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The Ligurian Units of Southern Tuscany

GIUSEPPE NIRTA (*), ENRICO PANDELI (*), (**), GIANFRANCO PRINCIPI (*), (**),
GIOVANNI BERTINI (**) & NICOLA CIPRIANI (*)

ABSTRACT

The reconstruction of the tectono-stratigraphical framework of the oceanic units (Ligurian Units Auctt.: Helminthoid Flysch Units, Vara Units, Lanciaia Fm.) cropping out in southern Tuscany is difficult because of the complex tectonics which characterize this sector of the Northern Apennines. Moreover, the widespread occurrence of Miocene-Pliocene and Quaternary sedimentary covers interrupt the areal continuity of the outcrops of the structural pile.

To reconstruct the stratigraphic-structural evolution of the Ligurian Units (LU) of southern Tuscany and to compare their sedimentary and compositional features in areas crossed by the CROP-18 profile, the authors performed sedimentological, biostratigraphical, petrographical and structural studies on some key outcrops (Gambassi-Montaione, S. Donato in Poggio, Northern Monti della Gherardesca, Micciano-Libbiano and Serrazzano, Lanciaia-Montecastelli Pisano). Data from geothermal wells were also used in the regional correlation of units.

The Cretaceous helminthoid flysches have been grouped into a single formation, the Monteverdi Marittimo Fm., subdivided into three members: (i) the Larderello Member; (ii) the Montaione Member; (iii) the San Donato Member. These represent different parts of the oceanic basin. The Larderello Member (Flysch Calcareo-Marnoso, Flysch di Monteverdi M.mo Auctt.) represents normal sedimentation in the middle part of the basin; the Montaione Member (Flysch di Montaione, Flysch di Chianni, Flysch di Castelluccio Auctt.) was deposited in the inner (western?) part and close to an ophiolitic ridge because of the occurrence of ophiolitic olistoliths and breccias; while the San Donato Member (Formazione di S. Donato: BORTOLOTTI, 1962) represents the distal eastern part of the turbiditic system.

Even though the LU of southern Tuscany were affected by a complex polyphasic evolution (including out-of-sequence thrusting), we can recognize the sequence of five main tectonic units (from bottom to top of the pile): Morello Unit, Castelnuovo Val di Cecina Unit (e.g. Marly-Calcareous Flysch Unit, Auctt.), Vara Unit (Lower Ophiolitiferous Unit Auctt.) and Lanciaia Fm., Castelluccio Unit (Montaione Flysch Unit Auctt.) and Montignoso Unit (Upper Ophiolitiferous Unit Auctt.). The Lupicaia Creek Unit (Montecatini Sandstones Unit Auctt.) is also present locally at the top of the pile (Montecatini Val di Cecina and south of the Montaione-Gambassi areas).

In the Early to Late Paleocene, the thrusting of the Vara Unit onto the Monteverdi M.mo Fm. occurred and was sealed by the sedimentation, in a piggyback basin, of the Lanciaia Fm., which can be considered an earlier Epiligurian unit. From the Late Eocene the Lanciaia Fm. was deformed by the out-of-sequence thrusting of the Castelluccio Unit and, finally, of the Montignoso Unit.

The main structural features of the LU have an «anti-Apenninic» trend (N80 to N110) superimposed by a late «Apenninic» (N150 to N180) trend. The former trend involved the LU at least until Middle-Late Eocene, while is not recognizable in the Tuscan Units, and the Neogene deposits which preserve only the Apenninic orientation. Moreover, the regional distribution of the Cretaceous-Eocene ophiolitic debris in the flysch sequences reflects the anti-Apenninic trend.

The above said data lead us to hypothesise, at least for the Ligurian Units of this sector of the Northern Apennines, a structural evolution probably linked, until the Middle-Upper Eocene, to a transpressive tectonic context.

KEY WORDS: *Northern Apennines, southern Tuscany, Ligurian Units, tectono-sedimentary evolution, ophiolitic olistoliths and olistostromes.*

RIASSUNTO

Le Unità Liguri della Toscana Meridionale.

La ricostruzione dell'evoluzione stratigrafico-strutturale delle unità oceaniche (Unità Liguri Auctt.) affioranti nella Toscana a sud dell'Arno è complicata dalla complessa situazione tettonica che caratterizza questo settore dell'Appennino. Inoltre la diffusa presenza dei sedimenti Mio-Pliocenici e Quaternari interrompe la continuità areale degli affioramenti della sottostante pila tettonica.

Per accrescere le conoscenze stratigrafiche sulle Liguridi della Toscana Meridionale nelle aree interessate dal profilo CROP-18, gli autori hanno condotto studi sedimentologici, biostratigrafici, petrografici e strutturali in affioramenti chiave (Gambassi e Montaione, FI; San Donato in Poggio, FI; Monti della Gherardesca settentrionali, PI; Micciano, Libbiano e Serrazzano, PI; Lanciaia-Montecastelli Pisano, PI) che hanno portato alla ricostruzione della loro complessa evoluzione tettono-sedimentaria. Inoltre i dati dei pozzi geotermici sono stati utilizzati per creare un punto di contatto tra la geologia di superficie e quella del sottosuolo e porre un importante fattore di controllo per quanto riguarda le correlazioni a carattere regionale.

I flysch a helmintoi cretacei sono stati raggruppati in un'unica formazione, la Formazione di Monteverdi Marittimo, distinta in tre Membri: i) Membro di Larderello, ii) Membro di Montaione, iii) Membro di S. Donato. Il Membro di Larderello (Flysch Calcareo-Marnoso Auctt.) rappresenta la normale deposizione nella parte centrale del bacino; il Membro di Montaione (Flysch di Montaione Auctt.) si è deposto nella parte più interna (occidentale?) del bacino prossimo ad un rilievo ophiolitico che lo riforniva di brecce e olistoliti; il Membro di S. Donato (Formazione di S. Donato: BORTOLOTTI, 1962) rappresenta la parte orientale distale del sistema turbiditico.

Benché le Unità Liguri della Toscana meridionale siano state interessate da un'intensa tettonica polifasica (comprendente thrust fuori sequenza) sono state riconosciute cinque principali unità tettoniche sovrapposte, che dal basso verso l'alto sono: Unità Morello, Unità di Castelnuovo Val di Cecina (Unità del Flysch Calcareo-Marnoso Auctt.), Unità Vara (Unità Ophiolitifera Inferiore Auctt.) e Formazione di Lanciaia, Unità di Castelluccio (Unità del Flysch di Montaione Auctt.), Unità di Montignoso (Unità Ophiolitifera Superiore Auctt.). Localmente (zona di Montecatini Val di Cecina e a sud di Montaione), è presente in cima alla pila strutturale l'Unità del Torrente Lupicaia (Unità delle Arenarie di Montecatini Auctt.).

Tra il Paleocene Inferiore e il Paleocene Superiore l'Unità Vara si sovrappone alla Formazione di Monteverdi M.mo. Questa sovrapposizione è sigillata dalla sedimentazione della Formazione di Lanciaia (Paleocene Superiore-Eocene Inferiore-Medio) che quindi può essere considerato un primo esempio di successione epilogica.

Dall'Eocene Superiore la Formazione di Lanciaia viene sovrascorsa in fuori sequenza dall'Unità di Castelluccio, prima, e di Montignoso, dopo.

Le strutture tettoniche principali delle Unità Liguri presentano un trend «antiapenninico» (N80-N110) al quale si sovrappone una

(*) Dipartimento di Scienze della Terra, Università di Firenze, Via G. la Pira, 4 - 50121 Florence, Italy; e-mail: giuseppe.nirta@geo.unifi.it

(**) ENEL Green Power, Pisa.

(***) CNR - Istituto di Geoscienze e Georisorse, sezione di Firenze, Via G. La Pira, 4 - 50121 Florence, Italy.

strutturazione «appenninica» (N150-N180) tardiva. L'orientazione antiappenninica interessa le Unità Liguri almeno fino all'Eocene Medio-Superiore. Le Unità Toscane e i sedimenti neogenici invece mostrano unicamente la strutturazione appenninica. Inoltre, anche la distribuzione geografica del detritismo ophiolitico cretaceo-eocenico dentro le sequenze flyschoidi liguri riflette a scala regionale un trend antiappenninico.

I dati sopra esposti evidenziano per le Liguridi di questo settore dell'Appennino Settentrionale un'evoluzione tettonica verosimilmente legata a transpressione almeno fino all'Eocene Medio-Superiore.

TERMINI CHIAVE: Appennino Settentrionale, Toscana Meridionale, Unità Liguri, evoluzione tettono-sedimentaria, olistoliti e olistostromi ophiolitici.

INTRODUCTION

Within the CROP-18 project, the study of the tectonic and stratigraphic evolution of the Ligurian Units of southern Tuscany adds new data to the structural interpretations of the inner part of the Apennine Chain. The study of such units is complicated by their dismembering due to both the tectonic polyphasic shortening and the successive low-angle (e.g. Reduced Tuscan Series: SIGNORINI, 1949; GIANNINI *et alii*, 1971; GIANNINI & LAZZAROTTO, 1975; DECANDIA *et alii*, 1993) and high-angle extensional phases (e.g. development of Neogene basins: BERTINI *et alii*, 1991; CARMIGNANI *et alii*, 1994). Moreover, the presence of widespread Neogene and Quaternary sedimentary cover interrupts the continuity of the outcrops of the underlying tectonic pile. This problem can be partly solved only in the Larderello geothermal region by the data obtained from the numerous wells (MAZZANTI, 1966; LAZZAROTTO & MAZZANTI, 1976).

For reconstructing the paleogeographical setting and scanning the tectono-sedimentary evolution of the Ligurian Units of southern Tuscany, the authors carried out stratigraphical, structural, biostratigraphical and petro-

graphical studies on typical outcrops of such units (fig. 1): (a) Gambassi-Montaione area; (b) San Donato in Poggio area; (c) Sassa area in the northern Monti della Gherardesca; (d) Micciano, Libbiano and Serrazzano area; (e) Lanciaia-Montecastelli Pisano area. In particular, the last three areas are directly affected by the CROP-18 profile.

The study includes: (i) detailed 1:10,000 scale mapping with special regard for the relationship between turbiditic successions and the ophiolitic bodies, and between them and the syntectonic sedimentation (e.g. Lanciaia Fm.); (ii) biostratigraphical dating (calcareous nannofossils) of the turbiditic deposits to define the points of the beginning and end of the sedimentation, which can be related to main tectonic events (ABBATE & SAGRI, 1982; PRINCIPI & TREVES, 1984; SESTINI *et alii*, 1986); (iii) petrographical modal analyses according to the Gazzi-Dickinson method (GAZZI, 1966; DICKINSON, 1970; DI GIULIO & VALLONI, 1992) on samples collected in the arenaceous portion of the Monteverdi Marittimo Fm. cropping out in the Montaione and Sassa areas, which allow us to obtain information about the source areas of the helminthoid flysches and of the ophiolitic detrital inputs; (iv) structural consideration of the tectonic pile of the Ligurian units. The stratigraphic-tectonic reconstruction was refined by subsurface data from geothermal wells in the Larderello geothermal area (kindly supplied by Enel Greenpower S.p.A.).

GEOLOGICAL FRAMEWORK OF THE LIGURIAN UNITS OF SOUTHERN TUSCANY

The Ligurian-Piedmont Ocean opened during the Jurassic between Adria (a promontory of the Africa Plate) and Europe, and represented the westernmost portion of the Tethys Ocean. From the Late Cretaceous the movement between the Adria microplate and the European plate changed from divergent to convergent, causing the consumption and shortening of the Ligurian-Piedmont Ocean (oceanic phase). After the continental collision, the ensialic shortening of the Adriatic margin and the over-thrusting of the Ligurian Units onto it began (ensialic phase); these events lead to the east-vergent Northern Apennines fold and thrust belt (ABBATE *et alii*, 1980; PRINCIPI & TREVES, 1984; VAI & MARTINI, 2001 with references therein).

In the geological literature the oceanic Ligurian Units (Ligurids *Auctt.*) were divided into Internal and External (ELTER & RAGGI, 1965). The Internal Ligurids (IL) are represented by an ophiolitic unit (Vara Unit) topped by arenaceous and arenaceous-pelitic turbidites (e.g. Gottero Flysch, etc.). Helminthoid calcareous-marly flysches deriving from the NW sector (e.g. Monte Antola Flysch, Marina di Campo Fm.) are also present. According to ABBATE & SAGRI (1982) and PRINCIPI & TREVES (1984), in a context of subduction complexes, these units could be related to a trapped crust environment.

The External Ligurids (EL and hereafter; Trebbia Unit, Monte Caio Flysch, Southern Tuscany Helminthoid Flysch complex, Monte Penna/Casanova Complex, Bagnza Supergroup and Morello Unit) mainly consist of turbiditic units detached from the original oceanic substratum at the level of the base complexes (i.e. pre-flysch units). These mainly calcareous-marly turbiditic successions derived from northern and southwestern areas

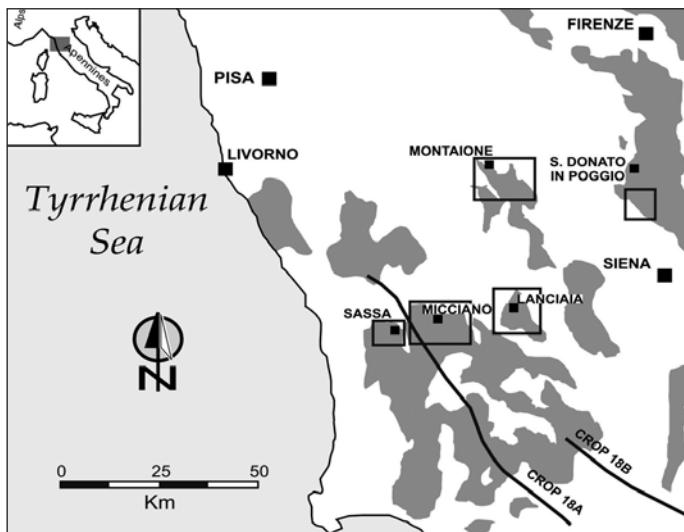


Fig. 1 - Distribution of the Ligurian Units in southern Tuscany. The study areas are evidenced by the boxes. CROP-18 seismic profile is shown.

- Distribuzione delle Unità Liguri nella Toscana sud-occidentale. Le aree studiate sono evidenziate da rettangoli. È riportata l'ubicazione delle linee sismiche CROP-18.

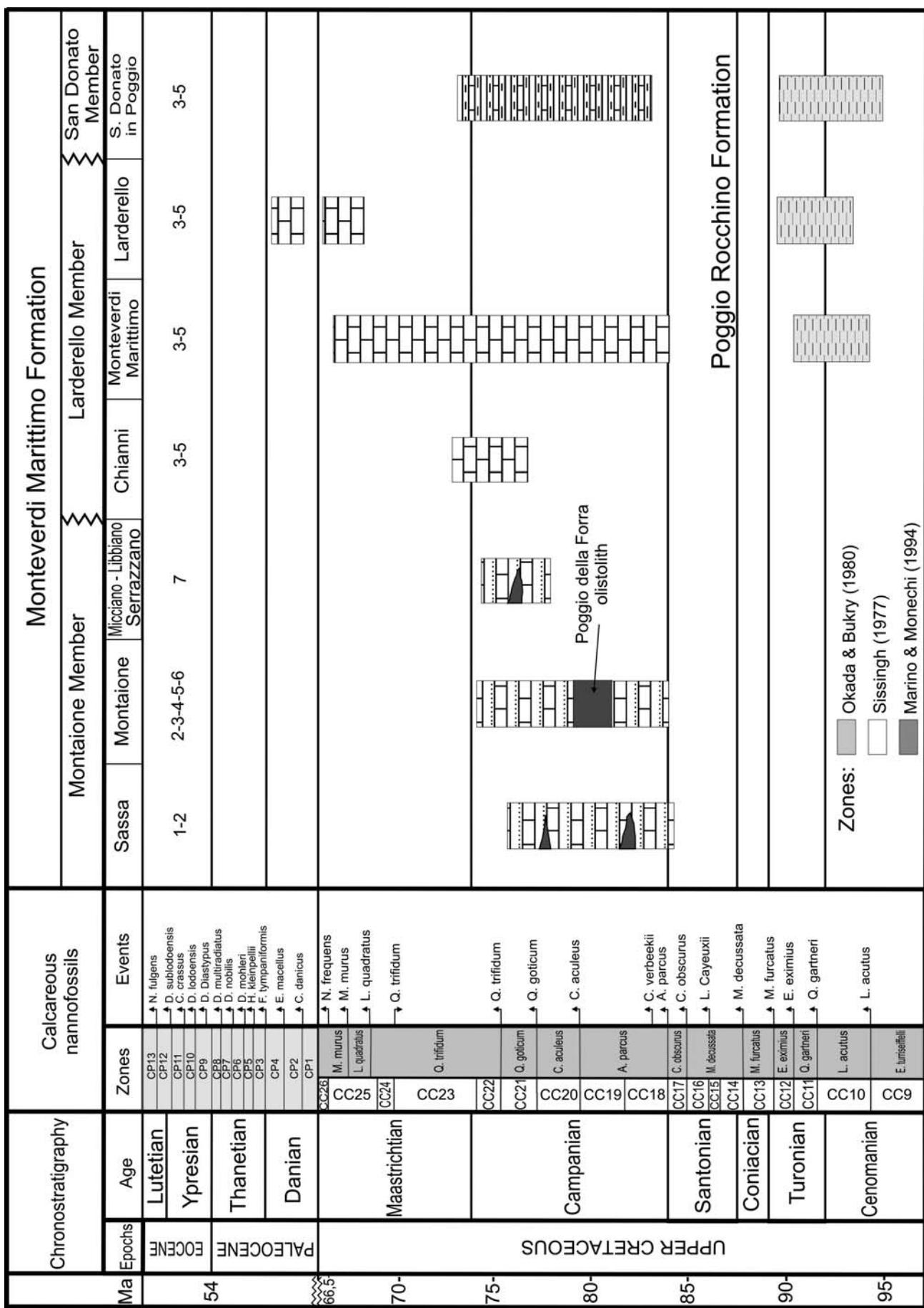


Fig. 2 - Chrono- and biostratigraphic correlation among the southern Tuscany outcrops of the Monteverdi Marittimo Fm. and Poggio Rocchino Fm. 1) COSTANTINI *et alii* (1993); 2) COBIANCHI IN NIRTA (2002); 3) MARINO (1988); 4) GARDIN IN CISCATO (1992); 5) MARINO & MONECHI (1994); 6) GARDIN *et alii* (1994); 7) GARDIN IN BIANCO (1996). – Correlazione crono- e biostratigrafica degli affioramenti della Formazione di Monteverdi M.m. e di Poggio Rocchino in Toscana Meridionale. 1) COSTANTINI *et alii* (1993); 2) COBIANCHI IN NIRTA (2002); 3) MARINO (1988); 4) GARDIN IN CISCATO (1992); 5) MARINO & MONECHI (1994); 6) GARDIN *et alii* (1994); 7) GARDIN IN BIANCO (1996).

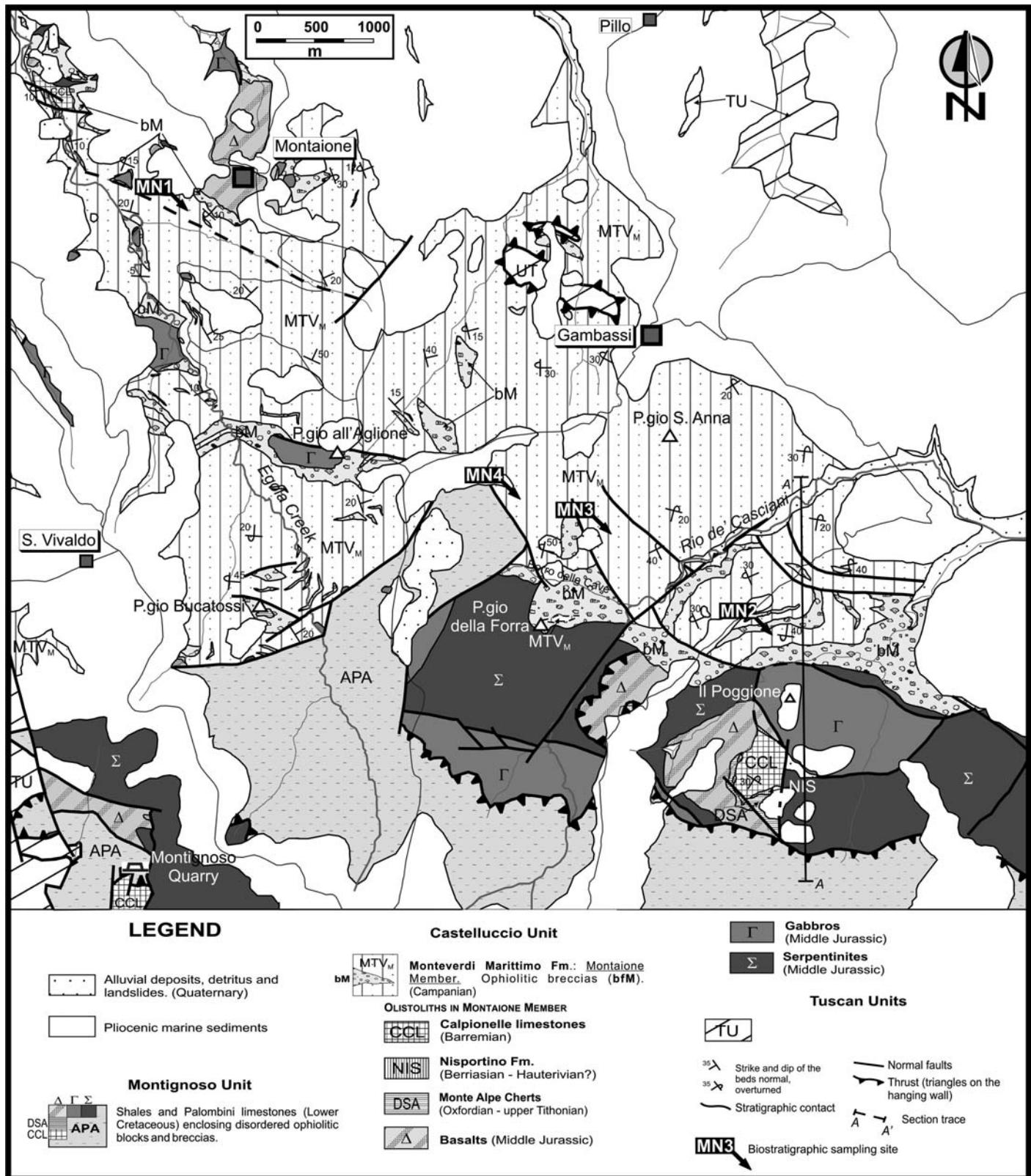


Fig. 3 - Geological map of Montaione-Gambassi area.
– Carta geologica dell'area di Montaione-Gambassi.

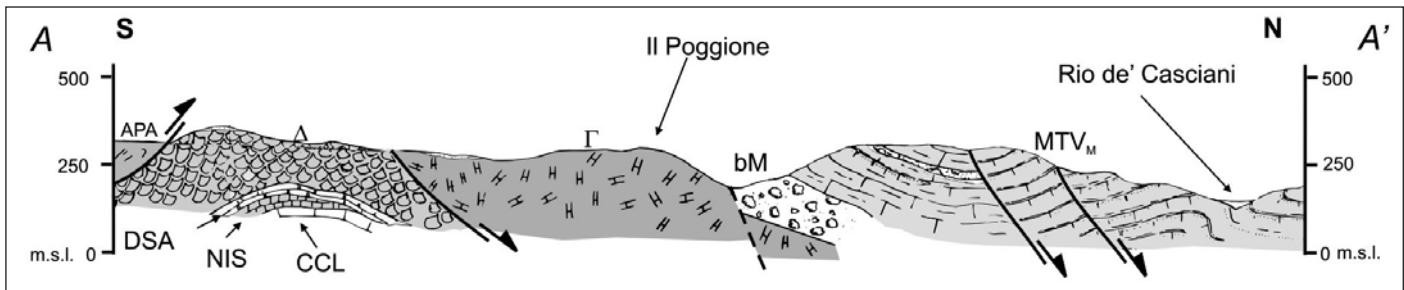


Fig. 4 - Geological cross section across the Montaione-Gambassi area.
– Sezione geologica nell'area di Montaione-Gambassi.

(e.g. Monteverdi M.mo Formation; PAREA, 1965; SAGRI, 1969a). The nature of their basement (oceanic vs. thinned continental crust) is debated (e.g. BERTOTTI *et alii*, 1986), but most authors considered it to be oceanic basement because of stratigraphical and structural considerations (ABBATE *et alii*, 1980, 1984; PRINCIPI & TREVES, 1984; BORTOLOTTI *et alii*, 2001).

From Upper Paleocene-Lower Eocene times, piggy-back basins formed on the already deformed LU. These basins were filled by shaly-calcareous deposits rich in olistoliths and olistostromes (Epiligurian sequence: PRINCIPI & TREVES, 1984).

Southern Tuscany is a typical outcrop area for the Apennine oceanic units, which were indicated in the geological literature with different names in the different areas, because of the fragmentation of the outcrops and the consequent difficulties in making regional correlations.

According to our studies, five main oceanic tectonic units can be distinguished in southern Tuscany (fig. 14). Moreover, all the Upper Cretaceous helminthoid flysches (MARRONI *et alii*, 1992; GARDIN *et alii*, 1994) of this area can be considered as members (Montaione Member, Larderello Member, S. Donato Member) of the Monteverdi Marittimo Fm. (see discussion). In particular, from bottom to top of the orogenic pile, the following oceanic tectonic units are present (for each unit, in brackets, the previous stratigraphic denomination is shown):

Morello Unit (*Supergruppo della Calvana*, ABBATE & SAGRI, 1970; *Unità di Monte Morello*, BOCCALETI *et alii*, 1987). It includes (from bottom to top):

Pietraforte Formation (*Upper Cretaceous*). It is composed of a regular alternation of medium to fine-grained quartzose-calcareous sandstones and dark grey shales. The thickness of the beds ranges between a few centimetres and 15-20 cm (max 50 cm).

Sillano Formation (*Upper Cretaceous-Lower Eocene*). This is made up of alternating greyish shales, thinly bedded Pietraforte-like sandstones, light brown to grey calcareous marls, 15 cm to about 1 m thick brown and green-grey marly limestones, and iron-grey, occasionally graded calcarenites with 5 to 20 cm thick beds. Frequently these lithologies, near the contact with the Pietraforte Fm., are replaced by red, greenish and grey shales with centimetre-thick green to reddish marly limestones and rare fine-grained calcareous sandstone of Pietraforte-type beds (*Villa a Radda Formation Auctt.*).

M. Morello Formation (*Lower Eocene-Middle Eocene*). This is represented by alternating white to light brown marly limestones, grey-yellowish calcarenites and shales. The marly calcareous portions prevail. The thickness of the carbonate beds ranges from 30 cm to more than 1 m.

Castelnuovo Val di Cecina Unit (*Marly-Calcareous Flysch Unit; Monteverdi-Lanciaia Unit p.p.*; COSTANTINI *et alii*, 1991, 1993). This unit is represented by the Larderello Member (*Marly-Calcareous Flysch, Chianni Flysch, Monteverdi Marittimo Flysch* p.p.: LAZZAROTTO & MAZZANTI, 1964; 1966; GIANNELLI *et alii*, 1965; BANNINO & CERRINA FERONI, 1968; COSTANTINI *et alii*, 1993) and the San Donato Member (*Chianni Flysch p.p., San Donato in Poggio Formation*: BORTOLOTTI, 1962) of the Monteverdi Marittimo Fm. (Santonian-Lower Paleocene). Locally also a Cenomanian-Lower Turonian (MARINO & MONECHI, 1994) pelitic-calcareous base complex is present, which we named the Poggio Rocchino Fm. (*Shales, Siltstones and Calcarenites with Pythonella; Poggio Rocchino Shales and Limestones*, COSTANTINI *et alii*, 1993; CARTOGRAFIA GELOGICA 1:50,000, FOGLIO 295-POMARANCE, 2002).

The Larderello Member consists of repeated 5 to 10 m thick turbiditic bodies made up of basal light grey calcarenite with frequent yellowish alteration at the base, grading upwards into marly limestone, marl and shale or fine-grained limestone; sandstone intercalations are rare.

The San Donato Member is recognizable only in the San Donato-Sant'Agnese area. It differs from the Larde-

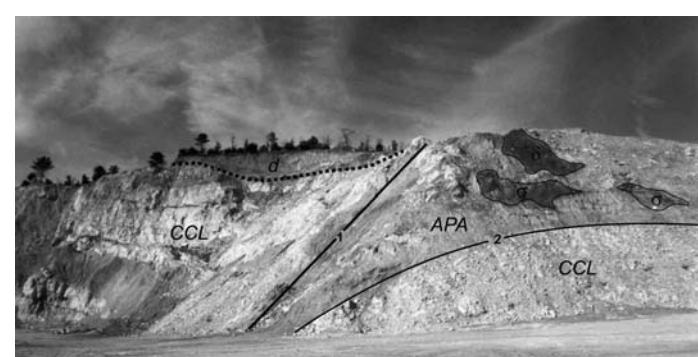


Fig. 5 - The Montignoso Unit cropping out in the Montignoso quarry. d: detritus; CCL: Calpionella Limestone; APA: Argille a Palombini; σ: breccia monogenica di basalto; σ: olistolite di serpentinita; 1: faglia; 2: contatto tettonico.

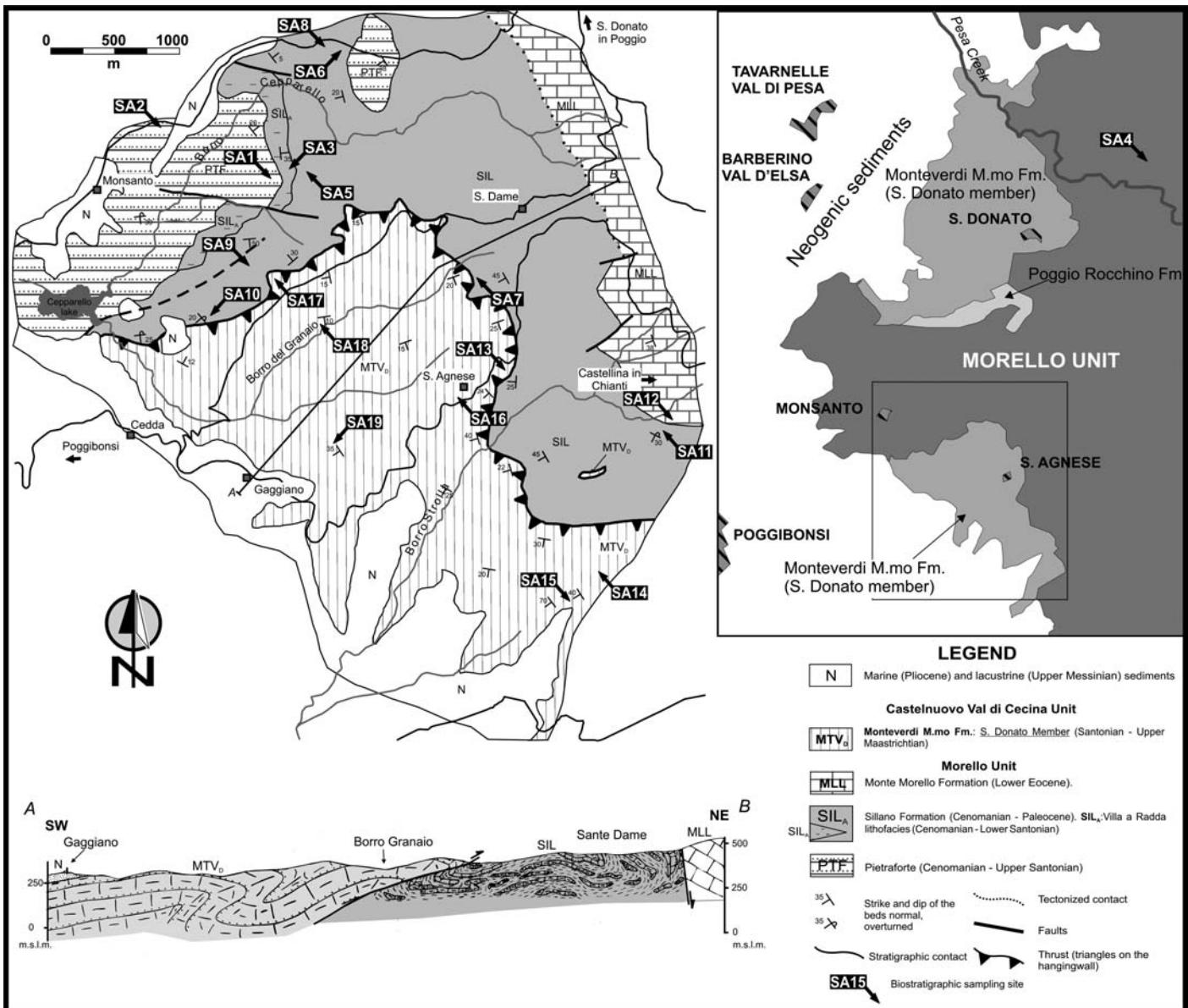


Fig. 6 - Geological map and cross section of San Donato in Poggio-S. Agnese area.
– Carta e sezione geologica dell'area di San Donato in Poggio-S. Agnese.

rello member essentially in the low mean thickness of the beds and for the higher amount of the pelitic lithotypes. It consists of alternating: (a) 1-8 m thick calcareous marls, marls and grey to dark grey marly limestones with a local calcarenitic base; (b) graded fine-grained calcarenites, 30-50 cm thick, sometimes amalgamated up to 3 m thick bodies; (c) shaly marls (up to 2 m thick); (d) scattered beds 5-20 cm thick of more or less calcareous finegrained sandstones.

The Poggio Rocchino Fm. represents the base complex of the Monteverdi M.mo Fm. and is present with scattered outcrops only in the San Donato-Sant'Agnese and Lanciaia-Montecastelli P.no areas. The lithologies are represented mostly by often manganeseiferous shales, siltose shales with penetrative scaly cleavage which include intercalations of isolated, up to 10 m thick bodies of calcarenites, marly limestones and marls similar to those of the Monteverdi Marittimo Fm. The transition between

two formations is gradual, by decrease of the terrigenous component and increase of carbonates.

Vara Unit and Lanciaia Fm (Lower Ophiolitiferous Unit Auctt. and Lanciaia Fm.; Monteverdi-Lanciaia Unit p.p.: LAZZAROTTO & MAZZANTI, 1976; COSTANTINI *et alii*, 1993). This includes an oceanic basement (serpentinites, gabbros), and a volcanic (basalts) and sedimentary Jurassic to Lower Cretaceous sedimentary cover (Monte Alpe Cherts, Calpionelle Limestones, Palombini Shales). The Vara Unit is unconformably overlain by the Epiligurian Lanciaia Fm. (Upper Paleocene-Middle Eocene) which in the typical outcrops in the Lanciaia-Montecastelli P.no area is represented by the following lithological associations (from bottom to top):

a) breccias of very variable thickness (10-200 m) mainly composed of angular serpentinite fragments (from

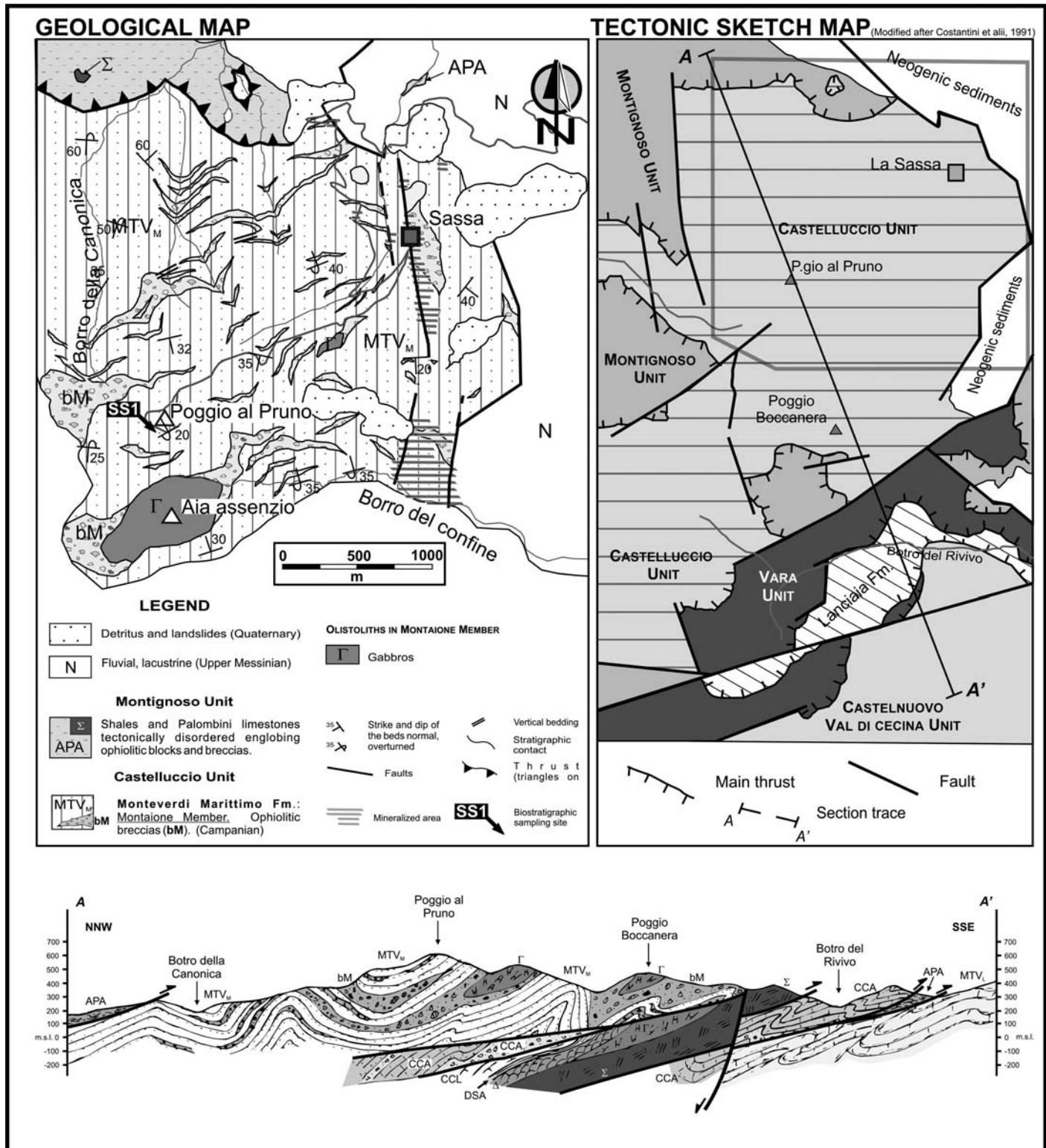


Fig. 7 - Geological sketches and cross section in the Sassa area.
- Carta geologica schematica e sezione dell'area di Sassa.

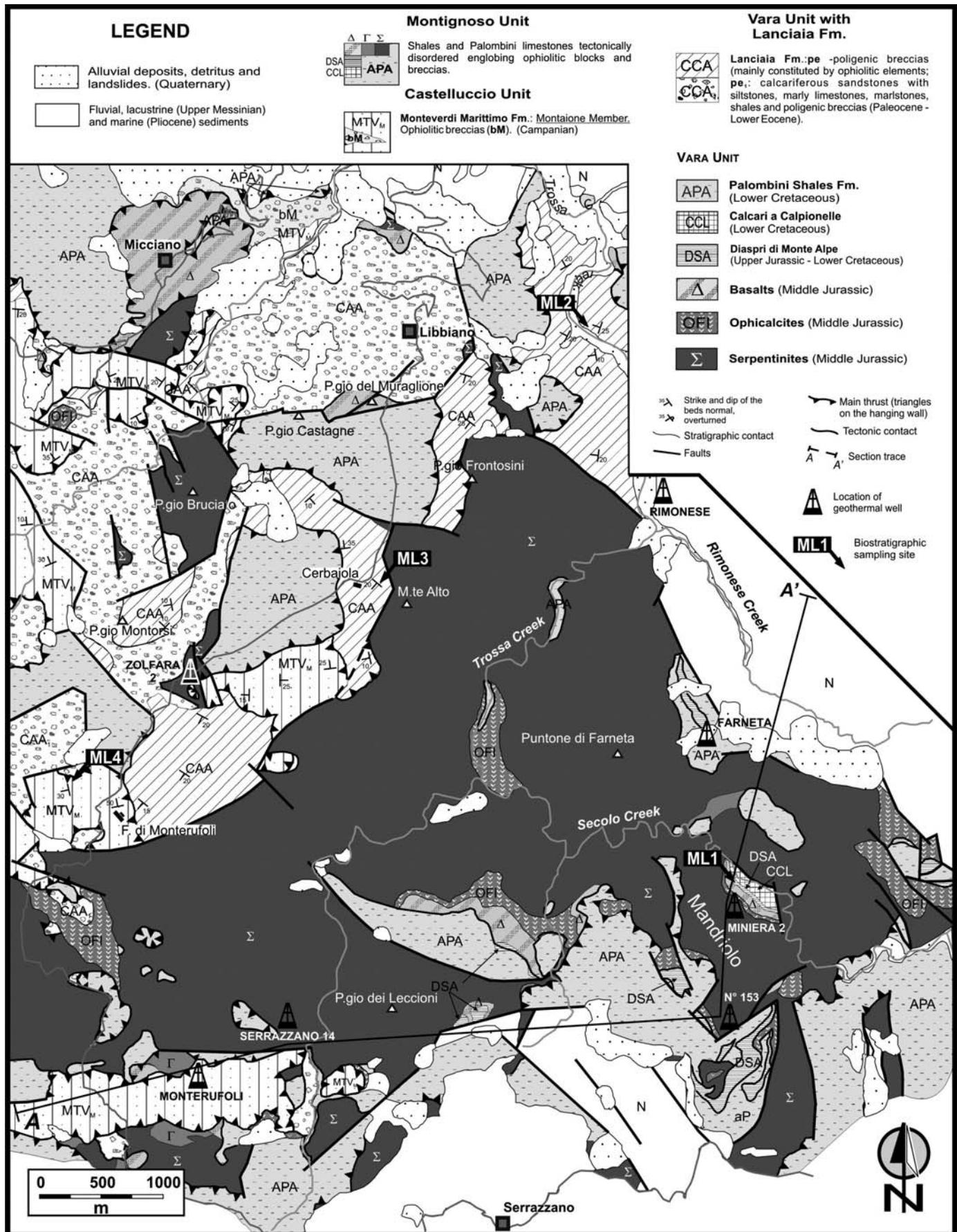


Fig. 8 - Geological map of Micciano-Libbiano-Serrazzano area. Geological cross section in fig. 9.
– Carta geologica dell'area di Micciano-Libbiano-Serrazzano. Sezione geologica in fig. 9.

TABLE 1
Montaione area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
MN1	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>W barnesae</i> , <i>M. decussata</i> , <i>A. parcus constrictus</i> , <i>L.</i> , <i>maleformis</i> , <i>C. aculeus</i> , <i>Braarudosphaera</i> sp., <i>P. cretacea</i>	CC20, CC21 after Sissingh (1977).	middle Campanian	Cobianchi in Nirta, 2002
MN2	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>A. parcus</i> , <i>P. cretacea</i> , <i>L. cayeuxii</i> , <i>C. obscurus</i> , <i>E. eximius</i> , <i>C. verbeekii</i> , <i>M. furcatus</i>	CC18 after Sissingh (1977).	early Campanian	Gardin in Ciscato, 1992
MN3	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>C. aculeus</i> , <i>A. parcus</i> , <i>C. obscurus</i> , <i>A. magnificus</i>	CC20 after Sissingh (1977).	early Campanian	Gardin in Ciscato, 1992
MN4	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>Q. gothicum</i> , <i>Q. trifidum</i> , <i>C. aculeus</i> , <i>A. parcus</i>	CC21, CC22 after Sissingh (1977).	late Campanian	Gardin in Ciscato, 1992

a few millimetres to 1 m), without any sorting and scarcely cemented. Towards the basal contact with the ophiolites, the sedimentary breccia is replaced by serpentinite or gabbro breccias, which locally presents some tectonically brecciated zones.

b) Rhythmic sequence of minute ophiolite-bearing breccias and sandstones intercalated, at rather regular intervals, with thinner sequences of calcarenites and siltstones.

c) Calcarenite, calcilutite and siltstone sequences alternated with marly pelites; moreover, intercalations of ophiolitic sandstones and silty marl beds can be found.

d) Alternating ophiolitic breccias, calcareous marls and reddish to greenish shales.

Castelluccio Unit (*Montaione Ophiolitiferous Unit*: CARTOGRAFIA GEOLOGICA 1:50,000, FOGLIO 295-POMARANCE, 2002). It is represented by the Montaione Member (*Montaione Flysch*; *Castelluccio Flysch*; *Podere Taucci Member*: BORTOLOTTI & LAZZERI, 1964; LAZZAROTTO & MAZZANTI, 1966; CERRINA FERONI & MAZZANTI, 1967; CERRINA FERONI *et alii*, 1968; BRANDI *et alii*, 1968; CONSTANTINI *et alii*, 1991) of the Monteverdi Marittimo Fm.

The Montaione Member is represented by T_{c-e} and occasionally T_{b-e} , generally incomplete turbiditic calcarenites and sandstones with marly-shaly interbeds and olistostromes. The bed thicknesses range from some centimetres to 1-2 metres. Locally the thickness of the marls is up to 10-15 m. The sandstones/pelite ratio (= S/P) is generally <1 but it becomes ≥ 1 nearby the olistostrome event.

The olistostromes normally have a massive structure; a crude inverse grading can be observed in the thicker ones. The clasts (from submillimetric to some metres) are angular and are made up of ophiolites and Palombini limestones (i.e. polygenic breccia). The olistoliths usually associated with the olistostromes locally reach kilometric dimensions, for example the Poggio della Forra olistolith (Montaione-Gambassi area).

Montignoso Unit (*Upper Ophiolitiferous Unit*, Auct.; *Palombini Shales Ophiolitiferous Unit*: CARTOGRAFIA GEOLOGICA 1:50,000, FOGLIO 295-POMARANCE, 2002). This is

mostly made up of locally chaotic Palombini Shales (Lower Cretaceous-Cenomanian?), which include Ophiolitic masses of even greater dimensions. Palombini Shales consist of dark grey shales, iron-grey siliceous limestones and minor medium to finegrained quartzarenite beds. The ophiolitic bodies (metres to several hundred metres in size) within the Palombini Shales can be ascribed to tectonic slices and, in some cases, to olistoliths locally associated with sedimentary breccias slipped into the Palombini Shales sedimentary basin.

In the Montecatini Val di Cecina area the Montignoso Unit is topped by the **Lupicaia Creek Unit** (Montecatini Sandstones Subunit, BERTINI *et alii*, 2000) which consists of medium to coarse-grained arkosic sandstones (MAZZANTI *et alii*, 1963; SAGRI, 1969b), similar to the Cretaceous-Paleocene sandstones of the Internal Ligurian Units (e.g. Gottero, Monghidoro, Ghiaieto).

Vara, Montignoso and Lupicaia Creek units pertain to the IL, while Morello, Castelnuovo Val di Cecina and Castelluccio units pertain to the EL.

FIELD DATA

In the following paragraphs, the lithostratigraphical, biostratigraphical (fig. 2) and structural data obtained from each type-area (locations in fig. 1) are given.

MONTAIONE-GAMBASSI AREA

The outcropping Ligurian succession (MAZZANTI, 1961; BORTOLOTTI & LAZZERI, 1964; CERRINA FERONI *et alii*, 1968; MARINO, 1988; CISCATO, 1992; NIRTA, 2002) can be ascribed to two tectonic units: the Castelluccio Unit and the overlying Montignoso Unit (fig. 3).

Castelluccio Unit

The Montaione Member of this area is characterized by an olistolith of kilometric dimensions (Poggio della Forra olistolith) which locally modified the sedimentary features in the basin.

The olistolith is lithologically heterogeneous: serpentinites (spinel-bearing lherzolite), gabbros, basalts and the Jurassic pelagic cover (fig. 4; CISCATO, 1992).

Analyses of the calcareous nannoplankton of the Montaione Member point to a Lower to Upper Campanian time interval (zones CC18, CC19, CC20 and CC21 after SISSINGH, 1977; MARINO, 1988; MARINO & MONECHI, 1994; GARDIN *et alii*, 1994; COBIANCHI IN NIRTA, 2002; tab. 1). In particular, samples of flysch close to the basal contact with the Poggio della Forra olistolith show a Middle Campanian age. After the sliding, the sedimentation of the Montaione member resumed in the Middle-Upper Campanian (Borro delle Cave, zones CC20, CC21 and CC22 after SISSINGH, 1977; GARDIN IN CISCATO, 1992; tab. 1) with a more abundant marly-shaly component. South of Montaione the overturned Flysch beds stratigraphically under the basaltic olistolith can be referred to Middle-Upper Campanian (CC20 and CC21 zones after SISSINGH, 1977; COBIANCHI IN NIRTA, 2002; tab. 1).

The main fold axes in the Castelluccio Unit have a WNW-ESE (50-90N) trend and vergence toward the SSW. These folds are superimposed upon by large open folds with NE-SW (150N-180N) axes and NE vergences. A WNW-ESE trend is clearly recognizable only in the Castelluccio Unit, while the NE-SW trend is recognizable in all the LU, in the Tuscan Units and in the Neogene sediments.

Montignoso Unit

This unit represents a large part of the southern portion of the studied area, even though it shows good outcrops only in the quarry north of Montignoso (fig. 5). Generally, the contacts between the Palombini Shales and the ophiolites are tectonic in nature. But locally, blocks of highly altered ophiolites (generally serpentinites) associated with ophiolitic breccias with subrounded to rounded clasts show stratigraphic relationships with the Palombini Shales and could be interpreted as olistoliths (Montignoso quarry).

SAN DONATO IN POGGIO-S. AGNESE AREA

In this area (fig. 6) it is possible to observe the tectonic superposition of the more external (eastern) portion of the Monteverdi Marittimo Fm. (San Donato Member, SAGRI 1969b) on the Sillano Fm. of the Morello Unit through a SW-dipping low-angle (about 15°) thrust surface (BORTOLOTTI, 1962; MARINO, 1988; MARINO & MONECHI, 1994).

Morello Unit

The contacts between the Pietraforte Fm. and the Sillano Fm and between the latter and the Monte Morello Fm. are often tectonized.

Nannofossil datings performed by MARINO (1988) in the Pietraforte Fm. point to a Cenomanian to Upper Santonian age (zones CC9, CC14, after SISSINGH, 1977; tab. 2). Samples collected in the Sillano Fm. near the contact with the Pietraforte Fm., east of Monsanto (MARINO, 1988; tab. 2), show a Cenomanian age (zone CC9 after Sissingh, 1977), while those near the contact with the M. Morello Fm., east of S. Dame, are of Lower Paleocene age (zone CP4 after OKADA & BUKRY, 1980; MARINO 1988; MARINO in press). The age of the Monte Morello Fm. is

Lower Eocene (zone CP9 after OKADA & BUKRY, 1980; MARINO, 1988; MARINO in press).

Castelnuovo Val di Cecina Unit

This is the easternmost outcrop of the Monteverdi Marittimo Fm. (S. Donato Member) and probably represents the distal part of the turbiditic system (SAGRI, 1969b). The flysch succession in the S. Donato in Poggio area yielded an age from the Santonian (zone *C. obscurus* after MARINO & MONECHI, 1994) to the Campanian/Maastrichtian boundary (zone *Q. trifidum* after MARINO & MONECHI, 1994). In the same area some silty-clay outcrops probably related to the Poggio Rocchino Fm. are Cenomanian-Turonian in age (zones *E. turrisieffelti-E. eximus*; after MARINO & MONECHI, 1994). In the S. Agnese area the age ranges from Coniacian/Santonian (zone CC14 after SISSINGH, 1977; MARINO, 1988; tab. 3) to Upper Maastrichtian (zone CC26 after SISSINGH, 1977; MARINO, 1988; tab. 3).

SASSA AREA

In this area (fig. 7) the analyses were focused on the Montaione Member, whereas the details of the other Ligurian Units (Castelnuovo Val di Cecina Unit, Vara Unit and Lanciaia Fm., Montignoso Unit) can be found in COSTANTINI *et alii* (1993, with references therein).

Castelnuovo Val di Cecina Unit

In the upper part of the Larderello Member some bodies of ophiolitic breccias, identical to those founded in the Montaione Member, are present (COSTANTINI *et alii*, 1993). This ophiolitic debris probably pre-dates the tectonic emplacement of the Vara Unit in the flysch basin.

In the Botro del Rivivo area (4 km south of Sassa) COSTANTINI *et alii* (1993) assumed the contact between the Lanciaia Fm and the underlying Monteverdi Marittimo Fm. (Larderello Member) to be stratigraphic. Given the lack of good outcrops, hydrothermal alteration along this contact, and taking into account the subsurface data, we consider it to be of a tectonic nature (see Discussion).

Vara Unit and Lanciaia Formation

The Vara Unit (mostly made of serpentinites) is tectonically superposed on the Larderello Member and is unconformably capped by the Lanciaia Fm. We also refer the ophiolites interposed between the Castelluccio Unit and the Lanciaia Fm. to a tectonic slice of the Vara Unit thrust over the Lanciaia Fm. (see Discussion).

In the Lanciaia Fm. cropping out in this area (*Podere Castellaro Fm.*, MAZZANTI, 1967; COSTANTINI *et alii*, 1993), the basal ophiolitic breccias of the Lanciaia-Montecastelli type-section are scarce or absent.

In some cases this formation, dated Late Paleocene-Early Eocene by COSTANTINI *et alii* (1993), tectonically rests on the Castelnuovo Val di Cecina Unit.

Castelluccio Unit

The main lithological features of the Montaione Member are identical to those observed in the Montaione outcrops.

COSTANTINI *et alii* (1993) ascribe the Montaione Member to the Early Campanian (zone CC17, CC18 and CC19 after SISSINGH, 1977). The samples collected in the upper part of the flysch show a Late Campanian age

TABLE 2
S. Donato-S. Agnese area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
SA1	Pietraforte Fm.	MMU	<i>Discorhabdus sp.</i> , <i>G. diplogrammus</i> , <i>M. pemmatoides</i> , <i>W. barnesae</i> , <i>W. Biporta</i> , <i>C. crenulatus</i> , <i>E. turriseiffelii</i> , <i>E. floralis</i> , <i>L. carniolensis</i> , <i>P. cretacea</i> , <i>Z. embergeri</i>	CC9 after Sissingh (1977).	upper Cenomanian	Marino, 1988
SA2	Pietraforte Fm.	MMU	<i>W. Britannica</i> , <i>C. crenulatus</i> , <i>M. pemmatoides</i> , <i>E. eximius</i> , <i>M. decussata</i>	CC14 after Sissingh (1977).	Coniacian/ Santonian	Marino, 1988
SA3	Sillano Fm. (Villa a Radda Fm. Auctt)	MMU	<i>W. Barnesae</i> , <i>E. turriseiffelii</i> , <i>P. cretacea</i> , <i>C. crenulatus</i> , <i>Discorhabdus sp.</i> , <i>M. pemmatoides</i> , <i>G. diplogrammus</i> , <i>B. constans</i> , <i>L. carniolensis</i>	CC9 after Sissingh (1977).	Cenomanian	Marino, 1988
SA4	Sillano Fm. (Villa a Radda Fm. Auctt)	MMU	<i>W. Barnesae</i> , <i>P. cretacea</i> , <i>C. crenulatus</i> , <i>E. turriseiffelii</i> , <i>G. diplogrammus</i> , <i>M. decussata</i> , <i>T. orionatus</i> , <i>C. aculeus</i>	CC14 after Sissingh (1977).	Coniacian/ Santonian	Marino, 1988
SA5	Sillano Fm.	MMU	<i>W. Barnesae</i> , <i>P. cretacea</i> , <i>B. constans</i> , <i>C. crenulatus</i> , <i>G. diplogrammus</i> , <i>Discorhabdus sp.</i> , <i>E. turriseiffelii</i> , <i>T. orionatus</i> , <i>M. pemmatoides</i> , <i>M. chiastius</i> , <i>R. asper</i> , <i>W. Biporta</i> , <i>C. litterarius</i> , <i>L. acutus</i>	CC9 after Sissingh (1977).	Cenomanian	Marino, 1988
SA6	Sillano Fm.	MMU	<i>M. decoratus</i> , <i>M. decussata</i> , <i>P. fibuliformis</i> , <i>C. eherembergi</i> , <i>C. crenulatus</i> , <i>L. carniolensis</i> , <i>P. cretacea</i>	CC14 after Sissingh (1977).	Coniacian/ Santonian	Marino, 1988
SA7	Sillano Fm.	MMU	<i>C. crenulatus</i> , <i>M. decussata</i> , <i>P. cretacea</i> , <i>W. Barnesae</i> , <i>L. cayeuxii</i> , <i>R. anthophorus</i>	CC16 after Sissingh (1977).	Santonian	Marino, 1988
SA8	Sillano Fm.	MMU	<i>M. decussata</i> , <i>P. cretacea</i> , <i>W. Barnesae</i> , <i>Broinsonia cf. B. enormis</i> , <i>L. cayeuxii</i> , <i>P. fibuliformis</i> , <i>C. obscurus</i> , <i>C. eherembergi</i> , <i>E. turriseiffelii</i> , <i>M. decoratus</i> , <i>R. anthophorus</i>	CC17 after Sissingh (1977).	upper Santonian	Marino, 1988
SA9	Sillano Fm.	MMU	<i>M. decussata</i> , <i>W. Barnesae</i> , <i>C. eherembergi</i> , <i>C. crenulatus</i> , <i>P. cretacea</i> , <i>V. stradneri</i> , <i>Broinsonia cf. B. enormis</i> , <i>L. cayeuxii</i> , <i>P. fibuliformis</i> , <i>M. decoratus</i> , <i>M. murus</i> , <i>L. quadratus</i>	CC25 after Sissingh (1977).	Maastrichtian	Marino, 1988
SA10	Sillano Fm.	MMU	<i>Broinsonia cf. B. enormis</i> , <i>M. decoratus</i> , <i>M. decussata</i> , <i>P. cretacea</i> , <i>C. crenulatus</i> , <i>E. turriseiffelii</i> , <i>P. fibuliformis</i> , <i>W. barnesae</i> , <i>M. murus</i> , <i>L. quadratus</i> , <i>N. frequens</i>	CC26 after Sissingh (1977).	upper Maastrichtian	Marino, 1988
SA11	Sillano Fm.	MMU		CP4 after Okada & Bukry (1980).	Early Paleocene	Marino, 1988, Marino in prep.
SA12	Monte Morello Fm.	MMU		CP9 after Okada & Bukry (1980).	Early Eocene	Marino, 1988, Marino in prep.
SA13	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>M. decussata</i> , <i>W. barnesae</i> , <i>Broinsonia cf. B. enormis</i> , <i>C. eherembergi</i> , <i>P. cretacea</i> , <i>E. eximius</i> , <i>E. turriseiffelii</i>	CC14 after Sissingh (1977).	Coniacian/ Santonian	Marino, 1988

TABLE 2 (*Continued*)
S. Donato-S. Agnese area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
SA14	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>M. decussata</i> , <i>P. cretacea</i> , <i>W. Barnesae</i> , <i>C. ehrenbergi</i> , <i>C. obscurus</i> , <i>L. cayeuxii</i>	CC17 after Sissingh (1977).	Santonian	Marino, 1988
SA15	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>Broinsonia cf. B. enormis</i> , <i>C. obscurus</i> , <i>C. ehrenbergi</i> , <i>M. decussata</i> , <i>P. cretacea</i> , <i>W. barnesae</i> , <i>G. diplogrammus</i> , <i>L. cayeuxii</i> , <i>A. parcus</i> , <i>C. crenulatus</i> , <i>C. margerelii</i> , <i>E. turriseiffelli</i> , <i>Gartnerago</i> sp., <i>M. decoratus</i> , <i>T. orionatus</i>	CC18 after Sissingh (1977).	lower Campanian	Marino, 1988
SA16	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>Broinsonia cf. B. enormis</i> , <i>M. decussata</i> , <i>C. ehrenbergi</i> , <i>P. cretacea</i> , <i>W. barnesae</i> , <i>Biscutum</i> sp., <i>C. crenulatus</i> , <i>L. cayeuxii</i> , <i>M. decoratus</i> , <i>P. fibuliformis</i> , <i>C. obscurus</i> , <i>C. aculeus</i>	CC20 after Sissingh (1977).	lower Campanian	Marino, 1988
SA17	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>M. decussata</i> , <i>W. barnesae</i> , <i>A. parcus</i> , <i>C. ehrenbergi</i> , <i>C. crenulatus</i> , <i>L. cayeuxii</i> , <i>M. decoratus</i> , <i>P. cretacea</i> , <i>Q. gothicum</i> , <i>Biscutum</i> sp., <i>C. obscurus</i> , <i>C. aculeus</i> , <i>Discorhabdus</i> sp., <i>E. turriseiffelli</i> , <i>L. carniolensis</i> , <i>Q. trifidum</i> , <i>R. levis</i>	CC22 after Sissingh (1977).	upper Campanian	Marino, 1988
SA18	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>M. decussata</i> , <i>W. barnesae</i> , <i>P. cretacea</i> , <i>C. obscurus</i> , <i>C. ehrenbergi</i> , <i>L. cayeuxii</i> , <i>G. diplogrammus</i> , <i>R. levis</i>	CC23 after Sissingh (1977).	upper Campanian / lower Maastrichtian	Marino, 1988
SA19	Monteverdi M.mo Fm. (S. Donato Member)	CCU	<i>M. decussata</i> , <i>W. barnesae</i> , <i>C. ehrenbergi</i> , <i>C. crenulatus</i> , <i>P. cretacea</i> , <i>V. stradneri</i> , <i>Broinsonia cf. B. enormis</i> , <i>L. cayeuxii</i> , <i>M. decoratus</i> , <i>P. fibuliformis</i> , <i>C. aculeus</i> , <i>C. litterarius</i> , <i>E. gorkae</i> , <i>E. turriseiffelli</i> , <i>M. murus</i> , <i>L. quadratus</i>	CC26 after Sissingh (1977).	upper Maastrichtian	Marino, 1988

(zone CC21 after SISSINGH, 1977; COBIANCHI IN NIRTA, 2002; tab. 4).

As in the Montaione-Gambassi area, in this unit two main tectonic events are recognizable. The first event produced tight to close folds with N50-N80 trending axes and westward vergences. With the secondary event are associated generally open folds with N150 to N200 axes directions and eastwards vergence. The folds associated with the first tectonic event are clearly recognizable only in the Castelluccio Unit and seem to affect only the LU. In fact,

the nearby Neogene Guardistallo Basin (W of Sassa area) records just the effects of the late event (CERRINA FERONI et alii, 2004).

Montignoso Unit

The unit is characterized by Palombini Shales generally of a chaotic nature including scattered metric to decametric ophiolitic bodies (usually serpentinites). The relationship between these bodies and the Palombini Shales is never clearly observed.

TABLE 3
Sassa area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
SS1	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>W barnesae</i> , <i>M. decussata</i> , <i>Lucianorhabdus</i> spp., <i>C. obscurus</i> , <i>A. parcus parcus</i> , <i>A. parcus constrictus</i> , <i>Eiffellithus</i> spp., <i>Tranolithus</i> spp., <i>U. gothicus</i>	CC21 after Sissingh (1977).	middle Campanian	Cobianchi in Nirta, 2002

TABLE 4
Micciano-Libbiano-Serrazzano area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
ML1	Monte Alpe Cherts	VVU	<i>P. amphitreptera</i> , <i>Z. ovum</i> , <i>P. ordinarium</i> , <i>A. apiarum</i> , <i>A. suboblongus suboblongus</i> , <i>S. elegans</i>	UAZ 9 – 11 after Baumgartner et alii (1995)	middle-late Oxfordian to late Kimmeridgian-early Tithonian	Chiari in Bianco, 1996
ML2	Lanciaia Fm.		<i>C. pelagicus</i> , <i>E. subpertusa</i> , <i>E. formosa</i> , <i>S. radians</i> , <i>S. moriformis</i> , <i>P. martini</i> , <i>Chiasmolithus</i> sp., <i>Discoaster</i> spp., <i>D. binodatus</i> , <i>D. barbadiensis</i> , <i>D. diastypus</i> , <i>D. rosetta</i> , <i>D. mirus</i> , <i>P. specifica</i> , <i>T. orthostylus</i>	poorly preserved association	not older than Early Eocene	Gardin in Bianco, 1996
ML3	Lanciaia Fm.		<i>C. pelagicus</i> , <i>D. multiradiatus</i> , <i>Fasciculitus</i> spp., <i>T. orthostylus</i>	poorly preserved association	not older than Early Eocene	Gardin in Bianco, 1996
ML4	Monteverdi M.mo Fm. (Montaione Member)	CSU	<i>W. barnesae</i> , <i>M. decussata</i> , <i>P. cretacea</i> , <i>C. ehrenbergi</i> , <i>C. crenulatus</i> , <i>S. cretaceus</i> , <i>A. cymbiformis</i> "N", <i>E. turriseiffeli</i> , <i>Z. spiralus</i> , <i>A. parcus parcus</i>	poorly preserved association	late Campanian	Gardin in Bianco, 1996

TABLE 5
Lanciaia-Montecastelli Pisano area.

SITE	FORMATION	UNIT	ASSOCIATION	BIOZONE	AGE	REFERENCES
LN1	Lanciaia Fm. (basal breccias)		<i>C. pelagicus</i> , <i>S. cf. moriformis</i> , <i>D. multiradiatus</i> , <i>D. lenticularis</i> , <i>P. bisulcus</i> , <i>E. subpertusa</i> , <i>F. tympaniformis</i> , <i>T. tovae</i> , <i>S. radians</i> , <i>E. macellus</i> , <i>M. inversus</i> , <i>Z. bijugatus</i> , <i>Ch. cf. consuetus</i> , <i>D. cf. elegans</i> , <i>T. craticulus</i> , <i>Chiasmolithus</i> sp., <i>N. concinnus</i> , <i>D. mohleri</i> , <i>Toracosphaera</i> sp., <i>E. formosa</i>	CP8 after Okada & Bukry (1980)	Late Paleocene	Gardin in De Siena, 1992
LN2	Lanciaia Fm. (clasts in the basal breccias)		<i>M. decussata</i> , <i>P. cretacea</i> , <i>W. barnesae</i> , <i>L. carniolensis</i> , <i>C. aculeus</i> , <i>C. crenulatus</i> , <i>A. parcus</i> , <i>M. decoratus</i> , <i>Z. diplogrammus</i> , <i>R. antophorus</i> , <i>R. cymbiformis</i> , <i>Argkhangeskiella</i> sp., <i>R. cf. levius</i>	CC20 after Sissingh (1977).	middle - late Campanian	Gardin in De Siena, 1992

MICCIANO-LIBBIANO-SERRAZZANO AREA

In this typical and well studied area (MAZZANTI, 1966; LAZZAROTTO, 1966; LAZZAROTTO, 1967; MAZZANTI, 1967; LAZZAROTTO *et alii*, 1995) the Ligurian Units are represented by the Castelnuovo Val di Cecina Unit, Vara Unit, Lanciaia Fm., Castelluccio Unit and Montignoso Unit (fig. 8).

Castelnuovo Val di Cecina Unit

In the studied area there are no outcrops of this unit, but its presence in the subsurface is testified to by the Enel borehole data.

Vara Unit and Lanciaia Formation

The Vara Unit is mainly represented by the serpentinites that crop out over a large area. In some weakly extended outcrops, serpentinites are associated with gabbros, ophicalcites and Jurassic volcano-sedimentary cover formations. At Mandriolo a stratigraphical succession is still clearly recognizable and consists of serpentinites overlaid by ophicalcites and, in their turn, by pillow basalts capped by Monte Alpe Cherts (middle-late Oxfordian to late Kimmeridgian-early Tithonian; zones UAZ 9-11 after BAUMGARTNER *et alii*, 1995; CHIARI IN BIANCO, 1996; tab. 5) and the Calpionelle Limestones (BIANCO, 1996; CASTELLI, 1996).

The structural setting of the Vara Unit is characterized by broad recumbent folds and imbricated tectonic slices, as can be detected by the presence of closely associated normal and reverse series with similar strikes and dips. In the Micciano-Libbiano-Serrazzano area these structures are also confirmed below the surface by the Enel wells, which show portions of the volcanic-sedimentary cover with normal and reverse polarity intercalated within serpentinites (fig. 9).

The Lanciaia Fm. crops out widely in the northwestern sector of the map between the Micciano and Libbiano villages to the north and the Monterufoli Farm to the south.

The fossiliferous assemblage found in the samples of the Trossa Creek can be referred to an age not older than Early Eocene (GARDIN IN BIANCO, 1996; tab. 5). Early Eocene is also the age of the clay-silty Cerbaiola outcrop (GARDIN IN BIANCO, 1996; tab. 5). These data agree with the ages (zones CP10 and CP11 after OKADA & BUKRY, 1980) given by LAZZAROTTO *et alii* (1995) for the same area and for the Botro Botticella outcrop (SW of M. Alto).

The Enel wells of the Micciano-Libbiano-Serrazzano area (Monterufoli, Zolfara 2, Rimonese and Farneta wells, see fig. 9 and fig. 13) reveal that the Lanciaia Fm. is tectonically interposed between the Vara Unit and the Castelnuovo Val di Cecina Unit. This situation seems to be localized along an ENE-WSW alignment from T. Rimonese (5 km SW of Pomarance) up to Botro del Rivivo (4 km south of Sassa) where this superposition crops out.

Castelluccio Unit

The first work in this area considered the Montaione Member to be the upper portion of the Lanciaia Fm. (Podere Taucci Member; CERRINA FERONI & MAZZANTI, 1967; BRANDI *et alii*, 1968), and only later was it correlated with the Sassa and Montaione outcrops (COSTANTINI *et alii*, 1991).

The samples show generally scarce and poorly preserved Late Cretaceous fossil associations, generally of late Campanian age (GARDIN IN BIANCO, 1996; tab. 5).

The flysch appears extremely tectonized. The main folds are open to close with E-W oriented axes and southward vergences.

Montignoso Unit

The chaotic Palombini Shales of the Micciano area include an altered mass of brecciated basalt. The contact between the two lithologies is indicated by a compact breccia with centimetre-sized clasts of basalt and limestone.

LANCIAIA-MONTECASTELLI PISANO AREA

This is another typical area for the LU in the Larderello geothermal region (LAZZAROTTO & MAZZANTI, 1976) (fig. 10, fig. 11).

Castelnuovo Val di Cecina Unit

In this area the Larderello Member lies stratigraphically on the Poggio Rocchino Fm. (BANNINO & CERRINA FERONI, 1968; COSTANTINI *et alii*, 1993; LAZZAROTTO *et alii*, 2002).

The upper part of the Larderello Member sampled along the Pavone Creek shows a late Maastrichtian age (zone *M. murus* after MARINO & MONECHI, 1994).

Dating of the Poggio Rocchino Fm. near the contact with the Monteverdi Marittimo Fm. (Poggio Scarpinata, immediately east of the studied area) yielded late Campanian to Turonian ages (zones *E. turrisieiffelii* and *L. acutus* after MARINO & MONECHI, 1994).

Tectonism of this unit is represented by a main deformational event characterized by tight to isoclinal folds with WSW-ENE trending axes and SSW vergence. In some cases a strong tectonic lamination affected original overturned folds and produced a series of imbricate tectonic slices (LAZZAROTTO, 1967). These deformations coexist with a late folding event characterized by gentle to open folds with NW-SE axial orientation and NE vergence.

Vara Unit and Lanciaia Formation

In the Vara Unit, serpentinites (lherzolite) and gabbros (olivine and/or clinopyroxene Mg-gabbro), with local basaltic dykes, largely prevail on the volcano-sedimentary cover. Under the microscope the serpentinites show a structure deriving from lherzolites in which serpentinization has led to the replacement of the primary paragenesis.

The contacts between serpentinites and gabbros are often tectonic with local cataclasites (P.gio Lunghieri).

The unconformity of the Lanciaia Fm. on the Vara Unit is observable (SIGNORINI *et alii*, 1963; MAZZANTI, 1966; LAZZAROTTO & MAZZANTI, 1976) in the outcrops crossed by the Pavone Creek and in the type-section along the Cecina River (Tormentaia quarry). Here, in the upper part of the basal breccias, at least four graded fining-upwards cycles, passing from breccias to ophiolite-bearing sandstones, are recognizable (BENVENUTI *et alii*, 2001).

In the literature a Late Paleocene to Early-Middle Eocene age (zones CP10, CP11 and CP12 after OKADA & BUKRY, 1980; MARINO & MONECHI, 1994) was defined for the Lanciaia Fm. on the basis of planktonic foraminifera (SIGNORINI *et alii*, 1963; LAZZAROTTO & MAZZANTI, 1966,

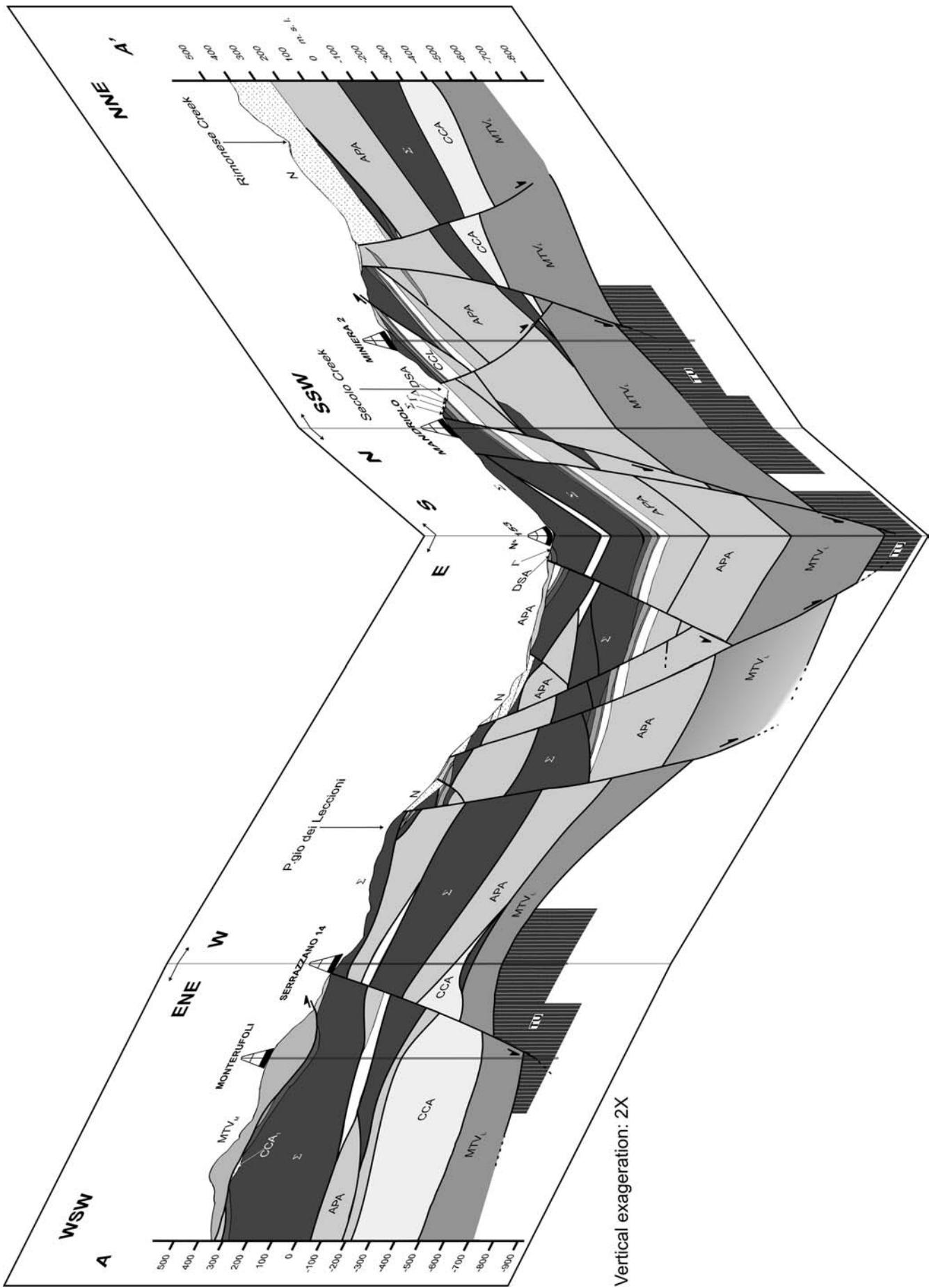


Fig. 9 - Geological cross section across the Micciano-Libbiano-Serrazzano area.
- Sezione geologica nell'area di Micciano-Libbiano-Serrazzano.

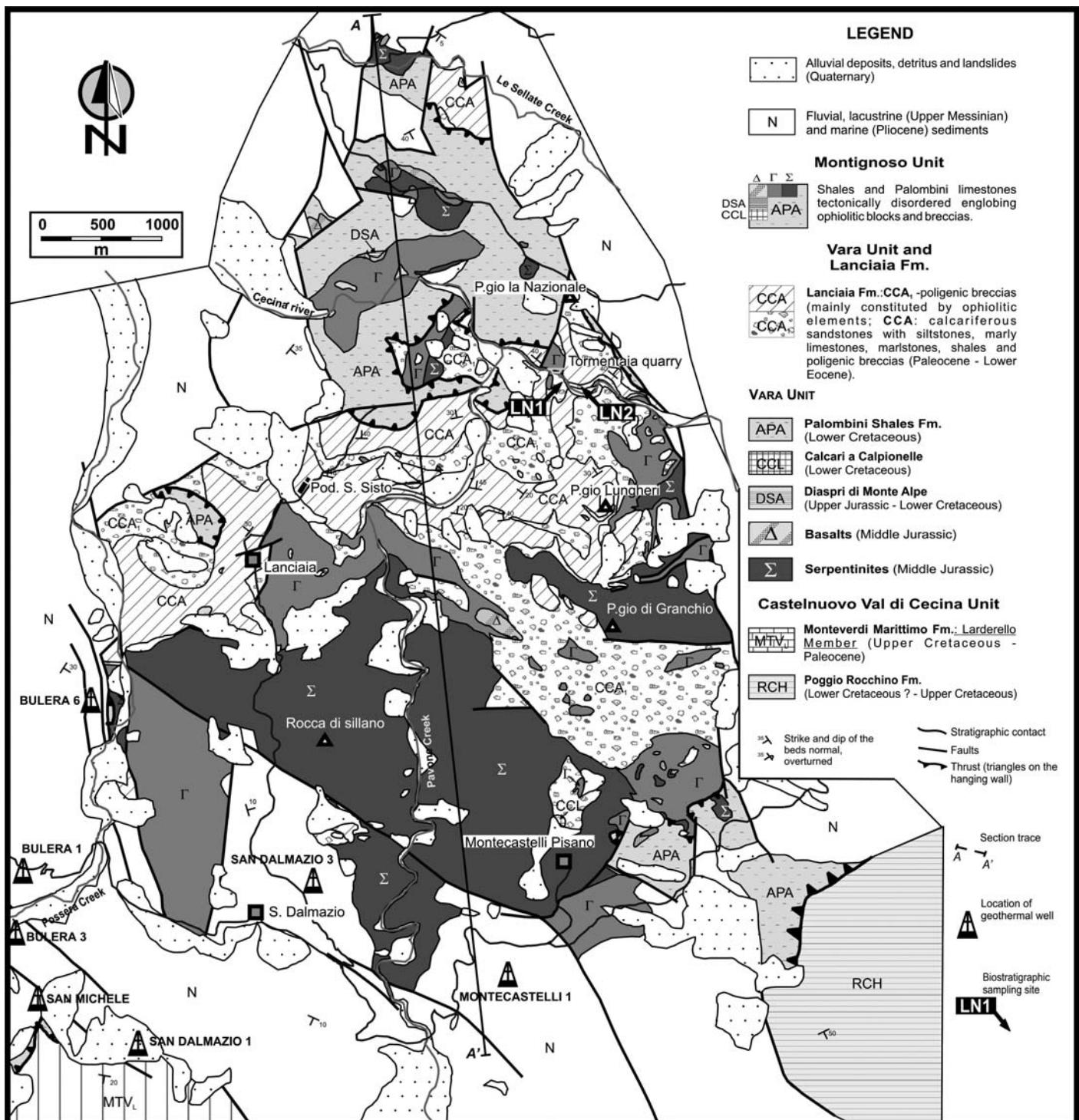


Fig. 10 - Geological map of Lanciaia-Montecastelli Pisano area.
– Carta geologica dell'area di Lanciaia-Montecastelli Pisano.

1976; LAZZAROTTO, 1966; MAZZANTI, 1966; GIANNINI & LAZZAROTTO, 1972) and calcareous nannoplankton (MARINO, 1988; MARINO & MONECHI, 1994). Marly intercalations within the basal ophiolitic breccias in the Tormentaia Quarry section along the Cecina River show Late Paleocene nannofossil associations (zone CP8 after OKADA & BUKRY, 1980; GARDIN IN DE SIENA, 1992; tab. 6). Some marly clasts included in the same breccias are characterized by a Middle-Late Campanian nannofossil

association (zone CC20 after SISSINGH, 1977; GARDIN IN DE SIENA, 1992; tab. 6) which suggests that it derives from the Monteverdi M.m. Fm. of a tectonized inner paleogeographical area (DE SIENA, 1992).

Except some gentle wide-angle folds, no important deformations are observable in the Lanciaia Fm. The bed dip never exceeds 35°, and no reverse attitudes have ever been found. In some cases deformed layers with isoclinal folds and ophiolitic blocks embedded in undeformed strata

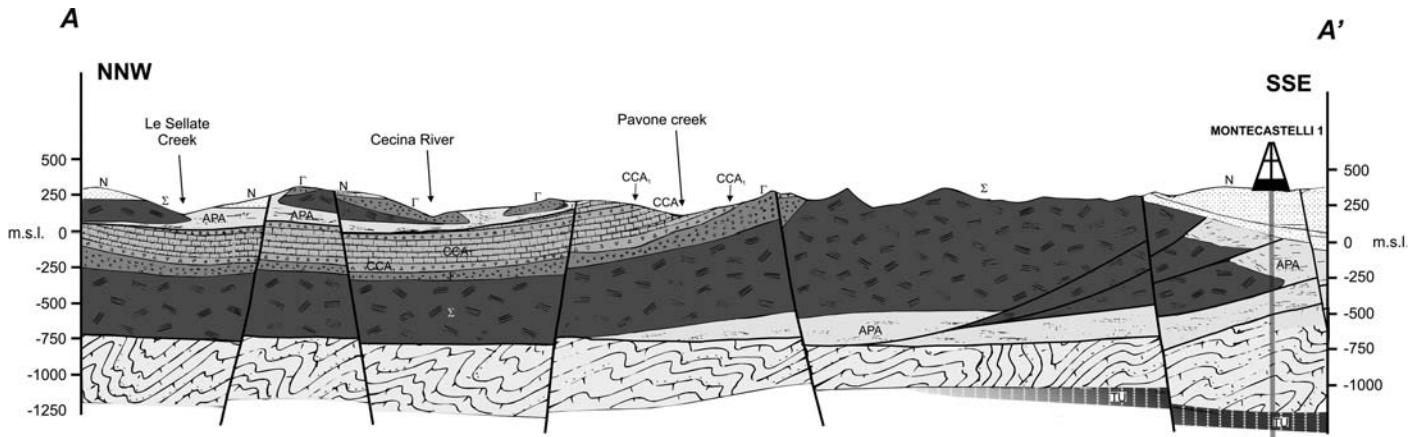


Fig. 11 - Geological cross section across the Lanciaia-Montecastelli Pisano area.
– Sezione geologica dell’area di Lanciaia-Montecastelli Pisano.

have been observed. These deformations are probably related to intraformational slumping linked with the emplacement of the ophiolitic olistoliths (DE SIENA, 1992).

Montignoso Unit

The lithological and structural features of this unit are quite similar to those observed in areas already considered. The recognizable folds do not show any preferential distribution. The nature of the contacts between the Palombini Shales and the enclosed ophiolitic bodies is difficult to establish, but the greater part of these seem to be tectonic.

PETROGRAPHICAL DATA

To investigate the relationship between turbiditic sedimentation and ophiolitic inputs, a preliminary petrographical study on the Montaione Member of the Montevertide M.m. Fm. was carried out. A detailed analysis was made using a storage and management data-processing system (CIPRIANI *et alii*, in press). This was applied to 18

thin sections from sandstone samples collected at the base of the turbiditic beds in the Montaione Member cropping out at Montaione (9 samples) and Sassa (9 samples).

The data from the two areas were tabulated on ternary (DICKINSON *et alii*, 1983) and binary diagrams (CHIOCCHINI & CIPRIANI, 1992; CHIOCCHINI & CIPRIANI, 1996) and show a similar composition (fig. 12). The only difference is the higher quartz content, and in particular quartz without undulatory extinction (fig. 12b) in the Sassa samples, which could be connected to the well-known Neogene silicification effect in this area (e.g. Pseudofilone of Sassa, LOTTA, 1910; MAINERI, 1991; BALDI *et alii*, 1995).

Moreover, two distinct petrofacies are recognizable in the ternary diagrams (fig. 12a; NIRTA, 2002). The first one comprises well-sorted arkose with low ($Q/F \leq 1$) to medium ($Q/F > 1$) compositional maturity; the low proportion (< 15%) of lithic fragments derives from lowgrade metamorphic rocks (phyllites) and siliciclastic rocks (siltstones). The second petrofacies is represented by poorly sorted sandstones with an evident and variable (in quantity) lithic component and scarce compositional maturity;

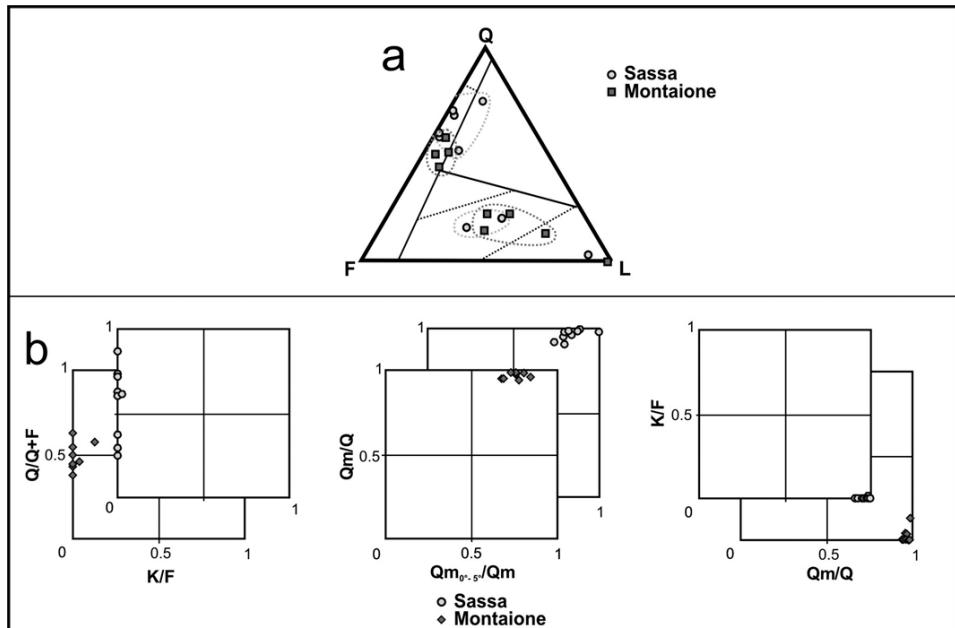


Fig. 12 - Petrographical data on the Montaione Member (Sassa and Montaione areas): a) ternary diagram; b) binary diagrams. Q: quartz, F: feldspar, L: lithic, Qm: monocrystalline quartz, Qm₀₋₅: monocrystalline quartz without undulatory extinction (< 5°).

– Dati petrografici nel Membro di Montaione (aree di Sassa e Montaione): a) diagramma ternario; b) diagrammi binari. Q: quarzo, F: feldspato, L: litici, Qm: quarzo monocristallino, Qm₀₋₅: quarzo monocristallino senza estinzione ondulata (< 5°).

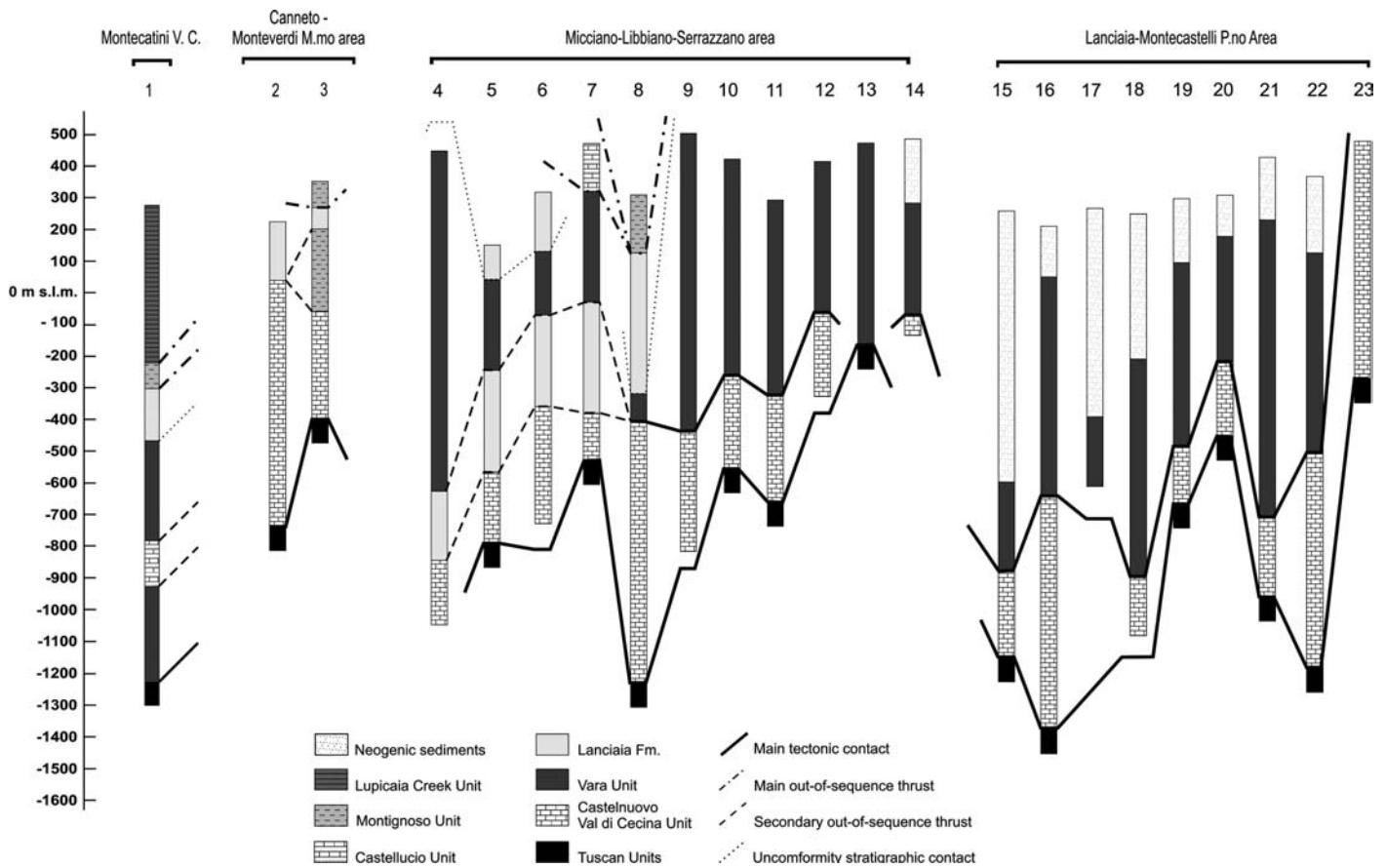


Fig. 13 - Correlations between the Ligurian Units crossed by wells in geothermal region. Wells: 1) Montecatini1; 2) MV7; 3) MV5; 4) Zolfara2; 5) Rimonese; 6) Farneta1; 7) Monterufoli; 8) Le Sughere; 9) 153; 10) Mandriolo; 11) Miniera2; 12) 122 S. Ippolito; 13) 118; 14) 117 Segarelli; 15) Bulera2; 16) Bulera6; 17) Bulera5; 18) Bulera1; 19) Bulera3; 20) San Michele; 21) San Dalmazio; 22) Montecastelli1; 23) Mitigliano.

– Correlazioni tra le Unità Liguri attraversate dai sondaggi in zone geotermiche. Pozzi: 1) Montecatini1; 2) MV7; 3) MV5; 4) Zolfara2; 5) Rimonese; 6) Farneta1; 7) Monterufoli; 8) Le Sughere; 9) 153; 10) Mandriolo; 11) Miniera2; 12) 122 S. Ippolito; 13) 118; 14) 117 Segarelli; 15) Bulera2; 16) Bulera6; 17) Bulera5; 18) Bulera1; 19) Bulera3; 20) San Michele; 21) San Dalmazio; 22) Montecastelli1; 23) Mitigliano.

the lithic fragments are represented by (in order of abundance): serpentinites, siltstones, shales and limestones.

The arkosic petrofacies is related to broad and mature turbiditic systems, fed by crystalline rocks probably derived from a continental block in an erosional phase. On the other hand the litharenitic petrofacies represents the dismantling of ophiolitic highs near to the flysch basin, and is compositionally similar to the olistolith and olistostrome bodies present in the Montaione Member.

Mixing between the two petrofacies is clearly observable in the QFL ternary diagram. This is partly due to a tractive reworking phenomenon caused by successive flows on already deposited materials.

DISCUSSION

The performed study allows the correlation of the different Cretaceous helminthoid flysch units of southern Tuscany from Monteverdi Marittimo to Western Monti del Chianti, which were defined in the past with different names in different outcrop areas. In particular we group all these units into a single formation, i.e. the Monteverdi Marittimo Fm., which is divided into three members: the Larderello Member, the Montaione Member and the S. Donato Member. Biostratigraphical data point to a

Lower-Middle Campanian to Lower Maastrichtian age for the Montaione Member, and an Upper Santonian-Upper Maastrichtian/Lower Paleocene age for the Larderello and S. Donato Members (MARINO, 1988; MARINO & MONECHI, 1994; GARDIN *et alii*, 1994; fig. 2). In agreement with LAZZAROTTO & MAZZANTI (1964, 1976) and LAZZAROTTO *et alii* (1990), the shaly-siltose formation of Upper Cenomanian-Turonian age (*Shales, Siltstones and Calcarenites with Pithonella; Poggio Rocchino Shales and Limestones*: COSTANTINI *et alii*, 1993; LAZZAROTTO *et alii*, 2002; MARINO & MONECHI, 1994) that crops out south of Monteverdi Marittimo and east of Montecastelli Pisano (COSTANTINI *et alii*, 2002b), has been referred to the basal complex of the Monteverdi Marittimo Fm. (Poggio Rocchino Fm. in this paper) as well as the similar succession present at the base of the S. Donato Member in the S. Donato-S. Agnese area. The Larderello Member is a typical helminthoid flysch of the Northern Apennines, made up of turbiditic beds consisting of basal calcarenous or calcareous sandstone passing upwards into marly limestone, marls and shales. The Montaione Member differs from the former in the greater content of arenaceous lithotypes and the presence of olistostromes and ophiolitic olistoliths. The S. Donato Member (SAGRI, 1969b) is characterized by a low S/P ratio and by ophiolitic-grain-free, thinly bedded turbidites.

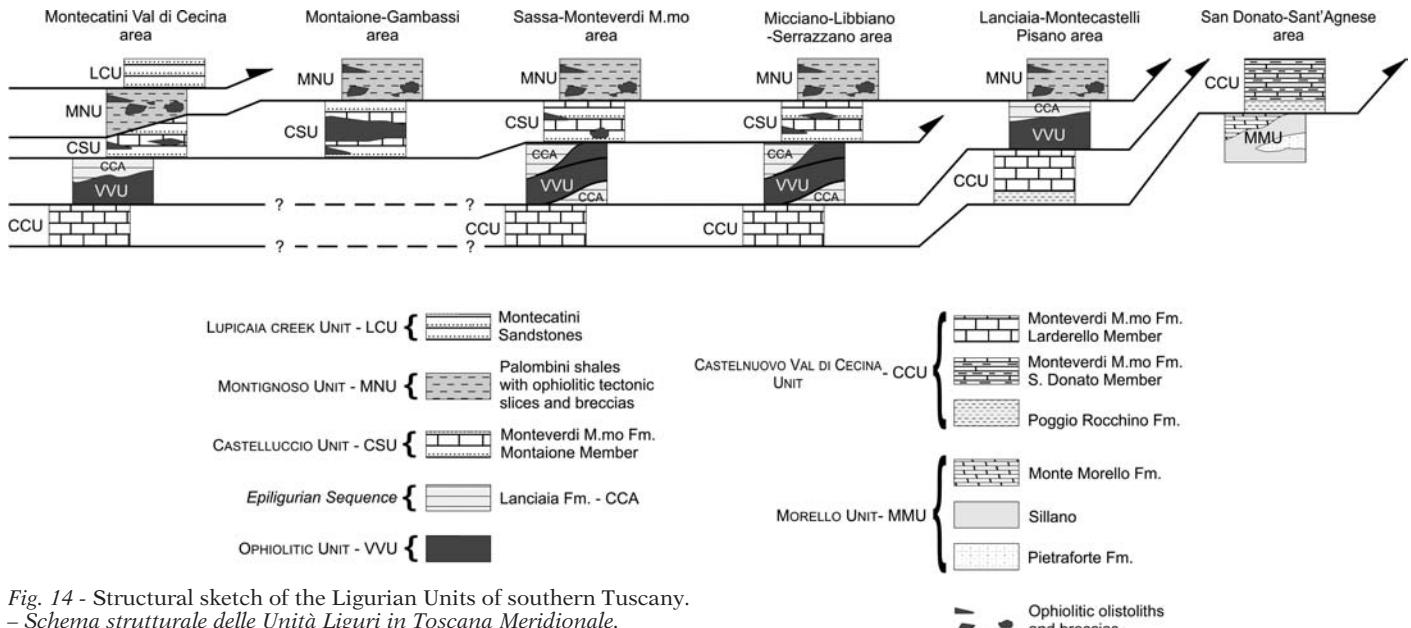


Fig. 14 - Structural sketch of the Ligurian Units of southern Tuscany.
– Schema strutturale delle Unità Liguri in Toscana Meridionale.

On the basis of the sedimentological features, the Montaione and Larderello members can be related to the central part of the turbiditic system while the S. Donato Member represents the fringe area (SAGRI, 1969b). Moreover, the huge ophiolitic detrital input in the Montaione Member suggests that its deposition was close to a tectonically active ophiolitic relief. Considering the absence of ophiolitic inputs in the Larderello and S. Donato members and the tectonic piling of the units, the ophiolitic ridge can be paleogeographically positioned to the present W-NW of the Montaione Member outcrops.

The grouping of the Cretaceous helminthoid flysches of southern Tuscany was proposed by SAGRI (1969b), who referred them to the M. Antola Fm. of the Ligurian Apennines. But biostratigraphical and paleocurrent data suggest that the flysches of southern Tuscany and of Liguria belong to different depositional systems (see also GARDIN *et alii*, 1994). In fact, the helminthoid flysches of the Ligurian and Ligurian-Emilian Apennines have a younger age (RIO & VILLA, 1983 and 1987; RIO *et alii*, 1983; GENNA, 1988; MANIVIT & PROUD'HOMME, 1990; CERRINA FERONI *et alii*, 1991) and different source areas (NW for the former and WSW for the latter unit, SAGRI 1969a,b) compared with the southern Tuscany helminthoid flysches.

The ophiolitic detrital input in the helminthoid basin is also shown by the petrographical analyses carried out on the Montaione Member. These analyses reveal the presence of two petrofacies: one is represented by arkoses characterized by medium compositional maturity and continental supply (compositionally similar to the Upper Cretaceous-Paleocene arenaceous flysch of the IL: e.g. Gottero, Ghiaieto and Montecatini sandstones), while the other is represented by low maturity litharenites derived from the dismantling of an ophiolitic high.

In the Micciano-Libbiano-Serrazzano and Lanciaia-Montacastelli Pisano areas, the unconformity between the Vara Unit and the overlying Epiligurian Lanciaia Fm. is confirmed by our data. The basin in which the Lanciaia Fm. was deposited originated not later than the Upper Paleocene (zone CP8; OKADA & BUKRY, 1980).

In the Sassa-Canneto area and in the subsurface of the Micciano-Libbiano-Serrazzano area (data from geothermal wells) the Lanciaia Fm. is tectonically interposed between the Vara and the Castelnuovo Val di Cecina Unit.

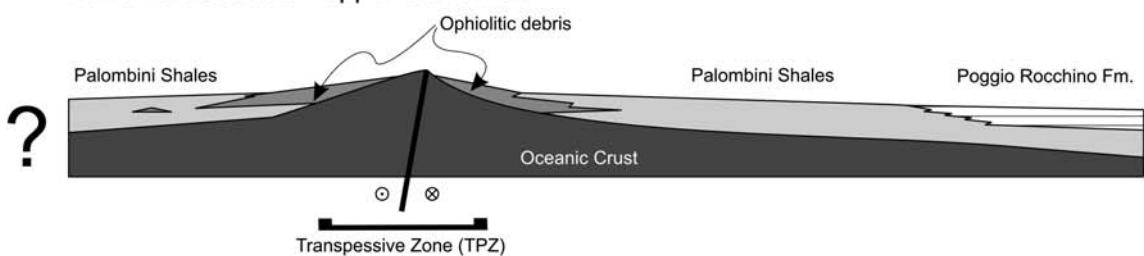
The structural surveys performed in the field integrated with the borehole data (fig. 13) allow us to refer the Ligurian terrains to five main tectonic units (fig. 14). From bottom to top of the Ligurian tectonic pile they are: (i) the Morello Unit (ii) the Castelnuovo Val di Cecina Unit, (iii) the Vara Unit and Lanciaia Fm., (iv) the Castelluccio Unit, (v) and the Montignoso Unit. Moreover, the Lupicaia Creek Unit can be distinguished at the top of the Ligurian tectonic stack in the Montecatini Val di Cecina zone, but also in isolated outcrops south of the Montaione-Gambassi area (MACCANTELLI, 1994; COSTANTINI *et alii*, 2002a).

The Castelluccio, Lupicaia Creek and Montignoso units have been emplaced, from an internal position, on to the other LU through out-of-sequence thrusts of regional importance. However, for the Montignoso Unit a gravitational emplacement from the inner to the external area cannot be excluded. The tectonic setting of this unit (made up of ophiolitic rocks enclosed in the Palombini Shales) and the poorly preserved outcrops hamper a more precise analysis. Nevertheless, in a few outcrops in the Montaione-Gambassi area, sedimentary relationships between pelagic Palombini Shales and ophiolitic ololiths and breccias are also observable.

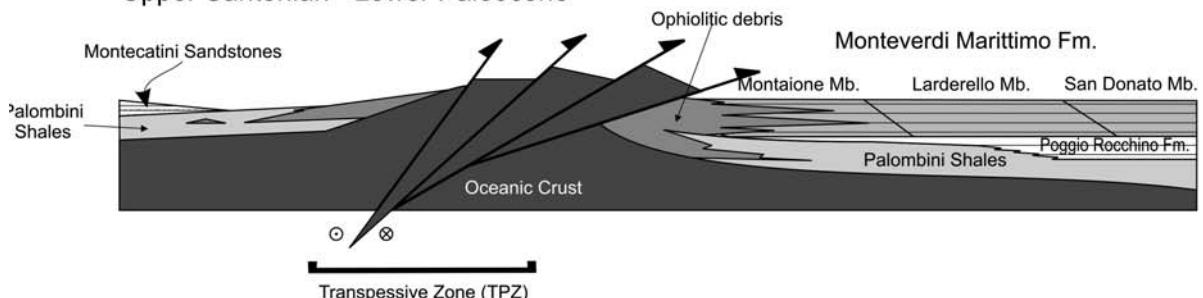
Further structural complications, also evidenced by the wells in the Larderello geothermal area, are related to minor out-of-sequence thrusts. This is the case of the overthrusting of the Vara Unit on to the Lanciaia Fm. This thrust, aligned WSW-ENE in the Sassa area (Botro del Rivivo), pre-dated the emplacement of the Castelluccio and Montignoso units.

Two folding phases are recognized in the studied areas. The oldest phase documented at any scale is characterized by close to isoclinal folds whose axes are WSW-ENE oriented and SSE-vergent. This is also the alignment of the already mentioned out-of-sequence thrust involving the Lanciaia and the Vara Unit, as well as of the major morphostructural elements recognizable in the Ligurian

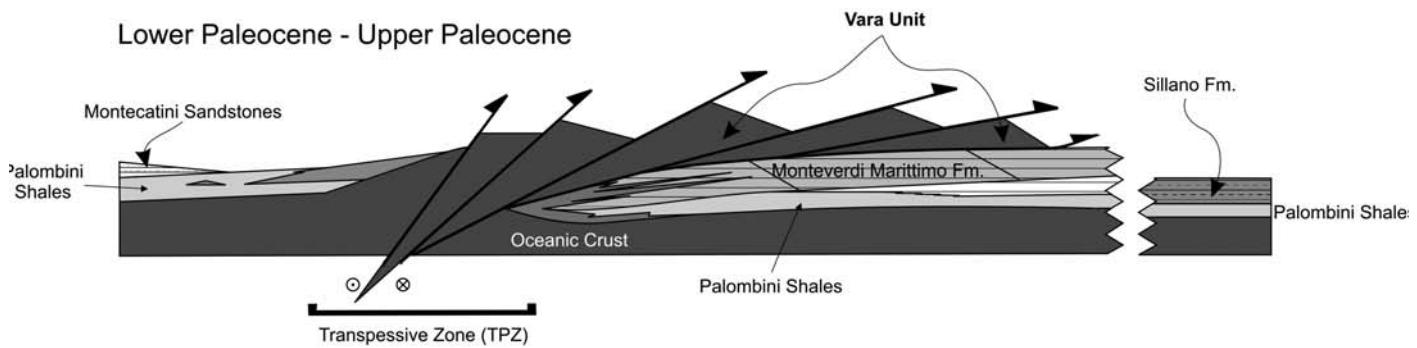
Lower Cretaceous - Upper Santonian



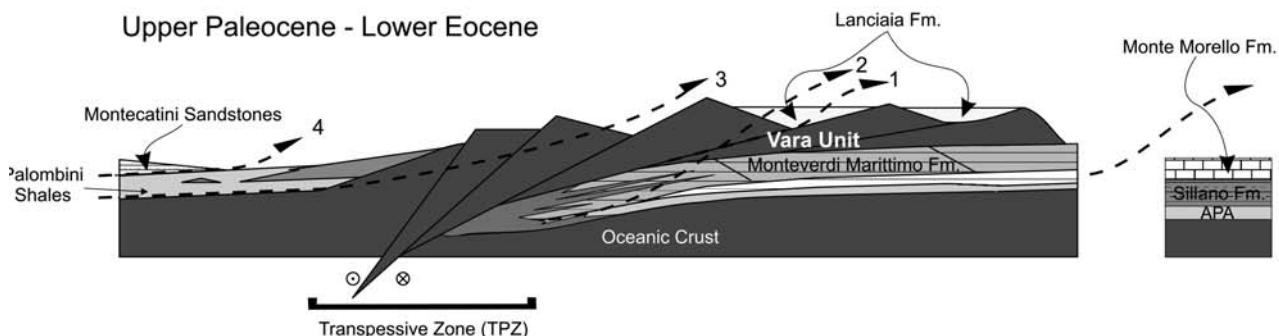
Upper Santonian - Lower Paleocene



Lower Paleocene - Upper Paleocene



Upper Paleocene - Lower Eocene



Middle/Upper Eocene - Lower Miocene

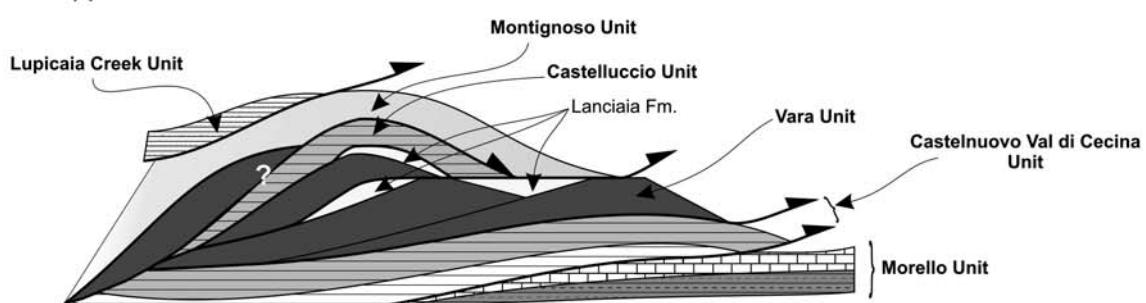


Fig. 15 - Sedimentary-tectonic evolution of the Ligurian Unit in southern Tuscany.
- Evoluzione tettonica e sedimentaria delle Unità Liguri in Toscana Meridionale.

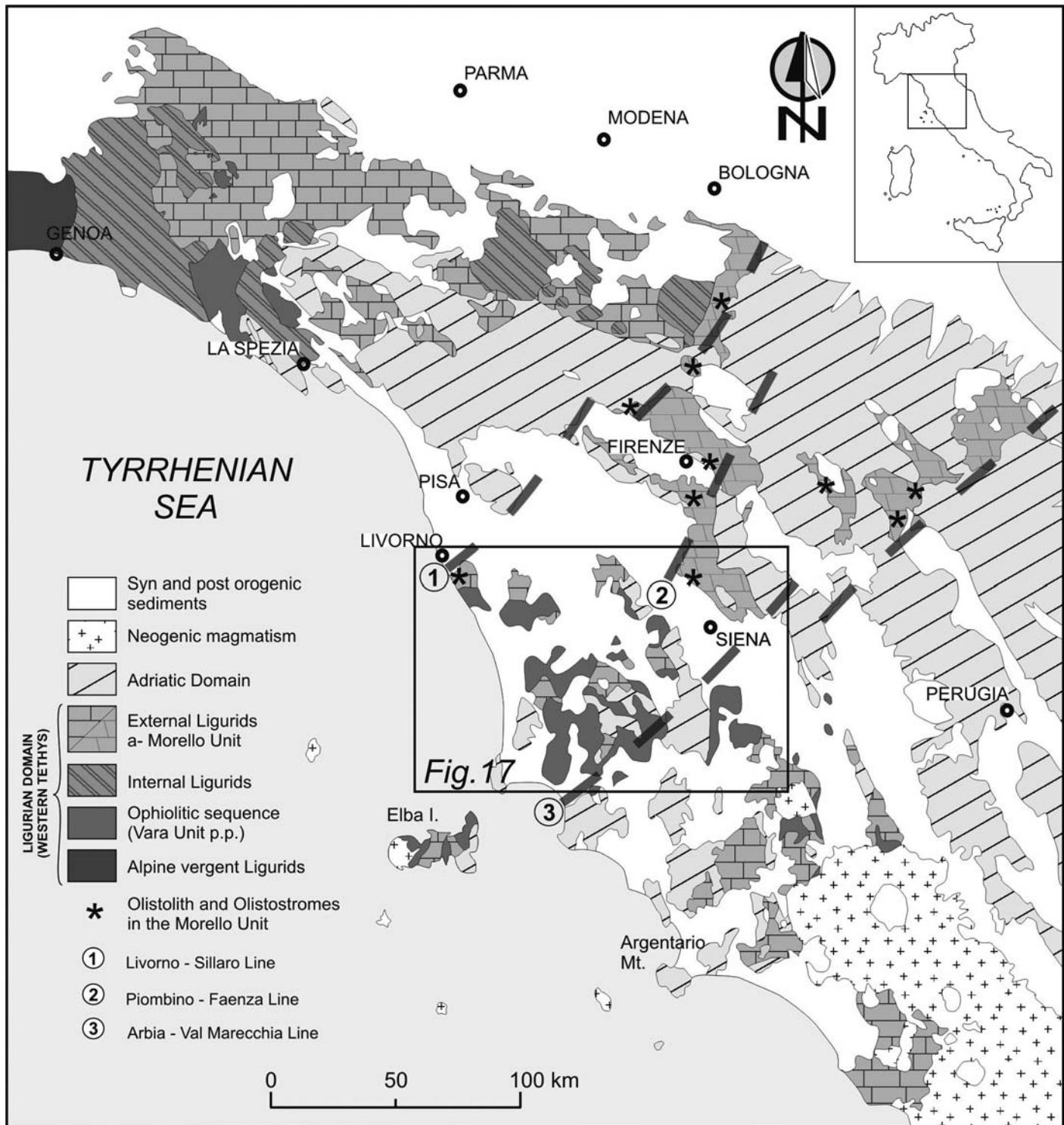


Fig. 16 - Relationships between the Livorno-Sillaro, Piombino-Faenza and Arbia-Val Marecchia tectonic lines, the distribution of the Monte Morello Unit and of the ophiolitic debris therein.
 - Relazioni tra le linee tectoniche Livorno-Sillaro, Piombino-Faenza e Arbia-Val Marecchia, l'ubicazione degli affioramenti dell'Unità Morello e del detritismo ophiolitico in essa presente.

Units in the studied areas (main thrusts, geographical distribution of tectonic units, olistolith alignment, etc.). This tectonic alignment is not recognizable in the Tuscan Units and in the Neogene deposits. The younger tectonic folding phase is represented by decimetre- to kilometre-scale fold structures from open to close in shape, with NW-SE ori-

ented axes and NE-vergence. These latter tectonic deformations affect all the tectonic units in the studied areas.

Although the relationships between the two fold families are not clearly visible in the field, the absence of the WSW-ENE oriented event in the Tuscan Units and in the Neogene deposits (COSTANTINI *et alii*, 1993; CERRINA

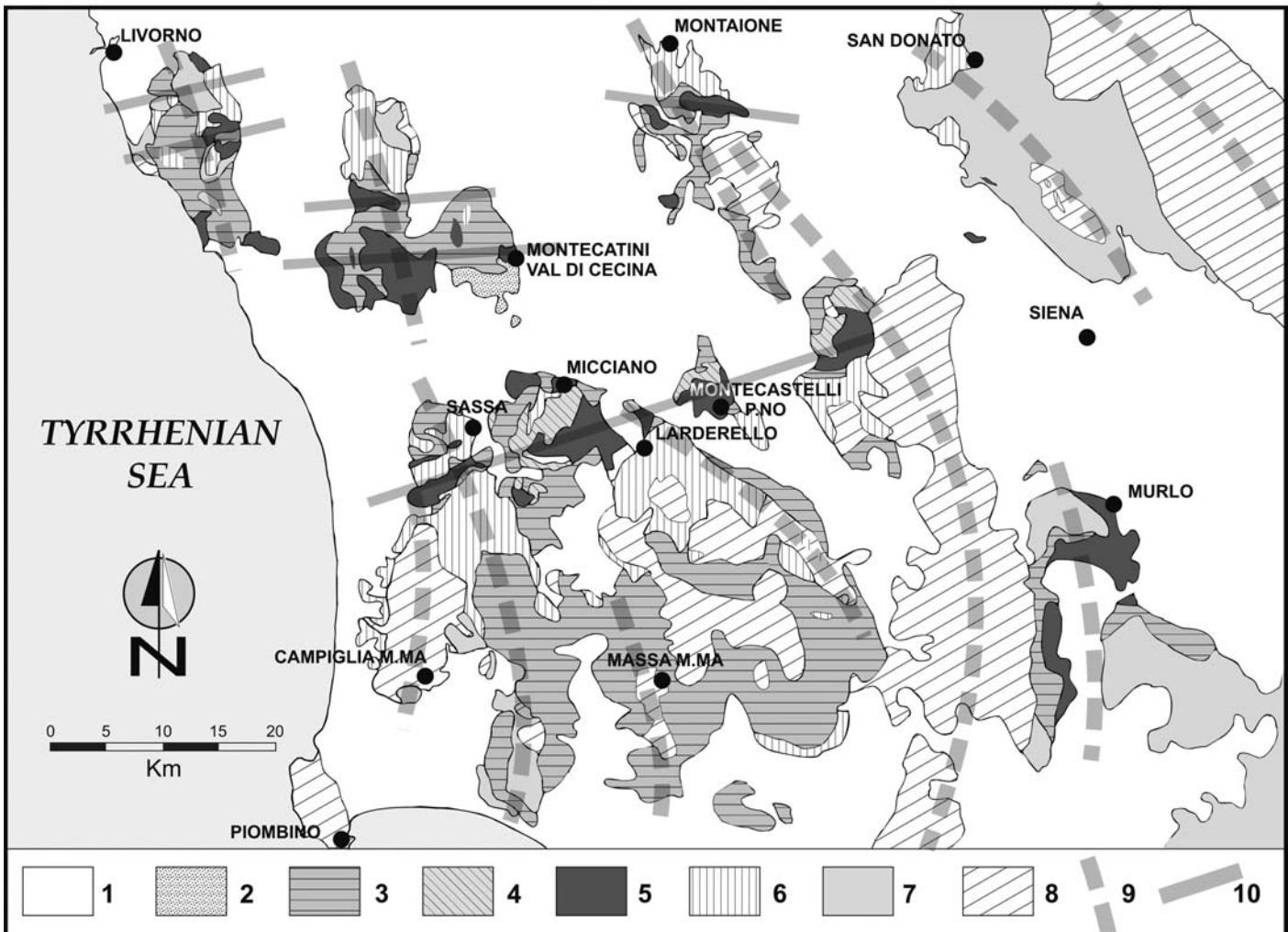


Fig. 17 - Main apenninic and antiapenninic structural features in southern Tuscany. 1) Neogene-Quaternary sediments; 2) Lupicaia Creek Unit; 3) Montignoso Unit; 4) Lanciaia Fm.; 5) ophiolites (Vara Unit p.p.); 6) Castelnuovo Val di Cecina Unit; 7) Morello Unit; 8) Subligurian and Tuscan Units; 9) inferred Apenninic structural alignments; 10) inferred antiapenninic structural alignments.

– Principali lineamenti tectonici appenninici e anti-appenninici in Toscana Meridionale. 1) sedimenti neogenici-quaternari; 2) Unità del Torrente Lupicaia; 3) Unità di Montignoso; 4) Formazione di Lanciaia; 5) ophioliti (Unità Vara p.p.); 6) Unità Castelnuovo Val di Cecina; 7) Unità Morello; 8) Unità Subliguri e Toscane; 9) lineamenti strutturali appenninici dedotti; 10) lineamenti strutturali anti-appenninici dedotti.

FERONI *et alii*, 1989, 2004), the stronger tectonic effects and the major frequency in comparison with NW-SE orientated events lead us to consider the former as representative of the main tectonic event, and the latter as part of a subsequent secondary event.

This structural situation differs from that characterizing the tectonic units of the Ligurian and Tuscany-Romagna Apennines, where the main structures show the typical NW-SE orientation, parallel to the Apennine chain (Apenninic trend). This situation can be related to a complex structural evolution that, during the early shortening phases, favoured tectonic transport from the NNW towards the SSE (with actual references), thus creating structures perpendicular to Apennine chain (anti-Apenninic trend). These were re-elaborated by a later folding event with Apenninic orientation.

In order to explain this anomalous situation, this paper proposes a palinspastic reconstruction that takes into account transpressional lineaments which may have affected the tectonic evolution of the oceanic basin, thus creating atypical structural orientations (ABBATE *et alii*,

1980; MARCUCCI *et alii*, 1982; VESCOVI, 1993; FAZZINI & GARDIN, 1994; MARRONI & TREVES, 1998). During the closure phase in some sectors of the Ligurian-Piedmontese Ocean, the role of subduction was probably attenuated by transpressional reactivation of oceanic transforms perpendicular to the continental margins (FAZZINI & GARDIN, 1994). Successively, during the tectonism accompanying continent-continent collision, subduction prevailed by imprinting the previous structures with a NE-SW Apenninic tectonic orientation.

Clearly, from a geodynamic point of view, other sectors of the Apennine orogen must be examined in order to validate or rule out this hypothesis. In any case, the collected data allow us to define a preliminary model of the tectono-sedimentary evolution of the LU in this sector of the Northern Apennines (see the reconstructions in fig. 15).

LOWER CRETACEOUS-UPPER SANTONIAN

In this period the oceanic basin was clearly dominated by the shaly-silty sedimentation represented by the

Palombini Shales. By the beginning of the Upper Cretaceous, the sedimentation was already affected by the first compressional pulses, as testified by the presence of ophiolitic breccias in the upper part of the Palombini Shales belonging to the Montignoso Unit. This detrital input probably derived from the oceanic transform faults successively activated as transpression zones (ABBATE *et alii*, 1980). These lineaments were NW-SE oriented (with paleogeographical references), almost perpendicular to the ocean margins (ABBATE & SAGRI, 1982).

Ophiolitic input is instead absent in the sedimentation area of the Poggio Rocchino Fm. (Cenomanian-Turonian); this can therefore be positioned in a distal area with respect to the ophiolitic inputs. In any case, it is probable that the Poggio Rocchino Fm. is heteropic with the coeval portion of the Palombini Shales.

UPPER SANTONIAN-LOWER PALEOCENE

Between the upper Santonian and lower Campanian, the deposition of the Monteverdi Marittimo Fm. took place. The emplacement of ophiolitic material, locally of great size (e.g. Poggio della Forra Olistoliths in the Montaione-Gambassi area), occurred in the Montaione Member. The ophiolitic source was probably an intraoceanic transpressional structure, such as for the Palombini Shales of the Montignoso Unit.

In a more internal sector the sedimentation of the Montecatini Sandstones began in the Maastrichtian. These probably derive from the erosion of the Corsica-Sardinia margin, similar to the scenario hypothesized for the siliciclastic flysches of the IL (e.g. Gottero Sandstones; Ghiaieto Sandstones). BERTINI *et alii* (2000) reported some ophiolitic olistostromes and olistoliths within these sandstones, in the Montecatini Val di Cecina zone. Nevertheless, observations carried out as part of this study in the Montecatini Val di Cecina area did not confirm this report, and in general the sandstones do not contain ophiolitic grains.

LOWER PALEOCENE-UPPER PALEOCENE

In this period an important compressional event led to the tectonic superposition of the Vara Unit on the basin of the Monteverdi Marittimo Fm. The main deformations observed in the Monteverdi Marittimo Fm. and the tectonization of the Vara Unit can be ascribed to this time interval.

UPPER PALEOCENE-LOWER EOCENE

The superposition of the Vara Unit on the Castelnuovo Val di Cecina Unit is sealed by the sedimentation of the Lanciaia Fm. starting from Upper Paleocene-Lower Eocene times (MACCANTELLI & MAZZEI, 1993; LAZZAROTTO *et alii*, 1995). The deformation of the Lanciaia Fm. is much less than that of the underlying units (e.g. Vara and Castelnuovo Val di Cecina Units). The Lanciaia Fm. was deposited on an already largely deformed substratum with an uneven morphology which was tectonically unstable as suggested by synsedimentary slumps and by the abundant inputs of coarse ophiolitic material (piggy-back basin). Taking into account the geometric stacking of the LU, the structural observations and the geographical distribution of the Lanciaia Fm., the sources

of the detrital ophiolitic input can be inferred to be in the northwestern quadrants. Breccia bodies are mainly present at the base of the formation, levelling out the bottom morphology, and thus showing greater thickness in the more depressed zones and less thickness (or absence) in the higher zones. Besides the ophiolitic clasts, the middle-upper Campanian marly clasts found in the breccias suggest that, in the environs of the Lanciaia sedimentation basin, an Upper Cretaceous flyschoid unit (i.e. the Monteverdi Fm.) was also tectonized.

From Upper Paleocene-Lower Eocene times the instability of the Lanciaia Basin increased, breccia levels became common in the higher portion of the formation, and sedimentation was coming to an end.

MIDDLE/UPPER EOCENE-LOWER MIocene

After the end of the Lanciaia Fm. sedimentation, the compressional climax resulted in thrust surfaces, which led to a doubling the Vara-Lanciaia Fm. succession. This situation can actually be observed at the surface only in the Canneto-Sassa area (Botro del Rivivo), but was confirmed in the subsurface by Enel surveys (fig. 13). Successively later out-of-sequence thrusts occurred (Castelluccio Unit, Montignoso Unit and Lupicaia Creek Unit). In fact, the Montaione Member (Castelluccio Unit) and the Larderello Member (Castelnuovo Val di Cecina Unit) show two very different structural positions: the former is high in the pile of the LU and the latter is in the deepest position, but always below the Vara Unit. This situation can be explained by the effect of a late out-of-sequence thrust of the Montaione Member, which was settled into a higher structural position just after the thrust of the Vara Unit (COSTANTINI *et alii*, 1993; BERTINI *et alii*, 2000). Nevertheless, the superposition of the Vara Unit on to the Castelluccio Unit is never documented, either at the surface or at depth. So the Montaione Member (differently from the Larderello Member) was never thrust by the Vara Unit; in this hypothesis the geometry of the present superposition could be the result of a complex evolution, linked to the effects of the transpressional tectonics.

The Castelluccio Unit thrust is observable in the Sassa, Micciano-Serrazzano, Castellina Marittima and Montaione areas, while it does not occur in the Monte-castelli Pisano-Lanciaia area, where, in fact, the Lanciaia Fm. is affected only by the thrust of the Montignoso Unit. This is also supported by the gentle monoclinal tectonic setting of the Lanciaia Fm. in this area (DE SIENA, 1992). Instead the Montignoso Unit thrust is ubiquitous at a regional scale.

Only in the area of Castellina Marittima is another late out-of-sequence thrust observed through which the Montecatini Sandstones (Lupicaia Creek Unit) lie on the Montignoso Unit. In the same time span, in the more external sectors, the Castelnuovo Val di Cecina Unit thrust on to the Morello Unit.

During the Lower-Middle Miocene, an extensional tectonic regime, associated with the Tyrrhenian Basin opening, dominated in this sector of the Northern Apennines, first through a ramp-flat-ramp low-angle faulting event (Lower Miocene-upper Tortonian) and then a high-angle normal faulting event (BALDI *et alii*, 1994; BERTINI *et alii*, 1991; DECANDIA *et alii*, 2001). This composite polyphase tectonics strongly modified the geometric relationship between the LU.

During the Neogene, compressional tectonics continued to play an important role, as shown by the shortening deformations recorded in the Neogene deposits of southern Tuscany (BERNINI *et alii*, 1992; BONINI *et alii*, 2001; BONINI & SANI, 2002).

CONCLUSIONS

The data obtained by interdisciplinary studies carried out on the LU improve our knowledge of the geology of the Ligurian structural pile and its structural evolution in the zone crossed by the CROP-18 seismic profile.

The sedimentological, petrographical and biostratigraphical analyses allow us to ascribe the Cretaceous helminthoid flysches cropping out south of the Arno River to a single formation (Monteverdi Marittimo Fm.). Moreover, structural observations on the outcropping units and the data from geothermal wells allow the subdivision of the LU into five main imbricated units (Morello Unit, Castelnuovo Val di Cecina Unit, Vara Unit and Lanciaia Fm., Castelluccio Unit, Montignoso Unit). In these units (WSW-ESE) peculiar structural alignments have been recognized; they lead to the hypothesis that transpressional structures formed along pre-existing lines of weakness (oceanic transforms). Therefore the subduction played a secondary role in the evolution of this sector of the Apennines, and probably fully acted only during the Eocene phases of ocean consumption.

Moreover, with the beginning of the ensialic phase of the orogenesis, the transverse structures which led to the piling-up of the LU in this sector of the Apennines were likely to have been inherited as passive elements, which affected the different sectors of the chain with different movement rates (e.g. Livorno-Sillaro and Arbia-Val Marecchia line; fig. 16; BORTOLOTTI, 1966; LIOTTA, 1991; FAZZINI & GARDIN, 1994; BARTOLE, 1995).

To verify this hypothesis, further studies are required, but it is interesting to note: (a) the parallelism existing among these lines and the structural orientation of the LU in the studied area (fig. 17); (b) the occurrence of ophiolitic detritus in the Morello Unit just along these lines (Monti Livornesi, Figline di Prato and Barberino del Mugello along the Livorno-Sillaro line; Monti Rognosi-Pieve Santo Stefano along the Arbia-Val Marecchia Line; fig. 16).

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