Neogene deformation and granite emplacement in the metamorphic units of northern Apennines (Italy): Insights from mylonitic marbles in the Porto Azzurro pluton contact aureole (Elba Island)

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ABSTRACT

In the northern Tyrrenian Sea, late Miocene intrusions (Monte Capanne pluton and Porto Azzurro pluton) were emplaced at upper crustal levels (<0.2 GPa) in the thrust systems of Elba Island. The emplacement of intrusive rocks is currently explained in the context of late Miocene extensional tectonics. New detailed structural data collected along a continuous natural cross section through the contact aureole of the Porto Azzurro pluton (eastern Elba) where strain localization has occurred within two west-dipping decameter-scale carbonate shear zones, namely the Calanchiole and Felciaio shear zones, are reported here. These shear zones, characterized by a lithological difference with calcite and dolomite marbles dominant in the Calanchiole and Felciaio shear zones, respectively, exhibit a similar rheological behavior. They represent two weakened layers in which west-dipping mylonitic foliation, sheath folds, boudinage structures, and upright folds developed within the contact aureole. Moreover, in correspondence with the Felciaio shear zone, the inversion of metamorphic facies occurs. Meso- and microstructural data give evidence that most of the deformation and displacement in the shear zones was coeval with contact metamorphism and developed under metamorphic conditions retrograde from pyroxene hornfels to hornblende-hornfels facies. Geometric and kinematic features indicate that both shear zones correspond to ductile thrusts, which led to internal stacking of the contact aureole. Therefore, at Elba Island, emplacement of intrusive rocks coeval with late Miocene crustal shortening gives a new perspective on relations between tectonics and magmatism in the northern Apennines.

INTRODUCTION

In orogenic belts characterized by intrusive magmatism coeval with active tectonics, the relationship between the deformation structures and the mineral growth in contact aureoles is one of the most effective and commonly used criteria when defining spatial and temporal relationships between magmatism, metamorphism, and deformation. However, as stated by Paterson and Tobisch (1992), the rates at which the different processes operate (i.e., deformation, mineral growth, crystallization, and cooling of intrusive rocks) strongly influence the development of the final structures and textures. These criteria are particularly useful in lower and mid-crustal conditions where the rates of the different operating processes are quite similar, which allows better constraints on their relative relationships and the timing of pluton emplacement (i.e., pre, syn, post) with respect to deformation events (Paterson and Fowler, 1993). On the other hand, in upper crustal conditions, the crystallization and cooling processes of intrusive rocks are significantly faster than the strain rates associated with regional bulk deformation ($10^{-13}$ $s^{-1}$–$10^{-15}$ $s^{-1}$), which makes the interpretation and reconstruction of tectonic evolution more complicated and often ambiguous (Paterson and Fowler, 1993). In this scenario, high-strain zones, which might be characterized by strain rates that approach the crystallization-cooling rate (Paterson and Tobisch, 1992), are the best candidates to better define the exact timing relationship between the pluton-contact aureole system and deformation at the upper crustal levels.

Carbonate rocks, which consist primarily of calcite and dolomite, can play an important role in the rheological behavior of the upper crust. In comparison to dolomites, calcite-rich carbonates are able to accumulate large amounts of strain and record deformation by crystal-plastic flow even in upper crustal conditions (Burkhardt, 1990). Several studies, concerning the localization of deformation, highlight the development of high-strain zones in calcite-rich units with mylonitic microstructures achieved by progressive deformation and dynamic recrystallization processes, whereas brittle structures and high strength characterize dolomite units (Busch and van der Pluijm, 1995; Bestmann et al., 2000; Ulrich et al., 2002). Early experimental works performed on single crystals or coarse-grained dolomites supported these field observations and reported higher fracture and flow strengths for dolomite than for calcite at comparable conditions (Handin et al., 1967; Barber et al., 1981, 1994). On the other hand, some field studies have documented the occurrence of ductile behavior of dolomites, which underwent deformation at metamorphic conditions ranging from lower greenschist to amphibolite facies (White and White, 1980; Newman and Mitra, 1994; Leiss and Barber, 1999). According to White and White (1980), in the relatively fine-grained (30 µm) dolomites of the Flinton group (southeast Ontario), which deformed in the amphibolites facies (T $\approx$600 °C), large amounts of deformation were accommodated at the microscopic scale by grain boundary diffusion and sliding mechanisms. High-temperature syn-intrusive deformation structures in the metamorphosed calcite-dolomite sequences across the contact aureole of the Adamello pluton (Southern Alps) have also been described (Brack, 1983; Delle Piane et al., 2008). In this case, outcrop evidence (i.e., ptygmatic folds and boudinage structures) suggests that calcite behaved as the strong phase relative to dolomite at the time of deformation. Only recently, experimental investigations,
performed on natural and synthetic dolomites (Delle Piane et al., 2008; Davis et al., 2008), indicate that, under high-temperature deformation conditions, the strength of fine-grained dolomite and calcite aggregates deformed by diffusion creep can show much less contrast in rheology. As a consequence, fine-grained dolomites may even exhibit low strength and be exploited as lubricating layers under specific deformation conditions.

This paper focuses on the deformation features of strongly sheared carbonate hornfelses from two ductile high-strain zones within the contact aureole of the Porto Azzurro pluton in eastern Elba Island. Along a continuous natural cross section through the western side of the contact aureole, meso- and microstructural observations on strained hornfels rocks, coupled with the analysis of mineral assemblages, show an inversion of metamorphic zone distribution associated with strain partitioning within two lithologically different carbonate shear zones (dolomite-rich and calcite-rich marble units). Shear zone development was coeval with the granite emplacement and led to internal stacking of the contact aureole with consequent inversion of metamorphic zonation and thickness increase. Based on these results, a suitable reconstruction of the tectonic evolution of the Porto Azzurro pluton contact aureole is proposed and discussed in the tectonic context of the eastern Elba Island and in the frame of evolution of the northern Apennine as well. In particular a new perspective of the relations between late Neogene tectonic and magmatism in the northern Tyrrhenian Sea–northern Apennine is addressed.

NORTHERN APENNINE GEOLOGICAL OUTLINE

The northern Apennine (Fig. 1) is an orogenic belt developed during the Tertiary at the boundary between the Europe and Adria continental margins after closure of the Ligure-Piemontese Ocean or Ligurian Tethys (Boccaletti et al., 1971; Elter, 1975; Molli, 2008 and references therein). The architecture of the northern Apennine nappe belt results from progressive crustal shortening, thrusting, and eastward stacking of oceanic and continental-derived units related to the westward subduction of the Adria microplate underneath the European plate (Corsaro-Sardinian block). Crustal deformation began in the Eocene, first affecting the inner oceanic domains (Ligurian and sub-Ligurian domain) and then continuing in the late Oligocene–early-middle Miocene to involve the proximal side of the Adria continental margin (Tuscan domain) and the more external zones (Umbrian domain) in the late Miocene.

As a result, the nappe system of the northern Apennine inner (Tyrrenhian) margin consists from top to bottom of the following tectonic units (Fig. 1):

1. Ligurian units, which consist of Jurassic ophiolite complexes covered by Upper Jurassic–Paleocene deep-water sediments and Cretaceous–Paleocene flysch sequences. These units, considered as remnants of the Mesozoic Liguro-Piemontese ocean (Elter, 1975), were deformed at shallow structural levels as they reached sub-greenschist-facies peak conditions.

2. Tuscan units, consisting of Adria-derived continental units deformed at different structural levels: (a) Tuscan Nappe, which is made up of unmetamorphic to very low-grade metamorphic formations of Late Triassic to early Mio- cene age and (b) Tuscan Metamorphic Units, which are, on the whole, characterized by a Paleozoic basement unconformably overlain by Permian–Triassic or Late Triassic–Oligocene metamorphic sequences. These units crop out in tectonic windows, forming an arcuate belt from the Apuan Alps in the north to the Monte Argentario promontory at the south (i.e., mid-Tuscan ridge) and represent the deepest exposed structural levels of the northern Apennine orogenic wedge. Indeed, the Tuscan Metamorphic Units suffered peak metamorphic conditions ranging from high-pressure greenschist facies, developed at 0.6–0.8 GPa and 400–500 °C (Mg-chloritoid and kyanite in metapelites of the Massa Unit in the Alpi Apuane; Molli et al., 2002), to high-pressure and/or low-temperature blueschist facies realized at 0.6–1.0 GPa and 350–380 °C Fe-Mg carpholite in metapelites of the Monti Leoni–Monticiano Roccastrada unit in the Montagnola Senese area; Giorgetti et al., 1997) and at 1–1.2 GPa and 350–420 °C (Ver- rucano of Monte Argentario; Theye et al., 1997).

Other continental- and ocean-derived metamorphic units outcrop in some islands of the Tuscan Archipelago (northern Tyrrhenian Sea; Fig. 1). These units show high-pressure and low-
temperature peak blueschist-facies conditions (Fe-carpholite and glaucophane in metapelites) at 1.0–1.5 GPa and 350 °C in the Gorgona and Giglio islands (Jolivet et al., 1998), whereas the metamorphic units of Elba Island (see below) were deformed under greenschist-facies conditions that reached 0.4 GPa and 350 °C during the main phase of the nappe stacking in the northern Apennine (Franceschelli et al., 1986).

A polyphasic deformation characterizes these metamorphic units, which show an early generation of structures associated with underthrusting and synmetamorphic nappe-fold formation, followed by overprinting structures related to exhumation and uplift (Carmignani and Kliger, 1990; Molli and Vaselli, 2006). In the Alpi Apuane, early deformation (D1) was realized at 27–20 Ma, whereas later synmetamorphic deformation (D2) predated 11 Ma (Kligfield et al., 1986; Balestrieri et al., 2003).

Since the late Miocene, the northern Apennine inner margin has been the site of anatetic magmatism (Tuscan Magmatic Province; Serri et al., 1993). The most common products are represented by acidic intrusive rocks, a large volume of which occurs as Pliocene–Pleistocene intrusions (at 3–5 km depth) in the currently active Larderello geothermal field (Bertini et al., 2006). In the northern Tyrrhenian Sea, intrusive and volcanic rocks, ranging in age between 8.4 and 3 Ma, crop out in the islands of Capraia, Giglio, Montecristo, and Elba (Fig. 1). The emplacement of magmatic intrusions in the inner margin of the northern Apennine is currently explained in the context of crustal extension related to late Miocene–Pliocene opening of the Tyrrhenian Sea as a backarc basin (Malinverno and Ryan, 1986; Keller and Coward, 1996; Jolivet et al., 1998). However, since the 1990s, this model of crustal extension in the northern Apennine has been strongly criticized, and several structural studies give evidence of Pliocene crustal shortening and coaxial magmatism (Boccaletti et al., 1997; Boccaletti and Sani, 1998; Cerrina Feroni et al., 2006; Musumeci et al., 2008).

**GEOLOGICAL SETTING OF ELBA ISLAND**

In the northern Tyrrhenian Sea, Elba Island is one of the westernmost portions of the northern Apennine belt close to the western side of Alpine belt of northern Corsica (Figs. 1 and 2A). In relation to its position and the occurrence of stacked tectonic units intruded by late Miocene large plutonic bodies, Elba Island represents a key area in the northern Apennines.

The structural setting of Elba Island was first described by Trevisan (1950) and reported in the geological map by Barberi et al. (1967), and it is composed of five main complexes that were interpreted as deriving from a unique succession, deformed, and partly metamorphosed by granitic intrusions. This first interpretation was successively modified by several authors (Pertusati et al., 1993; Keller and Coward, 1996; Bortolotti et al., 2001), who recognized the occurrence of sedimentary and metamorphic tectonic units derived from both continental (Adria) and oceanic (Ligurian) domains. The structure of the northern Apennine on Elba Island (Fig. 2A) consists of five tectonic units, which are stacked toward the NE and organized into two thrust complexes. The upper complex is an imbricate fan of three thrust sheets made up of sedimentary and low-grade metamorphic rocks belonging to Ligurian units and Tuscan Nappe. From top to bottom, they correspond to (1) Cretaceous–Paleogene flysch deposits, (2) Mesozoic ophiolitic rocks and sedimentary cover, and (3) Late Triassic–Jurassic carbonatic rocks with a thin slice of Permian–Triassic siliciclastic deposits at the base.

The lower complex (Figs. 2A and 2B) consists of two metamorphic units, namely the Calamita Unit followed upward by the Ortona Unit. The Calamita Unit is made up of high- and medium-grade pelitic-psammitic hornfels rocks (Calamita Schists) deriving from early Carboniferous flysch deposits (Musumeci et al., 2011), followed by thin slices of Middle Triassic metasedimentary (Verrucano Formation) and Early (? Jurassic Calanchiole marble (Garfagnoli et al., 2005). The Ortona Unit is an imbricate fan of Paleozoic and Mesozoic thrust sheets, which, from bottom to top, consists of (1) low-grade metasedimentary and metavolcanic (Ortanporphyrod, Middle Ordovician in age; Musumeci et al., 2011), (2) a thin slice of dolomite marble (Ortano marble, Early (? Jurassic in age) and (3) medium- and high-grade pelitic and carbonate hornfels rocks (Acquadulce unit Early (? Cretaceous in age; Pertusati et al., 1993).

According to reconstructions proposed by several authors (Keller and Coward, 1996; Pertusati et al., 1993; Bortolotti et al., 2001), the tectonic evolution of Elba Island can be summarized in two stages:

1. An early stage of folding and stacking that developed under very low metamorphic grade (i.e., anchizone) in the upper complex and low metamorphic grade (i.e., epizone) in the lower complex. In the Calamita Schists, albite + muscovite + chlorite mineral assemblages are considered as the record of this tectonic-metamorphic regional event (Garfagnoli et al., 2005), which is dated at 19 Ma in the Ortona Unit (Deino et al., 1992). This age is slightly younger than those recorded in the metamorphic units of the Apuan Alps (Kligfield et al., 1986) and can be considered as the upper limit of regional metamorphism related to the main phase of nappe stacking in the northern Apennine (Pertusati et al., 1993; Keller and Coward, 1996).

2. In the late stage (late Miocene), multiple magma inputs, spanning in ages from ca. 8 to 5.9 Ma, led to the emplacement of two large composite intrusive bodies together with systems of leucogranitic sills into the nappe stack of Elba Island (Dini et al., 2002). In particular, the Monte Capanne pluton in the west and the Porto Azzurro pluton in the east were emplaced in the upper complex and lower complex, respectively, with development to medium- to high-grade contact metamorphism that overprinted previous fabric and low-grade metamorphic mineral assemblages (Bouillin, 1983; Duranti et al., 1992; Garfagnoli et al., 2005). The emplacement of intrusive bodies was also accompanied by coeval deformation with the development of folds and fault zones. These structures, affecting the contact aureoles and the whole thrust systems, have been related to (1) the collapse of the oрогenic nappe pile during intrusive rocks emplacement (Pertusati et al., 1993; Garfagnoli et al., 2005), and (2) crustal extension linked to the opening of the Tyrrhenian Sea (Keller and Coward, 1996). In this frame, the Zuccale fault (ZF; Figs. 2B and 2C) is interpreted as an east-dipping low-angle fault (<10°), roughly coeval with granite emplacement, that crosscuts the nappe pile with eastward displacement of hanging-wall units from central to eastern Elba Island (Pertusati et al., 1993; Keller and Coward, 1996; Collettini et al., 2006). The geometry and amount of displacement of the Zuccale fault are shown in the geological cross section across eastern Elba Island (Fig. 2C). Along this section, the Zuccale fault has an eastward average dip of nearly 2°, and the main tectonic contact between upper complex and lower complex is displaced eastward by ~6 km, as also reported by Keller and Coward (1996).

**THE PORTO AZZURRO PLUTON CONTACT AUREOLE**

In eastern Elba Island, the emplacement of the Porto Azzurro pluton (5.9–6.2 Ma; Mainieri et al., 2003; Musumeci et al., 2011) was associated with the development of a wide contact aureole affecting the Calamita and Ortona units. The wide extent of contact aureole (~60 km²) throughout the Calamita peninsula and eastern Elba Island (Fig. 2B), testifies to the large size of the Porto Azzurro pluton. This latter is only exposed to the north of the Calamita peninsula (Valdana area), where it consists of medium-
Figure 2. (A) Tectonic sketch map of Elba Island (after Pertusati et al., 1993); (B) geological sketch map of southeastern Elba Island, box refers to the investigated area shown in Figure 3; (C) geological cross section from central to eastern Elba Island. ZF—Zuccale fault.
grained biotite monzogranite (Fig. 2B). Moreover, gravimetric data in the northern Calamita peninsula (Siniscalchi et al., 2008) and the finding of granitic rocks at 150–200 m in the mining boreholes in the eastern Elba Island (Bortolotti et al., 2001) also ensure that the roof of the intrusion is located at very shallow depths.

The contact aureole of the Porto Azzurro pluton has been described in detail by Duranti et al. (1992), and, in the Ortano and Calamita units at the north of Monte Arco (Fig. 2B), they documented a sequence of prograde metamorphic zones that range from biotite zone to andalusite–K-feldspar zone in the pelitic and/or psammitic hornfels rocks and from biotite zone to wollastonite zone in the carbonate hornfels rocks. The estimated pressure-temperature (PT) condition of contact aureole ranges from 300 °C (biotite zone) to 650 °C (andalusite–K-feldspar zone and wollastonite zone), with Pmax <0.18–0.2 GPa (Duranti et al., 1992). These PT conditions are diagnostic of a low-pressure/high-temperature (LP/HT) contact metamorphism (Pattison and Tracy, 1991) and indicate that the Porto Azzurro pluton was emplaced at a very shallow crustal level in the metamorphic units of the lower complex. The most complete exposure of the contact aureole occurs in the Valdana area to the west of the Calamita peninsula (Figs. 2B and 3), where a continuous natural cross section of the contact aureole through the Calamita Unit and the Ortano Unit is exposed along the coastline from the Calanchiole in the east to the Capo Norsi, at west (Fig. 3). In the following, the structural and metamorphic features observed along this section are described.

**Calanchiole–Capo Norsi**

**Section: Structural Setting and Metamorphic Zonation**

Along the investigated section (Figs. 3A and 3B), the contact aureole attains a large thickness of ~1.3 km and, in the west (Capo Norsi), abruptly ends against the west-dipping Capo Norsi thrust. This latter separates the upper complex, which did not experience a contact metamorphism, to the underlying medium-grade hornfels rocks of the contact aureole (Figs. 3A and 3B). As shown in Figure 3, the contact aureole consists of a lithologically heterogeneous multilayer stack composed of pelitic-psammitic, carbonate and calc-silicate hornfels rocks. On the whole, the growth of high-temperature/low-pressure (HT/PLP) mineral assemblages locally defines the main planar fabric observed in the field (Mazzarini et al., 2011). This foliation shows a mean N-S–trending and westward-plunging dip direction, and locally it is folded by decimeter-to decameter-scale, NNE-striking folds (Fig. 3C). These features are in agreement with the synkinematic recrystallization of metamorphic minerals and folding of high-grade metamorphic foliation in the hornfels rocks of Ortano Unit and in the Calamita Unit described by Pertusati et al. (1993), Garfagnoli et al. (2005), and Mazzarini et al. (2011).

Based on the peak mineral assemblages occurring in the hornfels rocks, the following succession of hornfels rocks and metamorphic zones can be recognized, moving from the Calamita Unit, which hosts the Porto Azzurro pluton, to the Ortano Unit (i.e., from east to west; Fig. 3).

**Andalusite Zone**

This zone is defined by the stable association of andalusite + cordierite + K-feldspar + biotite + muscovite (pyroxene hornfels facies) in high-grade pelitic-psammitic hornfels rocks of Calamita Schist cropping out along the northwestern side of the Calamita peninsula.

**Diopside Zone**

The assemblage of diopside + tremolite (pyroxene hornfels facies) characterizes the Calanchiole marble lying above the Calamita Schist in the western side of Calamita peninsula. In the diopside zone, retrograde mineral assemblages are represented by tremolite + talc association.

**Cordierite Zone**

The stable association of cordierite + K-feldspar + biotite + muscovite (hornblende-hornfels facies) occurs in medium-grade hornfels rocks of Calamita Schist cropping out in the Valdana below the Ortano Porphyry.

**Biotite Zone**

The low-grade biotite schists (metasandstone and phyllitic quartzite) of Ortano Porphyry are characterized by white mica + biotite assemblage (albite-epidote hornfels facies). In these low-grade rocks, contact metamorphism mainly resulted in the recrystallization of white mica and growth of biotite flakes.

**Diopside Zone**

In the Ortano marble, peak metamorphic conditions are recorded in the calcisilicate layers, where the stable association of diopside + Ca-rich plagioclase (pyroxene hornfels facies) defines the diopside zone. Retrograde mineral assemblages are represented by the association of fine-grained tremolite + white mica. In the dolomite marble hosting calcisilicate, the mineral association consists of dolomite + phlogopite + talc + calcite + quartz ± K-feldspar.

**Wollastonite Zone**

At the base of the Acquadolce unit, the wollastonite zone is defined by the stable association of wollastonite + diopside + Ca-rich plagioclase + biotite (pyroxene hornfels facies) in decimeter- to meter-thick impure marble and calcisilicate layers. The metapelites alternating within calcisilicate layers typically consist of high-grade hornfels with the stable association of andalusite + cordierite + K-feldspar + biotite + muscovite (pyroxene hornfels facies).

**Cordierite Zone**

At the westernmost end of the contact aureole (Capo Norsi), the cordierite zone is defined by the association of cordierite + K-feldspar + biotite + muscovite (hornblende-hornfels facies) in medium-grade spotted schists of the Acquadolce unit.

According to the metamorphic conditions of the LP/HT contact aureole (P <0.2 GPa; Pattison and Tracy, 1991), the metamorphic zones are characterized by temperatures ranging between 650 and 550 °C for the andalusite and wollastonite zones and 600–500 °C for the diopside zone. The occurrence of mineral assemblages described above indicates an anomalous distribution of metamorphic zones across the contact aureole that does not match a normal decrease of the metamorphic grade moving away from rocks hosting the intrusive body (i.e., the Calamita Schist). In particular, an inverted metamorphic zonation is highlighted by the sudden increase of the metamorphic grade corresponding to the Ortano marble, given that the high-grade (pyroxene hornfels facies) diopside and wollastonite-bearing hornfels of Ortano marble and the Acquadolce unit structurally overlie the low-grade (albite-epidote hornfels facies) biotite schists of Ortano Porphyry (Figs. 3A and 3B).

**Shear Zones in the Porto Azzurro Pluton Contact Aureole**

Throughout the contact aureole, the deformation was localized in two carbonate shear zones, namely the Calanchiole and Felciaio shear zones (Figs. 3 and 4). Microstructures of samples collected throughout the Calanchiole and Felciaio shear zones were studied using optical and scanning electron microscopy (SEM) in conjunction with quantitative image analysis carried out on digital micrographs and SEM images. An automated grain boundary detection method by geographic information system (GIS) software was employed on the digital images (Li et al., 2008) to perform microstructural analysis (Appendix 1). The Calanchiole and Felciaio shear zones (Fig. 4) developed within carbonates sequences...
Figure 3. (A) Geological sketch map of western side of Porto Azzurro contact aureole (Valdana area) with location of the Calanchiole–Capo Norsi investigated section (dotted line AB), showing tectonic units with contact metamorphism mineral assemblages (in brackets), intrusive rocks, and main tectonic structures. CNT—Capo Norsi thrust; CSZ—Calanchiole shear zone; FSZ—Felciaio shear zone. (B) Schematic Calanchiole–Capo Norsi cross section showing the geometry and distribution of contact aureole metamorphic zones together with the peak metamorphic assemblages (in brackets). See text for explanation. (C) Equal-area lower hemisphere stereonet showing poles of foliation and fold axes from the contact aureole.
Figure 4. Cross sections through the Calanchiole shear zone (A) and Felciaio shear zone (B) including lithotypes, structures, and sample locations. (C) Equal-area lower hemisphere projections showing poles of the mylonitic foliation (Sp), stretching and mineral lineation (Lp), axes deforming Sp and sheath fold axes.
belonging to the Calanchiole marble and Ortano marble, respectively, which are characterized by the different mineralogical composition of the carbonate matrix. Indeed, calcite marbles are dominant in the Calanchiole shear zone, whereas, in the Felciaio shear zone, mylonitic deformation mainly involved dolomite marbles (Figs. 4A and 4B). The Calanchiole and Felciaio shear zones are marked by strongly sheared carbonate hornfels showing a similar structural association (Fig 4C), which consists of (1) a transpositive N-S–trending and W-dipping mylonitic foliation (Sp) parallel to the shear zone boundaries; (2) a nearly E-W–trending mineral and stretching lineation (Lp); and (3) decimeter- to decameter-scale, NNE-striking folds with tight to open hinges and asymmetrical limbs gently overturned toward the east, which deform both the Sp, Lp, and shear zone boundaries.

Calanchiole Shear Zone

In the northwestern portion of the Calamita peninsula, the Calanchiole shear zone is completely exposed at the Calanchiole beach. Based on the proportion of dynamically recrystallized grains in the bulk rock (Sibson, 1977), differently strained calcite marbles, ranging from protolith (<10%) to protomylonite (10%–50%) and mylonite (50%–90%), can be recognized.

Protolith

Outside the shear zone (Figs. 4A and 5A), the calcite marble protolith is represented by massive gray carbonate hornfels including centimeter- to decimeter-thick, diopside-bearing calc-silicate layers, which define a macroscopic foliation (Fig. 5B).

The microstructure of the marble protolith consists of an equigranular and coarse-grained calcite aggregate, which includes minor amounts of dolomite, diopside, tremolite, and quartz (Fig. 6A). The calcite grain size varies between 300 µm and 2.5 mm with an average aspect ratio (i.e., short/long axis) of 0.86 (Fig. 7A). The long axes of the grains are preferentially oriented subparallel and at high angle to the main foliation, whereas conjugate grain boundaries oriented at an angle of 35° to the main directions of the grain long axes can be observed (Fig. 7A). Generally, grain boundaries are more regular, being sutured and serrated. Optical strain features such as undulose extinction and deformation bands and a high twin lamellae density characterize calcite grains (Fig. 6A). In the interior of grains, two twin sets can be observed, though, in many cases, a dominantly oriented subparallel and at a low angle (10°–25°) clockwise and anticlockwise with respect to the grain long axes (Fig. 6A). Generally, the twins are straight or slightly bent and become narrower toward grain boundaries or have lensoid shape. In some cases, twins showing a sigmoidal pattern can be observed. Small grains (10–80 µm) occur at a few places along the grain boundaries and the thick twins of the coarse grains. These small grains, which show sharp extinction and no twins, are more than 70% of the total number of grains but occupy only 2%–3% of the total area (Fig. 7A). Coexisting diopside + tremolite + quartz + calcite associations can be observed in the calc-silicate layers. In many cases, the extent of metasomatic alteration and weathering in these layers precludes accurate microstructural observations; nevertheless, where observable, the high-grade mineral assemblages consist of elongated polygonal crystals with straight grain boundaries.

Protomylonite

Approaching the lower shear zone boundary (Fig. 4A), a progressive grain-size reduction characterizes protomylonitic microstructures. In these microstructures, large calcite porphyroclasts surrounded by fine-grained recrystallized grains define distinct core-mantle microstructures (Fig. 6B). The calcite porphyroclasts show a broad grain-size distribution ranging from diameters of 180 µm to 1.25 mm and are characterized by an average aspect ratio of 0.67 (Fig. 7B). The grain long axes, which are between 190 µm and 2.0 mm in length, are preferentially anticlockwise oriented with respect to the main foliation at an angle of 10°–30°. Some porphyroclasts with a long axis oriented at a high angle with respect to the main foliation also exist (Fig. 7B). Generally, porphyroclasts show strong undulose extinction, deformation bands, and subgrains (20–40 µm in size) along the grain boundaries (Fig. 6B). Sets of thick twins curved or lensoid in shape are common, tapering toward the grain boundaries. Moreover, twin sets oriented at a high angle to the main foliation contain secondary thin twins or show irregular sutured boundaries. Typically, in the interior of extremely elongated porphyroclasts (aspect ratio <0.2) oriented at a low angle to the main foliation, a well-developed single set of twins parallel to the grain long axis can be observed (Fig. 6C).

The recrystallized grains, which are characterized by a grain size of 35 µm on average, cover ~25%–35% of the total area but represent the majority of grains, which results in a bimodal grain-size distribution as shown in the relative frequency histograms of grain-size distribution (Fig. 7B). The recrystallized grains are strain free and preferentially occur along
the grain boundaries of porphyroclasts and in narrow recrystallization bands (100 μm or less thick) oriented parallel to the main foliation (Sp). A weakly developed anisotropy in the orientation of the grain long axes characterizes the recrystallized grains, whereas a more uniform distribution of the grain boundaries can be observed (Fig. 7B).

**Mylonite**

The core of the Calanchiole shear zone is marked by calcite marble mylonites (Fig. 4A). Within the shear zone, the strain intensity varies from centimeter-thick anastomosing white mylonitic bands surrounding gray cores of protomylonites to decimeter-thick homogeneous light-colored mylonite layers (Figs. 4A and 5C). Typically, a bleached region occurs along the contact between the white mylonite and gray protomylonite. This color banding defines the Sp foliation within the Calanchiole shear zone (Fig. 5C). Yellowish dolomite layers along the Sp foliation are usually stretched and/or broken and form asymmetric bookshelf boudins within calcite marble mylonites (Fig. 5D).

The mylonitic marble microstructure, strongly reworked by dynamic recrystallization processes, shows a few porphyroclasts embedded in a homogeneous matrix of fine-grained grains. A unimodal and symmetric distribution of the grain boundaries showing a primary direction oriented 45° anticlockwise to the Sp foliation can be observed (Fig. 7C). As a result, the grain-shape and grain boundary orientation in the fine-grained calcite matrix define a secondary oblique foliation (Sb) with respect to the main foliation Sp (Fig. 6E).

The porphyroclasts have been additionally sheared and partially consumed by recrystallization processes because they show reduced dimensions (100–350 μm) and rounded shape (Fig. 6D). Some dolomite grains (~300 μm in size) can be recognized along the millimeter-thick level parallel to the main foliation.
Figure 7. Grain-size distribution and grain-shape analysis of differently sheared calcite marble from Calanchiole shear zone. (A) Calcite marble protolith (samples Te 105); (B) calcite marble protomylonite (Te 104); (C) calcite marble mylonite (sample Te 50). The characteristic frequency histograms of grain-size distribution by number and area fractions (in percent) versus grain diameter (d) (in logarithmic scale) are presented.
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These dolomite grains are characterized by low internal strain and are often fractured. Recrystallization of the fine-grained calcite matrix was accomplished by the growth of tremolite + talc mineral associations, which occur as 2–3-mm-thick layers oriented parallel to the Sb foliation (Fig. 6F).

Feliciaio Shear Zone

The Felciaio shear zone is located on the west side of the Valdana area, where it marks the contact between the Acquadolce unit and the underlying Ortano Porphyroid. The most complete section of the Felciaio shear zone, which shows strong thickness variation along strike, is exposed at the Felciaio beach, where it consists of a decameter-thick sequence of mylonitic rocks that involve the entire Ortano marble sequence. As a result, mylonitic rocks are widespread and protolith or protomylonite are not preserved.

Mylonite

In the Felciaio shear zone, mylonitic microstructures characterize fine-grained dolomite marbles, which include boudins of calcite marble, calc-silicate hornfels, and minor pelitic schist (Figs. 4B, 8A, and 8B). Mineral assemblages of dolomite marbles are characterized by dominant occurrence of dolomite (Fig. 9A) with local association of variable amounts of calcite, phlogopite, talc, chlorite, and K-feldspar.

Mylonitic dolomite marbles, which are light gray to white on fresh surfaces and yellowish to beige when weathered, show a prominent shearing and are characterized by a penetrative, bedding-parallel, Sp foliation, which transposes a previous foliation (Fig. 8B). The latter is mainly evident within impure dolomite marbles enriched in phyllosilicates (Fig. 8C).

Boudinage structures of calcite marble layers (centimeter- to decimeter-thick) deformed within fine-grained dolomite marbles can be often observed. Calcite boudins show different geometries, ranging from asymmetrical, isolated boudins to regular, elliptical pinch and swell structures (Fig. 8D).

Calcite marble layers are also involved in decimeter- to meter-scale intrafoliar isoclinal folds with highly curvilinear fold hinges (Fig. 8E). They can be classified as sheath folds according to Ramsay and Huber (1987) because hinges vary more than 90°. Moreover, deformed stretching and/or intersection-type lineations, which lie on the fold hinges, are characterized by a distribution of orientations along the great
circles (Fig. 8E) that define an ESE-WNW–oriented slip vector (a-direction; Ramsay, 1967). The development of shear folds can be viewed as result of passive rotation of early formed folds toward the extension direction during progressive simple shear (Cobbold and Quinquis, 1980). A rough estimate of shear strain can be obtained using the model of Lacassin and Mattauer (1985) in which the angle between fold hinge and transport direction is dependent on the amount of the simple shear and the shape of original fold (Ramsay, 1980). The geometrical features of the shear folds in the Felciaio shear zone, defined by the angle between the fold axes in the two lateral hinges (α = 20°–25°) and the shape ratio (amplitude/wavelength = 2.5–3) on the YZ plane, indicate a shear strain of γ = 6–8.

Centimeter- to decimeter-thick calc-silicate layers occur at the lower shear zone boundary, marking the contact with the underlying biotite schists of Ortano Porphyroid (Fig. 8F). They consist of banded granofelses, which show sharp transition to schistose fabrics by increasing the preferred orientation, grain size, and/or amount of sheet silicates. Some boudinage structures of calc-silicate layers deformed within the fine-grained dolomite marbles also occur in the lower part of the Felciaio shear zone. In the calc-silicates, peak mineral assemblage consists of coarse-grained diopside + Ca-rich plagioclase association. These high-grade mineral associations form lensoid enclaves within a mylonitic foliation defined by synkinematic growth of fine-grained tremolite + white mica associations (Fig. 9B).

Typically, mylonitic dolomite marbles show a microstructure that consists of relatively equant dolomite grains with a mean size ranging from 20 to 100 μm (Fig. 9A). A few secondary phases (~2%–3%) consist of phlogopite, talc, quartz, and minor K-feldspar and chlorite heterogeneously distributed within the dolomite matrix or concentrated in horizons, which define a spaced schistosity parallel to the Sp foliation. Moreover, some deformed phlogopite-talc-rich levels also occur within microlithon domains (Fig. 9C). Weak optical strain features within the fine-grained dolomite matrix can be recognized. The dolomite grains show sharp or smooth undulose extinction with little or no evidence for subgrains or recrystallized grains. In the interior of many grains, twins are absent or with limited development, and only a few grains show two sets of thin boundaries. The intensity of the grain-shape–preferred orientation varies from weak to strong alignment in the samples analyzed. The two end members and typical transitional type of the microstructures observed are shown in Figure 10. In one case (Fig. 10A), aggregates of very small dolomite grains (mean size 25 μm) are characterized by an equant polygonal microstructure with straight to slightly curved grain boundaries that reveal a nearly bimodal symmetric distribution. In the other case (Fig. 10C), larger dolomite aggregates (mean size 85 μm), showing a marked grain flattening (average aspect ratio of 0.6), have curved to lobate grain boundaries and display a unimodal asymmetric distribution, which is aligned at low and high angles with respect to the main foliation Sp.

Microstructural features intermediate between those described above characterize the sample shown in Figure 10B, in which dolomite grains with a mean grain size of 65 μm reveal a unimodal nearly symmetric distribution of the grain boundaries.

**FABRIC ANALYSIS AND INTERPRETATION**

Rocks usually deform by a combination of several simultaneously active mechanisms, and the development of dynamic microstructures is associated with progressive deformation and recrystallization. Microstructural studies of naturally and experimentally deformed carbonate rocks have provided information on the deformation mechanism operating in
Figure 10. Grain-size distribution and grain-shape analysis of mylonitic dolomite marbles from Felciaio shear zone. Grain-shape fabric consists of (A) equant polygonal microstructures with straight to slightly curved grain boundaries that meet in triple points at angles of nearly 120° (sample Te 73); (B) disequigranular microstructures showing shape-preferred orientation and predominantly straight grain boundaries (sample Te 43); (C) microstructures exhibiting strong shape-preferred orientation, larger grains and curved to lobate grain boundaries (sample Te 01).
carbonate shear zones developed under variable thermal conditions and tectonic setting (White and White, 1980; Schmid et al., 1987; Bestmann et al., 2000; Pieri et al., 2001; Davies et al., 2008; Delle Piane et al., 2008). In addition, symmetry of microstructures can give information about strain regime (e.g., coaxial versus non coaxial deformation) and kinematics in the deformation history of a shear zone (e.g., Paterson and Weiss, 1961; Wenk and Christie, 1991; Means, 1994). Indeed the symmetry of the deformation regime is reflected in the symmetry of the resultant grain shape fabric, with monoclinic and orthorhombic microstructures interpreted as indicators for simple shear (i.e., non coaxial deformation) and pure shear (i.e., coaxial deformation), respectively (e.g., Wenk et al., 1987; Bestmann et al., 2000). Thus, from the above described microstructures, it is possible to estimate the deformation mechanisms, strain regime, and kinematics characterizing the Calanchiole and Felciaio shear zones.

**Deformation Mechanisms in the Calanchiole Shear Zone**

The coarse-grained calcite marble protolith at the base of the Calanchiole shear zone shows highly irregular grain boundaries, which suggest an extensive grain boundary migration recrystallization mechanism. On the other hand, few (in area fraction) small grains along grain boundaries can be related to incipient subgrain rotation. In addition, based on undulose extinction and deformation bands as well as on the high twin density, intracrystalline deformation and twinning can be inferred as deformation mechanisms accommodating the limited amount of strain in the calcite marble protolith. Irregular twin morphologies (types III and IV of Burkhard, 1993) indicate intracrystalline deformation along with twin boundary migration at temperatures well above 250 °C (Ferrill et al., 2004).

Core-mantle microstructures and recrystallization bands are the characteristic features of the protomylonite, indicating further deformation by dynamic recrystallization within the Calanchiole shear zone. Strong undulose extinction, deformation bands and polygonization into subgrains are optical strain features that suggest intense intracrystalline deformation in the calcite porphyroclasts. Core-mantle microstructure and the approximately same sizes of subgrains and new grains indicate that recrystallization occurs mainly by progressive subgrain rotation with localization of recrystallized grains at the grain boundaries and/or within recrystallization bands.

In the mylonite, the original microstructure is almost completely recrystallized to a homogeneously fine-grained matrix. Although few porphyroclasts still present exhibit prominent twinning and high intracrystalline deformation, the small grains of the matrix are generally free of twins and with sharp extinction. Sub-grain rotation followed by slow grain boundary migration can be inferred as the dominant recrystallization process in the mylonite. Therefore, in contrast to the protolith and protomylonite, twinning and intracrystalline deformation do not contribute to the bulk deformation of the fine-grained mylonite.

In summary, coarse-grained fabric in the calcite marble protolith was attained by static grain growth with grain boundary migration recrystallization as the dominant processes (Covey-Crump, 1997). Moreover, small grains along the grain boundaries testify for subgrain rotation due to an early stage of deformation.

Coexisting diopside-tremolite-calcite-quartz metamorphic assemblages in the calcite marble protolith and in the intercalated calcisilicate layers suggest that the grain growth process may be related to high-temperature conditions (T 500–600 °C) achieved during peak contact metamorphism. Subsequently, strain localization resulted in progressive recrystallization of the coarse-grained calcite marble protolith into a fine-grained mylonite. Strain localization corresponded to retrograde metamorphic conditions, as highlighted by the occurrence of synkinematic tremolite + talc in association with dolomite and quartz in the dynamically recrystallized fine-grained calcite matrix. This mineral assemblage indicates a temperature of ~450 °C at a low-pressure condition (2 GPa; Puhan, 1995). Progressive subgrain rotation, accompanied by subordinate grain boundary migration, was the dominant process of dynamic recrystallization in the calcite marble mylonite. Moreover, the incipient contribution of diffusion processes might be expected by considering the small grain size of the calcite matrix and the high-temperature deformation conditions achieved.

**Deformation Mechanisms in the Felciaio Shear Zone**

In the fine-grained dolomite marbles of the Felciaio shear zone, the following meso- and microstructural features can be recognized:

- **High-temperature deformation conditions**, which can be inferred by the occurrence of diopside + Ca-rich plagioclase in the peak metamorphic assemblages found in the calcisilicate rocks intercalated within mylonitic dolomite marbles. These mineral associations indicate temperatures up to 600 °C (Slaughter et al., 1975) and are preserved in low-strain domains embedded into a fine-grained matrix composed of tremolite + white mica mineral assemblages developed at slightly lower temperatures (~450–500 °C). Moreover, metamorphic assemblages, which define the mylonitic foliation in the fine-grained dolomite marbles, are characterized by the coexistence of phlogopite + talc + quartz ± K-feldspar, indicating a temperature of ~940 °C at low-pressure conditions (2 GPa; Puhan and Johannes, 1974; Puhan, 1995).

- **High-strain conditions**, which are indicated by the occurrence of a penetrative, bedded-parallel metamorphic foliation axial planar of sheath folds, asymmetric boudinage structures, and folding of a transposed foliation within the dolomite matrix (Cobbold and Quinquis, 1980).

Ubiquitously fine-grained dolomite matrixes, showing an equigranular polygonal microstructure with no evidence of intracrystalline deformation. Straight to slightly curved or lobate grain boundaries are decorated by submicron-scale voids and are aligned according to a bimodal asymmetric distribution with respect to the Sp foliation. In addition, a variable amount of very fine-grained secondary phases (sheet silicates, quartz, and ore mineral grains) occur along the grain boundaries in the dolomite matrix.

Switched rheological behavior between calcite and dolomite, which is highlighted by the occurrence of folding and boudination of calcite layers embedded in the dolomite matrix, that is, from dolomite behaving in a less competent way than calcite. Such anomalous competency contrast between the two carbonates can be observed during deformation under high-temperature conditions. In particular, extrapolating laboratory measurements to a representative tectonic strain rate of 10⁻¹² s⁻¹ and carbonate matrix with a grain size of 100 μm, such an inversion of the relative strength occurs at temperatures of ~550 °C, given that calcite is deforming through dislocation creep and dolomite through grain-sensitive size (GSS) mechanisms (Delle Piane et al., 2008).

All these observations may indicate that diffusion creep involving grain boundary diffusion and sliding played a major role during the localization of deformation in the Felciaio shear zone. Indeed, solid-state diffusion is usually inferred as a high-temperature process and may be promoted by small grain sizes because diffusion paths are relatively short. Similarly, grain boundary sliding is regarded as the most likely deformation mechanism for very fine-grained aggregates of equant grains that have undergone high strain. Secondary phases along the grain boundaries can promote the diffusion movement of elements and facilitate the grain sliding past each other. Moreover, secondary phases can also affect grain boundary migration.
recrystallization, and grain growth so as to maintain smaller grain sizes, favoring GSS deformation mechanisms. From a microstructural point of view, weak or absent intracrystalline deformation characterizes the interior of grains deformed by diffusion creep. Curved-to-lobate grain boundaries may be connected to solid-state diffusion processes, whereas the presence of voids along grain boundaries is a possible indication of grain boundary sliding. Finally, a grain boundary distribution with two main directions oriented at low and high angles to the shear plane may be due to grain boundary sliding (Drury and Humphreys, 1988). Thus, strain localization in the Felciaio shear zone was accommodated by GSS flow of the fine-grained mylonites. Deformation developed under metamorphic condition retrograde from pyroxene hornfels to hornblende-hornfels facies as testified by the synkinematic growth of phlogopite + talc and/or tremolite + white mica in the mylonitic foliation of dolomite marble and calcisilicate, respectively.

**Strain Regime and Kinematics of Deformation**

In the Calanchiole shear zone, calcite marble protolith shows a grain-shape fabric characterized by a grain-boundary distribution with respect to the main directions of the grain long axis, corresponding to a mosaic of lozenge-shaped grains from which it is not possible to infer any sense of shear (Fig. 7A). The anisotropy of grain-shape fabric increases in the protomylonite as shown from the distribution of porphyroclast long-axis orientation characterized by an anticlockwise-oriented primary direction at low angle to the Sp foliation (Fig. 7B).

In the calcite marble mylonite, progressive deformation is associated with the development of different types of grain-shape fabric for different grain-size fraction. The fine-grained recrystallized matrix defines a marked secondary oblique foliation (Sb) oriented at 45° anticlockwise to the Sp foliation, whereas most of the porphyroclasts are oriented at 30° anticlockwise to the Sp foliation (Fig. 7C).

In the Felciaio shear zone, two preferred orientations of grain boundaries characterize some grain-shape fabrics of mylonitic dolomite marbles. In particular, the pattern of grain boundary distribution consists of a main maximum oriented parallel to low angle with respect to the Sp foliation and a second maximum aligned in an oblique direction rotated clockwise from the normal to the Sp foliation (Fig. 10C).

Therefore, in the Calanchiole and Felciaio shear zones, the orientation of both the secondary foliation and the porphyroclast long axis with respect to the shear zone boundaries indicate an overall monoclinic symmetry of the grain-shape fabrics. This feature is consistent with a dominant noncoaxial bulk strain regime during localization of deformation in the two carbonate shear zones. At the mesoscopic scale, the close occurrence of asymmetric boudinage structures and shear folds (these latter characterized by bulk shear strain of $\gamma = 6–8$), are further evidence of dominant noncoaxial deformation (Cobbold and Quinquis, 1980; Skjernaa, 1980; Mies, 1993).

As regards the kinematics of deformation, in mylonitic rocks the sense of shear can be unequivocally determined by the asymmetry of microstructures. In the described shear zones, the angular relationship between the oblique foliation Sb and the shear zone boundaries is a reliable shear sense indicator (Passchier and Trouw, 1996) that is consistent with an overall top-to-the-east sense of shear. Moreover, kinematics resolved by microstructures are strongly consistent with mesostructural data. Indeed, in both shear zones, the widespread occurrence of asymmetric boudinage structures evidenced by asymmetric bookshelf boudins and elliptical pinch and swell structures (Figs 5D and 8D) indicate top-to-the-east sense of shear.

**CALANCHIOLE AND FELCIAIO SHEAR ZONES: A KEY TO LATE MIocene TECTONICS INTERPRETATION**

The data presented in this paper lead us to make the following statements about the relationships between deformation and magmatic intrusion emplacement in the northern Apenines nappe stack of central-eastern Elba Island:

1. Calanchiole and Felciaio shear zones represent two main ductile shear zones within the Calamita and Ortano units (Fig. 11), and this development results from active deformation and strain localization in the contact aureole coeval with late Miocene contact metamorphism (6.2 Ma; Musumeci et al., 2011) related to the Porto Azzurro pluton emplacement.

2. The synkinematic mineral assemblages (\(\text{Tr} + \text{Te} + \text{Cc} + \text{Do} + \text{Qtz} \text{ and } \text{Te} + \text{Do} + \text{Cc} \pm \Phi\)) in the mylonitic marbles are consistent with deformation developed under thermal conditions ranging from pyroxene to hornblende-hornfels facies (500–450 °C), while the high-grade mineral assemblage (\(\text{Di} + \text{Ca-rich Plg}\)) and microstructures are preserved in millimeter to decimeter low-strain domains, where small subgrains and undulose extinction indicate coeval deformation under high-temperature and low-strain conditions. The highest thermal conditions of deformation with temperature above 550 °C (pyroxene-hornfels facies) are mainly recorded by switching of rheological behavior between calcite and dolomite layers in the dolomite marble of the Felciaio shear zone. Because this high temperature (\(T > 550 °C\)) is very close to the thermal peak of contact metamorphism (\(T = 600 °C\)), the development of the Calanchiole and Felciaio shear zones can be considered coeval to the Porto Azzurro pluton emplacement and cooling. In this scenario, the occurrence of high-grade mineral assemblages preserved in poorly deformed domains can be explained as result of crystal growth rate faster than strain rate under thermal peak condition. On the other hand, after thermal peak, faster strain rates approaching mineral growth rates led to the synkinematic growth of tremolite, phlogopite, and talc assemblages on the mylonitic foliation during the retrograde (cooling) stage of contact aureole.

3. (3) The westward moderate dip (30°–40°) of mylonitic foliation coupled with a top-to-the-east sense of shear led to slicing and stacking of hornfels rocks with increasing contact aureole thickness (Fig. 11), which is evidenced by a tectonic slice of medium and high metamorphic grade carbonate hornfels (Calanchiole marble) along the Calanchiole shear zone and stacking of high metamorphic grade hornfels (Acquadolce unit and Ortano marble) onto low metamorphic grade hornfels (Ortano Porphyroid) in correspondence with the Felciaio shear zone.

4. (4) Both shear zones are capped by the west-dipping Capo Norsi thrust (CNT; Fig. 11); this main tectonic structure lying at the base of the upper complex is responsible for the eastward thrusting of unmetamorphic and/or very low grade units onto medium- and high-grade hornfels rocks of the contact aureole (i.e., Acquadolce unit and Ortano marble). These geometrical relationships indicate that the final emplacement of the upper complex above the lower one postdated contact aureole development (6.2 Ma; Musumeci et al., 2011).

5. (5) The Calanchiole and Felciaio shear zones cannot be related to the activity of the Zuccale fault. Both shear zones are crosscut by the Zuccale fault and displaced eastward in the hanging-wall block of this fault, as shown in Figure 12A. In particular, in the hanging-wall of the Zuccale fault, the Monte Arco thrust and the Ortano cataclasite (Bortolotti et al., 2001) correspond to the Capo Norsi thrust and Felciaio shear zone, respectively. In addition, the eastward displacement of contact aureole isograds (Duranti et al., 1992), the absence of magmatic dikes crosscutting the fault zone, and the dominant occurrence of cataclasites containing abundant clasts of hornfels rocks (Mazzarini and Musumeci, 2008) are evidence that the Zuccale fault activity...
largely postdates granite emplacement and contact metamorphism (Pertusati et al., 1993).

Thus, Calanchiole and Felciaio shear zones predating the activity of Zuccale fault can be regarded as key structures for deciphering the late Miocene tectonics in the northern Apennines inner margin. Based on these conclusions, the following possible models for the formation of the Calanchiole and Felciaio shear zones and more in general for late Miocene active deformation coeval with intrusive rock emplacement in the eastern Elba Island are considered.

**Magmatic Ballooning**

Some of the deformation structures described above (i.e., upright folds and synmetamorphic foliations) have been reported by Pertusati et al. (1993) and Garfagnoli et al. (2005) and related to pluton emplacement processes. In the hornfels rocks of the Ortano Unit, Pertusati et al. (1993) reported the occurrence of west-dipping foliations with synkinematic recrystallization that increases toward the zone of high metamorphic grade. More recently, in the Calamita Schist, Garfagnoli et al. (2005) describe mesoscopic folds with spaced crenulation cleavage deforming the fabric of high-grade hornfels rocks. However, the structural observations in the Valdana area and in detail along the Calanchiole–Capo Norsi section provide a clear picture of relationships between the intrusive body and deformation structures. The structural setting of the contact aureole is characterized by (1) the absence of a strain gradient decreasing away from the contact with intrusive rocks (i.e., from Calamita peninsula to Capo Norsi); (2) the diffusion of deformation structures over a large distance throughout the contact aureole not restricted to the contact with intrusion; (3) the regular attitude of the foliations, lineations, and fold axes; and (4) the constant eastward vergence of shear zones and folds on the western side of the contact aureole. All of these features are evidence of a regional-scale (far-field) deformation instead of a local deformation. Thus, contact aureole deformation interpreted as the effect of granite emplacement (i.e., magmatic ballooning) must be disregarded. Furthermore, according to Paterson and Fowler (1993), the effects of strain imposed by the emplacement of intrusive rocks are limited to a narrow zone at the contact with host rocks, and, more generally, the strain recorded by deformed contact aureoles mostly reflect syn- to postemplacement regional deformation.

**Crustal Extension: Low-Angle Synthetic Shear Zones**

Some models of late Miocene tectonics in the northern Apennines inner margin have emphasized the role of low- to high-angle normal faults to accommodate crustal extension (Keller and Coward, 1996; Collettini et al., 2006). In light of the extensional model, the Calanchiole and Felciaio shear zones might be interpreted as synthetic Riedel shears (R planes) of an eastward-dipping, low-angle fault predating the activity of the Zuccale fault (Fig. 12B). Assuming for both shear zones a minimum initial dip of 30°E, the present-day dip of 30°–40° W would impose a counterclockwise rotation of ~60°–70°, resulting from the tilting of the hanging-wall block and/or warping of the main low-angle fault. The main problems with this model are (1) the high values of fault rotation exceed the value of 57° calculated in the Basin and Range province, a region that experienced a large amount of crustal extension (Westaway and Kusznir, 1993); (2) as a consequence of the assumed fault rotation, the Felciaio shear zone would lie below the Calanchiole shear zone (Fig. 12C), which does not fit the geometrical relationships recognized in the field, with the Calanchiole shear zone, which lies in the footwall of Felciaio shear zone (Fig. 12A); and (3) the documented inversion of metamorphic grade along the Felciaio shear zone is not consistent with normal fault displacement. Moreover, the low-pressure conditions of contact metamorphism (P <0.2 GPa; Duranti et al., 1992) mean that the metamorphic rocks hosting the Porto Azzurro pluton were at a very shallow crustal level before granite emplacement, which is a further line of evidence that argues against the proposed model of crustal extension with the exhumation of metamorphic rocks (Collettini...
et al., 2006). Therefore, geometrical, structural, and metamorphic features argue against the hypothesis that the Calanchiole and Felciaio shear zones correspond to extensional structures related to an eastward-dipping detachment predating the Zuccale fault.

*Shortening Deformation: Duplex Thrust System*

The westward dip of shear zones, no evidence of fault rotation (i.e., reorientation of original east-dipping structures), and the top-to-the-east sense of movement put forward the suggestion that the Calanchiole and Felciaio shear zones represent originally west-dipping reverse shear zones (Fig. 12D). In particular, as regards the final architecture of the contact aureole, this model of reverse faulting can explain clearly...
The limited exposure of the Porto Azzurro pluton does not allow recognition of deformation structures in the intrusive rocks. However, on the eastern side of Calamita peninsula (i.e., the eastern part of the contact aureole; Fig. 2), several leucocratic sills characterized by mylonitic and cataclastic fabrics are emplaced within ductile and/or brittle west-dipping reverse fault zones (Cruden et al., 2009; Mazzarini et al., 2010a). Moreover, in this area, large-scale folding of high-grade hornfels with syntectonic emplacement of magmatic sills and growth of tourmaline veins (Mazzarini et al., 2011) matches the proposed model of late Miocene shortening well.

**Tectonic Structures and Granite Emplacement in the Inner Side of Northern Apennine**

The northern Apennines hinterland (Tyrhenian side) comprises several sedimentary basins spanning in age from the Tortonian to the Pliocene and Quaternary, and characterized by different lithologies and depositional environments (Bossio et al., 1993; Martini and Sagri, 1993). Since the 1960s, the evolution of these basins has been related to the formation of the Tyrrenian basin, which has been regarded as a backarc basin of the northern Apennine chain. Following this model, the hinterland basins have been related to an extensional tectonic regime and interpreted as grabens or half-grabens bounded by normal faults for which often a listric geometry has been assumed (Martini and Sagri, 1993). In addition, since the late Neogene magmatism is roughly associated in space and time with sedimentary basins, the emplacement of magmatic rocks has also been related to crustal extension (Collettini et al., 1998; Rossetti et al., 1999). Seismic reflectors (K-horizon) interpreted as extensional shear zones in the Larderello geothermal field, and the Zuccale fault in the Elba island, have been regarded as the evidence of crustal extension coeval with granite emplacement (Cameli et al., 1993; Collettini et al., 2006; Smith et al., 2011). Although this model has been largely followed, straightforward field evidence about the role of extensional faults in the emplacement of igneous rocks (i.e., granite melts exploiting fault zones) has not previously been given. In contrast, based on field data revision and evaluation of magmatic strain rate versus tectonic strain rate in the Larderello geothermal field, Accocella and Rossetti (2002) argued that in the northern Apennine upper crust (i.e., the site of Tuscan granites emplacement) extensional faults do not exert a role in the emplacement of granitic magmas. These granitic magmas ascend through subvertical fractures and are emplaced as laccoliths by means of roof lifting. Moreover, in the Larderello geothermal field, Bertini et al. (2006) ruled out the interpretation of the K-horizon as an extensional fault and argued that it corresponds to a deep seated reservoir hosting a fluid in its supercritical state. On the other hand, since the 1990s, a wealth of field and structural data has been presented that suggest that the evolution of the hinterland basins were controlled by shortening deformation related to the activity of major thrust anticlines at the basin margins (e.g., Boccaletti et al., 1992 and references therein). In particular, basin-fill architecture, recording syn depositional uplift of the margins and contractional structures as folds and reverse faults in the sedimentary deposits, result from activity of the thrust anticlines during basin development (e.g., Bonini et al., 1999; Bonini and Sani, 2002). A relevant example comes from the Sassa-Guardistallo basin located in the most internal part of the northern Apennines (i.e., nearby the Tyrrenian Sea coast). According to Cerrina Ferroni et al. (2006), the deposition of late Tortonian–Pliocene sedimentary units was controlled by the growth of a thrust-related, large-scale basement fold (i.e., Pizzachera thrust anticline), which activity is recorded by the late Messinian–early Pliocene syntectonic sedimentation and internal duplex within the basin. In the southern side of the Larderello geothermal field, the Gavorrano anticline and the Perrolla syncline give further lines of evidence of early Pliocene shortening (Musumeci et al., 2008). In particular, the Gavorrano anticline is a NS-striking, large-scale thrust ramp fold exploited by the synkinematic emplacement of the early Pliocene Gavorrano granite at its core (Musumeci et al., 2005). The emplacement of early Pliocene igneous bodies during the antiformal flexuring testifies to close spatial and temporal relationships between thrusting and magma emplacement at shallow crustal levels with the core of anticlines representing preferential sites for magma emplacement. Thus, the Gavorrano anticline gives direct and straightforward evidence of relations between crustal shortening and igneous rock emplacement in the hinterland sector of the northern Apennine (Musumeci et al., 2008).

The above-reported structural data from the Calanchiole and Felciaio ductile shear zones in central-eastern Elba Island document that the final structural setting of the northern Apennine strongly results from late Miocene, eastward-thrusting, coeval with granite emplacement. Indeed, at the regional scale, the strike direction and eastward kinematics of the above-described Calanchiole and Felciaio shear zones structures fit with those of the late Messinian–early Pliocene thrusts and anticlines in southern Tuscany. In conclusion, offshore (Elba Island)
management functions, which automatically generate the shape and several other attributes of the grains. From the grain GIS database, created characteristics of grains such as shape, orientation, and spatial distribution have been quantified and analyzed. Grain-size analysis was performed by measuring grain areas and calculating the diameters of the equivalent circles (i.e., circles with the same area as the cross-sectional shape). For each sample studied, the main statistical parameters (i.e., minimum and maximum absolute values, average grain sizes, median, mode, and standard deviation) of the measured data were reported, as well as diagrams expressing characteristic frequency histograms of grain-size distribution. Shape factors of grains such as short/long axis ratio were derived, and rose diagrams representing the orientation of particle long axes and grain boundary segments are plotted. The GIS database also provides a frame of local or regional-scale crustal extension (Pertusati et al., 1993; Keller and Coward, 1996; Garfagnoli et al., 2005) can be ruled out. Moreover, the geological meaning of the Zuccale fault as a long-lived extensional fault with a domal structure due to pluton inflation (Collettini et al., 2006; Smith et al., 2011) must be completely reconsidered in the light of these new field and structural data from the Porto Azzurro pluton contact aureole.

CONCLUSIONS

The Porto Azzurro contact aureole in eastern Elba Island gives clear evidence of synkinematic contact metamorphism, which is related to the emplacement of intrusive rocks during active tectonics. The building of deformation structures coeval with the thermal peak and retrograde cooling evolution of the contact aureole highlight that, at the upper crust level, hornfels rocks can record coeval deformation, if the strain is strongly partitioned within shear zones. In addition, the geometry of deformation structures and the internal stacking of the contact aureole indicate that deformation is related to far-field crustal shortening. Finally, because Elba Island is a key area in the northern Apennines–northern Tyrrhenian Sea system, the described shear zones give clear indications that, in the upper crust of the northern Apennines, magmatic activity was coeval with crustal shortening during the development of out-of-sequence thrust systems. This suggestion rules out the previous interpretations emphasizing the role of crustal extension and gives a new perspective about tectonic regime and mode of granite emplacement in the late Neogene evolution of the northern Apennines–northern Tyrrhenian Sea system.

APPENDIX: AUTOMATED GRAIN BOUNDARY DETECTION BY GIS SOFTWARE

According to Li et al. (2008), the raster format of the images is converted to vector format and refined using editing tools in the GIS environment to obtain a straightforward match between the input images and the final vectorized grain outlines. The grain boundary map of the sample analyzed is then built by GIS data


Theye, T., Reinhardt, J., Goffe, B., Jolivet, L., and Brunet, C., 1997, Ferro and magnesio carpholite from the Monte Argentario (Italy): First evidence for high-pressure metamorphism of the metasedimentary Verrucano sequence, and significance for P-T path reconstruction: European Journal of Mineralogy, v. 9, p. 859–873.


