Boll. Soc. Geol. It., Volume Speciale n. 3 (2005), 103-118, 5 ff.

Neogene post-collisional evolution of the internal Northern Apennines: insights from the upper Fiora and Albegna valleys (Mt. Amiata geothermal area, southern Tuscany)

FILIPPO BONCIANI, IVAN CALLEGARI, PAOLO CONTI, GIANLUCA CORNAMUSINI (*) & LUIGI CARMIGNANI

ABSTRACT

The southern Tuscany represents the internal portion of the Northern Apennines. Its geological setting is particularly complicated due to two main tectonic phases: a first compressional syn-collisional phase (Late Cretaceous-Early Miocene) that led to nappe building and km-scale tectonic features; a later extensional post-collisional phase (Early Miocene-Pleistocene) led to uplift and unroofing of the thickened crust is linked to the anticlockwise Apennine rotation and Tyrrhenian Sea opening.

The upper valleys of the Fiora and Albegna rivers in southern Tuscany represent a key area to reconstruct the post-collisional tectonic and sedimentary evolution of this sector of the Apennine chain. This area is characterized by a tectonic nappe stack built during the syn-collisional phase, unconformably overlain by Miocene-Pliocene depositional units, referable to a few sedimentary cycles. The sedimentary-tectonic evolution for the study area, as recognizable by field data, is the result of a sequence of different deformative and depositional events. The compressive event (Early Miocene) led to crust thickening and emplacement of the Ligurian units onto the Tuscan Nappe. Later on, a first extensional event (Early-Middle Miocene) developed low-angle normal faults. This event was responsible of a strong tectonic elision and crustal thinning, forming the «serie ridotta», characterized by a megaboudinage tectonic setting and developing structural-morphological depressions, probably seat of shallow-marine deposition. A second extensional event (Late Miocene) developed west-dipping listric normal faults, increasing the megaboudinage depressions. In the study area, the activity of west-dipping normal faults caused the deformation of the tectonic nappe stack with the development of regions with steep east-dipping attitude of bedding. In these regions east-dipping normal faults affected the steep dipping bedding, so to form structural depressions in which tectonic delaminated slices, usually Ligurian units, were emplaced. Moreover, such structural depressions represented also the basins of the Late Miocene continental-marine sedimentation. A third extensional episode (Pliocene) developed with high-angle normal faults which dissected all the previous structures. During this extensional event graben and half-graben basins formed, and the Early Pliocene marine transgression with filling of deep elongated basins parallel to the chain, developed.

KEY WORDS: *sedimentary basins, extensional tectonic, normal faulting, Miocene-Pliocene, southern Tuscany*.

RIASSUNTO

Evoluzione neogenica post-collisionale della parte interna dell'Appennino Settentrionale: implicazioni dalle alte valli del Fiora e dell'Albegna (area geotermica del Monte Amiata, Toscana meridionale).

La parte interna dell'Appennino settentrionale rappresenta un'area a crosta continentale fortemente assottigliata a seguito di processi estensionali, sviluppati a partire dal Miocene inferiore-medio, collegati con l'apertura del Bacino Algero-Provenzale e del Mare Tirreno settentrionale (CARMIGNANI *et alii*, 1994).

L'area compresa tra le alte valli dei fiumi Fiora ed Albegna rappresenta un'area significativa in cui è riconoscibile la sovrapposizione di più eventi deformativi postcollisionali. Quest'area è caratterizzata da un assetto geologico alquanto complesso, legato alle fasi deformative di strutturazione della catena appenninica e della successiva estensione neogenica. Si riconosce una pila strutturale data dalla sovrapposizione di più unità tettoniche, formatasi nella fase orogenica appenninica, la quale è stata poi dislocata a partire dal Miocene inferiore-medio da strutture tettoniche distensive a geometria «*flat-ramp-flat*» legate allo sviluppo della «serie ridotta» (vedi in DECANDIA *et alii*, 1993) e nel Miocene superiore e nel Pliocene da faglie normali ad alto angolo.

La pila strutturale è costituita dal basso verso l'alto da:

– Unità metamorfiche del Basamento Toscano, le quali non affiorano, ma sono state incontrate in sondaggi profondi (ELTER & PANDELI, 1991).

– Unità tettonica della Falda toscana, costituita da una successione sedimentaria che va dalle evaporiti della Formazione Anidriti di Burano-Calcare cavernoso del Triassico superiore, al Macigno dell'Oligocene superiore.

– Unità tettonica di Santa Fiora, derivata dalla deformazione del Dominio Ligure Esterno, e costituita dalla Formazione delle Argille Varicolori, dalla Formazione della Pietraforte e dalla Formazione di S. Fiora, di età compresa tra il Cretacico inferiore ed il Cretacico sup.-Paleocene.

– Unità tettonica Ofiolitifera, derivata dalla deformazione del Dominio Ligure Interno, e costituita dalla Formazione delle Argille a palombini, contenente localmente blocchi di ofioliti.

Alla pila di unità tettoniche si sovrappongono, tramite una forte discordanza angolare, le successioni sedimentarie neoautoctone, deposte durante la fase deformativa estensionale, quali una inferiore del Miocene medio di ambiente marino marginale, una intermedia del Miocene superiore di ambiente prevalentemente continentale e subordinatamente marino, ed una superiore del Pliocene, di ambiente marino. Si riconosce inoltre, una successione villafranchiana di ambiente continentale.

L'assetto tettonico dell'area è determinato dalla sovrapposizione di più eventi deformativi di carattere compressivo pre e sincollisionale, e di carattere distensivo postcollisionale.

Le alte valli del Fiora e dell'Albegna sono caratterizzate dalla presenza di importanti allineamenti strutturali orientati circa NNW-SSE. Tra questi, gli alti strutturali sono costituiti da nuclei di affioramenti della Falda Toscana, comprendenti termini carbonatici giurassici, termini pelitico-calcarei della Scaglia toscana ed in taluni casi termini arenacei del Macigno. I nuclei a serie toscana, rappresentati a partire da ovest, dalle dorsali di Roccalbegna-alta valle dell'Albegna, di Semproniano-Poggio Murella, di Poggio della Vecchia-Elmo, sono disposti parallelamente tra loro. Le aree strutturalmente ribassate costituiscono altrettante fasce parallele ad orientazione appenninica, caratterizzate da forte elisione tettonica con sovrapposizione di unità liguri direttamente sui termini più bassi della Falda Toscana, spesso direttamente sulle evaporiti triassiche. Sempre all'interno delle zone ribassate (versante orientale dell'alto corso del Fiume Albegna, valle del Fiume Fiora, area ad est di Castell'Azzara-Elmo), al di sopra delle unità liguri in discordanza stratigrafica, si trovano i depositi continentali del Miocene superiore. Nel complesso, la struttura geologica assume il carattere di un *megaboudinage* (DECANDIA *et alii*, 2001; PANDELI *et alii*, 2002; BROGI,

(*) Centro di Geotecnologie, Università di Siena, Via Vetri Vecchi 34, San Giovanni Valdarno (AR). Dipartimento di Scienze della Terra, Università di Siena, Via Laterina 8, Siena (cornamusini@unisi.it)

2003; 2004b) che interessa la crosta superiore. I rispettivi *megaboudin*s sono rappresentati da nuclei a serie toscana comprensivi di tutta o buona parte della successione, delimitati lateralmente da zone di interposizione in cui si ha la sovrapposizione di unità liguri direttamente sul Calcare cavernoso o su termini della Falda Toscana interessati da forti omissioni di serie.

Nell'area in esame sono riconoscibili faglie estensionali classificabili in quattro gruppi, che si differenziano in base alla geometria, all'entità della dislocazione, alla direzione di immersione ed alla posizione rispetto ai nuclei di Falda Toscana.

In base agli elementi emersi è possibile ipotizzare per l'area posta a sud del Monte Amiata, un quadro evolutivo tettonico-deposizionale che ha previsto nell'ambito della fase postcollisionale, una successione di episodi deformativi e deposizionali.

L'evoluzione strutturale e deposizionale neogenica dell'area è riconducibile a tre principali episodi deformativi legati alla tettonica estensionale postcollisionale, inquadrabili negli eventi distensivi riconosciuti da Baldi *et alii* (1994).

Il primo evento estensionale, datato al Miocene inferiore-medio (Decandia *et alii*, 1993; Carmignani *et alii*, 1994), ha determinato la formazione di faglie dirette a geometria *flat-ramp-flat* immergenti verso est, accompagnate da forti elisioni tettoniche («serie ridotta»), che hanno prodotto un *megaboudinage* asimmetrico nei livelli superficiali della crosta.

Il *megaboudinage* ha quindi determinato la formazione di strutture asimmetriche, ciascuna delle quali costituita da un settore a modesta elisione caratterizzato da nuclei di serie toscana e da un settore a forte elisione, in cui le unità liguri poggiano direttamente sulle evaporiti toscane. Durante questo evento deformativo si sono venute ad individuare delle prime blande depressioni morfologico-strutturali, che hanno probabilmente rappresentato la sede della sedimentazione dei depositi del Miocene medio della Toscana meridionale. Si vengono così ad individuare i primi bacini sedimentari neogenici toscani, che in questa ipotesi troverebbero collocazione in un regime estensionale relativo alla sedimentazione neoautoctona.

Il secondo evento distensivo è inquadrabile nell'evento del Miocene medio-superiore, in cui si sviluppano faglie listriche che in profondità si raccordano al tetto delle filladi paleozoiche (Baldi *et alii*, 1994). In tale evento si attivano faglie dirette che in base alla loro ubicazione sembrano risentire del controllo strutturale esercitato dai megaboudins formatisi con il primo evento estensionale, le cui strutture vengono ad essere deformate. Durante questa fase il tetto della «serie ridotta» ha assunto una posizione strutturalmente ancora più depressa, in cui si sono venuti a configurare i bacini del Miocene superiore, a sedimentazione lacustre. La geometria di tali bacini sembra essere vincolata ai sistemi di faglie attivati in questo evento, ma che si sovrimpongono e risentono anche delle depressioni formatesi durante la «serie ridotta».

Il terzo evento estensionale, datato al Pliocene, è caratterizzato dalla formazione di sistemi di faglie listriche che si esauriscono a livelli crostali profondi, in corrispondenza di una fascia di taglio al passaggio fragile/duttile delimitata al tetto dall'orizzonte K (Cameli *et alii*, 1993). Questo sistema di faglie ha determinato la formazione di depressioni tettoniche di tipo *graben* o *semigraben* (Martini & Sagri, 1993) ad orientazione appenninica. Sempre durante questa fase, si sono formati bacini marini profondi che hanno caratterizzato la sedimentazione pliocenica del retropaese appenninico.

Termini chiave: *bacini sedimentari, tettonica estensionale, megaboudin, Miocene-Pliocene, Toscana meridionale.*

INTRODUCTION

The internal region of the Northern Apennines represents a zone of continental crust strongly thinned (Calcagnile & Panza, 1981), as consequence of the post-collisional extensional process, developed since the the end of the Early Miocene (Carmignani *et alii*, 1994; 2001; 2004 *cum bib*), and linked with the opening of the Algerian-Provençal Basin and of the Northern Tyrrhenian Sea (Carmignani *et alii*, 1995; Jolivet *et alii*, 1990, 1998; Decandia *et alii*, 1998; Liotta *et alii*, 1998).

The southern Tuscany, hinterland of the Northern Apennines, results to be therefore a large zone interested by the extensional Neogene phases, in which, the geothermic area of the Mt. Amiata constitutes a very important and representative sector in order to reconstruct the relationships between the different structures to the deformative events.

In the framework of the Geological Cartography Project of the Tuscany Region, new field work, including a 1:10.000 scale geological mapping, is carried out for the area placed south of the geothermic region of the M. Amiata (southern portion of the CROP18B seismic profile). The study area extends for almost 230 km^2 and it is included between the high valleys of the Albegna and Fiora rivers (fig. 1). The data emerged from the field work allow some considerations about the relationships between the structural and stratigraphical evolution of the tectonic units of this sector of southern Tuscany, and in particular between the units involved in the collisional tectonics and the Neogene depositional successions. We discuss the fitting and the integration of the reported data within the depositional-tectonic evolution framework hypothesized by numerous Authors (Baldi *et alii*, 1994; Carmignani *et alii*, 1995; Decandia *et alii*, 2001) for this portion of the Northern Apennines.

PREVIOUS STUDIES

Previous researches in this area, with the exception of the most recent ones, only discuss the local geological setting, but without fitting in a larger evolutive geological model. The study area has been the object of several geological studies, especially during the years '70 and '80, when the geothermic research has to meet with a considerable growth. Among the more important works it is worth to mention: the geological map at scale 1:50.000 by Calamai *et alii* (1970) and the geological maps by Bettelli (1980a) and Bettelli *et alii* (1990) with the relative explanatory notes (respectively Bettelli, 1985 and Bonazzi *et alii*, 1992). A wide part of the area is included also within the Sheet 332-Scansano of the Geological Map of Italy at scale 1:50,000, with the explanatory notes of Cestari *et alii* (1981), and of the Sheet 129-S. Fiora, of the Geological Map of Italy at scale 1:100.000, with explanatory notes of Jacobacci *et alii* (1967). Other works of regional geology are of Elter (1955), Losacco (1959) and Decandia *et alii* (1994) for the Castell'Azzara area.

In the attempt to compare the geological framework of this sector of southern Tuscany, with geological setting of the Northern Apennines, Bettelli (1980b) and Bettelli *et alii* (1979, 1980) point out the presence of the «Canetolo Complex» in this area. The northern sector of the study area has been studied also by Pandeli *et alii* (2002; 2003), who provided new stratigraphical and structural data about the setting of the orogenic complex. Other observations are those of Crescenti & Giussani (1969), who emphasized the presence of overthrusting within the Tuscan succession in the M. Labbro area, and the works of Brogi & Lazzarotto (2002) and Brogi (2003; 2004a) who recognised thrusting also in the Tuscan succession for the western sector of M. Amiata.

Among works dealing with stratigraphy of the area, important are those of Canuti & Marcucci (1971) for the «Tuscan succession» and of Boccaletti & Sagri (1964) for the Ligurian complexes.

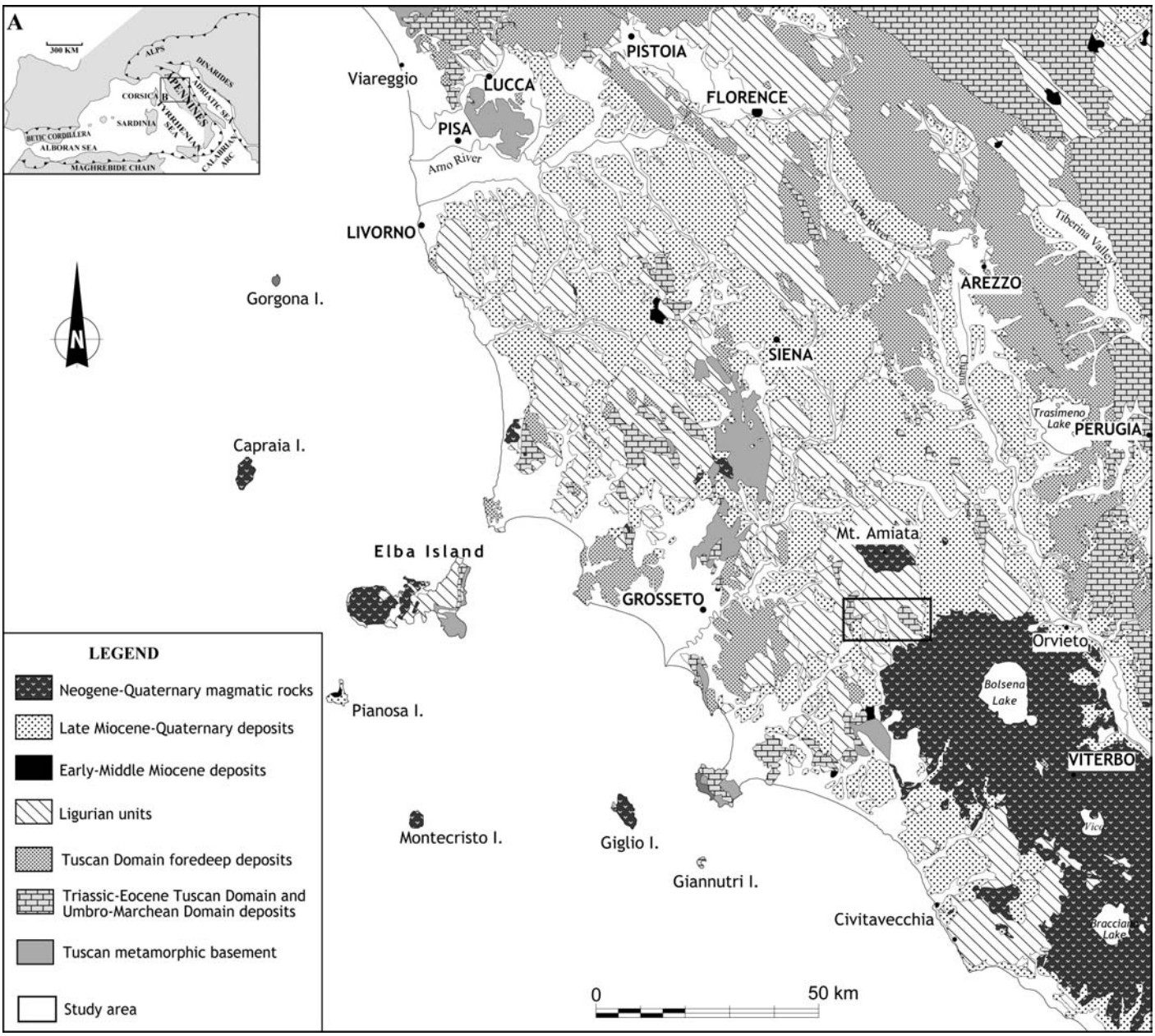

Fig. 1 - Geological sketch map of the Internal Northern Apennines with the location of the study area (rectangle in fig. 1B).
– Schema geologico della parte interna dell'Appennino settentrionale, con l'ubicazione dell'area studiata (rettangolo della fig. 1B).

As far as it concerns the stratigraphy and the tectonic of Neogene deposits of the Albegna River Basin, we remind to the papers of BONAZZI *et alii* (1980), of ZANCHI & TOZZI (1987) and of BOSSIO *et alii* (1993, with references therein).

GEOLOGICAL FRAMEWORK

The study area is located between the high valleys of the Fiora and Albegna rivers, and is characterized by a complicated geological setting, resulting from the pre-, syn- and post-collisional deformative phases of the Northern Apennines (fig. 2).

It is delimited to the north by the volcanic complex of the M. Amiata, to the east by the Neogene Basin of Radicofani, to the south-east by the volcanic complex of the Vulsini Mountains, to the south-west by the Neogene Albegna Basin. The study area is a wide regional structural high, with outcrops of units of pre-Neogene age (deformed both by the orogenic compressional tectonic, and by the extensional postorogenic tectonics) and Neogene units of continental to marginal marine environments (affected only by the extensional tectonics).

The orogenic nappe stack, formed by tectonic units originated by different paleogeographic domains, was formed during the compressional-collisional phase, ended in the Early Miocene in the Tuscany area. Since the Early-Middle Miocene up to the Plio-Pleistocene, the area became part of the internal sector of the Northern Apennines and has been affected by extensional tectonics and crustal thinning, with the development of sedimentary

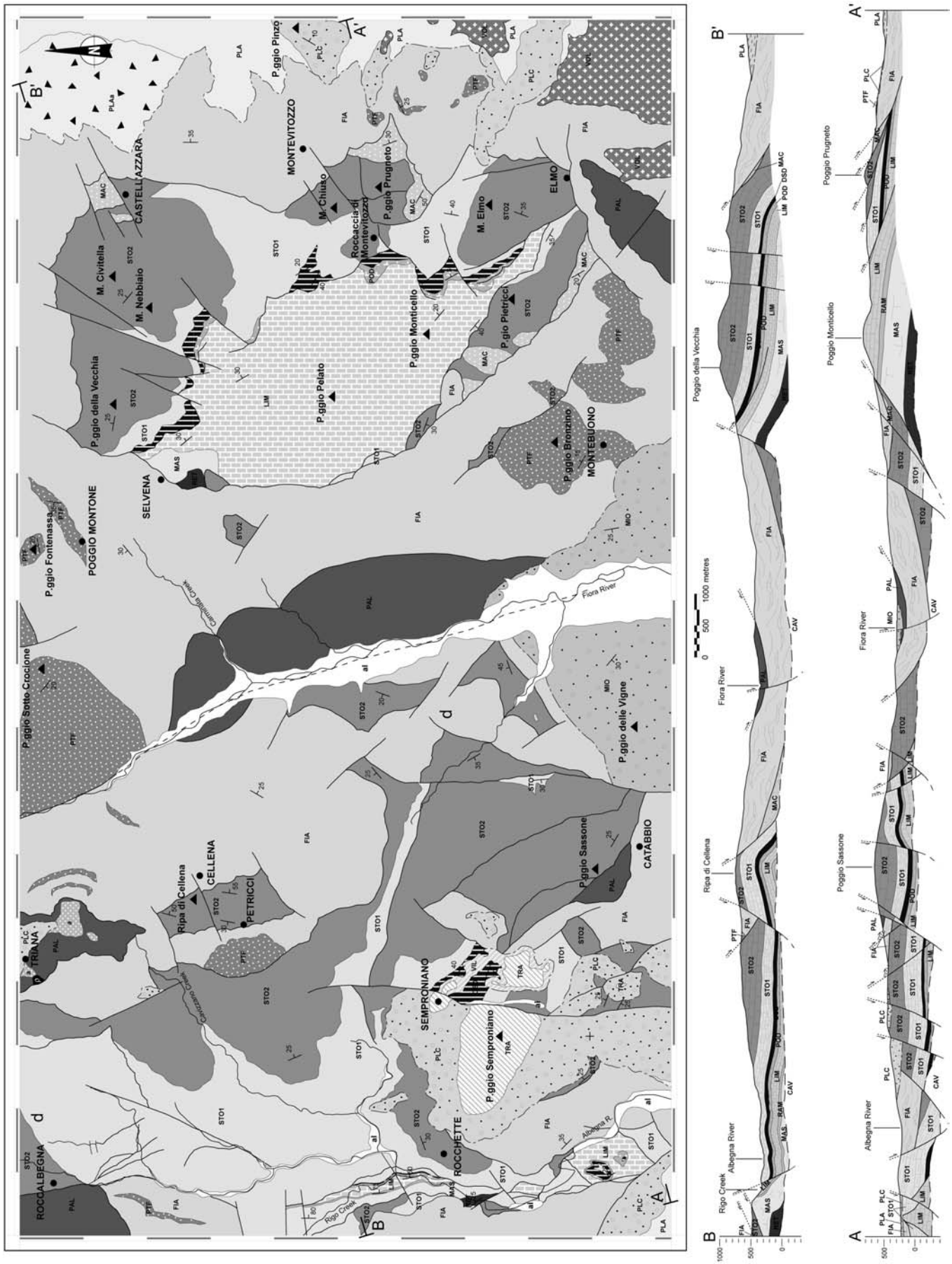

Fig. 2 - a) Geological map and cross-sections of the area between the upper Albegna and Fiora valleys. *– a) Schema geologico e sezioni geologiche dell'area compresa tra le alte valli dell'Albegna e del Fiora.*

basins (CARMIGNANI *et alii*, 1994; 1995). The Neogene extensional phase can be subdivided in different extensional events, that have led to the development of tectonic structures and basins with significantly different tectonic and stratigraphic features.

The Neogene depositional and structural evolution of the area is referable to three main extensional deformative events, as recognized for the Metallifere Hills by BALDI *et alii* (1994).

The first extensional event, here referred to as «serie ridotta» event, dated to the Early-Middle Miocene (DECANDIA *et alii*, 1993; CARMIGNANI *et alii,* 1994) led to formation of low-angle normal faults with flat-ramp-flat geometry and strong extension (120%) (BERTINI *et alii*, 1991).

The following extensional events (Late Miocene up to Pleistocene) developed listric faults and narrow elongated structural depressions (graben type, MARTINI *et alii*, 2001 with references therein), with reduced extension (BERTINI *et alii*, 1991).

The second extensional event affected the «serie ridotta» setting during the Late Miocene, with development of listric faults that at depth represent the top of the Palaeozoic basement (BALDI *et alii*, 1994).

The third extensional event began in the Early Pliocene, and was characterized by the formation of listric fault systems. These faults flatten at deep crustal levels, in correspondence of a shear zone at the brittle/ductile transition, known as the «K horizon» (CAMELI *et alii*, 1993).

STRATIGRAPHIC AND TECTONIC UNITS

Based on field work, we recognize a nappe stack made of the superposition of tectonic units (formed during the main orogenic apenninic phase and later displaced by extensional tectonics), that fit well with the regional tectonic setting known for the whole southern Tuscany (LAZZAROTTO *et alii*, 2002 *cum. bib*.).

The nappe superposition is represented from bottom to top (fig. 3):

– the metamorphic units of the Tuscan basement, which never crop out, but have been recognised in deep drillings (ELTER & PANDELI, 1991).

– the Tuscan Nappe Unit, consisting of a sedimentary succession, that ranges from the evaporites of the Upper Triassic «Anidriti di Burano-Calcare Cavernoso» Fm. to the Upper Oligocene-Lower Miocene «Macigno» Fm..

– The «Santa Fiora-M. Morello» Unit, derived from the External Ligurian Domain. It includes the «Argille Varicolori» Fm., the «Pietraforte» Fm., and the «S. Fiora» Fm., from Early Cretaceous to Late Cretaceous-Paleocene in age.

– The Ophiolitic Unit derived from the deformation of the Internal Ligurian Domain, and constituted by the «Argille a palombini» Fm., that locally contains blocks of ophiolites.

The tectonic setting of this area resulting from collisional tectonics is less complicate than northern or western areas (see in BROGI & LAZZAROTTO, 2002 with references therein). To respect of these last, in the study area are not present neither the Helminthoid Flysch tectonic unit, nor the «Argille e calcari» Subligurian tectonic unit.

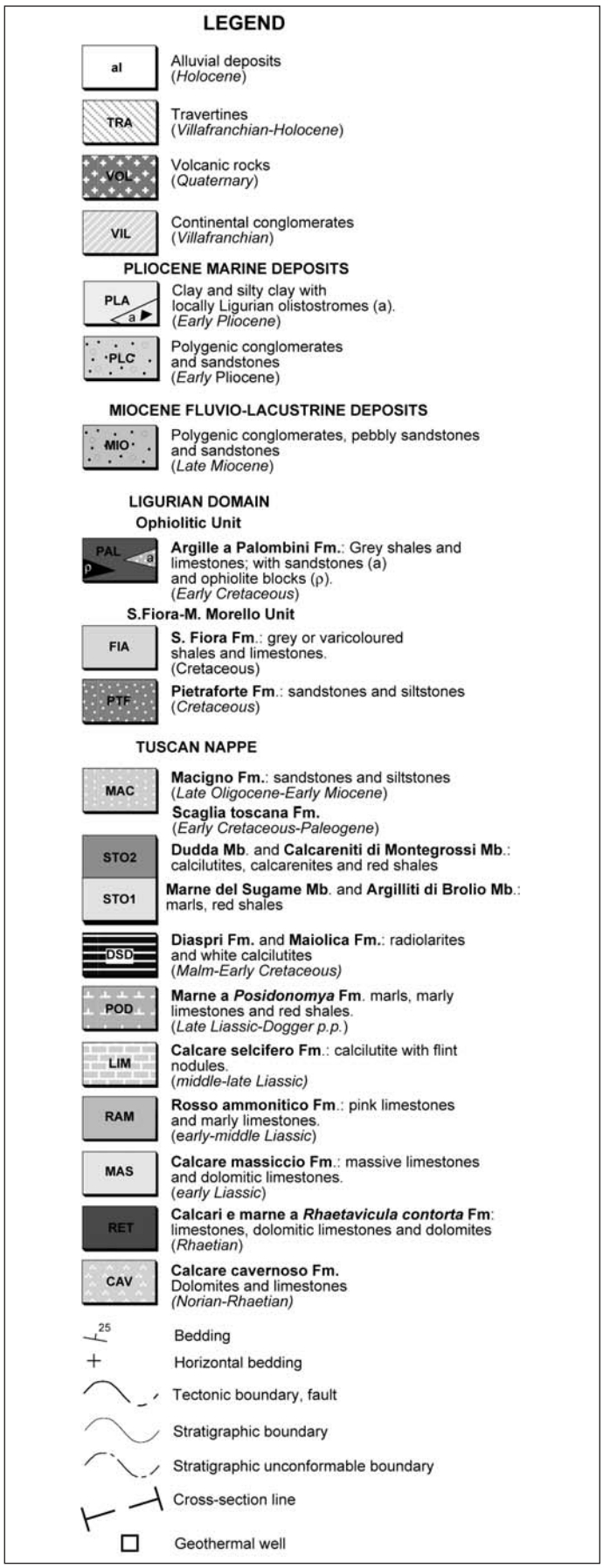

Fig. 2 - b) Legend of fig. 2a.
– b) *Legenda della fig. 2a.*

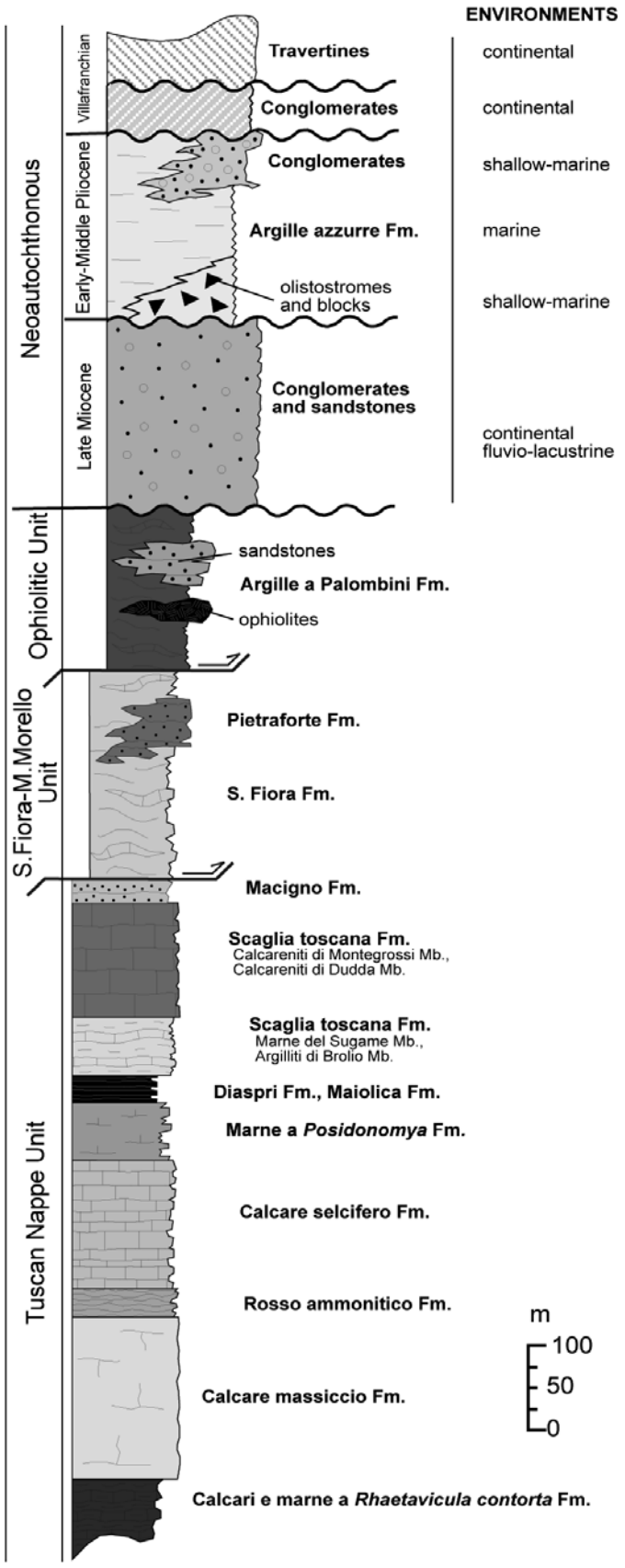

Fig. 3 - Sketch showing the relationships among the tectonic units and the neoautochthonous succession. For the neoautochthonous succession the depositional environments are also reported.
– Schema dei rapporti tra le unità tettoniche e la successione neoautoctona dell'area in studio. Per la successione neoautoctona sono inoltre indicati a lato gli ambienti sedimentari.

The sedimentary successions of the Neoautochthonous depositional cycles, sedimented during the extensional phases, lies above the deformed tectonic units through marked angular unconformities. The Neoautochthonous successions for the area south of the M. Amiata, are organized in several main depositional cycles, which are from the lowest: a shallow-marine succession Middle Miocene in age (for which some authors placed these deposits in a compressional setting, see in MARTINI *et alii*, 1995), an Upper Miocene succession, mainly of continental environment, a Pliocene succession of marine environment, and a Villafranchian succession of continental environment.

THE TUSCAN NAPPE UNIT

The Tuscan Nappe Unit is represented in the study area by a succession which ranges from the «Calcare Cavernoso» Fm. (Late Triassic) to the Chattian-Aquitanian «Macigno» Fm.. The terms of this unit crop out along a N-S to NW-SE direction, in the areas of Roccalbegna-Rocchette-Semproniano and of Castell'Azzara-Selvena-Elmo, and to a smaller extent in the area of Cellena (fig. 2). The lower portion of the outcropping succession, Triassic-Early Cretaceous in age, is represented by the «Calcari a *Rhaetavicula contorta*» Fm., the «Calcare Massiccio» Fm., the «Calcare Rosso ammonitico» Fm., the «Calcare Selcifero» Fm., the «Marne a *Posidonomya*» Fm., and the «Diaspri» Fm. The «Maiolica» Fm. crops out in a narrow area in the Albegna R. valley, between Poggio il Sasso and Rocchette, and more widely, in the area between Selvena, M. Rotondo and Elmo. The upper part of the Tuscan Nappe, represented by the «Scaglia Toscana» and by the «Macigno» Fm., is well exposed between Roccalbegna and Semproniano, at the Ripa of Cellena, on the southern and eastern sides of M. Rotondo and at the M. Civitella, M. Vitozzo, M. Elmo. The «Scaglia Toscana» (Early Cretaceous to Oligocene), rests on the «Maiolica» Fm., or where this is absent, directly on the «Diaspri» Fm. Inside the «Scaglia Toscana» Fm. of the Chianti Mts. minor stratigraphic units have been mapped (CANUTI *et alii*, 1965; FAZZUOLI *et alii*, 1996). These lithostratigraphic units, starting from the bottom, are: – dark red shales with thin layers of greenish-grey siliceous calcilutites and levels of cherts, to which follow black shales with thin manganesiferous levels («Argilliti di Brolio»), the maximum thickness is of 60 metres; – marls, calcareous marls and pink shaly marls, with interlayered grey marly limestones, with the thickness of few hundreds metres («Marne del Sugame»); – interlayered beds of calcilutites, calcarenites, dark red and grey shales, for a maximum thickness of a few tens of metres («Sottonummulitico» Member); – calcarenites and calcirudites in thick and amalgamated beds, sometimes with dark grey jasper nodules, with a thickness of a few hundreds of metres («Calcareniti di Montegrossi» or «Nummulitico» *Auctt*.); – interlayered beds of calcilutites, calcarenites, marls and brown or dark red shales for a maximum thickness of 70-80 metres («Argilliti e calcareniti di Dudda»). The «Macigno» Fm. outcropping in the eastern sector of the area represents the youngest formation of the Tuscan Nappe. This formation rests on to the «Scaglia Toscana», often with a tectonic boundary at the base (Elmo, Castell'Azzara). The «Macigno» Fm. is made of siliciclastic sandstones and siltstones of dark grey colour, of tur-

bidite character. The «Macigno» Fm. outcropping in the internal southern Tuscany, is dated at the late Chattian-Early Aquitanian (COSTA *et alii*, 1997; CORNAMUSINI *et alii*, 1999).

S. FIORA-M. MORELLO UNIT

The formations belonging to this tectonic unit are widely exposed in N-S and NW-SE oriented outcrops (fig. 2). The main outcrops are: north of M. Civitella, between Castell'Azzara and Montevitozzo, south of Elmo, along the Fiora River valley, between Semproniano and Catabbio, and on the western side of the Albegna River valley.

This tectonic unit consists of formations which are (from the bottom): the «Argille Varicolori» Fm. made of manganesiferous varicoloured and greenish-grey shales, with interlayered siltstones and calcilutites, the whole corresponding to the «Villa la Selva» Fm. of COSTANTINI *et alii* (1978) and to the «Scopi di Barabao» Unit of CESTARI *et alii* (1981) of Early Cretaceous age (COSTANTINI *et alii*, 1978; BETTELLI, 1980b; 1985). The «Argille Varicolori» Fm. is followed upward by the «S. Fiora» Fm., widely outcropping. The «S. Fiora» Fm., correlable with the «Sillano» Fm. of northern Tuscany (BOCCALETTI *et alii*, 1987), is formed of an alternating of grey-brown or dark red shales and calcilutites, with minor calcarenites, sandstones and siltstones. Within the «S. Fiora» Fm. thick levels (a few tens of meters) of marls occur, correlatable with the «Marne di Castelnuovo dell'Abate».

In the «S. Fiora» Unit turbidites of the «Pietraforte» Fm. are also documented. They crop out widely as lenticular bodies, east of Poggio Prugneto, to Montebuono, to the west of Petricci, and in the northern sector between Selvena and Triana. The «Pietraforte» Fm. is made of beds of sandstones, siltstones, and of microrudites with a mainly siliciclastic composition, and with minor carbonate content. On the basis of the sandstone/mud ratio, we recognize some lithofacies, which are the ruditic lithofacies («Cicerchina»), the arenaceous l., the arenaceous-mud l. and the mud-arenaceous l. The «Pietraforte» Fm. shows relationships of heteropy with the «S. Fiora» Fm., in particular with its middle-upper portion.

The age of the «S. Fiora» Fm. in the Northern Apennines, is ascribed to the Late Cretaceous-Eocene, although in the southern Tuscany it seems to have a distribution from the Aptian/Albian to the Late Cretaceous (COSTANTINI *et alii*, 1978; PANDELI *et alii*, 2002)

THE OPHIOLITIC UNIT

The Ophiolitic Unit is represented in the study area only by the «Argille a palombini» Fm. It crops out in a marginal way, west of Roccalbegna, northwest of Catabbio, near Triana, near Elmo and in the Fiora River valley (fig. 2). It is constituted by dark grey shales, with fine-grained limestone beds, lightly siliceous of pale grey or greenish colour. The outcrops of Triana and of Elmo are characterized by the presence of plurimetric ophiolitic blocks (metagabbros, basalts, serpentinites, ophicalcites and ophiolitic breccias) and their sedimentary cover («Diaspri», «Calcari a Calpionelle»), dispersed in the shales, and by lenticular horizons of quartzarenites. The «Argille a palombini» Fm., Early Cretaceous in age, is characterized by a strong internal deformation.

THE NEOAUTOCHTHONOUS SUCCESSION

The Neoautochthonous Succession has an age ranging from Miocene to Pleistocene. The deposits are organized in syn-extensional successions, separated by angular unconformities: the succession «S» (that does not crop out in the study are, but just a few km to south) (Langhian-Serravallian) (GIANNINI, 1957; MARTINI *et alii*, 1995), formed of shallow marine sandstones and conglomerates; the succession «M» («serie lignitifera» *Auctt*., Turolian (Late Miocene) in age (BOSSIO *et alii*, 1998 *cum bib*), is formed by conglomerates, sandstones and clays of continental environment; the succession «P» (Early-Middle Pliocene) (BOSSIO *et alii*, 1998 *cum bib*) is made of conglomerates, sandstones and clays of marine environment; at the top a syn-post extensional succession «V» Villafranchian (Late Pliocene-Early Pleistocene) in age, is present, which is made of conglomerates and sandstones of continental environment.

These successions show differences in age, in the depositional environment, and for the stratigraphic position and relationships with the substratum. Indeed, while the last two successions lie directly through unconformities over the other Miocene terms and of the pre-Neogene tectonic nappe stack, the succession «S» and «M» lays exclusively over Ligurian units, and the succession «M» also onto the succession «S».

Succession «S»

The deposits of the succession «S» have been considered here also if they do not crop out directly in the study area, because the neighbourhood of the outcrops (just few kilometers south of the area), their stratigraphic position intermediate between Miocene deposits of the «M» succession and the orogenic unit stack, their singnificance and importance in the Miocene evolution of this portion of the chain.

The deposits of the «S» succession are called «Arenarie di Manciano» and have been referred to the Langhian-Serravallian (DESSAU, 1951; GIANNINI, 1957; MARTINI *et alii*, 1995). They lie unconformably onto the Ligurian formations, particularly onto the «S. Fiora» Fm, and lie below the Upper Miocene succession (succession «M») through another angular unconformity (unpublished geological maps of the Authors of this paper). The outcrops, together with the other Middle Miocene outcrops of the southern Tuscany-northern Latium (Ponsano, in GIANNINI & TONGIORGI, 1959; FORESI *et alii*, 1997; 2004, Rencine, in PASINI & SANDRELLI, 1977; MAZZEI *et alii*, 1981; BOSSIO *et alii*, 2002, Tarquinia and Pescia Fiorentina, in FONTANA, 1980a,b; CORNAMUSINI & PASCUCCI, 2000), represents key-elements for the definition of the start of extension in the hinterland of the Northern Apennines. They have been considered semiallochthonous deposits (Epiligurian units) relative to compressional basins (BALDACCI *et alii*, 1967; SESTINI, 1970; MARTINI *et alii*, 1995), whereas more recently they have been considered as the first sediments of the Neoautocthonous depositional phase (CARMIGNANI *et alii*, 1994, 1995; ELTER & SANDRELLI, 1995).

It is worth note that recently BARBIERI *et alii* (2003), based on strontium isotope analysis ascribed the outcrops of Manciano, Capalbio and Tarquinia, to the Late Messinian; this age results to be controversial and in contrast with field data and other stratigraphic data present in literature.

Succession «M»

The deposits of the succession «M» crop out in the high Fiora Valley (BETTELLI, 1985; BONAZZI *et alii*, 1992) on the east side (Montebuono) and on the west side (Catabbio) of the river. They lie with an angular unconformity over the Ligurian formations of the S. Fiora and Ophiolitic units (fig. 2), to form a small basin. The succession, of continental environment, is organised in a lower portion mainly formed of clays and silty-clays with interlayered lenticular beds of sandstones and conglomerates, and in an upper portion mainly formed of conglomerates. For the lower portion, the conglomerate-sandstone beds are particular evident on the east side of the outcrop, near the bottom of the succession. The conglomerate and sandstone beds, often form couples relative to a same depositional event, with internal organization, as a crude gradation, cross and plane-parallel lamination and imbrication of clasts. The clasts are polygenic and well rounded with a flattened or subspheric shape. Conglomerates present clast-supported or minor matrix-supported fabric. The beds are laterally lenticular.

The upper portion of the succession crops out on the west side of the outcrop, near Catabbio. It is formed of polygenic matrix-supported conglomerates, organized in crudely stratified beds, with poor internal organization, crude sedimentary structures, which are imbrication, cross-stratification, high heterometry and sphericity of clasts. Sandstone beds are also present interlayered with conglomerates.

The conglomerates of the upper portion lie onto the clays and sandstones of the lower portion, through a minor unconformity, evidenced also by the direct superposition of the former onto the ligurian formations at the west edge of the outcrop (Catabbio). So, based on sedimentary features and on the fossil associations (presence of ostracods, *Characee* oogons, *Bythinia*, etc.) the lower portion results to be referred to the «serie lignitifera» *Auctt.* of Late Tortonian-Early Messinian age, whereas no data constraints (with the exception of the absence of marine fossils in the matrix, so to think about a continental environment) are present for the latter, if of the same age, or to attribute to the Late Messinian («lago-mare» facies, see in BOSSIO *et alii*, 1993; 1998).

Succession «P»

The Pliocene deposits crop out in the eastern and middle-western sector of the study area, infilling two distinct basins. The outcrops of the eastern sector belong to the Radicofani Basin, while the outcrops of Semproniano represent the northernmost portion of the Albegna Basin; another small outcrop is located northeast of Triana. Differently from the Miocene succession, the Pliocene succession is characterized by horizontal to moderately dipping beds. These deposits lie with an angular unconformity over all the pre-Neogene formations (Ligurian and Tuscan Nappe formations), as visible in the Semproniano area (fig. 2) and over the older Neogene units. In this area fossiliferous poorly cemented sandstones, with thin levels of conglomerates, pass towards the south to clays and sandy clays, probably representing a transition from marine shoreface deposits to a deeper environment. Differently, near Triana village, poorly rounded and strongly heterometric poligenic conglomerates with abundant clay-sandy matrix crop out; they rest onto only the Ophiolitic Unit.

The western border of the Radicofani Basin, located at the eastern edge of the study area, is prevalently represented, towards the depocentre, by blue-grey clays, while to the basin edge, where the Pliocene deposits lie stratigraphically over the Ligurian units, marginal deposits are present. These last are constituted by conglomeratic-sandy bodies and by thick bodies of shaly-calcareous olistostromes derived from the Ligurian units (BETTELLI *et alii*, 2001; CALLEGARI *et alii*, 2003). The former are present along the southern part of the edge (Poggio Pinzo and east of Elmo), whereas the latter substitute the former along the northern part of the edge (east of Castell'Azzara), to set a complex depositional architecture for the marginal facies of the Radicofani Basin. The two kinds of succession show vertical organizations recalling thickening-coarsening upward trends, which are for the former clays up to clays with Ligurian formation blocks, up to olistostromes, and for the latter clays up to sandstones, up to conglomerates, to evidence relationships of a regressive onlap sequence.

Succession «V»

The succession «V», cropping out in the Semproniano area and east of Elmo, lies unconformable also on the Pliocene formations. In the Elmo area, this succession is made of poligenic and monogenic conglomerates, scantily organized, poorly sorted and with reddish matrix; sometimes they also contain big sized blocks derived from the Mio-Pliocene conglomerate deposits. Reddish clay levels, referable to palaeosoils and indicative of fluvial/lacustrine environment, are frequent. For the Semproniano area, the Villafranchian deposits are represented by alternating conglomerates, sandstones and reddish clays (palaeosols), with travertine beds on the top. Travertines are mainly developed in the area west to the village, directly over the Pliocene sandstones.

THE STRUCTURAL SETTING

The tectonic setting of the area (fig. 4) is the result of the superimposition of pre- and syn-collisional compressive and post-collisional extensional structures.

The high Fiora Valley is characterized by the presence of alignments, NNW-SSE oriented, which are structural highs constituted of Tuscan Nappe succession, that include Jurassic carbonate formations, mud-calcareous terms of the «Scaglia Toscana», and the «Macigno» Fm.

Fig. 4 - Tectonic sketch map of the study area with interpreted cross-sections. The main structural alignments characterizing the study area are reported. The relationships between the tectonic structures and fault development are reported, both in the tectonic sketch map and in the cross-sections. The *flat-ramp* setting of the *megaboudins* is highlighted by the dashed blue lines in the cross-sections.
– *Schema tettonico dell'area in studio, con sezioni interpretate. Sono riportati i principali lineamenti strutturali caratterizzanti l'assetto tettonico dell'area. Le relazioni tra le strutture tettoniche ed in particolare tra i vari sistemi di faglie e la loro sequenza temporale sono rappresentati sia nello schema tettonico, sia nelle sezioni geologiche schematiche. L'assetto a* flat *e* ramp *dei* megaboudins *è inoltre evidenziato dalle linee tratteggiate azzurre nelle sezioni geologiche.*

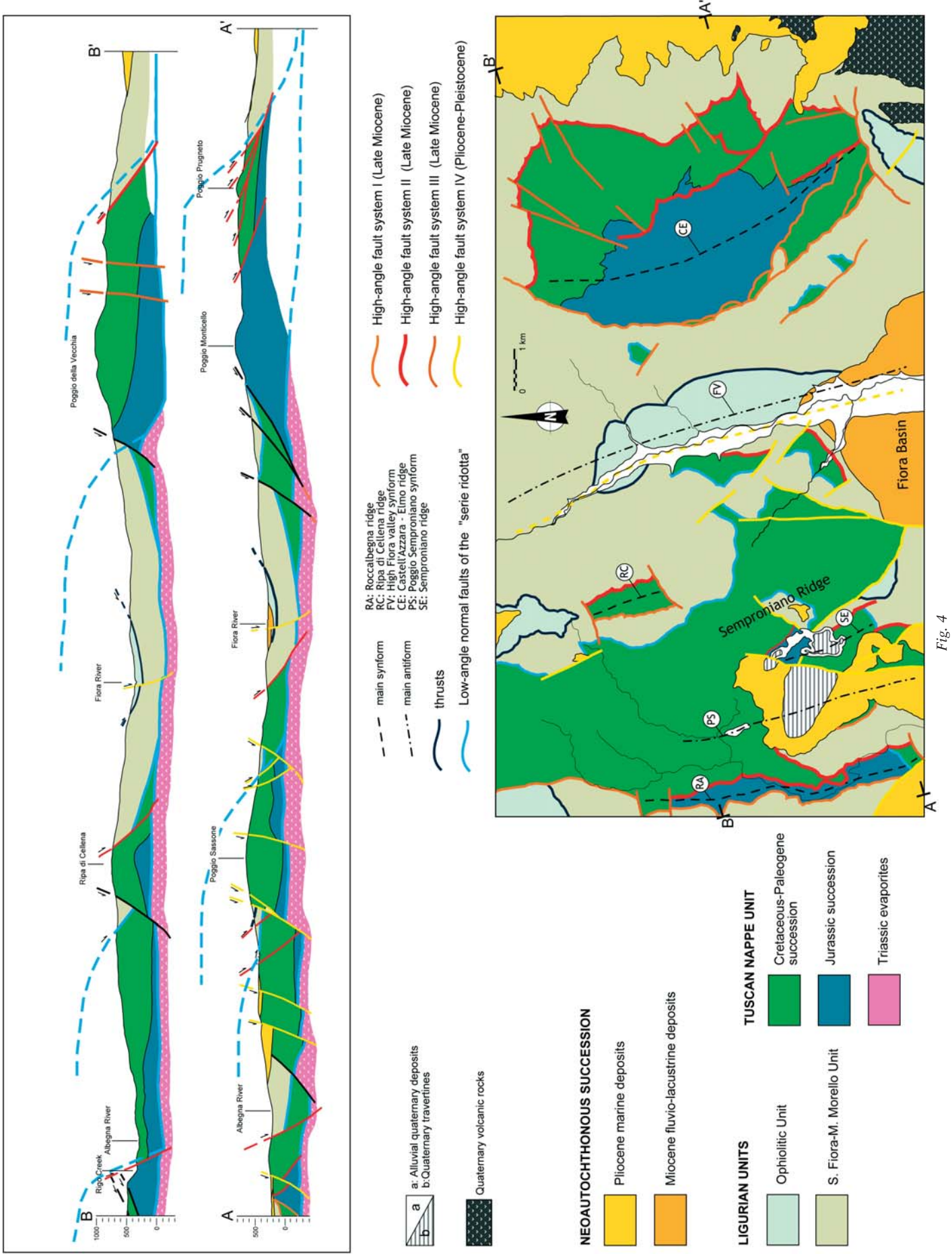
B
B'
A
A'
Poggio della Vecchia
Poggio Monticello
Poggio Prugneto
Poggio Sassone
Ripa di Cellena
Ripa Creek
Albegna River
Fiora River
1000
500
0
RA: Roccalbegna ridge
RC: Ripa di Cellena ridge
FV: High Fiora valley synform
CE: Castell'Azzara - Elmo ridge
PS: Poggio Semproniano synform
SE: Semproniano ridge
main synform
main antiform
thrusts
Low-angle normal faults of the "serie ridotta"
High-angle fault system I (Late Miocene)
High-angle fault system II (Late Miocene)
High-angle fault system III (Late Miocene)
High-angle fault system IV (Pliocene-Pleistocene)
a: Alluvial quaternary deposits
b:Quaternary travertines
Quaternary volcanic rocks
NEOAUTOCHTHONOUS SUCCESSION
Pliocene marine deposits
Miocene fluvio-lacustrine deposits
LIGURIAN UNITS
Ophiolitic Unit
S. Fiora-M. Morello Unit
TUSCAN NAPPE UNIT
Cretaceous-Paleogene succession
Jurassic succession
Triassic evaporites
Sempronian Ridge
Fiora Basin
1 km
N
RA
RC
PS
SE
FV
CE

Fig. 4

They are located from west to east in the following ridges (fig. 4): Roccalbegna-high Albegna Valley, Semproniano-Poggio Murella, Poggio della Vecchia-Elmo.

The structurally low areas form parallel alignments with Apenninic orientation as well. They are characterized by a strong tectonic elision, with emplacement of Ligurian units over the lowermost terms of the Tuscan Nappe, or directly over the Triassic evaporites. These structural depressions (high Albegna Valley, Fiora River Valley, the area east of Castell'Azzara-Elmo ridge) were then filled with Miocene deposits, that unconformably lie onto the Ligurian units

On the whole, the geological structure shows a «megaboudinage» setting (DECANDIA *et alii*, 2001; PANDELI *et alii*, 2002; BROGI, 2003; 2004b), that involve the upper crustal rocks. The megaboudins are represented by rocks of the Tuscan Nappe, laterally delimited by zones in which the superimposition of Ligurian units directly over the Calcare Cavernoso Fm. or over lower Tuscan Nappe formations, occurs. Based on geophysics and drilling data, BROGI (2003) recognized megaboudins oriented NNE-SSW for the Mt. Amiata area. In the our study area, located to the south of Mt. Amiata, based on outcrops data, the megaboudins are oriented NNW-SSE. They are bordered by normal faults with orientation ranging from NNW-SSE to N-S, faults that displaced the Ligurian units and the upper part of the Tuscan Nappe succession. In detail, the western and the central parts of each structural high are constituted by formations of the Tuscan Nappe with subhorizontal bedding attitude or gently dipping toward east; the eastern sides strongly dip toward east, up to the vertical or overturned attitude of beds (fold of Mt. Civitella-Roccaccia of Monte Vitozzo, fold of Ripa of Cellena and fold of the Albegna Valley). Fault systems linked both with collisional and extensional phases are recognizable in the study area. They have been differentiated on the basis of fault geometry, relationships with sediments, cross-cutting relationships, entity of dislocation, dip direction and position respect to the Tuscan Nappe megaboudins.

In more detail, we recognize a thrust system linked to the building of the orogenic stack, a system of low-angle normal faults (Low-angle normal fault system of the «serie ridotta»), a westward dipping normal fault system with apenninic orientation (High-angle fault system I), an eastward dipping normal fault system with apenninic orientation (High-angle fault system II), an high angle fault system with antiapenninic orientation (High-angle fault system III), an high angle fault system with apenninic orientation cutting also Pliocene sediments (High-angle fault system IV).

THRUSTS

Thrusts represent the primary tectonic structures delimiting the units of the nappe stack, formed during the pre- and syncollisional phases. They only locally have been preserved, often inside the Ligurian units stack, in particular between the Ophiolitic Unit and the S. Fiora Unit. The tectonic chaoticity of the units and the bad conditions of the outcrops do not allow to verify if the thrusts show signs of later extensional reactivations during the postcollisional phases.

Thrusts are characterized by low-angle fault planes, as recognizable in the area south to Elmo, in the Fiora River valley, north to Catabbio, south to Roccalbegna and near the Triana village.

LOW-ANGLE NORMAL FAULT SYSTEM OF THE «SERIE RIDOTTA»

Low-angle normal faults with flat-ramp-flat geometry, dipping toward east, have been recognized. They led to strong tectonic elision, typical of the «serie ridotta» setting (DECANDIA *et alii*, 1993). Such faults delimit the structural highs from the structural depressions, where the Ligurian units (hanging wall) are emplaced directly onto the lowest Tuscan Nappe formations (the Triassic evaporites) at the footwall.

In the southern part of the geological map (fig. 2), the low-angle normal fault between Triana village and the Fiora Valley, represents a ramp that more to the east becames horizontal and delimits the megaboudin of the high Albegna Valley in the footwall, and the megaboudin of the M.Civitella-Poggio Pelato in the hangingwall. The Triana fault is displaced by a later high angle normal faults and it was then sealed by Pliocene sediments (NW of Ripa di Cellena). Another portion of tectonic ramp is detectable in the valley of the Albegna River.

Each megaboudin is therefore limited by two low-angle normal faults (extensional duplex in BROGI *et alii*, 2003), characterized by a western portion with strong crustal thinning and superposition of the Ligurian units directly over the Triassic evaporites (i.e. high Fiora Valley) and by an eastern portion with minor tectonic elision and Tuscan Nappe outcrops (i.e. M. Civitella-Elmo).

HIGH-ANGLE FAULT SYSTEM I

High angle normal faults delimit to the west the megaboudins. These faults show apenninic orientation and dip direction toward west. They cut the «serie ridotta» faults, moreover uplifting the structure originated with the megaboudinage setting, with the development of structural highs, which are the Tuscan Nappe nuclei (fig. 4). These faults, displaced further the Ligurian units at the hangingwall, and uplift the Tuscan nappe at the footwall (fig. 4).

The main faults of this system are the Selvena fault with associated minor faults (Poggio Pietricci and Poggio Bronzino faults), which borders the Tuscan Nappe nucleus of Poggio Pelato-Elmo, the Roccalbegna-Fosso Rigo fault, which borders the nucleus of Fosso Rigo-Fiume Albegna, and the minor Petricci fault, which delimits the small nucleus of Ripa di Cellena.

The faults of this system cut the «serie ridotta» low-angle faults and are themselves cut by faults belonging at the younger systems, mainly Plio-Pleistocene faults.

The age of this fault system is referable to the Late Miocene, because they cut the «serie ridotta» faults, Middle Miocene in age (CARMIGNANI *et alii*, 1994; 1995) and because they are sealed by Pliocene sediments (see the fault SW of Poggio Semproniano and Fosso Rigo-Fiume Albegna fault, in the southwestern corner of fig. 4).

HIGH-ANGLE FAULT SYSTEM II

Normal faults with listric geometry and Apenninic or north-south orientation, east-dipping, are also present (Castell'azzara-M. Elmo area, high Albegna Valley, Cellena). Such faults are located to the eastern edge of the Tuscan Nappe megaboudin, displacing the low-angle normal faults referable to the «serie ridotta»

These faults (fig. 4) show middle angle dipping (outcrop of Castell'Azzara) or high angle dipping (Ripa di Cellena and Fiume Albegna outcrops). They displaced and further on lowered the Ligurian units to respect the Tuscan Nappe. So, these faults produced again lowering and delamination of the whole nappe stack, with the further uplift of rocks belonging to the Tuscan nappe succession; moreover they show an orientation and dip direction subparallel to the steep sides of the antiformal structures. As well recognizable at the eastern side of the Castell'Azzara antiformal structure, the attitude of the tectonic boundaries assumes an imbricate setting, with tectonic slivers of rocks belonging to the Tuscan nappe and to the Ligurian units, delimited by detachment fault planes dipping toward east (faults of the Castell'Azzara-M.Elmo area, Cellena fault, Albegna fault).

We observe moreover that this tectonic setting characterizes also the northern and southern pericline areas of the Tuscan Nappe antiformal structures, where the faults dip toward north-northeast (Monte Civitella) and southwest (Monte Elmo-Poggio Pietricci) respectively.

The faults of this system have been sealed by Pliocene sediments (Montevitozzo fault to east of Mt. Elmo, Rocchette-Albegna River fault and fault placed to west of Catabbio), whereas they displaced the fault of the «serie ridotta». The faults of this system locally cut also the faults of the west-dipping system (as recognized west of Elmo, see fig. 4), so we infer that the two systems are coeval or more probably the former subsequent to the latter, both of Late Miocene age.

High-angle fault system III

These faults have short extension in map view, mainly antiapenninic orientation (strike ranging between N5°E and N 80°E), with vertical or high angle fault planes. They delimit the nuclei of the megaboudins at their northern and southern terminations, or cut these last. They have mainly normal displacement, since they lowered the overlying units, as observable for the terminations of the Tuscan Nappe outcrops of the Ripa di Cellena and of the Poggio Pelato. Only locally, based on geometry of the dislocated formation boundaries, some of these faults show strike-slip component of displacement, as for the faults of Mt. Civitella, Montevitozzo, Cellena and Rigo Creek.

The faults of this system cut the faults bordering the megaboudins, but they are not displaced by more recent Pliocene faults.This system therefore could be dated at the Late Miocene.

High angle fault system IV

This system comprises high angle normal faults displacing Pliocene sediments and cutting the other fault systems and are not related with the megaboudinage setting. The orientation of these faults is mainly apenninic, although some are N10°-40°E oriented.

Miocene and Pliocene deposits are displaced by these faults (respectively faults located near Poggio delle Vigne and southwest of the Albegna River), and some have been sealed by Villafranchian conglomerates (surroundings of Semproniano village), whereas others seem to have displaced also the Pleistocene travertines (Semproniano fault). Therefore, the activity of this fault system could be ascribed at a time interval between the Pliocene and the Pleistocene.

The normal faults affecting the Pliocene sediments of the Radicofani Basin, forming «horst» and «graben» or «semigraben» structures (Liotta, 1996), which western edges have been detected at the eastern side of the geological map of fig. 2, belong to this system.

DISCUSSION

The structural setting of the southern area of the Mt. Amiata, as well as of the whole southern Tuscany, is the result of a complex tectonic and sedimentary evolution. In more detail, a pre- and syn-collisional compressional phase and a post-collisional extensional phase have been recorded (fig. 5). The last is subdivided in a few Neogene events (Baldi *et alii*, 1994; Bossio *et alii*, 1998; Decandia *et alii*, 2001; Carmignani *et alii*, 2001). The data obtained from this research, in the Fiora-Albegna valleys area, are discussed in the framework of the extensional tectonic evolution.

The studied area is characterized by the presence of tectonic structures referable to all the tectonic phases, both compressional and extensional, affecting the southern Tuscany (Decandia *et alii*, 2001 with references therein).

Regard to the compressional deformation, the area is characterized by a nappe stack developed during the Apenninic collisional phases, with the emplacement of deformed tectonic units belonging to different paleogeographic domains. It is worth to note for the study area, the absence of the Argille e calcari Subligurian Tectonic Unit, that on the contrary it is present in the northern and western areas. This could be explained with an «irregular» emplacement of the «Argille e calcari» Unit during the collisional stacking, i.e. a differentiated eastward advancing of the unit probably due to the action of syn-collisional strike-slip faults

Regarding to the extensional setting, a megaboudin structure is well developed in the area, as observed also in northern more areas by Brogi (2004b).The megaboudins are constituted by rocks belonging to the Tuscan Nappe succession, which are laterally bounded by sectors characterized by strong tectonic elision. These extended sectors are characterized by outcrops of Ligurian units, strongly deformed and often resting directly over the Triassic evaporites (flat tectonic contact), or over the upper levels of the Tuscan Nappe (ramp). The Triassic evaporites represent the main detachment level of the «serie ridotta» (Bertini *et alii*, 1991; Baldi *et alii*, 1994).

The megaboudinage process led to formation of asymmetric structures, each constituted of a sector with moderate elision (characterized by antiformal outcrops of Tuscan Nappe rocks) and of a sector with strong elision, where Ligurian units lie directly over the Tuscan evaporites.

According to Brogi (2004b), the *megaboudinage* structure could be referred to the first extensional event responsible of the strong tectonic elision, called «serie ridotta» process (Lavecchia *et alii*, 1984; Bertini *et alii*, 1991; Decandia *et alii*, 1993), active in the time span between the end of the Early Miocene and the Middle Miocene (Carmignani *et alii*, 2001, with references therein). Differently to Brogi (2004b), the megaboudins here recognized, have a different orientation (apenninic orientation NNW-SSE, instead of NNE-SSW) and an opposite asymmetry. In detail, investigated megaboudins

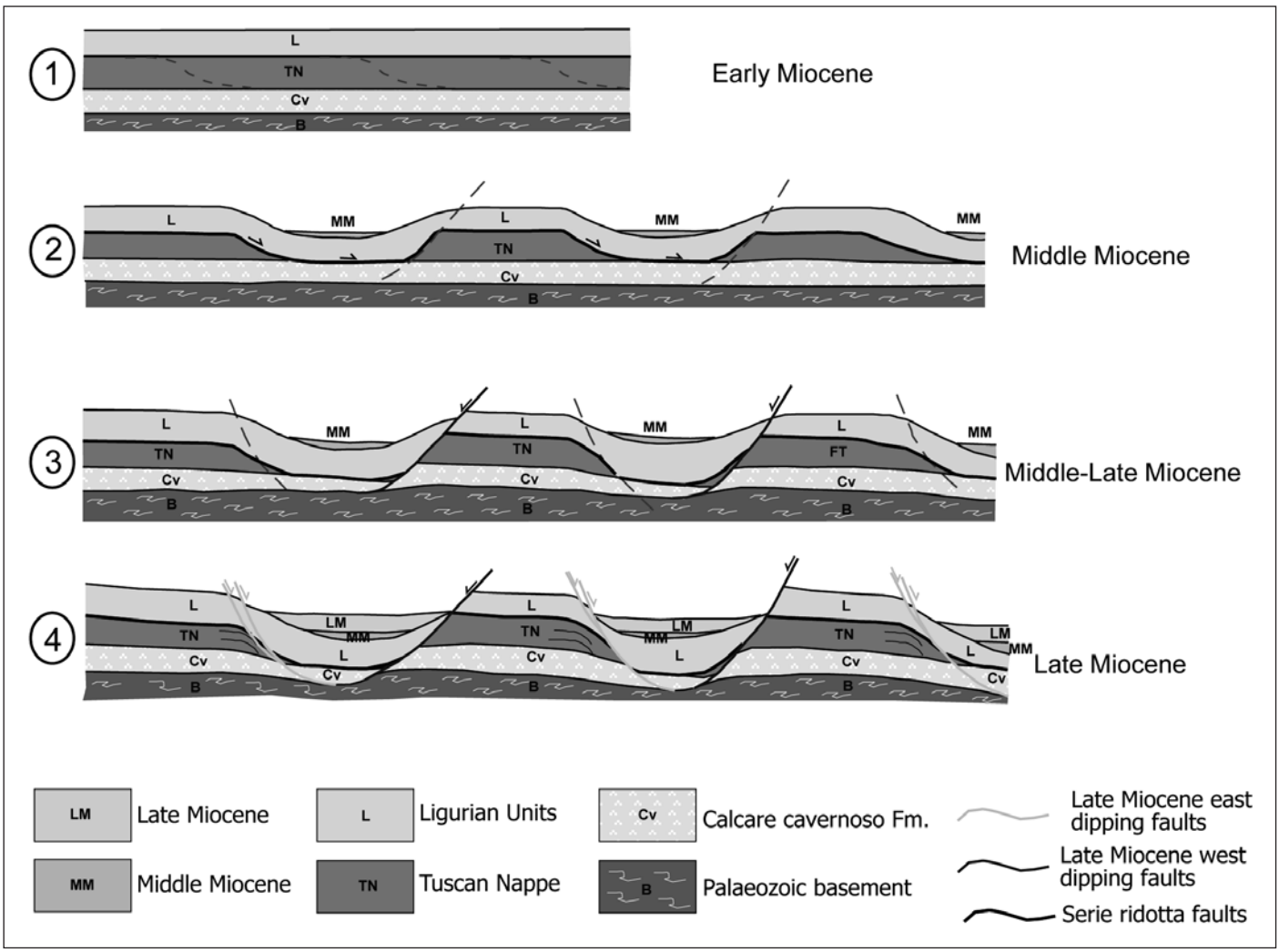

Fig. 5 - Sketch (not to scale) showing the tectonic and sedimentary evolution for the area during the Miocene; L) Ligurian units, FT) Tuscan Nappe Unit, Cv) Triassic evaporites, B) basement, Mm) Middle Miocene deposits, Lm) Upper Miocene deposits (with the dotted lines are represented the faults will develop during the next event). 1) The orogenic stack was definitively piled in the Early Miocene; 2) during Middle Miocene east-verging low-angle extensional faults affected the orogenic stack, producing *flat-ramp-flat* structures, typical of the «serie ridotta» setting; marginal marine deposition in the structural lows also developed; 3) during Middle-Late Miocene the structural lows increased subsidence, due to west-verging normal faults developed at the east side of the same depressions; 4) during Late Miocene the structural lows increase subsidence again, due to the tilting toward east of the megaboudins and to the development also of east-verging normal faults on the west side of the depressions, up to become wide basins filled with continental and marine deposits, unconformably lying onto Ligurian units and also onto Middle Miocene deposits.

– Schema (non in scala) che rappresenta il modello di evoluzione tettonica e sedimentaria durante il Miocene, ipotizzato per l'area in studio; L) Unità Liguri, FT) Unità della Falda Toscana, Cv) evaporiti triassiche, B) basamento, Mm) depositi del Miocene medio, Lm) depositi del Miocene superiore (con le linee tratteggiate sono indicate le faglie che si sviluppano nell'evento successivo a quello rappresentato). 1) La pila tettonica orogenica è stata definitivamente formata nel Miocene inferiore; 2) durante il Miocene medio, faglie dirette a basso angolo, est-vergenti, hanno interessato e dislocato la pila orogenica, producendo strutture flat-ramp-flat, *tipiche della «serie ridotta»; una sedimentazione di ambiente marino marginale si è sviluppata nelle depressioni strutturali formatesi; 3) durante il Miocene medio-superiore, le depressioni strutturali hanno subito un incremento della subsidenza, dovuto allo sviluppo di faglie normali ovest-vergenti sul lato orientale delle stesse depressioni; 4) durante il Miocene superiore, si ha un ulteriore incremento della subsidenza delle depressioni strutturali, dovuto al basculamento verso est dei megaboudins e allo sviluppo di faglie dirette est-vergenti sul lato occidentale delle stesse depressioni, sino a determinare la formazione di ampi bacini sedimentari, riempiti da depositi continentali e marini, in giacitura discordante sia sulle unità Liguri, sia sui depositi del Miocene medio.*

shows east-dipping beds on the east side and subhorizontal bedding on the west side, leading to outcropping the Tuscan Nappe lowermost formations.

As a consequence of the megaboudin structure of the upper level of the crust, morphological and structural depressions formed, corresponding to the main lower flats of the extensional tectonic contacts where the Ligurian units lie directly onto the Triassic formations; this agree with results of recent researches in the Mt. Amiata area (Brogi, 2003; 2004b).

It is worth note that the age inferred by various Authors for this first extensional event is Middle Miocene, based the age of the shallow marine post-tectonic sediments of southern Tuscany, as the «Arenarie di Manciano» (Langhian-Serravallian in Giannini, 1957 and in Martini *et alii*, 1995). These sediments have been supposed by some Authors as deposited in compressional-thrust-top basins, similar to those for the «Epiligurian» successions of the Emilian Appennines (Baldacci *et alii*, 1967; Sestini, 1970; Martini *et alii*, 1995). But data

reported by CARMIGNANI *et alii* (1994; 1995) and DECANDIA *et alii* (2001) set the extension for the hinterland of the Northern Apennines at the end of the Early Miocene-Middle Miocene. So, we put forward the hyphotesis that the megaboudin depressions could represent also the place of sedimentation. In such a case, the Middle Miocene shallow marine sediments of southern Tuscany, the «Arenarie di Manciano» just outside the study area, could be interpreted as the deposits infilling these first extensional basins. This can be observed SE of the study area, where the «Arenarie di Manciano» lies only on to the Ligurian formations (unpublished data of the authors). This setting corresponds at main flats of the «serie ridotta», where Ligurian formations lie tectonically onto the stratigraphically lower horizons (Calcare Cavernoso Fm.). This hypothesis needs of further data from all southern Tuscany to be confirmed.

In such a case, the «Arenarie di Manciano» could represent the first deposits marking the tectonic inversion for this sector of the Northern Apennines, during the Langhian-Serravallian, in agreement with the opening age of other sectors of the Tyrrhenian area (Peloritani Mts. in LENTINI *et alii*, 1995; Calabrian Arc in MATTEI *et alii*, 2002). Such basins could have the same geodynamic and morphologic significance of the Serravallian deposits of the Tuscan Shelf, defined as syn-rift by PASCUCCI *et alii* (1999).

The megaboudinage setting of the Early-Middle Miocene appears to be deformed and dissected by normal faults. In detail, later normal faults affected the terminations of the megaboudins, producing a more pronounced uplift of the Tuscan Nappe nuclei. This led to a dome-like structure of the megaboudins, bordered by apenninic normal faults, lowering again the «serie ridotta» depressions, where the Ligurian units directly overlie the Triassic evaporites.

The dome building of the Tuscan Nappe nuclei were then bordered by antiapenninic faults, as recognized at their northern and southern edges. As showed for the Castell'Azzara Ridge, the megaboudins are often delimited toward north and south by faults with antiapenninic (NE-SW) orientation, may be transtensional, or with only strike-slip displacement (transfer faults in DECANDIA *et alii*, 1994). On the whole, the faults that delimitate the Tuscan Nappe nuclei, confer to the structure a shape as an asymmetric structural prolonged dome (WISE *et alii*, 1979; ZANCHI & TOZZI, 1987).

The faults dissecting the Middle Miocene «serie ridotta» setting, appear to be locally sealed by Pliocene sediments and cut by Plio-Pleistocene faults, so we infer for them a Late Miocene age. This age agree with the second extensional event of BALDI *et alii* (1994), but we hypothesize a difference in the style of the deformation. The above Authors and many others, infer an «horst-graben» tectonic setting, while we suggest that the development of the normal faults of this Late Miocene event is controlled by the megaboudin structures belonging to the first extensional event. This is based on the evidence that the Late Miocene faults are located at the edges of the megaboudins.

Furthermore, field data suggest a two-stage activity for these faults during uplift. In the western edge of each megaboudin, it is possible to observe listric faults dipping toward west, that further lowered the hangingwall of the megaboudins, so to increase the subsidence in the structural depression already formed after the «serie ridotta» event. During this second extensional event, uplift and tilting of rocks in the footwall of the main west-dipping normal faults occur, resulting in areas with prevailing east dipping bedding attitude. During this uplift and tilting of the stratigraphic succession, east-dipping normal faults developed together with east facing folds, as well developed in the Tuscan succession for the eastern part of the megaboudins.

These new created morpho-structural depressions, act like basins for the sedimentation of the Late Miocene deposits, mainly of continental environment, which correspond to both «serie lignitifera» (Late Tortonian-Early Messinian) and «serie di lago-mare» (Late Messinian) (BOSSIO *et alii*, 1993; 1998 with references therein). In conclusion, the geometry of such basins were determined by the developing fault systems, but also strictly conditioned by the morpho-structural depressions already formed during the previous «serie ridotta» tectonic event. This is also supported by field data, because the Late Miocene successions overlie only on the Ligurian units, representing the top of the above depressions and they are located right on the central portion of them (depocentral sector of the basins corresponding to the maximum tectonic elision); BROGI (2004b) based on field and borehole data get similar results for the northernmore Mt. Amiata area.

According to this interpretation, it is suggestive to suppose that all Upper Miocene successions of the basins of southern Tuscany formed in this tectonic setting (see also in BROGI, 2004b), since these successions overlie on to Ligurian units exclusively (i.e. Upper Miocene successions of the Cinigiano-Baccinello Basin in BOSSIO *et alii*, 1994, and in BENVENUTI *et alii*, 2001; of the Albegna Basin in BETTELLI 1980a and in BETTELLI *et alii*, 1990; of the Valdorcia and Velona Basins in BOSSIO *et alii*, 1991; 1993; 1998 and in SANI *et alii*, 1998).

The Upper Miocene basins seem to be characterized by a constant ratio between tectonic subsidence and clastic feeding amount, as showed by the thickness of fluvial/lacustrine environment deposits.

The Miocene structures are then dissected by a normal faults system developed during the Pliocene-Pleistocene. This faults system led to the formation of tectonic depressions, graben or half-graben type (MARTINI & SAGRI, 1993) with Apenninic orientation. The fault systems of this event don't seem to be strongly controlled by the structures originated during the «serie ridotta» event. Faults displaced all the previous structures, causing also the transgression of the marine sediments either over the Miocene structural highs and lows. In the latter case, the Pliocene deposits lie unconformably over the Miocene deposits, over the Ligurian units and the Tuscan Nappe unit. Still during this event, deep marine basins characteristic of the Pliocene sedimentation of the internal part of the Northern Apennines, formed. Their distribution shows a clear NNW-SSE striking direction, with a narrow and elongated shape, like the Radicofani Basin. Moreover, the presence at the western edge of the Radicofani Basin of thick olistostromes, derived by the Ligurian formations, in the Pliocene clays (CALAMAI *et alii*, 1970; LIOTTA 1996; BETTELLI *et alii*, 2001; CALLEGARI *et alii*, 2003), suggests their genesis as the result of the combined action of normal faults and the uplift of the Mt. Amiata area, this last in part also due to the presence of a batholite intrusion (ACOCELLA, 2000; ACOCELLA *et alii*, 2002).

CONCLUSIONS

Structural and stratigraphic investigations in the area south of M. Amiata in southern Tuscany, have led to unravel the sedimentary evolution and the Neogene post-collisional extensional tectonics for this sector of the Apennine chain. The evolution fit well with models known for the hinterland of the Northern Apennines, as BALDI *et alii* (1994) proposed for the Metallifere Hills of Tuscany. Yet, some differences have been evidenced, in particular about the features of the deformation and the basins formation.

The most important results of our investigations are the followings.

The geological setting of the area is characterized by a megaboudinage with the presence of asymmetric megaboudins formed by rocks belonging to the Tuscan Nappe succession, separated by areas with strong tectonic elision. They have been produced by an extensional phase, that interested the whole orogenic stack.

Deformative and extensional structures characterized by different geometry and features, referable to three extensional events, are recognizable.

During the first extensional event (end of the Early Miocene-Middle Miocene), normal faults with flat-ramp-flat geometry dipping towards east developed (Low-angle normal fault system). They led to strong crustal thinning, bringing in the flat zones to the emplacement of the Ligurian units directly over the Tuscan Triassic evaporites and pre-evaporite units. During this event the megaboudins formed. In the second extensional event (Late Miocene), the low-angle faults were dissected in the western limbs of the Tuscan Nappe antiformal structures by listric and high-angle west-dipping normal faults (High-angle fault system I). These displacements led to uplift of the Tuscan succession and its tilting towards east. This evolution led also to the development of middle- to high-angle east-dipping normal faults systems (Fault system II). These latter faults are located at the east side of the Tuscan Nappe antiforms or nuclei, affecting also the above Ligurian units. Consequence was an increase of structural depressions and basins, in which the Ligurian units were tectonically and in part gravitationally emplaced, and the Upper Miocene continental successions deposited.

The third extensional event (Pliocene-Pleistocene) is characterized by high-angle normal faults (High-angle fault system IV), with Apennine orientation, that cut all the previous structures, forming new narrow and elongated structural depressions with the sedimentation of the Pliocene deposits.

WSW-ENE faults, belonging at the High-angle fault system III, have been also recognized. They are related to transtensional or transfer faults, produced during mainly the Miocene event, either during the Pliocene event.

The Upper Miocene continental deposits (lacustrine and fluvial-lacustrine environments) lie exclusively over Ligurian formations strongly thinned in the «serie ridotta» structures, and are deposited within tectonic basins closed to the megaboudin morpho-tectonic depressions, produced during the first extensional event.

On this basis also the Middle Miocene deposits of the southern Tuscany (i.e. «Arenarie di Manciano») can be considered neoautochthonous deposits. They deposited in shallow basins, developed during the first extensional event.

Furthermore, it is worth note that the Neogene tectonic and depositional evolution detected for the southern Tuscany shows strong analogies, both in timing and in tectonic style, with the Amantea Basin in the Calabrian Arc (MATTEI *et alii*, 2002), so to outline an homogeneous evolutive framework for the whole Tyrrhenian Basin.

ACKNOLEWDGEMENTS

We thank our collegues of the Earth Sciences Department of Siena for the constructive discussions. Moreover, we are grateful with the referees D. Cosentino and an anonymous one for the careful and useful observations.

REFERENCES

ACOCELLA V. (2000) - *Space accomodation by roof lifting during pluton emplacement at Amiata (Italy)*. Terranova, **12**, 149-155.

ACOCELLA V., PASCUCCI V. & DOMINICI G. (2002) - *Basin deformation due to the laccolith emplacement at Radicofani (southern Tuscany, Italy)*. Boll. Soc. Geol. It., Vol. spec. **1**, 749-756.

BALDACCI F., ELTER P., GIANNINI E., GIGLIA G., LAZZAROTTO A., NARDI R. & TONGIORGI M. (1967) - *Nuove osservazioni sul problema della Falda Toscana e sulla interpretazione dei Flysch arenacei tipo «Macigno» dell'Appennino Settentrionale*. Mem. Soc. Geol. It., **6** (2), 213-244.

BALDI P., BERTINI G., CAMELI G.M., DECANDIA F.A., DINI I., LAZZAROTTO A. & LIOTTA D. (1994) - *La tettonica distensiva post-collisionale nell'area geotermica di Larderello (Toscana meridionale)*. Studi Geol. Camerti, Vol. spec. **1**, 183-193.

BARBIERI M., CHIOCCHINI U. & MADONNA S. (2003) - *Nuovi dati sull'età dell'Arenaria di Manciano (Miocene) sulla base dei valori di rapporto isotopico $^{87}Sr/^{86}Sr$ (Italia centrale)*. Boll. Soc. Geol. It., **122**, 351-354.

BENVENUTI M., PAPINI M. & ROOK L. (2001) - *Mammal Biochronology, UBSU and paleoenvironment evolution in a post-collisional basin: evidence from the Late Miocene Baccinello-Cinigiano basin in southern Tuscany, Italy*. Boll. Soc. Geol. It., **120**, 97-118.

BERTINI G., CAMELI G.M., COSTANTINI A., DECANDIA F.A., DI FILIPPO M., DINI I., ELTER F.M., LAZZAROTTO A., LIOTTA D., PANDELI E., SANDRELLI F. & TORO B. (1991) - *Struttura geologica fra i monti di Campiglia e Rapolano Terme (Toscana meridionale): stato attuale delle conoscenze e problematiche*. Studi Geologici Camerti, **1**, 155-178.

BETTELLI G. (1980a) - *Carta geologica dell'area compresa fra le alte valli del F. Albegna e del F. Fiora*. Ist. Geol. Univ. Modena.

BETTELLI G. (1980b) - *Le unità tettoniche del complesso ligure fra il fiume Albegna e il fiume Fiora (Toscana Meridionale)*. Mem. Soc. Geol. It., **21**, 157-161.

BETTELLI G. (1985) - *Geologia delle alte valli dei fiumi Albegna e Fiora (Toscana meridionale)*. Geol. Rom., **24**, 147-188.

BETTELLI G., BONAZZI U. & FAZZINI P. (1979) - *Il «Complesso di Canetolo» nella Toscana meridionale*. Atti Soc. Nat. e Mat. di Modena, **109** (1978).

BETTELLI G., BONAZZI U. & FAZZINI P. (1980) - *Il complesso alloctono ligure nella Toscana meridionale*. Mem. Soc. Geol. It., **21**, 163-188.

BETTELLI G., CONTI S., PANINI F. & VANNUCCHI P. (2001) - *Depositi caotici nella successione pliocenica del Bacino di Radicofani (Toscana meridionale): relazioni con la tettonica estensionale*. Atti della Riunione scientifica *Studi per l'interpretazione del Profilo sismico CROP18*, Stato di avanzamento, Siena, Dicembre 2001, 49-56.

BETTELLI G., BONAZZI U., FAZZINI P., FONTANA D. & GASPERI G. (1990) - *Carta geologica del bacino del F. Albegna*. Ist. Geol. Univ. Modena, S.EL.CA. Firenze, 1990.

BOCCALETTI M. & SAGRI M. (1964) - *Strutture caotiche nell'Appennino.* 1) *Età, assetto e giacitura del complesso argilloso-calcareo affiorante nella parte occidentale del Foglio 129 «S. Fiora»*. Boll. Soc. Geol. It., **83** (4), 461-524.

BOCCALETTI M., DECANDIA F.A., GASPERI G., GELMINI R., LAZZAROTTO A. & ZANZUCCHI G. (1987) - *Note illustrative della Carta strutturale dell'Appennino Settentrionale*. Pubbl. n. **429** (1982), Tipografia Senese, Siena, 203 pp.

BONAZZI U., FAZZINI P. & GASPERI G. (1992) - *Note alla carta geologica del Fiume Albegna*. Boll. Soc. Geol. It., **111**, 341-354.

BONAZZI U., FREGNI P. & GASPERI G. (1980) - *Il bacino neoautoctono del F. Albegna*. Mem. Soc. Geol. It., **21**, 267-271.

BOSSIO A., MAZZEI R., SALVATORINI G. & SANDRELLI F. (2002) - *Geologia dell'area compresa tra Siena e Poggibonsi («Bacino del Casino»)*. Atti Soc. Tosc. Sc. Nat., Mem., Serie A, **107**, 69-86.

BOSSIO A., COSTANTINI A., FORESI L.M., MAZZEI R., MONTEFORTI B., SALVATORINI G. & SANDRELLI F. (1991) - *Notizie preliminari sul Pliocene del Bacino del medio Ombrone e della zona di Roccastrada*. Atti Soc. Tosc. Sc. Nat., Mem., Serie A, **98**, 259-269.

BOSSIO A., COSTANTINI A., FORESI L.M., MAZZEI R., MONTEFORTI B., RADI L., SALVATORINI G. & SANDRELLI F. (1994) - *Carta geologica dell'area del Medio-Ombrone*. Cartografia S.EL.CA., Firenze.

BOSSIO A., COSTANTINI A., LAZZAROTTO A., LIOTTA D., MAZZANTI R., MAZZEI R., SALVATORINI G. & SANDRELLI F. (1993) - *Rassegna delle conoscenze sulla stratigrafia del neoautoctono toscano*. Mem. Soc. Geol. It., **49**, 17-98.

BOSSIO A., COSTANTINI A., FORESI L.M., LAZZAROTTO A., MAZZANTI R., MAZZEI R., PASCUCCI V., SALVATORINI G., SANDRELLI F. & TERZUOLI A. (1998) - *Neogene-Quaternary evolution in the western side of the Northern Apennines (Italy)*. Mem. Soc. Geol. It., **52**, 513-525.

BROGI A. (2003) - *Il megaboudinage della Falda Toscana nell'area geotermica del Monte Amiata e relazioni con la tettonica distensiva miocenica dell'Appennino Settentrionale*. GeoActa, **2** (CD), 33-36.

BROGI A. (2004a) - *Assetto geologico del nucleo di Falda Toscana affiorante nel settore occidentale del Monte Amiata (Appennino Settentrionale): strutture pre- e sin- collisionali relitte preservate durante lo sviluppo della tettonica distensiva post-collisionale*. Boll. Soc. Geol. It., **123**, 443-461.

BROGI A. (2004b) - *Miocene extension in the inner Northern Apennines: the Tuscan Nappe megaboudins in the Mt. Amiata geothermal area and their influence on Neogene sedimentation*. Boll. Soc. Geol. It., **123**, 513-529.

BROGI A. & LAZZAROTTO A. (2002) - *Deformazioni sin-collisionali nella Falda Toscana a SW del Monte Amiata (Toscana meridionale): il sovrascorrimento del Monte Aquilaia*. Boll. Soc. Geol. It., **121**, 299-312.

BROGI A., LAZZAROTTO A., LIOTTA D., NICOLICH R. & RANALLI G. (2003) - *L'orizzonte K nella crosta dell'area geotermica di Larderello (Toscana meridionale)*. Boll. Soc. Geol. It., **122** (2), 103-116.

CALAMAI A., CATALDI R., SQUARCI P. & TAFFI L. (1970) - *Geology, geophysics and hydrogeology of the Monte Amiata Geothermal fields*. Geothermics, **1**.

CALCAGNILE G. & PANZA G.F. (1981) - *The main characteristics of the litohosphere-astenosphere system in Italy and surrounding regions*. Pure Appl. Geophys., **199**, 865-879.

CALLEGARI I., CORNAMUSINI G., CONTI P. & CARMIGNANI L. (2003) - *Depositi caotici liguri nel Bacino pliocenico di Radicofani (Castell'Azzara, Toscana meridionale)*. Congresso FIST, Bellaria 2003.

CAMELI G.M., DINI I. & LIOTTA D. (1993) - *Upper crustal structure of the Larderello geothermal field as a feature of post-collisional extensional tectonics (Southern Tuscany, Italy)*. Tectonophysics, **224**, 413-423.

CANUTI P. & MARCUCCI M. (1971) - *Lacune della Serie Toscana.* 6) *Stratigrafia della base degli Scisti Policromi (Scaglia Toscana) nelle aree di Roccalbegna, Castell'Azzara, Semproniano, M. Selvi e M. Canino (Toscana Meridionale)*. Boll. Soc. Geol. It., **90** (3), 315-380.

CANUTI P., FOCARDI P. & SESTINI G. (1965) - *Stratigrafia, correlazione e genesi degli Scisti Policromi dei Monti del Chianti.* Boll. Soc. Geol. It., **84** (6), 93-166.

CARMIGNANI L., CONTI P., CORNAMUSINI G. & MECCHERI M. (2004) - *The internal Northern Apennines, the Northern Tyrrhenian Sea and the Sardinia-Corsica block*. In: Crescenti U., D'Offizi S., Merlini S. & Sacchi R. Eds., Geology of Italy. Special Volume of the Italian Geological Society for the IGC 32 Florence-2004, 59-77.

CARMIGNANI L., DECANDIA F.A., FANTOZZI P.L., LAZZAROTTO A., LIOTTA D. & MECCHERI M. (1994) - *Tertiary extensional tectonics in Tuscany (Northern Apennines, Italy)*. Tectonophysics, **238**, 295-315.

CARMIGNANI L., DECANDIA F.A., DISPERATI L., FANTOZZI P.L., LAZZAROTTO A., LIOTTA D., OGGIANO G. & TAVARNELLI E. (1995) - *Relazioni tra il bacino balearico, il Tirreno Settentrionale e l'evoluzione neogenica dell'Appennino Settentrionale*. Studi Geol. Camerti, vol. spec., **1995** (1), 255-268.

CARMIGNANI L., DECANDIA F.A., DISPERATI L., FANTOZZI P.L., KLIGFIELD R., LAZZAROTTO A., LIOTTA D., MECCHERI M. (2001) - *Inner Northern Apennines*. In: Vai G.B. & Martini I.P. Eds., Anatomy of an Orogen. The Apennines and Adjacent Mediterranean Basins. Kluwer Ac. Pubs., 197-214.

CESTARI G., CHIOCCHINI U., DI BATTISTINI G., FARAONE D., GALLO F., MANGANELLI V., PANNUZI L., PANSERI CRESCENZI C., SALVATI L., VERNIA L., ARDANESE L.R. & GIRADINI G. (1981) - *Note illustrative del Foglio 332 Scansano. Carta Geologica d'Italia alla scala 1: 50.000.* Serv. Geol. d'Italia, 52 pp.

CORNAMUSINI G. & PASCUCCI V. (2000) - *Sedimentary features and significance of the Tarquinia outcrops of the Manciano Sandstones (Middle Miocene) in the Northern Apennines evolutive framework*. In: Riassunti del Convegno della Società Geologica Italiana «Evoluzione geologica e geodinamica dell'Appennino». Perugia, febbraio 2000, 110-112.

CORNAMUSINI G., COSTANTINI A. & LAZZAROTTO A. (1999) - *Torbiditi carbonatiche nel Macigno di Poggio Ritrovoli (Toscana meridionale)*. Boll. Soc. Geol. It., **118**, 31-40.

COSTA E., DI GIULIO A., PLESI G., VILLA G. & BALDINI C. (1997) - *I flysch oligo-miocenici della trasversale Toscana Meridionale-Casentino: dati biostratigrafici e petrografici*. Atti Ticinensi Sci. Terra, **39**, 281-302.

COSTANTINI A., LAZZAROTTO A. & MICHELUCCINI M. (1978) - *Le formazioni liguri nell'area a sud del Monte Cetona (Toscana meridionale)*. Atti Soc. Tosc. Sc. Nat., Ser. A, **84**, 25-60.

CRESCENTI U. & GIUSSANI A. (1969) - *Osservazioni sugli Scisti Policromi della Toscana meridionale: il sovrascorrimento di M. Labbro (F.129, «S. Fiora» - Grosseto)*. Boll. Soc. Geol. It., **88** (2), 347-362.

DECANDIA F.A., LAZZAROTTO A. & LIOTTA D. (1993) - *La «Serie ridotta» nel quadro dell'evoluzione geologica della Toscana meridionale*. Mem. Soc. Geol. It., **49**, 181-190.

DECANDIA F.A., LAZZAROTTO A. & LIOTTA D. (2001) - *Structural features of southern Tuscany, Italy*. Ofioliti, **26** (2a), 287-300.

DECANDIA F.A., LAZZAROTTO A., LIOTTA D., CERNOBORI L. & NICOLICH R. (1998) - *The Crop03 traverse: insights on post-collisional evolution of Northern Apennines*. Mem. Soc. Geol. It., **52**, 427-439.

DECANDIA F.A., ELTER P., LAZZAROTTO A., LIOTTA D. SPALLONE S. & STEA B. (1994) - *Structural features of the Castell'Azzara Mountains*. Mem. Soc. Geol. It., **48**, 509-513.

DESSAU G. (1951) - *Geologia dei depositi di antimonio e d'altri minerali del gruppo dei Monti Romani (Comune di Manciano, Maremma toscana).* Boll. Soc. Geol. It., **70**, 1-64.

ELTER P. (1955) - *Geologia della regione di Castell'Azzara a Sud del Monte Amiata*. Boll. Soc. Geol. It., **74**, 317-337.

ELTER F.M. & PANDELI E. (1991) - *Structural features of the metamorphic Palaeozoic - Triassic sequences in deep geothermal drillings in the Monte Amiata area (SE Tuscany, Italy)*. Boll. Soc. Geol. It., **110**, 511-522.

ELTER F.M. & SANDRELLI F. (1995) - *La fase post-nappe della Toscana meridionale: nuova interpretazione sull'evoluzione dell'Appennino Settentrionale.* Atti. Tic. Sc. Terra, **37**, 173-193.

FAZZUOLI M., PANDELI E. & SANDRELLI F. (1996) - *Nuovi dati litostratigrafici sulla Scaglia toscana (Scisti policromi) dei Monti del Chianti (Appennino settentrionale)*. Atti Soc. Tosc. Sc. Nat., Mem., Ser. A, **103**, 95-104.

FONTANA D. (1980a) - *Confronti tra arenarie mioceniche nella Toscana meridionale.* Mem. Soc. Geol. It., **21**, 85-87.

FONTANA D. (1980b) - *Caratteri petrografici e sedimentologici delle Arenarie di Manciano nella Toscana meridionale*. Miner. Petrog. Acta, **24**, 77-94.

FORESI L.M., PASCUCCI V. & SANDRELLI F. (2004) - *L'Arenaria Miocenica di Ponsano (Toscana, Italia): evoluzione paleoambientale e biocronostratigrafica.* Boll. Soc. Paleont. It., **36**, 213-230.

FORESI L.M., BAMBINI A.M., MAZZEI R., PICCINELLI B. & SANDRELLI F. (2004) - *La base dell'Arenaria di Ponsano nella sua area tipo e nella zona di Casole d'Elsa (Toscana).* Atti Soc. Tosc. Sc. Nat., Mem., Serie A, **108**, 1-6.

GIANNINI E. (1957) - *I fossili dell'Arenaria di Manciano (Grosseto).* Paleontol. Ital., **51**, 97-103.

GIANNINI E. & TONGIORGI M. (1959) - *Stratigrafia neogenica toscana,* 1) *L'arenaria elveziana di Ponsano (Volterra)*. Boll. Soc. Geol. It., **78**, 83-103.

JACOBACCI A., MARTELLI N. & NAPPI G. (1967) - *Note illustrative della Carta Geologica d'Italia alla scala 1:100.000, Foglio 129 Santa Fiora.* Serv. Geol. d'Italia, Roma.

JOLIVET L., DUBOIS R., FOURNIER R., GOFFÉ B., MICHARD A. & JOURDAN C. (1990) - *Ductile extension in Alpine Corsica*. Geology, **18**, 1007-1010.

JOLIVET L., FACCENNA F., GOFFE B., MATTEI M., BRUNET C., ROSSETTI F., CADET J.P., FUNICIELLO R., THEYE T., STORTI F. & D'AGOSTINO N. (1998) - *Mid-crustal shear zones in postorogenic extension: example from the Northern Tyrrhenian Sea*. Journ. of Geop. Res., **103**, 12113-12160.

LAVECCHIA G., MINELLI G. & PIALLI G. (1984) - *L'Appennino Umbro-marchigiano: tettonica distensiva ed ipotesi di sismogenesi.* Boll. Soc. Geol. It., **103**, 467-476.

LAZZAROTTO A., SANDRELLI F., FORESI L.M., MAZZEI R., SALVATORINI G., CORNAMUSINI G. & PASCUCCI V. (2002) - *Note Illustrative della Carta Geologica d'Italia alla scala 1:50.000, Foglio 295 Pomarance.* Servizio Geologico d'Italia, L.A.C. Firenze, 2002, 140 pp.

LENTINI F., CARBONE S., CATALANO S., DI STEFANO A., GARGANO C., ROMEO M., STRAZZULLA S. & VINCI G. (1995) - *Sedimentary evolution of basins in mobile belts: examples from the Tertiary terrigenous sequences of the Peloritani Mountains (NE Sicily)*. Terra Nova, **7**, 161-170.

LIOTTA D. (1996) - *Analisi del settore centro-meridionale del bacino pliocenico di Radicofani (Toscana Meridionale)*. Boll. Soc. Geol. It., **108** (2), 219-235.

LIOTTA D., CERNOBORI L. & NICOLICH R. (1998) - *Restricted rifting and its coexistence with compressional structures: results from the Crop03 traverse* (*Northern Apennines, Italy)*. Terranova, **10**, 16-20.

LOSACCO U. (1959) - *Ricerche geologiche nella Toscana meridionale.* 1) *Stratigrafia e tettonica del gruppo di M. Civitella-M. Elmo (Grosseto)*. Boll. Soc. Geol., It., **78**, 1-32.

MARTINI I.P. & SAGRI M. (1993) - *Tectono-sedimentary characteristics of Late Miocene-Quaternary extensional basins of the Northern Apennines, Italy*. Earth Sci. Rev., **34**, 197-233.

MARTINI I.P., CASCELLA A. & RAU A. (1995) - *The Manciano Sandstone: a shoreface deposit of Miocene basin of the Northern Apennines, Italy.* Sedimentary Geology, **99**, 37-59.

MARTINI I.P., SAGRI M. & COLELLA A. (2001) - *Neogene-Quaternary basins of the inner Apennines and Calabrian arc*. In: Vai G.B. & Martini I.P. Eds., Anatomy of an Orogen: the Apenniens and adjacent Mediterranean basins. Kluwer Academic Publishers, 375-400.

MATTEI M., CIPOLLARI P., COSENTINO D., ARGENTIERI A., ROSSETTI F., SPERANZA F. & DI BELLA L. (2002) - *The Miocene tectono-sedimentary evolution of the southern Tyrrhenian Sea: stratigraphy, structural and palaeomagnetic data from the on-shore Amantea basin (Calabrian Arc, Italy)*. Basin Research, **14**, 147-168.

MAZZEI R., PASINI M., SALVATORINI G. & SANDRELLI F. (1981) - *L'età dell'Arenaria di Ponsano nella zona di Castellina Scalo (Siena)*. Mem. Soc. Geol. It., **21**, 63-72.

PANDELI E., BERTINI G., CASTELLUCCI P. & MORELLI M. (2002) - *Le coperture sedimentarie toscane e liguri della regione del M. Amiata (Toscana sud-orientale): nuovi dati sul loro assetto stratigrafico e tettonico*. Atti della Riunione scientifica *Studi per l'interpretazione del Profilo sismico CROP18*, 2° Stato di avanzamento, Castelnuovo V.C., Marzo 2002, 69-77.

PANDELI E., BERTINI G., CASTELLUCCI P. & MORELLI M. (2003) - *The Ligurian, Sub-Ligurian and Tuscan Units of the Monte Amiata geothermal region (south-eastern Tuscany): new stratigraphic and tectonic data*. GeoActa, **2** (CD), 134-136.

PASCUCCI V., MERLINI S. & MARTINI I.P. (1999) - *Seismic stratigraphy of the Miocene-Pleistocene sedimentary basins of the northern Tyrrhenian Sea and western Tuscany (Italy)*. Basin Research, **11**, 337-356.

PASINI M. & SANDRELLI F. (1977) - *L'Arenaria di Ponsano nell'area a sud-est di Castellina Scalo (Siena)*. Riv. It. Paleont. Stratig., **83**, 641-664.

SANI F., MORATTI G. & BONINI M. (1998) - *The geodynamic evolution of the Northern Apennines: insights from the Neogene-Quaternary basins.* Annales Tectonicae, **12**, 145-161.

SESTINI G. (1970) - *Sedimentation of the late geosynclinal stage*. Sedim. Geol., **4**, 445-479.

WISE D.U., FUNICIELLO R., PAROTTO M. & SALVINI F. (1979) - *Domini di lineamenti e fratture in Italia*. Pubbl. Ist. Geol. Paleont. Univ. Roma, **49**, 1-53.

ZANCHI A. & TOZZI M. (1987) - *Evoluzione paleogeografica e strutturale recente del Bacino del Fiume Albegna (Toscana meridionale)*. Geologica Romana, **26**, 305-325.

Manoscritto pervenuto il 21 Settembre 2004; testo approvato per la stampa il 21 Marzo 2005; ultime bozze restituite il 26 Aprile 2005.