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THE INTERNAL NORTHERN APENNINES, THE NORTHERN TYRRHENIAN SEA AND THE SARDINIA-CORSICA BLOCK

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ABSTRACT: In this paper we review the evolution of the internal area of the Northern Apennines, northern Tyrrhenian Sea and the Sardinia-Corsica block, focusing on the post-collisional evolution. The discussion follows the Author's point of view, but for the reader interested in a deeper knowledge of the geology of the area many in text citations are added and a comprehensive reference list is presented.

We first shortly introduce the stratigraphy of the area, in the framework of the geodynamic evolution of the western margin of the Apulia microplate, the adjacent Ligurian ocean and the European Sardinia-Corsica microplate. After a general overview of the nappe structure resulting from collisional tectonics is presented for the whole area. The post-collisional evolution is discussed in more details, and we separately present data relative to the Sardinia-Corsica block, the northern Tyrrhenian Sea, northern Tuscany and southern Tuscany. We distinguish: a) a Late Oligocene-Early Miocene collisional stage, with continuing collision of the European continent with the Apulia microplate; b) an Early-Middle Miocene stage linked to the opening of the Algero-Provençal basin; c) a Late Tortonian-Quaternary stage linked to the opening of the Tyrrhenian Sea.

INTRODUCTION

The Northern Apennines are a fold-thrust belt originated during the Tertiary by the collision between the Apulia (or Adriatic) microplate related to the African plate (fig. 1), and the Briançonnais microplate (Sardinia-Corsica massif), related to the European plate (BOCCALETTI *et alii*, 1971; SCANDONE, 1979; MANTOVANI *et alii*, 1985; DERCOURT *et alii*, 1986; STAMPFLI *et alii*, 1991; 2001). Two main different hypotheses exist regarding the relationship between the Sardinia-Corsica massif and the Alpine and Apennine chain:

1. The nappes in Northeastern Corsica are considered to be the southern continuation of the Western Alps ("Alpine Corsica"). Only later the Sardinia-Corsica massif acted as hinterland of the Apennine chain (BOCCALETTI *et alii*, 1971; MATTAUER & PROUST, 1976; DURAND-DELGA, 1984).
2. The Eastern Corsica-Northern Apennines system originated as an accretionary wedge, produced by subduction of the Apulia microplate under the Sardinia-Corsica massif during the Late Eocene-Early Miocene.. At the same time tectonic units, with mostly African (top-NE in present-day coordinates) transport direction, developed in the Apennines, while European (top-W) transport direction is observed in Corsica (PRINCIPI & TREVES, 1984; TREVES, 1984; CARMIGNANI *et alii*, 1995). In this model the Balearic (or Algero-Provençal) basin and the Tyrrhenian Sea opened in successive phases, in the Early Miocene and Late Miocene respectively.

Other ideas and interpretations are proposed by other authors and most of them are reported in the following (for a more complete overview of the geodynamic evolution of the area the reader is referred to: MALINVERNO & RYAN, 1986; ZITELLINI *et alii*, 1986; ROYDEN *et alii*, 1987; KASTENS *et alii*, 1988; PATACCA & SCANDONE, 1989; SARTORI, 1989; KASTENS & MASCLE, 1990; MASCLE & REHAULT, 1990; PATACCA *et alii*, 1990; SARTORI, 1990; BARTOLE *et alii*, 1991; HAAN & ARNOTT, 1991; LAUBSCHER *et alii*, 1992; CARMIGNANI *et alii*, 1994b; KELLER *et alii*, 1994; ALBARELLO *et alii*, 1995; BARTOLE, 1995; CARMIGNANI *et alii*, 1995; FACCENNA *et alii*, 1997; CARMINATI *et alii*, 1998; GUEGUEN *et alii*, 1998; JOLIVET *et alii*, 1998; BRUNET *et alii*, 2000; JOLIVET & FACCENNA, 2000; CARMIGNANI *et alii*, 2001a; 2001b; EDEL *et alii*, 2001; FINETTI *et alii*, 2001; LUCENTE & SPERANZA, 2001; SARTORI, 2001; SARTORI *et alii*, 2001; VAI & MARTINI, 2001; GELABERT *et alii*, 2002).

STRATIGRAPHY

In the Northern Apennines-Sardinia-Corsica orogenic wedge we recognise tectonic units originated, from the Africa continent, from the European margin and relics of the Tethys oceanic crust. A palinspastic reconstruction of the European-Apulia continental margin in the Late Jurassic is illustrated in fig.2.

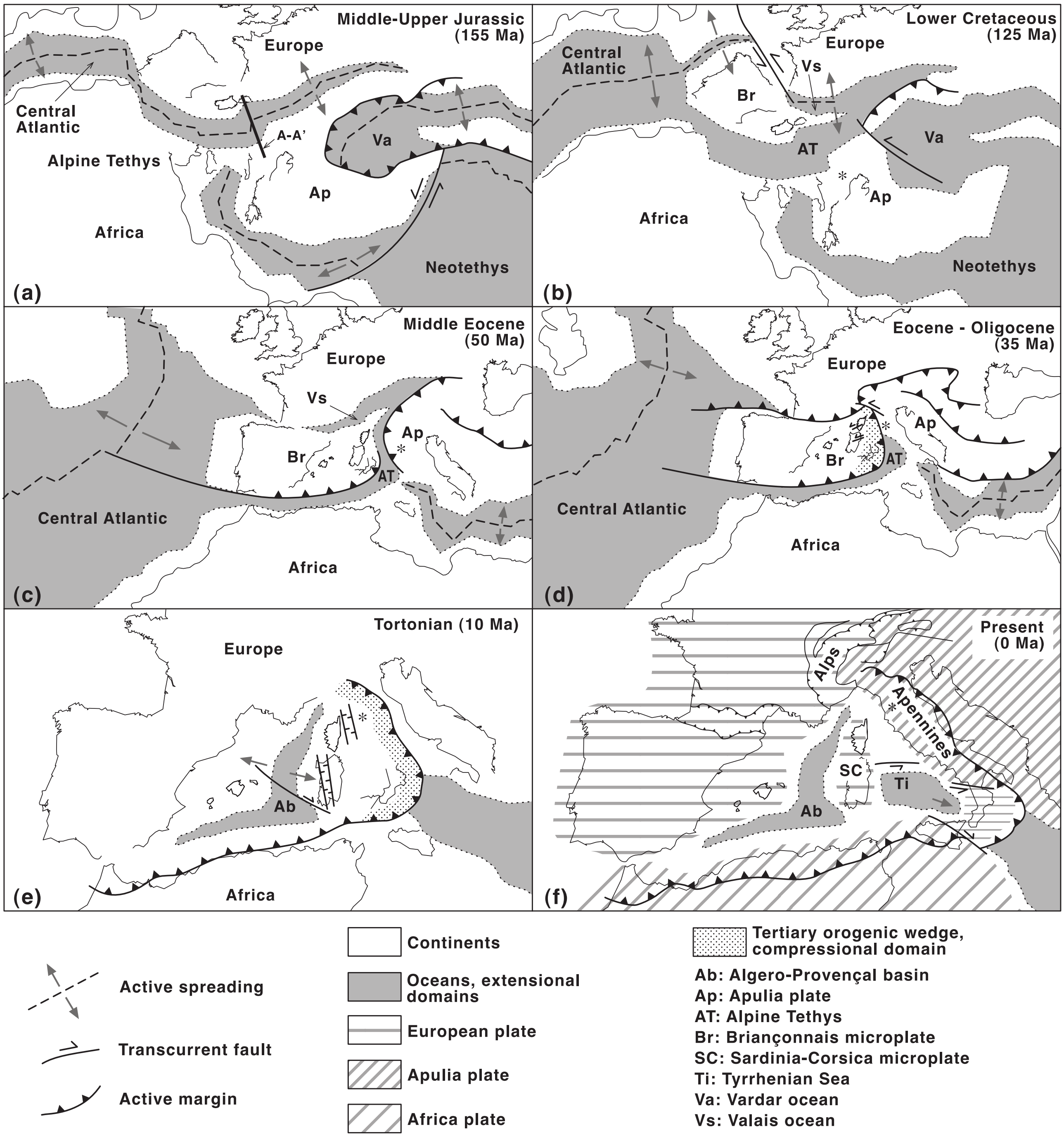

Fig. 1 - Plate reconstruction for the western Mediterranean area, after Stampfli et alii (1998; 2001) and Gueguen et alii (1998), modified. Asterisks roughly indicate position of Tuscany; A-A' is the trace of fig. 2 reconstruction. Transcurrent fault in the Tyrrhenian Sea in (f) indicates the 41°N parallel lineament.

The European margin is now outcropping in Sardinia and in Corsica, and is made up of a Variscan basement, locally covered by Carboniferous-Permian continental deposits and Triassic carbonate sediments.

A main transgression marks the starting of the Jurassic platform carbonate sedimentation, followed by Cretaceous limestones and Tertiary limestones, conglomerates and turbidite sandstones (see CARMIGNANI *et alii*, 2001b, for a complete reference list and enclosed 1:500000 and 1:200000 geologic maps of Sardinia and Corsica). In the whole, it is a classic European-Briançonnais type succession.

Ocean-derived successions outcrop in northern Corsica, in the Tuscan archipelago and in Italy. In Corsica they are characterised by Jurassic ophiolites and their Jurassic-Early Cretaceous sedimentary cover, overlain by Cretaceous-Oligocene flysch sequences. The oceanic realm is named in the Italian geologic literature "Ligurian domain", and is part of the Alpine Tethys (Elter *et alii*, 1966; Elter & Pertusati, 1973; Elter, 1975; Bortolotti *et alii*, 2001b; Marroni *et alii*, 2001). It is furthermore separated in:

1. Internal Ligurian Domain, characterised by the presence of Jurassic ophiolites and their Late Jurassic-Cretaceous sedimentary cover (cherts, Calpionella limestone and Palombini shales) associated with a Cretaceous-Paleocene siliciclastic turbidite sequence (Lavagna slates, Gottero sandstones and Bocco/Colli-Tavarone shaly complex).
2. External Ligurian Domain, characterised by the presence of Cretaceous-Paleocene calcareous-dominant flysch sequences (Helminthoid flysch) associated with complexes or pre-flysch formations called "basal complexes". The pre-Cretaceous substrate is represented in part by ophiolites and in part by continental crust, therefore it is a domain that joined the oceanic area to the Apulia continental margin (fig.2).

Moving toward the Africa continent the "Subligurian Domain" is distinguished. This is a Paleogene sequence (Canetolo Unit), intensely deformed, whose original extent and substratum are unknown. This sequence was probably deposited in an area of transition between the oceanic and the Apulia continental crust.

The western margin of the Apulia continental margin outcropping in the Italian peninsula is represented by the Tuscan Domain, where we can further distinguish (fig.2):

1. The Internal Tuscan Domain (Tuscan Nappe), with non-metamorphic (to low-grade metamorphic) formations of Late Triassic to Early Miocene age.
2. The External Tuscan Domain ("Autochthon" Auct. tectonic unit in the Alpi Apuane area), affected by greenschist facies metamorphism, with a Mesozoic-Tertiary succession that covers a Paleozoic basement with Hercynian deformation.
3. The Massa Unit, now structurally interposed between the Tuscan Nappe and the "Autochthon" Auct., exclusively made of rocks from Paleozoic to Triassic age.

The continental origin of the Tuscan Domain is testified by the pre-Mesozoic rocks, the Tuscan Paleozoic basement, substrate of the Tuscan successions (review in Conti *et alii*, 1991; Pandeli *et alii*, 1994). This Paleozoic basement is characterised by metasedimentary and metavolcanic sequences showing similarities with the successions of the Variscan chain in Sardinia (Gattiglio & Meccheri, 1987; Conti *et alii*, 1993).

During Late Carboniferous/Permian a trans-extensional regime characterised the Tuscan domain with development of narrow continental sedimentary basins bounded by faults and characterised by unconformities and abrupt changes in sedimentary facies (Rau & Tongiorgi, 1974). During the Middle Triassic evidence of further crustal attenuation is provided by the Anisian-Ladinian extensional basins in which marine platform sediments (Diplopora-bearing marbles) are associated with alkaline basaltic flows and breccias. This sequence testifies that a Triassic aborted rifting stage affected the Tuscan Domain (Martini *et alii*, 1986).

The continental sedimentation was later re-established through the deposition of the Upper Ladinian(?)-Carnian Verrucano sediments. These deposits grade upward to shallow water carbonates (Norian Dolomites "Grezzoni") or evaporites ("Calcare Cavernoso") during the renewal of the rifting process. Shallow water carbonatic deposition occurred all over the continental margin during the Rhaetian to Early Liassic. Locally it was interrupted by uplift, emersion and development of scree breccias (Rhaetian-Liassic boundary).

Early to Middle Jurassic block faulting and progressive subsidence of the Apulia continental margin were associated with the dismembering of the carbonate

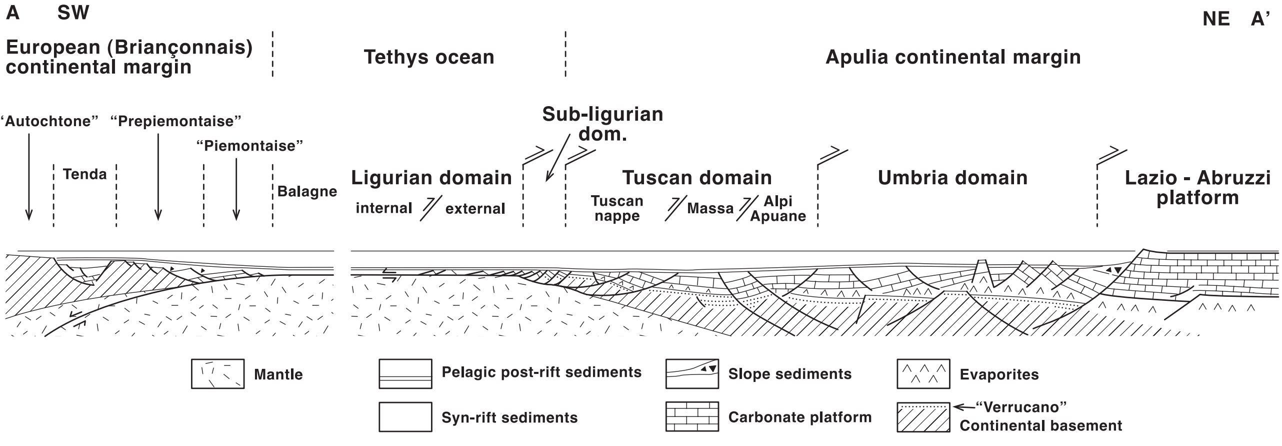

Fig. 2 - Palinspastic reconstruction of the western continental margin of Apulia, Tethys ocean and adjoining European margin during the late Jurassic (after Hoogerdujin Strating, 1990; Marroni *et alii*, 1998; Bernoulli, 2001; Peybernès *et alii*, 2001; Rossi *et alii*, 2002, modified). SW and NE are referred to present day coordinates; location of this section is approximately located in fig.1a.

platforms and the oceanisation of the Ligurian Tethys (Malm) far West. Drowning of carbonate platform is testified by Middle Jurassic-Cretaceous to Tertiary pelagic carbonates and shales grading upward to Oligocene-Lower Miocene sandstones and shales ("Macigno" and "Pseudomacigno").

As a whole, the Mesozoic to Tertiary stratigraphic evolution of the Tuscan Domain reflects deposition in a rifted continental margin which evolved into a clastic foredeep before being involved in the Late Oligocene/Miocene Apenninic tectonics.

All the above-described successions of the Tuscan Domain are involved in the Tertiary collisional evolution of the western Apulia continental margin. Unconformably above this formations are post-orogenic Tertiary-Quaternary deposits ("neoauthochton" in the Italian geologic literature), only slighlty deformed and with regional unconformities in the succession. These deposits permit us to unravel the post-collisional evolution of the area and they will be discussed in more detail in the following.

Far East paleogeographic domains (Umbria domain and Lazio-Abruzzi platform) do not crop out today in the hinterland area of the Northern Apennines and therefore are not discussed here (see VAI & MARTINI, 2001, for references).

THE COLLISIONAL EVOLUTION

During Late Oligocene-Early Miocene collision of the Briançonnais microplate with the Apulia continental margin (fig.1d) led to: a) strike-slip tectonics in Sardinia and southwestern Corsica; b) deformation and metamorphism in the easternmost European succession now outcropping in north-eastern Corsica ("Alpine Corsica"); c) deformation and emplacement of the ocean-derived Ligurian and Sub-ligurian units onto the internal Tuscan Domain; d) development of tectonic melanges with HP paragenesis; e) segregation of the Tuscan Nappe and its overthrust onto the external Tuscan domains, which underwent of greenschists facies metamorphic units (fig.3, fig.4).

In Sardinia and Corsica continental collision led to transpressional structures in the Variscan basement along NE-SW and E-W fault systems (CARMIGNANI *et alii*, 1992; 1994a; 1995; PASCI, 1997). To constrain the age of deformation is important to remark that: a) conglomerates containing clasts of Lutetian age are involved in thrusts in transpressive fault zone (Cuccuru 'e Flores Conglomerates, DIENI & MASSARI, 1965; ALVAREZ & COCOZZA, 1974; CARMIGNANI *et alii*, 1992) and unconformably rest on both the Paleozoic basement and the Jurassic-Lower Cretaceous cover; b) in eastern Corsica analogous conglomerates with Lutetian clasts rest on the Paleozoic basement and on the Mesozoic-Eocene cover (AMAUDRIC DU CHAFFAUT, 1973; EGAL, 1992), these conglomerates are involved in "European verging" thrusts together with oceanic crust relics; c) the faults of the Sardinia rift, which developed in the Burdigalian, cut the transpressive faults; d) significant conglomerate deposition in north-eastern and central Sardinia occurred syntectonically in strike-slip pull apart basins (OGGIANO *et alii*, 1995; FUNEDDA *et alii*, 2000; CARMIGNANI *et alii*, 2001b). Thick conglomerate, sandstone and limestone succession deposited in southern Sardinia (Cixerri, Ussana, Gesturi, Villagreca, Isili, Ales, Marmilla). From the above considerations follows that Tertiary compressional tectonics of the Sardinia-Corsica block is of Late Oligocene (post-Lutetian) - Early Miocene (pre-Burdigalian) age. Compression is linked with westward subduction of oceanic crust, as testified by diffuse Oligocene-Miocene calc-alkaline volcanism in central and southern Sardinia. The opening of the Algero-Provençal (Balearic) basin and of the Sardinia rift followed this compression.

Deformation in the Alpine Corsica is characterised by large-scale thrust sheets with both top-East and top-West tectonic transport (DURAND-DELGA, 1978; COHEN *et alii*, 1981; MATTAUER *et alii*, 1981; DURAND-DELGA, 1984; GIBBONS *et alii*, 1986; WARBURTON, 1986; WATERS, 1990; DURAND-DELGA & ROSSI, 1991; MALAVIEILLE *et alii*, 1998; LAHONDÈRE *et alii*, 1999). Different opinions exist on the significance of these different trasport directions: they can be relate in the whole to the collisional evolution, or in part produced during the post-collisional extensional tectonics.

Tertiary tectonics led to emplacement of the Ligurian and Sub-ligurian domains above the Tuscan Domain, with a top-East transport direction (ELTER, 1975). The Ligurian units also suffered earlier deformations due to the Cretaceous tectonics very well documented in the Alps. Today the Ligurian units show a very complicate internal structure, with several thrust sheets with evidence of polyphase deformation; these thrust sheets have many different local names in northern and southern Tuscany (more information in: BURGASSI *et alii*, 1985; COSTANTINI *et alii*, 1995; BERTINI *et alii*, 2000; BORTOLOTTI *et alii*, 2001b).

The collision zone between Europe and Africa is marked by a West-dipping high-strain tectonic melange, characterised by ocean- and continent-derived mylonitic rocks, constant SW-NE oriented stretching lineations, top-East shear sense and very high pressure assemblages. Due to later extension, these melanges are found in small outcrops in southern Tuscany (Argentario) and in the Tuscan archipelago (Giglio, Gorgona). In more detail, the Gorgona Island and the western part of the Giglio Island and of the Argentario promontory are made of HP metamorphic rocks with glaucophane and lawsonite relics in metabasites, and Fe-Mg carpholite in metapelites (P=1.2-1.4 GPa, T=300-350°) (LAZZAROTTO *et alii*, 1964; DECANDIA & LAZZAROTTO, 1980; CAPPONI *et alii*, 1997; THEYE *et alii*, 1997; ROSSETTI *et alii*, 1999; BRUNET *et alii*, 2000). All these metamorphic rocks are today the only remnant of the Tertiary collisional orogenic wedge.

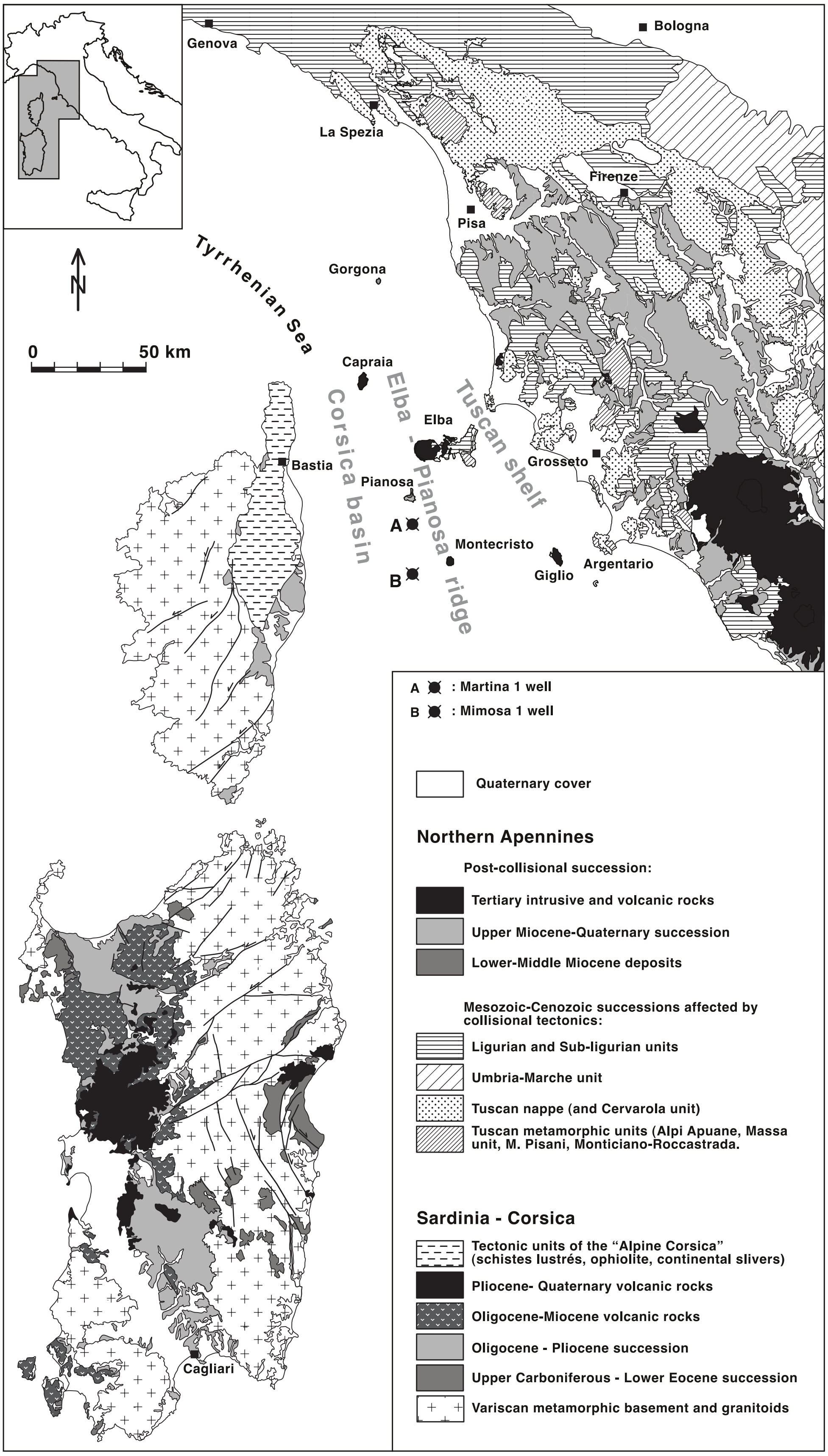

Fig. 3 - Tectonic sketch map of the internal northern Apennines, northern Tyrrhenian Sea and the Sardinia-Corsica block.

Tectonic features developed during emplacement of the Tuscan Nappe onto the external Tuscan Domain can be studied in detail in Tuscany, where these tectonics units widely outcrop. Top-East transport of the Tuscan Nappe occurs along a regional-scale floor thrust that runs in the "Calcare Cavernoso" formation, a Norian dolomite formation with intercalated evaporite levels.

The compressive tectonics is only indicated by a foliation that developed specially in shaly rocks, within the thermobaric limits of the anchizone (Cerrina Feroni *et alii*, 1983). Angular relationships between bedding and foliation constantly indicate a top-NE tectonic transport direction.

Emplacement of the Tuscan Nappe led to development of greenschists facies metamorphism of the underlying Tuscan units (Alpi Apuane, Monti Pisani, Monticiano-Roccastrada). The metamorphic units are characterised by km-scale NE-facing isoclinal folds, with associated syn-metamorphic axial plane foliation, the main regional foliation now recognizable in the field, which often completely transposed the original bedding. Stretching lineations are consistently SW-NE oriented. Axes of minor folds are also SW-NE oriented and commonly sheath-like non-cylindrical folds occur (Carmignani *et alii*, 1978; Kligfield, 1979; Carmignani & Kligfield, 1990; 2001a). The radiometric age of this metamorphic event is about 27 Ma (Late Oligocene, Kligfield *et alii*, 1986), which agrees with the biostratigraphic data related to the youngest formation involved in deformation (Dallan Nardi, 1976).

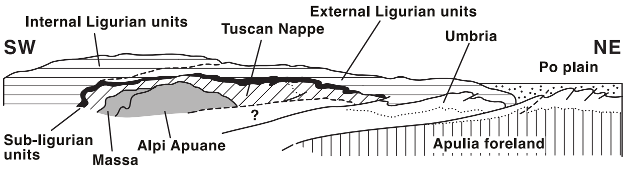

Fig. 4 - Schematic cross section of the Northern Apennines at the end of collisional phases (after Elter, 1975). Gray pattern indicate metamorphic units.

THE POST-COLLISIONAL EVOLUTION

The end of traspression in Sardinia and Corsica marks the end of the convergence between the European and the Apulia continental margins and the end of regional scale compressional events in Tuscany. Starting Early Miocene (Burdigalian), due to slab retreat, the Apennine compressional front migrates eastward (fig.1e), so the tectonic regime changed from compressive to extensional: the earlier Apenninic orogenic wedge is now affected by widespread exhumation and extensional tectonics.

This tectonic evolution starts in the Burdigalian and can be divided in two main extensional events:

a) a first extensional event of Early-Middle Miocene age, linked to the opening of the Algero-Provençal (Balearic) basin, the anticlockwise rotation of the Sardinia-Corsica block and the opening of the northern Tyrrhenian Sea (Corsica basin) (fig.1e).

b) a second extensional event of late Tortonian-Quaternary age, linked to the opening of the southern Tyrrhenian sea, the south-eastward migration of the Calabrian Arc and the ongoing retreat of the subducted lithosphere in the Northern Apennine.

In the following we briefly discuss the tectonic features and the sedimentary evolution of the different areas during the post-collisional evolution. An overview of the main events is reported in fig. 5.

THE SARDINIA-CORSICA BLOCK

After collision Sardinia and Corsica rotate counter clockwise of about 30°, leading to the opening of the Algero-Provençal basin. Rotation was complete in the Middle Burdigalian (18-19 Ma ago) or possibly in Langhian (15 Ma) (De Jong *et alii*, 1969; Alvarez, 1972; Edel & Lortsher, 1977; Montigny & Edel, 1981; Rehault *et alii*, 1984; Van der Voo, 1993; Vigliotti & Langenheim, 1995; Speranza, 1999; Deino *et alii*, 2001; Speranza *et alii*, 2002). This rotation led to a an extensional regime in the Sardinia-Corsica block.

In northern Corsica the extensional regime resulted in ductile deformation with exhumation of the greenschists facies metamorphic rocks of the Tenda core complex (Jolivet *et alii*, 1990; 1991). Age of deformation is constrained by limestone deposition of Burdigalian-Langhian age (St. Florent limestones) above the exhumed metamorphic rocks (Orszag-Sperber & Pilot, 1976). In the easternmost Corsica onshore Aleria basin, a stratigraphic succession ranging in age from Early Miocene to Late Pliocene crops out (Magné *et alii*, 1975; Orszag-Sperber & Pilot, 1976). This succession has been subdivided in stratigraphic units bounded by unconformities, marking important environmental changing and uplift/subsidence (Loye-Pilot & Magne, 1989; Bossio *et alii*, 2000; Cornamusini *et alii*, 2003). The presence of Burdigalian deposits on already exhumed metamorphic rocks confirms that the extension was already active in the Burdigalian (Jolivet *et alii*, 1990).

In Sardinia counter clockwise rotation led to the formation of a N-S oriented regional graben structure, the Sardinia rift (Cherchi & Montadert, 1982; Thomas & Gennesseaux, 1986), filled with continental conglomerates and sandstones passing upsection to shallow-marine sandstones, marls and limestones (Gesturi, Fangario, Pirri, "Sabbie inferiori", "Calcari inferiori", "Sabbie superiori"). These deposits are also found in southern Corsica (Bonifacio) and mark a regional trasgression in the whole Balearic-Provençal realm. Starting late Tortonian (Kastens *et alii*, 1988; Sartori, 1989; Mascle & Rehault, 1990) the opening of the southern Tyrrhenian Sea led to the formation of the eastern passive margin of the Sardinia-Corsica block. This extensional tectonics proceeds up to Quaternary, with development in central and southern Sardinia of N-S striking east-dipping normal faults. In this time span in Sardinia first deposited a Tortonian-Messinian succession with platform limestones passing to lagoon and then evaporite limestones (Pietra Cantone, Tramezzario, Pietra Forte, Calcari superiori), this evolution reflects the Messinian "salinity crisis" of the whole Mediterranean area. After the Messinian regression an Early Pliocene trasgression occurs, with deposition of marine conglomerates, sandstone and marly clay. Thick continental Pliocene-Quaternary deposits (Samassi) close the succession. Because deposition of the late Tortonian-Quaternary succession is contemporaneous with extensional tectonics, angular unconformities characterised the succession, together with widespread volcanic activity of alkaline, transitional and subalkaline affinity (Capo Ferrato, M. Arci, Montiferro, Logudoro, Campeda, Abbasanta, Marmilla and Orosei).

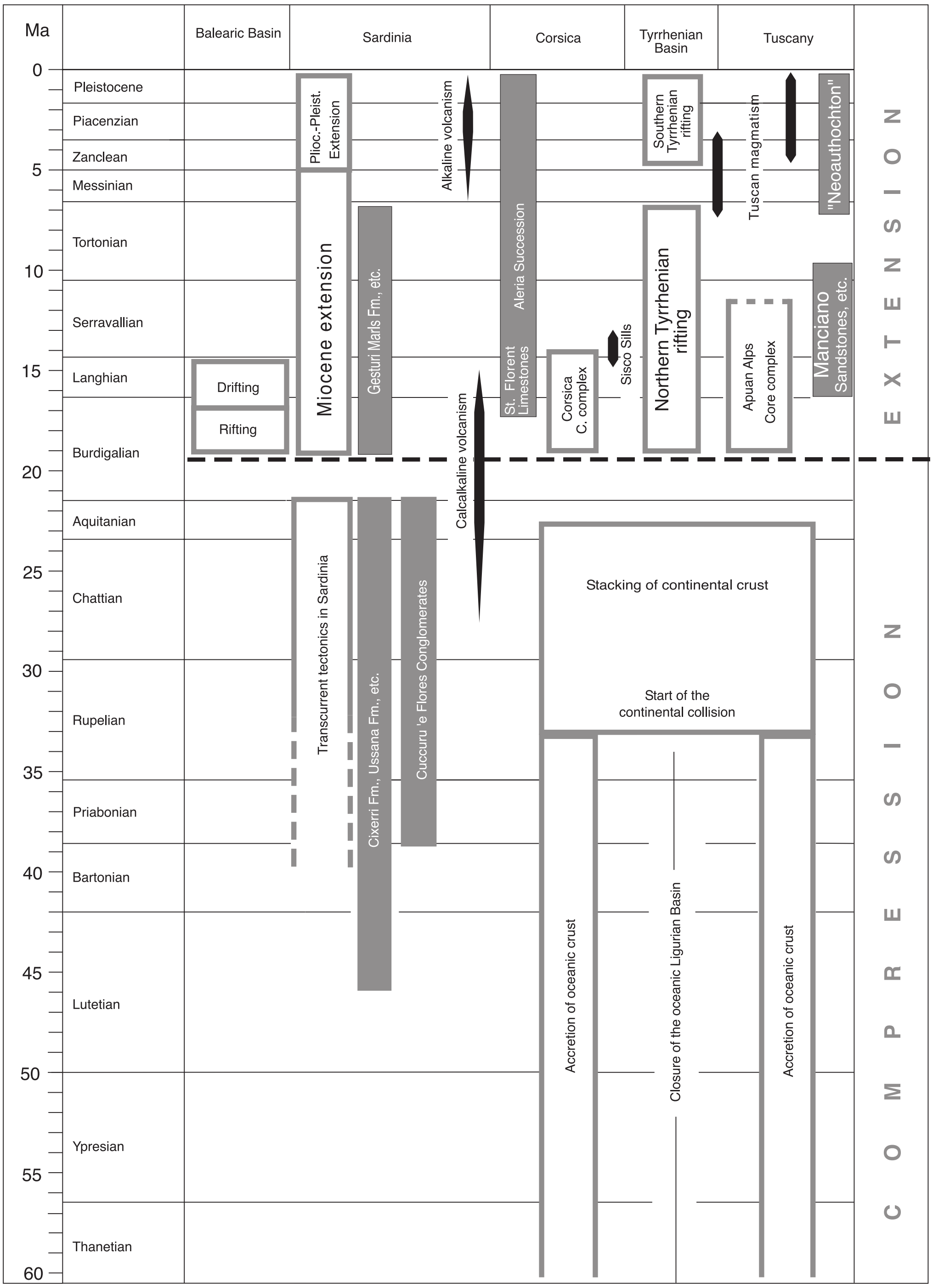

Fig.5 - Main geodynamic events in the northern Apennines, Tyrrhenian Sea and Sardinia-Corsica area (after CARMIGNANI *et alii*, 2001b).

The products of this magmatic activity again suggest that Sardinia changed from an Oligocene-Early Miocene compressional setting with a magmatic arc to an intraplate and passive margin. For a complete reference list about Tertiary and Quaternary sedimentary formations and volcanic succession of Sardinia see CARMIGNANI *et alii* (2001b, with enclosed 1:200,000 geological maps).

THE NORTHERN TYRRHENIAN SEA

The northern Tyrrhenian Sea separates the northern Apennines of the Tuscany coast (Italy) from Corsica (France) (fig. 3), and it is separated from the southern Tyrrhenian Sea along the 41° N parallel lineament (fig. 1f). The northern Tyrrhenian Sea shows a more regular flat and deeper western part (Corsica Basin), and a more irregular eastern part (Tuscan Shelf), characterised by structural highs (ridges) and depressions (basins) (fig. 6). The two parts are separated by an important structural-morphological high, which is the N-S Elba-Pianosa Ridge (WEZEL, 1982).

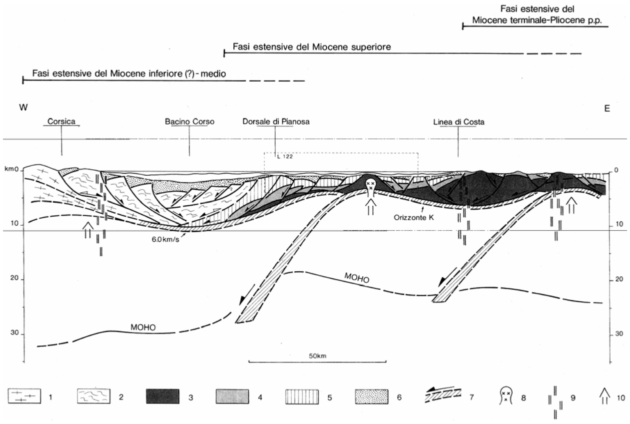

Fig. 6 - Post-collisional ithospheric extension between Corsica and Tuscany (after BARTOLE *et alii*, 1991). 1: metamorphic basement; 2: ophiolites, calcschists and Balagne unit; 3: Tuscan paleozoic basement; 4: Tuscan Nappe; 5: Ligurian units; 6: Neogene syn-rift deposits (white are the post-rift sediments); 7: detachment; 8: granite intrusion; 9: volcanic rocks; 10: crust uplift.

The northern Tyrrhenian Sea developed since Early-Middle Miocene as a half-graben (GABIN, 1972): first the Corsica Basin opened, then since late Tortonian extensional tectonics moved eastward and other basins formed between Corsica and Tuscany. This is due to the progressive eastward migration of the tectonic system, that caused the diachronous extensional regime, affecting the Corsica Basin in the Early-Middle Miocene and the Tuscan Shelf only the Middle-Late Miocene (BARTOLE *et alii*, 1991; PASCUCCI *et alii*, 1999; SARTORI, 2001).

The main stratigraphic-structural units of the northern Tyrrhenian Sea are (from the bottom):

a) a substratum consisting of highly deformed metamorphic and non-metamorphic units that represent the Tertiary collisional orogen: mainly ocean-derived tectonic units (remnants of the Jurassic Tethys ocean) and Apulia continent tectonic units (portion of the accretionary-orogenic wedge);

b) a thick mainly clastic succession, Paleocene?-Eocene to Oligocene in age, infilling the Corsica Basin, as recognizable also on the western side of the Elba-Pianosa Ridge, interpreted like episutural or piggy-back deposits lying on top of the wedge (BARTOLE, 1995; CORNAMUSINI *et alii*, 2002);

c) a clastic succession, Miocene-Pliocene in age, widespread in the whole northern Tyrrhenian Sea, recording syn-rift and post-rift deposits (BARTOLE, 1995; PASCUCCI *et alii*, 1999); these deposits rest unconformably on the episutural Eocene-Oligocene succession in the Corsica Basin, whereas in the Tuscan Shelf they rest directly onto the tectonic units deformed by the collisional tectonics.

A lot of geological literature has been produced on this area, particularly studies of offshore deep and industrial seismic profiles, also bringing different point of views (ZITELLINI *et alii*, 1986; BARTOLE, 1990; BARTOLE *et alii*, 1991; MAUFFRET & CONTRUCCI, 1999; PASCUCCI *et alii*, 1999; FINETTI *et alii*, 2001; CORNAMUSINI *et alii*, 2002; PASCUCCI, 2002), whereas for a full overview of the geological framework of the area see BOCCALETTI *et alii* (1990), BARTOLE (1995), CARMIGNANI *et alii* (1995), SARTORI (2001). A synthesis is reported in fig.7.

The Corsica Basin is filled with about 8-9 kilometres of clastic deposits (MAUFFRET & CONTRUCCI, 1999; MAUFFRET *et alii*, 1999; SARTORI, 2001); with seismic analysis researchers recognised for the Corsica Basin-Tuscan Shelf some seismic-stratigraphic units separated by unconformities (GABIN, 1972; ALERIA, 1980; BACINI SEDIMENTARI, 1980; ZITELLINI *et alii*, 1986; MARIANI & PRATO, 1988; PATACCA *et alii*, 1990; BARTOLE *et alii*, 1991; BARTOLE, 1995; LAZZAROTTO *et alii*, 1995; PASCUCCI *et alii*, 1999).

Two drilled boreholes, the AGIP Martina 1 and Mimosa 1 located on the Elba-Pianosa Ridge at the east side of the Corsica Basin (fig. 3), confirmed the presence of thick Tertiary clastic successions, unconformably lying on the deformed substrata (BARTOLE, 1995). These successions consist of siliciclastic deposits organized in a lower stratigraphic unit, Early-Middle Miocene in age, an intermediate stratigraphic unit of Oligocene age, and a higher, Late Burdigalian in age (CORNAMUSINI *et alii*, 2002). The first two units are interpreted as episutural-piggy-back deposits, whereas the latter is referred to the initial rifting phase of the basin.

Data from the onshore Pianosa Island show an Early Miocene succession (Marina del Marchese Fm.) unconformably topped by Middle Pliocene sediments (DALLAN, 1964, 1967; COLANTONI & BORSETTI, 1973). Recently FORESI *et alii* (2000) documented an angular unconformity subdividing the Marina del Marchese Fm. in two portions, a lower one of Burdigalian age of marine environment and an upper one of Late Tortonian age of

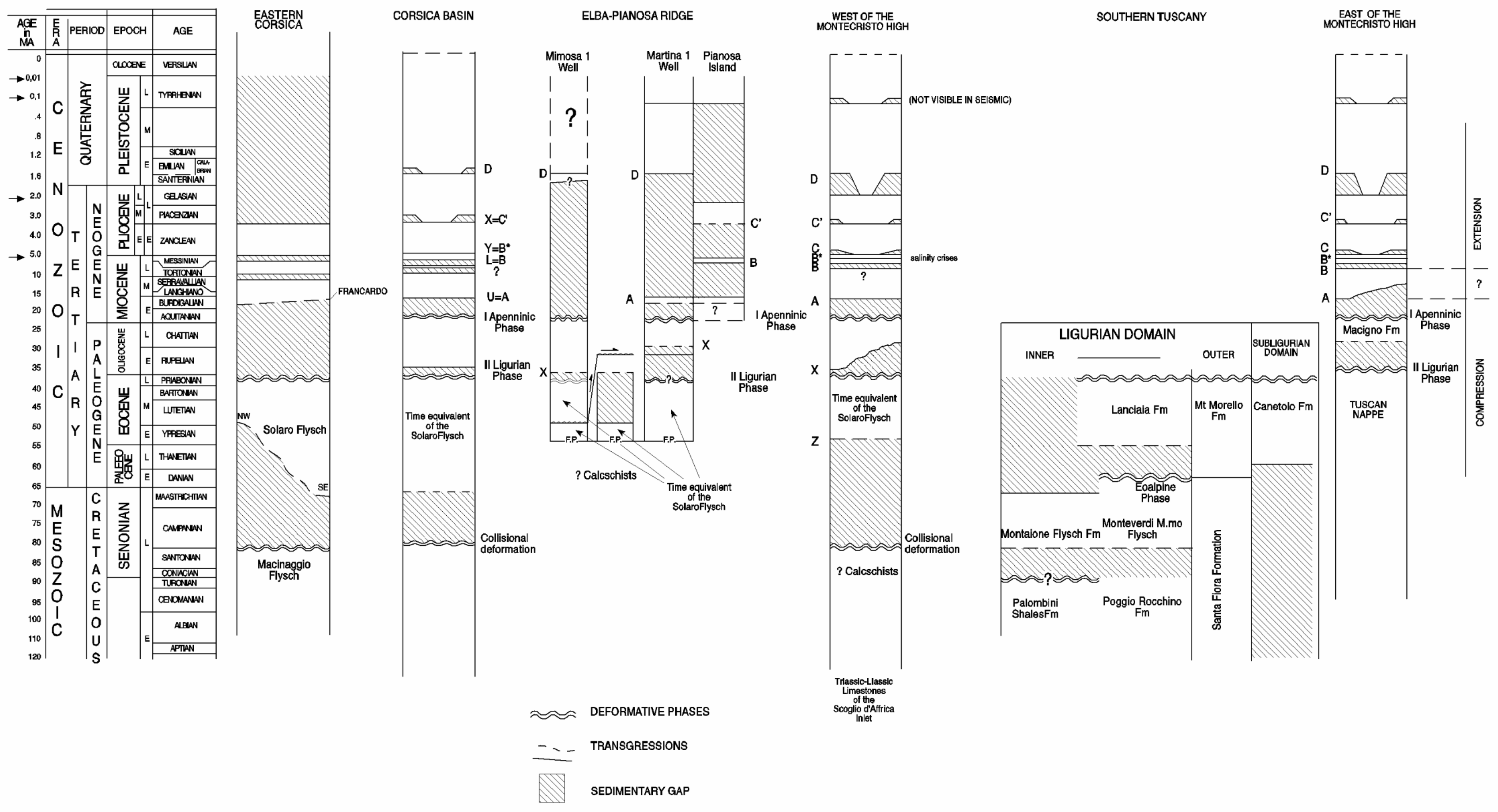

Fig. 7 - Stratigraphic columns of the Mesozoic and Cenozoic successions of eastern Corsica, Corsica Basin, Elba-Pianosa Ridge, Tuscan Shelf, (west and east of the Montecristo High), and of the Ligurian and sub-Ligurian successions of southern Tuscany. X, Y, L, U are the Neogene unconformities recognised in the Corsica Basin by ZITELLINI *et alii* (1986). Z=bottom of the Eocene strata; X=bottom of the Oligocene strata; A=bottom of upper Burdigalian-?Serravallian strata; B=bottom of upper Tortonian-Messinian deposits; B*=bottom of upper Messinian deposits; C=bottom of lower Pliocene deposits; C'=base of middle Pliocene deposits; D=base of Quaternary deposits (after CORNAMUSINI *et alii*, 2002).

fresh-water environment, up to brackish-water - marine environment on top (Early Messinian) (BOSSIO *et alii*, 2000; FORESI *et alii*, 2000). The Burdigalian sequence can be correlated with the coeval succession of the Elba-Pianosa Ridge, identified in the Martina 1 borehole. Seismic reflection profiles in Tyrrhenian Sea just south of the Pianosa Island show that the Miocene sediments cropping out at Pianosa Island are discordant on a pre-Neogene susbstratum (BARTOLE, 1990; BARTOLE *et alii*, 1991). The Miocene sediments of Pianosa Island are part of a sedimentary sequence that thickens toward the west, until it reaches between 3000 and 4000 meters in the Corsica Basin.

The Tuscan Shelf is characterised by the presence of minor extensional basins filled of Miocene-Pliocene sediments. Moreover, the Tuscan Shelf is also characterised by the presence of several islands belonging to the Tuscan Archipelago. The Elba Island, the larger one, shows a complex geological framework, with a polydeformed stack of tectonic units, formed during the collisional orogenic phases (TREVISAN, 1950, 1953; KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; BORTOLOTTI *et alii*, 2001a). The western part of the Elba Island, as well as other islands of the Tuscan Archipelago (Montecristo, Giglio, Capraia) are made of magmatic rocks emplaced in a extensional tectonic regime (BOUILLIN, 1983; PERTUSATI *et alii*, 1993; KELLER *et alii*, 1994; WESTERMANN *et alii*, 1994; DANIEL & JOLIVET, 1995; JOLIVET *et alii*, 1998; ROSSETTI *et alii*, 1999), and changing in age following the tectonic migration, younging eastward from 15.2 Ma to 0.4 Ma (see SERRI *et alii*, 2001, for a complete reference list). In the Langhian, in eastern Corsica, alkaline igneous rocks are represented by the Sisco dykes, dated at 15.2 Ma, the oldest of the Northern Tyrrhenian Sea (CIVETTA *et alii*, 1978) interpreted by some authors to record the initial stages of rifting of the Northern Tyrrhenian Sea.

THE NORTHERN TUSCANY

In northern Tuscany (fig. 8), the first extensional event of Early-Middle Miocene age developed tectonic features very similar to those found in Alpine Corsica: i.e. ductile deformation and exhumation of metamorphic rocks. Younger Late Tortonian-Quaternary evolution produced NW-SE striking normal faulting, which developed graben structure (Garfagnana, Lunigiana) and that played a key role in the development of the NW-SE oriented Tyrrhenian coast. The best example of superposition of tectonic structures during extension and exhumation is in the Alpi Apuane area (fig. 3), we therefore discuss the post-collisional evolution of this sector of the Apennine orogen from observations from this well exposed area.

In the Alpi Apuane all the compressional (D1) structures and tectonic contacts are overprinted by different generations of later structures (D2). The D2 structures are represented by syn-metamorphic, variously sized high strain zones and well developed fold systems mainly associated with a low dipping to sub-horizontal axial planar foliation (S2) of crenulation type associated with different generations of brittle faults, that accomodate the most recent (Quaternary) tectonic history.

According to classical interpretations (CARMIGNANI *et alii*, 1978; 1979; 1990) a complex mega-antiform with Apennine trending axis (nearly N 130°-170°), and corresponding to the entire width of the Alpi Apuane window, was realized as result of the D2 history. All around the antiform, second order asymmetric folds facing away from the dome crests are described and, at scale of the whole Alpi Apuane, reverse drag-folds having "S" and "Z" sense of asymmetries can be observed on the southwestern and northeastern flanks, respectively. These minor structures form series of folds at different scale (from centimeters to kilometers) with variable shapes depending on rock competence and structural position within the folded multilayer, but also on the orientation and intensity of development of D1 structures. The tectonic meaning of D2 structures however has been object of different interpretations during the years:

- they formed during a post-nappe refolding related to a continuous contractional history;
- they produced as reverse drag folds overprinting complex highly non-cylindric D1 sheath folds during late rebound by vertical isostatic reequilibration of former thickened crust;
- they born as passive folds related to distributed shear within kilometric scale shear zones accomodating crustal extension .

Possibly different folding mechanisms were active during D2 deformation. Based on recent work, we point out here that all major km-scale D2 folds show a facing direction that is opposite to the dip direction of the main high-angle normal faults that border the Alpi Apuane window (fig. 8). In the northern Alpi Apuane major D2 folds face SW and the main border fault is located in the Garfagnana valley and dips NE. In the southern Alpi Apuane main D2 folds face NE and here the main high-angle normal faults are those of the Versilia area (between Massa and Viareggio) dipping SW. We suggest that normal faults and folds are closely related and their development should be more or less contemporaneous: we interpret the folding event as due to gravity tectonics consequent to the uplift of footwall rocks during normal faults activity (see lower left inset in fig. 8). It is important to note that normal faulting and uplift is very recent in this area (Quaternary in age), hence also the development of the "ductile" D2 deformation might be very much younger than previously supposed.

This kind of structures are evident also in the La Spezia area, where late SW-facing folds developed in the footwall of a regional NE-dipping normal fault (La Spezia fault). This also occurs north-east of Castelnuovo Garfagnana (fig. 3) where large faults dip SW (Corfino) and late folds show a north-eastward facing. In this area the north-eastward transport direction of folds locally can develop thrusts in the overturned limb of the km-scale folds (see lower left inset in fig. 8), these thrusts can be responsible of some “anomalous” nappe superposition found in the area, with emplacement of Tuscan units above Ligurian units.

THE SOUTHERN TUSCANY

Southern Tuscany represents the hinterland of the Northern Apennines, where portions of the collisional orogenic wedge dismembered by the extensional tectonic outcrop, as well as the sedimentary sequences linked to the rift and post-rift phases, that lie unconformably onto the deformed units. The southern Tuscany, delimited to north along the Arno Valley (in correspondence of the Livorno-Sillaro tectonic transversal line, BORTOLOTTI, 1966), is characterised by high rates of extension, with the development of structural highs and lows. The highs are characterised by outcrops of Palaeozoic-Lower Miocene formations deformed and metamorphosed by the collisional phases, whereas the lows are characterised by the infilling of sediments relative to the postcollisional tectonics, ranging in time from Miocene to Pleistocene. Southern Tuscany shows features linked to the rifting and crustal thinning processes, so that the lithosphere thickness is estimated to be about 30 km (CALCAGNILE & PANZA, 1981; DECANDIA *et alii*, 1998). Consequently, high heat flow (average 120 mW/m^2, locally in geothermal fields reach up to 1000 mW/m^2) (MONGELLI *et alii*, 1989; MONGELLI & ZITO, 1991; DELLA VEDOVA *et alii*, 2001) and positive Bouguer anomalies (ELTER *et alii*, 1975; GIESE *et alii*, 1981) are common.

Collisional tectonic of the orogenic wedge started in the Late Eocene and ended in the Early Miocene, when initiate the postcollisional phases accompanied by tectonic extension that caused the formation of rifting/post rifting basins.

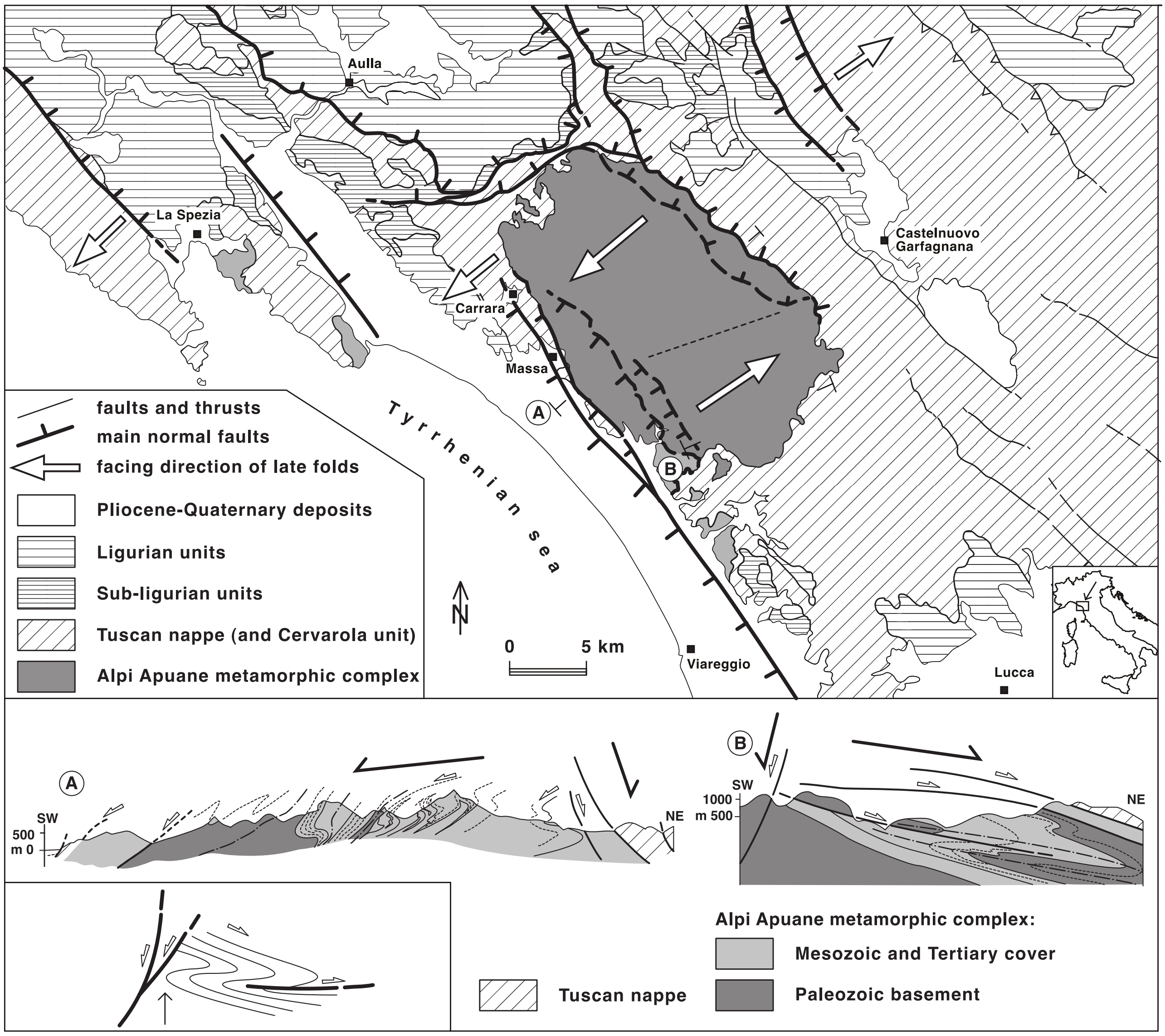

Fig. 8 - Tectonic sketch map of northern Tuscany.The major tectonic lineaments and structures linked with Quaternary uplift are outlined.

These basins are filled with a Neogene sedimentary succession unconformably overlying the orogenic substratum. This succession, also called "neoauthoctonous" in the Italian geological literature, has been subdivided in stratigraphic units separated by unconformities (see BOSSIO *et alii*, 1998, with references therein), which are (fig. 9): a) Middle Miocene up to lower Tortonian shallow marine deposits (Ponsano, Rencine and Manciano sandstones); b) upper Tortonian-lower Messinian continental up to shallow marine deposits (Lignitiferous Unit, Acquabona-Spicchiaiola Unit, Castelnuovo Unit); c) upper Messinian evaporites and continental deposits Lago-Mare Unit); d) Lower-Middle Pliocene marine deposits (Pliocene I Unit, Pliocene II Unit); e) Middle-Upper Pliocene up to Pleistocene continental deposits (Pliocene III Unit, Chiani-Tevere-Montescudaio Unit).

It is worth note that the first Middle Miocene succession is still placed by some Authors in a compressional context, considering them piggy-back deposits, correlated with the Lower-Middle Miocene successions of the Emilia Apennines (MARTINI *et alii*, 1995, with references therein).

Extension was also accompanied by widespread Late Miocene-Quaternary magmatism deriving from mixing of crustal and mantle sources (SERRI *et alii*, 1993, 2001).

In more detail the initiation of post-collisional extensional tectonics in southern Tuscany has usually been dated as late Tortonian on the basis of the age of the oldest deposits that fill Late Miocene-Pliocene grabens of southern Tuscany. However, recent works show that the beginning of the extension occurred much earlier, in the Early-Middle Miocene (BERTINI *et alii*, 1991; DECANDIA *et alii*, 1993; CARMIGNANI *et alii*, 1994b; 1995; 2001a).

The Neogene extension is subdivided in three extensional events (BALDI *et alii*, 1994; DECANDIA *et alii*, 2001), characterised by different tectonic structures and basin filling: a first event of the Early-Middle Miocene (Burdigalian-Langhian), a second event of the Late Miocene (Serravallian-Messinian) and a third event of the Pliocene-Pleistocene (fig. 9).

The first extensional event developed low-angle normal faults and it was responsible of strong tectonic elision and crustal thinning, forming the "serie ridotta" structural condition (TREVISAN, 1955; GIANNINI *et alii*, 1971; LAVECCHIA *et alii*, 1984; BERTINI *et alii*, 1991), through flat-ramp-flat faults geometry and the structuration of asymmetrical megaboudinage at shallowcrustal levels (BERTINI *et alii*, 1991; BALDI *et alii*, 1994; BROGI, 2003; BONCIANI *et alii*, 2004). In the "serie ridotta" of southern Tuscany, the highest units in the nappe stack (Ligurides) frequently overlie directly deepest units (even the metamorphic substrata), with remarkably tectonic omission of the stratigraphy (BERTINI *et alii*, 1991). The regional main flats of the faults are located at the base or within the Ligurian units and at the base or within the Triassic evaporitic "Calcare Cavernoso" Fm., whereas the ramps dissected the Tuscan Nappe (CARMIGNANI *et alii*, 2001a, with references therein). The amount of extension in southern Tuscany that was needed to produce the "serie ridotta", is estimated greater than 120% (BERTINI *et alii*, 1991; CARMIGNANI *et alii*, 1994b). Following this first event, marine sediments were deposited discordantly on the Ligurian units (CARMIGNANI *et alii*, 2001a). The first deposits are Langhian (Manciano Sandstones, GIANNINI, 1957; FONTANA, 1980), whereas the most recent deposits of this event are late Serravallian-early Tortonian (Ponsano Sandstones, MAZZEI *et alii*, 1981; FORESI *et alii*, 1997).

A second extensional event (Late Miocene) developed with listric normal faults that dissected all previous structures and formed basinal depression where lacustrine to marine sedimentation took place (late Tortonian-early Messinian). These deposits represent the real rifting-sediments of the southern Tuscany, lying unconformably onto Middle Miocene sediments and overall onto Ligurian units and subordinately onto the other units of the orogenic stack (BROGI, 2003; BONCIANI *et alii*, 2004). Sometimes Miocene sediments show folds and thrusts that some Authors explain as the effect of compressional tectonic events (BERNINI *et alii*, 1990; BOCCALETTI *et alii*, 1992; 1995; BONINI & SANI, 2002).

A third extensional event (Pliocene-Pleistocene) developed with NNW-SSE and N-S high-angle normal faults which dissected all the previous structures.

These listric faults flattened in deep crustal levels, in correspondence of a shear zone located at the "brittle/ductile" transition, delimited at the top by the "K-horizon" (CAMELI *et alii*, 1993; BROGI *et alii*, 2003). During this event, graben and half-graben basins formed (MARTINI & SAGRI, 1993), and the Early Pliocene marine transgression with filling of deep elongated basins parallel to the chain, developed.

The stretching produced by high-angle normal faults is approximately 6-7% (BERTINI *et alii*, 1991; CARMIGNANI *et alii*, 1994b). Pliocene deposits are overall marine, whereas for the Late Pliocene-Pleistocene they are of continental environment. The Early Pliocene transgression was very widespread and determined the unconformably deposition of Pliocene sediments on to Miocene sediments and on to all units of the pre-Neogene tectonic stack (BOSSIO *et alii*, 1993; 1998). Since Middle Pliocene, southern Tuscany was affected by rapid surface uplift, that caused the final neoautochtonous regression (DALLMEYER & LIOTTA, 1998). Moreover, the main tectonic graben depressions were dissected transversally by transfer zones (BARTOLINI *et alii*, 1982; LIOTTA, 1991).

CONCLUSIONS

The hinterland area of the Northern Apennines records an history of compression followed by progressive tectonic extension. We recognize, (after Cretaceous-Eocene deformations only recorded in the obducted oceanic Ligurian units):

a) a Late Oligocene-Early Miocene stage, with continuing collision of the European continent with the Apulia microplate yielding to underplating, formation of an orogenic wedge and compressional deformation in the European and Apulia margin;

b) an Early-Middle Miocene stage linked to the opening of the Algero-Provençal basin, with ductile extensional tectonics in the overthickened orogenic wedge, producing extension in the Apennines, in Corsica and in the Corsica Basin;

c) the final late Tortonian-Quaternary stage linked to the opening of the southern Tyrrhenian Sea, when extension migrates eastward and affected the whole Tuscany.

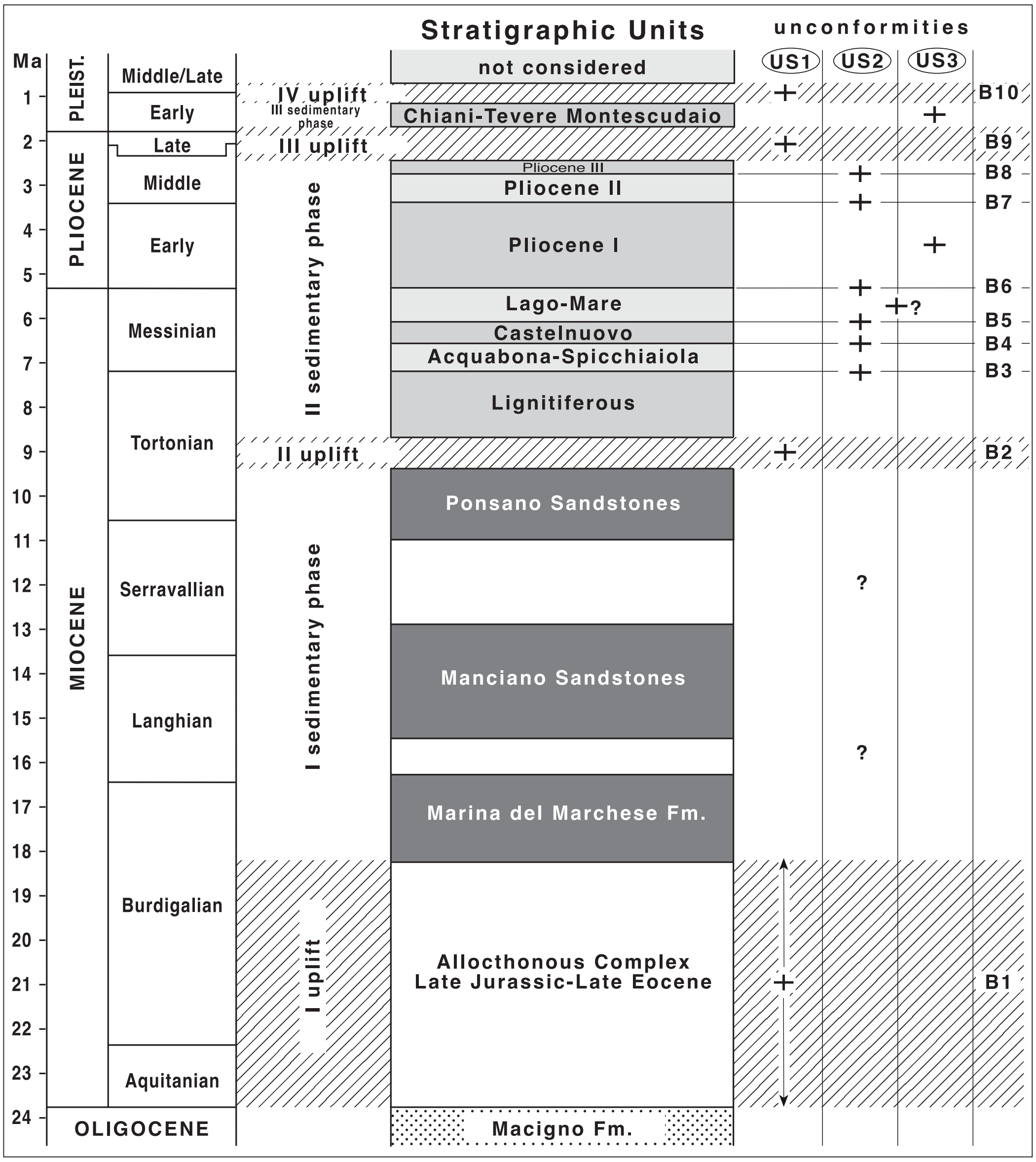

Fig.9 - Chronostratigraphic distribution of the depositional-stratigraphic units recognized in southern Tuscany (from BOSSIO *et alii*, 1998): the lower-middle Miocene formations (late Burdigalian-early Tortonian) are represented in dark grey; those relative to the late Tortonian-middle Pleistocene time interval are shown in light greys; stratigraphic gaps are with oblique lines. Every uplift is followed by a sedimentary interval. The post-Pleistocene sedimentary interval has not been considered. B1, B2…B10, indicate unconformities that are unit boundaries: US1 – first order unconformities, recognized in the whole western part of the Northern Apennines; US2 – second order unconformities, local, for those the relative conformity is recognizable; US3 – third order unconformities, local, for those is not possible to recognize the relative conformity. The symbol "+" represents uplift at the regional scale and/or local. The symbol "?" represents a doubt interpretation due to the scarcity of data.

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