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Mapping of Shear Sense Indicators on the Mavra Vounakia Peninsula, Syros

Thea Bisander

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Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

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submitted by

Thea Bisander

Department of Geological Sciences

Stockholm University

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Supervisor: Uwe Ring

Abstract

The exhumation of the Cycladic Blueschist Unit (CBU) in the Aegean sea is a well debated subject. This study has constructed a map of the shear sense indicators found on the greenschist overprinted southwestern part of Syros, the Mavra Vounakia peninsula, for trying to reveal information about the retrograde metamorphic deformation. Both top-to-the-east and top-to-the-west shear sense indicators associated with the greenschist overprint were found. No overprinting criteria or other clear evidence of different deformation events, such as spatial arrangement or appearance, could be found between the opposite senses of shear. The spatial distribution was arranged by top-to-the-W and top-to-the-E senses of shear forming patches of clusters over the study area, and the top-to-the-E ones appearing very abundantly on the east coast. The direction of shear on the Mavra Vounakia peninsula diverged slightly from the average of Syros. In conclusion, the exhumation of the CBU has, at least on the Mavra Vounakia peninsula, been accompanied by at least one deformation event, if not more, where both top-to-the-E and top-to-the-W shear sense indicators formed. No evidence was found that supported two deformation events for the opposite senses of shear. Further, the deformation appears to have had a slightly different orientation on the Mavra Vounakia peninsula relative to the rest of Syros.

1. INTRODUCTION

The island of Syros, in the Aegean sea, holds a wide range of particularly well preserved high pressure rocks. It lies in the heart of the Cycladic Blueschist Unit (CBU) which have drawn many geologist through time for the study of its metamorphic history. Syros contains the best preserved blueschist and eclogite facies rocks found within the CBU and have therefore been a well visited location for someone wishing to explore any kind of processes linked to orogenic events (eg., Cliff *et al*., 2017; Schumacher et al., 2008; Bond *et al*., 2007; Putlitz et al., 2005).

However, the deformation accompanying the exhumation of the CBU is still a debated subject. Both top-to-the-east and top-to-the-west shear sense indicators have been documented on the island. But it is unknown whether these both developed during the retrograde metamorphic event and if so, if they belong to separate or one and the same deformation event. Different approaches have been taken on the subject, whereas etc. Trotet *et al.* (2001) and Rosenbaum *et al*. (2002) find that the greenschist overprint indeed is accompanied by penetrative deformation, while etc. Kieter *et al.* (2004) interpret the deformation as solely linked to prograde metamorphism and that the exhumation caused no deformation which overprinted the prograde one. Understanding the deformation linked to the exhumation of the CBU is important for understanding the exhumation itself and for this reason it is going to be the subject of this study.

The southwestern part of Syros, known as the Mavra Vounakia peninsula, diverges from the more northern parts in that it received a severe greenschist overprint, in part due to greater amounts of fluid involved during the exhumation of the CBU (Hecht, 1985; Keiter *et al*., 2011). Since most of the island got exhumed still remaining the high pressure metamorphism in blueschist facies and eclogite facies they display an ultimate location for research on a fossilized subduction zone. However, the exhumation history is presumably best preserved in the southwest, since the greenschist overprint have been connected and dated together with the retrograde metamorphic event (Trotet *et al*., 2001). But so far, the Mavra Vounakia peninsula's structural features have been poorly investigated. The structural mapping have been performed in relatively large scale or the focus have mainly been on the northern parts (Cliff *et al.,* 2017; Bond *et al.,* 2007; Philippon *et al.,* 2011).

This study therefore aims to, in greater detail than done before, map and investigate the shear sense indicators preserved on the southwestern part of Syros to find out whether or not the greenschist overprint is associated with any penetrative deformation event. If shear sense indicators are found, this study will attempt to determine if both top-to-the-W and top-to-the-E indicators exist. In case of them both appearing, overprinting criteria and spatial arrangement will be studied to see if they belong to different or one and the same deformation event. Further, a secondary aim is to use this information in the attempt to build a greater understanding of the exhumation history of the CBU.

2. GEOLOGICAL SETTING

2.1 Tectonometamorphic history of Syros

Syros belongs to an orogen called the Hellenides which spatially curves over the subducting Hellenic slab in the Mediterranean sea. This subduction zone was created in the Cretaceous by the closure of several interconnected ocean basins belonging to the Tethyan sea and the collision and subduction of the microcontinent Apulia under Eurasia (Ring *et al.,* 2010). The CBU on Syros is estimated to have been buried to the depth where it reached the conditions of 15-19 kbar and 500-550°C which is the upper pressure limit for the stability field of the epidote-blueschist facies, it is also the deepest exhumed rocks in the Hellenides. This prograde metamorphic event is dated to have peeked in the Eocene (Philippon *et al.,* 2011; Ashley *et al.*, 2014; Schmädicke & Will, 2003).

As mentioned before, the retrograde metamorphic path of the CBU is still subject to controversial research (eg. Philippon *et al.,* 2011; Kieter *et al.,* 2004; Trotet *et al.,* 2001; Rosenbaum *et al.,* 2002). The greenschist overprint found on Syros have been dated to around 18-25 Ma (Altherr *et al.,* 1982*;* Bröcker *et al.* 1993). However, where greenschist overprint is found it relates to shear zones or where fluid infiltrating can be interpreted. Therefore the recrystallization to a greenschist mineral assemblage is not necessary at the exact time when the CBU entered greenschist facies conditions but rather connected to an event of fluid infiltration (Bröcker *et al.* 1993). The exhumation is believed to have been connected to the roll-back event when the African slab retreated and resulted in back-arc extension and several detachments on regional scale (Ring *et al.* 2010). The processes which led to the final exhumation involve theories such as: (1) Ductile exhumation, offset by buoyancy forces or a deformation event in the Eocene and the Oligocene, where the CBU was exhumed via an extrusion wedge. The theory involves late stage brittle deformation and horizontal compression as products of the back-arc extension (Ring *et al.,* 2007; Xypolias *et al*., 2003). (2) Extensional unroofing by syn-orogenic and post-orogenic processes involving back-arc extension, time interval being Eocene-Miocene

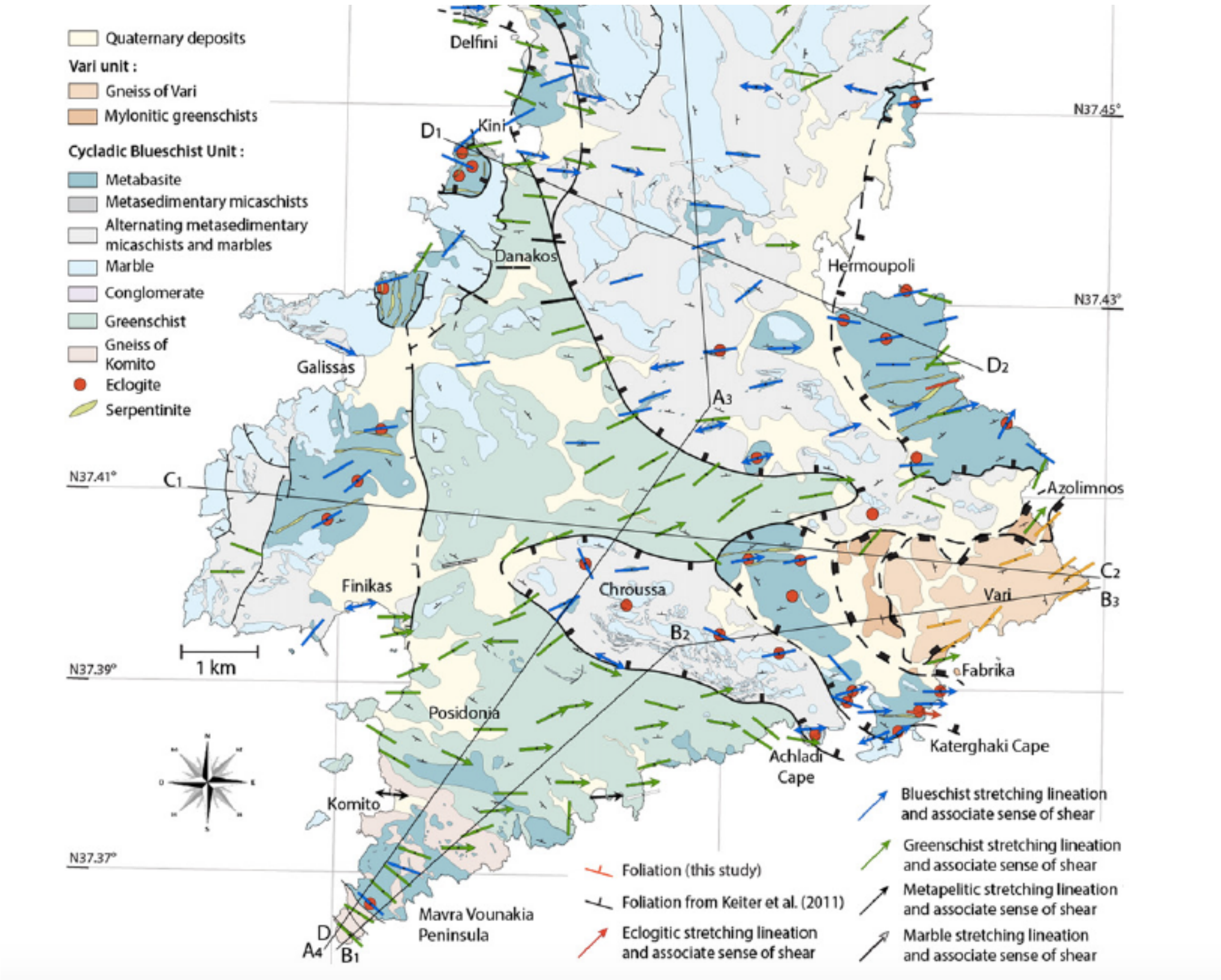

Figure 1. Map from Laurent et al. (2016) of the south part of Syros, including the Mavra Vounakia peninsula, showing lithology, stretching lineation and sense of shear. Only in the top east corner of the peninsula and around Finikas have shear sense indicators been marked for the study area.

(Trotet *et al.,* 2001). (3) Initially Eocene exhumation via an extrusion wedge and then a final unroofing by extensional processes in the Oligocene-Miocene (Huet *et al.,* 2009; Rosenbaum *et al.,* 2002). (4) A relatively passive uplift of the CBU on low angle detachment faults where no major penetrative deformation occurred after peak metamorphism (Keiter *et al.,* 2004).

2.2 Petrology of southwest Syros

The southwest part of Syros, the area of interest for this study, has a severe greenschist overprint. There is only a few localities which in meter scale still preserve blueschist relicts. Other parts of Syros have a more patchy spatial arrangement of greenschist overprint, but it gradually increases towards the south. (etc. Keiter *et al.,* 2011; Laurent *et al.,* 2016; Hecht, 1985).

Figure 1 is a map constructed by Laurent *et al.* (2016) showing a part of Syros, including the study area which is the most southerly cape. As illustrated in figure 1 the Mavra Vounakia peninsula have a basement of metabasites interlayer with felsic gneiss (Laurent *et al.,* 2016), referred to in this paper as the *Komito gneiss* (Keiter *et al.,* 2011). Further north, towards Posidonia in the west and Mega Yalos in the east, the structurally basal unit outcropping on Mavra Vounakia is overlain by fewer metabasites, thin marble layers, quaternary deposits and abundant albitic micaschist (Laurent *et al.,* 2016). Quartzite appears throughout the whole study site as meter scale layers (Keiter *et al.,* 2011). The rocks in the southwest is likely to have been from the same protolithic sequence, only distinguished from the rest of the island by metamorphic grade (Hecht, 1985). As earlier mentioned the difference in metamorphic grade is believed to be due to greater fluid infiltration in the stronger retrogressed areas, this is interpreted by large quartz veins, patchy silification, occasionally Fe-oxide ores in connection to marble layers and veins and impregnations by monomineralic albite (Keitler *et al.,* 2011). The hydrothermal activity isolated to the more southern part of Syros is possibly linked to a magmatic intrusion (Ballhaus *et al*., 2001).

Komito gneiss

The Komito gneiss outcrops on a large portion of the Mavra Vounakia peninsula. It is in close competition with the schists as being the most common rock type on the southwestern cape. The gneiss is believed to have a sedimentary protolith and is fine- to medium-grained, with an Ab + Qz + white mica paragenesis. The foliation is parallel and widely spaced. The Komito gneiss is often associated with quartz veins which can reach up to 3m thickness and have at places conglomeratic intercalations (Keiter *et al.* 2011).

Greenschists

Greenschists are the most common rock type on the southwest of Syros. On the Mavra Vounakia peninsula the greenschists are dominantly calcite and epidote-bearing metabasites, they have a massive texture and crop out as blocky structures. Together with the metabasites but mainly further north towards Finikas and Mega Yalos albitic greenschist; Ab + Act + Chl ± Qz dominate. They are finer grained than the massive metabasites with a parallel and tight foliation (Keiter *et al.,* 2011; Laurent *et al.,* 2016).

Quartzite

Joining the greenschists and Komito gneisses all over the southwestern cape are meter-thick layers of quartzite. They are similar to the gneisses in there mineral assemblage Ab + Qz + white mica, but have a red coloration and are intrafolial folded. At places they cary garnet porphyroblasts reaching cm scale. They occur in close correlation to the albitic greenschists and the two often laterally grade into one another (Keiter *et al.,* 2011).

Marble, Serpentinite, Quaternary deposits

Rocks which appear only in smaller quantities and have less importance for this study are serpentinite and quaternary deposits. Marble are present in larger scale but were not be the focus of this study. The occurrences of these rocks are concentrated around the wester part of the study area, around Finikas and Posidonia (Keiter *et al.,* 2011; Laurent *et al.,* 2016). They will be mapped where they appear in mappable outcrop size. However, their structural features have not been the subject for the research of this paper.

2.3 General structure of SW Syros

The southwestern part of Syros, especially the Komito gneiss, is recognized as the structurally basal unit for the CBU and zircon dating (by U-Pb SHRIMP) have given an age of 300 Ma (Tomaschek *et al.,* 2008). The sedimentary-volcano unit, in the south called the Pyros unit, has a stratigraphic location which is situated over the gneiss and consists of the metabasites, albitic schists, quartzite and marbles which yields an age of about 330-350 Ma (Philippon *et al.,* 2011). The southwest is separated from northern units which are initially structurally higher by the Achladi-Delfini shear zone (Laurent *et al*., 2016). This contact between the north and south units have been interpreted in different ways. Laurent *et al.* (2016) in agreement with Trotet *et al.* (2001) argue that the Achladi-Delfini shear zone represents a gap in metamorphic grade between the greenschist facies- and the blueschist- to eclogite facies rocks and that it consists of a ductile detachment. In contrast Philippon *et al.* (2011) and Keiter *et al.* (2004, 2011) describes the contact as a thrust fault related to subduction processes and questioned the existence of such a sharp boundary for the metamorphic grades. Schumacher *et al.* (2008) is supporting the latter by referring to the occurrence of glaucophane + aragonite/calcite and their indications of the P-T-path for the high pressure rocks.

2.4 Earlier research on the retrograde metamorphic deformation

Research conducted on Syros with the aim to reveal information about the exhumation history have yielded many different answers. Keiter *et al.* (2004) conclude that the exhumation most likely must have occurred by simple shear along low angle detachment faults and that the major part of the CBU was left untouched by any penetrative deformation after peak metamorphism due to static conditions. This conclusion is based on the observation of abundant aragonite- and lawsonite pseudomorphs. The authors argue that these minerals would have been destroyed if penetrative deformation was present during the retrograde metamorphism. Bond *et al.* (2007) questions this by discussing the P-T stability field in which the CBU was exhumed. According to their study much of the exhumation occurred under conditions where aragonite and later blueschist-eclogite were stable and that only the last 30% of the exhumation was during greenschist facies. Therefore, deformation which earlier had been interpreted as related to the subduction could actually have been connected to the early exhumation of the CBU.

Philippon *et al.* (2011) describes that top-to-the-S/SW shear sense indicators is observed in the north of the island as well as in lawsonite pseudomorphs and concludes that this deformation event was associated with the subduction. Top-to-the-E/NE shear sense indicators were found all over the island, including the greenschist overprinted southwestern part and they interpreted these as belonging to the exhumation. Laurent *et al.* (2016) agreed with the abundant top-to-the-E/NE shear over the whole island but in contrast to Phillippon *et al.* (2011) they argued that these shear sense indicators also affected the lawsonite pseudomorphs and the pseudomorphs would therefore have been deformed during the exhumation. This interpretation is questioning the assumption by Keiter *et al.* (2004) that the lawsonite pseudomorphs were proof of absence of penetrative deformation after peak metamorphism.

Where opposite senses of shear is observed Philippon *et al.* (2011) stress the importance of reevaluating the cause of their formation. Laurent *et al.* (2016) discuss the possibility of subduction related shear zones of top-to-the-S/SW sense of shear being reactivated during exhumation operating top-to-the-N/NE sense of shear, which would explain where opposite shear sense indicators are found. Bond *et al.* (2007) and Rosenbaum *et al.* (2002) argues for regional coaxial extension during exhumation and the opposite indicators are only a question of the host rocks preference based on their properties. Philippon *et al.* (2011) take a critical stand towards the, in their opinion, hasty interpretations of the opposite senses of shear and argue that for example conjugate shear bands can develop as a result of viscosity differences between layers and does not necessary mean coaxial strain on regional scale. Huet *et al.* (2009), Jolivet *et al.* (2009) and Gautier & Brun (1994) interpret the opposite senses of shear as synchronous and connected to both the subduction and the exhumation and as being the result of ductile flow.

The subject is indeed one of conflicting interpretations and do need to be revisited and reevaluated. None of the studies mentioned have in detailed mapped the Mavra Vounakia peninsula's shear sense indicators (Philippon *et al.,* 2011; Laurent *et al.,* 2016; Keiter *et al.,* 2011). Laurent *et al.* (2016) mapped the top east corner of the peninsula, where they have documented top-to-the-NE senses of shear, and around Finikas where opposite senses of shear are marked as well as one marker for top-to-the-W sense of shear in figure 1.

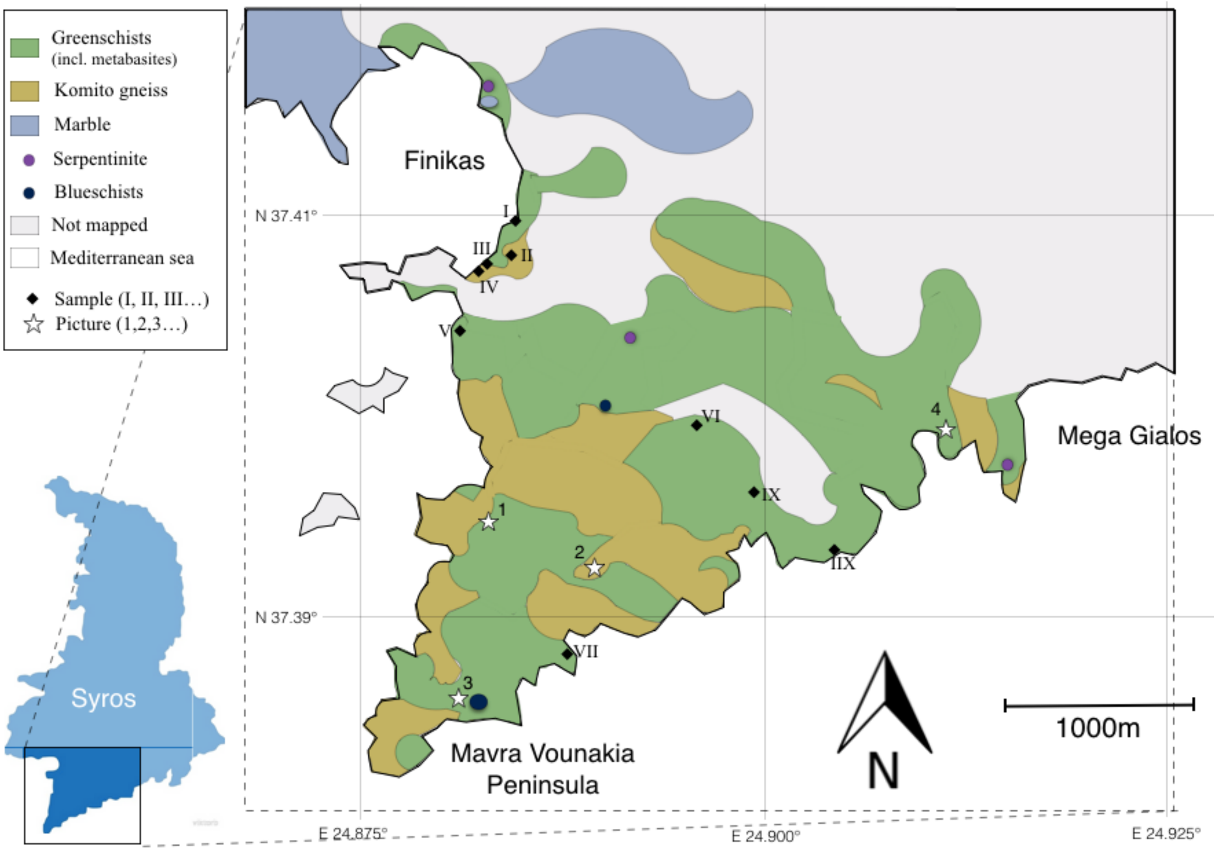

Figure 2. Map of the study area, the Mavra Vounakia peninsula on the southwestern part of Syros, Greece. Only lithologies and locations of samples and pictures have been marked.

3. METHODS

The mapping and data collection for this study have been conducted by the author during a two week interval in March 2019, with initial supervision from the structural geologist Uwe Ring from the Department of Geological Sciences at Stockholm University. The mapped area reaches from a line drawn from the village of Finikas to the village of Mega Yalos and the the whole cape south of that line. The maps used for the field work were aerial photographs from Google Earth on a scale of 1:5000 overlain with transparent paper for the markings and notes. The study's main focus have been the structural setting but the lithologies have also been taken into account and mapped based on the description of the various rock types summarized by Keiter *et al.* (2011). Locations which have not been mapped within the study area have been left out for reasons such as very steep terrain, no bare outcrops and private owned land etc.

The strike and dip of the foliation together with the trend and plunge of the stretching lineations were mapped at each location using a compass. Approximately 200 measurements were taken. Where they were visible, shear sense indicators were also marked on the map. These have been determined with criteria used from Simpson & Schmid (1983) and Fossen (2016).

At 9 locations samples were collected and made into thin sections which were perpendicular to the foliation and parallel to the stretching lineation. The samples were collected where no shear sense indicators could be found in the field, where opposite shear senses were found or where further information on the shear sense was suitable. The samples were later systematically analyzed in microscope to determine if shear sense indicators were present, based on Simpson & Schmid (1983), and if so, if they supported the orientation observed in the field or not.

4. RESULTS

Figure 2 is the the result of the mapping conducted for the studies containing the lithologies of the area. Sample locations along with location of pictures have also been marked out for reference where they are mentioned in the study. The southwest of Syros is dominated by Komito gneiss along with metabasites and schists, all of which have a greenschist overprint, in agreement with earlier mentioned papers. Where blueschist relicts have been found they are marked in figure 2. For simplicity the quartzite have not been marked in the map since it appeared in close contact with both the greenschist and the gneiss all over the south cape, but only in meter scale thick layers. However, serpentinite and marble have been marked since they were rarer even though they did not appear in larger scale than the quartzite did.

4.1 General structure: Foliation and lineation

As seen in figure 3, the foliation planes dip directions varies a lot on the Mavra Vounakia peninsula. However, analyzing the rose diagram it is possible to detect a slight preference for the foliation planes in trending NE-SW. Further, the foliation planes are generally dipping quite steeply. The stretching lineations are shallowly plunging and oriented E/SE-W/NW, seen in the stereogram/ rose diagram in figure 4, with the majority of the measurements being between 60° and 150° as well as between 240°-330°.

4.2 Shear sense indicators: Mesostructures

The shear sense indicators found on the Mavra Vounakia peninsula varied depending on the rock type, figure 5 shows some examples. The massive, blocky metabasites which abundantly outcropped in the middle of the cape, a bit inshore, usually had smaller scale indicators, such as shear bands or C' and S' structures. The komito gneiss and the albitic mica schists usually contained large, boudinaged quartz veins, deformed porphyroclasts or asymmetric structures, along with shear bands in a larger scale than the metabasite. The quartzite was closely associated with deformed porphyroclasts or C' and S' fabric, as well as some shear bands and quartz veins.

Figure 4 shows the stretching lineations and the associated senses of shear where they were visible in the field or after analyzing the samples collected. Opposite shear sense indicators as well as measurements of the lineation where no shear sense indicators were found are also marked.

Top-to-the-E shear sense indicators

Top-to-the-E sense of shear, marked with red arrows in figure 4, was abundant along the east coast of the cape as well as appearing spread out over the rest of the study area. The stereogram/rose diagram in figure 6 shows that the stretching lineations associated with top-to-the-E sense of shear are slightly more centered around the E-W trend of orientation than that of the whole set of data outlined in figure 4. The stretching lineations are dominantly between 90°-120° to 270°-300° which means that the top-to-the-E shear sense is directed towards 90°-120°. Of all the measurements taken, 46 % were interpreted as having top-to-the-E sense of shear based on indicators such as shear bands, boudinaged quartz veins, crystal defor-

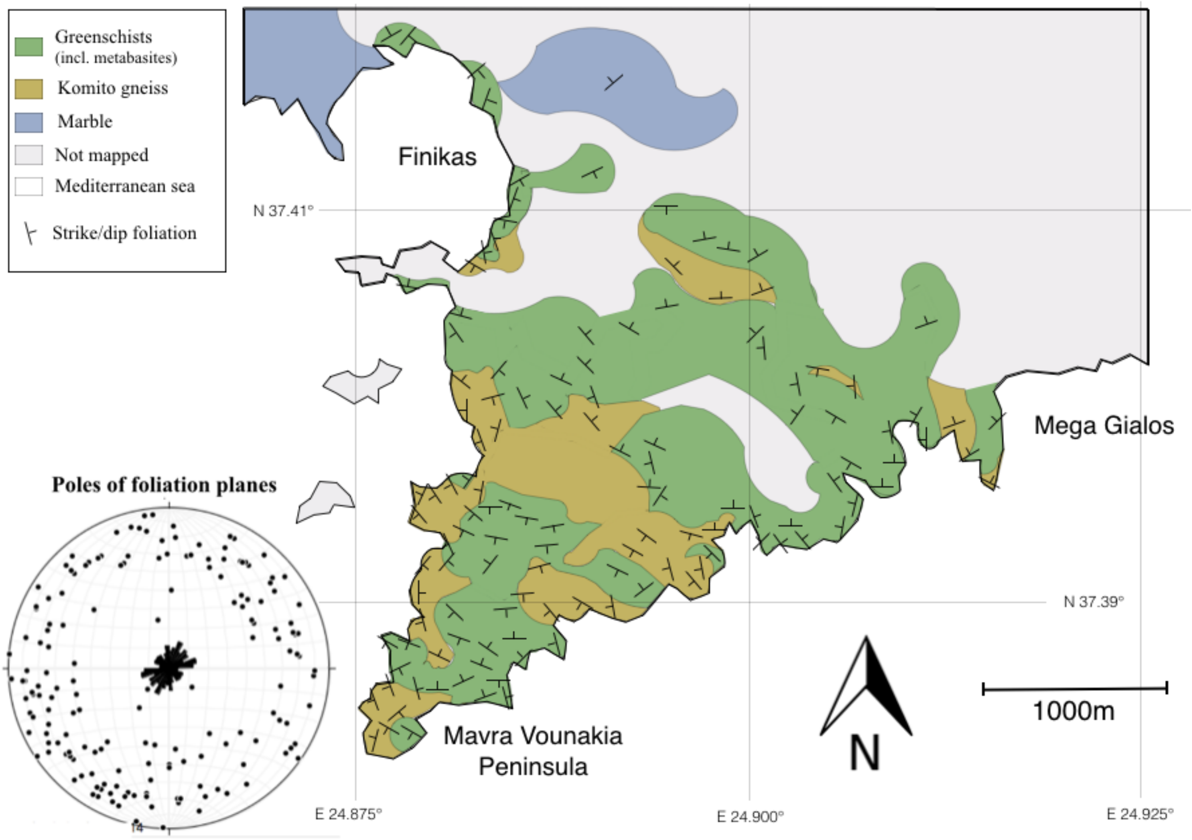

Figure 3. Map of the Mavra Vounakia peninsula with the foliation. The poles of the foliation have been plotted in a stereogram and rose diagram.

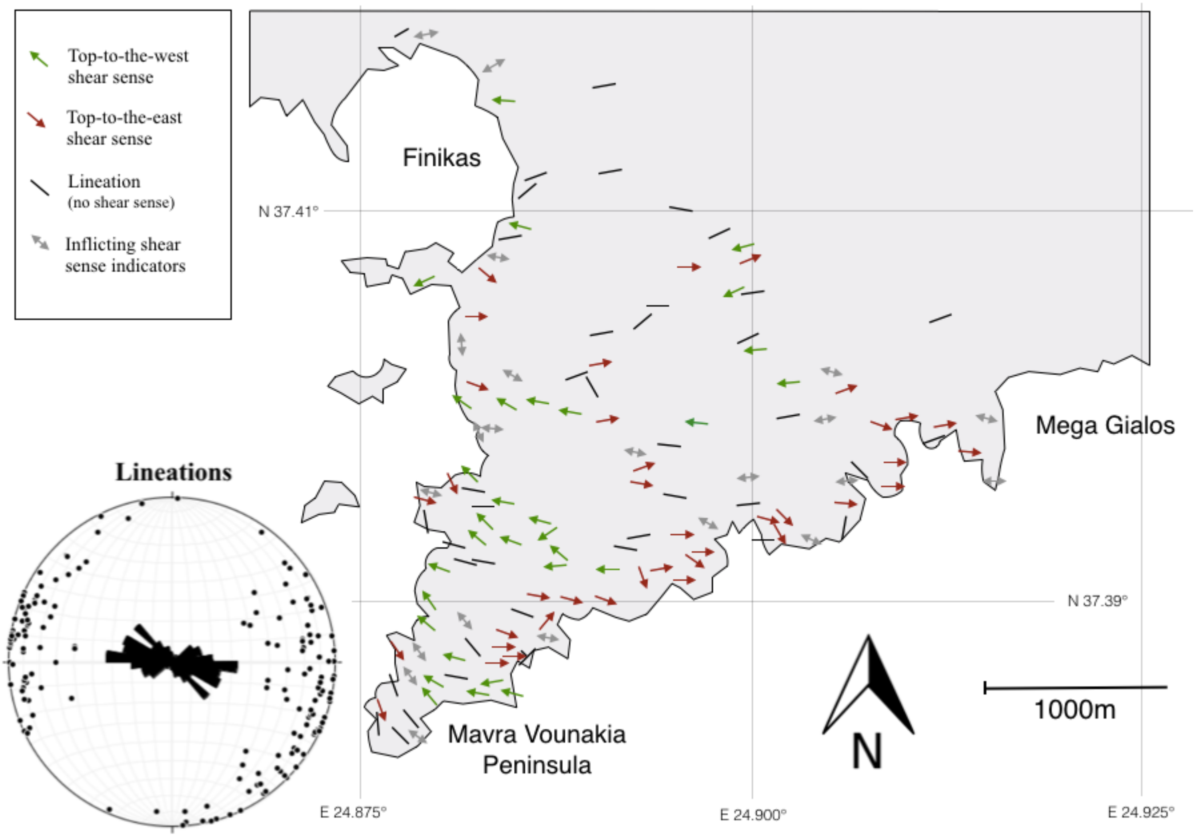

Figure 4. Map of the Mavra Vounakia peninsula showing the stretching lineations and associated sense of shear. The stretching lineations have been plotted in a stereogram and rose diagram which show a WNW-ESE trend.

mation and asymmetric figures. Table 1 is showing the percentage of times where the different shear sense indicators were base for interpreting the shear sense in the field. As seen the majority of the interpretations were based on shear bands. Top-to-the-E shear sense indicators consisted of a slightly higher percentage deformed/boudinaged quartz veins, but a slightly lower percentage of asymmetric figures as indicators than the total. The top-to-the-E shear sense indicators are found in equal amounts in the gneiss and in the metabasite/schists.

Top-to-the-W shear sense indicators

Not only top-to-the-E shear sense indicators were found in the study area. Top-to-the-W sense of shear was interpreted in 28 % of the locations studied and they are marked with green arrows in figure 4. They were equally distributed over the whole study area with the exception of the east coast where almost only east indicators were found. The stretching lineations associated with top-to-the-W shear sense indicators are not as centered around the E-W orientation as those of the top-to-the-E shear sense indicators, seen in figure 7. However, the average of the stretching lineation's orientations still leads to the direction of the top-to-the-W senses of shear being between 270°-300°. Table 1 shows that, like the top-to-the-E shear sense indicators, the interpreted top-to-the-W shear sense indicators are dominated by shear bands, with a slightly lower percentage of deformed quartz veins and higher percentage of asymmetric figures than the total. Unlike the top-to-the-E shear sense indicators, 75 % of the top-to-the-W shear sense indicators are found in the metabasites/schists where only 25 % of them are found in gneisses.

Figure 5. Shear sense indicators. 1) Shear band in greenschist with top-to-the-W sense of shear. 2) A winged porphyroclast in a gneiss with top-to-the-W sense of shear. 3) C' and S' fabric in a quartzite with top-to-the-E sense of shear. 4) Boudinaged quartz vein in a schist with top-to-the-E sense of shear.

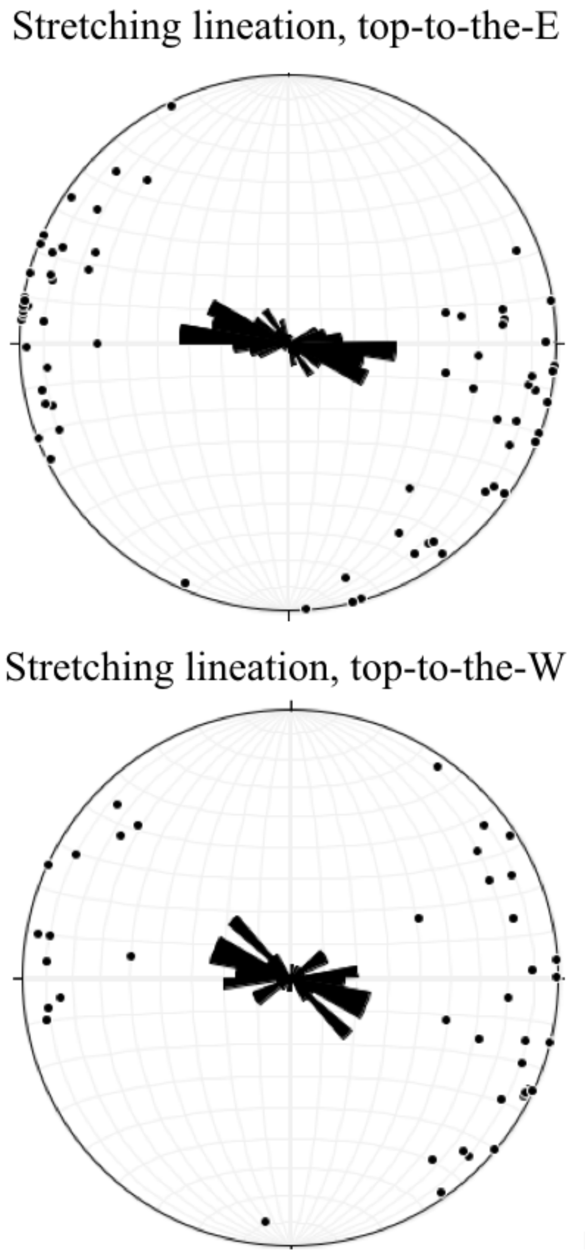

Figure 6. Stretching lineations associated with top-to-the-E and top-to-the-W senses of shear plotted on two different stereograms/rose diagrams.

Shear sense based on:	Top-to-the-E	Top-to-the-W	Total
Shear bands	59 %	58 %	58 %
Deformed quartz veins	18 %	12 %	16 %
Deformed porphyroclasts	13 %	14 %	14 %
C' and S' fabric	4 %	4 %	4 %
Asymmetric figures	6 %	12 %	8 %

Table 1. Shear sense indicators and the percentage of times that interpretation of the sense of shear in the field was based on them.

Conflicting shear senses

16 % of the locations where measurements were taken, the outcrop showed conflicting shear sense indicators. Both top-to-the-E and top-to-the-W shear sense indicators were found, at places only a few centimeter from each other. The different senses of shear were at the majority of the locations indicated by the same kind of indicators. No overprinting criteria could be found between the conflicting indicators. Where lawsonite pseudo-morphs were found, which was approximately 7 locations, they were associated with both top-to-the-W and top-to-the-E shear sense indicators.

Post-foliation folding

At a few locations, but far from all of them, local post-foliation folding were detected with the fold axis subparallel to the stretching lineations. The foliation which had been folded were at places containing shear sense indicators which indicated different directions of shear dependent on which limb they belonged to. Post-foliation folding were only detected and visible in approximately 15 % of the outcrops analyzed. These 15 % were equally distributed between locations with a trend of top-to-the-W and a trend of top-to-the-E shear senses.

4.3 Shear sense indicators: Microstructures

Following is a short description of the findings and observations made from analyzing the thin sections made from the samples collected. The locations of the samples are marked on the map in figure 2. The orientation of the stretching lineations along with possible shear senses in the field are available in table 2.

Sample 1

Viewed under the microscope, sample 1 shows a penetrative foliation of aligning white mica- and chlorite crystals. Quartz, epidote and amphibole appears in patches all over the sample but does not contribute to the foliation. Chlorite together with some white mica makes up three visible shear bands. Two smaller ones and one that cuts across half of the thin section, figure 7. These shear bands indicate top-to-the-W.

Sample	Lineation	Shear sense in the field	Shear sense in thin section
1	232°N	Not visible	Top-to-the-W
2	81°N	Not visible	Top-to-the-E
3	101°N	Inflicting	Top-to-the-E
4	115°N	Top-to-the-E	Top-to-the-E
5	101°N	Top-to-the-E	Inflicting
6	275°N	Not visible	Top-to-the-W
7	290°N	Not visible	Inflicting
8	114°N	Inflicting	Not visible
9	96°N	Inflicting	Inflicting

Table 2. Stretching lineation, shear sense in the field and shear sense in the thin section for all of the samples.

Sample 2

Sample 2 contains a lot of quartz interlayered with white mica minerals. Albite appears in small quantitates. The mica minerals are at two places cutting across the foliation made up by quartz and mica and is interpreted as shear bands in top-to-the-E direction. C' and S' structures are also found which supports the top-to-the-E shear sense.

Sample 3

Sample 3 is like sample 2 very quartz- and mica-rich. It contains small amounts of chlorite. In the middle of the thin section there is a large asymmetric structure where the mica crystals are bending around a center of chlorite and quartz. The structure is interpreted as top-to-the-E. Further, throughout the section, the mica crystals are forming a C' and S' fabric around quartz and albite crystals, also this structure is interpreted as top-to-the-E, figure 7.

Sample 4

Sample 4 contains minor amounts of quartz, along with albite and epidote. Chlorite is the most common mineral, overprinting the other minerals throughout the whole sample. Epidote crystals are aligned with an angle to the overall foliation, possibly indicating that the shear sense was top-to-the-E but that the crystals did not have time to align completely. Apart from that the sample contains no other shear sense indicators.

Sample 5

Sample 5 is a quartz-rich rock, it contains a large structure in the middle with the crystals aligning in a top-to-the-W direction, figure 7. Mica minerals are surrounding a core of quartz, epidote, chlorite and albite which forms an asymmetric structure. However, the mica crystals are in other parts of the section bending down as shear bands in eastern direction which indicates top-to-the-E shear sense direction. Sample 5 is interpreted as containing opposite shear sense indicators.

Sample 6

Sample 6 is similar to sample 4 in that the whole thin section is overprinted by chlorite which is the most common mineral, at some places it is still biotite. It also contains albite, mica, some quartz and a few epidote crystals. An asymmetrical cluster of crystals appears to have been dragged out with top-to-the-W sense of shear. In another part of the section the mica and chlorite is forming C' and S' fabric around albite crystals also indicating top-to-the-W.

Sample 7

Sample 7 is also overprinted with a lot of chlorite. Further, it contains an abundant amount of albite and epidote and minor amounts of small quartz crystals. In the thin section the chlorite is at two places bent down to form what is interpreted as shear bands top to the west, figure 7. But also visible are albite crystals which have been turned top to the east with tails of chlorite. Sample 7 is interpreted as containing opposite shear sense indicators.

Sample 8

Sample 8 is very rich in epidote, chlorite and mica minerals, some biotite and minor amounts of quartz. The foliation is not as clear as the other samples and the crystals are aligning in sort of a wavy pattern, creating possible shear bands in both directions. Further, crystal inclusions in the mica and chlorite minerals are turned in both directions which indicates both top-to-the-E and top-to-the-W shear senses. Since the sample lacks a clear foliation it is hard to tell if the structures viewed and described are shear sense indicators at all.

Sample 9

Sample 9 shows a strong sense of shear with thin, elongated minerals aligning with the foliation. It contains quartz, albite, mica, epidote and chlorite. Crystals are dipping to both top to the west and top to the east, but no tails or strain shadows are found which could help when determining the shear sense. The sample is interpreted as containing conflicting shear sense indicators.

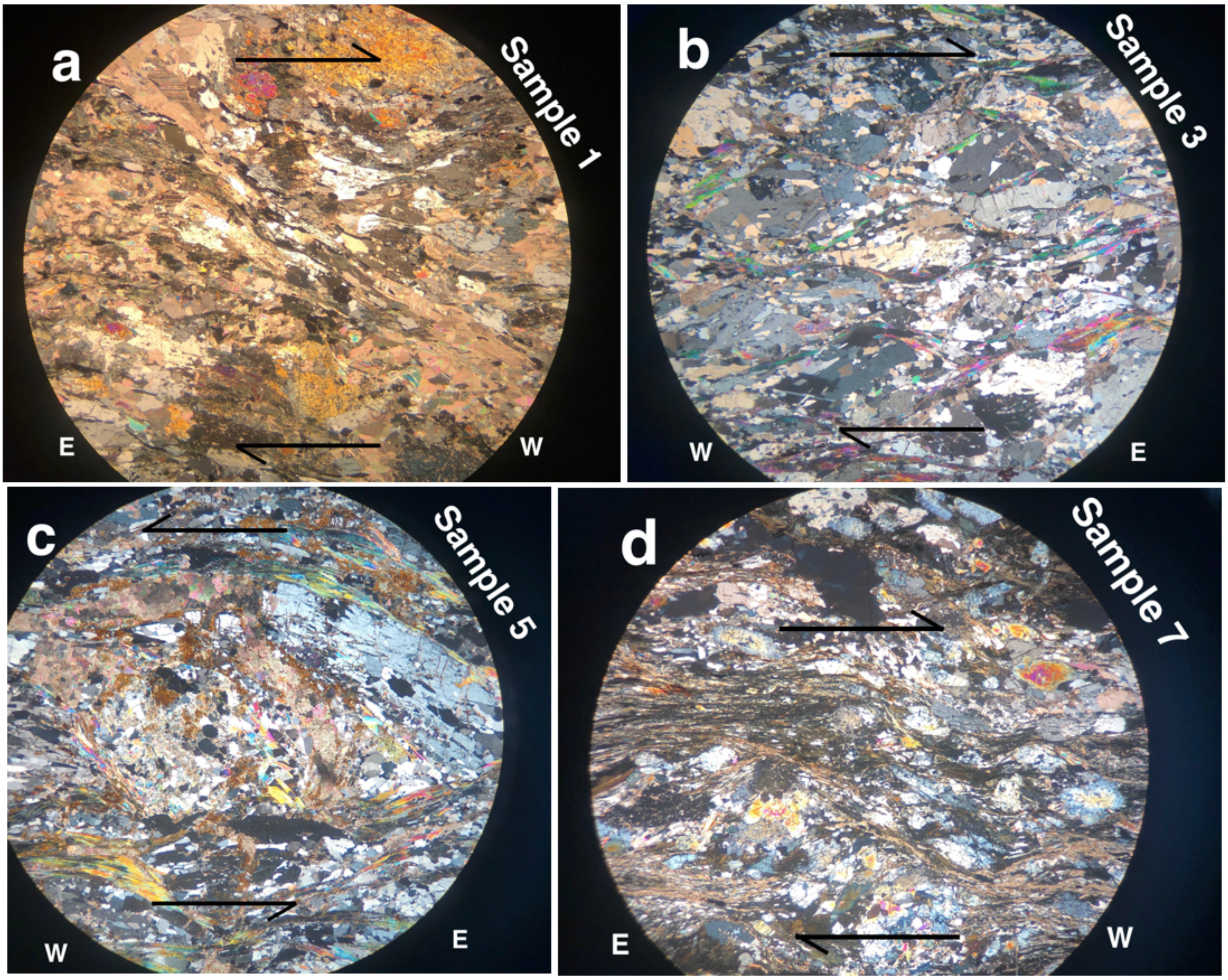

Figure 7. Shear sense indicators in the thin sections. a) Shear band in sample 1 with top-to-the-W sense of shear. b) C' and S' fabric in sample 3 with top-to-the-E sense of shear. c) Asymmetric structure top-to-the-W in sample 5. d) Shear band in sample 7 with top-to-the-W sense of shear.

Summary: Microstructures

The analysis of the thin sections showed shear sense indicators in both directions as well as opposite shear sense indicators in three of the samples. No overprinting criteria could be found within the samples with opposite shear sense indicators. Top-to-the-E shear senses were abundantly connected to C' and S' fabric, which were absent in association with top-to-the-W shear senses. Apart from that, no other difference between the top-to-the-E and top-to-the-W shear sense indicators could be found.

The sense of shear conducted from the samples have also been marked in figure 5, together with the senses of shear interpreted in the field.

5. DISCUSSION

5.1 Different shear senses and their spatial distribution

Keiter *et al.* (2004) argued that no penetrative deformation was taking place in the CBU after peak metamorphism. This was questioned by etc. Laurent *et al.* (2016), Philippon *et al.* (2011) and Bond *et al.* (2007) and this study shows results which would support the latter authors. Shear sense indicators are found which meet criteria for them being formed together with the greenschist facies; chlorite, together with white mica, are the minerals which makes up the shear sense indicators in most of the thin sections. Further, field observations does not support that the greenschist overprints the shear sense indicators that are found, but instead seems to be formed synchronous with them. The theory by Keiter *et al.* (2004) is therefore, at least on the southwestern part of the island, not applicable.

Laurent *et al.* (2016) and Philippon *et al.* (2011) dedicated top-to-the-E/NE shear to the retrograde metamorphic event. Indeed, top-to-the-E shear sense indicators are found in this study as well, but also top-to-the-W. Top-to-the-W shear has earlier been connected to the subduction process on the basis that it was mainly found in the northern parts of Syros and associated with blueschist/eclogite facies (etc. Bond *et al.,* 2007; Laurent *et al.,* 2016; Keiter *et al,* 2004, 2011). Laurent *et al.* (2016), in figure 1, showed opposite senses of shear around Finikas and Komito, which this study is supporting. But the results in this study show that, even though not as many as the top-to-the-E shear sense indicators which constitute 46% of all the locations where measurements were taken, top-to-the-W shear sense indicators were found in 28% of the locations and many of them were documented without top-to-the-E indicators in close association which could be interpreted as opposite senses of shear. This does not necessarily contradict the earlier studies, since none of the mentioned ones above have marked the shear senses on the Mavra Vounakia in their papers (etc. Laurent *et al.,* 2016, fig 1), or showed other results which shows shear sense directions on the peninsula. Even if the result of this study does not directly contradict their findings it does open up for further research on the topic since it seems unlikely for top-to-the-W shear sense indicators, in the amount found in this study, to be isolated to the peninsula.

Looking at the distribution of the two different shear senses in figure 4 the top-to-the-E indicators dominate the east coast of the peninsula which is in agreement with the map from Laurent *et al.* (2016) which have marked top-to-the-E/NE shear sense in the top east corner around Mega Yalos. Apart from the east coast's abundance in top-to-the-E senses of shear, the spatial distribution of the different shear senses does not show a clear pattern. They do however appear in patches which locally show preference for one shear direction above the other which could be interpreted as in agreement with Bond *et al.* (2007), Rosenbaum *et al.* (2002) or Philippon *et al.* (2011) in their theory of conflicting shear senses as a result of the preferences of the host rocks, based on their different properties.

5.2 Orientation of the stretching lineations on the Mavra Vounakia Peninsula

The average orientation of the stretching lineations on the Mavra Vounakia peninsula diverges from that of more northerly parts of the study area as well as even further north. Philippon *et al.* (2011) and Laurent *et al.* (2016), when discussing the shear senses documented on Syros, described the orientation of these shear senses and therefore also the stretching lineations as trending SW to NE, on a regional scale. As seen in figure 1, other orientations of the stretching lineations which are trending more E to W are also documented on the rest of the island, but the main trend is a SW to NE one when they discuss the stretching lineations with associated shear senses. In figure 5. these orientations can be found around Mega Yalos and Finikas as well as the area in between. But on the Mavra Vounakia peninsula and in the major parts of the measurements taken in this study, the orientations of the stretching lineations show trends more NW/W to SE/E. However, looking at figure 1, the map from Laurent *et al.* (2016), their documented stretching lineations on the Mavra Vounakia is similar to this study's measurements, but that is not taken into account in their discussion of the shear senses since they have not documented any shear senses on the peninsula.

Figure 6 and 7 show the variations in stretching lineation orientations depending on which sense of shear they are associated with. Looking at these figures the top-to-the-W and the top-to-the-E shear does only slightly diverge from one another. Of course more measurements need to be taken to investigate this more accurate but only based on this study's measurements it appears that the two shear senses have at least a very similar, if not the same, orientation. The small difference in average orientation of the lineations between the top-to-the-W and top-to-the-E senses of shear is probably a result of the fact that a lot of the data for the top-to-the-E senses of shear comes from the east coast which has a slightly more SE-NW trend, independent of the direction of the shear.

5.3 Different ones or one and the same deformation event?

No matter the direction of the shear, the deformation event affecting the Mavra Vounakia peninsula does not show any proof of belonging to a time before peak metamorphism, the majority of the shear sense indicators are associated with a severe greenschist overprint. The exception is where small scale blueschist relicts are found, places which for some reason were untouched by the retrograde metamorphic event, most likely due to a local lack of fluid.

Even though both the top-to-the-W and top-to-the-E senses of shear belong to the exhumation it does not take out the possibility that the two senses of shear belong to different deformation events which both occurred under greenschist facies conditions. It is however hard to determine the timing, if it is the same or not, for the opposite senses of shear. In the results where opposite shear senses were found they were not associated with any visible evidence of that overprinting had occurred which would support two deformation events, but that is not enough to conclude that they belonged to the same deformation event.

As discussed earlier, the orientations of the stretching lineations associated with the different shear senses do show a slight difference. But other than that, the top-to-the-W shear sense indicators and the top-to-the-E shear sense indicators do not diverge markedly from one another. In table 1, the results of the different shear sense indicators which was the base for the interpretation of the shear senses in the field do not differ between top-to-the-E and top-to-the-W for more than a few percent, which is within the margin of error and can be overlooked. Neither in the microstructures were there any significant differences between the two senses of shear.

If the opposite senses of shear were the result of reopening of subduction related shear zones in the exhumation, as Laurent *et al.* (2016) were suggesting, then there should have been some kind of overprinting criteria and/or a systematic difference between the subduction related indicators and the exhumation related ones. But the result does not point to such findings and consequently does not support the theory for opposite shear sense indicators proposed in that study.

The result does seem to be consistent with both the hypothesis proposed by Bond *et al.* (2007) and Rosenbaum *et al.* (2002) discussing the exhumation as the result of coaxial extension and only local preference deciding the direction of shear, as well as the one proposed by Huet *et al.* (2009) and Jolivet *et al*. (2009) where the opposite senses of shear appeared synchronous in both the subduction and the exhumation due to ductile flow. Both of these alternative would explain why opposite senses of shear are observed with such similar appearances as they show and without any overprinting criteria. The fact that the shear sense indicators spatial distribution shows that they for some reason have formed in clusters rather than just randomly over the study area would support Bond *et al.* (2007) and Rosenbaum *et al.* (2002) over Huet *et al.* (2009) and Jolivet *et al*. (2009). But further research needs to be done on the subject to be able to discuss the cause of formation more accurately. As discussed by Philippon *et al.* (2011) the opposite senses of shear do not need to reflect a regional scale coaxial deformation. In fact the deformation event could have been non-coaxial and the shear sense indicators that opposite the direction of the regional scale shear are the result of, for example, a viscosity differences between layers.

5.4 Post-foliation folding

Sometimes occurring together with the opposite senses of shear was a folding which post-dated the foliation. Since the fold axes were subparallel to the stretching lineations, their orientation remained more or less the same, but it could have inversed the shear sense indicators. This was observed at a few locations. So the folding was, at least at a few locations, the source for the opposite senses of shear. However, opposite senses of shear were observed at many locations where no post-foliation folding could be detected. It is of course a possibility that the folding was not visible in outcrop scale and was in fact a much larger structure which affected the shear sense indicators, but it is a far reach and nothing in the results supports such a conclusion.

It is the interpretation that the post-foliation folding is having a minor role in the distribution or appearances of inflicting shear senses on the Mavra Vounakia peninsula. Supporting this is the fact that the locations which showed folding appeared both in areas with top-to-the-W trend and top-to-the-E trend and no pattern could be found which connects one shear sense direction to the folding. Therefore, it is more likely that the the folding only had an affect on a small, local scale.

5.5 Exhumation history

Regarding the exhumation history of the CBU, it is difficult to discuss any regional scale theories based on the result from this study. However, the rocks of the Mavra Vounakia peninsula have undergone a greenschist overprint with accompanying deformation. It is therefore possible to determine that they have not been exhumed as part of a coherent passive unit, as proposed by Keiter *et al.* (2004). But the data collected is not comprehensive enough to say for certain that this has not been the case for other parts of the CBU.

At least one, if not more, deformation events took place during the exhumation of the greenschist overprinted unit of the CBU. More research needs to be done to determine the connection between the top-to-the-W and top-to-the-E shear sense indicators to say for certain that they belong to the same deformation event, but all the results collected point towards them being formed during one and the same event. However, it is still a possibility that more than one deformation event occurred during the exhumation and had impacts on the shear sense indicators on the southwestern cape.

Further, the Mavra Vounakia peninsula was according to the direction of the lineations measured in this study as well as by Laurent *et al.* (2017) subject to a slightly different direction of shear than the average direction which supposedly affected the island. The cause of this is still not investigated, but it is most likely connected to the exhumation.

6. CONCLUSION

In this study, structural mapping of the southwestern part of Syros has lead to the conclusion that the greenschist overprint is accompanied by at least one deformation event. Both top-to-the-E and top-to-the-W shear sense indicators were found, as well as locations with opposite shear sense indicators, with top-to-the-E indicators being the most common. The direction of shear was found to be between either 60°-150° or between 240°-330°, which is, anti clockwise, slightly more E-W trending than the average of Syros.

No clear evidence of that the opposite senses of shear belong to different deformation events could be found, including no visible overprinting criteria in the field nor in the microstructures, as well as no pattern in their spatial arrangement that would suggest different deformation events. The post-foliation folding documented in the area is concluded to not have an affect on the regional scale distribution and direction of the shear senses.

The explanation which holds the greatest support in the results for the opposite senses of shear, according to the interpretation of their appearance and spatial arrangement, is that they formed as a result of local preference in their host rock. However, it is hard to say if non-coaxial or coaxial strain operated on regional scale.

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