Bachelor Thesis

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Structural mapping and tectonometamorphic analysis of high-pressure rocks in Eastern Sikinos, Cyclades, Greece

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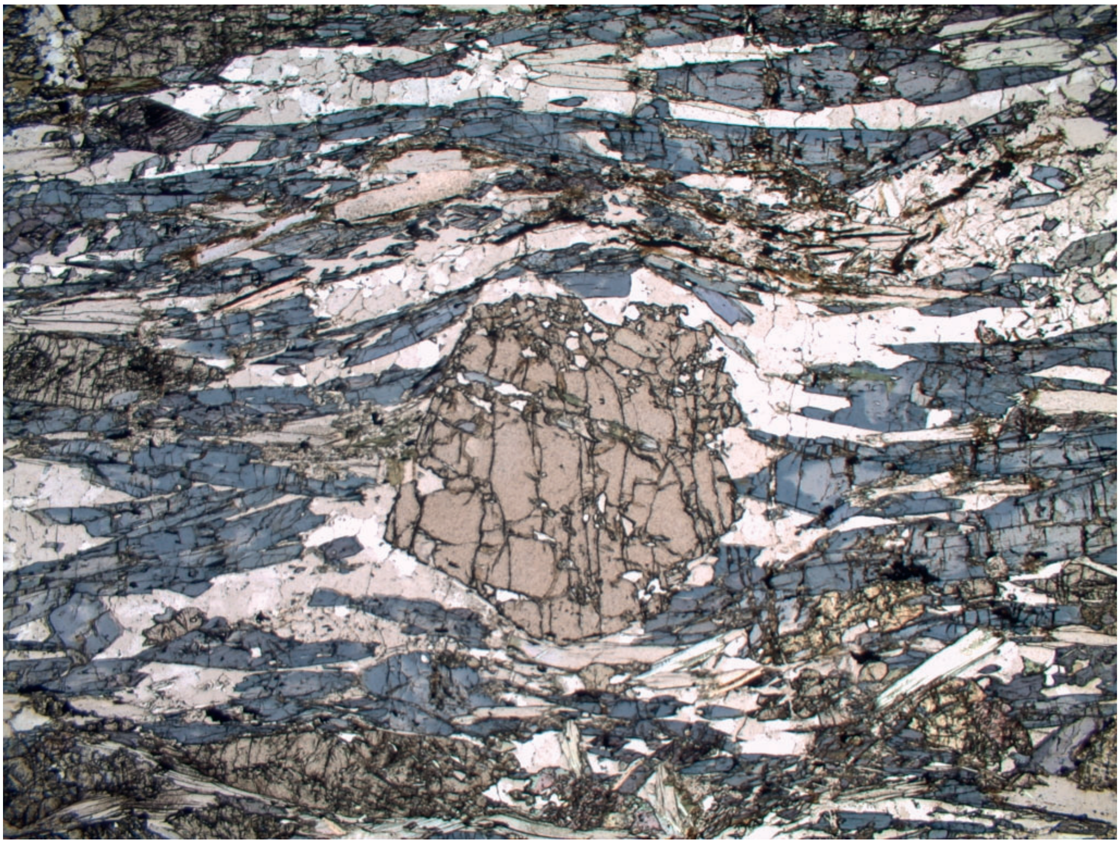

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Contents

Abstract

This bachelor thesis investigates the structural and metamorphic evolution of metamorphic rocks in Eastern Sikinos, Cyclades, Greece. Field mapping and thin section petrography reveal a tectonometamorphic history dominated by subduction-driven deformation and subsequent exhumation during slab-rollback. Blueschist-facies rocks exhibit a top-to-the-North shear sense, consistent with subduction processes, while greenschist-facies overprints indicate a top-to-the-South shear, reflecting later extensional tectonics. Thin section analysis shows significant chloritisation and retrograde minerals in greenschist-facies samples. Preservation of glaucophane in blueschist-facies rocks is found to varying degrees of decomposition. These findings support indications of a bivergent extension, influenced influenced by slab rollback and exhumation.

1. Introduction

Sikinos is an island in the Southern Cyclades, a chain of islands in the Aegean Sea in Greece. The geology of Sikinos is dominated by rocks of the Cycladic Blueschist Unit, which shows examples of spectacular high-pressure rocks.

These rocks have been studied extensively on islands such as Syros, Sifnos, and Naxos in the Cyclades archipelago. In contrast, other islands – like Sikinos in the southern Cyclades – have received relatively little attention from geologists. The tectonic history of Sikinos has been examined more closely since Augier et al. (2015) started to investigate Sikinos and neighbouring Folegandros, taking abundant structural measurements.

1.1 Objectives

Glodny and Ring (unpublished data) have dated two blueschist samples from Sikinos, sample SIK 20-8 from Agios Georgios Bay in the NE provided an age of 38.6 ± 1.3 Ma and sample SIK 20-11 from near Chora an age of 30.4 ± 2.0 Ma. With the background of standard orogenic models (e.g., Platt, 1986), this would suggest that the older blueschist in the NE was thrust onto the younger blueschist in the W.

The goal of the thesis was to investigate the mineralogy and the structural relationship between the two outcrops of Cycladic blueschists of different ages. Throughout the project, the objective is to systematically map the area between the two dated blueschists. In the field, tasks included measuring the strike and dip of the foliation, as well as the trend and plunge of the stretching lineation. The shear sense was determined both in situ on a mesoscopic scale and in the laboratory through thin section interpretation.

An important aspect was to correlate the metamorphic mineral assemblage of the rocks with the P-T evolution and their respective significance throughout subduction, decompression and exhumation.

In conclusion, the objectives are to

1. map structures and rock types in the field.
2. take samples from different sites for analysis in thin sections.
3. report the findings of the practical work in a concise report and discuss the results in the context of earlier research.

2. Geological Setting

Southern Greece, with the Aegean Sea, is famous for its rocky archipelagos, shaped by millennia of human settlement. Volcanic islands such as Santorini and Milos have become popular tourist destinations. Beneath this veneer of human history lies a complex system of geologic structures, driven primarily by the northward subduction of the African plate beneath the Eurasian plate and subsequent slab rollback (Ring et al., 2010) during the Tertiary (Brun and Sokoutis, 2010). The underlying orogenic system in the eastern Mediterranean is commonly known as the Hellenides – or sometimes as the Hellenides-Taurides, when including related orogenic structures in Turkey.

2.1 The Hellenides within a Continental Context

Modern plate margins show an almost globally active convergent system that has formed many of the modern mountain ranges, the so-called Alpine System. Developing since the Cenozoic and still active, it is divided into two major complexes: the Alpine-Himalayan (or Tethyan) belt and the Circum-Pacific orogenic belt. They differ fundamentally in their tectonic activity: continent collision dominates the Alpine-Himalayan belt, and subduction dominating the Pacific belt (Papanikoláou, 2021, p. 2). The Alpine-Himalayan belt stretches along the margins of Laurasia and Gondwana, from the Iberian Peninsula through the Alps, Balkans, Caucasus, and Himalaya to Indonesia (Papanikoláou, 2021, p. 2; Storetvedt, 1990).

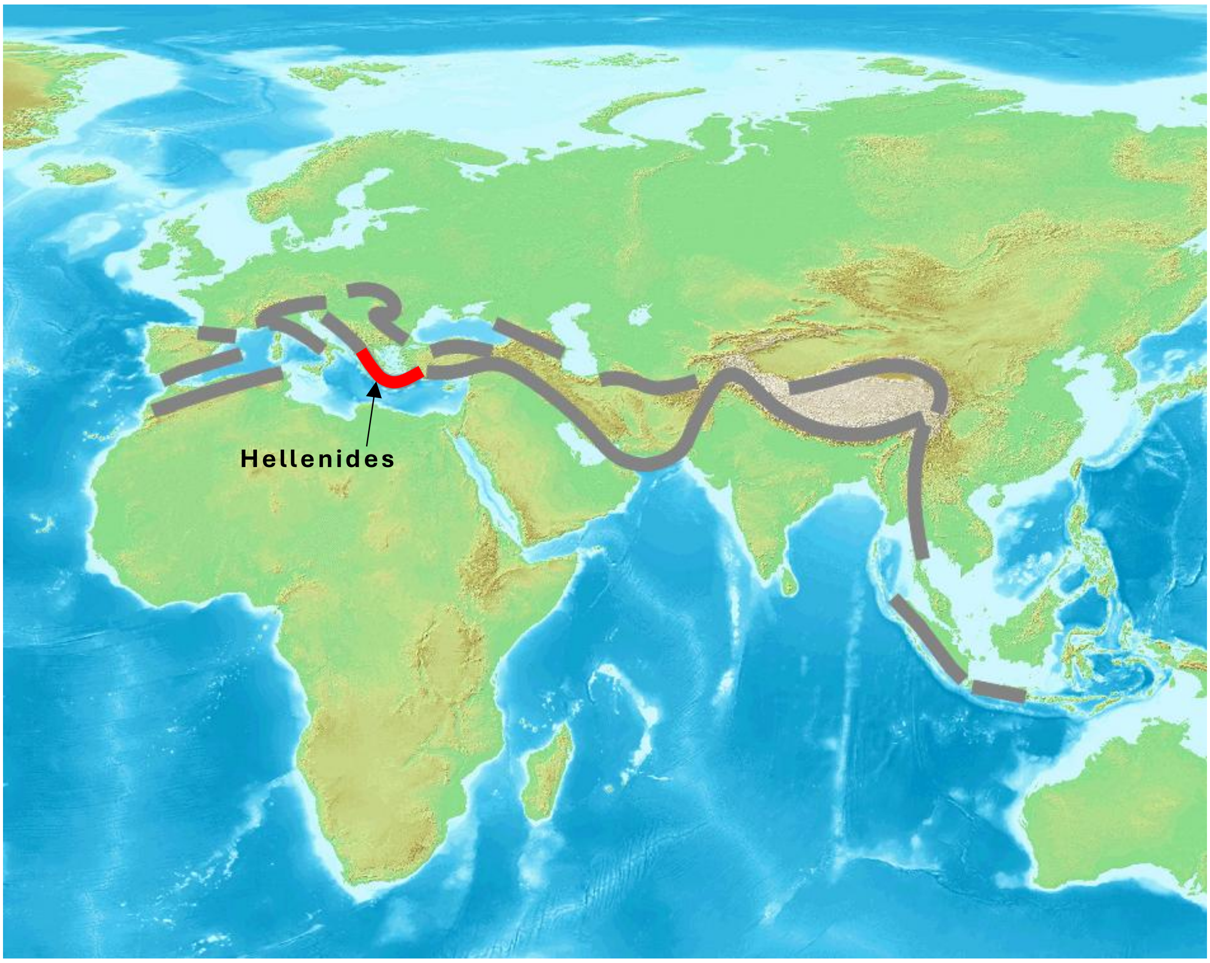

Figure 1: An overview over the Alpine-Himalayan System. Image by Jo weber, German Wikipedia, released into the public domain, with added emphasis of the Hellenides (in red).

Modern Europe displays evidence of the Tethyan orogenic belt along the major mountain chains of its southern margin. The Tethyan orogens extends along the Mediterranean and include the Atlas, the Alps, the Apennines, the Dinarides (Balkan) and the Hellenides (Balkan/Greece). The Tethyan system then extends into modern Turkey through the Taurides.

The Hellenides stretch in an arcuate shape from the Ionian Sea through the Aegean Sea, with Crete and Rhodes at their southern limits, before continuing towards the Dodecanese. Beyond the Dodecanese, they extend on to the Turkish mainland, where they are called the Taurides. South of the central orogenic system lies the Hellenic arc and trench systems, offshore Rhodes, Crete and the Ionian Islands. This arc and trench system delimits the southern front of the Aegean microplate, which to the northwest terminates in the Kefalonia-Preveza transform fault and in the East along structures that lie subparallel to the Anatolian coast (Papanikoláou, 2021, p. 6).

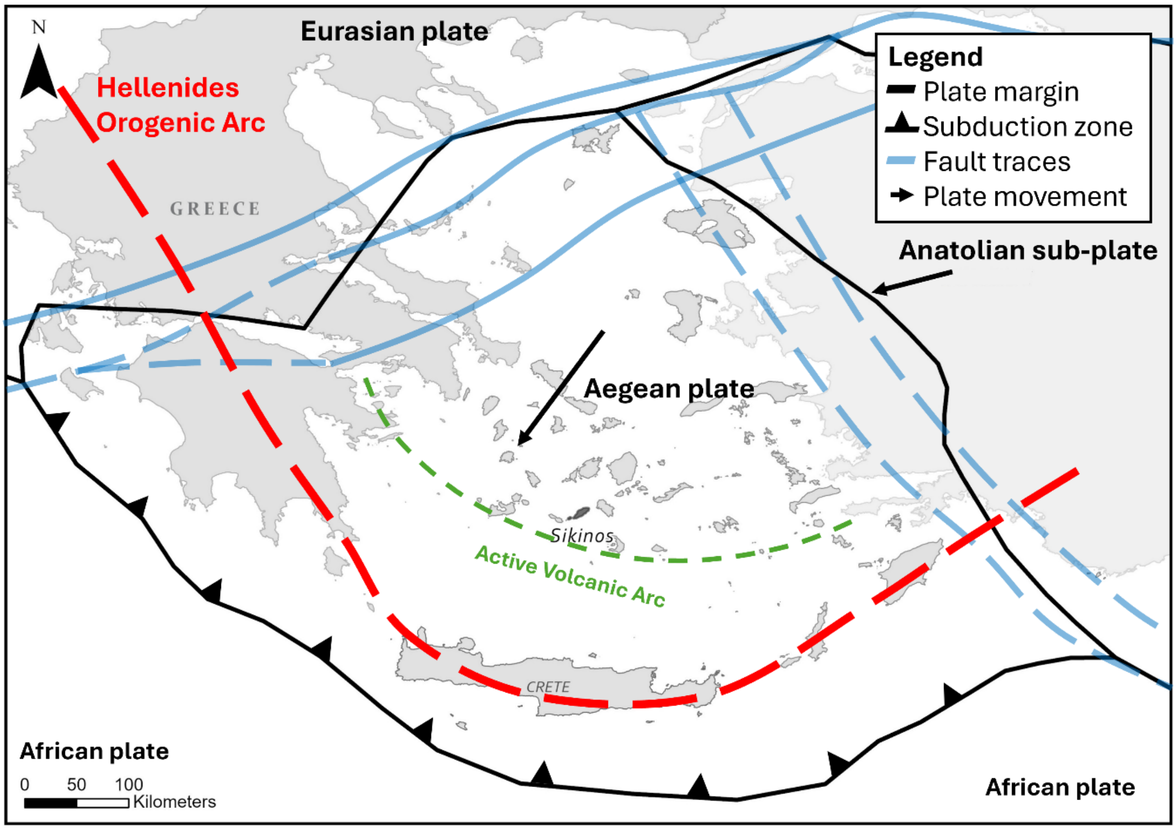

Figure 2*: A geographical overview of Sikinos within the Cyclades, SE of Attica on the Greek mainland, and bordering the Turkish east coast. Background map sourced in ArcGIS from OpenStreeMap and GADM. Tectonic structures after Papanikoláou (2021).(Papanikoláou, 2021) Plate borders sourced from Github repository (Anthelius, 2014)* after Peter *Bird (2003).*

The Hellenides formed as a result of the convergence between the African and Eurasian tectonic plates, where a subduction zone has been active since the Eocene (Augier et al., 2015). The convergent process has resulted in a complex system of trenches, volcanic arc activity, and crustal deformation. Over time, slab rollback and trench retreat initiated the back-arc extension and thus uplift of the arcuate orogen, forming a series of islands and mountains, extending from the Ionian Sea to the western Aegean Sea, by exhumation (Ring et al., 2010).

2.2 The Geologic Setting of the Cyclades and Sikinos

Sikinos, together with Folegandros and Ios, is part of the Southern Cyclades and was exhumed in the back-arc basin and does not have recent volcanic history, unlike nearby Santorini and Milos, which are part of the active volcanic arc. In general, the Aegean islands are part of an orogenic belt whose current architecture was largely shaped by slab rollback, rather than by purely collisional convergence (Augier et al., 2015). On Sikinos, the related detachment systems are called the West Cycladic Detachment System (WCDS), that shows primarily a top-to-the-South shear sense, and the North Cycladic Detachment System (NCDS), with a primarily top-to-the-North shear sense (Augier et al., 2015; Ring and Glodny, 2021). The nappe stack (Augier et al., 2015), in the Cyclades is composed of the:

a) Pelagonian Unit (not found on Sikinos and therefore not further discussed)
b) Cycladic Blueschist Unit (CBU)
c) Cycladic Basement

A small part of the bedrock of Sikinos consists of Cycladic basement, found mainly on the southern coast of the island, while the overlying CBU covers the rest of the island, compare Figure 3, which is used with permission from Ring and Glodny (2021). Folegandros to the West consists mainly of the CBU, while Ios, to the East, has a massive core of basement with CBU attached to the northern and southern tips (Augier et al., 2015).

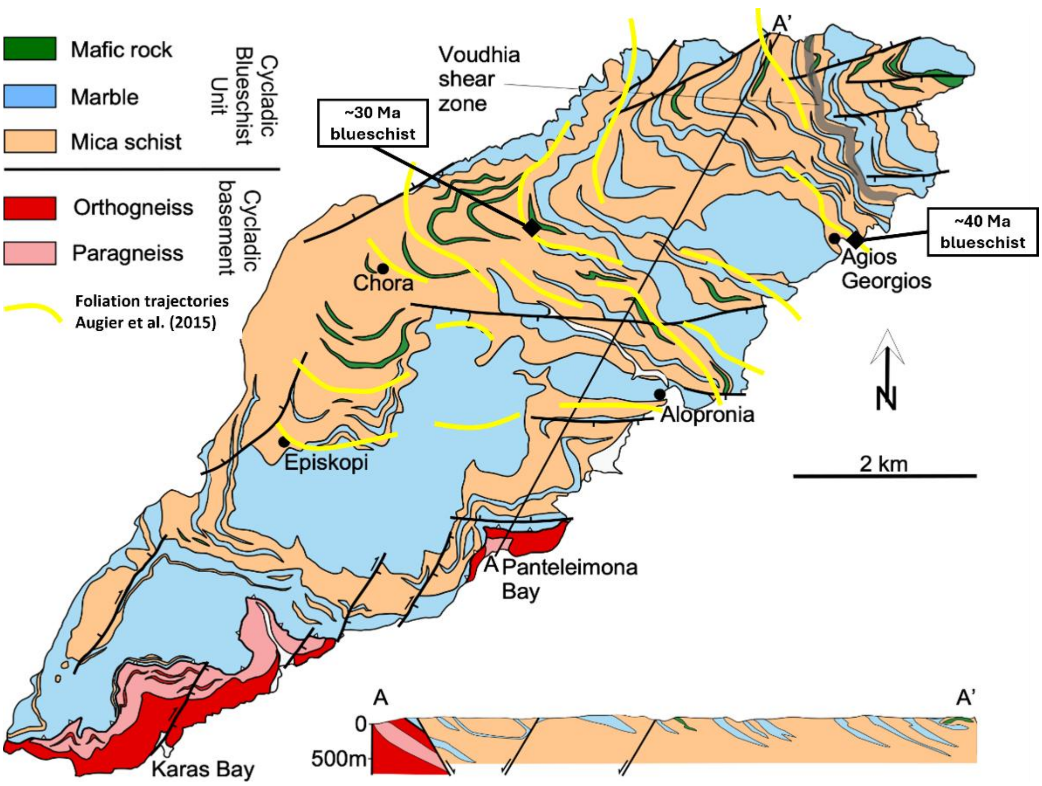

***Figure 3**: An overview over Sikinos, based on Ring and Glodny (2021) with additional foliation trajectories in yellow, extracted from Augier et al. (2015). The dating of the blueschists is based on unpublished data from Glodny and Ring. The CBU and Cycladic basement are shown as well.*

The basement consists of pre-Alpine metamorphic rocks such as metagranodioritic gneiss, and metamorphose aplitic (metaaplitic) dikes, metavolcanics (quartz porphyry), garnet-mica schist, and amphibolite (Ring and Glodny, 2021). These rocks, that originate from the Carboniferous (325—310 Ma), underwent multiple metamorphic events, from early Carboniferous metamorphism over Tertiary HP metamorphism, before it underwent near-isothermal decompression and greenschist-facies overprint (Augier et al., 2015). The overlying CBU sequence, is a 6–7 km thick (Augier et al., 2015) unit composed of calcitic and dolomitic marble, mica schist, and metabasite lenses (eclogite, blueschist, and greenschist) of the passive-margin (Ring and Glodny, 2021).

The metamorphic rocks in Sikinos were found to generally dip shallowly towards North (Ring and Glodny, 2021), exhibiting normal faults that towards both North and South, resulting from North-to-South extension. Several shear zones, which have been mapped by Augier et al. (2015, fig. 2), suggest that the island, as a block, has been tilted towards the Northeast.

Augier et al. (2015) have taken structural measurements, to estimate the sense of shear, over larger parts of Folegandros and Sikinos. Their results show distinct north and northeast kinematics for blueschist-facies (top-to-the-North/Northeast shear sense), while the greenschist-facies shear sense is less obvious, showing some top-to-the-South shear sense. Ring and Glodny (2021) determined that high pressure rocks (blueschist-facies) exhibited more often even top-to-the-South shear sense or a mixed top-North/top-to-the-South shear sense, while greenschist facies rocks during decompression and exhumation showed a dominant top-to-the-South sense of shear.

2.2.1 Cycladic Blueschist Unit

This Cycladic Blueschist Unit on Sikinos, is made up mainly of metapelites and marbles, including a “significant component” of metabasites (Augier et al., 2015) – it is, as such, considered a composite unit. The CBU has undergone blueschist-facies conditions during the subduction period, which have later been overprinted by greenschist-facies conditions. In Ring and Glodny (2021), the Cycladic Blueschist Unit across the Cycladic archipelago has been divided into three nappes, reflecting their sheetlike structure and sideways displacement, and dated to about 53, 40, and 30 Ma respectively.

On Sikinos, two different outcrops of blueschist have been dated: one at Agios Georgios Bay to about 40 Ma, and the other, at the beginning of the road to Agios Georgios and Chora to 30 Ma (Glodny & Ring, unpublished), see **Figure 3**. This relationship implies tectonic movement after subduction and these two outcrops were going to delimit the area of interest for this project in the North and East. In general, production of high-pressure metamorphic rocks follows an age gradient with high-pressure rocks becoming progressively younger toward the South (Ring et al., 2010). These high-pressure rocks forming today beneath Crete are not part of the CBU.

2.2.2 Cycladic Basement

The CBU is settled on top of the Cycladic basement, which has a complex pre-Alpine history, mainly consisting of granodiorites and metapelites. The outcropping basement unit is not found within the field area.

Uplift of the two units has been is linked to two separate stages: the first one occurring during the subduction in the Eocene, by means of a subduction channel or an extrusion wedge, the latter occurring in the Oligocene and Miocene during back-arc tectonics and post-orogenic extension (Augier et al., 2015).

2.2.3 A Short Review of Petrology in the Context of Sikinos

Clayey, pelitic rocks that undergo diagenesis have a common mineral assemblage of muscovite + chlorite + albite + quartz + clay minerals. During prograde metamorphism, epidote, biotite and chloritoid can be produced while the rock experiences increased pressure at low temperatures (LT). With further pressure increase, the temperatures remain relatively low (in a subduction environment) while pressure reaches high-pressure (HP) conditions, and the rock enters blueschist facies. In blueschist-facies conditions, glaucophane, lawsonite, and phengite form. At blueschist-facies conditions, and even higher pressures associated with eclogite-facies conditions, garnet will form. During decompression, and later exhumation, the process is reversed (retrograde metamorphism), and the rock will travel from HP-LT to LP-LT (low pressure – low temperature) conditions, undergoing greenschist-facies metamorphism again, causing a re-equilibration and consumption of HP-minerals.

The igneous protoliths on Sikinos were either felsic (granodiorites in the Cycladic basement) or basic in the intrusions, which can be found throughout the CBU as metabasite-lenses embedded in the mica-schists.

Metabasites on Sikinos are mainly derived from mid-ocean ridge basalts (Augier et al., 2015) that contain originally plagioclase, amphibole, and pyroxene. During greenschist-facies conditions, chlorite + epidote + albite + quartz will be found, and at blueschist conditions, glaucophane + lawsonite (or epidote) + quartz + garnet will occur, compare Philpotts and Ague (2009, p. 423) for an overview of common minerals in different facies.

2.2.4 Tectonics on Sikinos

Shear sense indicators, such as deformed quartz veins, mica fish, and strain shadows around porphyroblasts, can provide an insight into the movement of crustal blocks in relation to other. Quartz veins can become stretched and asymmetrically deformed, their tails stretched along the dominant transport direction. Mica fish form by the rotation and recrystallisation of phyllosilicates such as micas, that align with the shear plane. This is comparable to strain shadows around porphyroblasts, such as millimetre-scale garnet or amphibole develop: shear forces cause a rotation of the crystal and new minerals form in the strain shadow, indicating the direction of the rotation. These shear sense indicators form while minerals undergoing recrystallisation.

Faulting during extension can reactivate earlier thrust structures that occurred during subduction or can form with a new top-to-the-trench direction. Exhumation leads to bivergent faulting, both top-to-the-trench (i.e., South in the Cyclades) and top-to-the-overriding-plate (i.e., North in the Cyclades, away from the trench). The dip of the bedding foliation during exhumation will be relatively shallow. In the Cyclades, a rotation of the crust has been recorded by Augier et al. (2015), causing an oblique shearing. This is recorded by lineations in the metamorphic rocks, aligning the micaceous minerals along the plunge. Compare Philpotts and Ague (2009, chap. 17) for an overview of deformation and textures of metamorphic rocks.

3. Methods

The field work was done in October 2024 on Sikinos, collecting samples from different sites within the field area, and assessing the relative shear sense in outcrops. Samples were collected mainly from two smaller sub-areas that showed evidence of exposed blueschist and that were not covered by recent sediments. Besides the mapping of strike and dip, plunge and trend, and shear sense indicators, a general mapping of the exposed rock types was attempted.

The area was defined together with Uwe Ring. The area in the bed of a seasonal stream valley area had been identified as a focus point throughout the field study, where Augier et al. assumed a small shear zone (2015). This area was examined and discussed in greater detail, while other parts, especially of the highlands, have been examined to a lesser extent. The highlands are mainly composed of marble and dolomitic marble with few metabasite inclusions.

The field work resulted in two related data sets:

a) Measurements from the field, including the site coordinates, strike and dip of the foliation, trend and plunge of the stretching lineation, mesoscopic shear sense indicators, and finally remarks regarding mineral composition and rock type.
b) Data from microscopic thin section analysis that were cut from 11 taken samples.

3.1 Mapping

In the field, all data was written down manually and later transcribed into Excel sheets, which allowed the easy extraction of sub-data sets for rock types, strike-and-dip, and trend and plunge.

Mapping was done in ArcGIS, using base data from OpenStreetMap, GADM, Copernicus and OpenDEM. The reference system was set to WGS 84/ UTM 33N. Detailed geologic maps of the region are not found as open data, except on a regional scale, for example through the European Geological Data Infrastructure (EGDI) on a scale of 1:5 million, as well as from the US Geological Society (USGS), but were deemed to coarse.

3.2 Shear Sense Indicator Analysis

Taking a shear sense reading from an outcrop requires some interpretation. A shear zone can stretch several kilometres, while mesoscopic shear sense indicators are found on all scales, often several metres and down to microscopic level. The challenge is to assign the found shear sense indicators to

a) the right metamorphic conditions, i.e., blueschist-facies during subduction or greenschist-facies during retrograde metamorphism and exhumation and
b) differentiate the causing events that led to deformation. Later deformations can overprint the original shear sense, which requires to approach shear sense indicators carefully. Passchier and Williams (1996) call it the "problem of non-ideal sections".

Shear sense indicators have been noted by the author in the field, and in some cases – such as ambiguous observations – a picture has been taken, with the orientation of the picture noted. Transport directions need to be recorded in outcrops roughly perpendicular to the plane of strike, which sometimes make it hard to find appropriate outcrops, i.e., on Sikinos shear sense indicators should follow the roughly North to South axis of the dip.

3.3 Thin Section Analysis

Thin section analysis was performed mainly in the laboratory at Stockholm's university. After getting a good overview over structures and mineral composition, the LAS EZ Imaging Software for Windows was used to take photographs of relevant areas within the thin section. The magnification of the images taken was often set to 2.5x, but some of the images have been taken at 10x magnification for greater detail, see the discussion of thin sections below. White balance and exposure were cautiously set in the LAS EZ software directly after taking the image, to give the best possible reproduction of the thin sections.

4. Results

For a better understanding of the area of interest, it was decided to undertake a survey of the most prevalent rock types. The two dominant rock types are (dolomitic) marble, dominating the highlands and along the coast, and rocks that are broadly classified as micaschist, with different levels of chloritisation. The micaschists contain both rocks of the greenschist-facies and of the blueschist-facies. In many cases, incipient chloritisation has been observed. Micaschists contain often porphyroblasts like garnet (up to 5 mm in size) and less often prismatic glaucophanes and epidotes.

The bedrock composition has been investigated at the same sites as the structure points and extrapolated with help of overview images on Google Maps and on several hikes throughout the area. Blueschist has been found in three areas, while weathered metabasites in the greenschist-facies were found in adjacent areas.

At sites 3.3 and 3.5 (for site locations, see **Figure 8**) the mica-schist showed large porphyroblasts of garnet and accumulations of epidote on several outcrops. Even the site clusters 4.x and site 8.7, further up the seasonal stream bed, showed interesting porphyroblasts, making these preferred sites to collect samples. Chloritoid was found at Dialiskari Beach but was first identified in thin section analysis in the laboratory.

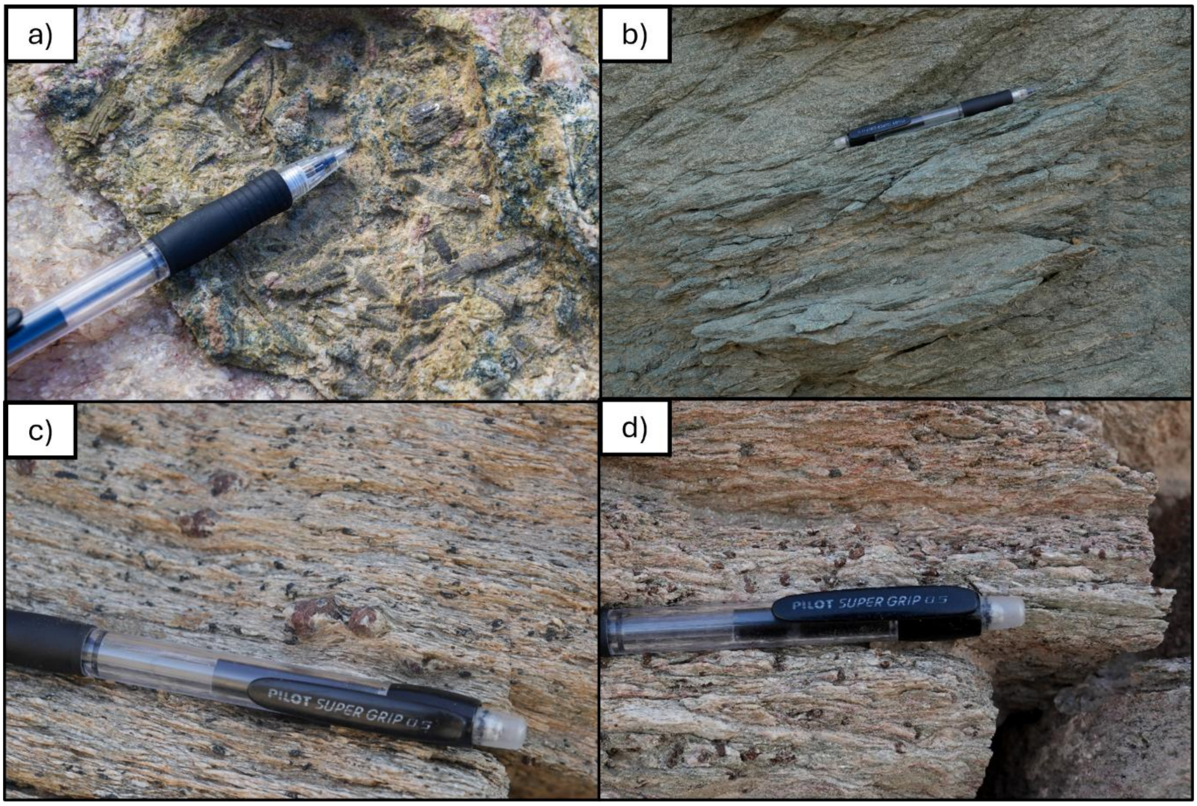

Figure 4*: Some examples of rocks in the field. In picture a) a massive accumulation of epidote is shown; b) shows a typical metabasite layer that is found on several sites, with an intense green colour. Pictures c) and d) show typical accumulations of large garnet porphyroblasts. These were found abundantly around Dialiskari Beach and east of Alopronia. The porphyroblasts have been used to determine shear sense in-situ*

The best-preserved outcrops of blueschist were found around site 6.2, but remnants of blueschist in different stages of decomposition were even found at sites clusters 3.x, 4.x, and 5.x.

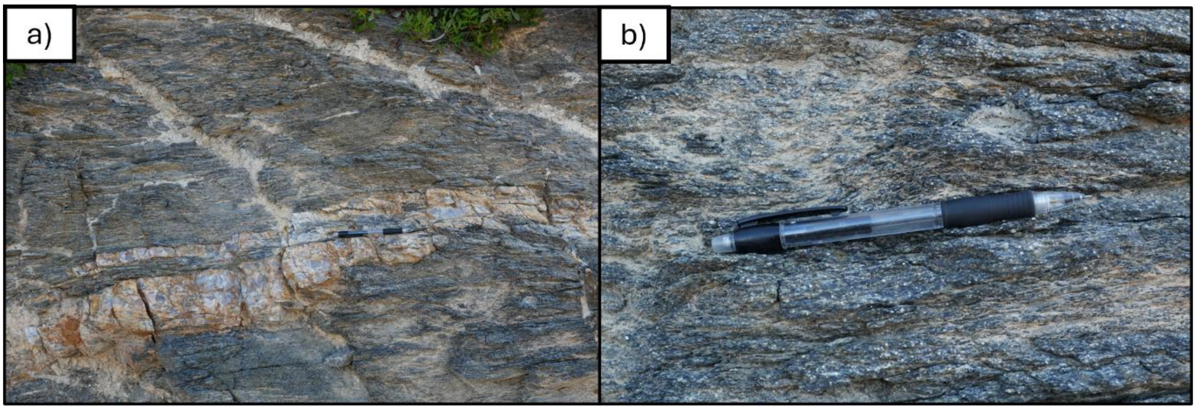

***Figure 5**: An example of a well-preserved blueschist outcrop (a), even though closer examination shows signs of albitisation, which forms during decompression. Pictures taken from outcrops in the vicinity of site 6.2, where even a thin section sample was prepared from.*

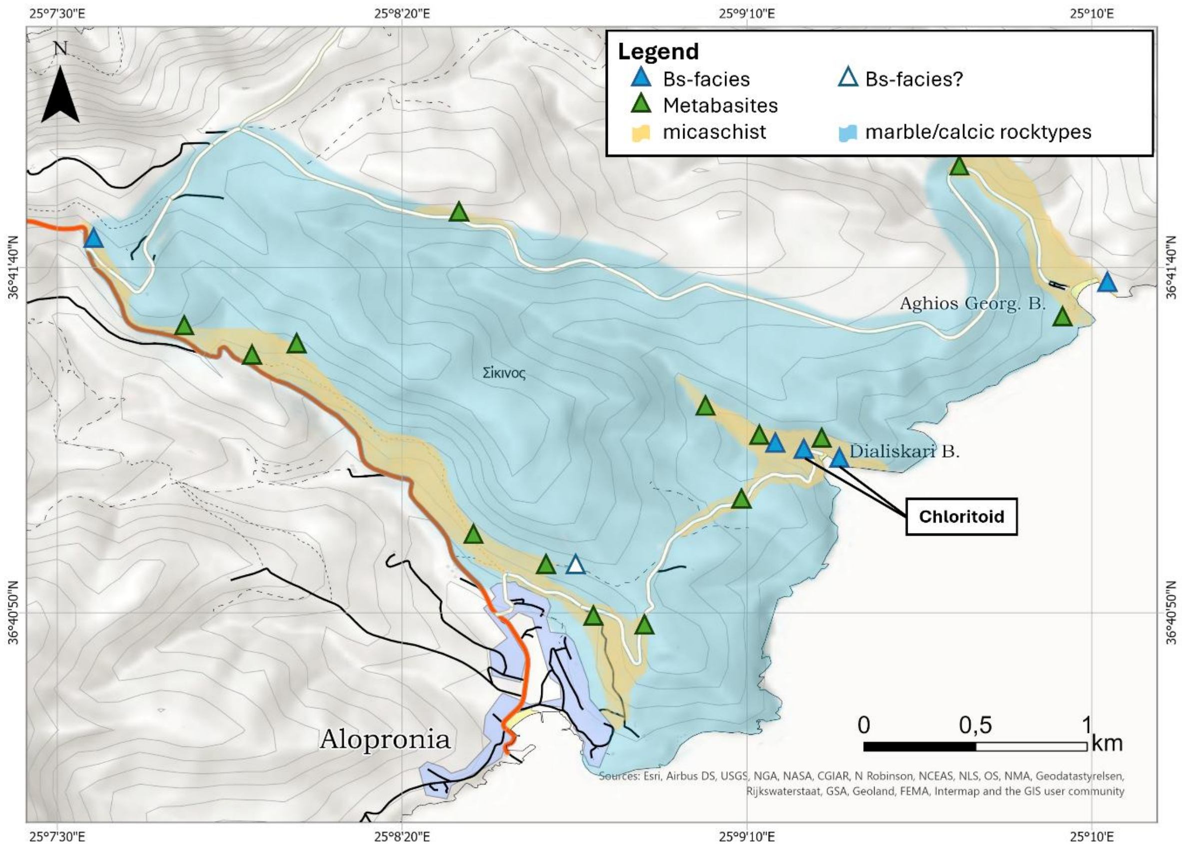

***Figure 6:** An overview over the mapped rock types. The areas are extrapolated from sampling sites, with some of them shown. The abbreviations in the legend, Bs, stands for (remnant) blueschist-facies minerals. Green-coloured triangles show the position of metabasites, which are associated with epidote and greenschist-facies minerals.*

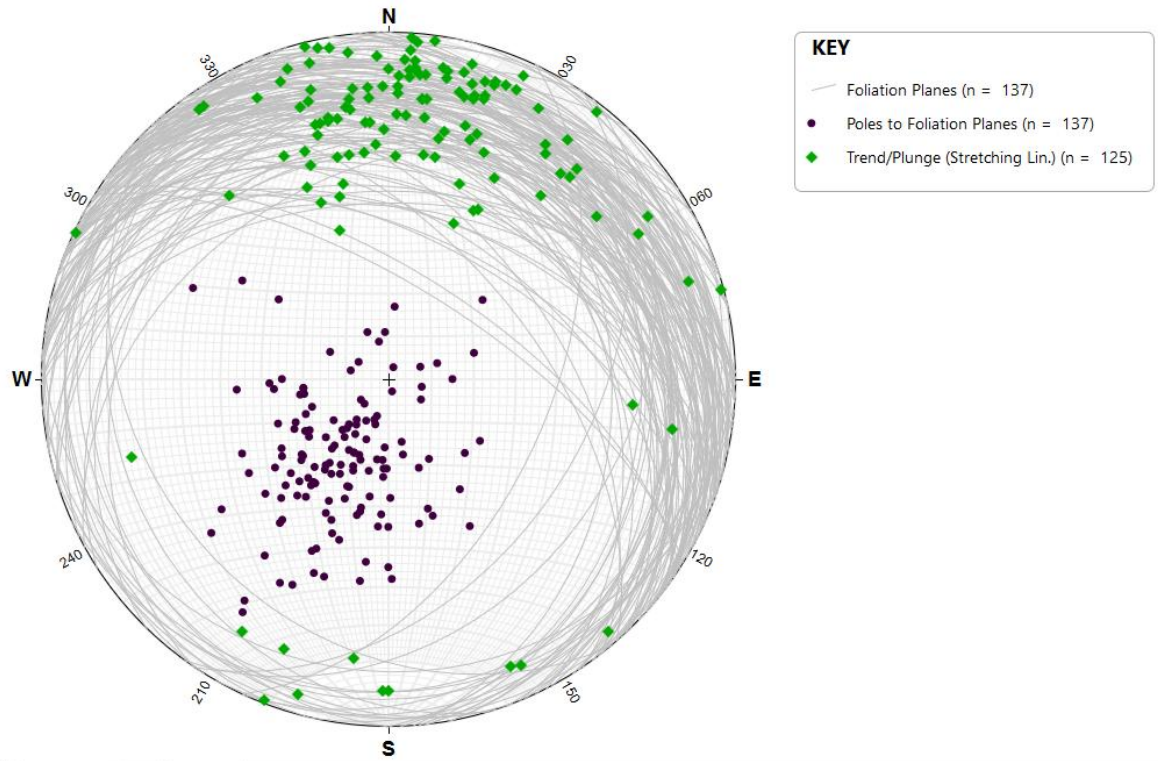

***Figure 7**: A stereonet for the field measurements of structural orientation parameters. The foliation planes have been plotted as great circles in grey, with their poles plotted as black dots. A general shallow dip towards Northeast has been observed. Generally, most of the stretching lineation (in green) follow roughly the same direction towards North, but even with some trending more towards the Northeast. This plot was generated with Stereonet v. 11 (2020).*

The stereonet that was generated from the measured strike/dip and trend/plunge data, shows a general subhorizontal foliation that dips shallowly towards the Northeast, with stretching lineation along a North-South axis. This agrees with the field measurements of foliation planes, shown in **Figure 9**. In the stereonet, the foliation planes are plotted as great circles (in grey) with their poles as black dots, while the stretching lineations (green dots) show a roughly northern orientation, with some variability between 330 N and 060 E.

The strike and dip data has been compared to the foliation trajectories as described by Augier et al. (2015). **Figure 9** shows that the measured foliation planes coincide relatively well with the foliation trajectories of Augier et al.

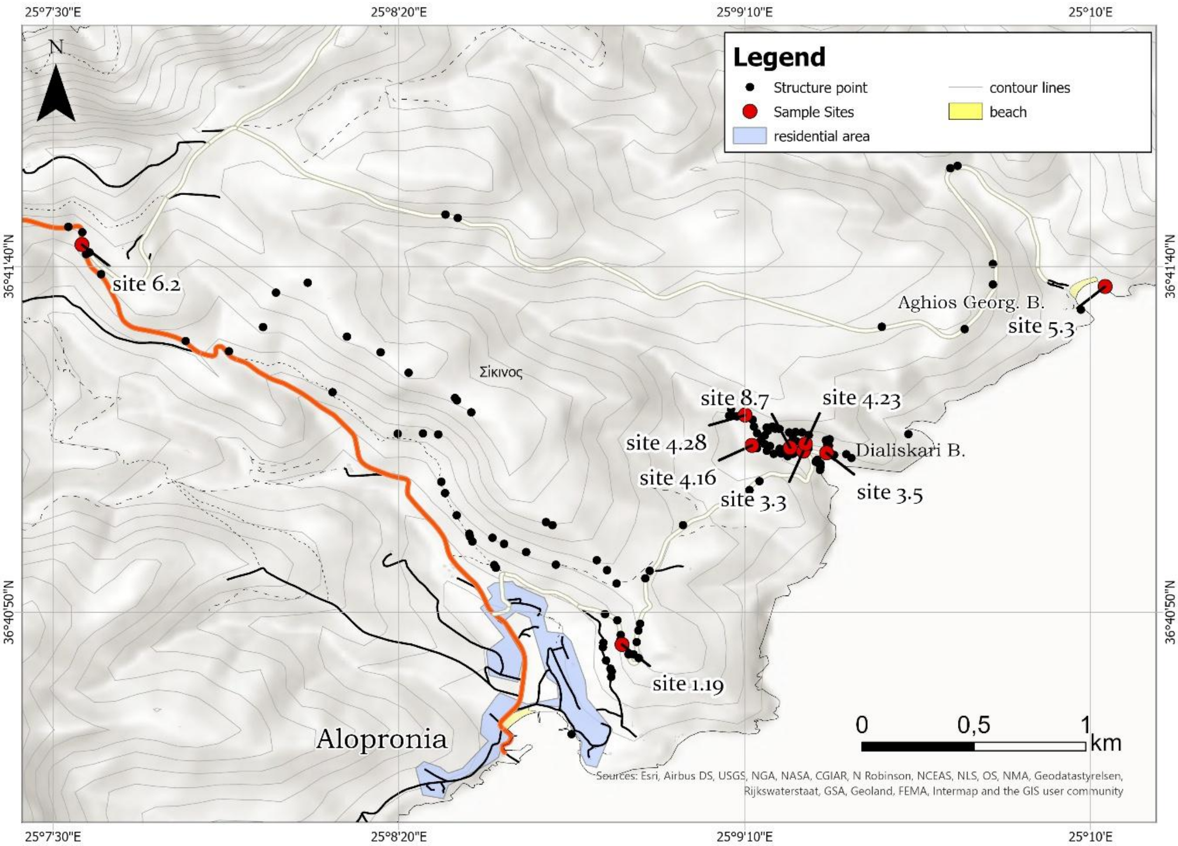

***Figure 8**: An overview over the sample sites that yielded rock samples for later thin section analysis. Structural orientation (strike/dip) were measured at 137 sites and stretching lineations in the same planes at 125 sites.*

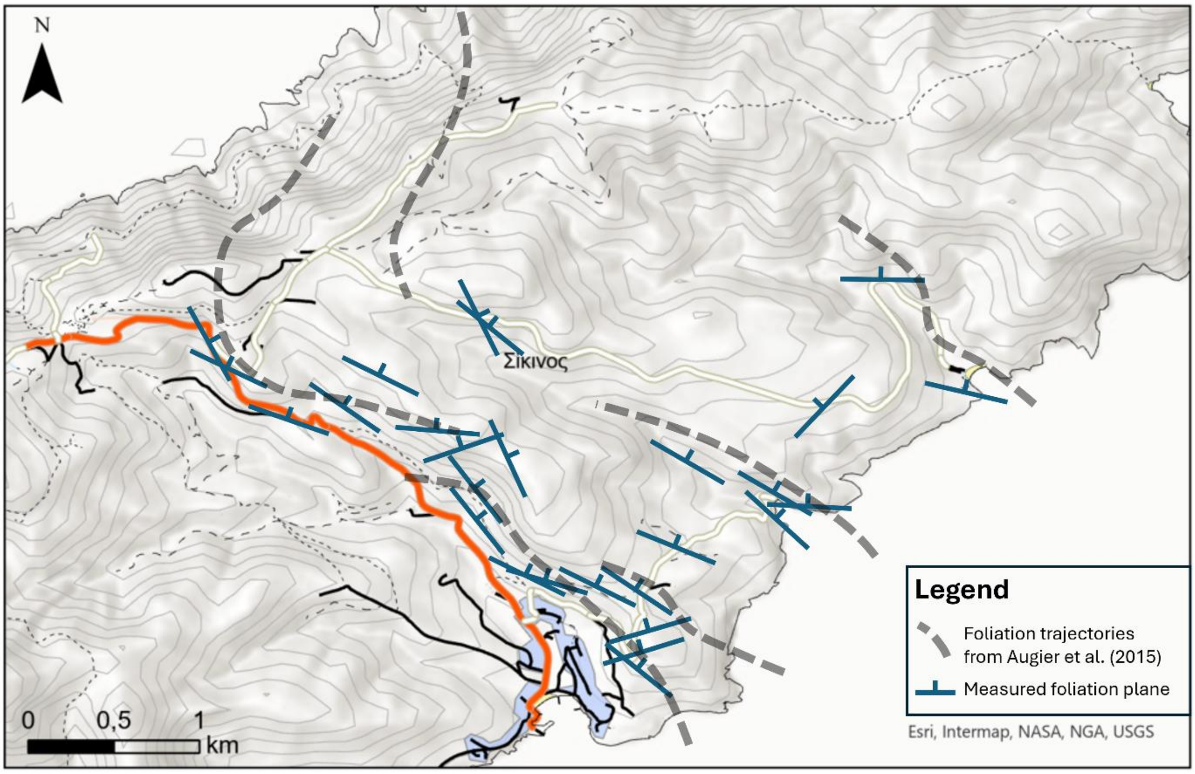

***Figure 9**: Selected measured foliation planes, after excluding outliers and close-by duplicates. These measurements reproduce relatively well the foliation trajectories that were extracted from Augier et al. (2015).*

4.1 Description of Shear Sense Indicators in the Field

Shear sense indicators were recorded wherever possible. Good shear sense indicators are, for example, shear bands in the foliation and deformed quartz veins as well as mica fishes. On a smaller scale, pressure shadows around porphyroblasts can be good indicators of the sense of shear – especially when looking for millimetre-scale garnet crystals. Since a lot of measurements were taken, the following images are used to exemplify what was recorded in the field and later mapped.

Shear sense indicators show mixed top-to-the-North/South for most of the outcrops, especially around Dialiskari Beach and the blueschist outcrop around site 6. Greenschist outcrops showed a clearer picture, with a dominant top-to-the-South sense of shear, for example in the cluster just east of Alopronia, or inland of Dialiskari Beach.

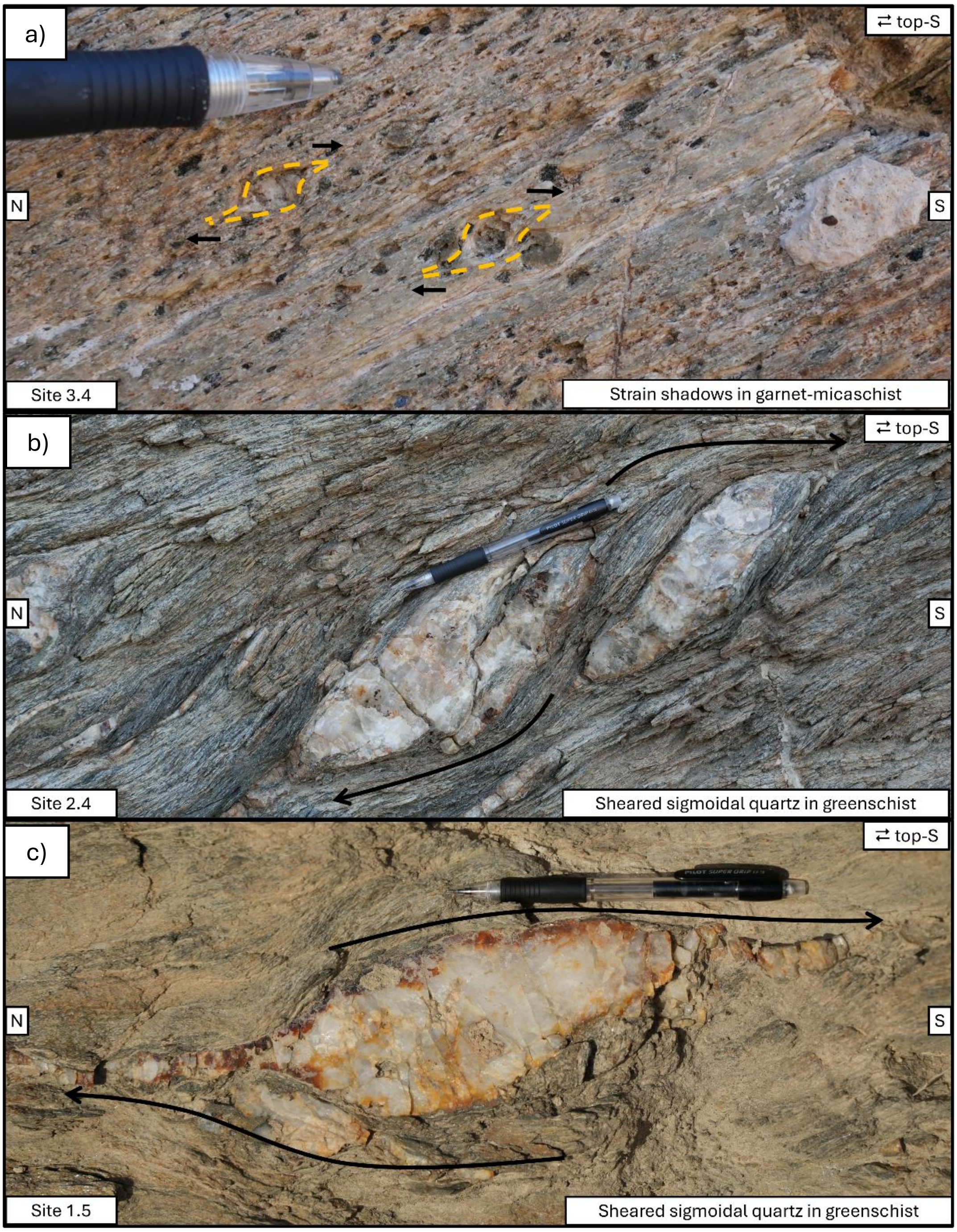

***Figure 10**: Some examples of mesoscopic shear sense indicators. Image a) shows the empty sockets of garnet porphyroblasts, with strain shadows of mica that have manifested around the holes. Image b) and c) show different sheared sigmoidal quartz veins with a strain shadow of mica (chlorite) indicating the shearing direction, as well as tails of stretched quartz.*

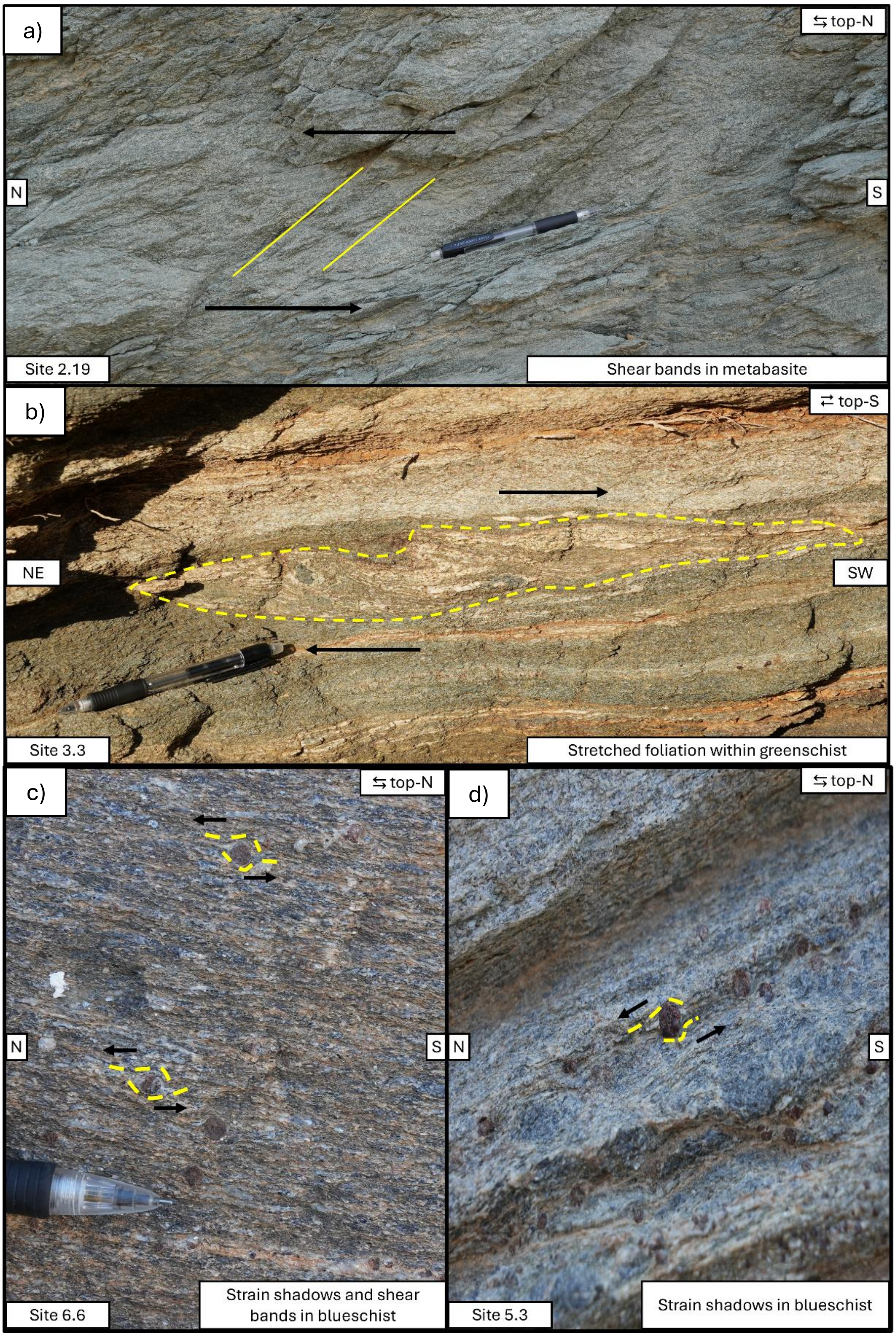

Figure 11*: More examples of shear sense indicators found in the field. Image a) shows some shear bands in a metabasite. Image b) shows different layers being stretched out, possibly formed by similar mechanisms that overturn folds (compare Carreras et al. (2005, fig. 15)). Image c) shows examples, very similar to* ***Figure 10*** *a) with garnet porphyroblasts still embedded in the blueschist and surrounded by strain shadows. Image d) was taken at Agios Georgios Bay where a possible contact between greenschist and remnant blueschist was found.*

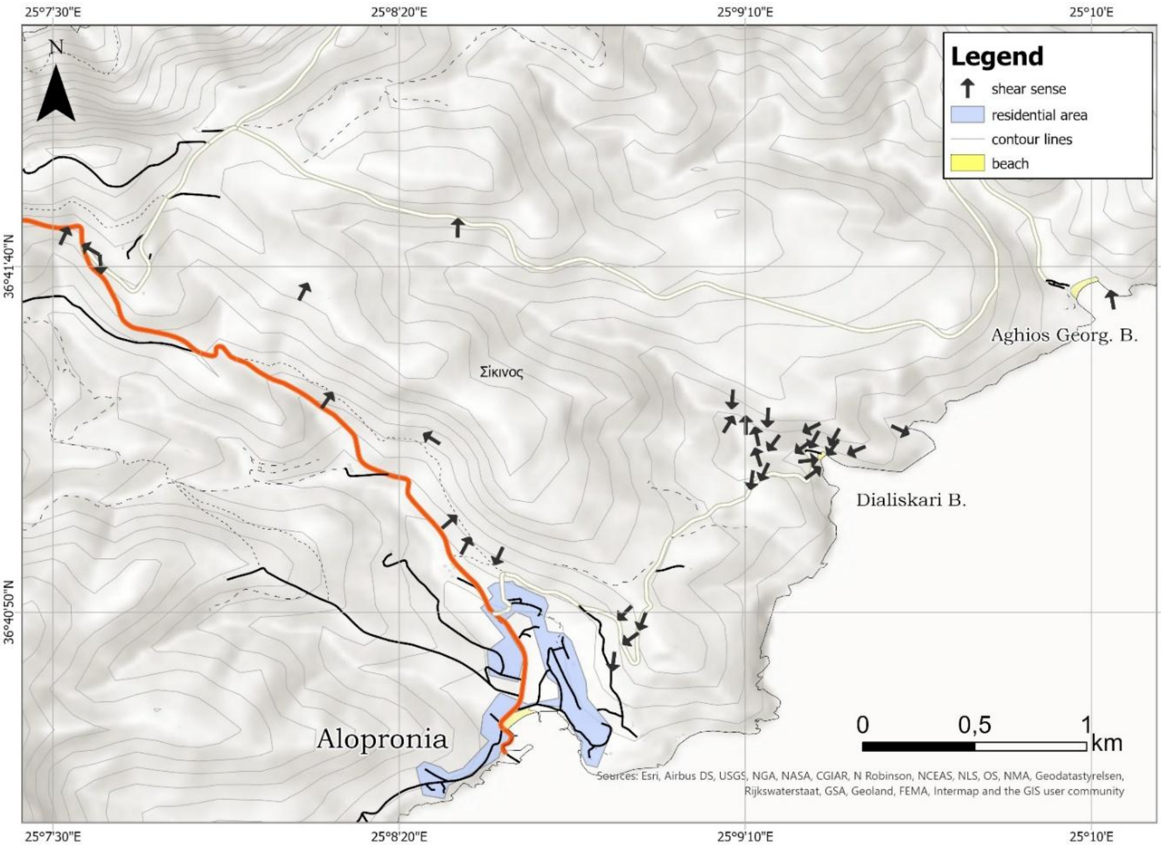

***Figure 12**: A summary of the shear sense indicators gathered on a mesoscopic scale. The blueschists in the NW and at Agios Georgios Bay show a top-to-the-North sense of shear, while the field of indicators around Dialiskari Beach is mixed, showing a clearer top-to-the-South in greenschist facies rocks (for example just east of Alopronia). In other outcrops, e.g., the blueschist outcrops, some top-to-the-North sense of shear was found, but the results were less obvious.*

4.2 Description of the Thin Sections through Microscopy

The 11 hand samples taken at various sites, have been cut and prepared as thin sections at the University of Würzburg in Germany. Sample designations are always the same as the sample site, see **Figure 8**, which means that sample 1.19 was taken from site 1.19. In very few cases, two samples were taken from the same site, shown by an attached number in the sample name, i.e., sample 5.3 and 5.3.2 are both from site 5.3.

The sites for the hand samples were decided on-site, based on the apparent mineralogy and on context of the surrounding geology. Therefore, most of the samples (sample clusters 3.x and 4.x) have been taken within a relatively small area within the seasonal stream valley – where evidence of greenschist and blueschist was recorded. For reference, the samples 1.19, 5.3, 5.3.2, 6.2, and 8.7 were taken outside of the stream valley. While it was expected that most samples would have an overprint from decompression – resulting in chloritisation and albitisation – it was the goal to find evidence of shear sense within preserved blueschist.

The annotations found in the thin sections are as follows:

Grt	Garnet	**Gln**	Glaucophane
Ms	Muscovite	**Ep**	Epidote
Qz	Quartz	**Cal**	Calcite
Chd	Chloritoid	**Op**	Opaque minerals
Chl	Chlorite	**Ab**	Albite

Table 1: *Overview over the abbreviations of common minerals, used in the thin sections below. After (Whitney and Evans, 2010).*

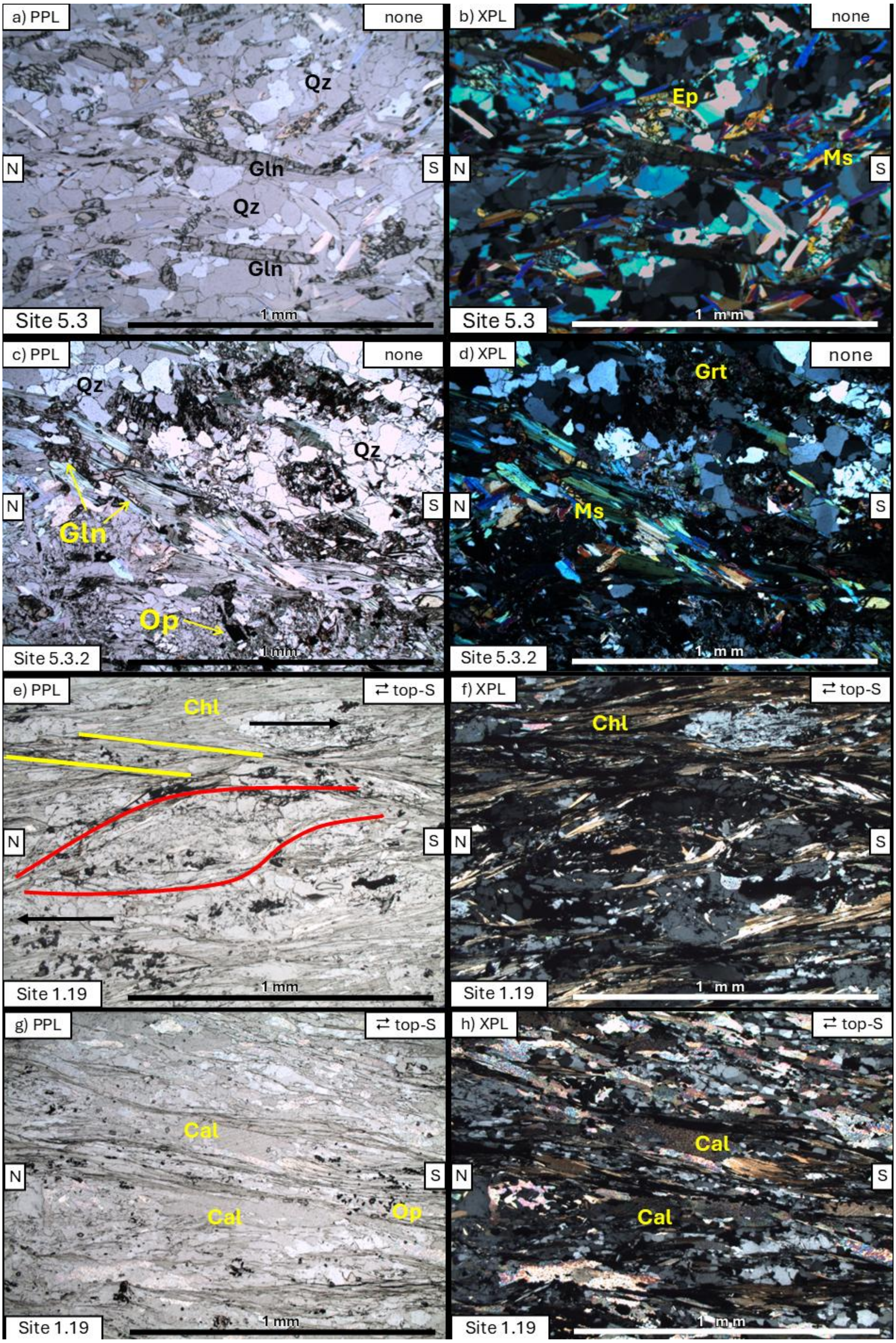

Figure 13*: Thin section images of the samples 5.3, 5.3.2, and 1.19. Images a) and c) show very strongly decomposed glaucophane but show no shear sense indicators. Images e) and g) are from the same sample and show the calcitic nature of some of the greenschist samples. Especially in image g) the calcite is clearly identified and occurs together with opaques. The shear sense is top-to-the-S, as are other field indicators from the vicinity of this sample, shown by shear bands and strain shadows.*

SAMPLE 5.3

This sample was collected from the northern shore of the Agios Georgios Bay. In the thin section, a lot of quartz is evident along with remnants of glaucophane that is relatively well preserved. In cross-polarized light (XPL) the presence of epidote and muscovite is observed. There is no discernible shear sense, and the sample shows no signs of advanced chloritization; it originates from a site that has been classified as blueschist facies before.

SAMPLE 5.3.2

Obtained from the same locality as Sample 5.3 on the northern shore of Agios Georgios Bay and similarly shows no shear sense or advanced chloritization. The rock is dominated by a quartz matrix containing garnet and a minor amount of opaque minerals. Very little, decomposed remnants of glaucophane can be seen in the PPL image. The garnet can only be seen in the cross-polarised view, showing no clear structure at all.

SAMPLE 1.19

Collected to the east of Alopronia, along the dirt road leading to Dialiskari Beach. It displays a top-to-the-South shear sense that are indicated by well-developed shear bands and mica fish structures. The thin section is heavily chloritized but also contains calcite and a few opaque minerals. The calcite can be identified both in PPL and XPL by its unique parallel lines in PPL and the black-and-white colouration in XPL.

SAMPLE 3.3

The sample was taken just above Dialiskari Beach and shows a clear top-to-the-South shear sense, indicated by multiple shear bands. Garnet porphyroblasts appear to be in the early stages of chloritization and show a well-developed strain shadow caused by the shearing forces. The few remnants of glaucophane are surrounded by a matrix of muscovite, epidote, quartz; some biotite (brown) is found as well, which is relatively rare among the samples.

SAMPLE 3.5

Taken next to Sample 3.3 on Dialiskari Beach, the sample is interesting because of the crystals of chloritoid that are found. Otherwise, the sample contains lot of muscovite and minor chlorite. The overall shear sense is dominantly top-to-the-South, with the chloritoid phenocryst appearing to be sheared and rotated. Clear tails of mica have grown in the strain shadow.

SAMPLE 3.5.2

From the same outcrop as 3.5 at Dialiskari Beach, this sample confirms the top-to-the-South shear sense. The sample is composed of chloritoid, chlorite, quartz, and some opaques. A closer view shows the chloritoid with a larger magnification of 10x; chloritoid is identified by a distinct high relief and a dark green colour in PPL, as well as black colour cut with green streaks in XPL. It is unclear if the chloritoid in Figure 12 e) was once a single phenocryst of chloritoid that has been split under strain, or two smaller crystals, but the shear band dividing them is very clear.

SAMPLE 4.16

This sample was collected at the base of the seasonal stream bed leading to Dialiskari Beach. It contains several larger garnet porphyroblasts that show abundant cracks and exhibit chloritization along the crystal faces. Opaque minerals are abundant, particularly in the images with larger magnification (Figures 13c) and 13d)). They seem to have grown along the garnet edges. Epidote and muscovite are present. No overall shear sense is apparent, and it seems that deformation has been mostly coaxial. In some garnets a top-to-the-North shear component can be suggested. Chloritoid is abundantly present in the spaces between larger crystals (high-relief, green coloured minerals).

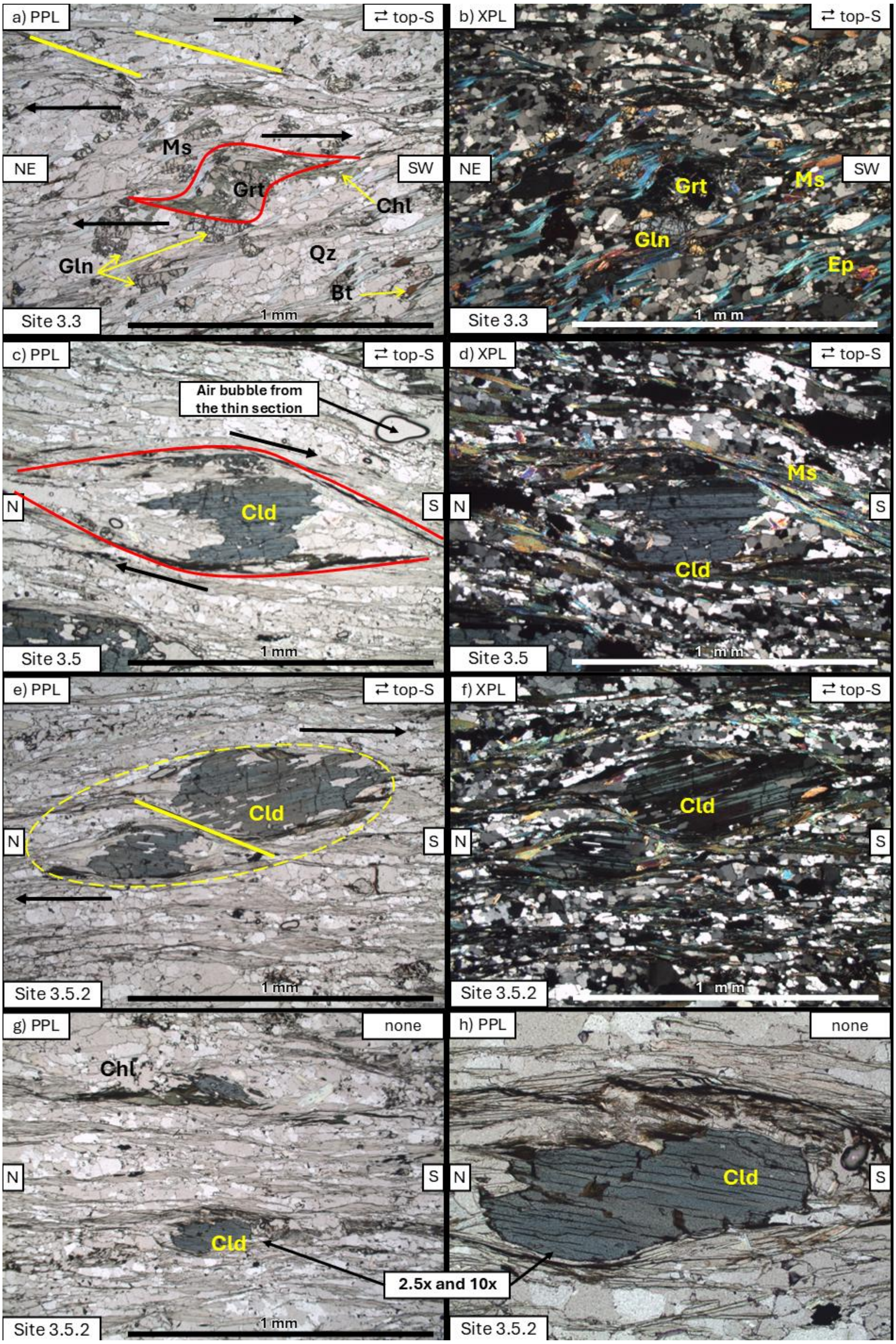

Figure 14: *Thin section images of samples 3.3, 3.5, and 3.5.2. at Dialiskari Beach. These samples show clear signs of chloritoid (Cld) in all thin sections. Image g) and h) show the same chloritoid at the usual (2.5x) and greater magnification. Image a) shows both shear bands (yellow) and strain shadows around the heavily decomposed garnet (red). In image c) a rotated, decomposed chloritoid shows signs of shearing with top-to-the-S direction. Image e) could indicate either one broken up chloritoid phenocryst that is sheared top-to-the-S.*

SAMPLE 4.23

The sample was cut along an East-West axis, which is a different axis than the major North-South axis found in the other samples. The top-to-the-West kinematic and is therefore an outlier in comparison to other samples that have been taken. Larger porphyroblasts of glaucophane are present but these show signs of decomposition, as can be seen by frayed edges and holes in the crystals. Garnet is undergoing chloritisation and epidote is present in the rock.

SAMPLE 4.28

Taken from the wall of the seasonal stream valley near Dialiskari Beach. The sample is characterized by extremely strong chloritization with massive chlorite growths. In the lower half, abundant amounts of remnant glaucophane can be observed, still in good condition. There is significant epidote between the chlorite and the glaucophane. Shear sense is mainly top-to-the-South as observed by shear bands.

SAMPLE 6.2

This outcrop was found along the main road approximately one kilometre before Chora at the crossroads to Agios Georgios Bay. It represents a good example of blueschist facies. The thin section is dominated by glaucophane, which aligns with the observations in the field, where the rock was found to be dark blue. Both glaucophane and garnet exhibit heavy jointing, but there is minimal chloritization. Deformation appears to be controlled primarily by coaxial deformation, with a negligible shear sense. Some epidote is present in the sample.

SAMPLE 8.7

The sample was collected just north of Alopronia, below the marble highlands. It contains only minimal remnants of glaucophane. Garnet is heavily jointed and fragmented, the joints filled by chlorite. Epidote and opaque minerals are abundant in the sample. No clear shear sense can be established from the thin section.

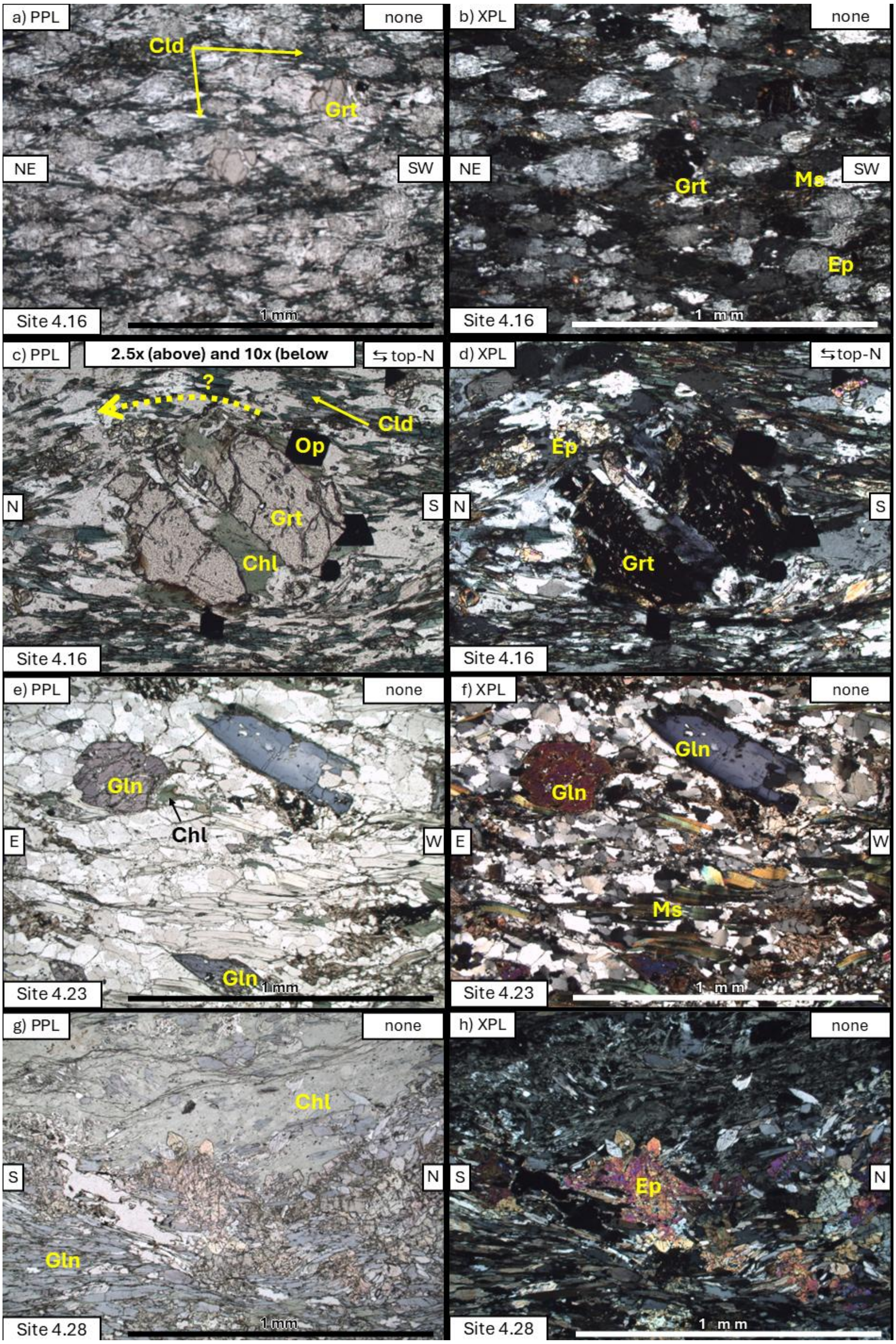

***Figure 15**: Thin sections from samples 4.16, 4.23, and 4.28, collected inland of Dialiskari Beach. Images a) through d) no sense of shear but reveal both chloritoid and chlorite. The dark green minerals in both PPL images are chloritoid, with chlorite much lighter green. There is an indication of a slight top-to-the-N rotation, but it is not a high-pressure remnant. In the remaining images, no clear shear sense is visible and glaucophane is starting to decompose. There is a massive accumulation of glaucophane in image g), that is replaced by epidote and chlorite towards the top part. These samples are examples pf heavy chloritisation and can be associated with retrograde metamorphism.*

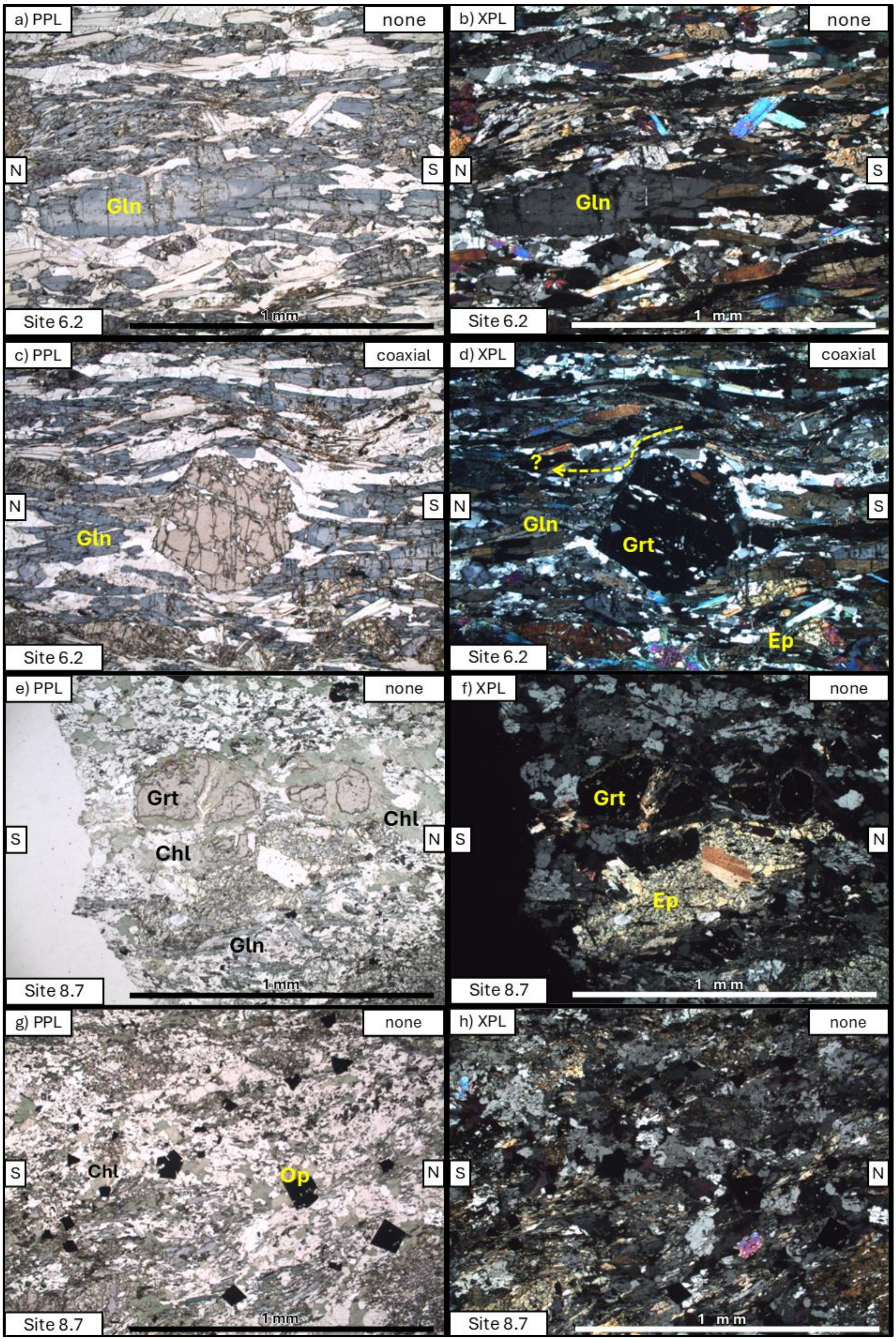

***Figure 16**: Thin sections from samples 6.2 and 8.7. Images a) through d) show no chloritisation of the glaucophane, but do not show any concrete sense of shear either. There could be an indication of a slight top-to-the-N rotation in the jointed garnet porphyroblast in image c), but it is not clear enough. Top-to-the-N would fit the mesoscopic shear sense indicators measured in the field, but the thin section is considered coaxial. Sample 8.7 in images e) to h) shows both very clear chloritisation in image e) and epidote (image f) and distinct accumulations of opaque minerals. No shear sense can be derived.*

5. Discussion

Due to the agricultural history of Sikinos, with extensive terrace cultivation, as well as recent infrastructure, such as roads and developed areas, the mapping sites are slightly biased, and constrained, to accessible outcrops. These are mainly found in the dolomitic and calcitic highlands or in eroded valleys, such as stream beds. In general, the terrain is covered by loose sediment, often as colluvium or rain-wash.

The previous work which has been mainly conducted by Augier et al. (2015) and resulted in a majorly top-to-the-North sense of shear, while Ring and Glodny (2021) showed that top-to-the-South sense of shear was especially prevalent within rocks that were overprinted by greenschist-facies conditions. The results of this field work coincide partially with earlier findings, especially within the greenschist outcrops.

#	Shear Sense	Metamorphic Facies	Metamorphic Interpretation
5.3	None discernible	Blueschist facies	High-pressure rock with well-preserved glaucophane. Presence of epidote and muscovite indicates early retrograde influence.
5.3.2	None discernible	Blueschist facies	Quartz-dominated matrix with garnet and minor opaques. The presence of garnet implies high-pressure conditions, with little retrograde chloritisation.
1.19	Top-to-the-South	Greenschist overprint (Retrograde)	Well-developed shear bands and mica fish indicate a clear top-to-the-South kinematics. Heavy chloritisation and calcite indicate retrograde re-equilibration, with breakdown of HP phases. The abundant occurrence of calcite points to the influence of hydrothermal metamorphism.
3.3	Top-to-the-South	Decompression (Early retrograde)	Top-to-the-South sense indicated by shear bands. Garnet porphyroblasts are starting to chloritise. A few glaucophane remnants persist in matrix. This indicates early retrograde decompression.
3.5	Top-to-the-South	Greenschist overprint (Retrograde)	The occurrence of chloritoid and abundant muscovite, as well as minor chlorite indicates that the rock is in an advanced retrograde stage.

3.5.2	Top-to-the-South	Greenschist overprint (Retrograde)	Dominated by chloritoid with chlorite, quartz, and some opaques indicates retrograde metamorphism.
4.16	No distinct shear sense overall (coaxial?)	Greenschist overprint (Retrograde)	Garnet porphyroblasts are heavily jointed and show chloritization along their margins; abundant chloritoid is present between crystals. Deformation is mainly coaxial, possibly with a slight top-to-the-North component.
4.23	None discernible	Decompression (Early retrograde)	Degrading glaucophane (frayed edges and holes) and chloritisied garnet with epidote show the onset of retrograde metamorphism, as the HP minerals break down.
4.28	None; Top-to-the-South (*)	Greenschist overprint (Retrograde)	Despite the preservation of some remnant glaucophane, extremely strong chloritization and significant epidote indicate more advanced retrograde metamorphism and greenschist overprint.
6.2	Coaxial; Top-to-the-North (*)	Blueschist facies	This is the clearest example of HP-blueschist with glaucophane and garnet that show heavy jointing but minimal chloritisation. Coaxial deformation and very little shear are shown.
8.7	None discernible	Greenschist overprint (Retrograde)	Minimal remnants of glaucophane and heavily jointed, chloritised garnet (joints filled with chlorite), plus abundant epidote, and opaques point to an advanced retrograde stage.

***Table 2**: A summary of the thin section analyses and shear sense markers from the field, with their respective shear sense and metamorphic interpretation. Shear sense marked with an asterisk (*) was determined with the help of mesoscopic indicators in the same site and is therefore not derived from the thin section.*

The tectonometamorphic history of the island can be summarised in three stages.

The first stage is subduction, causing the rock to experience significant pressure – at low temperatures. The rocks enter the blueschist facies. Under these conditions, glaucophane becomes stable (as well as lawsonite and phengite, see (Augier et al., 2015)), incorporating aluminium and sodium, while garnet incorporates aluminium.

During the second stage, the decompression phase, the rocks begin to ascend due to increasing buoyancy. The pressure decreases, but temperatures remain relatively high. These conditions cause a change in the mineral equilibrium and high-pressure minerals, such as garnet and glaucophane start to break down. During the process of decomposition, water, sodium (Na) and aluminium (Al) are freed – as well as other divalent and trivalent cations – and are mobile. This lays the foundation for the formation of albite, incorporating sodium, and chloritoid, incorporating mobile aluminium. During this stage, epidote and chlorite also start to appear. Accessory minerals such as pyrite and hematite can appear under the influx of hydrothermal fluids.

During the third stage, the rock is getting exhumed and reaches more stable conditions of lower pressure and lower temperature, causing an mineralogic overprint in the greenschist-facies. This results in the abundant formation of chlorite and epidote and can even cause the appearance of other micaceous minerals (muscovite). Some relics of the high-pressure phase survive but show clear signs of breaking up and subsequent chloritisations in thin sections. Albite becomes stable.

The thin section samples show a dominantly top-to-the-South sense of shear, especially associated with retrograde greenschist facies metamorphic conditions. Some blueschist outcrops show mesoscopic top-to-the-North shear sense indicators, but this observation is not supported by the thin sections that were analysed; instead, a coaxial deformation is found. Some of the top-to-the-South samples show only a slight retrogressive overprint from early decompression, while others a show a very strong greenschist facies overprint. This could be explained by a thrusting episode during which the older blueschist (dated to ~40 Ma), now structurally higher, was emplaced above the younger blueschist (~30 Ma).

The bivergent shear sense could be associated with the tectonic history of the Aegean orogenic arc; a northward direction during subduction, which is preserved in the remnant blueschist, followed by a southward direction during the exhumation, caused by slab-rollback and trench retreat.

6. Conclusion and Outlook

The rocks on Sikinos that belong to the Cycladic Blueschist Unit have undergone three discernible stages on a clockwise P-T-t path: subduction (high pressure, low temperature), decompression (decreasing pressure), and exhumation (decreasing pressure and temperature).

Especially within the greenschist-facies rock, top-to-the-South sense of shear has been recorded. Augier et al. (2015) described top-to-the-South deformation “only seldom in the metamorphic succession” but dominant in greenschist rocks. In this field study, abundant top-to-the-South evidence has been found, which corresponds with the findings of Ring & Glodny (2021). The limited access to blueschist samples, that are not heavily albitised or chloritised, makes it a challenge to prove this unequivocally, but the sampled outcrops of blueschist indicated either a top-to-the-North sense of shear or a coaxial deformation.

In summary, the regional structures underwent two main deformation events, recorded in the two subsequent metamorphic facies, from early high-pressure blueschist-facies conditions – with a top-to-the-North shear sense preserved from the compressional phase – to a later retrograde greenschist-facies overprint with a dominant top-to-the-South shear associated with exhumation, driven by slab rollback and trench retreat.

Additional data complicates the picture by suggesting that older blueschists have been thrust atop younger blueschist units and greenschists – indicating a nappe emplacement event during the compressional phase. The older nappes preserved their early top-to-the-North shear sense by detaching and being emplaced over the younger rocks and retaining the subduction imprint during exhumation.

For future research, it would be of interest to acquire more samples of other blueschists for geochronological dating and detailed structural analyses, to get a better understanding of the possible nappe emplacements. This could also mean to expand field research to neighbouring islands, thus improving the understanding of the geological history in a regional context.

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8. References

Allmendinger, R.W., 2020. Stereonet v.11.

Anthelius, H., 2014. World tectonic plates and boundaries.

Augier, R., Jolivet, L., Gadenne, L., Lahfid, A., Driussi, O., 2015. Exhumation kinematics of the Cycladic Blueschists unit and back-arc extension, insight from the Southern Cyclades (Sikinos and Folegandros Islands, Greece): EXHUMATION OF THE SOUTHERN CYCLADES. Tectonics 34, 152–185. https://doi.org/10.1002/2014TC003664

Bird, P., 2003. An updated digital model of plate boundaries. Geochem. Geophys. Geosystems 4, 2001GC000252. https://doi.org/10.1029/2001GC000252

Brun, J.-P., Sokoutis, D., 2010. 45 m.y. of Aegean crust and mantle flow driven by trench retreat. Geology 38, 815–818. https://doi.org/10.1130/G30950.1

Carreras, J., Druguet, E., Griera, A., 2005. Shear zone-related folds. J. Struct. Geol. 27, 1229–1251. https://doi.org/10.1016/j.jsg.2004.08.004

Papanikoláou, D., 2021. The geology of Greece, 1st ed. ed, Regional geology reviews. Springer international publishing, Cham.

Passchier, C.W., Williams, P.R., 1996. Conflicting shear sense indicators in shear zones; the problem of non-ideal sections. J. Struct. Geol. 18, 1281–1284. https://doi.org/10.1016/S0191-8141(96)00051-X

Philpotts, A.R., Ague, J.J., 2009. Principles of igneous and metamorphic petrology, 2nd ed. ed. Cambridge university press, Cambridge, UK.

Platt, J.P., 1986. Dynamics of orogenic wedges and the uplift of high-pressure metamorphic rocks. Geol. Soc. Am. Bull. 97, 1037. https://doi.org/10.1130/0016-7606(1986)97<1037:DOOWAT>2.0.CO;2

Ring, U., Glodny, J., 2021. Geometry and Kinematics of Bivergent Extension in the Southern Cycladic Archipelago: Constraining an Extensional Hinge Zone on Sikinos Island, Aegean Sea, Greece. Tectonics 40, e2020TC006641. https://doi.org/10.1029/2020TC006641

Ring, U., Glodny, J., Will, T., Thomson, S., 2010. The Hellenic Subduction System: High-Pressure Metamorphism, Exhumation, Normal Faulting, and Large-Scale Extension. Annu. Rev. Earth Planet. Sci. 38, 45–76. https://doi.org/10.1146/annurev.earth.050708.170910

Storetvedt, K.M., 1990. The Tethys Sea and the Alpine-Himalayan orogenic belt; mega-elements in a new global tectonic system. Phys. Earth Planet. Inter. 62, 141–184. https://doi.org/10.1016/0031-9201(90)90198-7

Whitney, D.L., Evans, B.W., 2010. Abbreviations for names of rock-forming minerals. Am. Mineral. 95, 185–187. https://doi.org/10.2138/am.2010.3371