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Structural and Kinematic Evolution of the Thassos Metamorphic Core Complex, Greece

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Abstract

This bachelor thesis investigates the structural and kinematic evolution of the metamorphic footwall on Thassos Island, Greece, with particular focus on a major tectonic boundary along the southwestern margin of the island between metamorphic footwall rocks and non-metamorphosed sediments in the hanging wall. Thassos, an island in the northern Aegean Sea, forms part of the Miocene Southern Rhodope Core Complex (SRCC). Field mapping was conducted along an approximately NE-SW transect, broadly parallel to the regional stretching lineation. A total of 153 foliation measurements and 103 stretching-lineation measurements were combined with observations of mesoscopic shear-sense indicators, the southwestern fault zone, and petrographic analysis of four thin sections.

Foliation orientation varies considerably along the transect, whereas stretching lineations show a consistent NE-SW trend. Mesoscopic shear-sense indicators consistently record top-to-the-SW movement, and deformation structures in the thin sections are broadly compatible with the same regional kinematic pattern. Fault breccia occurs at the southwestern tectonic boundary, where two measured fault surfaces dip 28° and 38° . These shallow dips, together with the NE-SW stretching lineations and the top-to-the-SW shear sense, support a low-angle extensional interpretation of the boundary. The investigated thin sections record metamorphism and ductile deformation within the footwall, but they do not demonstrate a systematic increase in strain intensity or decrease in metamorphic grade toward the southwestern contact. The juxtaposition of metamorphic footwall rocks against unmetamorphosed Neogene sediments of the Limenaria Basin nevertheless represents a pronounced metamorphic and thermal discontinuity. The results are consistent with southwest-directed low-angle normal faulting along a shallowly dipping extensional system, while the precise relationship between ductile footwall deformation, later brittle faulting, and development of the Limenaria Basin remains unresolved.

1. Introduction

1.1 Background

Thassos Island, in the northern Aegean Sea, forms part of the Southern Rhodope Core Complex (SRCC), a major extensional structure within the Rhodope Massif of northern Greece and southern Bulgaria (Brun and Sokoutis, 2007, 2018). Metamorphic core complexes expose rocks that were exhumed from mid-crustal levels during large-magnitude continental extension, commonly through a combination of ductile shearing in the footwall and displacement along low-angle, brittle extensional faults (Lister and Davis, 1989). On Thassos, exhumation produced widespread NE-SW stretching lineations and predominantly top-to-the-SW shear sense indicators (Wawrzenitz and Krohe, 1998; Brun and Sokoutis, 2007).

The Cenozoic extensional evolution of the Aegean is linked to retreat of the Hellenic subduction system and associated extension of the overriding plate (Jolivet and Brun, 2010; Ring et al., 2010). Within the northern Aegean and southern Rhodope, this regional extension resulted in exhumation of metamorphic rocks and development of the SRCC. The present structure of Thassos therefore records both an older compressional tectonometamorphic history and its later modification during extensional exhumation (Wawrzenitz and Krohe, 1998; Brun and Sokoutis, 2007).

Along the southwestern margin of Thassos, metamorphic rocks are juxtaposed against the unmetamorphosed Neogene clastic sediments of the Limenaria Basin (Brun and Sokoutis, 2007, 2018). The nature of this boundary is important for reconstructing the extensional history of the island. Low-angle extensional is commonly associated with exhumation of the Thassos core complex (Dinter and Royden, 1993; Wawrzenitz and Krohe, 1998), whereas Brun and Sokoutis (2018) proposed a more complex ramp-flat extensional system in which inherited crustal shortening related structures were reactivated during later extension and basin development. The occurrence of Neogene basin sediments associated with the southwestern fault system requires younger extensional activity even if part of the fault geometry exploited an older thrust surface. Structural and kinematic observations toward this boundary can therefore be used to evaluate how the metamorphic footwall was exhumed and how the southwestern margin developed.

1.2 Aim and Objectives

The aim of this study is to investigate the structural and metamorphic evolution of the metamorphic footwall toward the major extensional boundary in southwestern Thassos and to evaluate whether the observed geometry and kinematics are consistent with a low-angle normal-fault system. Rather than attempting to measure within the poorly exposed detachment fault zone itself along the entire transect, the study maps structural and metamorphic changes toward the southwestern boundary and examines whether strain becomes increasingly localized toward it.

The specific objectives are:

1. Map the structural geometry along a transect approximately parallel to the regional tectonic transport direction, using the NE-trending stretching lineations as a kinematic guide.
2. Characterize deformation toward the southwestern tectonic boundary, where the metamorphic footwall is juxtaposed against the unmetamorphosed conglomeratic succession of the Limenaria Basin, and investigate whether strain intensity increases toward the boundary.
3. Analyze the metamorphic discontinuity toward the southwestern boundary and investigate whether the sampled metamorphic footwall records a systematic decrease in metamorphic grade toward the SW.
4. Test the low-angle normal-fault model by determining whether the structural geometry and shear-sense indicators are consistent with predominantly top-to-the-SW displacement within the ductile-to-brittle extensional system approaching the southwestern boundary.

2. Geological Setting

2.1 Tectonic framework and position of Thassos

The Rhodope Massif is a high-grade metamorphic complex extending across northern Greece and southern Bulgaria and covering more than 30,000 km² (Kounov and Gerdjikov, 2024). Modern tectonic syntheses subdivide the massif into major Upper, Intermediate and Lower lithotectonic terranes, representing a stack of Alpine syn-metamorphic nappe units subsequently affected by Cenozoic extension (Kounov and Gerdjikov, 2024).

Thassos Island lies in the southern Rhodope and represents the southeasternmost exposure of the Southern Rhodope Core Complex (Figure 1), which exhumed deep structural levels of the Rhodope metamorphic pile (Brun and Sokoutis, 2007; Kounov et al., 2015; Kounov and Gerdjikov, 2024). More specifically, Thassos belongs to the Pirin-Pangaion Unit of the Lower Rhodope Terrane (Kounov and Gerdjikov, 2024). The Pirin-Pangaion Unit includes Variscan orthogneiss basement, dated at approximately 300-280 Ma, and a thick Mesozoic carbonate succession commonly referred to as the Falakron series (Wawrzenitz and Krohe, 1998; Kounov and Gerdjikov, 2024). The unit records a strong Cenozoic metamorphic and extensional overprint related to exhumation of the southern Rhodope.

This tectonic position is important because the structures exposed on Thassos form part of a regional extensional system rather than an isolated island-scale fault system. The island preserves both the earlier nappe architecture of the Rhodope and younger structures formed or reactivated during Cenozoic exhumation (Brun and Sokoutis, 2018).

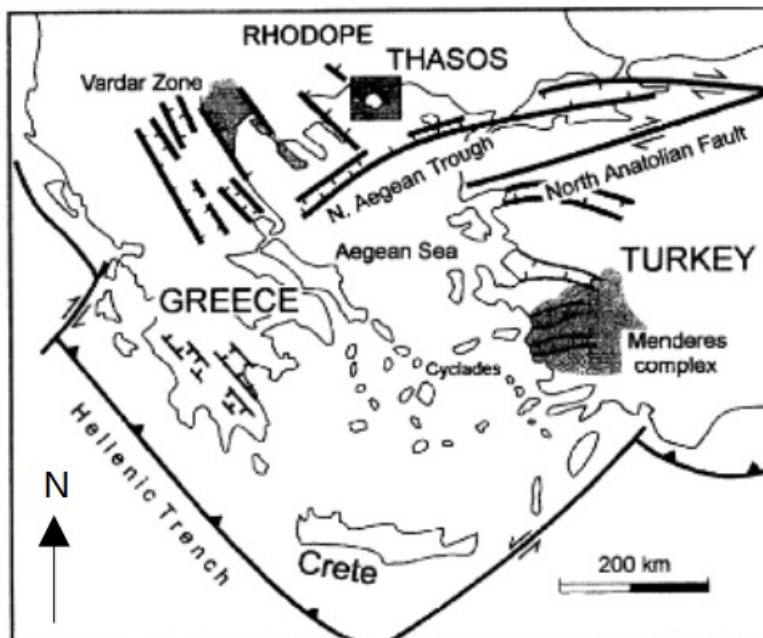


Figure 1. Simplified structural map of the Aegean region showing the location of Thassos and its regional tectonic setting. The map also shows the Vardar Zone, Menderes Massif, Cyclades, Hellenic Trench and major regional structures. Thassos is indicated by the box. From Wawrzenitz and Krohe (1998), modified after Beck and Schermer (1994).

2.2 Slab rollback and extension

The Cenozoic geological evolution of the Aegean is closely related to retreat of the Hellenic subduction system and extension of the overriding plate (Jolivet and Brun, 2010; Ring et al., 2010). When the rate of subduction exceeds the rate of plate convergence, the subduction hinge retreats relative to the overriding plate, promoting extension within the overriding lithosphere (Figure 2). Interaction of the Hellenic slab with a 660-km discontinuity may further facilitate slab retreat and large-scale extension as the slab progressively drapes over the discontinuity (Ring et al., 2010). Subduction of the Cycladic Blueschist Unit began during the Paleogene, whereas major rollback-related extension in the Aegean developed later. In the Rhodope Massif to the north of the Aegean Sea, core-complex exhumation was underway by the middle Eocene and continued into the Miocene (Brun and Sokoutis, 2007, 2018). On Thassos, the main extensional deformation recorded by the metamorphic core complex began by approximately 26-23 Ma (Wawrzenitz and Krohe, 1998).

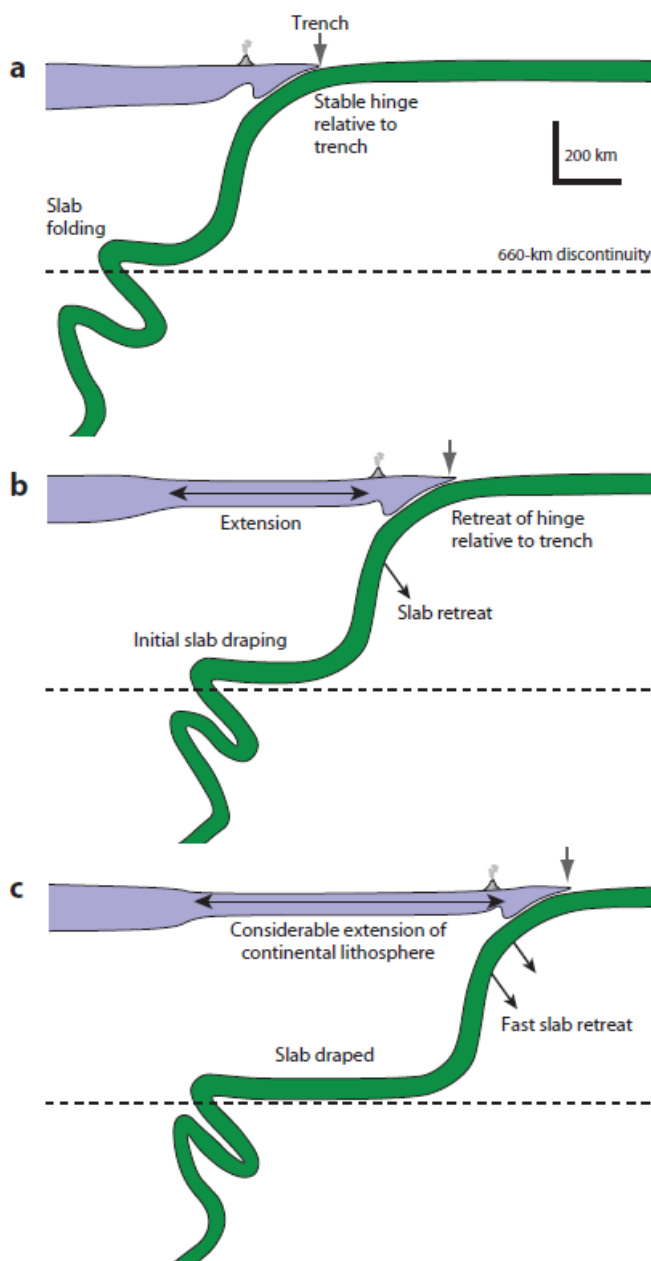


Figure 2. Conceptual model illustrating the interaction of a subducting slab and the development of slab retreat. Progressive draping of the slab is associated with retreat of the subduction hinge and increasing extension of the overriding plate. From Ring et al. (2010), modified from Schellart (2005).

In the North Aegean, extension was initially accommodated by exhumation of metamorphic core complexes and displacement along low-angle extensional systems (Brun and Sokoutis, 2018). A major change in the regional extensional regime occurred during the middle Miocene, when accelerated slab rollback was associated with a transition from localized core-complex development toward a broader wide-rift mode (Brun and Sokoutis, 2018). This later extension segmented earlier core complexes and promoted formation of sedimentary basins across the northern Aegean. Ring et al. (2010) estimated total Cenozoic extension across the Aegean microplate at approximately 300-320 km.

2.3 Lithotectonic units of Thassos Island

The metamorphic succession of Thassos is commonly divided into three superimposed structural units: Lower, Intermediate and Upper Units (Figure 3) (Wawrzenitz and Krohe, 1998). These units record the earlier tectonometamorphic architecture as well as its later modification during extensional exhumation. They should not be interpreted simply as three units separated by three independent Cenozoic detachment faults; Wawrzenitz and Krohe (1998) instead describe progressive localization from a detachment-parallel ductile shear zone toward discrete low-angle extensional structures.

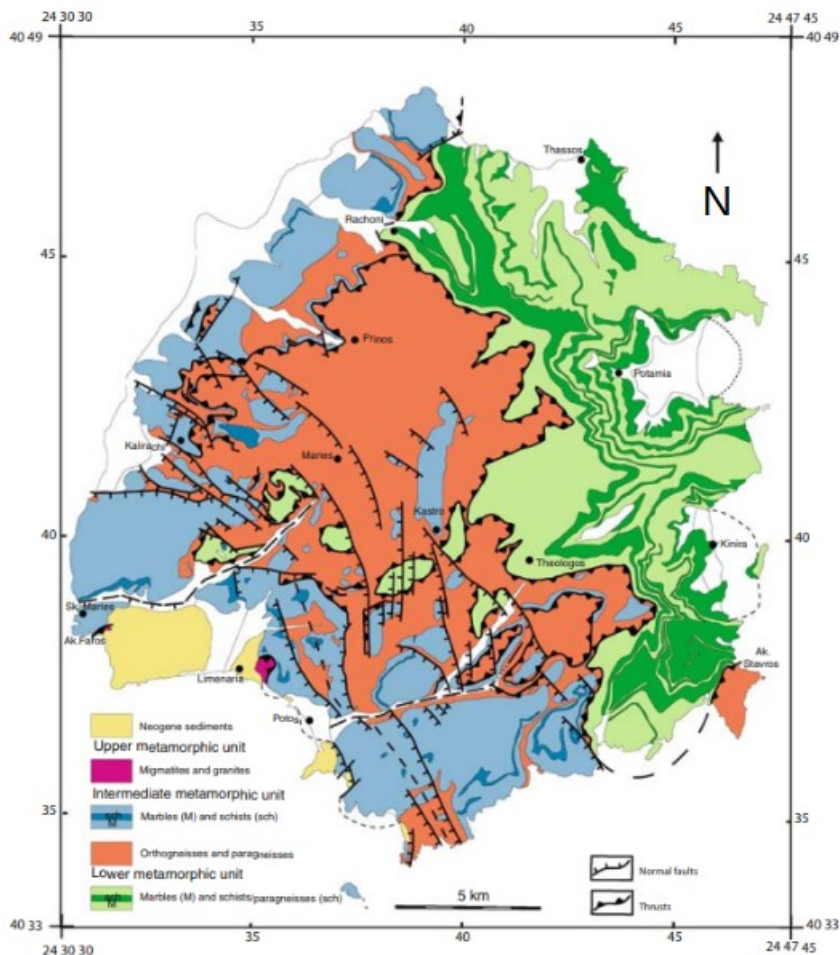


Figure 3. Geological map of Thassos showing the principal metamorphic units, lithologies, Neogene sediments and major mapped thrust and normal faults. Lithological boundaries are mainly based on Zachos (1982), whereas the major thrusts and normal faults were mapped by Brun and Sokoutis (2007). From Brun and Sokoutis (2007).

The Lower Unit occupies the structural core of the island and is dominated by marbles with intercalations of mica schists and paragneisses. These rocks are pervasively affected by the extensional deformation and locally show strong mylonitic fabrics (Wawrzenitz and Krohe, 1998).

The Intermediate Unit structurally overlies the Lower Unit and includes orthogneisses, paragneisses and amphibolites that are also extensively deformed and locally mylonitic (Wawrzenitz and Krohe, 1998).

The Upper Unit forms structurally higher parts of the metamorphic pile and contains comparatively less affected high-grade gneisses and migmatitic rocks. In the extensional reconstruction of Wawrzenitz and Krohe (1998), it behaved more rigidly relative to the strongly sheared rocks below during exhumation.

2.4 Tectonometamorphic evolution and kinematics

Wawrzenitz and Krohe (1998) describe the extensional evolution of the Thassos metamorphic core complex by two principal stages. An early stage, established by approximately 26-23 Ma, was characterized by pervasive non-coaxial deformation and predominantly top-to-the-SW shear. Deformation was distributed through a ductile, detachment-parallel shear zone within the metamorphic rocks rather than being restricted to a single brittle fault surface.

From approximately 21 Ma onward, deformation became increasingly localized while the metamorphic complex underwent plastic upwelling and doming. Wawrzenitz and Krohe (1998; Figure 4) describe formation of the approximately 15-km-wide Thassos gneiss dome and continued low-angle extensional displacement into the Miocene. The deformation field was locally polydirectional, including antithetic top-to-the-NE shear on the eastern flank of the dome, although the regional kinematic pattern is dominated by NE-SW stretching and top-to-the-W/SW transport.

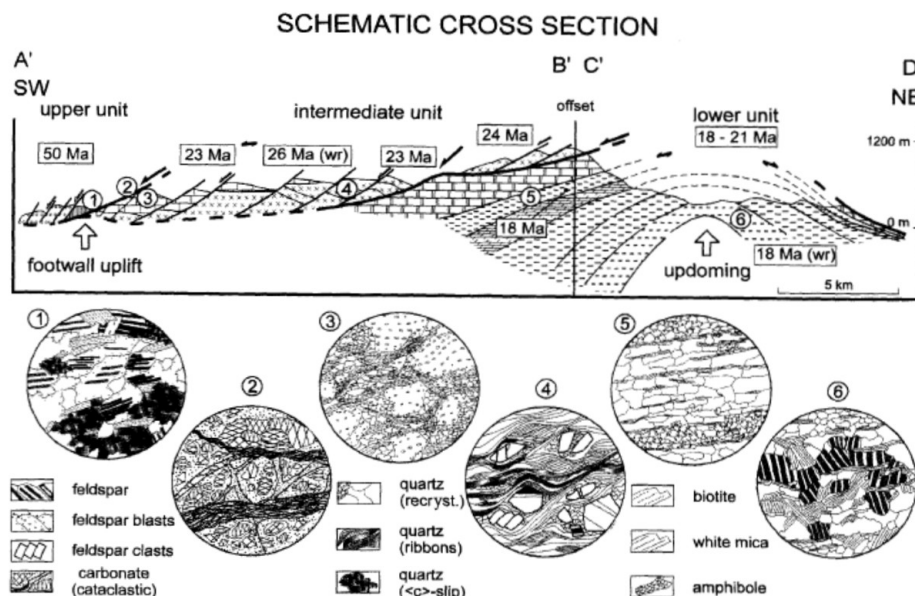


Figure 4. Schematic SW–NE cross-section across Thassos showing the structural relationships between the upper, intermediate and lower units, together with footwall uplift and doming of the metamorphic core. Numbers indicate published age constraints, and the numbered circular insets show characteristic mineral fabrics at different structural positions. From Wawrzenitz and Krohe (1998).

Exhumation was accompanied by decreasing pressure and temperature and a progressive change in deformation mechanisms. Bestmann et al. (2000) documented strain localization in calcite-marble shear zones during cooling, showing that ductile deformation continued under retrograde conditions. At still lower temperatures and shallower crustal levels, brittle deformation produced cataclastic rocks and fault breccias. This progression records the transition from ductile to brittle deformation during exhumation; it should not be described as metamorphic telescoping, because the extensional system produced horizontal stretching rather than compression of metamorphic zones.

2.5 The southwestern margin: the Limenaria Basin and detachment debate

The southwestern margin of Thassos exposes the transition between the metamorphic core and the unmetamorphosed Neogene sedimentary succession of the Limenaria Basin (Brun and Sokoutis, 2007, 2018). The basin contains conglomeratic sedimentary rocks that occur structurally to the metamorphic rocks along the southwestern coast. The boundary therefore juxtaposes rocks with very different tectonometamorphic histories.

The tectonic interpretation of this boundary is debated. Dinter and Royden (1993) and Wawrzenitz and Krohe (1998) placed Thassos within a regional low-angle extensional detachment system responsible for exhumation of the Rhodope metamorphic core complex. Brun and Sokoutis (2018), however, argued that the basal Limenaria contact should not simply be regarded as the original core-complex detachment. Their model involves ramp-flat extension and reactivation of inherited structures, including an older thrust was associated with the formation of the Limenaria Basin (Figure 5).

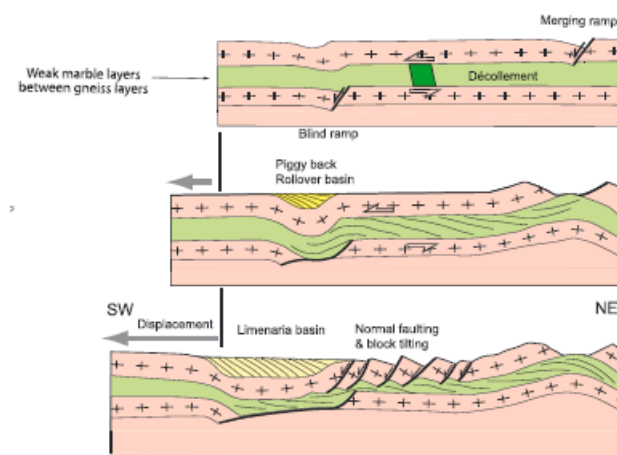


Figure 5. Three-stage model for the development of the ramp-flat extensional system beneath the Limenaria Basin, showing the proposed blind ramp, décollement, rollover development and subsequent normal faulting and block tilting. From Brun and Sokoutis (2018), Figure 18b.

The presence of Neogene basin sediments associated with this fault system is an important constraint on the reactivation model. Even if part of the low-angle geometry originated as a Mesozoic thrust, the structural relationship with the younger basin requires Cenozoic extensional reactivation or faulting during or after sedimentation. Thus, the competing interpretations concern whether the observed southwestern low-angle structures represent the principal extensional detachment, reactivated inherited structures, or components of a more complex ramp-flat extensional system.

The tectonic contact also represents a pronounced metamorphic discontinuity between the metamorphic footwall and unmetamorphosed basin sediments. This contrast is consistent with substantial exhumation and crustal thinning, but it does not by itself quantify the amount of horizontal tectonic transport or prove that the presently exposed brittle contact is identical to the earlier ductile detachment system. Structural geometry, shear sense, strain distribution and the relationship between ductile and brittle deformation therefore provide important constraints on the tectonic interpretation of the southwestern margin.

3. Methods

3.1 Fieldwork and structural mapping

For logistic reasons, fieldwork was conducted on Thassos, Greece, already in October 2025. The investigated area follows an approximately 25 km transect across the eastern to southwestern part of the island, from the Skala Potamia area toward Potos and the Limenaria Basin, with additional mapping along selected inland roads (Figure 6). Field observations and structural measurements were concentrated along the road network, where bedrock exposures were readily accessible. Large parts of the surrounding area are densely vegetated and contain relatively few accessible outcrops.

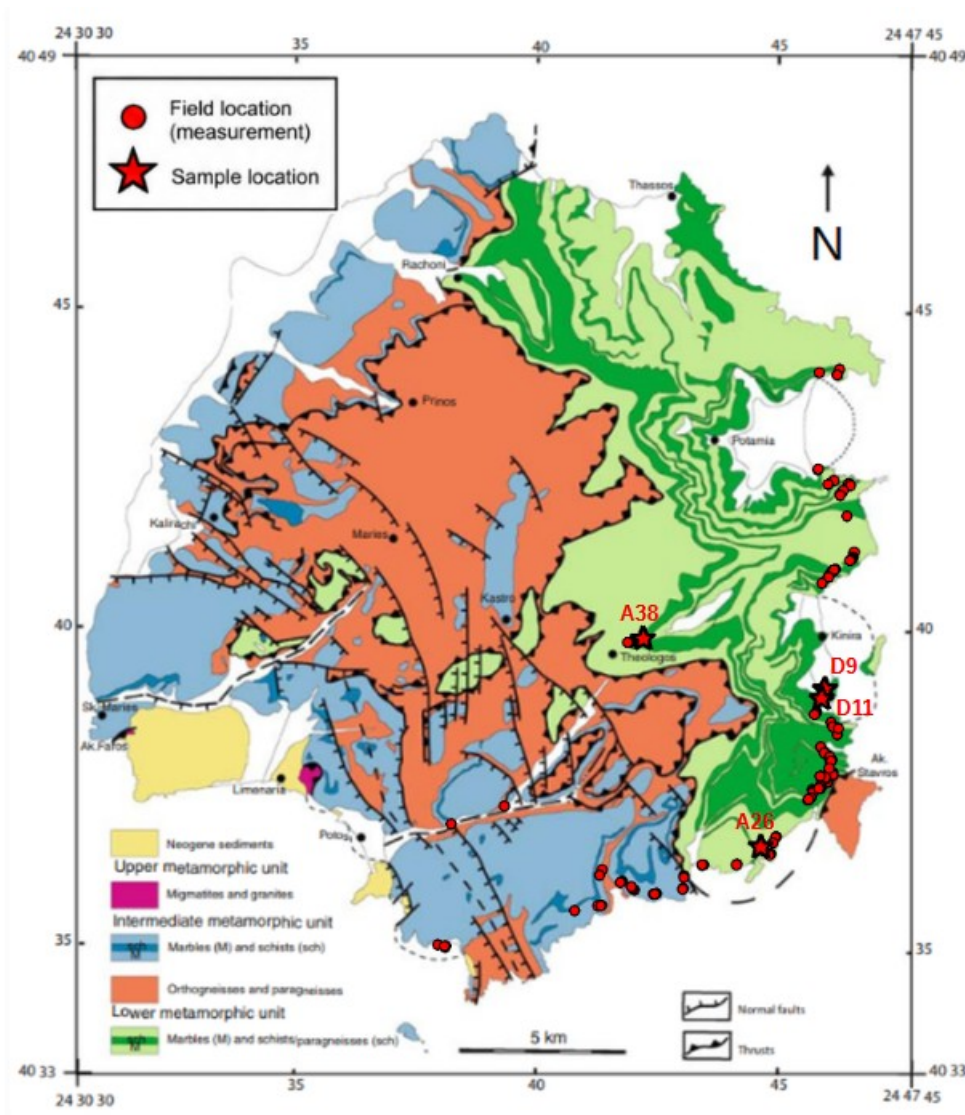


Figure 6. Geological map of Thassos showing the locations of field measurements and samples used in this study. Red circles indicate field measurement localities and red stars indicate the four samples (D9, D11, A26 and A38) selected for thin-section analysis. Geological base map from Brun and Sokoutis (2007).

Structural measurements were made at suitable outcrops using a Krantz geological compass and clinometer. The strike and dip of the metamorphic foliation were recorded together with the trend and plunge of mineral stretching lineations where these could be identified. Multiple measurements were taken at several localities to document local variations in the structural fabric. In total, the dataset comprises 153 strike-and-dip measurements and 103 trend-and-plunge measurements.

The geographic coordinates of measurement localities were recorded in the field, stored in Google Maps and subsequently plotted on a geological map of Thassos (Figure 6). Sample locations were

recorded separately and added to the same map. Foliation measurements were also plotted on a separate geological map using conventional strike-and-dip symbols to illustrate their spatial distribution and orientation (Figure 7).

The major tectonic contact in southwestern Thassos was examined separately. The contact zone was located in the field and documented by photographs, and fault breccia was identified along the contact. Two direct measurements of fault dip were made using a clinometer. These measurements were kept separate from the foliation dataset and their locations are shown in Figure 7.

Field observations also included the identification and photography of mesoscopic shear-sense indicators. The geographic orientation of the observed structures was recorded in the field where possible so that their apparent shear sense could be related to the regional reference frame. Particular attention was given to asymmetric structures suitable for determining the direction of shear. Additional observations included lithology, changes in structural orientation, deformation features and the character of geological contacts.

3.2 Structural data analysis

The strike-and-dip and trend-and-plunge measurements were compiled following fieldwork and checked for consistency before plotting. The structural measurements were plotted on stereographic projections. Foliation measurements were represented by great circles and corresponding poles, while stretching lineations were plotted according to their measured trend and plunge. This allowed the orientation and dispersion of both structural datasets to be examined.

Foliation measurements were also plotted geographically using conventional strike-and-dip symbols. The stereographic and geographic representations were used together to document changes in structural orientation along the investigated transect.

3.3 Sampling and thin-section preparation

Rock samples were collected from 11 localities along the investigated transect. Samples were selected from accessible outcrops based on lithology and the presence of structures suitable for further investigation. Sample locations and relevant field observations were recorded at the time of collection.

The collected samples were cut at Stockholm University. Four samples, D9, D11, A26 and A38, were selected for detailed petrographic and microstructural analysis and prepared as thin sections. The orientation of the samples was retained where possible so that structures observed in thin section could be related to their field orientation.

3.4 Petrographic analysis

The four thin sections were examined using a petrographic microscope in both plane-polarised light (PPL) and cross-polarised light (XPL). Initial examination at low magnification was used to determine the general mineral assemblage and fabric of each sample. Selected areas were then examined and photographed at higher magnification to investigate individual minerals and deformation microstructures in greater detail.

Minerals were identified from optical properties including colour, relief, cleavage, extinction behaviour, twinning and interference colours. The identified mineral assemblages were compared

between the four samples to document mineralogical differences along the transect and to evaluate whether the samples provided evidence for relative changes in metamorphic conditions. Overview scans of the complete thin sections were compared with higher-magnification microscope photographs so that individual mineral and microstructural observations could be related to the larger-scale fabric of each sample.

3.5 Microstructural and shear-sense analysis

Microstructural analysis focused on deformation features capable of recording shear sense. These included deflection of mica-defined foliation around grains and mineral aggregates, asymmetric quartz- and feldspar-rich lenses, oblique mica-rich fabrics and other asymmetric deformation structures (Passchier and Trouw, 1995).

Shear sense was determined from the geometry and asymmetry of these structures rather than from the inclination of individual mineral grains alone. Where possible, several structures within a sample were considered together before a shear direction was assigned.

Because an apparent shear direction observed in thin section can only be translated into a geographic direction when the section orientation is known, the orientation of each thin section was considered during the analysis. Hand-specimen geometry and recorded cutting orientations were used as references where available. Image-relative movement was therefore distinguished from geographic shear direction where the orientation of the corresponding section could not be established with confidence.

Shear-sense observations from the four thin sections were compared with the orientation data obtained from the corresponding field measurements and with geographically oriented mesoscopic shear-sense indicators.

4. Results

Field mapping along the southern and eastern parts of Thassos resulted in a dataset of structural measurements, field observations and rock samples collected along the investigated transect.

The structural dataset consists of 153 measurements of foliation strike and dip, 103 measurements of stretching-lineation trend and plunge, and two measurements of the tectonic contact in southwestern Thassos. Four rock samples, D9, D11, A26 and A38, were selected for thin-section analysis.

Structural measurements were collected along the complete investigated transect, extending from the eastern part of the study area, including samples D9 and D11, southwards past sample A26 and towards the southwestern tectonic contact. The inland part of the transect includes several measurement localities as well as sampling locality A38. Foliation orientations vary considerably between different parts of the transect, while the stretching lineations remain more consistently NE-trending. The spatial variation in foliation orientation is also visible on the structural map (Figure 7).

4.1 Structural measurements

4.1.1 Foliation

Foliation measurements show considerable variation in orientation along the investigated transect (Figure 7). In the northeastern and eastern part of the transect, strikes include a group with more E–W to NW–SE orientations, approximately 85° – 140° . Along the eastern and southern parts of the transect, the dominant foliation is characterised by approximately N–S to NE–SW strikes, commonly between approximately 160° and 220° . This variation is also visible in the distribution of foliation planes and their poles on the stereonet.

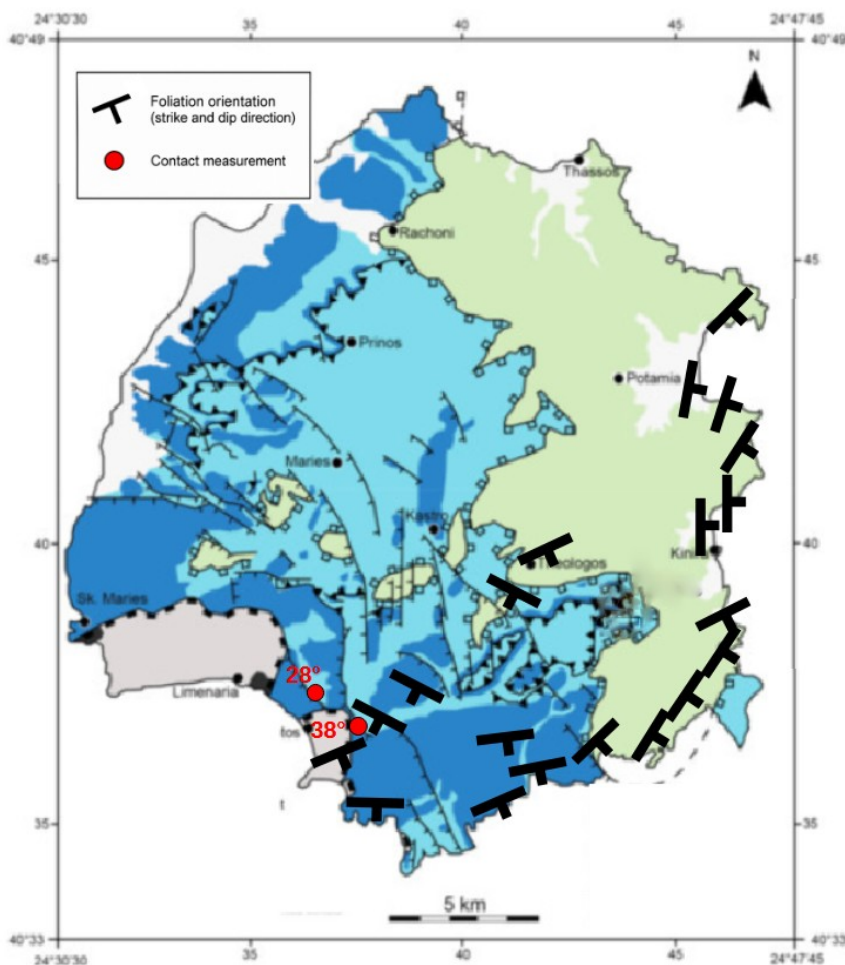


Figure 7. Geological map of Thassos showing representative foliation orientations along the investigated transect and the locations of two direct measurements of the southwestern tectonic contact. Black strike-and-dip symbols represent spatially grouped measurements from the complete foliation dataset. Red dots indicate the locations of the two contact measurements, with measured dip angles of 28° and 38° . Geological base modified from Tarantola et al. (2019), after Wawrzenitz and Krohe (1998) and Brun and Sokoutis (2007). Base map from Tarantola instead of Brun and Sokoutis because of higher visibility of foliation symbols compared to background colors.

Despite the variation in strike, the measured foliations are predominantly shallow to moderately dipping. Dip angles range from approximately horizontal to 40° , with a mean of approximately 19°

and a median of 19° . Most measurements fall below 30° , although locally steeper dips of $30\text{--}40^\circ$ were recorded.

The combined stereonet (Figure 8) illustrates the broad variation in foliation orientation. The great circles representing the foliation planes show substantial dispersion, and the corresponding poles form a broad distribution rather than a single concentrated cluster. This is consistent with the spatial variation in strike observed on the structural map.

4.1.2 Stretching lineation

The stretching lineations show a considerably more consistent orientation than the foliations. Of the 153 structural measurement sites, 103 include measurements of trend and plunge.

Most stretching lineations trend towards the northeast, predominantly between approximately 060° and 075° . The mean trend is approximately 067° and the median trend is 066° . The lineations are generally shallowly plunging, with a mean plunge of approximately 11° and a median plunge of 10° . Individual plunge measurements range from approximately horizontal to 30° .

This concentration is clearly visible on the stereonet, where the stretching lineations form a relatively narrow cluster in the northeastern quadrant (Figure 8). In contrast to the changing orientation of the foliation planes, the NE-trending stretching lineation remains comparatively consistent throughout the investigated area.

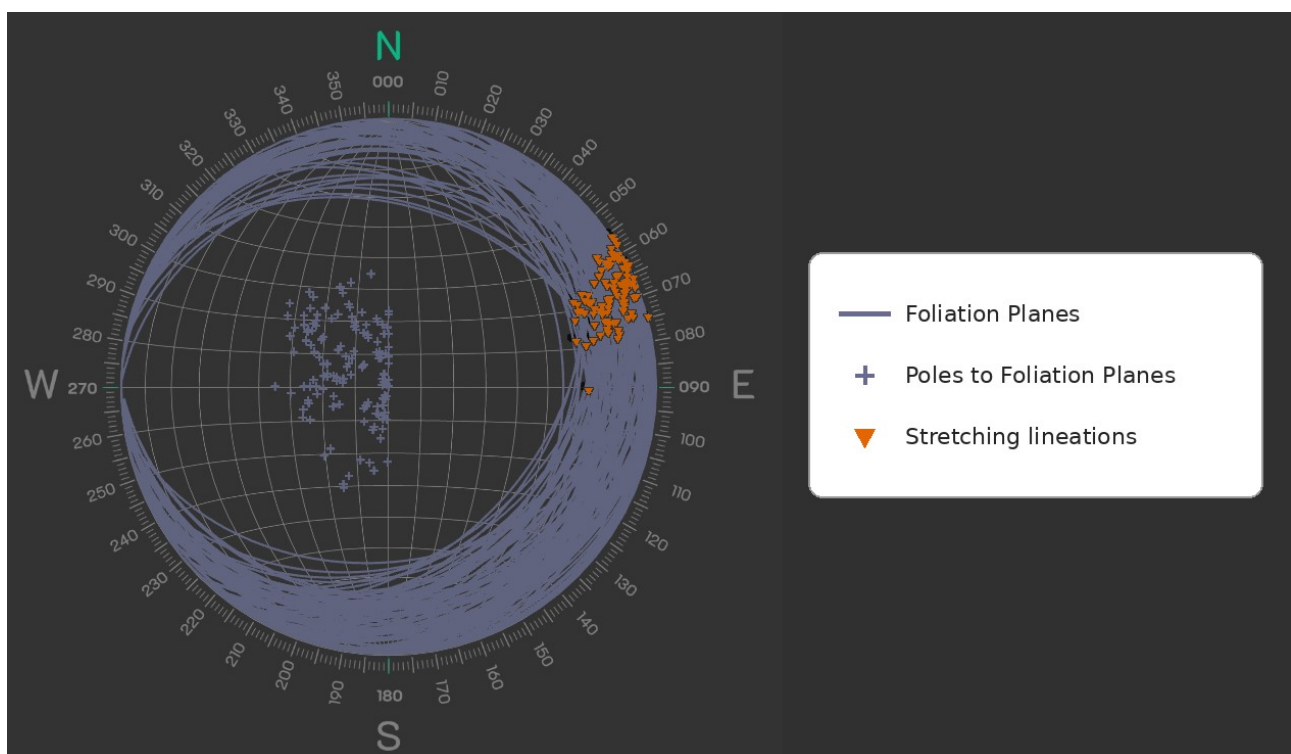


Figure 8. Lower-hemisphere stereographic projection of foliation and stretching-lineation measurements from the investigated transect. Foliations are plotted as great circles with corresponding poles, and stretching lineations are plotted as points. The lineations form a comparatively well-defined NE-trending cluster, whereas the foliation orientations show greater dispersion. Stereonet generated using Visible Geology.

4.1.3 Tectonic contact

The tectonic contact was located in the southwestern part of the investigated area, where a zone of fault breccia is exposed (Figure 9). The breccia occurs along the contact between the metamorphic rocks and the sedimentary rocks of the Limenaria Basin and provides a distinct field expression of the fault zone.

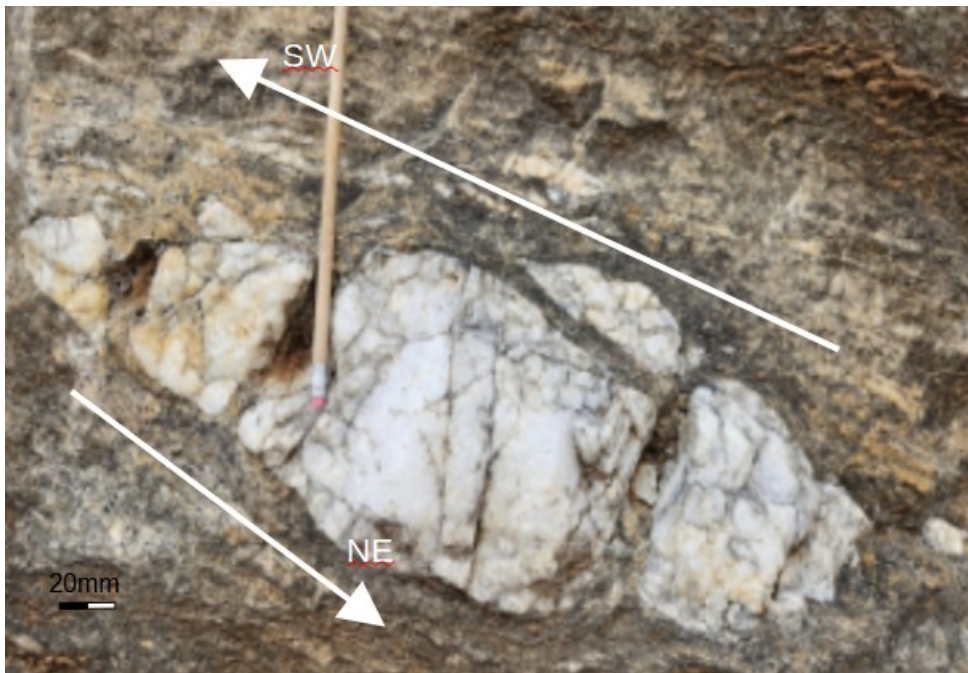
Two direct measurements closer to the tectonic contact yielded dip angles of 28° and 38° (Figure 7). The exposed fault zone therefore dips at a low to moderate angle at the measured localities. These measurements were treated separately from the foliation dataset because they represent measurements of the tectonic contact rather than the internal metamorphic fabric of the footwall rocks.



Figure 9. Close-up of fault breccia within the contact zone, showing strongly fractured and brecciated rock cut by darker deformation bands.

4.1.4 Field shear-sense indicators

Mesoscopic shear-sense indicators were observed at several localities along the investigated transect. The indicators include asymmetric deformation structures within the metamorphic rocks (Figure 10). Where the structures were sufficiently well exposed and their geographic orientation could be established, they consistently indicate a top-to-the-SW sense of shear.



a



b

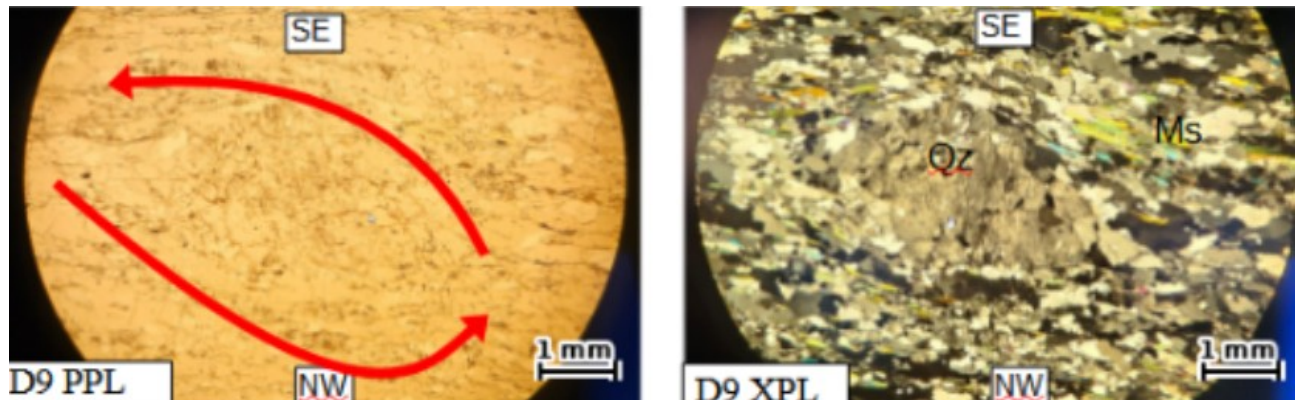
Figure 10. Mesoscopic shear-sense indicators observed along the investigated transect. White arrows indicate the interpreted shear sense, and NE–SW labels show the geographic orientation of each photograph. The structures are viewed from opposite sides in (a) and (b), resulting in reversed image orientation. Both indicate top-to-the-SW shear.

4.2 Thin-section observations

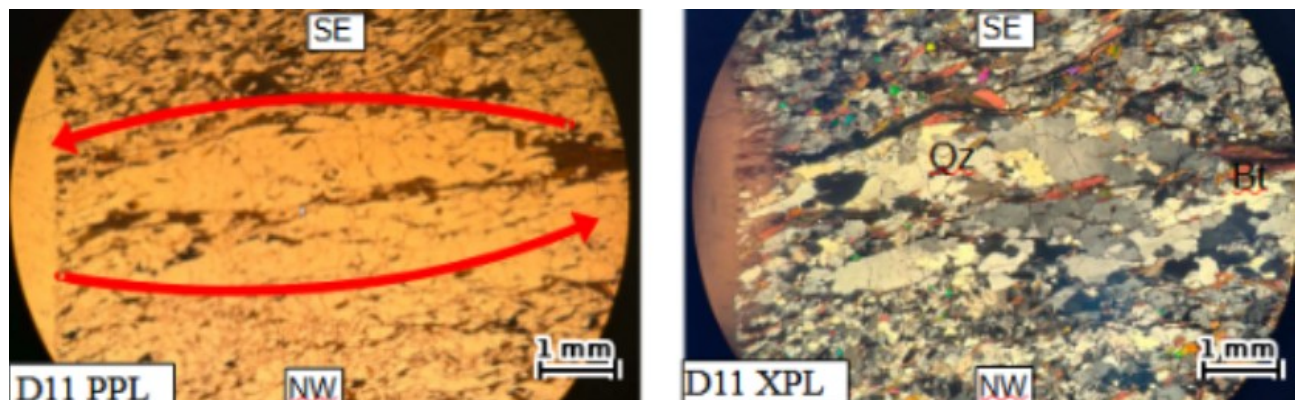
Four samples, D9, D11, A26 and A38, were selected for microscopic analysis. The thin sections display varying mineral assemblages and textures but all show evidence of deformation. Overview

photographs in plane-polarised light (PPL) and cross-polarised light (XPL) are shown in Figure 11. Higher magnification images of diagnostic minerals are shown separately in XPL in Figure 12.

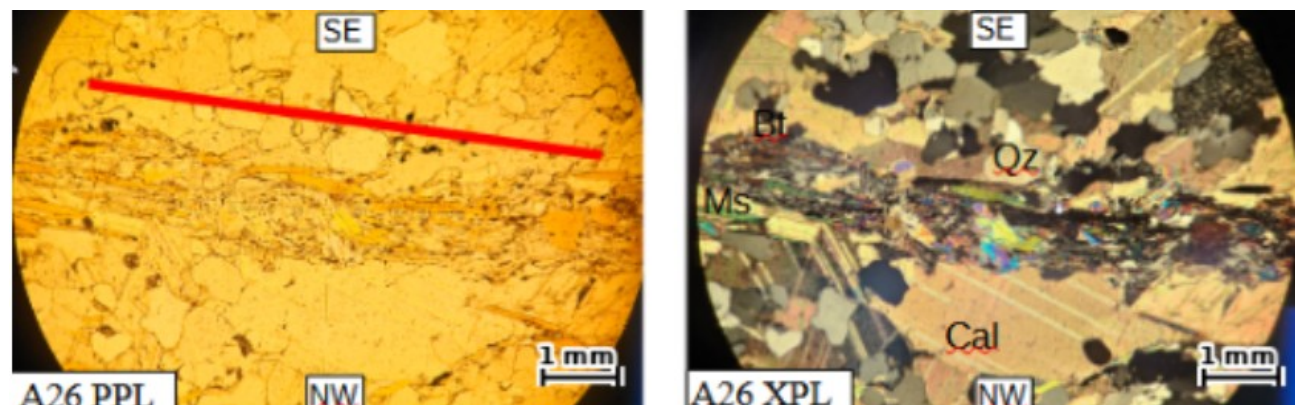
Particular attention was given to the orientation of muscovite- and biotite rich fabrics, deformation around mineral grains and aggregates, and asymmetric microstructures that could be used to determine shear sense. Microstructural analysis of samples D9, D11, A26 and A38 revealed deformation structures at the microscopic scale. Shear-sense indicators observed in the thin sections predominantly indicate top-to-the-SW shear, consistent with the sense of shear recorded by the mesoscopic field structures.



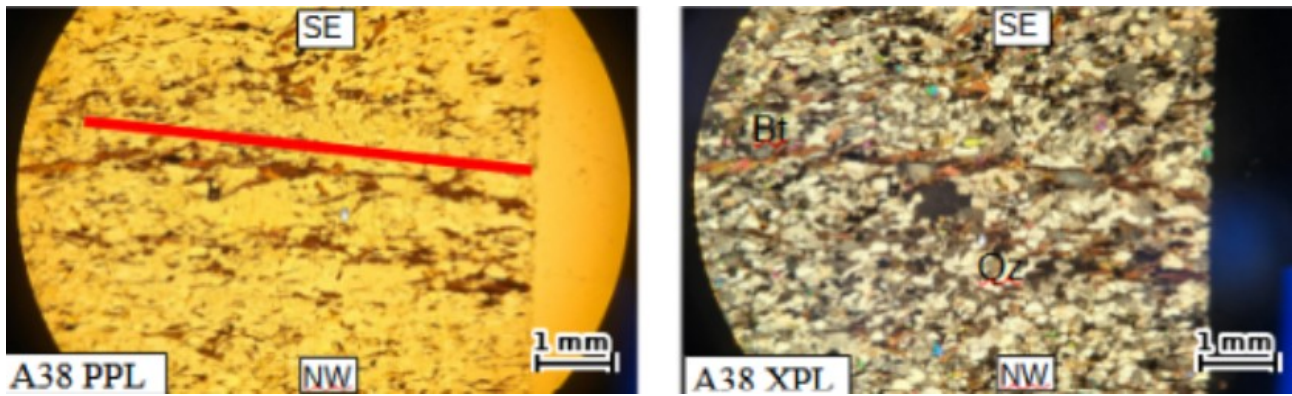
a



b

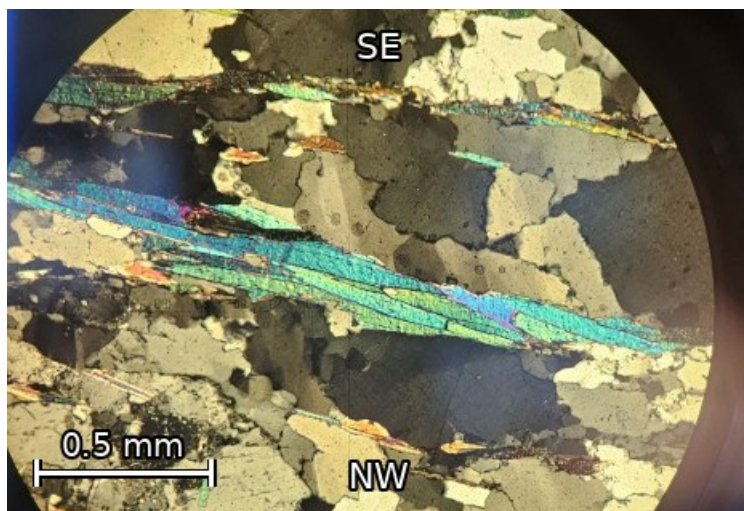


c

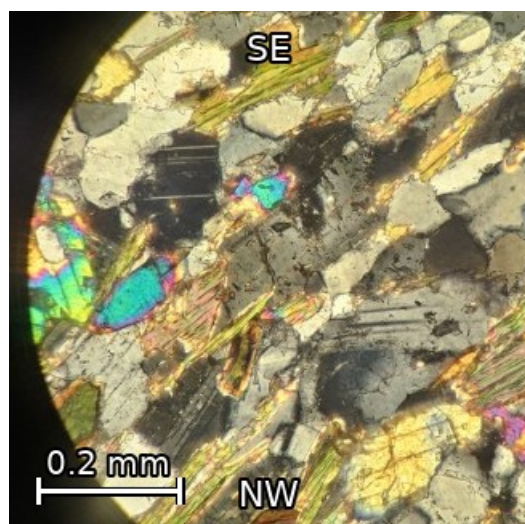


d

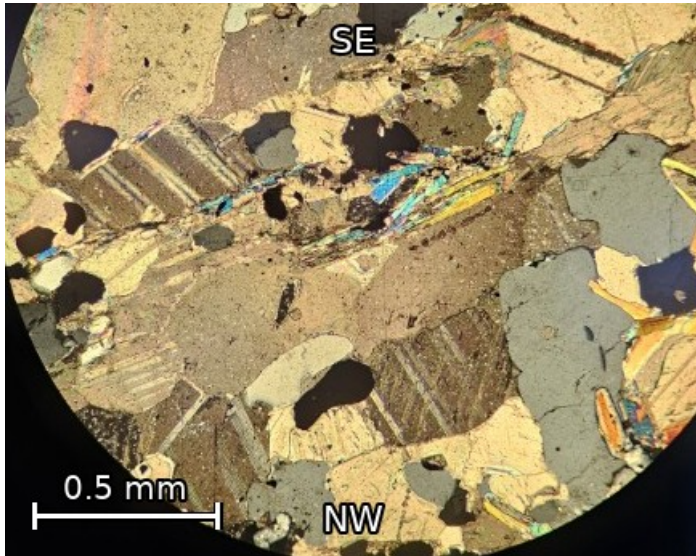
Figure 11. Representative PPL and XPL photomicrographs of samples D9 (11.a), D11 (11.b), A26 (11.c) and A38 (11.d), showing the main mineral assemblages and deformation structures observed in thin section. Mineral abbreviations indicate identified minerals, and red lines and arrows highlight the orientation and asymmetry of selected deformation structures. Geographic orientation is indicated by SE and NW. Qz = quartz, Ms = muscovite, Bt = biotite and Cal = calcite.



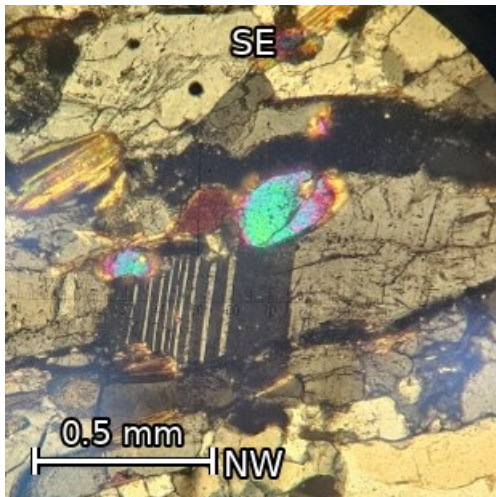
a



b



c



d

Figure 12. Higher magnification microphotographs of thin sections in XPL. D9 (a) showing elongate muscovite grains with bright interference colours defining the foliation. D11 (b) showing brightly birefringent epidote grains within a quartz–biotite assemblage. A26 (c) showing abundant calcite characterised by twin lamellae. A38 (d) showing epidote with high interference colours and plagioclase characterised by polysynthetic twinning.

4.2.1 Sample D9

Sample D9 is strongly foliated, with the fabric defined predominantly by aligned muscovite and elongate quartz-rich domains. Quartz occurs abundantly within the matrix and in larger aggregates. The contrast between the mica-rich foliation and more competent quartz-rich domains produces locally pronounced deflection of the surrounding fabric.

One of the most prominent structures is a relatively large quartz-rich lens or "eye", around which the surrounding muscovite-rich foliation is deflected. The mica-rich fabric wraps around the competent domain and records heterogeneous deformation around the lens.

The hand specimen and microscopic structures together are consistent with an approximately top-to-the-SW shear sense.

Based on its quartz–muscovite assemblage and strongly foliated texture, D9 is interpreted as a quartz–muscovite schist, shown in higher magnification in Figure 12.a.

4.2.2 Sample D11

D11 consists predominantly of quartz and biotite, with epidote also identified in the thin section. The sample displays a well-developed foliation defined by aligned biotite and elongate quartz-rich domains. The foliation is locally deflected around larger quartz-rich domains, and several biotite-rich bands occur oblique to the dominant fabric. These structures indicate non-coaxial deformation. Asymmetric relationships between the biotite-rich foliation and more competent domains provide an approximately top-to-the-SW sense of shear. Epidote occurs as part of the mineral assemblage and is shown at higher magnification in Figure 12.b.

Based on its quartz–biotite assemblage, epidote content and foliated texture, D11 is interpreted as an epidote-bearing quartz–biotite schist.

4.2.3 Sample A26

A26 is distinguished from the other investigated samples by the occurrence of calcite. Calcite is readily identifiable in XPL by its characteristic twinning and forms an important component of the mineral assemblage. Quartz and muscovite are also present.

The sample shows a heterogeneous fabric in which mica-rich domains and calcite-bearing areas are variably deformed. Calcite grains locally contain prominent twin lamellae (Figure 12.c).

Several domains display an asymmetric relationship between the main fabric and oblique deformation bands. These structures indicate non-coaxial deformation and are broadly compatible with top-to-the-SW shear.

The abundance of calcite together with quartz and muscovite indicates that A26 is best classified as a muscovite-bearing marble.

4.2.4 Sample A38

A38 was collected from the inland part of the investigated transect, away from the southwestern contact. It displays a particularly strong and continuous foliation. The fabric is dominated by aligned biotite together with quartz- and feldspar-rich domains. Plagioclase and epidote are both present in the mineral assemblage (Figure 12.d).

The strong foliation can be followed across much of the thin section and is locally deflected around coarser quartz- and feldspar-rich domains. In the XPL overview and higher-magnification images, biotite-rich bands locally occur oblique to the dominant foliation.

The orientation is an approximately top-to-the-SW sense of shear.

Based on its foliated texture and quartz–biotite assemblage, with plagioclase and epidote, A38 is interpreted as an epidote-bearing quartz–biotite schist containing plagioclase.

4.3 Summary of microscopic observations

All four investigated thin sections display a penetrative metamorphic fabric, although its intensity and mineralogical expression differ between samples. Muscovite and biotite are important fabric-forming components, commonly defining the foliation together with elongate quartz-rich domains. Calcite is particularly characteristic of A26, whereas epidote is present in D11 and A38. Plagioclase is confirmed in A38.

Deformation is expressed by alignment of muscovite and biotite, as well as deformation of quartz-rich lenses. Asymmetric structures observed in the samples are broadly compatible with a top-to-the-SW shear sense, although the quality and certainty of the individual shear-sense indicators differ between samples.

The microscopic shear-sense observations are therefore consistent overall with deformation directed approximately towards the southwest along the investigated transect.

5. Discussion

5.1 Structural pattern along the transect

The structural measurements cover the metamorphic rocks from the inland part of the study area towards the southwestern contact. The data show changes in the orientation of the foliation along the transect, while the stretching lineations remain much more consistent. This suggests that the metamorphic footwall does not have a single uniform foliation orientation, even though the main stretching direction is preserved across much of the investigated area.

The NE-SW orientation of the stretching lineations agrees with the regional structural pattern described for the Southern Rhodope Core Complex by Brun and Sokoutis (2007). They documented mainly NE-SW stretching lineations and related them to large-scale extensional exhumation. Wawrzenitz and Krohe (1998) also described widespread extensional deformation during exhumation of the Thassos metamorphic core complex. The lineations measured in this study are therefore consistent with the regional extension direction previously described for Thassos and the Southern Rhodope Core Complex.

The greater variation in foliation orientation does not necessarily conflict with this regional pattern. Thassos was affected by doming, folding and later faulting during and after exhumation (Wawrzenitz and Krohe, 1998; Brun and Sokoutis, 2007). These processes can modify the orientation of earlier foliations. For this reason, a single average foliation orientation would not represent the complete dataset well, whereas the stretching lineations provide a clearer indication of the dominant stretching direction along the transect.

5.2 Shear sense and tectonic transport

The NE-SW stretching lineations show the main stretching direction, but they do not by themselves establish the sense of tectonic transport. This requires independent shear-sense indicators. Mesoscopic shear-sense indicators observed at several field localities consistently indicate top-to-the-SW movement. The microstructures observed in the thin sections show the same general shear sense, although some indicators are clearer than others.

The agreement between field and microscopic observations strengthens this interpretation because the same general shear sense is recorded at different scales. Top-to-the-SW deformation has previously been described on Thassos by Wawrzenitz and Krohe (1998), who documented widespread top-to-the-SW-directed non-coaxial deformation during extensional exhumation. Brun and Sokoutis (2007) also described mainly NE-SW stretching within the regional extensional system. The combination of NE-SW stretching lineations and top-to-the-SW shear-sense indicators in this study is therefore consistent with the previously described kinematics of Thassos and the Southern Rhodope Core Complex.

Some caution is needed when interpreting the microscopic shear-sense indicators. Thin sections are two-dimensional cuts through three-dimensional structures, and their appearance depends on section orientation. Some microstructures show deformation without providing a clear movement direction. The shear-sense interpretation is therefore based on several indicators together, particularly the geographically oriented mesoscopic structures, rather than on individual microscopic structures alone.

5.3 Petrography, metamorphic conditions and thermal gradients

The four investigated thin sections are from different metamorphic rock types. D9 is interpreted as a quartz-muscovite schist, D11 and A38 as epidote-bearing quartz-biotite schists, with A38 additionally containing plagioclase, and A26 as a muscovite-bearing marble. These classifications are based on the observed mineral assemblages and textures.

The difference between A26 and the other samples is important when comparing metamorphic conditions. A26 contains abundant calcite together with quartz and muscovite, whereas the other samples are silicate-rich schistose rocks. Mineral assemblages depend strongly on bulk-rock composition and therefore cannot be compared directly as a simple metamorphic sequence. Differences between the samples do not necessarily represent differences in metamorphic grade.

Calcite in A26 commonly shows deformation twins. Calcite deformation has previously been studied in marble shear zones on Thassos. Bestmann et al. (2000) documented deformation and progressive strain localization in these marbles during decreasing pressure-temperature conditions associated with exhumation. The calcite twins in A26 therefore provide evidence of deformation, but they cannot by themselves be used to assign a specific deformation temperature or peak metamorphic temperature to the sample.

Epidote occurs in D11 and A38. Epidote is common in greenschist-facies assemblages but may remain stable into the transition towards amphibolite-facies conditions (Maruyama et al., 1983). Its presence alone is therefore insufficient to determine the metamorphic facies of D11 or A38. The epidote may represent lower-grade metamorphism or retrograde mineral growth during cooling from higher-grade conditions.

Quantitative P-T estimates for the four investigated samples are beyond the scope of this bachelor thesis because no mineral-chemical analyses or thermobarometric calculations were carried out. Published geothermobarometric estimates from amphibole gneisses on Thassos nevertheless

provide useful regional context. Metamorphic conditions of approximately 620°C and 4.7 kbar have been reported for the lower unit and approximately 580°C and 2.4 kbar for the intermediate unit (Bestmann et al., 2000).

The published P–T estimates correspond to unusually high apparent temperature-depth gradients if pressure is converted directly to lithostatic depth. Assuming a representative continental crustal density of approximately 2700 kg/m³, 1 kbar corresponds to approximately 3.7 km depth. The estimate of 620°C at 4.7 kbar therefore corresponds to approximately 17.4 km depth and an apparent temperature-depth gradient of about 36°C/km. In contrast, 580°C at 2.4 kbar corresponds to approximately 8.9 km depth and an apparent gradient of about 65°C/km. The latter value is exceptionally high compared with typical steady-state continental geothermal gradients.

One possible explanation for such a high apparent gradient is rapid extensional exhumation of the metamorphic footwall. During rapid exhumation, advection of hot rocks toward shallower crustal levels can perturb the thermal field and modify the geometry of isotherms. Two-dimensional thermal modelling of the Simplon normal-fault system demonstrates that exhumation-related thermal perturbation can complicate interpretations based on a constant geothermal gradient (Grasemann and Mancktelow, 1993). The approximately 65°C/km value calculated from the published Thassos P–T estimate may therefore reflect a transient and tectonically perturbed thermal regime rather than a steady-state crustal geotherm. This interpretation remains tentative because the P–T estimates, pressure-to-depth conversion and timing of metamorphism and exhumation all carry uncertainties.

The occurrence of epidote in D11 and A38 could represent retrograde re-equilibration during exhumation rather than the maximum metamorphic conditions experienced by these rocks. This interpretation is compatible with the cooling and exhumation history described for Thassos. Wawrzenitz and Krohe (1998) documented progressive extension and exhumation of the metamorphic core complex, while Bestmann et al. (2000) showed that deformation in Thassos marble shear zones continued under decreasing P–T conditions, including deformation at approximately 300–350°C. The observed mineral assemblages can therefore be discussed within a cooling and retrograde history.

The four thin sections do not demonstrate a systematic decrease in metamorphic grade towards the southwestern contact. Their different bulk-rock compositions make direct comparison difficult, and exposure close to the contact is limited. No thin sections from the immediate contact zone were analysed. A southwestward metamorphic or thermal gradient within the footwall may be compatible with the regional exhumation history, but it cannot be demonstrated quantitatively from these four samples.

There is nevertheless a clear thermal and metamorphic discontinuity across the southwestern tectonic boundary. Metamorphic rocks in the footwall are juxtaposed against unmetamorphosed sedimentary rocks of the Limenaria Basin. This places rocks that record mid-crustal metamorphic temperatures next to sediments with no comparable metamorphic history. Such juxtaposition is characteristic of extensional exhumation, in which hotter, deeper crustal rocks are brought towards the surface relative to cooler upper-crustal rocks and sediments. This discontinuity is stronger

evidence for a tectonically produced thermal contrast at the southwestern boundary than the available samples are for a gradual thermal gradient within the footwall. The temperatures recorded by the metamorphic rocks and the later basin sediments are not necessarily synchronous, however, so they should not be used to calculate a present-day spatial geothermal gradient across the contact.

5.4 Deformation from ductile to brittle conditions

The structural observations also record changing rheological conditions during exhumation. The metamorphic footwall contains foliations, stretching lineations and asymmetric structures produced under ductile conditions, whereas the southwestern contact contains fault breccia produced by brittle fragmentation. This change is consistent with deformation continuing as the rocks were exhumed and cooled.

Bestmann et al. (2000) documented progressive strain localization in Thassos marble shear zones under decreasing P-T conditions, including deformation at approximately 300-350°C. The field observations are compatible with this general evolution from ductile deformation at depth towards increasingly brittle behaviour at shallower crustal levels. However, the occurrence of ductile fabrics in the footwall and brittle breccia at the southwestern boundary does not demonstrate that they formed during one continuous deformation event. The breccia may record later localization or reactivation during continued extension. This distinction is important when evaluating whether the exposed southwestern fault represents the brittle continuation of the earlier ductile shear system. The conceptual relationship between low-angle normal faulting, footwall exhumation, isotherm deflection and shallow brittle deformation is illustrated in Figure 13.

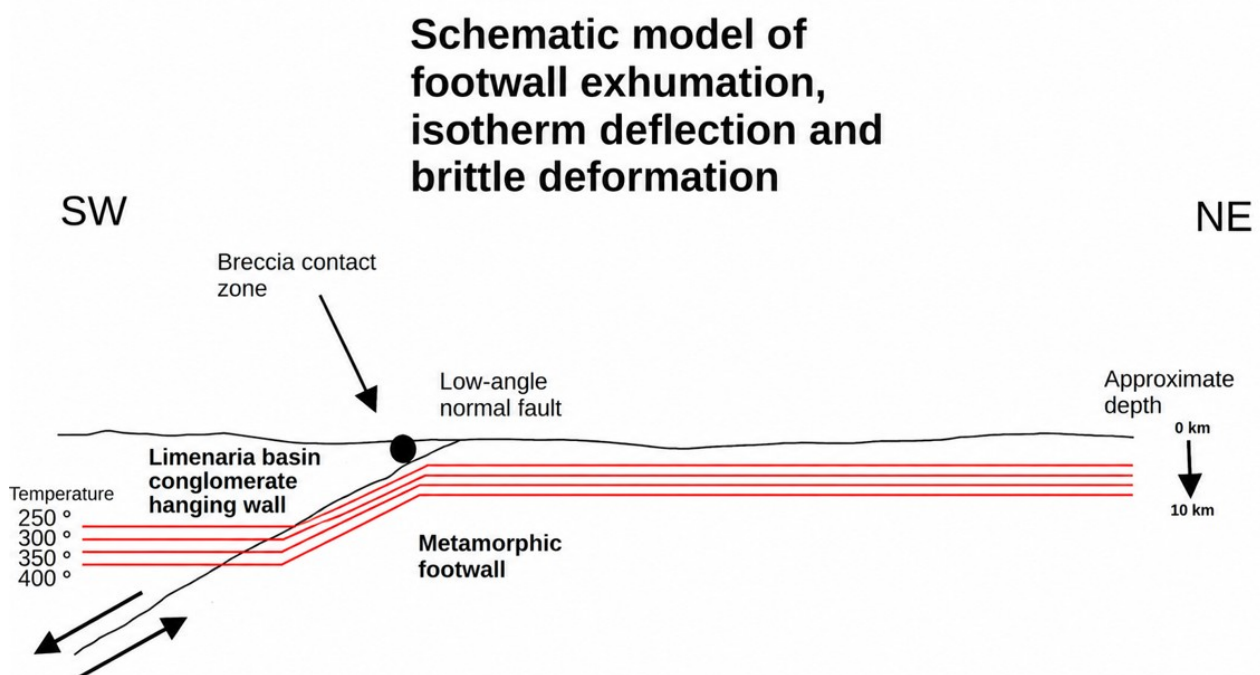


Figure 13. Schematic model of footwall exhumation along a low-angle normal fault, showing associated isotherm deflection and shallow brittle deformation. Approximate depths and isotherms are schematic. Not to scale.

5.5 Southwestern tectonic contact

The southwestern tectonic contact was identified in the field as a fault zone containing breccia. This provides direct evidence of brittle deformation and supports interpretation of the boundary as a tectonic contact rather than simply a change in rock type. Two measurements of the exposed fault zone gave dip angles of 28° and 38°. Although only two measurements were obtained, both indicate low- to moderately dipping fault surfaces at these localities and are compatible with low-angle extensional faulting.

Previous studies have proposed different interpretations of the extensional structures of Thassos and the Southern Rhodope. Dinter and Royden (1993) interpreted the Strymon Valley detachment system as an important structure in extensional exhumation of the Rhodope metamorphic core complex, while Wawrzenitz and Krohe (1998) described low-angle normal detachment faulting during exhumation of the Thassos metamorphic core complex. Brun and Sokoutis (2007, 2018) emphasized a more complex extensional evolution involving ductile core-complex deformation, low-angle structures and development of the Limenaria Basin. The measured dips of 28° and 38° in this study are therefore important because they independently support a low-angle to moderately low-angle extensional geometry at the southwestern boundary.

The contact contains fault breccia and has measured dips around 30°, while the metamorphic footwall contains NE-SW stretching lineations and predominantly top-to-the-SW shear-sense indicators. The structural geometry and kinematics therefore point in the same general direction: southwest-directed extension accommodated by shallowly dipping structures. These observations support a low-angle normal-fault interpretation of the southwestern boundary.

The data do not, however, establish the complete history of the exposed fault. Fault breccia demonstrates brittle faulting but does not independently determine its age, total displacement or relationship to the earlier ductile deformation. The exposed fault could represent brittle localization or reactivation within the same long-lived extensional system. The present observations therefore support low-angle normal faulting at the southwestern margin but cannot determine whether all ductile and brittle structures formed during the same stage of exhumation.

5.6 Implications for exhumation of the Thassos metamorphic core complex

The structural observations indicate that the metamorphic footwall records a coherent NE-SW extensional system with predominantly top-to-the-SW tectonic transport. Together with the low fault dips measured at the southwestern contact, the data support exhumation dominated by shallowly dipping extensional structures in the investigated area. This agrees with the regional kinematic framework described for Thassos and the Southern Rhodope Core Complex by Wawrzenitz and Krohe (1998) and Brun and Sokoutis (2007).

At a larger scale, this deformation formed part of the Cenozoic extensional evolution of the northern Aegean and the exhumation of metamorphic core complexes (Jolivet and Brun, 2010; Ring et al., 2010). The combination of high-temperature metamorphic rocks, retrograde deformation during cooling, top-to-the-SW kinematics and low-angle brittle faulting is consistent with progressive tectonic exhumation of the Thassos footwall. The Limenaria Basin records the sedimentary response to this extensional evolution, although the available data do not establish the precise timing between ductile exhumation, brittle faulting and basin deposition.

5.7 Limitations

Several limitations affect the interpretation of the results. Structural measurements were mainly collected along roads and accessible outcrops. The distribution of the measurements therefore partly

reflects the availability of exposed bedrock rather than uniform sampling across the study area. Only two direct measurements were obtained from the southwestern tectonic contact. The measured dips describe the fault geometry at these two locations but should not be used to define an exact average dip for the entire contact. More measurements along the fault zone would be needed to determine how much its orientation varies.

The petrographic analysis is based on four thin sections representing rocks with different bulk compositions. This limits the ability to establish a systematic metamorphic or thermal gradient along the transect. Quantitative P-T estimates for the investigated samples were beyond the scope of this bachelor thesis because no mineral-chemical analyses or thermobarometric calculations were carried out. In particular, epidote in D11 and A38 cannot by itself establish their peak metamorphic facies or P-T conditions.

The microscopic shear-sense interpretation also has limitations. The appearance of microstructures depends on thin-section orientation, and some structures show deformation without giving a clear movement direction. Agreement between the microscopic observations, the geographically oriented mesoscopic field indicators and the regional lineation pattern increases confidence in the overall top-to-the-SW interpretation, but some uncertainty remains for individual microstructures.

Finally, the fault breccia demonstrates brittle deformation at the southwestern contact, but the available data cannot determine its age. The present study therefore cannot establish whether the exposed brittle fault and the earlier ductile shear structures developed continuously within the same extensional system or during separate stages of deformation.

6. Conclusion

This study investigated the structural and metamorphic evolution of the metamorphic footwall towards the southwestern tectonic boundary of Thassos. The structural data show considerable variation in foliation orientation along the transect, whereas stretching lineations are comparatively consistent and trend mainly NE-SW. Mesoscopic shear-sense indicators consistently record top-to-the-SW movement, while the investigated thin sections show the same general kinematic pattern, although individual microscopic indicators are less certain. Together, these observations support southwest-directed tectonic transport during extensional deformation of the Thassos metamorphic core complex.

Petrographic analysis confirms that the footwall contains metamorphic rocks with different bulk compositions and mineral assemblages. Quantitative P-T estimates for the investigated samples were beyond the scope of this bachelor thesis. Published data nevertheless show that the Thassos metamorphic succession experienced high-temperature metamorphism followed by cooling and retrograde deformation during exhumation. The four thin sections do not demonstrate a systematic southwestward decrease in metamorphic grade. A pronounced metamorphic and thermal discontinuity nevertheless occurs at the southwestern boundary, where the metamorphic footwall is juxtaposed against unmetamorphosed sediments of the Limenaria Basin.

The southwestern boundary is marked by fault breccia, and the two measured fault surfaces dip 28° and 38°. These low to moderately low dips, together with NE-SW stretching lineations and top-to-the-SW shear sense in the footwall, support a low-angle normal-fault interpretation of the southwestern margin. The available evidence does not establish the age or complete displacement history of the brittle fault, and therefore cannot determine whether the exposed fault and the earlier

ductile shear structures developed continuously or during separate stages of the extensional evolution.

Overall, the results support southwest-directed exhumation of the Thassos metamorphic core complex along shallowly dipping extensional structures, accompanied by cooling from ductile metamorphic conditions towards brittle deformation at shallower crustal levels. The structural observations agree with the regional kinematic framework of the Southern Rhodope Core Complex, while the exact temporal relationship between ductile exhumation, brittle faulting and development of the Limenaria Basin remains unresolved.

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References

- Beck, M. E. & Schermer, E. R. 1994. Aegean paleomagnetic inclination anomalies: Is there a tectonic explanation? *Tectonophysics*, 231, 281–292. DOI: 10.1016/0040-1951(94)90039-6.
- Bestmann, M., Kunze, K. & Matthews, A. 2000. Evolution of a calcite marble shear zone complex on Thassos Island, Greece: Microstructural and textural fabrics and their kinematic significance. *Journal of Structural Geology*, 22, 1789–1807. DOI: 10.1016/S0191-8141(00)00112-7.
- Brun, J.-P. & Sokoutis, D. 2007. Kinematics of the Southern Rhodope Core Complex (North Greece). *International Journal of Earth Sciences*, 96(6), 1079–1099. DOI: 10.1007/s00531-007-0174-2.
- Brun, J.-P. & Sokoutis, D. 2018. Core complex segmentation in North Aegean, a dynamic view. *Tectonics*, 37(6), 1797–1830. DOI: 10.1029/2017TC004939.
- Dinter, D. A. & Royden, L. 1993. Late Cenozoic extension in northeastern Greece: Strymon Valley detachment system and Rhodope metamorphic core complex. *Geology*, 21(1), 45–48. DOI: 10.1130/0091-7613(1993)021<0045:LCEING>2.3.CO;2.
- Grasemann, B. & Mancktelow, N. S. 1993. Two-dimensional thermal modelling of normal faulting: The Simplon Fault Zone, Central Alps, Switzerland. *Tectonophysics*, 225(3), 155–165. DOI: 10.1016/0040-1951(93)90277-Q.
- Jolivet, L. & Brun, J.-P. 2010. Cenozoic geodynamic evolution of the Aegean. *International Journal of Earth Sciences*, 99(1), 109–138. DOI: 10.1007/s00531-008-0366-4.

- Kounov, A. & Gerdjikov, I. 2024. On the Rhodopean protoliths and their Middle Jurassic to Early Cretaceous evolution. A review. *Geologica Balcanica*, 53(1), 29–85. DOI: 10.52321/GeolBalc.53.1.29.
- Kounov, A., Wüthrich, E., Seward, D., Burg, J.-P. & Stockli, D. 2015. Low-temperature constraints on the Cenozoic thermal evolution of the Southern Rhodope Core Complex (Northern Greece). *International Journal of Earth Sciences*, 104, 1337–1352. DOI: 10.1007/s00531-015-1158-2.
- Lister, G. S. & Davis, G. A. 1989. The origin of metamorphic core complexes and detachment faults formed during Tertiary continental extension in the northern Colorado River region, U.S.A. *Journal of Structural Geology*, 11(1–2), 65–94. DOI: 10.1016/0191-8141(89)90036-9.
- Maruyama, S., Suzuki, K. & Liou, J. G. 1983. Greenschist–amphibolite transition equilibria at low pressures. *Journal of Petrology*, 24(4), 583–604. DOI: 10.1093/petrology/24.4.583.
- Passchier, C. W. & Trouw, R. A. J. 1995. *Microtectonics*. Berlin, Heidelberg: Springer-Verlag. DOI: 10.1007/978-3-662-08734-3.
- Ring, U., Glodny, J., Will, T. & Thomson, S. 2010. The Hellenic subduction system: High-pressure metamorphism, exhumation, normal faulting, and large-scale extension. *Annual Review of Earth and Planetary Sciences*, 38, 45–76. DOI: 10.1146/annurev.earth.050708.170910.
- Schellart, W. P. 2005. Influence of the subducting plate velocity on the geometry of the slab and migration of the subduction hinge. *Earth and Planetary Science Letters*, 231(3–4), 197–219. DOI: 10.1016/j.epsl.2004.12.019.
- Tarantola, A., Voudouris, P., Eglinger, A., Scheffer, C., Trebus, K., Bitte, M., Rondeau, B., Mavrogonatos, C., Graham, I., Etienne, M. & Peiffert, C. 2019. Metamorphic and metasomatic kyanite-bearing mineral assemblages of Thassos Island (Rhodope, Greece). *Minerals*, 9(4), 252. DOI: 10.3390/min9040252.
- Wawrzenitz, N. & Krohe, A. 1998. Exhumation and doming of the Thasos metamorphic core complex (S Rhodope, Greece): Structural and geochronological constraints. *Tectonophysics*, 285(3–4), 301–332. DOI: 10.1016/S0040-1951(97)00276-X.
- Zachos, S. 1982. *Geological map of Greece, Thassos sheet*. Scale 1:50,000. Athens: Institute of Geology and Mineral Exploration (IGME).