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Key Points:

- Structures are interpreted to reflect forced return flow in subduction channel
- Structures in high-pressure and greenschist-facies rocks indicate sustained lithospheric shortening
- New and novel interpretation of subduction-related structures in Cycladic Blueschist Unit

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Forced Return Flow Deep in the Subduction Channel, Syros, Greece

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Abstract We present the results of a detailed structural study in the Cycladic Blueschist Unit at Fabrika on Syros Island, Greece, and discuss their significance for tectonic processes at the subduction interface. Some samples record top-to-the-west shear reflecting prograde (burial), peak high-pressure (HP) and initial decompression (exhumation) conditions. Other nearby samples record top-to-the-east shear during HP metamorphism and exhumation. Some rocks re-equilibrated at greenschist-facies conditions and record top-to-the-west shear. Greenschist-facies top-to-the-west shear is also found at the base of non-HP upper units above the Fabrika HP sequence. We interpret the HP structures to reflect forced return flow and incipient formation of an extrusion wedge in the subduction channel. The HP top-to-the-west structures resulted from thrusting along the base of the wedge and started to form during burial before the rocks reached their deepest point. The HP top-to-the-east structures reflect deformation near the top of the developing extrusion wedge. After considerable exhumation during ongoing subduction, out-of-sequence, top-to-the-west thrusts emplaced the non-HP upper units above the exhuming extrusion wedge ~10 Myr after the wedge initially formed. Our work suggests that the HP rocks were considerably exhumed during sustained lithospheric shortening in the subduction channel by forced return flow. Because return flow is controlled by the velocity of the subducting slab, it may explain why HP rocks can be exhumed at subduction rates. On the regional scale we find that four distinct HP belts were sequentially accreted and exhumed between ~50 and 20 Ma suggesting continuous subduction-channel return flow in the Hellenic subduction zone.

1. Introduction

Direct field observations of exhumed subduction complexes show that the plate boundary, or plate interface, is a fault or shear zone of variable thickness (Vannucchi et al., 2012; Agard et al., 2018) that has a low shear strength (Tackley, 2000). Vannucchi et al. (2012) described the plate interface as being characterized by two tectonic contacts, the upper “roof décollement” and the “basal décollement”. The domain in between both décollements is referred to as the channel (Agard et al., 2018, their Table 1). Depending on the thickness of the plate interface it can either be considered a single fault, the subduction thrust (with possible multiple strands) (i.e., the channel is of negligible width), or a channel, the subduction channel (i.e., the thickness of the channel is distinctly wider than that of the décollements) (Agard et al., 2009; Gerya et al., 2002). De Franco et al. (2007) suggested that the amount of incoming sediment atop the subducting plate controls whether a wider subduction channel or a narrow subduction thrust forms. The sediments are envisaged to act as a lubricating layer facilitating subduction. When the thickness of this sediment layer is small, an appropriate description of the plate interface might be one of a single or several faults. Depending on sediment supply to the subduction zone, a plate interface may change from a single (multiple) discrete thrust(s) to a subduction channel and vice versa (De Franco et al., 2007). Rowe et al. (2013) proposed that the thickness of the shallow plate interface between about 1- and 15-km depth is ~100–350 m. Below 15 km the thickness of the plate interface is largely unknown but might be at the kilometer scale (Agard et al., 2018, their Table 1). The subduction rock record can be used to constrain interplate thickness or geometry, and also to help determine whether the plate interface has a constant width, is tapering downward and decrease to almost zero at great depths, or varies with time at a given depth (Shreve & Cloos, 1986). Field studies may also allow to constrain whether deformation is rather localized on one or multiple faults or shear zones or distributed within a wider subduction channel.

Agard et al. (2009) suggested that the burial, accretion and exhumation of high-pressure (HP) rocks in subduction settings is best explained by a subduction channel rather than a discrete subduction thrust. The

Figure 1. Schematic illustration of forced corner flow in subduction channel. Sediments atop subducting plate form interplate channel-like unit; fluid release during prograde metamorphism drives hydration of mantle wedge above subduction channel; at depth tapering channel geometry forces subducting material into corner triggering return flow. Note that entire setting contractional and lithospheric shortening causes thrusts in overriding plate. Inset shows return-flow-driven extrusion wedge and discrete shear zones with opposing shear senses at bottom and top of wedge as shown for Cyclades by many studies.

subduction channel is considered a narrow zone defined by material that is characterized by a long-term velocity gradient with respect to both plates. It is a widely applied concept in Tectonics for explaining decoupling between the subducting and the overriding plate and tectonic processes along this interface (Agard et al., 2009). The prevailing view is that during subduction the oceanic crust and the overlying sediments are dragged down to considerable depth on top of the subducting plate within a relatively thin subduction channel (Figure 1) (Cloos & Shreve, 1988; Shreve & Cloos, 1986). Based on low seismic velocities, the presence of an interplate, water-rich, channel-like zone of about 1–8 km thickness has been proposed (Abers, 2005; Eberhart-Phillips & Martin, 1999; Oncken et al., 2003; Tsuru et al., 2002).

Burial of rocks in subduction zones and associated prograde metamorphism causes dehydration of the rocks and release of fluids, which are considered to trigger hydration of the mantle wedge above the subduction zone (Cloos & Shreve, 1988). Penniston-Dorland et al. (2018) argued that at, depending on bulk composition and pressure, temperatures of 500–700 °C amphibole and pyroxene form at the expense of the sheet silicates producing drier rocks. Because of this progressive dehydration at increasing depth less fluids are available for the hydration of the mantle wedge and it is likely that the subduction channel becomes narrower downward as illustrated schematically by Gerya et al. (2002, their Figure 3), Agard et al. (2009, their Figure 1), Vannucchi et al. (2012, their Figure 1), Friederich et al. (2014, their Figure 1), and Penniston-Dorland et al. (2018, their Figure 1). In other words, dehydration reactions and mantle hydration control, in part, the shape of a downward tapering channel (Figure 1). Penniston-Dorland et al. (2018) also argued that dry and hence stiff rheologies at HP conditions favor the formation of thick, coherent tectonic units. In this case, the width of the subduction channel would be at the km-scale at depths where HP rocks are largely dehydrated. In contrast, Agard et al. (2018, their Figure 2) considered a nontapering subduction channel that keeps a constant thickness from shallow to deep parts of the plate interface.

Numerical modeling has simulated tectonic processes in the subduction channel (Gerya et al., 2002; Gerya & Stöckhert, 2002). The numerical simulations provide insight into the self-organizing, large-scale flow patterns and temperature field of subduction zones, primarily controlled by rheology, phase transformations, fluid budget, and heat transfer, which are all interrelated. In general, these models describe the subduction channel as a dynamic feature that varies in space and time along the same plate boundary. A common geometry of the models by Gerya et al. (2002, their Figures 4–10 and 12) is a downward tapering subduction

Figure 2. Simplified tectonic map of Aegean Sea region showing major tectonic units of Hellenides, oceanic Vardar-Izmir-Ankara suture zone (red), major thrusts, low- and high-angle normal faults and Cycladic islands referred to in text. Note that Pindos, Tripolitza, and Ionian units considered External Hellenides.

channel that favors forced return flow of low-viscosity material near the bottom of the wedge. The models provide support that exhumation in subduction channels can occur at rates similar to plate velocities.

When a large continental piece (i.e., passive margin or continental block) enters the subduction zone, it may also be dragged by “continental subduction” into the subduction channel, but generally only during a restricted period of time (~10 Myr; e.g., Ernst, 2001; Chopin, 2003). The introduction of major volumes of low-density continental material is thought to be choking subduction, which then stops or steps outboard of the continental block (e.g., Stern, 2004).

One of the first-order problems in geology is that the assumptions, simplifications, and predictions of theoretical considerations and numerical simulations far outstrip field observations and laboratory data. Nature is much more complicated than numerical and scaled analogue material models can simulate. In the Cycladic HP rocks in Greece (Figure 2), the formation of extrusion wedges has been widely proposed. Ring, Gldony et al. (2007) and Ring, Will, et al. (2007) demonstrated simultaneously operating opposite shear senses at the lower, thrust-type, and the upper, normal-type shear zone of the extrusion wedge (inset in Figure 1) and that the latter are typically a few kilometers in thickness and operated for ~10 Myr. Other studies (e.g., Chatzaras et al., 2006; Huet et al., 2009; Peillod et al., 2017; Ring et al., 2011) followed this concept and proposed extrusion wedges in the Hellenic subduction zone. Ring and Yngwe (2018) showed in Crete (Figure 2) that an extrusion wedge was cut by middle/upper crustal out-of-sequence thrusts during exhumation and sustained lithospheric shortening (Figure 1). The previous work suggests that the Cyclades and Crete are excellent examples to study return-flow processes in a subduction channel. Nonetheless, the cited studies largely described exhumation-related (i.e., decompression from a metamorphic point of view) structures. To the best of our knowledge, there is no published direct field evidence of the kinematics of extrusion-wedge-type structures that formed on the way down and at the very bottom, tapering corner of the subduction channel where return flow is being generated.

In this article, we describe deformation structures from HP rocks in South Syros for testing whether these structures might reflect forced return flow near the bottom end of a subduction channel. We argue that the HP structures formed as the material could not subduct anymore because of space problems in the tapering channel and returned up the subduction zone. We then attempt to apply the return-flow model to the larger scale and discuss the exhumation of HP rocks across the Cyclades.

2. Setting

2.1. Hellenides

The Hellenides in the eastern Mediterranean form an arcuate orogen to the north of the Hellenic margin (Figure 2), along which north northeastward subduction of the African plate beneath Eurasia is accommodated. The Aegean Sea region in the Hellenides is a world-class laboratory for studying HP rocks, mainly those of the Cycladic Blueschist Unit (CBU) (e.g., Ague & Nicolescu, 2014).

The Hellenides can be subdivided from top (north) to bottom (south) into (1) the Rhodope-Balkan Zone, (2) the Vardar-Izmir-Ankara Zone, (3) the Pelagonian Zone, (4) the Cycladic Zone, and (5) the External Hellenides (Dürr et al., 1978; Robertson et al., 1991) (Figure 2). In this article we focus on the Cycladic Zone in the central Aegean Sea, which consists of stretched continental fragments of the Adriatic plate and can be subdivided into three tectonic units (Ring et al., 1999), which are from top to bottom: (1) the Upper Unit; (2) the CBU, and (3) the Basal Unit. The CBU itself can be tectonically split up from top to bottom into at least three separate members: (a) an ophiolitic mélange, (b) a Permo-Carboniferous to latest Cretaceous passive-margin sequence, and (c) a Carboniferous basement nappe. The Basal Unit, as part of the External Hellenides, consists of Mesozoic and early Cenozoic platform carbonates found in several tectonic windows (Avigad & Garfunkel, 1989; Ring et al., 2001) (Figure 2).

In the Cyclades, the Hellenide Orogeny commenced in the early Cenozoic causing subduction and sustained HP metamorphism between ~53 and ~24–21 Ma (Lagos et al., 2007; Ring & Layer, 2003; Tomaschek et al., 2003; Wijbrans et al., 1990). The large age span for HP metamorphism may reflect stages of underthrusting at ~50, ~40, ~30, and ~22 Ma, and subsequent exhumation in extrusion wedges of distinct nappes of the CBU. Ages for HP metamorphism of about 53 to >46 Ma have been reported from structurally high units of the CBU, mainly from the ophiolitic mélange on Syros (Cliff et al., 2016; Lagos et al., 2007; Putlitz et al., 2005; Tomaschek et al., 2003; Uunk et al., 2018), and also possibly from Samos, where Ring and Layer (2003) reported ages of >45 Ma. The next younger set of ages for HP metamorphism is between 44 and 38 Ma from the passive-margin sequence of the CBU in Tinos (Bröcker et al., 1993), Syros (see below), Naxos (Bolhar et al., 2017; Peillod et al., 2017; Cao et al., 2017), and the upper tectonic unit of the passive-margin sequence on Sifnos (Dragovic et al., 2012; Ring et al., 2011). Ages of about 33–30 Ma for HP metamorphism were reported from the lower tectonic unit of the passive-margin sequence in South Sifnos (Wijbrans et al., 1990; Ring et al., 2011) and Evia (Ring, Glodny, et al., 2007). Finally, ages of 24–21 Ma have been described from the Basal Unit in the Cyclades (Ring et al., 2001; Ring & Layer, 2003), coeval with HP metamorphism of the Cretan HP rocks (Seidel et al., 1982; Jolivet et al., 1996; Ring & Reischmann, 2002).

There are a few, seemingly separate, lower-pressure metamorphic overprints of the HP rocks. A first greenschist-facies one in the Eocene has been documented in Samos and the Menderes Zone of western Turkey and is associated with the emplacement of the CBU onto the greenschist-facies Menderes nappes between 43 and 34 Ma (Hetzel & Reischmann, 1996; Ring & Layer, 2003; Ring, Will, et al., 2007). Another greenschist-facies overprint in the Oligocene at ~33–27 Ma occurred in the passive-margin sequence in South Syros and South Naxos (Maluski et al., 1987; Peillod et al., 2017; Skelton et al., 2019). Finally, there was a regionally widespread Miocene greenschist-/amphibolite-facies metamorphic overprint at ~22–11 Ma (Jolivet & Brun, 2010; Kumerics et al., 2005; Ring et al., 2010; Wijbrans & McDougall, 1988). The latter is associated with large-scale continental extension starting at ~23–21 Ma (Ring et al., 2010), accompanied by the intrusion of S- and I-type plutons between 17 and 11 Ma (Bolhar et al., 2010), and its onset at ~22 Ma was coeval with HP metamorphism in the Basal Unit and on Crete. The earlier greenschist-facies overprints are about coeval with the ~40- and ~30-Ma HP metamorphic events in structurally deeper CBU nappes and appear to be associated with initial exhumation of HP nappes. The ages of these greenschist-facies overprinting episodes are typically smeared out over relatively long periods of time (ca. 5–10 Myr) reflecting heterogeneous, fluid-controlled recrystallization of the exhuming HP rocks (Peillod et al., 2017; Uunk et al., 2018).

Figure 3. Tectonic map of Syros with N-S and E-W cross sections (simplified from Keiter et al., 2011) with various isotopic ages (see text for explanation); subdivision of CBU follows general descriptive scheme of Ring et al. (1999).

2.2. Geology of Syros

Syros is mainly made up of the ophiolitic mélangé and passive-margin sequence of the CBU (Figure 3). In the southeast, the CBU is tectonically overlain by the non-HP Upper Unit and the uppermost Vari Unit (Aravadinou & Xypolias, 2017; Soukis & Stöckli, 2013) (note that on Syros the Upper unit has been subdivided into an Upper Unit and the uppermost Vari Unit).

The ophiolitic *mélange* is at the structurally highest level of the CBU and consists of blocks of metagabbro, eclogite, felsic gneiss, glaucophanite, jadeitite, and ultramafic rocks in a matrix composed of chlorite-talc schist (Hecht, 1984; Keiter et al., 2011; Marschall & Schumacher, 2012). In North Syros, a slice of the passive-margin sequence occurs within the ophiolitic *mélange*. This succession provided ages of up to 53–50 Ma for the prograde to peak-HP overprint (Cliff et al., 2016; Lagos et al., 2007; Laurent et al., 2017; Lister & Forster, 2016; Putlitz et al., 2005; Tomaschek et al., 2003; Uunk et al., 2018) (Figure 3). Some of these ages have been variably reset during eclogite- and subsequent blueschist- to greenschist-facies deformation (Cliff et al., 2016; Lister & Forster, 2016; Uunk et al., 2018) with ages as young as about 42–41 Ma.

The tectonically underlying passive-margin sequence of the CBU represents thinned continental crust consisting of a ~2-km-thick succession of marble, dolomite, calcschist, metapelite, metaconglomerate, quartzite, chert, and metabasite. This sequence yielded ages of around 40 Ma for HP metamorphism in central and southern Syros (Cliff et al., 2016; Laurent et al., 2017; Skelton et al., 2019; Uunk et al., 2018) (Figure 3). Cliff et al. (2016) argued that locally Rb-Sr ages of ~35–30 Ma still reflect blueschist-facies conditions. Laurent et al. (2017) described a rather large spread of $^{40}\text{Ar}/^{39}\text{Ar}$ ages of 48.5–40.3 Ma from Fabrika in south-eastern Syros. The problem with the latter ages is their large scatter of 8 Myr. It is known that fluid transport in HP metamorphic rocks may be limited, in a sense that such rocks may remain as closed systems on centimeter to meter scales (see Warren et al., 2012, p. 63ff), so extraneous/inherited Ar is present in one locality (where the fluid system was closed for Ar escape) but absent only a few meters away. Local excess Ar leads to overestimation of ages and poor reproducibility. In such cases, the youngest $^{40}\text{Ar}/^{39}\text{Ar}$ age is usually close to the true age for HP metamorphism, which at Fabrika has been independently constrained to 42–40 Ma by Rb-Sr dating (Skelton et al., 2019).

Pressure-temperature (P-T) conditions of both tectonic units of the CBU are estimated at ~15–20 kbar (equivalent to depths of 55–75 km if an average density of 2,700 kg/m³ was assumed) and ~500–550 °C (Behr et al., 2018; Laurent et al., 2016; Philippon et al., 2013; Ring et al., 2010; Schumacher et al., 2008; Skelton et al., 2019). Within uncertainties of the P-T estimates it appears as if there is no detectable metamorphic break between and within the two tectonic units of the CBU. However, the ages of the HP overprint demand that the ophiolitic *mélange* was initially thrust upon the passive-margin sequence and the two units present two distinct nappes. Based on P-T estimates in glaucophane-bearing marble in the passive-margin sequence, Schumacher et al. (2008) argued that the stacking of thrust units was completed before the metamorphic peak, that is, during burial and prograde metamorphism. Laurent et al. (2016) proposed that the contact between the ophiolitic *mélange* and the passive-margin sequence was subsequently reworked by extensional shearing. The lack of any detectable metamorphic breaks across the contact suggests limited displacement during extension.

In large parts the passive-margin sequence is overprinted by greenschist-facies metamorphism. The timing of the greenschist-facies overprint is not well constrained. Bröcker et al. (2013) published Rb-Sr ages ranging from ~30–20 Ma, whereas Skelton et al. (2019) reported a Rb-Sr age of ~27 Ma for the end of the greenschist-facies overprint at Fabrika (Figure 3). The latter age agrees with Maluski et al. (1987), who reported a $^{40}\text{Ar}/^{39}\text{Ar}$ white-mica age of ~30 Ma from mylonitic, greenschist-facies CBU at the contact to the Upper Unit near Fabrika (Figure 3). $^{40}\text{Ar}/^{39}\text{Ar}$ white-mica ages of ~35–31 Ma for transitional-blueschist-facies shearing in the Kini shear zone (Lister & Forster, 2016) are slightly older.

At the northeastern end of the Fabrika CBU section, rocks of the Upper Unit overly the CBU along a low-angle tectonic contact (Soukis & Stöckli, 2013) (Figure 3). These authors showed that there is greenschist-facies, mylonitic, light-green chlorite schist at the base (Upper Unit), which is tectonically overlain by quartzofeldspathic gneiss and amphibolite of the Vari Unit. Several tens of meters thick serpentinite constitute the main tectonic contact to the overlying Vari Unit (Soukis & Stöckli, 2013). The tectonic contacts, and also large parts of the Upper and Vari units are characterized by strong brittle deformation, which is expressed by a network of mainly NE dipping, low-angle to steep cataclastic zones that overprint a preexisting, greenschist-facies, mylonitic foliation (Soukis & Stöckli, 2013; own mapping results, see below). Maluski et al. (1987) argued that their $^{40}\text{Ar}/^{39}\text{Ar}$ age for greenschist-facies mylonitization near Fabrika dates the emplacement of the Upper Unit above the CBU. Zircon and apatite fission track ages of 21–11 Ma from the Vari Unit and 12–10 Ma for the CBU (Ring et al., 2003) are related to top-to-the-NE low-angle normal faulting at the base of the Vari Unit. The zircon and apatite (U-Th)/

He ages of Soukis and Stöckli (2013) corroborated this scenario with lower-plate CBU rocks recording rapid cooling at ~12–9 Ma, whereas the Vari Unit shows older ages of up to ~16 Ma (zircon) and 14.5 Ma (apatite). The fission track and (U-Th)/He ages reflect cooling from approximately 240 to 70 °C and are distinctly younger than the greenschist-facies mylonite age reported by Maluski et al. (1987), strongly suggesting a two-phase tectonic history of the Upper and Vari units with greenschist-facies mylonitization at ~30 Ma followed by Miocene low-angle normal faulting at ~10 Ma associated with rapid cooling of the CBU below the upper units.

2.3. Fabrika Section

A well-exposed coastal section of the CBU passive-margin sequence is exposed at Fabrika in southeastern Syros, which exposes various mafic layers alternating with carbonate-quartz rocks. Because carbonates and quartzites tend to be impermeable for metamorphic fluids (Skelton et al., 1995), some of the mafic rocks preserve mineral assemblages formed during prograde and peak high-pressure metamorphism (Skelton et al., 2019). For this reason, the section at Fabrika is ideally suited as a natural laboratory for the study of the interplay between metamorphism, fluid flow, and structural development in subduction zones (see also Kotowski & Behr, 2019). Therefore, we have mapped the Fabrika section at the 1:500 scale (Kleine et al., 2014; Skelton et al., 2019; this study) (Figure 4). The section is divided by a number of approximately NW striking late normal and strike-slip faults, and a ~50-m-wide zone comprising scattered, up to 2-m-sized eclogite-facies ultramafic blocks with ~10-cm-thick blueschist/greenschist-facies rinds, which Skelton et al. (2019) interpreted to represent a ~30- to 27-Ma-old greenschist-facies shear zone.

In the field, Skelton et al. (2019) classified the mafic rocks as eclogite, blueschist, and greenschist (Figure 4). Eclogite is fine grained with 1- to 10-mm-large garnet porphyroblasts and occasional, up to 10-mm-long prisms of glaucophane and epidote in a matrix of omphacite and phengite. Blueschist is fine grained with garnet porphyroblasts ranging in size from 1 to 10 mm and up to 10-mm-long prisms of epidote. Both eclogite and blueschist have the same mineral assemblages, only the modal abundances of the HP minerals are different (Skelton et al., 2019).

Greenschist is also fine grained and contains albite porphyroblasts, ranging in size from 2 to 5 mm in a matrix of chlorite, white mica, actinolite, and quartz. Occasional HP relics are garnet (with similar prograde core-to-rim zoning as observed in blueschist samples), which is partly replaced by chlorite or rimmed by albite. Also, cores of some actinolite grains are composed of a sodic-calcic amphibole (winchite) (Skelton et al., 2019). Two types of carbonate-quartz rocks are observed, one of which is quartz rich and contains abundant white mica and 5- to 20-mm garnet porphyroblasts, which often have chlorite rims or are completely chloritized. The other lacks garnet porphyroblasts, is basically a marble, and contains only small amounts of quartz and white mica (Figure 4). Some boudinaged eclogite layers occur in the marble and give it a conglomeratic appearance (Laurent et al., 2016).

Evidence for HP metamorphism is abundant at Fabrika (Skelton et al., 2019). Eclogite and blueschist is preserved alongside and within carbonate-quartz layers. Eclogite is often altered to blueschist along shear bands and veins. According to Kleine et al. (2014), glaucophane is stabilized by higher $X(\text{CO}_2)$ with respect to omphacite. Skelton et al. (2019) demonstrated that the occurrence of eclogite and blueschist at Fabrika is controlled by bulk composition with eclogite forming in carbonate-free lithologies and blueschist in carbonate-bearing lithologies. A corollary of this finding is that in carbonate-free eclogite the breakdown of omphacite to glaucophane is related to a first fluid-infiltration event during incipient decompression. The fluids are commonly channeled through quartz veins. In the carbonate-bearing blueschist, omphacite, and glaucophane are stable together and veins contain carbonate. Skelton et al. (2019) showed that both eclogite and blueschist yielded the same P-T conditions during prograde (11–14 kbar and 380–460 °C), peak HP metamorphism (18–21 kbar and 520–570 °C), and a less well-defined, early decompressional (12–18 kbar and 470–560 °C) overprint (Figure 5). Thermobarometric data show that garnet grew during prograde and peak HP metamorphism, as well as incipient decompression (Figure 5) (Skelton et al., 2019).

The garnet fabrics bear important information on the distinction between prograde and decompression structures. Some garnet has synkinematic inclusion trails (internal fabric, S_i) that show continuity between the various growth zones of the garnet and the matrix (external fabric, S_e). Sample 15SY03 (Figure 5) serves

Figure 4. Geologic map with faults draped over high-resolution digital elevation model of Fabrika section; note ultramafic blocks not in place; locations of samples mentioned in text and photos shown in Figure 7 indicated. Diagrams on upper left show fault-slip data from various outcrops at Fabrika; stereonet depicts great circles to fault planes with pole of striation on that fault plane and arrow indicating hanging wall slip direction; principal strain axes ($X > Y > Z$) shown. All outcrops, except FS1, show NNE to ENE directed horizontal extension marked by black arrows.

as an example. S_1 is mainly made up by phengite, quartz, and opaques and is sigmoidally deflected in the garnet. The sigmoidal deflection indicates synkinematic growth of the entire garnet and that the sense of curvature (rotation) did not change during growth (cf. Passchier & Trouw, 2005). This demonstrates that the synkinematic garnet can be used to constrain the kinematics of deformation during the prograde

Figure 5. P-T path of HP and greenschist-facies rocks (Skelton et al., 2019) and backscattered electron images of garnet from samples 15SY03 and 15SY05. Garnet in 15SY03 shows S-shaped internal foliation (S_i) oblique to external foliation (S_e) and continuity of S_i and S_e (red line) (note that angle of S_i steeper in core demonstrating progressive rotation of growing garnet); garnet in sample 15SY05 shows no synkinematic S_i and no distinct continuity of inclusions from garnet rim (delineated by red line) into matrix (note that minerals in strain shadows on lower left and upper right of garnet stop at red line). P-T work of Skelton et al. (2019) indicates that garnet core grew during prograde compression (squares), inner rim at peak HP conditions (diamonds), and outer rim during initial decompression (circles) for eclogite (red) and blueschist (blue) samples, indicating that garnet 15SY03 with syntectonic fabric grew continuously from burial via peak-P under-plating and subsequent initial exhumation (red curved arrow in P-T path) and that sense of internal rotation of S_i relative to S_e remained unchanged during burial and exhumation; note that core, inner, and outer rims defined by element distribution data of Skelton et al. (2019).

compression (burial) stage of HP metamorphism, as well as during peak HP conditions and initial decompression (exhumation) (red line in P-T path in Figure 5). Because of the continuity between internal and external fabric, it follows that the sense of rotation between the garnet and the matrix did not change during the burial, peak HP, and decompression stages. In other words, the shear sense during subduction and burial was the same as the shear sense during initial exhumation. In the same outcrop, garnet from sample 15SY05 does not show a sigmoidal deflection pattern. Some of these garnets have asymmetric strain shadows in which glaucophane grew. Given that Skelton et al. (2019) showed that the outermost garnet rims and the matrix minerals define the P-T conditions during initial decompression (circles in P-T path in Figure 5), the asymmetric strain shadows must be a fabric that developed during decompression, that is, exhumation. The various textural relations of garnet growth and the P-T history are important for constraining the tectonic processes during subduction, HP metamorphism and initial exhumation/decompression and will be further described below.

Three multimineralline Rb-Sr isochrons yielded consistent ages of 41.6 ± 1.5 , 41.4 ± 0.5 , and 39.6 ± 1.2 Ma from both eclogite and blueschist and date peak HP conditions (Skelton et al., 2019). Kleine et al. (2014) showed that blueschist at outcrop A (Figure 4) was preserved alongside a greenschist-facies shear zone. At greenschist-facies conditions, the rocks were infiltrated by localized, deformation-controlled metamorphic fluids. Where the fluids contained CO_2 , blueschist-facies minerals were preserved, elsewhere greenschist formed. The end of this greenschist-facies metamorphism at 2–6 kbar and 380–520 °C is dated at 26.9 ± 0.4 Ma (Skelton et al., 2019).

3. Previous Structural Work and Subduction Channel Tectonics

Philippon et al. (2011) reported top-to-the-south/SW shear sense during prograde HP metamorphism from the ophiolitic mélange and also the passive-margin sequence (their Figure 4, Oceanic and Pyrgos units in their nomenclature). Evidence for shearing during prograde HP metamorphism is inferred from lawsonite pseudomorphs associated with the shear-sense indicators (Philippon et al., 2013). There appears to be some confusion with the usage of the terms “prograde” and “retrograde” metamorphism in the literature and therefore we define those terms here. Prograde reactions are endothermic and driven by increasing

temperature (Bucher & Frey, 1994, p.59). Detailed pseudosection analysis by Philippon et al. (2013) showed that lawsonite grew during increasing pressure and temperature (what we refer to as “prograde compression,” i.e., burial) and then was pseudomorphed during incipient, slight decompression (i.e., exhumation) but still increasing temperature, which they describe as “retrograde” (Philippon et al., 2013, their Figure 8). However, because temperature is still increasing, the lawsonite pseudomorphs are prograde (and we refer to this stage as “prograde decompression” very close to the HP peak). In summary, according to Philippon et al. (2011, 2013), top-to-the-south/SW structures formed during burial (prograde compression) and prograde decompression (exhumation) near the HP peak. Skelton et al. (2019) reported lawsonite pseudomorphs in garnet cores corroborating that these pseudomorphs formed during prograde compression.

Philippon et al. (2011) related the top-to-the-south/SW shear sense to thrusting of the ophiolitic mélange on top the passive-margin sequence. Detailed work in North Syros by Ridley (1984) and Keiter et al. (2004) already proposed top-to-the-south/SW thrusting of the ophiolitic mélange onto the passive-margin sequence based on the geometries of folds that formed during prograde compression. Philippon et al. (2011) also mapped top-to-the-NE shear senses across the entire island and ascribed them to “retrograde metamorphism” related to exhumation following top-to-the-south/SW thrusting. These authors envision that the top-to-the-NE structures formed when the upper plate of the subduction zone underwent core-complex-type extension (Philippon et al., 2011).

Laurent et al. (2016) also mapped widespread top-to-the-east/NE shear-sense indicators in the CBU across the entire island and proposed that the CBU was exhumed by top-to-the-east/NE extensional shearing from eclogite-facies conditions all the way up into the brittle crust. The Laurent et al. (2016) study proposed four major top-to-the-east/NE extensional shear zones, three within the CBU and another one separating the latter from the Upper and Vari units. However, there are no apparent breaks in HP P-T conditions across the proposed major extensional shear zones in the passive-margin sequence (cf. Schumacher et al., 2008). Laurent et al. (2016) concluded that most of the deformation in the CBU of Syros was acquired during exhumation and that this deformation was heterogeneously distributed and preferentially localized along extensional shear zones.

Rosenbaum et al. (2002) studied HP microstructures in North Syros and concluded that a first (prograde compressional) deformation event is only recorded as internal foliations (inclusion trails, S_1) in garnet. They found no major asymmetries of S_1 and ascribed them to coaxial deformation. The surrounding matrix is made up by garnet, omphacite, glaucophane, white mica, and quartz and is also supposed to largely reflect a coaxial fabric. Rosenbaum et al. (2002) concluded that the HP structures reflect coaxial flattening in the subduction zone.

This brief review highlights some disagreement about the early structures that formed during prograde and peak HP metamorphism, as well as incipient decompression/exhumation. The studies by Ridley (1984), Keiter et al. (2004) and Philippon et al. (2011) proposed top-to-the-south/SW thrusting of the ophiolitic mélange onto the passive-margin sequence. However, it remains ambiguous whether these structures formed in a subduction channel or along a subduction thrust. Both Philippon et al. (2011) and Laurent et al. (2016) called for large-scale extensional deformation associated with initial decompression/exhumation.

The general orientation of the stretching lineations in Syros is E-W (Philippon et al., 2011, their Figure 4; Laurent et al., 2016, their Figure 4; this study). The orientation of stretching lineations in rocks of the CBU on most other Cycladic islands is about NNE-SSW. It is largely unknown why there is such a disparity. A simple explanation might be that Syros has undergone clockwise rotation of some 50–80° since the mid/late Miocene. The only reliable paleomagnetic data are from 11.55 ± 0.43 Ma dacitic dikes on nearby Tinos Island showing clockwise rotation of $27 \pm 16^\circ$ (Avigad et al., 1998). However, on Tinos the stretching lineations have the typical NNE-SSW trend.

For addressing whether or not the HP structures in the passive margin sequence of the CBU are related to shortening or extension, and whether their formation is better explained by a subduction-channel or subduction-thrust model, we conducted a detailed study in a well-exposed small area at Fabrika in Southeast Syros (Figures 3 and 4).

Figure 6. (a) Structural map of Fabrika section showing orientation of main foliation and stretching lineation; arrow heads show sense of shear of tectonic top for HP and greenschist-facies kinematic indicators deduced in outcrop and thin section. (b) Poles to foliation planes. (c) Stretching lineations. (b and c) Lower-hemisphere projections, Kamb contours, contour interval 2σ .

4. Structures in Cycladic Blueschist Unit at Fabrika

4.1. Field Relations

We systematically mapped the main foliation and stretching lineation (Figure 6). Both structures formed at HP conditions. This is evidenced by an alignment of pristine omphacite, glaucophane and garnet in the foliation (Figures 7a–7c) and stretching lineation and the crosscutting of the HP foliation by veins containing glaucophane (Figures 7b–7h). Subsequently, both foliation and stretching lineation are partially overprinted at greenschist-facies conditions as demonstrated by, in part complete, chloritization of garnet (Figures 7j–7m) and the breakdown of omphacite and glaucophane. Both HP- and greenschist-facies deformation structures

Figure 7. Mesoscopic structures at Fabrika. (a) Shear bands and S-C-type structures in pristine eclogite indicating top west displacement outlined by yellow lines and half arrows; shear bands associated with glaucophane growth (red arrows in all images), white arrow indicates S-plane in S-C structure. (b) Eclogite with asymmetric, omphacite-filled strain shadows around garnet recording mainly top west shear sense but top east also occurs (black arrows provide shear sense); shear bands display consistent top west shear sense (yellow half arrows); quartz vein in upper left (white arrow head) shown in (c). (c) Steep quartz vein cross-cutting pristine eclogite; glaucophane grows into vein (red arrows); quartz vein interpreted as top east displacing flanking structure, note asymmetric omphacite-bearing strain shadow around garnet provide monoclinic top west shear sense (arrows); same outcrop as in (b). (d) West dipping quartz vein in eclogite; vein associated with glaucophane growth (red arrows) in shear band indicating top west shear sense (half arrows indicate inferred shear sense). (e) West dipping shear bands in glaucophane-eclogite, top west shear sense; width of photo 26 cm. (f) Asymmetric shear-band-type eclogite boudin in marble, top east shear sense; note no alteration at marble-eclogite contact. (g) Top east displacing shear band structures in eclogite (indicated by yellow lines and half arrows) filled with quartz and glaucophane. (h) Steep shear bands/normal faults in eclogite in which quartz and glaucophane grew; top east sense of shear. Red arrows indicate glaucophane growth associated with veins and shear bands; west and east for all photos indicated at top. (i) Asymmetric eclogite boudin in marble-quartz layer indicating top east sense of shear; note no alteration at marble-eclogite contact. (j) Garnet synkinematically altered to chlorite + quartz at rims in carbonaceous quartzite, chlorite growth at expense of garnet (indicated by blue arrows) projects from garnet rim into shear bands (thin black line at top of garnet marked by two half arrows); some small garnets completely chloritized; asymmetric strain shadows and shear bands indicate top west shear sense. (k) Same rock with similar fabrics indicative of top west shear at greenschist-facies conditions; blue arrows indicate chloritization of garnet, some small garnets completely chloritized. (l) Top west displacing shear bands/low-angle faults (marked by half arrows) in retrogressed blueschist; garnet thoroughly chloritized (blue arrows) indicating greenschist-facies conditions. (m) Altered blueschist with almost completely chloritized garnet (blue arrows), asymmetries of strain shadows and shear bands provide top west shear sense (shown by half arrows). (n) Decameter-scale, top west greenschist-facies shear zone in quartz-carbonate rock, black lines trace foliation. (o) Low-angle, top west displacing ductile/brittle shear zone filled with orange-brown carbonate material, small-scale high-angle faults (dashed white line) sole out in low-angle fault (white line); shear sense top west. (p) High-angle carbonate (+ quartz) filled NE dipping normal fault in greenschist; thin strip of blueschist (yellow arrow) preserved adjacent to fault zone. West and East for all photos indicated at top; refer to Figure 4 for localities of outcrops.

Figure 7. (continued)

are parallel to each other and are therefore shown together in the stereonet in Figures 6b and 6c. The foliation generally dips moderately to the northeast (Figure 6b) and the stretching lineation trends subhorizontally E-W (Figures 6c). Pristine eclogite has abundant garnet with asymmetric strain shadows filled with omphacite, glaucophane, white mica, epidote, and quartz and indicate either top-to-the-west or top-to-the-east shear senses, whereas the greenschist-facies shear senses are dominantly top-to-the-west. The alternating shear senses in the Fabrika rocks are not due to post-shearing folding about axes

subparallel to the stretching lineation. In the following description, we have subdivided the kinematic indicators into HP top-to-the-west, HP top-to-the-east and (sub)greenschist-facies top-to-the-west kinematic indicators and first describe outcrop structures followed by a microstructural description. In addition, we show high-angle faults postdating the greenschist-facies shear-sense indicators (Figures 4 and 6).

4.1.1. Top-to-the-West Structures at HP Metamorphism

In eclogite and blueschist outcrops, top-to-the-west kinematic indicators are asymmetric strain shadows, S-C structures, shear bands, flanking structures, the latter of which are in part associated with the shear bands, and asymmetric eclogite boudins (Figures 7a–7e). Omphacite, garnet, and glaucophane are the main HP minerals forming these structures. The S-C structures formed in coarse-grained parts of the eclogite where the S planes have angles of 30–45° to the foliation (Figure 7). Figure 7c shows asymmetric strain shadows made up by omphacite and glaucophane around garnet. Shear bands usually formed at angles of 10–20° to the main foliation and the deflection of the foliation provides the top-to-the-west shear sense. In some cases (e.g., Figure 7e), the angle between the main foliation and shear bands can be up to about 30° (e.g., Figure 7d). The veins are associated with glaucophane growth (see also below). Asymmetric eclogite boudins are common. Some of the boudins are isolated with a stubby shape (Figure 7i), whereas others occur as shear-band-type boudins (Figure 7f) and are long and thin (cf. Passchier & Coelho, 2006).

In eclogite, quartz veins crosscutting the main, eclogite-facies foliation are common (Figures 7c, 7d, 7g, and 7h). Close to and inside these quartz veins there is abundant glaucophane, the growth of which appears to have been controlled by a fluid containing CO₂ (cf. Kleine et al., 2014). There are also cases where the veins are solely composed of quartz. The veins appear to reflect fluid infiltration during initial exhumation. If so, the replacement of omphacite by glaucophane reflects initial decompression in the blueschist-facies. In some cases, there are no alteration haloes around the veins. This might imply that the fluid flowing through the rock was in chemical equilibrium with the minerals that were forming at that time, i.e. fluid flow occurred at HP conditions. However, we cannot rule out the possibility that fluid flow occurred later and was too fast to interact with and alter the country rock. The presence of glaucophane in some veins and haloes indicates that they formed at blueschist-facies conditions. The quartz veins themselves are often flanking structures (Grasemann et al., 2003; Passchier, 2001).

If the vein in Figure 7c was interpreted as a flanking structure that formed during initial decompression, it would yield a top-to-the-east sense of shear that overprints the top-to-the W asymmetric strain shadow around garnet adjacent to the vein. In this case, shortening would be very steep, subperpendicular to the foliation reflecting almost pure-shear deformation. An alternative interpretation would be to regard the monoclinic top-to-the-west strain shadows and the quartz vein as one composite structure that formed in the same strain field. The quartz-veins could then be interpreted to reflect antithetic slip comparable to bookshelf structures (B. Grasemann, written communication, December 2, 2019).

4.1.2. Top-to-the-East Structures During HP and Initial Decompression

Top-to-the-east kinematic indicators in eclogite and blueschist are also shear bands and flanking structures (Figures 7g and 7h), as well as asymmetric eclogite boudins (Figures 7f and 7i). The majority of the asymmetric eclogite boudins in outcrop B record top-to-the-east shear sense. We analyzed 36 boudin structures in total and 27 of them provide a top-to-the-east shear sense (see also Laurent et al., 2016), but top-to-the-west asymmetric boudins occur as well. Most of the asymmetric boudins in outcrop B are of the shear-band type (Figure 7f). Top-to-the-east shear-band-type quartz veins are in part steep, dipping at ~30–50° to the east and are associated with glaucophane growth adjacent to the veins (Figures 7c, 7g, and 7h).

4.1.3. Greenschist-Facies Top-to-the-West Structures

In quartz-carbonate rocks, especially at the southwestern end and the central part of the section (Figures 4 and 6), abundant chloritized, centimeter-sized garnets show a dominantly top-to-the-west shear sense associated with the replacement of garnet by chlorite (Figures 7j and 7k). We analyzed 69 chloritized garnet structures and 61 of them provide a top-to-the-west shear sense, the remaining 8 yield a top-to-the-east shear sense. In cases, garnet is completely chloritized. Chlorite in the replacement textures has a preferred alignment consistent with top-to-the-west shear (Figures 7j and 7k). Epidote veins in greenschist show flanking structures indicative of top-to-the-west shear. Asymmetric strain shadows around albite porphyroblasts also yield a top-to-the-west sense of shear. Some outcrops, especially in blueschist, show strong greenschist-facies alteration and shear bands/low-angle normal faults, as well as asymmetric strain shadows around chloritized garnet supply a top-to-the-west shear sense (Figures 7l and 7m). There also top-to-the-west shear

zones at the decameter scale in rocks showing greenschist-facies assemblages (Figure 7n). At the waning stages of and/or after greenschist-facies metamorphism abundant carbonate veins were emplaced. Usually, the carbonate has an orange to brown color due to a late-stage, subgreenschist-facies alteration of calcite to dolomite (Schumacher et al., 2008). These veins crosscut structures containing chloritized garnet. A first generation of these veins is subparallel to the foliation and shows top-to-the-west shear sense. Subsequently, the carbonate veins formed in top-to-the-west shear zones at a low angle to the main foliation (Figure 7o). The latest set of structures are moderately to steeply dipping normal faults (Figure 7p). Commonly, these faults are also filled with orange-brown carbonate. Fault-slip analysis indicates predominantly NE-SW extension (Figure 4). E-W striking faults have normal and/or dextral oblique-slip kinematics, whereas NW striking faults sinistral oblique-slip or normal kinematics (Figure 6).

The chloritization of the garnets is syntectonic and the reaction of garnet to chlorite is a result of the greenschist-facies overprint at Fabrika. Likewise, the growth of albite occurred at greenschist-facies conditions (Skelton et al., 2019). Therefore, the inferred top-to-the-west sense of shear is interpreted to reflect deformation at greenschist-facies conditions. The greenschist-facies top-to-the-west structures are associated with the subsequent top-to-the-west low-angle faults.

4.2. Microstructures

The outcrop-scale HP kinematic indicators show both top-to-the-west and top-to the-east senses of shear. The work of Skelton et al. (2019) indicated that garnet grew during prograde compression, peak HP metamorphism, and initial decompression (Figure 5). Therefore, microscopic observations of kinematic indicators associated with garnet are critical for deciding whether the structures formed before, during, or after peak HP metamorphism.

4.2.1. Top-to-the-West HP Microstructures

Especially in samples from outcrop C (Figure 4) there are abundant garnets with an S-shaped internal foliation (S_i) (Figures 8a–8f). The internal foliation started to form during prograde compression (Figure 5) and comprises omphacite, phengite, epidote, and quartz, in some garnets glaucophane. In a number of cases, S_i continues into the strain shadows around garnets and into the matrix or external foliation (S_e , external is relative to garnet). This is illustrated in Figure 8b, which shows in detail the interface between garnet with curved inclusion trails (S_i) and its strain shadow. In sample 15SY03, the sense of curvature of the internal foliation in these garnets is the same as in garnets with continuous internal and external foliation from samples in the same outcrop. The strain shadows around garnet and in S_e are commonly overgrown by omphacite and glaucophane (Figure 8b).

In line with most workers, we assume that the inclusion trails in garnet are passive markers and have not been significantly displaced by the growing garnet (cf. Passchier & Trouw, 2005). Therefore, the deflection of the matrix around the rigid garnet can be used as a sense-of-shear indicator and the sense of curvature of the internal S-shaped garnet fabrics provides top-to-the-west shear sense. The same top-to-the-west shear sense has also been observed in mesoscopic structures in outcrop C (Figures 7b and 7c) and in other places in the Fabrika section.

4.2.2. Top-to-the-East HP Decompressional Microstructures

Some of the garnets have curved inclusion trails that do *not* continue into the matrix foliation (Figures 8a, 8d, and 8f). In eclogite and blueschist samples recording top-to-the-east shear sense, we did not observe that S-shaped inclusion trails continue into S_e around the garnet. Garnet with inclusion trails which are not continuous with S_e often show asymmetric strain shadows yielding top-to-the-east shear senses. In other samples, for instance 15SY05 (Figure 5), zoned garnets appear to have statically overgrown minerals and HP structures in the matrix depict a top-to-the-east shear sense. Some garnets have no S_i and have asymmetric strain shadows in which mainly glaucophane but also omphacite are stable. Most of these garnets provide a top-to-the-east sense of shear (56 out of a total of 77 analyzed microstructures).

4.2.3. Microscopic Greenschist-Facies Top-to-the-West Structures

The microstructures of the greenschist-facies deformation fabrics are characterized by partial to complete breakdown of garnet to chlorite, albite, carbonate, and quartz (Figures 9a and 9b). Chlorite, white mica, albite, carbonate, and quartz thoroughly replace the interiors of the garnet and also extend into and make up the asymmetric strain shadows around the decomposed garnets. These composite structures yield a top-to-the-west shear sense. The structures are especially abundant in the quartz-muscovite-garnet-

Figure 8. HP microstructures at Fabrika. (a) Internal inclusion trails (S_i) in garnet not continuous with S_e in matrix; S_i shows sinistral rotation with respect to S_e ; Omp: omphacite; sample SY15/5. (b) Close-up of garnet with curved S_i continuing into strain shadow, rim of garnet shows quartz and white mica of strain shadow incorporated into growing garnet as elongated inclusions, curvature of S_i in garnet caused by relative rotation between garnet and S_e indicating synkinematic growth, S_i depicts sinistral rotation with respect to S_e , and omphacite and glaucophane (Gln) grew in strain shadow; sample 15SY03. (c) Garnet with slightly curved S_i continuous with S_e ; sample SY15/5. (d) Garnet with S_i oblique to S_e ; S_i does not continue into matrix and shows sinistral rotation with respect to S_e ; asymmetric strain shadows around garnet also indicate sinistral (top west) shear; sample SY15/5. (e) Garnets with S_i oblique to S_e in matrix; angle between S_i and S_e varies between $\sim 80^\circ$ and $\sim 110^\circ$; S_i not continuous with S_e ; omphacite and glaucophane overgrew S_e ; S_i shows sinistral rotation with respect to S_e , especially rim of garnet in center decomposes into phengite and quartz; sample SY17/3. (f) Garnet with subhorizontal, slightly curved S_i , asymmetric strain shadow provides top east sense of shear; sample SY17/4. Internal and external foliations are marked with yellow lines, west and east for all orientated thin sections indicated at top; refer to Figure 4 for localities of samples.

carbonate rocks (Figure 4). In altered blueschist, the chloritization of garnet is commonly associated with and followed by the formation of orange-brown carbonate veins. In greenschist, garnet is replaced by chlorite and white mica or rimmed by albite (Figure 9c), white mica (phengite) is partly replaced by chlorite, and rutile rimmed by titanite (see also Skelton et al., 2019). Actinolite grains have winchite cores, and veins in the greenschist are filled by epidote and quartz. The greenschist-facies structures record a top-to-the-west shear sense.

Replacement of glaucophane and epidote by calcite indicates carbonation after blueschist-facies metamorphism (Kleine et al., 2014). Also, replacement of garnet, glaucophane and calcite by albite points to

Figure 9. Greenschist-facies microstructures in CBU at Fabrika and in Vari Unit. (a) Large garnet thoroughly replaced by quartz, chlorite (e.g., white arrow within garnet) and calcite (red arrow), asymmetric top west strain shadows associated with chloritization (e.g., white arrows at garnet margin); sample SY17/9, same outcrop as Figures 7j and 7k. (b) Similar fabric as in (a) providing top west shear sense deduced from asymmetric strain shadows (white arrow at bottom right shows synkinematic chlorite and red arrow calcite replacing garnet and extending into strain shadow); white line shows margin of former garnet; sample SY17/10. (c) Garnet with embayments at rim showing greenschist-facies alteration to albite and white mica (white arrows), albite also occurs in interior of garnet, slightly asymmetric strain shadow provides top west shear sense; sample SY17/7. (d) Top west shear bands in quartzofeldspathic gneiss of Vari Unit; refer to Figure 10 for sample location. West and east for all orientated thin sections indicated at top; refer to Figures 4 and 10 for localities of samples.

decarbonation at greenschist-facies conditions (Kleine et al., 2014). There is a tendency for this replacement to occur at garnet/glaucophane contacts confirming that albite formed at a time when garnet and glaucophane were no longer stable together, that is, at greenschist-facies conditions.

5. Structures in Upper Units

Because Maluski et al. (1987) argued that their $^{40}\text{Ar}/^{39}\text{Ar}$ age of 30.3 ± 0.9 Ma is related to greenschist-facies mylonitization and emplacement of the upper units above the CBU, and Skelton et al. (2019) reported a slightly younger age for the end of greenschist-facies deformation at Fabrika of 26.9 ± 0.4 Ma, we mapped greenschist-facies deformation structures in the upper units to see how they relate to those in the CBU passive-margin sequence at Fabrika.

The actual contact between the CBU and the upper units is not exposed (see detailed map of Soukis & Stöckli, 2013) (Figure 10). At Gria Pounta, chloritic schist and metabasite of the upper units occur just above the contact with the CBU and have a penetrative subhorizontal foliation made up by quartz, albite, white mica, and chlorite, in addition actinolite occurs in the metabasite. This foliation is associated with an ENE trending stretching lineation (Figures 10a and 10b) marked by elongated chlorite-quartz-albite aggregates. Abundant shear bands (Figure 11a) and asymmetric boudins (Figures 11b and 11c) supply a top-to-the-WSW sense of shear.

Quartzofeldspathic gneiss of the Vari Unit also shows top-to-the-WSW shear bands (Figure 9d). Along the coastal section south of Gria Pounta, felsic gneiss and retrogressed amphibolite of the Vari Unit similarly provide a top-to-the-WSW sense of shear (Figure 11d). In strongly retrogressed quartz-chlorite-white mica schist of the passive-margin sequence of the CBU directly underlying the upper units northwest of Gria

Figure 10. Structural map of upper units (modified from Soukis & Stöckli, 2013) showing orientation of main foliation and stretching lineation (arrowheads point down plunge), normal faults, localities of photos shown in Figures 9 and 11, and stations for fault-slip analysis. (a) Poles to foliation planes. (b) Stretching lineations. Both plots lower-hemisphere projections, Kamb contours, and contour interval 2σ . (c–f) Fault slip analysis; see caption to Figure 4 for explanation. All data show simple patterns of NE dipping normal faults indicating NE to ENE directed extension.

Pounta, abundant shear bands also yield a consistent top-to-the-WSW shear sense (Figure 11e) (see also Aravadinou & Xypolias, 2017). In some parts of the Vari Unit tight folds with axes subparallel to the ENE trending stretching lineation postdate the development of the shear sense indicators and locally re-fold them.

In chlorite schist of the Upper Unit at the coast east of Fabrika, asymmetric quartz boudins also provide a top-to-the-WSW shear sense (Figure 11f). In the overlying Vari Unit, chlorite and quartz filled veins show pinch-and-swell structures that have been rotated forming flanking structures and top-to-the-WSW shear sense (Figure 11g). The penetrative foliation with the flanking structures is cut by subhorizontal, cataclastic shear zones (Figure 11h). Riedel shears and P foliations associated with the cataclastic shear zones suggest top-to-the-NE displacement. The subhorizontal faults are cut by high-angle normal faults (Soukis & Stöckli, 2013) (Figure 10a). There are two generations of high-angle faults, an older one striking preferentially NW-SE is cut by E-W striking normal faults. Fault-slip analysis in some of these normal faults yields a consistent NE-SW extension direction (Figures 10c–10f).

Figure 11. Mesoscopic structures in upper units. (a) Top WSW S-C structures and shear bands in chlorite-mica schist of Upper Unit; width of photo 18 cm. (b) Asymmetric actinolite-chlorite-quartz boudin in amphibolite showing top WSW shear sense, Vari Unit. (c) Relatively steep shear bands indicating top WSW displacement in amphibolite of Vari Unit. (d) Shallowly WSW dipping shear bands in amphibolite of Vari Unit; top WSW sense of shear. (e) Ductile to brittle top WSW shear bands in chloritic schist of CBU at contact to Upper Unit. (f) Asymmetric quartz vein in chlorite-mica schist of Upper Unit, top WSW sense of shear sense. (g) Flanking fold in chloritic, gneissic schist of Vari Unit, foliation in schist (marked with black line) deflected against center of crosscutting chlorite-quartz vein suggesting top WSW sense of shear. (h) Chlorite-quartz vein similar to (h) cut by subhorizontal, cataclastic fault associated with Riedel shears (arrows). WSW and ENE for all photos indicated at top; refer to Figure 10 for localities of outcrops.

6. Discussion

We have documented HP and greenschist-facies deformation structures in the CBU at Fabrika and in the directly overlying upper units east of Fabrika. Some of the HP structures record top-to-the-west shear sense and some of these structures formed when garnet was growing during prograde compression, peak HP and decompression. In other words, the sense of rotation did not change during burial and exhumation and therefore reflects thrust-type deformation. There are also top-to-the-east kinematic indicators recorded in the HP rocks, among them veins crosscutting the HP foliation. The top-to-the-east structures developed at a late stage of garnet growth during HP metamorphism and incipient decompression and are thus related to exhumation.

There is no unique interpretation for explaining the structures. We start the discussion with our preferred interpretation of forced return flow at the tapering end of the subduction channel. Then we present an alternative explanation in which the contrasting shear senses are related to heterogeneous general-shear flow. Finally, we broaden the discussion by looking regionally at subduction/exhumation processes across the Cyclades and Crete.

6.1. Forced Return Flow in Subduction Channel?

The top-to-the-west and top-to-the-east kinematic indicators occur spatially very close to each other, sometimes in different parts of the same outcrop (e.g., outcrop C in Figure 4). In outcrop C (e.g., Figure 7c), decompressional glaucophane-bearing top-to-the-east structures overprint top-to-the-west omphacite- and garnet-bearing structures but the overall kinematic significance of the steep top-to-the-east vein in Figure 7c is a matter of interpretation. The top-to-the-west shear sense indicators started to form earlier during prograde compression. Both, top-to-the-east and top-to-the-west, structures kept forming during exhumation. In other places, there are no systematic overprinting relationships between top-to-the-east and top-to-the-west structures. The association of both sets of kinematic indicators and their relation to HP metamorphism suggests that they reflect the same, single, composite deformation event deep in the Hellenic subduction zone. Our preferred interpretation is that the structures formed where subduction-related return flow occurred, that is, in the turnover zone between downward and upward flow (Figures 1 and 12). If this interpretation was accepted, the Fabrika rocks would record the stage when the downward transported material did no longer subduct and started its return back toward the surface. We argue that we were only able to work out the subtle differences in the relation between the different shear sense indicators and HP metamorphism because we focused over several field seasons on a well-exposed, small section of the HP rock sequence in Syros.

The kinematic indicators with opposite shear sense at Fabrika are not as systematically arranged as those described in Ring, Glodny, et al. (2007) and Ring, Will, et al. (2007) from Samos/West Turkey and Evia. In the latter studies all structures developed during decompression/exhumation (Figure 12a) and no structures could be found that formed during burial-related prograde compression. The thrust-type structures at the base of the extrusion wedge show a transition from blueschist- to greenschist-facies metamorphism, whereas the structures at the top of the wedge have a tendency to record greenschist-facies metamorphic conditions only. We argue that the differences between the Fabrika structures and Samos/West Turkey/Evia structures reflect their formation at various levels of the subduction channel. The structures described in Ring, Glodny, et al. (2007) and Ring, Will, et al. (2007) are from shallower levels where the subduction channel is possibly wider and the bottom and top parts of the extrusion wedge had developed discrete shear zones farther apart from each other (inset of Figure 1). In contrast, the Fabrika structures formed at greater depth, possibly near or at the tapering end of the channel at (near)peak HP metamorphic conditions where downward and upward flowing material and the different shear senses at the bottom and top of the forming extrusion wedge develop in close proximity (Figure 12a). It may well be that other batches of rock from the channel have been further subducted and either got lost into the mantle or started their return to the surface at some later stage but are not exposed in the Fabrika section. All structures forming at the bottom end and higher up in the extrusion wedges resulted from subduction and lithospheric shortening and thus are interpreted to reflect processes in a subduction channel.

The results of the modeling study of Gerya et al. (2002) suggest that material returns from depth at multiple levels and then amalgamates in a tectonic mélange. The flow patterns and structures predicted by the

Figure 12. (a) Forced return flow in subduction channel largely inferred from mapped structures at Fabrika. Top west kinematic indicators started to form first while rocks on burial trajectory during prograde compression (1 in sketch); synkinematic garnets indicate that top west structures continued to grow at peak HP metamorphism (maximum depth where return flow initiated) and initial exhumation; top east kinematic indicators (2 in sketch) formed during initial exhumation. Deformation at 35–31 Ma in Kini shear zone (Lister & Forster, 2016) (3 in sketch) envisaged to represent later stage of exhuming extrusion wedge at transitional blueschist-facies conditions either at bottom or top of wedge as shear sense unknown. (b) Interpretation of greenschist-facies top west structures due to thrusting of Upper and Vari units onto CBU extrusion wedge, structures marked with A formed in overriding plate (represented by greenschist-facies deformation in Upper and Vari units), structures marked with B developed at greenschist-facies conditions in extruding CBU section at Fabrika.

numerical simulations are, in part, controlled by the assumed linear Newtonian rheology (Gerya et al., 2002). The rocks at Fabrika show pronounced mineral deformation by non-Newtonian (power law) dislocation-glide mechanisms, which makes direct comparisons difficult. Other simulations of forced return flow in orogenic wedges (e.g., Allemand & Lardeaux, 1997; Guinchi & Ricard, 1999) have been

compared to coherent HP nappes in the Western Alps at the kilometer scale, with the various nappes being characterized by different P-T conditions and contrasting P-T histories. So far, P-T work in Syros appears to show largely similar P-T conditions of about 15–20 kbar and 500–550 °C, but we acknowledge that there is some variability in the P-T estimates. Schumacher et al. (2008) explicitly argued that there are no discernable metamorphic breaks between the HP rocks in the passive-margin sequence. This suggests that the Syros HP rocks were detached from the downgoing plate at broadly similar depths. Penniston-Dorland et al. (2018) suggested that the tectonic development of large, coherent units in the subduction channel is controlled by the rheology of the deforming heterogeneous material and the width of the channel. The work in Syros would suggest that the km-scale HP nappes reflect the thickness of the subduction channel at that scale. Such a view would suggest that kilometer-scale nappes would form in dry and stiff rheologies.

Because the structures developing in a subduction channel in part track the exhumation of the HP rocks, they should show some decompressional deformational overprint in the greenschist facies. Therefore, a critical question is how the greenschist-facies top-to-the-west kinematic indicators in the CBU at Fabrika and the adjacent upper units fit into the subduction-channel interpretation. We envisage two possible explanations (Figure 12b). (1) They could be related to the emplacement of mid/upper crustal nappes as proposed for instance by Ring and Yngwe (2018) for Crete (scenario A in Figure 12b). (2) They might reflect relatively high level structures representing later stages of deformation along the basal thrust of the extrusion wedge (scenario B in Figure 12b). We believe that the kinematic and temporal association of the greenschist-facies structures at Fabrika with those in the Upper and Vari units is important. All greenschist-facies structures record top-to-the-west/WSW shear sense and formed at ~30–27 Ma (Maluski et al., 1987; Skelton et al., 2019). This suggests that these greenschist-facies structures are related to each other and reflect the emplacement of the mid/upper crustal Upper and Vari units above the CBU. The extrusion wedge had reached higher levels in the subduction channel at ~30–27 Ma and the overriding plate was emplaced above the wedge. This model combines the two possible explanations shown in Figure 12b and marks a stage when the subduction zone moved further outboard.

Because the Cyclades are characterized by prominent, large-scale extensional detachments (Jolivet & Brun, 2010; Ring et al., 2010), another critical question is whether the top-to-the-west/WSW emplacement of the upper units was due to lithospheric extension or shortening? Middle/late Miocene top-to-the-west/SW extensional deformation has been described from the West/South Cyclades detachment system (Grasemann et al., 2012; Ring et al., 2011). The mid-Oligocene greenschist-facies structures from Southeast Syros are too old to be related to the West/South Cyclades detachment system. However, they are of the same age as HP metamorphism on the nearby islands of Evia (Ring, Will, et al., 2007), Sifnos (Ring et al., 2011; Wijbrans et al., 1990), and possibly even parts of Syros (Cliff et al., 2016). This temporal connection makes it likely that the greenschist-facies top-to-the-west structures are related to sustained E-W lithospheric shortening reflecting the late or final stages of deformation in the subduction channel when the extruding HP wedge came into contact with deforming rocks of the overriding plate (Figure 12b).

6.2. General-Shear Flow Along Subduction Thrust?

We discussed our preferred model that the alternating shear senses are related to forced return flow in a subduction channel. An alternative interpretation would be that the contrasting shear senses reflect heterogeneous general-shear deformation in the subduction zone. The general-shear flow may have had spatially varying pure-shear components and the coaxial flattening envisaged by Rosenbaum et al. (2002) may reflect pure-shear flattening along certain segments of the subduction interface, or general-shear flow with a low kinematic vorticity number. Overall, the general-shear deformation along the subduction interface would need to be heterogeneously distributed with variable pure- and simple-shear components.

If the general-shear model was preferred, the partly burial-related, prograde HP structures at Fabrika would demand that general-shear flow was related to thrusting along the subduction interface as the kinematics must encompass underthrusting during subduction. The asymmetric fold structures reported by Ridley (1984) and Keiter et al. (2004), and the prograde lawsonite fabrics described by Philippon et al. (2011) would fit a thrust scenario. Heterogeneous general-shear deformation would probably better fit with a subduction-thrust rather than a return-flow model. However, the general-shear thrust-type scenario does not readily explain the exhumation of the HP rocks of the passive-margin sequence. It also appears that the

thickness of the deforming zone and the kilometer-scale nappes are too wide for favoring a subduction-thrust interpretation.

6.3. Subduction and Exhumation Processes in Hellenic Subduction Zone

We now look at large-scale subduction/exhumation relationships in the Tertiary Hellenic subduction zone by incorporating age data introduced in the beginning of this article. Important for the following discussion are the various peak HP stages of different CBU nappes at ~50, ~40, and ~30 Ma, HP metamorphism in Crete at 24–21 Ma, and the various, exhumation-related, greenschist/amphibolite-facies overprints at ~40, ~30, and 21–11 Ma. We propose a progressive four-phase underplating/exhumation history.

The earliest phase of HP metamorphism in the CBU peaked at 53–50 Ma (Tomaschek et al., 2003; Lagos et al., 2007; Lister & Forster, 2016; Cliff et al., 2017; Laurent et al., 2017; Uunk et al., 2018) (Figure 13a). How these structurally high nappes were exhumed is not understood. Work in North Syros demonstrates that the ophiolitic *mélange* was thrust onto the passive-margin sequence of the CBU (Keiter et al., 2004; Philippon et al., 2011; Ridley, 1984) after ~53–50 Ma. Better constrained are processes associated with the ~40-Ma HP belt when parts of the passive-margin sequence experienced HP metamorphism (Figure 13b). Data from Samos/West Turkey show that the ophiolitic *mélange* was exhumed by normal faulting to midcrustal levels at this stage (Ring, Will, et al., 2007). Contemporaneously, the passive-margin sequence (slice/nappe 1) was thrust onto the Carboniferous basement in the Cyclades (Gupta & Bickle, 2004; Huet et al., 2009; Peillod et al., 2017) and the Menderes continental block in West Turkey (Gessner et al., 2001) (Figure 13b). In the next conceptual step, the final stage of HP metamorphism of the southernmost part of the CBU passive-margin sequence at ~30 Ma took place (Figure 13c, slice/nappe 2). This is largely contemporaneous with initial underthrusting of the Cretan HP rocks at 36–32 Ma (Thomson et al., 1998) and out-of-sequence thrusting of the Upper and Vari units onto the passive-margin sequence in Syros (Maluski et al., 1987; this study). Our model suggests overall lithospheric shortening from ~50 to ~30 Ma in the Cyclades. Finally, the youngest currently exposed HP rocks in the Aegean Sea formed in Crete and in the Basal unit in the Cyclades at 24–21 Ma (Seidel et al., 1982; Jolivet et al., 1996; Ring et al., 2001) (Figure 13d). These HP rocks are also interpreted to have been exhumed in an extrusion wedge (Chatzaras et al., 2006). At this time in the early Miocene the retreat of the Hellenic subduction system affected the Cyclades, which started to extend rapidly (Jolivet & Brun, 2010; Ring et al., 2010). At a later stage of wedge extrusion in Crete, probably at ~17–14 Ma, the non-HP Tripolitza and Pindos units were emplaced by out-of-sequence thrusting onto the Cretan HP rocks (Ring and Yngwe, 2018). The scenario at ~24 to 14 Ma shows lithospheric shortening in the south (Crete) and lithospheric extension in the north (Cyclades) and both regions are more than 100 km apart from each other.

Our tectonic synopsis explains the successive stages of HP metamorphism between ~50 and ~20 Ma by sustained lithospheric shortening in the Hellenic subduction zone. We realize that the categorization of the subduction processes into four distinct stages is a simplified approach (Figure 13). However, our summary highlights that each cycle lasted for ~10 Myr and each progressively underthrusting slice/nappe experiencing a HP overprint during underplating triggered the development of an extrusion wedge above it. This pattern appears to be a diagnostic tectonic process in the Hellenic subduction zone. It is also in line with theoretical considerations arguing that subduction of continental crust only occurs for a restricted period of time of ~10 Myr (e.g., Chopin, 2003; Ernst, 2001) causing the subduction zone to clog-up and step outboard (e.g., Stern, 2004). We envisage that the arrival and underthrusting of continental crust in the Hellenic subduction zone may have triggered out-of-sequence thrusting of the rock units in the overriding plate onto the extruding HP rocks.

The proposed four-stage subduction, HP metamorphism, exhumation model in Figure 13 appears to be supported by the ages from the Cyclades and Crete as discussed above. There are plenty of age data from Syros, and they provide more detail and complexity. For instance, Cliff et al. (2016) suggest that their Rb-Sr ages from the passive-margin sequence reflect blueschist-facies conditions as young as 35–30 Ma. If so, the Syros age data may suggest an alternative model of continuous channel return flow in which material with an age spread of about 10 Myr (between 40 and 30 Ma) occurs in the passive-margin sequence. It may also be feasible that the passive-margin sequence on Syros is made up by two different tectonic units (similar to slices 1 and 2 in Figures 13b and 13c).

Figure 13. Inferred sequential underplating and exhumation in subduction channel in Tertiary Hellenic subduction zone; schematic sketches illustrating first-order processes; categorization of events into four distinct stages represents technical attempt; processes may have been more continuous. (a) First stage of HP metamorphism at ~53–50 Ma (e.g., ophiolitic mélange in Syros) and subsequent thrusting of HP rocks onto incoming Adriatic passive-margin sequence (now passive-margin sequence of CBU) (note that 1 stands for first underplated slice/nappe of passive-margin sequence); incoming continental crust caused outboard stepping of subduction zone. (b) Second stage of HP metamorphism at ~42–38 Ma (peak HP metamorphism of slice/nappe 1 of passive-margin sequence); return flow at this stage documented in rocks from Fabrika; Adriatic passive margin (slice/nappe 2) enters subduction zone; along strike to east Menderes continental block enters subduction zone and overthrust by CBU passive-margin sequence at ~43–37 Ma; >45 Ma HP rocks exhumed by greenschist-facies normal shearing at ~37 Ma (Ring, Will, et al., 2007) in Samos/West Turkey) (note that Menderes block only shown once in (b); also at this stage 41- to 38-Ma HP rocks from Naxos exhumed during (near)isothermal decompression leading to greenschist-facies metamorphism at 36–32 Ma (Peillod et al., 2017)). (c) Final stage of HP metamorphism of CBU passive-margin sequence at ~33- to 30-Ma (slice/nappe 2) coeval with thrusting of Upper and Vari units onto extruding rocks in SE Syros at 30–27 Ma. (d) Cretan HP rocks undergoing peak HP metamorphism at 24- 21Ma coeval with onset of large-scale extension, amphibolite/greenschist-facies metamorphism (22–11 Ma), and plutonism (17–11 Ma) due to slab rollback in Cyclades >100 km to north; at final stage of wedge extrusion out-of-sequence thrusting of Tripolitza and Pindos units above extruding wedge (Ring and Yngwe, 2018) similar to situation at ~33–30 Ma in SE Syros. Note that younger processes better resolvable, especially upper-plate deformation.

We interpret the various HP belts and their exhumation in extrusion wedges to reflect sustained return-flow processes that persisted in a Hellenic subduction channel for at least ~30 Myr. It appears that the subduction channel changed with time as the oldest HP belt is largely made up by serpentinite mélangé and the younger belts by more coherent kilometer-thick HP nappes made up by previously thinned continental crust.

7. Concluding Remarks

Spatially closely related HP structures recording opposite senses of shear were mapped in rocks of the CBU at Fabrika in Syros. Top-to-the-west structures started to form during the burial stage of metamorphism and are therefore not related to exhumation. Top-to-the-east structures are probably related to exhumation as they formed at or after the peak of HP metamorphism and ensuing decompression. We interpret all HP structures to reflect forced return flow deep in the subduction channel and the incipient formation of an extrusion wedge. Because forced return flow is controlled by the velocity of the subducting slab, we suggest that this process explains why HP rocks can be exhumed at subduction rates. At an advanced stage of the extruding wedge, rocks of the overriding plate were thrust onto the extruding CBU wedge during sustained subduction-related lithospheric shortening. It follows that most of the exhumation of the HP rocks in the Cyclades occurred in a shortening setting.

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