Tectonics of the Syros blueschists (Cyclades, Greece): From subduction to Aegean extension

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Received 9 October 2010; revised 24 March 2011; accepted 4 April 2011; published 1 July 2011.

[1] On Syros, high-pressure metamorphism affects a lithological pile that is composed of, from base to top: (1) the Komito-Vari granitic basement, (2) a margin sedimentary sequence that is predominantly made of marbles and schists (the Pyrgos and Kastri units), and (3) the Kambos metaophiolitic mélange. The tectonic history occurred in three main stages. During the first stage, in the mid-Eocene, the Kambos oceanic unit was thrust southward on top of the sedimentary pile. Top-to-the-south-southwest ductile senses of shear are synchronous with prograde high-pressure metamorphism and associated with this thrusting event. The second stage corresponds to a top-to-the-northeast ductile shear that affects the whole metamorphic pile and is synchronous with the metamorphic retrogression from eclogite to greenschist facies. However, the Kambos oceanic unit remained partly undeformed, as shown by significant volumes containing undeformed lawsonite pseudomorphs. No major extensional detachment related to this exhumation event outcrops on the island. The localized semibrittle to brittle deformation of the third stage is associated with the postmetamorphic development of (1) a ramp-flat extensional system at the island scale, whose southward minimum displacement is estimated at approximately 7 km, and (2) two sets of steeply dipping strike-slip faults with a normal component, trending either east–west or around north–south, indicating that the mean stretching and shortening directions are trending NNE–SSW and ESE–WNW, respectively. This sequence of major tectonic events and their relationship to metamorphism are interpreted within the framework of the subduction of the Pindos Ocean and then of the Adria continental passive margin.

Citation: Philippon, M., J.-P. Brun, and F. Gueydan (2011), Tectonics of the Syros blueschists (Cyclades, Greece): From subduction to Aegean extension, *Tectonics*, *30*, TC4001, doi:10.1029/2010TC002810.

1. Introduction

[2] The surface exposure of high-pressure rocks is generally taken to be the result of burial in subduction zones followed by exhumation back to the surface. Deformation associated with exhumation is often intense and earlier deformations are consequently either erased or obscured and therefore difficult to recognize. This could explain why most recent structural studies of high-pressure (HP) rocks focus on exhumation processes. For this same reason, distinguishing between subduction and exhumation-related deformation obviously remains a scientific challenge with respect to two main aspects: (1) establishing criteria and techniques to identify and characterize subduction-related deformation and (2) describing and quantifying the whole subduction-exhumation cycle.

[3] On Syros Island (Cyclades, Greece), eclogites and blueschists occur that display an exceptional preservation of pseudomorphs of HP minerals, such as lawsonite [*Keiter et al.*, 2004] and aragonite [*Brady et al.*, 2004] in particular. Specific mechanisms of exhumation must have contributed to the preservation of these minerals that attest to the earlier tectonic history of the Syros blueschists. The purpose of the present study was to identify these mechanisms and their significance in order to understand the subduction-exhumation cycle in the Cyclades. Because of its mineralogical variety, Syros has been the focus of numerous studies in geology, petrology, geochronology and structural geology. The distinction between subduction- and exhumation-related deformations has never been clearly documented in the high pressure metamorphic rocks of the Cyclades. We carried out extensive structural mapping on Syros, which allowed us to distinguish between three main deformation events whose geometry and kinematics are characterized. Balanced cross sections are constructed and restored showing (1) that the flat-lying fault occurring across the whole island within the Syros blueschists is not a synmetamorphic detachment responsible for their exhumation and (2) that the gneissic Vari unit is the basement of the blueschist metamorphic pile, implying that the hypothesis of a so-called "Vari detachment" can no longer be considered. These

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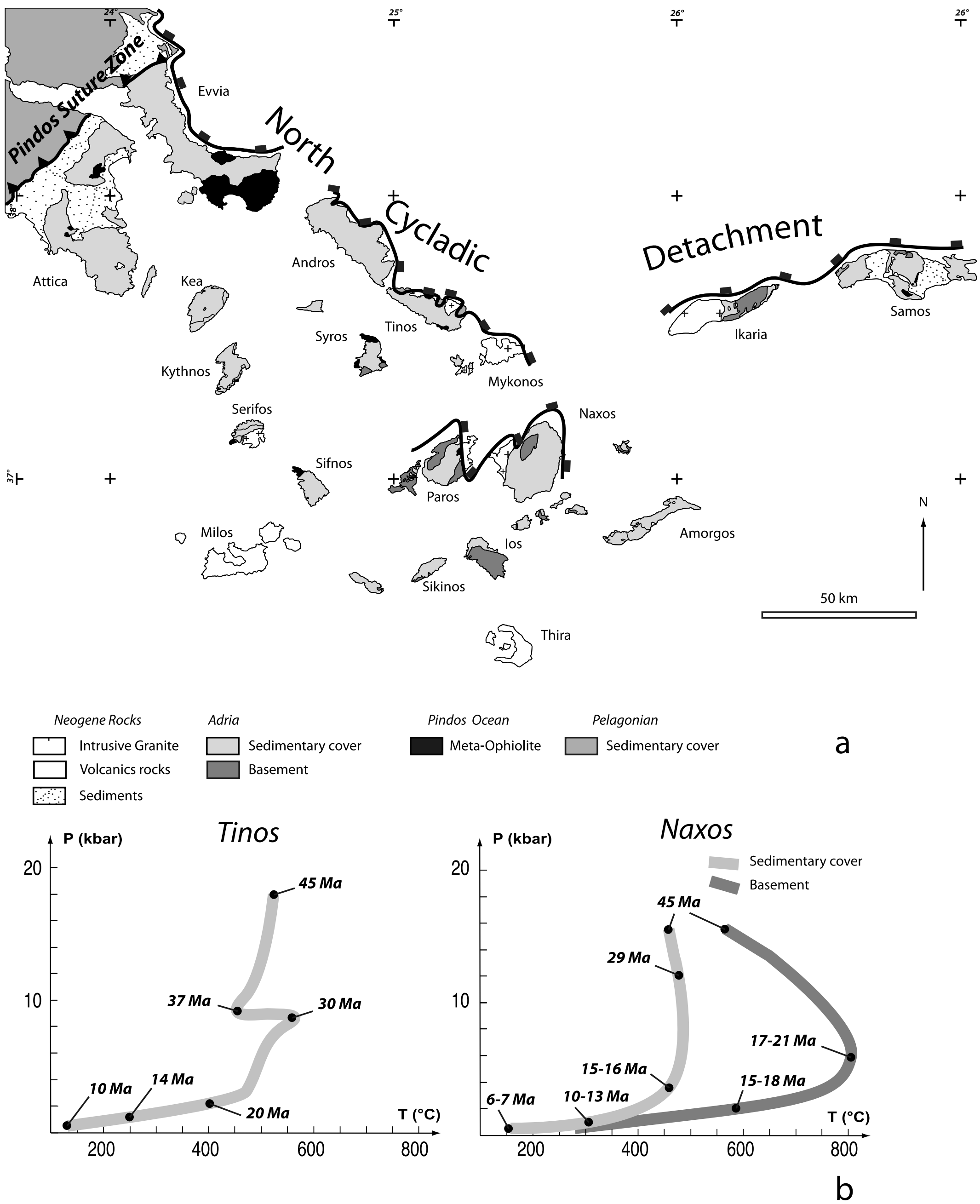

Figure 1. The Cycladic blueschists unit, lithology, metamorphism, and geochronological synthesis. (a) General map of the Cyclades, showing the different lithologies outcropping in the Aegean Sea: the Cycladic blueschists unit is in the strict sense composed of the Adria plate sedimentary cover and basement and the Pindos Ocean. The Pelagonia plate lies above the CBU. The Neogene rocks are either intrusives (granites, volcano) or deposed (sediments) on top of the CBU and Pelagonia. Syros Island is located in the central Cyclades, and the three rock types of the CBU all outcrop on the island. (b) Two representative PT paths of (1) the high-pressure metamorphism (left diagram, Tinos island example [*Parra et al.*, 2002]) and (2) the high-temperature event affecting the Cycladic Blueschist Unit (right diagram, Naxos island example [*Duchêne et al.*, 2006]).

results are discussed at the regional scale for the Cyclades Islands, within the framework of the Hellenic subduction.

2. Geological Setting

[4] The Cycladic Blueschist unit (CBU) mainly outcrops in the central Aegean Sea, Evvia and Attica (Figure 1a) [*Bonneau and Kienast*, 1982]. Within this framework, Syros and Sifnos Islands display the best-preserved evidence of the high-pressure metamorphism. The CBU is a structural pile composed of three units, from bottom to top: (1) a pre-Alpine granitic basement, (2) a margin sedimentary sequence principally made of marbles and schists, and (3) a meta-

ophiolitic mélange with a decreasing metamorphism from blueschist facies to greenschist facies through the pile [*Bonneau et al.*, 1980a, 1980b; *Ridley*, 1984]. The CBU units are exposed below nonmetamorphosed Cretaceous to Paleogene limestones and ophiolites belonging to the Pelagonian overriding plate. The CBU underwent a prograde high-pressure metamorphism in the Eocene [*Bonneau and Kienast*, 1982; *Putlitz et al.*, 2005]. A retrogression to greenschist facies metamorphism during exhumation occurred around 35 Ma (Figure 1b) [*Wijbrans et al.*, 1990; *Parra et al.*, 2002]. A high-temperature metamorphic event was superimposed on previous metamorphic events in the central part of the Cyclades from the late Oligocene to late Miocene [*Jansen and Schuilling*, 1976], culminating in basement migmatization on the islands of Mykonos, Paros, and Naxos (Figure 1b) [*Lister et al.*, 1984; *Gautier et al.*, 1993; *Vanderhaeghe*, 2004; *Duchêne et al.*, 2006]. Finally, this metamorphic evolution finished with the emplacement of several granite plutons in the CBU between 18 and 10 Ma [*Altherr et al.*, 1982].

3. General Structure

[5] Our structural map of Syros Island (Figure 2a) integrates *Hecht*'s [1984] geological map and our extensive structural mapping. The geological pile is composed of four structural units, from bottom to top: (1) the Komito-Vari basement unit, (2) the Pyrgos volcanic and sedimentary sequence, (3) the Kastri volcanic and sedimentary sequence [*Schumacher et al.*, 2008], and (4) the Kambos oceanic series. Bedding-parallel high-pressure foliation trajectories in Figure 2a were drawn from 866 foliation measurement sites. On average, foliations dip to the N–NW with a mean ENE–WSW trend. However, in the Kini area, they define an antiform with a NE plunging axis. At the island scale, the initial sedimentary/volcano-sedimentary sequence is well preserved and kept its original continuity on top of the crystalline basement up to the Triassic [*Keay*, 1998; *Tomaschek et al.*, 2003]. However, to the south, the Kastri and Kambos units form an allochtonous slice on top of the Pyrgos unit and the Komito-Vari basement unit (Figure 2a).

3.1. The Komito-Vari Basement

[6] The Vari orthogneisses on southeastern Syros and the southwestern Komito orthogneisses (Figure 2a) were initially interpreted as the basement of the CBU, on the basis of structural mapping [*Bonneau et al.*, 1980a, 1980b]. The protolith of the Vari orthogneiss is a granite pluton whose crustal emplacement is dated at 240–243 Ma (U-Pb SHRIMP dating on zircon) [*Keay*, 1998; *Tomaschek et al.*, 2003]. The Komito gneiss (Figure 2b) yields an age of 300 Ma (U-Pb SHRIMP dating on zircon) [*Tomaschek et al.*, 2008].

[7] PT conditions in the Vari unit have been estimated from greenschist facies, ~7 kbar, (Phengite Si substitution) [*Maluski et al.*, 1987] to blueschist facies conditions, 12 kbar and 550°C (Figure 2b) [*Tomaschek and Ballhaus*, 1999]. The age of the blueschist facies metamorphism has been estimated to be from 53.5 ± 1.3 to 37.3 ± 1.3 Ma and around 30.3 ± 0.9 for the greenschist facies ($^{40}Ar/^{39}Ar$ on phengites) [*Maluski et al.*, 1987] (Figure 2b). It is important to recall here that the same metamorphism ages are found in the overlying sedimentary sequence and oceanic unit [*Baldwin*, 1996; *Putlitz et al.*, 2005].

[8] Our mapping of foliations in the Vari unit defines an open upright antiform, trending ENE–WSW, that is, cut to the north and to the south by steeply dipping normal faults trending east–west (Figure 3). Toward the west, the antiform whose amplitude decreases plunges below the Pyrgos unit. This shows that the Vari unit is located at the base of the CBU, in agreement with *Bonneau et al.* [1980a, 1980b], *Tomaschek and Ballhaus* [1999] and *Tomaschek et al.* [2008]. Moreover, our field observations have not revealed any evidence for a flat-lying detachment that would separate the Vari unit from a supposedly underlying CBU, as proposed by *Gautier* [1995], *Trotet et al.* [2001a] and *Ring et al.* [2003].

[9] The Komito gneiss, which makes up most of the southwestern part of the island, is a lateral equivalent of the Vari unit. Both define the Komito-Vari basement that is the lowest unit of the new structural pile proposed in this study (Figure 2a): a Hercynian orthogneiss (Komito) intruded by a Triassic pluton (Vari).

3.2. The Volcano-Sedimentary Sequences of Pyrgos and Kastri

[10] From base to top, the two volcano-sedimentary and marbles sequences lying on top of the Komito-Vari basement (Figure 2a) are the Pyrgos and Kastri units. They mainly differ in the presence of dolomitic marbles within the Pyrgos unit. The presence of microfossils (Foraminiferous Forschiidae) give a deposition age of 330–350 Ma for the marbles of the Pyrgos unit [*Pohl*, 1999; see *Schumacher et al.*, 2008]. Metatuffites close to the top of the Kastri unit have been dated as 243 ± 2 Ma (SHRIMP analyses of U/Pb on zircon) [*Keay*, 1998; *Tomaschek et al.*, 2003] (Figure 2b). The whole volcano-sedimentary sequence, as well as the intercalated marbles, have been metamorphosed in the blueschist facies from 8 to 17 kbar at 350–500°C (Figure 2b) [*Trotet et al.*, 2001b; *Schumacher et al.*, 2008]. Contrary to the Kastri unit, the Pyrgos unit is retromorphosed almost everywhere in the greenschist facies [*Trotet et al.*, 2001b]. Breccias and gouges indicate that the flat-lying contact at the base of the Kastri unit (white hemispheric symbols; Figure 2a) is a displacement plane, called the Kastri basal fault in the present study.

3.3. Oceanic Crust

[11] The rocks have an oceanic crust affinity at the top of the lithological pile. They consist of coarse-grained metagabbros (Kambos and Kini areas), fine-grained metabasalts and metavolcanites (Palos Peninsula, Airport, Galissas and Kini) and serpentinic schists (Finikas, base of the Kambos gabbros). A marble sequence has been tectonically intercalated in this igneous rock unit (Palos Peninsula) (Figure 2a). Eclogite metamorphism has been estimated in the range of 19–24 kbar and 500–580°C (Figure 2b) [*Gitahi*, 2004; *Holley et al.*, 2004; *Trotet et al.*, 2001b]. The U-Pb SHRIMP age of magmatic zircons are between 240 Ma and 80 Ma, providing an age estimate of the basic protolith (Figure 2b) [*Tomaschek et al.*, 2008; *Bulle et al.*, 2010]. High-pressure metamorphism is estimated at 52 Ma (Lu-Hf dating on garnet [*Lagos et al.*, 2007]). Syros Island displays

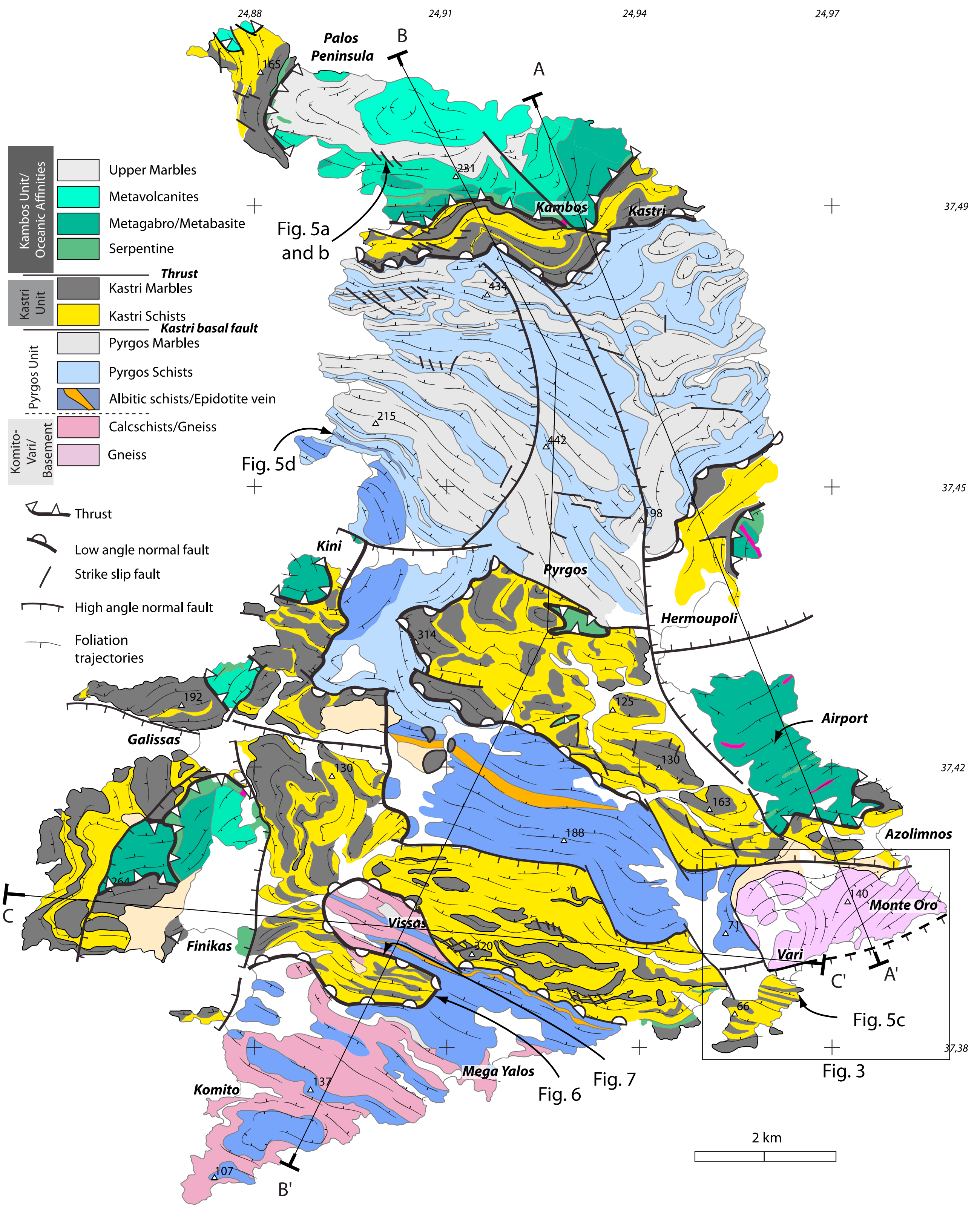

Figure 2a. Detailed map of Syros showing the four different units delineated in our structural study. The main tectonic contacts are a thrust (triangle symbols) and a low-angle fault system (hemispheric symbols). Foliations trajectories have been drawn from 866 foliation measurements and show the 3-D structure of the island.

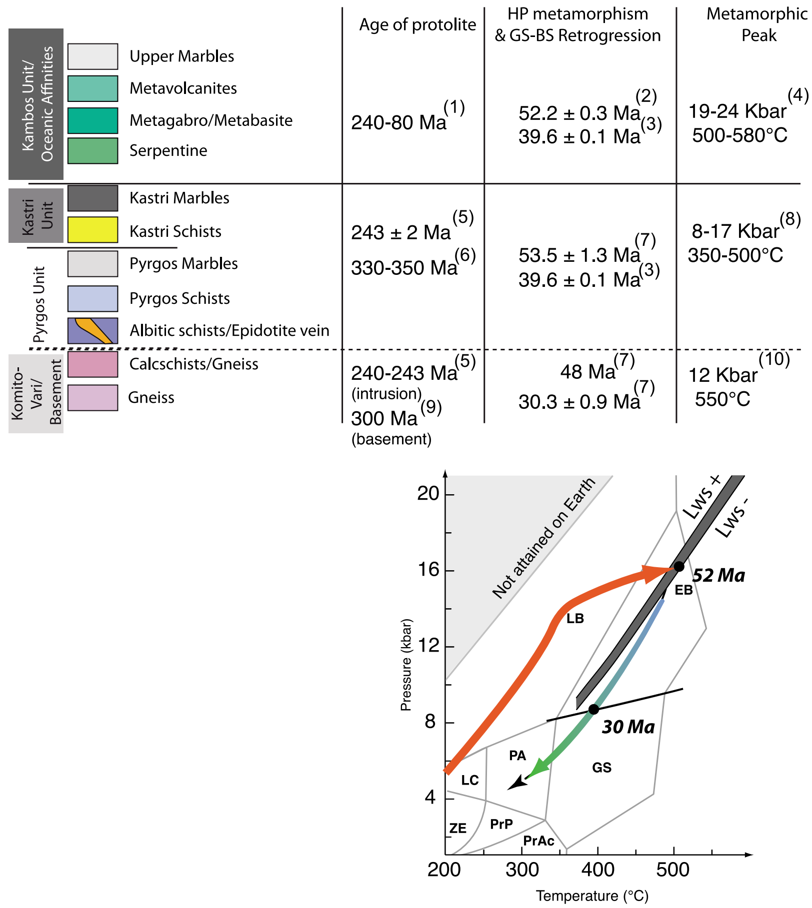

Figure 2b. Geological pile on Syros Island showing the ages of the protolite, metamorphism, and blueschist (BS) to greenschist transition (GS). Superscript numbers indicate the following citations: (1) *Bulle et al.* [2010], (2) *Lagos et al.* [2007], (3) *Baldwin* [1996], (4) *Holley et al.* [2004], (5) *Keay* [1998] and *Tomaschek et al.* [2003], (6) *Pohl* [1999], (7) *Maluski et al.* [1987], (8) *Schumacher et al.* [2008], (9) *Tomaschek et al.* [2008], and (10) *Tomaschek and Ballhaus* [1999]. Geochronological data are plotted in the PT path after *Schumacher et al.* [2008]. Facies are EB, epidote-blueschist; GS, greenschist; LB, lawsonite blueschist; LC, lawsonite-chlorite; PA, pumpellyite-actinolite; PrAc, prehnite-actinolite; PrP, prehnite-pumpellyite; and ZE, zeolite.

a complete lithological pile of the Cycladic Blueschist unit, from the Hercynian basement to its overlying sedimentary sequence up to the Triassic [*Keay*, 1998; *Tomaschek et al.*, 2003], on top of which the Pindos oceanic crust was thrust.

4. Ductile Deformation

[12] Most rocks display a stretching lineation on foliation surfaces that are most frequently marked by glaucophane in blueschists, assemblages of quartz and chlorite in greenschists and fine corrugations and streaks on foliation planes of marbles. At the island scale, stretching lineations display an "arcuate pattern" from a mean 30°N trend to the north to a mean 90°N trend to the south [*Ridley*, 1982] (Figure 4).

4.1. Top-to-the-Southwest Shear, Prograde Blueschist Metamorphism, and Thrusting of Oceanic Units

[13] To the north of the island, the Kambos unit (oceanic crust), with serpentinite at the base, is thrust on top of the metasedimentary Kastri unit (white triangular symbols in Figure 4). The thrusting was interpreted by *Bonneau et al.* [1980a, 1980b] as related to ophiolite emplacement prior to high-pressure metamorphism. *Schumacher et al.* [2008] also argued that the stacking of thrust units was completed before the metamorphic climax using P-T estimates in glaucophane-bearing marbles. Along the thrust plane, folding indicates thrusting toward the south [*Ridley*, 1982]. Our mapping of shear criteria (black arrows in Figure 4) shows top-to-the-south-southwest senses of shear, in agreement with the conclusions of *Ridley* [1982] and *Keiter et al.* [2004]. The occurrence of sheath folds indicates an increase in strain intensity close to the thrust zone.

[14] The Kambos unit is characterized by the widespread occurrence of lawsonite porphyroblast pseudomorphs whose development was synchronous with a top-to-the-south sense of shear at millimeter to meter scale (Figures 5a and 5b), showing that thrusting was not prior to but

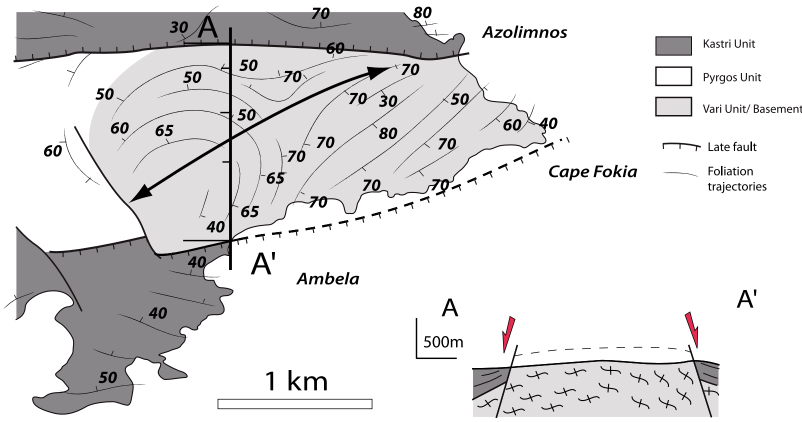

Figure 3. Detailed work on the Vari unit. Map of the Vari orthogneiss foliation trajectories have been drawn from 89 foliation measurements. Cross section AA′ is north–south directed and shows the geometry of the northern and southern contacts of the Vari unit with the other lithologies of the island.

instead synchronous with metamorphism, contrary to the results published by *Bonneau et al.* [1980a, 1980b] and *Schumacher et al.* [2008]. As the lawsonite stability field corresponds to a narrow range of low temperatures, located on the prograde path of the Syros blueschist rocks [*Schumacher et al.*, 2008, Figure 12], the top-to-the-south sense of shear occurred during prograde metamorphism (i.e., subduction). The preservation of lawsonite pseudomorphs indicates that shearing stopped prior to their destabilization [*Keiter et al.*, 2004; *Philippon et al.*, 2009].

4.2. Top-to-the-Northeast Shear, Retrograde Greenschist Metamorphism, and Exhumation

[15] Top-to-the-northeast shear affects all four units of the island (white arrows in Figure 4), whereas top-to-the-southwest shear is mostly preserved in the oceanic unit and seldom in the metasedimentary units. The top-to-the-northeast shear, as observed in the transition from eclogites and blueschists (Figure 5c) to greenschists (Figure 5d), indicates that it occurred during retrograde metamorphism, that is, decompression [*Trotet et al.*, 2001b]. This pervasive deformation is linked to the exhumation of the unit from its maximum depth of burial up to the middle to lower crustal levels and has been described as a continuum of ductile extensional deformation from eclogite facies to greenschist facies [*Trotet et al.*, 2001b] (Figures 5b and 5c). Geochronological data indicate that the eclogite facies occurred at 52 Ma [*Lagos et al.*, 2007] (Lu/Hf on garnet), the blueschist facies is dated from 53 to 35 Ma and finally, the greenschist facies is dated at 30 Ma [*Maluski et al.*, 1987] (^{39}Ar/^{40}Ar on phengites).

5. Ramp-Flat Extensional System

[16] The southern part of the Syros map (Figure 2a) shows two large klippes of the Kambos and Kastri units lying unconformably on top of the Pyrgos unit. Conversely, to the north, the Kambos and Kastri units lie conformably on top of the Pyrgos unit. This island-scale structural pattern results from a predominantly postmetamorphic ramp-flat type extension.

5.1. The Kastri Basal Fault

[17] Where it can be observed directly, the major flat-lying basal contact of the Kastri unit displays meter thick gouges and breccias that reworked the metamorphic rocks in a brittle fashion. This indicates that displacement along this tectonic contact took place in the brittle crust. At the outcrop scale, southward senses of motion are marked by semibrittle shear zones, pull-apart-type Ca-Qz veins and series of Riedel-type small faults.

[18] Figure 6 is a landscape view of an area in the vicinity of Vissas, showing the Kastri unit lying on top of the Pyrgos unit. Inside the Kastri unit, marble layers dip northward and are cut by a low-angle normal fault dipping gently southward. The offset of marble layers and their sigmoid shape along this fault indicates a top-to-the-south sense of displacement. At the outcrop scale, close to the basal contact, semibrittle shear zones associated with calcite-filled tension gashes (Figure 7) also indicate a top-to-the-south sense of shear. Two mean directions of displacement are reported in Figure 8 for the two main klippes in the south of the island.

5.2. Cross Sections

[19] The ramp-flat geometry of the Kastri basal fault at the island scale is illustrated by three cross sections (see location in Figures 2a and 8). Cross sections AA′ and BB′ are nearly parallel to the north-south direction of displacement (Figure 8). From base to top, the fault hanging wall is made up by the Kastri sedimentary unit, the Kambos oceanic units, the footwall by the Komito-Vari basement unit and the Pyrgos sedimentary unit.

[20] Sections AA′ and BB′ show that in the north of the island, in the vicinity of Kambos, the Kastri basal fault is parallel to the foliation-parallel lithological layering of the Kastri and Pyrgos units that are gently dipping to the north. In other words, it is a décollement. In the southern part of the island, from Hermoupoli to the southern coast, the fault hanging wall is lying with a southward shallow dip on top of the northeast dipping foliation of the footwall. Crosscutting relationships show that the hanging wall comes into contact with deeper footwall levels toward the south. These geometrical hanging wall-footwall relationships, the southward

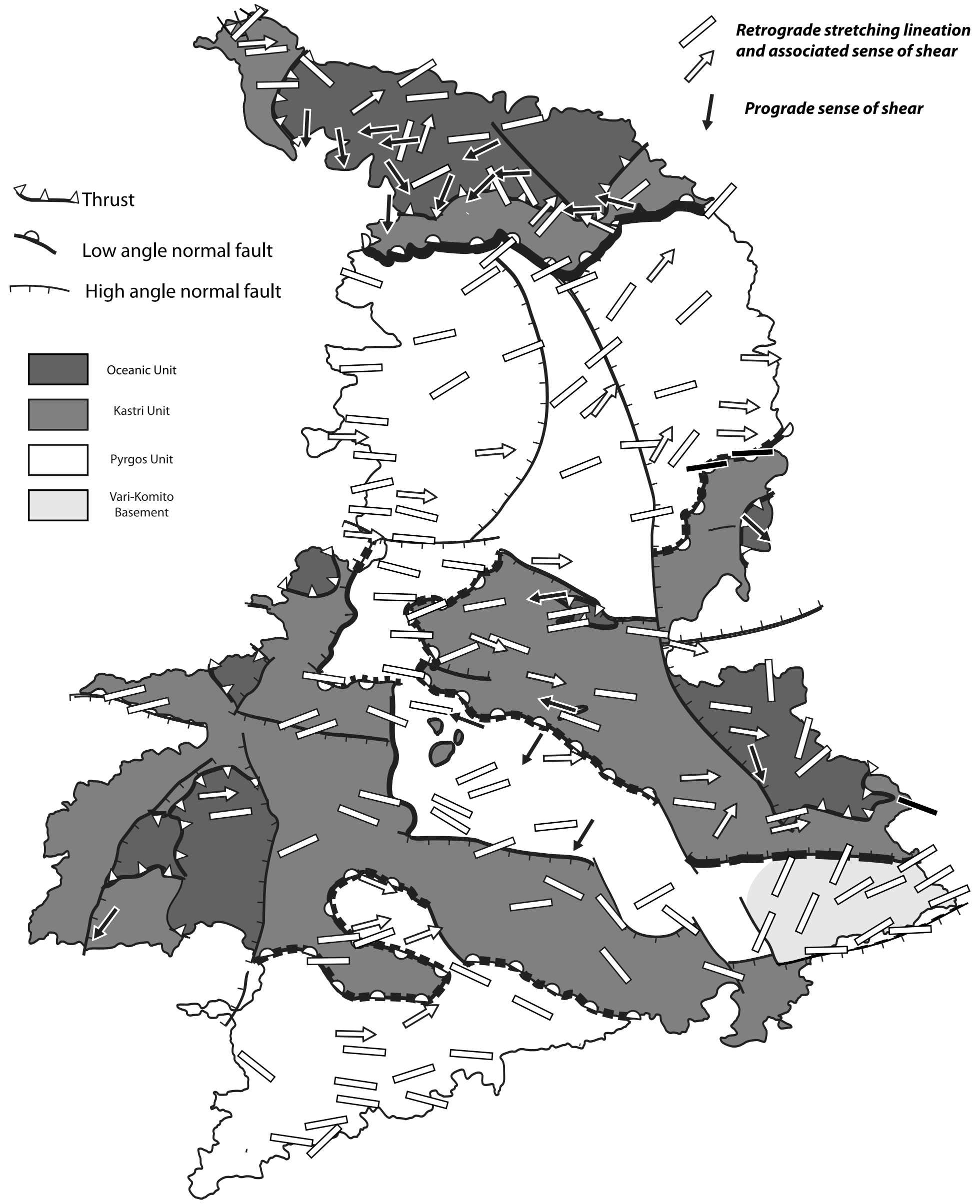

Figure 4. Structural schema of Syros Island showing the four main units that constitute the island shown in shades ranging from dark gray to white: Kambos oceanic units, Kastri unit, Vari unit, and Pyrgos unit. The deformations observed in the field consist of prograde shearing associated with lawsonite pseudomorphs, shown by black arrows. The retrograde stretching lineation and associated sense of shear are shown by the white bars and arrows.

sense of displacement and associated brittle deformation indicate that the Kastri basal fault is a regional-scale extensional detachment dipping southward that developed at a late stage of the island evolution, under postmetamorphic conditions. Sections AA′ and BB′ also show that the whole pile is affected by the Kini antiform (Figure 2a), which has an half wavelength of approximately 5 km. A few of the short wavelength folds with a NE–SW axis trend (Figure 8) are likely to be related to basement faulting at a deeper level (Section AA′, Figure 9).

[21] Cross section CC′, which is close to perpendicular to the direction of displacement, shows the flat-lying attitude of the detachment systems along strike.

[22] At a late stage of evolution, the Kastri basal fault was cut by two sets of steeply dipping faults trending either east–west or approximately north–south (Figures 8 and 9). These faults have an average steep dip (around 70–80°) significantly steeper than purely normal faults that is compatible with the observed sinistral strike-slip component. The sense of dip of the east–west trending normal faults changes from northward to the east (Section AA′, Figure 9) of the Finikia fault (Figure 8) to southward to the west (Section BB′, Figure 9). The Finikia fault, which is dipping to the east, combines normal and sinistral strike-slip components. The observed strike-slip component along the Finikia fault is kinematically compatible with the change of dip of the EW

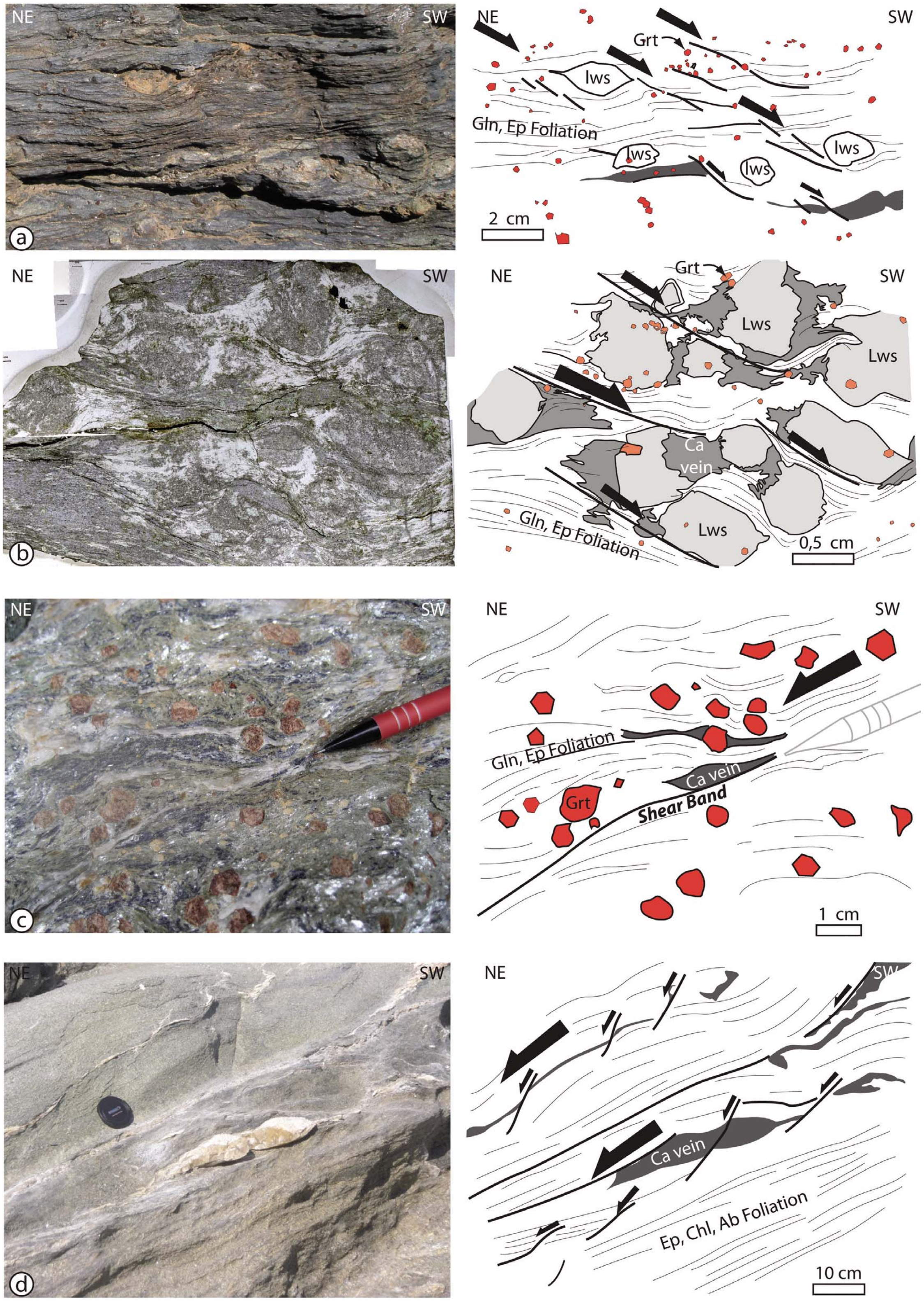

Figure 5. Microstructures and macrostructures observed in the Syros rocks. (a) Field photograph of a garnet-, glaucophane-, and lawsonite-bearing rock, displaying top-to-the-southwest sense of shear. (b) Thin section showing top-to-the-southwest sense of shear in lawsonite-bearing blueschists (belonging to the Kambos unit, north of the island). (c) Field photograph of a garnet-, glaucophane-, and epidote-bearing rock, recognized as eclogite facies rocks by *Trotet et al.* [2001a] (Ormo Ambelos area), displaying top-to-the-northeast sense of shear. (d) Greenschist facies rocks with albite, chlorite, epidote, and calcite paragenesis, showing a top-to-the-northeast sense of shear.

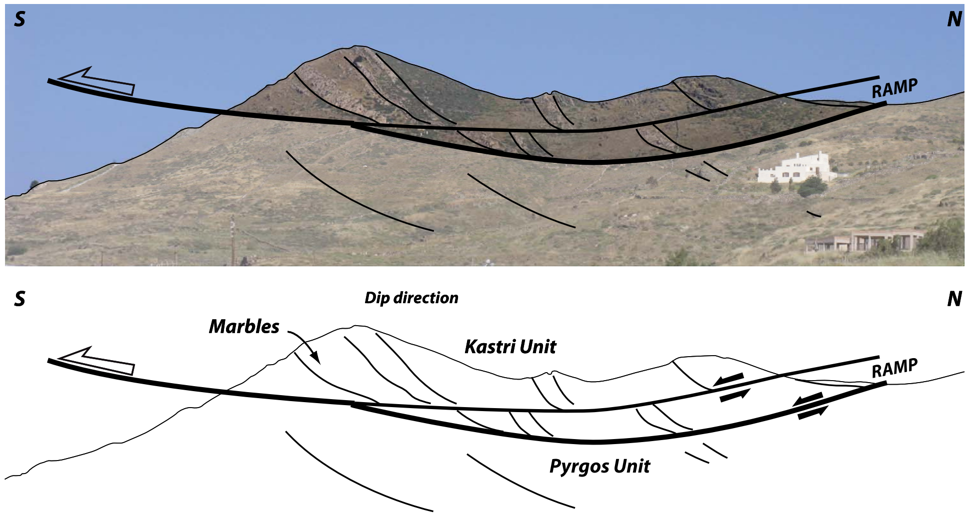

Figure 6. Field evidence of displacement along the ramp-flat system. The Kastri basal contact between the Kastri marbles and underlying Pyrgos marbles (in the vicinity of Vissas). A top-to-the-south displacement is shown by the offset of the marble layers in the Kastri unit.

trending normal faults in its hanging wall and footwall. This strongly suggests that the two sets of steeply dipping normal faults are at least partly contemporaneous and accommodate transtensional deformation. In fact, during this late brittle deformation event, the whole Cycladic domain is simultaneously affected by normal and strike-slip faults coeval with large-scale folding with north–south trending axes [*Angelier*, 1977; *Papanikolaou*, 1978, 1980; *Avigad et al.*, 2001; *Philippon*, 2010]. In addition, these deformations are associated to large-scale block rotations [*Morris and Anderson*, 1996; *Avigad et al.*, 1998]. Unfortunately, the Syros island is too small to allow a full description and analysis of the complex relationships between these synchronous faults, folds and block rotations.

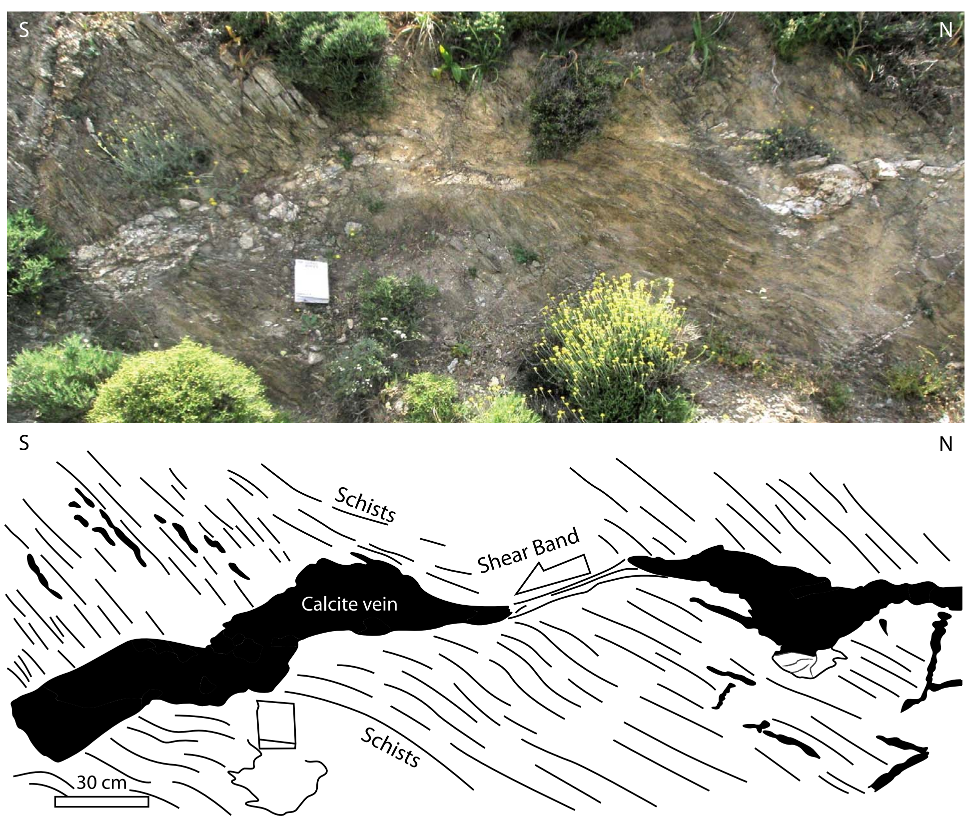

Figure 7. The contact within the schist is also observed in the vicinity of Vissas. The deformation is located on a shear band filled by calcite and indicating a top-to-the-south sense of shear.

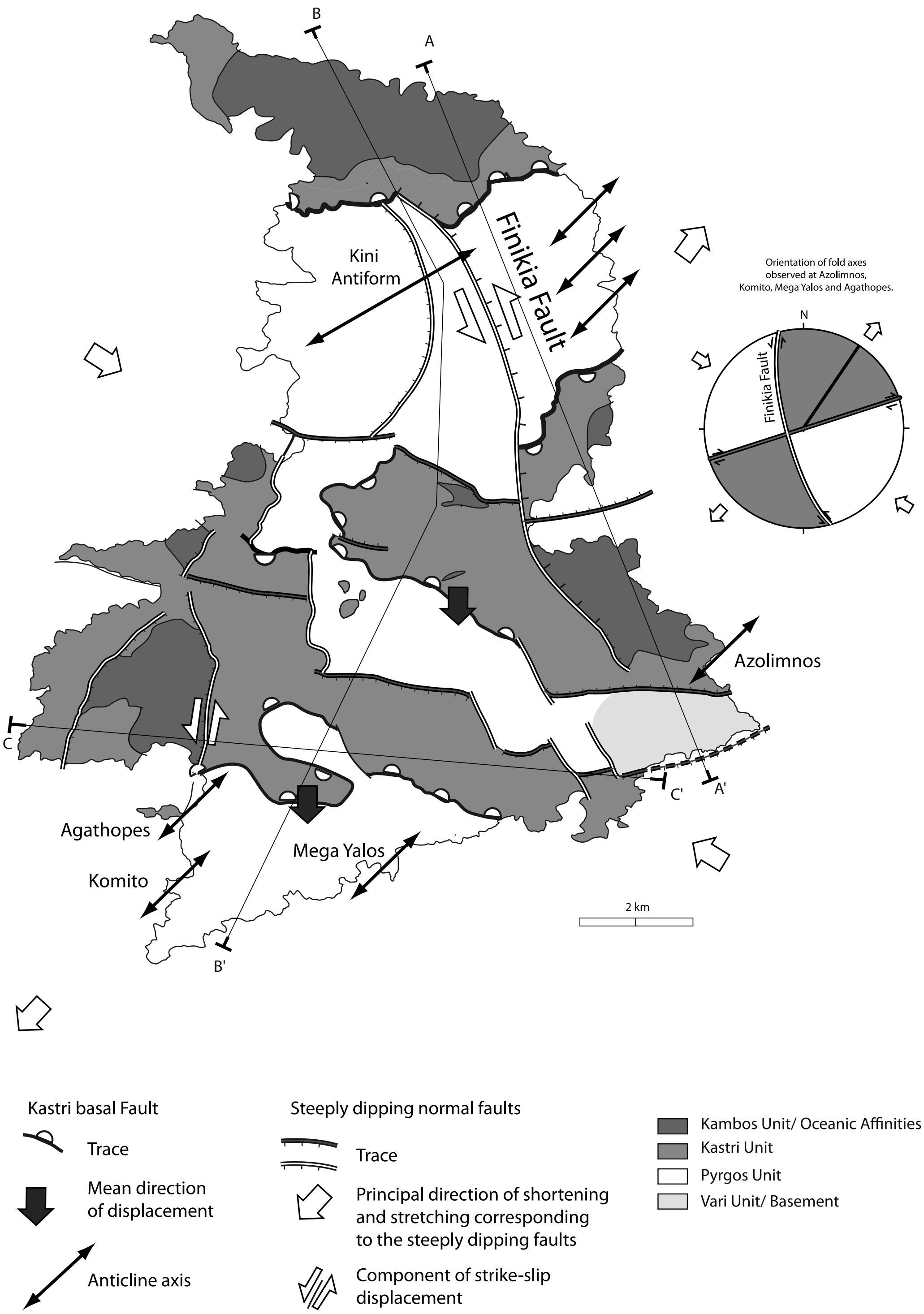

Figure 8. Structural map of Syros Island showing the main tectonic features related to extension: the ramp-flat extensional system (hemispheric symbols) are cross-cut by the steeply dipping normal fault network. This network shows two orientations: north–south, which is accompanied by a strike-slip motion on the faults in white lines, and an east–west network, either south or north dipping, in dark gray lines. White arrows show the principal direction of shortening and stretching corresponding to the steeply dipping faults. Black arrows show the mean direction of displacement along the Kastri basal fault.

[23] In addition to the two sets of large normal faults described in the previous paragraph and shown in both the structural map (Figure 8) and cross sections (Figure 9), some local observations also need to be considered here. In north–south trending strain corridors in Komito, the Agathopes, Mega Yalos and Azolimnos folds and crenulation of foliation, with N30 trending axes, also indicate a sinistral strike-slip component, such as along the faults trending like the

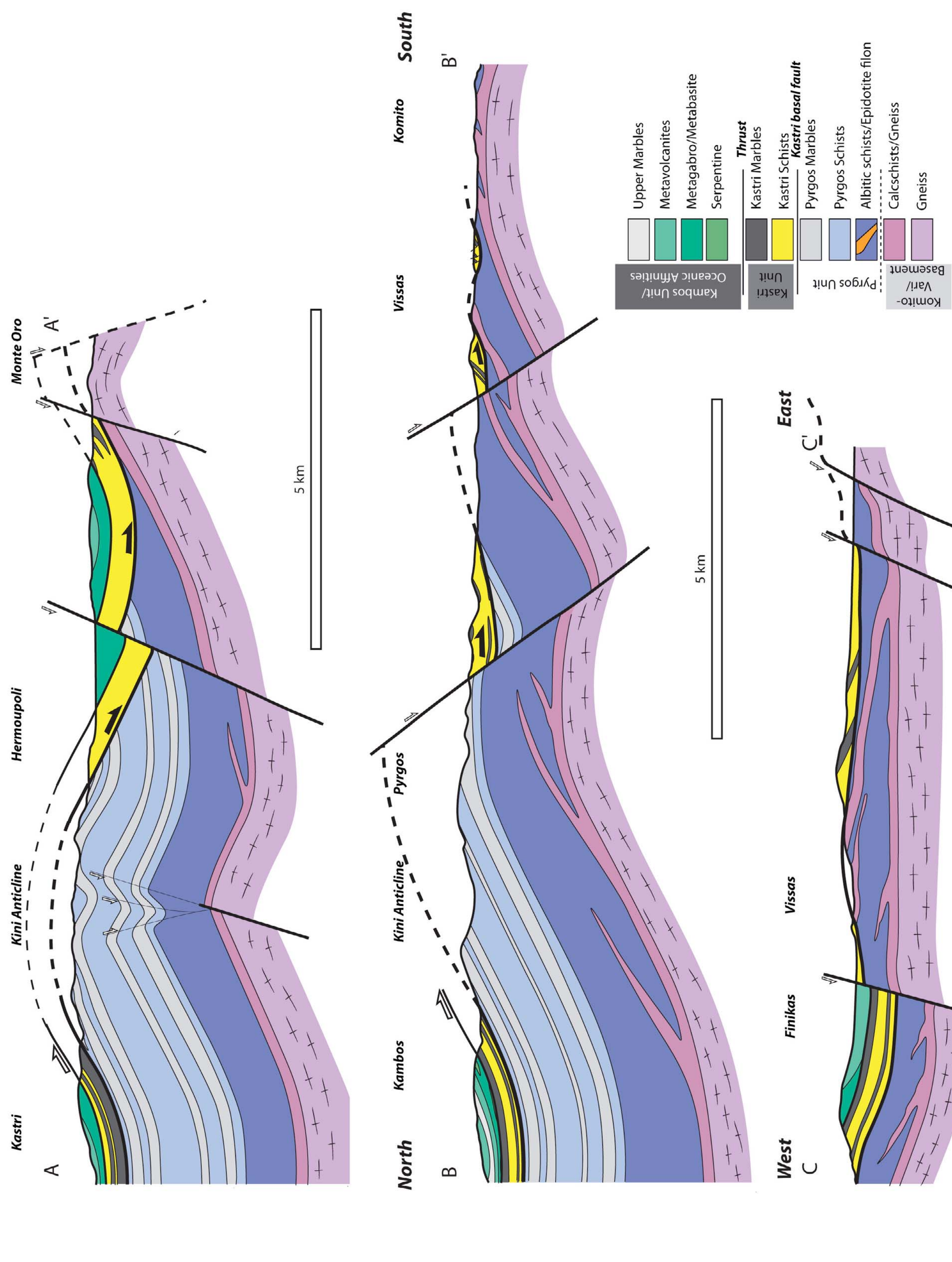
A
A'
Kastri
Kambos
Kini Anticline
Hermoupoli
Monte Oro
5 km
North
South
B
B'
Pyrgos
Vissas
Komito
West
East
C
C'
Finikas
Vissas
Kambos Unit/
Oceanic Affinities
Upper Marbles
Metavolcanites
Metagabro/Metabasite
Serpentine
Thrust
Kastri Unit
Kastri Marbles
Kastri Schists
Kastri basal fault
Pyrgos Unit
Pyrgos Marbles
Pyrgos Schists
Albitic schists/Epidotite filon
Komito-Vari/Basement
Calcschists/Gneiss
Gneiss

Figure 9

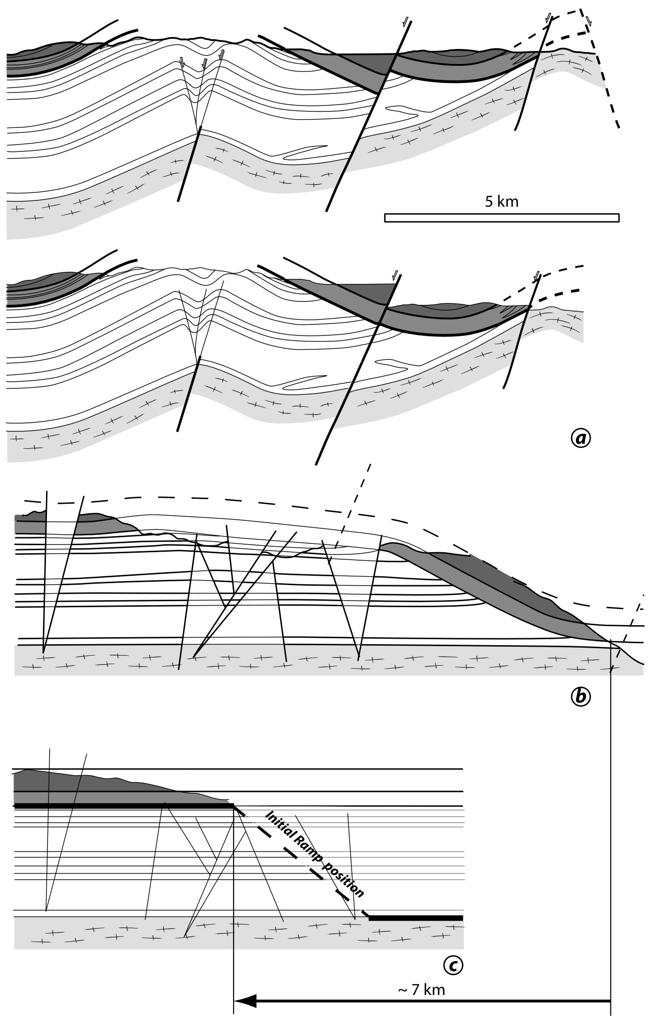

Figure 10. Restoration of cross section B by (a) removing the displacement along the steeply dipping normal faults, (b) unfolding, and (c) removing the displacement along the ramp. The initial position of the ramp is found by removing the space obtained during the unfolding of the Kini antiform.

large Finikia fault (Figure 9). This late extensional system developed in response to the mean directions of stretching and shortening trending NNE–SSW and ESE–WNW, respectively (stereo diagram in Figure 9). The southward direction of displacement along the ramp-flat extensional system is slightly oblique to the principal axis of stretching mentioned above. Finally, it is important to stress again here that this extensional event occurred under dominantly brittle conditions with a top-to-the-south displacement unrelated to the previous dominantly ductile extension whose sense of shear is top-to-the-northeast.

[24] The Komito-Vari unit is the deepest exposed level of the Syros lithological pile in the core of a broad anticline, as shown in sections AA′ and BB′. Late east–west trending normal faults affect the antiform in the Vari area but do not change the whole polarity of units as observed in the detailed mapping (Figure 3). Therefore, both the local-scale structural study of Vari and the coherence between the regional-scale cross sections AA′ and BB′ confirm the basement position of the Komito-Vari unit [*Bonneau et al.*, 1980a, 1980b].

5.3. Cross Section Restoration

[25] Figure 10 shows a two-step restoration of cross section AA′ (Figure 10a). In the first step, displacements along the steeply dipping faults are removed (Figure 10b). The second step consists in (1) unfolding the Kini anticline and (2) moving back the most southern extremity of the hanging wall (Kambos and Kastri units) to the upper end of the ramp (Figure 10c). This gives a minimum displacement of approximately 7 km.

[26] The development of the ramp-flat extensional systems is summarized in two steps in Figure 11, on the basis of analog experiments by *McClay and Scott* [1991] and *Roure et al.* [1992]. The hanging wall forms a rollover antiform that is not observed on Syros but which would likely occur offshore. Because the rollover is not observed, the total amount of displacement cannot be fully evaluated and instead, only a minimum value is given.

[27] The restoration illustrates that this detachment system used two décollement layers that are, from top to base: (1) the interface between the Kastri and Pyrgos units, suggesting that a weaker layer existed at this level in the sedimentary pile and (2) the interface between the Pyrgos sedimentary unit and the Komito-Vari orthogneissic basement (Figure 11a). The two décollements were connected by a southward dipping ramp crosscutting the Pygos unit with a restored angle of about 45°. During ramp-flat extension, the unloading of the footwall by 4 km of hanging wall led to a flexure that brought the movement surface into a rather flat-lying attitude.

6. Discussion

[28] The tectono-metamorphic history of Syros is illustrated in three stages in the PT path proposed by *Schumacher et al.* [2008] (Figure 12). Stage 1 shows the thrusting of the oceanic unit on top of the subducting Adria passive margin in the mid-Eocene. During stage 2, the upper plate of the subduction is submitted to core complex–type extension (Southern Rhodope Core Complex) [*Brun and Sokoutis*, 2007] and the Adria crust that is decoupled from the subducting lithospheric mantle [*Brun and Faccenna*, 2008] is exhumed up to the middle to lower crustal level. The CBU exhumation that started soon after stage 1 is accommodated by trench retreat. Stage 3 is dominated by core complex–

Figure 9. Cross sections of Syros Island showing the geometry and relationship between the constitutive units of the island. The AA′ and BB′ cross sections show the evolving relationship of the ramp-flat system from north to south. North of the island, a flat contact is observed and the oceanic/Kastri units are lying on Pyrgos marbles. The central part of the island presents a ramp-type contact. Finally, the southern part of the island shows a flat contact between the oceanic/Kastri units and the basement. The east–west CC′ cross section shows the lateral behavior of the ramp-flat system.

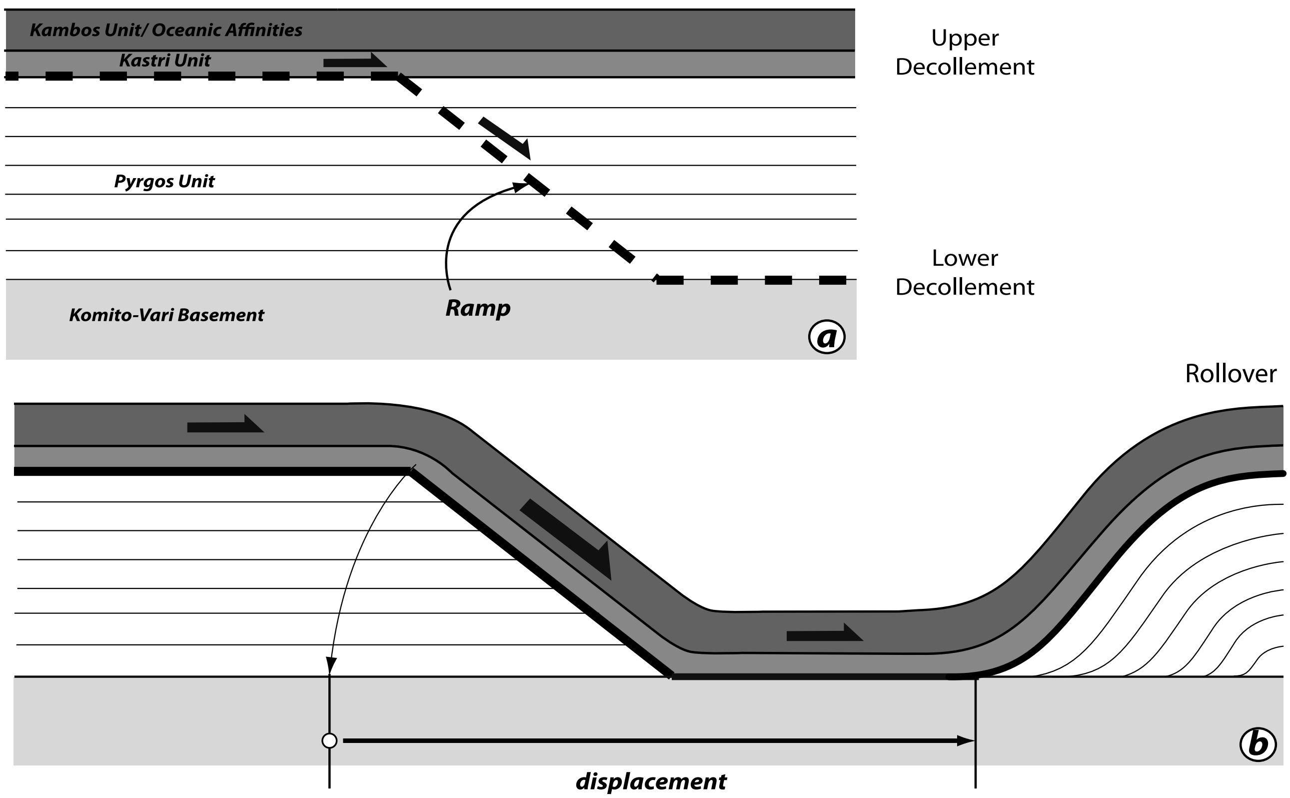

Figure 11. Schematic sketch showing the development of the ramp-flat system from its initiation (a) inside the metamorphic pile to (b) the displacement of the unit along the ramp-flat contact.

type extension in the central Cyclades (Naxos-Paros-Mykonos) which is controlled by (1) the North Cycladic Detachment [*Jolivet et al.*, 2010] and (2) distributed normal faulting at the regional scale. During this stage, Syros underwent southward ramp-flat extension, giving a detachment internal to the CBU, followed by steeply dipping normal faulting.

6.1. Structural Record of Subduction in the Cyclades

[29] This study shows that the occurrence of lawsonite pseudomorphs is an extremely useful tool to identify deformations related to prograde metamorphism and therefore attributable to subduction. Senses of shear prior to lawsonite destabilization are top-to-the-south-southwest. It is not unlikely that similar senses of shear described at many different places in the Cyclades could also be related to subduction. In particular, the southwest-directed shear observed in the southern Cyclades could be reexamined in this way (for Serifos, Kea, and Kythnos, see *Iglseder et al.* [2009]; for Kythnos, see our own observations). Interestingly, the top-to-the-southwest shearing on Ios is interpreted as related to either a southwest dipping extensional detachment [*Forster and Lister*, 2010] or to thrusting toward the southwest [*Huet et al.*, 2009].

6.2. No Synmetamorphic Detachment in Syros

[30] *Ridley* [1984, Figure 6, p. 760] interpreted the Vari orthogneiss as the "roof of the convergence zone in which the blueschist metamorphism took place" and later put on top of the CBU by a low-angle normal fault. Since *Maluski et al.* [1987] obtained a Cretaceous age for the high-pressure metamorphism in the Vari unit (similar to those observed in the Pelagonian by *Seidel et al.* [1981]), it has been described as a klippe of the upper Pelagonian block lying on top of the CBU. Consequently, and as initially suggested by *Ridley* [1984], a detachment is supposed to separate the orthog-

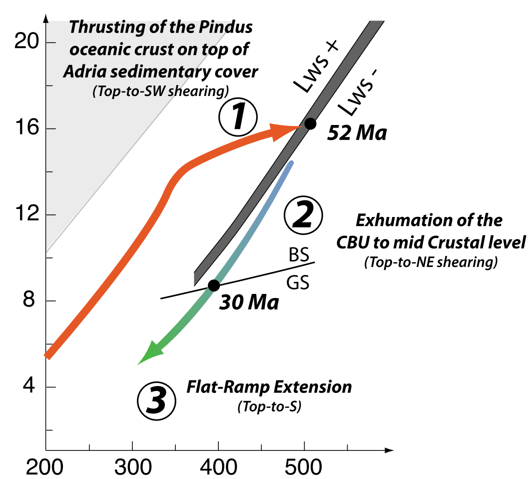

Figure 12. The three main tectonic stages recorded by the Syros blueschists: (1) burial down to lawsonite-blueschist facies accompanied by a top-to-the-south sense of ductile shear, (2) exhumation with a top-to-the-northeast sense of ductile shear, and (3) top-to-the-south localized ramp-flat extension. The PT path [from *Schumacher et al.*, 2008, Figure 12] shows the blueschist (BS) to greenschist (GS) transition and the lawsonite breakdown (Lws^+/Lws^- line).

neisses from the underlying CBU [*Gautier*, 1995, Figure 2.8, p. 293], the so-called Vari detachment [*Trotet et al.*, 2001a; *Ring et al.*, 2003], and is considered to locally represent the North Cycladic Detachment System [*Jolivet et al.*, 2010].

[31] Three lines of argument show that the hypothesis of the so-called Vari detachment cannot be maintained and confirm the basement interpretations of *Bonneau et al.* [1980a, 1980b], *Tomaschek and Ballhaus* [1999], and *Tomaschek et al.* [2008]. First, not a single piece of field evidence has been found in favor of a shallowly dipping detachment separating the Pyrgos and Vari units. Second, detailed mapping in the Vari area shows that the Vari unit appears as an antiform seated below the Pyrgos unit, in agreement with *Bonneau et al.* [1980a, 1980b], *Tomaschek and Ballhaus* [1999], and *Tomaschek et al.* [2008]. Third, the construction of two cross sections passing through Komito to the west and Vari to the east, separated by a distance of more than 5 km, displays the same cover-basement relationship. This last piece of evidence is responsible for the use of the term Komito-Vari unit.

6.3. Top-to-the-Northeast Shearing

[32] If the Vari detachment does not exist, then the tectonic significance of shearing top-to-the-northeast must be reconsidered. It is noteworthy that the bedding-parallel foliation bears two opposite and nonsynchronous shear indicators. Shear top-to-the-south-southwest is prograde while shear top-to-the-north-northeast is retrograde. Thus, the foliation that was created during top-to-the-south-southwest shear was reactivated by a top-to-the-north-northeast shear during metamorphic retrogression in the less competent lithologies. At the regional scale, the Pindos suture zone, which separates the CBU from the Pelagonian block, trends NNE–SSW and is cut at right angles by the North Cycladic Detachment System (Figure 1). This suggests that exhumation accommodated by top-to-the-northeast shearing could correspond to the reactivation of the Vardar Suture Zone, prior to the development of the North Cycladic Detachment.

6.4. Opposite Senses of Shear in Ductile Deformation

[33] The existence of opposite senses of shear in the CBU, which has been identified a long time ago [e.g., *Gautier and Brun*, 1994], has been interpreted in various ways. On Syros, as well as on other Cyclades islands, they are considered to develop synchronously either (1) resulting from convergent ductile flow from below the opposite limbs of a core complex [*Gautier and Brun*, 1994; *Jolivet and Patriat*, 1999; *Tirel et al.*, 2009] or (2) as conjugate shear zones in a coaxial deformation [*Rosenbaum et al.*, 2002; *Bond et al.*, 2007]. On the basis of these observations, *Bond et al.* [2007, p. 220] concluded that "it is 'symmetrical' pure-shear-dominated configuration [*Malavieille*, 1993, Figure 16b] that provides a better description of the crustal-scale deformation". The evidence on Syros for top-to-the-south-southwest shear related to thrusting of the oceanic unit on top the sediments of the Adria margin prior to top-to-the-northeast shear related to exhumation suggests that the synchronism of shear indicator development requires a reevaluation. Coaxial deformation giving rise to conjugate shear bands can develop on a small scale if, in particular, viscosity contrasts between layers favor strain partitioning. Indeed some good examples of this exist on Syros. However, transposing this type of kinematic pattern to the crustal scale (e.g., at the whole Cyclades scale) would also require a careful check of the synchronicity of shearing events on the regional scale.

[34] On the scale of the whole Cyclades Islands, opposite senses of shear, top-to-the-southwest to the south and top-to-the-northeast to the north, were recently interpreted as being synchronous and reflecting both downward (subduction) and upward (exhumation) ductile flow within a northeast dipping subduction channel [*Huet et al.*, 2009; *Jolivet et al.*, 2009]. Here again the synchronicity of shear indicator development must be checked carefully. In addition, it would be necessary to show that top-to-the-south-southwest shear is located in the lower part of the CBU and top-to-the-northeast in the upper part. This is not in agreement with the fact that to the north on Syros, as well as on the south Cyclades islands, the part of the CBU that is observed corresponds to the base of the sedimentary cover lying on top of the Adria basement.

6.5. Ramp-Flat Extension

[35] During ramp-flat extension on Syros, footwall unloading due to the removal of 4 km of hanging wall led to a flexural rebound that brought the movement surface into a flat-lying attitude. Contrary to previous interpretations, this detachment was not originally dipping at a low angle. In our opinion and experience, this is more to also apply to other so-called low-angle detachments in the Cyclades realm. A second important inference is the fact that such detachments are postmetamorphic. Of course, they may significantly contribute to the whole exhumation process of metamorphic rocks but as they develop in the semibrittle to brittle crust, they are not directly related to the metamorphic history. In addition, the southward sense of displacement is opposite to the top-to-the-northeast ductile sense of shear associated with the retrogressive metamorphism. Therefore, using the top-to-the-south sense of shear as an indicator of the dominant kinematics of metamorphic rock exhumation would be misleading. This upper crust low-angle faulting is only a late feature of Aegean extension. As such late faults most likely also occur at other places in the Cyclades, their identification is necessary to avoid incorrect conclusions concerning the history of blueschist exhumation.

7. Conclusions

[36] The structural analysis presented in this paper shows that the tectonic history of the Syros blueschist unit can be summarized in three major stages. The first stage corresponds to the thrust emplacement of the Kambos oceanic unit on top of the Kastri unit. The oceanic units show evidence of pervasive ductile shear synchronous with prograde high-pressure metamorphism with a top-to-the-south-southwest thrust sense. The age of thrusting cannot be directly constrained on Syros, but the sediments of the Kastri unit are attributed to the Triassic. However, as demonstrated by paleontological evidence from Evvia [*Dubois and Bignot*, 1979] and Attica [*Katsikatsos et al.*, 1986a, 1986b], the youngest sediments of the CBU are nummulitic flysch, giving a maximum mid-Eocene age for

the thrusting [*Shaked et al.*, 2000]. This is in agreement with the 52 Ma age obtained for eclogite facies metamorphism on Syros [*Lagos et al.*, 2007].

[37] The second stage corresponds to a pervasive top-to-the-northeast ductile shear affecting the whole metamorphic pile. This second major deformation event, which is synchronous with the metamorphic retrogression from eclogite to greenschist facies [*Trotet et al.*, 2001b], left some volumes of the Kambos oceanic unit almost undeformed, as shown in particular by the undeformed lawsonite pseudomorphs. No major detachment related to this event outcrops on the island.

[38] The third stage corresponds to semibrittle to brittle deformation. It started with a ramp-flat extension using two décollement levels: (1) the interface between the Kastri and Pyrgos sedimentary units and (2) the interface between the Pyrgos sedimentary unit and the underlying Komito-Vari orthogneiss basement. The southward minimum displacement along this late detachment is approximately 7 km. During the late evolution of this deformation event, two sets of steeply dipping normal faults trending either east–west or approximately north–south affect the whole metamorphic pile.

[39] This study also shows that, contrary to most previous kinematic studies, there is no synmetamorphic detachment in Syros and that the opposite senses of shear associated to ductile deformation were not synchronous and resulted, first, from subduction-related thrusting and, second, from exhumation-related extension. We suggest that these conclusions gained in the Syros Island should have important implications at the scale of the entire Cycladic Archipelago.

[40] **Acknowledgments.** The present work was financially supported by the ANR-EGEO project. We are extremely grateful to L. Jolivet for having introduced us to Syros geology and for the field trip that he organized especially for us on Tinos and Mykonos. Great thanks are due to A. Eude and L. Tual, who helped with the structural mapping. Discussions at various stages of the project with L. Jolivet, P. Agard, B. Huet, and L. Labrousse, in particular within the framework of the ANR-EGEO project, have been very useful and stimulating. However, the data and interpretations presented here are entirely our own. We thank the two anonymous reviewers for very constructive comments and suggestions.

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