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Article

Deformation Pattern of Well-Preserved High-Pressure Rocks (SE Syros, Cyclades)

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Abstract: New detailed geological/structural mapping as well as field-based structural analysis were carried out to investigate the deformation pattern of well-preserved high-pressure rocks of the Blueschist Unit exposed on SE Syros (Cyclades, Greece). Our new geological mapping revealed the occurrence of a metasedimentary sequence underlain by a meta-igneous sequence. The contact between these two sequences displays typically interfingering patterns in map-scale due to folding. The earlier ductile deformation phase recognized in the mapped area, is associated with the development of a penetrative foliation, which was formed under eclogite/blueschist facies conditions at peak conditions. The subsequent main deformation phase occurred at blueschist facies conditions synchronous with the early stages of exhumation of the high-pressure rocks. This phase is mainly associated with the formation of map-scale WNW-trending folds and a pervasive axial planar foliation linked with ESE-directed shearing. The main deformation ceased within blueschist facies conditions and exhumation of the rocks to greenschist facies conditions took place under very weak deformation. Greenschist retrogression observed in the southwestern part of the mapped area seems to be controlled by fluids rather than by intense deformation. Our results indicate that the high-pressure rocks of the Blueschist Unit exposed on Syros Island represent a large-scale pod of low deformation under blueschist to greenschist facies conditions, likely occupying the core of an extrusion wedge.

Keywords: geological mapping; structural mapping; structural analysis; blueschist unit; hellenides

1. Introduction

Syros Island, situated in the central part of the Cyclades, is renowned worldwide for its extensive exposures of exceptionally well-preserved high-pressure (HP) rocks of the Blueschist Unit (Cycladic Massif) [1,2] (Figure 1a: inset). HP rocks originated during Hellenides formation at Eocene-Oligocene times in the course of the Alpine orogenesis. Despite the extensive study of these rocks for about four decades, encompassing petrological, geochronological, and structural studies, diverse interpretations, regarding mainly the structural evolution and the exhumation mechanism of the HP rocks, hinder our understanding of the processes that controlled the exhumation and preservation of these rocks [2–13]. Currently, two main contrasting modes have been proposed for the exhumation of the HP rocks of the Blueschist Unit in the Cyclades and by extension on the island of Syros. In the first mode, the Blueschist Unit was exhumed in the footwall of a series of syn- and post-orogenic NE-dipping detachment faults (e.g., [10,14]). In Syros Island, three such detachment faults were operated each individual at different times under eclogite/blueschist, blueschist/greenschist, and greenschist facies conditions [10]. According to this model, well-preserved HP rocks occur typically in the higher structural levels of the Blueschist Unit. In the second mode, ductile-stage exhumation of the Blueschist Unit from eclogite/blueschist to greenschist facies conditions occurred via a ductile / wedge extrusion under an overall compressional tectonic setting (e.g., [15–18]). For Syros Island, it is suggested that the Blueschist Unit was exhumed either as a coherent slice via a NE-directed extrusion or as two or three coherent slices via SW-directed extrusions [11,13,19]. According to this model, well-preserved HP rocks should represent low-strain pods occurred at the core of the extrusion [16]. These contrasting interpretations clearly indicate the need for more detailed studies of the structural evolution of the Blueschist Unit, to better understand the processes controlled the preservation of these rocks.

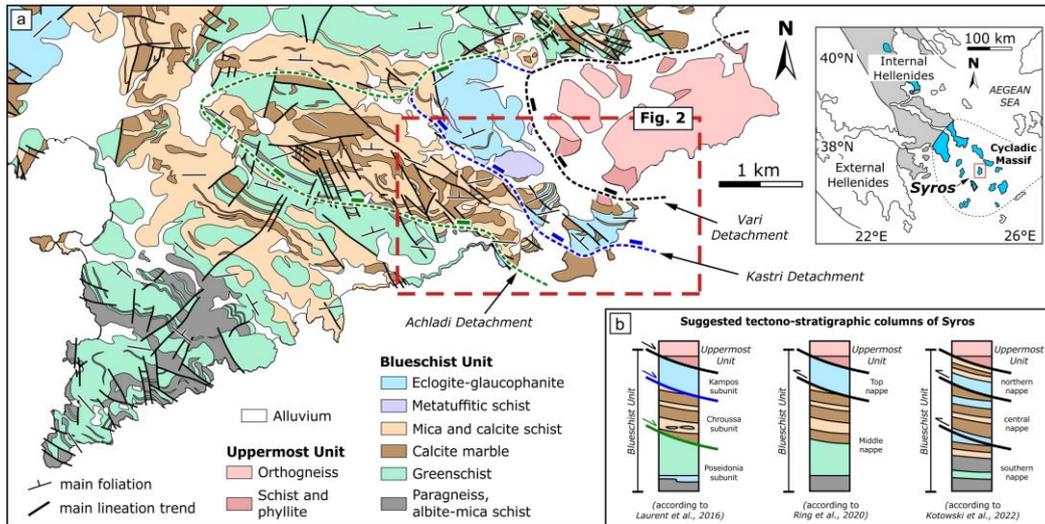


Figure 1. (a) Geological/structural map of south Syros area showing the major lithologies and structures (after [2,9,11]). Red dashed box indicates the location of the map in Figure 2. Inset shows a simplified geological map of the Hellenides showing the position of Syros Island within the Cycladic Massif (blue color). (b) Suggested tectono-stratigraphic columns for Syros Island (according to [9,13,19]).

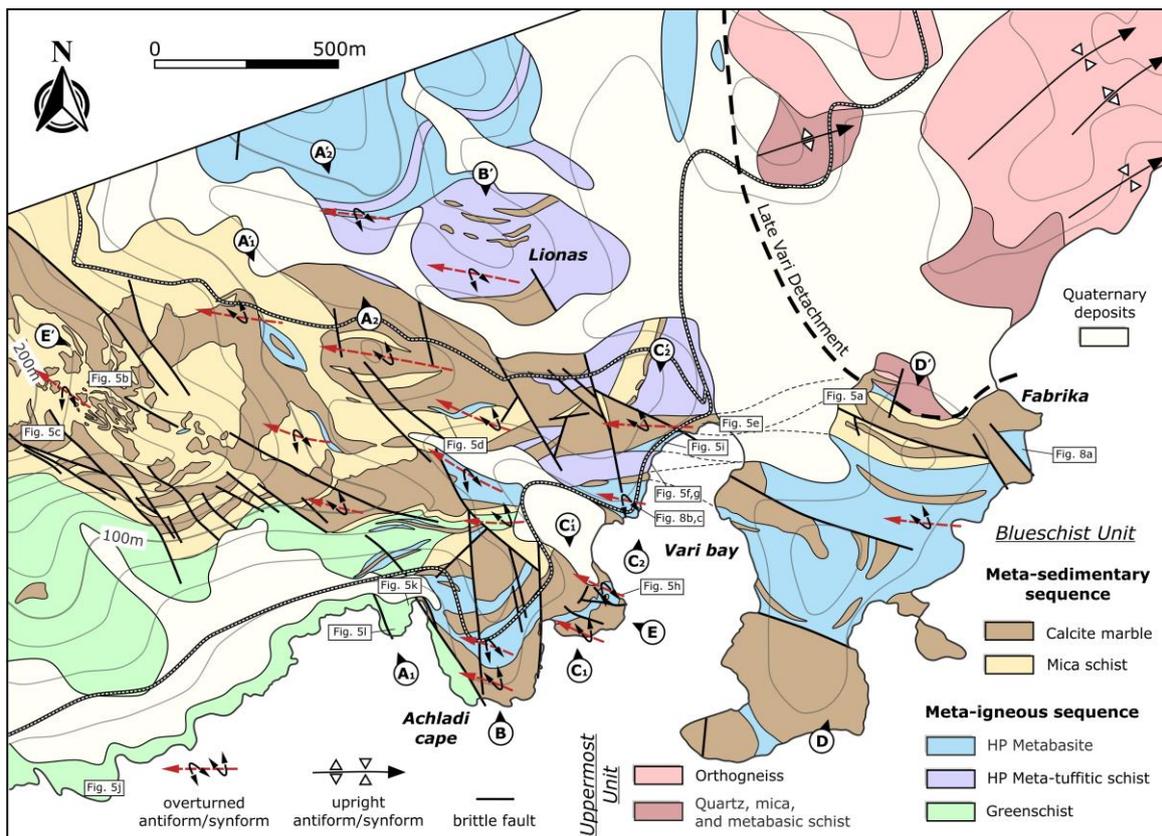


Figure 2. The new geological/structural map of SE Syros showing the major rock groups and the orientation of map-scale fold axes of the main deformation phase recognized in the study area. The location of the map is given in Figure 1. Lettered sections A1-A1', A2-A2', B-B', C1-C1', C2-C2, D-D', and E-E' refer to the composite cross-sections in Figure 3. The locations of the outcrop-scale photographs illustrated in Figures 5 and 8 are also shown.

A key area to address all the above-mentioned controversies about the structural evolution and exhumation of the Blueschist Unit is the southeastern part of Syros Island, where the entire structural/metamorphic pile of the island is exposed in a restricted area (Figure 1a, b). In addition, in this area, the presence of a series of extensional detachment faults has been suggested [9] (Figure 1a, b). According to Laurent et al., [9], exhumation-related deformation progressively localized toward the base of the Blueschist Unit, synchronous with the transition from eclogite/blueschist to greenschist facies conditions, along large-scale ductile detachment faults, allowing the preservation of HP rocks towards the higher structural levels of the unit. Therefore, SE Syros area represents a key locality to study the exhumation-related structures to discriminate among the different modes of exhumation of the Blueschist Unit.

In this work, the geometry and kinematics of the HP rocks on SE Syros were described through detailed geological and structural re-mapping on a scale of 1:5000 as well as detailed structural analysis. The purpose of this study is twofold: on the one hand to shed light to the currently controversial structural evolution of the HP rocks exposed on Syros and on the other hand to investigate the exhumation processes that controlled the preservation of these HP rocks.

2. Geological and structural setting

Rocks exposed on Syros Island belong to the nappe stack of the Cycladic Massif, which originated during the Hellenides formation in Eocene-Oligocene times (e.g., [20]) (Figure 1a: inset). The Cycladic Massif comprises a nappe pile composed of the lower Basal Unit, the intermediate Blueschist Unit, and the higher Uppermost Unit. Syros Island is composed of rocks belonging to the Blueschist Unit, with the only exception its SE part, where rocks of the Uppermost Unit are also exposed (Figure 1a). The Blueschist Unit generally consists of calcite marble, mica/calcite schist, eclogite and blueschist, meta-tuffitic schist as well as greenschist and paragneiss (Figure 1a) (e.g., [2,12]). The Uppermost Unit (i.e., Vari Unit) is represented by a sequence of quartz, mica and metabasic schists overlaying by felsic orthogneiss [11] (Figure 1a). Several studies have attempted to subdivide the Blueschist Unit on Syros into distinct subunits based on lithological, metamorphic, geochronological, and structural criteria (e.g., [9,13,19,21]) (Figure 1b). Regardless of the suggested number of subunits and their formation conditions, all studies agree that the imbrication and formation of distinct subunits within the Blueschist Unit occurred during the exhumation of the rocks from eclogite to greenschist facies conditions.

Within the Blueschist Unit, metamorphic peak conditions have generally been estimated at 1.5-2.3 GPa and 500-550°C (e.g., [1,6,22,23]). Available geochronological data reveal that peak conditions were attained at 55-40 Ma (e.g., [13,21,24,25,26]). Retrograde blueschist facies metamorphism dated at ~50-40 Ma took place at ~450-500 °C (e.g., [13,27,28]), whereas retrogression in greenschist facies conditions observed mainly in the southern part of Syros, has been dated at 35-18 Ma [22,29].

In terms of deformation, the Blueschist Unit on Syros Island has been affected by a main deformation phase mainly expressed by a penetrative foliation, which dips generally towards NW to NE. This foliation is axial planar to generally NE-SW oriented tight to isoclinal folds, whereas it contains a well-developed lineation defined mainly by aligned blueschist facies minerals (Figure 1a) (e.g., [2-5,9,13,30,31]). The lineation varies in orientation from more NE-SW in the north to E-W in the central and more NW-SE in the south part of the island (e.g., [9,30,32]). In turn, a temporal variation in lineation orientation, from (W)NW-(E)SE at deep subduction levels to (W)SW-(E)NE during exhumation has recently been reported from north Syros [12].

Structures formed during the main deformation phase have been linked to thrusting and multiple tectonic repetitions of meta-sedimentary and meta-igneous rocks that took place at deep subduction levels close to peak conditions (e.g., [4-6,12]). In this case, greenschist facies retrogression of the rocks in southern Syros is assumed to be a static process [33-35]. In contrast, other authors have suggested that the main deformation phase is exclusively associated with the exhumation of the rocks from eclogite to greenschist facies conditions either under net extension or net compression [3,9,10,13,36]. In the first case, it is suggested that the rocks were exhumed via a series of (E)NE-dipping extensional detachment faults, i.e., Vari, Kastri, and Achladi detachment faults [9] (Figure

1a, b). In the second case, it is considered that the rocks were exhumed via a mechanism of wedge/ductile extrusion(s) between a basal thrust and an upper normal-sense detachment operating under an overall compressional tectonic setting (e.g., [11,13]). According to Aravadinou & Xypolias (2017) [11], the Vari Detachment represents the roof fault of a NE-directed extrusion indicating opposite top-to-SW shearing. In turn, other authors suggest NE-directed shearing for the Vari Detachment, which is linked with a SW-directed extrusion [13,36].

Throughout the marbles on Syros, the penetrative occurrence of columnar coarse-grained calcite, which is oriented at high angles to both main foliation and axial planes of isoclinal folds, has been reported [5,7,12,37]. This columnar microstructure, interpreted as pseudomorphs after aragonite, postdates the main deformation fabrics and was formed within the stability field of aragonite under nearly static conditions [12,37]. The extensive occurrence of this microstructure indicates that deformation was weak or absent during exhumation at greenschist facies conditions [12].

3. Results

Detailed geological and structural mapping enable us to produce an updated geological / structural map for SE Syros at a scale of 1:5000, which significantly improves previous ones [2,9]. The new map is illustrated in Figure 2. Mapping results coupled with field-based structural analysis led us to unravel the deformation history of the Blueschist Unit. These results are synthesized in a series of cross-sections (Figure 3) depicting the structural architecture and the main deformation features of the study area. Mapping and structural results are described in detail in the following subsections.

3.1. Mapping results

Geological mapping revealed that the Blueschist Unit in SE Syros can be subdivided into two main sequences, the meta-sedimentary and the meta-igneous sequence. Rock groups presented in this study are in general accordance with the categorization of Keiter et al. (2011) [2]. The meta-sedimentary sequence consists mainly of two main rock groups: (a) calcite marble with non-mappable dolomitic marble layers / lenses and bands of calcite and mica schist of a few centimeters up to ca. 5 meters in thickness, and (b) mica schist, which is alternated in outcrop to map-scale with calcite and quartz schist (Figure 2). Generally, the contacts between different schists are blurred and, in some cases, gradational, whereas calcite schists typically occur close to the contact with calcite marbles. It is noted that diagnostic minerals of eclogite-/ blueschist-facies metamorphism such as blue amphibole and garnet are typically present in the main parageneses of mica schist rock group. In turn, the meta-igneous sequence is composed of three rock groups: (a) HP metabasite, (b) HP meta-tuffitic schist, and (c) greenschist (Figure 2). HP metabasite consists of eclogite, glaucophanite and blueschist alternated in outcrop scale. Eclogite typically occurs as lenses / pods within glaucophanite / blueschist. In a few cases, eclogite and glaucophanite pods were recognized within calcite schist close to contacts with calcite marble. HP metabasites are commonly characterized by minor presence of retrograde minerals such as chlorite, epidote, and green amphibole. HP meta-tuffitic schist is composed of banded mafic and felsic layers alternating on a centimeter to several meters. Mafic bands typically contain blue amphibole and garnet, whereas felsic bands are composed of feldspar, quartz, and white mica. Greenschist group comprises mainly greenschist, epidote schist, albite-bearing greenschist, epidotite, and minor chlorite schist. Locally (e.g., west of Achladi cape), bands of quartzofeldspathic schist and felsic gneiss up to ca. 3 meters thick are interleaved with greenschist and epidote schist (Figure 2). These alternations seem to be the retrograde equivalent of the HP meta-tuffitic schist rock group. In accordance with previous studies [11], the Uppermost Unit is mainly represented by orthogneiss and quartz, mica and metabasic schist (Figure 2).

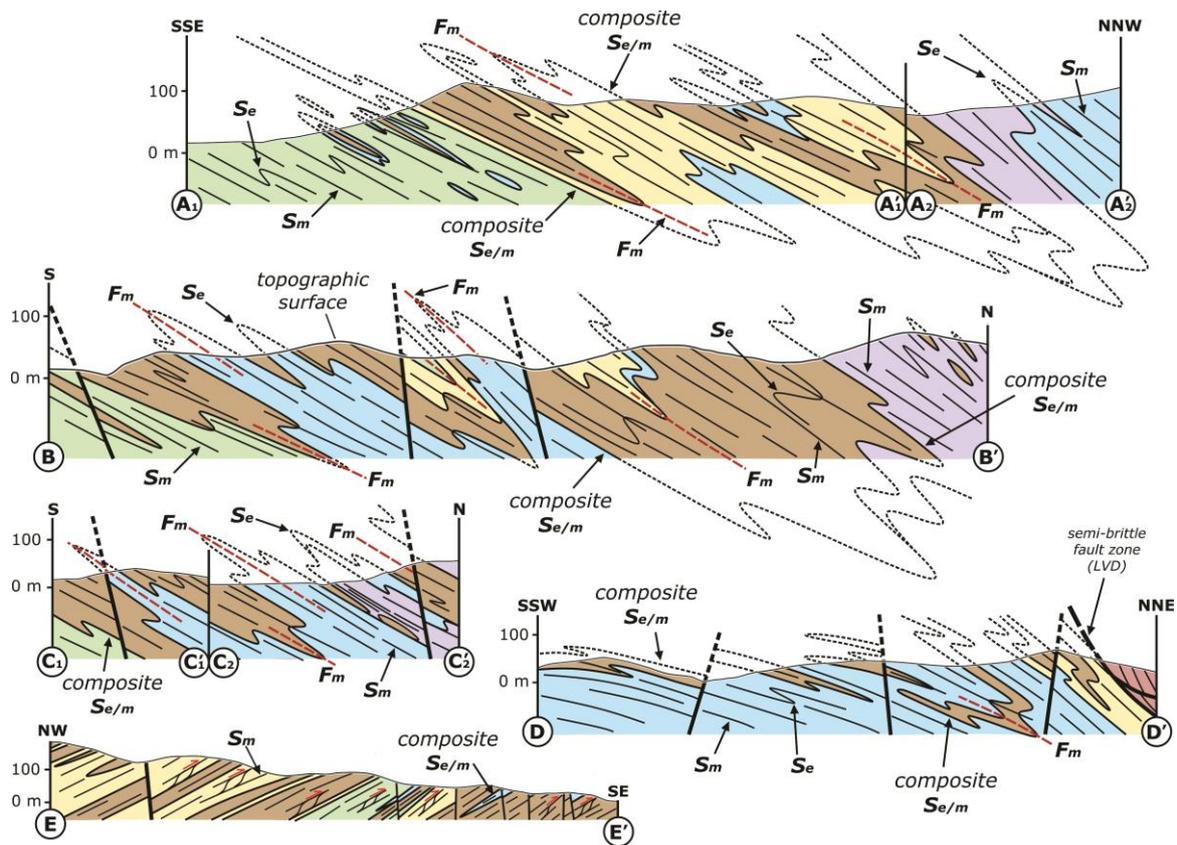


Figure 3. Composite cross-sections (A1-A1', A2-A2', B-B', C1-C1', C2-C2, D-D', E-E') depicting the internal structural architecture of the Blueschist Unit in SE Syros. Locations of the individual cross-sections are shown in Figure 2.

The larger part of the study area is occupied by rocks of the Blueschist Unit, whereas Uppermost Unit is restricted on its northeastern part. Specifically, the meta-sedimentary sequence mainly occupies the central part of the study area defining roughly a (W)NW-trending zone (Figure 2). Along this zone, rocks of the meta-sedimentary sequence are dominant towards the NW with only minor mappable exposures of meta-igneous rocks, whereas moving southeastwards, larger exposures of rocks of the meta-igneous sequence are recorded (Figure 2). Rocks of the meta-igneous sequence generally occupy the northern and southwestern part of the map (Figure 2). Specifically, HP metabasite and HP meta-tuffitic schist are mainly observed in the northern part, whereas greenschist rock group typically occurs in the southwestern part of the study area. Note that occurrences of outcrop to map-scale well-preserved HP metabasites were recorded within greenschists implying that these rocks were escaped the greenschist facies retrogression (Figures 2 and 3). Typically, contacts between the two sequences and between individual rock groups are not sharp and straight showing an interfingering pattern (Figure 2).

3.2. Structural analysis

Structural analysis reveals that rocks of the Blueschist Unit are affected by a main deformation phase (D_m). A common structural feature of the D_m is the abundant occurrence of close to isoclinal folds (F_m) (Figure 3). F_m folds are observed in various scales from outcrop to map-scale deforming an early S_e foliation, which is mainly recognizable in the fold hinges (Figures 3, 4a, b and 5a-l). Throughout the area, F_m folds deform the contact between the two main rock sequences as well as the contacts between different rock groups (Figures 3 and 4). Note that F_m folds are also observed within the greenschist group in the southwestern part of the study area (Figures 2, 3 and 5j-l). F_m folds are responsible for the extensive repetitions, from outcrop- to map-scale, of the rocks belonging to

the meta-sedimentary and the meta-igneous sequence. As a result, the meta-igneous rocks can be observed structurally below and above rocks of the meta-sedimentary sequence (Figures 3 and 4b).

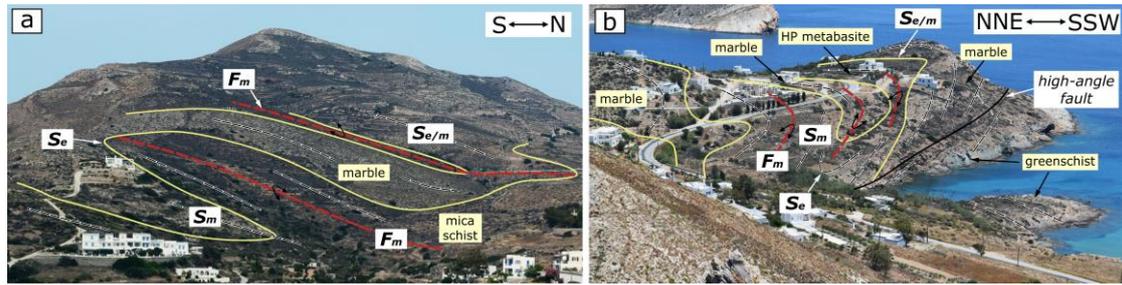


Figure 4. (a, b) Panoramic view showing major D_m -related structures and fabrics that deform (a) marbles and mica schists of the meta-sedimentary sequence and (b) the early contact between the meta-sedimentary and meta-igneous sequence; in both photographs the field of view is 0.5 km wide.

Several F_m folds were mapped based on marker horizons (i.e., rock contacts) and the vergence of associated outcrop-scale parasitic folds (Figures 2 and 3). Map-scale F_m folds vary in tightness from tight to isoclinal, whereas they trend generally WNW-ESE with moderately inclined axial planes (Figures 2 and 3). They have commonly distinct patterns of long limb - short limb asymmetry displaying mainly S-shaped geometry when they viewed towards the west, whereas Z-shaped geometry is locally observed in the northern part of the study area (Figure 3). This pattern of F_m folds is linked with a major F_m synform which displays an S-shaped geometry looking towards the west (Figure 3). This map-scale structure is linked with several outcrop-scale parasitic F_m folds. These folds generally have shallow to moderately (mean plunge 40°) W- to NW-plunging axes, with a mean WNW orientation (mean orientation 295°) (Figure 6a). F_m fold axial planes dip typically moderately (mean dip 45°) towards NW (mean orientation 310°) (Figure 6b). F_m folds are characterized as moderately inclined to reclined in style since, in several outcrops, the pitch of the hinge line on the axial plane is more than 80° [38].

The main D_m phase is also characterized by the development of an S_m planar fabric, which is typically axial planar to F_m folds (Figures 3 and 5). S_m varies from a crenulation cleavage to a mylonitic foliation, but it is typically observed as a well-developed foliation. However, in competent lithologies such as eclogites or within rocks that were not strongly affected by D_m phase, S_m is weakly developed or absent (Figure 5c, i). S_m dips generally moderately towards NW to N, with the trajectories displaying, in map-view, a generally NE-SW orientation (Figures 6c and 7a). However, in various locations, S_m is characterized by a more E-W orientation. Based on the rock type, the S_m foliation is typically defined by mineral aggregates such as quartz, calcite, epidote, and omphacite as well as by pervasive alignment of blue amphibole and white mica flakes.

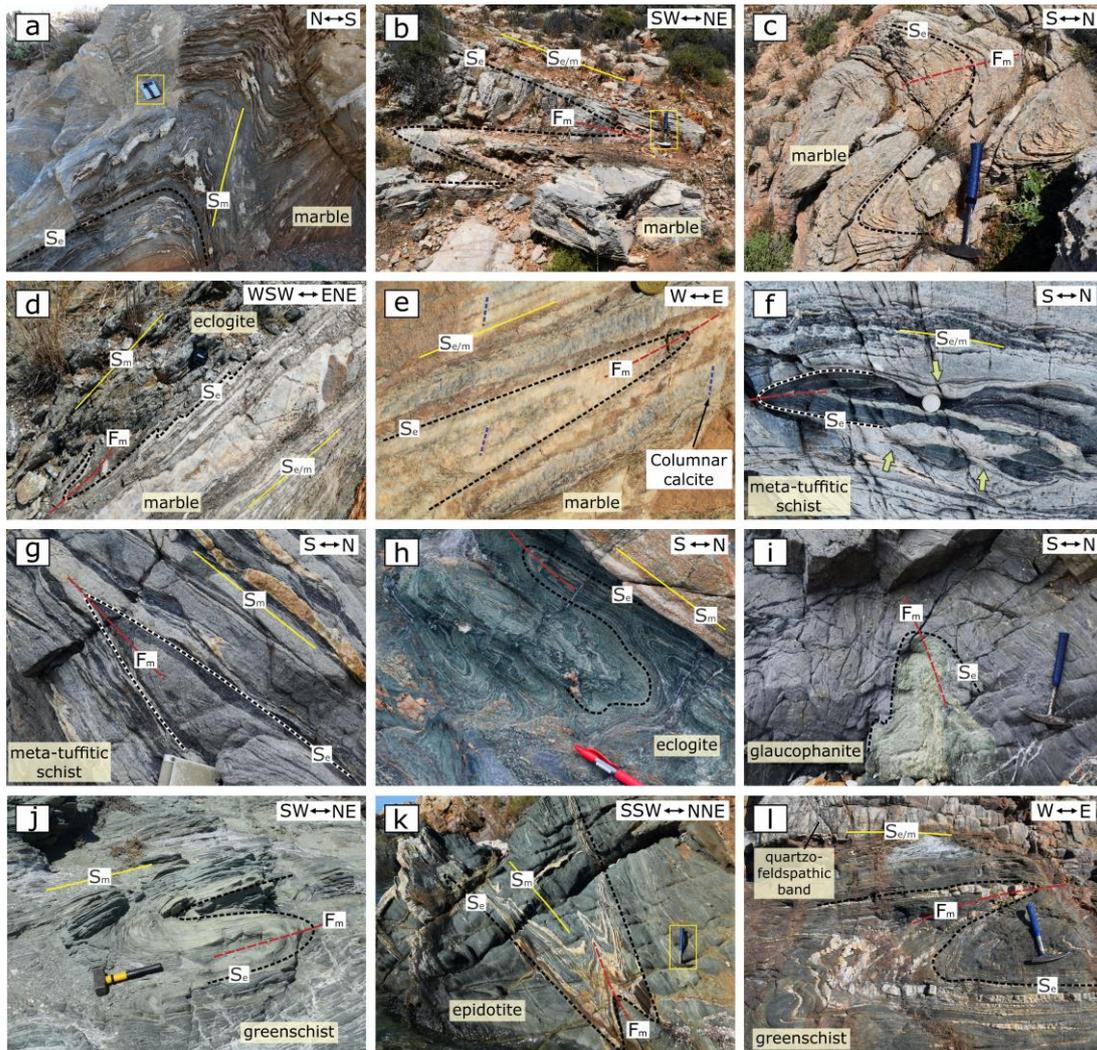


Figure 5. (a-l) Photographs of D_m structural fabrics recognized within each rock type and their relationship with the earlier D_e structures. (a-c) S_e foliation is deformed by close to isoclinal F_m folds within marbles. (d) F_m folds define the contact between marble and eclogite. (e) Marble displaying columnar calcite grains that oriented at high angles both to $S_{e/m}$ foliation and axial plane of isoclinal F_m fold. (f-g) Isoclinal F_m folds deforming the S_e foliation within meta-tuffitic schists; eclogite defining the S_e foliation is folded by F_m isoclinal folds (f). Green arrows in (f) indicate boudinage of the isoclinally folded eclogite. (h-i) F_m folds deforming the early S_e foliation within eclogite (h) and glaucophanite (i). (j-l) F_m folds and axial planar S_m foliation within greenschist (j), epidotite (k), and greenschist with bands of quartzofeldspathic schist and felsic gneiss (l).

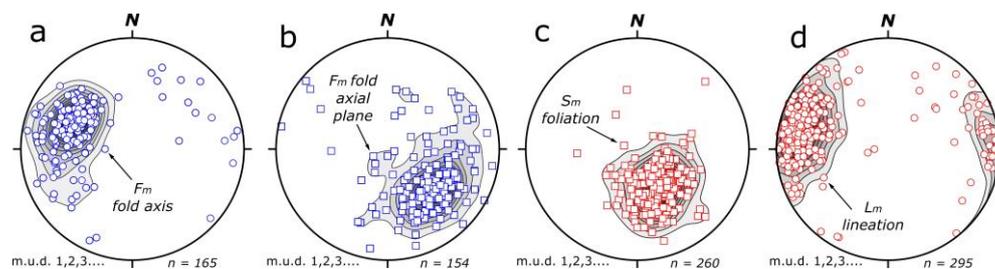


Figure 6. Stereoplots (lower-hemisphere, equal-area projections) of structural data of the main deformation phase (D_m) recognised in SE Syros showing (a) F_m fold axis, (b) pole to F_m fold axial, (c) pole to S_m foliation and (d) L_m lineation; m.u.d., multiples of uniform distribution.

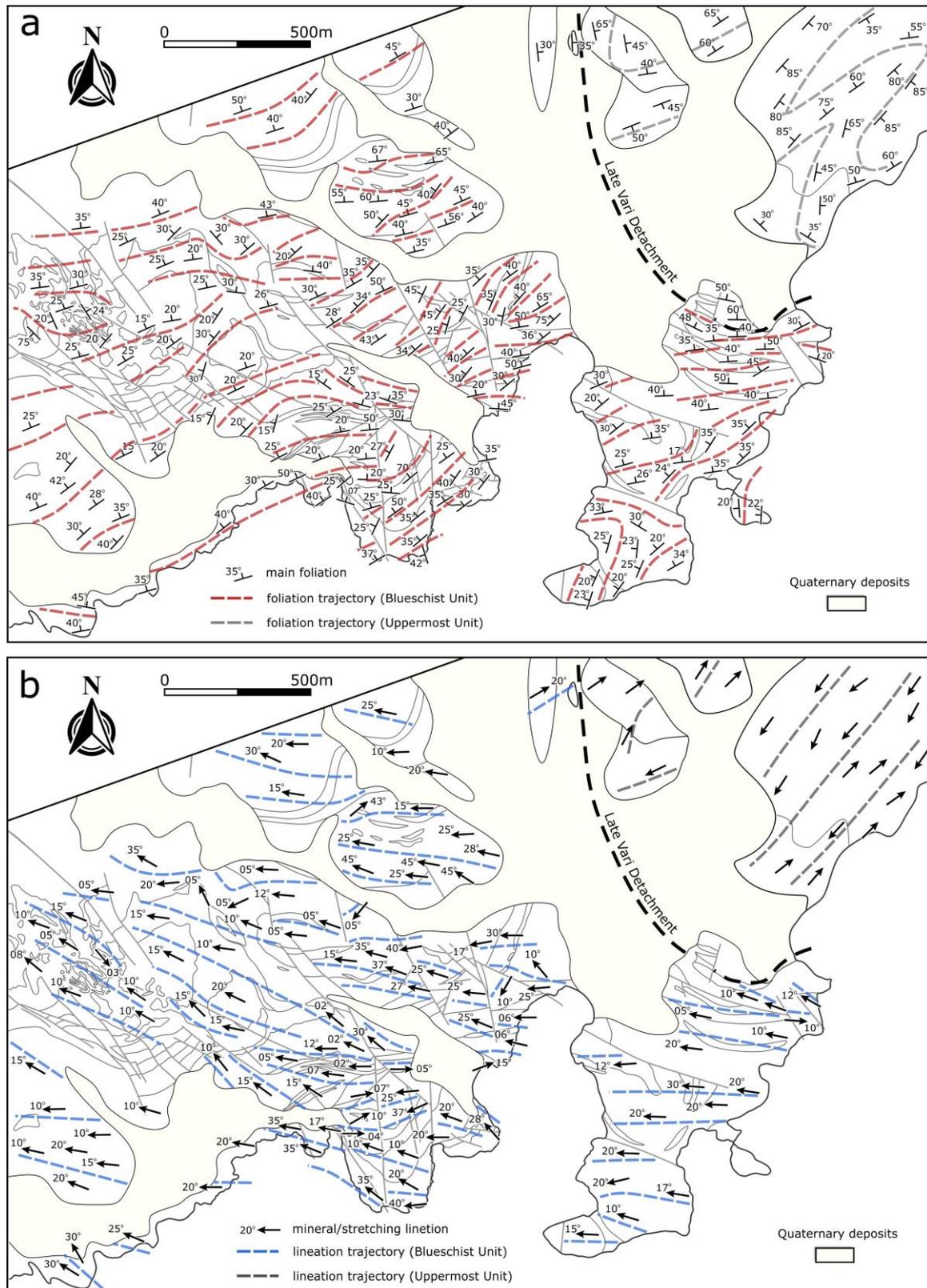


Figure 7. Trajectory maps of the main (a) foliation and (b) lineation recognized within the Blueschist and the Uppermost Unit in SE Syros.

The S_m clearly transposes the early S_e foliation within F_m hinge zones, whereas on the limbs of tight to isoclinal folds both S_m and S_e are indistinguishable from one another due to their coplanarity and, thus, they are considered as a composite $S_{e/m}$ foliation (Figures 3 and 5). This composite $S_{e/m}$

foliation typically marks the contacts between different rock types as well as the contact between the meta-sedimentary and meta-igneous sequence (Figure 3). In close F_m folds, S_m is aligned with the axial planes transposing the early S_e foliation both in the fold hinges and limbs (Figure 5a). Within the S_m foliation planes, a well-developed mineral/stretching lineation (L_m) was recognized. L_m lineation is also recognized within the composite $S_{e/m}$ foliation planes, revealing that the S_e foliation has been reused by the D_m deformation. Within both S_m and $S_{e/m}$, L_m is defined by aligned blue amphibole needles, streaky micas, and epidote, quartz, and calcite aggregates. L_m mainly plunges shallowly to moderately towards W to NW with a mean plunge 20° toward 290° (Figure 6d) oriented subparallel or at small angles to the F_m fold axes (Figure 6). In a few sites, a NE-trending mineral/stretching lineation coexisting with the dominant WNW-trending lineation is also recorded. This secondary lineation orientation is defined by the same minerals as the main L_m lineation orientation. On the map, L_m lineation orientation does not present any significant spatial variation presenting a general W- to NW-trending orientation (Figure 7b).

As mentioned above, intensity of S_m varies from a crenulation cleavage to a mylonitic foliation. Mylonites typically display a few meters thickness observed in various structural levels and within all rock groups, whereas they do not systematically define the contacts between different lithologies. Also, it is noted that there is no significant localization of D_m within the greenschist rock group. In sites where S_m is well-developed to mylonitic, a variety of shear sense indicators were recorded including typically C- and C' type shear bands, sigmoids, and garnet porphyroclasts (Figure 8a–c). These indicators display a consistent top-to-ESE to E shearing. An opposite top-to-WNW shearing is observed in only one site within meta-tuffitic schists located at the coastline west of the Vari bay.

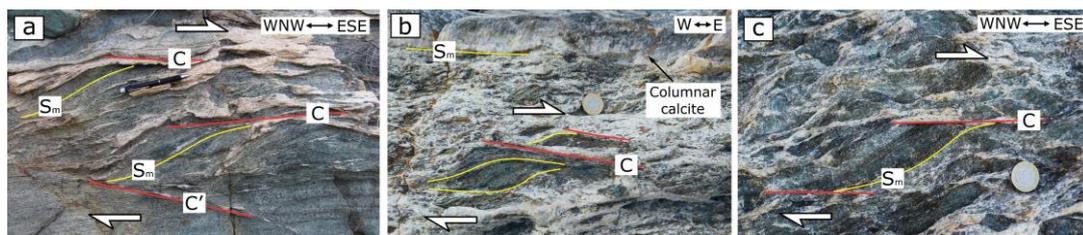


Figure 8. Representative photographs of D_m kinematic indicators showing consistent top-to-the-ESE sense of shear. Location of the photographs is shown in Figure 2.

Structures of the main D_m deformation phase are, locally, overprinted by boudinages and semi-ductile to brittle shear bands displaying asymmetry towards NE. These structures were recorded within all rock groups of the meta-igneous sequence as well as within calcite marbles (Figure 5f). Also, it is noted that, throughout the study area, calcite marbles are characterized by the presence of columnar calcite oriented at high angles to both the S_m foliation and the F_m axial planes (Figures 5e and 8b). Finally, all the above-mentioned ductile structures were affected by high-angle brittle faults, which strike mainly NW-SE and display typically strike-slip or normal movements (Figures 2 and 3) (see Keiter et al. (2011) [2] for a detailed description).

Our results from the structural analysis of the Uppermost Unit are in accordance with previous work [11]. Specifically, orthogneisses are manifested by outcrop- to map-scale cylindrical folds, which deform the main foliation (Figure 7a). These folds are commonly upright and show open to close geometries. The fold hinges typically plunge moderately towards the NE, while the associated axial planes strike NE-SW (Figure 2). A strongly developed stretching lineation trending NE-SW parallel to the fold hinges and is also observed (Figure 7b). Lineation is oriented almost perpendicular to the L_m lineation recorded within the underlying Blueschist Unit (Figure 7b). The contact between Uppermost and Blueschist units were observed near Fabrika area, and it is marked by a major semi-brittle to brittle fault zone, the Late Vari Detachment, as has also been described by Aravadinou & Xypolias (2017) [11] (Figures 2 and 3).

4. Discussion

4.1. Synthesis

Geological / structural mapping revealed that the rocks exposed at the southeast part of Syros Island can be grouped into two main sequences, based on the lithology's protolith, the meta-sedimentary and the meta-igneous sequence (Figures 2 and 3). The meta-sedimentary sequence consists of calcite marble and mica schist, whereas the meta-igneous sequence composed of HP metabasite, HP meta-tuffitic schist, and greenschist. Greenschists were included in the meta-igneous sequence since they are mainly represented by metabasic rocks locally characterized by alternations with quartzofeldspathic / gneissic bands, which are possibly equivalent of the HP meta-tuffitic schists occurred in the northern part of the area. Also, locally within the greenschists, HP metabasic rocks were preserved revealing that this group was also originally metamorphosed under blueschist facies conditions. Rocks of the meta-sedimentary sequence roughly define a (W)NW-trending zone, which widens towards the NW, surrounded by rocks of the meta-igneous sequence (Figure 2). In map-view, the repetition of the two sequences combined with the observed interfingering pattern of the rocks should be controlled by folding (Figures 2 and 3).

Restoration of the nappe stack recorded in SE Syros showed an original tectonostratigraphic succession in which the meta-igneous is overlain by the meta-sedimentary sequence (Figures 3 and 9a). This relationship between the meta-sedimentary and meta-igneous sequences could be either primary or the result of tectonic emplacement during D_e or even an earlier deformation phase. Although it is difficult to draw a safe conclusion, it seems that the first possibility is more plausible since there is no strong evidence for an increasing strain gradient towards the contact between the two sequences (Figure 9a). Structural analysis indicates an early S_e foliation recognizable in rocks of both sequences including eclogites (Figure 9a). Considering that the subsequent main D_m phase operated within blueschist facies conditions, and it is related with folding and transposition of the S_e foliation in eclogites, the S_e foliation should have been formed within eclogite to blueschist facies conditions, which, according to the available metamorphic data (e.g., [28]), corresponds roughly to peak conditions (Figure 9: PT diagram).

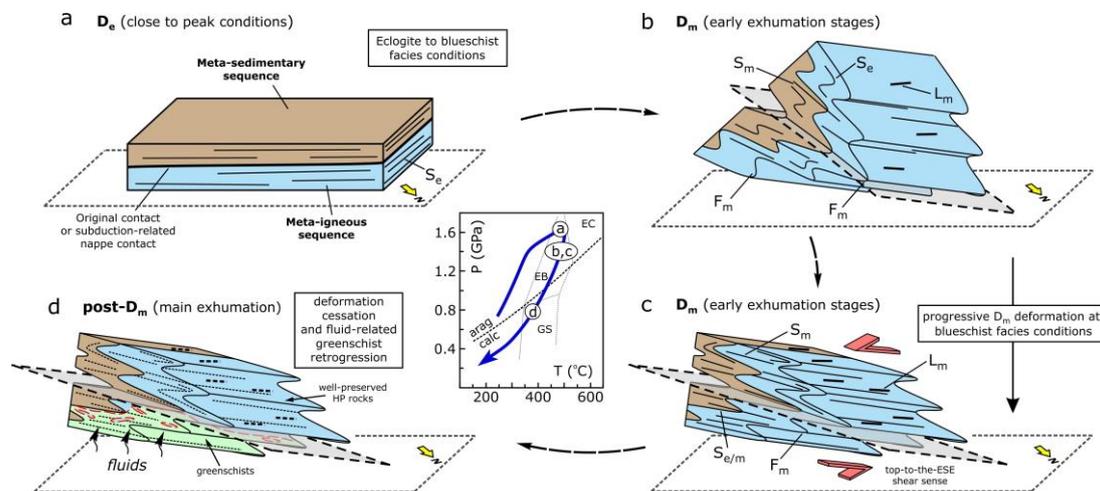


Figure 9. Block diagrams showing the tectono-metamorphic evolution of the Blueschist Unit in SE Syros. (a) The meta-igneous sequence was overlain by the metasedimentary sequence close to peak at eclogite/blueschist facies conditions. (b) Development of F_m folds and (c) development of penetrative S_m foliation and L_m lineation associated with ESE-directed shearing at blueschist facies conditions during the early stages of exhumation. (d) Cessation (static conditions) of deformation at blueschist facies conditions and exhumation of the rocks to greenschist facies conditions as a rigid body. Retrogression at greenschist facies conditions observed in the lower structural levels of the succession was likely controlled by fluids rather than by intense deformation. P-T diagram (after [28]) showing the potential conditions of each recorded deformation phase within the Blueschist Unit in SE Syros.

The original succession displaying the early S_e foliation was folded by map-scale moderately inclined to reclined (F_m) folds oriented (sub)parallel to WNW-trending mineral/stretching lineation (L_m). These folds are associated with a major synformal structure, which deforms the early contact between the meta-sedimentary and the meta-igneous sequence (Figures 3 and 9b). The meta-sedimentary sequence occupies the center of the map-scale synform, whereas rocks of the meta-igneous sequence occur roughly structurally below and above rocks of the meta-sedimentary sequence. Outcrop-scale F_m folds are linked with the development of an axial planar S_m foliation, which transposes or is coplanar to the early S_e forming a composite $S_{e/m}$ foliation (Figure 9c). S_m , composite $S_{e/m}$ and L_m are defined, among others, by blue amphibole needles, whereas well-developed to mylonitic S_m is associated with a consistent top-to-the E(SE) shearing (Figure 9c). A similar sense of shear has also been reported from mylonitic rocks in north Syros as well as in other Cycladic Islands such as Evia, Sifnos and Andros interpreted to occur under blueschist facies conditions during peak to early stages of exhumation [12,16,18,39]. Similar to these studies, D_m deformation in SE Syros should have occurred at the early stages of exhumation under blueschist facies conditions. This is also supported by the extensive preservation of columnar calcite grains within calcite marbles throughout the study area. Growth of this columnar microstructure has been interpreted to occur within the aragonite stability field during (nearly) static conditions (see also [12,37,40]) revealing that D_m phase should have ceased when the rocks were still within blueschist facies conditions (Figure 9: PT diagram). Preservation of this columnar microstructure within marbles indicates that deformation was very weak or absent during exhumation of the rocks from blueschist to greenschist facies conditions (see also [7,12,37]) (Figure 9d). Our observations showed that the weak post- D_m phase should be locally expressed by top-to-(E)NE asymmetric boudinage and shear bands formed within blueschist to greenschist facies conditions (see also [35]).

A series of evidence suggest that the retrogressed greenschists recorded in the southwestern part of the study area were not formed under intense deformation and strain localization at greenschist facies conditions, but they share a common deformation history with the well-preserved HP rocks (Figure 9d). 1) Extensive occurrence of columnar calcite within mappable to outcrop-scale marble exposures which are in contact with greenschists; if greenschist retrogression was related to intense deformation, then columnar calcite should be obliterated due to dynamic recrystallization. 2) Absence of both S_m or post- S_m mylonites and strain localization at the contact between rocks of the meta-sedimentary sequence and greenschists. 3) Preservation of the D_m structures and fabrics orientation (i.e., foliation, lineation, and fold axis orientation) within greenschists. 4) Abundant presence of preserved blue amphibole needles defining the lineation within greenschists. This evidence indicates that retrogression within greenschist facies conditions probably took place under nearly static conditions rather than under intense deformation. Thus, the transition from blueschists to greenschists was likely controlled by other factors such as presence of fluids as has also been proposed by previous studies [34,35] (Figure 9d).

4.2. Exhumation mode of the Blueschist Unit

Our results from SE Syros indicate that the Blueschist Unit was affected by a distributed pervasive deformation (D_m) linked with an ESE-directed shearing that was operated at blueschist facies conditions during the early exhumation stages. Subsequent main exhumation of the rocks from blueschist to greenschist facies conditions was associated with very weak or absence of deformation; note that the greenschist retrogression observed in the lower structural levels of the Blueschist Unit was likely controlled by the presence of fluids under static conditions. Similar results have recently been reported for the Blueschist Unit at the northern part of the Syros Island [12] implying that the Blueschist Unit throughout the island was exhumed from blueschist to greenschist facies conditions without significant internal deformation. Overall, our results suggest that the Blueschist Unit was initially exhumed under intense ESE-directed distributed deformation at blueschist facies conditions, whereas its main exhumation from blueschist to greenschist facies conditions was took place without significant internal deformation as a nearly rigid body. This exhumation-related deformation pattern is in contrast with models suggesting that the exhumation of the Blueschist Unit was associated with

a single deformation phase that was progressively operated from eclogite to greenschist facies conditions forming a series of extensional detachment faults [9,10]. In turn, our proposed deformation pattern could fit well with a mechanism of extrusion wedge as has also been suggested for the exhumation of the Blueschist Unit in several studies for Syros and other Cycladic areas (e.g., [11,13,16,18,19]). The well-preserved HP rocks of the Blueschist Unit on Syros should occupy the core of the extrusion wedge since it is well-documented that the extrusion-related deformation is typically concentrated at the bounding faults of the wedge (Figure 10) ([41], and references therein; [16]). This conclusion is also supported by the deviation between the structures orientations recorded within the Blueschist and the Uppermost Unit. Specifically, the dominant ESE-WNW orientation recorded within the Blueschist Unit is almost normal to the NE-SW orientation observed in the rocks of the Uppermost Unit ([11]; this study). NE-SW orientation within the Uppermost Unit has been linked with the NE-directed extrusion of the Blueschist from blueschist to greenschist facies conditions (main exhumation) [11]. Dominant ESE-directed shearing recorded within the rocks of the Blueschist Unit in SE Syros implies that they have not recorded the deformation associated with the main exhumation of the unit further supporting the assumption that these rocks were exhumed as a nearly rigid body from blueschist to greenschist facies conditions. Therefore, our results in combination with previous studies in Cycladic islands indicate that the Blueschist Unit was exhumed via a ductile extrusion at the early exhumation stages, whereas their main exhumation, from blueschist to greenschist facies conditions, was achieved by wedge extrusion.

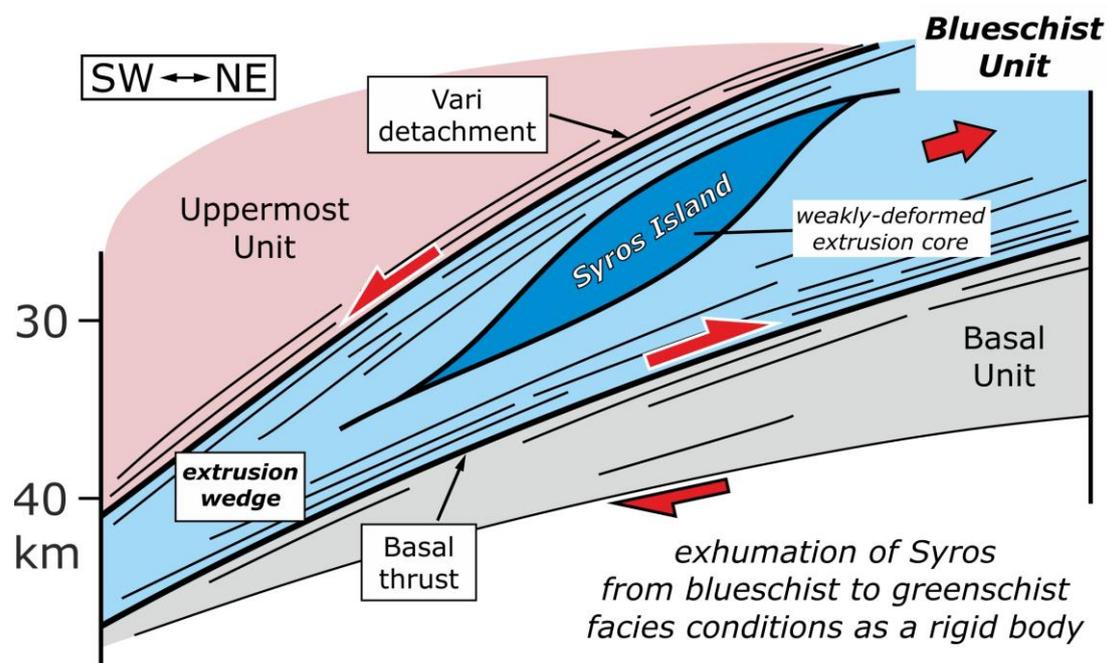


Figure 10. Proposed tectonic model for the main exhumation of the Blueschist Unit from blueschist to greenschist facies conditions. Well-preserved HP rocks of Syros Island likely occupy the weakly-deformed core of the extrusion wedge.

5. Conclusions

Detailed geological/structural mapping and field-based structural analysis within the Blueschist Unit in SE Syros area enabled us to draw the following conclusions:

- (1) Geological mapping revealed the occurrence of two main rock sequences, a metasedimentary underlain by a meta-igneous sequence, the contact of which displays an interfingering pattern on the map.
- (2) The earlier ductile deformation (D_e) is linked to a penetrative foliation, which was formed at the deep subduction levels under eclogite/blueschist facies conditions.
- (3) The main deformation D_m operated at blueschist facies conditions synchronous with the early stages of exhumation of the high-pressure rocks. This phase is associated with the formation of map-scale folds that trend subparallel to a WNW-plunging lineation as well as with an axial planar foliation, which is typically related to an ESE-directed shearing.

- (4) During the main exhumation of the rocks from blueschist to greenschist facies conditions, deformation was weak or absent.
- (5) Greenschist retrogression observed in the southwestern part of the mapped area seems to be controlled by fluids rather than by intense deformation at greenschist facies conditions.
- (6) Well-preserved HP rocks of the Blueschist Unit exposed on Syros Island represent a large-scale pod of low deformation under blueschist to greenschist facies conditions, which occupy the core of an extrusion wedge.

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