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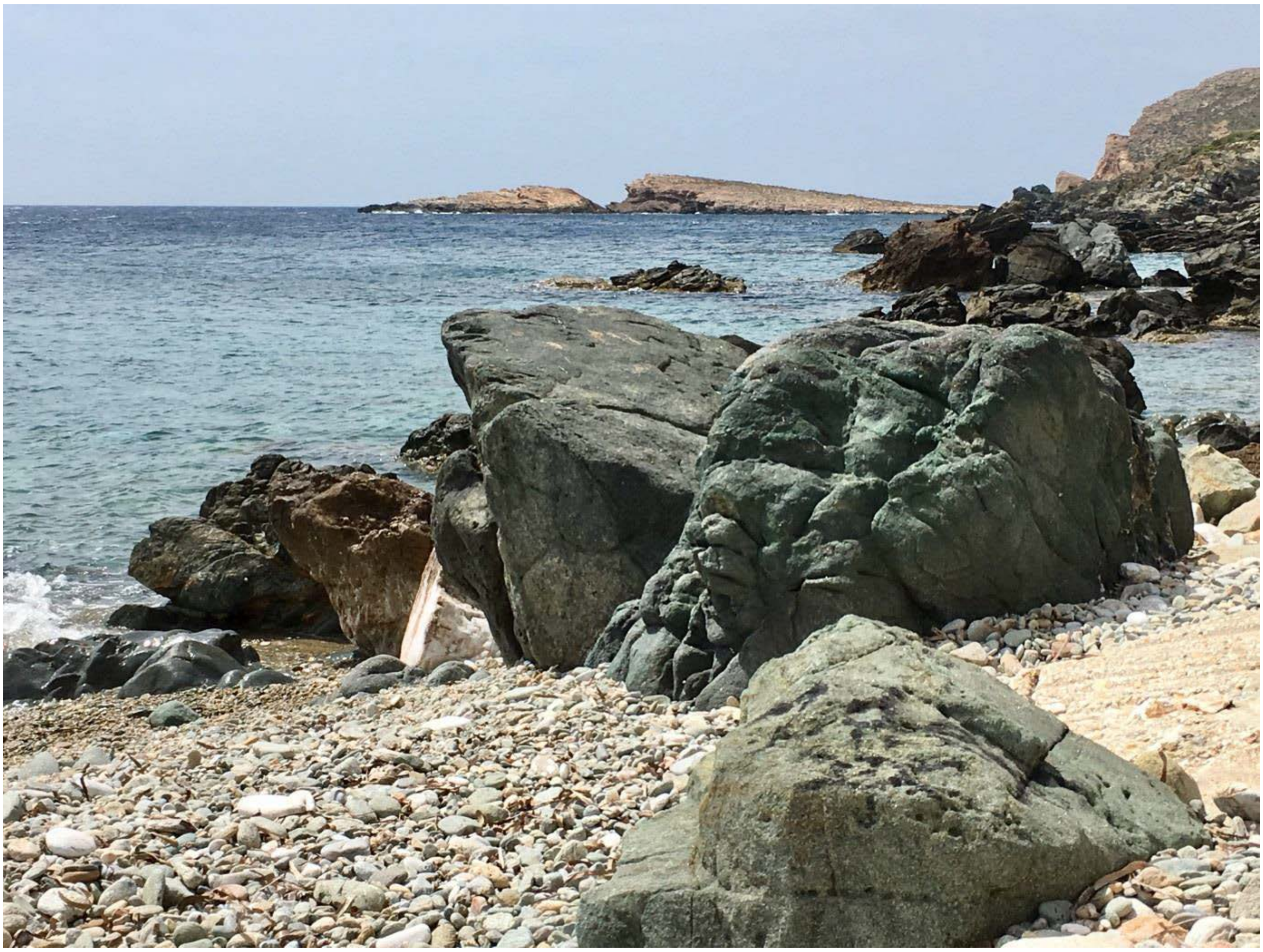
Retrograde metamorphism of ultramafic rocks on Syros, Greece

Karin Lodin



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Department of Geological Sciences
Stockholm University
SE-106 91 Stockholm

Abstract

Ultramafic knockers with a blueschist/greenschist rind metamorphosed at high pressure and low temperature conditions are exposed on SE Syros, Greece. They provide a record of metamorphic processes in subduction zones. In this study, mineral modes and reaction textures from thin sections of an ultramafic eclogite knocker were analysed petrographically. Here, I suggest that the knocker has retrogressed from eclogite facies in two stages. Firstly, retrogression occurred at blueschist facies conditions and secondly at greenschist facies conditions. Both stages of retrogression were accompanied by metamorphic fluid flow which resulted in hydration reactions. Greenschist facies rocks were found to be spatially restricted to the melange zone within which the knockers were situated. Furthermore, and based on previous work, a quiescent gap of 11-16 Ma can be inferred to have occurred after eclogite/blueschist facies metamorphism and before the onset of greenschist facies metamorphism. I hypothesise that the fluid flow was absent or sparse during this quiescent period and resumed due to tectonic emplacement of the Vari Unit above the Cycladic Blueschist Unit. I further conclude that metamorphic fluid flow was channelled through the melange zone which contained the knockers at blueschist and eclogite facies conditions. This study corroborates previous findings underpinning the importance of metamorphic fluid flow in metamorphic reactions.

Index

Introduction

Rocks metamorphosed at high pressure (HP) - low temperature (LT) conditions provide a record of the metamorphic processes in subduction zones. HP-LT metamorphic rocks can be exposed at the surface as the result of exhumation of material buried deep down in a subduction zone. Normally, HP-LT mineral assemblages are replaced at conditions associated with exhumation such as lower pressure, higher temperature and exposure to metamorphic fluids. Therefore, HP-LT mineral assemblages formed at blueschist and eclogite facies conditions tend to be overprinted at lower pressure conditions such as in the greenschist facies and the record of the former subduction process are usually therefore erased [1, 2]. However, in a few places in the world, HP-LT mineral assemblages can be found preserved intact without mineral replacement at the surface. Several theories exist as to why this occurs. However, a general consensus is that rapid exhumation is an essential component in creating conditions where HP-LT can be preserved [3-6].

HP-LT metamorphism is generally restricted to accretionary prisms in subduction zones [7]. The accretionary prism will provide enough pressure due to the weight of the thickening prism. Furthermore, the subducting oceanic lithosphere beneath the prism is cool and therefore the conditions for LT metamorphism are fulfilled. As the wet and compressed subducted plate is pushed further down, the rocks will be exposed to higher temperature and pressure and massive amounts of fluids will be released from the wet oceanic plate [8]. The released fluids will enable fluid-rock interactions to occur as the liberated fluids move upwards. The fluids may either interact or equilibrate with the rocks that they encounter. Fluid migration will occur either focused through structurally weak parts of the rock or pervasively through the entire rock volume [2, 9, 10]. Exhumation of rocks metamorphosed under HP-LT conditions can occur through the accretionary wedge or through the subduction channel and back to the surface [7, 11]. In most cases, HP-LT mineral assemblages are overprinted and replaced during the exhumation process when exposed to different temperature and pressure conditions. Furthermore, when metamorphic fluids flow along structural channels within the rock such as shear zones, fold hinges, vein-fractures or with permeable rock layers, replacement of HP-LT minerals usually occur in the areas affected by fluids. The composition of fluids can however, in some cases, maintain the conditions required to preserve a HP-LT mineral assemblage instead of causing its replacement. HP-LT mineral assemblages can also be preserved during conditions where the availability of fluid is limited and late deformation is sparse or lacking.

One of the most spectacular locations in the world where HP-LT rocks can be observed is on the island, Syros in Greece. On the SE Coast of this island at Fabrika Beach, mafic rocks with eclogite, blueschist and greenschist facies mineral assemblages juxtaposed with one another on scales of centimetres to meters. The reason why HP-LT (eclogite and blueschist facies) and LP (greenschist facies) rocks coexist in this small area is a matter of debate. However, several conditions associated with regional preservation of these rocks have been found in the area. Firstly, Syros is located in the back-arc of the Hellenic subduction zone and the rocks on Fabrika Beach have thus been subjected to rapid exhumation [4, 12-14]. Secondly, highly metamorphosed 1-2m sized blocks called knockers are randomly distributed along a 50-m-wide section of Fabrika Beach. Knockers are almost exclusively found in the tectonic melange of subduction complexes and are known to occur as blocks in shear zones together with rocks of lower metamorphic grade [15]. Such melanges are known to be highly permeable and thus strongly affected by metamorphic fluid flow [16]. The ultramafic eclogite knockers at Fabrika have a rind consisting of greenschist/blueschist facies minerals while eclogite facies minerals are preserved in the interior of the knockers. This is therefore an excellent example of local preservation of eclogite facies minerals at blueschist and greenschist facies conditions.

The aim of this thesis is to find out what reaction or reactions formed the greenschist/blueschist facies rind of the knockers on Fabrika Beach so as to learn about the fluid conditions in a subduction zone melange.

Regional geological setting

The Aegean Sea is located southeast of mainland Greece. In the Aegean Sea, approximately 220 islands of varying size including Syros, form the Cyclades archipelago. The islands in the archipelago form a circle around the island of Delos and the area is therefore referred to as the Cycladic (circular) archipelago. Geologically, the Cyclades belong to the Attic-Cycladic metamorphic core complex belt which consists of two structurally different units [17, 18].

The upper unit consists of sedimentary rocks, ophiolites, greenschist-facies rocks, granitoids and medium-P-high-T rocks of Cretaceous age [2, 19, 20]. The lowest part in the lower unit consist of a crystalline basement overlain by the Cycladic Blueschists Unit (CBU) [21]. The CBU is a sequence of metamorphosed volcano-sedimentary rocks. The upper and the lower unit is separated by low-angle detachments with normal faults [22]

The Cyclades area in the Aegean Sea represents a high-pressure belt in a back-arc zone. The subduction zone itself was active when the African plate was forced to subduct beneath the Eurasian plate due to the convergence between Eurasia and Africa resulting in the Alpine orogeny.

The subduction of sedimentary and magmatic rocks took place during the Eocene at approximately 53-30 Ma and peak pressure metamorphism has been estimated to about 50-52 Ma throughout the Cyclades [23, 24].

There are several theories describing the tectono-metamorphic evolution of the Cyclades, where the controversies mostly concern the exhumation history. Exhumation of HP-LT rocks involved crustal scale extensional zones where the Cycladic Blueschist Unit was progressively exhumed by a continuum of accretion at the base of the orogenic wedge. The detachments permitted a rapid exhumation of rocks along a cold geotherm and HP-LT assemblages could therefore be preserved [5, 11]. The exhumation is believed to have been relatively fast due to the slab retreat [22]. Thus, regional preservation of HP-LT assemblage in the CBU could have been due to rapid exhumation [25, 26].

In fact, exhumation of HP-LT metamorphic rocks with associated retrograde metamorphism from blueschist-facies to greenschist-facies conditions is suggested to have occurred in two stages extended over a long time period at temperatures between 400-500° C and pressure about 0.8-1.0 GPa [2, 27-29]. The first stage took place during the Eocene with exhumation within the subduction channel and is thus referred to as "syn-orogenic exhumation".

The second stage took place during the Oligocene and Miocene with exhumation below detachments in the back-arc region and crustal extension. The second stage of exhumation is referred to as "post-orogenic exhumation" [11, 22, 30]. The post-orogenic crustal extension and detachments during the Miocene are thought to have formed the Aegean Sea [5, 31].

Geology of Syros

Syros consists of a series of high pressure tectonic nappe stacks [4]. The nappes include a greenschist-facies basement, metasedimentary marble-schist and a metabasite unit [4]. A simplified geological map of Syros is presented in Fig 1.

The main part of Syros belongs to the CBU except for the Vari Unit. This unit consists of greenschist and an orthogneiss called the Vari-gneiss [13]. The Vari detachment separates the Vari unit from the CBU [4, 5]. The CBU on Syros can be divided into two parts. The first part is a volcano-sedimentary sequence consisting of quartzite, metapelites, metabasic rocks, marble and cherts [2, 32]. The second part is a meta-ophiolitic mélange which is composed of meta-gabbro, ultra-basic rocks, felsic gneiss, glaucophanites and eclogites [2, 32].

All rocks belonging to the CBU on Syros experienced HP-LT blueschist-eclogite facies metamorphic conditions during early burial in the Eocene [13, 29, 33]. However, the peak conditions for metamorphism as well as the exhumation history are subject of debate. Several studies have tried to elucidate when the high-pressure metamorphism of the CBU took place.

Meta-igneous rocks from northern Syros have been interpreted, based on U-Pb zircon geochronology, as being relics of oceanic crust protoliths formed at about 80-75Ma [33]. Based on geochemical evidence, it has been suggested that these protoliths were oceanic crust from the back-arc basin of the convergent plate margin of the Cretaceous part of the Tethys Ocean [4, 34]. Other researchers disagree and have interpreted those zircons as metamorphic and have thus dated the peak metamorphism in the metabasite mélanges to approximately 52 Ma [33]. This approximate age for high pressure metamorphism is also supported by results from Ar-Ar dating of white mica [3, 33] and Lu-Hf dating of the peak paragenesis garnet-omphacite [35].

Some researchers like Schumacher and Keiter suggest that the Cycladic Unit was a single coherent continental fragment with identical metamorphic and structural evolution [4, 36]. They suggest a single P-T evolution with peak conditions producing blueschists and eclogites at 1.5-1.6 GPa and 500°C [4, 21, 36]. Others are in favour of the idea that Syros consisted of

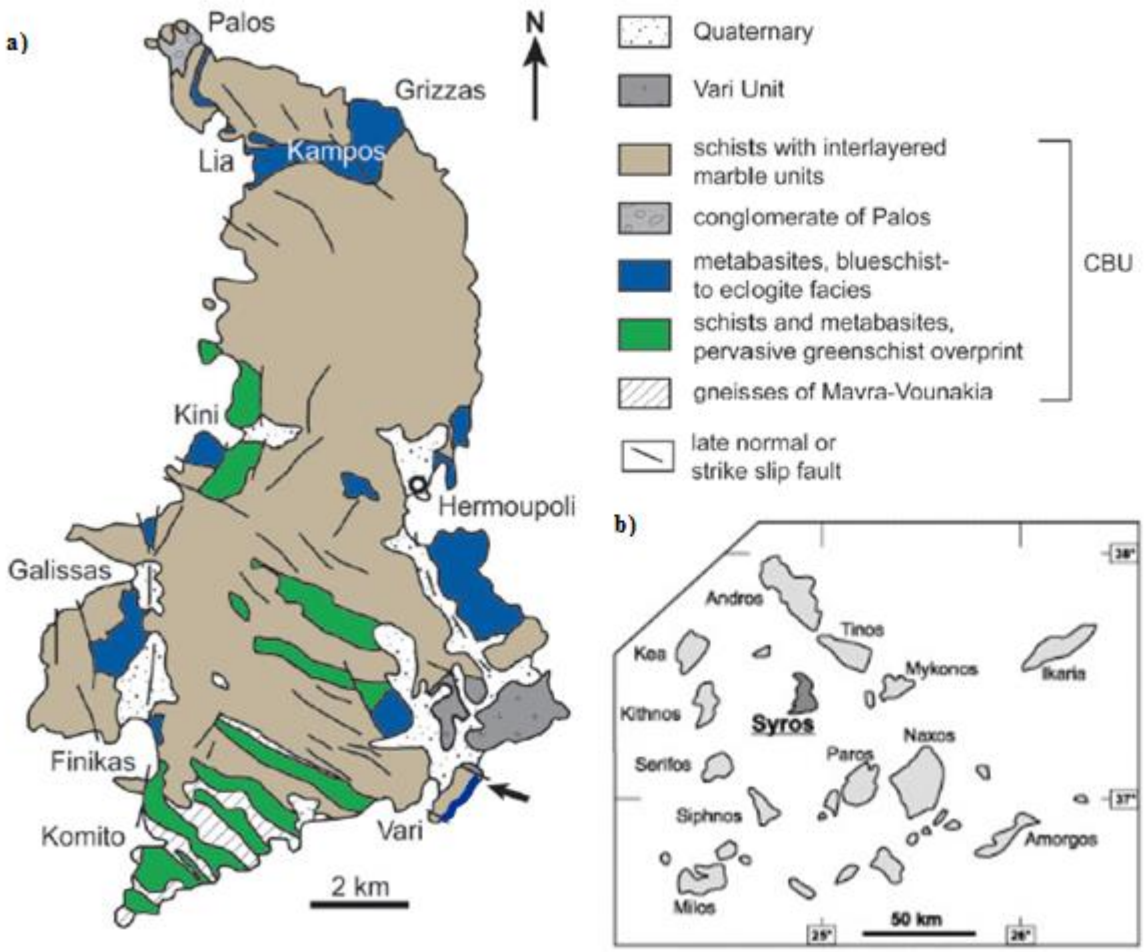

Fig 1. (a) Simplified geological map of Syros (modified after Keiter [4] and Kleine [2]). The arrow indicates the study area on Fabrika Beach. CBU - Cycladic Blueschist Unit.(b) The Cyclades archipelago (copied from Keiter [4]).

three metamorphic units separated by normal shear zones and that the different units with contrasting retrograde P-T history have been juxtaposed due to tectonic events during exhumation [29, 37]. For instance, an upper sequence of the CBU has been suggested to have experienced peak metamorphism at 53-50 Ma [33] and the lower sequence at approximately 40 Ma [38]. Trotet et al. conducted research on the tectono-metamorphic evolution of Syros and Sifnos islands and suggested that the Cycladic blueschists were exhumed progressively by a continuum of accretion at the base of the orogenic wedge [5]. They therefore suggested that peak metamorphism occurred at 1.9 GPa and 525° C followed by different retrograde P-T paths depending on the structural level within the wedge at which the rocks were located. Other researchers suggest that the HP-LT rocks on Syros have a rather uniform P-T history. It has been suggested that the differences in mineral facies could be a consequence of the different assemblages in the protoliths rather than due to a different P-T history [39, 40]. In a recent publication by Skelton et al. [41], we suggest that blueschists and eclogites on Syros experienced the same metamorphic history with prograde lawsonite blueschist facies at 1.2-

1.9 GPa and 410-530° C. This was followed by peak blueschist/eclogite metamorphism at 1.5-2.1 GPa and 520-580° C (Fig 2).

During the Miocene, the HP-LT metamorphism was followed by spatially heterogeneous greenschist-facies metamorphism [4]. Retrograde metamorphism from blueschist-facies to greenschist-facies is thought to have occurred during the Miocene. According to Bröcker the metamorphism in greenschist facies has been dated to 25-21 Ma and according to Skelton et al., greenschist facies metamorphism ended at approximately 27Ma [41, 42]. However, the timing of the greenschist facies overprint has yet to be more precisely constrained. The final stages of exhumation of the CBU are assumed to have taken place between 12 and 8 Ma [25, 27, 29].

On Syros, preservation of HP-LT rocks has occurred on both regional and local scales. The heterogeneous nature of preservation of eclogite and blueschist facies rocks and retrograde overprinting at greenschist facies conditions probably has multiple explanations. In addition to exhumation which affects pressure and temperature, metamorphic fluids have been shown to be of importance with regards preservation of HP-LT mineral

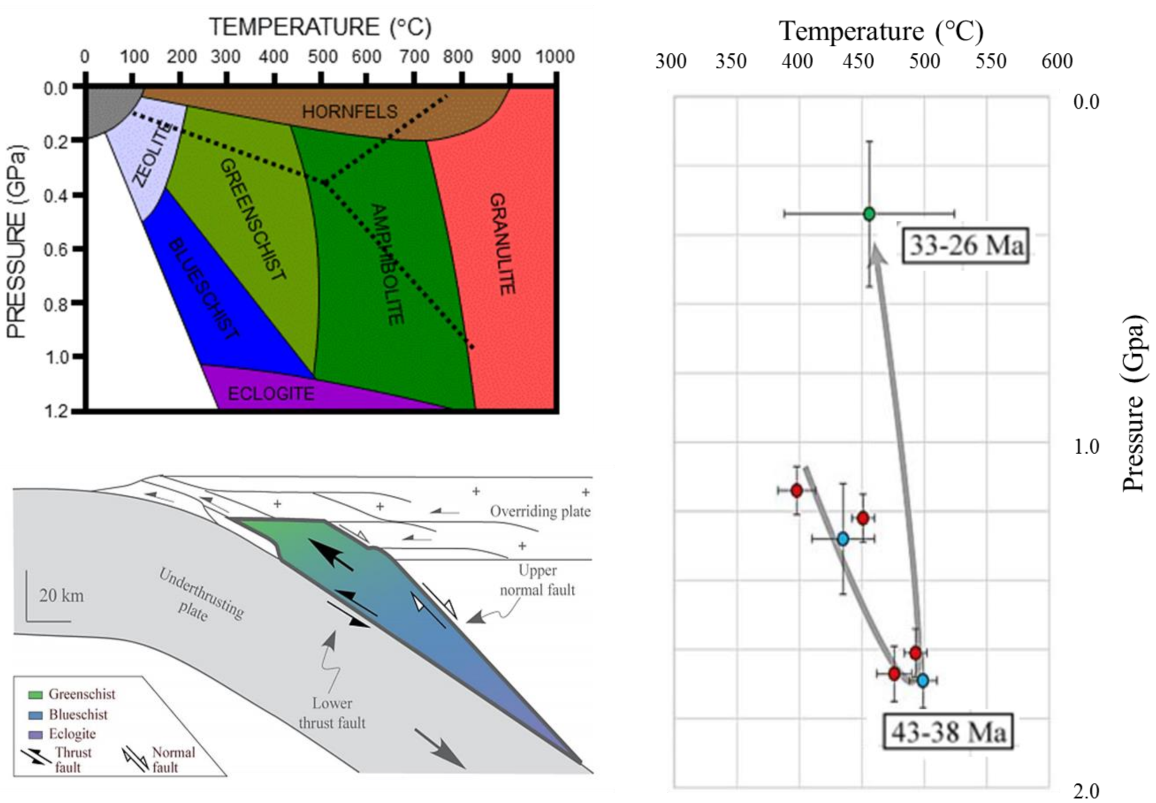

Fig 2.a) Metamorpic facies diagram from Eskola showing the approximate P-T fields of the metamorphic facies. b) A schematic subduction zone with an extrusion wedge. Gradient colour illustrates the retrogression of the HP-rocks into greenschist-facies metamorphism (copied from Peillod[40]). c) Estimated P-T path of blueschist/eclogite overprinted by greenschist facies rocks on Syros (copied from Peillod and then inverted [40]).

Facies	Typical mineral assemblage according to Eskola's definition	Observed mineral assemblage on Fabrika Beach
blueschist	glaucophane +/- epidote +/- actinolite	glaucophane + calcite + epidote + phengite + garnet + quartz
greenschist	albite + chlorite +actinolite +/- epidote +/- calcite	albite + chlorite + actinolite + epidote + quartz
eclogite	omphacite + garnet +/- kyanite	omphacite + garnet + quartz

Fig 3. Metamorphic facies as defined by Eskola (1915) and observed mineral assemblage in each metamorphic facies on Fabrika Beach

assemblages. Metamorphic fluid flow events are shown to have occurred on Syros during both prograde and retrograde metamorphism [2, 36].

There is also evidence of post-metamorphic fluid-events in this area. At Fabrika, fluid-induced overprinting as well fluid-induced preservation of HP-LT assemblages have been documented [43]. Both regional and local scale preservation of HP-LT assemblages could be due to the presence or absence of metamorphic fluids or due to fluid composition effects [2, 44-46]. Schliestedt et al. showed that regional pervasive fluid infiltration was responsible for fluid-related overprint of HP-LT rocks in the Cyclades during exhumation [47]. Other studies have showed that retrogression from blueschist to greenschist on Syros was facilitated by metamorphic fluid flow within the range of 500° to 350° C and pressure of 0.9-0.4 GPa [36, 48]. Kleine et al showed that blueschist facies minerals have been preserved and retrogression inhibited due to the presence of fast-flowing carbon-dioxide-bearing fluids in a shear zone on Fabrika Beach [2].

Material and methods

Locality description

The study was conducted on Fabrika Beach, which is located close to a small village called Vari on the SE coast of Syros. The entire coastal section of Fabrika is shown in Fig 4. The section is composed of alternating mafic rocks, which based on their appearance in field can be classified as eclogites, blueschists and greenschists. These alternate on scales of decimetres to metres. The mafic layers are interspersed with quartz-carbonate units.

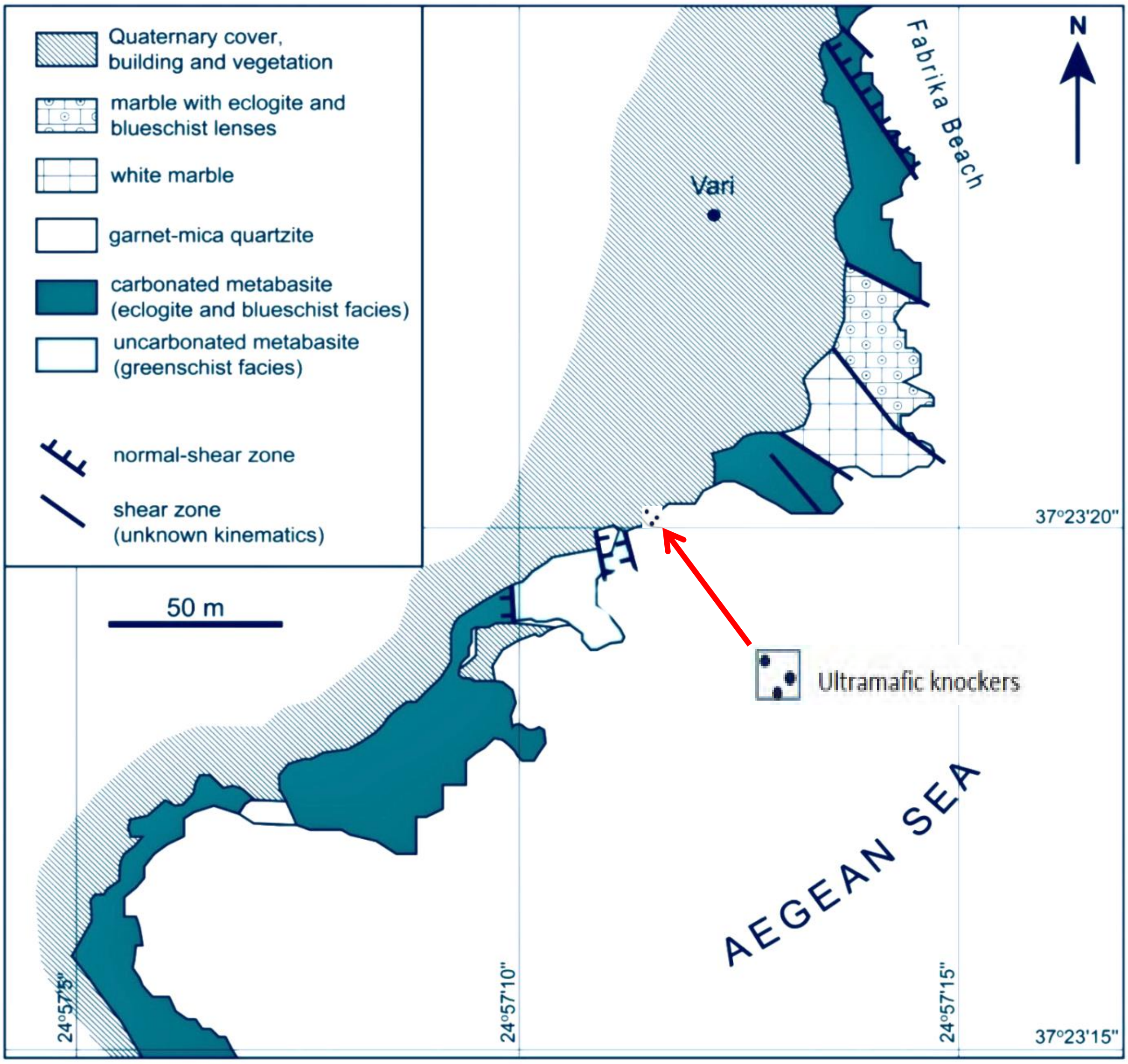

Fig 4. Geological map of Fabrika Beach, SE Syros, copied and slightly modified from Kleine [2]. The locality of studied outcrop with the ultramafic knockers is marked with an arrow. The knockers are not to scale in this figure.

Outcrop description

The outcrop on Fabrika Beach which was chosen for this study is at 37°23’20.55’’N, 24°57’12.49’’E (fig 5).

Sampling

In total, one main sample was collected from the top of the knocker. The sample included the rim at the top and elongated 12 cm downward. It was prepared by Prof Alasdair Skelton and then sent to Vancouver Petrographics in Canada, where five thin-sections were produced.

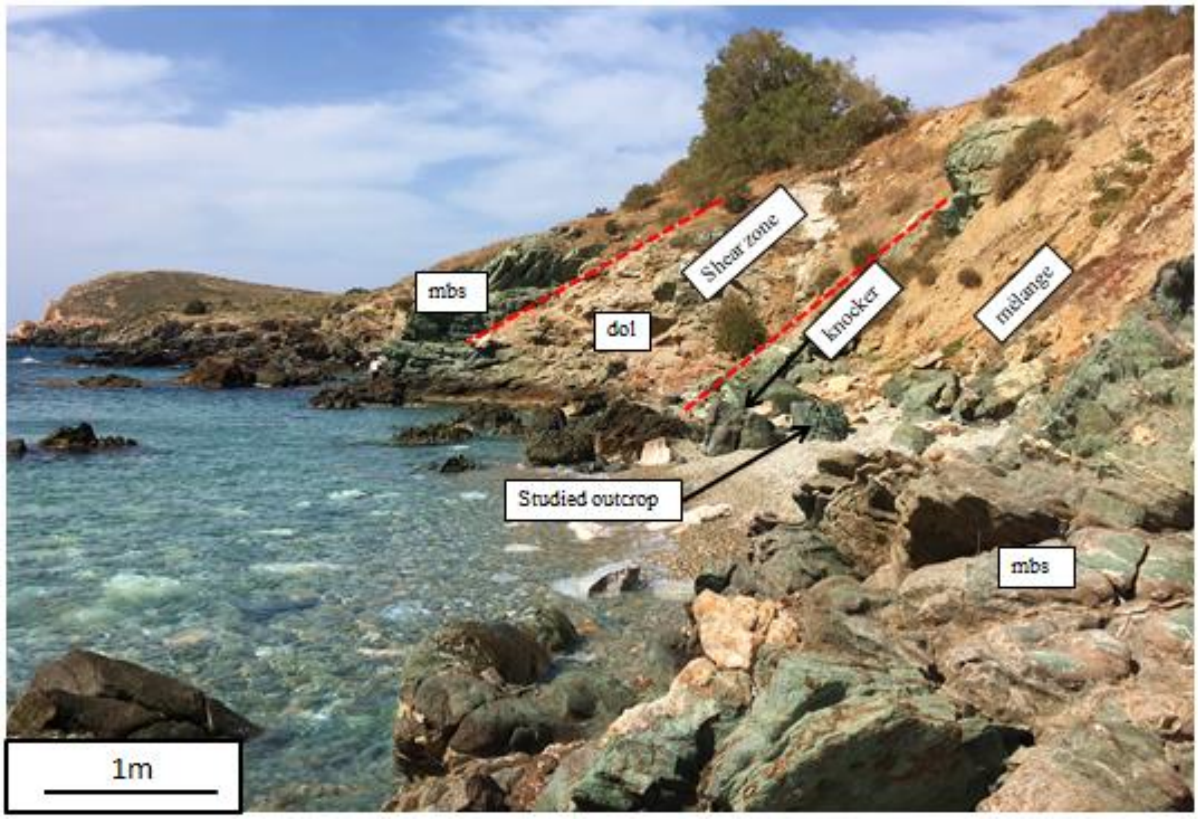

Fig 5. Overview of the study area on Fabrika Beach. The studied outcrop is labelled as "studied outcrop"and a second knocker is marked with a black arrow. The borders of the melange zone are marked with a red dotted line. mbs - metabasites (blueschist- to eclogite facies), dol - dolomite

Analytical method

Mineral modes and reaction textures in each thin-section were studied using a petrographic microscope (Leica) and point counting stage. Mineral mode was calculated by estimation of the mineral proportions by point counting. Five hundred points were counted per thin section and each thin section was counted three times in order to increase the accuracy. The standard deviation (σ) for each counted mineral was calculated according to the following equation by Van der Plas and Tobi [49]:

$$\sigma = \sqrt{p\,(100 - p)/n}$$

In the equation, p = the counted mineral in percent of the total volume of the thin section and n = the number of points counted. In this study n = 3x500=1500 points counted.

Statistics

In order to test if the mean values of the estimated mineral modes from the rind and the interior of the knocker statistically differed from each other, student's t-test was used.

STATA® 14.0 (StataCorp, LP, Texas, USA) were used for analyses. An α-level of 0.05 was used to test for significance.

Results

The knocker from which the sample collected for this study was taken is located in a 50-m-wide melange on Fabrika Beach. The melange disrupts sections of mafic and quartz-carbonate layers which dominate the rest of the coastal section. Within the melange, several ultramafic knockers each of which is 1-2 meters in diameter are found. The knockers seem to be randomly distributed.

Field relations

On the coastal section shown in Fig 5 quartz-carbonate units alternate with mafic layers along the entire section. As indicated in the figure, the section is divided by a 50-m-wide zone where the ultra-mafic knockers are found. The zone is thus inferred to be a melange. Coexistence of eclogite, greenschist and blueschist in close proximity to one another can be found on both sides of the melange zone. An example is shown in Fig 7. The greenschist facies rocks are spatially restricted to to an area stretching approximately 50 m E and 100 m SW from the knocker area.

Field observations

The ultramafic knocker which was used for sampling (on the right hand side in Fig 6a) measures 1,2m x 1m approximately. Another similar knocker is situated next to the studied knocker. The mafic rocks in the knocker were initially classified based on their appearance in the field. The interior of the knocker was observed to consist mostly of eclogite without any obvious foliation. The eclogite is green in colour and fine-grained. It has a high content of red garnet porphyroblasts measuring 1-12 mm in diameter with the majority within the range of 4-10 mm. The green matrix is dominated by omphacite. The knocker has a blueschist/greenschist rind measuring 2-15 cm (in average approximately 10 cm). The blueschist is blue in colour, fine-grained and has a weak foliation. Similar to the eclogite, the blueschist has a high content of red garnet porhyroblasts measuring approximately 2-12 mm in diameter. The blue mineral is glaucophane. In places the blueschist rind transitions into greenschist. The greenschist is fine-grained, green in colour and contains albite porphyroblast measuring 1-4 mm.

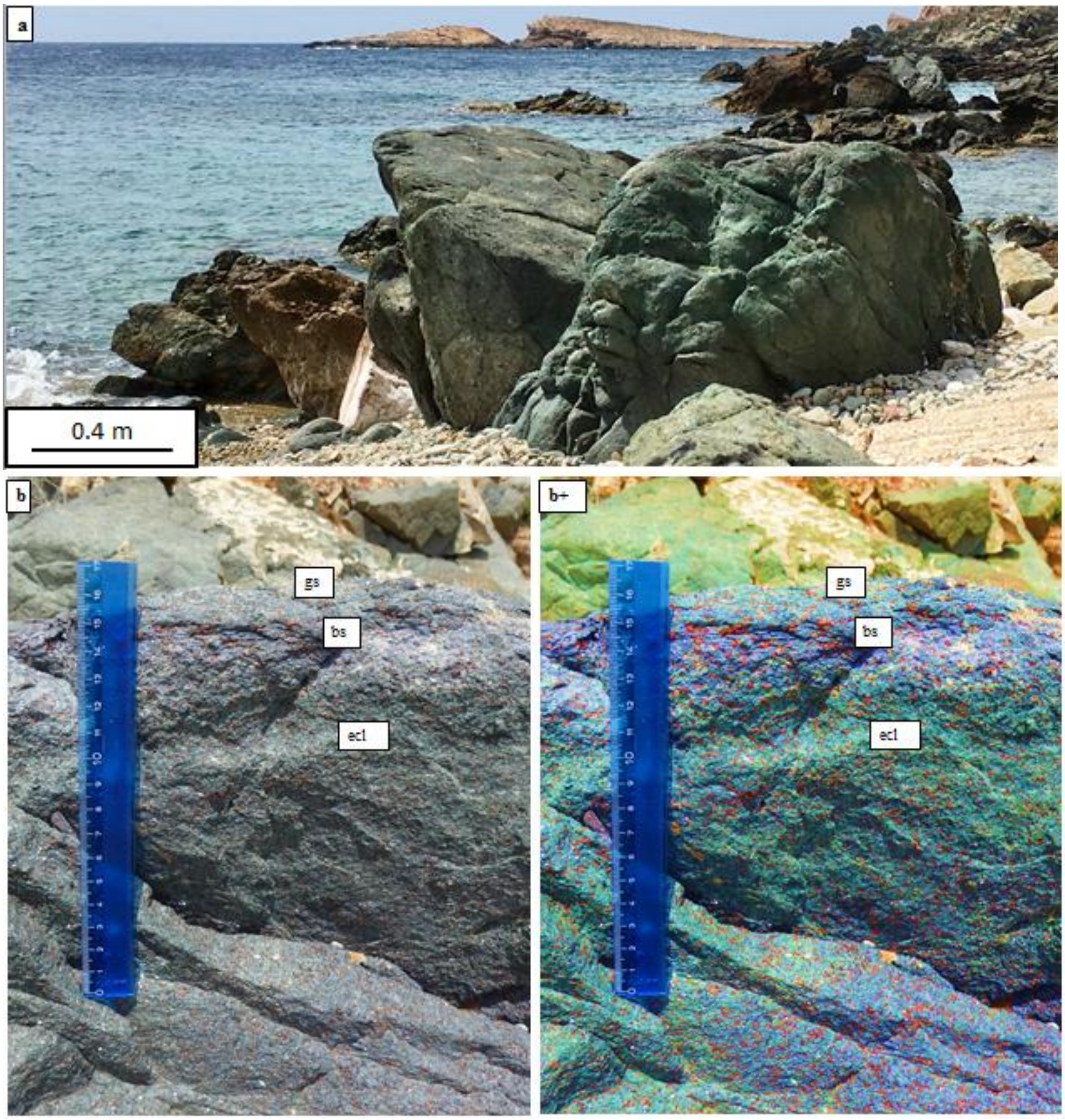

Fig 6. a) Overview of the knockers. The knocker closest in view is the studied outcrop. b) Close view of the outcrop, original colour. b+) Close view of the outcrop, colour enhanced 270%. gs - greenschist, bs - blueschist, ecl - eclogite

Petrographic studies

In total, five thin sections evenly distributed from the rind of the knocker and 12 cm downwards were collected. Two thin sections (1-2) were retrieved from the rind of the knocker and three thin sections (3-5) from the interior. The positions of the midpoints of thin sections 1-5 are at 1, 2, 4, 6 and 9 cm from the rind.

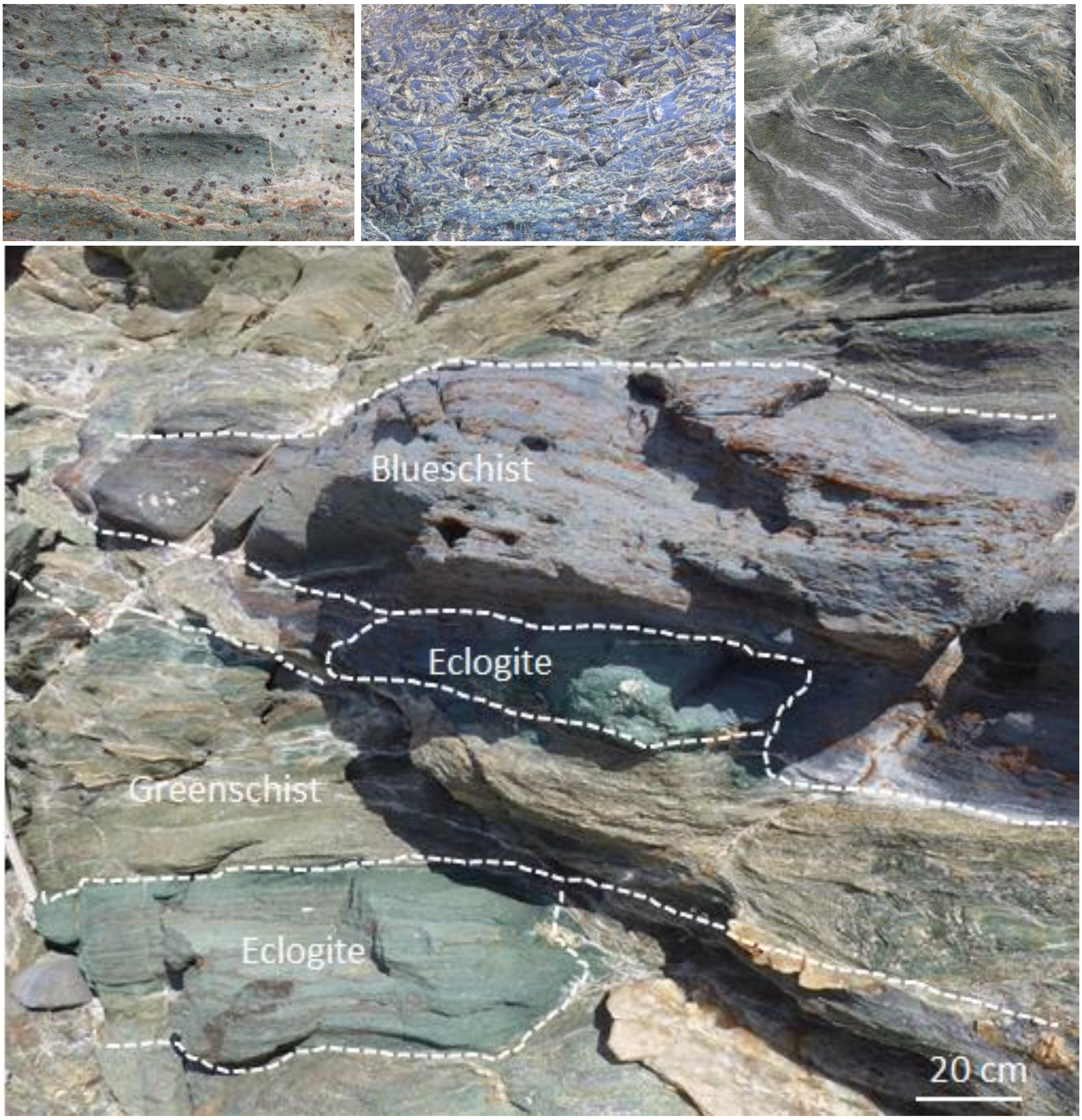

Fig 7. Field relations showing the coexistence of eclogite, greenschist and blueschist in close proximity to one another on Fabrika.

The rind of the knocker - thin section 1 and 2

Thin sections 1 and 2 (1-2cm) cover the blueschist/greenschist rind of the knocker (Fig 8), but also a few millimetres of the outmost part of the interior of the knocker. The main minerals in thin section 1 and 2 are the blueschist facies minerals glauchophane ($\bar{x}$ =24.4 %), phengite ($\bar{x}$ =21.0 %), garnet ($\bar{x}$ =19.6 %) and epidote ($\bar{x}$ =12.3 %). The samples also contain the eclogite facies clinopyroxene omphacite ($\bar{x}$ =12.6 %). In thin section 1 and to a lesser extent in thin section 2, small areas which are dominated by greenschist facies minerals were observed. These areas contain chlorite ($\bar{x}$ =2.5 %), epidote ($\bar{x}$ =12.3 %), and small amounts of albite ($\bar{x}$ =1.7 %) and quartz ($\bar{x}$ =2.9 %). Point counting errors are given in table 1a, appendix.

Fig 8. Scanned thin section of the rim area of the ultramfic knocker in plain polarised light (thin section 2). gl - glaucophane, g -garnet. chl - chlorite.

The interior of the knocker - thin sections 3-5

Thin sections 3-5 (4-9 cm) are all representative samples from the eclogite part of the knocker (Fig 9). The interior part of the knocker is classified as eclogite facies metabasalt due to the rich abundance of omphacite in combination with garnet. These thin sections contain the eclogite facies minerals omphacite ($\bar{x}$ =20.3 %), garnet ($\bar{x}$ =22.7 %), phengite ($\bar{x}$ =29.8 %), quartz ($\bar{x}$ =3.1 %) and rutile ($\bar{x}$ =1.3 %). The thin sections also contain patches of blueschist facies minerals glaucophane ($\bar{x}$ =6.9 %) and epidote ($\bar{x}$ =12.2 %). Point counting errors are given in table 1b, appendix.

Modal data

Modal data for each thin section were estimated by point counting. Modal data are listed in Table 1 and graphically represented in Figure 10. Thin section 1 and 2, from the rind of the knocker, consist mainly of blueschist and greenschist facies minerals. Thin section 1 differs slightly from thin section 2 in that thin section 1 has a higher content of blueschist facies mineral such as glaucophane (28.0% vs 20.8%) and more than double the amount of the greenschist mineral chlorite compared to thin section 2 (3.6% vs 1.4%). Although not statistically significant, there is a slightly higher abundance of phengite in thin section 2 compared to thin section 1 (22.4% vs 19.6%). As graphically illustrated in figure 10, the

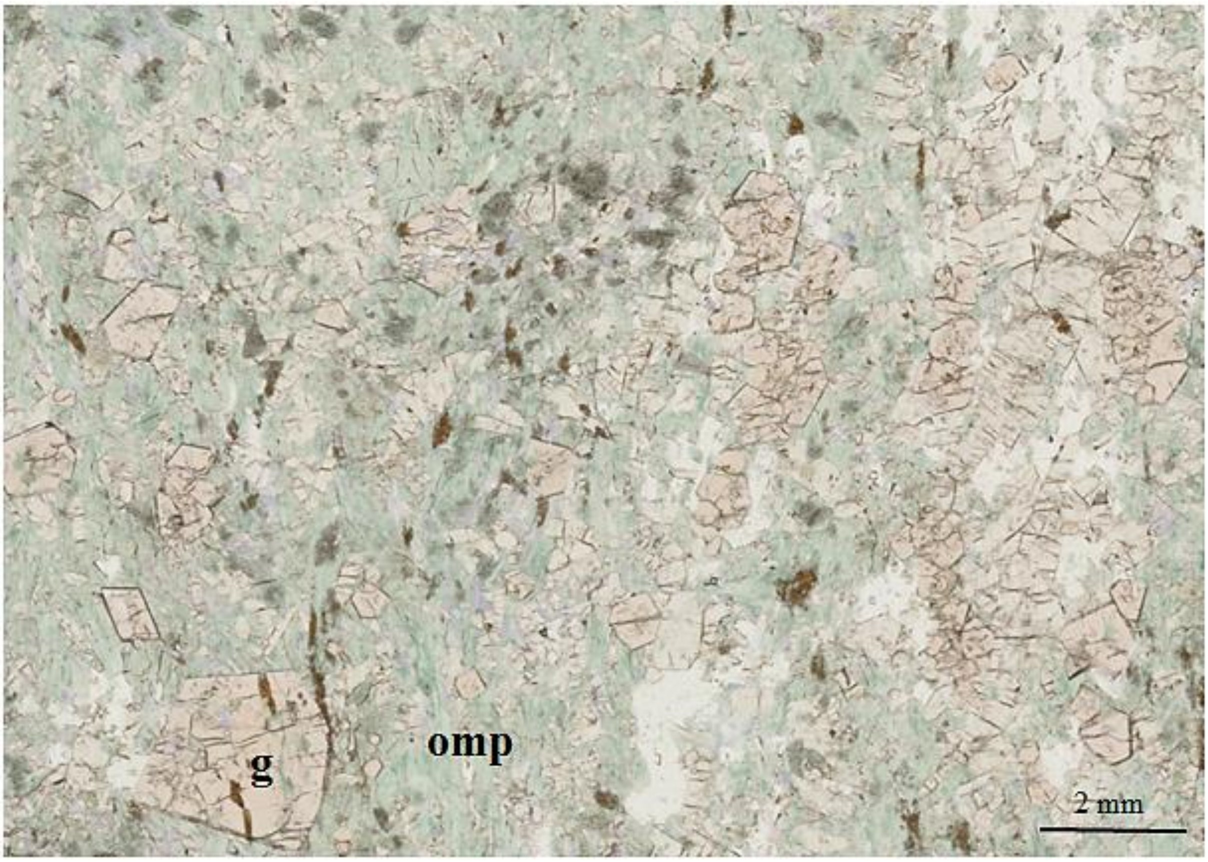

Fig 9. Scanned thin section of the interior area of the ultramfic knocker (thin section 4) in plain polarised light.omp - omphacite, g -garnet.

mineral modes in the rind (thin sections 1-2) differ from the mineral modes in the interior (thin sections 3-5) of the knocker.

The interior consists of statistically significantly more omphacite compared to the rind (interior $\bar{x}$ =20.3 %, rind $\bar{x}$ =12.6 %, p=0.018). Glaucophane is found to be much more abundant in the rind compared to the interior (rind $\bar{x}$ =24.4 %, interior $\bar{x}$ =6.9 %, p=0.008). This was an expected finding as the visual inspection indicates a clear blueschist rind at the knocker.

Chlorite is largely restricted to the rind of the knocker (thin sections 1-2) and only occurs in trace amounts in the interior of the knocker (thin sections 3-5). However, the differences in chlorite mode are not statistically significant (p = 0.31).

Albite, epidote, garnet, quartz, rutile and phengite are evenly distributed throughout the knocker and its rind. There are no statistical differences in their modes between the rind and the interior (p>0.05). Results are presented in Table 2. It is worth noting that patches of greenschist in the rind samples were not point counted separately. Thus mineral modes in the rind samples represent mixtures of blueschist and greenschist facies areas of the thin section.

The results from point counting are graphically illustrated in Fig 10. In the graphs representing omphacite and glaucophane, the curves nearly mirror each other. In the rind (thin section 1 and 2), the amount of omphacite is lower compared to the interior (thin section 3-5). Similarly, the amount of glaucophane is higher in the rind area compared to the interior of the knocker. Thus, the results indicate that omphacite is being replaced by glaucophane in the rind area. Furthermore, chlorite abundance is higher in thin section 1 whereas the amount of garnet is lower. In thin section 2-5 the relationship between chlorite and garnet are nearly the opposite with high abundance of garnet and low abundance of chlorite. This suggests that garnet is being replaced by chlorite in the rind area represented in thin section 1. A similar but slightly vaguer tendency can be seen regarding phengite and chlorite where the curves suggest that phengite is being replaced by chlorite in the rind area.

Table1. Mineral modes (%) for thin sections from the ultramafic knocker. Thin section 1 is closest to the rim of the knocker.

	Thin section				
	rind		interior		
	1	2	3	4	5
Albite	1,8	1,6	2,0	2,0	1,8
Chlorite	3,6	1,4	1,6	1,8	0,8
Epidote	11,6	13,0	12,2	11,6	12,8
Garnet	16,8	22,4	23,0	18,6	26,4
glaucophane	28,0	20,8	8,2	6,4	6,2
omphacite	13,6	11,6	19	19,4	22,6
phengite	19,6	22,4	30,8	34,4	24,4
quartz	3,0	2,8	2,6	3,6	3,2
rutile	1,8	3,2	1,4	1,8	0,8
unidentified	0,2	0,8	0,2	0,4	1,0

Table2. Comparison of mineral mode between the rind and the interior of the knocker using student's t-test

	rind		Interior		t-test
	mean	SD	mean	SD	p-value
albite	1.7	0.1	1.9	0.1	0.133
chlorite	2.5	1.6	1.4	0.5	0.313
epidote	12.3	1.0	12.2	0.6	0.894
garnet	19.6	4.0	22.7	3.9	0.455
glaucophane	24.4	5.1	6.9	1.1	0.008**
omphacite	12.6	1.4	20.3	2.0	0.018*
phengite	21	2.0	29.8	5.0	0.108
quartz	2.9	0.1	3.1	0.5	0.585
rutile	2.5	1.0	1.3	0.5	0.167
unidentified	0.5	0.4	0.5	0.4	0.936

*p<0.05; **p<0.01;***p<0.001

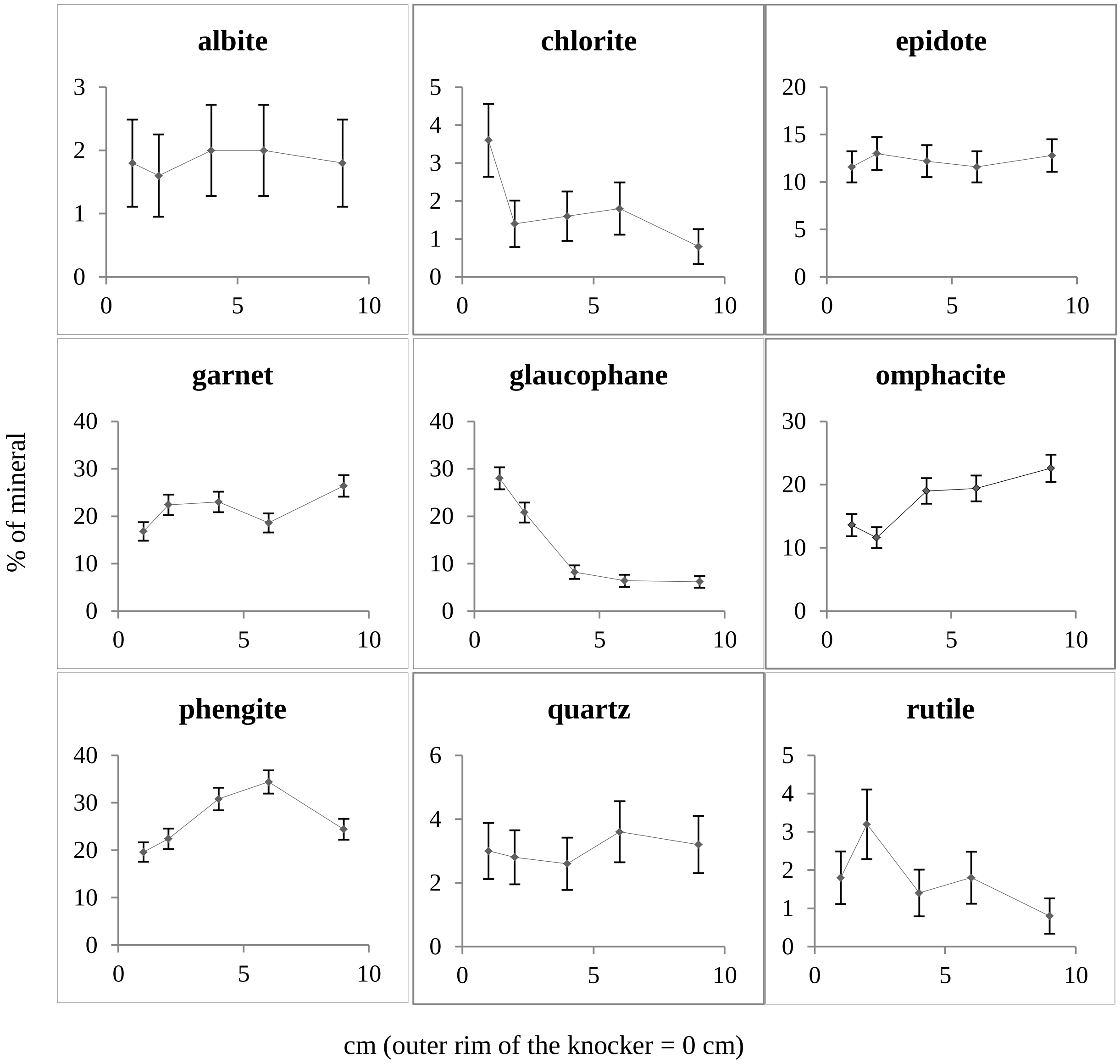

Fig10. Mineral mode (%) for each mineral identified in the knocker for the five thin sections analysed, distributed at 1,2, 4, 6 and 9 cm distance from the rim of the knocker. Error bars indicate calculated standard deviations for each counted mineral/section.

Rock textures

The rind of the knocker - thin section 1-2

The rind consists mainly of greenschist and blueschist facies minerals. These are weakly foliated parallel to the edge of the knocker. The blueschist contains fine-grained prismatic crystals of glaucophane measuring approximately 0.1-1mm and phengite measuring <0.6 mm. Where present, chlorite is equally fine-grained. Euhedral epidote porphyroblasts are scattered randomly in the matrix and in a few places the epidote seem to have a preferred orientation. Since the porphyroblasts are intact without veins cross-cutting them it is likely that no major deformation event has taken place during or after their growth.

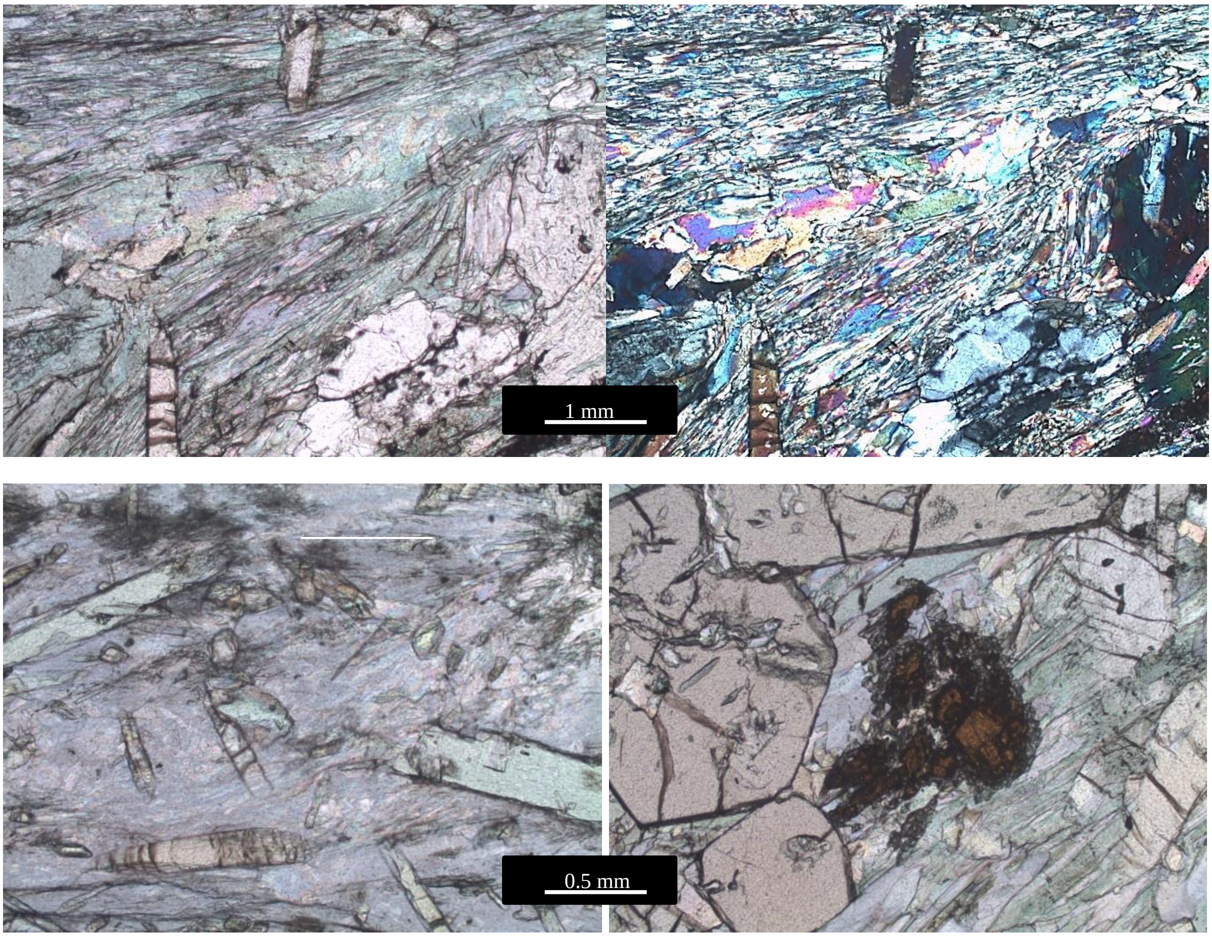

Fig 11. The rind of the knocker (thin section 2). a) Fine-grained crystals of glaucophane embedded in an even more fine-grained matrix of phengite, epidote and chlorite weakly foliated parallel to the knocker rind. Left panels under plain polars and right panels under crossed polars. c) Fine-grained glaucophane matrix with large euhedral crystals of epidote without a preferred orientation in plane polarised light. d) Rutile. On the left hand side an euhedral garnet with inclusion of pseudomorph lawsonite is shown in plane polarised light.

Euhedral garnets measuring between approximately 2 and 12 mm in diameter are randomly distributed throughout the knocker without an obvious pattern. All garnets are euhedral to subhedral and poikiloblastic with inclusions of glaucophane, epidote and omphacite which nucleated and grew during HP-LT conditions (fig 12). Because glaucophane is stabilised in iron-rich environments, we can infer that the garnets are likely to be of almandine-type, a conclusion which is supported by previous research [2, 36]. Generally, the inclusions in the garnets are located in the centre of the garnets rather than in the rim. In the rim area, inclusions are sparse. The minerals that can be found as inclusions in the centre of the garnet have probably been consumed in the rim area due to reactions making the rim of the garnet.

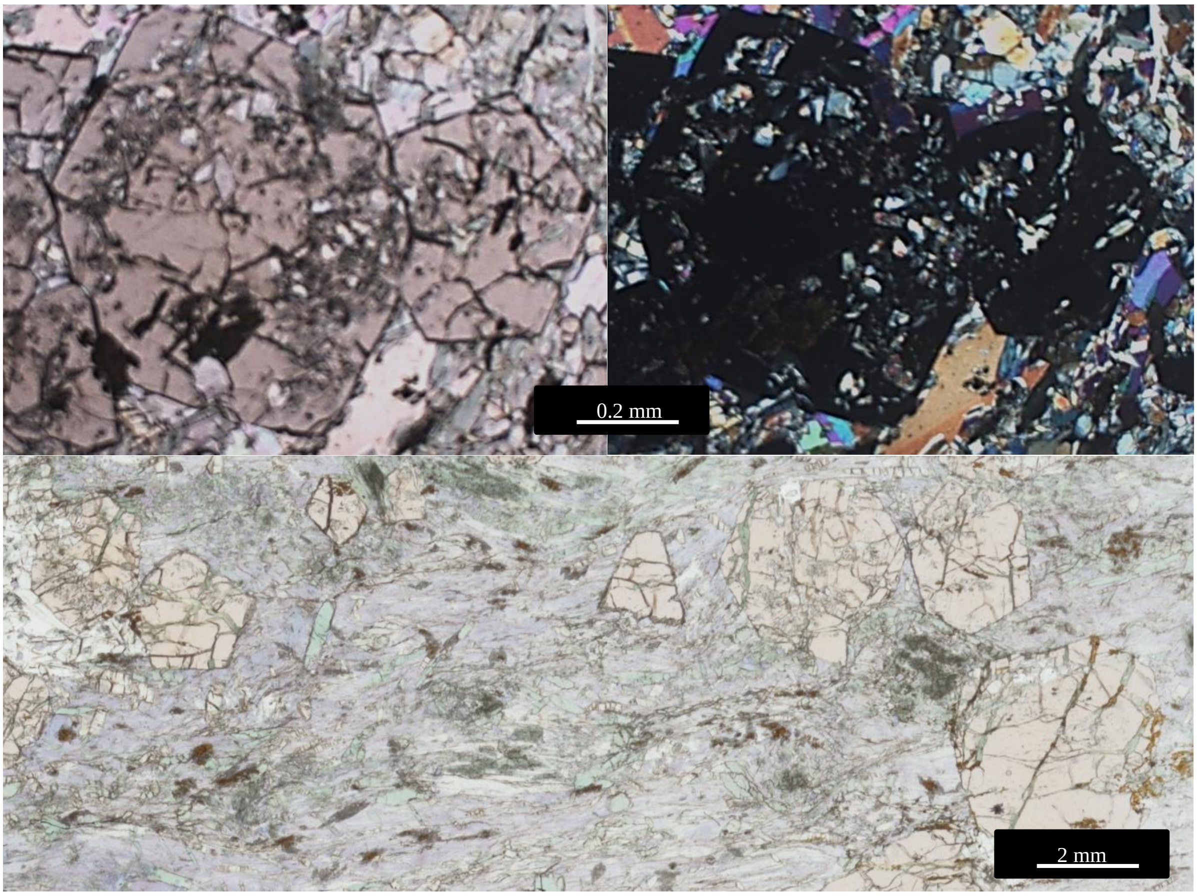

Fig 12. a) Euhedral poikiloblastic garnets with inclusions of epidote. Left panels under plain polars and right panels under crossed polars. b) Scanned thin section of the rim area of the ultramfic knocker in plain polarised light (thin section 2) showing subhedral and euhedral garnets in association with foliated glaucophane. gl - glaucophane, g -garnet.

In the scanned thin section 2 from the rind (fig 12c) metamorphic foliation is visible where glaucophane crystals appear to be aligned. The chlorite crystals on the other hand, seem to lack a preferred orientation. This could be indicative of chlorite growth after the foliation event.

The interior of the knocker - thin sections 3-5

The interior consists mainly of the minerals omphacite, epidote, garnet and phengite and are therefore classified as an eclogite facies meta-basalt [51]. The matrix is fine-grained with abundant porphyroblastic garnets.

Similar to the rind samples, the garnets are euhedral and measure between approximately 2 and 12 mm in diameter with the majority measuring between 6 and 10 mm in diameter. The garnets tend to be larger in the interior of the knocker compared to the garnets in the rind. The garnets are evenly distributed throughout the knocker without an obvious pattern. All garnets are euhedral to subhedral poikiloblasts with inclusions of glaucophane, epidote, omphacite and phengite.

Phengite (white mica) appears to have been formed in two generations: small matrix-sized crystals measuring <0.6 mm and larger crystals measuring <3.0-3.5mm. The smaller phengite crystals have a preferred orientation whereas the larger crystals are randomly orientated. Phengite occurs in close proximity to euhedral porphyroblasts of epidote. The epidote porphyroblasts are randomly orientated and have different shapes where some are euhedral, some subhedral and a few elongated.

Reaction textures

Reaction textures were identified in the thin sections using a petrographic microscope. Only a few reaction textures are visible in the thin sections derived from the interior of the knocker. In the outermost part of the interior in thin section 2 in the eclogite area a reaction texture is observed whereby omphacite is partly replaced by glaucophane. A generalized reaction is:

omphacite + water → glaucophane

The interior of the knocker analysed in this study consists of eclogite. Eclogites are formed during high or ultrahigh pressure and high temperature metamorphism in subduction zones. The reaction where omphacite is being replaced by glaucophane occurs as eclogite is replaced by blueschist (Fig 13a). During this reaction, water from the subducting slab was added to the eclogite causing its hydration at blueschist facies conditions and thus, the eclogite was metamorphosed into blueschist.

In the rind of the knocker several reaction textures are found. One frequent texture is replacement of garnet by chlorite (Fig 13b and c). It is likely that chlorite has formed at the expense of the garnet at greenschist facies conditions. A generalized reaction is:

garnet + water → chlorite

Other observed reaction textures are glaucophane being replaced by chlorite (Fig 14b) and phengite being replaced by chlorite (Fig 14a). Generalized reactions are:

glaucophane + water → chlorite

phengite + water → chlorite + K^+

The reaction textures where garnet, glaucophane and phengite are replaced by chlorite can be interpreted as textural evidence of retrogression at greenschist facies conditions. This is also

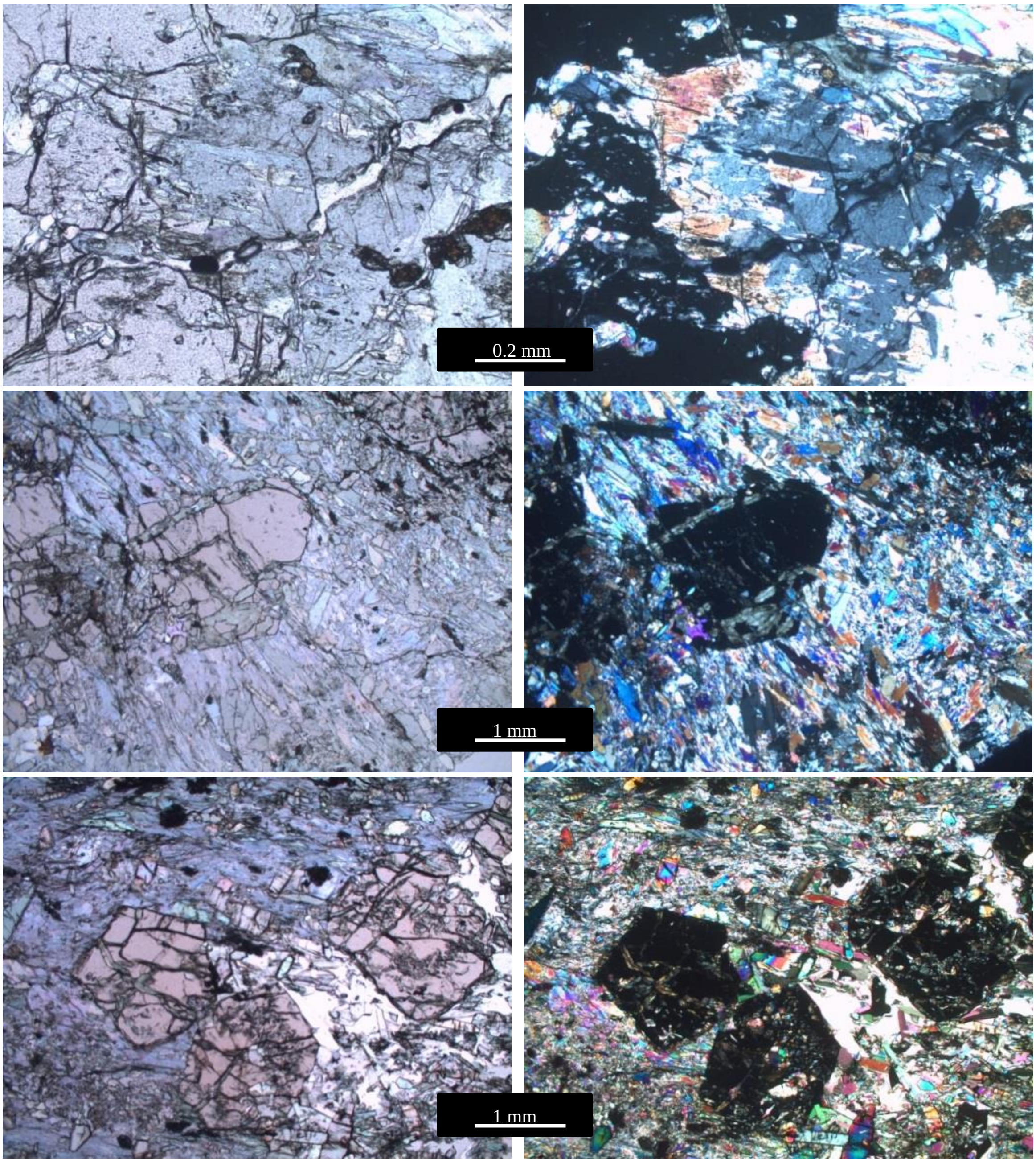

Fig 13. Photomicrographs of reaction textures in the rim area of the knocker. (a) replacement of omphacite by glaucophane. (b) and (c) replacement of garnet by chlorite. Left panels under plain polars and right panel under crossed polars.

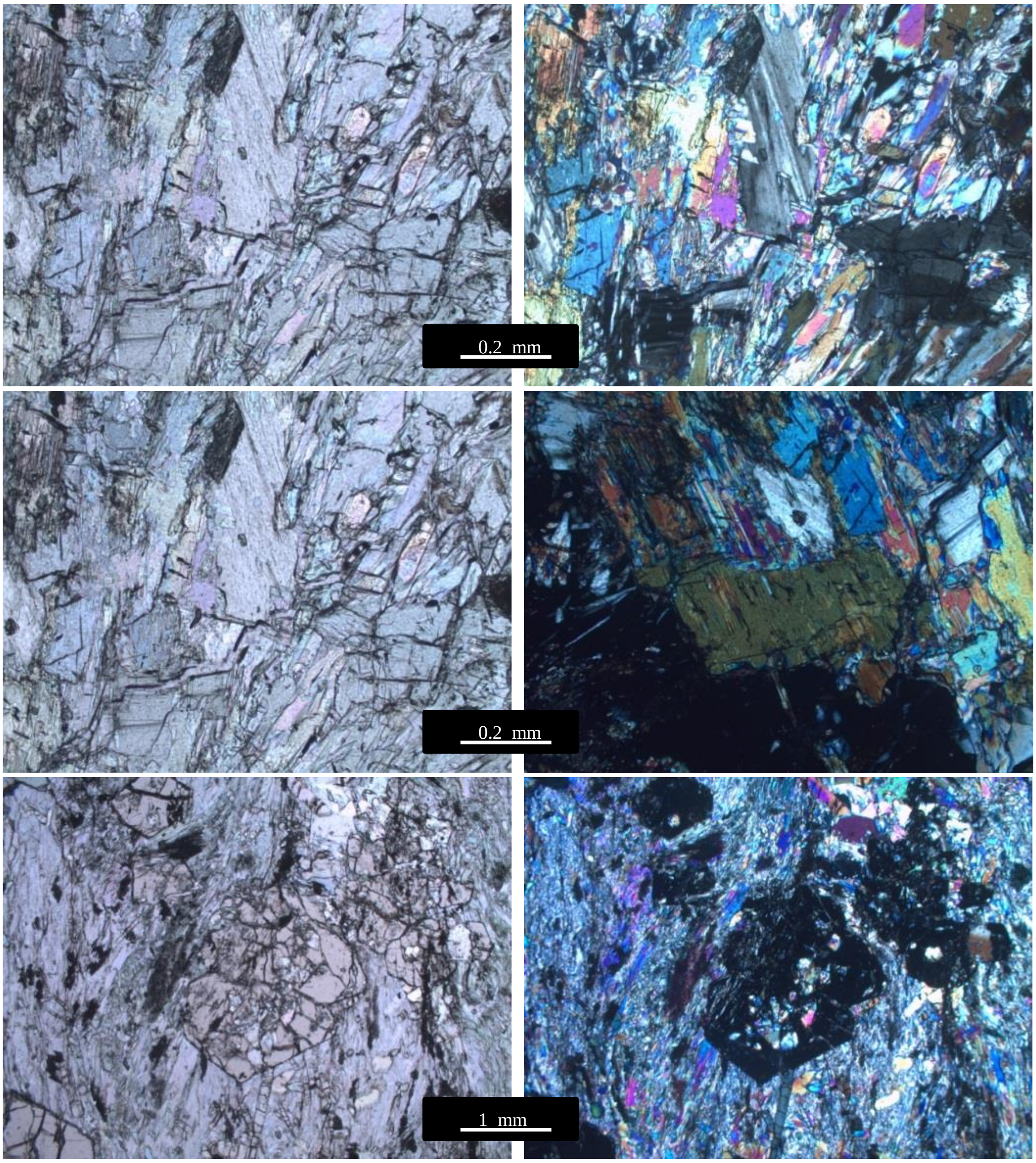

Fig 14. Photomicrographs of reaction textures in the rim area of the knocker. (a) replaement of phengite to chlorite. (b) replacement of glaucophane to chlorite. (c) pseudomorph replacement of lawsonite to phengite. Left panels under plain polars and right panels under crossed polars.

consistent with the surrounding environment in the melange where the rocks almost entirely are retrogressed at greenschist facies conditions.

There are also reaction textures showing garnets with diamond shaped inclusions (Fig 14c). Due to the shape of the inclusions they are interpreted to be former lawsonite entirely pseudomorphed by phengite. The breakdown of lawsonite in the presence of glaucophane is a prograde reaction. Lawsonite cannot be produced in greenschist facies. Thus, the fact that lawsonite pseudomorphs are found in the greenschist areas of thin section 1 infers that the greenschist must have been formed later than the blueschist.

Discussion

In this study an ultra-mafic eclogite knocker from Fabrika Beach on Syros, Greece, was analysed. Based on field observations and mineral assemblage the knocker was determined to consist of eclogite with a blueschist/greenschist rind. The knocker preserves evidence of two retrograde metamorphic stages: at blueschist and greenschist facies conditions. In order to find out what reactions formed the greenschist/blueschist rind, mineral modes were estimated and reaction textures were studied from thin sections.

The knocker's history before the formation of the blueschist/greenschist rind includes subduction followed by exhumation, presumably through the extrusion wedge. The eclogite knocker was exposed to different pressure and temperature conditions and exposed to metamorphic fluid flow at some stages during exhumation. Alteration of mineral assemblage and retrogression of the rind occurred after the formation of eclogite. Here, I suggest that the rind of the knocker has been partly retrogressed from eclogite facies and has been overprinted in two stages in presence of metamorphic fluids.

The first stage of retrogression occurred at blueschist facies conditions: omphacite reacted with water to form glaucophane. This interpretation is supported by the data retrieved from point counting. When comparing mineral modes between the thin sections representing the rind and the interior a replacement of omphacite to glaucophane is indicated by the shift in proportions of the respective minerals. Furthermore, reaction textures showing omphacite being replaced by glaucophane are found in both thins sections collected from the rind area (Fig 13a). In a recent study we have suggested prograde lawsonite blueschist facies metamorphism occurring at 1.2-1.9 GPa and 410-530° C [50]. This was followed by a synchronous peak eclogite/blueschist facies metamorphism at 1.5-2.1 GPa and 520-580° C at 41.2 ± 1.7 Ma. The first stage of retrogression that affected the knocker is assumed to have occurred during this period at blueschist facies conditions.

The second stage of retrogression occurred at greenschist facies conditions. During this stage, garnet, and to a lesser extent also glaucophane and phengite were replaced by chlorite also as a result of hydration reactions. The graphs illustrating mineral modes indicate the replacement of garnet by chlorite in the outermost rind area. In a similar manner, a replacement of glaucophane and phengite by chlorite can also be inferred. Textural evidence of retrogression at greenschist facies conditions was also found in the outermost part of the rind. These textures are replacement of garnet, phengite and glaucophane by chlorite (Figs. 13c-d, 14a-b).

In the field, greenschist was found to be spatially restricted to a section of the beach alongside the melange zone that contains the knockers (Fig. 4). Thus, no greenschist retrogression was observed on the surrounding rocks exposed on Fabrika Beach. The area holding the knocker is interpreted to be a melange zone where fluid flow has been channelled. Previous studies have suggested a gap in the metamorphic history of the Fabrika area with a quiescent period of up to 11-16 Ma after eclogite/blueschist facies metamorphism occurred and before greenschist facies metamorphism took place [50]. During this period, the metamorphic fluid flow was absent or sparse. In order to end the quiescent period a change in the environment leading to resumed fluid flow must have to have occurred. It has been suggested that the greenschist facies retrogression ended close to the time when the Vari Unit was emplaced above the Cycladic Blueschist Unit [50, 52]. Therefore, one plausible hypothesis is that the tectonic event leading to the emplacement of the Vari Unit ended the metamorphic quiescent period by triggering channelled metamorphic fluid flow in the melange zone surrounding the knocker. During this stage, metamorphic fluids caused alteration of the formerly blueschist facies rind of the knocker at greenschist facies conditions. This interpretation is supported by the observation that greenschist facies minerals are only found in the outermost part of the rind that encases the knocker.

There were no obvious veins found in the knocker either in the field or in thin section. However, several cross-cutting veins were observed in the rocks in close proximity to the knocker. These veins are associated with localised replacement of eclogite and blueschist by greenschist facies minerals [50]. This finding supports the hypothesis argued for here that retrogression only occurred in the presence of metamorphic fluids.

Metamorphic fluids have not only caused replacement of eclogite/blueschist by greenschist facies minerals but also preservation of blueschist facies minerals at greenschist facies conditions. These fluids are CO_2-bearing [2]. This did not occur in the knocker from which it might be possible to infer that fluid flowing in the melange was H_2O dominated.

Conclusion

In this study, part of the metamorphic history of an ultramafic eclogite knocker on Syros, Greece, has been investigated. Here, we suggest a metamorphic history consisting of two stages of retrogression.

Based on estimated mineral modes and reaction textures in thin section, the first stage of retrogression was determined to have occurred in blueschist facies. During this stage, the rind area of the knocker retrogressed through hydration reactions whereby omphacite was replaced with glaucophane creating a blueschist rind of the knocker. The second stage of retrogression occurred after a period of metamorphic quiescence that may have lasted 11-16 Ma years [49]. During that stage, the rind area of the knocker was retrogressed at greenschist facies conditions through further hydration reactions whereby garnet, glaucophane and phengite were replaced by chlorite. Both stages of retrogression occurred in the presence of a metamorphic fluid. I infer that metamorphic fluid flow ceased after the first stage of regression and was absent during the quiescent period that followed. Due to tectonic events related to emplacement of the Vari Unit, I hypothesise that metamorphic fluid flow resumed thereafter and was channelled through the melange zone thus enabling retrogression at greenschist facies conditions.

Thus, this study underpins the importance of metamorphic fluid flows in metamorphic processes in that the ultramafic knocker only underwent retrogression when metamorphic fluids were present.

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Appendix

Table1. Mineral modes (%) and point counting errors (error) for thin sections from the ultramafic knocker. Thin section 1 is closest to the rim of the knocker. a) the rind area. b) the interior

1a.

rind						
	1	error	2	error	total $\bar{x}$	error
Albite	1,8	0.69	1,6	0.65	1.7	0.47
Chlorite	3,6	0.96	1,4	0.61	2.5	0.57
Epidote	11,6	1.65	13,0	1.74	12.3	1.20
Garnet	16,8	1.93	22,4	2.15	19.6	1.45
glaucophane	28,0	2.32	20,8	2.10	24.4	1.57
omphacite	13,6	1.77	11,6	1.65	12.6	1.21
phengite	19,6	2.05	22,4	2.15	21	1.48
quartz	3,0	0.88	2,8	0.85	2.9	0.61
rutile	1,8	0.69	3,2	0.91	2.5	0.57
unidentified	0,2	0.23	0,8	0.46	0.5	0.26
points (n)		1500		1500		3000

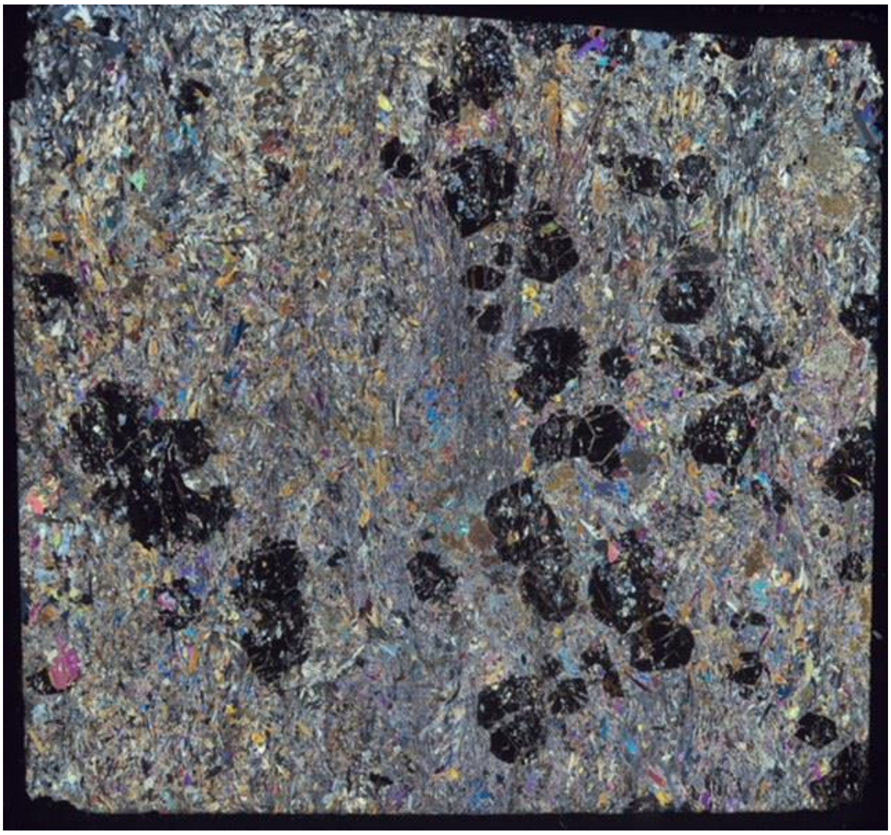
1b.

interior								
	3	error	4	error	5	error	total $\bar{x}$	error
Albite	2,0	0.72	2,0	0.72	1,8	0.69	1.9	0.41
Chlorite	1,6	0.65	1,8	0.69	0,8	0.46	1.4	0.35
Epidote	12,2	1.69	11,6	1.65	12,8	1.72	12.2	0.98
Garnet	23,0	2.17	18,6	2.01	26,4	2.28	22.7	1.25
glaucophane	8,2	1.42	6,4	1.26	6,2	1.24	6.9	0.76
omphacite	19	2.03	19,4	2.04	22,6	2.16	20.3	1.20
phengite	30,8	2.38	34,4	2.45	24,4	2.21	29.8	1.36
quartz	2,6	0.82	3,6	0.96	3,2	0.90	3.1	0.52
rutile	1,4	0.61	1,8	0.68	0,8	0.46	1.3	0.34
unidentified	0,2	0.23	0,4	0.33	1,0	0.51	0.5	0.21
points (n)		1500		1500		1500		4500

Scanned thin sections 1-5 are shown on the following pages. Thin section 1-2 - the rind. Thin section 3-5 - the interior. PPL - plane polarised light, CPL - crossed polarised light.

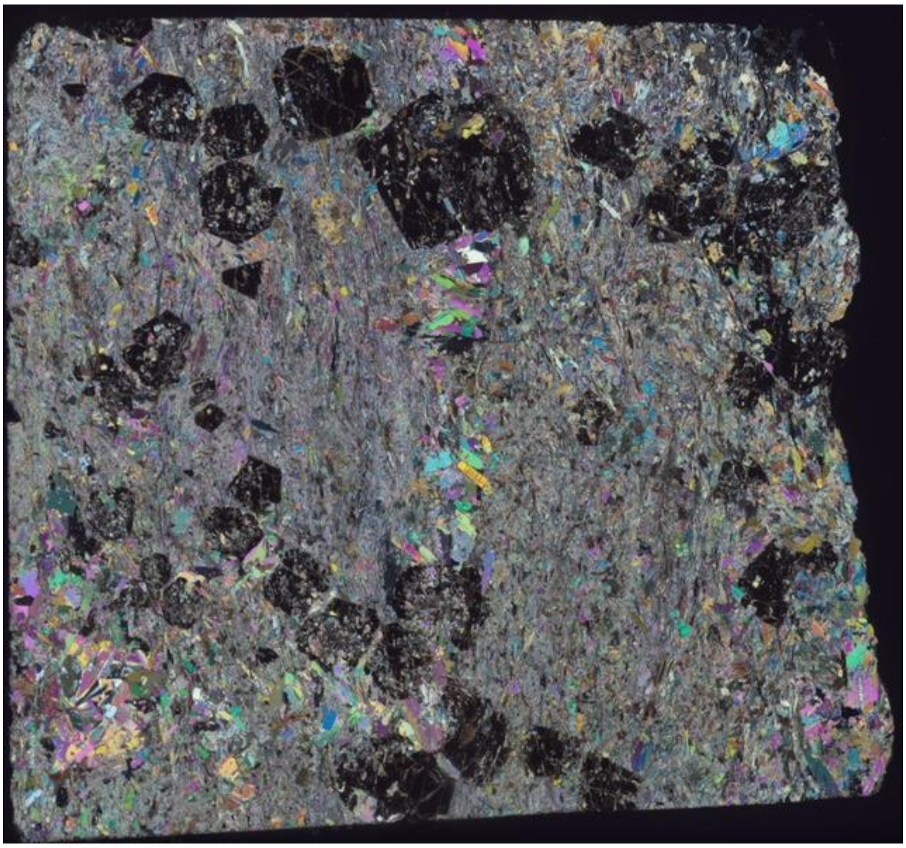
SYKL1, PPL

SYKL1, CPL

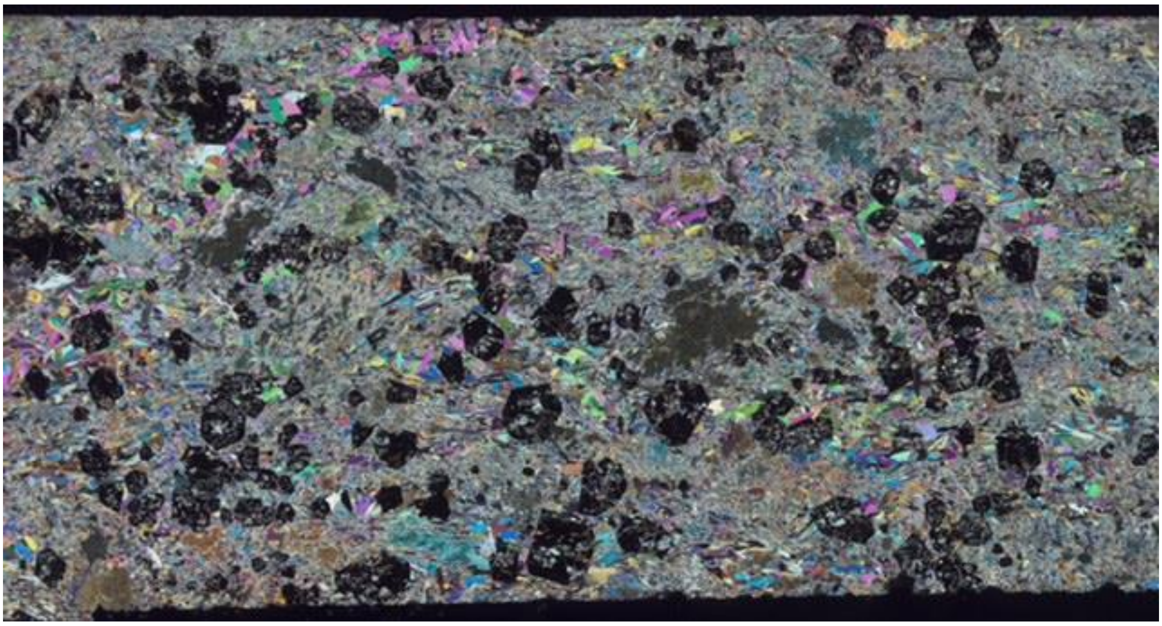


SYKL2, PPL

SYKL2, CPL



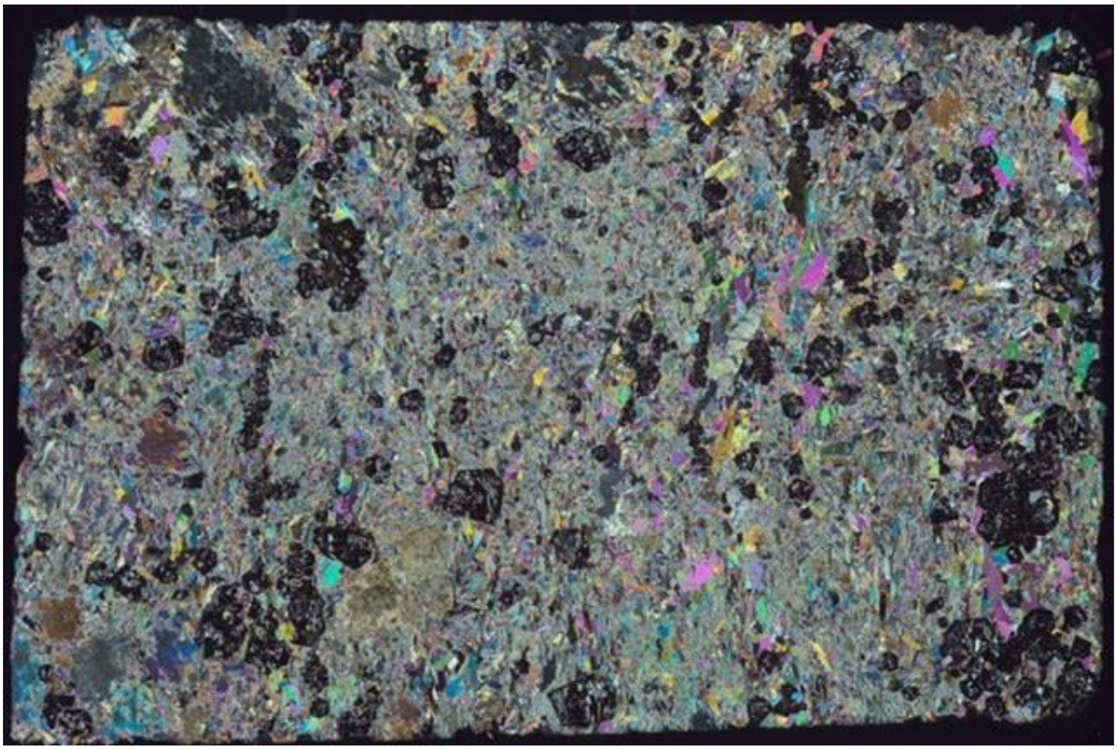
SYKL3, PPL



SYKL3, PPL

SYKL4, PPL

SYKL4, PPL



SYKL5, PPL

SYKL5, PPL