# Cyprus

**March, 2018**

**Field Excursion Guide**

החברה הגיאולוגית הישראלית

Israel Geological Society

ΤΜΗΜΑ ΓΕΩΛΟΓΙΚΗΣ ΕΠΙΣΚΟΠΗΣΗΣ

GEOLOGICAL SURVEY DEPARTMENT

REPUBLIC OF CYPRUS

1950

**Brief introduction to the Geology of Cyprus**

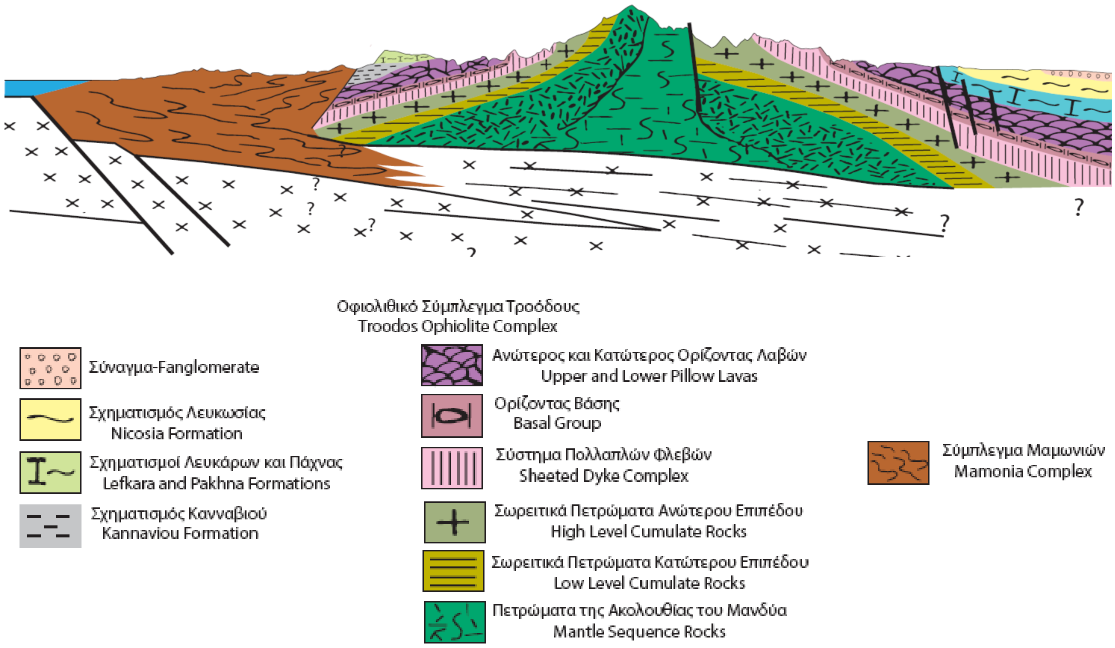
The island attracted a lot of attention during the 1960's when Gass and Masson Smith (1964) reported on a large positive anomaly beneath Troodos which Gass (1968) later interpreted as a section through a piece of Tethyan oceanic crust. Nevertheless, the island of Cyprus is a mosaic of terranes, with its tectonic structure and topography being controlled by its distinct four geological terranes: the Troodos Terrane, an autochthonous bedrock terrane which consists of a Turonian ophiolite sequence, the Arakapas Transform Sequence, an off-axis ophiolite sequence, the Mamonia Terrane consisting of Upper Triassic – Cretaceous sedimentary rocks and basalts; and the Keryneia Terrane, consisting of Carboniferous – Cretaceous limestones and Cretaceous – Miocene carbonate sediments and greywackes. All four terranes are covered by autochthonous sediments, usually referred to as the Circum-Troodos sedimentary succession.

Major geological terranes of Cyprus.

Cyprus is no doubt one of the first producers of copper in the world and probably one of the first countries, if not the first, where metallic copper was produced from the mining and smelting of cupriferous sulphide ore. The earliest finds were discovered at Ambelikou in the Skouriotissa mining area, and archaeometallurgical investigations, which included 14C dating of charcoal, gave an age of 2760 B.C. The first copper artefact is a hair ornament and dates back to 2800 B.C.

The early development of the copper industry in Cyprus, followed by its expansion and duration for more than 3,000 years, is evident from the ample ancient historical references and archaeological findings. Ancient mining workings such as shafts and galleries can be found widespread across the island. However, the most impressive evidence for the extent of the ancient copper industry in Cyprus is the widespread occurrence of ancient slag heaps. More than 110 such heaps have been found, scattered mostly on the pillow lava outcrops in the periphery of the Troodos Ophiolite.

Simplified geological map of Cyprus




Simplified cross section from Pafos (left) to Lefkosia (right) through Troodos, prepared by E. Tsiolakis, GSD.

**6:30 - 7:00 am Meeting point at the Lemesos Port**

**Stop 1: Harzburgite with Dunite, abandoned bridge, 487290E 3863225N**

At this stop there is an excellent exposure of harzburgite with dunite. The contact between them is sharp marked by a sudden change in orthopyroxene content. As the magma rises, it reacts with the surrounding rocks melting the clinopyroxenes but also some olivine. Inside the clinopyroxene crystal, chromiteis enclosed. As the melt ascends, it is enriched in chromite and clinopyroxene. When the magma is saturated with chromite it will dump it. This is the process for the formation of chromite ores in harzburgite mantle rocks.

**Stop 2: Layered Gabbro, 487948E 3863176N**

Go past the Troodos square and take the road to Platres. After 1800m you will see a government summer house made of green corrugated metal. Continue for 250 m, park on the left side of the road at 487808N, 3862936 and walk back upslope about 50 m. This fault-bounded block of layered cumulate rocks occurs within harzburgite. The cumulate sequence is comprised of layered gabbros, locally rich in olivine and minor pyroxenite and wehrlite. Thickness of layers varies between 1 and 40 cm, layers are relatively continuous. Features include ductile shear zones (especially z-shaped folds) and small dykes and veinlets of un-deformed, pegmatitic gabbro.

**Stop 3: Gabbro with Plagiogranite, Karvounas, 493553E, 3866519N**

Stop at the side of the road just after the big road junction at Karvounas. At this stop, massive vari - textured gabbro occurs with few irregular bodies of plagiogranite. During fractional crystallization and differentiation of magma, the first minerals that crystallize and accumulate at the bottom of the magma chamber are the minerals of olivine and chromite which are the main constituents of dunite. With further drop in temperature, the next mineral that accumulates is clinopyroxene which, with olivine and chromite are the main constituents of wehrlite. As the process continues, olivine becomes more rare and clinopyroxene more abundant creating pyroxenite. After the crystallization of the ferromagnesian - rich minerals the next mineral that crystallizes is plagioclase which, with some olivine and clinopyroxene, are the main constituents of gabbro, commonly occurring as layered gabbro. With this process, the magma becomes enriched in silica and water. The pressure in the magma chamber is raised exerting great pressure on the roof of the chamber. As a result, potassium –rich fluids penetrate the rocks above.

**Stop 4: Geopark Visitor Center and Asbestos Mine, Amiandos**

We will visit the Geopark's visitor center, the Amiandos mine elementary school for about one hour. You will get a chance to learn a lot about the geology of the Troodos ophiolite and other areas of the Geopark. In the historic asbestos mine near the village of Amiandos, we will see a unique multi-disciplinary large-scale mine rehabilitation project. The main chrysotile asbestos deposit is in the form of veins and occurs in a zone of intense serpentinization and brecciation within the tectonite harzburgite on the eastern side of Mt. Olympus. The veins vary in thickness from a few mm up to 1.5 cm with the average grade of the deposit being 0.8-1.0%. The serpentine mineral has three polymorph minerals: antigorite (high temperature polymorph at > 350$^{o}$C), lizardite and chrysotile (also known as asbestos) at 350$^{o}$C.

**Stop 5: Sheeted Dyke Complex, Galata village, 491240E, 3872420N**

Stop at the bakery parking lot on the main road and walk back about 60 m where you can view sheeted dykes on the east side of the road. The sheeted dyke complex represents the solidification of the ascending magma into channels, through which magma was transported from the magma chamber to the seafloor. It is a successive series of dykes which represent the occupation of space created from plate diversion at the spreading axis. The sheeted dyke complex is very extensive across the Troodos mountains. These intrusive rocks, locally referred to as diabase, have a basaltic to doleritic composition, their dyke orientation is NW – SE and are almost vertical. At this stop the dykes strike about 320$^{o}$ and dip 45$^{o}$ to the east. Besides the doleritic and diabasic dykes which are by far the most abundant rock types with well-preserved chilled margins, there is also a number of small basaltic dykes 20-50 cm wide which are seen intruding into the other two type of dykes. The intrusion of these dykes is the best indication of continued spreading.

**Stop 6 Skouriotissa ancient slag heaps**

The most impressive evidence for ancient mining and smelting on the island is provided by the widespread occurrence of slag heaps. The Skouriotissa area contains more than half of the total slag, c. 4.000.000 tones present in Cyprus and attests to its considerable importance as a mining district in antiquity. Mining at Skouriotissa and nearby Mavrovouni in the 1920's and early 1930’s encountered ancient workings in the form of galleries and shafts with timber supports. Among the ancient mining tools discovered are ladders, ropes, hand windlasses, wedges, nails, baskets, shovels and oil lamps. The surrounding forest provided abundant pine logs (*pinus helepensis*) both for timber support and the primary energy for smelting. Less commonly used as supports were the plane tree (*platanus orientelis*) and the small oak (*quercus alnifolia*).

The Skouriotissa slags and shafts indicate vigorous mining and smelting activity from the 19$^{th}$ century BC to the 7$^{th}$ century AD. Typically slag occurs in small buns, an indication that individual slag heaps represent hundreds or thousands of smelting processes were performed in small volumes in similarly sized furnaces that were almost completely destroyed in order to recover the resulting bun-ingot. An enormous amount of timber, as charcoal, must have been used in antiquity for the production of an estimated 200.000 tons of copper metal.

**Stop 7 Skouriotissa mine**

The Executive Director of Hellenic Copper Mines, Mr Constantinos Xydas will guide us through the Skouriotissa mine and the application of bio-leaching and hydrometallurgy processes including leaching and electro-winning for the production of 99,999% pure Cu cathodes. Additional information about the mineralization of the Skouriotissa mine is given in the back of this guide titled: "Volcanic -Hosted Sulfide Mineralization -Skouriotissa Region – Phoenix Mine".

**Stop 8 Klirou Bridge**

Recent studies have questioned the rigid two-fold division of the lava sequence. Clearly there can be no significant time difference between the two sequences (e.g. Baragar et al., 1989), and changes in metamorphic grade do not correlate with changes in chemical composition. Nevertheless, in almost all sections there is a change up the section from evolved (e.g. high in TiO2) to more primitive (low-TiO2) lavas and the field distinction generally holds. The most significant advance in our understanding of the extrusive section of the ophiolite came with the work of German volcanologist Hans-Ulrich Schmincke, who with his Ph.D. students remapped the lava sequence of the Akaki River area of N Troodos. They disregarded the LPL/UPL classification, instead treating the extrusives as a series of superposed "volcanoes". They mapped out twelve such "volcanoes", constituting a sequence possibly as thick as 1700m (1000m is usually regarded as typical elsewhere) (Schmincke et al., 1983; Schmincke & Rautenschlein, 1987; Schmincke & Bednarz, 1990). They identified the feeders and central cores to these "volcanoes", and the change in facies with distance from the centres.

**Stop 9: Abandoned gypsum quarry, Tochni village**

Time permitting we will stop in the village of Kalavasos to observe sequences of sediments representing the circum – Troodos sedimentary succession. Alternating bedded chalks and cherts are exposed along the road. These rocks belong to the "Chalk and Chert" stratigraphic unit of the Lefkara formation. At higher elevations cream to buff-brown chalks and marls of the Miocene Pakhna formation are topped by calcarenites. A lower basin exposed near the highway representing a significant event known as the "Messinian salinity crisis" composed of evaporite deposits of different varieties of gypsum like gypsiferous marls, saccharoidal gypsum, selenite gypsum, laminated gypsum and alabaster.

**16:30 - Return back to port**

**Local emergency and other useful telephone numbers**

Emergencies: 112 (police, fire, ambulance)

Cyprus Geological Survey: (+357) 22409213, Fax: (+357) 22316873

Field trip leader: Zomenia Zomeni: (+357) 96662699 (mobile)

**Health**

- Please inform the field trip organizers of any relevant medical condition.
- Weather may be rainy (unlikely), pleasant to warm with continuous sunshine at 18 to 25$^{O}$C.
- Use hat, sunglasses and sunscreen with appropriate UV blockers as needed.

**Safety**

- Please do not photograph any military installations you may see.
- Turn a rock with your foot before picking it up to avoid a surprise by a snake.
- Stay with the group. If you become separated, stay where you are and wait to be found. Ring the field trip leaders on their mobile telephones, if possible.
- Please exercise extreme care walking along or crossing roads.
- Avoid steep faces, slippery slopes and steep cliffs.
- Wear suitable boots with a good grip and ankle support.
- Use safety goggles when hammering rocks and ensure there is no-one nearby who may be hit by flying rock chips.

**Environment**

- All rubbish must be returned by the field group and disposed of properly.
- Only collect rock specimens for genuine scientific purposes. Where possible, collect samples from scree, otherwise take sample from inconspicuous parts of an outcrop.
- Leave the site undamaged so that other colleagues can enjoy it.
- Respect wildlife.
- Smoking: This year’s drought makes wildfires a serious risk. Please take utmost care when extinguishing cigarettes after smoking in the field.

## AN OVERVIEW OF THE GEOLOGY OF CYPRUS

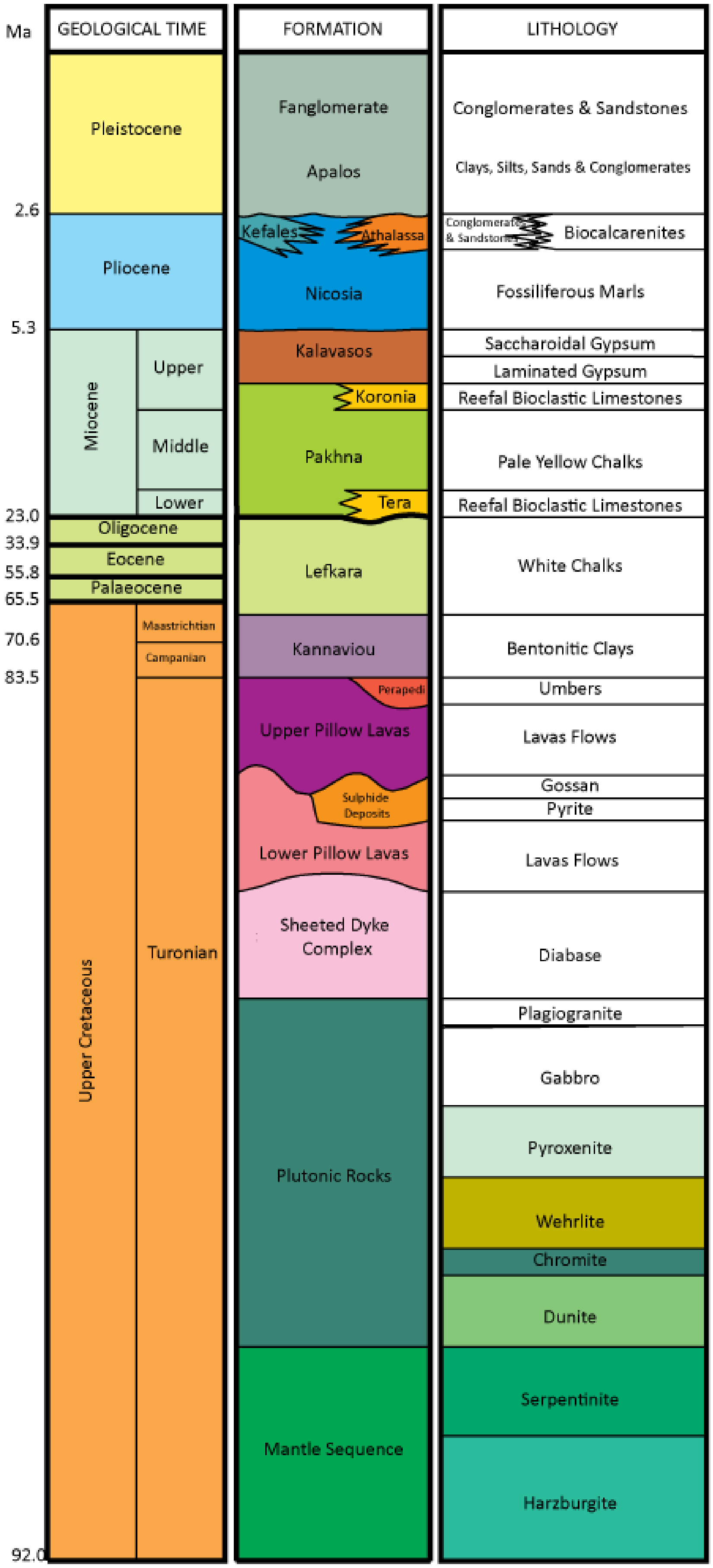
Cyprus is divided into four geological zones: (a) the Keryneia Terrane, (b) the Troodos Terrane or Troodos Ophiolite, (c) the Mamonia Terrane or Complex and (d) the Zone of the autochthonous sedimentary rocks.

The Keryneia Terrane is the northern-most geological zone of Cyprus and is considered to be the southern-most portion of the Tauro-Diranide Alpine Zone. It has an arciform disposition with an east-west direction and is characterized by southward thrusting. The base of the Zone is mostly composed of a series of allochthonous massive and recrystallized limestones, dolomites and marbles of Permian-Carboniferous to Lower Cretaceous age (350-135 Ma). These are stratigraphically followed by younger autochthonous sedimentary rocks of Upper Cretaceous to Middle Miocene age (67-15 Ma), on which the older allochthonous formations have been thrust southward.

The Troodos Terrane or the Troodos Ophiolite dominates the central part of the island, constitutes the geological core of Cyprus, appears in two regions (main mass of the Troodos mountain range and in the Limassol and Akapnou Forest south of the range) and has a characteristic elongated domical structure. It was formed in the Upper Cretaceous (90 Ma) on the Tethys sea floor, which then extended from the Pyrenees through the Alps to the Himalayas. It is regarded as the most complete and studied ophiolite in the world. It is a fragment of a fully developed oceanic crust, consisting of plutonic, intrusive and volcanic rocks and chemical sediments. The stratigraphic completeness of the ophiolite makes it unique. It was created during the complex process of oceanic spreading and formation of oceanic crust and was emerged and placed in its present position through complicated tectonic processes relating to the collision of the Eurasian plate to the north and the African plate to the south. The lower stratigraphy of the ophiolite appears topographically higher because of the way ophiolite was uplifted (diapirically) and to its differential erosion. The diapiric rising of its core took place mainly with episodes of abrupt uplift up to the Pleistocene (2 Ma).

The Mamonia Terrane or Complex appears in the Pafos district in the southwestern part of the island. It constitutes a series of igneous, sedimentary and metamorphic rocks, ranging in age from Middle Triassic to Upper Cretaceous (230-75 Ma). These rocks, which are regarded as allochthonous in relation to the overlying autochthonous carbonate successions and the Troodos ophiolite rocks, were placed over and adjacent the Troodos ophiolite during the Maastrichtian.

The Zone of the autochthonous sedimentary rocks, ranging in age from Upper Cretaceous through to Pleistocene (67 Ma to recent), covers the area between the Keryneia and Troodos Terranes (Mesaoria) as well as the southern part of the island. It consists of bentonitic clays, volcaniclastics, marls, chalks, cherts, limestones, calcarenites, evaporites and clastic sediments.



Ma
GEOLOGICAL TIME
FORMATION
LITHOLOGY
Pleistocene
Fanglomerate
Conglomerates & Sandstones
Apalos
Clays, Silts, Sands & Conglomerates
2.6
Pliocene
Kefales
Athalassa
Biocalcarenites
Nicosia
Fossiliferous Marls
5.3
Miocene
Upper
Kalavasos
Saccharoidal Gypsum
Laminated Gypsum
Koronia
Reefal Bioclastic Limestones
Middle
Pakhna
Pale Yellow Chalks
Lower
Tera
Reefal Bioclastic Limestones
23.0
Oligocene
33.9
Eocene
Lefkara
White Chalks
55.8
Palaeocene
65.5
Maastrichtian
70.6
Campanian
Kannaviou
Bentonitic Clays
83.5
Perapedi
Umbers
Upper Pillow Lavas
Lavas Flows
Sulphide Deposits
Gossan
Pyrite
Lower Pillow Lavas
Lavas Flows
Upper Cretaceous
Turonian
Sheeted Dyke Complex
Diabase
Plagiogranite
Gabbro
Plutonic Rocks
Pyroxenite
Wehrlite
Chromite
Dunite
Mantle Sequence
Serpentinite
Harzburgite
92.0

## THE TROODOS OPHIOLITE COMPLEX LITHOLOGY

The Troodos Mountain Range is the main geomorphologic feature of the island of Cyprus. It covers an area of about 3200 $km^2$ and its highest peak, Olympus, has an elevation of 1951 m. Formed in a Neotethyan supra-subduction zone by seafloor spreading at a constructive plate margin during the Turonian, the Troodos ophiolite terrane forms the central geologic zone and terrane on the island of Cyprus. It consists of a relatively intact and complete ophiolitic rock sequence. Its well-preserved structure and rock sequence makes the Troodos ophiolite unique in relation to the other Tethyan ophiolites. It includes all components of an ophiolitic sequence, an ultramafic core consisting mainly of serpentinized harzburgite, plutonic ultramafic and mafic rocks, a sheeted-dyke complex, a volcanic sequence of mostly pillowed lava flows and topped with iron-and manganese-rich hydrothermal sediments. Our trip will make a progression upwards through the ophiolite crustal sequence.

The Troodos Ophiolite is one of the best-preserved and most thoroughly studied ophiolite complexes in the world. The ophiolite exhibits a domical uplift that exposes a central core of harzburgite tectonite and serpentinite diapir, stratigraphically overlain successively by a mafic-ultramafic plutonic complex (Fig. 2), an extensive sheeted dike complex, extrusive volcanic rocks (Fig. 3) and sediments.

The plutonic complex crops out in two separate areas: (a) central Troodos in the vicinity of Mt. Olympus, and (b) the Limassol and Akapnou Forest area in the southeastern part of the Troodos Range. Tectonized harzburgite is the dominant rock type in the Mt. Olympus area, where it forms the central core of the Troodos massif. It is always coarse-grained with a xenomorphic granular fabric. Serpentinization is pervasive throughout the harzburgite mass and ranges from 40% to 100%. On the eastern side of Mt. Olympus, the harzburgite is totally serpentinized, intensely sheered with abundant chrysotile occurrences, serpentine breccias and breccia zones. Harzburgite tectonite invariably contains small amounts of dunite in the form of elongated bodies, the number and size of which increase towards the overlying main dunite, forming a transition zone between the two rock types (Michaelides, 1983; Panayiotou *et al.*, 1986). The main dunite passes gradually upwards into poikilitic wehrlite through a thin zone of clinopyroxene-bearing dunite (Greenbaum, 1972). Massive to banded wehrlite, lherzolite, websterite and clinopyroxenite form a transition zone between the poikilitic wehrlite and the overlying gabbro cumulates. The relationships between the ultramafic and gabbro cumulates are complicated by series of faults associated with the diapiric emplacement of the serpentinized harzburgite.

The base on the gabbro cumulates is normally occupied by melagabbros, followed by olivine gabbros, which occur either as layered olivine-rich gabbro or poorly layered olivine-deficient gabbro, passing upwards into the olivine-free pyroxene gabbro and the latter into magnetite-hornblende gabbros and diorites (Allen, 1975).

Finally the diorites are succeeded by plagiogranites. They are silicic rocks occurring as

discontinuous bodies and dykes between the gabbros and the Sheeted Dike Complex. The Sheeted Dyke Complex crops out over most of Troodos forming a concentric belt around the plutonic core. Both its lower and upper contacts with the gabbros and the pillow lavas, respectively, are transitional and rapid. Individual dykes within the complex range from a few centimeters to about 5 m across, but most are less than 2 m wide. They consist of fine-grained, generally aphyric, basalt and andesite with small amounts of olivine-and pyroxene-phyric basalt. Desmet *et al*. (1980) have suggested a standard succession of dykes from oldest to youngest of diabasic, doleritic, ultabasic and basaltic with rare screens of dolerite, granophyre and fine-grained gabbro. Many of the dykes are hydrothermally altered to greenschist facies assemblages, but the original igneous textures and their chilled margins are typically preserved.
The Sheeted Dike Complex grades upwards into the extrusive sequence, the Troodos Pillow Lava Series, which crops out in a discontinuous belt around the margins of the Troodos massif. Pillow lavas predominate in the sequence but massive flows, thin sheet flows, breccias and hyaloclastites are common. Dykes and sills occur throughout the sequence and they increase in abundance with depth.

The pillow lavas are traditionally divided into two units, the Upper and the Lower Pillow Lavas. The Upper Pillow Lavas are dominantly reddish-brown, olivine-and pyroxene-phyric lavas often with highly picritic zones, whereas the Lower Pillow Lavas are greenish-gray, aphyric, oversaturated basaltic lavas (Gass and Smewing, 1973). Work on volcanic glass compositions has revealed the presence of at least two magmatic suites on Troodos, an older andesite-dacite-rhyodacite assemblage with arc tholeiite affinities and a later picrite-basalt-basaltic andesite assemblage of boninitic affinities (Robinson *et al*., 1983; Schmincke *et al*., 1983). These lava suites correspond in general with the Lower and Upper Pillow Lava units, respectively, but their boundaries differ.

STRUCTURE

Structurally the Troodos Ophiolite consists of an elongated dome resulting from uplift caused by emplacement of the central serpentinite diapir (Gass, 1980). In the southern part of the ophiolite, the Arakapas Fault Zone, an E-W trending graben separates the main Troodos block from the Limassol Forest area. Both the Arakapas Fault and the Limassol Forest area are regarded as parts of the Arakapas Fossil Transform Fault (Gass *et al.,* 1994).

Outside the transform fault area, the ophiolitic rocks are little deformed. The pillow lavas on the flanks generally dip outward at angles of 5º to 40º. High-angle faults are common in the complex, particularly in the plutonic section and the pillow lavas (Searle and Panayiotou, 1980).

Mapping of the Troodos Ophiolite by the Cyprus Crustal Study Project revealed a number of N to NW trending grabens, which are characterized by listric to planar normal faults and structurally rotated dykes that dip symmetrically towards the axes of the grabens.

Normal faults appear to sole at depth into a ductile shear zone near the top of the gabbro section. Un-deformed mafic dykes cut the shear zone. The crosscutting relationships demonstrate that the normal faults and ductile shear zone formed near a spreading axis and in consequence the N and NW trending grabens most probably represent fossil axial valleys similar to those found along moderately slow-spreading ridges (Moores and Varga, 1984).

The magnetic vectors of the dykes and the lavas are inclined due west and have a dip indicating formation at a paleo-latitude of about 21-25º. These data suggest that the Troodos Ophiolite has migrated northward 10-15º and undergone $90^{o}$ anticlockwise rotation since its formation (Shelton and Gass, 1980).

## MINERALIZATION

Mineralization in the Troodos Ophiolite is largely restricted to chrysotile asbestos and chromite deposits in the ultramafic assemblage and massive sulfide deposits in the pillow lavas. Small scattered occurrences of sulfide mineralization are also present in the harzburgites and dunites, in the gabbros and sheeted dike complex, but no economically viable deposits have yet been discovered.

The main chrysotile asbestos deposit occurs in a zone of intense serpentinization and brecciation within the tectonite harzburgite on the eastern side of Mt. Olympus (Fig. 4 and 5). The mineralization occurs in veins, which vary in thickness from a few mm up to 1.5 cm. The average grade of the deposit was 0.8-1.0%.

The largest and economically important chromite deposits are confined to the transition (contact) zone between the tectonite harzburgite and the cumulate dunite, particularly in dunite apophyses and lenses within the upper part of the harzburgite (Greenbaum, 1977; Panayiotou et al., 1986). The exploitable deposits range from a few thousand to one million tons and appear in variously shaped layers, lenses and pods. The Cr2O3 content of the massive ore ranges between 45% and 51% with Cr/Fe ratio around 3.

The massive sulfide bodies in the pillow lavas are the classic examples of a distinct type of volcanogenic sulfide deposits related with the formation of the oceanic crust. The Cyprus ore-bodies show striking analogies with the polymetallic sulfide ore-bodies of the East Pacific Rise and an analogous process of formation is postulated (Oudin and Constantinou, 1984). They are lenticular, relatively small in size with typical horizontal dimensions of 50 m to 200 m, and maximum of 400 m. Their thickness is usually of a few tens of meters, though the largest bodies may have been over 100 m thick. The tonnage of the massive ores, containing over 40% S, range from a few thousand tons to 17 million tons, whereas their average copper content ranges from less than 0.5% to 4.5%. Chemically the massive ore contains almost entirely of sulfur and iron with minor amounts of copper and zinc and traces of cobalt, gold and silver. A number of ore-bodies are overlain by thick layers of ochre, a sediment consisting mainly of iron oxyhydroxides, which was formed by submarine weathering and leaching of the sulfides (Constantinou and Govett, 1972; Constantinou, 1980).

***ASBESTOS MINE – THE FIRST MINE REHABILITATION PROGRAMME IN CYPRUS***

Cyprus ranks as one of the most ancient sources of asbestos and since the beginning of the 19th century has become important in mining as the biggest chrysotile asbestos deposit in Europe. The deposit occurs in a zone of intense serpentinization and brecciation of the tectonite harzburgite with minor lenses of dunite. Chrysotile mineralization is in the form of veins (cross-fiber), which vary in thickness from a few millimeters up to 1.5 cm in length. The average grade of the deposit is 0.8 – 1.0% and the reserves are estimated to 60 million tons.

Thick veins may persist for several meters and contain cross-fiber chrysotile intimately associated with picrolite to form a composite vein-filling. In some cases the picrolite occupies the central parts of the vein, thereby reducing the fiber length, or likewise, the margins of the vein. The orientation of the veins is quite variable, some outcrops show a pseudoparallel pattern, whereas others show reticulate patterns.

The process included crushing and milling, screening, fibering and aspiration of several million tons of ore, with a content of 0.8 – 1.5% of the milled ore. Fiber was then graded as long or short grade fibers. The annual production varied from 20.000 to 40.000 tons of fibers. Between 1904 and 1988,(after which when the mining activities terminated), about 130,000,000 tons of rock were mined and about 1,000,000 tons of asbestos fibers were produced and exported to several European countries, resulting to a revenue of £75.000.000, while at the same time employment to thousands of people was offered.

Besides the economic benefits, this long lasting extensive mining activity had serious direct and indirect effects on the environment. The major environmental problems created, are the enormous open-pit mine, the extensive waste tips resting on steep slopes and infilling side valleys, as well as the pollution with fibers of the soil, the surface water and the downstream dams.

The necessity for rehabilitation of the area is obvious not only for aesthetic reasons but also for the safety and the health of the population of the nearby villages. The sudden closure of the mine in 1988 left the entire problem in the hands of the government and did not allow for any planned closure procedures to be initiated. Geotechnical investigations including slope stability analysis in collaboration with the BGS had shown the need for stabilization of the waste tips, some of which are over 150 m high. The barren waste product prevented the application of traditional reforestation methods and the hostile environment, deterred any use of the mine facilities.

Rehabilitation commenced with a preliminary appraisal of all issues involved and a course of action was undertaken by a multidisciplinary team, under the guidance of the GSD, comprised of geologists, regional planners, foresters and geotechnical engineers. Emphasis was placed on the stabilization of the waste tips and the re-profiled slopes, which are being covered by topsoil ready for reforestation. A recent study of the rocks that may contain Asbestos minerals in the Troodos region revealed that disturbed, un-restored areas of the mine constitute a moderate risk from the presence of airborne asbestos fibers. The same study proposed additional research with regard to fiber emission rates from soils especially by human induced dust creation such as ground works and off-road driving as additional risks. The development of a master plan for the eventual use of the area has recently been developed and discussed in public consultation.

## VOLCANIC-HOSTED SULFIDE MINERALIZATION IN SKOURIOTISSA MINE

### INTRODUCTION

The Phoenix deposit, containing approximately 20 million tons of copper ore of average grade 0.4% copper, is located in the metalliferous region of Skouriotissa, which has been mined periodically over almost four thousand years. The orebody is of the disseminated type; mineralization is mostly pyritic with secondary chalcocite being the main copper mineral. It is currently being mined by opencut methods and the ore is processed by hydrometallurgical techniques (solvent extraction and electrowinning) for the extraction of copper.

### HISTORICAL BACKGROUND

The deposits of Skouriotissa were known to the ancients as testified by the sizeable slag heaps that are still partly preserved (Fig. 7). The nature of the slag and discontinuities in the structure of the heaps suggest that the mines were operating periodically. On the other hand, the copper content of earlier red slags is much higher than the later black slag, by introducing umber in the ore mixture a source of manganese, to lower the melting point and viscosity of the melt thus achieving better separation of the heavier copper metal from the slag.

Reference to the deposits of Skouriotissa as a source of medicines is made by Dioskourides (1century AD) the founder of pharmacology and by Galen (2century AD) a Greek doctor, who described the mining operations at Skouriotissa, with particular emphasis to the extraction of chalcanthine (copper sulfate).

A detailed description of the history of mining in the area in recent times is presented by Cullis and Edge (1927) in a classic study of the Cyprus deposits and prospects, which were known at the time. Exploration was initiated in the early twentieth century, when the Skouriotissa (or Foukasa) deposit was discovered (1914), followed shortly afterwards by the Mavrovouni deposit (now in the Turkish occupied area). The Skouriotissa region became an important mining centre, continuously active until 1974 when, following the Turkish invasion of Cyprus, the American company operating the mines, Cyprus Mines Corporation (CMC), left the island. Although operations for copper continued on a limited scale through the 1980s, it was only the early 1990s that larger-scale mining, utilizing hydrometallurgical techniques, was initiated.

Previous work on the geology of the area includes a Ph.D. thesis by the former Director of the Cyprus Geological Survey (Constantinou, 1972), mainly focusing on the Foukasa mine, and a second Ph.D. thesis by Adamides, (1984) in which geological aspects of Foukasa and Phoenix are reported. Mineralogical studies on Phoenix were also carried out (Cameron, 1997; Nicolaides, 1999).

## GEOLOGY AND STRUCTURE OF THE SKOURIOTISSA MINING AREA

The mineral deposits of the Skouriotissa region are located within the Pillow Lava Series of the Troodos ophiolite. Rocks of the Sheeted Dyke Complex (diabase) are located to the south of the deposits, and they exhibit in many cases transitional contact with the Lower Pillow Lavas. West of the Phoenix deposit, a ridge of epidotized Basal Group rocks is exposed in the Aphisallos locality. However, in the environs of the deposits, the lithology is represented by pillow lava flows with a marked scarcity of dykes. These lavas are most probably members of the Upper Pillow Lavas.

The Foukasa deposit, east of Phoenix, was originally covered by umber and younger sediments (marls and limestones). As indicated in old CMC reports, remnants of these units were locally preserved also above the Phoenix deposit. In some cases, inter-bedding of mineralization with sedimentary units is described, as for example northwest of the Foukasa deposit. Although the evidence is not conclusive, it appears likely that the deposits were located within and above the Upper Pillow Lavas. This is in contrast to the majority of the sulfide deposits in Cyprus, which are located either within the Lower Pillow Lavas or at the contact with the Upper Pillow Lavas (i.e., between the Lower and the Upper Pillow Lavas).

The structural grain of the general area is northerly to northwesterly, as reflected in the trend of dykes in the Sheeted Dike Complex and the Lower Pillow Lavas. In the close environs of the Foukasa deposit, a major northwesterly fault, the Skouriotissa fault, plays an important role in displacing the Phoenix mineralization to the northwest from its original position as probably part of the Foukasa orebody, and in enriching the mainly low-grade pyritic mineralization to ore grade.

SELECTED REFERENCES

Adamides, N.G. (1984) Cyprus volcanogenic sulphide deposits in relation to their environment of formation. Unpublished Ph.D. thesis, University of Leicester, 383 p.

Adamides, N.G. (2001) The geology of Phoenix with an estimate of available resource. Unpublished internal report, Hellenic Copper Mines Ltd, 20 p.

Allen, C.R. (1975) The petrology of a portion of the Troodos plutonic complex, Cyprus. Unpublished Ph.D. thesis, Cambridge University.

Cameron, J.W. (1997) Reports on the mineralogy of Phoenix. Unpublished internal report, Hellenic Copper Mines Ltd, 5 p.

Constantinou, G. (1972) The geology and genesis of the sulphide ores of Cyprus. Unpublished Ph.D. thesis, University of London, 275 p.

Constantinou, G. (1980) Metallogenesis associated with the Troodos ophiolite. In Panayiotou, A. (ed.) Ophiolites, Proceedings, International Ophiolite Symposium, Cyprus (1979). Cyprus Geological Survey Department, p. 663¬674. Constantinou, G. (1987) Massive sulphide deposits. In Xenophontos, C. and Malpas,

J.G. (eds.), Field Excursion Guidebook. Troodos 87, Ophiolites and Oceanic Lithosphere Symposium, Nicosia, Cyprus Geological Survey Department, p. 92-113.

Constantinou, G. and Govett, G.J.S. (1972) Genesis of sulphide deposits, ochre and umber of Cyprus. Transactions Institute of Mining and Metallurgy, v. 81, p. 34-46.

Cullis, C.G. and Edge, A.B. (1927) Report of the cupriferous deposits of Cyprus. Crown Agents for the Colonies, London, 48 p.

Gass, I.G. (1980) The Troodos massif: its role in the unravelling of the ophiolite problem and its significance in the understanding of constructive plate margin processes. In Panayiotou, A. (ed.) Ophiolites, Proceedings, International Ophiolite Symposium, Cyprus (1979). Cyprus Geological Survey Department, p. 23-25.

Gass, I.G. and Smewing, J.D. (1973) Intrusion, extrusion, and metamorphism at constructive margins: Evidence from the Troodos Massif, Cyprus. Nature, v. 242, p. 26-29.

Gass, I.G., MacLeod, C.J., Murton, B.J., Panayiotou, A., Simonian, K.O. and Xenophontos, C. (1994) The Geology of the Southern Troodos Transform Fault Zone. Cyprus Geological Survey Department Memoir 9, 218 p.

George, P.R. (1975) The internal structure of the Troodos ultramafic complex, Cyprus.

Unpublished Ph.D. thesis, State University of New York at Stony Brook, 196 p.

Georgiou, E. (1987) Geology, petrology and mineral chemistry of the Akapnou Forest Plutonic Complex and the associated chromite occurrences, Cyprus. Unpublished Ph.D. thesis, University of Orleans (France), 281 p.

Greenbaum, D. (1972) Magmatic processes at oceanic ridges: Evidence from the Troodos massif, Cyprus. Nature, v. 238, p. 18-21. Greenbaum, D. (1977) The chromitiferous rocks of the Troodos ophiolite complex, Cyprus. Economic Geology, v. 72, no. 7, p. 1175-1194. Michaelides, A.E. (1983) The genesis of the chromites of the Plutonic Complex of Troodos, Cyprus. Unpublished Ph.D. thesis, University of Athens (in Greek).

Moores, E.M. and Varga, R.J. (1984) Extensional tectonics and possible abandoned axial valley, Troodos ophiolite, Cyprus. Transactions American Geophysical Union, 65, p.1115.

Nicolaides, S. (1999) Petrological and mineralogical report: Host-rock alteration and copper mineralogy of the Phoenix mine. Unpublished internal report, Hellenic Copper Mines Ltd, 66 p.

Oudin, E. and Constantinou, G. (1984) Black smoker chimney fragments in Cyprus sulphide deposits. Nature, v. 308, no. 5957, p. 349-353.

Panayiotou,A.(1978) The mineralogy and chemistry of the podiform chromite deposits in the serpentinites of the Limassol Forest, Cyprus.Mineral. Deposita, v. 13, p. 259-274.

Panayiotou, A. and Georgiou, E. (1984) Podiform chromite deposits in the serpentinized ultrabasics of the Limassol Forest plutonic complex, Cyprus. Cyprus Association of Geologists and Mining Engineers Bulletin, no. 2, p. 24¬37 (in Greek).

Panayiotou, A., Michaelides, A.E. and Georgiou, E. (1986) The Troodos chromite deposits of the Troodos Ophiolite Complex, Cyprus. In Petrascheck, W., Karamata, S., Kravchenko, G.G., Johan, Z., Economou, M. and Engin, T. (eds.) Chromites. Theophrastus Publications, Athens, p.161-198.

Petrides, G., Kramvis, S., Charalambous, M. and Akritas, D. (eds.) (1997) The Geology of Cyprus. Cyprus Geological Survey Department, Bulletin 10, 142 p. (in Greek).

Robinson, P.T., Melson, W.G., O'Hearn, T. and Schmincke, H.-U. (1983) Volcanic glass compositions of the Troodos ophiolite, Cyprus. Geology, v. 11, p. 400¬404.

Schmincke, H.-U., Rautenschlein, M., Robinson, P.T. and Mehegan, J.M. (1983) Troodos extrusive series of Cyprus: A comparison with volcanic crust. Geology, v. 11, p. 405-409.

Searle, D.L. and Panayiotou, A. (1980) Structural implications in the evolution of the Troodos massif, Cyprus. In Panayiotou, A. (ed.) Ophiolites, Proceedings, International Ophiolite Symposium, Cyprus (1979). Cyprus Geological Survey Department, p. 50-60.

Shelton, A.W. and Gass, I.G. (1980) Rotation of the Cyprus microplate. In Panayiotou, A. (ed.) Ophiolites, Proceedings, International Ophiolite Symposium, Cyprus (1979). Cyprus Geological Survey Department, p. 61-65.