SEG Student Chapter Leoben – excursion report

# Cyprus
# September 2022

Economic geology field trip lead by the
Department of Applied Geosciences and Geophysics of the
Montanuniversität Leoben

Organization:
Prof. J. Raith and Prof. R. Bakker
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# Content

# 1. Introduction

## 1.1. Excursion route and objective

As students and members of the Society of Economic Geologists (SEG) from the Montanuniversität Leoben (Austria), we had the chance to visit Cyprus during a SEG summer field trip. The field trip took place from 19th to 28th September 2022 and was led by our SEG Academic Sponsor Prof. Raith and Prof. Bakker. The main idea of this field trip was to study the famous Troodos Ophiolite sequence and the VMS deposits in Cyprus. We gained a lot of new information and insights about mafic and ultramafic rocks, the origin of the island of Cyprus and saw spectacular outcrops.

First, we want to thank the Geological Survey Department of Cyprus for guiding us around Cyprus. We received a perfect introduction about the origin of the island, about the geology and tectonics and a well-guided tour for the first couple of days. Furthermore, we want to thank Hellenic Minerals Ltd for the chance to see the closed Skouriotissa Copper Mine. Additionally, we as students, are grateful for the supportive Steward R. Wallace Funding (Round II 2021) that we have received from the Society of Economic Geologists. Special thanks are due to Mr. Altenberger and Mr. Bertrandsson Erlandsson, who supported the project. In addition, we got sponsorships from the LeGeo Leoben and our representatives for the field of Applied Geosciences. Finally, a special thanks goes to Prof. Raith, Prof. Bakker and Mrs. Tatschl for the organization and perfect execution during the field trip. It was a great experience.

## 1.2. Participants

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## 1.3. Geological Background

Cyprus attracts geologists and archaeologists alike due to its unique geology and mining history. The first copper of Cyprus was probably produced around 3000 BCE. Lots of archaeological artifacts and slag heaps were found on the island. The Skouriotissa mining area is assumed to be the oldest on the island. The copper was produced via smelting of copper-rich sulfide ore. Over one hundred slag heaps are known nowadays and old mine shafts and waste heaps are scattered around the island. Either the element Cu was named after Cyprus or vice versa.

The formation of Cyprus can be described through geological processes related to the movement of the African plate below the Eurasian plate about 90 Ma years ago. Ongoing subduction and the formation of new oceanic crust north of the subduction zone and finally an obduction of the oceanic rocks are important processes for the genesis of the Troodos Ophiolite. About 10 Ma years ago, carbonate sediments were deposited and later uplifted. The isolation of the Mediterranean region from the Atlantic Ocean about 6 Ma years ago resulted in a deposition of evaporitic rocks (gypsum).

The island of Cyprus can be divided into four major geological zones (Figure 1):

- The Pentadaktylos Zone (was not observed during the field trip)
- The Troodos Zone
- The Mamonia Zone
- Autochthone sedimentary rocks covering the base rocks (Circum Troodos or Mesaoria Basin).

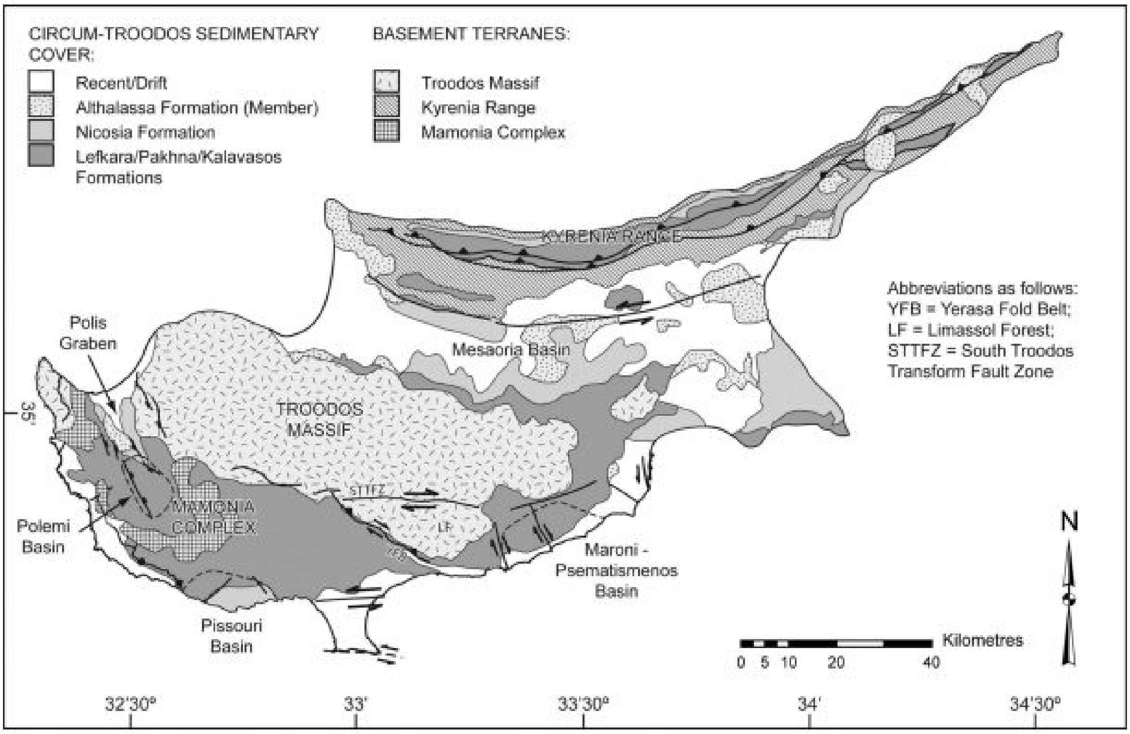

**Figure 1: Geological map of Cyprus with the major geological zones and shear zones (Kinnaird et al. 2011)**

The Kyrenia Mountains are the biggest part of the Pentadaktylos Zone. The orogen is about 160 km long and runs along the northern coast of Cyprus. The mountain range consists primarily of marble and dolomitic limestones and is surrounded by sediments. The sediments primarily consist of sandstones and marl (Ducloz 1972).

The Troodos Zone or Troodos Ophiolite forms the core of the island. Due to the fact that the sequence is stratigraphically complete, it is one of the best studied ophiolite sequences in the world. The ophiolite sequence is located north of the Arakapas fault zone and is like a recent oceanic crust. With ascending order (hanging to footwall), several parts can be distinguished:

(a) The central zone consists of peridotites (harzburgites, lherzolites and dunites), which are strongly serpentinized.

(b) A plutonic sequence with two types of gabbro, wehrlite, plagiogranite and pyroxenite. The origin of these types of rocks is from the partial crystallization of the magma chamber. This magma chamber is located beneath the zones of the sea floor spreading.

(c) An intrusive sequence with volcanic rocks. After spreading the magma ascends and forms the sheeted dikes complex. This complex is followed by volcanic rocks with two series of pillow lavas, the lower and upper pillow lava sequence or lava flows. The main composition of these rocks is basaltic.

(d) Different types of sediments, such as radiolarites and umbers (a chemical, Fe-rich sediment), deposited on top of the Ophiolite sequence (Dilek and Furnes 2009; Moores and Vine 1971).

The Mamonia Zone is subdivided into two different, tectonostratigraphic units – the Dhiarizos and Ayios Photios groups. The primary rocks of this formation are sedimentary rocks such as sandstones, limestone, radiolarites, volcanic rocks (pillow lavas) and metamorphic rocks like amphibolites and phyllites. The amphibolites are unique on the island and show a high-grade metamorphism. Due to its complex structure, it is interpreted as a mélange zone. The origin of this complex zone was a microplate that was thrust on the southern part of the Troodos. The age of these rocks is ranging from upper Triassic to lower Cretaceous (Robertson and Woodcock 1979).

After the genesis of the Troodos after the spreading of the ocean ridge at the latest Cretaceous, the first sediments started to be deposited. The deep sea became gradually shallower, and sedimentation began with the Kannaviou Formation, followed by the Moni and Kathikas Formations. These three formations mostly contain deep sea sediments (bentonitic clays, radiolarites) and volcaniclastics. At the late Maastrichtian, carbonate sediments from the Lefkara Formation including marls, cherts and chalks were deposited. Further to the hanging wall, the succession continues with the Pakhna Formation, which is similar to the Lefkara Formation with no chert layers. At the Messinian salinity crisis, the result of evaporation of the Mediterranean Sea, the Kalavasos Formation with mainly gypsum was deposited. After the Messinian salinity crisis, the Mediterranean Sea gets reconnected with the Atlantic Ocean and the final formation, the Nicosia Formation, with siltstones and marls, was deposited (Robertson 1977).

In former times, Cyprus has been active in the production of copper, gold, chromite as well as in the production of fibrous asbestos. Already in ancient times, people realized the mineral wealth of the Troodos mountains. Archeological investigations came to the result that production of copper started 2000 BCE up to almost 1000 CE (Kassianidou 2011). Very important indicators are ancient galleries and huge slag heaps with parts of pottery in some areas (Constantinou 1992). After a period of about one thousand years with almost no production, mining companies started production of ore again in the 20th century and became a very important part of the island's industry. The most important mining area for copper was in the volcanic sequence northwest of the Troodos Mountain range with the Mavrovouni, the Apliki and the Skouriotissa mine. The grades vary from 2-4.5%, but in the secondary enrichment zone up to 20 % and were mineable more easily than in other areas in the Mediterranean region (Constantinou 2007).

Currently there is no active mineral production for metals in Cyprus. In the Skouriotissa mine the mining activity has stopped a few years ago and nowadays they use their experience for the processing of imported nickel ore at the Skouriotissa mine site. Asbestos in the form of chrysotile was majorly mined in the area of serpentinized Harzburgite in the Troodos area during the 20th century. The grade of the ore was between 0.8 % and 1.0 % and it went through a beneficiation plant to enrich it before selling. The production stopped due to economic reasons regarding the bad image of Asbestos in the 1980s. The Amiantos mine was closed in 1988 with an estimated production of 1 Mt of asbestos fibers and the government of Cyprus has been responsible for the rehabilitation of the mine since 1992 (Constantinou 2015b).

Chromites are majorly found in the dunites of the Troodos Mountain range. The main form of chromite occurrences is podiform chromite deposits (McElduff and Stumpfl 1991). There have been mining activities in the 20th century, but they are closed now due to economic reasons. Beside the already mentioned historic mining activities, there is active mining for bentonite and gypsum going on. Most bentonite is used in the pet sector and is exported after treatment. Gypsum is used in different applications, for example in the cement production, as filler or as plaster (Constantinou 2015a).

# 2. 20th September Troodos Ophiolite Complex

The first day was all about the Troodos Ophiolite Complex. The complex consists of all typical ophiolitic sequences, such as serpentinized harzburgite, plutonic ultramafic and mafic rocks, sheeted dyke complex, pillow lava and Fe-/Mn- rich sediments.

## 2.1. Troodos UNESCO Global Geopark Visitor Centre

Coordinates: 34.926408N, 32.918601E

The day started at the Troodos Geopark Visitor Centre, where the exhibition visualizes the geological history of Cyprus. Together with beautiful rock samples the formations are very well described and easy to follow. Additionally, mining activities of former copper, chromite and asbestos mines are described. The name of copper even originated from the Latin name cuprum from Cyprus. The first copper production in Cyprus dates back to 1800 BCE. The chromite deposits are related to fractional crystallization of the ophiolite complex, at the contact of harzburgite and dunite, which was closer examined at the Atlanta trail on day four. A movie summarized the main points of the exhibition.

## 2.2. Geosite 10 Amiantos Fault

Coordinates: 34.93265676N, 32.92480323E

The Amiantos Fault is a N-S running reverse fault which is the eastern border of the ophiolite marking the tectonic contact between upper mantle rocks and cumulate rocks (Figure 2). The upper mantle rocks are black, heavily serpentinized harzburgites partly with fine picolite veins consisting of chrysotile and lizardite (Figure 3). The first serpentinization phase happened during the formation of the ophiolite in the Cretaceous and the second serpentinization appeared during the Neogene with relatively low temperatures. Mainly whitish gabbros occur as cumulate rocks (Figure 4).

**Figure 2: Tectonic contact between the heavily serpentinized harzburgite and the cumulate rocks**

**Figure 3: Heavily serpentinized harzburgite with picolite veins consisting of chrysotile and lizardite**

Figure 4: medium grained whitish gabbro of the overlaying cumulate rocks

## 2.3. Geosite 29 Sheeted Dyke Complex, Galata village

Coordinates: 34.9944149N, 32.90385471E

The outcrop shows rotated sheeted dikes that have been formed due to the extensional tectonic regime during the opening of the Neo-Tethys. The sheeted dikes consist of dark grey, fine grained basaltic rocks with well-preserved chilled margins and show a dipping of 45° (Figure 5). During the formation of the sheeted dikes the dipping has been vertical and due to the ongoing extension of the Neo-Tethys detachment faults have been formed, which led to the rotation and the low dipping angle of 45°.

Figure 5: Rotated sheeted dikes with a dipping angle of 45°

## 2.4. Slag Heap, Outside Skouriotissa mine

Coordinates: 35.09690992N, 32.88375514E

This outcrop is described in chapter 5.3.

## 2.5. Agrokipia mine

Coordinates: 35.04437047N, 33.14637117E

The Agrokipia mine is an open pit, where copper and sulfur were produced from 1952-1971. About 333,000 tons of ore were gained, containing 1 % copper and 38 % sulfur. The ore body is a lens that is located between the upper and lower pillow lavas (Figure 6). These two pillow lavas can be distinguished by the influence of hydrothermal alteration. The lower pillow lava is hydrothermally altered, whereas the upper one is not.

**Figure 6: Hydrothermal altered ore body of the Agropikia mine together with the upper pillow lavas**

## 2.6. Geosite 3 Lower Pillow Lavas, Maroulena River

Coordinates: 35.01190176N, 33.15424013E

The outcrop shows hyaloclastites and well-preserved pillow lavas with basaltic composition, which got intruded by vertical dikes (Figure 7). In pores of the basaltic pillow lavas, greenish celadonite can be found (Figure 8). The dikes have a N-S direction with a dipping of 70-80° and show chilled margins and chalcedony veins (Figure 9). Stratigraphically this outcrop is part of the lower volcanic sequence.


**Figure 7: Dikes cutting throw hyaloclastites and pillow lavas**


**Figure 8: Fine grained surface structure of a basaltic pillow lava**


**Figure 9: Chalcedon vein in a dike**

# 3. 21st September: The Circum-Troodos Sedimentary Sequence

For the second day of the field trip the focus was on the Circum-Troodos Sedimentary Sequence. During this day, different sedimentary formations were observed, starting with the Kannaviou Formation of the Lower Cretaceous up to the Pliocene Nicosia Formation.

## 3.1. Bentonitic clay quarry: Kannaviou or Moni Formation - Monagrouli Quarry

Coordinates: 34.76075617N, 33.226622E

The first stop belongs to Kannaviou or Moni formation and represents the Monagrouli quarry section which is located approximately 2 km NE of the Monagrouli village near the asphalt road to Asgata village. The Monagrouli quarry section (Figure 10) is characterized by a paleorelief of up to 60 m thick bentonitic clays that show alteration towards the top. The upward alteration consists of bentonitic clay layers which host clasts (sandstones, siltstones, limestones, metamorphic rocks) of different grain sizes mainly from the Mamonia Complex. The outcrop displays clay siltstone at the bottom and becomes much finer grained towards the top, showing thin layers composed of bentonitic clays. The bentonites themselves originate from altered ashes of volcanic eruptions, deposited in terrain depressions. However, they are not directly related to the ophiolite sequence. Consequently, this indicates additional volcanic activity besides ophiolite formation. Microfacially, radiolarians and planktonic foraminifera could be detected, therefore a chronological classification in Upper Cretaceous (Upper Campanian?) can be assumed.

**Figure 10: View over the Monagrouli quarry from S**

## 3.2. Pakhna-Lefkara border - Kalavasos Section

Coordinates: 34.76541156N, 33.30014427E

Near Kalavasos village is a road cutting section that illustrates the border from Lefkara Fm. to the Pakhna Fm. While the Lefkara Fm represents a deep marine environment close to the CCD, the Pakhna Fm is attributed to hemipelagic conditions. In the NE direction of the outcrop, altering layers of chalks and cherts can be recognized (Figure 11), which towards the top are attributed to the chalk member of the Lefkara Formation due to the disappearance of the chert layers (Figure 12). Towards the top, yellowish to pinkish chalk, marly chalk and siltstone of the Pakhna Formation can be seen (Figure 13).

The direct contact of a deep marine environment adjacent to hemipelagic depositional conditions and consequent Oligocene stratigraphic gas indicates a subduction zone with subsequent uplift.

**Figure 11: Alternating layers of cherts and chalks with marly in-betweens**

**Figure 12: Solely chalks (on the top of Figure 11)**

**Figure 13: Comparison of specimen from the different layers. From left to right: chalk + chert, yellowish chalk, reddish siltstone**

## 3.3. Evaporites: Kalavasos Formation - Tochni Village

Coordinates: 34.78315069N, 33.32249578E

In the immediate vicinity of the turnoff towards the village of Tochni calcareous sandstones that have formed around the uplift of Troodos can be observed. Recognizable are marly interlayers between thick banks of calcarenite. These layers are followed by clastic sediments that are believed to be deposited after medium transport distance (Figure 14 and Figure 15). Dark minerals originate from the Troodos complex. The common presence of calcareous sandstones as lenses within the clastic sediments give an indication that the Formation was deposited within a marine environment.

Furthermore, enormous evaporites can be found, more precisely laminated (Figure 16) and saccharoidal (Figure 17) gypsum with mostly large selenite crystals (Figure 18) representing the Messinian salinity crisis. The formation of the gypsum is part of a standard evaporite-sequence originating from a fault-controlled basin where hypersaline conditions prevailed.

**Figure 14: Mighty banks of calcarenite with marly interlayers followed by clastic sediments**

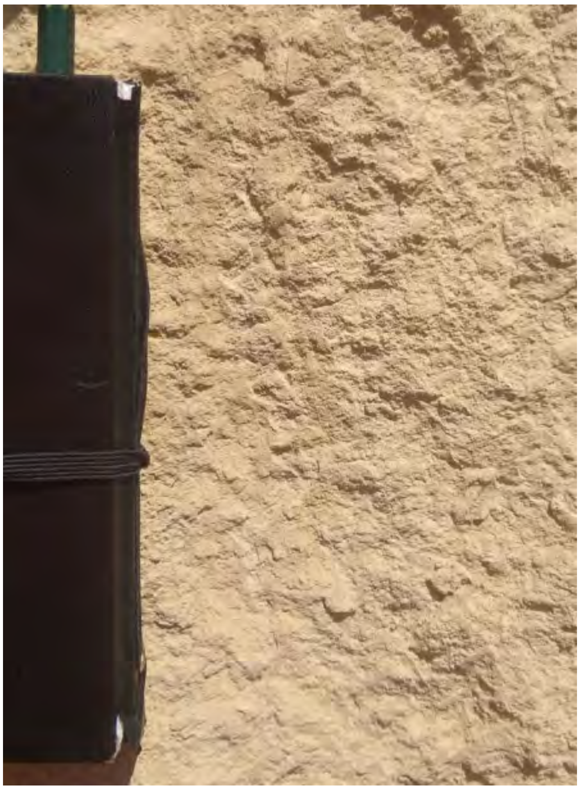

**Figure 15: Closeup on fine grained calcarenite**

Figure 16: Plate of laminated gypsum with erosional markers on the surface

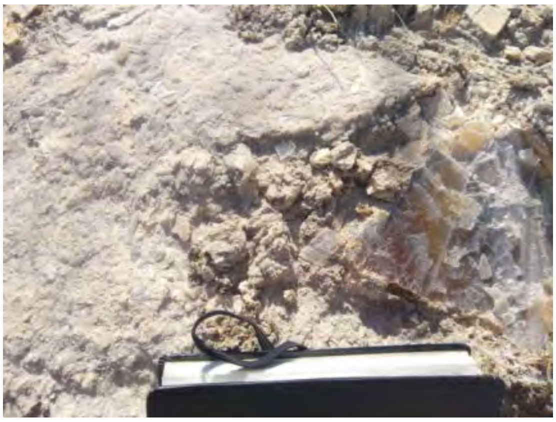

Figure 17: Saccharoidal gypsum crystals near selenite

Figure 18: Large selenite crystal

## 3.4. Pakhna Fm: Organic rich layers - Rizoelia Roundabout

Coordinates: 34.76491464N, 33.32135637E

About 600 m E of the roundabout of Rizoelia (in the direction of Paralimni) there is an outcrop, which contains chalk, marly chalk, marl and sapropelitic layers attributed to the uppermost part of the Pakhna Formation. Microfacies include organic-rich layers (planktonic foraminifera, Figure 19 and Figure 20) that can be dated to the upper Miocene. The organic-rich layers are due to anoxic conditions caused by plate movement and associated intermittent seawater inflow.

Figure 19: Chalk, marly chalk, and marl with sapropelitic layers

Figure 20: Closeup on specimen from the different layers of Figure 19

## 3.5. Nicosia Fm: Organic rich layers - Pyla Village

Coordinates: 34.99722673N, 33.6999783E

On the Larnaka-Agia Napa highway near the village of Pyla is a road outcrop comprising Pliocene sediments of the Nicosia Formation. Characteristic for this outcrop are alternating layers of cream-colored, very rich in planktonic, very large foraminifera and brown, organic-rich, oxidized marls (Figure 21 and Figure 22).


Figure 21: Overview of the layered, strongly eroded marly layers

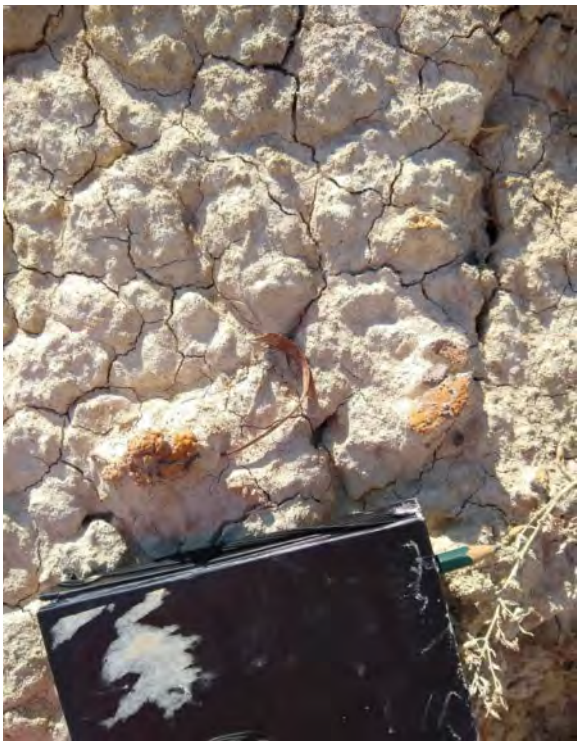
Figure 22: Closeup on Fe- and Mn- enriched oxidized nodules

## 3.6. Reef Limestone - Cape Greco

Coordinates: 34.99722673N, 33.06707656E

At this outcrop, reef limestones more than 150 m thick formed in the Miocene, containing a variety of marine life within their reef structures, e.g., corals, mussels, snails, algae (Figure 23, Figure 24). Benthic foraminifera also build up the reef structures. The thickness of the reef limestone is due to NW-SE controlled faulting and advancing subsidence.


Figure 23:Fossilized Coral reef structure


Figure 24: Closeup on a coral cross-section

# 4. 22nd September

## 4.1. Troodos visitor center

Coordinates: 34.922198N, 32.8781206E

The first stop of the day was at the Troodos visitor center. The geology of Troodos is shortly presented there and visitors can inform themselves about the botanic of Cyprus. A short video sums up the most important features.

## 4.2. Atalante Geo-trail

Coordinates: 34.92390718N, 32.87977652E (Start)

The Atalante Geo-trail is a fourteen kilometers long trail with many outcrops of rocks of the mantle sequence. Main rocks are harzburgites along with lenses of dunites. Another geologically interesting stop are two chromium mines along the trail. Most of the rocks were formed in 60 km depth in the Tethys Sea about 92 million years ago. On this field trip, we visited just a small part of the trail. Interesting points are marked in the report with coordinates.

## 4.3. Harzburgite

Coordinates: 34.9221971N, 32.8781203E

The first stop of the Atalante trail shows harzburgite (Figure 25). In general, harzburgite is a plutonic peridotite rock with a cumulative structure and consists mainly of olivine, which can be between 40 % and a maximum of 90 % by volume. However, olivine can be transformed into serpentine. Ultramafic rocks are magmatic and meta magmatic rocks with a very low silica content (less than 45 %), generally >18 % MgO, high FeO, low potassium and usually consist of more than 90 % mafic minerals. In Figure 26 the classification diagram for plutonic ultramafic rocks is presented. Harzburgites are residual ultramafic rocks that have lost melt through melting, more precisely basaltic melt (whereby clinopyroxenes and spinels have melted out, only orthopyroxenes have remained). Weathered ultramafites are easier to recognize (e.g., olivine becomes reddish-brown, or pyroxenes become darker or already serpentinized on some surfaces, become greenish and also bluish).

Figure 25: Harzburgite


Figure 26: Classification diagram for plutonic ultramafic rocks (after Streckeisen, 1973) https://www.mindat.org/

## 4.4. Pyroxenite

Coordinates: 34.9255895N, 32.8757497E

An outcrop of pyroxenite was on the next stop. Significant for this rock are mainly dark minerals, ortho- and clinopyroxene (Figure 27). Pyroxenite is an ultramafic mineral like harzburgite. The origin is the upper mantle sequence. The rock occurs as small intrusions or, like on this stop, in massive form. During the walk along the trail, a visible intrusion was near the visible pyroxenite (Figure 28). The boundaries of the intrusion are altered to a dark color.


Figure 27: Pyroxenite; significant dark minerals (clinopyroxene)

Figure 28: Intrusion in ultramafic rock. Boundaries are altered dark

## 4.5. Trail Point 22 - Boundary harzburgite - intrusion rocks

Coordinates: 34.919086N, 32.868209E

At point twenty-two are large crystals (cm range) with good cleavage in the rocks. These are most likely clinopyroxenes or amphiboles (dark). Brighter spots indicate plagioclase. The minerals and the structure of the in-situ rocks are pegmatitic and show the transition from harzburgite. Figure 29 shows the gabbro-pegmatite with contact to harzburgite.

Figure 29: Gabbro-pegmatite (left) with contact to harzburgite (right)

## 4.6. Outcrops and rocks along the trail

Many different outcrops indicate the composition of the minerals along the trail. On the one hand, wehrlite occurs with mainly clinopyroxene (Figure 30) and on the other hand, coarse-grained gabbro-diorite (Figure 31) with a higher feldspar content (plagioclase) as well as fine-grained gabbro (Figure 32).

Further along the path the concentration of chromite increases in the hand specimens (Figure 33). The chromite occurs as low graded and disseminated or as higher graded (or more accumulated) chromite schlieren. Moreover, there are coarse-grained pegmatitic gabbros (Figure 34).

Figure 30: Wehrlite

Coordinates: 34.918889N 32.868056E

Figure 31: Coarse-grained gabbro-diorite

Coordinates: 34.918889N 32.868056E

**Figure 32: Fine-grained gabbro**

**Coordinates: 34.923056N 32.856389E**

**Figure 33: Chromite schlieren**

**Coordinates: 34.920000N 32.864722E**

**Figure 34: Coarse-grained pegmatitic-gabbro**

**Coordinates: 34.923333N 32.856389E**

## 4.7. Adit one: chromite mine W Location 20

Coordinates: 34.9243049N, 32.8604293E

The three best known usable chromite deposits in the Troodos Mountain Range are those of Kokkinorotsos, Hadjipavlou and Kannoures. Figure 35 shows the Hadjipavlou mine, which was discovered in the harzburgite-dunite transition zone. Furthermore, this mine is the smallest mine out of the three before mentioned. From 1950 until 1954 it produced approximately 1,500 tons of high-grade ore with underground mining. There are different types of chromite ore such as the massif, nodular, scattered and banded (schlieren) types. The economically usable chromite deposits are of podiform type. Figure 36 shows chromite in dunite, which form bodies in harzburgite. Of course, the use depends on the chemical composition. Chromium is most frequently used in the metallurgy and refractory industry.

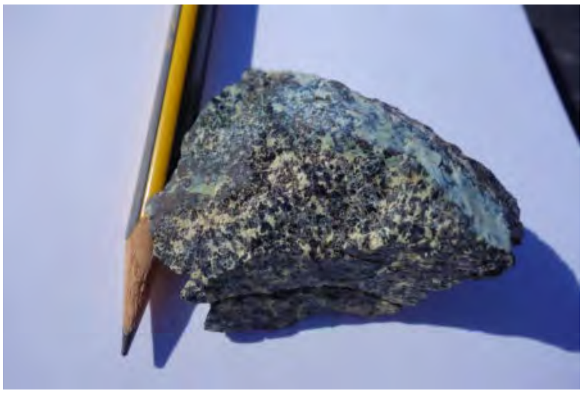
**Figure 35: Chromite**


**Figure 36: Chromite mine W – Hadjipavlou**

## 4.8. Adit two: chromite mine E

Coordinates: 34.9320758N, 32.8682018E

Figure 37 and Figure 38 show the chromite mine, which is located to the east of the trail. Here the rocks are tectonically broken, especially in the dunite (these in turn form bodies in the harzburgite). A thesis titled „Inclusions in chromite from Troodos (Cyprus) and their petrological significance“ was written here by a student from Montanuniversity Leoben. Nearby the second open adit was probably another historic adit, which is closed. Next to the entrance are visible chromite schlieren (Figure 39).

**Figure 37: Chromite mine E**

**Figure 38: Chromite mine E**

**Figure 39: Chromite schlieren**

**Coordinates: 34.931389N 32.865833E**

## 4.9. Transition to gabbro Location 22

Coordinates: 34.924574N, 32.8704958E

Figure 40, Figure 41 and Figure 42 show different gabbros of mainly fine-grained and coarse-grained types. Gabbro is formed on mid-ocean ridges by slow crystallization of the ascending mantle material. On the one hand, due to the slow cooling of the liquid magma, gabbro develops medium- to coarse-grained structure. On the other hand, due to the rapid cooling, the structure will be more fine-grained.

Figure 40: Fine-grained gabbro

Figure 41: Coarse-grained gabbro with stratification

Figure 42: Coarse-grained lense in fine-grained gabbro

## 4.10. Viewpoint Amiantos mine

Coordinates: 34.9326345N, 32.9129233E

The last stop of the day was the abandoned Amiantos mine (Figure 43). It has not been in operation since 1988. The Amiantos mine was a big deposit of asbestos-form chrysotile and the area of the mine is about 4.7 km² in total. Chrysotile mineralized in form of cm-thick veins in the ultramafic rocks of the Troodos due to the serpentinization of the ophiolites. Estimation of the totally produced asbestos is about 130 Mt. The general average grade is about 0.8 to 1.0 %.

After the closure of the mine in 1995 the rehabilitation work of the open pit started. The exploitation of the asbestos affected the whole environment in this area. Therefore, precautions like the reforestation and stabilizing of the bench slopes are necessary.

Figure 43: Viewpoint Amiantos mine

# 5. 23rd September

## 5.1. Introduction at the Skouriotissa mine

Coordinates: 35.08872998N, 32.88878627E

Provided by the courtesy of the company "Hellenic Minerals Ltd", that is located at Skouriotissa, a tour granting insight into the Skouriotissa mining history and the company's present activities regarding the production of nickel salt from lateritic material using hydrometallurgy, was granted. The Skouriotissa mine is now used for water storage, which supplies the hydrometallurgical plant nearby. As to not utilize water from local systems the water system is a closed system. Furthermore, for rehabilitation purposes, trees that can sustain themselves are planted. Leftovers from processing are used to restore premises. To avoid acid mine drainage a storm pond system has been installed and the bottom of the ponds are lined with plastics.

## 5.2. Skouriotissa mine viewpoint

Coordinates: 35.09406658N, 32.89038104E

The Skouriotissa mine (Figure 44) is assumed to be one of the oldest places for mining activity in Cyprus, since there are indications that mining occurred already in 1067 BC.

**Figure 44: View over Skouriotissa mine and Apliki mine in the distance (indicated by the red square)**

The Skouriotissa mine produced copper, gold, and silver until 2019. Mining first took place underground, but later moved above ground. Ancient galleries indicating older mining history can still be found within the pit. Skouriotissa was classified as a volcanogenic massive sulfide deposit, which also was linked to an associated gossan. The latter was enriched in silver and gold due to weathering and oxidation. Skouriotissa contained low grade ores (0.5-2.5 % copper content), resulting in conventional extraction methods like flotation being uneconomical in some cases. Therefore, copper processing involved heap leaching, hydrometallurgy, and electrowinning. Gold was produced using cyanide leaching. In the end, before the mine closed down, even the dumps were reworked. In its last year of production, the mine produced 201 kt of copper, 33 kg of gold and 97 kg of silver.

## 5.3. Slag heap in Skouriotissa

Coordinates: 35.09273385N, 32.88522822E

With more than 2 million tons of slag, the copper slag heap at Skouriotissa (Figure 45) represents the biggest one of 110 in Cyprus, dating back to the $4^{th}$-$7^{th}$ century (Roman to Byzantine), and thereby providing evidence for the extensive historical copper mining activity in Cyprus. The slag waste product of the furnace (Figure 46), was neatly piled forming a heap which still contains large amounts of pottery (Figure 47) as well as charcoal residues that later were used for radiocarbon dating. Furthermore, secondary minerals of ore deposits such as copper carbonates and hydrous sulfates are present. The slag heap may have even given the town Skouriotissa its name, which is derived from the Greek word for slag.

Figure 45: Slag heap in Skouriotissa

Figure 46: Part of a slag cake

Figure 47: Pottery contained in the slag heap

## 5.4. Skouriotissa mine

Coordinates: 35.09768225N, 32.88575641E

The Skouriotissa mine is associated with the Upper Pillow Lava, which can be seen in an outcrop at the edge of the Phoenix pit (Figure 48). The pillows are exceptionally well preserved, especially the distinctive margins created by rapid cooling of the 1200 - 1400°C hot lava, due to the contact with colder (~2°C) sea water. The Skouriotissa mine itself (Figure 49) can be divided into two different ore bodies separated by a fault. The older Fukasa ore body was described as a massive pyrite lens, overlain by ochre, umber and gossan. Mining activity in this part of the mine took place from ancient times to 1996 and its ore was processed by pyrometallurgy. A highly oxidized disseminated vein-type ore characterized the younger Phoenix ore body. Sulfide crystals such as pyrite and chalcopyrite are common. This part may have been the stockwork zone (feeder zone) of the deposit. This ore body was mined from 1996 to 2019 and its ore was only economical because of new processing techniques (heap leaching, whose waste can be seen in Figure 50, and hydrometallurgy).


Figure 48: Outcrop showing part of the Upper Pillow Lava


Figure 49: View of the Fukasa ore body (indicated by the red square) and Phoenix ore body of the Skouriotissa mine area


Figure 50: Heap leaching waste of the Skouriotissa mine

## 5.5. Epidotized sheeted dykes – Geosite 43 of Troodos UNESCO Geopark

Coordinates: 35.00268416N, 32.78971164E

The 45° rotated sheeted dykes represent hydrothermally altered (epidotized) as well as less altered dykes that interpenetrate each other (Figure 51). At temperatures of ~350°C, the circulation of hydrothermal fluids results in the formation of epidosites, an epidote and quartz bearing rock. The epidotization appears to be to be focused in the central part of the dyke (Figure 52), suggesting that fluid transport was via the central part of the basaltic dyke rather than from the margin. Occasionally chilled margins, a zone of fine-grained or glassy texture along the dyke margin, can be detected.


Figure 51: Outcrop showing epidotized sheeted dykes

Figure 52: Dyke with an epidotized central part (greenish)

## 5.6. Kykkos Monastery

Coordinates: 34.98328818N, 32.74121733E

Situated at an altitude of about 1300 m, northwest of the Troodos mountains, is the Kykkos Monastery (Figure 53, Figure 54). It was founded between the 11th and 12th century and is dedicated to Virgin Mary. Today, it not only represents one of the wealthiest monasteries of Cyprus but also hosts a museum of unique cultural and historical importance. One of the three famous icons attributed to Apostolos Loukas, manuscripts, holy objects, embroideries, and Cypriot antiques are part of the exhibition.

**Figure 53: Kykkos Monastery entrance**

**Figure 54: Exterior view of the Kykkos Monastery**

# 6. 24th September

## 6.1. Geosite 46 (Chandria)

Coordinates: 34.94464303N, 32.99782752E

This geosite is part of the plutonic sequence and is situated directly below the sheeted dyke complex. It shows different types of gabbros (layered olivine gabbro and foliated pale gabbro), which were intruded by plagiogranite and mafic dykes. Besides that, poikilitic wehrlite can be found. Some plagiogranite dykes exhibit chilled margins. Furthermore, the lighter rocks display a slight secondary hydrothermal alteration, indicated by the presence of epidote in the rocks. This geosite is a testament to a complex intrusion history involving different magma chambers.

## 6.2. Geosite 31 (Palaichori Village)

Coordinates: 34.91616952N, 33.0922205E

This geosite is part of the sheeted dyke complex and displays slightly weathered, subvertical dykes. They consist mainly of diabase and basalt. Many dykes exhibit chilled margins, which were created when the intruding material interacted with the surrounding material and started cooling at the borders of the intrusion. In the outcrop the chilled margins can be identified as a fine-grained black rim (Figure 55) at the edge of a coarser grained intrusion. The boundaries of the chilled margin towards the rock surrounding the intrusion are sharp, while the boundaries towards the center of the intrusion are diffuse. Some intrusions in this outcrop show two chilled margins, while others only have one present, indicating that the other margin was displaced by younger intrusions. Some of the joints seen at the site could be interpreted as columnar jointing seen in sheet flows in other outcrops. The outcrop also shows later formed faults and calcitic veining.

Figure 55: A chilled margin identified by its darker color

## 6.3. Geosite 2 (Kamara River)

Coordinates: 35.03816311N, 33.17751387E

Part of the Lower Pillow Lavas and sheet flows (Figure 56) are exposed here. Both were created by submarine volcanism, however while one magma had a higher viscosity and formed pillows, the other one had a lower viscosity and flowed on the ground for some time. Rapid cooling caused by cold sea water caused chilled rims in the pillows and columnar jointing in the sheet flows. Pores were also created when magma cooled and trapped gas could escape. Later some of these pores were intruded by fluids and are nowadays filled with zeolite. Furthermore, hyaloclastite by brecciation were formed and can now be found at this geosite. Some rocks in the outcrop exhibit a green color due to the presence of celadonite. This mineral was created by a low-grade hydrothermal alteration at a low temperature (~150°C) under anaerobic conditions. Interestingly, faults can only be found in the sheet flows, indicating tectonic processes while magmatism was still active.

Figure 56: different flow sheets exhibiting columnar jointing

## 6.4. Olivine-rich basalt

Coordinates: 35.03757795N, 33.17954283E

Near the geosite 2, a dyke containing fresh, large olivine crystals can be found. This can be interpreted as picrite basalt (magnesium-rich basalt) or as part of an olivine cumulate.

# 7. 25th September

## 7.1. Mamonia formation

On the seventh day of the excursion, a closer look on the Mamonia formation and rock types was done. This formation is the former subduction wedge between the African plate and the Cyprus ophiolite complex. This wedge got partly subducted and partly obducted onto Cyprus. The formation is a tectonic mélange, broken apart and mixed due to the passive margin. This formation is composed of sedimentary rocks, which were formed at deep to shallow marine environments or at the continental slope, and volcanic rocks from seamounts. The continental slope also experienced slides and formed olistoliths with transported blocks of rocks. The sediments are partly metamorphosed into greenschist to maximal amphibolite facies. The Mamonia Complex is divided into three areas, which differ in the marine environment from deep sea to shelf condition.

## 7.2. Aphrodite Hills

Coordinates: 34.6648690N, 32.6341869E

The first stop is a viewpoint on the south-east coast of Cyprus. Here rocks and Formations of the Mamonia formation are shown. These rocks include carbonate rocks as pelagic and reef limestones, as seen on the rock called Aphrodite hills, as well as radiolarites and volcanic rocks from underwater volcanoes/seamounts. Also, we could observe and differentiate reddish-brown colored rocks, which are volcanic rocks, from light colored rock made out of limestone. A closer look at the beach reveals a sandy gravel beach with well-rounded clasts. These gravels are composed of many different rock types found in Cyprus. The name of the location is derived from old myths, that Aphrodite got her origin here and this is the place where she got out of the water.

## 7.3. Seamount

Coordinates: 34.7613887N, 32.6273355E

Here we have seen pillow lavas derived from a seamount as part of the Mamonia Formation. The rocks show typical chilled margins and pillow structures. Evidence of ocean floor metamorphism was also seen in fibrous white zeolites phases in the rocks and in some epidote minerals. In part of the volcanic rocks previous gas bubbles are filled with white and brownish material later in the process producing a variolitic grain structure. Also, some small bright veins were observed on the face which are made up of quartz. The zeolites are laumontite, a fibrous white silicate mineral, which exhibited a radial fibrous to stem-like habitus. Some calcitic surface coating was observed on the weathered surfaces.

## 7.4. Milos Grill

Coordinates: 34.770786N, 32.639850E

The next stop shows deep water facies of the Ayros Fotios group. This group in the Mamonia formation includes cherts, mudstones and radiolarites. The rocks are typical for the deep marine environment below the CCD. These rocks have distinct alternating red and yellow colors. The reddish colored rocks are identified as mudstones with 3-7cm thick layers, while the yellowish layers are chert in thin layers down to some mm. The layer boundaries are not straight and the underside of some layers showed cast markers from the sedimentary process. Due to the depositional environment slumping and material slides could have also occurred. Some folds of tectonic origin were also observed showing tectonic compressional events after the sedimentary process. The overlying rocks are discordant river sediments made up of gravels from the Neogene.

## 7.5. Viewpoint Xeros Potamos Valley

Coordinates: 34.764279N, 32.598842E

Here we got an overview of the Xeros Potamos Valley. With the geological map of Cyprus, the different types of rocks and formations could be distinguished from afar by hand. Mostly dark rocks of volcanic origin in contact with bright rocks of the Lefkara and Pakhna Formation and typical serpentinized rocks of the Troodos complex, the formations below the Lefkara formation, are shown in a tectonic window.

## 7.6. Tectonic Mélange

Coordinates: 34.7674093N, 32.5402995E

The last stop showed part of the tectonic mélange. Here we have seen a plethora of rocks side by side mixed by tectonic movement/forces. The rocks include carbonate rocks, cherts, metabasite and breccia beside Troodos scales. The contacts between these different rocks are of tectonic origin and the breccia also may have derived from those movements. The rocks are lightly metamorphic and some showed schist with mica in ordered layers. Also, quartz veins and lenses are found in part of these rocks here. Two different angles of foliation were observed, which shows that at least two metamorphic events overprinted these rocks. The metamorphic grade could be greenschist or lower amphibolite facies.

# 8. 26th September: Au-bearing VMS deposits

## 8.1. Introduction

On the eighth day of the excursion, the objective was to explore further sites of VMS deposits and to look for primary features solely related to the deposition as well as secondary features created by alteration processes. Therefore, the abandoned mining district near the village of Mathiatis within the Nicosia District was visited. The deposits are situated at the northeastern rim of the Troodos ophiolite complex, inside mafic volcanogenic to subvolcanogenic sequences.

One of the main differences to the VMS deposits visited prior during the field trip (e.g., Mines of "Skouriotissa") is/are a later phase(s) of Au-mineralization(s) due to hydrothermal processes. The Au is carried as nano inclusions or within the crystal lattice of pyrite ($FeS_2$) minerals as so-called "invisible gold". The hydrothermal fluid causing the alteration must have been of siliceous character as the rocks affected by the alteration are strongly silicified and showing respective properties. The Au is of primary magmatogenic origin as it is derived from an ultramafic melt. Au is normally not found in primary ultramafic rocks as it behaves incompatible, causing it to remain in solution during fractional crystallization and to accumulate in the fluid. Due to this reason, it can be transported into hydrothermal systems where it is often associated with siliceous fluids. As host rocks for the primary deposition of disseminated Au-cations, felsic to intermediate differentiates such as plagiogranite as well as mafic differentiates such as diabase or basalt are very common. Hydrothermal fluids of either magmatogenic origin (high-T) or circulating seawater (low-T) leach those primary host rocks and are further concentrating the Au in the hydrothermal systems. A primary mobilization at high temperatures mainly driven by magmatogenic fluids takes place in the vicinity of the rift systems. There, the Au is transported via anion complexes and then trapped within the crystal lattice of crystallizing pyrite, for example around black smokers. A possible second mobilization by penetrating seawater at comparably low temperatures somewhere around 350-250 °C takes place at increasing distance away from the rift, where the Au deposited during the primary mobilization stage is again solved and mainly carried by reducing S-bearing anion complexes, together in a Si-rich fluid. These silica bearing fluids often form pure quartz and its varieties such as chalcedon and jaspis (Figure 57). The Au is subsequently enriched in quartz bearing parts and the grades can reach up to 30 g/t, constituting very high values for gold deposits.

**Figure 57: Sample of quartz varieties like jaspis and chalcedon**

The grades concerning economic deposits normally range from 1-10 g/t, depending on the details of the economic features, such as accessibility, ore type and mineralogy (*important for metallurgical processing*), logistics and so on. The Mathiatis pits were in operation from 1938 until the early 1970s (Mineral

Resources), extracting low-grade Cu-ore, with Au grades of up to 30 g/t. The main ore minerals are chalcopyrite and pyrite.

According to Caerus Minerals Resources PLC, the company owning the mining concessions, the historic focus of the operation was the lower grade copper and gold mineralization until the recovery of a massive pyrite body of high-grade pyrite ore containing copper at an average grade of 0.20 %. The reports state that Mathiatis North mined 2.1 Mt during this find. The focus of current exploration lies on reaching potential low-grade bulk targets and to extend the resource base along strike. Recent work carried out in 2007, returned consistent grades of 0.36 to 0.48g/t Au and 0.06 to 0.19 % Cu for the 75-metre-wide massive sulfide breccia at the base of the open pit. (Caerus Mineral Resources PLC)

## 8.2. Mathiatis North, historic open pit mine one

Coordinates: 34.9755261N, 33.34800713E

The upper part of the lithodem is composed of pillow basalts that have clearly been affected by alteration processes, as hydrothermal quartz-bearing veins are crosscutting the rocks and partly epidotization (Figure 60B) has taken place (*epidosite*). The veins are predominantly filled by quartz, but also calcite and epidote are abundant. In the footwall however, a more penetrative character of the hydrothermal alteration becomes visible as the rocks are strongly kaolinized and secondary macroscopic sulfide minerals are sometimes visible, exhibiting nearly idiomorph crystals (Figure 61A) on joint planes of the rock mass.

The hypothetical geological model has been discussed on site, which suggests an extensional regime, controlled by steep dipping normal faults (Figure 59). These faults may have strongly contributed to the oxidation and upgrade of the sulfidic orebodies. The water filling the lower pit levels is being used for agricultural (*olive trees*) purposes, as the pH is low but not too low. In the SE, orange zones and the weathered stockwork mineralization is visible. The remaining VMS deposit is underneath the waterline, and the sulfides appear mostly disseminated.

**Figure 58: View to the NE of the pit with steep dipping normal faults**

**Figure 59: Open pit, viewed from the entrance to the SE**

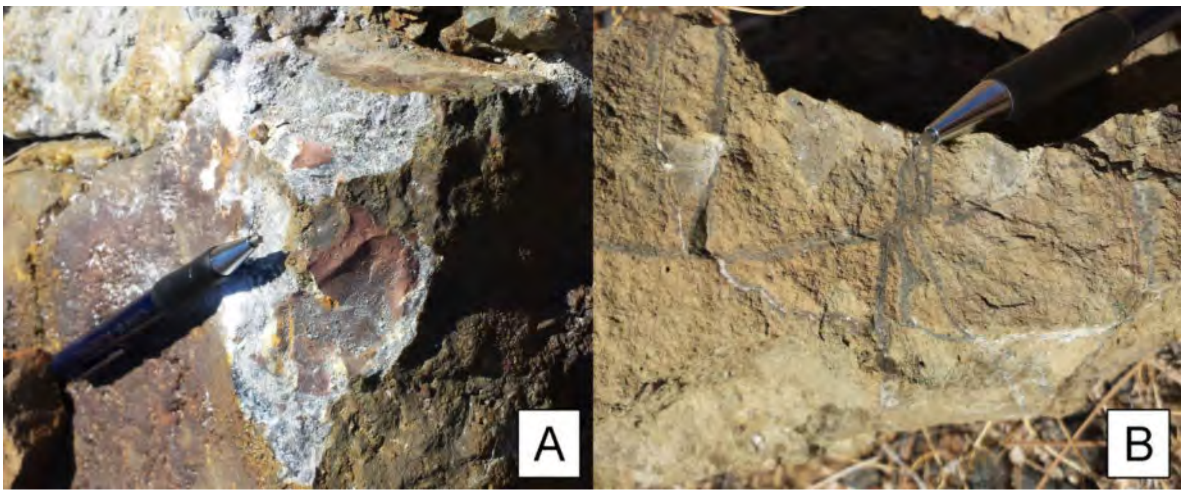


**Figure 60: Massive sulfide breccia (A); Partially epidotized basalt with quartz-bearing crosscutting veins (B)**

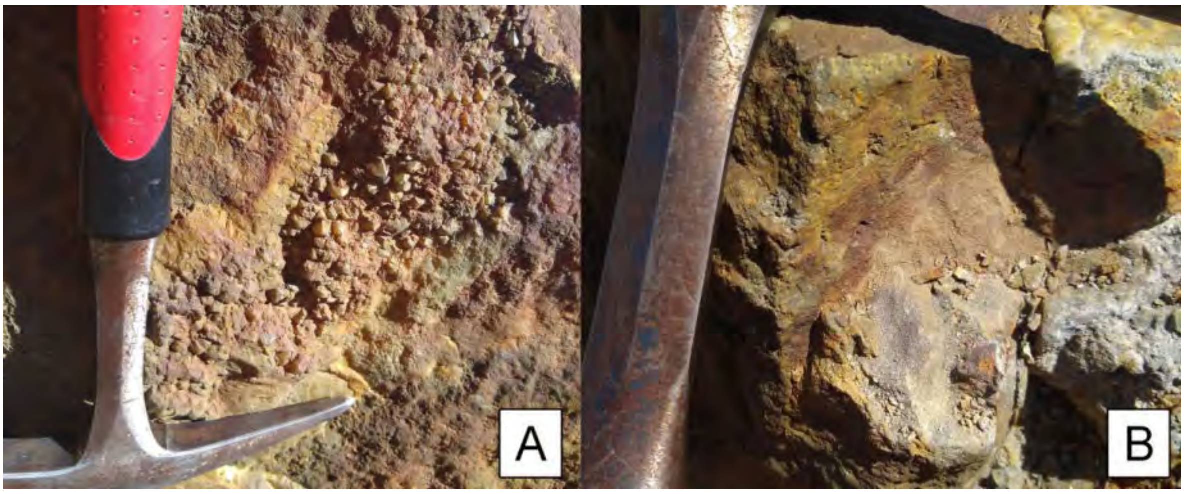


Figure 61: Subidiomorph crystals of quartz (A); Massive sulfides (B)

## 8.3. Mathiatis South, historic open pit mine two

Coordinates: 34.94895302N, 33.34740967E

The deposit is situated SE of Mathiatis (Figure 62), accessible via non-asphalted forestry roads. The upper parts of the pit walls mainly consist of a reddish to yellowish oxidation cap with mainly goethite and other limonitic Fe-hydroxides as mineral constituents (Figure 63A). Hematite, umber (Fe-Mn-Oxides) rhodochrosite and jarosite are also abundant. The bottom parts of the pit mainly consist of whiteish, strongly weathered and silicified pillow lavas (Figure 64B), containing high Au concentrations of up to 20 g/t. Moreover, strongly altered basalts appear which show slightly kaolinized gangues.

Figure 62: Mathiatis South with view to the NW

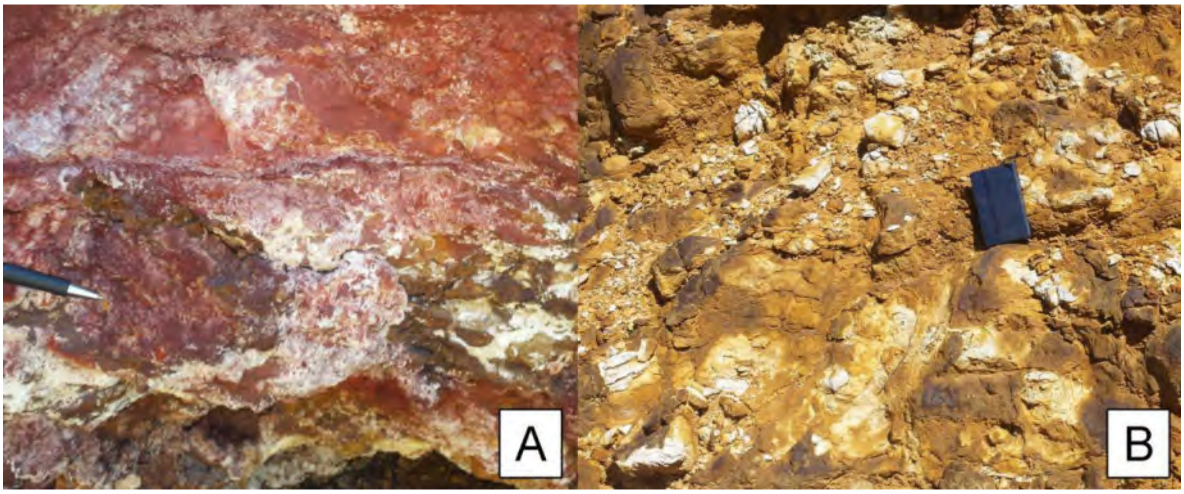


**Figure 63: Rhodochrosite and Fe-hydroxides (A); Silicified pillow lava (B)**

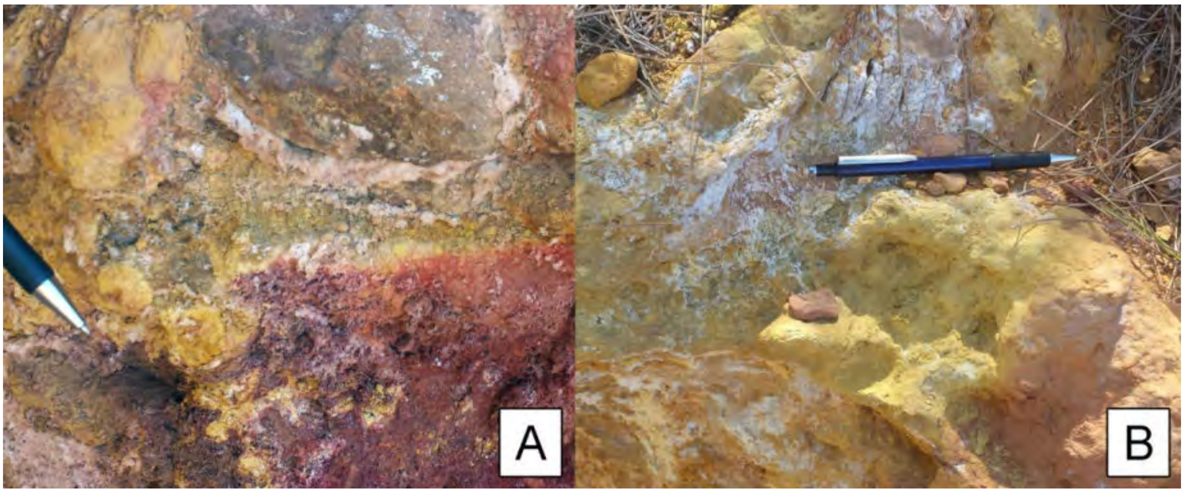


**Figure 64: Various secondary Fe-Hydroxides and Fe-Carbonates (A); Jarosite (B)**

## 8.4. Open pit mine three

Coordinates: 34.99243835N, 33.27683059E

This open pit is situated approximately 1 km W of the Monastery of Archangel Michael, between the villages Analiontas and Kapedes. The deposit is characterized by whitish to yellowish or pinkish hydrothermally altered and weathered pillow basalts that have been affected by a strong quaternary weathering. The rocks have been mineralized by hydrothermal Au ("*invisible gold*"). Well bedded black and yellow altered umber (*mixture of Fe- and Mn-oxides*, Figure 65A), yellow jarosite, white silica "sponge" (*silicified lava that has been leached of everything but quartz during weathering*, Figure 65B) can also be found.

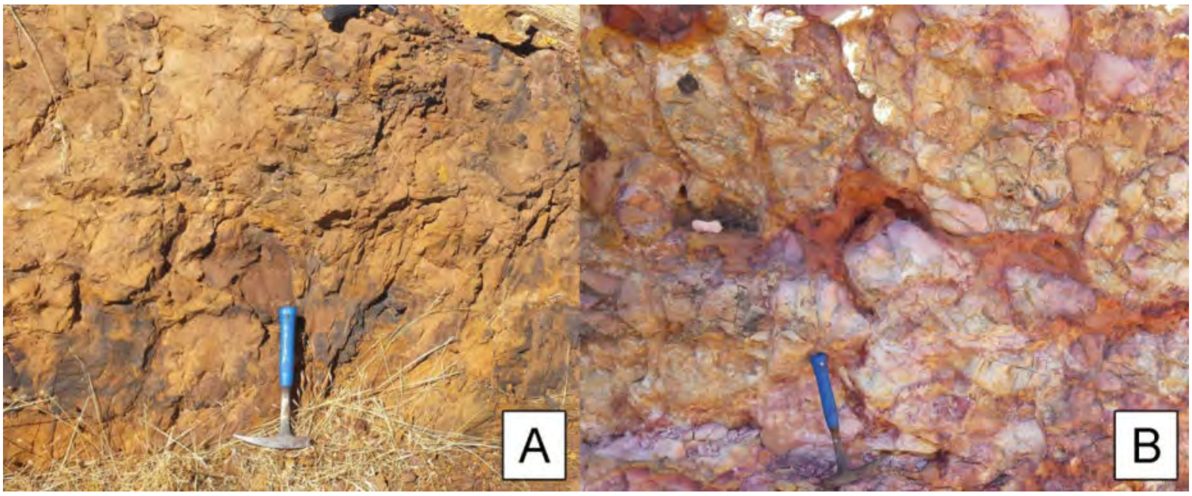


**Figure 65: Ochre brown strata with dark brownish parts containing umber (A); Strongly leached pillow lava (B)**

# 9. 27th September: Arakapas fault zone, SE of the Troodos ophiolite complex

## 9.1. Introduction

The ninth day of this excursion is focusing on a E-W trending transform fault, namely the Arakapas fault zone. This zone separates the units into northern and southern parts. In between the fault, various types of rocks can be found, which show typical structures for this setting like volcanogenic-breccious material and of course extensively reorganized ophiolitic rocks due to faulting. The transform fault shows a dextral sense of motion.

## 9.2. Viewpoint; Geosite 23

Coordinates: 34.84307585N, 33.25861761E

In general, the Arakapas valley marks the northern limit of the Lemesos forest and the spreading axis of the Neotethys Ocean was shifted by the fault 92 My ago. This event is comparable to mid-ocean ridges where these typical offset structures appear (e.g., Mid-Atlantic Ocean Ridge).

The rocks, as already mentioned, are of ophiolitic origin, but transformed by faulting and furthermore tectonically scaled. The valley appears strikingly deepened compared to the surrounding morphology (Figure 66). Considering the classic ophiolite structure of the rocks they seem to be more randomly distributed and some sections are missing due to reorganization of the material. Chemically, the basaltic rocks show high Mg contents (>8 %) and $TiO_2$ of <0.5%. These values are not typical considering the genesis and the Mg-rich basalts resemble Bornite, which is a Mg- and Si-rich mafic and volcanic rock. The linear depression of the ancient sea floor was later infilled by lava flows and intercalations with a big variety of volcaniclastic sediments derived from the steeper sides. These events can be traced by the occurrence of turbidite and debris flows. To sum up, a wide range of sediments – from coarse breccia to interbedded iron-rich mudstones and sands – is recordable. Within the E-W fault, local compression zones occur, which also led to the formation of characteristic basins with Cauliflower-structures.

**Figure 66: The Arakapas transform fault (illustrated by the red line)**

## 9.3. Polymict breccia, Geosite 30

Coordinates: 34.84750142N, 33.2445308E

This outcrop comprises matrix-supported rocks inserted in a reddish, fine-grained matrix. The components are mostly breccious, and the fabric can be described as polymict (Figure 67). Some larger sandstone blocks occur as part of an event where material input was given through slides. Fine layers of red mudstone appear in between the breccious rocks and may indicate calm sedimentation environments as well as reworked chemical sediments of umber.

On the one hand the lower coarse breccia sequence represents submarine debris flows and on the other hand the finer grained material on the upper units could be derived from volcaniclastic material created by turbidite flows. Altered grey sandstones of basaltic origin occur more often in the upper zones and the amount of breccia decreases. The turbidites show a typical graded bedding from coarse- to fine-grained and are in some parts completely preserved (*Bouma-sequence*; Figure 69 and Figure 68). In general, all these processes indicate a floor of a valley next to a steep slope. Primary contact with basaltic pillow lava is evident at the hanging wall, showing a partially fine graded character.

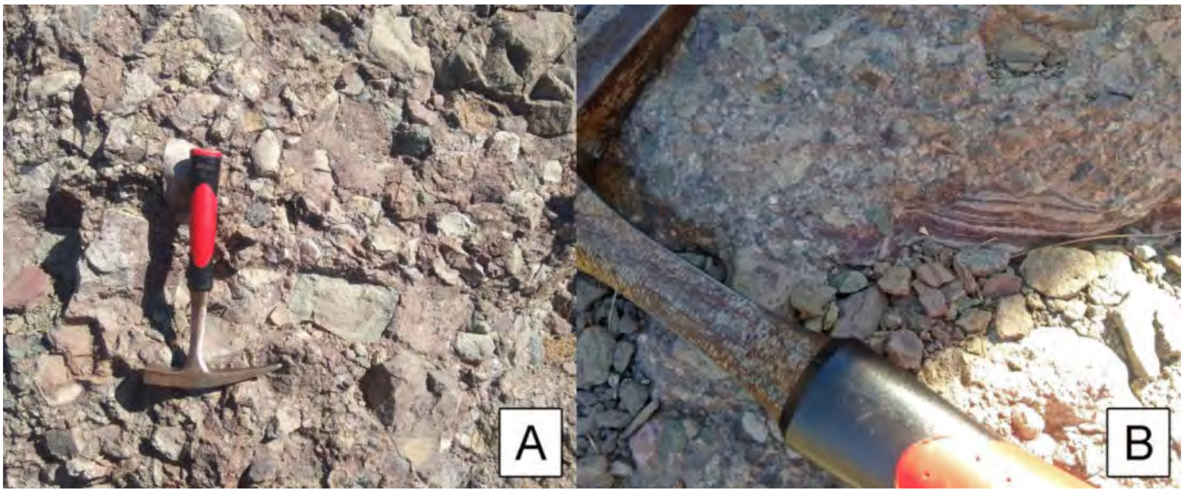


**Figure 67: Typical polymict and breccious rocks in between the fine grained, reddish matrix (A); Fine layers of red mudstone (B)**

**Figure 68: Overview of the outcrop**

**Figure 69: Turbiditic preserved sequence (arrow shows the direction into more fine-grained sediments)**

## 9.4. Steep dipping transform fault

Coordinates: 34,84296823N, 33,11544544E

This outcrop is part of the Arakapas fault with its typical green basaltic material (pillow lava) and reddish fault rocks above (Figure 70A). Moreover, some partially brecciated dykes appear and strike vertically through the pillows (Figure 70B).

Red colored areas appear on the surface of some fault zones, which can be explained as Fe-oxidations. Generally, the fault zones proceed from East to West and are steeply dipping. In between the pillow lava, a lot of breccia (Figure 71) can be found. Calcite veins and some quartzes have been recorded too.


**Figure 70: Pillow lava and fault rocks above (A) and dykes in between (B)**

**Figure 71: Reddish breccia (almost polymict) on the left and the typical pillow lava material to the right**

# 10. 29th September

Coordinates: 34.71090424N, 33.14264183E

On the last day of the excursion, the archaeological site of Amathous (Figure 72) was visited. According to mythology, Amathous is one of the four city-kingdoms of ancient Cyprus. There, the Greek hero Theseus is said to have left the pregnant Ariadne in the care of local women. Amathous was also considered an important cultural site for the goddess Aphrodite-Astarte.

Among the numerous archaeologically significant finds of the excavation site are the agora, the public baths, the temple of Aphrodite, early Christian basilicas and various tombs.

Geologically, in ancient times, the rocks found on the island were essentially used for the construction of various buildings. In addition, two other rocks could be recognized that do not originate from the island. These are granite (Figure 72) and marble (Figure 73).

**Figure 72: Overview on the central part of the Amathous archeological site**

**Figure 72: Column made out of granite**

**Figure 73: Column made out of marble**

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