The sub-Ligurian and Ligurian units of the Mt. Amiata geothermal Region (south-eastern Tuscany): new stratigraphic and tectonic data

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The sub-Ligurian and Ligurian units of the Mt. Amiata geothermal region (south-eastern Tuscany): new stratigraphic and tectonic data and insights into their relationships with the Tuscan Nappe

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ABSTRACT

A new geological survey and micropaleontological and petrographical studies were performed on the Ligurids l.s. in the Montalcino-Mt. Amiata area. The relationships between the Ligurids l.s., the Tuscan Nappe and the underlying Triassic-Paleozoic succession of the crystalline basement were also defined in the outcrops and at depth using data from ENEL deep geothermal wells. The results improve the stratigraphic and structural framework of southeastern Tuscany crossed by the southern transect of the CROP-18 profile. In particular, three main units have been distinguished within the Ligurids l.s. (from the geometric bottom to top): (*a*) the *Canetolo Unit (or Sub-Ligurian Unit*, ?Paleocene-Eocene), represented by dark grey to green shales with grey calcilutite and calcarenite beds, locally with K-feldspar-free, more or less calcareous sandstone intercalations; (*b*) the *Santa Fiora Unit,* consisting of a complex pile of tectonic elements made up of Cretaceous successions and, in particular, a dominant marly-calcareous flysch with local Pietraforte-like intercalations (Santa Fiora Formation) and of the siliciclastic turbiditic Pietraforte Fm. with its basal shaly-silty lithofacies (Manganesiferous Varicoloured Shales Fm.); (*c*) *Ophiolitiferous Unit,* mostly represented by often chaotic shales with siliceous limestone intercalations and quartz-arenites of Lower Cretaceous age (Palombini Shales Fm), which locally include ophiolitic olistoliths (mostly serpentinites locally associated with ophicalcites and ophiolitic breccias), Lower Cretaceous Murlo-like marls and Albian-Turonian olivine-basalt dykes, sills and pillow-lavas. The tectonic setting of the Ligurian, Sub-Ligurian and Tuscan units in the Mt. Amiata area is similar to that in southern Tuscany. In particular, the performed studies indicate a complex tectonic evolution which mostly occurred in the Lower Miocene to Pliocene time interval and including the following events: (1) syn-collisional and «serrage» folds and stacking of the units (Early Miocene-Middle Miocene); (2) tectonic lamination of the Tuscan Nappe (the so-called «Reduced Tuscan Sequence») and of the overlying Ligurian l.s. stack in the Serravallian-Lower Tortonian; (3) development of the intramontane continental to marine basins (Upper Miocene-Pliocene) and of high-angle faulting. A tectonic doubling of the Tuscan Nappe (recently defined also in other parts of the Mt. Amiata region and, further to the west, in the Larderello-Travale geothermal field: see text) is suggested for the Tuscan inlier of Poggio Zoccolino, where an upper tectonic element of Triassic carbonates and evaporites overlies the Upper Triassic to Tertiary Tuscan succession. At least some of these doublings (e.g. the Poggio Zoccolino doubling), generally related to the main Late Oligocene-Early Miocene shortening, could have taken place during the Burdigalian-Lower Tortonian time interval during which the regional Tuscan Nappe Front (Mt. Orsaro-Lima Valley-Mts. Chianti-Mt. Cetona structural alignment) was originated and syn-tectonic extension took place in front of the main crustal thrusts (onset of the «Reduced Tuscan Sequence»). This event also produced doublings in the underlying crystalline Triassic-Paleozoic successions which probably belong to the Umbrian Domain. Since ?Upper Miocene-Pliocene times, this complex tectonic pile was dismembered by high-angle normal fault systems (which mainly strike NW-SE, NE-SW and N-S) and produced the growth of the Siena-Radicofani and the Baccinello morphological-structural depressions and of the Montalcino-Mt. Amiata-Mt. Razzano ridge. The uplift of the Montalcino-Mt. Amiata area continued in more recent times (e.g. the outcrops of Lower Pliocene sediments at about 500 m between Montalcino and Castelnuovo dell'Abate, and at about 1000 m in the M. Labbro area) and is probably connected to the magmatic processes of the Quaternary Mt. Amiata volcano.

KEY WORDS: *Northern Apennines, Mt. Amiata, Ligurids, Tuscan Nappe, stratigraphy, tectonics.*

RIASSUNTO

L'unità sub-ligure e le unità liguri dell'area geotermica del Monte Amiata (Toscana sud-orientale): nuovi dati stratigrafici e tettonici e loro rapporti con la Falda Toscana.

È stato effettuato un nuovo rilevamento geologico e analisi micropaleontologiche e petrografiche delle Liguridi s.l. affioranti nell'area tra Montalcino e il fianco meridionale del Monte Amiata. Inoltre sono state esaminate, sia in superficie che nel sottosuolo (dati derivanti dai sondaggi profondi eseguiti dall'Enel nei campi geotermici del M. Amiata), le relazioni strutturali tra le Liguridi s.l., la Falda Toscana e le sottostanti successioni metamorfiche del basamento. I dati ottenuti permettono di migliorare le conoscenze relative all'assetto stratigrafico-strutturale della Toscana sud-occidentale attraversata dal profilo sismico CROP18. Nelle Liguridi s.l. sono state riconosciute tre unità principali (dal basso verso l'alto): *a*) *Unità Canetolo (o Unità Sub-ligure,* ?Paleocene-Eocene), rappresentata da un'alternanza di argilliti da grigio scure a verdi con intercalazioni di calcareniti e calcilutiti grigie e, localmente, anche di arenarie calcaree prive di k-feldspato; *b*) *Unità Santa Fiora*, rappresentata da una complessa pila tettonica di elementi strutturali costituiti da successioni cretacee ed, in particolare, da un flysch prevalentemente calcareo-marnoso con locali intercalazioni arenacee (Formazione di Santa Fiora) e dalle torbiditi silicoclastiche della Formazione della Pietraforte con, alla base, una unità argillitico-siltosa (Formazione della Argilliti Varicolori Manganesifere); *c*) *Unità Ofiolitifera,* costituita principalmente da argilliti caoticizzate con intercalazioni di calcari silicei e quarzo-areniti del Cretaceo Inferiore (Formazione delle Argilliti a Palombini), include localmente olistoliti ofiolitici (in prevalenza serpentiniti associate ad oficalciti ed a brecce ofiolitiche), marne del Cretaceo Inferiore (simili alle Marne di Murlo), dicchi, filoni strato e pillow-lavas olivin-basaltici dell'Albiano-Turoniano. L'assetto tettonico delle unità liguri, Sub-ligure e toscane nell'area del Monte Amiata è simile a quello tipico della Toscana meridionale. In particolare, gli studi effettuati evidenziano una complessa evoluzione tettonica che ebbe luogo per la maggior parte tra il Miocene inferiore ed il Pliocene che include: 1) piegamenti sin-collisionale e tardo-collisionali e la sovrapposizione delle diverse unità (Miocene

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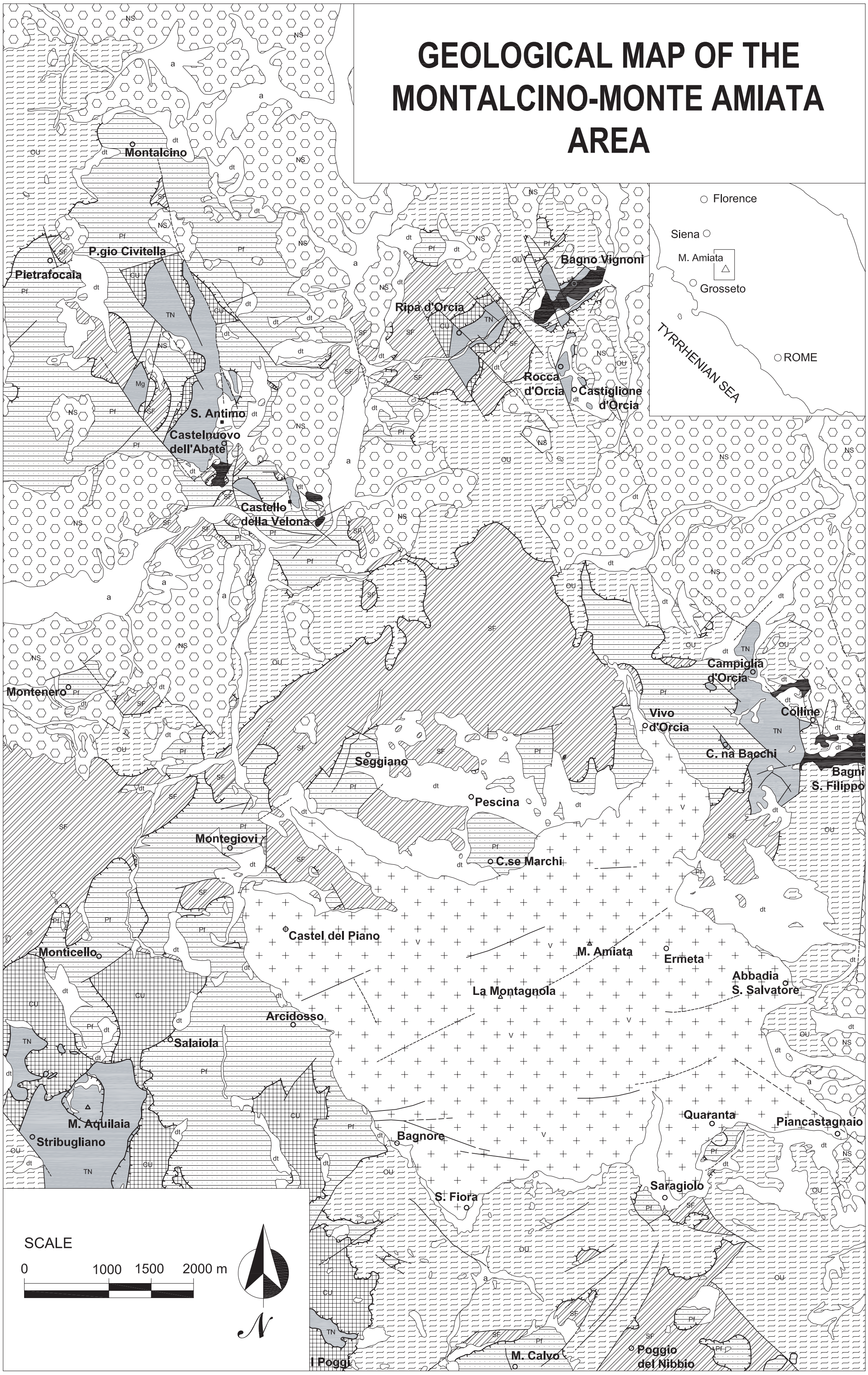


Fig. 1 - Geological sketch map of the Montalcino-Mt. Amiata area.
– *Carta geologica schematica dell'area tra Montalcino e il versante meridionale del M. Amiata.*

inferiore Medio); 2) la laminazione tettonica della Falda Toscana (la cosiddetta «Serie Toscana Ridotta») e delle sovrastanti liguridi s.l. nel Serravalliano-Tortoniano inferiore; 3) lo sviluppo di bacini intramontani da continentali a marini (Miocene superiore-Pliocene) e dei sistemi di faglie ad alto angolo. Un raddoppio tettonico della Falda Toscana (già definito anche in altre zone dell'area amiatina e, più ad ovest, nel Campo geotermico di Larderello-Travale: vedi testo) è stato riconosciuto anche per il nucleo a Serie Toscana di Poggio Zoccolino, dove un elemento tettonico superiore con carbonati ed evaporiti triassiche sovrasta la nota successione toscana di età Triassico superiore-Terziaria. Almeno alcuni di questi raddoppi (ad esempio quello di Poggio Zoccolino), generalmente riferiti all'evento principale sin-collisionale appenninico di età Oligocene superiore-Miocene inferiore, potrebbero invece essere avvenuti nell'intervallo temporale Burdigaliano-Tortoniano inferiore durante il quale si originò a scala regionale il Fronte della Falda Toscana (allineamento M. Orsaro-Val di Lima-Mt. del Chianti-M. Cetona) e fenomeni estensionali sin-tettonici ebbero luogo sul fronte dei principali accavallamenti tettonici crustali (inizio della formazione della «Serie Toscana Ridotta»). Questo evento produsse anche raddoppi nelle sottostante successioni metamorfiche del basamento che possono verosimilmente essere attribuite al dominio umbro. Dal ?Miocene superiore-Pliocene, questo complesso edificio tettonico fu smembrato da faglie ad alto angolo con direzione prevalentemente NW-SE, NE-SW e N-S che hanno prodotto lo sviluppo delle depressioni morfologico-strutturali di Siena-Radicofani e di Baccinello e della dorsale di Montalcino-Monte Amiata-Monte Razzano. Il sollevamento dell'area di Montalcino-Monte Amiata è continuata fino a tempi recenti (es. gli affioramenti di sedimenti del Pliocene inferiore sono stati sollevati a circa 500m tra Montalcino e Castelnuovo dell'Abate e fino a circa 1000m nell'area del Monte Labbro) ed è probabilmente connessa allo sviluppo dei processi magmatici legati all'edificio vulcanico del Monte Amiata.

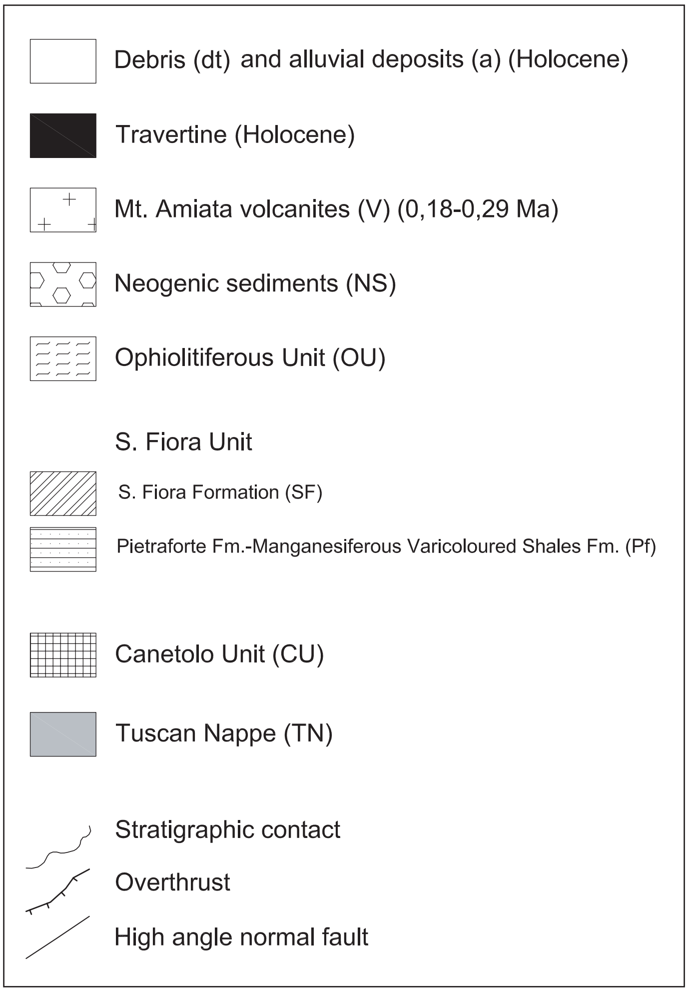
TERMINI CHIAVE: *Appennino settentrionale, Liguridi, Falda Toscana, Stratigrafia, Tettonica.*

INTRODUCTION

The Mt. Amiata region is located in southeastern Tuscany and shows the typical geological features of southern Tuscany (e.g. «Reduced Tuscan Sequence», high heat flow and geothermal fields, Miocene-Pliocene basins: see later). The geological papers about this region are few with respect to other areas of southern Tuscany (see references in GIANNINI *et alii*, 1971; BERTINI *et alii*, 1991; DECANDIA *et alii*, 2001). In particular, reference geological maps are: Sheet no. 129 (S. Fiora) of the 1:100,000 Geological Map of Italy (JACOBACCI *et alii*, 1967), Sheet no. 323 (Scansano) of the 1:50,000 Geological Map of Italy (CESTARI *et alii*, 1981) and the 1:50,000 geological map of the Monte Amiata Geothermal Region (CALAMAI *et alii*, 1970). With the exception of the papers of BORTOLOTTI (1962), BOCCALETTI & PIRINI (1964), BOCCALETTI & SAGRI (1964), MARCUCCI & PASSERINI (1980, 1982) and BRUNACCI *et alii* (1983), the geological monograph by CALAMAI *et alii* (1970) and the detailed studies on the Tuscan successions (see «Geological outline»), recent studies of the Ligurids l.s. of the Mt. Amiata area are lacking. In fact, the more recent studies on the Sub-Ligurian and Ligurian units in southeast Tuscany were performed in the surroundings of the study area (COSTANTINI *et alii*, 1977; BETTELLI *et alii*, 1980; MANGANELLI, 1982; BETTELLI, 1985). To improve the geological framework of the Mt. Amiata region crossed by the CROP-18 profile, we show the results of the geological studies (1:25,000 geological mapping, biostratigraphical and petrographical analyses) performed on the Sub-Ligurian and Ligurian Units cropping out between Montalcino, to the north, and the areas south of Mt. Amiata, and on their relationships with the underlying Tuscan units. The surface geology has been extrapolated at depth using the data from numerous geothermal wells drilled since 1950 by ENEL (CALAMAI *et alii*, 1970; PANDELI *et alii*, 1988; BERTINI & PANDELI, unpublished data) around the Mt. Amiata volcano.

GEOLOGICAL OUTLINE

The study area, dominated by the 1738 m high, Quaternary Mt. Amiata volcano (MAZZUOLI & PRATESI, 1963; FERRARI *et alii*, 1996), is located in southeastern Tuscany (fig. 1). It represents the central and northern part of a main Neogene morphological-structural high which extends towards the south as far as Viterbo in northern Latium (Montalcino-Mt. Amiata-Mt. Razzano Ridge: BALDI *et alii*, 1974; AMBROSETTI *et alii*, 1978; PASQUARÈ *et alii*, 1983) and is characterized by outcrops of Ligurids l.s. (BORTOLOTTI, 1962; BOCCALETTI & SAGRI, 1964; BORTOLOTTI *et alii*, 1970; GIANNINI *et alii*, 1971) and Tuscan Nappe (ELTER, 1955; LOSACCO, 1959a,b,c; GELMINI *et alii*, 1967; FAZZINI *et alii*, 1968; CANUTI & MARCUCCI, 1970, 1971; FAZZUOLI, 1974; CALAMAI *et alii*, 1970; DECANDIA *et alii*, 1994; BROGI & LAZZAROTTO, 2002). The mainly shaly-marly Ligurid units derived from the polyphase deformation evolution (from Late Cretaceous) of the Mesozoic Ligurian-Piedmontese oceanic Domain, which was paleogeographically interposed between the European



Legend fig. 1.

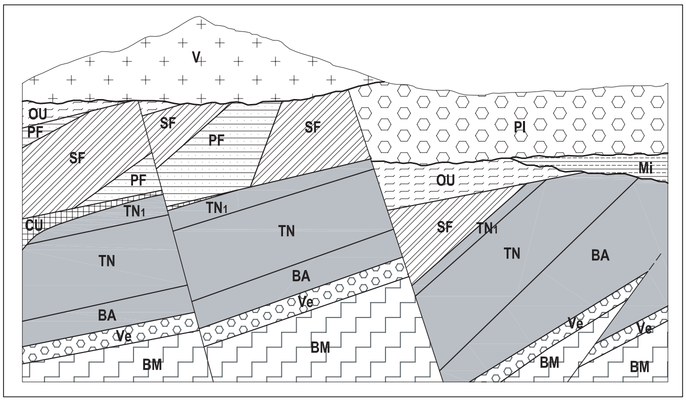


Fig. 2 - Stratigraphic-structural relationships between the Ligurian, Subligurian and Tuscan units in the Monte Amiata region. Metamorphic Units: Bm = Paleozoic successions, Ve = Triassic siliciclastic cover (Verrucano); Tuscan Nappe (Rhaetian-Lower Miocene formations): BA = Triassic evaporites, TN = inferior sub-Units, TN1 = superior sub-Unit (represented by the basal evaporites in the Poggio Zoccolino area); CU: Canetolo Unit; Santa Fiora Unit: SF = S. Fiora Fm., PF = Pietraforte Fm.-Manganesiferous Varicoloured Shales Fm.; OU: Ophiolitiferous Unit (Palombini Shales); Mi: Miocene deposits; Pl: Pliocene deposits; V: Monte Amiata Quaternary volcanic rocks.
– *Relazioni stratigrafico-strutturali tra le unità Liguri, Sub-ligure e Toscane nell'area del M. Amiata. Unità metamorfiche: Bm = successioni paleozoiche, Ve = copertura silicoclastica triassica (Verrucano); Falda Toscana (formazioni dal Retico al Miocene inferiore): BA = evaporiti triassiche, TN = sub-unità inferiore, TN1 = sub-unità superiore (rappresentata dalle evaporiti basali nell'area di Poggio Zoccolino); CU: Unità Canetolo; Unità Santa Fiora: SF = Formazione di S. Fiora, PF = Pietraforte-Argilliti Varicolori Manganesifere; OU: Unità ofiolitifera (Argilliti a Palombini); Mi: sedimenti miocenici; Pl: sedimenti pliocenici; V: vulcaniti quaternarie del Monte Amiata.*

(Corsica-Sardinia block) and African (Adria) continents (ABBATE *et alii*, 1986; BORTOLOTTI *et alii*, 2001 and references therein). Above the Paleozoic basement of the Adriatic paleomargin (Tuscan Domain), a Triassic to Lower Miocene succession was deposited (BORTOLOTTI *et alii*, 1970; GIANNINI *et alii*, 1971; FAZZUOLI *et alii*, 1994) and consists of: Upper Triassic evaporites (Burano Anhydrite) and carbonates, Upper Triassic-Hettangian carbonate platform (Rhaetavicula Limestone and «Calcare Massiccio») and Middle Jurassic-Cretaceous pelagic carbonatic-cherty (e.g. Cherty limestone, Tuscan chert, Maiolica) sediments, Cretaceous-Oligocene pelagic shales, marls and limestones («Scaglia Toscana»), and Upper Oligocene-Lower Miocene siliciclastic turbidites (Macigno Fm.). During Late Eocene-Oligocene times, continent-continent collision took place and both the continent-ocean transitional area (Sub-Ligurian Domain) and subsequently the Adriatic margin (Tuscan Domain) were deformed, imbricated and were thrust by Ligurian units (CARMIGNANI & KLIGFIELD, 1990; CARMIGNANI *et alii*, 2001 and references therein). In particular, the anchimetamorphic to non-metamorphic Tuscan Nappe and the underlying Tuscan metamorphic units were produced by this compressional event (FRANCESCHELLI *et alii*, 2004 and references therein).

The tectonic setting of the Tuscan Nappe in the Mt. Amiata area is similar to that seen in southern Tuscany, where inliers characterized by a «complete» stratigraphic Tuscan succession are separated by areas with «reduced» Tuscan successions («Reduced Tuscan Sequence»: SIGNORINI, 1949, 1964; GIANNINI *et alii*, 1971). This phenomenon is interpreted by some authors (BERTINI *et alii*, 1991; DECANDIA *et alii*, 1993, 2001; CARMIGNANI *et alii*, 1995, 2001) as the effect of low-angle normal faults activated in the Miocene during the early, post-tectonic extensional stages of the Apenninic orogen.

The Montalcino-Mt. Amiata-Mt. Razzano Ridge is bounded by NW-SE-trending, continental and continental-marine basins of Late Miocene-Pliocene age towards the west (the Cinigiano-Baccinello-Lower Orcia Valley Basin: LANDI *et alii*, 1995; BENVENUTI *et alii*, 2001) and east (the Siena and Radicofani basins: BOILA *et alii*, 1982; COSTANTINI *et alii*, 1982; BOSSIO *et alii*, 1993; LIOTTA, 1991, 1994, 1996; BONINI & SANI, 2002). Between Montalcino and Mt. Amiata, the coeval anti-Apennine (NE-SW) trending Velona Basin is also present (DAMIANI *et alii*, 1980; ROOK & GHETTI, 1997; BONINI *et alii*, 1999). Some authors interpreted these intermontane basins as grabens and semi-grabens formed during the extensional events in the hinterland of the orogenic chain (MARTINI & SAGRI, 1993; LIOTTA, 1996; MARTINI *et alii*, 2001 and references therein), whereas others (BONINI *et alii*, 1999; FINETTI *et alii*, 2001; BONINI & SANI, 2002) considered them as thrust-top basins due to the persistence of the contractional regime up to the Pleistocene.

At depth, below a locally thick (more than 1300 m in the Poggio Zoccolino area) Upper Triassic Burano Anhydrite at the base of the Tuscan Nappe, the deep geothermal wells of the Mt. Amiata fields intersect epimetamorphic ?Triassic Verrucano red beds and ?Devonian-Late Permian marine siliciclastics and carbonates (PANDELI *et alii*, 1988; PANDELI & PASINI, 1988; ELTER & PANDELI, 1991).

Since the end of the Early Pliocene, the Miocene-Pliocene basins emerged and their sediments were uplifted up to about 1000 m (e.g. the Lower Pliocene littoral deposits in the Mt. Labbro area), probably during the development of the 1.3 Ma Radicofani shoshonitic volcano (D'ORAZIO *et alii*, 1991) and of the Monte Amiata volcanic-plutonic system (PASQUARÈ *et alii*, 1983; GIANELLI *et alii*, 1988; MARINELLI *et alii*, 1993) and the Piancastagnaio and Bagnore geothermal fields (CALAMAI *et alii*, 1970; BATINI *et alii*, 2003).

THE LIGURIDS AND SUB-LIGURIAN UNIT OF THE Mt. AMIATA REGION

This study mainly focuses on the stratigraphy and tectonic setting of the Ligurids and Sub-Ligurian Unit; therefore, for details on the Tuscan Nappe the reader is referred to previous papers (see «Geological Outline»).

The 1:25,000 geological survey has been coupled with samples of carbonate-marly lithotypes for biostatigraphical analyses of the calcareous nannofossils (S. Monechi) and foraminifera. The biostratigraphical framework adopted in this study is based, for the Cretaceous, on species ranges documented by SISSINGH (1977) Zonation (codified as CC), PERCH-NIELSEN (1985) and BOWN (1992 and references therein) and, for the Paleogene, on the MARTINI (1971) and OKADA & BUKRY (1980) Zonations.

Petrographical analyses were also performed on the sandstones present in the different Ligurian and Sub-Ligurian Units (UBERTI, 1999) counting 500 points for each section and following the Gazzi-Dickinson method (see DI GIULIO & VALLONI, 1992 and references therein).

The data on the Sub-Ligurian and the Ligurian Units are shown, from bottom to top of the tectonic pile, in the following paragraphs (see also the enclosed geological map and sections in Table I and figs 1 and 2). Their relationships with the structures of the underlying Tuscan Nappe will be thoroughly described in the discussion.

STRATIGRAPHICAL DATA

In the Ligurids l.s., three main tectono-stratigraphic units were distinguished (from bottom to top of the pile): Canetolo Unit (or Sub-Ligurian Unit), S. Fiora Unit and Ophiolitiferous Unit.

Canetolo Unit (sub-Ligurian Unit)

This is mostly represented by dark grey/black, in places grey-greenish, shales with centimetre- to metre-scale (rarely up to 4 m thick) carbonate-marly beds («Argille e Calcari» Formation) (fig. 3). The latter are turbiditic, often graded grey biocalcilutites and biocalcarenites (locally with a coarse-grained to microconglomeratic basal level), sometimes with decimetre-metre thick calcareous marl bodies at the top (e.g. in the Monticello-Salaiola area). The carbonate lithotypes are found in bodies locally up to tens of metres thick (e.g. in the Salaiola area: see geological map) and show strong analogies with the Montegrossi Calcarenites of the Tuscan Nappe, but the former lack cherty nodules and lenses. In places, 5-30 cm thick intercalations of more or less calcareous, Tb-e, Tc-e quartzose-feldspathic-micaceous sandstones and siltstones are recognizable; coarse-grained, often amalgamated Macigno-like Ta, Ta/c-e and Ta/de beds occur only in the «I Poggi» area close to well BG23 (see southernmost area of the enclosed geological map in tab. I). The petrographical analyses performed by UBERTI (1999) point to an overall similar composition (fig. 4), but with a higher carbonate content (about 15%) and with a lack of K-feldspar grains relative to the classic Macigno sampled at Mt. Aquilaia (carbonate content <5%) (cf. also with the data about the typical Macigno of the Mts. Chianti in PANDELI *et alii*, 1994; CORNAMUSINI *et alii*, 2002). The apparent maximum thickness of the Canetolo Unit is about 200 m.

Its Eocene age is well testified by the fossiliferous content of the carbonate-marly lithotypes. In particular, the sampled limestones generally yielded Lower to Middle Eocene Globorotalidae (*Acarinina bullbrooki, Morozovella aragonensis, Morozovella crassata*), but rarely of Middle-Upper Eocene age (*Turborotalia cerroazulensis*), and Globigerinidae. The coarse-grained calcarenites also include echinoid debris, bryozoa, Miliolidae, Rotalidae, calcareous algae, *Nummulites sp., Discocyclina sp. and Alveolina sp.* The calcareous nannofossil samples show Lower-Middle Eocene associations (*Coccolithus pelagicus, Zygrhablithus bijugathus Reticulofenestra dictyoda, R. samudorovii, Discoaster* spp., *D. kuepperi, Sphenolithus anarrhopus* and *S. radians*) with few reworked Cretaceous species. Somewhere (e.g. the outcrops to the NW of Castelnuovo dell'Abate), only Cretaceous, probably reworked foraminifera (Globotruncanidae, Heterohelicidae and *Globigerinella cretacea*) and nannofossil (*Watznaueria barnease, Manivitella pemmatoidea, Cribrosphaerella erhenbergii, Prediscosphaera intercisa, P. cretacea, Aspidolithus parcus constrictus, Quadrum trifidum, Quadrum sissinghi, Reinhardites levis, Calculites obscurus* and *Ceratolithoides aculeus;* the co-occurrence of *Q. trifidum, A. parcus constrictus* and *R. levis* suggest an Upper Campanian interval, CC22-23 Zones of SISSINGH, 1977) assemblages were found.

Fig. 3 - Black shales with intercalated calcilutite and calcarenite beds of the «Argille e Calcari» Fm. (Canetolo Unit) along the Salaiola-Monticello road.
– *Argilliti nerastre con intercalazioni di strati calcilutitici e calcarenitici della Formazione delle «Argille e Calcari» Fm. (Unità Canetolo) lungo la strada tra Salaiola e Monticello.*

Santa Fiora Unit

This unit (S. Fiora Group of BRUNACCI *et alii*, 1983) is represented by two successions which show tectonic relationships (see later): the S. Fiora Fm. and the Manganesiferous Varicoloured Shales Fm.-Pietraforte Fm.

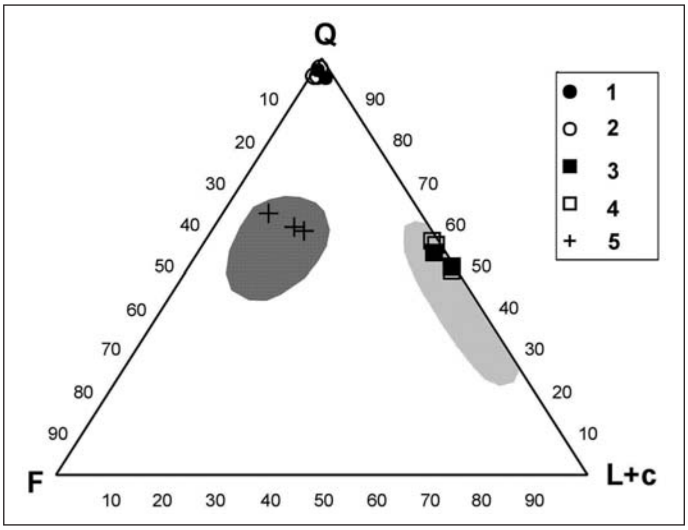


Fig. 4 - Essential framework (QFL+C) diagram of the sandstones in the Ophiolitiferous Unit (1 = quartzarenite intercalations in the Palombini shales; 2 = quartzarenites of the Quartzarenite Member), S. Fiora Unit (3 = Pietraforte; 4 = Pietraforte-like intercalations in the S. Fiora Fm.) and Canetolo Unit (5) of the Mt. Amiata region. Grey area = FQL+c field of the Macigno Fm. of the Tuscan Nappe (after PANDELI *et alii*, 1994; ARUTA *et alii*, 1998); light grey area = FQL+c field of the Pietraforte Fm. (after VALLONI & ZUFFA, 1984; FONTANA & MANTOVANI UGUZZONI, 1987; FONTANA, 1991).
– *Diagramma della composizione modale principale (diagramma QFL+C) delle arenarie nella Unità ofiolitifera (1 = intercalazioni quarzoarenitiche nelle Argilliti a Palombini; 2 = quarzoareniti del Membro Quarzoarenitico), nell'Unità S. Fiora (3 = Pietraforte; 4 = intercalazioni arenacee tipo Pietraforte nella Formazione di S. Fiora) e nell'Unità Canetolo (5) della regione del M. Amiata. Area grigia = campo della Formazione del Macigno della Falda Toscana (da* PANDELI et alii, *1994;* ARUTA et alii, *1998); area grigio chiara = campo della Formazione della Pietraforte (da* VALLONI & ZUFFA, *1984;* FONTANA & MANTOVANI UGUZZONI, *1987;* FONTANA, *1991).*

Fig. 5 - Alternating marly limestones, calcarenites and marly shales of the S. Fiora Fm. (S. Fiora Unit) crossed by calcite veins in a typical outcrop along the Vivo River valley.
– Alternanza di calcari marnosi, calcareniti e marne argillose della Formazione di S. Fiora (Unità S. Fiora) tagliate da vene di calcite fibrosa in un tipico affioramento della valle del Fiume Vivo.

Fig. 6 - Whitish calcareous marls intercalated in the calcareous-marly lithofacies of the S. Fiora Fm. (S. Fiora Unit) along the Vivo River valley.
– Marne calcaree biancastre intercalate nella litofacies calcareo-marnosa della Formazione di S. Fiora (Unità S. Fiora) lungo la valle del Fiume Vivo.

– *S. Fiora Fm.* It is a marly-shaly-calcareous flysch which has a maximum apparent thickness of about 500 m. In particular, the S. Fiora Fm. («Formazione argilloso-calcarea» of BETTELLI, 1985) consists of grey to dark grey, rarely reddish, shales and marly shales, alternating with centimetre to metre scale (up to 2m) beds of grey to light brown, sometimes «landscape»-like limestones and marly limestones, graded biocalcarenites, often siltose calcareous to shaly marls, and subordinately turbiditic calcareous sandstones and siltstones (fig. 5). The calcareous-marly lithotypes are locally very abundant (e.g. the Alberese-like «Castelnuovo dell'Abate» Marls of BORTOLOTTI, 1962; the Vivo River Formation of MANGANELLI, 1982) (fig. 6). All these lithotypes show typical light grey-tawny alteration coatings and are characterized by intersecting systems of cm-thick fibrous calcite veins (fig. 5). Particularly in the Poggio Nibbio area (southeastern part of the study area close to well PN2), the carbonate sandstone intercalations are more frequent also as lenticular, max 15-20 m thick bodies (the thickest are shown in the map in tab. I). These latter can be correlated to the Mt. Rufeno Sandstone Member occurring in the S. Fiora Fm. in its typical areas south of Mt. Cetona (COSTANTINI *et alii*, 1977). Their petrographical composition (UBERTI, 1999) is similar to the typical Pietraforte sandstones (fig. 4) (see also VALLONI & ZUFFA, 1984; FONTANA & MANTOVANI UGUZZONI, 1987; FONTANA, 1991) which is characterized by a relatively high content in sedimentary lithics. The microfossiliferous content of the carbonate and marly lithotypes points to an Aptian/Albian to Upper Cretaceous time interval. In particular, the common association of small Globigerinidae, *Globigerinella cretacea, Hedbergella sp., Ticinella sp., Stomiosphaera sp., Pithonella ovalis and Pithonella sphaerica,* Heterohelicidae, sponge spicules, radiolaria, *Globigerinelloides breggensis,* sometimes with *Praeglobotruncane delhrioensis, Praeglobotruncane stephani, Rotalipora appenninica,* and *Schakoina sp.* suggests a Cenomanian-Turonian age. Locally, Turonian-Maastrichtian Globotruncanidae (*Globotruncana sp., Globotruncana lapparenti, Globotruncana contusa*) were also found. The nannofossil content show typical Cretaceous assemblages with total abundance variations from common to abundant, and preservation from poor to moderate. In particular, the recognized assemblage ranges from the Aptian to Upper Campanian interval:

– Lower Aptian assemblage. This is characterized by the presence of *W. barnesae, P. embergeri, Z. diplogrammus, L. carniolensis, N. steinmanni, Hayesites irregularis, R. wisei, B. bigelowi, Micrantholithus* spp. and *R. angustus*. The co-occurrence of *R. angustus* and *H. irregularis* suggests the CC7 Zone of SISSINGH (1977).

– the Albian-Cenomanian assemblage (*Eiffellithus turriseiffeli* Zone CC9) is defined by the presence of *W. barnesae, Zygodiscus diplogrammus, E. turriseiffeli, R. asper, R. surrirella, P. cretacea, Braarudosphaera regularis, Lithastrinus floralis* and by the absence of *Microrhabdulus decoratus* and *Q. gartneri*.

– Upper Coniacian-Lower Santonian assemblage is defined by the previous assemblage and by the presence of the *Micula decussata* marker of the CC14 Zone.

– the Lower Campanian assemblage is characterized by the presence of *Aspidolithus parcus constrictus, C. aculeus* and *Q. gothicum* markers of the CC18, CC20 and CC21 Zones.

– the Upper Campanian assemblage (CC CC22-23 Zones) is represented by *Watznaueria barnease, Manivitella pemmatoidea, Cribrosphaerella erhenbergii, Prediscosphaera elkefensis, P. cretacea, Aspidolithus parcus constrictus, Arkhangeskiella cymbiformis, Quadrum trifidum, Reinhardites levis, Calculites obscurus* and *Ceratolithoides aculeus*.

– *Manganesiferous Varicoloured Shales Fm.-Pietraforte Fm.* This succession up to 1500 m thick (see SG1 well in C-C" geological cross-section of the enclosed geological map in tab. I), which is well exposed in the Montalcino and in the Seggiano-Arcidosso areas, consists of the turbiditic siliciclastic Pietraforte Fm. which rests stratigraphically on basal, mainly shaly-silty lithofacies (Manganesiferous Varicoloured Shales Fm.).

The *Manganesiferous Varicoloured Shales Fm.* («Argilloscisti varicolori Manganesiferi» of BETTELLI, 1985) are dark grey/black to grey-greenish shales and cm-thick siltstones with grey to grey-greenish, more or less siliceous, sometimes «landscape» limestones and subordinate hard carbonate sandstone intercalations, up to 50 cm thick (fig. 7). These lithotypes are often affected by typical widespread black manganese alterations.

The Aptian-Albian age of this formation, with apparent thickness up to 450 m, is given by small Globigerinidae, *Hedbergella sp.* and/or *Ticinella sp.* assemblages and by some common and varied nannofossil assemblages (*W. barnesae, P. embergeri, Z. diplogrammus, L. carniolensis, Nannoconus sp., Hayesites irregularis, Rucinolithus wisei, B. bigelowi, Micrantholithus* spp., *R. angustus, R. asper, R. surrirella, P. cretacea* and *E. turriseiffeli*) present in the carbonate beds.

The *Pietraforte Fm.* is generally represented by medium- to thick-bedded (locally more than 10 m), massive to crudely graded, arenaceous and arenaceous-pelitic lithofacies (e.g. Arcidosso), consisting of Ta, Ta/c-e, Tab/de, Ta/de and Tb-e, at times lenticular and amalgamated beds. Thin-bedded (max. 80 cm thick) pelitic-arenaceous lithofacies, characterized by arenite/pelite ≤1 and by Tc-e, Tde and Tb-e plane-parallel beds, are also present, expecially in the upper part of the formation (fig. 8), whereas conglomeratic-arenaceous lithofacies («Cicerchina» Auctt.) (fig. 9) can be recognized locally in the mostly arenaceous lower part (e.g. northeast of Seggiano). Varicoloured marly-shaly-calcareous bodies tens of metres thick are rarely intercalated in the siliciclastic succession (e.g. in the Seggiano area) or can be locally present at its top (BORTOLOTTI, 1962). The maximum apparent thickness of the Pietraforte Fm. is about 750-800 m. The fossil content of the sandstones and of the marly-calcareous intercalations consists of *Inoceramus* debris, Heterohelicidae, small Globigerinidae, *Hedbergella sp., Ticinella sp., Schakoina sp., Praeglobotruncana sp.* and Globotruncanidae *(Globotruncana sp., Globotruncana lapparenti),* which define an Upper Cretaceous age.

Ophiolitiferous Unit

This unit (Ligurian-Maremma Group of BRUNACCI *et alii*, 1983), whose apparent thickness can exceed 550 m, is represented by the Palombini Shale Fm. which show the best outcrops at the western edge of the Siena-Radicofani basins, south of the Orcia River and of the Mt. Amiata volcano. This formation consists of grey, dark grey and locally green shales with centimetre to about 1.5 m thick intercalations of grey to grey-greenish siliceous limestones (fig. 10) and rarely of grey, more or less calcareous quartzarenites and quartzose siltstones. The limestones locally show a laminated calcarenitic base and are often characterized by «anvil»-like alterations. Only in the areas south of Saragiolo, the monocrystalline quartz-rich, feldspar-poor siliciclastic rocks (UBERTI, 1999) (fig. 4), are relatively frequent (see Quartzarenite-rich Member in the enclosed geological map in tab. I). The typically chaotic nature of this mostly shaly formation (fig. 11) is generally due to landslides.

The rare fossils (radiolaria and rare Tintinnids) of the carbonate beds point to a Lower Cretaceous age. MARCUCCI & PASSERINI (1980, 1982) described calcareous nannofossil assemblages for the Palombini Shales of the study area that can be ascribed to late Lower Cretaceous age (Barremian-Aptian?).

Ophiolitic olistoliths, mostly serpentinites and ophicalcites, are locally (e.g. south and east of Rocca d'Orcia, east of Campiglia d'Orcia and south west of Abbadia SS.) included in the Palombini Shales Fm. Moreover, basaltic dykes, sills and pillow lavas («Selagiti» Auctt.) of Lower to Upper Cretaceous age (86.3±1.7 Ma and 97.1±2.3 Ma radiometric age in BRUNACCI *et alii*, 1983) are present within the Palombini Shales in the area south of Piancastagnaio. BRUNACCI *et alii* (1983) defined these magmatic rocks as oceanic, intra-plate alkaline olivine-basalts. Finally, a peculiar unfossiliferous lithological association of light grey marls and calcareous marls with rare calcilutitic and calcarenitic intercalations is present in the «Poggio della Ruota» area, south of Bagnolo. According to BRUNACCI *et alii* (1983), this lithofacies, which interfingers with the Palombini Shale Fm., can be correlated to the Lower Cretaceous Murlo Marls included in the Ophiolitiferous unit of the homonymous locality south of Siena.

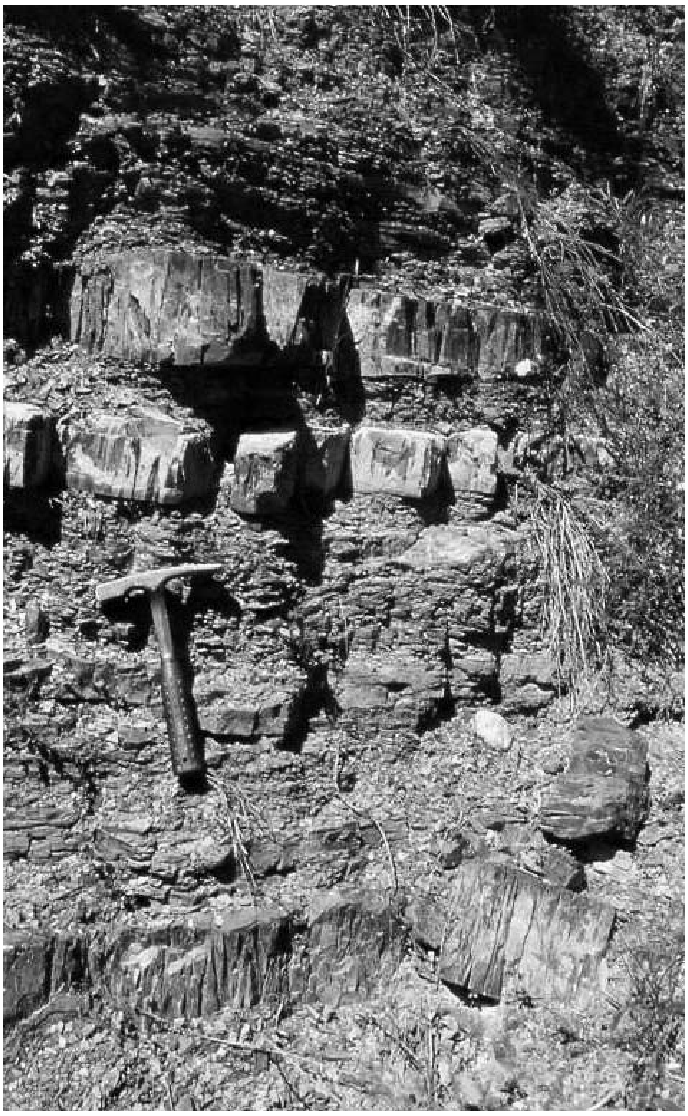


Fig. 7 - Centimetric to decimetric alternations of black manganesiferous shales and siliceous «landscape-like» limestones of the Manganesiferous Varicoloured Shales (S. Fiora Unit) in the surroundings of Vivo d'Orcia.
– *Alternanze centimetriche-decimetriche di argillite manganesiferi nerastri e di calcari silicei tipo «paesina» della Formazione dell'Argilliti Manganesiferi Varicolori (Unità S. Fiora) nei dintorni di Vivo d'Orcia.*

Fig. 8 - Pelitic-arenaceous, thin-bedded lithofacies of the Pietraforte Fm. (S. Fiora Unit) along the road from Castelnuovo dell'Abate to M. Amiata Scalo.
– *Litofacies pelitico-arenacea rappresentata da strati sottili della Formazione della Pietraforte (Unità S. Fiora) lungo la strada da Castelnuovo dell'Abate a M. Amiata Scalo.*

Structural Data

The structural features of the Canetolo Unit, S. Fiora Unit and Ophiolitiferous Unit and their relationships with the Tuscan Nappe are shown below:

Canetolo Unit

The Canetolo Unit is associated with the «complete» Tuscan Nappe inliers (Castelnuovo dell'Abate, Ripa d'Orcia and Mt. Aquilaia) and tectonically lies on different Tuscan formations (e.g. Macigno Fm., «Scaglia Toscana» Fm.); moreover, this unit seals the doubling of the Tuscan Nappe at Mt. Aquilaia (Brogi & Lazzarotto, 2002). Where the «reduced» Tuscan Nappe is present, the Canetolo Unit is strongly laminated or is missing. At the mesoscale, the internal structure of the prevailing pelitic-calcareous part of this unit mostly consists of east-vergent, close to isoclinal overturned folds with NNW-SSE-trending axes; these structures, locally laminated by reverse faults in the overturned limb, are locally refolded by symmetric to asymmetric (east-vergent), open to close folds.

S. Fiora Unit

The field and biostratigraphical data suggest a tectonic intercalation of the Manganesiferous Varicoloured Shales Fm.-Pietraforte Fm succession within the Santa Fiora Fm. of the Montalcino-Mt. Amiata area. For example, the tectonic superposition of the upper structural element of the S. Fiora Fm. on the Pietraforte Fm. is shown in the field by the unconformable contact of the former formation on the different lithofacies of the Pietraforte Fm. (e.g. in the Seggiano area). In the areas characterised by a strongly «reduced» Tuscan Nappe succession (mostly indicated by subsurface data), the lower S. Fiora slice can be completely laminated as well as the Manganesiferous Varicoloured Shales Fm., and the Pietraforte Fm. (locally affected by mercury mineralizations) directly lies on the Triassic evaporites (e.g. in the Poggio del Nibbio-Bagnolo subsurface). West of the Poggio Zoccolino area, the Manganesiferous Varicoloured Shales Fm. overlies the complex stack of the Poggio Zoccolino Tuscan inlier, where a tectonic slice of Triassic carbonates and evaporites probably overlies the Tuscan Mesozoic-Tertiary succession (see C'-C» geological section in tab. I and the «Discussion»). In the southern part of the study area, the Manganesiferous Varicoloured Shales Fm.-Pietraforte Fm. (e.g. that of the «Mt. Calvo» area) is also tectonically intercalated between the upper element of the S. Fiora Fm. and the Ophiolitiferous Unit.

Also in the S. Fiora Fm., polyphase folding is clearly recognizable and is similar to that of the Canetolo Unit. In particular, tight to isoclinal, locally rootless folds, centimetres to tens of metres in scale, which are characterized by NNW-SSE to NNE-SSW-trending axes and by east vergence, are deformed by open to close, often asymmetrical folds, generally with NNE-SSW to NE-SW-trending axes. The structural setting of the Pietraforte Fm. generally consists of wide monoclines which are locally affected by weak folding; only in places (e.g. along the road from Vivo d'Orcia to Pescina) the turbiditic formation shows an overturned attitude linked to up to kilometre-scale folds with Apenninic-trending axes. More complex local structures can be hypothesized from the geothermal well data; for example, in the Seggiano1 (SG1) well a probable top-to-east thrust doubled the folded Pietraforte Fm.-Manganesiferous Varicoloured Shales Fm. succession (see C'-C» geological cross-section in tab. I).

Ophiolitiferous Unit

In the Mt. Amiata area, the Ophiolitiferous Unit rests on each formation of the S. Fiora Unit and on the more or less «reduced» Tuscan Nappe (e.g. Bagno Vignoni-Rocca d'Orcia and Poggio Zoccolino areas, subsurface of the Piancastagnaio field). The internal structural framework of this unit is very complex and frequently affected by recent landslides. In fact, the outcrops generally consist of a chaotic assemblage of patches of carbonate beds in a dominant shaly-muddy matrix. The scatter of the axial plunge of the rare, often rootless, asymmetric to recumbent mesofolds recognizable in the Palombini Shales is due to the complex polyphase deformation evolution of the Ophiolitiferous Unit occurred in both the oceanic and syn-collisional stages.

Finally, the geological survey and the lithostratigraphical correlations between the geothermal wells show that the tectonic pile was dismembered by high-angle normal fault systems which mainly strike NW-SE, NE-SW and N-S, and locally these lineaments are sealed by ?Messinian-Lower Pliocene sediments (see also LIOTTA, 1996; BONINI & SANI, 2002). The throw of the NW-SE and N-S-trending faults locally exceeds 500 m (e.g. the normal fault SW of Saragiolo, close to the PC5 well, in the B-B' geological cross-section in tab. I).

DISCUSSION

This geological study gives new insights into the stratigraphy and tectonic setting of the Ligurids l.s. and their relationships with the Tuscan Nappe in the Montalcino-Mt. Amiata area.

As regards the Ligurids l.s., three main tectonic units were distinguished and mapped for the first time and correlated to well-known tectonic units of southern Tuscany (from bottom to top of the tectonic pile): the Canetolo Unit (or Sub-Ligurian Unit), the S. Fiora Unit and the Ophiolitiferous Unit.

The *Canetolo Unit* is generally associated with the more «complete» Tuscan Nappe inliers (e.g. Ripa d'Orcia, Castelnuovo dell'Abate, Mt. Aquilaia-Mt-Labbro). In the Mt. Aquilaia-Mt-Labbro area, wide outcrops of Scaglia Toscana were attributed in the past to the Argille e Calcari Fm. of the Canetolo Unit by BETTELLI (1985), because of their overall lithological similarities and Tertiary age, especially where they are in direct tectonic contact. Our study reveals that the difference between the two formations consists in the colour of the pelites (varicoloured for the Scaglia Toscana vs. generally dark grey for the Argille e Calcari Fm.) and in the absence of chert nodules and bands in the calcareous beds of the Argille e Calcari Fm. Moreover, the peculiar K-feldspar-free greywackes intercalated in the Argille e Calcari Fm. rule out their correlation with the Tuscan Macigno and strengthens analogies with similar siliciclastics present in the Canetolo Unit in the Tuscan-Emilian Apennines (e.g. Aveto sandstones: BRUNI *et alii*, 2003). In a few cases (e.g. NW of Abbazia di S. Antimo), the definite attribution of the outcrops to the Canetolo Unit is complicated by the common finding of only Upper Cretaceous (?reworked) microfossil assemblages in the calcareous-marly lithotypes.

In the overlying *S. Fiora Unit*, the Pietraforte Fm. with its mainly pelitic stratigraphic base (Manganesiferous Varicoloured Shales Fm.) is considered as a distinct tectonic sub-unit. Its lower tectonic boundary is often given by the superposition of the Lower Cretaceous Manganesiferous Varicoloured Shales Fm. (grading upwards into the Upper Cretaceous Pietraforte Fm.) on the Upper Cretaceous S. Fiora inferior tectonic element. The upper tectonic boundary of the Manganesiferous Varicoloured Shales-Pietraforte sub-unit is outlined by the unconformity produced by the superior S. Fiora tectonic element on different turbiditic lithofacies of the Pietraforte Fm. This tectonic framework of the S. Fiora Unit corresponds to that defined by BETTELLI *et alii* (1980) and BETTELLI (1985) in the valleys of the Fiora and Albegna rivers (south of the study area). The local presence of lenticular bodies of Pietraforte-like carbonatic sandstones in the S. Fiora Fm. (e.g. in the SE of the study area) can be interpreted as the western terminations of the Mt. Rufeno Sandstone Fm., which is stratigraphically intercalated in the typical S. Fiora Fm. of the S. Casciano dei Bagni area along the Mt. Cetona ridge (cf. COSTANTINI *et alii*, 1977). In any case, the overall compositional analogies between the sandstone intercalations of the S. Fiora Fm. and the Pietraforte Sandstone suggest a contiguous paleogeographical setting for both turbiditic deposits and, therefore, for the S. Fiora Fm. and the Pietraforte Fm.-Manganesiferous Varicoloured Shales Fm. successions.

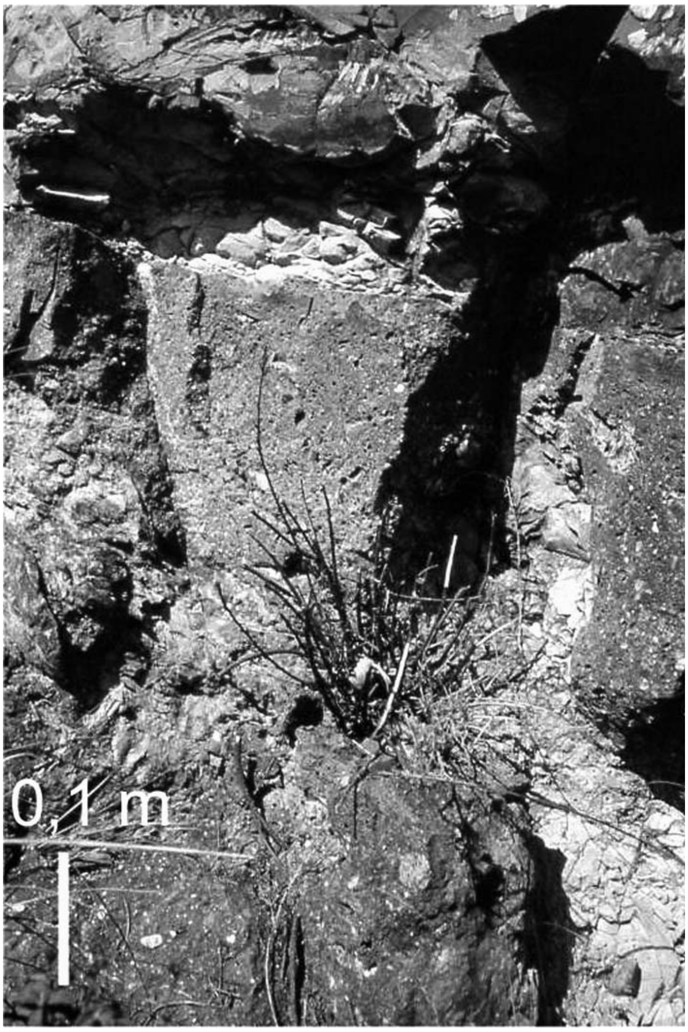


Fig. 9 - Conglomeratic-arenaceous lithofacies of the Pietraforte Fm. (S. Fiora Unit) in an outcrop north of Seggiano.
– *Litofacies conglomeratico-arenacea della Formazione della Pietraforte (Unità S. Fiora) in un'affioramento a nord di Seggiano.*

The *Ophiolitiferous Unit* of the Montalcino-Mt. Amiata area, as well as that exposed more to the east along the Mt. Cetona ridge (e.g. Castiglioncello del Trinoro) is mainly made up of the Palombini Shales Fm. which is a typical feature of the Upper Ophiolitiferous Unit within the Ligurian pile in Maritime Tuscany (COSTANTINI *et alii*, 1993; BERTINI *et alii*, 2000; «Montignoso Unit» of NIRTA *et alii*, 2005 and references therein). It is also worth noting the peculiar presence of Lower-Upper Cretaceous basic volcanic and subvolcanic rocks («Selagiti» Auctt.) in the Palombini Shales of the Mt. Amiata and Mt. Cetona areas, which still represent the younger magmatic event (alkaline within-plate basalts) of the Ligurian-Piedmontese oceanic domain. Our surveys also confirm the finding by BRUNACCI *et alii* (1983) in the Poggio della Ruota area (south of Bagnolo) of calcareous-marly lithofacies within the Palombini Shales. These peculiar lithofacies can be correlated with the Murlo Marl Fm. present in the lower part of the Palombini Shales along the Murlo ridge (between Montalcino and Siena). In contrast, we do not agree with these authors in the distinction of two different stratigraphical units («Unità Podere Ghiacciali» and «Unità di Fosso Marta II» of BRUNACCI *et alii*, 1983) in the Ophiolitiferous Unit.

The surface geology and its extrapolation at depth using data from geothermal wells and mercury mines (e.g Abbadia SS. and Siele mines: ARISI ROTA *et alii*, 1971) allow us to define a complex tectonic setting between the Ligurian units, the Canetolo Unit and the Tuscan Nappe (see fig. 1, and the enclosed geological map and sections in tab. I). Firstly, the internal structural frameworks of the Ligurian units (e.g. S. Fiora Unit) and the Canetolo Unit appear to be characterized by a similar polyphase folding evolution (i.e. the two Adriatic-vergent folding events) (fig. 12) which shows strong analogies with that inferred for the plastic structures of the Tuscan Nappe (cf. BROGI & LAZZAROTTO, 2002). The structural disharmonies between the tectonic units, linked to different rheological behaviours in the individual formations (e.g. the competent Pietraforte Fm. vs. S. Fiora Fm.), prevents direct correlation between the structures of the Canetolo and S. Fiora Units and those of the Tuscan Nappe, which are related to the Upper Oligocene-Miocene Apennine tectogenesis. These disharmonies also suggest that the main tectonic contacts were utilised many times during the emplacement of the Canetolo Unit and of the Ligurian Units on the Tuscan Nappe, first as thrust surfaces and successively as low-angle normal faults during the extension of the chain (see BERTINI *et alii*, 1991 and references therein).

In particular, the tectonic contacts between the inferior and superior S. Fiora Fm. elements with Manganesiferous Varicoloured Shales-Pietraforte succession, and the doubling of the latter succession in the Seggiano 1 (SG1) well, suggest that these internal thrusts originated before the final emplacement of the S. Fiora Unit above the Canetolo and/or Tuscan Nappe Units, and before the overthrusting of the Ophiolitiferous Unit. In particular, we think that at least part of these internal thrusts could have originated during the oceanic accretionary wedge stage in Eocene times (cw. PRINCIPI & TREVES, 1986; BORTOLOTTI *et alii*, 2001; NIRTA *et alii*, 2005).

Also in this part of Tuscany the typical «mega-boudinage» of the Tuscan Nappe («Reduced Tuscan Sequence») is easily recognised. In particular, two main alignments of the «complete» Tuscan inliers, which probably correspond to the axial culminations of main east-verging megafolds (or anticlinal stacks: see later), can be recognised: the N-S trending Castelnuovo dell'Abate-M. Aquilaia-Stribugliano-Roccalbegna alignment to the west, and the NW-SE to N-S trending Bagno Vignoni-Rocca d'Orcia-Poggio Zoccolino-Castell'Azzara alignment to the east. North and south of the Mt. Amiata volcano, these alignments are separated by an intermediate area characterized by the typical «reduced» Tuscan Nappe. In fact, most of the geothermal wells show a direct contact of the Ligurids on the Tuscan Triassic evaporites (e.g. SG1, BG10, PN2, PN3 and PN7 in the geological map and sections in tab. I; see also CALAMAI *et alii*, 1970). A similar tectonic reduction can also be present along the Bagno Vignoni-Castell'Azzara alignment (see also BROGI *et alii*, 2002), i.e. along the axes of the structures. In fact, the Poggio Zoccolino inlier can be traced to the south in the subsurface as far as Abbadia SS. (Amiata 1 and Amiata 2 wells in CALAMAI *et alii*, 1970; data of the Abbadia mercury mines: ARISI ROTA *et alii*, 1971), while in the Piancastagnaio geothermal field the typical strongly «reduced» Tuscan Nappe is present (CALAMAI *et alii*, 1970; PANDELI *et alii*, 1988; ELTER & PANDELI, 1991). Regarding the relationships between the Ligurids l.s. and the Tuscan Nappe, it is evident that in correspondence of the «complete» Tuscan inliers, the overlying pile of nappes generally consists of all the tectonic units from the Canetolo Unit to the Ophiolitiferous Unit (e.g. Ripa d'Orcia area, Mt. Aquilaia). Whereas the more or less «reduced» Tuscan Nappe is present, the Canetolo Unit is generally lacking, and the S. Fiora Unit or the Ophiolitiferous Unit overlie the Tuscan formations (e.g. Poggio Zoccolino, Bagno Vignoni-Rocca d'Orcia).

Tectonic doublings within the Tuscan Nappe are known in the geological literature of the Mt. Amiata region (M. Labbro: CRESCENTI & GIUSSANI, 1969; Bagnore geothermal field: CALAMAI *et alii*, 1970; Mt. Aquilaia area: BROGI & LAZZAROTTO, 2002; Bagno Vignoni: BROGI *et alii*, 2003b; Castelnuovo dell'Abate: BONINI & SANI, 2002), of the coastal Tuscany (Mts. Uccellina: CAMPETTI *et alii*, 1999) and of the Tuscan Nappe Front (Alfina geothermal field: BUONASORTE *et alii*, 1991; Rapolano-Trequanda-Mt. Cetona: BERTINI *et alii*, 1991), where the Ligurids are also implicated in these complex structures (e.g. Mt. Cetona and the Latera geothermal field: BUONASORTE *et alii*, 1987; COSTANTINI *et alii*, 1993 and references therein), and, more to the west, in the Larderello-Travale geothermal region (BROGI *et alii*, 2003a). Doublings of the Tertiary Tuscan formations and probable tectonic interpositions of the Canetolo Unit also occur in the Castell'Azzara Tuscan inlier (unpublished data of the authors). A peculiar Tuscan Nappe doubling occurs in the Poggio Zoccolino area (TONINI, 1996; PANDELI *et alii*, 2002; BROGI, 2004). Here, in the downthrown block of the high-angle normal fault which borders the Tuscan inlier, Triassic evaporites crop out at the «Colline» locality and are overlain by the Ophiolitiferous Unit. Such a sharp E-W «reduction» of the Tuscan succession appears difficult to achieve. Moreover, a few hundred metres to the E/SE, the thermomineral aragonite-rich vents and travertine deposits of the Bagni S. Filippo area (MALESANI & VANNUCCI, 1975; CIPRIANI *et alii*, 1977) suggest the presence at depth of a thick carbonatic reservoir consisting of Triassic-Tertiary formations such as at Bagno Vignoni and other geothermal areas of Tuscany (e.g. Rapolano, Saturnia, Monsummano, etc.). Therefore, we believe that the eastern prosecution of the Poggio Zoccolino inlier can be hypothesized below a tectonic slice of Burano Anhydrites of the «Colline» locality. A quite similar structure (i.e. the tectonic superposition of Triassic evaporites on to Triassic-Jurassic formations of the Tuscan Nappe) is shown by CALAMAI *et alii* (1970) in the subsurface of the Bagnore field (see Bagnore 8 well in geological cross-section 2). Moreover, the anomalously thick (more than 1300 m) Burano Anhydrite at the base of the Poggio Zoccolino succession (see S. Filippo 1 well in the geological cross-section 2 of Calamai *et alii*, 1970) probably suggests tectonic doublings also within the Triassic evaporites. The same tectonic superposition of Triassic rocks on the Poggio Zoccolino Tuscan inlier can be suggested by two Calcare Cavernoso outcrops not far northwest and west («Capanne Bacchi» locality) of the same inlier. This hypothesis is confirmed by the interpretation of seismic data by Brogi (2004).

According to Brogi & Lazzarotto (2002), the doublings of the Tuscan Nappe occurred during the main Late Oligocene-Lower Miocene shortening event of the Tuscan Domain (D1 or «Syn-Nappe phase» of Elter & Sandrelli, 1994, dated 27 Ma on the Apuan Alps by Kligfield *et alii*, 1986), whereas Bonini & Sani (2002) related most of them to the activation, or «out-of-sequence» compressional reactivations, of the Apennine thrusts in Middle-Late Pliocene times.

Our data, and geological considerations at a regional scale, suggest that at least part of the Tuscan Nappe doublings originated in the Burdigalian-Lower Tortonian time interval. In particular:

1) Given that the Macigno Fm. (the uppermost unit of the Tuscan Nappe) is involved in the doublings (e.g. Mt. Aquilaia), these latter occurred after the end of the foredeep siliciclastic sedimentation of the Macigno in eastern Tuscany (dated Early Aquitanian by Cornamusini, 2002) due to the overthrust of the Ligurids l.s. on to the inner part of the the Tuscan foredeep (Burdigalian event in Fazzuoli *et alii*, 1994);

2) Although the the Adriatic-vergent deformation of the Tuscan Nappe began during the D1 event at a regional scale (Pertusati *et alii*, 1967; Giammarino & Giglia, 1990; Elter & Sandrelli, 1995; Aque *et alii*, 2000), the most important shortening event affecting the eastern part of the Tuscan Nappe and the building-up of the east-verging Tuscan Nappe Front (Mt. Orsaro-Lima Valley-Mts. Chianti-Mt. Cetona structural alignment) occurred in the Middle Miocene («D2 event», dated 14-12 Ma, of Carmignani & Kligfield, 1990; Carmignani *et alii*, 2001; «Late Serravallian event» of Fazzuoli *et alii*, 1994; «Post-Nappe event» of Elter & Sandrelli, 1995 and references therein). During D2, the Ligurids l.s. were involved in the Tuscan Nappe Front (Buonasorte *et alii*, 1987; Costantini *et alii*, 1993 and references therein), and local doublings of the Tuscan succession also occurred (e.g. in the Lima Valley megafold: Fazzuoli *et alii*, 1998). The D2 structures were attributed to a post-Burdigalian «serrage» event of the structural pile (cf. Fazzuoli *et alii*, 1994; Jolivet *et alii*, 1998) or, according to a «core complex» extensional model (Carmignani & Kligfield, 1990; Carmignani *et alii*, 1995), to the first low-angle regional extensional stage of the orogenic chain. In the latter model, regional, Adriatic-vergent movement of the Tuscan covers from the isostatic rising Mid-Tuscan Metamorphic Ridge occurred. At the same time the outermost Tuscan successions (Cervarola-Falterona Unit) thrust over the innermost Umbrian Domain (Fazzuoli *et alii*, 1994; Aruta *et alii*, 1998). A successsive refolding event («Latest Serravallian-Early Tortonian event» of Fazzuoli *et alii*, 1994) of the Tuscan Nappe Front was recognized in the Lima Valley megafold (Fazzuoli *et alii*, 1998) and along the Mts. Chianti (Elter & Sandrelli, 1995).

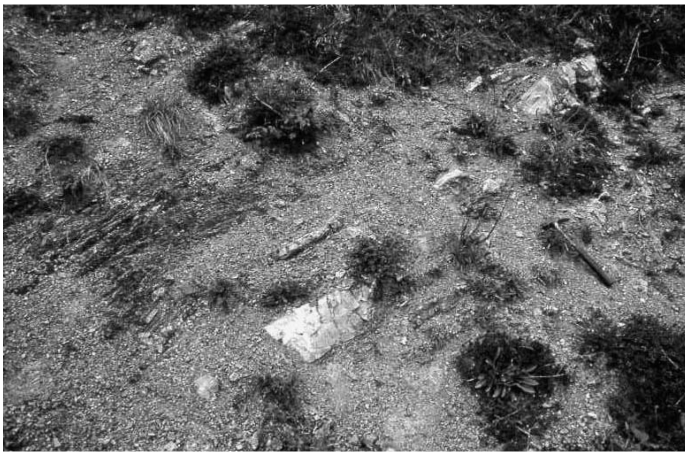


Fig. 10 - Shales with siliceous limestone interbeds of the Palombini Shales (Ophiolitiferous Unit) in a typical outcrop south of Bagni S. Filippo.
– Argilliti con intercalazioni di strati calcareo-silicei della Formazione delle Argilliti a Palombini (Unità Ofiolitifera) in un affioramento tipico a sud di Bagni S. Filippo.

Fig. 11 - A chaotic assemblage of the Palombini Shales (Ophiolitiferous Unit) in a typical outcrop south of Bagni S. Filippo.
– Argilliti a Palombini a giacitura caotica (Unità Ofiolitifera) affioranti a sud di Bagni S. Filippo.

Fig. 12 - Polyphase folding in the S. Fiora Fm. (S. Fiora Unit) in a cliff along the valley of the Orcia River (southwest of Ripa d'Orcia).
– Piegamenti polifasici nella Formazione di S. Fiora Fm. (Unità S. Fiora) in una scarpata lungo la valle del Fiume Orcia (sud-ovest di Ripa d'Orcia).

3) A complex tectonic stack of metamorphic and non-metamorphic Tuscan Units is present in the Larderello-Travale geothermal region (Tectonic Slice Complex: PANDELI *et alii*, 1991; ELTER & PANDELI, 1990, 1994), the Massa M.ma mining region (COSTANTINI *et alii*, 2002), along the Monticiano-Roccastrada Ridge (e.g. the tectonic intercalation of the Burano Anhydrite within the metamorphic sub-units of the Monticiano-Roccastrada Ridge: Belagaio well in fig. 4 of BERTINI *et alii*, 1991) and in the areas north (Pontremoli 1 oil well: ANELLI *et alii*, 1994) and northeast (Secchia Valley: ANDREOZZI *et alii*, 1987; PLESI *et alii*, 2000) of the Apuan Alps. Also in the crystalline successions of the Mt. Amiata subsurface, slices of Carboniferous-Permian rocks are tectonically intercalated within the Verrucano, and rare slices of the latter are recognizable within the Burano Anhydrite (ELTER & PANDELI, 1991; BERTINI & PANDELI, unpublished data from the geothermal wells). The rocks of the metamorphic slices were already affected by D1 deformation before their wedging, so that a probable syn-/post-D2 age can be suggested for the Tectonic Slice Complex (PANDELI *et alii*, 1991). Thus, these can be correlated to the Serravallian-Tortonian «out-of-sequence» shortening of the Tuscan (Macigno and Cervarola-Falterona Sandstones) and inner Umbrian (Marnoso arenacea succession of the Massicci Perugini Unit and of the Mt. Nero Unit) foredeep siliciclastic successions (FAZZUOLI *et alii*, 1994; ARUTA *et alii*, 1998 and references therein).

4) Possible minor compressive pulses affected the Mt. Amiata region in the Middle-Upper Pliocene (BONINI & SANI, 2002), but they did not produce significant re-arrangement of the tectonic pile (e.g. doublings). In fact, the Late Messinian-Lower Pliocene sediments seal the stack of different tectonic units.

Finally, it is worth mentioning that in the study area the Ophiolitiferous Unit tectonically lies on almost all of the underlying tectonic units (with the exception of the Canetolo Unit and the underlying Macigno Fm. of the Tuscan Nappe). This geometry, well-known in southern Tuscany, can be related to the delamination processes of the tectonic pile that occurred during the «reduction» of the Tuscan Nappe (BERTINI *et alii*, 1991; DECANDIA *et alii*, 1993). In this framework, the sealing of the Tuscan Nappe doublings by the Canetolo Unit in the Mt. Aquilaia area, and by the S. Fiora and Ophiolitiferous Units in the Poggio Zoccolino area, can be related to the final emplacement and internal re-arrangement of the Sub-Ligurian and Ligurian pile. These structures are then sealed by the Messinian-Lower Pliocene, continental to marine sediments (e.g. the Velona Basin).

To summarize the complex geological framework of the Mt. Amiata region, we have developed the following evolutionary scheme of the deformation events (see the simplified evolution sketch in fig. 12):

D1 EVENT (AQUITANIAN-BURDIGALIAN) (fig. 13a)

During the main northern Apennine shortening event, the Canetolo Unit and at least part of the Ligurids (i.e. S. Fiora Unit) overrode the Tuscan foredeep (Macigno Fm), and the deformation of the Tuscan succession began (definition of the Tuscan Nappe by the basal detachment horizon at the Burano Anhydrite and local onset of its doublings).

D2-D3 EVENTS (LATE SERRAVALLIAN-TORTONIAN) (figs. 13b and c)

All authors agree that at this time the Adriatic-vergent translation of the Tuscan units (Tuscan Nappe and Cervarola-Falterona Unit) above the innermost part of the Umbrian Domain occurred, either because of the movement of the Tuscan Nappe with respect to the isostatic rise of the Tuscan metamorphic core-complex (i.e. the Tuscan Metamorphic Ridge from Apuan Alps to Mt. Leoni), or because of the final «serrage» of the Tuscan Domain (during which the compressional exhumation of the Tuscan Metamorphic Ridge – e.g. the Monticiano-Roccastrada Ridge – occurred). In any case, the Tuscan Nappe at its front (e.g. the Mt. Cetona segment, which involved the Ligurids l.s. in the overturned megafold: BUONASORTE *et alii*, 1987; COSTANTINI *et alii*, 1993) lies on two Tuscan non-metamorphic slices which have overriden the Umbrian succession (see Alfina 15 Well: BUONASORTE *et alii*, 1991). We suggest that during this progressive D2 deformation event, the Tuscan Nappe and the overlying Ligurids l.s. of the Mt. Amiata region were also shortened, and many of the doublings of the Tuscan Nappe took place (fig. 13 b). During the movement of the Tuscan Nappe, doublings at the top of the underlying, partly ?Umbrian crystalline succession (denuded of its Upper Triassic-Tertiary cover) also occurred. Most of the terrigenous turbiditic formations at the top of the Tuscan and Umbrian units were detached at the level of the basal pelitic sediments (e.g. Scaglia Toscana) and thrust more to the east respect to their Mesozoic substratum producing independent structural fronts (ARUTA *et alii*, 1998 and references therein). During this event or soon after (D3 event) (fig. 13c), syn-tectonic extension (through low-angle and listric faults which flatten out in the Burano Anhydrite) affected the tectonic pile particularly at the front of the main crustal thrusts producing the mega-«boudinage» of the Tuscan Nappe and of the Ligurids l.s. and the refolding of the Tuscan Nappe Front. Possibly NE-SW, strike-slip shearing also developed and produced the N-S segmentation of the Tuscan Nappe along the axes of the main fold structures.

D4 EVENT (?MESSINIAN-QUATERNARY) (fig. 13d)

High-angle normal faults, which mainly strike NW-SE, NE-SW and N-S, dismembered the complex tectonic stack of units and allowed the development of the Radicofani and the Baccinello-Lower Orcia Valley basins and of the Montalcino-Mt. Amiata-Mt. Razzano ridge. The presence of a ridge separating the two basins at least since the Early Pliocene is indicated by detrital inputs coming from the ridge (east-fed deltaic sediments in the eastern part of the Baccinello-Lower Orcia Valley basin: GHINASSI, 2004; the Palombini Shale landslides or «olistostromes» at the western border of the Radicofani Basin: CALAMAI *et alii*, 1970; LIOTTA, 1996). Minor compressional pulses probably occurred in Pliocene times (BONINI *et alii*, 1999; BONINI & SANI, 2002). The uplift of the Montalcino-Mt. Amiata area has probably continued in more recent times, as shown by the outcrops of Lower Pliocene marine sediments at about 500 m between Montalcino and Castelnuovo dell'Abate (see geological map) and at about 1000 m in the Mt. Labbro area (CALAMAI *et alii*, 1970; GIANELLI *et alii*, 1988). According to geological-geo-

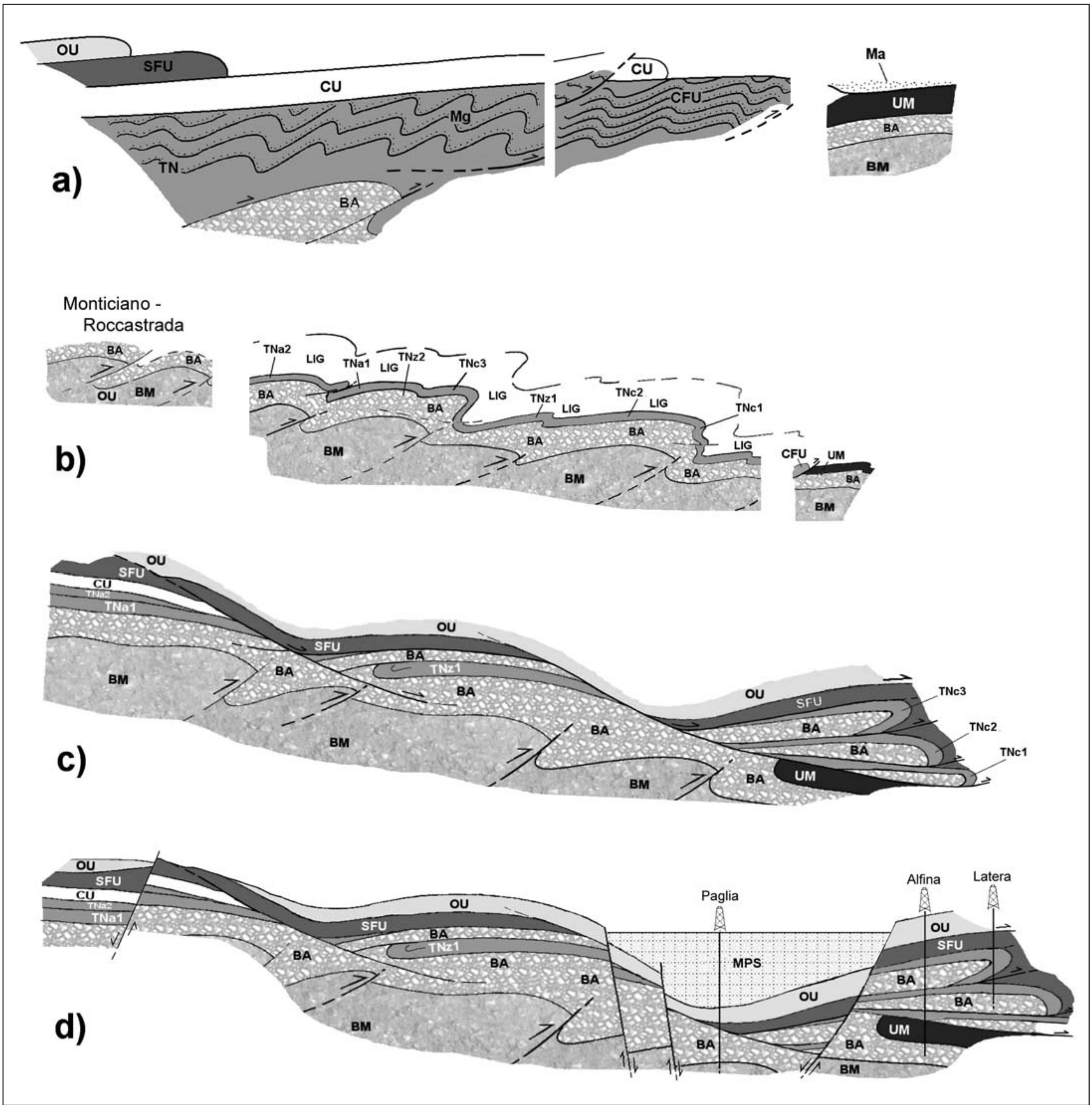


Fig. 13 - Scheme of the deformation evolution (a = D1, b = D2, c = D3, d = D4 events) of the Mt. Amiata area from the Aquitanian to Pliocene/Quaternary times. The Tertiary turbiditic siliciclastic successions at the top of the Tuscan and Umbrian Units (Macigno = Mg, Cervarola-Falterona Sandstone = CFU, Marnoso-arenacea = Ma) are not distinguished in the b, c and d stages. The thickness and areal extent of the units are indicative and not in scale. LEGEND: Miocene-Pliocene sediments = MPS; Ophiolitiferous Unit = OU; S. Fiora Unit = SFU; Canetolo Unit = CU; Tuscan Nappe = TN (and probable original Mesozoic substratum of the Cervarola-Falterona Unit): TNa_1 = Mt. Aquilaia inferior sub-unit, TNa_2 = Mt. Aquilaia superior sub-unit, TNz_1 = Poggio Zoccolino inferior sub-unit, TNz_2 = Poggio Zoccolino superior sub-unit, TNc_1 = Alfina 15 well inferior sub-unit, TNc_2 = Alfina 15 well superior sub-unit, TNc_3 = Mt. Cetona sub-unit; Burano Anhydrite Fm. = BA; Paleozoic-Mesozoic metamorphic succession = BM; Cervarola-Falterona Unit succession= CFU; Umbrian-Marchean, Mesozoic-Lower-Miocene successions = UM.

– Schema della evoluzione deformativa (eventi deformativi: a = D1, b = D2, c = D3, d = D4) dell'area del M. Amiata dall'Aquitaniano al Pliocene/Quaternario. Le successioni torbiditiche silicoclastiche terziarie a tetto delle unità toscane ed umbre (Macigno = Mg, Arenarie del Cervarola-Falterona = CFU, Marnoso-arenacea = Ma) non sono state distinte negli stadi b, c e d dello schema. Gli spessori e l'estensione areale delle diverse unità sono da considerarsi indicative e non è in scala. LEGENDA: sedimento mio-pliocenici = MPS; Unità Ofiolitifera = OU; Unità S. Fiora = SFU; Unità Canetolo = CU; Falda Toscana = TN (e probabile substrato mesozoico dell'Unità Cervarola-Falterona): TNa_1 = sub-unità inferiore del M.Aquilaia, TNa_2 = sub-unità superiore del M. Aquilaia, TNz_1 = sub-unità inferiore di Poggio Zoccolino, TNz_2 = sub-unità superiore di Poggio Zoccolino, TNc_1 = sub-unità inferiore del sondaggio Alfina 15, TNc_2 = sub-unità superiore del sondaggio Alfina 15, TNc_3 = sub- unità del M. Cetona; Anidridi di Burano = BA; successioni paleozoico-mesozoiche metamorfiche = BM; successione dell'Unità Cervarola-Falterona = CFU; successioni Mesozoiche-Mioceniche inferiori del Dominio Umbro = UM.

physical data, the uplift of these highest parts of the Montalcino-Mt. Amiata-Mt. Razzano ridge can be easily related to the magmatic processes of Mt. Amiata volcano (cf. GIANELLI *et alii*, 1988; MARINELLI *et alii*, 1993), which developed by NE-SW-trending feeder fractures (FERRARI *et alii*, 1996). These «anti-Apennine» tectonic lineaments probably represent the main pathways also for thermomineral vents at Bagni S. Filippo and Bagno Vignoni.

CONCLUSIONS

The geological studies performed in the Montalcino-Mt. Amiata area allow the following conclusions:

a) In the Ligurids sl., three main tectonic units were distinguished (from bottom to top of the pile): the Canetolo Unit (or Sub-Ligurian Unit), the S. Fiora Unit and the Ophiolitiferous Unit.

b) The successions of the Tertiary Canetolo Unit were distinguished from the coeval and lithologically similar Scaglia Toscana of the Tuscan Nappe; its interbedded sandstone bodies were diversified from the Macigno of the Tuscan Nappe on the basis of their peculiar composition (i.e. lack of K-feldspar);

c) The S. Fiora Unit consists of two Cretaceous successions (S. Fiora Fm. and Manganesiferous Varicoloured Shales-Pietraforte succession) which are separated by tectonic contacts;

d) The Ophiolitiferous Unit, which is mainly made up of Palombini Shales and includes Late Cretaceous basic volcanic and sub-volcanic rocks, could be correlated to the Upper Ophiolitic Unit (or Montignoso Unit) of southern Tuscany;

e) The tectonic setting of the Ligurian Units, the Canetolo Unit and the Tuscan Nappe is complex. Beyond probable pre-Oligocene deformation in the Ligurian Units (e.g. the S. Fiora Unit), all the units suffered the polyphase Apenninic tectogenesis: Lower Miocene to Middle Miocene syn-collisional and «serrage» stages, Serravallian-Lower Tortonian syn-tectonic extension and, finally, high-angle faulting due to post-tectonic extension in ?Messinian to Quaternary times.

f) The data in the previous paragraphs improve our understanding of the stratigraphic and structural framework of the southeastern part of Tuscany crossed by the southern transect of the CROP-18 profile, and has allowed the definition of a new model for the evolution of this area.

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