

The Troodos ophiolite of Cyprus: New perspectives on its origin and emplacement

P.T. Robinson and J. Malpas

P. T. Robinson, Centre for Marine Geology, Dalhousie University, Halifax, Nova Scotia, Canada, B3H 3J5.

J. Malpas, Department of Earth Sciences, Memorial University, St. John's, Newfoundland, Canada, A1B 3X5.

Abstract

The Cyprus Crustal Study Project, a combined field, drilling and laboratory study of the Troodos massif, has provided many new data and interpretations on the origin and emplacement of Troodos and other ophiolites. Troodos is now believed to have formed at several spreading axes in a supra-subduction zone environment resulting from the collision of the African and Eurasian Plates in the Late Cretaceous. Three major geochemical suites are recognized in the extrusive sequence of Troodos: an arc tholeiite suite, a depleted tholeiite suite and a highly depleted boninitic suite. Except in narrow subvertical zones beneath the sulphide orebodies, the lavas of Troodos have undergone only low temperature seawater-rock interaction, producing a series of alteration zones similar to those of in-situ oceanic crust.

Alteration in the lavas is nonpervasive and fresh volcanic glass occurs sporadically through the entire extrusive sequence. The massive sulphide orebodies are the products of high temperature hydrothermal solutions which vented on the seafloor along the flanks of axial grabens. Intrusive relationships between deformed and undeformed plutonic rocks and between plutonic rocks and sheeted dykes provide unequivocal evidence for the existence of multiple magma chambers beneath Troodos at the time of formation. Three structural grabens have been recognised from dyke attitudes on the north flank of Troodos and these are believed to represent fossil spreading axes. The grabens apparently formed by listric normal faulting during crustal accretion and mark the loci of hydrothermal vents around which the sulphide orebodies formed.

Introduction

The Troodos massif (Figure 1) is probably the most intensively studied and best-known ophiolite in the world. Data and interpretations produced by investigation of this body have played a major role in our understanding of ophiolites and in developing the ophiolite model for oceanic lithosphere.

Three main phases of investigation can be identified. In the nineteen fifties and early sixties, the massif was mapped carefully by members of the Cyprus Geological Survey and the results published in a series of memoirs (Wilson and Ingham, 1959; Carr and Bear, 1960; Bear, 1960; Gass, 1960;

Bagnall, 1960; Pantazis, 1967). During this phase of study, the compositions and structural relationships of the major units were worked out and the cogenetic nature of the igneous units was demonstrated (Wilson and Ingham, 1959). The intrusive nature of the sheeted dykes was recognized (Wilson and Ingham, 1959) and interpreted in terms of seafloor spreading (Gass, 1968).

A second phase of investigation was triggered by the landmark paper of Moores and Vine (1971) which identified the massif as an ophiolite (Figure 2). Because ophiolites were obviously formed in a spreading environment, they were assumed to represent segments of normal oceanic lithosphere formed at mid-ocean ridges. This assumption was challenged by Miyashiro (1973; 1975a; 1975b) who pointed out that the major element geochemistry of the Troodos lavas is

more compatible with formation in an island arc. His suggestion was strongly opposed by Hynes (1975), Moores (1975) and Gass et al. (1975) on the grounds that the Troodos lavas had been pervasively altered, thus obscuring their original geochemistry, and that the regional geology of Cyprus is incompatible with an arc environment. The resulting controversy stimulated continuing investigations of Troodos which produced many new data and interpretations but left unresolved the question of its origin. This phase of investigation culminated in 1979 with the International Ophiolite Symposium, at which the findings up to that point were summarized (See Gass, 1980; Panayiotou, 1980).

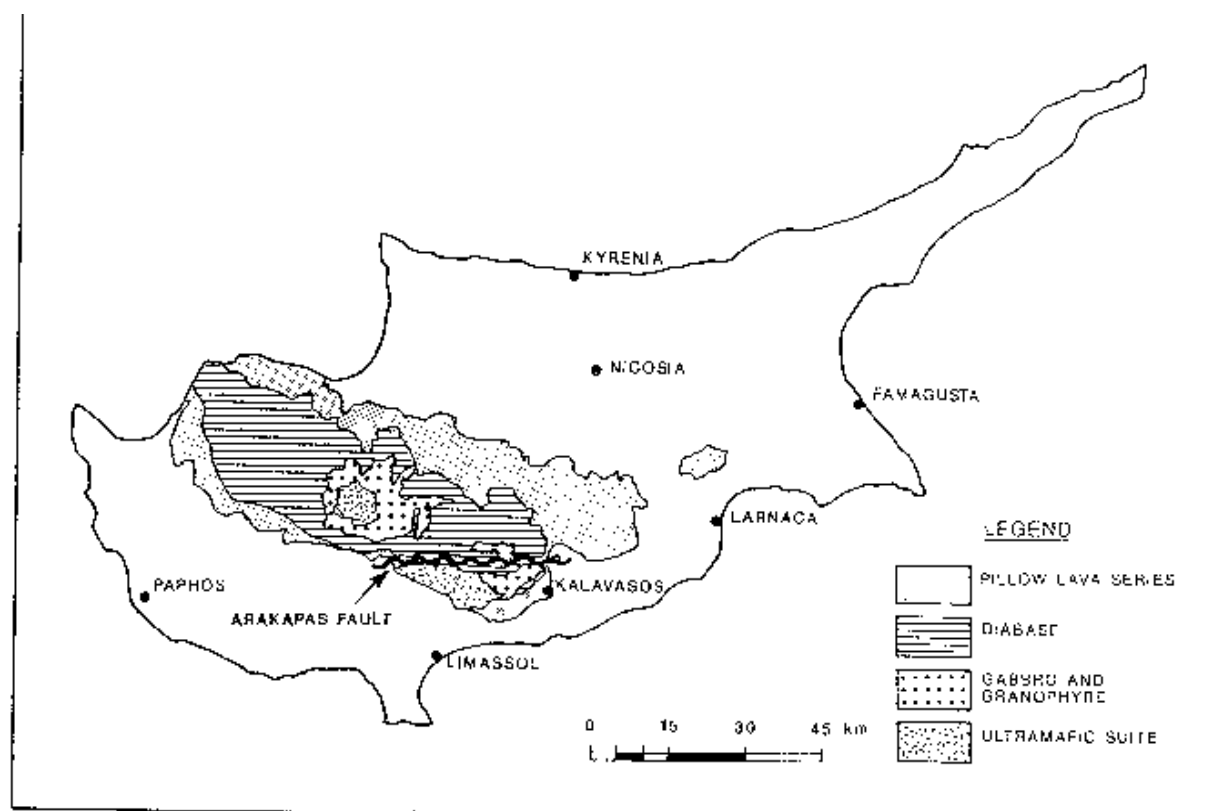


Figure 1. General geology of the Troodos ophiolite complex, southwestern Cyprus.

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In 1981, a third stage of investigation was initiated by the International Crustal Research Drilling Group (ICRDG) and the Cyprus Geological Survey Department. This work, which combined detailed field mapping, extensive research drilling and laboratory studies, was intended to resolve some of the outstanding problems regarding the origin and emplacement of the massif and to test the applicability of the ophiolite model to in situ oceanic lithosphere.

The Cyprus Crustal Study Project

Many new data and interpretations which have emerged from the Cyprus Crustal Study Project shed light not only on the origin of Troodos but of other ophiolites as well. In this paper we review the most important of these new findings and discuss their significance for the ophiolite model. Finally, we synthesize these results and present a model for ophiolite formation and emplacement.

In our opinion, the most important new findings of the Cyprus Crustal Study Project involve: 1) establishment of the primary geochemistry of the lavas, 2) recognition of structural domains in the sheeted dyke complex, 3) determination of the structure and petrology of the plutonic section, 4) development of new models for hydrothermal alteration and metallogenesis and 5)

identification of the probable tectonic environment of formation and the processes of emplacement of the ophiolite.



figure 2. The structure of the Troodos ophiolite compared with the seismic layering of in situ oceanic crust according to Moores and Vine (1971)

Lava geochemistry

For mapping purposes, the extrusive sequence was originally divided by the Cyprus Geological Survey into the Upper and Lower Pillow Lavas on the basis of colour, mineralogy, abundance of dykes and relationship to the sulphide orebodies (Figure 3). The Upper Pillow Lavas were described as reddish-brown, olivine-phyric rocks which overlie the massive sulphide orebodies. An older sequence of greenish-grey, generally aphyric, silica-oversaturated rocks was assigned to the Lower Pillow Lavas. In most localities, the boundary between the two was poorly defined; in others, it was placed at a local unconformity or layer of intercalated sediment.

Following a study of alteration in the lavas, Gass and Smewing (1973) and Smewing et al. (1975) concluded that the Lower Pillow Lavas and the Sheeted Dyke Complex are metamorphically conformable and assigned these two units to an Axis Sequence formed during a seafloor spreading event. The overlying Upper Pillow Lavas were believed to represent a later, off-axis sequence separated from the older rocks by a metamorphic discontinuity. In a few localities, this new stratigraphic boundary was believed to correspond to the previously defined contact between the Upper and Lower Pillow Lavas; elsewhere, it was placed either higher or lower in the section. Sampling across this boundary suggested a gradual geochemical transition from the Axis Sequence to the Upper Pillow Lavas (Smewing et al., 1975) but in general, the lavas were considered too altered to yield accurate data on the primary geochemistry.

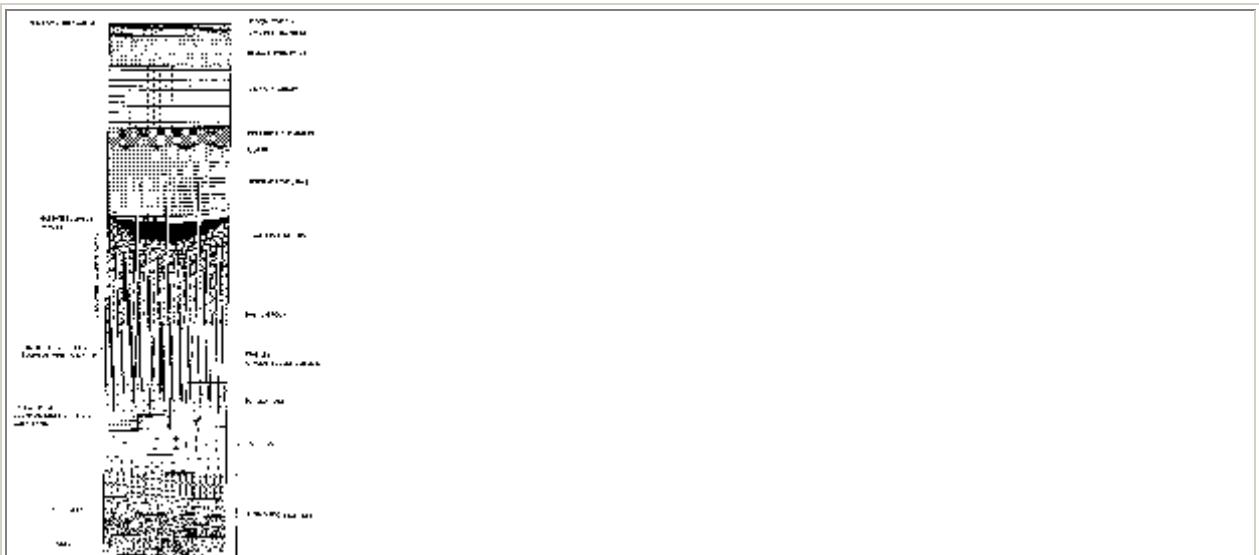
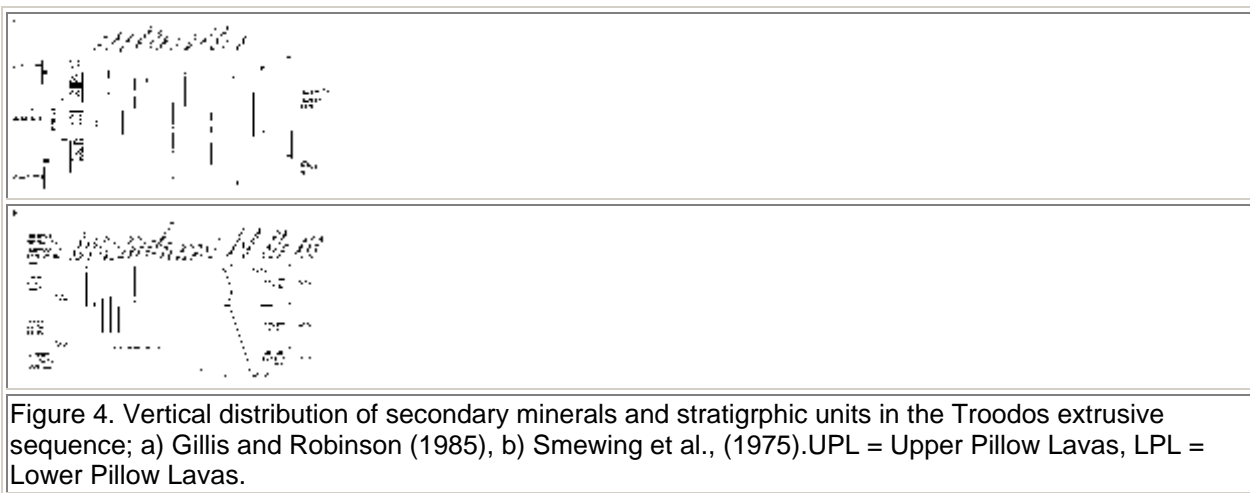


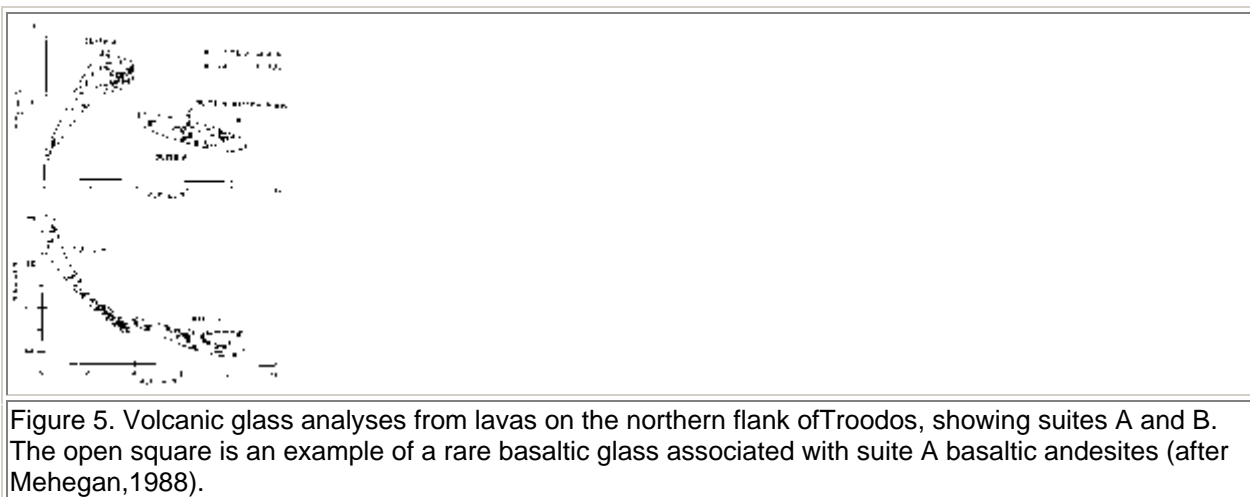
Figure 3. Lithologic units of the Troodos ophiolite showing the relationship between sulphide mineralization and Upper and Lower Pillow Lavas (after Constantinou, 1980)

Recent studies of the extrusive sequence have provided a much clearer understanding of alteration in the lavas and of their primary geochemistry. Except in narrow, subvertical zones of hydrothermal alteration beneath the sulphide ore deposits, the lavas have undergone only nonpervasive, low temperature interaction with seawater. Secondary mineral assemblages consist chiefly of clay minerals, zeolites and carbonates and were controlled largely by variations in permeability, lithology, water-rock ratios and proximity to intrusions (Gillis 1987;

Gillis and Robinson, 1985; 1988) (Figure 4). Neither the grade nor the intensity of alteration increases with depth in the extrusive section as originally suggested by Smewing et al. (1975) (Figure 4b). Fresh volcanic glass occurs sporadically through the section and persists downward to the very top of the sheeted dykes (Robinson et al., 1983; Mehegan, 1988). The red to reddish-brown colour of the Upper Pillow Lavas is due to low temperature oxidation of the olivine-phyric basalts and the depth to which the alteration penetrates the lava pile correlates inversely with the thickness of impermeable sediments, particularly the synvolcanic umbers, that overlie the extrusive sequence. Where the umbers are thick, such as in the Margi area, alteration is minimal and fresh glass occurs at the very top of the sequence. In other areas, where the umbers are thin or absent, pervasive oxidative alteration penetrates to depths of 200 metres or more. Volcanic glass in this zone is completely replaced by mixtures of calcite, smectite and analcime.



The presence of fresh volcanic glass throughout the extrusive sequence provides a unique opportunity to obtain primary compositional data on a range of rocks and minerals. Using major element data on both glasses and whole rock samples Robinson et al. (1983), Mehegan (1988) and Mehegan and Robinson (1985) were able to establish the presence of three major geochemical suites in the lavas: a relatively evolved island-arc tholeiitic suite (suite A), a depleted arc tholeiitic suite (suite B) and a highly depleted boninitic suite (suite C) (Figures 5 and 6). Suite A comprises a basalt-andesite-dacite-rhyodacite assemblage which occurs at the base of the lava pile on both the northern and southern flanks of Troodos. Rocks of this suite are generally aphyric to sparsely phyric and have a liquidus assemblage of plagioclase+clinopyroxene+ titanomagnetite+/- orthopyroxene. Although there are slight regional variations in this suite, all of the rocks are characterized by relatively high quantities of incompatible elements, particularly Y and Zr. Iron and TiO₂ show typical tholeiitic trends, increasing as fractionation proceeds to maxima at about 3.5 wt. % MgO and then decreasing rapidly in the more evolved samples.



Suite B consists of a picrite-basalt-basaltic andesite assemblage which occurs at the top of the extrusive sequence on the northern flank of Troodos. The rocks of this suite range from aphyric

to highly phyrlic and have a liquidus assemblage of olivine+ clinopyroxene+ orthopyroxene+ / - spinel. Plagioclase is conspicuously absent as a liquidus mineral in all but the most evolved samples. Glass compositions range from about 9 to 3.8 wt. % MgO with TiO₂ varying from 0.4 to 0.9 wt. %. These rocks form a high SiO₂-high MgO suite characterized by low Zr, Y and TiO₂ (Figure 5). The rocks of suite C are petrographically similar to those of suite B but are even more depleted chemically. These rocks occur only on the southern flank. Glass compositions in suite C range from about 10.2 to 5.5 wt. % MgO and TiO; ranges from about 0.2 to 0.4 wt. %. These extremely depleted rocks have phenocrystic orthopyroxene and U-shaped REE patterns, features typical of boninites. They are CaO-rich, SiO₂-poor rocks similar to the boninites found in Guam (Flower and Levine, 1988). The rocks of suite C are spatially associated with the Arakapas Fault Zone but a genetic relationship has yet to be demonstrated.

Although the relatively enriched lavas of suite A and the depleted lavas of suites B and C correspond approximately to the old Lower and Upper Pillow Lavas, respectively, the boundaries rarely coincide (Figure 4a). In addition, interfingering of the enriched and depleted lavas occurs in several localities.



Figure 6. Volcanic glass and whole rock analyses of lavas on the southern flank of Troodos showing suites A and C. Dashed lines enclose fields of suites A and B from Figure 5.

All of the Troodos lavas have compositions characteristic of an arc or forearc environment. Enrichment of low field strength elements and depletion of high field strength elements compared to N-MORB (Figure 7a and b) indicate a subduction-derived source contamination (Pearce, 1980; Alabaster et al., 1982). Fresh volcanic glasses from the lavas have isotopic ratios characteristic of subduction zone volcanism. For example, ⁸⁷Sr/⁸⁶Sr ratios from 0.7032 to 0.7040, ²⁰⁶Pb/²⁰⁴Pb ratios from 15.55 to 15.90 and ²⁰⁶Pb/²⁰⁴Pb ratios from 38.08 to 38.50 (Rautenschlein et al., 1985; Rautenschlein, 1987). This enrichment of Sr, Rb, K and Ba is indicative of subduction-derived source contamination.

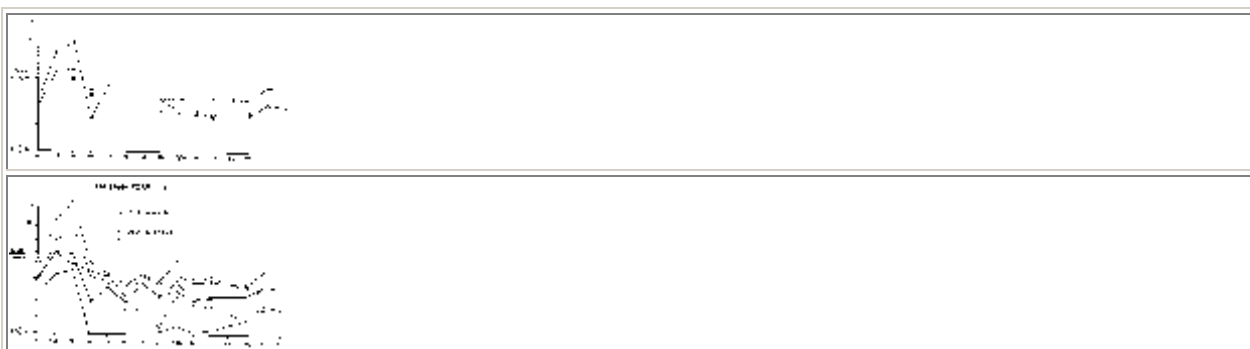


Figure 7. N-MORB normalized trace elements (and oxides) for suite A lavas (a) and comparing suite B lavas, inside stippled field, with Mariana forearc lavas (b).

The three magmatic suites cannot be derived from each other or from a common parental magma by any known process of fractional crystallization, magma mixing or wall rock assimilation. They are therefore believed to represent different parental magmas generated in a mantle wedge above a subducted plate which reflect different degrees of melting

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Thus, after years of discussion and dispute, the primary geochemistry of the Troodos lavas has been firmly established. All of the lavas were formed in a supra-subduction zone environment, probably in a nascent arc or forearc. Flower and Levine (1988) suggest that the compositions reflect splitting of a volcanic arc, prior to backarc spreading but this view is difficult to reconcile with the absence of an arc edifice.

Structure and composition of the Sheeted Dyke Complex

Studies of the sheeted dyke complex have provided a new understanding of the spreading history of Troodos and the process of crustal accretion in ophiolites. It was recognized at an early stage that the presence of a sheeted dyke complex required formation in an extensional regime (Gass, 1968). A statistical study of chilled dyke margins led Kidd and Cann (1974) and Kidd (1977) to conclude that Troodos formed at a single narrow axis of accretion that lay somewhere to the west of the present-day outcrops. However, more recent studies have demonstrated considerable variation in both the strike and dip of the dykes (Searle and Panayiotou, 1980; Verosub and Moores, 1981) and have revealed cross-cutting relationships between some dyke swarms. Verosub and Moores (1981) identified a number of domains defined by dyke orientations and suggested that the different structural attitudes reflect rotation due to extensional faulting at the spreading axis. Refining this model, Varga and Moores (1985) identified three structural grabens on the northern flank of Troodos which they believe represent fossil spreading axes. From west to east these are the Solea graben, Ayios Epiphaniou graben (now the Mitsero graben) and the Larnaca graben (Figure 8). Each of these structures is bounded by inward-dipping dyke swarms with relatively consistent strikes. Because the dipping dykes are perpendicular to the lava flows they cut, they are believed to have been intruded vertically and subsequently rotated to much shallower dips along listric normal faults on the graben walls. These faults appear to flatten with depth and merge into a broad shear zone or detachment surface below each graben. In a few localities, the detachment surface is cut by undeformed dykes, indicating that faulting occurred during crustal accretion. The presence of these structures suggests that the sheeted complex formed at several separate and temporally distinct axes. Eastward migration of the spreading axes by ridge jumping is suggested by asymmetry of the dyke domains on opposite sides of the grabens (Varga and Moores, 1985).

Because the dykes represent the conduits through which the lavas were transported to the seafloor, they should record the same range of compositions found in the extrusive sequence. Baragar et al. (1987) have shown that the dykes span the same compositional range as the lavas but do not record the sharp breaks in composition observed between the magmatic suites in the extrusive sequence. Furthermore, no consistent relationships have been found between age and composition in the dykes such as occur in the lavas. Thus, within each distinct spreading axis, it appears that dykes were intruded at a number of (overlapping) spreading centres.

The absence of sharp geochemical breaks in the dykes may be due in part to their relatively high grade of metamorphism. Most of the dykes contain assemblages of albite, actinolite, and titanomagnetite with minor chlorite and quartz. Considerable modification of the major oxides

has resulted from this alteration but separate magma groups can be recognized from variations in TiO₂, Zr, Y and REE. Local interlayering of these magma suites in the extrusive sequence indicates that separate melts existed simultaneously during crustal accretion. Baragar et al. (1987) suggest a model in which several discrete fractionating magma chambers, each with its own parental magma, occurred along the spreading axis or axes. From these centres, dykes were emplaced vertically and laterally along the ridge axis to form a mosaic of dyke compositions.

Structure and composition of the Plutonic Sequence

The nature of subrift magma chambers has been debated for many years. Are they relatively large, long-lived features that undergo continuous evolution or are they small, ephemeral features with independent paths of melt evolution? Early models (e.g., the infinite onion of Cann, 1974) postulated the existence of continuous systems but studies of crustal sections obtained by the Deep Sea Drilling Project suggested a number of separate, ephemeral magma supply systems (e.g., Flower et al., 1977; Flower and Robinson, 1981). Later studies suggested that the nature of subrift chambers is a function of spreading rate (Flower, 1980) and that the faster the spreading rate, the larger and more long-lived the individual chambers. Recent models of ridge segmentation argue for a central magma chamber within a given segment from which magma moves both vertically and laterally along the rift axis (Macdonald et al., 1984; Whitehead et al., 1984).

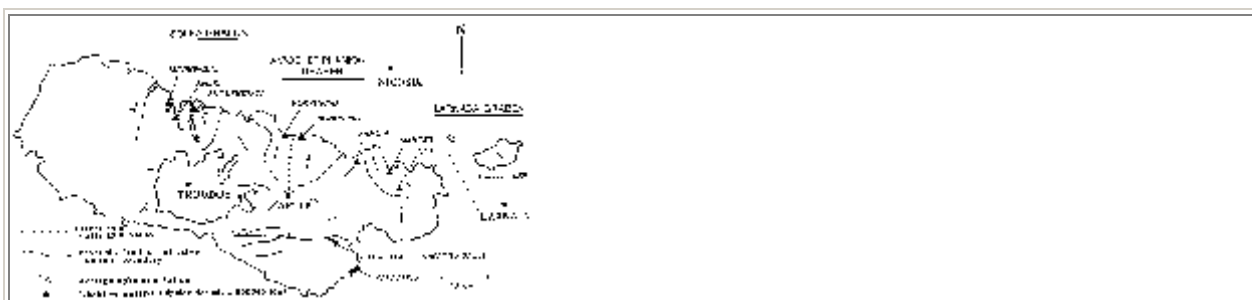


Figure 8. Location of major grabens on the northern flank of Troodos and their relations to major mining districts in the Troodos extrusives (after Varga and Moores, 1985).

Similar arguments have developed regarding the plutonic structure of ophiolites (Figure 9). Moores and Vine (1971) suggested that the plutonic sequence of Troodos formed from a number of small, separate magma chambers. Greenbaum (1972), however, envisaged formation of the Troodos cumulates in a single, continuously evolving magma chamber, a view later challenged by Alien (1975). Many models for other ophiolite complexes assume long-lived, continuously evolving chambers (e.g., Browning, 1984, Eithon et al., 1982).

New data produced by the Cyprus Crustal Study Project provide unequivocal evidence for multiple magma supply systems beneath Troodos. The three magmatic suites identified in the extrusive sequence cannot be related to one another by any known petrological process and, thus, each suite is considered to have been derived from a separate parental magma which maintained its compositional integrity from time of formation to time of eruption. Local interlayering of these suites in the extrusive sequence indicates that the magmas existed simultaneously at shallow levels beneath Troodos without undergoing significant mixing.

Direct evidence for multiple magma chambers has been obtained from field relations between the plutonic sequence and the sheeted dykes and between different plutonic bodies.

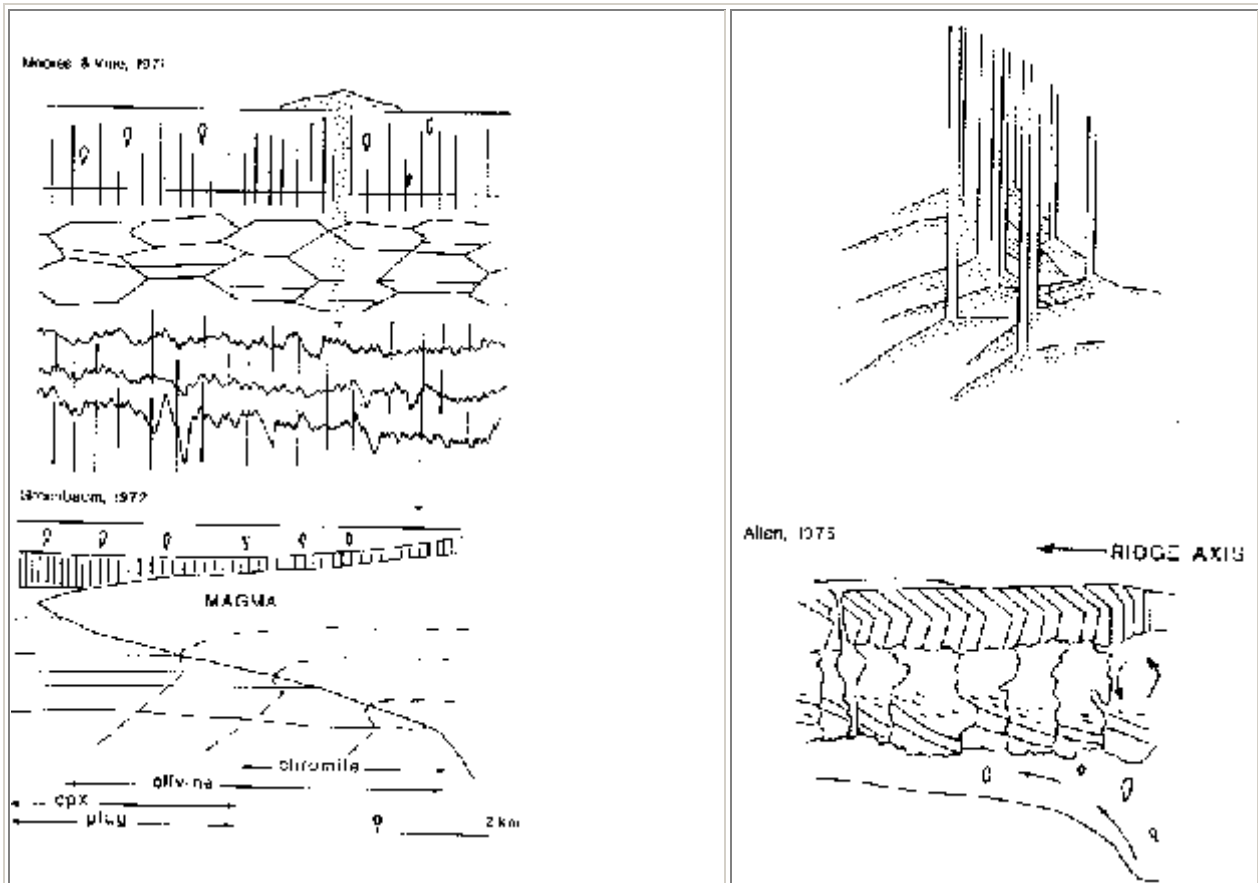


Figure 9. Various models of the Troodos magma chamber system. Multiple magma chamber models are those of Moore and Vine (1971) and Allen (1975). The model involving a single, long-live chamber is that of Greenbaum (1972)

Cross-cutting relationships between a number of lithological units can be observed in the ultramafic sequence on the north and west sides of Mt. Olympus. These occur on all scales from thin microgabbro dykes intruding dunite and harzburgite to single ultramafic plutons greater than 20 kilometres across cross-cutting harzburgite, dunite and layered gabbro. The older rocks are invariably affected by a high temperature penetrative deformation characterized by the development of L-S fabrics and small isoclinal folds. The fabric is generally parallel to compositional layering, but clearly cross-cuts layering in the hinges of isoclinal folds. In most places, deformation has led to the transposition of layering parallel to the tectonic fabric. These structures are believed to have resulted from upward and lateral movement of mantle material during spreading (Malpas et al., 1989).

Throughout the plutonic sequence, deformed rocks are intruded by a series of younger, essentially undeformed plutons which generally exhibit well preserved cumulate features and igneous textures. The most conclusive evidence of multiple intrusive relationships is the existence of xenoliths of deformed rock in the margins of these later undeformed intrusive bodies (Malpas et al., 1989).

Detailed mapping of the area between Palekhori and Troodos, in the vicinity of the Cy-4 borehole, has revealed that the upper part of the plutonic complex is formed of multiple intrusive bodies with compositions ranging from wehrlite to plagiogranite (Brace et al., 1987). Numerous small ultramafic bodies, up to several hundred metres across, intrude the high level gabbros (Malpas and Brace, 1987; Searle and Panayiotou, 1980). These small plutons postdate deformation of the gabbros and truncate both igneous layering and imposed foliations (Alien, 1975; Searle and Panayiotou, 1980). They consist of layered wehrlite, plagioclase-bearing wehrlite, lherzolite and olivine gabbro and are believed to represent the magma chambers from which the upper mafic lavas were erupted (Malpas and Langdon, 1984). It is possible that larger-scale, longer-lived magma chambers fed the lower pillow lavas but the presence of multiple

spreading axes in Troodos argues for multiple chambers at depth. The Cyprus Crustal Study Project Hole Cy-4, drilled in sheeted dykes and plutonic rocks, penetrated at least two fossil magma chambers (Thy, 1987; Malpas and Brace, 1987). Based on pyroxene compositions, gabbros in the upper part of the hole can be correlated with lower arc tholeiite lavas, whereas all of the gabbros below an intrusive contact at 1330 metres may correspond to the upper depleted pillow lavas (Figure 10).

Complex structural relationships between the sheeted dykes and gabbros also provide direct evidence of multiple intrusive events. At several locations, the sheeted complex has been intruded by high level gabbroic plutons, which in turn, may be cut by later dykes (Malpas and Brace, 1987). In still other cases, dykes can be observed to emanate from the gabbros (Figure 11).

Hydrothermal alteration and metallogenesis

The massive sulphide orebodies of the Troodos ophiolite have long been recognized as the products of hydrothermal circulation. Interest in these systems increased significantly with the discovery of active hydrothermal vents on modern spreading ridges (black smokers), around which similar deposits are being formed. Based on similarities in petrography and mineralogy, Oudin and Constantinou (1984) concluded that the Troodos orebodies are exhalative deposits similar to those being formed on modern ridge axes. Spooner (1977; 1980) demonstrated that seawater was the ore-forming fluid for the Troodos deposits and he proposed a general hydrothermal circulation system reaching to the top of the gabbros.

The structural controls for the orebodies were poorly understood but many deposits were thought to occur at the contact between the Upper and Lower Pillow Lavas. The orebodies are not randomly distributed geographically but rather occur in clusters of 3 or 4 which define several mining districts.

Recent studies have provided new insights into the structural controls of the orebodies and their mode of formation. Most appear to lie along normal faults associated with the grabens identified from dyke domains (Varga and Moores, 1985) and hence are concentrated along the old spreading axes (Figure 8). The orebodies may occur anywhere in the lower part of the lava pile but are not found in the uppermost olivine-phyric lavas, although they may be related to this phase of volcanism. For example, in the Solea graben, the ore deposits are associated with a period of renewed magmatism which followed crustal attenuation by normal faulting (Varga and Moores, 1985). This renewed volcanism was not geometrically related to the former spreading centre and was probably associated with intrusion of high level magma chambers from which the upper, depleted lavas were erupted.

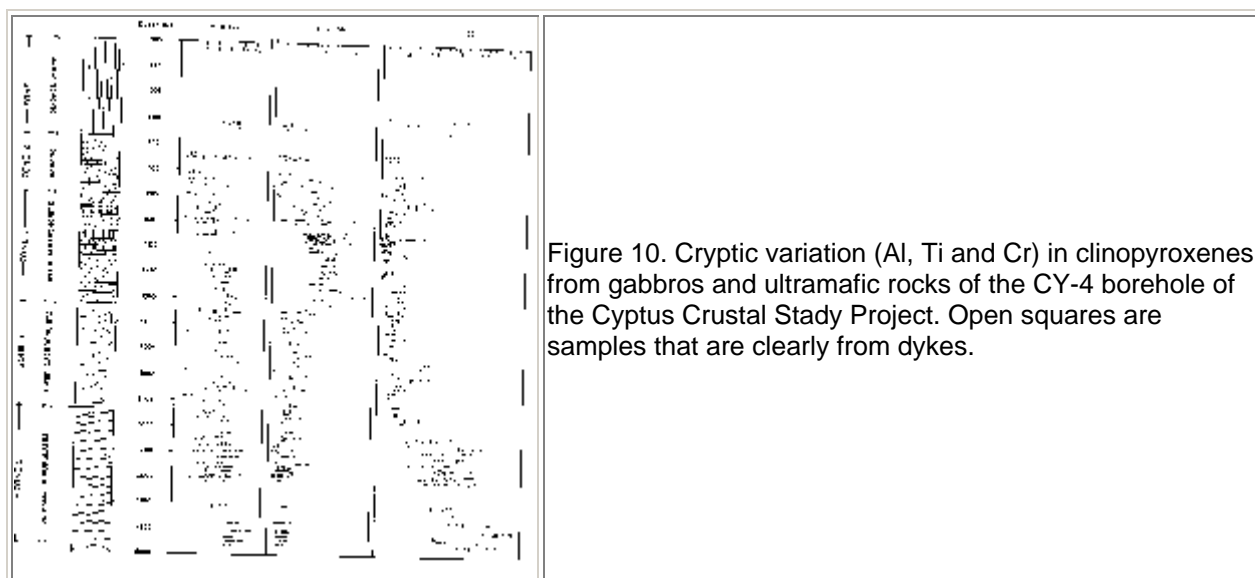


Figure 10. Cryptic variation (Al, Ti and Cr) in clinopyroxenes from gabbros and ultramafic rocks of the CY-4 borehole of the Cyprus Crustal Study Project. Open squares are samples that are clearly from dykes.

These magma chambers are currently represented by the small ultramafic plutons in the upper parts of the plutonic sequence (Malpas and Langdon, 1984).

Large (500-1000 metres wide) epidosite zones at the base of the sheeted dykes are believed to represent hydrotherm reaction zones directly above the high level plutons. Fluid inclusions in these rocks suggest reaction temperatures close to 350° (Cann et al., 1987; Schiffman et al., 1987) and in some cases higher (Malpas, unpublished data; Kelley and Robinson in press). The rocks are strongly depleted in Na, K, Ca, Rb, Cu, Zn and Mn, such that a zone about 2 kilometres long could provide the necessary metals for a large sulphide orebody (Richardson et al., 1987). Calculated fluid compositions are remarkably similar to those from modern black smokers but are relatively enriched in Fe, Cu and Zn, which may explain why the Troodos deposits are larger than most of those forming around modern vents.

These reaction zones are believed to pass upward through cylindrical alteration pipes into stockwork zones directly beneath the orebodies. Detailed study of one such stockwork zone beneath the Agropia B ore deposit, which was sampled in CCSP Hole Cy-2a, has revealed a silicified and argillized zone underlain by a propylitic transition zone which, in turn, grades downward into a subgreenschist zone. The latter is largely confined to a zone of dykes in the lower few hundred metres of drill-hole Cy-2A. Mineralization is in the form of pyrite-quartz veins and disseminated pyrite, locally accompanied by small amounts of sphalerite, chalcopyrite, and pyrrhotite. Unlike many of the Troodos deposits, the Agropia B orebody is a replacement deposit formed by mixing of high temperature (350°C) hydrothermal fluids and cold seawater in the upper part of the lava pile.

Hydrothermal alteration in Troodos is highly variable being extensive only in the sheeted dykes. These are pervasively altered to assemblages of albite + actinolite + titanomagnetite +/- chlorite +/- epidote, characteristic of the actinolite facies of Eithon and Stern (1978). In the extrusive rocks, high temperature alteration is restricted to the narrow stockwork zones directly beneath the orebodies and in the plutonic sequence to narrow fractures and veins.

The lavas have been subjected to variable degrees of low temperature alteration, the extent of which is controlled largely by permeability. Gillis and Robinson (1988) have defined a series of subhorizontal alteration zones in the lavas and correlated these with similar zones from in situ oceanic crust. These are: 1) a seafloor weathering zone characterized by oxidative alteration, high water/rock ratios and very low temperatures, i.e. ambient seawater, 2) a low temperature zone with moderate to low water/rock ratios and moderate temperatures (0-50°C), 3) a transition zone characterized by moderate to low water/rock ratios and moderate temperatures (50-100°C), 4) an upper dyke zone which has low water/rock ratios and temperatures (100-200°C) and 5) a mineralized zone which includes the massive sulphide deposits and associated mineralized stockwork zones. This zone is characterized by very high water/rock ratios and temperatures probably between about 100-300°C.

Origin and emplacement of Troodos

The many arguments over the tectonic environment in which the Troodos ophiolite formed have revolved around two main points: the geochemistry of the lavas and the regional geological relationships.

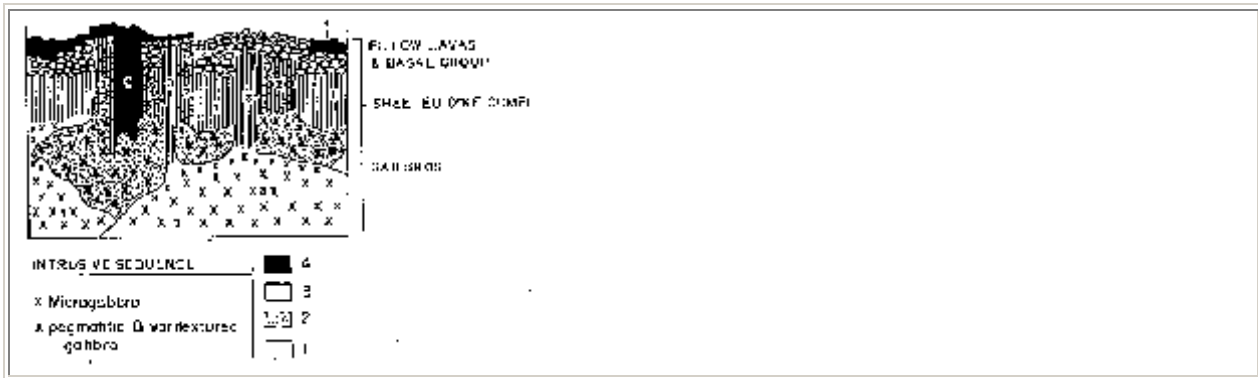


Figure 11. Schematic diagram of relationships between the sheeted dyke complex and the underlying gabbros showing how dykes may cut gabbros, emanate from gabbros, or be truncated by gabbroic plutons.

As outlined here, the lava geochemistry is now firmly established. Fresh volcanic glasses have provided data on original melt compositions, unaffected by alteration. The three magmatic suites previously defined all show geochemical signatures characteristic of formation above a subduction zone. We know of no other environment in which a source material depleted in high field strength elements can be selectively enriched in low field strength elements such as Sr, Ba, K and Th. Oxygen isotopic studies of the glasses by Rautenschlein et al. (1985) and Rautenschlein (1987) clearly show that this enrichment is not a secondary phenomenon related to alteration. Thus, we believe that the available data establish unequivocally that the ophiolite formed in a supra-subduction zone environment.

It is more difficult to determine the precise environment of formation within this broad zone. Comparison of geochemical data on Troodos lavas with those from modern subduction zones argues for formation in an arc or forearc. There are very close similarities between the rocks of the Marianas Arc of the Western Pacific Ocean and the boninites of Troodos which are CaO-rich, SiO₂-poor varieties similar to those found on the island of Guam. Backarc lavas in modern subduction zones have distinct geochemical signatures, and differ significantly from the Troodos lavas.

Can an arc or fore-arc origin for Troodos be reconciled with the regional geology? Much has been made in the past of the fact that there are no pyroclastic or epiclastic volcanic deposits in Troodos, as would be expected from an arc volcano (Gass et al., 1975; Moores, 1975; Hynes, 1975). Only the Kannaviou Formation of southern Cyprus contains both pyroclastic and epiclastic volcanic detritus. This formation, which is Maestrichtian in age and overlies the members of the Perapedhi Formation, consists of bentonite with interlayered volcanic sandstone and siltstone. As such, it may record an episode of explosive volcanism, but it postdates the Troodos massif and appears to be independent of it.

Another argument that has been used to oppose an arc origin is that the sheeted dyke complex clearly indicates that Troodos formed in an extensional environment and that only backarc basins are zones of spreading. We now know, of course that spreading can take place within arcs and that arc splitting is a common process.

We believe that the seemingly disparate geochemical and geological data can be integrated into a viable model for the development of Troodos and associated formations, the basic elements of which were proposed by Moores et al. (1984) This model postulates the following geologic history.

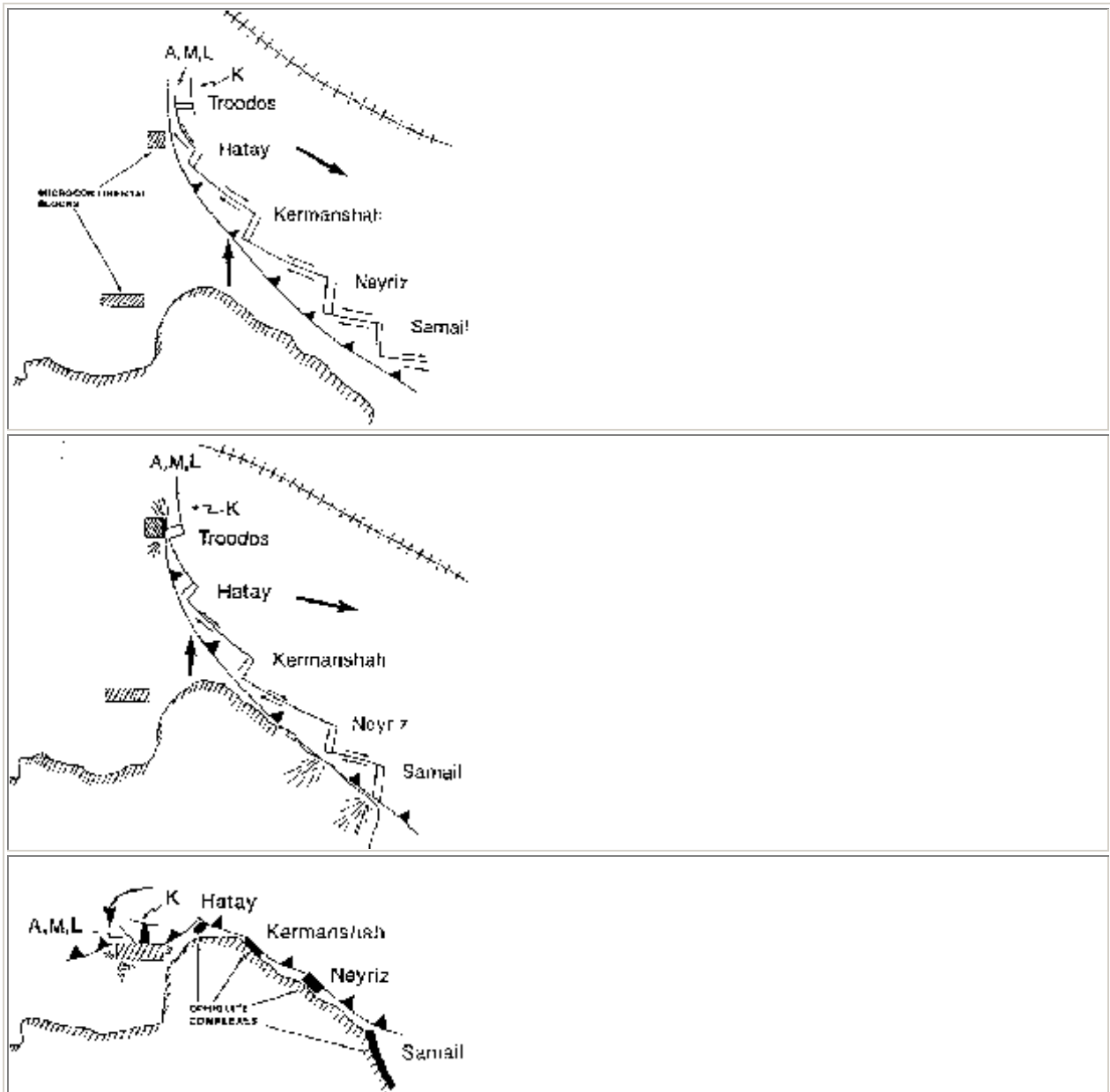


Figure 12. Development of the eastern Tethyan ophiolites in a supra-subduction zone environment caused by the oblique subduction of the north African plate and offset SSZ spreading (after Moores et al., 1984).

The Late Triassic was a period of continental rifting along the northern margin of Gondwana that gave rise to the Mesozoic Tethys Ocean. By Upper Triassic time, the ocean in the Oman region had an estimated half-width of 300 kilometres (Graham, 1980) but no Triassic ocean floor is recorded in the form of intact ophiolites. Remnants of old ocean floor might, however, be represented by the amphibolites of the Mamonia Complex in southwestern Cyprus (Malpas et al., in press). The rifting of the north Gondwana margin gave rise to a number of small ocean basins which were underlain by either true oceanic crust or attenuated and modified continental crust. These basins contained both microcontinental blocks and intraplate volcanic islands arc atolls that formed on the ocean floor. Passive margins were developed during the Jurassic and Early Cretaceous in the Cyprus region, but by Late Cretaceous time a young northeast-dipping, intra-oceanic subduction zone developed above which the oceanic crust now preserved as the Troodos ophiolite was formed. During Turonian time (Blome and Irwin 1985) some 200 kilometres of spreading took place above this subduction zone in an essentially pre-arc setting. The Arakapas fault represents a fossil transform formed in this spreading environment (Murton and Gass, 1986).

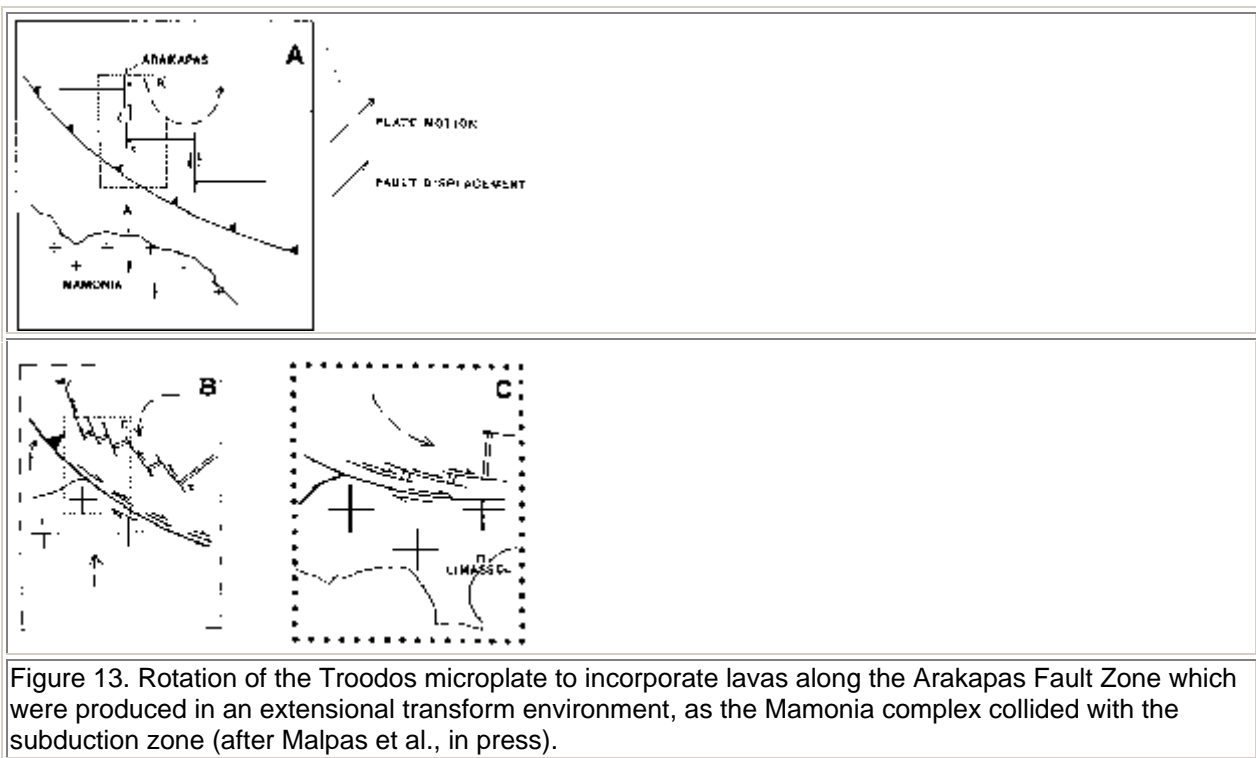
Almost immediately following its formation, the Troodos microplate commenced a counter clockwise rotation that finally amounted to some 90°. This appears to have been in response to

attempted subduction of a microcontinental sliver (Moore et al., 1984), or to the collision of the Arabian margin further to the east (MacLeod, 1988). During this period, the ophiolite remained submerged and was covered by a series of pelagic sediments.

Moore et al. (1984), therefore, postulate that Troodos formed at a spreading axis or axes above an oblique subduction zone and suggest that the Andaman Sea may provide a modern example (Figure 12). Highly oblique subduction would mean that plate consumption would be relatively small and presumably this would be reflected in the volume of arc-type magma produced. The nascent or immature arc formed above such a subduction zone would not develop large centre volcanoes but would instead form a thin crustal section. The spreading zone would thus be in relatively deep water allowing deposition of pelagic material on top of the ophiolite.

In this model, the Mamonia Complex of southwestern Cyprus is a complex terrain brought into proximity with the Troodos ophiolite by subduction processes. It represents collapsed passive margin and oceanic atoll assemblage that was juxtaposed against the ophiolite along strike-slip fault developed during rotation of the Troodos microplate (Swarbrick, 1980). It appears that the Arakapas Fault acted in part as a site of plate rotation such that characteristic high Mg depleted lavas of suite C were trapped along the suture between the Troodos and Mamonia terrains (Figure 13) (Malpas et al., in press; McLeod, 1988).

Uplift of Troodos to its present position took place episodically but was initiated about 20 million years after formation (Staudigel et al., 1986) and increased markedly in Miocene time (MacCallum and Robertson, this volume).



Summary

The Cyprus Crustal Study Project of the International Crustal Research Drilling Group has provided an opportunity to reinvestigate a range of geological problems associated with the Troodos ophiolite. It appears clear now that the ophiolite was produced at a consuming plate margin by crustal extension above a subducting lithosphere slab. The processes whereby the oceanic crust was accreted in this environment involved multiple magma chambers which, for the most part, developed independent of one another and which contained magmas derived by

partial melting of mantle sources with different degrees of depletion. These magma chambers produced a sheeted dyke complex and associated volcanic rocks at a series of spreading axes now recognized on the basis of dyke domains. The oceanic crust represented by the Troodos ophiolite was altered extensively at the sheeted dyke level but to a lesser extent and only locally in the extrusive rocks. Most of the sulphide orebodies lie in fault grabens associated with the old spreading axes and the metallic elements appear to have been derived by hydrothermal reactions in zones at the base of the sheeted dyke complex.

Troodos has been regarded as one of the classic occurrences of the ophiolite assemblage. The fact that it originated in a supra-subduction environment now begs the question of its correlation with oceanic crust formed at modern mid-ocean spreading ridges. However, it is quite possible that although the rocks are chemically distinct, the processes of crustal accretion in the two environments, especially where spreading rates are slow, are essentially the same. Conclusive proof is obviously required by deep drilling of in situ oceanic crust.

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