoic carbonates (Fig. 12c) are deformed into a crustal scale syncline and thrusted towards both the north (below the Ligurian Alps–Northern Apennines stack) and the south (south of the Insubric line). At the Monferrato front, the Lower Tertiary clastic sediments are tectonically squeezed below the base Pliocene unconformity, this last surface being only mildly folded. Below the Asti1 well the allochthonus Ligurides unit overthrusts the Po Valley crust and carries the Eocene-to-Pleistocene formations of the Tertiary Piedmont basin in a piggy-back fashion.

6.2.2. Cross-section 2 (Fig. 13)

The cross-section is NNE–SSW oriented and it runs through the central part of the Po Valley basin, in the eastern sector of the western domain. The Europe-Adria lithospheric mantle subduction zone is shown below the Alps, whereas folding of the Adria-Po Valley Moho surface dominates the crustal scale picture (Fig. 13b). Across the region (Fig. 13c), N-to-S thinning of the Mesozoic succession occurs so that the thickest section in the Belvedere area is structurally inverted by compression at the front of the Southern Alps. On the other side of the basin, at the front of the Apennines, thrusting in the Mesozoic and in the Tertiary sections cause thickening of the whole sedimentary pile. Across the whole area structures are both south and north verging and their interference in the central part of the basin defines the tectonic clash between the external domains of the Alps and Apennines (AACZ in Fig. 13c).

6.2.3. Cross-section 3 (Fig. 14)

The long section connects the Alps and the Apennines fronts, the two being approximately 150 km apart. Below the Po Valley basin the Moho is strongly folded and, like in the previous section, an intra-Adria-Po Valley major inflection point can be again suggested

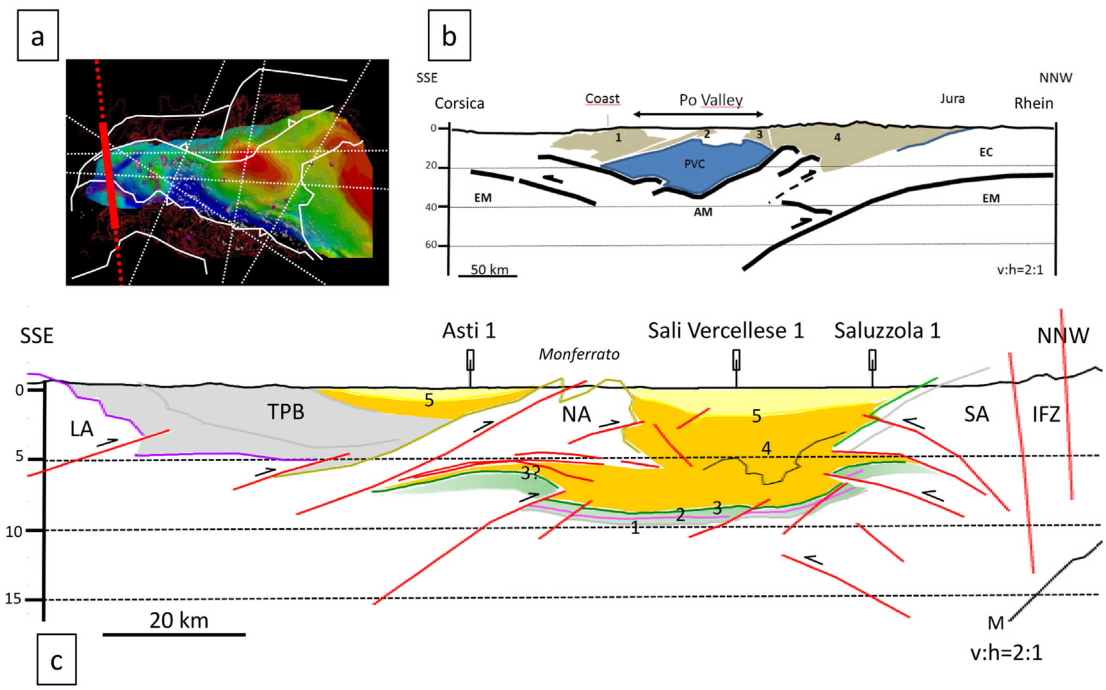

Figure 12. 3D Model Cross-section 1. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 12a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1 = Ligurian Alps; 2 = Northern Apennines (Allochthonous Ligurides, Monferrato Belt); 3 = Southern Alps; 4 = Western Alps. (c) Regional-scale section (red segment in Fig. 12a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines, Allochthonous Ligurides); BTLP = Bacino-Terziario-Ligure-Piementese sediments; LA = Ligurian Alps; SA = Southern Alps; IFZ = Insubric Fault Zone; M = Moho. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

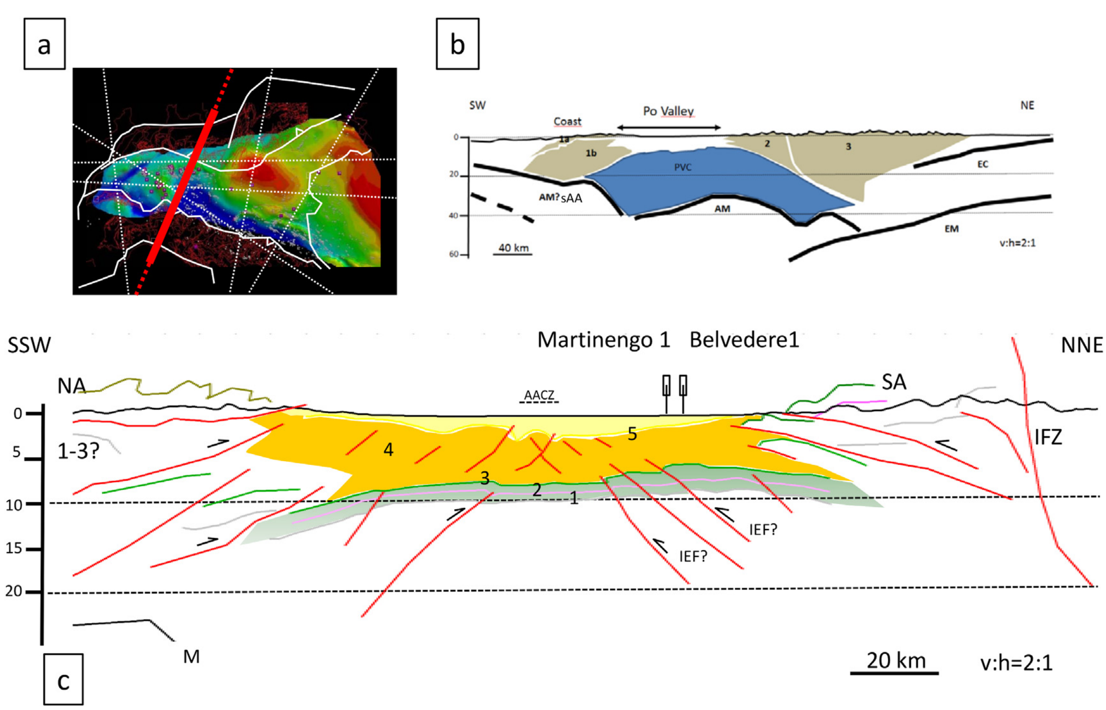

Figure 13. 3D Model Cross-section 2. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 13a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1 = Northern Apennines (Allochthonous Ligurides); 2 = Southern Alps; 3 = Western + Northern Alps. (c) Regional-scale section (red segment in Fig. 13a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines; SA = Southern Alps; IFZ = Insubric Fault Zone; AACZ = Alps–Apennines clash zone; M = Moho; IEF = Inverted extensional fault (?). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Fig. 14b; see paragraph 7.2 for discussion about such a lithospheric feature). Figure 14c illustrates how the Northern Apennines foothill-structures cut through the Mesozoic foreland and eventually deform the Miocene and Pliocene deposits (Cavone and Modena structures). As such, on the Apenninic margin, structures are disharmonically imbricated and intensively thrusted as they are displaced onto the foreland. Here, the related Mesozoic stratigraphic section, intruded by localized volcanic bodies (Cassano et al., 1986), is thickening towards the Alps (i.e. the Veneto Platform) whereas the overlying Plio-Pleistocene sedimentary wedge is thinned to nearly zero.

6.2.4. Cross-section 4 (Fig. 15)

Even longer than the previous one (i.e. the Alps and the Apennines fronts are 250 km apart) the cross-section links the Northern Apennines to the extreme eastern sector of the Southern Alps (the Friuli Alps). The two domains are separated by a wide and rigid Po Valley foreland unit (Fig. 15c), where the basement culmination of the Assunta1 well represents a kind of geometrical divide. With respect to the previous section, the structural disharmony between Tertiary and Mesozoic sediments is less obvious and, at the large scale, the derived structures appear to be conformably deformed and displaced on top of the basement (evaporites at base Triassic level?).

6.2.5. Cross-section 5 (Fig. 16)

The cross-section is oriented east–west and it cuts through the entire Po Valley foreland so that the western and eastern domains can be shown in terms of both sediment thickness and structural style. The western domain shows a) stratigraphic and tectonic thickening of the Tertiary clastic sediments, b) thin Mesozoic package and c) rather intense deformation of the structural units, with thrusting, possible local reactivation of the pre-Alpine extensional faults and inversion of the related half-graben basins. Conversely the eastern domain shows a thin Tertiary layer and a thick Mesozoic one, mostly Triassic in age. The domain appears gently domed and less deformed. The regional conformity among the deep and shallow model layers is outstanding over the entire section. Indeed, the shallow level deformation gradient, increasing from east to west, can be directly related to gentle folding, progressive tectonic imbrication and vertical expulsion of the Moho, in the same direction (Fig. 16b): from an average depth of 30 km below the mean sea level, that unit nearly reaches the surface at the Po Valley–Alps boundary.

6.2.6. Cross-section 6 (Fig. 17)

The cross-section runs slightly oblique to the Northern Apennines front, from WNW to ESE and it connects the Western Alps–Po Valley structural boundary with the northern-central Apennines zone. At the Moho level (Fig. 17b) the picture is similar to what has been already discussed for the previous cross-section. At the crust level (Fig. 17c), the western domain is again clearly shown with basement involvement by thrusting and inversion tectonics (i.e. the Lacchiarella inverted basin in figure). In the NW of the section, the collision between the Po Valley and the Western Alps is outstanding by extreme uplift of the Moho close to the Insubric Fault Zone (IFZ in figure) and the associated SE verging thrust-related structures. Towards the SE of the section, the Northern Apennines likely appear in the form of a major thrust-related anticline which involves the Mesozoic carbonates while pushing the very southern portion of the eastern Po Valley down to more than 10 km below the sea level.

6.2.7. Cross-section 7 (Fig. 18)

The cross-section intersects the Po Valley foreland and the external front of the Southern Alps along the east-west direction. At the crustal scale (Fig. 18b) the possible tectonic imbrication of the Moho so far observed (see Figs. 12b, 16b and 17b) is confirmed below the Western Alps. Across the rest of the region, the Moho is only gently buckled. At the Mesozoic and basement levels (Fig. 18c)

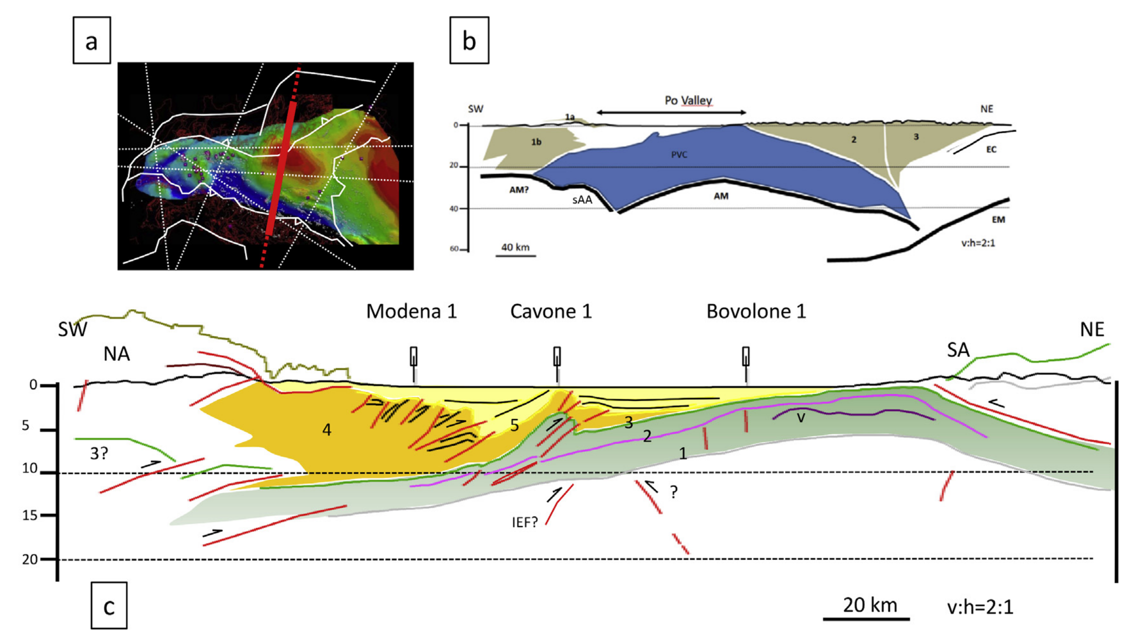

Figure 14. 3D Model Cross-section 3. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 14a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1a+1b = Northern Apennines (Allochthonous Ligurides + Autochthonous Mesozoic?); 2 = Southern Alps; 3 = Western + Northern Alps. (c) Regional-scale section (red segment in Fig. 14a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines; SA = Southern Alps; v = volcanics; IEF = Inverted extensional fault (?). Constraints to the Tertiary geometries from Cassano et al., 1986. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

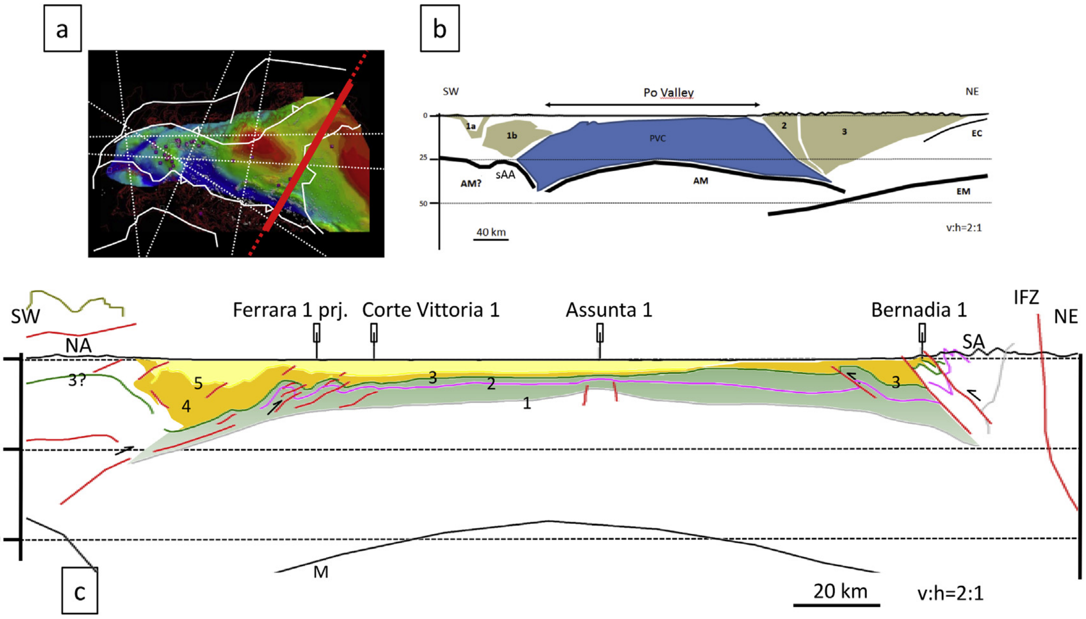

Figure 15. 3D Model Cross-section 4. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 15a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1a + 1b = Northern Apennines (Allochthonous Ligurides + Autochthonous Mesozoic?); 2 = Southern Alps; 3 = Eastern Alps. (c) Regional-scale section (red segment in Fig. 15a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines; SA = Southern Alps; IFZ = Insubric Fault Zone; M = Moho. Constraints to the Northern Apennines Tertiary and Mesozoic geometries from Cassano et al., 1987. Constraints to the Southern Alps geometries from Nicolai and Gambini, 2007, Boccaletti et al., 2010, Ponton, 2010. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the western domain is evidently separated from the eastern one: Triassic–Liassic extensional faults and pre-Pliocene thrusts intensively deform the Western domain causing local inversion of the Mesozoic basins. In the eastern domain the possible top Triassic and its basement mimic the Moho crustal geometry and they are cut by isolated normal faults or wrench-type swarms (Schio-Vicenza fault zone).

6.2.8. *Depth slicing*

Horizontal depth slicing of the volume has been used to visualize and analyse the deep structures versus the shallow ones.

In Figure 19a the Moho architecture is cut at a depth of 30 km below the sea level whereas the base-Pliocene geometries are derived from the oblique slicing of the related surface, to better account for its regional variable dip, generally increasing west-to-

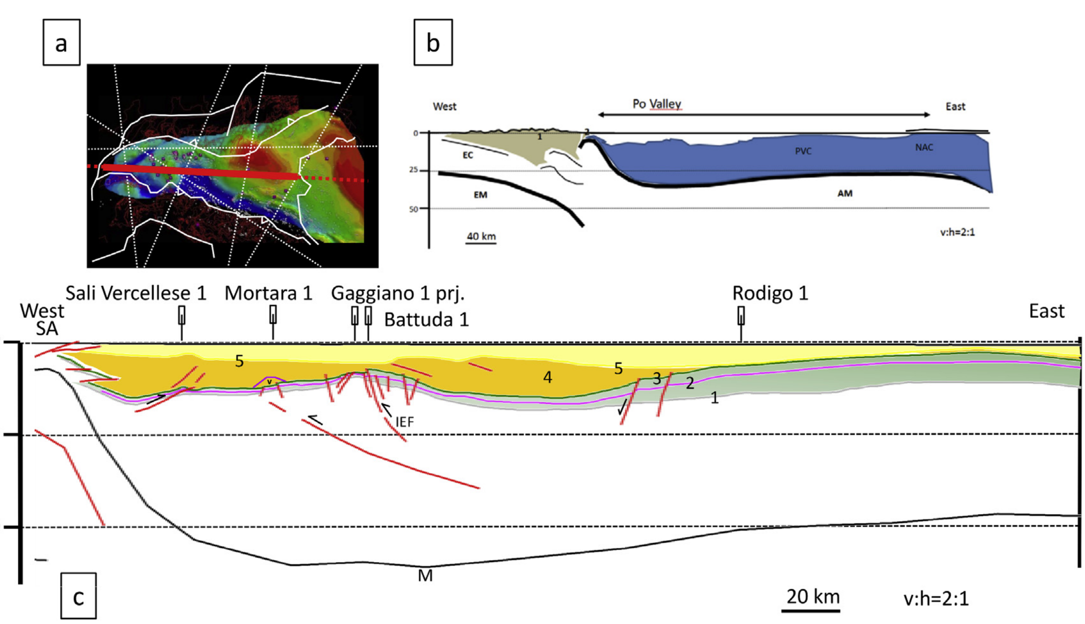

Figure 16. 3D Model Cross-section 5. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 16a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC=Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Moho; 1 = Western Alps; 2 = Southern Alps; 3 = Dinarides. (c) Regional-scale section (red segment in Fig. 16a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines; SA = Southern Alps; v = Eocene volcanics; IEF = Inverted extensional fault; M = Moho. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

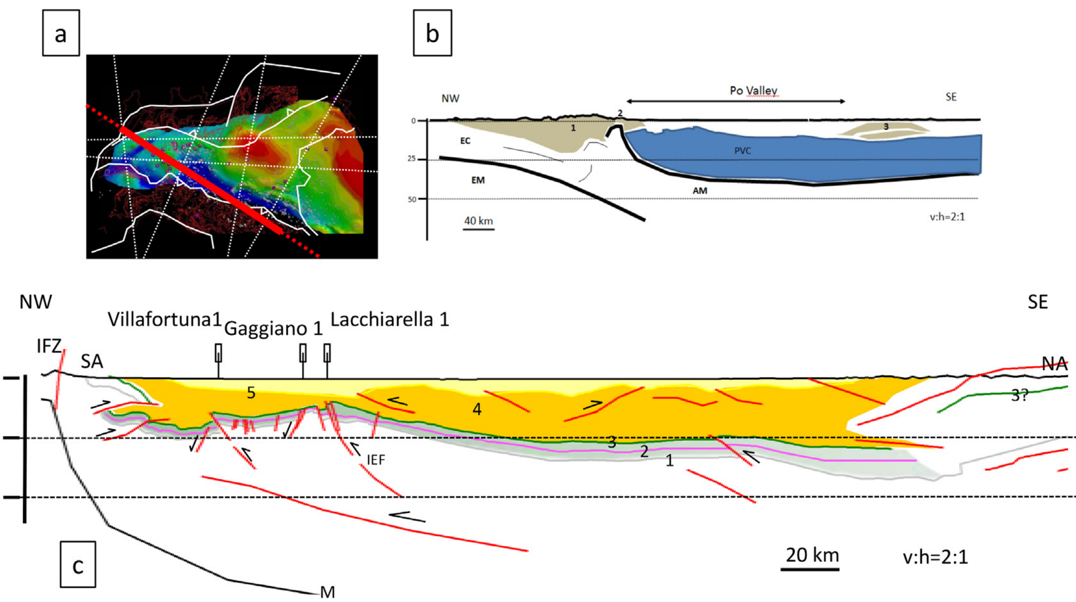

Figure 17. 3D Model Cross-section 6. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 17a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1 = Western Alps; 2 = Southern Alps; 3 = Northern Apennines. (c) Regional-scale section (red segment in Fig. 17a). 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; NA = Northern Apennines; SA = Southern Alps; IFZ = Insubric Fault Zone; M = Moho. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

east (2.5–5°). The integration of the deep and shallow slices shows that the base-Pliocene anticline-syncline structures are generally parallel to the Moho crustal directions, all through the eastern domain and the western domain. Here, the Monferrato structures which at the large view appear perpendicular to the Moho axis anticline (the two being W–E and NNE–SSW oriented respectively) become approximately parallel to that one (i.e. NS) once buried below the Plio-quaternary sediments of the Savigliano basin (Sb in Fig. 19a). Figure 19b allows the comparison between the 30 km Moho depth slice and the top Mesozoic contour geometries. The control of the Moho architecture on the top Mesozoic structures is outstanding so that: a) the eastern Po Valley Moho dome provides a SW dipping ramp-surface to the Mesozoic WNW–ESE oriented, NE verging thrusted folds, b) the western Po Valley dome-and-basin

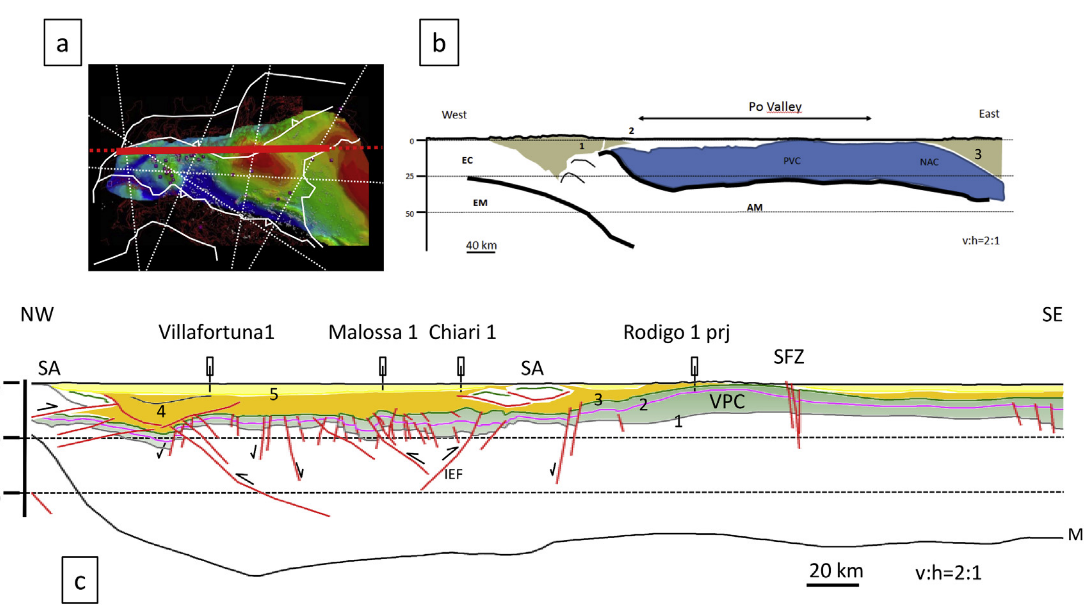

Figure 18. 3D Model Cross-section 7. (a) Location map by Top Mesozoic grid surface from this study. (b) Crustal-scale section (red dotted line in Fig. 18a). Black-thick line = Moho; EM = European Mantle; EC = European Crust; PVC = Po Valley Crust-to-Top Mesozoic; NAD = North Adriatic Crust-to-Top Mesozoic; AM = Adria (Po-Valley) Mantle; 1 = Western Alps; 2 = Southern Alps; 3 = Dinarides. (c) Regional-scale section (red segment in Fig. 18a); 1 = Near Top Basement; 2 = Near Top Triassic; 3 = top Mesozoic Carbonates; 4 = Cenozoic succession; 5 = Base-Pliocene unconformity; SA = Southern Alps; VPC = Venetian Platform Carbonate; SFZ = Schio-Vicenza Fault Zone; M = Moho. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

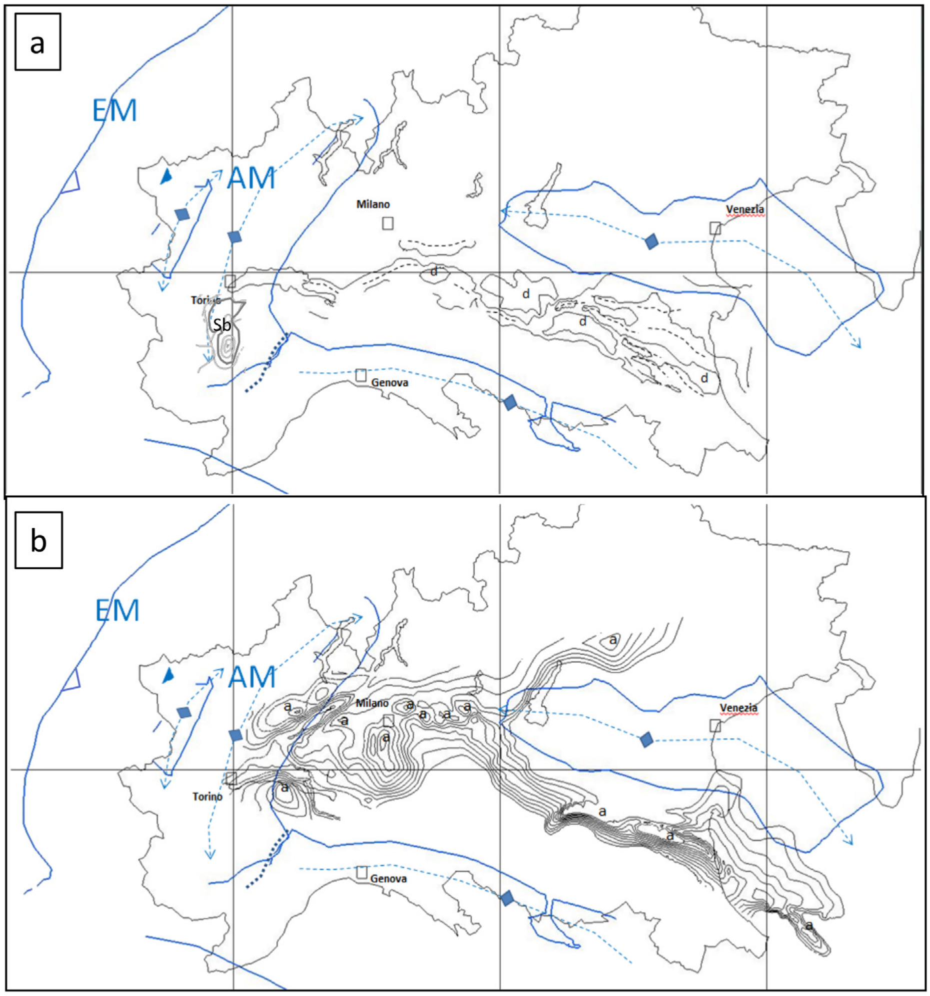

Figure 19. Moho horizontal-depth slice (dark blue) at 30 km below the mean sea level against base Pliocene depth slices (a) and structure contouring of the Mesozoic grid-surface (b). Blue dotted lines are thrusts and anticline axis of the Moho. EM = European Moho; AM = Adria Moho. Grid for scale is 200 km Figure 18a: black dot lines are fold hinges of the Pliocene structures; d = major Pliocene depocenters; AB = Asigliano basin. Figure 18b: a = major anticline culminations. Grid for scale is 200 km. See text for discussion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Mesozoic structures develop inside the crustal scale low that results from folding and thrusting of the Moho in the surrounding regions.

6.3. Isopach maps

The isopach maps of the crust, of the Mesozoic, of the Cretaceous–Jurassic and of the Triassic sedimentary formations were produced from the performed 3D model to infer the architecture of the Adria passive margin to which the Po Valley basin did belong in pre-Alpine time (see Discussion section).

The thickness map of the crust (Fig. 20a) shows a dramatic east-to-west thinning of the crust layer, from a thickness of about 30 km in the central Po Valley to less than 10 km close to the Western Alps boundary. Conversely, along the north–south direction, the crust thickness shows two maximum values of about 40 km below the Apennines and the Alps and a relative minimum value of 30 km below the Po Valley basin.

The isopach map of the Mesozoic formations (Fig. 20b) suggests a regional-scale thinning towards the west and the south. In more details, the thickness-related fabric indicates the presence of some basins and highs oriented N–S and NNE–SSW, perpendicular to the Alps and Apennines belt directions.

The thickness distribution of the Cretaceous–Jurassic sediments (Fig. 20c) confirms the thinning direction, to the south and the west, and the paleo-trends NS orientation already shown by the Mesozoic isopach. Possible dimensions of the related units are 5–10 km by 10–30 km, normal and parallel to the basin axis respectively.

The Triassic isopach (Fig. 20d) supports the Mesozoic thinning directions, to the west and south. Nevertheless, the detail depositional trends are, at the map scale, invisible in the western Po Valley and masked by the Veneto carbonate platform across a large part of the eastern Po Valley. Such trends become eventually evident by some Triassic basins recently interpreted on 3D seismic data at the boundary between the eastern Po Valley and the northern Adriatic domain (Franciosi and Vignolo, 2002). Like the Cretaceous-Jurassic ones, they are NNE–SSW oriented and their dimensions are 30–50 km by 80–100 km normal and parallel to the basin axis, respectively.

7. Discussion

The results from the performed 3D model leave a number of points open for discussion. They will be addressed hereafter by answers to selected questions.

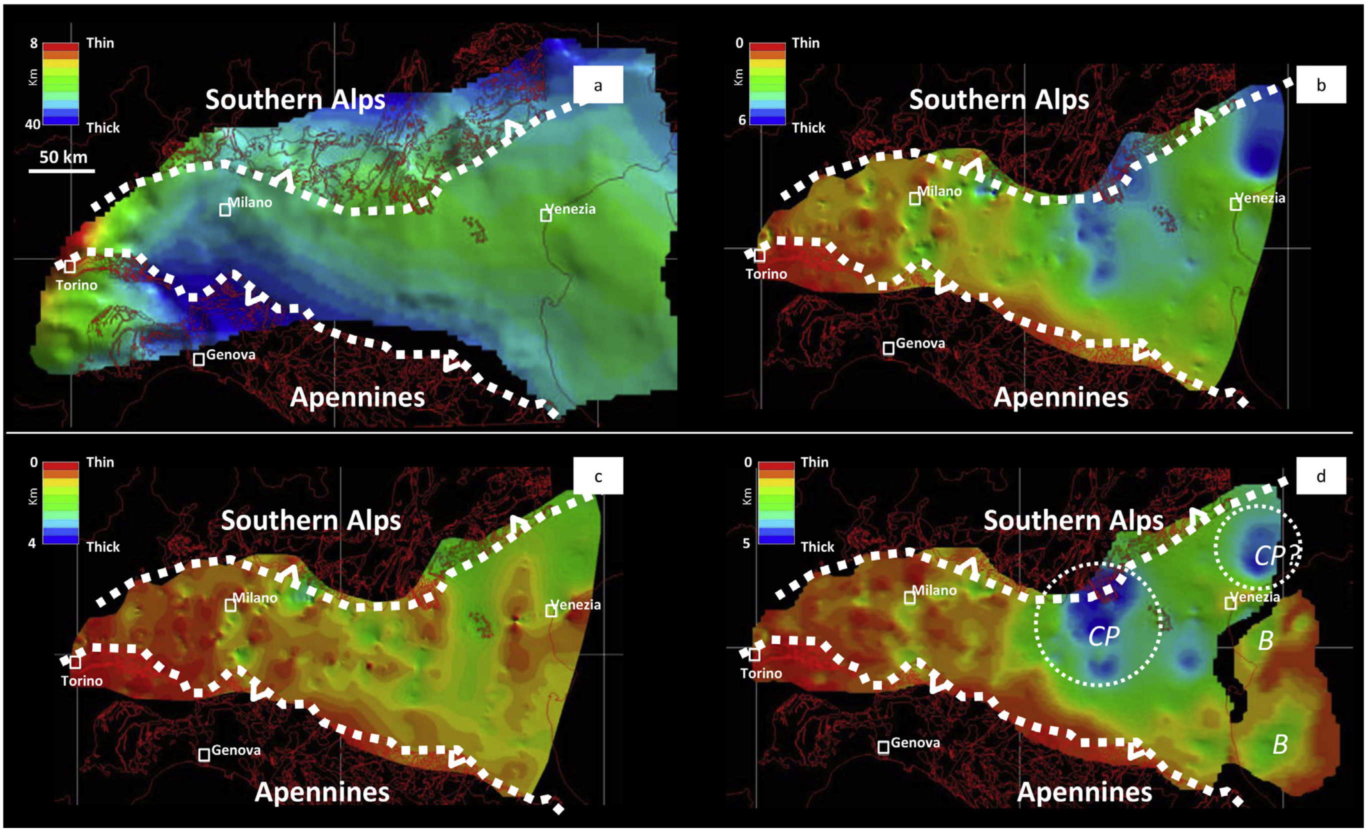

Figure 20. (a) Isopach map of the crust in the Po Valley basin. (b) Isopach map of the Mesozoic sedimentary successions in the Po Valley basin. (c) Isopach map of the Cretaceous–Jurassic sedimentary successions in the Po Valley basin. (d) Isopach map of the Triassic sedimentary successions in the Po Valley basin. (CP) Carbonate Platform facies from outcrops and wells; (B) Triassic basins from 3D seismic data (Franciosi and Vignolo, 2002); Outcrops, coast-line & northern Italy state boundaries in red. Grid in all maps is 200 km. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

7.1. Was the 3D model worth the effort?

It may sound obvious nevertheless the immediate answer is: yes, it was. Indeed, although the data that have been collected and put together are well known in the public domain, the final 3D geo-volume offers a new and interactive view of the structures that form the Po Valley basin, from the very deep Moho to the surface topography. Such integration allows the different interpretations published during the last 50 years to be compared and progressively validated. The model, despite the many uncertainties, is definitely a big step ahead for a modern review of the basin. It can be used as precious analog for the understanding of any other foreland-foredeep domain world-wide.

7.2. What is the major suggestion from the model in terms of present-day crustal architecture?

The model shows (Fig. 21; see all cross-sections in Figs. 12–18) at which level of deformation the present Adria-Po Valley crustal unit is caught in between the Alps and the Apennines belts, apparently detached and floating above the Moho mega-tectonics. Not surprisingly, inspection of the final geo-volume demonstrates that the Moho geometries and the supposed geodynamics definitely control the structure distribution at any of the model layers: in the western Po Valley domain, the horizontal torsion and vertical squeezing of the mantle is accommodated at the basement, Mesozoic and Cenozoic level by intense faulting, folding and tectonic over-thickening of the crust with large dispersion of the structural orientations. In the eastern Po Valley, lithospheric flexuring of the related Adria plate allows contrasting displacement of the Southern Alps and the Apennines onto the regionally bulged Po Valley foreland. Some possible NNE–SSW oriented transfer zones can be argued to be fragmenting the present Moho unit thus separating the western Po Valley domain from the eastern one (see TZ elements in Fig. 21).

The performed 3D model also points to the issue of a possible connection between the sub-Apenninic Moho and the Adria-Po Valley Moho. This hypothesis would imply that the Po Valley Moho is folded but not vertically offset below the Apennines while the underlying Adria mantle would undergo progressive delamination and subduction. Despite any tomography and crustal refraction acquisition (Margheriti et al., 2006, and reference therein), hard data about the Moho-mantle mechanical coupling or decoupling inside the Apennine subduction are still ambiguous. Nevertheless the aforementioned crustal framework, although largely debatable, would support some of the available models about the Apennine kinematics while eventually neglecting others. Indeed, Roure et al. (1991 and 2012) and the RETREAT working group (see Figure 1 in Picotti and Pazzaglia, 2008) propose similar kinematics for the southern and the northern Apennines respectively where delamination, subduction and wedging of the Adria mantle occur below a folded yet continuous Adria Moho surface. Conversely, Doglioni (1991, 1994), Doglioni et al. (1996) and Carminati et al. (2003) suggest steep subduction of the Adria slab and the related Moho below the Apennines. This model seems also the preferred one for Picotti and Pazzaglia (2008) when they try to integrate deep and shallow structures of the south-eastern segment (i.e. the Bologna region) of the Northern Apennines. The

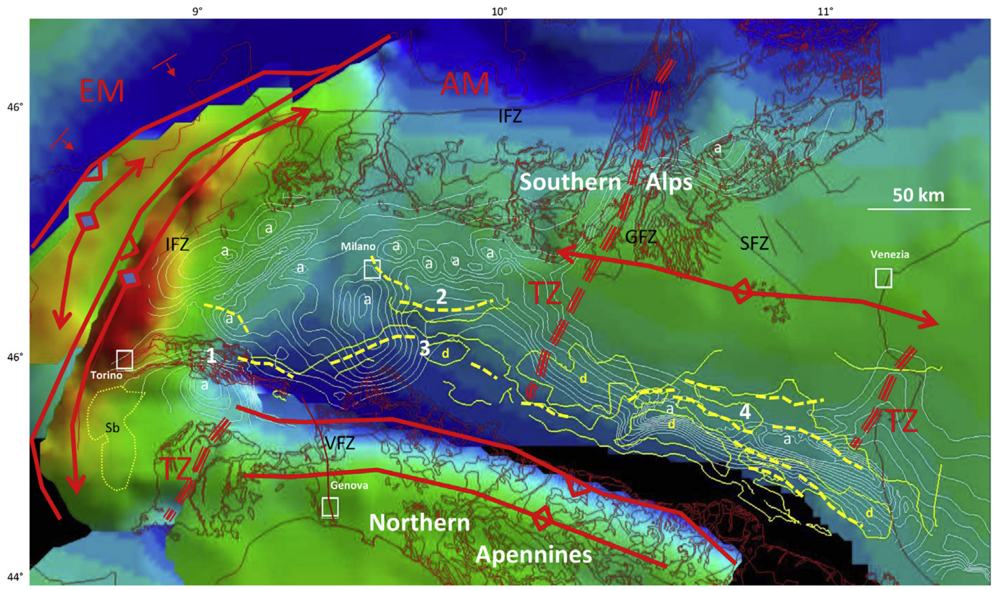

Figure 21. Tectonic summary in the Po Valley basin by Moho Mesh-surfaces (related tectonics in red), top Mesozoic contouring (white) and base Pliocene fold hinge distribution (yellow dot lines). EM = European Moho; AM = Adria Moho; TZ = transfer zone at Moho level. 1 = Monferrato Arch; 2 = Milano Arch; 3 = Emilian Arch; 4 = Ferrara-Romagna Arch; a = anticline culmination at top Mesozoic; d = depocenters at base Pliocene level. Sb = Savigliano basin. IFZ = Insubric Fault zone; VFZ = Villavernia Fault Zone; GFZ = Giudicarie Fault Zone; SFZ = Schio-Vicenza Fault Zone. Outcrops, coast-line & northern Italy state boundaries in red. 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.)

process would guide back-arc progradation and limited frontal compression across the belt while partly controlling the tectonic subsidence of the foreland. The in-progress integration of the 3D model structures with the earthquake data from the Italian catalogue (INGV) will eventually provide further insights on the issue.

7.3. What about the Po Valley unit within the so-called Alps–Apennines structural junction?

At the Alps–Apennines junction (see Figs. 4 and 21), the 3D model shows a very complex architecture of the Po Valley Moho, with possible NW verging tectonic imbricates, below the Western Alps (Figs. 12b, 16b, 17b) and a NW–SE oriented fold, with short limb towards the NNE, below the Northern Apennines (Fig. 13b). The Moho deformation in the region is accommodated within the Po Valley crust by intense folding and faulting, these being imaged by the dip-map of the carbonate surface-grid (see Fig. 11). Not by coincidence, the map shows that the structural complexity across the basin increases from NE to SW and it appears to reach its maximum in the extreme western Po Valley, the likely Alps–Apennines junction.

The described framework appears three-dimensionally consistent although neither in the model nor in the literature there are evidences of the possible transfer zone (see Fig. 4) that would allow the opposite motion between the Alpine and the Apennines Moho sectors.

7.4. What about the Po Valley structural style?

The 3D model analysis, through slicing of the volume and the isopach-map building, proves that the Po Valley structural style strictly refers to the interaction among the lithosphere dynamics, the related geometry and the paleo-margin architecture (thickness, stratigraphy, fault orientation).

Indeed thick-skinned tectonics can be largely demonstrated in the western Po Valley where a thin Mesozoic sequence is reported and modelled (see also Cassano et al., 1986; Bello and Fantoni, 2002; Fantoni et al., 2004; Picotti and Pazzaglia, 2008; Fantoni and Franciosi, 2010). As such, involvement of the basement prevails with local reactivation of the Triassic–Jurassic faults and inversion of the related extensional basins (see cross-sections in Figs.12 and 13, 16–18). In the region structures at the different stratigraphic levels are vertically coupled with local exception at the front of the thrust belts.

Conversely, in the eastern Po Valley, mainly thin-skinned tectonics occurs by folding and thrusting (see Figs. 14 and 15), these being likely controlled by a relatively thick Mesozoic package detached and displaced from the basement below (see also Cassano et al., 1986; Castellarin et al., 1985; Picotti and Pazzaglia, 2008; Toscani et al., 2006, 2009; Fantoni and Franciosi, 2010). Involvement of that basement becomes evident towards the Apennines and the Southern Alps yet it can also be speculated to enhance the regional doming of the foreland.

In detail, when referring to each of the Po Valley tectonic arches (and the related foreland), the structural style can be defined by some specific elements:

a. Monferrato Arch (see Fig. 12c): basement involvement, thrust-related structures across the Mesozoic carbonates and the Cenozoic succession; weak detachment (base of Gallare? Top of the Scaglia?) of the Cenozoic sediments from the Mesozoic one. A major detachment decouples the possible Mesozoic structures from the Ligurides Allochthonous in the Monferrato belt region.
b. Emilian Arch (see Figs. 13c, 16c, 17c): possible basement involvement and thrust-related structures across the Mesozoic carbonates below the Apennines. Thrust-related structures across the foreland Mesozoic carbonates, with structural inversion of extension-related basin and basement up-thrusts. The buried Emilian arch is essentially made by thrusts and folds in the Cenozoic succession which is almost completely detached (base of Gallare? Top of the Scaglia?) from the related substratum (compare structures at the base Pliocene grid with the top Mesozoic ones in Figs. 9 and 7 respectively).

c. Milano arch: this arch is essentially provided by thrust-related structures across both the Mesozoic carbonates and the Cenozoic succession, with basement involvement and local inversion of Triassic–lower Jurassic basins (Fig. 13c, northern sector, and 18c, the Malossa-Chiari structures in the western sector). A weak structural disharmony can be demonstrated among the different structural levels (basement, Mesozoic carbonates, Cenozoic succession) so that the major detachment would likely be intra-basement.
d. Ferrara-Romagna arch: the Mesozoic and Cenozoic structures are mechanically coupled at the large structural wavelength (Figs.14c and 15c; again, compare structures at the base Pliocene grid with the top Mesozoic ones in Figs. 9 and 7 respectively). In detail, close to the Northern Apennine front and on top of the major anticlines, the Cenozoic succession appears to be strongly decoupled from the Mesozoic one (top of the Scaglia level?), this being diffusely detached in its turn from the underlying basement (base Triassic detaching level?). A minor detachment level is likely located at the transition between the Miocene and the Pliocene successions. Eventually the basement is a) likely involved by thrusting below the Apennines, b) locally reactivated by compression in correspondence of extensional faults within the tectonic arch domain (IEF in Fig. 14c below the Cavone structure), c) buckled by folding into a crustal scale "pop-up" feature in the foreland.

7.5. *What is the 3D model contribution to the understanding of the Adria passive margin anatomy?*

The Po Valley is the remnant of the northern sector of the Adria plate which collided with the European plate during the Alpine orogeny. Therefore, and despite the great uncertainty, the isopach maps that have been derived from the 3D model can be used to speculate about the anatomy of the ancient Adria passive continental margin.

The isopach map of the crust implies thinning of the Po Valley lithosphere from east to west. This is then compatible with a former Adria passive margin thinning towards the present West orientation. Conversely, the same isopach-map shows some tectonic over-thickening of the crust to the north and south of the Po Valley basin, that is likely due to the Alps and Apennines orogenies. Deep over-thickening inside the foreland domain around the Milano area (see cross-sections in Figs. 16–18 and isopach-map of the crust in Fig. 20a) could be eventually due to some possible intra-plate tectonics that inverted the pre-alpine faulted blocks. Such a thickness distribution suggests that the ancient Adria plate was eventually much wider than what it shows at present.

In terms of the possible pre-compressional Mesozoic grain the Cretaceous–Jurassic isopach map and the analysis of the Triassic thickness distribution allow some primary NNE–SSW oriented trends to be speculated, with second order EW-oriented ones. Such extension-related fabric confirms and completes the results of a number of studies performed across the South Alpine outcrops (Bertotti et al., 1993; Fantoni and Scotti, 2003; Berra et al., 2009) and the ones provided by some regional studies from the industry in the Po Valley sub-surface (Bongiorni, 1987; Fantoni et al., 2003, 2004; Franciosi and Vignolo, 2002).

The integration of the extension-related fault trends coming from the literature and the performed 3D model allows the possible pre-alpine margin kinematics to be suggested:

a) during the Triassic, extension caused symmetric stretching of the Adria lithosphere in the western Po Valley and asymmetric stretching in the eastern Po Valley (i.e. towards the current Adriatic and Dinarides geological realms). Symmetric stretching led to a sort of chocolate-table tectonic fabric in the western Po Valley, with fault sets perpendicular to each-others (NNE–SSW and E–W). At the same time asymmetric stretching made N–S oriented faults the predominant ones in the eastern Po Valley.
b) In Liassic times, the margin was definitely stretched in the present-day E–W direction all through the Po Valley-Adria

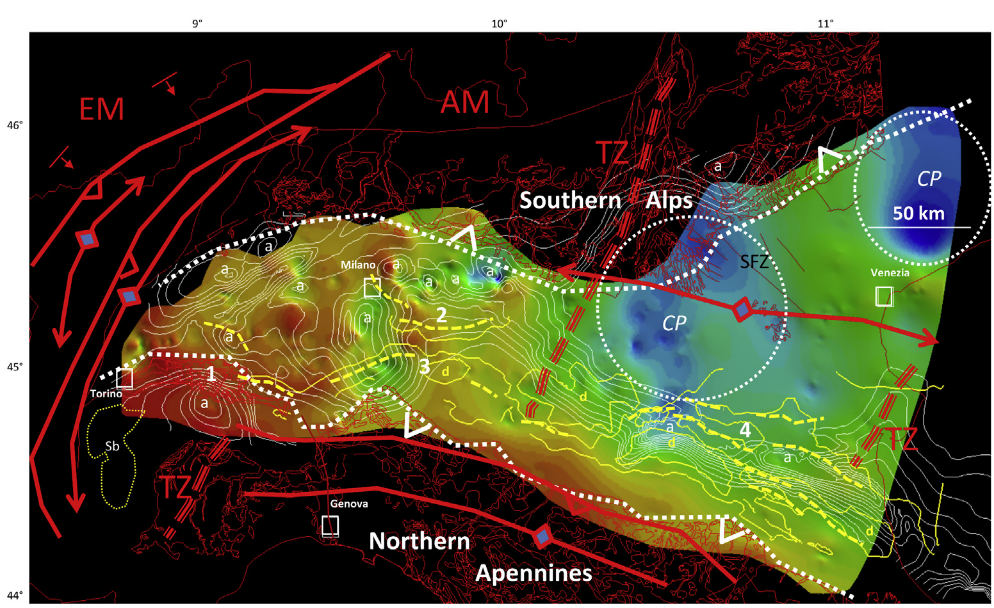

Figure 22. Structural interference and Tectonic heritage in the Po Valley basin by Mesozoic isopach-map, top Mesozoic contouring (white) and base Pliocene fold hinge distribution (yellow dot line). EM = European Moho; AM = Adria Moho; TZ = transfer zone at Moho level; CB = Triassic Carbonate Platform. 1 = Monferrato Arch; 2 = Milano Arch; 3 = Emilian Arch; 4 = Ferrara-Romagna Arch; a = anticline culmination at top Mesozoic; d = depocenters at base Pliocene level. Sb = Savigliano basin. IFZ = Insubric Fault zone; VFZ = Villavernia Fault Zone; GFZ = Giudicarie Fault Zone; SFZ = Schio-Vicenza Fault Zone. Outcrops, coast-line & northern Italy state boundaries in red. 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.)

micro-plate. The derived half-graben and horst features are hence univocally NS oriented.

7.6. What is the 3D model contribution to the understanding of the estension-compression structural interference that modelled the Adria-Po-Valley plate?

As by the above considerations, the entire Adria-Po Valley passive margin was modelled by the Mesozoic extension into highs and basins that were oriented at high angle with respect to the Alpine belts. Indeed, when comparing the 3D model isopach maps with the present structure orientation (Fig. 22), the heritage of the extension-related units on the current compressional ones becomes evident by the west-to-east change in structural style across the basin (see above):

a) thin Mesozoic and chocolate-table extension-related fault trends enhanced thick-skinned alpine tectonics and dome-and-basin structural fabric in the western Po Valley, west of Milan;
b) lateral change in facies of the Mesozoic sediments constrained the localized inversion of few of the Jurassic basins, to the east of Milan (see the Lacchiarella structure in Fig. 17 and the Chiari structure in Fig. 18);
c) in the eastern Po Valley, the presence and areal extension of a huge Triassic platform carbonate units locked the progression of both the South-Alpine and Northern Apennines fronts as they try to advance towards the Po Valley foreland;
d) although extremely speculative at present, the inferred NNE–SSW oriented transfer zones that separated into mega-compartments the Po-Valley pre-alpine crust possibly controlled the indentation of the margin into the European Plate and partly constrained the development of the Northern Apennines tectonic arches.

Once again the performed 3D model integrates and completes at the scale of the entire Po Valley basin what has been locally suggested by various papers in the past (Fantoni and Franciosi, 2010; Ravaglia et al., 2006; Doglioni and Carminati, 2008 and various references therein).

It is interesting to note that a similar structural interference can be observed all along the Adriatic foreland-foredeep domain, this being the prosecution of the Po Valley unit towards the SSE. Across that domain, caught between the central and southern Apennines from the west and the Dinarides–Albanides–Hellenides belts from

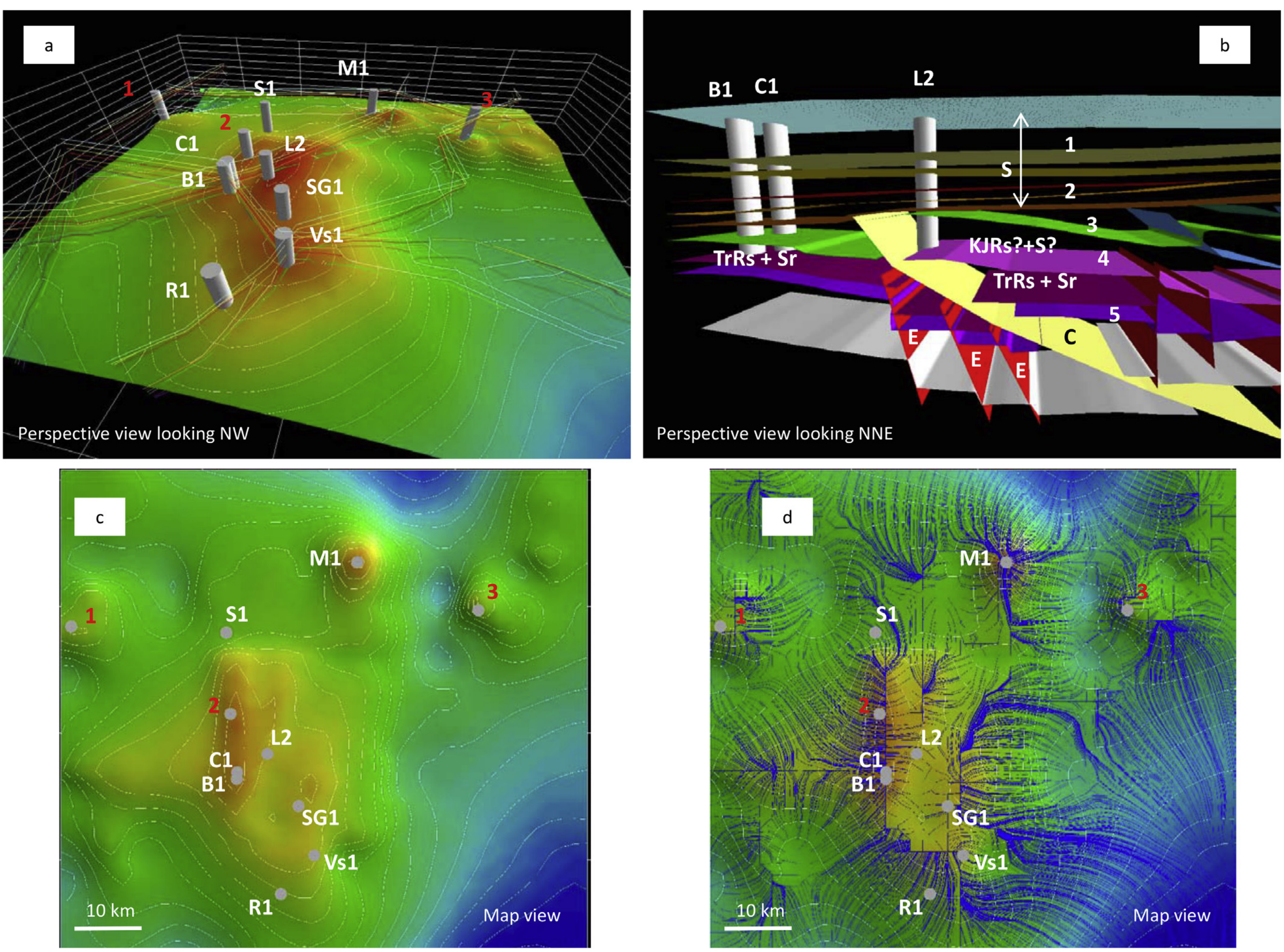

Figure 23. (a) Structures at the Top Mesozoic and source data for 3D model building in the Milano area. 1 = Villafortuna Field; 2 = Gaggiano Field; 3 = Malossa Field. Wells: L2 = Lacchiarella2, Mz1 = Monza1, B1 = Battuda1, C1 = Cerro1, S1 = Settimo Milanese1, Vs1 = Vallesalimbene1, R1 = Rea1. (b) Structural interference among extensional and compressional structures (modified from Cassano et al., 1986): 1 = Base Pliocene, 2 = Top Oligocene, 3 = Top Mesozoic Carbonates, 4 = Top Trias, 5 = Basement. E = Extension-related normal faults; C = contraction-related thrusts. TrRs + Sr = Triassic reservoir & source rock; KJRs?+S? = Cretaceous–Jurassic possible Reservoir + Possible Seal (see text for discussion); S = Seal. (c) Structural geometries at Top Triassic. (d) Migration paths at Top Triassic.

the east, the Jurassic–Cretaceous extensional units, NNE–SSW oriented are overprinted by the compressional ones, generally NW–SE oriented. The result of such an overprinting is outstanding on both the sides of the Adriatic region where the compartmentalization of the Apennines, and Dinarides–Hellenic thrust fronts often relates to pre-compression lateral facies transitions (Roure et al., 2004; Shiner et al., 2013).

7.7. What is the impact of the 3D model on the reviewing of the Mesozoic hydrocarbon system across the Po Valley basin?

The application of the performed 3D structural model to some exploration target validation across the Po Valley (Petroceltic internal reports) indicates that the model can be a precious tool especially during the regional scale play risk-analysis and hydrocarbon-system definition. Once some extra data are added to the base-framework, the model results would also become useful during the progressive and more refined lead–prospect evaluation.

Slicing across the regional 3D model provides a preliminary imaging of the possible trap types that can be found at the Mesozoic structural level.

The isopach maps derived from the 3D model give some guidelines about the Triassic and Jurassic tectonic trends and the related possible source thickness distribution across the basin.

Because the Cretaceus–Jurassic successions are a debated seal to the underlying Triassic reservoir, the ultimate (ubiquitous and laterally continuous) top seal to the Mesozoic traps is generally provided by the Tertiary clastic formations. Therefore the 3D model top Mesozoic depth map can be an immediate estimation of the possible top seal presence and efficiency.

The trap type that the model helps to define across the different Po Valley domains might be used to suggest a lateral-seal risk. As such, presence, geometry, age of the faults associated to the possible trap can be recognized from the model and the related juxtaposition diagram (Allan, 1989) can easily be approximated once the permeable rock formations are defined in the geometries under study.

In terms of reservoir, the Mesozoic isopach map can be used to define the reservoir-thickness domain whereas the trap-type that the 3D model allows to visualize, immediately contributes to a qualitative estimation of the distribution of the possible fracture sets that would be associated to the target structure. Eventually the performed 3D structural model would provide a preliminary support to the generation and migration issue by the integration of the different isopach maps into the necessary thermal-maturity model and by the qualitative visualization of the final hydrocarbon catchment areas and the related migration paths.

As an example of the 3D model application to the exploration workflow at the oil-field scale, Figure 23 illustrates the major steps in the evaluation of the Mesozoic play in the central area of the western Po Valley.

a. Figure 23a: the 3D model is built from the source data (sections, maps and wells) and rendered by depth of the top Mesozoic grid. Current burial of the structure is defined and, eventually, a dip-map can be derived to gain information about the possible fault trends and potential fracture sets with respect to the actual stress-field. By the Allan diagram analysis (Allan, 1989), lithology juxtaposition across the model faults can be defined.
b. Figure 23b: a refined 3D model building of the structure anatomy is performed so that 1) trap-type, 2) reservoir-seal-source presence-distribution from the wells, 3) fault geometries are investigated. At this stage, the structures supply the framework for compaction analysis and the possible thermal modelling across the selected area.
c. Figure 23c: the present depth geometries of the near top Triassic are visualized to constrain the possible top reservoir architecture. Reservoir presence and distribution can be added as attributes on the top grid; isopach maps can be built to understand the reservoir thickness distribution and the paleo-trends.
d. Figure 23d: the migration paths are derived from the model to check for drainage area distribution and potential accumulation (note Oil-field location).

7.8. What are the future applications of the performed 3D model?

The possible applications of the performed 3D structural model are multiple for both industry and academia. Despite the many uncertainties, the geo-volume that has been built can work as a geo-referenced 3D geological box where all kind of data and measurements can be input and analysed against the recognized geometries. In addition, the tectonic kinematics that built the basin architecture can also be studied from both 3D block restoration and 2D cross-sections sliced from the volume. As a result it can represent a powerful tool for different actions: in the hydrocarbon domain the comparative analysis between the exploration results and the 3D model structures can supply a way to review the past exploration strategy and support the future one. The modelled geometries can also provide understanding and operational suggestions for methane and CO_2 storage within the basin. Finally, the reconstructed crustal scale architecture of the model can also be referenced as a unique geometrical support in the analysis of the Po Valley earthquake catalogue (INGV) and the review of the derived seismogenic zonation.

For all of the aforementioned applications it is to be said that the model needs strong refining at the structure scale, so that all of the crustal layers, from basement to base Pliocene, will be able to perfectly tie to the well information and the available seismic data. Very likely a number of additional, local scale 3D models will be used to tackle the goal and interact with the crustal scale one.

8. Conclusions

A 3D model of the Po Valley basin from the Adriatic to the Western Alps has been built by integration and consistency check of the available data-set. It is definitely an interactive model and it shows by its geometrical continuity and consistency all of the principle layers from the Moho to the digital topography.

The performed 3D Model represents a unique result in the region as it is able to illustrate the Po Valley architecture like none of the previous work in the area did so far. Also, the model can be seen as a possible analog to other deformed foreland-foredeep basins around the world.

Results from the modelling show how the Moho crustal-scale architecture strongly constrains geometry and distribution of all of the structures that have been built at any of the shallowest model layers. The structure reconstruction illustrates the structural interference between Triassic–Jurassic extension and late Cretaceous–Tertiary compression from the crustal to the oil-field scale.

While a review of the exploration results and strategy in the basin against the 3D model structures is currently in progress, a number of future applications (CO_2–CH_4 storage, earthquake analysis among them) could be eventually supported by the final geo-volume once refined to its maximum detail.

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