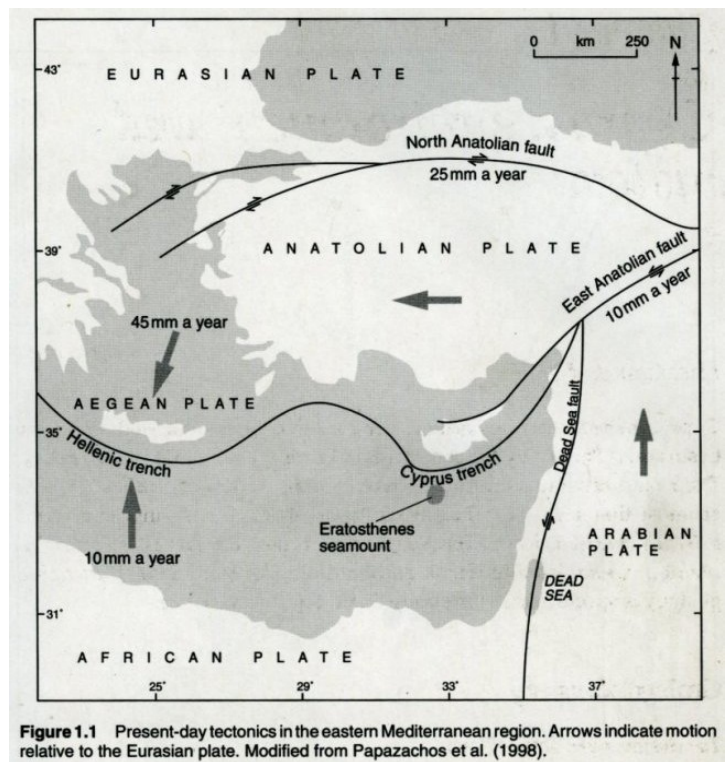




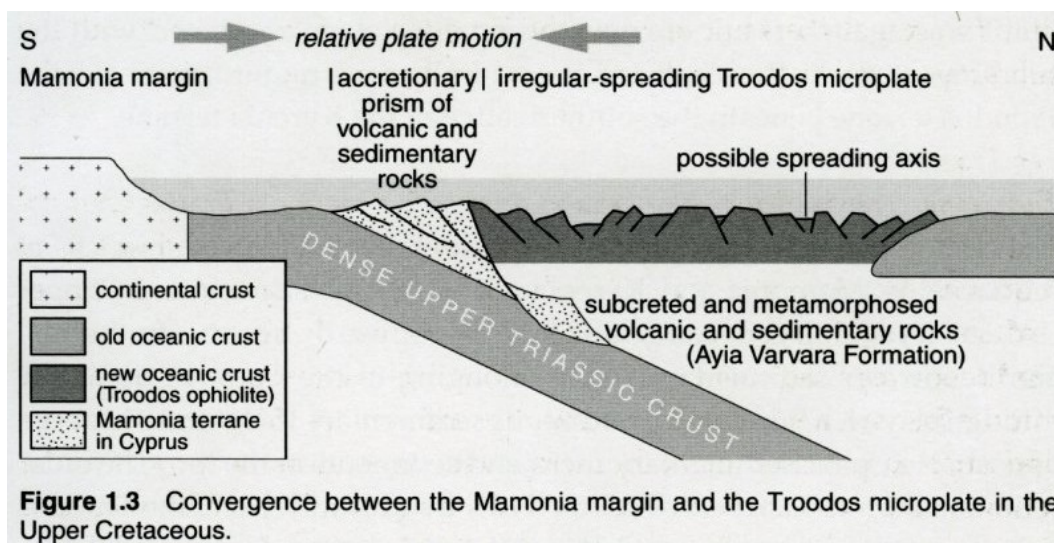
whether these involved the generation or destruction of oceanic lithosphere, the accretion of oceanic seamounts, or the collision of micro-continental blocks.



The remnants of plate interaction are preserved in Cyprus as three major terranes – 1) Troodos, 2) Mamonia and 3) Kyrenia - that give rise to distinctive relief, but also lie beneath a series of cover rocks known as the circum-Troodos sedimentary succession. These terranes represent pieces of lithosphere that have been brought together by tectonic processes, and the complex and varied geology that this has produced in Cyprus is repeated in neighbouring countries. For example, Troodos-like terranes have been identified from Greece in the west to Oman in the southeast, and they formed at the same time as the Troodos terrane, about 90 million years ago in the Upper Cretaceous.

1) *The Troodos terrane*

The Troodos terrane is considered to represent part of the Troodos microplate and it comprises a complete and relatively undeformed ophiolite sequence that preserves oceanic lithosphere formed during a period of seafloor spreading above a subduction zone (Fig. 1.3).



Since its formation, the Troodos ophiolite had rotated 90° anti-clockwise prior to the Lower to Middle Eocene, and it has moved northwards by 10-15°. It has also been updomed to produce an oval outcrop pattern of ultramafic rocks in the centre, which are surrounded successively by gabbros, sheeted dykes, and volcanic and sedimentary rocks (Fig. 1.2a).

This pattern is well developed in the Troodos massif, but somewhat disturbed in the southeastern portion of the ophiolite along the Arakapas Valley, which may represent the surface expression of a fossil transform fault, and, to its south, the structurally complex area referred to as the Limassol Forest. The ophiolite is important economically

because it is mineralized with copper-bearing sulphide deposits in the volcanic rocks and chromite and asbestos in the ultramafic rocks.

### 2) *The Mamonia terrane*

Compared with the huge bulk of ophiolitic rocks in the Troodos massif and Limassol Forest, rocks of the Mamonia terrane crop out within relatively small and isolated erosional windows in the southwest of Cyprus (Fig. 1.2a). The Mamonia rocks consist of a colourful, jumbled and deformed mixture of Triassic lavas, Mesozoic sedimentary rocks and subordinate metamorphic rocks, but associated with them are fault zones along which slivers of Troodos serpentinite and volcanic rocks occur. The Mamonia terrane probably records the break-up of a Mesozoic passive continental margin during a period of plate convergence with the Troodos microplate (Fig. 1.3). The Mamonia and Troodos rocks were brought together in the Upper Cretaceous through the continuing northward subduction of the Tethyan oceanic lithosphere that lay to the north of the Mamonia margin, a process that had already resulted in the formation of the lithosphere of the Troodos ophiolite during a period of seafloor spreading above the subducted slab. The contact between the two terranes is, therefore, a complex tectonic one.

### 3) *The Kyrenia terrane*

The Kyrenia terrane stretches east-west along the entire length of the mountainous northernmost part of Cyprus, the Kyrenia Range, and has structures reminiscent of a small Alpine-type fold and thrust belt. The terrane has a long and complex history and it contains the oldest rocks in Cyprus, which are shallow-water limestones of Permian age that occur as blocks in large-scale debris flows of Eocene age. These blocks are thought to be remnants of a carbonate bank that originated on the northern margin of Neotethys during its initial formation after the break-up of the supercontinent Pangaea. The carbonates continued to develop throughout the Triassic and Jurassic, but were tectonically disturbed and in places metamorphosed to marbles and schists in the Cretaceous, at the same time as the Troodos ophiolite was forming to the south. The platform carbonates and their metamorphic equivalents are overlain by less deformed successions of volcanoclastic sedimentary rocks, pelagic carbonates and volcanic rocks. The volcanic rocks and associated sedimentary rocks are similar in age and composition to those that lie immediately above the ophiolite in southwest Cyprus and may have formed in an island-arc environment. Overlying these rocks is a succession of pelagic carbonates with interspersed volcanic rocks that appear to have an ocean-island affinity. These within-plate volcanics suggest that the area was undergoing extension at this time (Maastrichtian to Upper Palaeocene), possibly related to the rotation of the Troodos microplate to the south.

During the Upper Eocene the Kyrenia rocks were severely disturbed and deformed by a period of south-directed thrusting that uplifted and exposed lithologies to erosion, with the consequent formation of large-scale debris flows and landslides (olistostromes) that poured off the advancing thrust sheets. Locally, some lithologies were metamorphosed, and schists and marbles formed. The deformed basement lithologies of the Kyrenia terrane are overlain by clastic sedimentary deposits, mostly of local derivation. Further uplift in Plio-Pleistocene time, along with the Troodos massif to the south, tilted the Kyrenia stratigraphy to steep angles. This uplift was again a result of compressional tectonics associated with the subduction zone to the south and, more locally, with underthrusting of the Troodos terrane beneath the southern edge of the Kyrenia terrane.

### *The circum-Troodos sedimentary succession and the uplift of Cyprus*

The circum-Troodos sedimentary succession onlaps and covers rocks of the Troodos, Mamonia and Kyrenia terranes. This succession is Upper Cretaceous to Holocene in age and it passes upwards from hydrothermal and deepwater sedimentary rocks belonging to the Troodos ophiolite, through clay-rich lithologies, calcareous sedimentary rocks and evaporite deposits, to clastic sedimentary rocks and sediments at the top. The older sedimentary rocks are best developed to the south and east of the Troodos massif, whereas the younger clastic rocks and sediments are most extensive between the mountainous areas defined by the Troodos and Kyrenia terranes. The deposition of the sedimentary cover reflects changes in tectonic activity and relative sea level that have taken place in a mainly compressional tectonic regime that has existed since the collision of the Troodos and Mamonia terranes in the Upper Cretaceous. The continuing effects of plate convergence and rotation resulted in pulses of compression and extension, with the development of local depositional basins and isolated highs, and the rapid uplift and erosion of the Troodos massif, which peaked in the Pleistocene.

Many parts of Cyprus began to emerge from the Mediterranean Sea during the Miocene, especially areas of the Kyrenia Range and Troodos massif, but it was not until about a million years ago, during the Pleistocene, that most of what is now the island of Cyprus was above sea level. The uplift continues to this day and is driven by the tectonic underthrusting of the continental crust of the African plate as a consequence of northward subduction beneath Cyprus. Underthrusting, currently of the Eratosthenes seamount south of the island, has produced uplift over a large area, including the Kyrenia Range and perhaps even the Misis Mountains in southern Turkey. More local uplift centred beneath Mount Olympos in the Troodos massif has resulted from subduction-driven serpentinite diapirism. The continued occurrence of earthquakes in and around Cyprus indicates that subduction is still taking place beneath the southern part of the island and that collision between Africa and Europe is continuing.

## *Landscape and topography*

The geology of Cyprus has a major influence on the landscape and topography of the island. As Cyprus was not glaciated during the most recent ice age, the landscape has been shaped mainly by tectonic upheaval, extensive erosion and mass movement, and deep incision by rivers. The highest ground is mostly occupied by rocks of the Troodos, Mamonia and Kyrenia terranes, and the lower ground is dominated by cover rocks of the circum-Troodos sedimentary succession.

The highest point on the island is Mount Olympos in the centre of the oval-domed bulk of the Troodos massif. At 1951 m above sea level, it towers above the 1024 m peak of Kyparissovouno, the highest point in the Kyrenia Range, whose hills and mountains form the narrow east-west-trending spine along the northern limit of the island. These mountain ranges and their foot-hills face one another across a central plain that lies below the 200 m contour. This plain and the widening plains to the west and east make up the Mesaoria (literally meaning "between the mountains") Plain, the western extent of which is sometimes referred to as the Plain of Morfou. Many other plains exist, but these are narrow strips of land sandwiched between the shoreline and the mountains. They are most abundant along the southern and eastern coasts, where there are also long sandy beaches in many bays and coves, and occasional salt lakes. By contrast, the western and northern coasts are more indented and rocky, owing to the mountainous and hilly terrain in these areas.

## *Climate and meteorology*

The seasonal rhythms of hot, dry and often humid summers, and changeable wetter winters, are typical of the intense Mediterranean climate experienced by Cyprus. Summer extends from mid-May to September or October, and winter from mid-November to mid-March. Spring and autumn are therefore short and are seasons of rapid changes in weather conditions. The frequently cloudless skies and long days in the summer months give rise to mean daily temperatures in July and August of 29°C on the Mesaoria Plain and 22°C in the semi-alpine Troodos Mountains. This may not seem very hot, but temperatures of over 40°C are known in Lefkosia and in sheltered mine pits and river canyons at low elevations. Winters are mild, with mean temperatures of 10°C on the central plain and 3°C on the highest parts of the Troodos.

The mountains of Cyprus are responsible for a microclimate over the island producing an average of about 500 mm of precipitation annually.

This means that Cyprus, like Lebanon, is relatively green arid lush, rather than being a semi-desert only a few hundred kilometres north of the Sahara. The winds in Cyprus are normally light to moderate, and broadly come from the west (from northwest around to southwest). They carry significant moisture, but the amounts of precipitation over the island are highly variable because of the influence of relief, particularly that of the Troodos. Precipitation is highest (400-1150 mm annually) on the southwestern windward slopes of these mountains and on Mount Olympos, and much lower on the Mesaoria Plain to the northeast, where only 300-350 mm falls annually. At least 60 per cent of the average annual precipitation falls during December, January and February. Some of this falls as snow above 1000 m on the Troodos from early December to mid-April, when it may accumulate to considerable thicknesses on northern slopes.

Thunderstorms may occur at any time of the year, but are most frequent from October to May. These storms are usually short lived, but often involve enough precipitation to cause mass movement on the higher slopes of the Troodos and within the clay-rich lithologies of southwest Cyprus. Dust storms are rare, but in spring it is not uncommon for the atmosphere to become filled with yellowish dust brought by strong winds (mainly the Khamsin) from the Arabian and African deserts.

## *Soils and agriculture*

The soils of Cyprus reflect its geology, geomorphology and climate, and give colour to the scenery. Perhaps the most distinctive are the red and orange-brown 'terra rossas' that develop on hard limestones, particularly in southeastern Cyprus, where they are deep and highly fertile, and are used for growing potatoes. In the south and southwest, the decomposition of limestones and marls gives rise to white lime-rich soils that are extensively cultivated, with vines particularly common in the districts of Pafos and Lemesos. Most of the broad river valleys are cultivated, because they host fertile alluvial soils, and groundwater is readily available. Soils on calcareous rocks often contain hard layers of caliche, which are undesirable because they reduce soil quality and subsurface drainage.

On the Troodos ophiolite, the volcanic rocks are overlain by a characteristic brown soil; weathering of sheeted dykes produces a reddish-brown cover dominated by unconsolidated rock fragments. Higher on the Troodos massif, soils are usually thin and sandy, particularly on gabbro, but many slopes are too steep to support a soil cover at all. Partly weathered gabbros become friable and may retain water, so that even up to 900 m or so they are

often fertile and highly cultivated. The sparse depleted soils on the ultramafic rocks are able to support only a few species of trees and shrubs that can tolerate the unusual chemistry of these soils.

Agriculture is a major industry in Cyprus and for this reason intense use is made of fertile land almost everywhere. The hillslopes reflect this very well, with their extensive terraces, some dating back hundreds if not thousands of years to Roman times. The cultivated areas occupy many of the lower hills, parts of the coastal plains and the Mesaoria Plain. The northern coastal plain is particularly noted for its olive and carob trees, and deciduous fruit trees are grown in many of the island's fertile mountain valleys. Vineyards are abundant on the southern and western slopes of the Troodos, where vines can grow at elevations of up to 1000 m in the mild climate. However, it is the Mesaoria Plain that is most extensively cultivated because of its high fertility and flat relief. This and other lowland areas yield vegetables, fruits, olives, carobs, almonds, cereals and fodder crops.

The intensive cultivation of soil involves the application of fertilizers, pesticides and herbicides, and these may eventually find their way into soil, sediment and water. This is not the only impact of agriculture, as many of the cultivated areas receive relatively little rainfall and require extensive irrigation, an activity that accounts for 78 per cent of total water consumption in Cyprus. In order to cope with this demand and to supply domestic water, most of the large rivers draining the Troodos have been dammed and, as a consequence, there are no perennial rivers flowing to the sea. This means that many essential nutrients do not reach the coastal waters around Cyprus.

### *Flora and fauna*

Despite its small size and the impacts of agriculture and hunting, Cyprus hosts richly diverse flora and fauna. Its isolation has led to the evolution of a host of endemic species, but also there are many biological elements characteristic of the surrounding continents. Add to this the variations in topography, climate and soil type that yield a wide variety of habitats, and it is easy to understand why the rich diversity exists. The main habitats of the island may be classified as coastal (including wetlands), low hillsides below 1000 m, mountains above 1000 m, and cultivated land.

Of the 1800 species and subspecies of flowering plants in Cyprus, 128 are endemic and half of these occur in the Troodos, which, along with the Kyrenia Range, also hosts appreciable remnants of the dense forests that covered most of Cyprus in antiquity. The Troodos are covered with pine, dwarf oak, cypress, cedar, juniper, poplar, alder, maple and plane, and many of these trees at high elevations are tortuously twisted or split as a result of lightning strikes that causes sap within them to boil or explode. Where forest no longer exists and the land is uncultivated, the ground is covered by maquis and garigue. The maquis vegetation grows mainly on siliceous soil and includes plants such as rose laurel, arbutus, myrtle and rosemary. Garigue is a scrub vegetation that grows mainly on calcareous soils and includes gorse, caper, lentisk and thyme. Maquis and garigue are most common on hillsides below 1000 m, but maquis-type forests do fringe parts of the coastline.

The fauna of Cyprus is very varied and there are many species of bird, mammal, amphibian, reptile, insect and mite. For example, there are 357 listed species of bird on the island, and every year Cyprus becomes a vital stop-over for vast numbers of migratory birds on their flights between Europe and Africa. This is not only because of the island's location, but also because of the presence of the two coastal wetlands, both incorporating salt lakes, near Larnaka and Lemesos. Efforts are being made to conserve the wildlife of the island, and the moufflon and turtles (green and loggerhead) are all protected. The moufflon is a rare type of wild sheep that is found only on the island and it is the symbol of the Republic of Cyprus, appearing on its coins and as the corporate logo of Cyprus Airways. Attempts are also being made to raise awareness about the eight endemic species of snake on the island, all of which are most active in the spring and autumn, but are timid. Several are venomous, but it is only the blunt-nose viper, or koufi, that poses a real danger owing to the potency of its bite and venom. It is easily distinguished by a yellow horn-like tail and a blunt diamond-shape head.

### *Human history*

The history of human habitation and development of Cyprus has been a key part of the history of Western civilization and can be divided into some 13 periods stretching from 8000 BC until present, with civilization beginning to flourish during the Neolithic period. Cyprus lay at the centre of the ancient world (Asia Minor, Crete, Egypt, Greece, Mesopotamia and Syria), and its culture and development have been very much influenced by these countries. Because of its wealth of natural resources (minerals, rocks, sediment, water, fertile soils and wood), and its climate, topography and highly strategic position between the continents of Europe, Asia and Africa, Cyprus has been repeatedly invaded, settled and developed. This has resulted in a rich and diverse archaeological domain, but it has also left permanent imprints on the landscape, such as those resulting from extensive deforestation caused by the demand for charcoal to fuel early copper production.

The current population of the entire island is of the order of 800,000, 75 per cent of whom are Greek Orthodox. After the Turkish invasion in 1974, the island was split in two by the establishment of a buffer zone. The northern part of Cyprus, representing 38 per cent of the island, became occupied mainly by Turkish Cypriots, but also by Turkish settlers brought from the mainland. The land to the south of the buffer zone is inhabited predominantly by Greek Cypriots, but also by foreign-born immigrants and seasonal residents, and there are also two British sovereign bases here. Following the division of the island, Lefkosia remained the capital for both sides. Recent political agreements are allowing those living throughout Cyprus to access both the northern and the southern parts of the island.

The area to the south of the buffer zone has a huge transient population that arises from tourism, which is the island's principal industry that currently receives 2.7 million visitors each year. The government ambitiously plans to increase this to 4 - 5 million in the future, but it is hard to see how this will be achieved logistically and without huge impact on the environment and resources, especially water. By contrast, the area to the north of the buffer zone receives up to only 45,000 tourists annually.

## Chapter 2

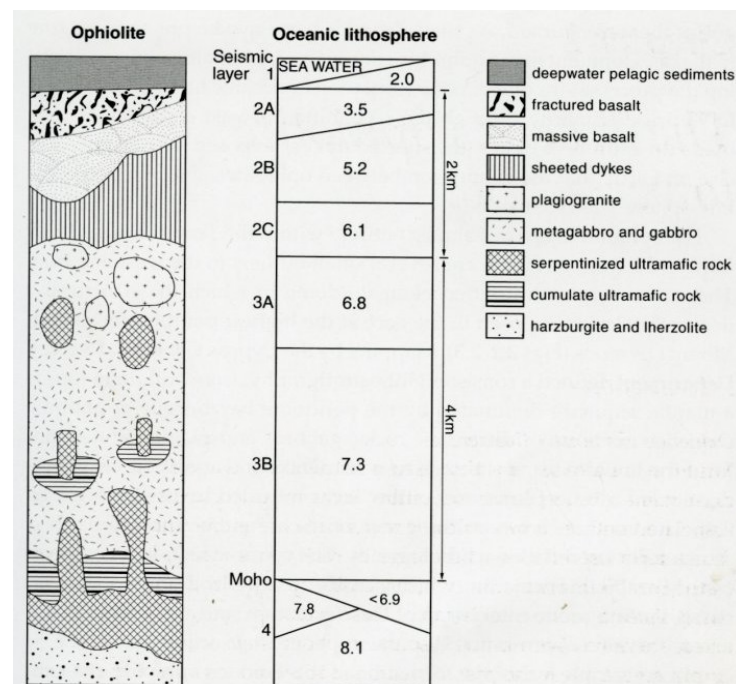
### The Troodos ophiolite: lower section

#### Introduction

##### *Ophiolites and oceanic lithosphere*

The term “ophiolite” was first used nearly 200 years ago by a Swiss geologist named Brongniart to describe occurrences of serpentinite found associated with gabbros, volcanic rocks and chert in mountain belts. It is thus a term used for an assemblage of rock types, which has also been called the “Steinmann trinity” (serpentine, pillow lava and radiolarian chert). Although the association of these rock types has long been recognized, there has been much discussion about their origin and mode of emplacement. Over the past 40 years the igneous portions of the assemblage have been confirmed as being genetically related to one another, a consistent ophiolite lithostratigraphy has been defined, and ophiolites have been accepted by scientists as representing fragments of uplifted oceanic lithosphere.

The composition and structure of *in situ* oceanic lithosphere have been determined through a variety of geophysical techniques, submersible dives and direct sampling methods such as dredging and drilling. These have revealed horizontal layering that is remarkably consistent throughout the oceans and which corresponds specifically to the velocities at which seismic waves travel through rocks of different densities. There is a striking correlation between the seismic layering of *in situ* oceanic lithosphere and the typical ophiolite lithostratigraphy (Fig. 2.1), lending support to the conclusion that ophiolites are indeed fragments of oceanic crust and uppermost mantle.



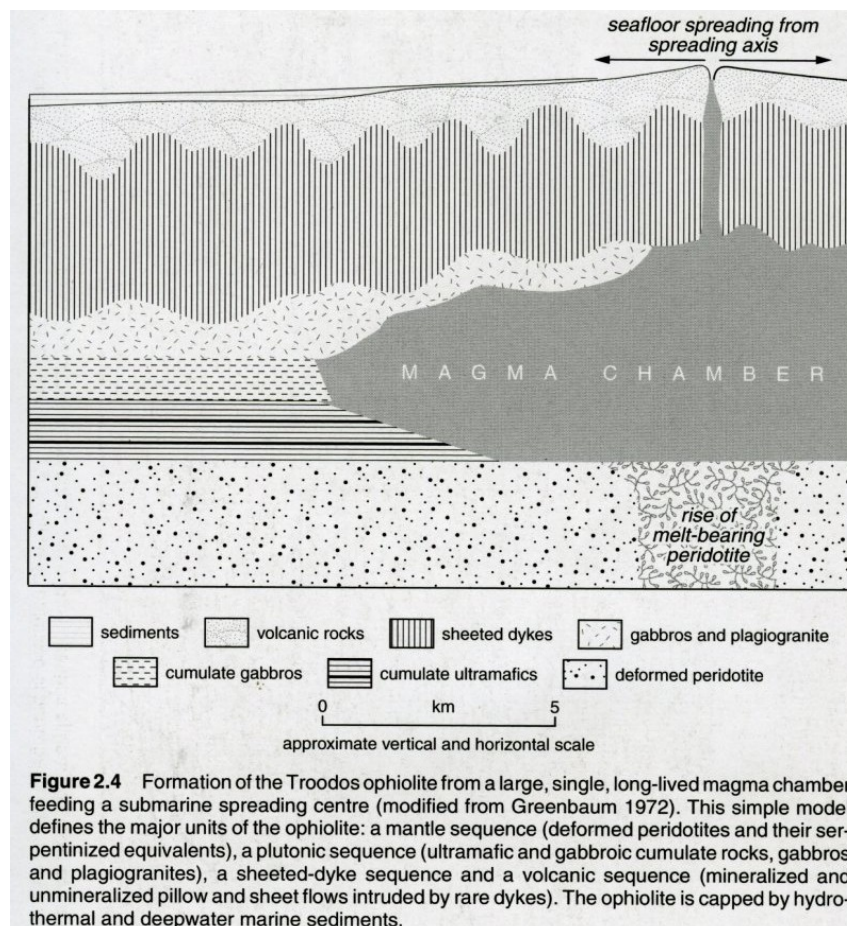
**Figure 2.1** Schematic composite sections of ophiolite lithostratigraphy and seismic layers of the oceanic lithosphere (modified from Harrison & Bonatti 1981 and Malpas & Robinson 1997). The increase in *P*-wave velocity (in  $\text{km s}^{-1}$ ) with depth reflects increasing rock density, the exception being the region yielding velocities of  $<6.9 \text{ km s}^{-1}$ , which corresponds with serpentinized ultramafic rocks. Although the correlation is striking, thicknesses of units in ophiolites do not always correspond with those of seismic layers. The mantle/crust, or layer 3B/4, boundary is called the Mohorovičić discontinuity (or Moho) after the Croatian seismologist who identified it in 1909.

When examined in detail, however, there are some fundamental differences between ophiolites and *in situ* oceanic lithosphere. As examples, measured thicknesses of rock units in ophiolites often do not correspond to the thicknesses of the seismic layers in the oceans, and there are notable inconsistencies between the mineralogical and chemical compositions of ophiolitic rocks and those of *in situ* oceanic lithosphere. The composition of many ophiolitic lavas is much more like that of island arcs than of mid-ocean ridges, and many mafic and ultramafic rocks in ophiolites and arc environments contain much more pyroxene than their ocean-floor equivalents. It seems likely, therefore, that many, if not all, ophiolites were formed in spreading environments above subduction zones, which is why they are known as supra-subduction zone ophiolites.

### The Troodos ophiolite

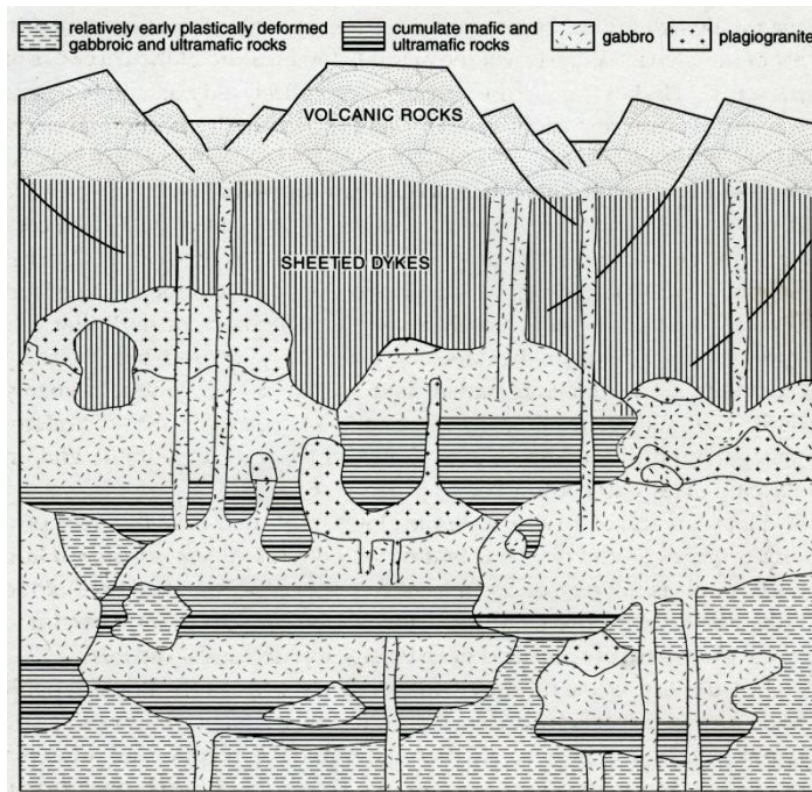
The Troodos massif and adjacent Limassol Forest are together undoubtedly one of the most remarkable examples of an ophiolite anywhere in the world and, because of superb preservation, exposure and accessibility, one of the most studied. As such, Troodos has played a pre-eminent role in the development of the ophiolite concept and, by analogy, in constraining the processes involved in the formation of oceanic lithosphere. It was in Cyprus, primarily through the recognition of vast expanses of rock made up entirely of dykes (the sheeted dykes), exposed here as nowhere else on Earth, that the connection between ophiolites and *in situ* oceanic lithosphere was first made.

The ophiolite crops out almost entirely within the Troodos massif and Limassol Forest, but there are several small outliers to the west and east. The massif forms an uplifted elongate dome in which the structurally deepest rocks are exposed in the core at the highest point on the island, Mount Olympos. Mapping by the Cyprus Geological Survey Department defined a consistent lithostratigraphy, from bottom to top, of a mantle sequence dominated by the peridotite harzburgite, a plutonic sequence made up of ultramafic rocks, gabbros and plagiogranites that form the lower crust, a sheeted-dyke sequence, and a volcanic sequence dominated by sheetflows and pillow lavas intruded by dykes. The contacts between these sequences are either sharply defined structurally or gradational lithologically. The volcanic sequence is capped by the Perapedhi Formation, which is made up of hydrothermal and deep-water marine sedimentary rocks. This formation and the volcanic and sheeted-dyke sequences make up the upper crustal section.



In very simple terms, the formation of the Troodos ophiolite at a submarine spreading centre may be viewed as follows (Fig. 2.4). Upwelling mantle beneath the lithosphere partially melted to produce melt and a solid residue, the latter now represented by the mantle sequence. The melt migrated through the rising mantle to form the crustal rocks. The plutonic sequence crystallized from melt accumulated in a magma chamber within the crust, while sheeted dykes acted as conduits for the transport of melt from the magma chamber to submarine volcanoes, from which lavas were erupted onto the sea floor. This model provides a useful overall framework for studying the

ophiolite, but field and laboratory evidence shows that it is too simple. The mantle, plutonic and sheeted-dyke sequences exhibit abundant evidence for successive and multiple injections of melts of variable compositions and the existence of many relatively small magma chambers. The repeated injection and crystallization of melt took place in a dynamic spreading environment, such that rocks formed early in the process were often deformed prior to the injection and crystallization of later melts (Fig. 2.5).



**Figure 2.5** Conceptual model for the formation of the Troodos ophiolite by multiple injection and crystallization of magma bodies beneath a submarine spreading zone, possibly containing several spreading centres (adapted from Malpas 1990). Spreading-related deformation continued during crystallization of plutonic rocks, so that those formed early are usually more deformed than later ones. Detail omitted for sheeted dykes and volcanic rocks.

The volcanic sequence is similarly complex. The mineralogical and chemical compositions of lavas are very variable and they suggest that the parent melts must have been derived from different mantle sources, perhaps at different times, beneath the spreading centre. This compositional variation within the lavas is also important because it allows conclusions to be drawn about the tectonic environment in which the ophiolite formed. Several types of broadly basaltic to andesitic lava have been identified, and these are virtually indistinguishable from basaltic to andesitic rocks of volcanic islands such as the Marianas and other western Pacific island arcs. Clearly, these lavas are different from those formed at mid-ocean spreading centres such as the Mid-Atlantic Ridge. It is concluded, therefore, that the Troodos ophiolite formed at a spreading centre above a subducting slab of Tethyan oceanic lithosphere (see Fig. 1.3). Magmatism ceased well before a full island arc, similar to the Aleutian Islands, could form. The supra-subduction origin of ophiolitic lavas was first recognized in Cyprus and led to the hypothesis that most ophiolites were formed in very immature island-arc environments.

Another remarkable feature of the Troodos ophiolite is an obvious lineament that runs east-west across the southern margin of the Troodos massif, separating it from the Limassol Forest to the south. This is the Arakapas Valley, which is believed to be the surface expression of a fossil transform fault, akin to those that segment seafloor spreading centres in modern ocean basins. In the Arakapas Valley and the adjacent Limassol Forest, the lithologies are all essentially ophiolitic, but they do not show the regular lithostratigraphy of the region north of the valley. Instead, their interrelationships suggest significant tectonic disturbance and exposure of deeper parts of the oceanic lithosphere on the sea floor, as is common within and close to present-day oceanic transform faults.

The Troodos ophiolite is extensively mineralized. During magmatic activity at the spreading centre, chromite deposits formed in seams and lenses at the top of the mantle sequence and at the very base of the crust. Higher up in the crust, in the sheeted-dyke and volcanic sequences, heat from cooling magma and rock drove hydrothermal circulation of sea water. The hydrothermal fluid vented on the sea floor as black-smoker hot springs and also resulted in the formation of sulphide deposits in the upper crust that contain significant concentrations of copper, zinc and gold. These metalliferous deposits are known as Cyprus-type massive sulphide deposits, and their distribution appears to be fault controlled, as each one is closely associated with a major fault that was apparently active while the deposit was forming. Hydrothermal activity continued well after magmatism had ceased, as sea water, probably derived from oceanic lithosphere subducted beneath the Troodos microplate, entered ultramafic rocks and altered them to serpentinite and, in extreme cases, chrysotile asbestos.

Many ophiolites have a metamorphic sole at their base that was produced during initial displacement of the ophiolite while it was still hot. Such a unit is not obviously present in Cyprus, because the base of the ophiolite is not exposed, but metamorphic rocks of the Mamonia terrane in the southwest of the island have been suggested as candidates.

### *The mantle sequence*

There are few places on Earth's surface where rocks from the mantle are exposed. One of these is at the highest point of the Troodos massif, at the heart of this domed structure. Here, rocks of the uppermost mantle have been brought to the surface by substantial uplift (of the order of 5-10 km) and erosion of the oceanic lithosphere, which has been going on since the Upper Cretaceous. These mantle rocks are dominated by harzburgite and, to a much lesser extent, dunite and lherzolite. Other notable, but very minor, rock types are chromitite, pyroxenite and gabbro.

Harzburgite is composed of olivine, orthopyroxene and minor chromite, but occasionally clinopyroxene occurs and may reach concentrations high enough for the peridotite to be classified as a lherzolite. These minerals are usually deformed and aligned, defining a foliation that was produced by high-temperature plastic flow of the mantle associated with seafloor spreading. On a regional scale, this foliation trends roughly northwest-southeast and dips steeply, which implies that it is primarily a remnant of mantle upflow beneath a spreading centre. However, a component of the dip of the foliation may be associated with much later serpentinite diapirism that caused uplift of the ophiolite. The harzburgite is a residue of extensive partial melting and subsequent efficient melt extraction. In order for the original mantle peridotite to have melted so extensively, water must have been involved to reduce the melting point. Such a situation is often possible in a wedge of mantle above subducted, hydrated, oceanic lithosphere, which lends further support to the argument that the ophiolite formed in a supra-subduction zone environment.

Dunite is composed almost entirely of olivine, but also minor chromite and occasional pyroxene. It occurs throughout the mantle sequence, but is most abundant along the western extent of the harzburgite, where it marks the transition zone from the top of the mantle sequence to the base of the crustal sequence. Dunite in harzburgite occurs as veins, dykes and bodies of less regular shape that are either concordant or discordant with respect to the foliation in the host. The foliation in dunite is defined by grains of chromite and is usually parallel to that in the adjacent harzburgite, suggesting that dunite was formed, and then deformed, in the mantle. Contacts at all scales between harzburgite and dunite may be either sharp or gradational, and well defined xenoliths and diffuse patches of harzburgite may occur within dunite. Three mechanisms have been proposed for the formation of dunite in the mantle sequence and the mantle-crust transition zone: early crystallization of olivine from intruded melt; melt-harzburgite reaction (whereby pyroxene was dissolved to leave an olivine residue); or, in extreme cases, complete melting out of orthopyroxene from harzburgite.

Pyroxenite, as the name suggests, is mainly made up of pyroxene, and it occurs throughout the mantle sequence and mantle-crust transition zone as bands, veins and dykes, which are either concordant or discordant with respect to the foliation in the host rock. As with dunite, pyroxenite is most abundant in the transition zone, particularly at the base of the plutonic sequence. The origin of the pyroxenite remains puzzling, but it probably formed during fractional crystallization of melt.

Chromite is present throughout all of the peridotites and pyroxenites in the mantle sequence, but is normally a very minor mineral phase disseminated throughout the host rock. Only in a few localities is it concentrated, sometimes forming a rock known as chromitite. These chromitites are generally of crude lozenge shape (known as podiform chromitite), but also occur as layers, veins and dykes. The size, shape, chromite content and texture of these bodies varies greatly, with concentrations of chromite reaching 100 per cent in some massive ores. Where present, the dominant silicate mineral between the chromite grains is olivine or its altered equivalent. Chromitites are always encased in dunite, which exhibits the same features and field relations as the unmineralized dunites described above. The formation of chromitite is, therefore, closely linked to that of its enclosing dunite and it involved a combination of fractional crystallization of melt and melt-harzburgite reaction.

All of the ultramafic rocks exhibit some degree of serpentinitization, which is most pronounced in the central and eastern parts of the mantle sequence, where there is extensive shearing, shattering and brecciation. The dominant rock here is bastite serpentinite, formed by the hydration of olivine (to form serpentine) and orthopyroxene (to form bastite) at temperatures up to several hundred degrees Celsius. The bastite serpentinite cropping out in the mantle sequence represents the top of a huge serpentinite diapir that is partially responsible for the upward doming of the ophiolite. A former asbestos mine sits within a zone of extreme alteration in and around Pano Amiantos. Here, veins of whitish fibrous chrysotile asbestos, which formed when fluids migrated through the serpentinite, are associated with pale-green picrolite. Another product of serpentinitization is the cream dykes of rodingite that crop out in the area, especially northwest of Kato Amiantos. During serpentinitization, calcium and silica are liberated from pyroxene and enter the fluid phase, which then produces rodingite either by direct mineral precipitation or by alteration of pre-existing gabbroic dykes. Serpentinitization continues today, enabled by

percolating meteoric water and trapped sea water, and is recorded by the hyperalkaline and saline composition of spring waters emerging from the mantle sequence.

### *The plutonic sequence*

The Troodos plutonic sequence is the part of the ophiolite that lies between the mantle sequence and the sheeted dykes. It represents the lower part of the oceanic crust and it comprises a variety of peridotites, pyroxenites, gabbros, diorites and plagiogranites, and rocks that lie compositionally between these lithological types. In very general terms, most of the ultramafic rocks lie at the base of the sequence, in or immediately above the dunitic part of the mantle-crust transition zone or its faulted equivalent, and the most evolved rocks (diorites and plagiogranites) occupy the top. This broad and simple ophiolite lithostratigraphy led in the past to suggestions that the plutonic sequence may have been derived from a single large fractionating magma chamber (Fig. 2.4), but field relations show that this is not the case. The complex history of accretion of the lower oceanic crust involved the repeated injection, fractionation and crystallization of batches of magma in a spreading zone that may well have contained several small spreading centres (Fig. 2.5). Intrusion was aided by the dilation of the oceanic crust associated with spreading, which in turn resulted in brittle failure of the colder upper oceanic crust and plastic deformation of the hotter lower crust.

Field relations permit subdivision of the plutonic sequence into early and late plutons based on crosscutting intrusive relationships and type and extent of deformation (Fig. 2.5). The subdivision is clearer in the lower plutonics, but becomes less distinct in the upper part of the sequence, where the degree of plastic deformation is less pronounced. The lowest rocks comprise dunite, wehrlite and a variety of pyroxenites and gabbros, all of which display banding in places. The lowermost ultramafic rocks probably represent the top of the mantle-crust transition zone, the base of which is dunite in contact with harzburgite. The banding resulted from high-temperature plastic deformation, which is also characterized by strong lineations and foliations, and small isoclinal folds. These features are also seen in the mantle lithologies and they suggest that primary igneous textures, layering and intrusive contacts in most of the mantle sequence and the early plutons were significantly modified by deformation and recrystallization caused by plastic flow associated with mantle upwelling and seafloor extension in the spreading zone.

Many of the deformed rocks of the plutonic sequence, and some parts of the mantle sequence, are intruded by relatively undeformed plutons that clearly preserve igneous features, although in places they also preserve zones of high-temperature deformation. These plutons are made of plagioclase-bearing peridotites, pyroxenites, gabbros, diorites, plagiogranites and dykes of microgabbro. In the lower part of the plutonic sequence, these plutons are dominated by peridotites and pyroxenites, particularly along a 1-2 km-wide north-south-trending zone to the west of Mount Olympos, but plutons higher in the sequence tend to contain more fractionated rock types. This relationship suggests that magma that fed the higher-level plutons was derived from larger plutons at deeper levels that were undergoing fractional crystallization. Magma in the high-level plutons continued to fractionate, ultimately leading to the crystallization of the final products of magmatic differentiation (magnetite-rich gabbros, diorites and plagiogranites), which generally lie immediately beneath the sheeted dykes.

The uppermost part of the plutonic sequence has a complex contact with the sheeted dykes. In most exposures of this contact, plutonic rocks intrude sheeted dykes, indicating that the construction of the dyke unit was almost complete before the intrusion of plutons ceased. In fewer exposures, screens of plutonic rock are sandwiched between dykes, showing that dykes continued to intrude after the plutons had solidified. In yet other exposures, the dyke and plutonic rocks are separated by a low-angle fault. Where plutons intrude into sheeted dykes, these dykes have been partially to completely metamorphosed or assimilated, which is particularly evident in bodies of plagiogranite that contain xenoliths of sheeted dykes. Hybrid diorites occur where assimilation of mafic xenoliths by evolved magma was so extensive that the xenoliths are barely or no longer recognizable. A variety of hybrid rocks were also produced by magma mixing, during which basaltic magma intruded plagiogranitic magma, in places chilled against it and in others mixed with it.

Some plagiogranites and diorites contain large quantities of the hydrous mineral epidote, which probably indicates introduction of water into the magma by assimilation of hydrothermally altered sheeted dykes. Much of this assimilated water was released by magma as it crystallized and it may have contributed to the hydrothermal fluids that ultimately led to mineralization at or near the sea floor. Pegmatitic gabbros - very eye-catching coarse-grain rocks - are particularly common near diorites and plagiogranites, but they also occur throughout the plutonic sequence and in parts of the mantle sequence. Most appear to have crystallized from water-bearing magmas, but their precise origin is not clear.

Gabbro is by far the most abundant rock type in the plutonic sequence. Its primary mineralogy is plagioclase (40-75%), clinopyroxene (25-60%), orthopyroxene ( $\leq 25\%$ ) and olivine ( $\leq 25\%$ ), but amphibole, titanomagnetite and quartz may also be present. Variations in the proportions and textures of primary minerals result in many types of gabbro, the most widespread being two-pyroxene gabbro (plagioclase, clinopyroxene and orthopyroxene) and norite (plagioclase and orthopyroxene). Alteration of the primary minerals leads to further variation in gabbro types.