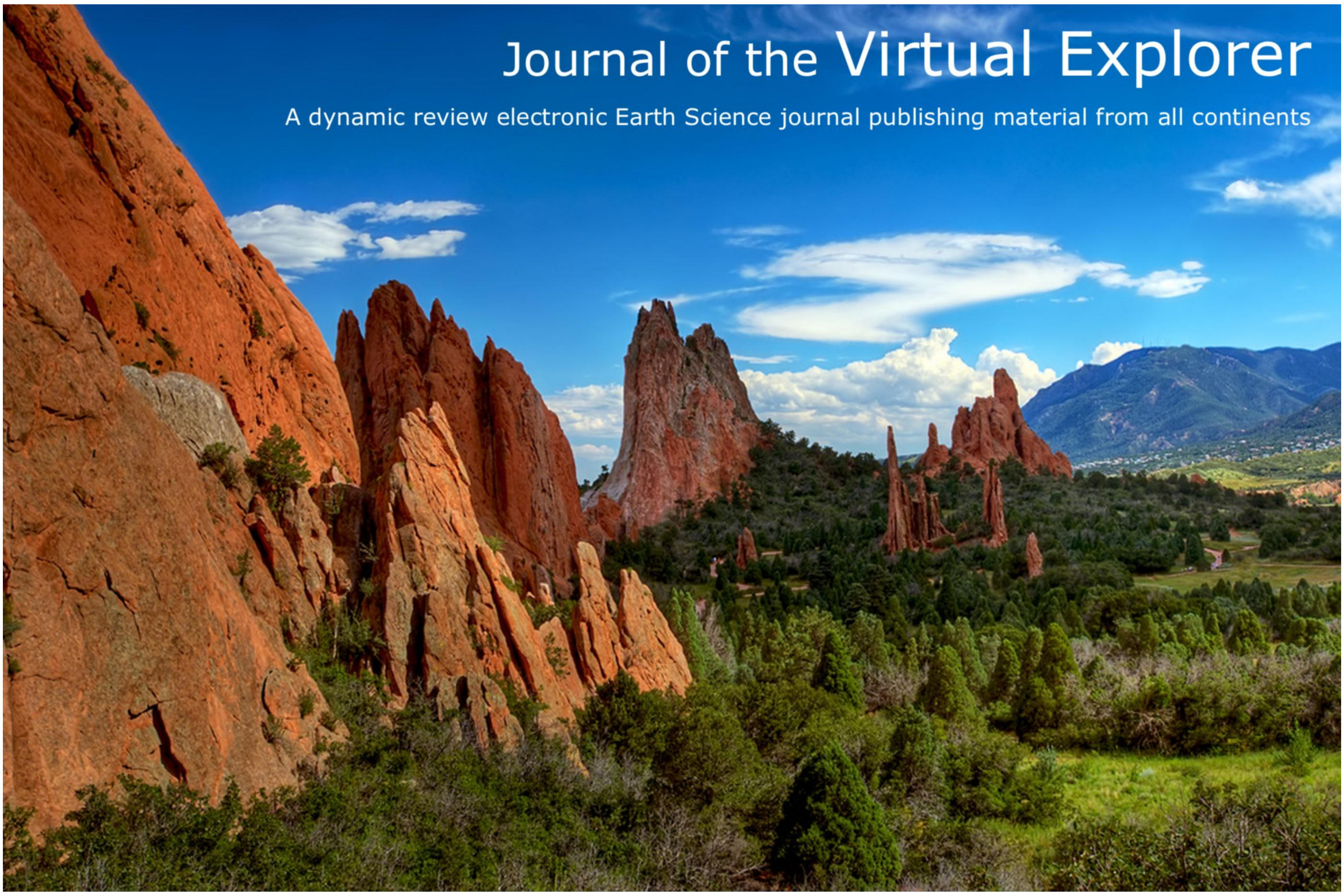

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Geology of the Western Alps-Northern Apennine junction area: a regional review

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Abstract: This paper aims at describing some aspects of the Alps-Apennines orogens and their relationship in space and time with special focus on their junction area. After an historical outline of the subject, the main morphostructural, geophysical and tectonic domains of the system will be outlined. The result of recent research and a review of structural and thermochronometric data of the exhumed units in the mountain belts and on the sedimentation and deformation record in the surrounding basins will be used to constrain key events of the geological history. An analysis of crustal-scale cross sections across the Western Alps, Northern Apennine and Western Po Plain altogether with a presentation of the main exposed and buried boundary faults and their time activity are presented. We will try to constrain the evolution of the Western Alps/Northern Apennine junction area by analyzing and comparing the main elements of the growing and interfering segments of the orogens providing some remarks on recently proposed kinematic interpretations and point out open problems and our ongoing research.

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Introduction

The Alps and the Apennines are two mountain ranges in Italy that belong to the central-western Mediterranean region. For a long time, differences and transition between the two ranges, both at least partially facing to the Po Plain, have been discussed considering them as independent geological domains. On the contrary, they represent part of a continuous Alpine orogenic system derived from a complex space-time interaction between the two major European and African plates, and intervening oceanic domains and minor microcontinents. Past and present-day geological features of the Alps/Apennines junction area show structures and sedimentation history associated with complex interfering processes developed during the successive stages of growth of the different segments of the orogenic system related with subduction frames which changed and reversed during time.

The relationships between the Western Alps and the Northern Apennine represent, therefore, a classical and still debated problem in the geology of the Central Mediterranean which finds in the NW parts of the Italian peninsula a topical ground of discussion.

In particular for the junction area, the following general aspects are worth pointing out:

- presence of tectonic units with similar lithostratigraphic features and comparable structural evolution;
- at least in part coeval age of tectonic events and deformations;
- superficial continuities of tectonic units across the Western Alps/Northern Apennine boundary.

These features were partially derived from a paleogeographic heritage of the Alpine and Apenninic realms which were laterally continuous and shared the rifting and the drifting stages of the Ligurian Tethys (Elter 1975; Piccardo 1977; Laubscher and Bernoulli 1977; Stampfli *et al.* 1998; Manatschal and Bernoulli 1999; Rampone and Piccardo 2000; Lemoine *et al.* 2001; Piccardo this volume), the ocean which during the Late Mesozoic separated paleoEurope from the southern paleocontinent Adria/Apulia (the “Africa promontory” of Argand 1924). The diachronous closure of this ocean (Dal Piaz 1974; Hunziker and Martinotti, 1984; Laubscher, 1988; Dewey *et al.* 1989; Polino *et al.* 1990; Stampfli *et al.* 1998; Lemoine *et al.* 2001; Michard *et al.* 2002; Schmid *et al.* 1996, 2004; Beltrando *et al.*, 2010 and references; Dal Piaz this volume) during Cretaceous to Eocene and the following Oligocene/Miocene Europe/Adria collision characterized the evolution of the Alps and the early stages of evolution of the Apennines, while the opening of the Provençal basin in the Oligocene and that of the Tyrrhenian sea from the Middle Miocene (in the wake of retreating Adria subduction) represent the key events of the Apenninic evolution (Elter *et al.* 1975; Laubscher 1971, 1988; 1991; Scandone 1979; Doglioni 1991; Rosenbaum and Lister, 2004; Schettino and Turco, 2006, Argnani, 2009).

The dynamic evolution of the orogenic system(s) and the geometric and kinematic interactions between the two chains are problems still under investigation.

Presently, two opposite contrasting interpretative models are under debate (for a more detailed overview see Molli, 2008 and Vignaroli *et al.* 2008):

1) According to some authors, the Alps and the Apennines are related to two coeval and opposite-dipping subduction (east-vergent or “alpine” and west-vergent or “apenninic”) active since Late Cretaceous. Major objections to this interpretation concern the structures and evolution of Alpine Corsica and the recognition of the boundary element(s) between the Alps and the Apennines;

2) Alternatively, diachronous east-vergent “alpine” subduction (Late Cretaceous-Middle Eocene) was followed by west-vergent apennine (Late Eocene-onward) subduction. Subduction flip and complex space and time interactions between only partially independent orogens characterize this group of models. The timing, way and causes for reversal of subduction represent major points of discussion.

The present models of the Alps/Apennines relationships derive from more than one century of research which will be briefly outlined hereafter to provide a historical perspective on the treated problem (see Gelati and Pasquarè, 1970; Castellarin, 1994; 2001 for a more complete historical presentation).

In the 19th century the topic was principally faced from a lithologic point of view highlighting the presence of mainly metamorphic rocks as characteristic of the Alps, in contrast to widespread exposures of sedimentary rock-types in the Apennines. In this frame the Sestri/Voltaggio line (east of Genoa) was soon recognized as the possible surface boundary between the two chains. With the recognition of nappe architecture for the Alps (Argand, 1924) some authors suggested also the identity of some structural elements in the two orogens (Pennidic domain of the Alps correlated with metamorphic units exposed in some tectonic windows in the Northern Apennine e.g. Staub, 1933). Subsequently, structural elements such as folds and orogen-scale vergences, together with large scale geometry and general lithostratigraphic features, were quoted as the main distinction between the two chains. In particular it was pointed out that western vergences are characteristic of the Alps, whereas the opposite i.e. eastern vergences can be observed in the Apennines.

The contributions of Elter *et al.* (1966); Laubscher (1971), Scholle (1970), Boccaletti *et al.* (1971), Haccard *et al.* (1972); Sturani (1973), Elter and Pertusati (1973), Dal Piaz (1974), Debelmas (1975), Alvarez *et al.* (1974) and Grandjacquet and Haccard (1977) were the first to analyze in modern terms the relationships between the western Alps and the Northern Apennine, laying the basis for present research on the subject.

In the 80’s, papers by Treves (1984) and Principi and Treves (1985), expanding on former propositions of Scholle (1970) and Scandone (1979), presented the interpretation of the Apennine as an accretionary wedge and suggested the presence of a wide east-west-striking, distributed zone of deformation north of the Voltri Massif. For the authors this domain accomodates the displacement between the opposite-dipping Alpine (i.e. eastward) and Apenninic (i.e. westward) subduction zones, drawing a direct comparison with the present convergent setting of New Zealand.

Laubscher (1988, 1991), Polino *et al.* (1992); Schumacher and Laubscher (1996); Polino *et al.* (1994); Piana (2000); Mosca *et al.* (2009) underlined the nature of the problem for the boundary between the Alps and the Apennines in its 3D-kinematics.

Doglioni (1991), Doglioni *et al.*, (1998) and Carminati *et al.*, (2004) make an overall comparison foregrounding the general distinct characters of the two chains in terms of both geological and geophysical expression and the different positions of basal décollement, very deep in the Alps and more shallow in the Apennines. These general features are related to the deep geometry of underlying subduction following or opposing the “eastward” undulated mantle flow (Doglioni *et al.*, 1999). Within this general model they underlined the problem in terms of the time interference between the southern prolongation of the Alps and the Apennines, with incorporation of segments of the former in the inner side of the latter, although no detailed analyses or definition of the boundary problems were ever attempted.

The surface boundary between the Alps and Apennines has been traditionally placed along the Sestri Voltaggio Zone or the Sestri Voltaggio Line (Cortesogno *et al.*, 1979; Cortesogno and Haccard, 1984; Hoogerdujn Strating, 1991). The Sestri Voltaggio Zone is a km-wide north-south oriented structural domain which includes different metamorphic tectonic units in contact with unmetamorphic units (historically ascribed to the Northern Apennine). Several interpretations for this structural domain have been proposed. The Sestri Voltaggio line was interpreted as a transform fault kinematic boundary between Alps and Apennine (Scholle, 1970; Elter and Pertusati, 1973; Sturani, 1973; Ten Haaf, 1975), as a thrust fault, which juxtaposes rocks from different crustal levels (Cortesogno and Haccard 1979, Cortesogno and Haccard, 1984; Capponi, 1991; Castellarin, 1994), as a dextral strike-slip fault (Giglia *et al.*, 1996, Crispini 1996, Crispini and Capponi 2001) or transpressional oblique-slip fault (Spagnolo *et al.* 2007, Crispini *et al.* 2009) and extensional detachment (Hoogerdujin Strating, 1991; 1994; Vignaroli *et al.*, 2008; 2009). Miletto and Polino (1992) considered the Sestri/Voltaggio zone a major backthrust zone of Alpine units above Apenninic ones. Crispini (1994); Crispini and Capponi (2001); Capponi and Crispini (2002); Crispini *et al.* (2009) describe the details of the tectonics of the zone and suggest an evolving structural significance from early nappe contacts to the more recent Oligo-Miocene age shallow crustal reactivations.

Sturani (1973) and Elter and Pertusati (1973) were the first to point out that whatever was the original significance of the Sestri-Voltaggio Zone, the sealing of the basal Tertiary Piemonte Basin (TPB) on the internal structures of the Sestri Voltaggio zone, the Ligurian Alps and parts of the Ligurian units implies a subordinate role of the Sestri-Voltaggio zone in the Alps/Apennines kinematics. They also indicated in the Villalvernia-Varzi-Ottone-Levanto line (Elter and Pertusati, 1973) the kinematic boundary between metamorphic and unmetamorphic units originally part of the pre-Late Eocene Alpine orogen (dominated by western vergences) and other Ligurian units with “only Apenninic eastward” history. They firstly introduced the idea of a complex interference between two evolving orogenic systems.

Relations between the Western Alps and the Northern Apennines are deeply related with another classical issue in Alpine geology, the origin of the tight curvature of the Western Alps, a crucial point for any kinematic restoration and paleogeographic reconstruction on the inner side of the Alpine belt (e.g. Gougel, 1963; Laubscher, 1971; Debelmas, 1986; Giglia *et al.*, 1996; Schmid and Kissling, 2000). The main question, faced in different contributions (e.g. Argand, 1916; Gougel, 1963; Laubscher, 1971; Debelmas, 1972; Elter and Pertusati, 1973; Debelmas, 1986; Malavieille *et al.*, 1984; Chouckroune *et al.*, 1986; Ricou and Siddans, 1986; Laubscher, 1988; Lacassin, 1989; Vialon *et al.*, 1989; Platt *et al.*, 1989; Hoogerdujin Strating *et al.*, 1991; Vanossi *et al.*, 1994; Giglia *et al.*, 1996; Schmid and Kissling, 2000; Ford *et al.*, 2006) is whether the shape of the Western Alps arc simply derives from a torsion superimposed on a more linear chain, or it reflects an inherited pre-collisional physiography later tightned during the Alpine orogeny.

Geological setting and deep structures

Any attempt to analyze the relationships between the Western Alps and the Northern Apennines implies a definition and understanding of the present geometries and tectonic setting of various geological domains as well as the successive kinematic stages of retrodeformation of structures only locally directly observable (Laubscher, 1971; Elter and Pertusati, 1973; Laubscher 1988; 1991; Polino *et al.*, 1993; Schumacher and Laubscher, 1996; Mosca *et al.*, 2009 and references therein).

As a matter of fact, the junction area between the two chains includes three major geomorphological domains (Figs. 1-4), each largely composite from a geological point of view, corresponding to:

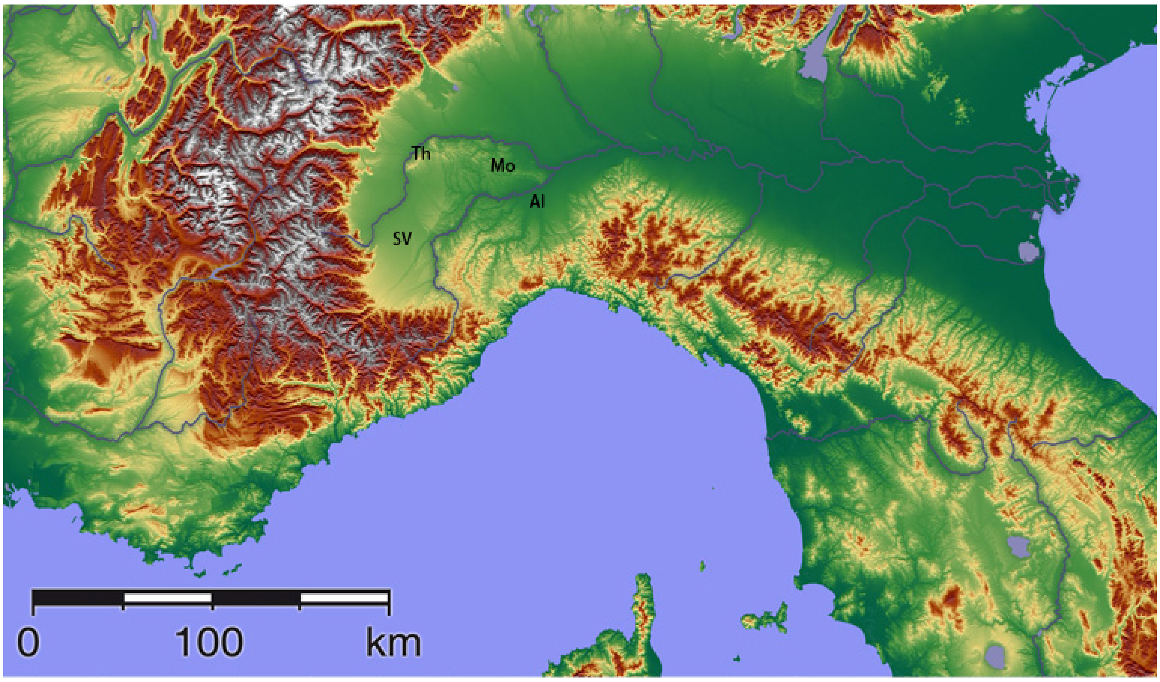
- a south-western undersea region, the Ligurian Sea --belonging to the Liguro-Provençal basin and to the Northern Tyrrhenian sea--;

- an “S-shaped” mountain range formed by the Cottian-Maritime, Ligurian Alps and the northern sector of the Apennines;

- a north-eastern region comprising former exhumed sectors of the orogenic belt partially subsided during Oligocene-Miocene (to form the so-called Tertiary Piemonte basin) and during the Neogene to form foredeep basins resting on Adria Mesozoic carbonate successions and covered by thick alluvial sediments of the present Po plain.

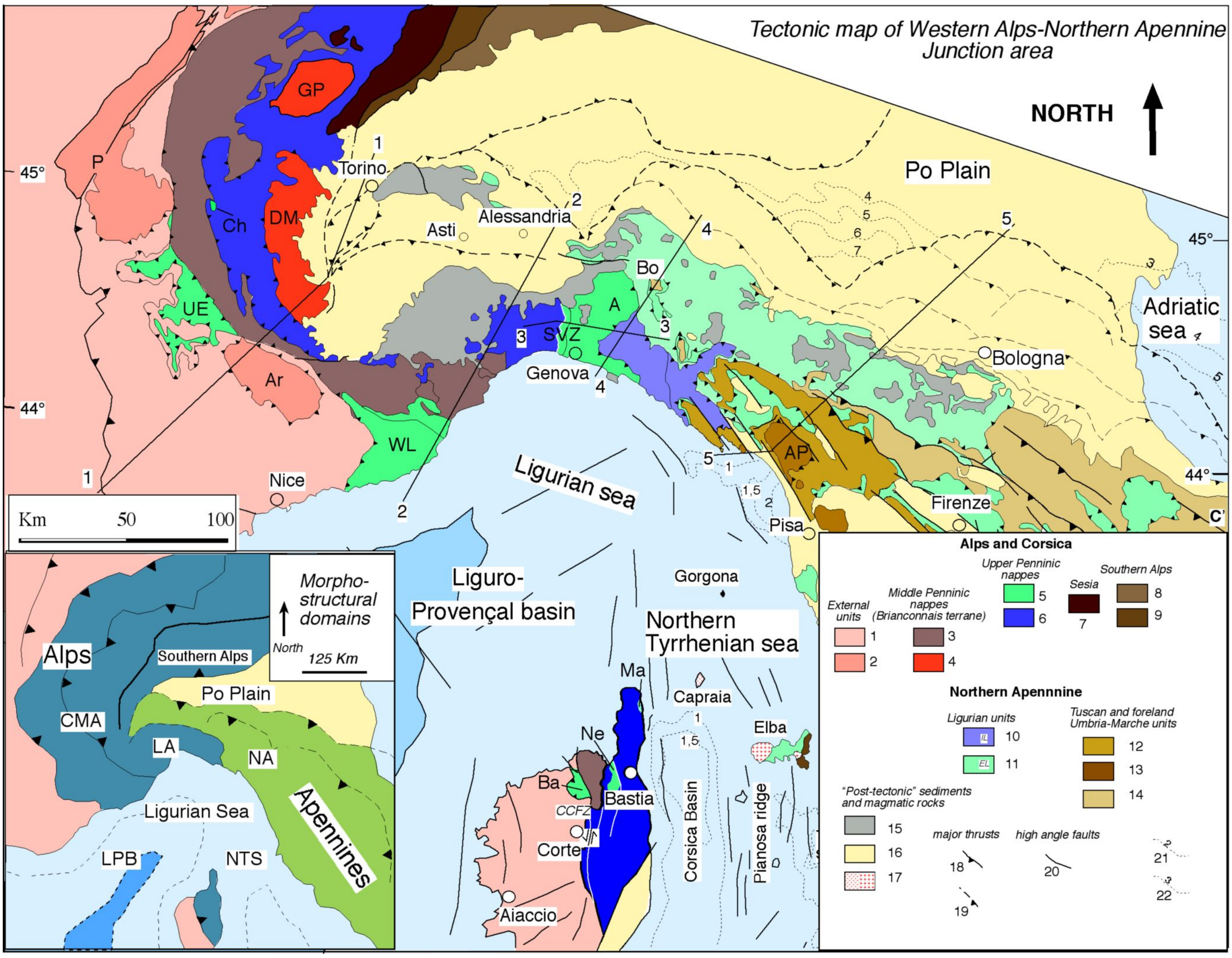
Structures in all the three geological domains record, at different degrees, the interfering relationships between two growing and evolving orogens as described below.

Figure 1. Relief image of north west Italy and adjacent region.



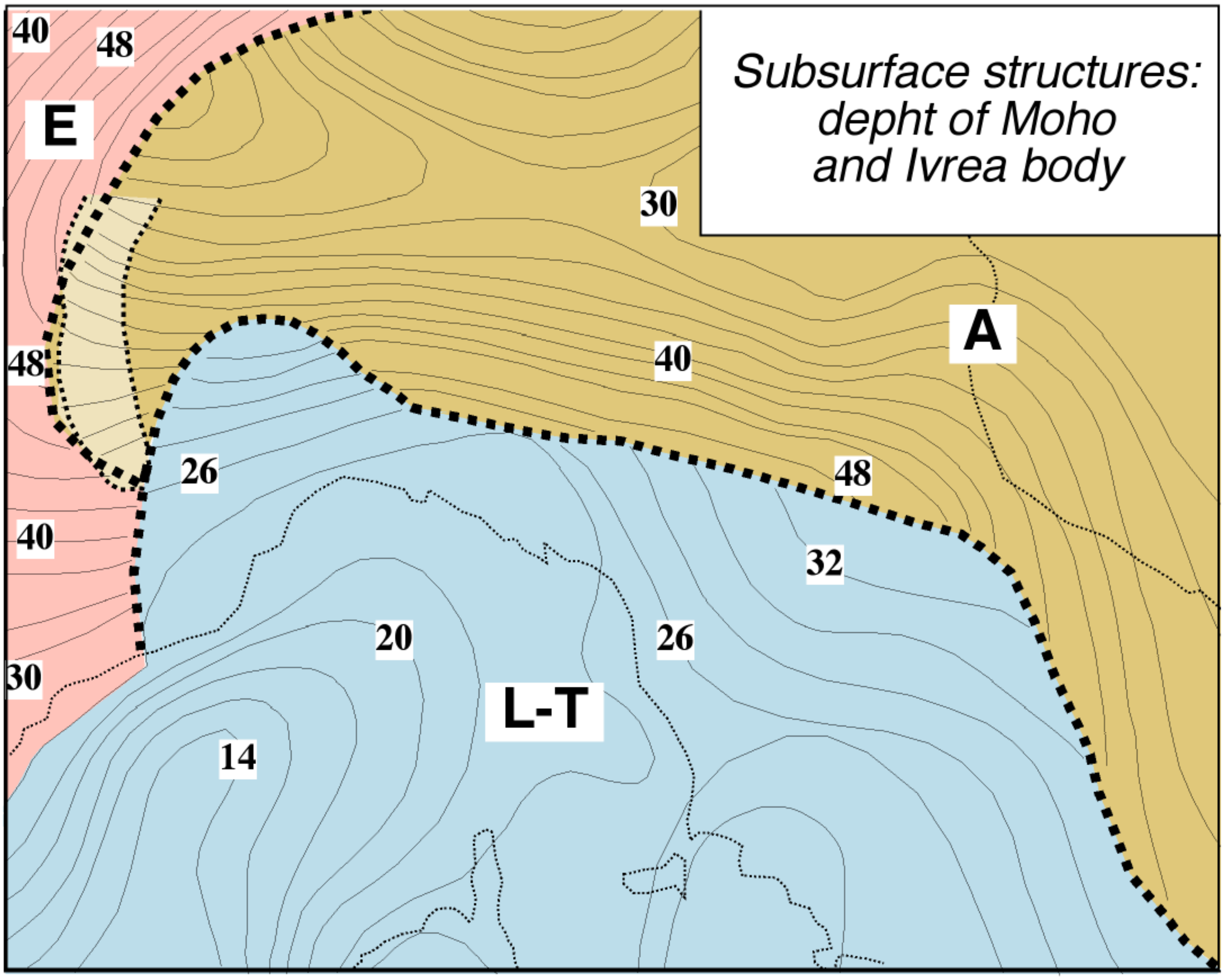
(after Wikipedia commons; http://commons.wikipmedia.org.wiki). AL, Alessandria basin; La, Langhe hills; MO, Monferrato hills;, SV, Savigliano plain; TH, Torino, hills.

Figure 2. Tectonic map of Western Alps/Northern Apennine junction area, with inset of the main structural domains of the system.



In the inset: CMA Cottian-Maritime Alps; LA Ligurian Alps, NA Northern Apennine; LPB Liguro-Provençal basin (dark blue oceanic crust); NTS Northern Tyrrhenian sea. In the map the main tectonic and lithostratigraphic units of the system are shown. For the Western Alps: (1,2) Europe-derived external Alpine units and external part of Corsica. 1) Alpine foreland units; (2) External massifs (Ar, Argentera and P, Pelvoux); (3) Middle Penninic Briançonnais nappes in the Alps and the Tenda unit in Corsica (4) Middle Penninic Internal Massif (DM, Dora Maira and GP, Gran Paradiso); (5) Upper Penninic Helminthoid Flysch: UE, Ubaye-Embrunais, Western Liguria Helminthoid Flysch (WL) and the Antola unit (A). With the same color are also represented the ophiolitic non-metamorphic unit of Chenaillet (Ch) and Sestri Voltaggio Zone (SVZ) and in Corsica Balagne (Ba), Nebbio (Ne) and Macinaggio (Ma) units; (6) Schistes Lustrés composite nappe system; (7) Sesia and related units ("lower Austroalpine nappes"); (8) Adria lower crust of the Southern Alps (Ivrea); (9) Adria upper crust basement and cover of the Southern Alps; Northern Apennine: (10) Internal Ligurian units, IL; (11) External Ligurian units (EL) and SubLigurian (Canetolo) units; (12, 13, 14) Adria-derived Tuscan and external foreland Umbria-Marche units; (12) Tuscan nappe; (13) Tuscan metamorphic units; (14) Cervarola and Umbria-Marche foreland units; (15) Post-tectonic cover of Tertiary Piemontese basin and Epiligurian units; (16) Neogene and Quaternary sediments of Po Plain and inner Tuscany (17) Magmatic rocks of Southern Tuscany, volcanic and intrusive bodies; major thrusts at surface (18) and in subsurface (19); (20) high angle normal and trascurrent faults; (21) sediment thickness in seconds TWTt for the Tyrrhenian Sea; (22) Pliocene isobaths (in Km) in the Po Plain and Adriatic sea.

Figure 3. Map of crust-mantle configuration of the Western Alps/Northern Apennine junction area.

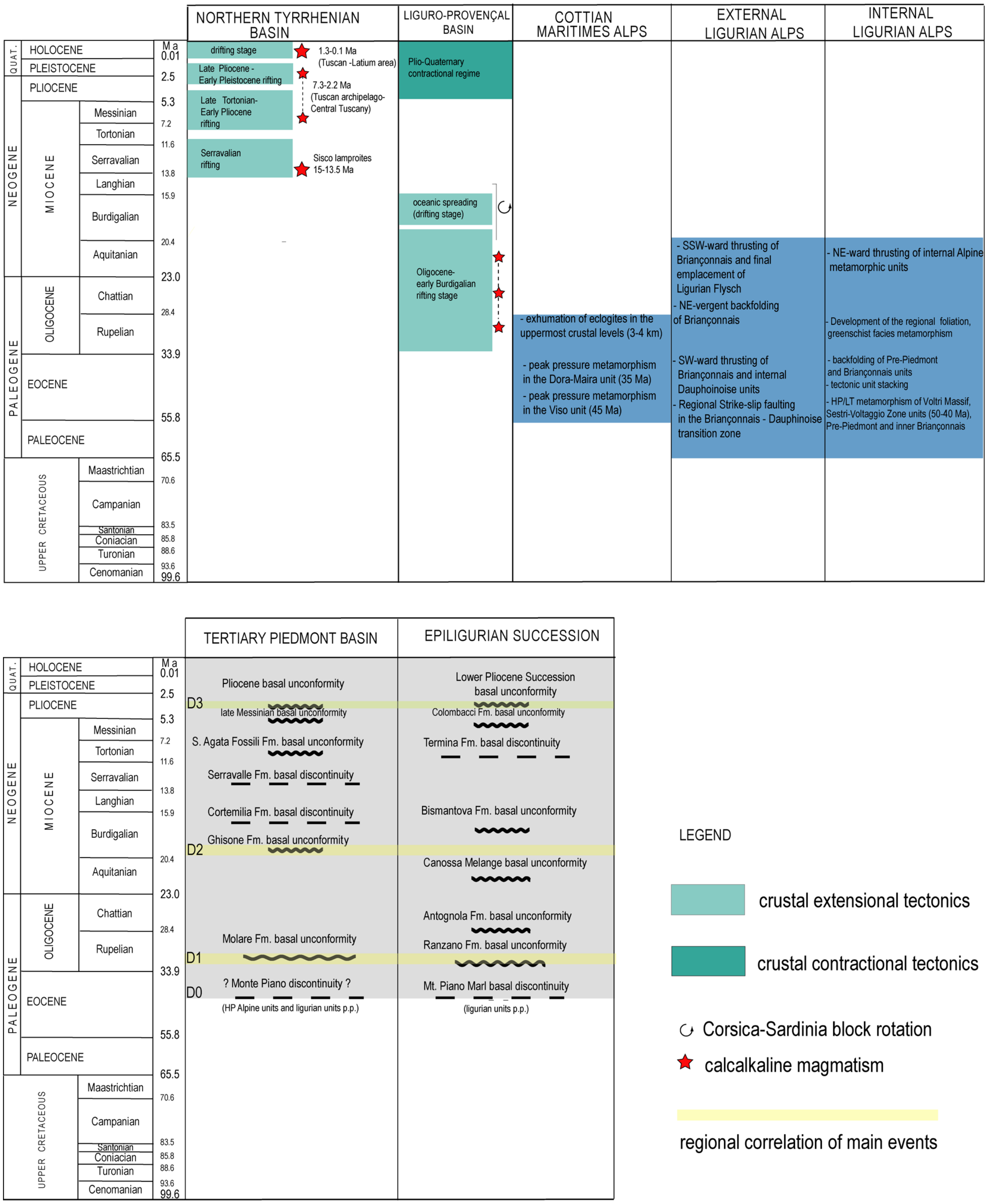


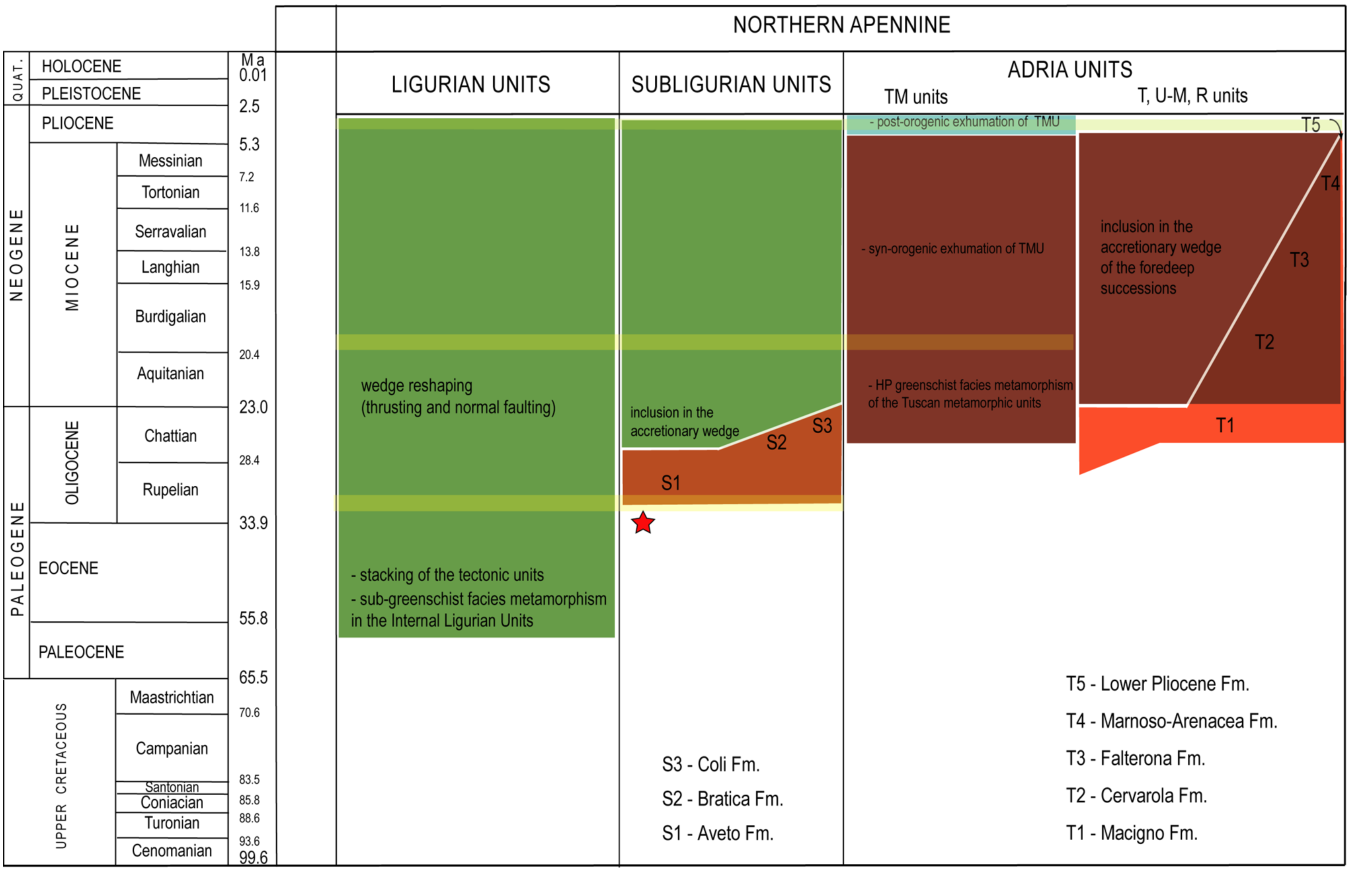
Contour intervals of 2 Km. Dashed lines indicate the limits between the European (E), Adriatic (A) and Ligurian-Tyrrhenian (L-T) Mohos. The Ivrea geophysical body is also reported. From Lanza, 1984; Laubscher, 1988; Cassinis *et al.*, 2002, Waldhauser *et al.*, 1998; Schmid and Kissling, 2000; Scafidi *et al.*, 2009 and references therein.

The 3D Moho configuration of the junction area (Fig. 3) also reflects this complex evolution and it is characterized by three Moho sub-interfaces (Solarino *et al.*, 1997; Waldhauser *et al.*, 1998; Dezes and Zigler, 2002; Cassinis *et al.*, 2002; Scafidi *et al.*, 2009): the European Moho, southward dipping; the Adriatic Moho, characterized by updoming below the Po plain, shallow northward dip in the north and a southward underthrusting below the Apennines; the Ligurian Moho located at shallow depth beneath the Ligurian sea and the Apennines with a slightly north-dipping attitude and further south, the Tyrrhenian Moho.

A significant element in the deep structure of the area is represented by the Ivrea body (Fig.3), which is geophysically defined as having: high density and magnetic susceptibility, seismic velocity and positive Bouger anomaly corresponding to material of lower crust or upper mantel origin (Lanza, 1984; Solarino *et al.*, 1997; Scafidi *et al.*, 2009). This is in agreement with its surface correlative represented by ultramaphic rocks of lower crustal and upper mantle origin exposed just south of the Insubric line in the Central Alps (Lanza, 1984; Solarino *et al.*, 1997; Ford *et al.*, 2006; Schmid and Kissling, 2000; Schmid *et al.*, 1996; Scafidi *et al.*, 2009).

Figure 4. Age of the main geological events in the domains of the of Western Alps/Northern Apennine junction area.





TM units: Tuscan Metamorphic units; T, U-M, R units: Tuscan, Umbro-Marche and Romagna units.

JVE subscribers can download a full size version of figure 4 at http://virtualexplorer.com.au/article/2010/215/apennine-alps/media/figure04-full.png.

The south-western domain: the Liguro-Provençal and Northern Tyrrhenian basins

The south-western domain includes an undersea region geologically belonging to two different provinces: the Liguro-Provençal basin and the northern part of the Tyrrhenian basin (Fig.1,2,4).

Both basins are presently interpreted by most authors (for alternative views see Boccaletti *et al.*, 1982) as Late Oligocene to Miocene back-arc basins developed in relationships with Apulian westward subduction and eastward slab retreat (Patacca and Scandone, 1989; Doglioni, 1991). These basins are therefore parts of the Northern Apennine geodynamic system, since they developed during its successive stages of evolution (Gueguen *et al.*, 1998; Faccenna *et al.*, 1998).

The rifting stages in the Liguro-Provençal basin are dated to Oligocene to Early Miocene (Aquitanian–early Burdigalian) and are associated with important calcalkaline magmatism on land (Lustrino *et al.*, 2008). The following oceanic spreading (drifting stage) occurred in the Burdigalian (19–16 Ma) with formation of an atypical oceanic crust (Gueguen *et al.*, 1998; Fanucci and Morelli, 2003; Rollet *et al.*, 2002) characterized by discontinuous tholeitic volcanic edifices settled within the exhumed mantle, related with slow-to very slow (less than 1-2 cm/yr) tectonically controlled oceanic spreading (Chamot-Rooke *et al.*, 1999; Rollet *et al.*, 2002). The drifting stage and oceanic accretion were associated with the anticlockwise Corsica-Sardinia block-rotation of 30° (Speranza *et al.* 2002; Maffione *et al.*, 2008) or 45-50° (Gattacceca *et al.*, 2007). The rotation occurred after Aquitanian and was essentially completed at about 15 Ma according to Gattacceca *et al.* (2007). A third of the total amount of rotation occurred at a rate of c.15°/Ma between 20.5 and 18 Ma (Rehault *et al.*, 1986; Gattacceca *et al.*, 2007)

It is important to notice that the (trans-) extensional processes of the Liguro-Provençal basin partially occurred in an area previously forming the external southern zone of the Pyreneean range (whose north-westward continuation is not well defined) where orogeny had stopped c.10 Myr earlier (Seranne 1999; Lacombe and Jolivet 2005).

The present day tectonic activity of the western part of the domain (westernmost part of Liguro-Provençal basin) is characterized by contractional reactivations of previously developed extensional structures in relationship with ongoing tectonics of the southwestern Alps (e.g. Eva and Solarino, 1997; Bigot Cormier *et al.*, 2006; Sue *et al.*, 2007; Larroque *et al.*, 2009).

The south-eastern segment of the domain geologically belongs to the Northern Tyrrhenian Sea which separates the Northern Apennine from Corsica and is subdivided into two main parts (Figs. 2 and 4): a western domain—the Corsica basin—and an eastern one— the Tuscan shelf, separated by the north–south elongated Elba–Pianosa Ridge (Bartole *et al.* 1991; Carmignani *et al.* 1995; Mauffret and Contrucci 1999; Pascucci *et al.* 1999; Cornamusini *et al.* 2002).

The north/south structures are poorly defined in their northern prolongation and the general structural trends turned to north-west/south-east in the eastern Ligurian sea. The major structure in the eastern side is represented by the Plio-Quaternary Viareggio basin (Fanucci and Nicolich, 1984; Bernini *et al.*, 1990; Argnani *et al.*, 1997)

The Northern Tyrrhenian Sea developed since early Middle Miocene with the rifting of the half-graben of the Corsica basin and then since Late Tortonian (Middle–Late Miocene) with the rifting of the eastern part of the Tuscan shelf.

The formation of Miocene and younger basins was associated with magmatism which also shows an eastward-younging trend between Middle Miocene and Quaternary. Sisco lamproites (alkaline sills) in eastern Corsica represent the oldest magmatic rocks (15–13.5 Ma), while intermediate age magmatism (7.3–2.2 Ma) characterizes the intrusive and volcanic bodies of the Tuscan Archipelago and Central Tuscany (e.g. Capraia, Elba, Giglio, Orciatico, Montecatini Val di Cecina). The easternmost and recent (1.3–0.1 Ma) magmatism can be found in the Tuscan–Latium area at Mt. Cimini, Mt. Vulsini, Mt. Amiata and Larderello (Civetta *et al.* 1978; Lavecchia and Stoppa 1990; Serri *et al.* 1993; Musumeci *et al.* 2002; Rosenbaum and Lister, 2002; Conticelli *et al.*, 2009 and this volume).

The "S-shaped" mountain range

The junction area between the Alps and the Apennines includes an "S-shaped" mountain range formed by the Cottian and Maritimes Alps (the southern part of Western Alps), the Ligurian Alps and the northern sector of the Apennines (Fig.2).

The Cottian and Maritime Alps (CMA)

The Cottian-Maritime and the Ligurian Alps consist of several tectonic units that can be stratigraphically referred to the major paleogeographical domains of the western Tethys. From WSW to ENE they are the European continental margin; the Briançonnais/sub-Briançonnais domains (distal part of the European continental margin or independent terrane according to different interpretations e.g. Lemoine *et al.*, 2001 ; Stampfli *et al.*, 1998 ; Schmid *et al.*1996, 2000) and finally the Ligurian oceanic realm.

The external zones of the orogen in the Cottian and Maritime Alps are exposed west of the Frontal Briançonnais Fault (FBF). They comprise a foreland thrust system, forming the Digne and Castellane-Nice arcs, which consist of Eocene-Oligocene foreland basin sequences floored by thick Mesozoic carbonates of the Dauphinois domain (Sinclair, 1996; Ford *et al.*, 1999). These sediments lay on a Variscan basement exposed in the Argentera Massif (Bigot-Cormier *et al.*, 2006), and are in turn overlain by the very-low-grade Embrunais-Ubaye nappes, consisting of Late Cretaceous – Paleocene Piedmont-Ligurian Flysch and Helmintoid Flysch of the Parpaillon Nappe (Kerchove, 1969; Michard *et al.*, 2004).

East of the Frontal Briançonnais Fault, blueschist-to-greenschist facies units are exposed inside the so-called Briançonnais fan. The western part of the Briançonnais fan consists of Briançonnais cover sequences of Carboniferous-to-Eocene age and, in places, Subbriançonnais sequences stacked along the Frontal Briançonnais Fault (Fabre, 1961; Gidon 1962; Michard 1967; Barfety *et al.*, 1996). Peak pressure in these units never exceeds 2 GPa (Agard *et al.* 2002; Malusà *et al.* 2002; Ganne *et al.* 2006). The eastern part of the Briançonnais fan consists of Briançonnais basement units (Desmons, 1992; Malusà *et al.* 2002, Ganne *et al.* 2006), continental margin cover rocks, calcschists and ophiolites (Caron 1977; Agard *et al.* 2002; Schwartz *et al.* 2007). In the Queyras "Schistes Lustres", kilometer-scale metaophiolites slivers embedded within Mesozoic metasedimentary rocks (Lemoine and Tricart, 1986; Lagabrielle *et al.*), show increasing PT conditions ranging from LT-blueschist facies condition to the west, to transitional blueschist-eclogite facies to the east, just west of the Viso unit. These ophiolitic nappes are topped by the non-metamorphic Chenaillet ophiolites (Lemoine *et al.* 2001; Scharwz *et al.* 2007).

Higher-pressure units crop out in an innermost position in front of the Western Po Plain. The Dora-Maira unit, i.e. the southernmost Internal Crystalline Massif of the French literature, chiefly consists of metasedimentary and metagranitoid rocks (Vialon, 1966), and is classically referred to the distal European margin (Lemoine 1986, 2000) or to the northern tip of the Briançonnais-Iberia terrane (Stampfli *et al.*1998). The Dora-Maira unit displays an eclogite facies metamorphic overprint of Alpine age, locally reaching ultra-high pressure conditions as inferred in the Brossasco-Isasca slice (ca. 3 GPa at 35 Ma) (Chopin *et al.*1991; Compagnoni, 2003; Rubatto and Hermann 2001). The Dora-Maira unit is overlain by eclogite-facies ophiolites, like those exposed in the Viso unit. The Viso ophiolites reached a peak pressure >2 GPa at ca 45-40 Ma, and were exhumed (see below) at shallow crustal level at ca 20 Ma (Cliff *et al.* 1998; Messiga *et al.*, 1999; Schwartz *et al.* 2000, 2007; Rubatto and Hermann 2001).

The Ligurian Alps (LA)

The Cottian Maritime Alps pass southeastward to the Ligurian Alps LA through a composite fault zone boundary described below. The Ligurian Alps represent a peculiar sector of the belt where different tectonic units were distinguished (more than 20 units according to Seno *et al.* 2005a). According to paleogeographical reconstructions (e.g. Vanossi 1980; Lemoine *et al.* 1986; Stampfli 1993; Dal Piaz 1999), it may be assumed that the different tectonic units originally belonged to the continental European/Briançonnais margin(s), including part of its more distal margin (Prepiedmont of the authors), and to the Piemonte-Ligurian oceanic domain.

In the external zone of the belt (Fig.8 and see below) the units of the Dauphinois-Provençal domain of the Nice arc are directly overthrusted (in the western Ligurian Alps) by the Paleocene-Upper Cretaceous Flysch nappes subdivided from southwest to northeast into three major units: S.Remo, Moglio Testico and Alassio-Borghetto (Helminthoid Flysch nappes of Western Liguria; Vanossi *et al.*, 1984; Seno *et al.* 2005). The Helminthoid Flysches represent the top of the LA nappe stack and overthrust at their north/north-east termination (Eastern Ligurian Alps) the Prepiedmont and Briançonnais units.

The Briançonnais units are divided in External units and Internal units, composed of a Pre-Namurian basement (exposed only in the Internal units; Seno *et al.*, 2005), volcanic and continental clastic deposits (Permian to early Triassic in age; Cortesogno *et al.*, 1993; Seno *et al.*, 2005) with a detached Meso-cenozoic cover sequence. The external units display a very low to low-grade Alpine metamorphic overprint (anchizone up to greenschist facies; Seno *et al.* 2005) whereas the Internal Briançonnais units reach peak conditions up to $P \approx 1.3$ GPa and $T > 400°C$ (Cabella *et al.*, 1994).

The Prepiedmont units show a stratigraphic succession and basement features different from those of the Briançonnais thoroughly described by Dal Piaz (this volume), while the basement units are overprinted by Alpine metamorphism estimated at $P = 1.5$ GPa and $T = 550 \pm 30$ C° (Cortesogno *et al.*, 2002).

Starting since Late Eocene up to Early Oligocene, the Prepiedmont and Briançonnais units underwent a SSW-ward directed stacking (and see below), followed by an almost co-axial backfolding event, whose intensity decreases towards the outer SW sectors. A later phase (Late Oligocene-Early Miocene ?) of thrusting and associated development of large scale open folds, verging SSW, finally occurred resulting in a complex transpressional setting, with juxtaposed folded and sheared domains occurring at several scales (Gosso *et al.*, 1983; Seno *et al.*, 2005; Piana *et al.*, 2009).

The innermost units of the LA are represented by the HP-LT units of the Voltri Massif (or Voltri Group, Chiesa *et al.* 1975) and by three tectonometamorphic units (Cravasco-Voltaggio-Montenotte-CNMU, Gazzo-Isoverde-GIU, Figogna unit-FU) historically referred to as the Sestri–Voltaggio Zone (Cortesogno and Haccard 1984).

The Voltri Massif consists of two main tectonometamorphic units (Voltri Unit and Palmaro-Caffarella Unit, Capponi and Crispini, 2009) composed by high pressure metamorphic ophiolites. The ophiolites consist of serpentinites with metagabbros and metabasites, metasediments and mantle peridotites, with peak eclogite (450–500 °C and 1.3–2.0 GPa for the Voltri Unit; Messiga and Scambelluri, 1991, Liou *et al.* 1998, Federico *et al.*, 2005) or blueschist (c.a. 350-400 °C and 1.2 GPa for the Palmaro-Caffarella Unit; Desmons *et al.* 1999) syntectonic alpine metamorphism, strongly overprinted by greenschist facies fabrics (Capponi and Crispini 2002). These units show superposed deformation structures, formed at different crustal conditions. Subduction related structures are represented by eclogite facies foliation and rootless hinges of isoclinal folds, occuring all over the massif as early relic structures. Deformations linked to the exhumation and nappe stacking are represented by Na-amphibole greenschist to greenschist facies s.s. folds and schistosities. These are the most evident structures in the field and control the contacts between different lithologies (Capponi and Crispini 2002, Federico *et al.* 2009 and bibliography therein).

The last stages of the tectonic evolution in the Voltri Massif are characterized by superposed brittle-ductile and brittle structures linked to transpressional tectonics (described in Spagnolo *et al.* 2007; Crispini *et al.* 2009).

The GIU and the CVMU units are separated from the Voltri Massif by the Sestri-Voltaggio Line (Cortesogno and Haccard 1984) that at present is a steeply dipping N-S oriented km-scale fault. Most deformation predated the Oligocene, since the main structures are sealed by the Oligocene-Miocene formations of the Tertiary Piemontese Basin, even if later reactivations can be locally observed (see below). To the east the units of the Sestri-Voltaggio zone are in contact with very low-grade flysch units (Ronco, Mignanego and Montanesi Units Capponi and Crispini, 2008) and the unmetamorphosed Antola flysch unit (correlated with the External Ligurian units; Abbate and Sagri 1984 and references; Ellero, 2000; Cerrina *et al.* 2002; Levi *et al.* 2006).

The CVMU and the FU are metaophiolitic units and are re-equilibrated respectively in low-T blueschist facies (T= 300-350° C and Pmin= 0.8-1.0 GPa for the CVMU; Cabella *et al.*, 1994, Desmons *et al.* 1999) and pumpellyite–actinolite facies conditions (T= 300-350° C and P= 0.7, Desmons *et al.* 1999). The GIU comprises carbonate rocks and shales of Triassic to early Jurassic age, which attained the same blueschist facies metamorphic conditions of CMVU. The FU shows a polyphase structural evolution but developed at lower metamorphic conditions.

The timing of the high pressure metamorphic events in the internal units of the Ligurian Alps are constrained between ca. 50 Ma (eclogite facies) and 40 Ma (blueschist facies) in metaophiolitic rocks (Federico *et al.* 2005). Greenschist-facies retrogression during exhumation is locally dated at ca. 33 Ma (Federico *et al.* 2005). In the continental units of the Internal Briançonnais Early (Middle?) Eocene metasediments record blueschist facies overprint (e.g. Seno *et al.*, 2005).

The Northern Apennine (NA)

The uppermost units of the Northern Apennine nappe stack are represented by the Ligurian units. These units can be subdivided on the basis of stratigraphic and structural features into two main groups (Elter 1975) well defined in the Ligurian–Emilian Apennine (Fig.2): the Internal Ligurian Units and the external Ligurian units. The former are characterized by the presence of ophiolites and an Upper Jurassic to Lower Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with Upper Cretaceous–Paleocene turbiditic sequences (Molli, 2008 and ref.). The Internal Ligurian units are considered as remnants of the Liguro-Piemontese ocean or Ligurian Tethys. The External Ligurian Units are, on the other hand, distinguishable for the presence of the typical Cretaceous–Paleocene calcareous dominant sequences (the Helminthoid Flysch) associated with complexes or pre-flysch formations called ‘basal complexes’. According to their stratigraphic differences, two main subgroups of units can be recognized (Molli, 1996; Marroni *et al.* 1998 and references): those associated with ophiolites and with ophiolite derived debris, and others without ophiolites and associated with fragments of Mesozoic sedimentary sequences and conglomerates with Adria affinity (Sturani 1973; Zanzucchi 1988; Molli, 1996). Because of their age (Elter *et al.* 1966; Wildi 1985; Zanzucchi 1988; Gasinski *et al.* 1997; Daniele and Plesi 2000) and composition, these coarse-grained conglomerates (Salti del Diavolo Conglomerates) have been compared since the early 1970s with those of Pre-alpes Romandes (Mocausa conglomerates of the Simme Flysch) implying a common palaeotectonic setting on the distal side of the Adria continental margin (e.g. Elter 1997; Stampfli *et al.* 1998; Lemoine *et al.* 2001 and references). As a whole, the External Ligurian units can be regarded as relicts of the former ocean–continent transition area and of the distal Adria continental margin in the Apenninic transect (Molli 1996; Marroni *et al.* 1998 and references therein). The Internal Ligurian units suffered polyphase deformation and metamorphism in sub-greenschist facies conditions (prehnite–pumpellyite in metabasic rocks), whereas the External Ligurian units were deformed at shallow structural levels (diagenesis–anchizone transition in pelites).

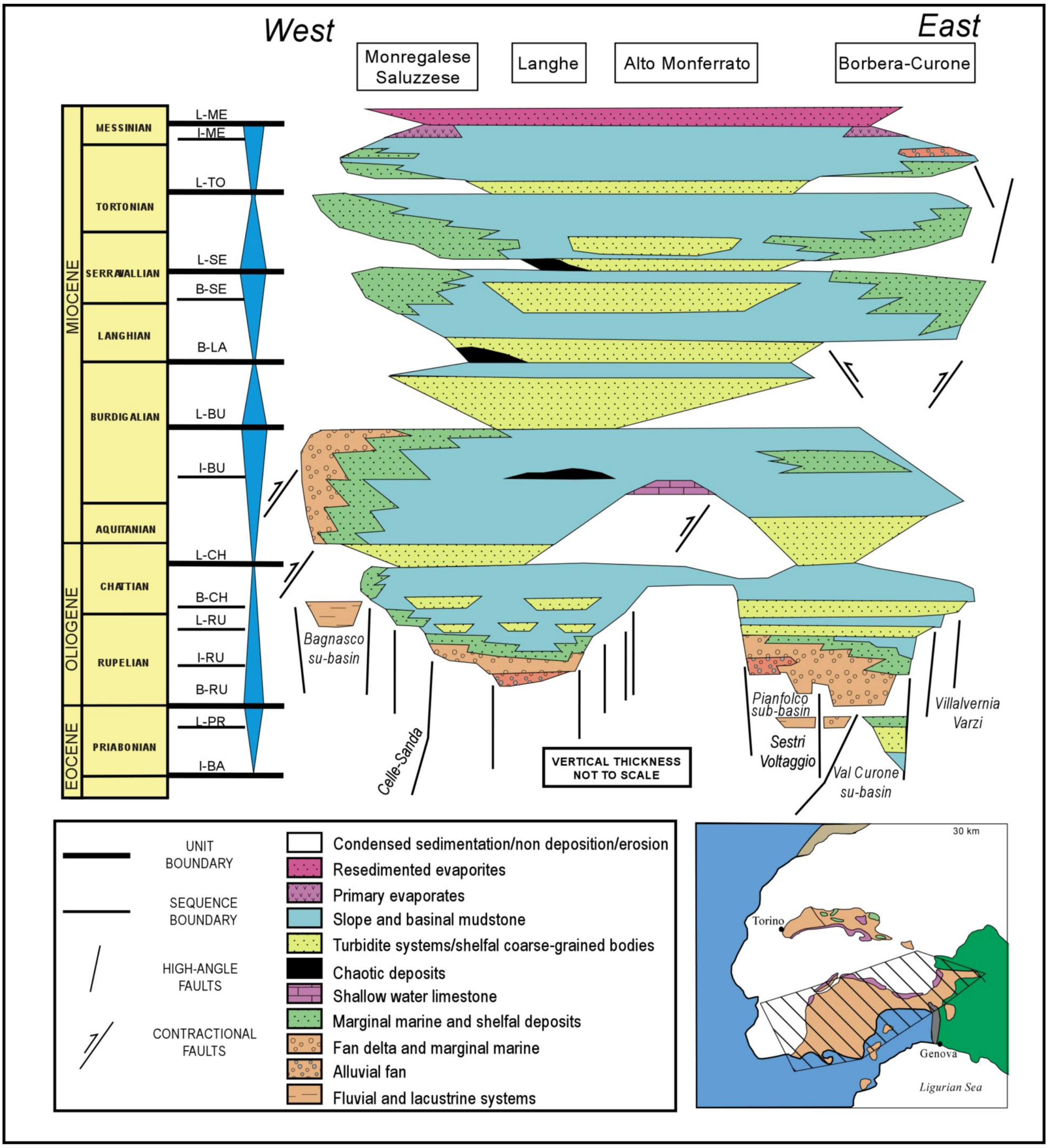
Among the Ligurian units, the Antola Nappe deserves a special mention. From the lithostratigraphic point of view, this unit can be correlated with the External Ligurian units (Abbate and Sagri 1984 and references; Cerrina *et al.* 2002; Levi *et al.* 2006), even though it occupies a structural position at the top of the Internal Ligurian units, in contrast to the other External Ligurian units which are structurally below the Internal Ligurian units. Moreover, it is classically correlated with the Helminthoid Flysch of the Ligurian and Maritime Alps and therefore played a special role during the pre-Oligocene evolution of the Alps/Apennine orogenic system (Elter and Pertusati 1973; Elter 1997; Corsi *et al.* 2001) as we will see hereafter.

The sub-Ligurian units crop out geometrically below the composite Ligurian system and are characterized by a strong thickness variability at the regional scale. The sub-Ligurian units are represented (Plesi 1975; Cerrina Feroni *et al.* 2002 and references therein) by Cretaceous–Eocene sequences mainly formed by sandstones and shaly-calcareous deposits (Ostia–Scabiazze and Canetolo fms) followed by Oligocene–lower Miocene (Aquitanian) siliciclastic and marly deposits (Aveto–Petrignacola and Coli units). Within the Cretaceous–Paleogene sequence, unconformities and depositional hiatuses (Vescovi 1993, 1998) of Early, Middle and Late Eocene age are documented, whereas volcanoclastic deposits with calc-alkaline affinities (the Aveto–Petrignacola fm.) are dated to the lower Oligocene. For its age and composition, the Aveto–Petrignacola fm., has been associated with calc-alkaline volcanic centres located on the inner (Adria) side of the Alpine belt (Boccaletti *et al.* 1971; Ruffini *et al.* 1995; Cibin *et al.* 1998).

The original substratum of the sub-Ligurian units is unknown, although it can be considered transitional between the oceanic Ligurian and continental Tuscan domains and probably characterized by a thinned continental crust like part of the External Ligurian domain (Ghiselli *et al.* 1991; Cerrina Feroni *et al.* 2002). The lower Oligocene–Aquitanian part of the sequence can be connected with the early accretional and thrust top basins of the Apennine wedge and bears similarities with siliciclastic turbidites at the top of the Tuscan units. The sub-Ligurian units were deformed at shallow structural levels (anchimetamorphic conditions in pelites, Cerrina *et al.* 1985) starting from Rupelian (*c.* 30 Ma) (Cerrina *et al.* 2002, 2004 and references). Below the sub-Ligurian units lie the so called Tuscan units which are representative of the former proximal side of the Adria continental margin (i.e. the Tuscan Domain). These units are formed by continental successions subdivided into different thrust sheets, some of which were deformed at shallow structural levels (e.g. the Tuscan nappe), whereas others were more deeply involved in the collisional stack and metamorphosed during Late Oligocene-early Miocene (Kligfield *et al.*, 1986; Monie *et al.*, 2000) in high- and medium-pressure greenschist facies conditions (up to 0,6-0,8 GPa and 450 °C in the Alpi Apuane and 1 GPa and 350 °C further south in the Montagnola Senese-Argentario Theye *et al.*, 1997; Giorgetti *et al.*, 1998; Molli *et al.*, 2000; Liotta, 2002), forming the so-called Tuscan metamorphic units. These units crop out (Fig. 5) in tectonic windows forming an arcuate belt from P. Bianca in the north through the Alpi Apuane, M. Pisani, Montagnola Senese and M Romani in the south, along the so-called Mid-Tuscan metamorphic ridge. The stratigraphic evolution of the Tuscan sequences testifies the sedimentation on a passive continental margin during Mesozoic rifting and post-rifting stages related with the Ligurian ocean opening (Bernoulli *et al.*, 1979; Bernoulli, 2001; Ciarapica and Passeri, 2002). Sedimentary response to regional-scale contraction and tectonic inversion is recorded during the Cretaceous and Eocene within the Scaglia fm. where conglomerates and unconformities can be observed (Fazzuoli *et al.*, 1994). The sedimentary history in the Tuscan domain ends during the Oligocene and Early Miocene with siliciclastic turbidites (Pseudomacigno and Macigno) interpreted as clastic wedges of Apennine foredeep and wedge top basins. Umbria-Romagna-Marche units are well exposed in the southernmost outer Northern Apennine where they are characterized by Jurassic to Palaeogene carbonates and Mio-Plio-Pleistocene marine clastic sediments deposited in a foredeep and/or in wedge top basins which evolved during thrusting. These units are mainly represented in outcrop exposure by a turbiditic clastic wedge (Marnosa–Arenacea fm. and Laga fm.)

deformed as a classical foreland fold and thrust belt (Calamita *et al.*, 1994; Tavarnelli, 1997; Coward *et al.*, 1999; Barchi *et al.*, 2001).

Figure 5. Wheeler diagram showing the stratigraphic framework of Tertiary Piedmont Basin.



From Rossi *et al.*, 2009: principal and minor sequence boundaries, major syndepositional tectonic elements, lithostratigraphic units and gross facies distribution are shown. Unconformities (from bottom to top): B-PR, base Priabonian; I-PR, intra-Priabonian; L-PR, Late Priabonian; B-RU, base Rupelian; I-RU, intra-Rupelian; L-RU, Late Rupelian; B-CH, base Chattian; L-CH, latest Chattian; I-BU, intra-Burdigalian; L-BU, Late Burdigalian; B-LA, base Langhian; B-SE, Base Serravallian; L-SE, Late Serravallian; L-TO, Late Tortonian; I-ME, intra-Messinian; L-ME, Late Messinian. See Rossi *et al.*, 2009 for a detailed description of unconformity-bounded units.

Late- to post-orogenic sediments (Late Eocene to Pliocene in age) of continental to shallow marine origin can be locally observed lying unconformably on the Helminthoid Flysch units in the northern part of the belt where they form the so called Epiligurian units (Elter 1975) as illustrated below. Further south, other Late- to post-orogenic sediments (Oligocene to Pliocene in age) form basins within the Northern Tyrrhenian realm and Southern Tuscany (Cornamusini *et al.*, 2002; Brogi *and Liotta*, 2008.

The north-eastern domain

The north-eastern domain includes the Po Plain and the marine realm of the Adriatic sea further south-east (Figs. 1,2). The Po Plain identifies a *c.* 500 Km long east-west trending Neogene basin, bordered to the north by the south-vergent fold and thrust belt of the southern Alps, and to the south by the north/north-east vergent structures of the Apennines (Roure *et al.*, 1990; Mosca *et al.*, 2009).

The western termination of the Po Plain in spite of its name shows a very changing geomorphology. From the geomorphological point of view it can be subdivided into a few main provinces (Fig.1): the hilly systems of the Torino Hill-Monferrato to the north and of the Langhe to the south, where Upper Eocene-Oligocene to Miocene rocks are exposed, together with their interposed Savigliano and Alessandria plains, in turn separated by the Asti hills (Fig. 1,2,5).

The Upper Eocene-Oligocene to Miocene successions outcropping in the present map view (Fig.5) record partially different tectono-depositional histories, but they belonged to a single Cenozoic depositional realm, which in this paper will be referred to as Tertiary Piedmont Basin (TPB). The northern outcrops (Monferrato and Torino Hill areas of the literature) are described below as the northern Tertiary Piedmont Basin to distinguish them from the southern ones (Monregalese, Langhe, Alto Monferrato and Borbera-Curone areas of the literature) of the southern Tertiary Piedmont Basin. The primary lateral continuity of the northern and southern TPB successions as well as their relationships are masked by Pliocene to Holocene successions, that fill the Savigliano and Alessandria depocenters (Mosca, 2006).

As identifiable in Fig.5 and 6, the south TPB sediments unconformably rest on nappe-stack of the LA and non-to-low metamorphic Ligurian units. They are characterized by siliciclastic deposits (reaching thickness on the order of 4000 m in its central-western part), and form at the regional scale a gentle north-westward dipping monocline showing great facies variability. Upper Eocene deposits are preserved only locally to the east (Borbera-Gruea area) and consist of mudstones (Monte Piano Marls) upward followed by quartz-rich turbidites (Pizzo d’Oca) and shelf to marginal-marine facies (Rio Trebbio unit) (Cavanna *et al.*, 1989; Di Giulio, 1989; Mutti *et al.*, 1995; Di Giulio and Galbiati 1995).

In the southern TPB, continental to transitional facies are characteristic of Upper Eocene-Lower Oligocene successions (Lorenz 1969; Cavanna *et al.*, 1989, Ghibaudo *et al.* 1985; Gelati *et al.* 1993; Mutti *et al.* 2002; Rossi *et al.*, 2009); shelf to slope marly successions with turbidites were deposited during Late Oligocene and Early Miocene times (Cavanna *et al.*, 1989, Ghibaudo *et al.* 1985; Gelati *et al.* 1993; Mutti *et al.* 2002; Rossi et al, 2009) followed by development of shelfal environments in the Early Burdigalian (Alto Monferrato area: d’Atri, 1990; Piana *et al.*, 1997).

By contrast, the northern TPB shows more condensed successions on locally outcropping Ligurian Helminthoid Flysch units (Elter *et al.*, 1966; Sturani, 1973a). These Helminthoid Flysch units show the same general characters of the External Ligurian units originally deposited from the distal stretched side of the Adria continental margin. In general, lowermost portions of these outcrops consist of basinal mudstones (Monte Piano Marls), followed in the Oligocene-Miocene by shallow water clastic and carbonate facies (e.g. Clari *et al.* 1995; Dela Pierre *et al.* 2002a); relative coarse-grained facies significantly characterize the western outcrops (Torino Hill area e.g. Bonsignore at al. 1969; Sturani 1973), resting on a buried south-verging South-Alpine belt (Mosca 2006; Mosca *et al.* 2009).

The uppermost portions of the outcropping TPB strata are represented by widespread homogenous marly sediments of Tortonian age, and by discontinuous evaporites and lagoon clays recording the Messinian salinity crisis, often in form of chaotic and/or resedimented assemblages (Irace *et al.*, 2005; Dela Pierre *et al.*, 2002b).

In present outcrop exposures, lowermost Pliocene deposits are typically represented by marine clays followed upward by Pliocene sand-rich marginal marine and Pleistocene to Holocene continental successions (Boni, 1984; Carraro, 1996 and references therein).

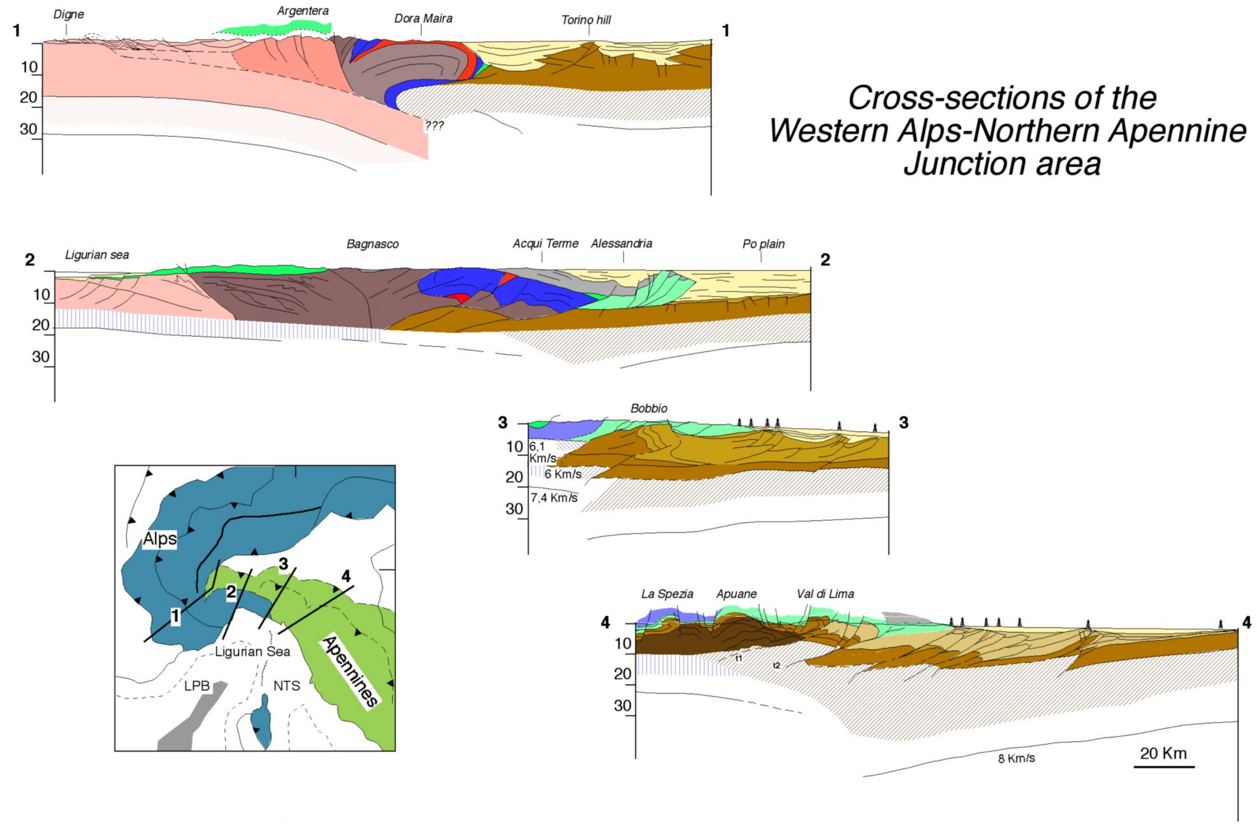
So, the present configuration of the WPP implies that the 3D tectono-depositional evolution of this area must be necessarily reconstructed considering features of present-day outcrops as well as their buried prosecutions, namely integrating field and subsurface data as will be seen later on.

Western Alps/Northern Apennine junction area: structures.

Relevant shallow and deep structures across the Western Alps/Northern Apennine junction area are illustrated through geological cross-sections of Figs. 6 and 9.

Cross-section 6.1 is representative of the Cottian Maritime Alps the southernmost segment of the Western Alps, and to the north/northeast includes the present day Po Plain domain and its subsurface features. The cross-section is mainly based on Ford *et al.* (2006) and Mosca *et al.* (2009) and includes some geological data derived from the “Geo-France 3-D”in Lardeaux *et al.* (2006), Bigot Cormier *et al.* (2006), Larroque *et al.* (2009).

Figure 6. Regional cross-sections across the Western Alps and Northern Apennine junction area.



Traces of the cross-sections in Figure 2. 6.1) from Digne to the Po plain. Mainly based on Ford *et al.* (2006), Mosca *et al.* (2009), Lardeaux *et al.* (2006), Bigot Cormier *et al.* (2006), Larroque *et al.* (2009); 6.2) from the Ligurian Sea to the Western Po Plain (modified after Mosca 2006). Structural data for the western side mainly came from Bigot Cormier *et al.*, 2002, 2006; Piana *et al.*, 2009, whereas for the N/NE side mainly from Piana *et al.*, 2009; Rossi *et al.*, 2009. Depth of Moho is from Waldahauser *et al.*, 1998; Cassinis *et al.*, 2002; cross-section across the Bobbio window after Molli (2008) and based on subsurface data in Biella *et al.* (1987); Cassinis *et al.* (1990); Laubscher *et al.* (1992); Cassano *et al.*, (1986); Toscani *et al.* (2006) and geological data contained in Elter *et al.* (1992); Labaume (1992); Bernini *et al.* (1997); Cerrina *et al.* (2002); Cross-section 6.4 (after Molli, 2008) is traced across the Alpi Apuane window. It includes data of Cassano *et al.* (1986); Labaume (1992); Castellarin (1992, 2001) for the external part and surface geology of Carmignani *et al.* (1978); Molli *et al.* (2000, 2002) and Molli and Vaselli (2006). Colors as in Fig.2.

In the SW part of the section below the Argentera Massif is drawn as a crustal blind thrust (Bigot Cormier *et al.*, 2006; Larroque *et al.*, 2009 and references) splaying southwest within the decollement level of the Triassic evaporites of the Castellane and Nice area. Deep-seated thrusting below the Argentera has been invoked to explain the denudation rate since 10 Ma with increase at 3.5 Ma in association with reverse and strike-slip faulting (see below) along the Argentera-Bersezio and Frama Morte fault zones Bigot-Cormier *et al.* 2006; Larrouque *et al.*, 2009). Deep-seated thrusting of the Ivrea-body is drawn according to Roure *et al.*, 1990; Ford *et al.*, 2006; Béthoux *et al.*, 2006; Larroque *et al.*, 2009). In the cross-section the Ivrea body extends below the Dora Maira which directly overlays its roof at *c.* 10 Km of depth. The Ivrea body played the special role of buttress during early collision of the European and Adriatic plates and those of indenter during later evolution (Laubscher, 1988; Roure *et al.*, 1990; Schmid and Kissling, 2000; Lardeaux *et al.*, 2006).

In the northeastern part of the section, complex interference between thrusts with opposite vergence produced the pop-up structure and the antiformal shape of the Torino Hill where well recognizable south-verging thrusts acting until Burdigalian time were followed by north-verging thrusts controlling the present northward translation of TPB over the Po Plain foredeep. Along the internal side of the metamorphic Alpine axial sector, the section shows the westernmost occurence of the non-metamorphic Ligurian units, buried by TPB succession. The Ligurian units progressively thin out from their eastern outcrop exposure toward the south between metamorphic units and the southwestern extension of the Adriatic units.

Cross-section 6.2 is representative of the “LA/NA” domain, which is characterized at surface levels by Alpine tectonic structures developed above a “Ligurian” Moho. The cross-section depicts the double-vergent transpressive system of the Ligurian Alps, that on the NE-side caused the superposition of slices of the metamorphic Alpine belt onto the Adria crust, with involvement of Ligurian non-metamorphic units (Helminthoid Flysches) and synorogenic Oligocene-Early Miocene terrigenous sediments of the Tertiary Piemonte Basin (see below), while on the SW side it induced, since Early Oligocene times, the stacking of the Ligurian Brianconnais thrust sheets, detached above the European-Ligurian crust, and the SW-vergent thrusting of Ligurian Brianconnais onto the Dauphinoise domain, with coheval superposition of Helminthoides Flysch at the top of the Ligurian Alps stack.

Cross-section 6.3 is traced across the Bobbio window, one of the most significant structures of the north-west Apennines. In the Bobbio window the Tuscan foreedeep deposits of the Bobbio Fm. are exposed below a composite system of Ligurian and subLigurian units. The Bobbio Fm. (upper Chattian-Burdigalian; Catanzariti *et al.*, 2002) can be subdivided into a lower member (Brugnello Shale) which is made of mudstones with intercalations of thin-bedded and fine grained sandstones, and an upper member (San Salvatore Sandstone) consisting of thick alternations of thick-bedded and coarse grained sandstones and sequences showing lithologies similar to those of the Brugnello Shale. The pre-foredeep deposits are represented by the Marsaglia Complex (Labaume, 1992) formed by debris flow breccias and olistoliths reworking Subligurian wedge-derived elements. The Bobbio Fm., together with the underlying Marsaglia Complex, is structured according to a kilometer scale syn-sedimentary NE-verging syncline developed at the front of the Early Miocene submarine thrust front of the Ligurian and SubLigurian wedge (Labaume, 1992). Stratigraphy, age and structural features of the Bobbio Formation allowed a direct correlation with the Early Miocene Cervarola foredeep system of which the sandstones outcropping in the Bobbio window would represent the northwesternmost outcropping extension (Reutter and Schluter, 1968; Plesi, 1975; Labaume, 1992). The cross-section is mainly based on available geological data contained in Elter *et al.* (1992); Labaume (1992); Bernini *et al.* (1997); Cerrina *et al.* (2002) and references; refraction seismic interpretations of Biella *et al.* (1987); Cassinis *et al.* (1990); Laubscher *et al.* (1992); and borehole-controlled reflection profiles for the external area (Cassano *et al.* 1986; Toscani *et al.* 2006). The southwestern part of the section is characterized by two crustal scale thrusts. The westernmost thrust which brings a 6-6.1 Km/sec layer to a depth of 5 Km is connected at the surface with the subLigurian overthrust surface (Molli, 2008). The layer, overlain by Ligurian nappes (Antola, Internal and External Ligurian units) can be interpreted as related to sub-Ligurian and External Ligurian basement. The first activation of this thrust which shows out-of-sequence relationships post-dating the synsedimentary emplacement of the Sub-Ligurian unit on top of the Bobbio Fm. can be constrained as post-Early Burdigalian (Labaume 1992; Elter *et al.* 1992). The second thrust displaces the top of Mesozoic Adria carbonates (reflector with velocity of 6 Km/sec) and bounds in subsurface the Bobbio composite structure. The development of the Bobbio crustal antiform produced the final emplacement (Tortonian in age) with eastward sliding away from the crest of the antiform of the Ligurian units on top of middle Miocene (Serravallian) sandstone reached in the Ponte dell'Olio deep hole (Elter *et al.* 1992 and references, Toscani *et al.* 2006). Along the profile the Moho gently dips west reaching a depth of c.40 Km southwest of Bobbio where it rises abruptly to a shallower position in the Ligurian-Tyrrhenian basin (Laubscher *et al.* 1992; Castellarin 1992, 2001).

Cross-section 6.4 (modified after Molli, 2008) is traced across the Alpi Apuane window. It includes data of Cassano *et al.* (1986); Labaume (1992); Castellarin (1992, 2001) for the external part and surface geology of Carmignani *et al.* (1978); Molli *et al.* (2000, 2002) and Molli and Vaselli (2006). In the cross-section the top of basement dips eastward from the Alpi Apuane metamorphic complex and reaches c.10 Km of depth east of the Val di Lima fold (Carmignani and Kligfield 1990; Argnani *et al.* 2003). The basement below is subdivided into two parts: the upper one is considered part of the Tuscan metamorphic units exposed in the Alpi Apuane, whereas the lower is interpreted as an external slice analogue of the basement reached in an Agip hole (Pontremoli hole) north of the Alpi Apuane (Anelli *et al.*, 1994; Montanini and Molli 1999; Molli, 2008). This second basement slice is floored by a thrust (t2) whose activity could be Tortonian to Messinian in age and overlies the more external basement and cover thrust sheets. The two internal crustal thrusts (t1 and t2) which correspond to the "Apuan Alps" and "Abetone" thrusts of Boccaletti and Sani (1998) are here considered as having a component of motions out of section, as structural data in their surface splays seem to indicate (e.g. Plesi *et al.* 1998; Cerrina *et al.*, 2002). Along the profile, the Moho is gently west dipping reaching a depth of c.50 Km and jumps to a shallower position in the Tyrrhenian Moho (references in Pialli *et al.* 1998; Castellarin 2001; Scafidi *et al.*, 2010).

Boundary Faults

Figure 7 presents the boundary fault zones playing a major role during the interaction between the evolving Alps and Apennines orogenic belts. In the scheme are also included some fault zones showing an ongoing seismic activity related with present-day tectonics.

Moving from the south/western to north-north/eastern zones and from younger to older structures the different fault systems are indicated with kinematics (where well-defined) also reported.

South-western Fault Zones: The boundary between the CMA and LA

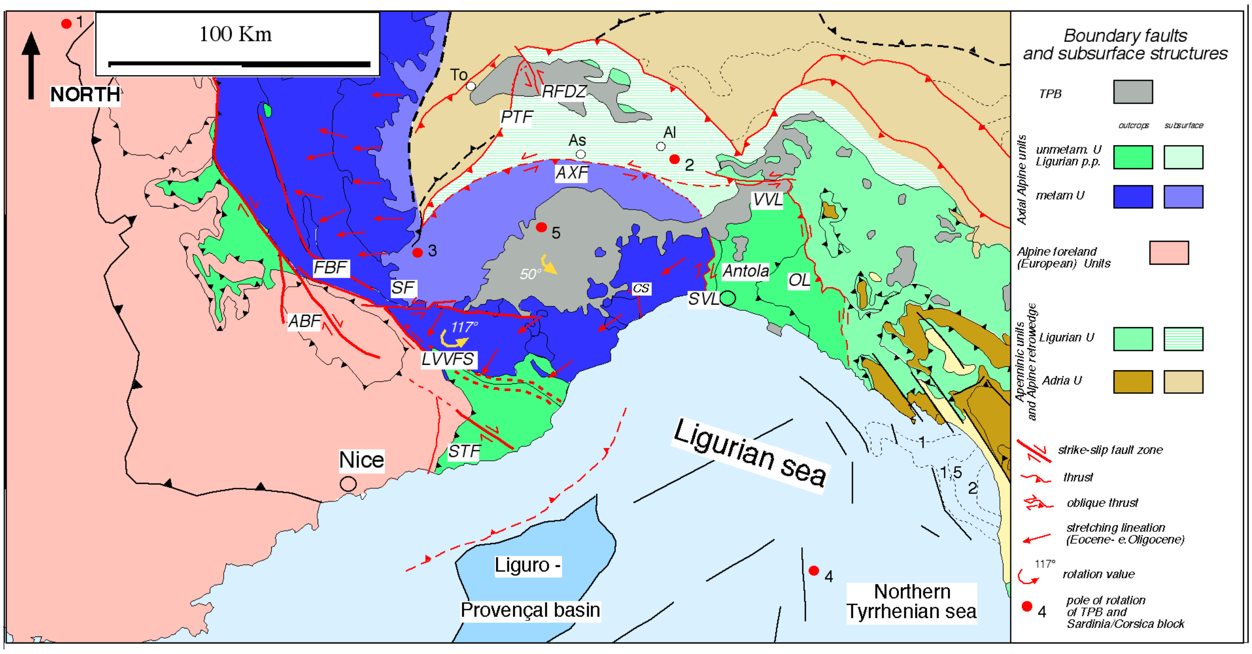
Since the early '70s, many authors invoked a Oligocene-onward, E-W sinistral strike slip fault zone placed at the southern boundary of the arc of the Western Alps, in the Maritime Alps (Laubscher, 1971; Guillame, 1980). Evidences of this major strike slip zone were documented by Ricou (1981) and Lefebvre (1983) along the so-called "Couloir de la Stura", where sinistral strike-slip displacement along a N110 fault zone (Stura Fault, SF and associated Preit and Frama Morte lines) affected the Mesozoic-Lower Oligocene succession that rests on the NE boundary of the Argentera Massif. The successions involved in the km-thick fault zone are steeply dipping and partially overturned to NE, while the net displacement of the fault zone, that locally merges with the Penninic Front, could be of the order of tens kilometers. The role of the Stura Fault have been underlined later by Ricou and Siddans (1986), Giglia *et al.* (1996) and Bigot-Cormier *et al.* (2006) who strongly remarked the role of strike-slip tectonics in the formation of the Alpine orogenic belt. Other evidences of transpressive, NE-vergent deformations along the Stura couloir were reported by Perello (1997) that documented the local overthrusting of Argentera massif onto the Stura valley Brianconnais succession and the lower Oligocene Annot sandstones.

More recently, Piana *et al.* (2009) described another km-scale, ESE-WNW transpressive fault zone (Limone-Viozene deformation zone) placed some kilometers to the south east of the Stura Fault eastern termination, that runs for many kilometers roughly along the boundary between the Ligurian Brianconnais and Dauphinois-Provencal domains. This seems to be a major sinistral transpressive zone active since the first Alpine tectonic stage of the external Ligurian Alps, although important later dextral reactivations occurred along several individual minor faults of the zone.

E-W strike-slip faults and shear zones are present along the boundary between the External and Internal Brianconnais units (i.e. the Verzera Fault zone, Piana *et al.*, 2009) and within the Internal Brianconnais, suggesting a possibile prolongation of the fault system in more eastern sectors and maybe in the Celle-Sanda fault zone that marks the boundary between the continental crust slices of the “Savona Crystalline units and the internal Ligurian Alps of the Voltri Unit meta-ophiolites (as inferred by Mosca *et al.*, 2009).

In this work, the Oligocene-Neogene kinematic boundary between the Western Alps arc and the Ligurian Alps is thus individuated in a wide corridor bounded to the north by the Stura Fault-Penninic Front, and that comprehends the E-W strike slip faults of Ligurian Brianconnais, the Limone-Viozene sinistral transpressive zone, the boundary faults of the NE side of the Argentera Massif (Bersezio Fault, Tricart, 2004; Bigot-Cornier *et al.*, 2006, the Bagni-Vinadio Fault, Perello *et al.*, 2000; Baietto *et al.*, 2009) and other minor faults such as the Saorge-Taggia fault that allowed since Early Oligocene an indipendent kinematics of Ligurian Alps with respect to the Maritime-Cottian Alps, with sinistral regional main transfer in the Oligocene followed by dextral movements in Late Miocene-Pliocene up to now.

Figure 7. Boundary faults and subsurface structures across the Western Alps/Northern Apennine junction area.



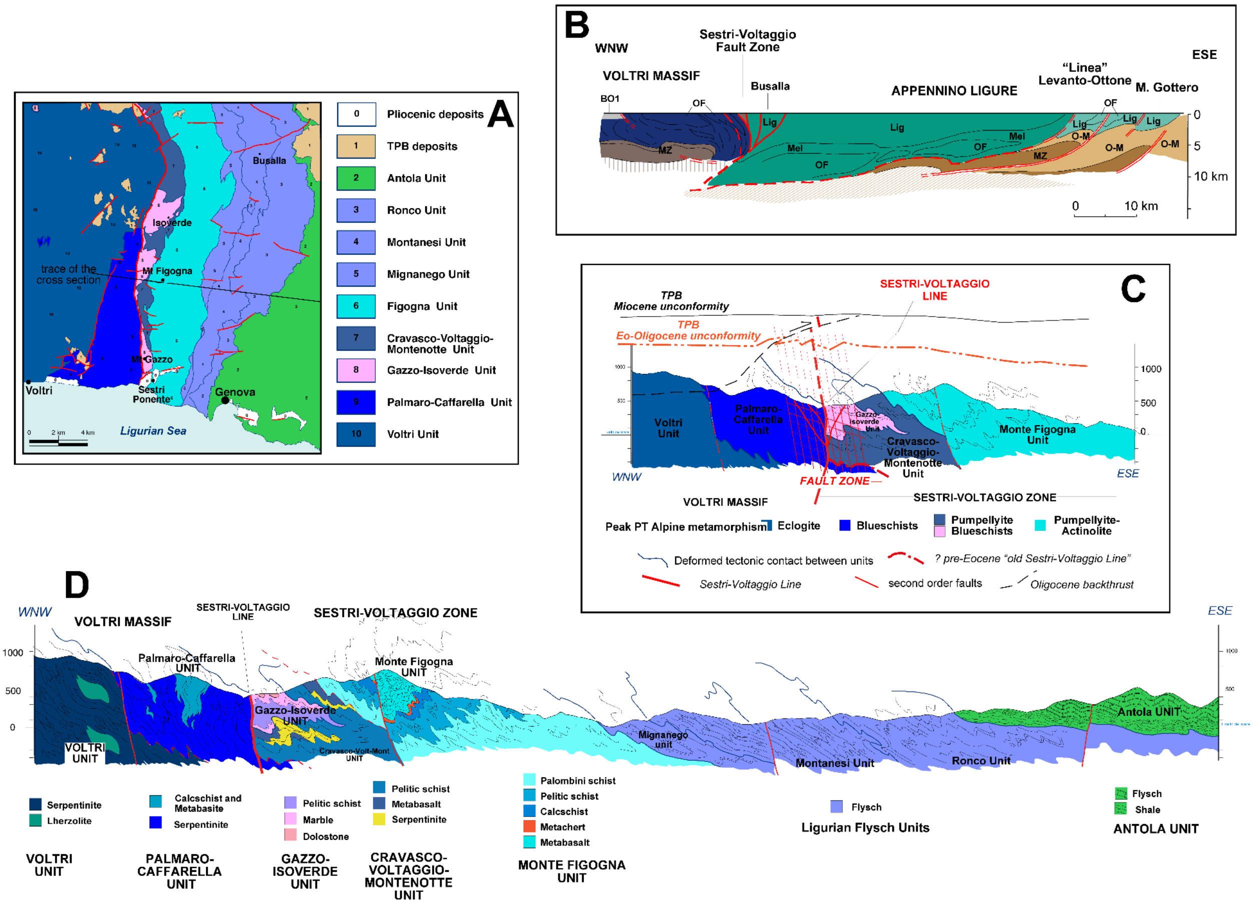
The figure reports the alpine foreland European-derived units; the inner Alpine nappe stack with metamorphic and unmetamorphic upper units (the same colors are used for the Alps s.s. and for their southern prolongation e.g. Ligurian Alps and Northern Apennine p.p.); Alpine retrowedge and the Apenninic units. All unit-types are reported in outcrop and subsurface occurences. Argentera Bersezio Fault System; CS, Celle Sanda; FBF, Frontal Briançonnais Front; LVVFS, Limone, Verzera, Viozene Fault System; OL, Ottone Levanto Line; PTF, Padane Frontal Thrust; RFDZ, Rio Freddo Deformation zone; SF, Stura Fault; STF; Saorge Taggia Fault; VVL Villalvernia Varzi L; Trace of fault zones, thrust and oblique thrust are also reported altogether with the stretching lineations on then main exhumation related foliation (Mid Eocene-early Oligocene in age) (after Menardi Noguera, 1988; Crispini and Capponi, 2001; Carminati, 2004; Seno *et al.*, 2006). Rotation value (after Collombet *et al.*, 2002; Maffione *et al.*, 2008 and references) are reported with the poles of rotation for Corsica-Sardinia and BTP basin according to different authors: 1) Elter and Pertusati, 1973; 2) Vanossi *et al.*, 1994; 3) Laubscher, 1988, 1991; 4) Rehault *et al.*, 1984; 5) Hogerdujin Strating *et al.*, 1994.

North-eastern Fault Zones: the boundary between the LA and NA

The AX fault (AXF)

A first order unexposed fault zone has been recently illustrated in subsurface below the Western Po Plain by Mosca *et al.*, 2009; Rossi *et al.* 2009. These authors indentified this boundary as the front of the Alpine axial sector (AXF). In this paper this medium to low angle fault zone marks the type of the present substratum of the Alps-Apennine junction (Figs. 6,7). It separates buried elements of the axial Alpine belt, here representing the northward prolongation of LA, made up of HP/LT metamorphic rocks and low grade to unmetamorphic units, (both parts of the same pre-Late–Eocene Alpine-orogenic wedge) by the Helminthoid Flysch units that constitute the bedrock of the Torino and Monferrato Late Eocene-Miocene sedimentary successions. These Helminthoid Flysch units are in physical continuity with External Ligurian units of the NA, which also overlie Adria-derived continental units.

Figure 8. Main tectono-metamorphic units.



a) Sketch showing the main tectono-metamorphic units in the area encompassing the Voltri Massif, the Sestri-Voltaggio Fault Zone and the Flysch Units of central Liguria (Ligurian Alps, see text for details). Trace of cross-section in Fig. 8d is shown; in red the main faults; b) General crustal scale cross section through SVZ and the sourronding domains redrawn and modified after Biella *et al.*, 1988; c) Symplified cross-section of the area close to the Sestri-Voltaggio Fault Zone. This can be considered as a high strain zone (Crispini *et al.*, 2009) characterized by intense shearing and fracturing. The "old Sestri-Voltaggio Line" is interpreted as an early nappe contact, later reworked at shallow crustal levels. A regional backthrusting (top to E-NE) phase involves both Oligocene TPB successions and the metamorphic basement; 8d) WNW to ESE cross-section (modified from Capponi and Crispini, 2008 - Foglio GENOVA 1:50.000) showing the simplified structural architecture at very shallow level of the area across the innermost units of the Ligurian Alps (Voltri Massif, Sestri-Voltaggio Zone and Flysch units).

The Padane Thrust Front (PTF)

The PTF is a South-dipping reflector sealed by Pleistocene sediments that marks the northern boundary of the Helminthoid Flysch units and their overlying Torino Hill and Monferrato successions, and separates them from the Tertiary and Mesozoic sediments resting on the subsurface Adria basement. The PTF is mostly a blind thrust whose vertical projection at surface roughly corresponds to the geomophologic southern boundary of the Po plain.

Between the AXF and PTF, several transpressive km-scale fault zones developed during Oligocene and Miocene times, controlling the physiographic features of the evolving sedimentary basins, as well as sedimentation rates and provenance and deposenter migration; among these structures, at least two (the Rio Freddo Deformation Zone and the Villalvernia-Varzi Line) are to be described hereafter in some detail.

The Rio Freddo Deformation Zone (RFDZ)

The RFDZ (Piana and Polino, 1994; 1995; Piana, 2000) marks the boundary between Torino Hill and Monferrato areas. The RFDZ and its minor associated structures strongly controlled the sedimentary evolution of the Oligocene syn-orogenic basins of the north-TPB at least until the Early Burdigalian, in a prevalent strike slip tectonic regime, transtensional during the Early Oligocene and transpressive in late Oligocene-Early Miocene (Dela Pierre *et al.*, 2003; Festa *et al.*, 2005).

The Villalvernia-Varzi Line (VVL)

The VVL line is a E-W trending high angle fault zone which, along the Staffora Valley (Oltrepò Pavese area), separates the clastic successions of the eastern TPB unconformably overlying the Antola Unit, to the south, from the Epiligurian Succession and the underlying Ligurian stacks at the top of Tuscan tectonic units of the Bobbio window, to the north (Figs.6,7). It is considered a fault with main sinistral strike slip movement developed during a synsedimentary activity recorded in the TPB and Epiligurian basins. Biella *et al.* (1988) recognized its subsurface features characterized by a steep attitude bounding at southwest the Tuscan foredeep units of the Bobbio tectonic window. Mosca *et al.* (2009) and Rossi *et al.* (2009) describe the VVL as a high-angle fault system characterized by an original extensional behavior accommodating the flexural tilting close to the southern edge of Adria, and since the Oligocene reactivated as contractional fault during the N-NE verging thrusting of Apenninic Ligurian units

The main activity of the VVL is considered to be Late Oligocene-Early Miocene in age by Laubscher *et al.* (1992) (see also Schumacher and Laubscher, 1996) who interpreted it as an outstanding sinistral transfer fault zone at the southern margin of the Adriatic indenter (Laubscher, 1988; Laubscher, 1991), parallel to the Insubric Line and with an opposite kinematics. In this framework the VVL was dissected by the post-Messinian thrusting, as the Adriatic indenter appears to have been inactivated in post-Miocene times (Schumacher and Laubscher, 1996).

According to Di Giulio and Galbiati (1995) the transpressive left-lateral activity of the VVL can be constrained using the sedimentary records since the middle-late Rupelian with two main stages of activity. The first stage occured during late Rupelian, whereas the second at Chattian/Aquitanian boundary. Recent tectonic activity along the Villalvernia-Varzi Line has been argued as well as the influence of this structure on the morphology and fluvial dynamics of the area (Meisina and Piccio, 2003). The kinematic evolution of the VVL is not yet completely well defined being missing a systematic structural study. This explains why the VVL line has been also interpreted as a high angle dextral strike slip fault zone (Cerrina Feroni *et al.*, 2002).

The Ottone-Levanto Line (OL)

The Ottone-Levanto was originally defined by Elter and Pertusati (1973) as the southern prolongation of the VVL. It has been considered as the frontal thrust separating the pre-Oligocene alpine structural nappe stack of the LA and TPB by the early Miocene NA (Laubscher, 1988). After the early original proposition no detailed structural studies have been devoted to the recognition and analyses of the surface expression of such line that according to the seismic data in Biella *et al.* (1988) is here considered as a post-Aquitanian deformation zone formed by three major splays rooting in a WNW dipping thrust (Fig.8b).

The Sestri Voltaggio Zone (SVZ)

The Sestri Voltaggio Zone is a km-wide north-south oriented structural domain that includes tectono-metamorphic units of the Alpine belt and it is limited to the west by the Sestri-Voltaggio Line and to the east is contact with very low grade and unmetamorphic Ligurian units (Fig.2,8). Actually the Sestri Voltaggio Zone can be considered as a high strain zone or fault zone and it can be better referred to as Sestri-Voltaggio Fault Zone. In the present-day map view it marks the contact among units of different paleogeographic derivation and reequilibrated at different P-T metamorphic conditions (Fig.8).

The WNW to ESE cross-section of Fig.8b,c (modified from Capponi and Crispini, 2008) shows the simplified structural architecture at very shallow level of the area across the innermost units of the Ligurian Alps (Voltri Massif, Sestri-Voltaggio Zone and Flysch units). The cross-section is representative of the geometric stacking of the units, of the relationships among the units and their internal structural arrangement. The poorly exposed contacts among the tectonic units are generally steeply dipping to the east so that the HP-LT units are the lowermost units and the very low grade Flysch units the uppermost units of the tectonic pile; the Antola Unit is in the top structural position, with a low-dipping tectonic contact. At the outcrop scale, the boundaries among the metamorphic units are folded shear zones commonly reactivated by strike-slip faults with the same longitudinal trend. Moreover the area close to the Sestri-Voltaggio Line (Fig.8) can be considered as a high strain zone (Crispini *et al.*, 2009) and is characterized by intense shearing and fracturing.

Figure 8d shows a schematic insight into the tectonic features close to the Sestri-Voltaggio Fault Zone. A regional top to E-NE backthrusting phase that involves Oligocene TPB successions and the metamorphic basement is described in the LA and testifies to a major tectonic activity lasting up to the Oligocene (d'Atri *et al.*, 1997; Capponi *et al.*, 2001; Piana *et al.*, 2006. ; Spagnolo *et al.*, 2007; Capponi *et al.*, 2009). In the same way the tectonic activity of the Sestri-Voltaggio Fault Zone possibly lasted up to Late Oligocene-early Miocene as the related subsidiary structures involve the Aquitanian–Burdigalian TPB deposits (Capponi *et al.*, 2009 and references therein). The SVFZ and the backthrusts can be inserted in the same tectonic framework where SVFZ acted as a dextral tear fault in the general migration of the LA towards NE-N.

Western Alps/Northern Apennine junction area: sedimentation and tectonics within evolving basins

Hereafter we will illustrate the major constraints on the tectonic evolution of the South Western Alps/Northern Apennine junction area as deriving from stratigraphic records in the prowedge of the Southern Western Alps (SW Alpine foreland) and the present day retrowedge represented by the Po plain hinterland including the former wedge top TPB. For the Northern Apennines the evolving wedge system, wedge top basins (Epiligurian) and foredeep units will be described.

Alpine foreland

The Ligurian Alps show, unconformable on both the Brianconnais and Dauphinoise Mesozoic successions, a Mid-Late Eocene succession, known as the "Priabonian Trilogy" Auct., interpreted as deposited during the early stages of subsidence of an underfilled Alpine foreland basin (Sinclair, 1997; Allen *et al.* 1991; Ford *et al.* 1999) and made up of three formations, namely the carbonate-ramp deposits known as Nummulitic Limestone, the Globigerina Marls and Ventimiglia Flysch (Lanteaume 1958; 1968; 1990; Campredon, 1977, Varrone, 2004).

This last formation consists of a several hundred-meter thick siliciclastic turbidites, laterally equivalent of the Annot sandstones, (Stanley 1961) referred to the Priabonian – Lower Oligocene? (Vanossi 1990). A basal unconformity separates the Brianconnais-Dauphinoise Mesozoic sediments (Santonian to Campanian in age) from the Eocene ones. This discontinuity surface is characterised by evidences of subaerial exposure and can be related to a period of significant uplift, emersion and erosion of the substratum in which some hundreds meters of Upper Cretaceous strata were removed. In the Dauphinoise domain, Lutetian continental deposits of Microcodium Formation, (Faure-Muret and Fallot 1954; Bodelle and Campredon 1968, Varrone, 2004) are also present, directly above the Cretaceous unconformity.

The TPB/WPP basin

During the Late Eocene a marine transgression ("EpimesoAlpine" basin sensu Mutti *et al.*, 1995), developed soon after the inception of the continental subduction of the European/Briançonnais margin of the LA, with a deep basin developed on a substratum consisting of the former exhumed alpine nappe stack. The sediments of that basin are presently preserved at the base of the south TPB succession (i.e. Borbera-Grue area), in Monferrato. In detail, Late Eocene basinal mudstones and quartz-feldspathic arenites were deposited over non-metamorphic Ligurian substrata (D0 stratigraphic regional discontinuity of Fig. 4), and are unconformably overlain by marginal marine ophiolitic-rich sandstones (Cavanna *et al.* 1989; Di Giulio 1989; Mutti *et al.* 1995; Dela Pierre *et al.*, 2003). The present central and southern part of TPB, resting on metamorphic units, were in a more marginal setting at that time, as recorded by deposition of fluvio-lacustrine facies overlain by alluvial fan deposits (Rossi *et al.*, 2009).

During the Oligocene, at a regional scale, sediments were mainly accommodated in two complex structural depressions consisting of fault-bounded, partly coalescing depocentres, resting to the south-west and north-east respectively of a major structural divide, representing the Alto Monferrato high.

In the southern areas (i.e. the region extending from the Alto Monferrato to the Monregalese-Saluzzese), a number of minor sub-basins developed over the Alpine axial sector. More to the east a more continuous depression developed and extends to the north in the subsurface towards the Monferrato area (Mosca *et al.*, 2009; Rossi *et al.*, 2009). The deposition during Early Rupelian was typically dominated by alluvial fan-to-fan delta conglomerates overlain by a complex alternation of paralic, marginal marine and shelfal facies, resting on different types of rock substrate (D1 regional discontinuity). Since Late Rupelian, a transgression associated with the occurrence of drowning-platform unconformities led to a dramatic marginward shift, toward the south and the west, of the fluvio-deltaic systems, that were replaced basinward by shelfal gravity flow-dominated coarse-grained bodies encased in marine mudstones.

Along southern basin margins, the deposition records a SW-ward diachronism of fluvio-deltaic deposits in relation to a regional transgression from the NE (Rossi *et al.*, 2009).

The Chattian-Aquitanian succession was dominated by turbidite systems which, along the western Alpine margin (Saluzzese and Monregalese areas; Mosca, 2006, Rossi *et al.*, 2009) and the adjacent Southalpine thrust-fold-belt are overlain by a gravel-rich alluvial fan to fan-delta unit that prograded eastwards and northwards. In large part of the north TPB and south TPB, progressive drowning of the platform depositional areas occurred, and slope marly sediments were widespread. Siliceous sediments formed in Aquitanian- Early Burdigalian over large part of the TPB, as recorded in this time span in several sectors of the Central Mediterranean area.

Successively, in the Early Burdigalian, an important inversion of the basin occurred, giving origin to chronostratigraphic gaps both in the Alto Monferrato and in the north TPB sector, where carbonate shelf sediments were deposited unconformably (D2 regional discontinuity) on the Late-Oligocene –Aquitanian sediments (d'Atri 1990; Piana *et al.* 1997; Dela Pierre et al, 1995).

During the Late Burdigalian - Early Langhian, a basin-wide turbidite system was deposited, showing lap-out terminations (D2a discontinuity) and lateral fringing toward structurally-high areas located to the east (Alto Monferrato area) and to the north (Monferrato area). Since the deposition of this succession, the TPB is characterized by a more regular physiography, being a larger and more uniform basin, bounded to the north and to the south by uplifting areas. In this time, the major depocentre was located in the Langhe area.

Since the Langhian, (D3 discontinuity) major depocenters for marine and turbidite systems were progressively shifted northward below the present Savigliano and Alessandria basins (Falletti *et al.*, 1995; Mosca, 2006; Mosca *et al.*, 2009), due to the combination of marginal uplift, basinward tilting and outward progradation.

The ongoing shortening led to the progressive reduction of the sediment accomodation space until the early Tortonian (D4 discontinuity), when homogenous marly sediments were unconformably deposited in most part of the TPB.

The Messinian Salinity Crisis was superimposed to this framework and most of the evaporites were widespread resedimented as mass flow deposits (D5 discontinuity) (Dela Pierre *et al.* 2002a; Irace *et al.*, 2005; Mosca 2006; Mosca *et al.*, 2009; Rossi *et al.*, 2009).

The westerly propagation of the north-vergent structures involved the north-western TPB since Late Miocene time. The occurrence in this area of Southalpine crust at shallow levels could have represented a major obstacle to the progressive westward propagation of the north-verging thrust systems. As a consequence, the regional N-S shortening was accommodated more to the south-west, as recorded since Late Miocene by pronounced activity of the fault systems at present buried in the Savigliano basin area (Mosca *et al.*, 2009)

In this framework the Savigliano and Alessandria depocentres evolved as highly subsiding sub-basins close to the lateral ramps of the north-verging Torino Hill-Monferrato tectonic arc.

Pliocene sediments record a re-establishment of normal-marine conditions after the Messinian Salinity Crisis: clay-rich open marine facies were deposited along previous basin margins (D6 discontinuity). Sedimentation continues upward with sand-rich marginal marine deposits ranging from Early to Middle Pliocene, followed in the Pleistocene by mainly continental deposits. Pliocene and younger deposits exceed 2 km in the Savigliano and Alessandria Basin depocenters, while they are only a few hundred meters thick in their interposed Asti region.

The Epiligurian basins

North of the VVL the TPB corresponds to the basin unconformably formed onto the Ligurian Units of the Northern Apennine. The sedimentary succession deposited in this basin is known as Epiligurian Succession (Ricci Lucchi, 1986) and it is now exposed in several scattered outcrops along the Emilian side of the Northern

Apennine from the Oltrepò Pavese area to that of Bologna (Fig.2).

The deposits of the Epiligurian Succession consist mainly of terrigenous clastics even if they include facies ranging from pelagic and hemipelagic deposits to siliciclastic turbidites and to shelf sandstones and calcarenites; the whole succession shows a maximum thickness of more than 5000 m. The Epiligurian Succession is characterized by ages ranging from Middle Eocene to Late Miocene-Pliocene and overlies the at least in part already deformed Ligurian Units. Starting from the early Oligocene the evolution of the Epiligurian Succession was related to the NNE-verging migration of the Apenninic accretionary wedge, which progressively incorporated the foredeep units of the Adria continental margin (Fig.4,6).

The Epiligurian Succession was therefore affected by contractional tectonics (thrusting and folding) as well as extensional deformation (low angle normal faults) which can be related with internal dynamics of evolving NA wedge (Costa and Frati 1997; Botti *et al.*, 2006; Molli *et al.*, 2000; Di Giulio *et al.*, 2002; Molli, 2005).

From a stratigraphic point of view, the Epiligurian Succession consists of unconformity-bounded units whose boundaries (major unconformities) are strongly controlled by sub-marine tectonics which often generated slumpings and olistostromes (sedimentary melanges). Five major unconformities that define the main lithostratigraphic units (Monte Piano, Ranzano; Antognola, Bismantova, Termina, Gessoso-solfifera and Argille Azzurre formations) occur.

The sedimentation of the Epiligurian Succession began in the Middle Eocene (Lutetian p.p.-Bartonian) with marls (Monte Piano Fm) deposited in a deep marine environment (Di Giulio *et al.*, 2002), locally preceded by muddy chaotic deposits and/or sandstone turbidites (Loiano Sandstone). The overlying basal unconformity of the Ranzano Fm, which often affects the Ligurian Units, testifies the vertical movements and submarine erosion of the Ligurian wedge from the Upper Eocene to the Lower Oligocene. The Ranzano Fm. is unconformably overlyain by the Antognola fm. starting from the Rupelian (Lower Oligocene) a system of siliciclastic turbidites (sandstones and conglomerates) recording a continuous subsidence of the Ligurian wedge up to Chattian-early? Aquitanian.

During this time span the NA accretionary wedge enlarges by frontal accretion at the toe wedge e.g. within the sub-Ligurian/Canetolo system (Bratica-Salsominore and Coli-Marra units) and by underplating of the distal Adria continental margin as recorded by the Tuscan units stacking.

The unconformity at the base of Contignaco Fm. is possibly the response of a low-angle normal fault-related subsidence during early exhumation and sin-contractional stacking of deepest parts of the wedge e.g. Tuscan units (Molli *et al.*, 2002; Molli, 2005; Fellin *et al.*, 2007; Molli, 2008).

The following Burdigalian regional major basal unconformity of the Bismantova Fm. shelf deposits (upper Burdigalian-Serravalian), can be connected with a major step of the migration of the Ligurian Units onto the Northern Apennine foredeep and in particular that corresponding with the emplacement onto the Cervarola Fm. of the Bobbio tectonic window (Labaume and Rio, 1994).

The base of the Bismantova Fm. represents also the beginning of a new Middle-Upper Miocene sedimentary cycle of the Epiligurian succession; the middle Miocene-Lower Miocene depositional cycle shows an overall shallowing trend which ends with a silica-rich marly sedimentary horizon (Contignaco Fm.) that records a Mediterranean scale biogenic-volcanogenic episode correlating through all domains of the Northern Apennine (Amorosi *et al.*, 1995). The regional unconformity below the Contignaco Fm. does not correspond to the base of the siliceous zone itself, but rather to the base of widespread resedimented deposits in debris flow or turbidite facies (Canossa Melange or Anconella Sandstone), marking an important Aquitanian tectonic event which affected the Northern Apennines (Ligurian wedge emplacement above the Coli-Marra Subligurian Unit and the Tuscan Nappe Macigno Fm). The Middle-Upper Miocene sedimentary cycle of the Epiligurian succession is characterized by a shallow to deep marine cycle evolving from the Bismantova Fm. to the Termina Fm. which is characterized by mudstone slope deposits with intercalations of thick bodies of resedimented sandstones and sedimentary melanges. These features indicate that the thrust top basins (where the Epiligurian succession were deposited) felt the effect of the Ligurian wedge evolution and also the base of the Termina Fm. marks a regional discontinuity possibly connected with the progressive thrusting of the underlying foredeep units and with the unroofing and exhumation processes the Tuscan metamorhic units of the Alpi Apuane region suffered from Middle Miocene to Middle Pliocene times (Molli, 2008).

The Termina Fm. evolved upward to the Gessoso-solfifera Fm. (Messinian) which is made up of both primary and clastic, resedimented evaporites with interbedded organic-rich shales, deposited during the evaporitic and postevaporitic stages of the Messinian salinity crisis.

The overlying major unconformity in the Epiligurian succession corresponds to the base of the upper Messinian Colombacci Fm. (mainly continental clastic deposits derived from Apenninic sources with subordinate clays and marly limestones) which postdates the intra-Messinian tectonic event of the Northern Apennine evolution, correlated with the beginning of the second stage of Northern Tyrrhenian Basin rifting.

The upper part of the Epiligurian succession, overlying the Colombacci Fm., is represented by a thick (more than 1500 m) mudstone-dominated succession deposited in a relatively deep marine environment (Argille Azzurre Fm.) spanning in age from lower Pliocene to Pleistocene. The Argille Azzurre Fm presents two regional unconformities: the lower one occurred in the lower Pliocene (G. puncticulata phase; Cerrina Feroni *et al.*, 2002, 2004; see also Vai, 1992) and recorded the involvement in the accretionary wedge of the youngest foredeep deposits (Marnoso-Arenacea Fm.) and the in-sequence overlying mainly marly post-foredeep deposits of lower Pliocene age (e.g. Cella Marl and Riolo Terme Fm.). The base of the lower Pliocene sedimentary cycle is locally marked by conglomerate and sandstone bodies (Monterumici Fm.; Borello Sandstone). The top of the lower Pliocene cycle is limited by the Middle Pliocene regional unconformity, well marked in the Romagna sector also by shelf carbonate deposits (Spungone Fm.), which points to the still active tectonics (thrusting and folding deformation) of the Northern Apennines during the Middle Pliocene.

The Adriatic foredeep successions

While the alpine wedge (Penninic and Ligurian units) at the Alps-Apennines junction was buried under deepwater sediments, a foredeep formed on Adria continental crust (Menard, 1988; Doglioni, 1993). The Adriatic foredeep was initially starved (Gallare-Aveto stage of Garzanti and Malusà, 2008), as attested by the Eocene - lower Oligocene Gallare Marl and Chiasso Fm to the north (Di Giulio *et al.*, 2001), and by the Canetolo Complex and Aveto Sandstone to the south (Catanzariti *et al.*, 1996; Elter *et al.*, 1999). Huge detrital supply started abruptly in late Oligocene times (Rögl *et al.*, 1975; Catanzariti *et al.*, 1996), soon after the climax of Periadriatic magmatism and the onset of denudation in the central Alps (Gansser, 1982). The Gonfolite clastics thus accumulated proximally in the Southalpine foredeep (Gelati *et al.*, 1988), while the Macigno turbidites accumulated distally in the Apenninic foredeep (Di Giulio, 1999).

The coarse-grained Gonfolite clastic wedge is discontinuously exposed north of Milano, and extends for ca 40 km N-S and ca 200 km E-W in the subsurface of the Po Plain (Pieri and Groppi, 1981; Di Giulio *et al.*, 2001; Mosca *et al.*, 2009; Rossi *et al.*, 2009). The basal Como Conglomerate consists of 2 km-thick conglomerates and pebbly sandstones of late Chattian - early Burdigalian age, lying over mid-Oligocene marls. The Como Conglomerate is interpreted as a fan delta fed from the north and passing southward to a deep-sea fan (Gelati *et al.*, 1988). Provenance from the rapidly exhumed Bregaglia Pluton and wallrocks has long been documented (Heim, 1919; Wagner *et al.*, 1979; Bernoulli *et al.*, 1993; Malusà *et al.* 2010). Gonfolite turbidites accumulated until the middle Miocene (Sciunnach and Tremolada, 2004) and were next accreted as S-vergent thrust sheets at the front of the Southern Alps, and unconformably sealed by Messinian deposits (Pieri and Groppi, 1981).

The foredeep clastic wedges of the Northern Apennine are thick successions of turbidite sandstones feeding longitudinal basins ahead the thrust fronts (Ricci Lucchi, 1986) as well as in depozones on top of the wedge itself. They are classically subdivided into tectonostratigraphic units arranged as thrust sheets, bound on top by Ligurian units and detached at different levels in the underlying stratigraphic sequence. From SW to NE, major units are the chiefly Chattian-lower Aquitanian Macigno Fm, the upper Chattian-Aquitanian Modino Fm, the upper Chattian-Burdigalian Cervarola Fm, and the Burdigalian-lower Messinian Marnoso-Arenacea Fm (Cerrina Feroni *et al.*, 2004; Catanzariti *et al.*, 2009).

The Macigno turbidites have a fairly constant thickness (2.5 to 3 km) over most outcrop areas, extending ca 50 km NE-SW and 250-300 km NW-SE. Sedimentation was contiguous with that of Gonfolite clastics (Lorenz, 1984; Gelati *et al.*, 1988). Detrital modes indicate a prominent crystalline source, with upward decreasing subordinate supply from intermediate volcanic rocks, and negligible sedimentary detritus (Di Giulio, 1999). Sedimentary detritus becomes more important in the youngest units (Valloni and Zuffa, 1984). Based on basin-fill patterns, paleocurrents, petrographic signatures, and geochronological data, a generic axially Alpine provenance has long been inferred (Lorenz, 1984; Valloni and Zuffa, 1984), with the exceptions of the episodic calcareous megaturbidites fed from the south (Gandolfi *et al.*, 1983; Talling *et al.*, 2007) and some debated lateral radial supply for the southern Tuscany Macigno (Cornamusini *et al.*, 2002; Butler 2009). Nevertheless, identification of specific sources within the Alps is controversial (see Garzanti and Malusà, 2008). Focused erosion of the Lepontine Dome has been recently recognized as the dominant source of detritus feeding the Adriatic foredeep, based on independent lines of evidence including petrographical and geochronogical signatures of the clastic wedges (Garzanti and Malusà, 2008). The marked topographic gradient between the rapidly exhumed Central Alps and the rapidly subsiding Adriatic foredeep favoured long-distance sediment transfer, which continued through the Miocene.

Foredeep sandstones of the Northern Apennine are topped by slope marlstones and in places by shelf calcareous sandstones that document the uplift and deactivation of the foredeep (closure facies sensu Ricci Lucchi, 1986b). Synsedimentary emplacement of the Ligurian wedge onto the foredeep succession is attested by large chaotic beds and olistostromes of wedge Ligurian or Subligurian affinity (Elter and Trevisan, 1973; Castellarin *et al.*, 1987; Labaume and Rio, 1994; Argnani and Ricci Lucchi, 2001; Lucente and Pini, 2003).

Western Alps-Northern Apennine junction area: the role of the Corsica-Sardinia block rotation

The major role of the Corsica-Sardinia block-rotation in shaping the Western Alps-Northern Apennine junction area and in the fragmentation of the former prolongation of the Alpine chain in the western Mediterranean has been suggested for more than 40 years (Boccaletti and Guazzone, 1971; Debelmas, 1972; Elter and Pertusati, 1973; Alvarez *et al.*, 1974; Vanossi *et al.*, 1980; Laubscher, 1988; Vanossi *et al.*, 1994). Recently acquired paleomagnetic data (Maffione *et al.*, 2008) completing those of Bormioli and Lanza, 1995; Muttoni *et al.*, 1998, 2000; Collombet *et al.*, 2002; Carrapa *et al.* 2003, help better defining timing and magnitude in rotation between the TPB, the underlying Ligurian Alps and the Corsica-Sardinia block (Speranza *et al.*, 2002; Gattacceca *et al.*, 2007).

Fig. 7 reports the documented amounts of block rotations and their timing in the different domains and units (see also Ciffelli and Mattei this volume). Although paleomagnetic studies from different working groups and sites have different reference frame (Africa or Europe), they can be considered comparable (see Maffione *et al.*, 2008) thanks to the documented negligible rotation relative to the geographic north of the two major plates during Tertiary times (e.g. Besse and Courillot, 2002; Maffione *et al.*, 2008).

For the Brianconnais units of the LA, rotations (with respect to stable Europe) along vertical axis between 47°-117° were dated as post-late Oligocene by Collombet *et al.* (2002), although some rock samples refer to highly strained domains that have suffered important rotational deformations. For the TPB basin Bormioli and Lanza (1995), Carrapa *et al.* (2003) and more recently Maffione *et al.* (2008) documented in lower Oligocene-Middle Miocene sediments, counterclockwise rotation (up to c. 50°) (with respect to Africa) during Aquitanian-Serravalian time. Although a detailed structural and paleomagnetic integrated study was not performed by Maffione *et al.* (2008), the result of their statistic oroclinal tests allowed them to exclude that differential rotations occured in the different studied sites of TPB, thus supporting the idea that the basin rotated as a whole. Following these conclusions (but see below) a major concern is relative to the pole of rotation of the system which has been located differently as illustrated in Fig.6 (Debelmas, 1972; Elter and Pertusati, 1973; Laubscher, 1988; Vanossi *et al.*, 1994; Hoogerdujin Strating *et al.* 1994; Ghelardoni, 1994). The AXF basal thrust (Mosca *et al.*, 2009) whose kinematics possibly changed through time could be indicated as the major structure which accomodated the roto-translational displacement of the LA sector. The possible lateral (?) surface splays of the AXF fault can be identified along a VVL and eastward in the OLL.

Constraints for tectonic models and some remarks on recent interpretations

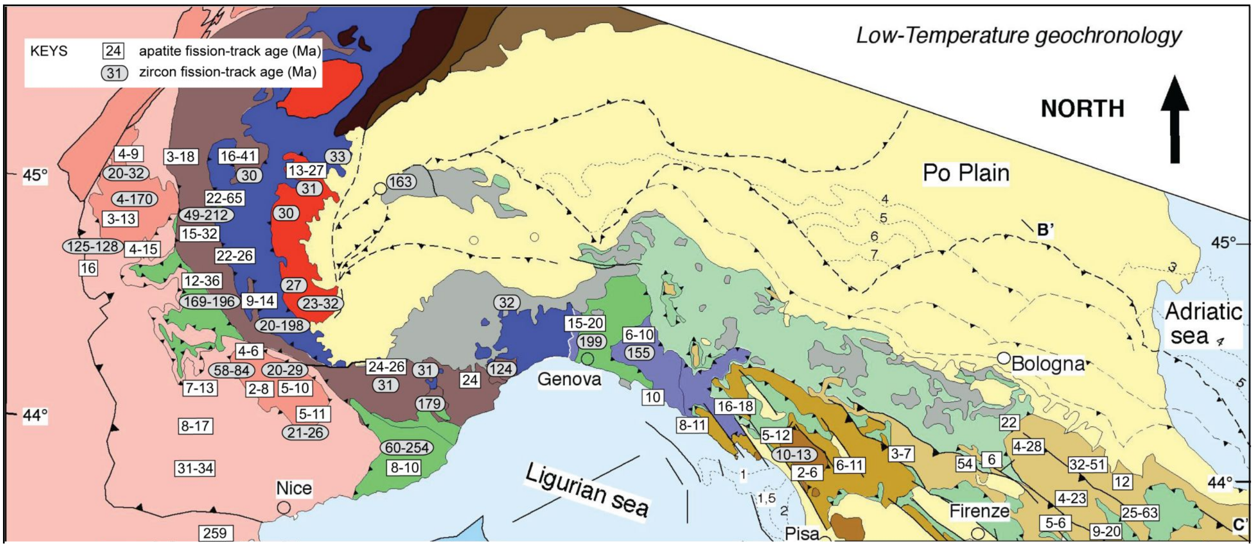
On the basis of the presented data we illustrate hereafter the major constraints that have to be taken into account for a kinematic modelling of the Western Alps/ Northern Apennine junction area.

Constraints from thermochronology

The region between the southern Western Alps and the Northern Apennine exhibits a complex pattern of exhumation in the uppermost crustal levels, nicely imaged by fission-track (FT) data on zircon and apatite (Fig. 9). These geochronological systems constrain burial and exhumation of rocks across the 240° and the 120°-60°C isothermal surfaces (Gallagher *et al.* 1998), corresponding to ca.7 km and 3-4 km depth for a 30°C/km paleogeothermal gradient (Malusà *et al.* 2006).

In the Western Alps, FTs on apatite are generally completely reset during the Alpine orogeny (Fügenschuh *et al.* 1999; Malusà et al 2005). A remarkable exception is represented by the Chenaillet unit, which always resided at shallow levels in the nappe stack (Carpena and Caby, 1984; Schwartz *et al.* 2007). In the northwestern Alps, apatite FT data define a regional pattern with decreasing ages moving from the axial sector of the belt towards the European foreland (Malusà *et al.* 2005).

Figure 9. Bedrock fission-track data on apatite and zircon.



After Carpena and Caby 1984, Abbate *et al.*, 1994 ; Balestrieri *et al.* 1996, Seward *et al.* 1999, Fügenschuh *et al.* 1999, Vance 1999, Ventura and Pini 1999, Bigot-Cormier *et al.* 2000, Bogdanoff *et al.* 2000, Sabil and Menard 2000, Tricart *et al.* 2001, Ventura *et al.* 2001, Carrapa 2002; Balestrieri *et al.* 2003; Foeken *et al.* 2003 ; Fügenschuh and Schmid 2003; Balestrieri *et al.* 2004, Malusà *et al.* 2005, Bigot-Cormier *et al.* 2006, Fellin *et al.* 2007, Schwartz *et al.* 2007, Tricart *et al.* 2007, Labaume *et al.* 2008.

To the south, apatite FT ages show an opposite trend and get younger eastward, at least west of the Dora-Maira unit (Tricart *et al.* 2007). Evident breaks across major faults (e.g. Tricart *et al.* 2001; Malusà and Vezzoli 2006) and across lower-order faults (e.g. Bigot-Cormier *et al.* 2006; Malusà *et al.* 2006; 2009) testify to active tectonics during and after exhumation. In general terms, the External Massifs and the westernmost units of the Briançonnais fan experienced higher exhumation rates than most of the axial Western Alps since the Miocene (Malusà *et al.* 2005; Vernon *et al.* 2008). Such a differential exhumation was probably accommodated by reverse motion along the W-dipping Internal Houiller Fault (Malusà *et al.* 2009), by normal reactivation of the E-dipping Brianconnais Fault and associated Longitudinal Faults (Barfety and Gidon, 1975; Fabre *et al.*, 1982; Tricart *et al.*2001), and by forward propagation of the external thrusts located beneath the External Massifs (Gratier *et al.* 1989).

In the Western Alps, an along-strike gradient with increasing fission-track ages from north to south is also described (Fügenschuh and Schmid, 2003; Malusà *et al.*, 2005). To the south, in the Maritime Alps, the zircon fission-track system is sometimes not reset, as observed in large areas of the External Massifs and in the Helmintoid Flysch nappes, where burial never exceeded 7 km (Seward *et al.* 1999; Vance 1999; Bernet *et al.* 2001; Foeken *et al.* 2003; Bigot-Cormier *et al.* 2006). Such along-strike gradient implies higher exhumation rates in the northern sector of the Western Alps with respect to the southern sector. This may be due to an increasing importance of crustal shortening that promoted erosion to the north (Malusà *et al.* 2005; Malusà and Vezzoli, 2006), coupled with a greater influence of Apenninic subsidence to the south (Doglioni, 1994; Garzanti and Malusà 2008).

In the Ligurian Alps, apatites are generally reset during the Alpine orogeny (Carrapa 2002), whereas zircons locally yield unreset Mesozoic ages (Vance 1999; Bernet *et al.* 2001). In these latter areas, burial was thus in the range of 3-4 km to less than 7 km, like in the Internal and External Ligurian units of the Northern Apennine where apatite FT ages are in the range of 20-6 Ma, and zircon FT ages exceed 150 Ma (Balestrieri *et al.* 1996). In the Cervarola, Macigno and Modino sandstone, apatite FT ages range between 3 and 10 Ma, and the extent of exhumation of the nappe pile ranges between 5 and 7 km (Ventura *et al.* 2001). Apatite FT ages from the Marnoso-arenacea Fm record instead post-depositional burial ranging between 5 km and less than 2.5 km. The missing section, eroded in the last 5-4 Ma, would consist of foredeep successions and overlying Ligurian units (Zattin *et al.* 2002). In an innermost position, geochronological data from the Apuane Alps indicate that the Apuane rocks were structurally buried to 15–30 km at about 20 Ma, to be exhumed across the 240°C isothermal surface at 10–13 Ma, and finally reach the 70°C isothermal surface by 5 Ma. The Macigno Fm in the Apuane region reached its maximum depth of 7 km at 20-15 Ma (Fellin *et al.* 2007).

Constraints from TPB basin

The characters of the large-scale depositional units, define a long-term, major transgressive-regressive cycle from Late Eocene to Miocene (Rossi et al, 2009). The maximum transgression took place in the Late Burdigalian and coincides with the maximum rate of tectonic space creation. This is recorded by the deposition of a km-thick basinwide and highly efficient turbidite system. This system separates the older southwestward coastal onlap and aggradation from the younger outbuilding related to the Middle Miocene uplift recorded along both the southwestern and southeastern basin margins, sometimes punctuated by forced regression pulses (Rossi *et al.*, 2009)

Then, since Middle-Upper Miocene major accumulation and subsiding areas were roughly in the present central TPB, i.e. Savigliano and Alessandria basins, bounded to the north by continuous and progressive uplift of northern TPB arc (Torino Hill and Monferrato)

The TPB and its underling and adjacent substrata experienced kilometers-scale vertical movements (subsidence and exhumation) following the Late Eocene-Early Oligocene stages of major contraction. Upward and downward movements were active in different places at the same time and the sites of maximum exhumation and subsidence migrated through time (Mosca 2006; Mosca et al, 2005; Bertotti *et al.*, 2006). In detail, the southern segment of the Alpine metamorphic system were rapidly exhumed and eroded during (Late Eocene-) Lower Oligocene times; after the Lower Oligocene clastic sedimentation, the southern Tertiary Piedmont Basin (namely the southernmost basin domains) experienced major km-scale subsidence and underwent subsequent exhumation. By contrast, the internal side of the Western alpine arc was more stable, recording since the Late Oligocene a more generalized subsidence. This pattern of vertical movements for TPB and its substrata, characterized by variations in magnitude and even sign through time and space, and its correlation with shift of major TPB depocenters have been interpreted as related with crustal folding (Bertotti e Mosca, 2009). Alternative, they may have developed, at least in part, during progressive rotation of the southernmost part of the alpine axial belt (Ligurian Alps domain) to reach the present position.

Some remarks on recent interpretations

A solution to the relationships between Western Alps/Northern Apennine junction area has been recently proposed by Vignaroli *et al.* (2008), Maffione *et al.* (2008) and Vignaroli *et al.* (2009). The model suggests that the eclogitic-bearing units of the Voltri Massif were exhumed in an extensional transfer domain which accomodated an opposite outward migration of the Alpine and Apennine thrust fronts since about 35/30 Ma. It is mainly based on a interpretation of the deep structure derived by 3-D tomography, new paleomagnetic data (Maffione *et al.*, 2008) and a re-interpretation of surface geology in Central Liguria in particular around the Voltri Massif.

The extensional domain was controlled by a progressive development of a low-angle detachement fault system with a general top-to-west kinematics and progressive steepening of the eastern side of the footwall (eastern flank of Voltri Massif) by a rolling-hinge mechanism to produce the final asymmetric doming of the eclogitic units. A comment with detailed compared overall architecture and tectono-metamorphic history of the area has been provided by Capponi *et al.*, (2009) with reply of Vignaroli *et al.*, (2009).

On the basis of the geological data presented in this paper we discuss some points of the broad regional tectonic aspects of this model (included also in Maffione *et al.* 2008 and Vignaroli *et al.*, 2009) inviting the reader to refer also to the comment by Capponi *et al.*, (2009) with reply of Vignaroli *et al.*, (2009) for a more local regional discussion.

A first point concerns the large scale tectonic frame of the supposed 35/30 Ma onward opposite retreating subductions. This setting, fitting part of the geological history (up to Pliocene) of the Apennines, is not supported by the data of the southwestward Alpine foreland which do not record any lithospheric flexure and related space regional accomodation postdating-34 Ma as the absence of significant foreland propagation testifies (Ford *et al.*, 2006; see above).

Moreover, the model does not really solve the problem of the exhumation of the deep seated metamorphic rocks of the Voltri Massif which reached the surface in the Late Eocene-early Oligocene as testified by sedimentary record of TPB basin and its unconformably overlapping. Exhumation was therefore basically achieved before the time of the supposed opposite retreating (as claimed in Vignaroli *et al.*, 2008).

Finally, all the pre-early Oligocene structures of the Ligurian Alps including the Voltri Massif and the Ligurian units on top of it cannot be considered related with the Apenninic subduction system (as claimed in Vignaroli *et al.*, 2009) but instead formed as all authors recognized (see references in the paper) within an alpine east-southeastward dipping subduction. This is well testified by the overall architecture of the belt, the superficial continuites of the alpine nappe stack from Cottian-Maritime to Ligurian Alps, the tectono-metamorphic history and kinematics data available.

Conclusion and open problems

The present-day morphostructural domains of the Western Alps/Northern Apennine junction area result from a kinematically complex interaction between interfering orogenic systems active since the Oligocene and related to the opposite-dipping east-southeast “alpine” and west-northwest “apenninic” subductions.

Within parts of the present morphostructural domains, however, reworked and reactivated structures of a formerly continuous Late Cretaceous/mid-Eocene intraoceanic and continental subduction-related “alpine” wedge are preserved and incorporated within the younger “apenninic” system.

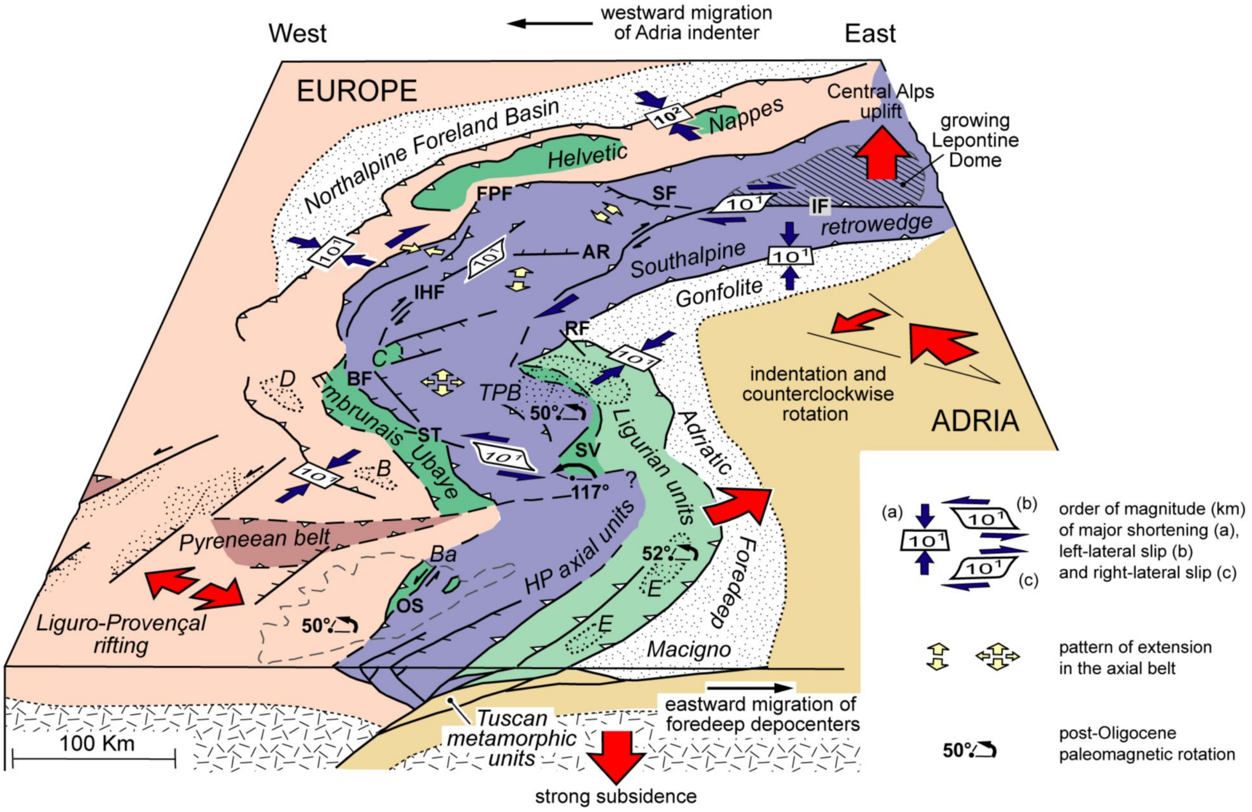
From north to south in the junction area between Western Alps and Northern Apennine the following domain can be recognized:

- Domain of Cottian-Maritime Alps represents the southwesternmost segment of the Western Alps it mantains the complete alpine signature from surface to deep crustal levels. Although the deep structure of the southernmost part of this domain is still uncompletely known due to the lack of seismic data of other alpine segments (ECORS CROP and NFP-20 in particular Roure *et al.*, 1990; Schmid and Kissling, 2000; Lardeaux *et al.*, 2006) major differences in the overall architecture can be observed if compared with other western Alps transects (e.g. Schmid *et al.*, 2004). This can be primarily the result of the Apenninic kinematic interference;
- Domain of Ligurian Alps/Tertiary Piemonte Basin/ Ligurian units p.p. This crustal segment records the complex interactions in space and time between two evolving and interfering Alps/Apennines system. The domain includes a segment of the axial Alpine system, the Ligurian Alps, recording a peculiar syn to late-to collisional evolution characterized by a very fast exhumation occured as soon after the inception of continental subduction recorded in the Brianconnais/European crust. This process occured in a span time between 50 Ma - age of the early involvement of continental subduction in Corsica southernmost prolongation of the alpine system (Doglioni, 1991; Molli, 2008, Molli and Malavieille, 2010; Doglioni *et al.* this volume) - and the 35 Ma age of involvement of thinned continental crust of the Dora Maira unit in the CMA

(Ford *et al.*, 2009; Beltrando *et al.*, 2010; Dal Piaz this volume).

The fast exhumation was possibly developed and enhanced within a transpressive zone which may have laterally constricted the subduction channel (Federico et al. 2007, Crispini *et al.*, 2009) and thus accelerated extrusion similarly to what occured some My later for the Dora Maira (Ford *et al.*, 2006). As alternative or concurrent mechanism for the fast exhumation, a northward propagation of the slab detachment could be envisaged (Molli, 2008; Molli and Malavieille, 2009; Molli and Malavieille, 2010).

Figure 10. Conceptual 3D reconstruction of the Western Alps-Northern Apennine junction area at the latest Oligocene-earliest Miocene.



At that time, two opposite dipping subduction system were active after Eocene subduction reversal affecting the southern (Corsica-Liguria) segment of the Alpine system. In deep blue, axial Alps and their southern prolongation in Corsica; in deep green, uppermost units of the alpine nappe stack, including the Chenaillet unit (Ch), the Helminthoid Flysch units of Swiss Prealps, Embrunais-Ubaye and Ligurian Alps, the Antola unit, the Balagne (Ba), Nebbio and Macinaggio units in Corsica; in light green, Ligurian and sub-Ligurian accretionary wedge of Apennines.

Thrust-sheet-top basins (B, Barrême; D, Dévoluy) and foreland basins on European crust according to Ford and Lickorish (2004); basins on Adria crust and atop the axial belt (E, Epiligurian basins; TPB, Tertiary Piedmont Basin) according to Garzanti and Malusà (2008). Amount of shortening and lateral slip during Eocene – early Miocene as summarized by Malusà *et al.* (2009) and reference therein. Southern face of the 3D model inspired by Doglioni *et al.* (1998) (CROP M-12A, CROP-03, CROP M-16). Major faults: AR, Aosta-Ranzola; BF, Briançonnais; FPF, Frontal Pennine; IF, Insubric; IHF, Internal Houiller; OS, Ostriconi; RF, Rio Freddo; SF, Simplon; ST, Stura; SV, Sestri-Voltaggio.

Beside paleomagnetic data (e.g. Collombet *et al.*, 2002; Maffione *et al.*, 2008), the interconnection between the Southalpine part of the Adriatic foredeep, filled by the Gonfolite clastic wedge, and the Apenninic part filled by the Macigno-Modino clastic wedge (Garzanti and Malusà, 2008) is a strong argument supporting the Neogene rotation of the whole Tertiary Piedmont – Ligurian Alps block.

The axial domain of the LA were later on rapidly buried under shallow to deep-water sediments as result of the inception of the opposite west-ward Apenninic subduction starting to the south (Doglioni, 1994; Molli, 2008;

Malusà *et al.*, 2008; Molli and Malavieille, 2010). A partial reshaping of the deep structure with the presence of the Ligurian Moho testified the “Apenninic” reworking of this crustal sector;

- Domain of the NA shows accretionary wedge units (the Ligurian/sub Ligurian nappe stack) overlying continental derived basement (Alpi Apuane) but mainly detached cover units Adria-derived. The nappe stack in the westernmost part of the belt was strongly excised during Mid-Late Miocene sin-contractional exhumation of the deeper wedge units related with east-ward retreating of Apenninic subduction and later on (from Pliocene to present) further thinned by crustal-scale extension (Molli, 2008 and references).

The deep configuration of the major domains forming the Western Alps/Northern Apennine junction area can be therefore considered as the result of the complex interference of different orogenic processes such as the late collisional indentation of Europe and Adria, the development of structures related with opposite dipping subduction after a subduction flip and the kinematic development of the northern Apennines in a frame of slab retreat with the related opening of the backarc Liguro-Provençal basin and then the Tyrrhenian sea in the wake of Apenninic subduction.

The different structures formed during this complex geodynamic evolution are still far to be completely well understood and between others two major still open problems are hereafter highlight:

i) The problem of the rotation pole/pole(s)

One kinematic problem related to the Western Alps/Northern Apennine junction area concerns the back rotation of the LA and TPB basin after the preliminary retro-deformation of structures developed since the end of rotation c.16 Ma onward.

The kinematic balancing has to address the question of location of a single and fixed pole or the successive poles and the way in which they migrated in space and time. Moreover, the whole rotation model vs. differential block rotation or domino-like accomodation are different kinematic solutions with obvious major implications for the retro-deformation of the structures.

To unravel this problem an accurate 3D-balancing (Schumacher and Laubscher, 1996; Piana and Polino, 1995; Mosca *et al.*, 2009) of the major structures has to be achieved by combined structural, sedimentological and paleomagnetic data altogether with the new acquisition of high resolution 3D-seismic profiles.

ii) The role of the Pyreneean-Provençal deformation and its heritage

The geology of the junction area and the relationhips between Alps and Apennines have been described in this paper as a kinematic problem of the structural heritage of a former single and continuous orogenic system (the pre-Late Eocene Alps) partially reworked during the development of a younger “Apenninic” orogenic system (from the Late Eocene onward). However, another important element plays a possibly relevant, although almost unknown role, that is the eastern prolongation of the North Pyrenean fault and the development of the Pyrenean orogen itself (Malavieille, 1983; Lacombe and Jolivet, 2005). These structures were active and formed during Eocene times in response to the displacement and collision between the Iberia and the European plate (Lagabrielle and Boudinier, 2008 and ref.). The Pyreneen orogen and related structures found their prolongation on land with the Languedoc-Provençe belt, undersea in the Gulf of Lyon, and further east north of Corsica where one might expect an interference with the Late Eocene Alpine system (Fig.10). Complex structures are to be expected in such an area now in part reworked in western Liguria, a point still demanding focussed analyses.

In conclusion, although highly debated for more that one century the subject of the relationships between the Alps and the Apennines is a still uncompletely solved problem. The Western Alps/Northern Apennine junction area, in particular, hides and preserves most of the solutions of this 3-D kinematic problem therefore it might be considered a sort of type area for studying the geological processes occurring at interfering orogens, thus challenging present and future research.

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