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Coexistence of contractional and extensional tectonics during the northern Apennines orogeny: the late Miocene out-of-sequence thrust in the Elba Island nappe stack

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In the northern Tyrrhenian Sea, the Elba Island is one of the westernmost portions of the northern Apennine inner belt. One of its noteworthy features is the anomalous tectonic repetition of continental-derived (Tuscan Unit) and oceanic-derived (Ligurian units) thrust sheets, lately intruded by late Miocene granitoids. Moreover, in detail, a slice of strongly deformed Ligurian peridotites results tectonically sandwiched between two thrust sheets of Tuscan units. This tectonic setting results from a middle Miocene folding and thrusting of the Apenninic nappe stack with development of large-scale antiform and out-of-sequence thrust. In central-eastern Elba Island, the folding of an imbricate stack is bracketed between Langhian (middle Miocene) and Messinian (late Miocene). Consequently, the anomalous repetition of Tuscan and Ligurian units thrust sheets gives evidence of middle-late Miocene shortening deformation post-dating nappe stack and pre-dating late Miocene–Pliocene granite emplacement. We suggest that the architecture of the Elba Island nappe stack documents the coexistence of early-middle Miocene contractional and extensional tectonics in an overall convergent tectonic setting in the westernmost zone of northern Apennines. Extensional tectonics in the upper portion of the wedge, balancing transient gravitational instabilities due to over-thickened conditions, were followed by a renewal of contractional deformation leading to development of large-scale out-of-sequence thrust responsible for inversion of the stack order.

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KEY WORDS northern Apennines; Elba Island; nappe stack; large-scale folding

1. INTRODUCTION

The northern Apennines belt (Fig. 1) is a stack of NE- to E-verging thrust sheets off-scraped from oceanic and continental lithosphere during the convergent-related processes occurred during the Upper Cretaceous–Eocene closure of the Ligurian–Piedmont ocean (Boccaletti *et al*., 1971; Carmignani *et al*., 2001) and the consequent Miocene collision between the European and the Adriatic continental margins. The deepest tectonic units of the northern Apennines nappe pile consist of a metamorphic unit (Tuscan metamorphic units) that crop out along an arcuate structure from the Apuan Alps in the north to the mid-Tuscan Ridge in the south (Fig. 1) and in other minor outcrops (e.g. Elba Island). They record a polyphase tectono-metamorphic evolution during which they acquired an HP–LT to Barrovian metamorphic imprint (Franceschelli *et al*., 2004). These metamorphic units are overlain by very-low metamorphic grade and/or un-metamorphic units of the Tuscan Nappe and the overlying Ligurian units. The Tuscan Nappe, deriving from the Adria continental margin, is made up of an Upper Triassic to early Miocene sedimentary sequence. The Ligurian units considered as remnants of the Mesozoic Liguro-Piemontese ocean consist of Jurassic ophiolite complexes covered by Upper Jurassic–Paleocene deep-water sediments and Cretaceous Paleocene flysch sequences (Elter, 1975). These units were deformed at shallow structural levels as they reached subgreenschist-facies peak conditions.

Collisional-related deformation in the northern Apennines (i.e. crustal shortening and nappe stacking) has been constrained in the late Oligocene–early Miocene (Boccaletti *et al*., 1971). In the middle Miocene (Langhian–Serravallian),

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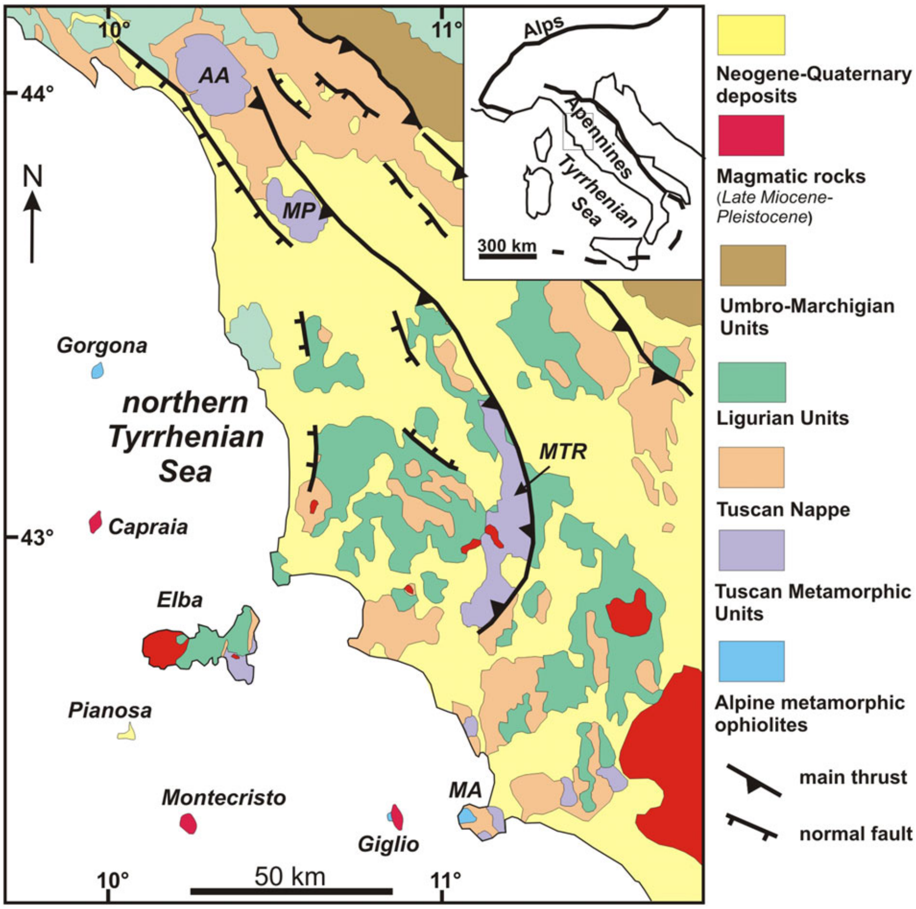

Figure 1. Tectonic sketch map of northern Apennines with location of Elba Island. AA, Apuan Alps; MP, Monti Pisani; MTR, mid-Tuscan Ridge; MA. Monte Argentario. [Colour figure can be viewed at wileyonlinelibrary.com]

it was followed by a renewed deformation event, which led to the tectonic omission of a large part of the Tuscan Nappe stratigraphic sequence and the superimposition of Ligurian units onto the Triassic basal formation of the Tuscan Nappe or, in some instances, onto the metamorphic rocks of the Tuscan metamorphic units. This structural setting (known as 'serie ridotta': Giannini *et al*., 1971; Bertini *et al*., 1994) has been interpreted as the result of either middle Miocene extension of the chain (Carmignani *et al*., 1994; Jolivet *et al*., 1998) or crustal shortening with the development of an out-of-sequence thrust at the base of the Ligurian units (Finetti *et al*., 2001).

The late Miocene post-collisional tectonic evolution of the inner part of the northern Apennines nappe pile is still debated. Some authors believe that this sector of the belt experienced extensional tectonics accommodated by low-angle and high-angle normal faulting and consequent development of intermontane sedimentary basins, crustal thinning and magmatism (Elter *et al*., 1975; Malinverno and Ryan, 1986; Carmignani and Kligfield, 1990; Martini and Sagri, 1993). Other authors, instead, suggest that the sedimentary basins evolution was affected by continuous shortening until the late Miocene–early Pliocene (e.g. Boccaletti *et al*., 1992; Moratti and Bonini, 1998; Cerrina Feroni *et al*., 2006; Bonini *et al*., 2014 and reference therein).

Located in the northern Tyrrhenian Sea, the Elba Island (Fig. 1) represents a key area to deciphering the Miocene–Pliocene post-collisional structural evolution of the northern Apennines inner zone. The central-eastern portion of the island is made by a stack of sedimentary and metamorphic tectonic units derived from both continental and oceanic domains (Trevisan, 1950; Keller and Coward, 1996; Bortolotti *et al*., 2001) (Fig. 2). Since the late Miocene, the nappe stack was intruded by magmatic rocks (M. Capanne pluton: *ca*. 6.8 Ma, Porto Azzurro pluton: *ca*. 5.9 Ma; e.g. Dini *et al*., 2002) and then affected by extension with development of a low-angle normal fault (i.e. Zuccale Fault; Keller and Pialli, 1990; Pertusati *et al*., 1993; Keller and Coward, 1996). As shown in Figure 2, a noteworthy feature of the central-eastern Elba Island nappe stack is the occurrence of a strongly tectonized slice of Ligurian peridotites

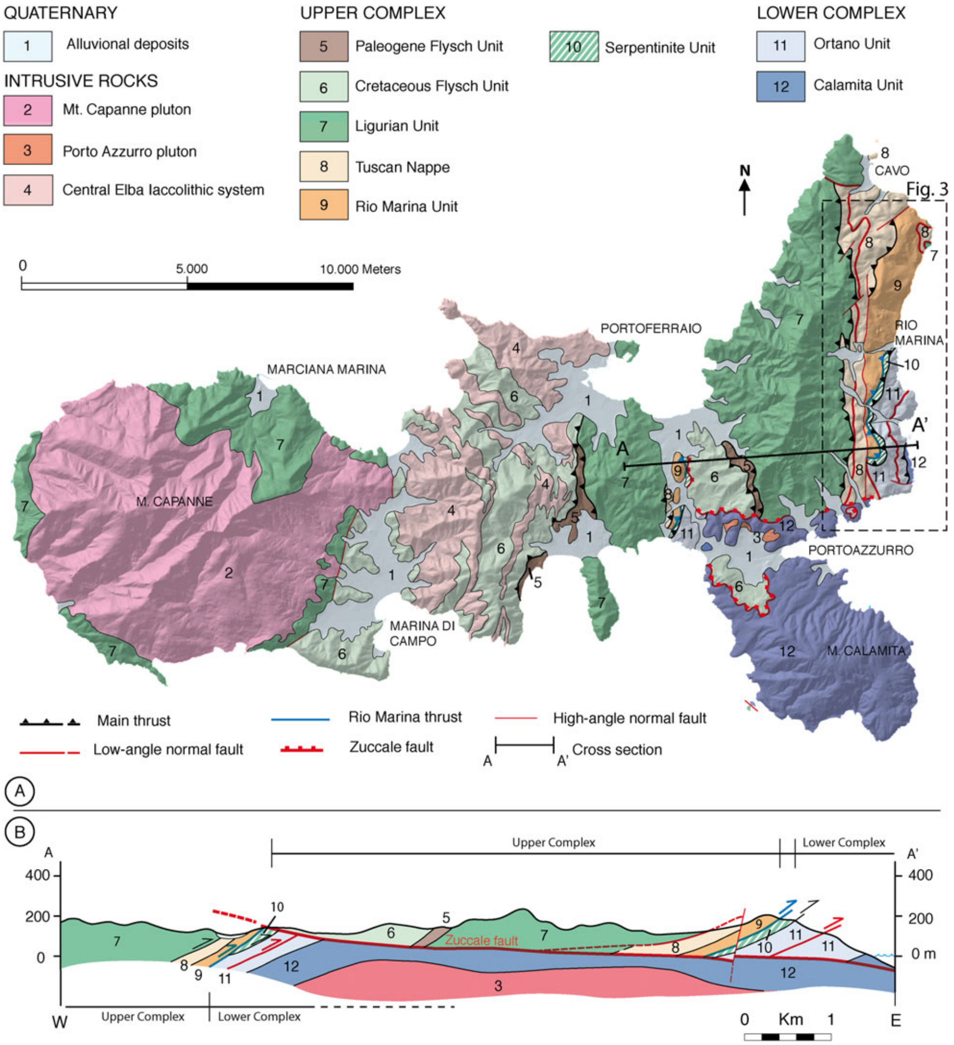

Figure 2. (a) Geological sketch map of Elba Island (modified form Mazzarini *et al.*, 2011). (b) Geological cross-section across nappe stack from central to eastern Elba Island. [Colour figure can be viewed at wileyonlinelibrary.com]

(complex IV of Barberi *et al.*, 1967) tectonically sandwiched between two thrust sheets of Tuscan units (complex II and complex III of Barberi *et al.*, 1967).

We present the results of new detailed field investigations carried out in the eastern Elba Island in order to unravel the processes responsible for the tectonic repetition of Tuscan and Ligurian units in the nappe stack and to propose a new model for the Neogene tectonic evolution of the Elba Island.

2. GEOLOGICAL OUTLINE OF THE ELBA ISLAND NAPPE STACK

In the central and eastern sectors of Elba Island (Fig. 2), the NE-stacked tectonic units are organized in two complexes separated by a main thrust zone (Barberi *et al.*, 1967; Pertusati *et al.*, 1993; Keller and Coward, 1996; Musumeci and Vaselli, 2012).

The Lower Complex consists of two Tuscan affinity metamorphic units, namely, the Calamita Unit and the Ortano Unit (Fig. 2), that experienced (1) early-middle Miocene polyphase deformation under regional low-grade metamorphic conditions (greenschist facies) and (2) late Miocene contact metamorphism (amphibolite and greenschist facies) related to Porto Azzurro pluton emplacement (Garfagnoli *et al.*, 2005; Musumeci and Vaselli, 2012). The Upper Complex (Fig. 2) consists of thrust sheets made up of sedimentary and/or low-grade metamorphic rocks of Tuscan and Ligurian affinity. From top to bottom, they are (1) Paleogene flysch Unit and Cretaceous flysch Unit, (2) Mesozoic Ligurian Unit, (3) Tuscan Nappe and (4) Rio Marina Unit. A slice of intensely tectonized serpentinized peridotites (number 10 in Fig. 2) derived from the Ligurian–Piedmont

Ocean marks the boundary between the lower and the upper complexes.

According to Keller and Coward (1996), Pertusati *et al.* (1993) and Bortolotti *et al.* (2001), the Elba Island nappe stack records a D_1 syn-collisional phase in the early-middle Miocene and a D_2 post-collisional phase marked by emplacement of intrusive rocks during the late Miocene. During the D_1 (*ca.* 19 Ma in the Ortano Unit; Deino *et al.*, 1992), the folding and the stacking of tectonic units developed under very low-grade metamorphic conditions (i.e. anchizone) in the Upper Complex and under low-grade metamorphic conditions (i.e. epizone) in the Lower Complex (as testified by relics of albite + muscovite + chlorite mineral assemblages in the Calamita Unit; Garfagnoli *et al.*, 2005). Recent finding of glaucophane-bearing metabasite lenses in the Ortano Unit not overprinted by contact metamorphism indicates that some portions of metamorphic units experienced early Miocene high-pressure metamorphism (Bianco *et al.*, 2015). E-verging thrusts separating the Lower Complex and Upper Complex as well as thrust sheets documented within the Upper Complex trend N–S/NNE–SSW. Mesoscale fold axes strike from N–S to NNE–SSW, and according to Keller and Coward (1996), fault cut-off trends in the thrust sheet, asymmetric folds and stretching lineations on thrust planes indicate an overall E-vergence.

The D_2 phase is marked by multiple magma inputs (*ca.* 8–5.9 Ma, Dini *et al.*, 2002) emplaced in the nappe stack as two main intrusive bodies (Monte Capanne pluton and Porto Azzurro pluton) and a system of leucogranitic sills. 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. Their emplacement produced medium-grade to high-grade contact metamorphism in the host rocks that overprint previous fabrics and mineral assemblages (Bouillin, 1983; Duranti *et al.*, 1992; Garfagnoli *et al.*, 2005). Folds and fault zones coeval with the emplacement of these intrusive bodies have been related to either (1) the collapse of the orogenic nappe pile during intrusive rocks emplacement (Pertusati *et al.*, 1993; Garfagnoli *et al.*, 2005) or (2) the crustal extension related to the opening of the Tyrrhenian Sea (Keller and Coward, 1996). The Zuccale Fault (Fig. 2) in central-eastern Elba Island is the most prominent structure related to the D_2 late Miocene post-collisional phase (Keller and Coward, 1996; Collettini and Holdsworth, 2004). It corresponds to a normal E-dipping low-angle fault ($<5°$) that cross-cuts the nappe pile and the intrusive rocks with an eastward displacement of about 6 km (Fig. 2b; Keller and Coward, 1996; Musumeci *et al.*, 2015).

Recent investigations contrast to these reconstructions suggesting that shortening deformation occurred simultaneously with the pluton emplacement (i.e. *ca.* 5.9 Ma: Maineri *et al.*, 2003) and that crustal extension occurred lately. In the south-eastern Elba Island, in fact, Mazzarini *et al.* (2011) and Musumeci and Vaselli (2012) documented the development of large-scale upright folds and reverse ductile shear zones (i.e. Calanchiole and Felciaio shear zones, see fig. 3 in Musumeci and Vaselli, 2012) synchronous with the HT–LP metamorphic blastesis produced by the Porto Azzurro pluton emplacement (i.e. the hornfels rocks of the Calamita and Ortano units). Moreover, in detail, Mazzarini *et al.* (2011) documented that in the hornfels of the Calamita Unit, the occurrence of high-temperature hydrothermal fluid circulation (tourmaline-bearing veins) developed during the growth of an N–S striking and E-verging kilometre-scale antiform-deforming contact aureole.

3. LITHOSTRATIGRAPHY OF THE EASTERN ELBA NAPPE STACK

The nappe stack cropping out in the north-eastern part of Elba Island is constituted by the Lower and the Upper Complexes (Fig. 2). From the bottom to the top, the Lower Complex consists of the following units (Figs. 2 and 3):

- Calamita Unit. It crops out in the southernmost part of the study area and consists of andalusite–biotite-bearing pelitic hornfels (Calamita Schist; Musumeci *et al.*, 2011) intruded by centimetre-thick to decimetre-thick late Miocene leucogranitic sills belonging to the East Elba dyke complex (Mazzarini and Musumeci, 2008). The Capo d'Arco Schist, previously assigned to the Ortano Unit (Duranti *et al.*, 1992), is now included in the Calamita Unit (Table 1) due to the presence of diagnostic cordierite–andalusite-bearing mineral assemblages and leucogranitic sills (Mazzarini *et al.*, 2011).
- Ortano Unit. This unit consists from bottom to the top of three subunits: (1) the Ortano Porphyroid, made up of low-grade metasandstone and metavolcanite; (2) the Ortano Marble, constituted by decametre-thick white marble hornfels with dolostone and brecciated dolostone at the base; and (3) the Acquadolce subunit, a sequence of medium-grade and high-grade carbonate and pelitic hornfels (diopside-bearing marble and cherty marble, andalusite-bearing hornfels and cordierite-bearing spotted schists). Recently, Bianco *et al.* (2015) reported the occurrence of metabasite lenses hosted within marbles and pelites affected by HP/LT low-grade metamorphism. The Ortano Porphyroid and the Ortano Marble are attributed to the Tuscan domain (Pertusati *et al.*, 1993) with the former deriving from the Palaeozoic basement (Middle Ordovician volcanic arc; Musumeci *et al.*, 2011) and the

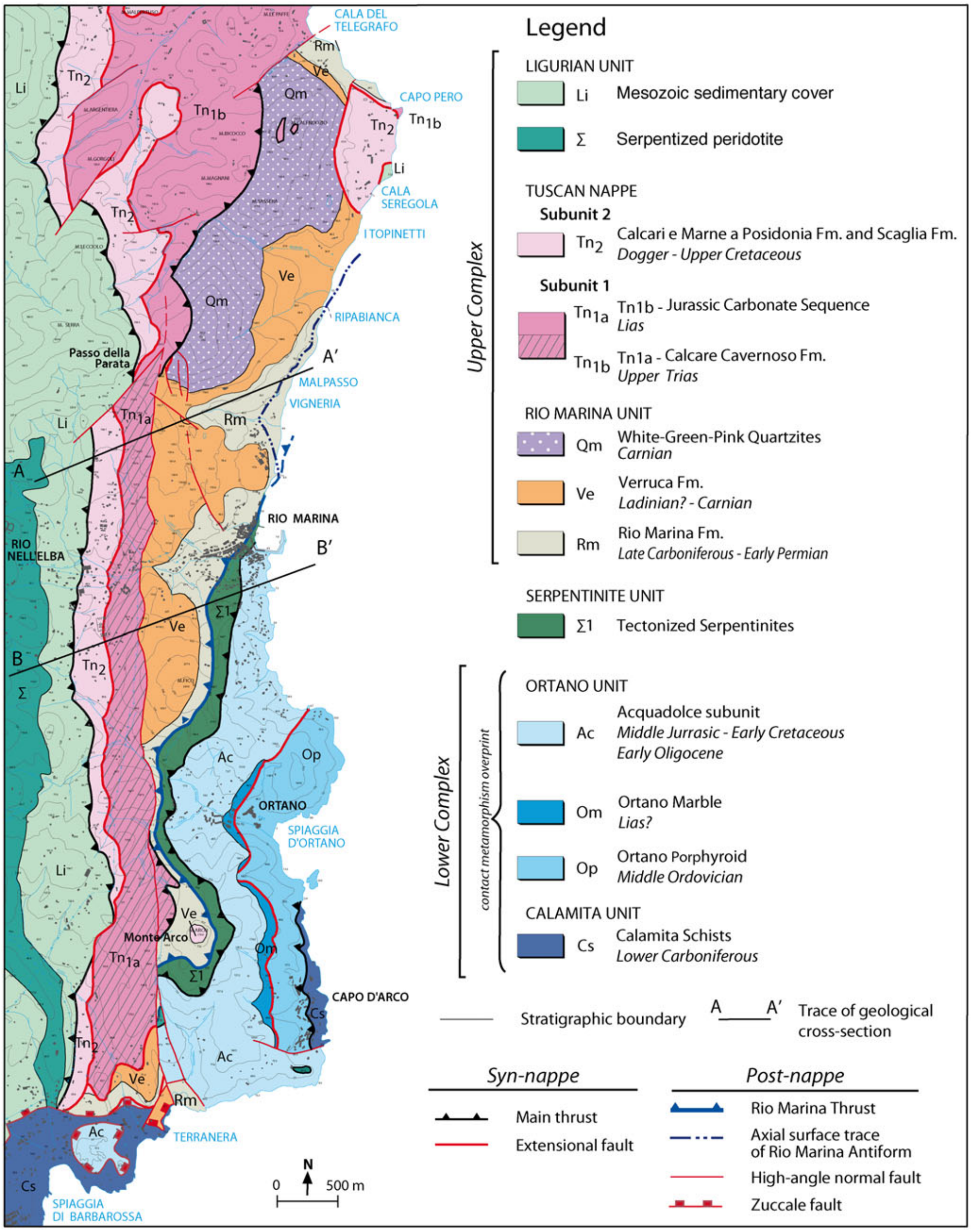

Figure 3. Detailed geological map of the Eastern Elba nappe stack reporting syn- and post-nappe stacking tectonic structures and late Miocene–Pliocene low-angle (Zuccale Fault) to high-angle fault zones. [Colour figure can be viewed at wileyonlinelibrary.com]

latter representing a Lower Mesozoic carbonatic platform sequence (Barberi *et al*., 1967).

On the basis of microfaunas preserved in limestone lenses intercalated within pelitic hornfels, Duranti *et al*. (1992) suggested a Lower Cretaceous age for the Acquadolce subunit. The attribution of Acquadolce subunit is a matter of a long debate (Table 1). Barberi *et al*. (1967) correlated this unit to the Middle Jurassic Calcari e Marne a Posidonia Fm. of the Tuscan Nappe, while Pertusati *et al*. (1993) proposed a correlation to the Palombini ‘Shales’ Fm. of the Inner Ligurian Unit on the basis of Lower Cretaceous age reported by Duranti *et al*. (1992). Bortolotti *et al*. (2001) suggested that the Acquadolce subunit could be correlated to the HP/LT metamorphic units cropping out in the Western Alps (i.e. Ligurian–Piedmont units of the Corsica–Alpine belt). More recently, on the basis of the geochemical signature of metabasite lenses, Bianco *et al*. (2015) suggest a correlation with the sedimentary sequence of Tuscan domain. However, the lithological association of this unit (marble,

Table 1. Comparative table of proposed lithostratigraphic columns in the Elba Island nappe stack

Barberi *et al.*, 1967		Duranti *et al.*, 1992		Bortolotti *et al.*, 2001		This work		
Complex III		Complex III		Grassera Unit	Cavo formation	Upper Complex	Tn2	Scaglia Fm.
	‘Posidonia alpina’			Tuscan Nappe	Posidonia marlstone			Calcari e marne a Posidonia Fm.
	‘Calcari a liste di selce’				Limano cherty limestones			Calcare selcifero inferiore Fm.
	‘Rosso Ammonitico’				‘Rosso Ammonitico’		Tuscan Nappe	Rosso Ammonitico Fm.
	‘Calcari grigio scuri’				Grotta Giusti limestone			Grotta Giusti limestones
							Tn1	
	‘Calcare Massiccio’				‘Calcare Massiccio’			Calcare Massiccio Fm.
					M.te Cetona Fm./Pania di Corfino Fm			Rhaetavicula contorta limestone
	‘Formazione evaportica’				‘Calcare Cavernoso’			Calcare Cavernoso Fm.
	Verrucano Group			Monticiano Roccastrada Unit	Pseudomacigno Fm./ varicoloured sericitic schists		Rio Marina Unit	
	‘Arenarie quarzifere’				‘Maiolica’-type/Capo Castello Calcschits			
					Capo Pero limestones/ Valle Giove limestones			White-green-pink quartzites
					Verrucano Group			Verruca Fm.
					Rio Marina Fm.			Rio Marina Fm.
Complex II		Complex II						
	‘Serpentiniti’		Rio Marina Serpentinite Unit	Acquadolce unit	Serpentinites		Serpentinite Unit	Tectonized serpentinites
	‘Filladi calcarifere’		Punta dell’Acquadolce/ carbonate scist unit		Phyllites and metasiltones	Lower Complex	Ortano Unit	Acquadolce unit (spotted schists and cherty marble)
	‘Calcescisti e cipollini’				Calcschists			
	‘Marmo’		Ortano Marble Unit		Valdana Marbles			Ortano marble
	‘Formazione evaportica’			Ortano Unit	Silver-grey phyllites and quarzites			
					Blackish quarzites and phyllites			
	‘Porfiroidi e scisti porfirici’		Ortano Porphyroids		Phorphyroids			Ortano Porphyroid
	‘Scisti arenacei’		Capo Arco Schist Unit		Capo d’Arco Schists			
Complex I	‘Marmi’	Complex I		Porto Azzurro Unit	Crystalline dolostones and dolomitic limestones		Calamita Unit	Calanchiole Marble
	‘Dolomie e calcari dolomitici’							Barabarca Quarzites
	‘Quarziiti’ e ‘Gneiss del Calamita’				Mt. Calamita Fm.			Calamita Schists
Tectonic unit	Lithostratigraphic unit	Tectonic unit	Lithostratigraphic unit	Tectonic unit	Lithostratigraphic unit		Tectonic unit	Lithostratigraphic unit

cherty marble and grey pelites) differs from that documented in the Palombini Shales Fm. (black shale with isolated lenses of limestone), and consequently, the correlation with the Inner Ligurian units can be excluded. Recent U/Pb dating on detrital zircons from the metapelites documented the presence of idiomorphic detrital zircon grains younger than 32 ± 1 Ma (Sirevaag, 2013). This age and the idiomorphic shapes suggest that these detrital zircons are derived from the Cenozoic magmatic rocks of the Sardinian volcanic arc (Sirevaag, 2013). Thus, the deposition age for the metapelites of the Acquadolce subunit can be bracketed between Lower Cretaceous (Duranti *et al.*, 1992) and late Eocene–early Oligocene (Sirevaag, 2013), simultaneously to the deposition of the Scaglia Fm. in the Tuscan domain (Fazzuoli *et al.*, 1985; Catanzariti *et al.*, 1996).

In conclusion, on the basis of lithological associations, we propose that the Acquadolce subunit belongs to the Tuscan domain (Table 1). In detail, we interpret the lower carbonate portion of the subunit as equivalent to the Middle Jurassic Calcare Selcifero Fm. and Calcare and Marne a Posidonia Fm. (Keller and Pialli, 1990), whereas its upper portion (i.e. spotted pelitic–psammitic schist) can be correlated to the Lower Cretaceous–early Oligocene Scaglia Fm. Consequently, we are in agreement to Keller and Pialli (1990) that interpreted the Ortano Marble and Acquadolce subunits as a condensed/reduced sequence of the typical Tuscan Nappe cropping out in northern Tuscany.

From the bottom to the top, the Upper Complex consists of the following units (Fig. 2):

- Rio Marina Unit. It is made by fossiliferous phyllite and metasandstone of Late Carboniferous–Early Permian age (Rio Marina Fm.; Perrin, 1974) covered by phyllite, metasandstone with metaconglomerate and white-green quartzite of Middle–Upper Trias (Qm and Ve in Fig. 3; Deschamps *et al.*, 1983) referable to the Verruca Fm. described by Rau and Tongiorgi (1974).
- Tuscan Nappe. This unit consists of two subunits (Tn1 and Tn2, Fig. 3) separated by a tectonic contact corresponding to a low-angle fault zone (see below). The lower subunit (Tn1) is made up of Upper Triassic carbonate breccia (Calcare Cavernoso, Tn1a in Fig. 3) covered by a Lower Jurassic carbonate sequence starting with massive limestone (Calcare Massiccio Fm.), limestone with chert nodules (Grotta Giusti limestone Fm.), nodular limestone (Rosso ammonitico Fm.) and limestone with cherty nodules (Calcare selcifero inferiore Fm.) (Tn1b in Fig. 3).

The upper subunit (Tn2, Fig. 3), cropping out from north of Porto Azzurro, to the south, to the Cavo area, to the north (Figs. 2 and 3), is made up mainly by varicoloured slate and silty slate with limestone lenses (Scaglia Fm.) of Upper Cretaceous age (Perrin and Neumann, 1970). Calcari e Marne a Posidonia Fm. (Middle Jurassic) occurs only as tectonized lenses at the lower boundary of the Tn2 subunit.

Bortolotti *et al.* (2001) interpreted the Tn2 subunit as an independent tectonic unit (i.e. Grassera Unit; Table 1) characterized by anchimetamorphic conditions that could be correlated to the 'Schistes Lustrés' of the Ligurian–Piedmont units cropping out in Gorgona and Giglio islands and in the Argentario promontory (Fig. 1). In the northern Apennines, the 'Schistes Lustrés' are the highest tectonic units of the nappe pile, lying above both the Tuscan Nappe and the un-metamorphic Ligurian units. They are characterized by glaucophane, lawsonite and/or Mg-carpholite minerals suggesting HP/LT blueschist facies metamorphism (Mazzoncini, 1965; Decandia and Lazzarotto, 1980; Capponi *et al.*, 1990). However, considering the tectonic position of Tn2 subunit (below the un-metamorphic Ligurian Unit; Fig. 3), the lack of relicts of blueschist facies metamorphic assemblages, the lithological association and the age of fossiliferous contents in the limestone lenses, we suggest that the Tn2 subunit is correlated to the Calcari e Marne a Posidonia Fm and Scaglia Fm. of the Tuscan Nappe (Table 1). This is in agreement to what previously suggested by Perrin and Neumann (1970) and successively confirmed by Camarlinghi (1987).

At the map scale, the Tn2 lies tectonically above the Upper Triassic–Lower Jurassic carbonate formations of the lower subunit and locally above Upper Palaeozoic phyllites of Rio Marina Fm. and Middle Triassic metasandstone of Verruca Fm. (Fig. 3).

- Ligurian Unit. It is constituted by a thick ophiolitic complex of Jurassic age made up of ultramafic (serpentinized peridotite) and mafic (gabbro, diabase and pillow basalt) rocks with Upper Jurassic–Lower Cretaceous sedimentary cover (Bortolotti *et al.*, 2001) including red-greenish radiolarite (Diaspri Fm.; Callovian–Berriasian), fine-grained calcilutite (Calcari a Calpionelle Fm., Late Berriasian–Early Valanginian) and dark-grey shale with siliceous calcilutite (Argille a Palombini Fm., Neocomian–Albian).
- Paleogene Flysch Unit (Colle Reciso Fm. of Bortolotti *et al.*, 2001). It consists of grey shale with minor intercalations of limestone and marlstone whose fossiliferous content indicates a Paleocene–Eocene age (Raggi *et al.*, 1965) and intercalations of ophiolitic breccia and calcareous microbreccia of middle Eocene age (Raggi *et al.*, 1965).
- Cretaceous Flysch Unit (Raggi *et al.*, 1965; Barberi *et al.*, 1967). It is made up of two formations: the Ghiaieto Fm. and the Marina di Campo Fm. (Aiello *et al.*, 1977; Bortolotti *et al.*, 2001). The Ghiaieto Fm. is grey shale upward followed by medium to coarse-grained arkosic turbidite. The Marina di Campo Fm. consists of a rhythmic succession of calcareous sandstone, marly limestone, marls and black shale followed by a turbiditic deposit

made up of arkoses and conglomeratic levels. On the base of its fossiliferous content (Aiello *et al*., 1977), the Marina di Campo Fm can be correlated to the Helminthoid Flysch of the external Ligurian domain.

The Lower Complex and the Upper Complex are separated by a thick slice (150–200 m) of intensely tectonized peridotite and serpentinized peridotite (Serpentinite Unit, Figs. 2–4) cropping out from Mt. Arco, to the south, to Rio Marina, to the north (Fig. 3). Intense deformation is testified by multiple N–S striking and westward-dipping shear planes marked by serpentine recrystallization.

4. ARCHITECTURE OF THE EASTERN ELBA NAPPE STACK

The eastern Elba nappe stack is a large-scale monoclinal structure in which west-dipping thrusts (i.e. the thrust separating the Lower and Upper Complexes as well as the thrust sheets within the Upper Complex) and mesoscale folds generally strike from N–S/NNW–SSE (Figs. 2–4, 5c and 5d). Stretching lineations on thrust planes, vergence of asymmetric folds and fault cut-off trends in the thrust sheet are consistent with an overall E-verging displacement in the nappe stack (Keller and Coward, 1996).

As shown in Figure 3 and described above, the tectonic units of eastern Elba Island have a stacking order that does not match with the order documented in the other portions of the northern Apennines. The Serpentinite Unit with Ligurian affinity, in fact, is tectonically sandwiched between two tectonic units derived by the Tuscan domain: the Rio Marina Unit above and the Ortano Unit below (Figs. 3 and 4).

In the study area, the entire pile of tectonic units is affected by Alpine deformation. A polyphase evolution with at least two ductile deformation events (D_1 and D_2) took place under metamorphic conditions ranging from anchizone in the Upper Complex to epizone (lower greenschist facies) in the Lower Complex (Garfagnoli *et al*., 2005). D_1 led to the development of the nappe stack under prograde metamorphic conditions, while D_2 deformed the previous structures under retrograde metamorphic conditions. These two events generated different systems of folds and shear zones that are heterogeneously distributed throughout the nappe stack.

4.1. *Syn-nappe emplacement thrusting and folding*

In the study area, the main structures are related to the D_1 stacking phase. During this phase, the Ligurian units have been thrusted onto the Tuscan Unit, and, lately, they have been stacked together onto the Calamita and Ortano Units (i.e. the Lower Complex). At the mesoscale, D_1 phase produced centimetre-size to decimetre-size isoclinal and sub-isoclinal, not cylindrical, folds with A_1 axes striking NNW–SSE that gently to moderately plunge both toward north and south (Fig. 5c). The S_1 axial planar foliation is a spaced cleavage in the Tuscan Nappe and a continuous and penetrative cleavage in the Rio Marina, Ortano and Calamita Units. In these units, S_1 foliation represents the main foliation at the outcrop scale. At the map scale, the S_1 foliation defines a large-scale homoclinal structure (Figs. 2 and 4) with

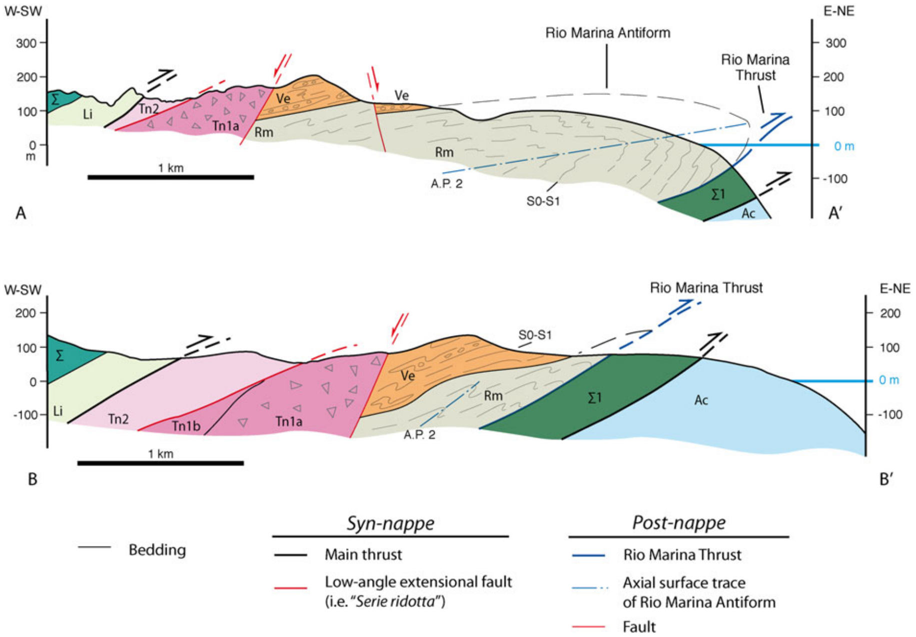

Figure 4. Geological cross-section of the Rio Marina Antiform (traces of cross-sections are shown in Fig. 3). Symbols as in Figure 3. [Colour figure can be viewed at wileyonlinelibrary.com]

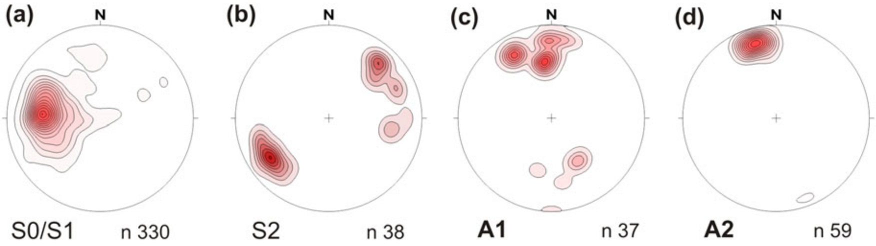

Figure 5. Lower-hemisphere equal-area projection of D_1 and D_2 structures, contour line 2%. (a) S_0/S_1 foliation dip direction. (b) S_2 foliation dip direction. (c) A_1 axial directions. (d) A_2 axial directions. [Colour figure can be viewed at wileyonlinelibrary.com]

an N–S orientation and a gently to moderately dip toward west (Fig. 5a). S_1 foliation is associated to a stretching mineralogical lineation (L_1), defined by syn-kinematic calcite and quartz crystals growing in strain shadows around polycrystalline aggregates and pyrite crystals and by elongated white mica aggregates in metasandstones. L_1 orientation is fairly constant in the study area and ranges between NE–SW and E–W. At the microscopic scale, the S_1 foliation is generally highlighted by granoblastic levels of quartz and subordinate feldspar, with local reorientation of detrital grains in metasandstones (i.e. Rio Marina Fm.) and lepidoblastic levels of mica (white mica + sericite ± chlorite). The S_1 is axial planar foliation of isoclinal microfolds deforming quartz-rich layers and/or veins. Strain shadows containing quartz and white mica around hard objects like crystals of pyrite and/or, rarely, around polycrystalline aggregates of quartz (e.g. in the Scaglia Toscana Fm.) are associated with the S_1 foliation.

4.1.1. Extensional faulting in the Tuscan Nappe

The Tn2 subunit is generally in contact with the Upper Triassic–Lower Jurassic formations of the Tn1 subunit (Fig. 3) and occasionally with the metamorphic formations of the Rio Marina Unit (i.e. the Verruca Fm. and Rio Marina Fm. in the Cala Seregola area, to the north, and west of Terra Nera area, to the south; Fig. 3). In the section from Terra Nera and Cala del Telegrafo (Fig. 3), tectonic contact between Tn1 and Tn2 is marked by a low-angle fault zone that led to a strong tectonic excision of the original lithostratigraphic sequence with the Upper Cretaceous Scaglia Fm. of the Tn2 laying on the Liassic formations of the Tuscan Nappe (Tn1b) and on the Late Carboniferous–Middle Triassic formations of the Rio Marina Unit (Figs. 3 and 4). The tectonic contact is well exposed west of Rio Marina (Passo della Parata) and along a coastal section at Capo Pero (Figs. 3 and 6). In the former zone, intensely sheared marls and pelites mark the fault zone and separate Upper Triassic vacuolar limestone (Calcare Cavernoso Fm.) from the overlying Middle Jurassic marls and limestone (Calcari and Marne a Posidona Fm., Dogger) (Fig. 6a). At Capo Pero (Fig. 6b and 6c), the fault zone is marked by decimetric-thick dark breccia with carbonate clasts and separates the Lower Jurassic cherty limestone (Calcare Selcifero Fm.) from the overlying Upper Cretaceous varicoloured slate with limestone lenses (Scaglia Fm.). A metre-thick slice of intensely folded and sheared marls and marly limestone (Calcari e Marne a Posidonia Fm., Dogger) is preserved within the fault zone (Fig. 6c).

4.2. Post-nappe structure: the Rio Marina Antiform

D_2 deformation phase deforms the D_1 tectonic stack and develops under retrograde metamorphic conditions. D_2 structures are represented by close to tight folds (Fig. 7a) with NNW and N–S striking the folds axes (A_2) that gently to moderately plunge toward north and south (Fig. 5d). The NNW-striking S_2 axial plane foliation is a crenulation cleavage that gently dips toward WSW and ENE in the normal and inverted limbs respectively making a divergent fan with respect to axial plane surfaces (Fig. 5b).

The most important structure produced during the D_2 event is the Rio Marina Antiform (Figs. 3, 4 and 7b), a NW–SE-striking kilometre-scale fold exposed along the coastline from Rio Marina to Cala Seregola (Figs. 3 and 4). The antiform hinge zone and the normal limb are well exposed along the coastline north of Rio Marina (Figs. 3, 4a, 7b and 7c). The inverted limb is exposed in the Vigneria–Malpasso area where phyllites and metasandstones of the Rio Marina Fm. show vertical bedding (S_0) and subparallel cleavage (S_1) that rotate to a westward dip in the inverted limb (Fig. 7b and 7c). The Rio Marina Antiform is characterized by gently to moderately NW plunging A_2 axis (5°–30°; Fig. 7f) and an axial planar foliation shallowly dipping toward west. In phyllites and metasandstones, the S_2 axial plane foliation is a crenulation cleavage that locally evolves in continued and penetrative slaty cleavage that represents the main foliation in the outcrop. The S_1 and S_0 foliations as well as F_1 folds are recognizable in the hinge zones of the antiform, mainly in the pelitic–psammitic lithologies of Rio Marina Fm. and Verruca Fm. (Fig. 7d). At the microscopic scale, the S_2 axial plane foliation is a gradational to discrete crenulation cleavage (Passchier and Trouw, 1996) mainly highlighted by alignment of white mica, chlorite and opaque oxides.

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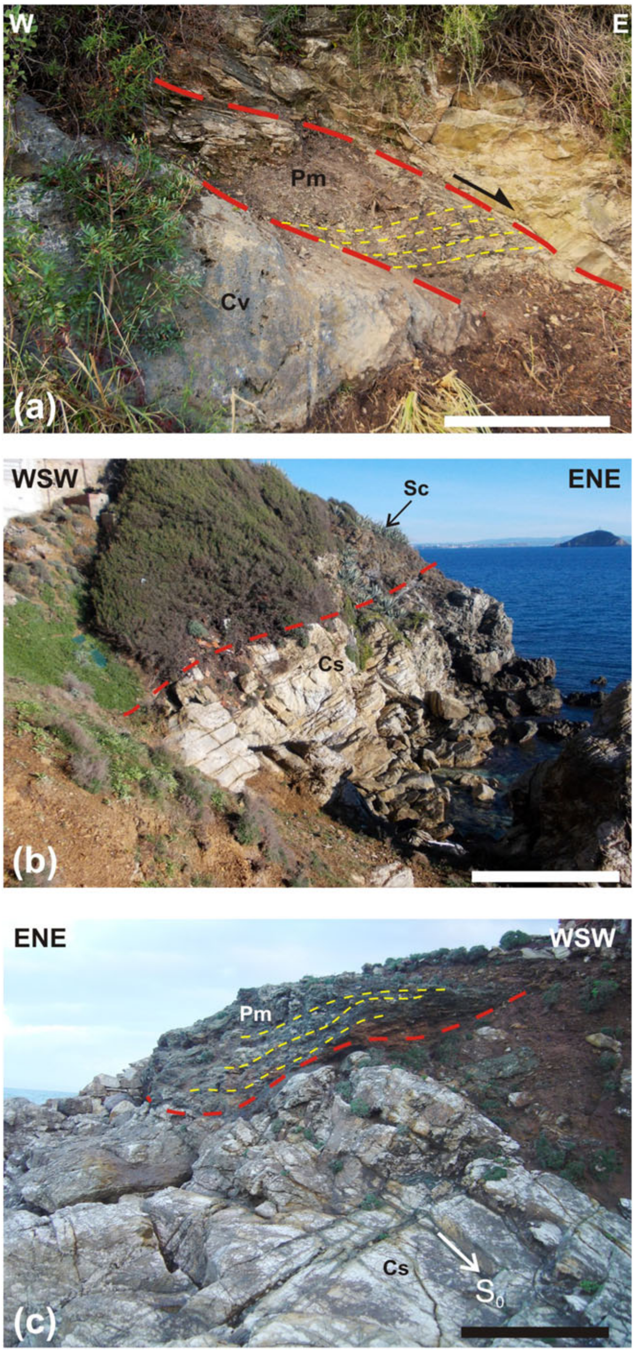

Figure 6. Tuscan Nappe. Field relation between Tn1 and Tn2 subunits. (a) Passo della Parata: east-dipping fault zone separating Upper Triassic vacuolar limestone (Cv) from overlying Middle Jurassic marls and limestone (Pm). Red dashed line: lower and upper boundaries of fault zone; yellow dashed lines: foliation in the fault zone. Scale bar: 50 cm. (b) Capo Pero: Lower Jurassic Calcare Selcifero Fm (Cs) separated through a fault (red dashed line) by the overlying Upper Cretaceous Scaglia Fm. (Sc). Scale bar: 2 m. (c) Detail of the Capo Pero fault zone (red dashed line), locally marked by intensely deformed beds (yellow dashed lines) of marls and marly limestone (Pm), above the underlying west-dipping Calcare Selcifero Fm. (Cs), white arrow: dip of sedimentary bedding. Scale bar: 1 m. [Colour figure can be viewed at wileyonlinelibrary.com]

The eastward verging antiform refolded thus the early nappe stack leading to the unusual tectonic interfingering of Tuscan and Ligurian units. Thus, the Serpentinite Unit cropping out below the Rio Marina Unit corresponds to the laminated inverted limb of the antiform (Figs. 3, 4a and 4b). Southward of Rio Marina, the antiform-inverted thinned limb is cross-cut by a tectonic contact, which we call here the Rio Marina Thrust (Figs. 3 and 4). This tectonic contact can be identified from the town of Rio Marina to the slopes of Monte Arco, at the top of the Serpentinite Unit. As shown in the map (Fig. 3) and in the cross-section (Fig. 4), the Rio Marina Thrust cross-cuts the antiform as a consequence of progressive thinning of the inverted limb. Remains of the inverted limb are testified by the intensely sheared serpentinite slices (i.e. Serpentinite Unit) cropping out to the south of Rio Marina (Figs. 3, 4 and 7e).

Field evidences show that the Rio Marina Antiform and Rio Marina Thrust are in turn cross-cut by the Zuccale Fault (see Fig. 2; Pertusati *et al*., 1993; Musumeci *et al*., 2015) and successively by high-angle normal and strike-slip faults (Callegari *et al*., 2013).

5. DISCUSSION

5.1. *Tectonic model*

Like the rest of the northern Apennines, the nappe stack of Elba Island recorded polyphase tectonics starting since the late Oligocene–early Miocene deformation as a consequence of the continental collision between the Adria microplate and Corsica–Sardinia block (Keller and Coward, 1996; Carmignani *et al*., 2001). On the basis of the structural data described above, as well as on the revised lithostratigraphy of tectonic units, the evolution of the eastern Elba Island nappe stack can be divided into three main stages (Fig. 8): (1) the early-middle Miocene stage, (2) the middle-late Miocene (Serravallian–Tortonian) stage and (3) late Miocene (Messinian)–early Pliocene stage.

5.1.1. *The early-middle Miocene stage*

During this time interval, westward underplating and deformation of the Apenninic accretionary wedge produced the early nappes stack. Deeply underplated portions (represented by Calamita Unit, Ortano Unit and Rio Marina Unit) experienced blueschist (Bianco *et al*., 2015) to lower greenschist facies conditions (pyrophyllite zone, Franceschelli *et al*., 1986) at *ca*. 19 Ma (early Miocene—Burdigalian; ^{39}Ar/^{40}Ar muscovite: Deino *et al*., 1992). This age is slightly younger than those recorded in the metamorphic units of the Apuan Alps (*ca*. 27 Ma; Kligfield *et al*., 1986) and might be interpreted as recording a late stage of exhumation. During the early Miocene, the architecture of the Elba Island results analogous to

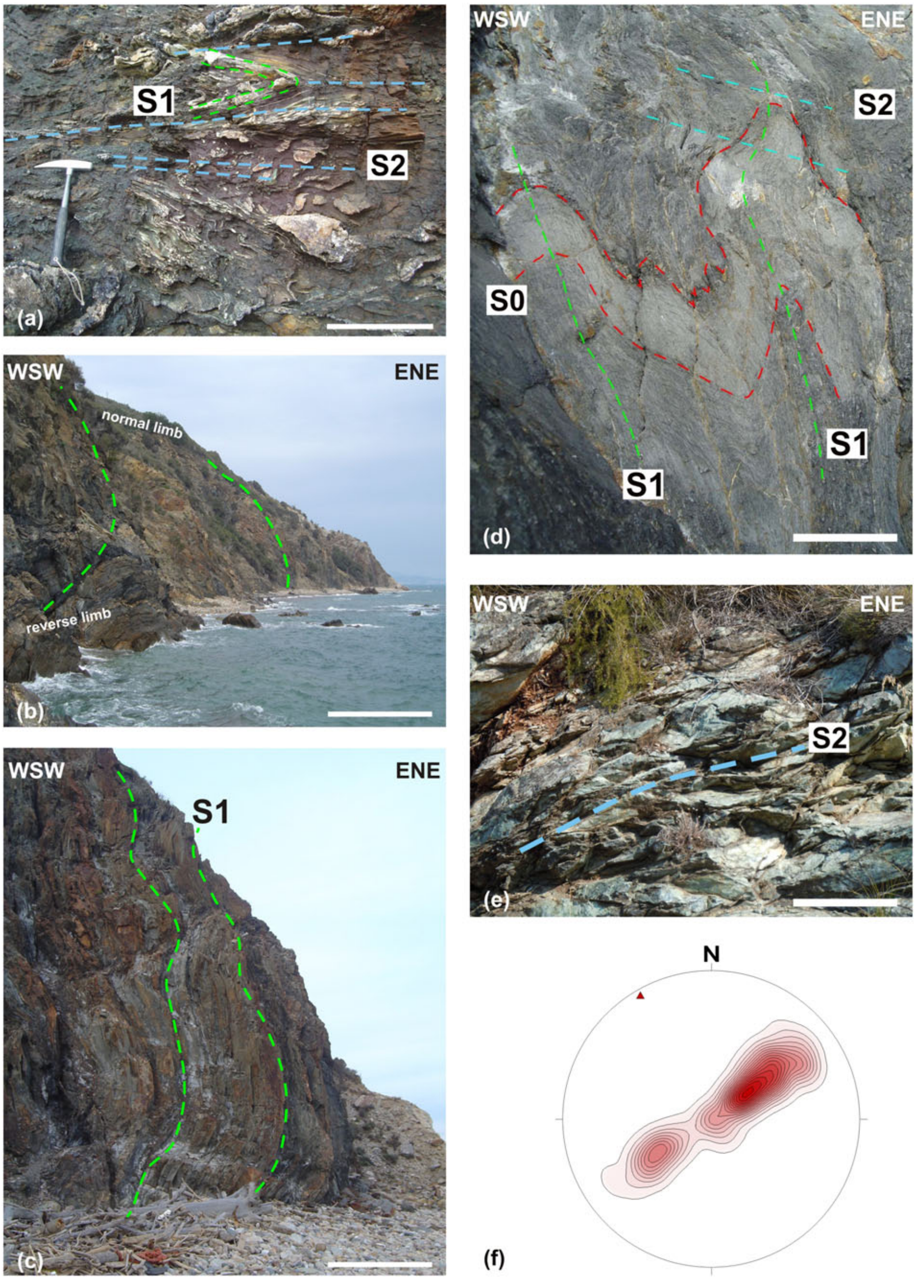

Figure 7. (a) Detail of folded S_1 foliation (green dashed lines) and S_2 cleavage (light blue dashed lines) axial planar foliation of F_2 folds in the Calcari and Marne a Posidonia Fm. at Cala Seregola (see Fig. 3 for location), scale bar: 30 cm. (b) Panoramic view of the Rio Marina Antiform hinge zone along the coast from Vigneria to Topinetti (see Fig. 3 for location). Scale bar: 20 m. (c) Hinge zone of Rio Marina Antiform at Vigneria. Green dashed lines indicate the vertical attitude of folded S_1 foliation. Scale bar: 5 m. (d) Field relationships between S_0 bedding (red dashed lines), S_1 foliation (green dashed lines) and S_2 foliation (light blue dashed lines) in the hinge zone of Rio Marina Antiform cropping out at Vigneria. Decimetre-scale F_1 folds with sub-vertical S_1 foliation are deformed by east-verging decimetre-scale F_2 open folds with sub-horizontal to gently dipping S_2 foliation axial plane cleavage. Scale bar: 30 cm. (e) Detail of the strongly tectonized serpentinites in the reverse limb of the Rio Marina Antiform marking the Rio Marina Thrust in the Ortano valley (see Fig. 3 for location). Scale bar: 1 m. (f) Lower-hemisphere equal-area projection of S_1 foliation dip directions from the Vigneria area. The scattering of S_1 foliation indicates that the Rio Marina Antiform is a fold with NW–SE striking (N145°E) fold axis (red triangle). [Colour figure can be viewed at wileyonlinelibrary.com]

what is classically documented in northern Apennines: the Ligurain Units at the top, then the Tuscan Unit and at the bottom of the nappe stack the Tuscan Metamorphic Units. This architecture was dismembered by the action of a low-angle extensional fault that produced a drastic reduction within the Tuscan Nappe with Cretaceous–Paleogene pelagic deposits

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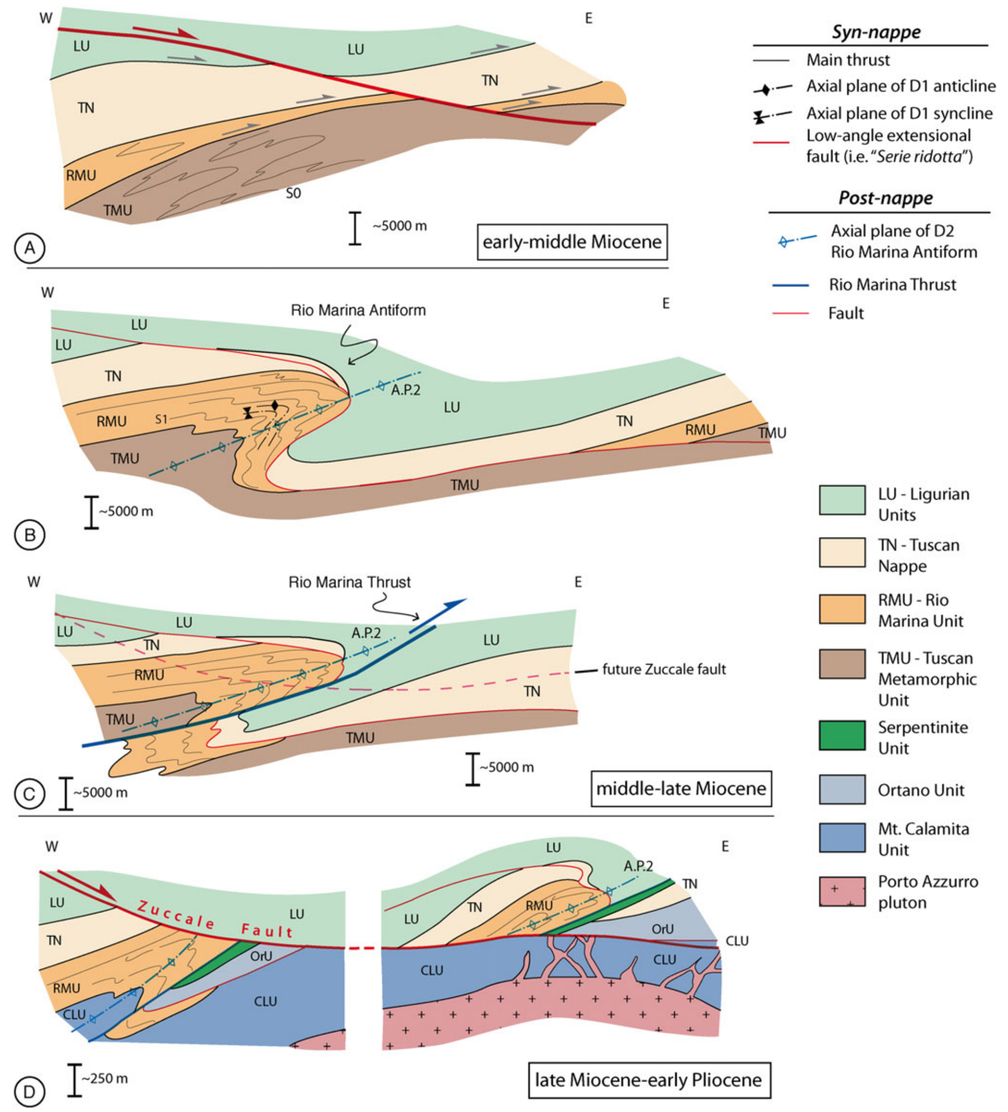

Figure 8. Evolutionary model of eastern Elba Island nappe stack during early-late Miocene (see text for explanation). [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e. Scaglia Fm.) directly in contact with the Upper Triassic–Lower Jurassic carbonate platform (i.e. Calcare Cavernoso Fm.) and the direct juxtaposition of the Ligurian Unit onto the basal Upper Triassic carbonate formations of the Tuscan Nappe (Fig. 8a). This structural setting is well documented in other portions of the northern Apennines. In particular, in central and southern Tuscany, this structural setting is known as 'serie ridotta' (Giannini *et al*., 1971), and it is interpreted as the result of an extension regime that affected the Apenninic chain during the middle Miocene (Decandia *et al*., 1993; Carmignani *et al*., 2004). According to Carmignani *et al*. (2001), the extensional regime responsible for the 'serie ridotta' is produced by the gravitational collapse at a shallower structural level of the over-thickened wedge. In the Apuan Alps (Northern Tuscany), this extensional event is constrained by ^{39}Ar–^{40}Ar dating on syn-kinematic muscovite at *ca*. 14–11 Ma (Carmignani and Kligfield, 1990). Its upper limit, instead, is constrained in southern Tuscany by the Langhian age of the first marine sediments discordantly deposited on the Ligurian units at the top of 'serie ridotta'. Recently, Bonini *et al*. (2014) bracketed the extensional tectonic documented in southern Tuscany between *ca*. 17 and *ca*. 14 Ma. According to the same authors, the diachronous occurrence of extension documented in southern and northern Tuscany might be explained as a variation of the structural setting along the strike of the belt.

5.1.2. The middle-late Miocene (Serravallian–Tortonian) stage

The Elba Island nappe stack was folded by a northeast verging kilometre-scale overturned antiformal fold with a long normal limb gently dipping westward and a short steeply dipping reverse limb (i.e. the Rio Marina Antiform; Fig. 8b). The fold has a NW–SE trending axis and associated axial plane foliation. Continued deformation led to a progressive thinning of the reverse limb until the development of a thrust with a top-to-the E sense of shear that completely transposed the inverted limb (i.e. the Rio Marina Thrust; Fig. 8c). The movement of the Rio Marina Thrust accentuated the thinning and the delamination of the Ligurian Unit located in the reverse limb. In this reconstruction, the Serpentinite Unit cropping out between the Upper Complex and the Lower Complex marks the thrust surface. In central Elba, the occurrence of the reverse limb is testified by some tectonic slices of intensely deformed phyllites and carbonate rocks interleaved within the Serpentinite Unit. The final architecture of the Rio Marina Antiform is so characterized by two west-dipping normal limbs corresponding to the Lower Complex and Upper Complex separated by the Serpentinite Unit (Fig. 8c). The thrusting of the Rio Marina Antiform post-dated the end of middle Miocene extension (Langhian) and predated the late Miocene (Messinian) emplacement of intrusive rocks at *ca*. 6.2–5.9 Ma (Maineri *et al*., 2003; Musumeci *et al*., 2011). Thus, a Serravallian–Tortonian age can be likely proposed for the post-nappe stack fold and thrust in Elba Island.

5.1.3. The late Miocene (Messinian)–early Pliocene stage

The emplacement of the Porto Azzurro pluton (*ca*. 5.9–6.2 Ma, Maineri *et al*., 2003; Musumeci *et al*., 2011) widely affected the tectonic units of the Lower Complex (i.e. Calamita and Ortano Units). Metamorphic zoneography of the contact aureole is consistent with a normal thermal gradient traced upward from the Calamita Unit (host rock of Porto Azzurro pluton) toward the overlying Ortano Unit (Duranti *et al*., 1992; Musumeci and Vaselli, 2012; Fig. 8d). According to Duranti *et al*. (1992), also the Serpentinite Unit experienced contact metamorphism with temperatures ranging from 350 to 550 °C. This feature corroborates our model testifying that the Rio Marina Antiform and Rio Marina Thrust occurred before the Messinian emplacement of the intrusive bodies. Finally, during the early Pliocene, the Zuccale Fault crosscut both the Rio Marina Antiform and the Rio Marina Thrust leading to the current geometry of the eastern Elba Island nappe stack (Fig. 8d).

5.2. Elba Island nappe stack evolution

During the 1990s, the tectonic evolution of Elba Island and the northern Apennines in Tuscany was interpreted as reflecting two distinct tectonic events: the collisional and the post-collisional events. The earlier event (late Oligocene–early Miocene) was interpreted as being produced by crustal-scale shortening related to convergence and to continental crust subduction, whereas the later event (middle-late Miocene) was interpreted as the result of crustal extension related to either opening of the northern Tyrrhenian Sea (e.g. Keller and Coward, 1996) or collapse of the thickened wedge coeval with Late Miocene magma emplacement (Pertusati *et al*., 1993).

Notably, poor attention has been paid to the strongly tectonized slice of Ligurian serpentinites sandwiched between the two thrust sheets of Tuscan Units (the Serpentine Unit in Figs. 2–4). Keller and Pialli (1990) interpreted the serpentinites as evidence of an ‘out-of-sequence thrust’ accommodating deformation within the accretionary wedge during the late Oligocene–early Miocene collisional stage. Also, Pertusati *et al*. (1993) agreed on the presence of an out-of-sequence thrust on the top of the serpentinite slice, but they suggested that the thrust was activated by the lateral expansion of the Monte Capanne pluton (i.e. pluton ballooning) during magma emplacement.

Our model agrees with the presence of out-of-sequence thrust as proposed by Keller and Pialli (1990) and Pertusati *et al*. (1993) but strongly differs on their interpretation. In our reconstruction, in fact, the slice of serpentinites is located in the footwall of an out-of-sequence thrust developed during the middle-late Miocene post-collisional phase on the inverted limb of a kilometre-scale antiform (i.e. Rio Marina Antiform) folding a previous low-angle extensional fault (Fig. 8).

The relationship existing between pluton emplacement and out-of-sequence thrust motion as proposed by Pertusati *et al*. (1993) is confuted by structural and petrographical data. The structures related to the pluton emplacement (i.e. steeply dipping foliations and decimetre-size asymmetric collapse folds with centrifugal vergence around the pluton) are relatively small in size and limited to the first ~0.5 km of the host rocks. In addition, even if we restore the Rio Marina Antiform in its ‘original’ position before the activity of the Zuccale Fault (fault displacement ~6 km; Musumeci *et al*., 2015), it results to the location too far (i.e. ~8 km from the actual Monte Capanne pluton eastern edge) from the local stress field produced by the pluton emplacement. The direct relationship between pluton emplacement and out-of-sequence thrust motion is also confuted by Farina *et al*. (2010) that documented a main vertical expansion of the Monte Capanne pluton and a limited lateral expansion that produced only local tilting of overburden.

5.3. Implications for the dynamics of the northern Apennines accretionary wedge

The northern Apennines represents an orogenic belt wherein late Oligocene–early Miocene shortening of the accretionary wedge was followed by early-middle Miocene crustal extension (Boccaletti *et al*., 1971; Carmignani *et al*., 1994, 2001). Several models (e.g. collapse of orogenic wedge, lithospheric delamination, slab roll-back and slab break-off) have been invoked in order to explain the coexistence of shortening and extension regime (Malinverno and Ryan, 1986; Royden *et al*., 1987; Carmignani and Kligfield, 1990; Jolivet *et al*., 1998; Rossetti *et al*., 1999; Gvirtzman and Nur, 2001; Rosenbaum and Lister, 2004). Most of these models relate the extensional regime to the collapse of a thickened orogenic wedge (e.g. Carmignani *et al*., 1994) and to the coeval retreat of the Adria subducted slab (e.g. Rossetti *et al*., 1999) that moving toward the east had produced the opening of the northern Tyrrhenian Sea as a back-arc basin during the Late Miocene (*ca*. 10–5 Ma; Jolivet *et al*., 1998; Rosenbaum and Lister, 2004 and references therein).

However, according to Platt (1986), several factors (e.g. changes in subduction rate, thickness of the involved crust and related sediments and mode of accretion) strongly control the stability of an accretionary orogenic wedge. Consequently, the same factors control the spatial and temporal distribution of the tectonic regime within the orogenic wedge leading to complex deformation histories with alternation of shortening and extension and/or shortening at depth and extension at shallow crustal levels.

According to Carmignani *et al*. (2001 and references therein), in the metamorphic units of the Apuan Alps nappe stack (representative of the inner portion of the northern Apennines), the extension of the accretionary wedge was accommodated by the activity of extensional ductile shear zones and the development of collapse folds that overprint earlier foliation (i.e. S_1 foliation). In the overlying non-metamorphic units (Tuscan Nappe and Ligurian units), instead, several high-angle to low-angle extensional faults zones developed within the Ligurian units and at the base of the Tuscan Nappe (i.e. Calcare Cavernoso Fm.). Moreover, other minor extensional faults, located in correspondence of less competent layer and/or formations (i.e. Scaglia Fm.), further contributed to extension and thinning of the tectonic pile (Carmignani and Kligfield, 1990).

Recently, detailed field investigations coupled with apatite fission track analysis (Carlini *et al*., 2013) demonstrated that the extensional faults in the Ligurian units in the east and northeast sides of the Apuan Alps accommodated upper crustal-level gravitational instabilities induced by an increase in the thickness of the accretionary prism. Analogously, Clemenzi *et al*. (2014) demonstrated that the middle Miocene low-angle extensional fault affecting the Tuscan Nappe cropping out in the Val di Lima (east of the Apuan Alps dome) was controlled by over-thickening of the orogenic wedge within an overall compressive regime. Thus, deep-seated folding and thrusting contributed to the development of an over-thickened orogenic wedge, which underwent gravitational instability at upper crustal level (Carlini *et al*., 2013). These two examples provide a different perspective for the middle-late Miocene evolution in the inner northern Apennines, suggesting that the orogenic wedge underwent overall crustal shortening at depth and coeval gravitational destabilization in the uppermost levels. Moreover, Patacca *et al*. (2013) suggested an age not older than 13 Ma for the metamorphic peak in the Apuan Alps. Consequently, the age of the contractional deformation responsible of the nappe stacking and the extension regime documented at the top of nappe pile can be likely considered as coeval.

The structural evolution of the Elba Island nappe stack described in this study is consistent with the complex dynamics recently documented within the northern Apenninic orogenic wedge (Carlini *et al*., 2013; Clemenzi *et al*., 2014). The development of middle Miocene Rio Marina Antiform and the Rio Marina Thrust indicates that after the extensional faults affecting the Tuscan Nappe during the early-middle Miocene (17–14 Ma Bonini *et al*., 2014) in response to gravitational instability, the deformation in the inner portion of the orogenic wedge was accommodated by shortening with development of eastward-verging out-of-sequence thrusts and kilometre-scale folds. At the same time, in-sequence thrusts developed in the external portions of the belt (Bonini *et al*., 2001, 2014). This reconstruction differs with the model that suggests the middle-late Miocene crustal extension in the Tyrrhenian side of northern Apennines due to large-scale extensional tectonics. Instead, we suggest that extensional-related and contractional-related structures in the northern Apennines reflect the interaction between tectonic and gravitational body forces that interact to maintain equilibrium within an orogenic wedge (Davis *et al*., 1983; Platt, 1986) affected by crustal shortening.

6. CONCLUSIONS

The architecture of the Elba Island nappe stack documented in this study testifies for the coexistence and/or the alternation during early-middle Miocene of contractional and extensional tectonics during the northern Apennines orogeny. Their coexistence may be related to the internal dynamics of the orogenic accretionary wedge in an overall convergent tectonic setting. Extensional tectonics in the upper portion of wedge, balancing transient gravitational instabilities due to over-thickened conditions, were followed by a renewal of contractional deformation leading to development of kilometre-scale E-verging folds and large-scale out-of-sequence thrusts responsible for inversion of the stack order. Thus, out-of-sequence thrusting in Elba Island is related to regional-scale deformation coeval with the eastward translation of the main northern Apennines thrust front toward the more external domains.

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