STRUCTURAL EVOLUTION OF ANCHI-/EPIMETAMORPHIC UNITS OF CENTRAL AND EASTERN ELBA (ORTANO, ACQUADOLCE, MONTICIANO-ROCCASTRADA AND GRASSERA UNITS)

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ABSTRACT

The complex framework of the Elba tectonic pile has always been a matter of debate within the geology of the Northern Apennines and of the Tyrrhenian area. The structural data collected on the epi- and anchimetamorphic units of central and eastern Elba (Ortano Unit, Acquadolce Unit, Monticiano-Roccastrada Unit and Gràssera Unit) allow more detailed reconstructions of the complicate tectonic evolution of the Elba stack. Because of their similar structural framework, the Ortano Unit and the Monticiano-Roccastrada Unit acquired their main tectono-metamorphic imprints together as part of a single Paleozoic to Tertiary Tuscan-type succession. The probable Ligurian Piedmontese Acquadolce Unit, which occurs tectonically intercalated between the Tuscan epimetamorphic units, is characterized by a different tectono-metamorphic framework (e.g. shears show opposite sense relative to the Tuscan units). Moreover, the anchimetamorphic Gràssera Unit, that is another possible Ligurian Piedmontese unit, is located in between the non-metamorphic Ophiolitic Unit and the Tuscan Nappe. The present, complex piling up of Tuscan and Piedmontese units occurred within the time interval of 19 Ma (according to the radiometric age of the main foliation of the Acquadolce Unit) and 5 Ma (according to the radiometric age of the La Serra-Porto Azzurro granitoid which produced a well preserved thermometamorphic aureole throughout the stacked units). In more recent times (5-2 Ma), the uprising of the cooled La Serra-Porto Azzurro magmatic body remobilized the eastern Elba tectonic pile onto the Porto Azzurro Unit by low-angle detachment faults (Zuccale Fault). The whole Eastern Elba tectonic pile has been affected by a final, weak folding phase which occurred either during or immediately after the Zuccale Fault, and then by high angle normal faulting which is characterized be hematite-rich mineralizations.

INTRODUCTION

The tectonic units of the Elba Island derive from different paleogeographic domains of the Western Tethys ocean and of the Adriatic continental margin. Their tectonic assemblage represents a peculiarity in the geology of the Northern Apennines (Trevisan, 1951; Barberi et al., 1967a; 1969; Perrin, 1975; Keller and Pialli, 1990; Pertusati et al., 1993; Corti et al., 1996; Bortolotti et al., 2001). In fact, only in the Elba Island the final emplacements of the units of the tectonic stack are clearly linked to the uprise of Neogenic granitoids. Moreover, in the tectonic pile of central and eastern Elba, epi- or anchimetamorphic oceanic unit are tectonically sandwiched between Tuscan Metamorphic Units (Acquadolce Unit Auctt.: Duranti et al., 1992; Corti et al., 1996) and between the Tuscan Nappe and Ophiolitic Unit (Gràssera Unit Auctt.: Bortolotti et al., 1994; Corti et al., 1996). This complex structural stack developed during collisional-ensialic, Late Eocene-Miocene events, but also during the post-nappe extension of the Apenninic chain, during which the Tyrrhenian Sea was generated and the Messinian-Pliocene granitoid intruded the Tuscan crust (see below).

To better define the complex and debated evolution of the eastern Elba tectonic pile, structural studies at the meso- and micro-scale on the Ortano, the Acquadolce and the Monticiano-Roccastrada Units, in the eastern and in the central Elba, and on the Gràssera Unit in the Cavo-Rio Elba (Parata) area have been carried out.

GEOLOGICAL SETTING

After the geological map of Elba and the related notes of Lotti (1884; 1886), in the '50 and '60, researchers of the University of Pisa (Trevisan, 1950; 1951; Barberi et al., 1967a; 1967b; 1969; Marinelli, 1955; 1959; Raggi et al., 1965; 1966) offered a new synthesis and mapping of the whole Island which have represented the reference background for the successive works (e.g. Bortolotti et al., 2000). Trevisan and co-workers recognized the superposition of five tectonic units ("Complexes") of which the lowermost three belong to the Tuscan Domain and the uppermost two to the Ligurian realm (Fig. 1a).

During the last few years many advances were performed both on the stratigraphy (Deschamps et al., 1983; Pandeli and Puxeddu, 1990; Duranti et al., 1992; Bortolotti et al., 1994; Pandeli et al., 1995; Corti et al., 1996) and the structural setting of the Elba Island (Keller and Pialli, 1990; Pertusati et al., 1993; Daniel and Jolivet, 1995; Corti et al., 1996). Recently, a 1:10.000 scale geological survey of the Central-eastern Elba was carried out by Bortolotti et al. (2001). This new geological mapping shows evidences for a more complicated tectonic framework. The Elba's structural stack can be divided in nine, main tectonic units. From the bottom to the top of the structural stack, they are (Fig. 1b and 2):

1) Porto Azzurro Unit (ex Trevisan's Complex I) is made up of polydeformed and cornubianitized, andalusite- and albite-bearing quartz-muscovite-biotite micaschist, probably Paleozoic in age (Mt. Calamita Fm.) (Puxeddu et al., 1984). These rocks are capped by Triassic "Verrucano"-type quartzitic metasediments (Barabarca quartzites Auctt.), and Triassic?-Liassic? crystalline carbonate rocks. The swarm of aplitic dykes related to the La Serra-Porto Azzurro monzogranite (both dated about 5 Ma, according to Saupé et al., 1982) typically intrudes the Mt. Calamita Fm. The Porto Azzurro Unit is separated by a few meters thick cataclasites (Zuccale Fault Auctt.) from the overlying
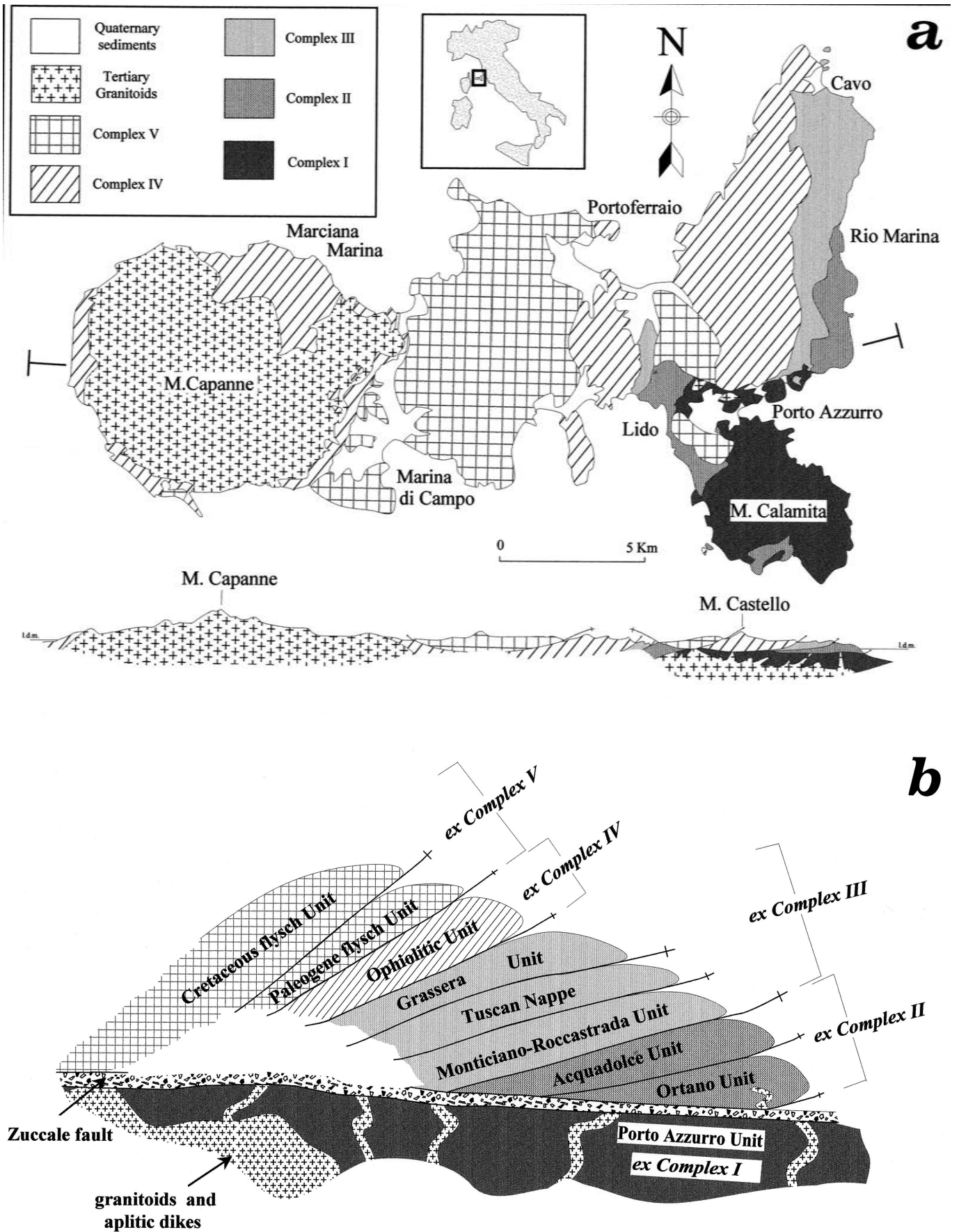
Fig. 1 - a. Geological sketch of the Elba Island according to Trevisan's model (redrawn from Barberi et al., 1969). b. Geological sketch of the central and eastern Elba tectonic pile according to Corti et al. (1996) and Bortolotti et al. (2001).
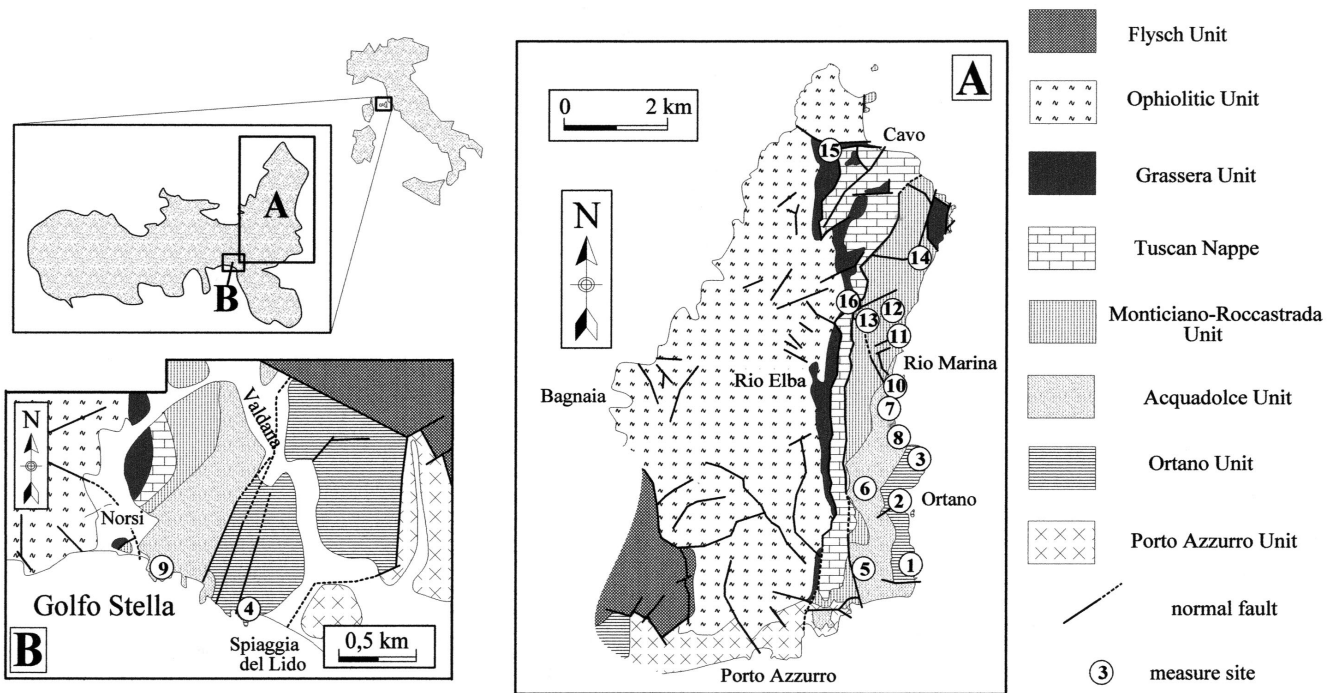
Fig. 2 - Geological sketch map of eastern Elba (A) and of the Golfo Stella - Valdana area (B) (according to Corti et al., 1996 and Bortolotti et al., 2000).

W-dipping imbricate Units.

2) Ortano Unit (upper part of the ex Complex II) consists, from bottom to top of: a) phyllite and andalusite-/cordierite-spotted micaschists with intercalation and metric bodies of quartzitic metasandstone (Ortano Schists Auctt.); b) acidic metavolcanites (Porphyroids Auctt.) and volcanic-rich metasediments (Porphyritic Schists Auctt.); c) upper metasiliciclastics (e.g. silver grey phyllite and quartzite). This succession as well as other similar lithologies in the Apuan Alps, were correlated to the Ordovician formations of Central Sardinia by Pandeli and Puxeddu (1990).

3) Acquadolce Unit (upper part of the ex Complex II) includes basal marble (Ortano Marble Auctt., renamed Valdana Marbles) passing upward into calcschists which, in turn, are capped by a succession of phyllites, metasiltstones and metagraywackes with local calcschist intercalations. The latter are often recrystallized or transformed into skarn bodies (e.g. Torre di Rio skarn: Tanelli, 1977). However, locally a Lower Cretaceous fossil association was reported (Duranti et al., 1992). The top of this Unit is marked by a foliated serpentinite slice. According to Corti et al. (1996), Bortolotti et al. (2001) and Pandeli et al. (2001), the Acquadolce Unit can be correlated to the HP-LT metamorphic oceanic units of the Gorgona Island.

4) Monticiano-Roccastrada Unit (lower part of the ex Complex III) consists of deltaic-neritic, graphite-rich phyllites and metasandstones of Late Carboniferous-Early Permian age (Rio Marina Fm.) and an overlying, continental-littoral, metasiliciclastics of Upper Ladinian?-Carnian ("Verrucano"). The Tuscan-type epimetamorphic succession, Mesozoic to Oligocene in age, was distinguished by Pandeli et al. (1995) in the Cavo area and can be interpreted as the upper part of this Unit.

5) Tuscan Nappe (upper part of the ex Complex III) is a non-metamorphic to anchimetamorphic succession which is composed by Triassic-Liassic platform carbonates and by Liassic to Dogger carbonate-cherty-marly sediments. At the base of this Unit, a vacuolar carbonate breccia ("Calcare Cavernoso" Auctt.) was recognized.

6) Gràssera Unit (uppermost part of the ex Complex III), most of this unit is made up of varicolored slates with syn-/post-tectonic quartz veins and rare manganesiferous chert and limestone intercalations, whereas the basal part is represented by pale brown calcschists. These sediments, generally correlated to the Dogger lithotypes of the Tuscan Nappe (*Posidonia* Marlstones Auctt.: e.g. Barberi et al., 1969), are attributed by Corti et al. (1996) and Bortolotti et al. (2001) to the Piedmontese oceanic Domain.

7) Ophiolitic Unit (ex Complex IV) is constituted by four main tectonic sub-Units (Bortolotti et al., 1994) and includes a Jurassic ultramafic/mafic basement and basalts capped by an Upper Jurassic to Lower Cretaceous sedimentary cover (Mt. Alpe Cherts, Nisportino Fm., Calpionella Limestones, Palombini Shales).

8) Paleogene Flysch Unit (ex Complex V p.p.) is formed by a Paleogene Flysch with shaly-marly lithotypes and intercalations of limestones, sandstones and ophiolitic breccias.

9) Cretaceous Flysch Unit. The uppermost unit is the Elba Flysch, Late Cretaceous in age, whose basal part is arenaceous-conglomeratic (Ghiaieto Sandstones Auctt.) and grades upward into a typical mainly calcareous-marly flysch (Marina di Campo Fm. Auctt.).

The present, complicated structure of the Elba's tectonic pile (Boccaletti et al., 1980; Principi and Treves, 1984; Keller and Pialli, 1990; Bartole et al., 1991; Pertusati et al., 1993; Bouillin et al., 1994; Daniel and Jolivet, 1995; Carmignani et al., 1995; Bartole, 1995; Corti et al, 1996; Keller and Coward, 1996; Bortolotti et al., 2001) is the result of several tectonic events occurred during: a) the Upper Cretaceous-Middle Eocene convergence within the Ligurian-Piedmontese Ocean with consequent formation of an accretionary prism; b) the Upper Eocene-Oligocene collision of the European Plate (Corsica block) with the Adria Plate; c) the Oligocene-Lower Miocene ensialic

shortening and "serrage" of the inner part of the Adria Plate (Tuscan Domain), including metamorphism of the deepest buried units and eastward overthrusting of the oceanic successions (Ligurian and sub-Ligurian Units); d) the Burdigalian to Pliocene extension which produced the dismembering of the Elba's tectonic pile, firstly by low-angle shear zones (e.g. the Zuccale Fault, active during the uplift of the granitoid bodies) and, during more recent times, by high-angle, mainly N-S trending, normal faults systems, which display hematite-mineralizations (De-shamps, 1980; Tanelli, 1983).

STRUCTURAL DATA

Structural analyses were performed both at the meso- (outcrops) and microscale (on thin sections) in order to de-fine the structural framework and evolution of the Ortano Unit, the Acquadolce Unit, the Monticiano-Roccastrada Unit, and the Gràssera Unit. The metasiliciclastic rocks of the Porto Azzurro Unit were not considered because of their later strong thermometamorphic imprint due to the intrusion of the La Serra-Porto Azzurro monzogranite onto the previ-ous deformations.

For the first three considered Units, typical structural sites were defined in eastern (from Capo d'Arco to the Rio Mari-na/Rialbano mining area (locations in Fig. 2) and central El-ba (coast from the Lido beach to Norsi). The Gràssera Unit was analyzed only in Eastern Elba (Cavo and Parata areas).

In the following paragraphs, observed deformation struc-tures and kinematic indicators are described for each of the studied units. In general, the deformative events (Dp = main deformation event; Dc = later crenulation event) and their related structures (Sp = main schistosity; C = later crenula-tion) have different origin and age for the different units (see below).

Ortano Unit (Fig. 3)

Structural data were collected from the Capo d'Arco Schists and Porphyroids outcrops (Fig. 2) that occur along the coast of Capo d'Arco Residence (site 1), at Ortano (site 2), at Capo Ortano (site 3) and north of Lido Beach (site 4).

These rocks are strongly pervaded by a secondary, main continuous foliation (Sp) which in general occurs parallel to the lithologic contacts, and is characterized by sin-kine-matic growth of [1]Ser/Mu+Qtz±Chl±Feld. Thermometamor-phic And is mimetic on Mu. The Sp is locally associated to decimetric/decametric isoclinal flame-like folds (Fig. 4). The main trend of their axis and intersection lineations is from N20° to N40°, with a plunge of about 20° towards NE or SW. Within the Sp foliation, an earlier secondary folia-tion (Sp-1= Mu+Qtz±Chl) is recognizable as microlithons. The polymineralogical lineations (Ser+Qtz±Chl and mimet-ic And) on Sp and Qtz ribbons have mainly a strike from N350° to N70° and a mostly 10°-30° NE or a SW plunge. In the Porphyroids, mantled σ-type porphyroclasts (see Fig. 8 in Duranti et al., 1992), shear folds, polycrystalline rib-bon quartz and domino-like structures are recognizable on XZ plane and related to Sp. All the previous structures point to a mainly "top to W/NW" sense of shear in sites 1
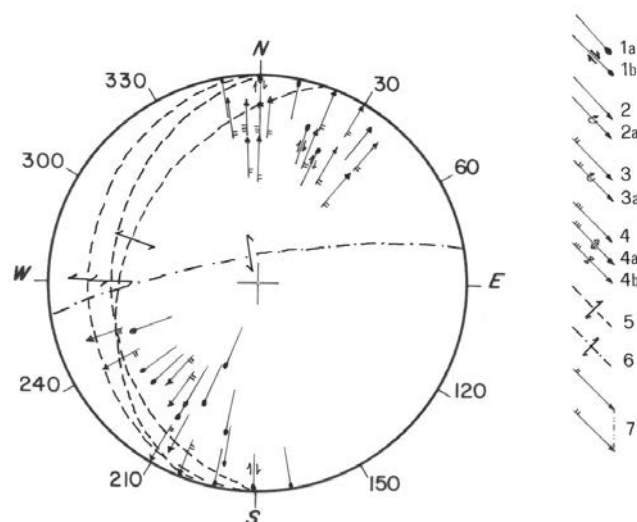

Fig. 3 - Schmidt stereonet, lower hemisphere projection, of structural data collected in the Ortano Unit. Legend: 1a- mono- and poly-mineralogical lineation, 1b- mono- and poly-mineralogical lineation with component of shear, 2- axis related to Dp folds, 2a- axis related to Dp folds with facing, 3- axis related to Dc folds, 3a- axis related to Dc folds with facing, 4- axis of later folds, 4a- later antiform, 4b- later synform, 5- Sp plane with com-ponent of shear, 6- C plane with component of shear, 7- degree of axial dispersion on foliation plane.

Fig. 4 - Decametric Dp isoclinal fold at the top of the Porphyroids (coast north of the Lido Beach).

and 4, while those of site 2 and 3 display a "top to N/NE" component.

In site 1 the aspect ratio of folds on XZ plane (Lisle, 1991) is about 1.42 (mean of the values obtained for both limbs and hinge), whereas in the site 3 a value of about 4.60 was obtained.

The Sp is deformed by a later event which is character-ized by metric/decametric, close to tight folds with round-ed/sub-rounded hinges, whose axes trend from N350° to N70° with a 10°-20° mainly NE or SW plunge (Fig. 5). Their millimetric- to centimetric-spaced zonal crenulation cleavage (C) produces intersection lineations (strike N30° to N60°) on Sp. A later, locally mineralized, fracture cleav-age (locally associated to gentle-open folds) trends about N-S. A post-C HT-LP static mineral assemblage (Bt, Mu, Crd, And) is also present.

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[1] Symbols of minerals: Mu=muscovite; Ser=sericite; Qtz=quartz; Chl=chlorite; Ab=albite; Feld=feldspar; San=sanidine; Bt=biotite; Crd=cordierite; And=andalusite; Cpx=clinopyroxene; Amph=amphibole; Wol=wollastonite; Grt=garnet, Cc=calcite.

Fig. 5 - Metric Dp isoclinal fold in the Capo d'Arco schists deformed by the Dc folding. Note the whitish post - Dc aplitic dyke (Capo Arco area).

Fig. 7 - Dp tight fold in the Phyllites of the Acquadolce Unit (South of the Norsi Beach).
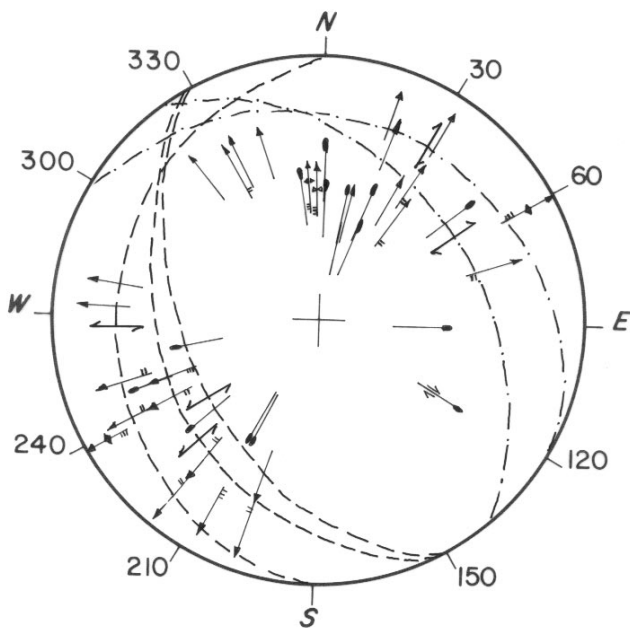

Fig. 6 - Schmidt stereonet, lower hemisphere projection, of structural data collected in the Acquadolce Unit. Legend in Fig. 3.

Fig. 8 - Dp isoclinal folds in calcschists bed of the Acquadolce Unit (dock of Rio Marina).

Acquadolce Unit (Fig. 6)

Data were collected in "phyllite, metasiltstone and metagraywake" rocks that occur along the road to Capo d'Arco Residence (site 5), along the road of Ortano (site 6), along the road from Rio Marina to Porticciolo (site 7 = Santa Filomena), in the Porticciolo area (site 8) and south of the Norsi Beach (site 9); data on the calcschist intercalations were collected in the Torre di Rio area (site 10).

The most evident mesostructures are centimetric to decametric tight/isoclinal folds with rounded hinges (Fig. 7). Their axis trend from N320° to N100° and plunge mainly to NW or SE. Their sub-centimetric-spaced axial plane foliation is a discrete crenulation cleavage, which often becomes a continuous secondary foliation (Sp = Ser+Qtz±Chl±Cc) (Fig. 8) which is pervasive and transposes previous structures (e.g. Sp-1 secondary foliation). Locally, sheath-type folds were also recognized. They are characterized by <(20°angles between axis on the Sp, a N30° to N150° strike and a 10°-20° NE or NW plunge. Thin section analyses in-

dicate local occurrence of Qtz and Ab pre- and syn?-Sp porphyroblasts (see Fig. 4 in Pandeli and Puxeddu, 1990 and Fig. 5 in Duranti et al., 1992).

The previous structures deformed a fine grained, continuous metamorphic layering (Sp1=Ser/Mu+Qtz±Chl±Ab±Cal), which in general occurs parallel to the lithologic boundaries, and is locally recognizable as intrafoliar relic (see Fig. 4 in Duranti et al., 1992). Sometimes, the Sp-1 occurs associated with centimetric/decimetric isoclinal folds.

The polymineralogic lineations (Mu+Qtz±Chl±Cc) on the Sp plane show similar orientations those described in the Ortano Unit (they strike mostly from N350° to N55°, and show a SW or NE plunge). The occurrence of intrafoliar isoclinal shear folds, polycrystalline ribbon quartz, and σ and δ porphyroclasts, "domino selcees", and shear bands on the [XZ] planes point to a "top to SW" sense of shear for most of the eastern outcrops, and a "top to SE" sense for site 5 and for the Norsi area. The finite strain on the XZ planes shows an aspect ratio of 1.56 (site 5) and 3.33 (site 10).

Successive deformation events produced: 1- open to close folds with thin, zonal crenulations (C) whose both axes and intersection lineations on the Sp trends mostly from N20° to N70°; 2- Later open to gentle folds characterized by widely-spaced fracture cleavage/kinks which trend is about N-S and N60° to N70°.

In the calcschist of Torre di Rio area (site 10), S-C planes show a "top to NE" sense of shear for the Dc. HT-LP miner-

als (Bt, Ms, And, Cpx, Amph, Wol, Grt) overprinted at least part of the later cleavages.

Monticiano-Roccastrada Unit (Fig. 9)

Within this Unit, we analyzed the outcrops of Rio Marina Fm. that are located in the Vigneria area (site 11) and along
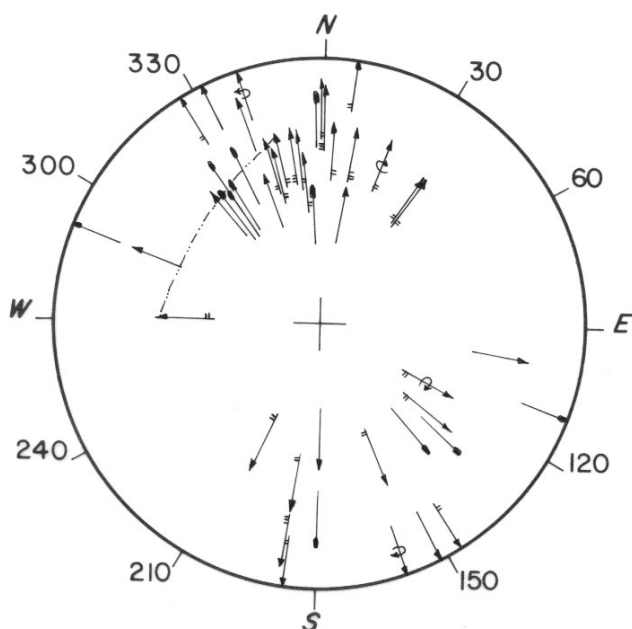

Fig. 9 - Schmidt stereonet, lower emisphere projection, of structural data collected about the Monticiano - Roccastrada Unit. Legend in Fig. 3.
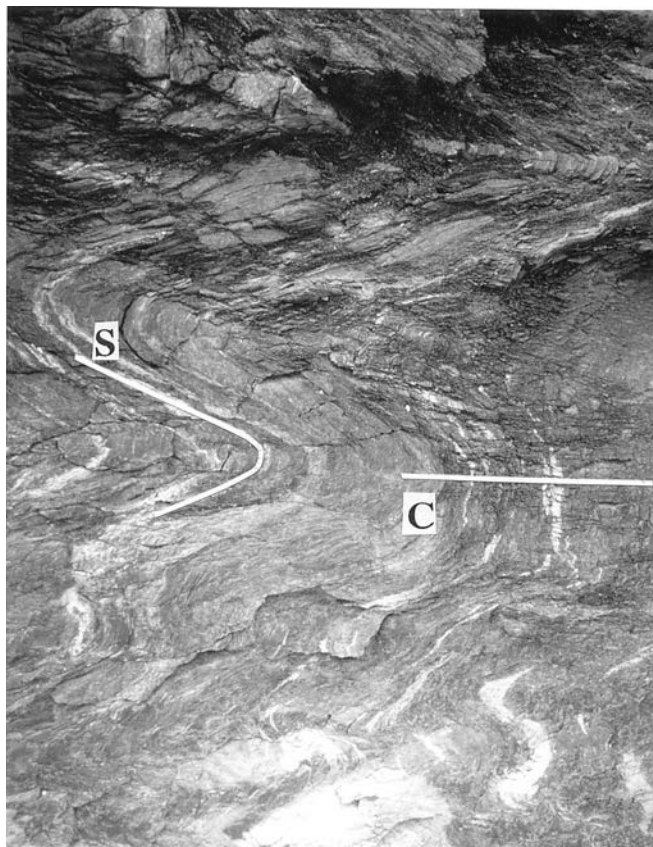

Fig. 10 - Dc close fold which deformed the Sp and Dp isoclinal fold within the "Verrucano" Phyllites (Valle Giove mine).

the road from Rio Marina to Cavo (site 12). The Verrucano of both Valle Giove mine (site 13), and Rialbano mine (site 14) was also studied.

Both formations are characterized by a fine-grained, continuous, and penetrative secondary foliation (Sp = Ser+Qtz±Chl) which is generally parallel to the bedding. Centimetric/metric isoclinal folds (that generally transpose bedding) are associated to Sp with axis oriented mostly from N320° to N10° and with an overall NW-trending plunge (Fig. 10).

Polymineralogical lineations are recognizable on Sp planes (Ser+Qtz±Chl). Reduction spots on Sp planes were recognized within the "Verrucano" and show an orientation of N320° to N360° and a N/NW - trending plunge. For them, the values obtained for the finite strain are about 5.32 on XZ plane, about 2.66 on XY plane and about 2.00 on YZ plane. The X axis is parallel to Sp. In the Rio Marina Fm. the finite strain on XY plane of Sp shows an aspect ratio of 1.27÷1.66.

The Sp foliation is deformed by decimetric/decametric open to tight folds with rounded/sub-rounded hinges, and axis generally with a N300° to N35° strike (plunge to NW). Spaced zonal to discrete crenulation cleavage (C) is associated to these folds which are characterized by a variable (mainly westward) dip of the axial plane (sub-vertical in the Rio Marina Fm of the Vigneria area). The vergence of these structures is generally towards NE, but in the Valle Giove mine NW-facing folds are also present. On XZ plane, rare S-C planes are present and indicate a "top to NE" component of shear sin-kinematic to Sp.

Later gentle/open folds with zonal crenulations or fracture cleavage, N-S trending axis and sub-horizontal axial planes are often recognizable. The post-C static crystallization of biotite was also recognized in thin sections.

Gràssera Unit (Fig. 11)

The structural features of the Cavo Fm. were observed in the Solana-Cavo area (site 15), while the basal calcschists were analyzed in the Parata area (site 16).

The pelitic lithotypes of the Cavo Fm. are characterized by a penetrative, secondary foliation that is morphologically defined as a slaty cleavage. The latter represents the main foliation at the mesoscale, and deformed (or sometimes transposes) both bedding and millimetric/centimetric Qtz±Cc veins (Fig. 12). This planar anisotropy is associated to close to tight folds whose axes strike between N280° to N40° and plunge ranges between 5°-20° towards the northern quarters; the axial plane is generally SE-plunging. A monomineralogical lineation (Ser and/or clay minerals) is recognizable on the Sp plane and it is oriented about N-S and dips towards N of about 10°-20°. In a siliceous-shaly horizon, radiolaria are deformed along the Sp and appears as σ-like porphyroclasts with a "top to SE" sense of shear. Their finite strain on the XZ plane shows an aspect ratio of about 3.57; it varies from X/Z = 0.4 to X/Z = 5.0 (mean value = 1.8) and the main axis (X) is generally parallel to the Sp.

The Sp is deformed by open to close folds whose axes generally trend from N300° to N50° and are either sub-horizontal or plunge to NNW of about 10°-40°. These folds are characterized by a locally penetrative fracture cleavage (Fig. 13) and crenulations which on the main foliation surface produce thin and closely spaced intersection lineations and rare mullions (Fig. 14). Moreover, the more competent
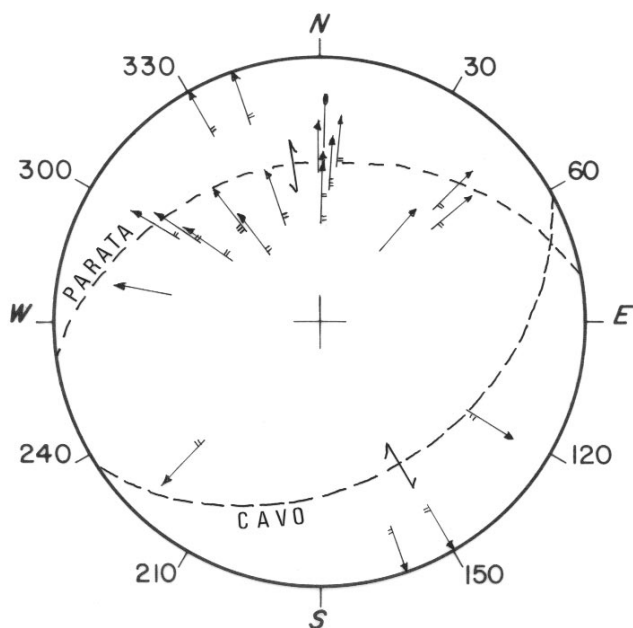
Fig. 11 - Schmidt stereonet, lower hemisphere projection, of structural data collected about the Gràssera Unit. Legend in Fig. 3.

Fig. 13 - Later fracture cleavage (C) in the Grassera Unit (Solana - Cavo area).

Fig. 12 - Bedding deformed by Dp and Dc folds (Solana - Cavo area).

Fig 14 - Irregular mullions associated to the C of the Cavo Fm. slates (Solana - Cavo area).

beds located in the external part of the hinge are locally subjected to boudinage. In some cases, a later deformation event is recognizable as symmetric kinks whose axes are characterized by a N320° to N5° strike and a 10°-30° NW plunge.

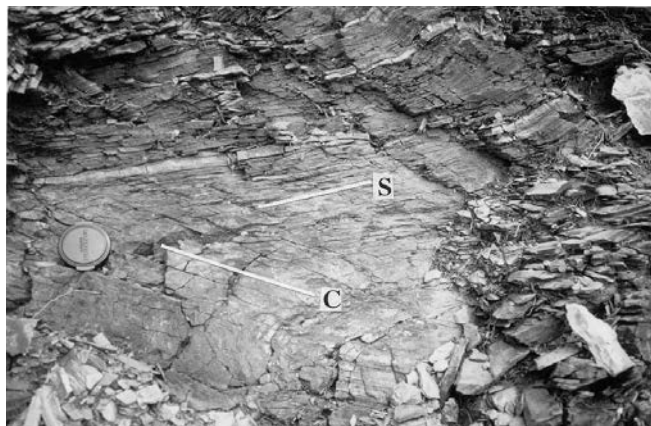In the basal calcschists horizon of the Cavo Fm., the mil-limetric spaced (up to 4 mm) main planar anisotropy (Sp) is instead related to close/tight folds (B3-type folds, axis: strike from N320° to N360° and 5°-30° NNW plunging) which transpose at high angle the previous foliation (Sp-1) which is recognizable in the microlithons. Rare interference figures between Sp and Sp-1 folds point to a coaxial-type folding. On the XZ plane, only a few kinematic indicators are recognizable (S-C planes or dominos) and they indicate a top to NW component of shear. The Sp is deformed by lat-er crenulation cleavage associated to open folds (axis: about N-S strike and 10° dip toward N) which produces thin inter-section lineation on the main foliation. The vergence of these folds cannot be determined.

DISCUSSION

The collected structural data reveal that the deformativonal framework of central and eastern Elba is not homogeneous for each of the anchi- to epimetamorphic Units that occur in the area.

The Paleozoic formations of the **Ortano Unit** show structural features similar to those observed in the metamorphic successions cropping out along the Mid Tuscan Ridge (Alpi Apuane-Monti Pisani-Iano-Monticiano Roccastrada Ridge-Mt. Leoni: Rau and Tongiorgi, 1974; Moretti, 1986; Carmignani and Kligfield, 1990; Carosi et al., 1995; Costantini et al., 1987/88; 1998). In particular the main continuous secondary foliation Sp is associated to east-vergent isoclinal folds which are later deformed by mostly coaxial, close to open folds with crenulation cleavage (Structural Domain I of Elter and Pandeli, 1993). The relics of the Sp-1 secondary foliation correspond to those found in the pre-Late Visean rocks of the Northern Apennines which are considered as the evidence of the Hercynian tectono-metamorphic event (Sudetic event: Pandeli et al., 1994).

The Mesozoic metasiliciclastics and calcschists of the **Acquadolce Unit** are deformed by a pervasive Sp (spaced discrete crenulations or pervasive schistosity) linked to tight/isoclinal folds. The latter refold a continuous metamorphic layering (Sp-1) which is generally well recognizable at the mesoscale and is also locally associated to isoclinal folds. Moreover, it is worth of note that the kinematic indicators recognized on the Sp of the Acquadolce Unit show an opposite sense of shear relative to those of the Ortano Unit (top to SW or SE for the Acquadolce Unit; top to NE or NW for the Ortano Unit). Later close to open folds with cleavages are also present.

The Permo-Carboniferous and Triassic metasediments of the **Monticiano-Roccastrada Unit** show a structural framework similar to that of the Ortano Unit. In fact, the Sp, which generally occurs parallel to the bedding and that is related to NE-vergent isoclinal folds, is coaxially deformed by open to tight folds mostly with a NE-facing (locally a NW vergence is also recognizable). A top to NE sense of shear is associated to Sp. A similar structural framework and, in particular, the strain data (reduction spots) was obtained in the correspondent metamorphic formations of the Monticiano-Roccastrada Ridge (Elter and Meccheri, 1994).

The structural features of the **Gràssera Unit** are different from those of the above mentioned Units. Firstly, the Sp is a slaty cleavage which is characteristic of anchimetamorphic to epimetamorphic conditions (see Pandeli et al., this volume). The locally penetrative and transpositive Sp is associated to close/tight folds which are later deformed by coaxial open/close folds. The latter are generally characterized by sub-horizontal axial planes, fracture cleavage, and rare mullions which point to a deformation occurred at a shallow structural level possibly close to the ductile/brittle transition. The rare kinematic indicators associated to Sp point to a top to SE sense of shear for the Cavo area. In the calcschist of the Parata area deformation is stronger and traspositive, and could be related to the basal shearing occurred during the emplacement of this Unit onto the Tuscan Nappe.

The collected structural data point to a complex piling up of the Elba tectonic units. In spite of the similar attitude of the mineralogic lineations lying on Sp (see also Duranti et al., 1992; Pertusati et al., 1993), the Acquadolce Unit has clearly a different tectonic imprint relative to both the underlying Ortano Unit (e.g. the opposite sense of shear for Dp in the above said Units), and the overlying Monticiano-Roccastrada Unit. Therefore, our data rule out the hypothesis that the Acquadolce Unit represents the original Mesozoic-Tertiary cover of the Ortano Paleozoic succession (Barberi et al. 1967a; 1967b; 1969; Perrin, 1975; Boccaletti et al., 1977; Keller and Pialli, 1990). The Acquadolce Unit acquired its main structural framework in more western paleogeographic area respect to the Ortano Unit; only later, the Acquadolce Unit was emplaced onto the Tuscan Paleozoic succession. This hypothesis is supported by the finding of Mesozoic fossils in the calcschists (Duranti et al., 1992) and by the 19.68±0.5 Ma age ($^{40}Ar/^{39}Ar$ radiometric data: Deino et al., 1992) for the Sp of the Acquadolce Unit, which suggest an Eo- or Meso-Alpine age for the Sp-1 foliation, and the probable attribution of such Unit to the Ligurian-Piedmontese Domain ("Schistes Lustrés" Auctt.: Corti et al., 1966; Bortolotti et al., 2001).

Another interesting structural datum is the evident change in the sense of shear for Dp of both the Acquadolce Unit and the underlying Ortano Unit from the northern (Rio Marina-Ortano) to the southern (Capo d'Arco) or southwestern (Spiaggia del Lido-Norsi) structural sites. In particular, both the top to SW sense within the Acquadolce Unit and the top to N/NE sense of shear within the Ortano Unit change southwards into top to SE and top to W/NW respectively; in other words the data point to a 90° rotation of these structural elements in both Units. The coincidence in the location of this structural boundary in the two Units suggests that the change in the sense of shear can be likely attributed to later deformation events which post-date the piling up of the Acquadolce Unit onto the Ortano Unit and the contact metamorphism (e.g. syn-/post-Zuccale detachments and folding: see later).

The Carboniferous-Triassic succession of the Monticiano-Roccastrada Unit shows structural features similar to those observed in the Ortano Unit. Moreover, similar features were recognized in the Tuscan Mesozoic-Tertiary epimetamorphic successions studied by Pandeli et al. (1995) and Bortolotti et al. (2001) in areas located NE (Capo Scandelli-Capo Castello-Isola dei Topi) and SE (Capo Pero) of Cavo. Therefore, we hypothesize that the Ortano Unit, the Monticiano-Roccastrada Unit and the Cavo epimetamorphic formations could be considered as wedged parts of a single stratigraphic succession which is similar to those cropping out in the continent along the Mid Tuscan Ridge (e.g. Monti Pisani, Monticiano-Roccastrada Ridge: Rau and Tongiorgi, 1974; Costantini et al., 1987/88; Bertini et al., 1991). The analogies of the structural-metamorphic framework of the previous units suggest that tectonic dismembering affected the pristine succession during the final stages or immediately later of Dc folding event (see Pandeli et al., 1991). These events could be connected to the extensional regime of the Tyrrhenian area (Pertusati et al., 1993; Carmignani et al., 1995; Bartole, 1995; Bortolotti et al., 2000). The same events produced the tectonic intercalation of the Acquadolce Unit within the Tuscan-type Ortano and Monticiano-Roccastrada Units, as well as sandwiching of the Gràssera Unit between the Ophiolitic Unit and the Tuscan Nappe. In fact, the structural contrast among the very low grade metamorphic lithotypes of the Gràssera Unit and the slightly deformed diagenetic to anchimetamorphic ones of the Palombini Shales (Ophiolitic Unit) and the Mesozoic formations of the Tuscan Nappe (see also Pandeli

et al., 2001) is evident.

The above mentioned, piled Units together with the Porto Azzurro Unit were then affected by thermometamorphism due to the La Serra-Porto Azzurro monzogranite (about 5 Ma: Saupé et al., 1982) as suggested by the vertical and areal distribution of the contact mineralogic associations (see also Duranti et al., 1992; Pertusati et al., 1993). In fact, an evident upwards decrease of the paleo-temperatures in the thermometamorphic aureole is recognizable throughout the stack of imbricate units (from Ortano Unit to Monticiano-Roccastrada Unit).

Finally, it is noteworthy that a latest event characterized by about N-S striking gentle-open folding and kinks is commonly observed in all the studied units. Probably, most of the latter deformations affected the whole imbricate stack after its final emplacement onto the Porto Azzurro Unit. The latter hypothesis is supported by the gentle folding of the upper part of the Mt. Calamita Fm., and of the overlying, post-intrusion, foliated cataclastic horizon (Zuccale Fault) in the Spiagge Nere-Terranera mining area (for details see Benvenuti et al., 2000).

CONCLUSIONS

The structural data collected in the anchi- and epimetamorphic units (Ortano, Acquadolce, Monticiano-Roccastrada and Gràssera Units) point to a complex evolution of Elba's tectonic pile. In particular, the present stacking derives mainly by a later and complex superposition of polydeformed units that belong to different structural and paleogeographic domains. The observed similarities of the deformational features within the Paleozoic successions (including relics of the Hercynian foliation) of the Ortano Unit and within the Carboniferous-Triassic to Mesozoic-Cainozoic formation of the Monticiano-Roccastrada Unit, suggest that both units belong to the same structural domain. Moreover, it is probable that both units derived from the wedging of a single stratigraphic succession, Paleozoic to Cainozoic in age, which corresponds to the typical Tuscan metamorphic succession exposed on the continent along the Mid Tuscan Ridge (from Alpi Apuane to Mt. Leoni). The Acquadolce Unit, a probable Piedmontese unit, imprinted either by the Eo- or the Meso-Alpine event, shows a different structural framework characterized by an evident opposite sense of shear within the Sp (dated about 19 Ma) respect to the surrounding Ortano and Monticiano-Roccastrada Units. The anchimetamorphic Gràssera Unit, another probable oceanic unit, is tectonically intercalated between two non-metamorphic units (the Ophiolitic Unit and the Tuscan Nappe). The wedging and the complex piling of the Tuscan and oceanic units occurred between 19 Ma (age of the Sp in the Acquadolce Unit) and 5 Ma (age of the La Serra-Porto Azzurro monzogranite). In fact the La Serra-Porto Azzurro monzogranite produced a thermometamorphic aureola which is still preserved throughout the structural stack. During the rise of the cooled magmatic body, the final emplacement of the imbricate tectonic pile onto the basal Porto Azzurro Unit occurred by a main low-angle normal fault (the Zuccale Fault). During this event (5-2 Ma according to Bouillin et al., 1994 and Daniel and Jolivet, 1995) or immediately later, the final gentle-open folding and kinking of the whole tectonic pile also took place, predating the N-S trending high-angle normal faulting and hematite-rich mineralizations.

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