The Porto Azzurro unit (Mt. Calamita promontori, southeastern Elba island, Tuscany): stratigraphic, tectonic and metamorphic evolution

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The Porto Azzurro Unit (Mt. Calamita promontory, south-eastern Elba Island, Tuscany): stratigraphic, tectonic and metamorphic evolution

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ABSTRACT

Elba Island has a key role in the reconstructions of the stratigraphic, tectonic, metamorphic and magmatic evolution of the Northern Tyrrhenian Sea and the inner part of the Northern Apennines chain. The Porto Azzurro Unit, cropping out in the south eastern part of Elba Island, is the deepest tectonic unit of the central-eastern Elba structural pile of Tuscan, Ligurian and Ligurian-Piemontese Nappes, which were intruded by Late Tortonian-Lower Pliocene granitoids and mainly acidic dykes. Moreover, in this part of the island, the relationships between the emplacement of the plutonic bodies and the final deformations of the tectonic stack are easily detectable. To improve our geological knowledge of south eastern Elba, the authors carried out 1:10,000 geological mapping of the Calamita promontory (mostly composed of the Porto Azzurro Unit) and performed petrographical and structural studies on its rocks. The Porto Azzurro Unit consists of a Paleozoic, probably pre-Carboniferous basement (Mt. Calamita Metamorphic Complex), which is unconformably overlain by the ?Triassic Verrucano metasiliciclastics (Barabarca Quartzites) and ?Upper Triassic-?Hettangian metacarbonates. In the Mt. Calamita Metamorphic Complex, five main lithofacies were recognized and mapped. In particular, garnet-bearing-, albite mica-schists (lithofacies *a*) geometrically underlie a phyllitic-quartzitic unit (lithofacies b); porphyroids (lithofacies e), metabasite bodies (lithofacies d) and graphite-rich siliciclastics (lithofacies c) are also present. The rocks of lithofacies a are similar to those of the ?pre-Paleozoic-?Paleozoic Micaschist Complex of the Larderello geothermal field, whereas the other lithofacies can probably be correlated with the ?Ordovician formations of the Tuscan Metamorphic Succession (e.g. Apuan Alps). The complex deformation-metamorphic evolution of the Porto Azzurro Unit consists of the following events: *a*) a Variscan tectono-metamorphic event (D_x), recognized in the Mt. Calamita Metamorphic Complex, which is defined by a pre-Alpine foliation and mineral relicts (garnet); *b*) two Alpine tectono-metamorphic folding events (D_1 and D_2) in the greenschist facies, which also deformed the Mesozoic cover; *c*) a later folding event (D_3) which probably occurred during or immediately after the thermometamorphic imprint (including the magnetite-rich skarn bodies), caused by Neogene magmatic intrusions; *d*) subsequently, the uplift of the magmatic bodies caused low-angle detachments within the Porto Azzurro Unit (between the Mt. Calamita Metamorphic Complex and the Mesozoic cover) and between the latter and the overlying tectonic units (e.g. Zuccale Fault between the Porto Azzurro Unit and the Cretaceous Flysch Unit); *e*) a final weak antiformal folding (D_4) of the whole promontory took place before the development of NW-SE and NE-SW trending high-angle normal fault systems, locally sealed by hydrothermal, sometimes Fe-rich mineralizations. The lithostratigraphical, tectonic, metamorphic and magmatic evolution of the Porto Azzurro Unit is similar to that detected for the Larderello geothermal region. Thus, the Mt. Calamita area can be considered as an older, but similar geological model for all future interpretations of the deep structure of southern Tuscany crossed by the CROP 18 profile.

KEY WORDS: *Northern Apennines, south-eastern Elba Island, Paleozoic-Mesozoic successions, tectonic and metamorphic evolution, granitoid emplacement.*

RIASSUNTO

L'Unità di Porto Azzurro (Monte Calamita, Isola d'Elba sud-orientale, Toscana): evoluzione stratigrafica, tettonica e metamorfica.

L'Isola d'Elba ha un ruolo chiave nella ricostruzione stratigrafica, tettonica, metamorfica del Tirreno Settentrionale e delle porzioni più interne della catena Appenninica settentrionale. L'Unità di Porto Azzurro, che affiora nella parte dell'Isola sud-orientale, è l'unità più profonda della pila tettonica dell'Elba centro-orientale, che è costituita da unità toscane, liguri e liguri-piemontesi, intruse da granitoidi e filoni, per lo più acidi, del Tortoniano sup.-Pliocene inferiore. In questa parte dell'isola, inoltre, sono ben esposte le relazioni tra corpi magmatici e deformazioni finali subite dalle varie unità. Al fine di migliorare le conoscenze geologiche relative all'Elba sud-orientale, gli autori hanno effettuato un rilevamento geologico alla scala 1:10.000 del Promontorio del Calamita (costituito per la maggior parte dall'Unità di Porto Azzurro) ed hanno eseguito uno studio petrografico e strutturale sui litotipi affioranti. L'Unità di Porto Azzurro è costituita da una successione paleozoica, probabilmente di età pre-carbonifera (Complesso Metamorfico di Monte Calamita), sormontata in discordanza stratigrafica dai meta-sedimenti silicoclastici del Verrucano triassico (Quarziti di Barabarca) e da successioni carbonatiche del ?Triassico superiore-?Hettangiano. Nel Complesso Metamorfico di Monte Calamita sono state distinte e cartografate cinque principali litofacies. In particolare, sui micascisti a granato ed albite (litofacies *a*), giace geometricamente un'unità filladico-quarzitica (litofacies b). Sono inoltre presenti porfiroidi (litofacies e), rocce silicoclastiche ricche in grafite (litofacies c) e livelli di metabasiti (litofacies d). Le rocce della litofacies a sono simili a quelle, di età ?pre-paleozoica-?paleozoica del Complesso dei Micascisti del campo geotermico di Larderello, mentre le altre litofacies possono essere correlate con formazioni ?Ordoviciane della successione metamorfica toscana (es. quella esposta sulle Alpi Apuane). La complessa evoluzione metamorfico-deformativa dell'Unità di Porto Azzurro può essere così schematizzata: *a*) evento tettono-metamorfico varisico (D_X), riconosciuto nel Complesso Metamorfico di Monte Calamita, testimoniato dalla presenza di relitti tessiturali (scistosità pre-alpina S_x) e mineralogici (granati); *b*) due eventi plicativi tettono-metamorfici alpini, con metamorfismo in facies di scisti verdi, che interessano anche le coperture mesozoiche; *c*) evento plicativo successivo (D_3), avvenuto probabilmente durante o immediatamente dopo la ricristallizzazione termometamorfica, dovuta ai granitoidi neogenici, alla quale sono legati anche i corpi di skarn a magnetite; *d*) successivamente la risalita dei corpi magmatici ha causato la formazione di detachment a basso angolo all'interno dell'Unità di Porto Azzurro (in particolare tra il Complesso Metamorfico di Monte Calamita e le coperture mesozoiche) e tra quest'ultima e le unità tettoniche sovrastanti (es. la faglia di Zuccale tra l'Unità di Porto Azzurro e l'Unità del Flysch Cretaceo); *e*) è seguito l'evento plicativo $D_{4,}$ che ha

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prodotto una blanda mega-antiforme, alla scala dell'intero promontorio. Infine si sviluppano faglie normali ad alto angolo ad andamento prevalentemente NW-SE e NE-SW, localmente interessate da mineralizzazioni a ossidi/idrossidi di ferro. L'assetto stratigrafico e l'evoluzione tettonica, metamorfica e magmatica dell'Unità di Porto Azzurro è molto simile a quella del campo geotermico di Larderello. Pertanto, il promontorio di M. Calamita può costituire un modello di riferimento per l'interpretazione della struttura profonda della Toscana meridionale attraversata dal profilo CROP 18.

TERMINI CHIAVE: *Appennino settentrionale, Isola d'Elba sud-orientale, successioni paleozoiche-Mesozoiche, evoluzione tettonica e metamorfica, messa in posto di granitoidi.*

INTRODUCTION

Elba Island, the biggest island of the Tuscan Archipelago, represents the westernmost outcrop of the Northern Apennines chain. The geological peculiarities of this island are not only linked to its complex tectonic pile of nappes and to the well-known Fe-rich ores, but also to the well-exposed interactions between Neogene magmatic intrusions and tectonics (TREVISAN, 1952; BARBERI *et alii*, 1969a; KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; BORTOLOTTI *et alii*, 2001; TANELLI *et alii*, 2001). Moreover, its geographical location, midway between Tuscany and Corsica, makes Elba Island a key place for the reconstruction of the extensional processes in the hinterland of the Northern Apennines (e.g. the opening of the Northern Tyrrhenian Sea) from the Early Miocene (BARTOLE *et alii*, 1991; BARTOLE, 1995). In this framework, the metamorphic rocks of the lowest tectonic unit (Complex I of TREVISAN, 1951 and BARBERI *et alii*, 1969; Porto Azzurro Unit of BORTOLOTTI *et alii*, 2001), exposed in the Mt. Calamita promontory (SE Elba: location in fig. 1) are poorly studied, perhaps because of their complex deformation and metamorphic evolution. In fact, such mostly pre-Alpine rocks (Calamita Schists *Auctt.*) suffered strong thermometamorphism and hydrothermalism related to Messinian-Pliocene magmatism, which locally obliterate the previous polyphase tectono-metamorphic framework. A similar younger geological framework is present at depth in the Larderello geothermal field (cfr. BATINI *et alii*, 1983; ELTER & PANDELI, 1990, 1996) located in southern Tuscany about 40 km distant from Elba. To improve the geological model of the geothermal field, crossed by the CROP-18 profile, the authors carried out 1:10,000 geological mapping, and lithostratigraphical,

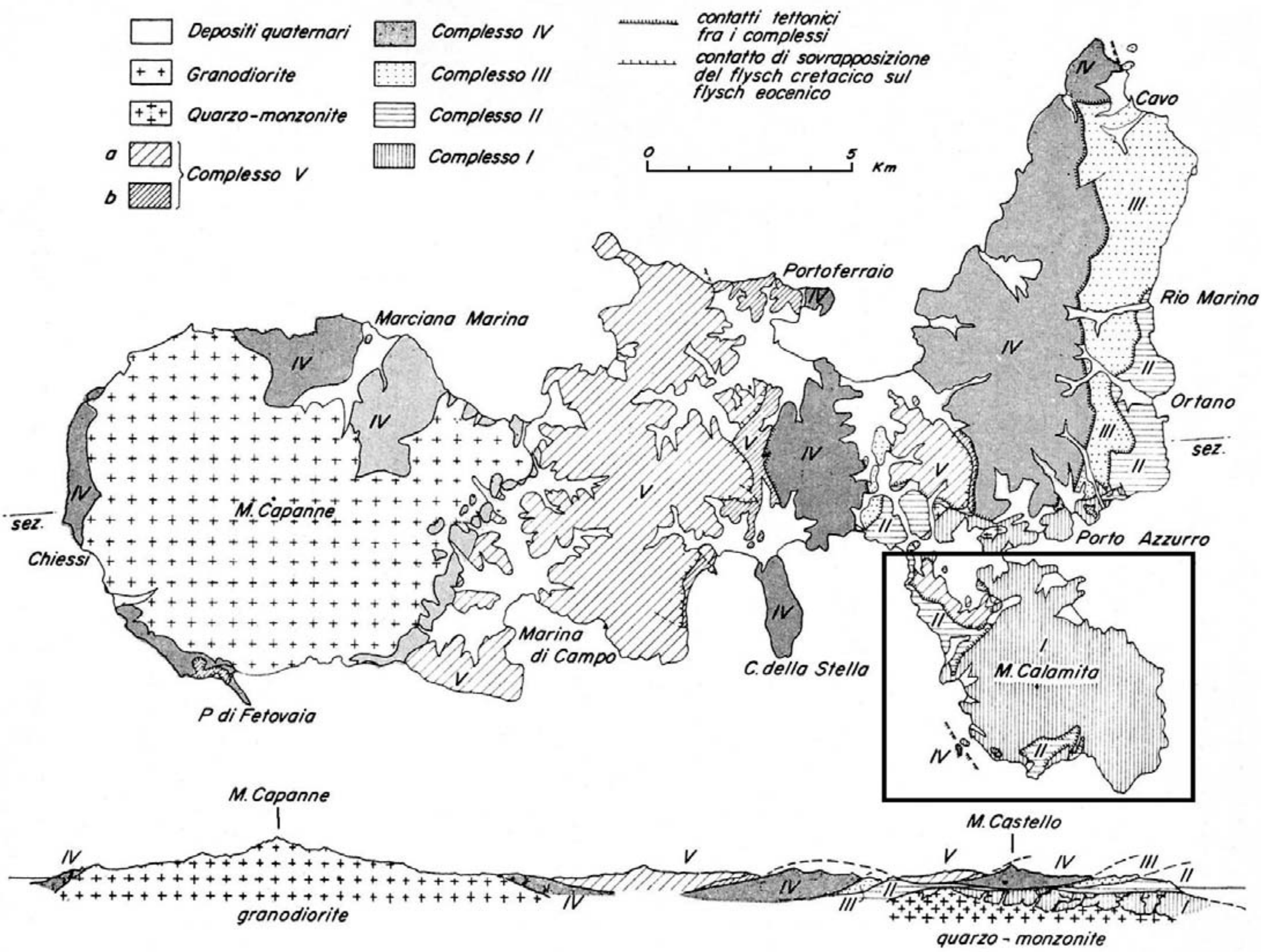

Fig. 1 - Tectonic sketch map of Elba Island according to BARBERI *et alii* (1969a) and location of the studied area (squared area).
– *Carta tettonica schematica dell'Isola d'Elba secondo* BARBERI et alii *(1969a) e localizzazione dell'area studiata (nel riquadro).*

petrographical and structural studies on the Porto Azzurro Unit to reconstruct its tectonic and metamorphic evolution and its relationships with the Neogene magmatic intrusions.

GEOLOGICAL FRAMEWORK

According to BARBERI *et alii* (1967a), the tectonic building of the Elba Island is composed of a structural pile of at least five main tectonic units («Complexes» of TREVISAN, 1950, fig. 1) of which the lowermost three belong to the Tuscan Domain, while the uppermost two relate to the Ligurian Domain.

In last ten years several papers have contributed to improve the tectono-stratigraphic framework of the island. In particular, BORTOLOTTI *et alii* (2001) performed 1:10,000 mapping of central-eastern Elba and proposed a new stratigraphic and tectonic model in which the five «Complexes» of TREVISAN were reinterpreted and renamed. BORTOLOTTI *et alii* (2001) recognised nine main tectonic units which are (fig. 2), from bottom to top of the tectonic stack:

1) *Porto Azzurro Unit* (TREVISAN's Complex I): this consists of ?Paleozoic mica-schists, phyllites and quartzites with local amphibolitic horizons (?Carboniferous-?Permian Calamita Gneiss: TREVISAN, 1950; BARBERI *et alii*, 1967a, 1969a,b; «Complesso scistoso basale di Capo Calamita»: BARBERI *et alii*, 1967b; Calamita Schists: PERRIN, 1975; Mt. Calamita Fm.: BORTOLOTTI *et alii*, 2001) and Triassic to Hettangian metasiliciclastics and metacarbonates. Particularly in the Porto Azzurro zone and in the eastern areas of the Calamita promontory, the Mt. Calamita Fm. is typically cross-cut by the aplitic and microgranitic dyke swarm of the La Serra-Porto Azzurro monzogranitic pluton (MARINELLI, 1959) of 5.1-6.2 Ma (SAUPÉ *et alii*, 1982; FERRARA & TONARINI, 1985), which produced a strong thermometamorphic imprint in the host rocks (MARINELLI, 1959; BARBERI *et alii*, 1967b). The contact with the overlying imbricated tectonic units is a cataclastic horizon, up to ten metres-thick, locally mineralised, linked to the well-known low-angle Zuccale fault, which post-dates the magmatic intrusions (KELLER & PIALLI, 1990; DANIEL & JOLIVET, 1995; PERTUSATI *et alii*, 1993; BORTOLOTTI *et alii*, 2001; COLLETTINI & BARCHI, 2004).

2) *Ortano Unit* (lower part of TREVISAN's Complex II): this comprises phyllites and quartzites (Capo d'Arco Schists, intruded by rare aplitic and more femic dykes), porphyroids and porphyritic schists, and phyllites, quartzitic metasandstones and metaconglomerates at the top. This succession has been correlated with the Ordovician formations of central Sardinia and of Apuan Alps (PANDELI & PUXEDDU, 1990). Also this unit suffered thermometamorphic recrystallization due to the Serra Porto Azzurro intrusion (DURANTI *et alii*, 1992). A vacuolar carbonate cataclasite, with clasts of phyllites and porphyritic schists at the base, marks the contact with the overlying unit.

3) *Acquadolce Unit* (upper part of TREVISAN's Complex II). The basal part is made up of locally dolomitic massive marbles, grading upwards to calcschists. The latter are capped by a thick siliciclastic succession, which includes some layers of calcschists containing a Lower Cretaceous microfauna (DURANTI *et alii*, 1992). BORTOLOTTI *et alii* (2001) and PANDELI *et alii* (2001a) consider this succession to be a metamorphosed oceanic Ligurian-Piemontese unit similar to the *Schistes Lustrés* of Corsica and Gorgona islands. The presence of a meta-serpentinite slice at its top is in agreement with this interpretation. The Mio-Pliocene thermometamorphic imprint is also evident in these rocks.

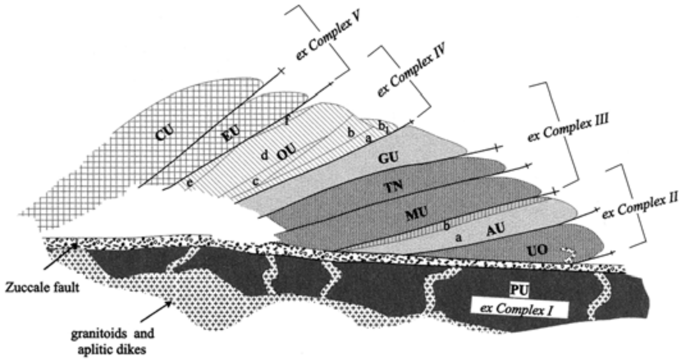

Fig. 2 - Central Eastern Elba tectonic sketch according to BORTOLOTTI *et alii* (2001). PU=Porto Azzurro Unit; UO=Ortano Unit; AU=Acquadolce Unit (*a* - Porticciolo sub-unit, *b* - S. Filomena sub-unit); MU=Monticiano Roccastrada Unit; TN=Tuscan Nappe; GU=Grassera Unit; OU=Ophiolitic Unit (*a* - Acquaviva sub-unit, *b* - M. Serra sub-unit., b_1 - Capo Vita sub-unit, *c* - Sassi Turchini sub-unit, *d* - Volterraio sub-unit, *e* - Magazzini sub-unit, *f* - Bagnaia sub-unit); EU=Paleogene Flysch Unit; CU=Cretaceous Flysch Unit.
– *Schema tettonico dell'Elba centro orientale secondo* BORTOLOTTI et alii *(2001). PU=Unità di Porto Azzurro; UO=Unità di Ortano; AU=Unità dell'Acquadolce (*a *- sub-unità del Porticciolo,* b *- sub-unità di S. Filomena); MU=Unità Monticiano Roccastrada; TN=Falda Toscana; GU=Unità del Grassera; OU=Unità Ophiolitica (*a *- sub-unità dell'Acquaviva,* b *- sub-unità di M. Serra,* b_1 *- sub-unità di Capo Vita,* c *- sub-unità dei Sassi Turchini,* d *- sub-unità del Volterraio,* e *- sub-unità di Magazzini,* f *- sub-unità di Bagnaia); EU=Unità del Flysch Paleogenico; CU=Unita del Flysch Cretaceo.*

4) *Monticiano-Roccastrada Unit* (lower part of TREVISAN's Complex III). This includes basal fossiliferous graphitic metasediments of Late Carboniferous-Early Permian age (Rio Marina Fm.), unconformably overlain by the detrital Verrucano succession (?Middle-Late Triassic). The epimetamorphic succession of Capo Castello, consisting of Upper Jurassic siliceous metalimestones to Oligocene metagreywackes, and the ?Mesozoic phyllitic-carbonate rocks of Capo Pero have been considered as part of the original cover of Verrucano (PANDELI *et alii*, 1995; BORTOLOTTI *et alii*, 2001).

5) *Tuscan Nappe Unit* (central part of TREVISAN's Complex III). This is represented by calcareous-dolomitic breccias (Calcare Cavernoso *Auctt*.) cropping out between Porto Azzurro and Rio Marina, and near Norsi-Valdana. Northwards, in the Cavo area, the overlying carbonatic (Pania di Corfino Fm., Cetona Fm. and «Calcare Massiccio», Late Triassic-Hettangian), carbonatic-cherty (Limano and Grotta Giusti Limestones and «Rosso Ammonitico», Middle-Late Liassic) and marly-carbonatic (Posidonia Marlstones, Dogger) non-metamorphic formations also crop out.

6) *Grassera Unit* (upper part of TREVISAN's Complex III). Most of the unit is made up of varicoloured slates and siltstones with rare metalimestone or meta-chert intercalations; basal calcschists also occur. These rocks, previously included in the «Posidonia Marlstones» of the Tuscan Nappe (BARBERI *et alii*, 1969a,b), differ from both

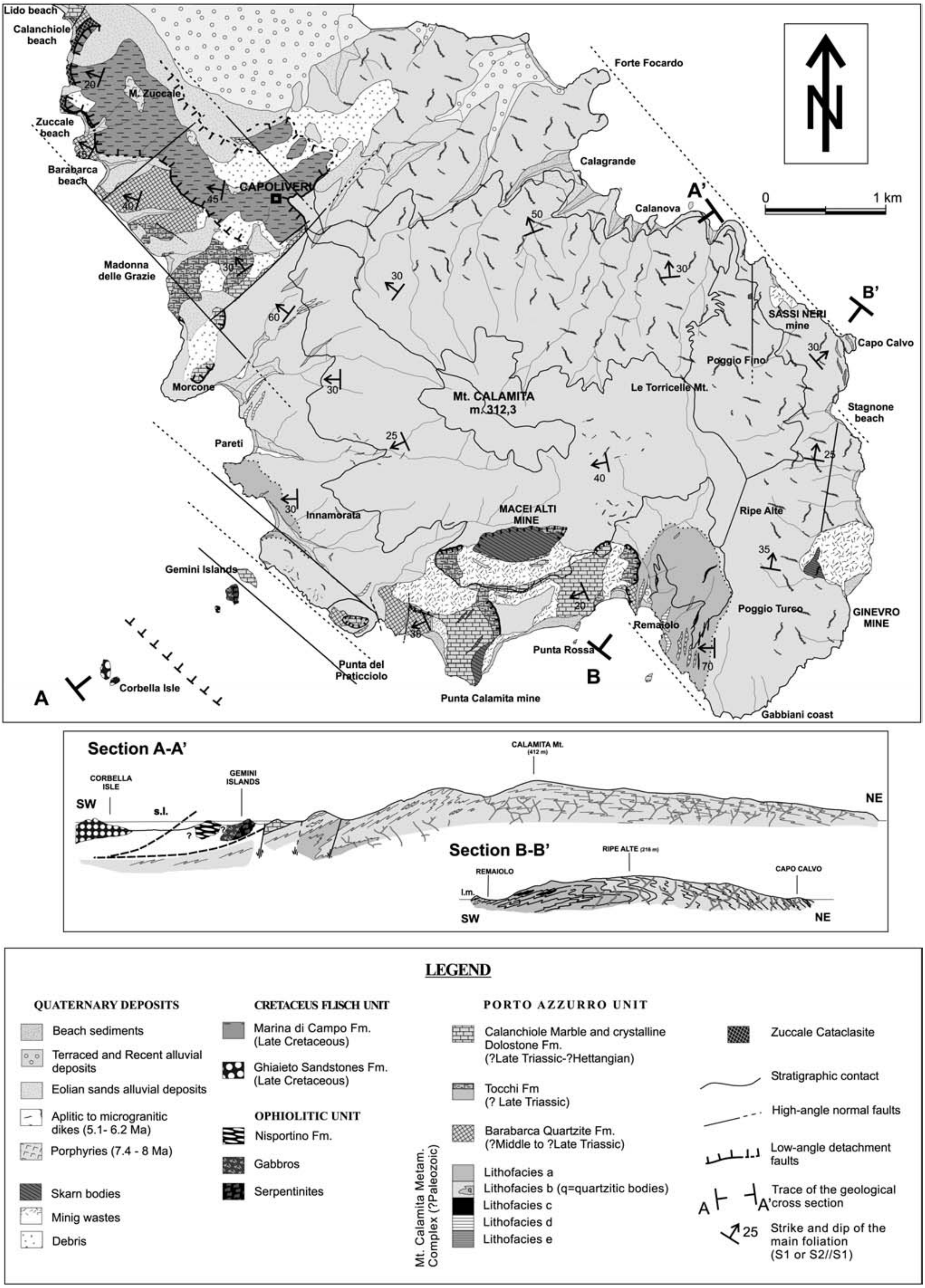
Lido beach
Calanchiole beach
M. Zuccale
Zuccale beach
Barabarca beach
CAPOLIVERI
Madonna delle Grazie
Morcone
Pareti
Innamorata
Gemini Islands
Corbella Isle
Punta del Praticciolo
Punta Calamita mine
Punta Rossa
Remaiolo
Gabbiani coast
MACEI ALTI MINE
Mt. CALAMITA m. 312,3
Le Torricelle Mt.
Poggio Fino
SASSI NERI mine
Capo Calvo
Stagnone beach
Ripe Alte
Poggio Turco
GINEVRO MINE
Calanova
Calagrande
Forte Focardo
N
0
1 km
A
A'
B
B'
Section A-A'
CORBELLA ISLE
GEMINI ISLANDS
CALAMITA Mt. (412 m)
SW
NE
s.l.
Section B-B'
REMAIOLO
RIPE ALTE (216 m)
CAPO CALVO
l.m.
SW
NE
LEGEND
QUATERNARY DEPOSITS
Beach sediments
Terraced and Recent alluvial deposits
Eolian sands alluvial deposits
Aplitic to microgranitic dikes (5.1- 6.2 Ma)
Porphyries (7.4 - 8 Ma)
Skarn bodies
Minig wastes
Debris
CRETACEUS FLISCH UNIT
Marina di Campo Fm. (Late Cretaceous)
Ghiaieto Sandstones Fm. (Late Cretaceous)
OPHIOLITIC UNIT
Nisportino Fm.
Gabbros
Serpentinites
PORTO AZZURRO UNIT
Calanchiole Marble and crystalline Dolostone Fm. (?Late Triassic-?Hettangian)
Tocchi Fm (? Late Triassic)
Barabarca Quartzite Fm. (?Middle to ?Late Triassic)
Mt. Calamita Metam. Complex (?Paleozoic)
Lithofacies a
Lithofacies b (q=quartzitic bodies)
Lithofacies c
Lithofacies d
Lithofacies e
Zuccale Cataclasite
Stratigraphic contact
High-angle normal faults
Low-angle detachment faults
Trace of the geological cross section
Strike and dip of the main foliation (S1 or S2//S1)

Fig. 3a

Tuscan and Ligurian lithotypes, show a slight metamorphism (up to the anchizone/epizone boundary) and tectonically lie on different formations of the Tuscan Nappe (PANDELI *et alii*, 2001b). Therefore, BORTOLOTTI *et alii* (2001) tentatively attributed also the Grassera Unit to Ligurian-Piemontese oceanic domain.

7) *Ophiolitic Unit* (TREVISAN's Complex IV). Within this Ligurian unit, BORTOLOTTI *et alii* (2001) recognized four main tectonic sub-units with Jurassic to Cretaceous formations (from bottom to top): *a*) Acquaviva sub-unit with serpentinites-ophicalcites, basalts, Mt. Alpe Cherts and Palombini Shales; *b*) Sassi Turchini sub-unit with serpentinites; *c*) Mt. Serra sub-unit with ophicalcites, Mt. Alpe Cherts, Nisportino Fm., Calpionella Limestones and Palombini Shales; *d*) Volterraio sub-unit with serpentinite, basalts, Mt. Alpe Cherts, Nisportino Fm. and Calpionella Limestones.

8) *Paleogene Flysch Unit* (lower part of TREVISAN's Complex V). This mainly consists of shales, marls with limestone, sandstone and ophiolitic breccia intercalations including fossils of Paleocene-Eocene age. KELLER & PIALLI (1990) and BORTOLOTTI *et alii* (2001) correlated this unit with the Epiligurian Lanciaia Fm. of southern Tuscany.

9) *Cretaceous Flysch Unit* (upper part of TREVISAN's Complex V). This Ligurian, Lower to Upper Cretaceous unit, consists of basal Palombini Shales and varicoloured shales, which vertically pass to turbiditic siliciclastic sandstones and conglomerates (Ghiaieto Sandstones) and these latter to alternating marlstones and marly limestones (Marina di Campo Fm.).

Both Flysch Units were intruded by aplitic and porphyritic dykes and laccoliths at about 7-8 Ma (DINI *et alii*, 2002).

The evolution of deformation of Elba Island can be dated back to the Variscan Orogeny, which affected the Mt. Calamita Fm. and the Ortano Unit (PANDELI & PUXEDDU, 1990). During the Upper Cretaceous-Eocene closure of the Ligurian-Piemontese Ocean, intraoceanic deformations of the Ligurian and the «*Schistes Lustrès*»-like units took place. The subsequent collision and ensialic shortening of the Adriatic margin occurred in the Upper Eocene/Oligocene to Lower Miocene time interval, during which the «*Schistes Lustrès*»-like, Ligurian and Tuscan Units were deformed and piled up. During ?Early-Middle Miocene times, extensional tectonics began and led to the thinning of the structural pile, the opening of the Tyrrhenian Sea and the uplift of magmatic bodies, such as the Mt. Capanne (about 6.8 Ma: JUTEAU *et alii*, 1984; FERRARA & TONARINI, 1993) and the Serra-Porto Azzurro (5.1-6.2 Ma: SAUPÉ, 1982; FERRARA & TONARINI, 1993; 5.9 Ma: MAINERI *et alii*, 2003) granitoids in Elba Island.

The emplacement of the magmatic bodies determined both a thermometamorphic and metasomatic imprint (e.g. skarn bodies: DIMANCHE, 1971; TANELLI, 1977) in the country rocks and gravitational detachments within the pile of nappes (TREVISAN, 1951; PERTUSATI *et alii*, 1993; DANIEL & JOLIVET, 1995; BORTOLOTTI *et alii,* 2001). A final high-angle, mainly N-S trending normal faulting dissected the Elba tectonic stack (BORTOLOTTI *et alii,* 2001) and was locally sealed by hematite-rich ores (DESCHAMPS *et alii*, 1983; LIPPOLT *et alii*, 1995).

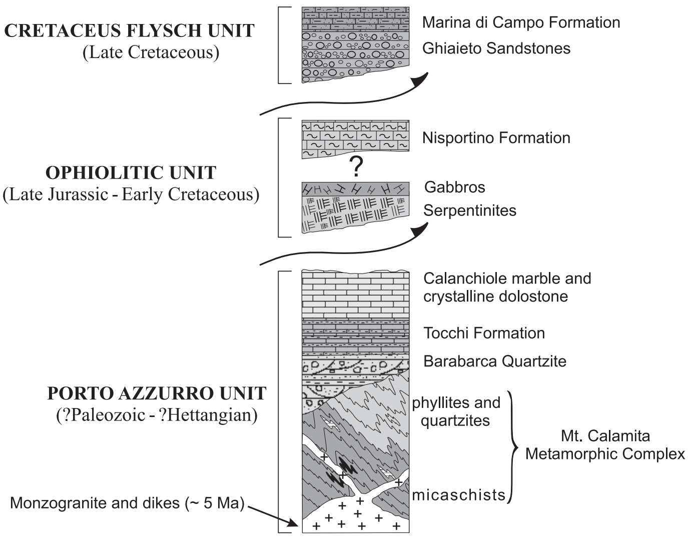

Fig. 3 - a) Geological sketch map and geological cross-sections of the Mt. Calamita promontory; *b*) Stratigraphic and structural sketch of the units cropping out in the Mt. Calamita promontory.
– a) *Carta geologica schematica e sezioni geologiche del promontorio del Monte Calamita;* b) *schema stratigrafico e strutturale delle unità affioranti nel promontorio del Monte Calamita.*

GEOLOGY OF THE CALAMITA PROMONTORY

Most of the Mt. Calamita promontory is made up of polymetamorphic rocks of the Porto Azzurro Unit. In fact, the Cretaceous Flysch Unit (Marina di Campo Fm.) tectonically lies, through the Zuccale Fault (KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; DANIEL & JOLIVET, 1995; KELLER & COWARD, 1996; BORTOLOTTI *et alii*, 2001; COLLETTINI & BARCHI, 2004) on top of the Porto Azzurro Unit only in the Capoliveri-Zuccale-Lido di Capoliveri area. Another minor outcrop of the Cretaceous Flysch Unit (Ghiaieto Ss.) is that of the Scoglio Corbella (southwest of the studied area). The Ophiolitic Unit crops out only in the outermost of the two Gemini Islands (Serpentinites and Gabbros) and in some emerging rocks (marls and marly limestones of the Nisportino Fm.) between the Scoglio Corbella and the Mt. Calamita promontory (fig. 3a). Quaternary deposits, mostly consisting of cemented sands locally characterized by large-scale cross-stratification (eolian sands and beach rocks: MAZZANTI, 1983; CENTAMORE *et alii*, 1988), are present in the western coast of the promontory and in the Calagrande-Calanova area.

The stratigraphic and structural study of the unfossiliferous Porto Azzurro Unit has always been difficult because of the Messinian-Lower Pliocene thermometamorphic overprint and skarn mineralizations, which locally completely obliterate previous textures and mineralogical associations of these polymetamorphic rocks. Apart from the ?Triassic metasiliclastics (Verrucano *Auctt*.; Barabarca Quartzites of PERRIN, 1975) and ?Triassic-?Hettangian metacarbonates (e.g. Calanchiole marble and crystalline dolostone), the underlying Mt. Calamita Fm. (BORTOLOTTI *et alii*, 2001) has been considered as an undifferentiated unit both in the 1:25,000 geological map (BARBERI *et alii*, 1967a) and in the Sheet 126 of the 1:100,000 Geological Map of Italy by BARBERI *et alii* (1969a,b). Only in the 1:25,000 map did BARBERI and coworkers distinguish amphibolite horizons. In the same

TABLE 1

Lithological, petrographical and textural features of the Porto Azzurro Unit in the Calamita promontory.
– *Caratteristiche litologiche, petrografiche e tessiturali dell'Unità di Porto Azzurro nel promontorio del Monte Calamita.*

UNITS		LITHOLOGY	TEXTURE	MINERALOGICAL ASSOCIATIONS		
				PRE/SYN ALPINE TECTONO-METAMORPHIC MINERALS	THERMOMETAMORPHIC MINERALS (HT/LP events)	HYDROTHERMAL MINERALS (post-tectonic veins)
Mt. Calamita Metamorphic Complex (?Pre Paleozoic - ? Early Paleozoic)	Lithofacies a	micaschists and phyllites	granolepidoblastic to porphyroblastic	Ms + Ab + Qtz + Chl ± Bt local pre-Alpine Grt, frequent Ab porphyroblasts with helicitic inclusion trails (Op ± Qtz ± Ms) Acc. Min.: Ap, Ox, Py, Ttn, Tur, Zrn	And + Bt + Ms or Bt ± And	Chl, Tur + Adu + Ab, Qtz + Chl, Ep
	Lithofacies b	quartizitic phyllites and quartzites	granolepidoblastic to granoblastic/ blastopsammitic	Qtz + Ms + Ser ± Chl (± Ab) millmetric levels with abundant Hem pigment, rare Ab; Acc. Min.: Ap, Hem, Py, Tur, Zrn	Crd + And + Bt (Ginevro and Sassi Neri area), And + Bt + Ms or Bt + Chl ± And skarn (Ginevro and Sassi Neri): FeAct +Feprg + Hbl + Mag + Py ± Lm	Qtz + Chl + Ep
	Lithofacies c	black quartzites and phyllites	granolepidoblastic to granoblastic	Qtz + Ms + Op ± Ab ± Chl abundant Opaque and organic matter pigment Acc. Min.: Ap, Ox, Tur	Bt or Bt + And	
	Lithofacies d	amphibolites	granolepidoblastic to nematoblastic	Hbl + Qtz + acid Pl (+Pli)+ Ms Acc. Min.: Ap, Ox, Ttn, Tur, Zrn	Bt + Tr-Act	Ep + Tr-Act
	Lithofacies e	porphyroids	granoblastic/ porphyroblastic	Qtz + Pl + Kfs + Bt porphyroblasts and aggregates of: Qtz, Pl, Kfs Acc. Min.: Ap, Ox, Ttn, Tur, Zrn	Bt	
Barabarca Quartzite (?Late Ladinian-?Carnian)		quartzities	blastopsammitic, granoblastic to granolepidoblastic	Qtz + Ser (± Ms) ± Chl. Acc. Min.: Ap, Hem, Tur, Ox (Fe)	Bt + And	Qtz, Qtz + Chl
Tocchi Fm. (?Carnian)		phyllites, calcschists and impure marbles	diablastic, nematoblastic to lepidoblastic	carbonate beds: Cal (or Cal ± Mg) ± Qtz ± Ab + Ox phyllitic beds: Ser + Chl + Qtz ± Ms + Ox Acc. Min.: Hem, Py, Mag, Ccp, Mrc, Tur	Bt + Act ± Tr skarn (Calamita Mine): Tr-Act + Adr + + Hd + Hem + Mag + Py	Qtz + Py + Mag + Tr-Act
Calanchiole Marble and Cristalline Dolostone (?Rhaetian-?Hettangian)		marbles and crystalline dolostones	granoblastic to xenoblastic	Cal + Dol ± Qtz ± Ser. Acc. Min.: Ap, Hem, Ox (Fe).	Cal + Tr ± Bt skarn (Calamita Mine): Adr + Hd + + Hem + Mag + Py	Cal, Cal + Hem

year, BARBERI *et alii* (1967b) recognized in the «Complesso scistoso basale di Capo Calamita» three petrofacies: «Scisti muscovitico-biotitici ad andalusite» and «Scisti muscovitico-biotitici con metablastesi plagioclasica» of possibly Paleozoic age, and «Scisti quarzoso-muscovitico-biotitici con intercalazioni di quarziti nella parte alta», which they correleted to the Triassic Verrucano. Successively, PUXEDDU *et alii* (1984) distinguished, on the evidence of petrography-geochemistry, four groups of rocks, which could be tentatively attributed to the Carboniferous (e.g. S. Lorenzo Group) and Lower Paleozoic (Lower Quartzite and Phyllite Fm. and Upper Quartzite and Phyllite Fm., and Boccheggiano Fm.) units of Tuscany (cfr. PANDELI *et alii*, 1994). The presence of Variscan rocks in the Mt. Calamita Fm. was also suggested by the local discovery of pre-Alpine foliation relics (PANDELI & PUXEDDU, 1990; FASANO *et alii*, 2001). As it regards the protolith of the thermometamorphosed amphibolite horizons within the Mt. Calamita Fm., in the Pareti-Morcone and in the Remaiolo areas (fig. 3a), BARBERI & INNOCENTI (1965) and BARBERI *et alii* (1967b) suggested a basic magmatic origin (Triassic volcanics? or tectonic slices of Ligurian basalts?); the same horizons were correlated to the within-plate Paleozoic metabasites of southern Tuscany by PUXEDDU *et alii* (1984). In any case, Ca-Mg-hornfels, locally associated with the amphibolite horizon of the Pareti-Morcone area, was interpreted by BARBERI *et alii* (1967b) as metamorphosed dolostone. A carbonatic protolith of Paleozoic age (e.g. Silurian dolostones of the Apuan Alps) was suggested also by DIMANCHE (1971) for the skarn intercalations of the Ginevro mining area (fig. 3a).

The data from our 1:10,000 geological map of the Mt. Calamita promontory, and from meso-/microstructural and petrographical studies on its polymetamorphic rocks, are discussed in the following paragraphs.

LITOLOGICAL AND PETROGRAPHICAL DATA

The non-fossiliferous Porto Azzurro Unit shows an apparent thickness of at least 800 m and consists of a recrystallized ?Triassic-Hettangian? cover succession which lies on the Mt. Calamita Metamorphic Complex (sensu INTERNATIONAL SUBCOMMISSION ON STRATIGRAPHIC CLASSIFICATION, 1987), made up of pre-Paleozoic? to Paleozoic formations.

From bottom to top, the following units were distinguished (see fig. 3a,b; see also table 1 for detailed petrographical data, mineral abbreviations as KRETZ, 1983, and Adularia = Adu, Marcasite = Mrc, Opaques = Op, Sericite = Ser, Fe-pargasite = Fe-prg):

– *Mt. Calamita Metamorphic Complex*. This metamorphic complex represents most of the outcrops of the Porto Azzurro Unit (fig. 4) and lies unconformably below the Verrucano metasediments (Barabarca Quartzites). In spite of the local strong thermometamorphic imprint (e.g. in the eastern part of the promontory) and magnetite-rich skarn mineralizations (e.g. the Ginevro and Sassi Neri areas; fig. 3a), at least four lithofacies can be distinguished.

– *Lithofacies a*. It mainly consists of silver grey, grey-brown to grey-greenish, quartzitic mica-schists and phyllites with local ochreous alteration. The muscovite and muscovite-biotite mica-schists typically include syntectonic albite porphyroblasts (fig. 5a). Rare garnet porphyroblasts also occur (fig. 5b). These latter are broken, chloritized and wrapped by the Alpine foliations (see below) and are sometimes recrystallized into thermometamorphic biotite pseudomorphic aggregates. These lithotypes crop out in the Poggio Turco-Remaiolo-Costa dei Gabbiani area (fig. 3a) and correspond to the «Scisti muscovitico-biotitici con metablastesi plagioclasica» of BARBERI *et alii* (1967b). Centimetre- to 2m-thick, dark grey to grey-brown quartzites are locally present as intercalations or, in the Pareti-Innamorata area (fig. 3a), as the dominant lithology. The contact with Lithofacies b is tentatively represented in the geological map (fig. 3a) as dotted lines.

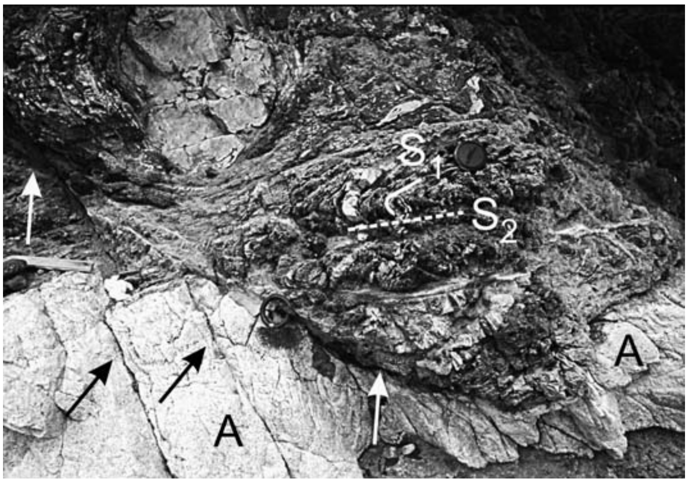

Fig. 4 - A typical outcrop of the phyllites and quartzites of the Mt. Calamita Metamorphic Complex (Cala di Mola area) affected by Alpine folding (S_1 and S_2 = Alpine foliations) and intruded by aplitic dykes (A); the latter are dissected by low-angle (white arrow) and, successively, by high-angle (black arrows) faults.
– Tipico affioramento delle filladi e quarziti del Complesso Metamorfico di Monte Calamita (presso Cala di Mola) caratterizzate da deformazioni alpine (S_1 and S_2 = foliazioni alpine) e intruse da dicchi aplitici (A); questi ultimi sono tagliati da faglie a basso (frecce bianche) e, successivamente, ad alto angolo (frecce nere).

– *Lithofacies b*. This is represented by centimetric to decimetric alternations of granolepidoblastic, often quartzose grey-greenish phyllites and grey granoblastic to blastopsammitic metasandstones. In particular, they are fine- to coarse-grained quartzitic metasandstones and chlorite-poor phyllites (fig. 5c), which locally include millimetre-scale alignments of Fe-oxides (e.g. in the areas west and north-west of Mt. Calamita). In any case, some samples collected NE of Mt. Calamita are albite-bearing metasandstones and phyllites which were probably rich in chlorite, now mostly transformed into thermometamorphic biotite. Lenticular bodies of quartzitic metasandstones, meters to tens of metres thick, have been distinguished in the Capoliveri-Morcone area (fig. 3a).

– *Lithofacies c*. This consists of alternating black phyllites and grano-lepidoblastic quartzites which are rich in organic matter (fig. 5d). They form decimetric to decametric lenticular bodies within lithofacies a in the Poggio Turco-Costa dei Gabbiani area (the thickest bodies are shown in fig. 3a). The contact with the mica-schists is locally gradual. Similar lithotypes (alternating grey to light grey quartzites and quartzose microconglomerates with layers of black phyllites) also occur in the Punta del Praticciolo (fig. 3a) coast, and were inter-

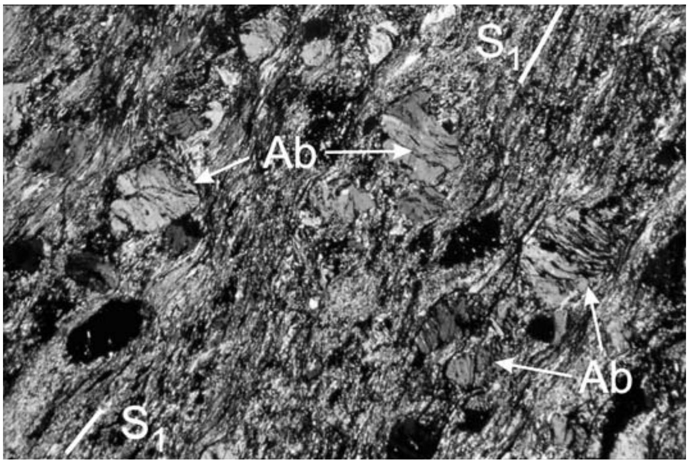

Fig. 5a

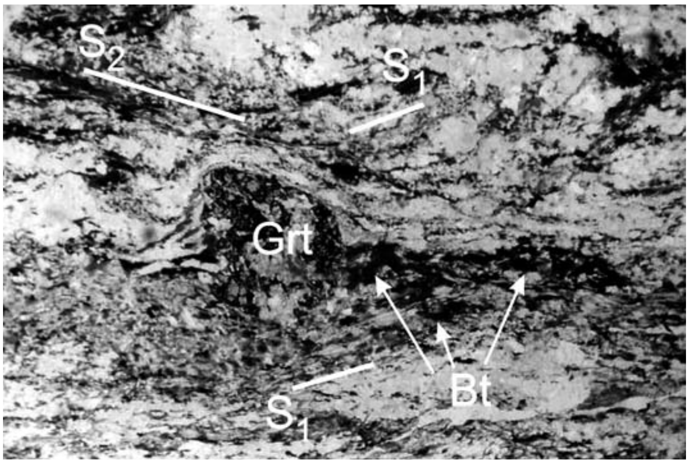

Fig. 5b

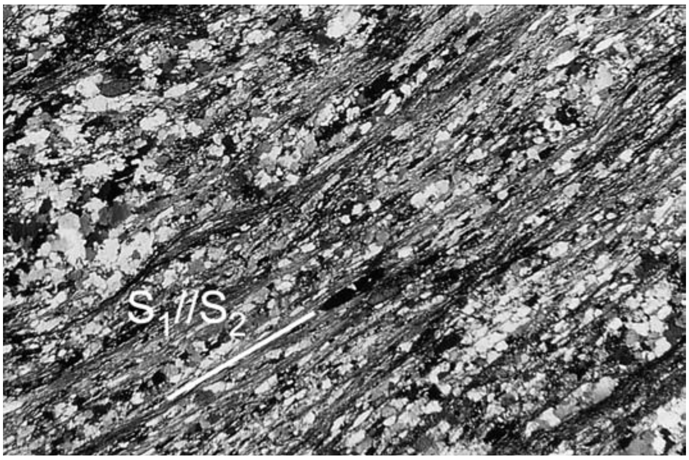

Fig. 5c

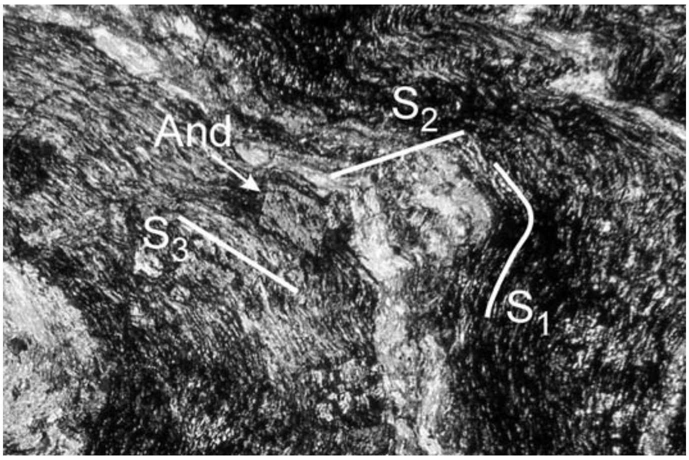

Fig. 5d

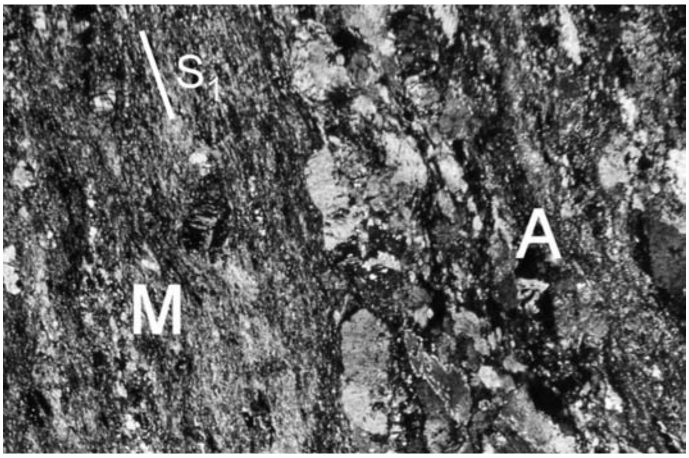

Fig. 5e

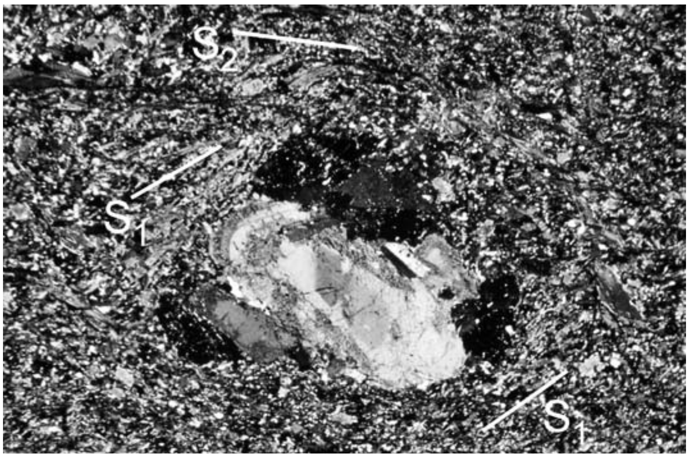

Fig. 5f

Fig. 5 - Photomicrographs of the lithofacies within the Mt. Calamita Metamorphic Complex: *a*) albite porphyroblasts (Ab) in the mica-schists of lithofacies a (crossed polars, 15×); *b*) Pre-S_1, fractured and chloritized garnet porphyroblasts (Grt) in the mica-schists of lithofacies a, Bt=static thermometamorphic biotite (parallel polars, 25×); *c*) quartzitic phyllite of lithofacies b (crossed polars, 10×); *d*) graphite-rich phyllite of lithofacies c (crossed polars, 10×) including post-S_2 static andalusite porphyroblasts (And); *e*) passage from mica-schists (M) of lithofacies a to amphibolite (A) of the lithofacies d (crossed polars, 15×); *f*) zoned and twinned, acidic plagioclase composite porphyroclast within the porphyroids of lithofacies e (crossed polars, 10×). S_1, S_2 = Alpine foliations.
– *Microfotografia delle litofacies all'interno del Complesso Metamorfico di Monte Calamita:* a) *porfiroblasti di albite (Ab) nei micascisti della litofacies a (nicols incrociati, 15×);* b) *porfiroblasti di granato pre-S_1, fratturati e cloritizzati (Grt) nei micascisti della litofacies a, Bt=biotite statica termometamorfica (nicols paralleli, 25×);* c) *filladi quarzitiche della litofacies b (nicols incrociati, 10×);* d) *filladi grafitose della litofacies c (nicols incrociati, 10×), che includono porfiroblasti di andalusite statica post-S_2;* e) *passaggio tra micascisti (M) della litofacies a alle anfiboliti (A) della litofacies d (nicols incrociati, 15×);* f) *porfiroblasto zonato e geminato di plagioclasio acido composito nei porfiroidi della litofacies e (nicols incrociati, 10×). S_1, S_2 = foliazioni alpine.*

preted as Carboniferous metasediments by PUXEDDU *et alii* (1984).

– *Lithofacies d*. This consists of green, banded light and dark-green to black amphibolites, which occur as lenses tens of meters thick in western (Pareti-Morcone), south-western (north of Punta del Praticciolo) and south-eastern (Remaiolo) areas of the promontory. The amphibolite to the east of the Remaiolo area shows transitional boundaries to the mica-schists by millimetre-scale alternations of the two lithologies (fig. 5e). At the microscale, the less thermometamorphosed samples are characterized by a granonematoblastic texture with albite-oligoclase+tremolite-actinolite (after hornblende)+ titanite; a post-tectonic metasomatic assemblage of garnet (grossular-andradite) ± hedembergite also occur, for example NE of Morcone (i.e.: Ca-Mg hornfels of BARBERI *et alii*, 1967b)

– *Lithofacies e*. Grey to dark grey rocks, which show a typical microaugen texture at the mesoscale and form discontinuous (mostly due to faulting), decimetres to some metres-thick horizons within the phyllitic-quartzitic lithotypes of the Capo Calvo area (east coast of the promontory). The porphyroclastic texture is due to pre-kinematic (magmatic) blasts, up to 1 cm in size, of feldspars (mostly acidic plagioclases), quartz and minor granoblastic/granular aggregates of quartz+plagioclase+k-feldspar in a quartzose-feldspathic-micaceous groundmass (fig. 5f). The latter is affected by the same pervasive foliation as the surrounding quartzose metapelites; this foliation appears parallel to the lithological contact and deformed by the D2 folding.

It is still difficult to define the geometric-stratigraphical setting of the Mt. Calamita Metamorphic Complex lithofacies, because of the polyphase folding (see later) and the presence of possible tectonic slices (see MARINELLI, 1959), but we hypothesize that Lithofacies a is at the geometric base of the succession as shown by the geological cross-sections in fig. 3a. The stratigraphical contact with the overlying Barabarca quarzite was locally affected by the Alpine syn-metamorphic folding.

In the ?Triassic-?Hettangian cover we distinguish the following informal formations:

– *Barabarca quartzite.* This unit widely crops out along the Zuccale-Barabarca coast; other minor exposures are located at Calanchiole (south of Spiaggia del Lido, see fig. 3a), south of the Innamorata Gulf, east of the Punta del Praticciolo and around the Remaiolo Gulf. Its maximum apparent thickness is about 50 m. The main lithotype is poorly-sorted-, quartzitic metaconglomerates («anageniti» *Auctt*.) and quartzites with typical white and pink quartz pebbles in a quartzose-micaceous matrix (fig. 6a). Quartzitic and phyllitic lithics, as well as black quartz+tourmaline clasts («tourmalinites», fig. 6b), are also present; these latter lithics characterize the ?Late Ladinian-Carnian Verrucano basal siliciclastics at the regional scale (CAVARRETTA *et alii*, 1989, 1992; PANDELI, 2002 *and references therein*). These blasto-psefitic/-psammitic rocks, which are medium- to thick-bedded (max. 1.5-2m) and locally normally graded, sometimes show centimetric to decimetric ±quartzose metapelitic intercalations, wine-red, grey or green in colour. Erosional contacts are frequently seen at the base of coarser beds. In the Barabarca and Calanchiole areas, the «anageniti»

Fig. 6a - Quartzose metaconglomerates («Anageniti») of the Barabarca Quartzite Fm. at Barabarca (T=tourmalinite clast).
– *Metaconglomerati quarzitici («Anageniti») della Formazione delle Quarziti di Barabarca presso Barabarca (T=clasto di tormalinolite).*

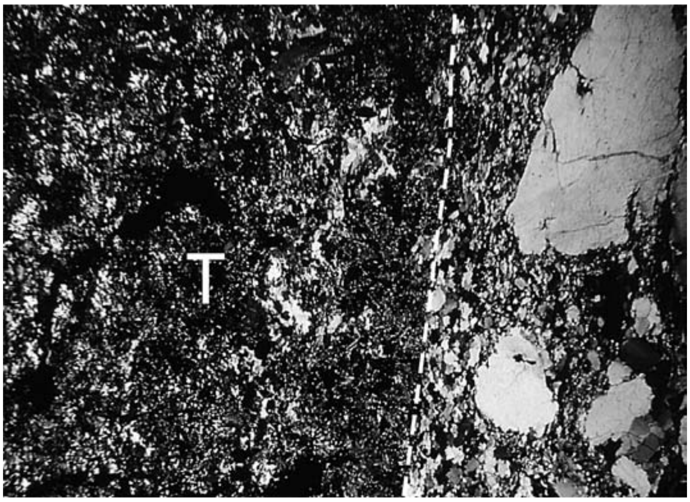

Fig. 6b - Photomicrograph of the contact (dashed line) between a tourmalinite clast (T) and the surrounding low-sorted quartzitic matrix in a meta-psephite of the Barabarca Quartzites Fm. (crossed polars, 15×).
– *Microfotografia del contatto (linea tratteggiata) tra un clasto di tormalina (T) e la circostante matrice quarzitica ben classata in una meta-psefite della Formazione delle Quarziti di Barabarca (nicols incrociati, 15×).*

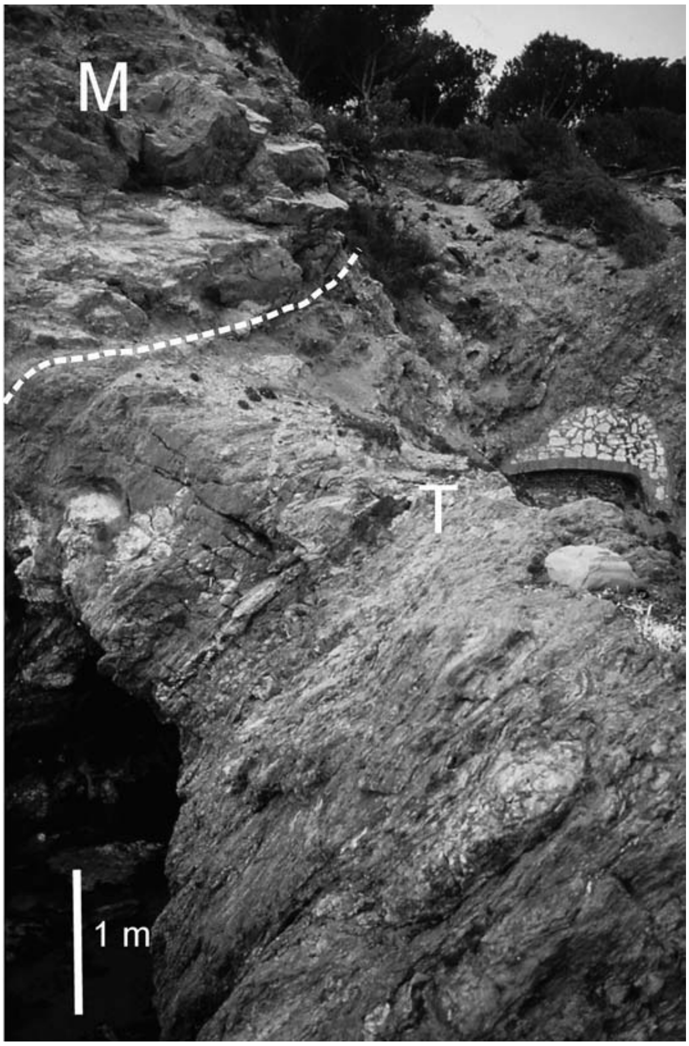

Fig. 7a - Stratigraphic passage from alternating phyllites and metacarbonate beds of the Tocchi Fm. (T) and the overlying Calanchiole marble and crystalline dolostone (M) at the Calanchiole beach.
– Passaggio stratigrafico tra l'alternanza di livelli filladici e carbonatici della Formazione di Tocchi (T) e i sovrastanti Marmi e dolomie cristalline delle Calanchiole (M) presso la spiaggia delle Calanchiole.

Fig. 7b - Photomicrograph of a calcschist of the Tocchi Fm. (crossed polars, 15×); S_1 and S_2 = Alpine foliations.
– Microfotografia dei calcescisti della Formazione di Tocchi (nicols incrociati, 15×); S_1 e S_2 = foliazioni alpine.

include and grade upwards into alternating fine- to very coarse-grained quartzites and grey, greenish and pinkish-violet, more or less quartzitic phyllites and metasiltstones. The contact with the overlying Tocchi Fm. is gradual (appearance of carbonate intercalations), but it is frequently tectonized.

– *Tocchi Fm.* This occurs at Calanchiole (south of Spiaggia del Lido), Madonna delle Grazie, and in the Calamita mining area (fig. 3) with a maximum apparent thickness of about 150 m. Where it is not affected by tectonism (it generally represents a preferential detachment horizon) or by mineralization (e.g. the Punta della Calamita skarn), it consists of alternating light grey to orange-yellow, impure, more or less dolomitic metadolostone and calcschist beds. They are up to 60 cm thick, green, grey-green and brownish sericitic-chloritic phyllites. The stratigraphical position and its lithological association is similar to the Carnian Tocchi Fm. of southern Tuscany (cfr. COSTANTINI *et alii,* 1980). At Madonna delle Grazie beach, this unit is strongly tectonized (Madonna delle Grazie cataclasite). The transition to the overlying carbonate unit (fig. 7a) is gradual (decrease in pelitic lithotypes).

– *Calanchiole marble and crystalline dolostone.* This unit, with a maximum apparent thickness of 170 m, crops out south of Capoliveri-Madonna delle Grazie, in the north-eastern Gemini Isle, in the Calamita-Punta Rossa mining area (fig. 8) (where it is largely affected by skarn mineralization, e.g. in the Macei Alti Mine) and at the Scoglio del Remaiolo (the little island south of Remaiolo in fig. 3a). The lower part generally consists of up to 1.5 m-thick beds of stratified, white to greyish (sometimes yellowish to reddish, because of Fe-oxides or hydroxides) marbles, with local millimetre to centimetre-scale phyllite and calcschist intercalations (e.g. between Calanchiole and Spiaggia del Lido and south of Madonna delle Grazie beach). The upper part consists of whitish massive to irregularly bedded, often saccaroidal marbles and crystalline dolostones (e.g. at Punta Calamita, figs. 3a and 8). A whitish and greyish banding can be locally present within the carbonate rocks. Correlation with the Upper Triassic (Grezzoni Fm.) and Hettangian (Marbles Fm.) metacarbonates has been suggested by all the authors (BARBERI *et alii*, 1967a, b; BARBERI *et alii*, 1969a,b).

The Porto Azzurro Unit is separated from the overlying Cretaceous Flysch Unit (Marina di Campo Fm.) by the Zuccale cataclasite (Zuccale Fault *Auctt*.: see below) (KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; DANIEL

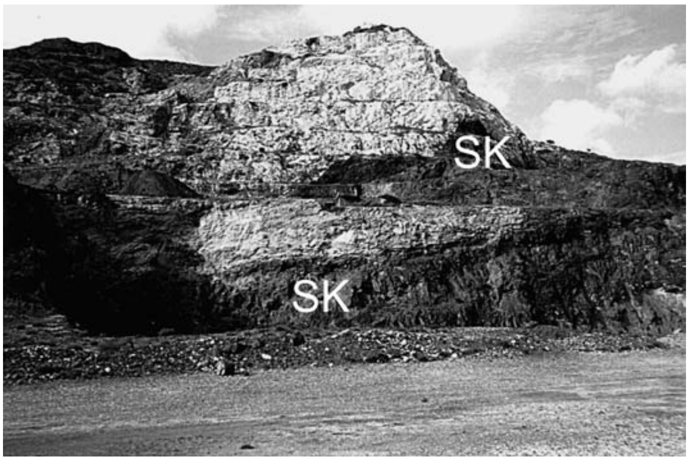

Fig. 8 - Whitish marbles in the upper part of the Calanchiole marble and crystalline dolostone at Punta Calamita; SK=skarn bodies.
– *Marmi biancastri nella parte alta dei Marmi e dolomie cristalline delle Calanchiole presso Punta Calamita; SK=mineralizzazioni a skarn.*

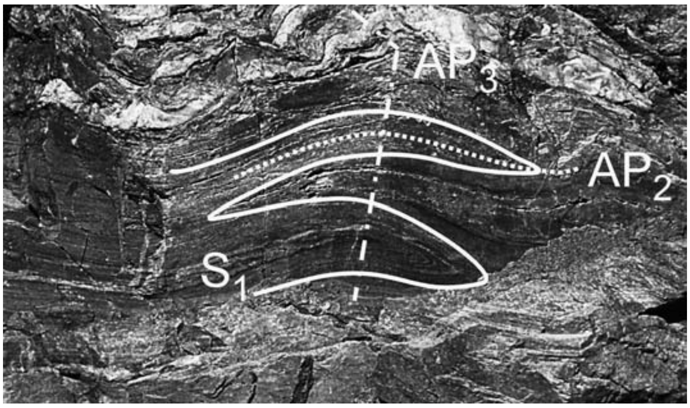

Fig. 9 - Alpine deformations within the quartzites of the Mt. Calamita Metamorphic Complex at the Innamorata beach; the main foliation (S_1) is isoclinally folded into F_2 (AP_2=F_2 axial plane); then, the F_2 folds are deformed into open D_3 folds, characterized by a subvertical axial plane (AP_3).
– *Deformazioni alpine nelle quarziti del Complesso Metamorfico di Monte Calamita presso la spiaggia dell'Innamorata; la foliazione principale (S_1) è piegata a formare le pieghe isoclinali F_2 (AP_2=piano assiale F_2); successivamente le pieghe F_2 sono deformate in pieghe F_3 aperte e caratterizzate da piano assiale sub-verticale (AP_3).*

& JOLIVET, 1995; KELLER & COWARD, 1996; BORTOLOTTI *et alii*, 2001; COLLETTINI & BARCHI, 2004).

TABLE 2

Blastesis evolution of the Porto Azzurro Unit. The Variscan evolution characterized only the units of Mt. Calamita Metamorphic Complex.
– *Evoluzione della blastesi nell'Unità di Porto Azzurro. L'evoluzione varisica ha interessato solo le unità del Complesso Metamorfico di Monte Calamita.*

	VARISICAN EVOLUTION	ALPINE EVOLUTION			
METAMORPHIC EVENT	M_x	MA_1	MA_2	MAT	MA_3
DEFORMATIONAL EVENT	D_x	DA_1	DA_2		DA_3
Qtz	=====	=====			
Ms	=====	=====		=====	
Ser		=====	=====		
Chl		=====	=====		
Ab		=====	==?==		
Pli	=====			==?==	
Bt	==?==	==?==		=====	
Grt	=====				
Op		=====	=====		=====
Cal		=====	==?==	=====	
Dol		=====		=====	
And				=====	
Crd				=====	
Kfs				==?==	
Hbl	==?==			==?==	
Tr-Act		==?==		=====	

STRUCTURAL DATA

All the formations of the Porto Azzurro Unit were affected by Alpine deformations and metamorphism (see also table 2 for details). In particular, the following plastic deformation events can be distinguished:

D_1 - This is defined by the main foliation at the meso- (fig. 9) and microscale (S_1= Ser/Ms+Qtz+Chl+Ab+Cc) (e.g.: figs. 5a and 11), which is continuous or sub-millimetre spaced and generally sub-parallel to the lithological partititions (e.g. Mt. Calamita Metamorphic Complex) or sedimentary bedding (e.g. Verrucano beds). This foliation is the axial plane foliation of isoclinal folds, which are rarely recognizable, because of the the strong transposition by the following D_2 event. During the D_1 event, the syntectonic growth of albite porphyroblasts and the breakage and chloritization of pre-S1 garnets occurred.

For the southern and southwestern areas, the stereonets in fig. 10 show for the rare D_1 folds N-S trending axes and a western dip of the axial surface, while at Cala Nova, probable D_1 folds are characterized by ENE-WSW trending axes and NE axial plane dips.

D_2 - The D_2 event is represented by tight to isoclinal folds with sharp or rarely rounded hinges. These are the most common folds recognizable at the mesoscale (tens of centimetres to tens of metres) all over the promontory (e.g. in the Innamorata area; fig. 9). Syntectonic quartz veins, folded by D_2 into close to tight folds (e.g. rootless F_2 hinges) are locally present. The associated axial plane foliation (S_2) is represented by a millimetre- to centimetre-spaced, zonal to discrete crenulation cleavage (figs. 5a and 11) made up of the alignment of opaque minerals and Ser/Ms blasts; locally, especially in the metapelitic lithotypes, this foliation is more pervasive (S2=Op+Ms/Ser±Chl±Qtz in fig. 7b).

Also in the case of the attitude of D_2 structures, significant variations are recognizable going around the promontory (fig. 10), probably due to later deformation events. At Barabarca and Innamorata, the F_2 axial planes dip towards the west or the south, and the axial plunge is about 10-20° towards the SW (also towards the NE in the Barabarca area). In the Remaiolo and Poggio Turco areas, F_2 have westward, 60-70° dipping axial planes and axes plunging at 50-60° to the SW. At Capo Calvo a northeastern F_2 axial plane dip and axes plunge is recognizable, whereas at Cala Nova they are both directed to the north. The vergence of F_2 is towards the southeast.

D_3 - D_3 folds are symmetric, mostly open, tens of centimetres to metres in size, and characterized by rounded hinges and generally steeply-dipping to subvertical axial planes (fig. 9). The S_3 zonal, spaced crenulation (S_3 in fig. 5b) is locally marked by the alignment of opaque minerals. The D_3 structural elements are well exposed only in

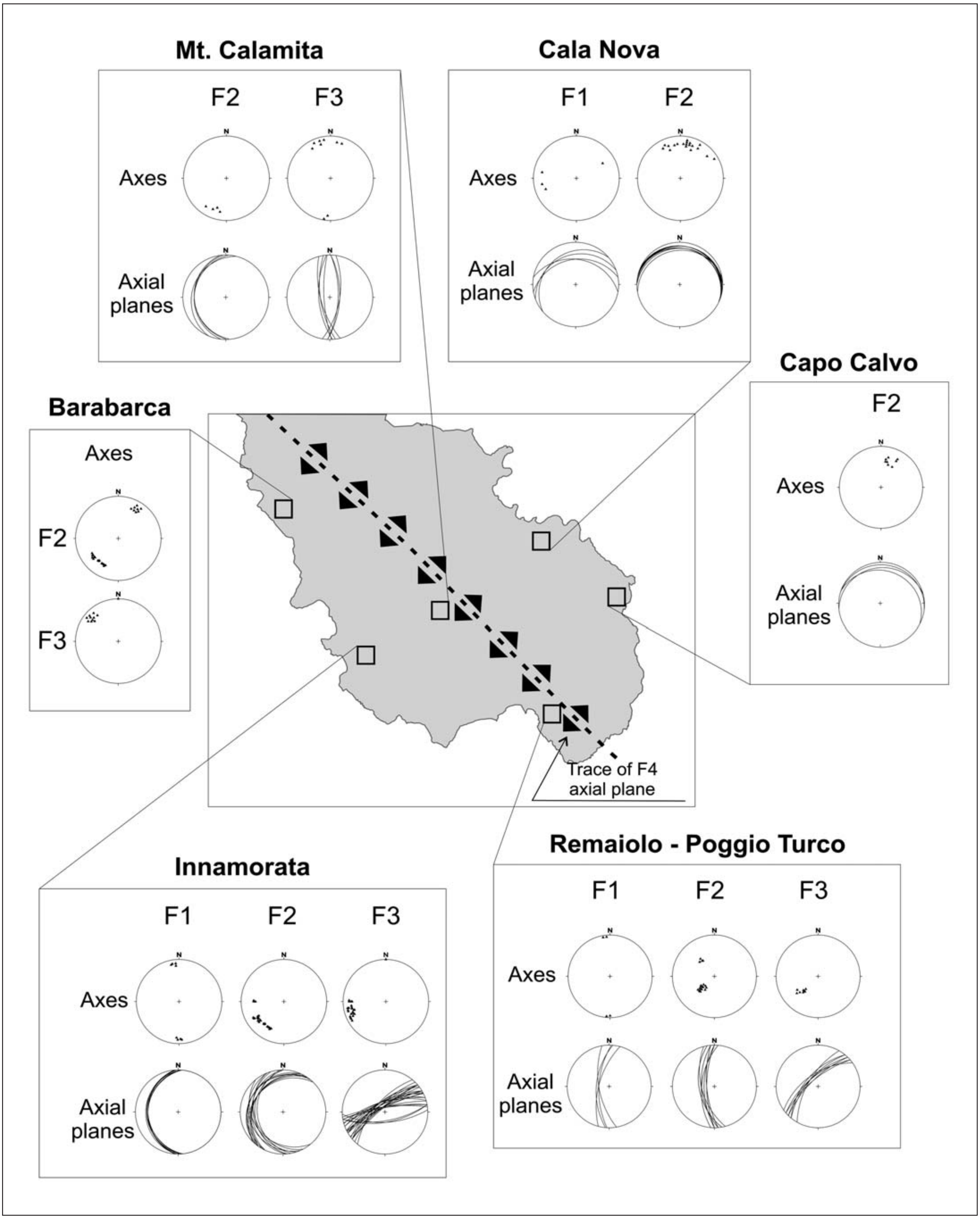

Fig. 10 - Distribution of the structural elements of the D_1, D_2, D_3 and D_4 folding events in the Calamita promontory (Schmidt nets, lower hemisphere).

– Distribuzione degli elementi strutturali degli eventi plicativi D_1, D_2, D_3 e D_4 nel promontorio del Monte Calamita (reticolo di Schmidt, emisfero inferiore).

the western and southern areas (fig. 10). In particular, in the Innamorata and Remaiolo-Poggio Turco areas the strike of the steep axial surface is about NE-SW and the axes plunge towards the SW. The latter is instead towards the NW in the Barabarca area and mostly towards N-NW in the Mt. Calamita area. It is noteworthy that the growth of thermometamorphic minerals (e.g. andalusite±biotite: see later fig. 14b) occurred before and after the D_3 crenulation event.

D_4 - The structures related to a possible D_4 folding event can be recognized only at the map scale. In particular, the areal distribution of the attitude of the main foliation and the orientation of the axes of the major folds (i.e. F_2 folds in fig. 10) outline an overall large-scale antiform in the Porto Azzurro Unit in the Mt. Calamita promontory, with a NW-SE trending axis (fig. 10). The presence of this megafold at the scale of the whole promontory was also suggested also by BARTOLE *et alii* (1991).

In some samples of the Mt. Calamita Metamorphic Complex, a pre-D_1 tectono-metamorphic event (D_x) can be also recognised. This is indicated by local intrafoliar relicts of pre-S_1 foliation (S_x=Ms±Chl±Qtz±Bt) (fig. 11), by the opaque-rich inclusion trails within zoned albite porphyroblasts which are discordant or truncated by S_1, and by relict garnet porphyroblasts within S_1 (fig. 5b). In the Paleozoic succession of the Northern Apennines, these structures and minerals are associated with the Variscan Orogeny, in particular the tectono-metamorphic Sudetic event (ELTER & PANDELI, 1990; CONTI *et alii*, 1991; PANDELI *et alii*, 1994).

Two main brittle deformations were also recognized:

Low-angle detachment faults. These structures are locally present within the Mt. Calamita Metamorphic Complex associated with metres to tens of metres-thick cataclastic horizons (mylonites and ultramylonites of MARINELLI, 1959), affecting the leucocratic dykes (e.g. top-to-east displacements along the north-eastern coast of the promontory: see fig. 7 in KELLER & PIALLI, 1990). In particular, the cataclasites are generally medium- to fine-grained cataclastic breccias with phyllitic-quartzitic, or white quartz (fig. 12), or quartz+feldspar±biotite (brecciated dykes?) clasts in a quartzitic or quartzitic-micaceus matrix. Some samples reveal that the thermometamorphism occurred before the cataclastic event. Moreover, tourmalinization processes locally affected such rocks before and/or after the cataclastic phenomena. In any case predate the youngest Fe-mineralization (e.g. at Punta di Cala Nova and in the Capo Calvo area, where the tourmalinized cataclasites are cut by high-angle fractures filled by Fe-minerals).

Other low-angle faults detach the Mesozoic cover formations (including the skarn bodies: e.g. Calamita mining area) from the original basement (Mt. Calamita Metamorphic Complex) or the carbonate units from the Verrucano (e.g.: the Madonna delle Grazie cataclasite). The tectonic superposition of the overturned F_2 Spiaggia del Lido-Barabarca-Madonna delle Grazie megafold, formed by the Mesozoic formations (Barabarca quartzite at the case), on the Paleozoic phyllites probably belongs to this same event.

The best known example of detachment in this area is the Zuccale fault (KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; DANIEL & JOLIVET, 1995; KELLER & COWARD, 1996; BORTOLOTTI *et alii*, 2001; COLLETTINI & BARCHI, 2004). This tectonically complex horizon, up to 7 m thick, is well exposed along the coast between Calanchiole and Zuccale, where it has a shallow (max 15°) dip to the west, and has two parts:

a) the *upper part* is a Fe-carbonate-rich breccia, brown in colour and at times vacuolar, made up of millimetre to 10 cm-sized, recrystallized and at times silicified clasts of mainly carbonate and minor pelitic and arenaceous rocks, derived from the overlying Cretaceous Flysch. S-C, C and C'-type fabric (see also PERTUSATI *et alii*, 1993 and COLLETTINI & BARCHI, 2004) suggest a «top-to-ENE» sense of shear (fig. 13a);

b) the *lower part* is a polymictic breccia with up to 5 cm sized thermometamorphosed quartzitic and phyllitic

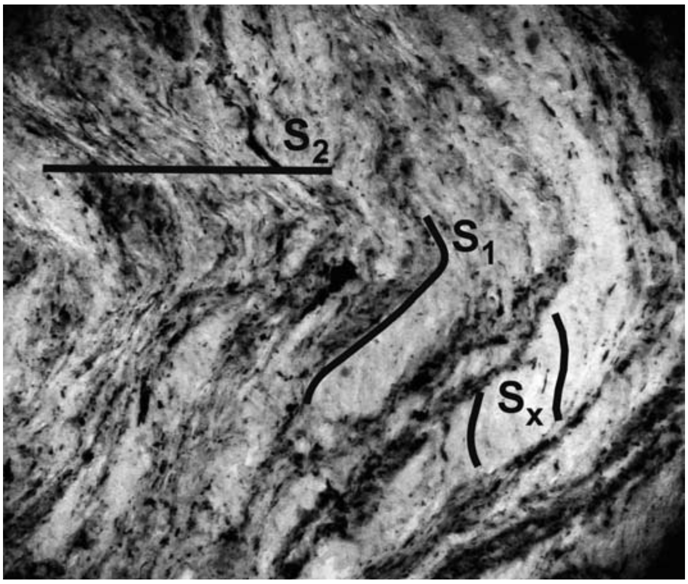

Fig. 11 - Photomicrograph of a F_2 fold, which deforms the main foliation S_1 and the previous (?Variscan) S_x foliation (parallel polars, 2,5×).
– *Microfotografia di una piega F_2, che deforma la foliazione principale S_1 e la foliazione S_x precedente (?varisica) (nicols paralleli, 2,5×).*

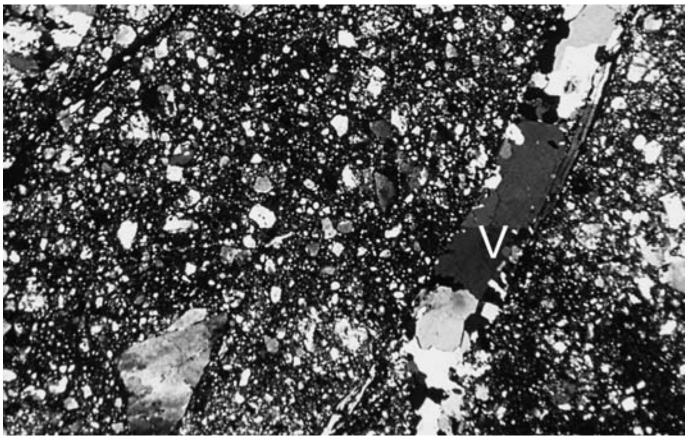

Fig. 12 - Photomicrograph of a quartz cataclasite associated with a low-angle fault, crossed by a quartz vein (V) in the Mt. Calamita Metamorphic Complex along the panoramic road from the Calamita mining area to Poggio Turco (crossed polars, 15×).
– *Microfotografia di una cataclasite quarzitica associata ad una faglia a basso angolo, tagliata da una vena di quarzo (V) nel Complesso Metamorfico di Monte Calamita, lungo la strada panoramica tra la miniera di Calamita e Poggio Turco (nicols incrociati, 15×).*

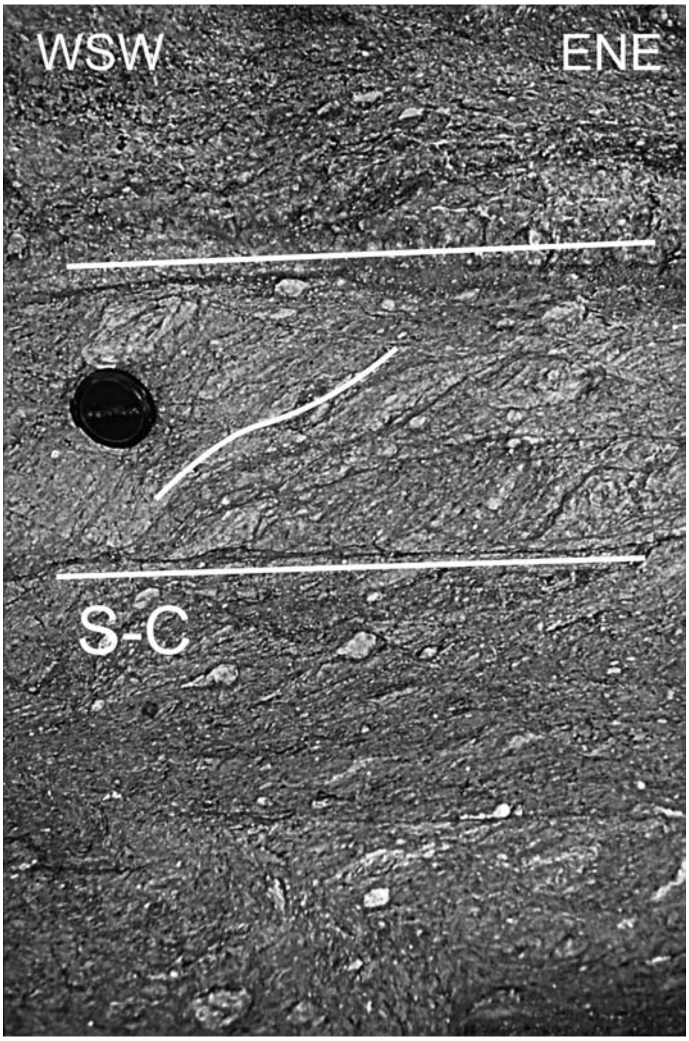

Fig. 13a - S-C-type fabric showing a «top-to-ENE» sense of shear in the upper part of the Zuccale cataclasite at Punta di Zuccale.
– *Fabric di tipo S-C, che indica un senso di taglio «top-to-ENE» nella parte alta della cataclasite associata alla Faglia di Zuccale presso Punta Zuccale.*

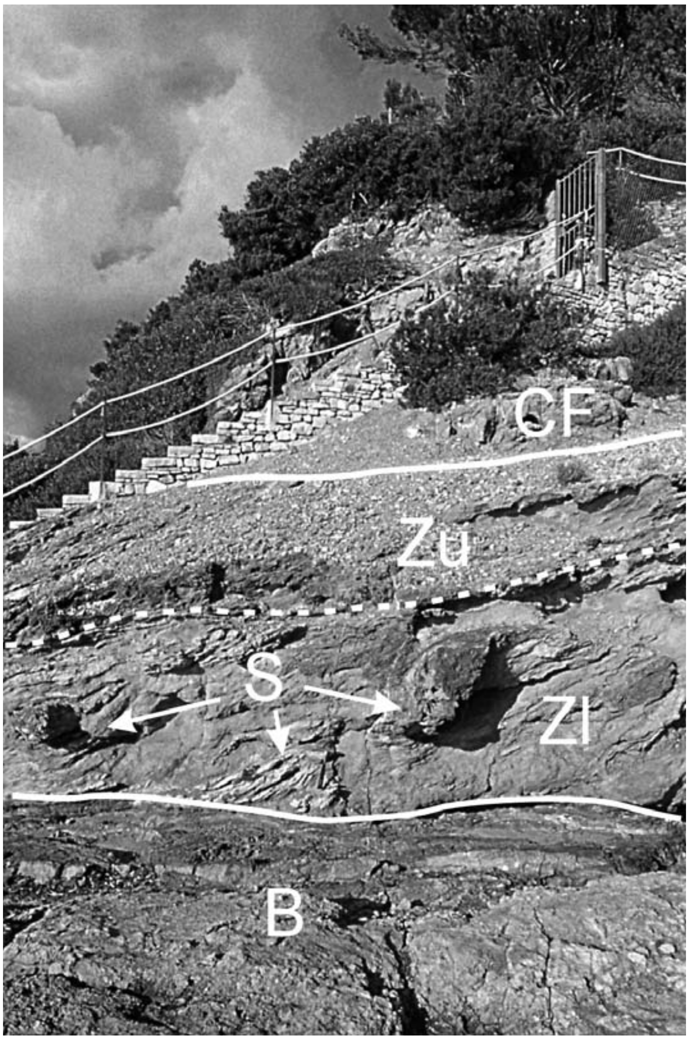

Fig. 13b - The Zuccale cataclasite at Punta di Zuccale. Zl=Lower part, Zu=upper part, B=Barabarca Quartzites, CF=Cretaceous Flysch Unit. Zl includes Verrucano and Tocchi Fm. slices (S).
– *Cataclasite di Zuccale presso Punta Zuccale. Zl=parte inferiore, Zu=parte superiore, B=Quarziti di Barabarca, CF=Unità del Flysch Cretaceo. Zl include scaglie di Verrucano e della Formazione di Tocchi (S).*

elements (from the Verrucano and Tocchi Fm.) in a foliated phyllosilicate and phyllosilicate-carbonatic matrix. Moreover, decimetre to metre-sized tectonic slices of Verrucano siliciclastics and of phyllite-carbonate alternations of the Tocchi Fm. are often present (fig. 13b). Mylonitic fabrics locally occur in the basal portion. Some tens of metres north of Punta Zuccale, where the brecciated footwall (Verrucano anagenites and Tocchi Fm.) of the Zuccale shear horizon is well exposed, W-E trending slickenside striae and calcite fibre veins are present at the base of the cataclastic horizon, which are deformed by weak N-S trending mesofolds.

High-angle faults. This is the last deformation event that affected the studied tectonic units, and it is represented by NW-SE and NE-SW-trending joints and high-angle normal faults, which cut both magmatic dykes and the low-angle locally tourmalinized detachment faults and are locally filled by Fe-oxides and hydroxides (e.g. at Punta di Cala Nova and Capo Calvo in fig. 3a). An evident system of NW-SE trending normal faults is present in the Innamorata-Praticciolo area which downthrow the Mesozoic covers (north-eastern Gemini Isle) towards the SW with respect to the Calamita Fm. and the Ophiolitic Unit (south-western Gemini Isle) with respect to the formers (fig. 3a).

Contact metamorphism and hydrothermalism

The Messinian-Lower Pliocene magmatism produced a wide metamorphic aureole in the country rocks of the studied area (Marinelli, 1959; Barberi *et alii*, 1967b). Our studies, in agreement with Marinelli (1959), reveal that the contact metamorphism which imprinted the Mt. Calamita Metamorphic Complex (see tables 1 and 2) is generally ascribed to the albite-epidote hornfels/hornblende hornfels facies and made up of green to brown Bt (after regional Chl)±And(±Ms). The skarn bodies of the Calamita mine (Tr-Act + Adr + Hd + Hem + Mag + Py) have a similar metamorphic grade. In the eastern areas, which are characterized by a complex network of aplitic to microgranitic dykes and skarn bodies with Fac+Feprg + Hbl + Mag + Py ± Lm (Sassi Neri and Ginevro mines in fig. 3a: DIMANCHE, 1971; TANELLI *et alii*, 2001), the static recrystallization is stronger (hornblende hornfels facies) and obliterates previous textures and mineralogical associations. In these areas, the finding of Crd (sometimes transformed into pinnite) associated with Bt, And (fig. 14a) and Ms is frequent. However, local higher temperature conditions are recorded in the Ginevro Mine where a Qtz+Kfs+Pl+Crd(+Bt) and rare Kfs+Crd+Pl+Crn were described by DIMANCHE (1971) in agreement with MARINELLI (1959). In the surroundings of Mt. Calamita and generally towards the north-west, there is an evident decrease in static recrystallization (regional chlorite is less transformed in static biotite; andalusite is present as discontinuous spots instead of sub-idiomorphic porphyroblasts).

Most of the hydrothermal veins hosted within the thermometamorphosed rocks of the Porto Azzurro Unit show a rather homogeneous composition (Qtz+FeCal+FeOx/idrox±Chl, Qtz+Chl+Adu±Tr-Act±Ti, Qtz+Adu+Chl+Ep, Qtz+Ep+Cal, Adu±Ep) over the whole promontory, although veins of Bt, Tur±Qtz, Qtz+Cc+Ab, Qtz+Ti+Bt+Pl and Cpx+Ti were seen locally in eastern areas.

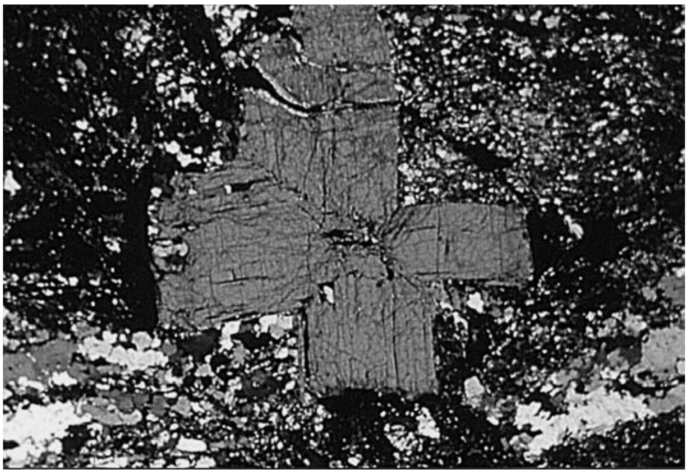

Fig. 14a - Sub-idiomorphic composite andalusite porphyroblasts in the Mt. Calamita Metamorphic Complex (crossed polars, 2,5×).
– *Porfiroblasti compositi sub-idiomorfi di andalusite nel Complesso Metamorfico di Monte Calamita (nicols incrociati, 2,5×).*

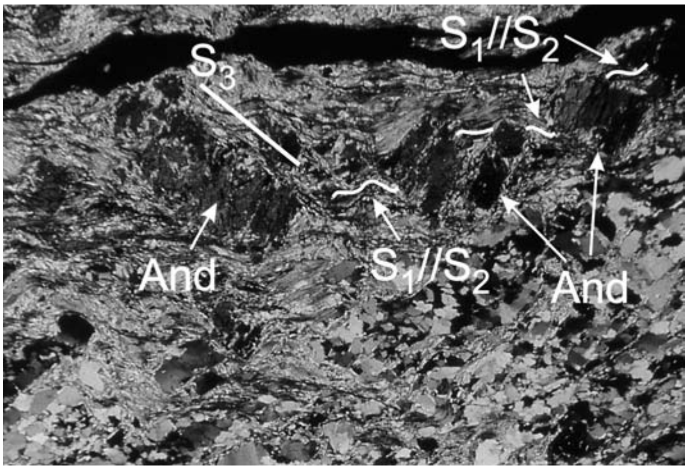

Fig. 14b - Pre- to syn-D_3 andalusite porphyroblasts (And) in the Mt. Calamita Metamorphic Complex. S_1, S_2 and S_3=Alpine foliations (crossed polars, 15×).
– *Porfiroblasti di andalusite da pre- a sin-D_3 nel Complesso Metamorfico di Monte Calamita. S_1, S_2 and S_3=foliazioni alpine (nicols incrociati, 15×).*

DISCUSSION

The data collected during this study improve our knowledge of the stratigraphic and magmatic-structural history of the Mt. Calamita promontory. From a stratigraphic point of view, in the polymetamorphic Porto Azzurro Unit we distinguish a Paleozoic basement (Mt. Calamita Metamorphic Complex) which is overlain by ?Triassic-?Hettangian cover units (Barabarca Quartzites, Tocchi Fm. and Grezzoni/Marmi) in agreement with previous authors (BARBERI *et alii*, 1967a,b; BARBERI *et alii*, 1969b). In spite of the lack of fossils, the reconstructed lithostratigraphy of the Porto Azzurro Unit strongly recalls that of the typical successions of the Tuscan Metamorphic Units, and in particular those of southern Tuscany (e.g. Monticiano-Roccastrada Unit: BERTINI *et alii*, 1991 *and references therein*).

The stratigraphic attribution of the lithofacies defined within the Mt. Calamita Metamorphic Complex is more difficult. The presence of pre-S_1 foliation (S_x) and minerals (garnet) only in the Mt. Calamita Metamorphic Complex, and their lack in the overlying Mesozoic formations, suggests a pre-Triassic age for the former lithodemic unit. In particular, at the regional scale, the pre-S_1 foliation and minerals are related to the Sudetian tectono-metamorphic event of the Variscan orogeny (CONTI *et alii*, 1991; PANDELI *et alii*, 1994 *and references therein*). Therefore the Mt. Calamita Metamorphic Complex is probably made up of pre-Carboniferous rocks.

In particular, *lithofacies a*, at the geometric base of the succession, shows similar petrographical and microstructural features to the Micaschist Complex (?Early Paleozoic or ?pre-Paleozoic), present at the base of the Monticiano-Roccastrada Unit, in the sub-surface of the Larderello Geothermal Region (ELTER & PANDELI, 1990, 1996; BERTINI *et alii*, 1991). In fact, acidic plagioclase porphyroblasts and the presence of pre-Alpine almandine are distinctive features in both units. The scarcity of these latter porphyroblasts in the Calamita mica-schists is in part due to their thermometamorphic transformation into biotite and/or can be related to the different chemistry of the protolith with respect to that of the Larderello mica-schists.

The metasiliciclastics of *lithofacies b* are characterized by a variable chlorite content (generally low, possibly due to its transformation into thermometamorphic biotite) and a lack or low content of acidic plagioclase blasts in the quartz-rich metasandstones. This features are also typical of the phyllitic-quartzitic units which underlie (Capo Arco Schists) and overlie the Porphyroids in the Ortano Unit of Eastern Elba (see figs. 1 and 2). BORTOLOTTI *et alii* (2001) attributed these rocks to the Late Ordovician metasiliciclastics of Tuscany (e.g. Upper Quartzite and Phyllite of the Apuan Alps; Buti banded quartzite and phyllite of the Mts. Pisani: PANDELI *et alii*, 1994 *and references therein*), which the authors generally correlate with the transgressive Caradocian sediments of central Sardinia (cfr. CARMIGNANI coord., 2001). The local presence of concentrations and bands of Fe-oxide agrees with this correlation (see also PUXEDDU *et alii*, 1984). The presence of the chlorite- and albite-rich Lower Phyllite and Quartzite (PUXEDDU *et alii*, 1984) has not been definitely confirmed by our sampling.

The graphite-rich *lithofacies c* contains frequent black quartzites which are known as lydites in the Silurian-Early Devonian units of Tuscany, such as the Orthoceras-bearing dolostone and Lydian stones of the Apuan Alps (CONTI *et alii*, 1991) and the Risanguigno Fm. of the Monticiano Roccastrada Unit (COSTANTINI *et alii*, 1987/88) and central Sardinia (CARMIGNANI coord., 2001). On the other hand, similar lithotypes mark the passage from Porphyroids/Porphyritic Schists to the overlying metasiliciclastics in the Ortano Unit succession (DURANTI *et alii*, 1992; BORTOLOTTI *et alii*, 2001) of probable ?Ordovician age .

The analysed amphibolites of *lithofacies d* of the Pareti-Morcone to Remaiolo areas, because of the high content of Ti minerals, are related to a basic magmatic protolith in agreement with BARBERI & INNOCENTI (1965), BARBERI *et alii* (1967b) and PUXEDDU *et alii* (1984). These metabasite horizons appear intercalated both in the micaschists (with a gradual transition in the Remaiolo area) and in lithofacies b (Pareti-Morcone). On the basis of Ti/100-Zr-Y and Ti content, PUXEDDU *et alii* (1984) related all these amphibolites to within-plate basalts as well as the ?Lower Paleozoic Valle del Giardino metabasites of the Apuan Alps and of Niccioleta Mine in southern Tuscany. Therefore, the amphibolitic horizons within the mica-schists of the Remaiolo area are different from those intercalated in the Micaschist complex of the Larderello subsurface and exposed in the Cerreto Pass area (north-west of the Apuan Alps), which were attributed to ocean floor basalts (PUXEDDU *et alii*, 1984; MOLLI *et alii*, 2002).

The orthometamorphic rocks of *lithofacies e* are affected by the D_1 and D_2 tectono-metamorphic events together with the surrounding phyllitic-quartzitic rocks, which are cut by non-foliated aplitic to microgranitic dykes dated to 5.2 to 6.1 Ma by SAUPÉ *et alii* (1982). These data suggest a pre-Miocene age for the protolith. Moreover, the thermometamorphic minerals grow onto S_1-S_2, and the radiometric age of the corresponding foliation in the metamorphic units of Tuscany is Late Oligocene-Middle Miocene (KLIGFIELD *et alii*, 1986; DEINO *et alii*, 1992; BRUNET *et alii*, 2000), and therefore rules out that these rocks could be considered foliated Messinian-Lower Pliocene dykes. Therefore, it is likely that lithofacies e correlates with the Ordovician Porphyroids of the Ortano Unit and the Apuan Alps. In any case, the Capo Calvo porphyroids are different from the Ordovician metavolcanic rocks because of the presence of intrusive or sub-intrusive textures (e.g. granular aggregates of Or+Qtz+Pl, lack of corroded quartz phenocrysts).

The lithostratigraphical and petrographical data of the Mt. Calamita Metamorphic Complex strongly recall those of the Variscan succession of the Northern Apennines and, in particular, of southern Tuscany. In fact, in the subsurface of the Larderello-Travale geothermal region, below the Triassic rocks, the lower part of the Monticiano-Roccastrada Unit consists of phyllite-quartzite units with local metabasite levels (e.g.: the Phyllitic-Quartzitic Complex) which overlie a deep Micaschist Complex (ELTER & PANDELI, 1990, 1994; 1996a; BERTINI *et alii*, 1991). Moreover, both the Larderello Paleozoic units suffered static high-temperature metamorphism due to Pliocene granitoid intrusion (BATINI *et alii*, 1983; MUSUMECI *et alii*, 2002; GIANELLI & RUGGIERI, 2002 *and references therein*)

The deformation evolution of the Calamita promontory and its relationships with the magmatic intrusions are more complex than previously hypothesized (see the synthetic sketch in fig. 15). The oldest tectono-metamorphic event (D_x), which is ascribed to the Sudetic event of the Variscan Orogeny, is only recognizable in the Mt. Calamita Metamorphic Complex. The Alpine deformations affected both the pre-Triassic rocks and the overlying Mesozoic cover formations. In particular, two main ductile events in the greenschist metamorphic facies (D_1 and D_2) firstly affected the Porto Azzurro Unit and show strong similiarities with the tectono-metamorphic events recognized in the Tuscan Metamorphic Units (CAMPETTI *et alii*, 1999; CARMIGNANI & KLIGFIELD, 1990; ELTER & PANDELI, 1994b; CAROSI *et alii*, 1997; CORSI *et alii*, 2001; COSTANTINI *et alii*, 1987/88). In the studied units, D_1 is the strongest shortening event («Tangential or Syn-Nappe phase»: CARMIGNANI & KLIGFIELD, 1990; CARMIGNANI *et alii*, 1994; ELTER & SANDRELLI, 1995; DECANDIA *et alii*, 2001), dated to about 27 Ma in the Apuan Alps by KLIGFIELD *et alii*, 1986), during which isoclinal folding and the associated very penetrative S_1 (main foliation at the meso-scale) was produced. During D_2 (dated to about 14-12 Ma in the Apuan Alps by KLIGFIELD *et alii*, 1986), the main foliation was isoclinally or tightly folded, and generally the D_1 structures were transposed. The asymmetries of the D_2 folds show an eastern (SE) vergence in agreement with the D_2 folds in the Ortano Unit and the Monticiano-Roccastrada Unit of eastern Elba (BORTOLOTTI *et alii*, 2001; ELTER & PANDELI, 2001). We have no data to attribute D_2 to the post-orogenic regional extension of the Northern Apennines chain («Post-Nappe phase», according to a «Core Complex» extensional model: CARMIGNANI & KLIGFIELD, 1990; CARMIGNANI *et alii*, 1994; ELTER & SANDRELLI, 1995; DECANDIA *et alii*, 2001) or to a final «*serrage*» event, possibly coupled with syn-orogenic extension (FAZZUOLI *et alii*, 1994; CAROSI *et alii*, 1995; JOLIVET *et alii*, 1998; BORTOLOTTI *et alii*, 2001; CAROSI *et alii*, 2002). We think that an Adriatic vergence of the D_2 folds in Elba does not fit well with the first «Core Complex»-like model. In fact, the latter suggests a centrifugal discharge (westwards in southern Tuscany) of the units from the so-called Tuscan Mid-Ridge (i.e. the Apuan Alps to Mt. Leoni regional structural lineament; the «paleo-apenninic antiform» of ELTER & SANDRELLI, 1994), which represents the main positive structure of the Tuscan Metamorphic Units in Tuscany.

The D_3 weak folding event recognized in the Porto Azzurro Unit probably occurred during the emplacement of the magmatic bodies (5.1 to 6.2 Ma according to SAUPÉ *et alii*, 1982). In fact, the petrographical and microstructural data reveal that the development of S_3 probably in part overlapped with the blastesis of the thermometamorphic minerals and the skarn mineralizations.

The preliminary data, which show an overall decrease in thermal recrystallization from the Ginevro mine towards the north-west of Mt. Calamita, mean it is difficult to make a direct linkage between the La Serra-Porto Azzurro pluton (cropping out northwards of the Mt. Calamita promontory) and the magmatic body present at shallow depths in the studied area, which could be related to an apophysis of the main La Serra-Porto Azzurro pluton. In any case, our data suggest that the top of the Mt. Calamita magmatic body is probably localized east of the Ginevro-Sassi Neri area.

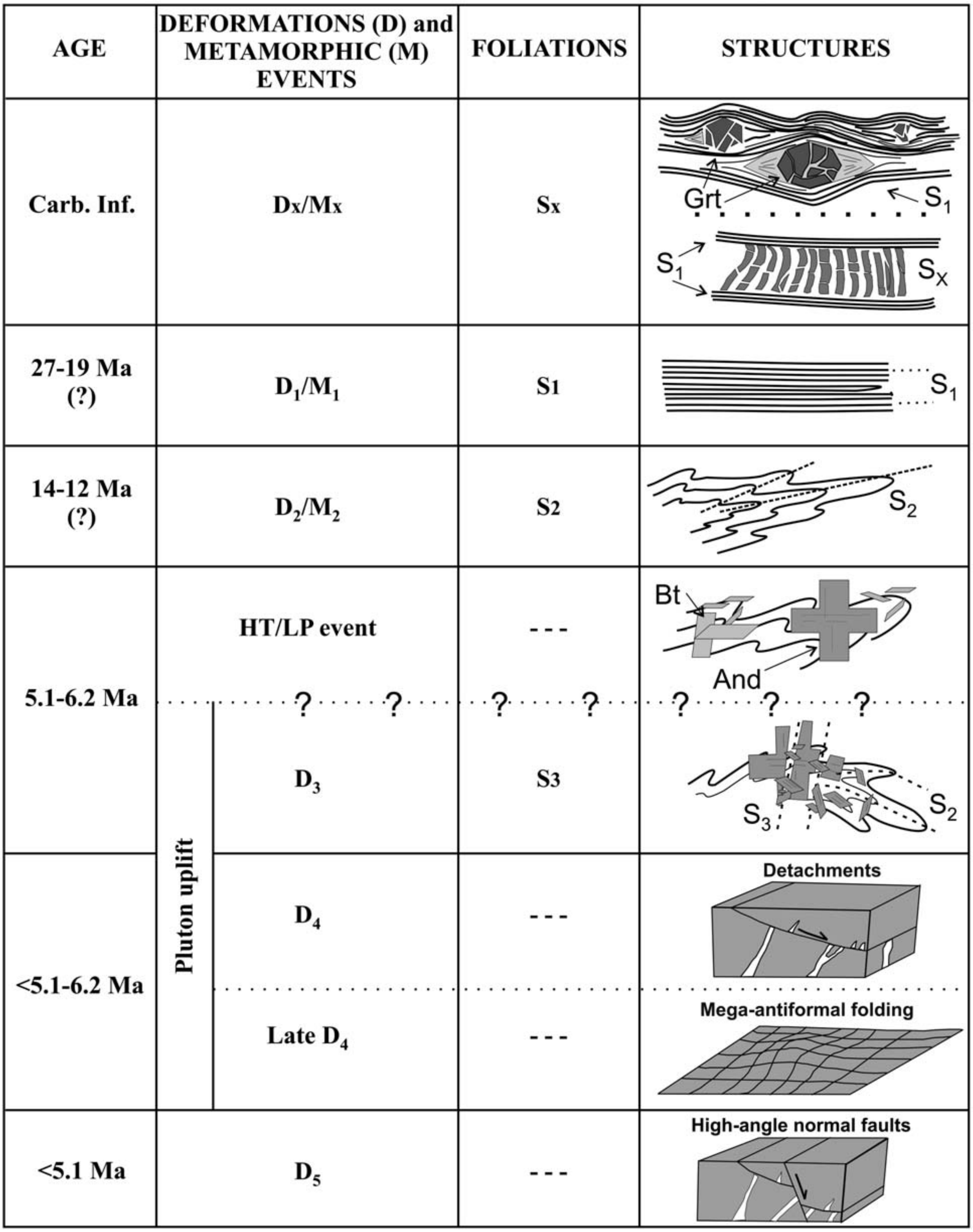

Fig. 15 - Sketch of the deformation-metamorphic evolution of the Porto Azzurro Unit (chronological data after KLINGFIELD *et alii*, 1986; SAUPÉ *et alii*, 1982; BRUNET *et alii*, 2000; DEINO *et alii*, 1992)
– *Schema dell'evoluzione tettono-metamorfica dell'Unità di Porto Azzurro (dati cronologici da* KLINGFIELD et alii, *1986;* SAUPÉ et alii, *1982;* BRUNET at alii, *2000;* DEINO et alii, *1992).*

After D_3 deformation and thermometamorphism, low-angle shearing (D_4 event) in Mt. Calamita and detachments between the Mt. Calamita Metamorphic Complex and the overlying Mesozoic units, possibly triggered by the uplift of the magmatic bodies, locally occurred (e.g. in the Calamita Mining area). The Zuccale cataclasite was also formed, after the magmatic intrusions and thermometamorphism, in a possibly fluid-rich, top-to-the-east shear zone (KELLER & PIALLI, 1990; PERTUSATI *et alii*, 1993; DANIEL & JOLIVET, 1995; KELLER & COWARD, 1996; BORTOLOTTI *et alii*, 2001; COLLETTINI & BARCHI, 2004). It is noteworthy of that the kinematic data collected in the Zuccale area suggest a western provenance for the Cretaceous Flysch, in particular from the Golfo Stella. Therefore, the Zuccale Fault in the studied area cannot be directly related to the uplift of the Calamita promontory or of the La Serra-Porto Azzurro pluton. The Cretaceous Flysch Unit probably came from an at-present collapsed high, to the west of the Calamita promontory (e.g.: an uplifted magmatic body in the Golfo Stella area?). In the last stages of the D_4 event all the previous structures were deformed into a major mega-antiform with a NW-SE axis, which is recognizable at the scale of the whole promontory (see geological sections in fig. 10). Also the Zuccale fault shows local weak folding and an overall antiformal attitude, from Zuccale to Porto Azzurro through Capoliveri areas. We think that this mega-structure can be related to the final uplift of the consolidated pluton. Finally, the NW-SE and NE-SW-trending high-angle normal faulting (D_5 event) occurred and modelled the western (e.g. the west-downthrown system of the Praticciolo-Innamorata-Gemini islands), southern (e.g. Remaiolo-Punta dei Ripalti) and eastern coasts (e.g. Capo Calvo-Forte Focardo alignment). These locally mineralized faults are probably coeval with the high-angle normal faults of eastern Elba (cfr. BORTOLOTTI *et alii*, 2001), which host Adu+Hem ores dated about 5 Ma (LIPPOLT *et alii*, 1995).

CONCLUSIONS

The 1:10,000 scale geological mapping of the Mt. Calamita promontory and the stratigraphical, petrographical and structural studies allow the following conclusions:

1) The Porto Azzurro Unit consists of Paleozoic, probably pre-Carboniferous successions (Mt. Calamita Metamorphic Complex), wich are unconformably overlain by the Triassic Verrucano metasiliciclastics (Barabarca Quartzites) and Upper Triassic-?Hettangian metacarbonates. The Mt. Calamita Metamorphic Complex mostly consists of a deep garnet-bearing, albite micaschist unit (lithofacies *a*), similar to the Micaschist complex of the Larderello subsurface, which underlies a phyllitic-quartzitic unit (lithofacies *b*), probably correlatable with the Ordovician formations of the Tuscan Mid-Ridge (e.g. Buti banded quartzite and phyllite in RAU & TONGIORGI, 1974) and the Ortano Unit in the eastern Elba. This correlation is also strengthened by the existence of local porphyroid-like horizons. The analysed amphibolite horizons of the Mt. Calamita Metamorphic Complex probably derive from the metamorphism of within-plate basalts.

2) The deformation and metamorphic evolution of the Porto Azzurro Unit is more complex than previously hypothesized. Apart from the relicts of the Variscan tectono-metamorphism recognized in the Mt. Calamita Metamorphic Complex, all the formations of the Porto Azzurro Unit suffered two Alpine tectono-metamorphic events (D_1 and D_2) under greenschist facies metamorphic conditions similar to most of the other Tuscan metamorphic units in Tuscany. In Messinian-Lower Pliocene times, the emplacement of anatectic granitoids produced thermometamorphism in the host rocks and weak D_3 folding, followed by low-angle detatchments. The uplift of the granitic body (D_4 event) produced the Apennine-trending mega-antiform at the scale of the whole promontory. Finally, this complex structural and magmatic assemblage was dissected by NW-SE and NE-SW-trending fault systems.

3) The stratigraphic and most of the structural and magmatic-hydrothermal evolution of the Calamita promontory show close analogies with that of the buried metamorphic units of the Larderello geothermal region (cfr. BATINI *et alii*, 1983; ELTER & PANDELI, 1990, 1993; PANDELI *et alii*, 1994; BERTINI *et alii*, 1991; DECANDIA *et alii*, 2001; MUSUMECI *et alii*, 2002; GIANELLI & RUGGIERI, 2002 *and references therein*). Thus, the Mt. Calamita area can be considered an analogous geological model for the studies of the deep structure of southern Tuscany, and in particular of the Larderello-Travale geothermal region, crossed by the CROP 18 profile.

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