## AGU Chapman Conference

# Detachments in Oceanic Lithosphere: Deformation, Magmatism, Fluid Flow, and Ecosystems

## *Field Handbook, May 2010*

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## Introduction

The Troodos ophiolite is a nearly intact mid-Cretaceous (91 million year old) slice of oceanic crust, exposed over an area of 40 by 100 km in the Troodos mountains of Cyprus and the foothills around them. Access by road to all parts of the ophiolite is straightforward. Troodos was one of the first ophiolites to be studied in detail and has had a profound influence on thinking about the ocean crust (see Cann 2003 and other papers from GSA Special Paper 373 in the reference list below). For example, it was in Troodos that Ian Gass (Gass, 1968) first recognised that the sheeted dyke complex there was de facto evidence for seafloor spreading, and that ophiolites thus represent on-land fragments of oceanic lithosphere.

The Troodos complex is particularly well known for its lava sequence which lacks any late metamorphic overprint, a superbly exposed sheeted dyke complex (Varga 2003), hydrothermal alteration including epidosites, and a large number of small massive sulphide deposits. In the three days of fieldwork for this meeting we will give a general overview of the ophiolite, and then concentrate on low-angle fault structures that may (or may not) have been formed in similar ways to oceanic detachments. If you are interested in other features of the ophiolite we recommend the excellent new field guide by Edwards et al. (2010) which, if you have a few days to spare before or after the conference, will guide you to many classic localities that we will not have time to visit.

The Troodos ophiolite was formed in a supra-subduction zone environment, as shown by lava geochemistry (Pearce, 2003), in a small ocean basin within the complex Tethyan ocean domain (Robertson et al., 1991). The spreading centre ran E-W at the time of crustal creation, but the ophiolite was rotated 90° anticlockwise soon afterwards, at the end of the Cretaceous. Now the general trend of the sheeted dykes runs N-S and the Arakapas Fault Belt, thought to be either a discrete transform fault or the northern edge of a broad transform-related domain, trends E-W. The low relief of the lava surface beneath the sedimentary cover (most of the fault scarps are less than 20 metres high) suggests that the spreading rate may have been greater than 60 mm/yr full rate, while the complexity of the gabbroic units suggests that the spreading rate was slow; an intermediate spreading rate seems a good estimate.

The ophiolite can be divided into three regions:

1) The main Troodos Massif north of the Arakapas Fault Belt, which preserves a Penrose-type ophiolitic stratigraphy, but with some complications as we shall see,
2) The east-west Arakapas Fault Belt, interpreted as the northern margin of a fossil transform fault or as a discrete transform fault,
3) The Limassol Forest Complex, south of the Arakapas Fault Belt, in which similar lithologies to those of the main Troodos Massif are seen, but in complex structural relationships with one another, including low-angle extensional faults. As you will see, the interpretation of this area is subject to intense controversy.

We will spend the first field day in the Troodos Massif and the other two in the Limassol Forest and to a small extent the Arakapas Fault Belt. Through the generosity of the Geological Survey Department of Cyprus, we are able to provide all of you with copies of their Limassol Forest maps, the results of mapping by Chris MacLeod and Bramley Murton whilst PhD students of Ian Gass at the Open University. When you see the terrain you will see what a Herculean task this was!

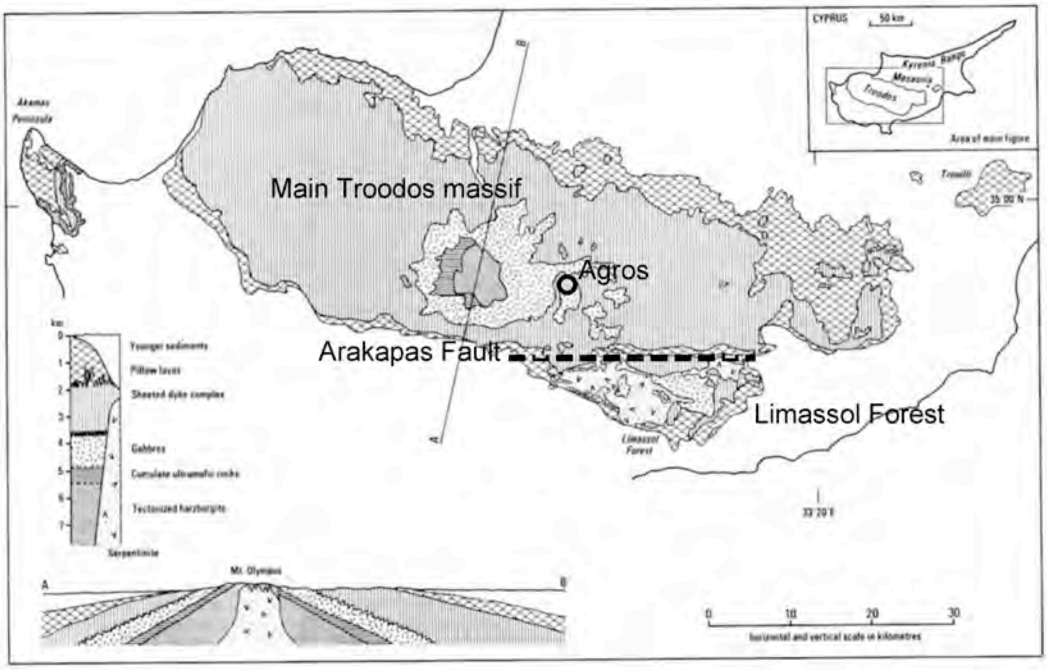
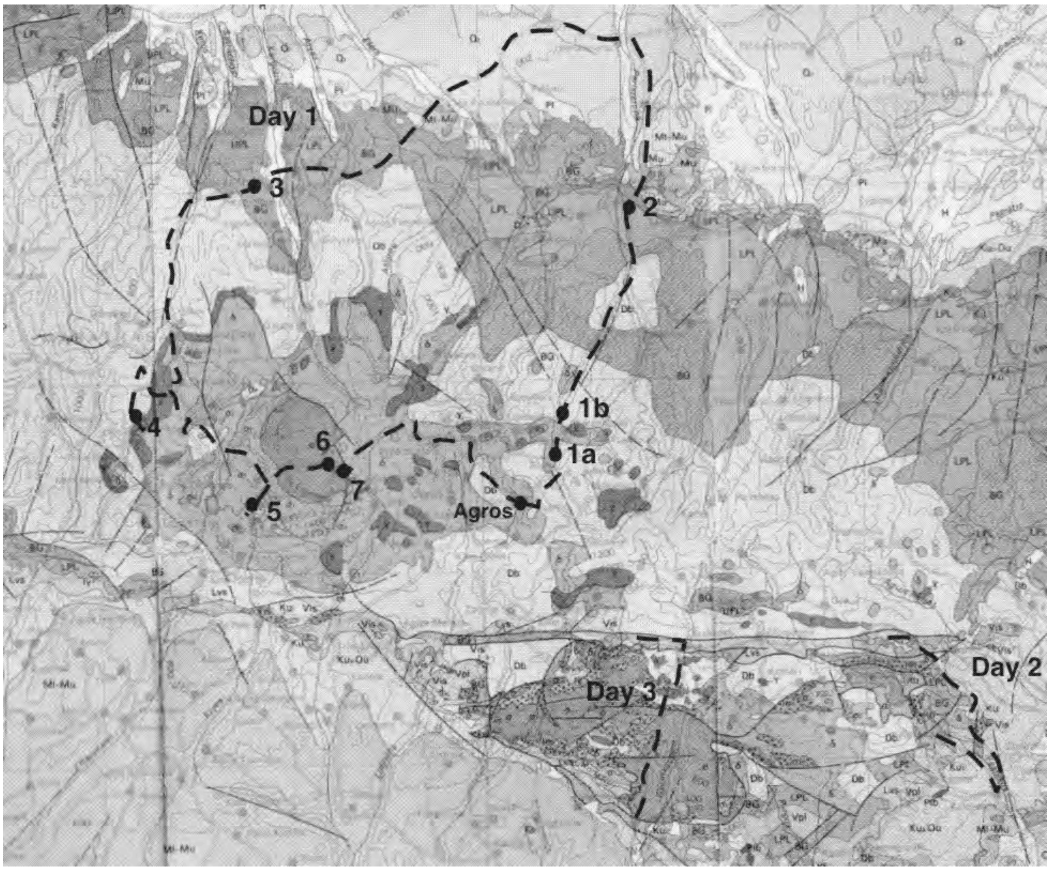


Figure 1: Outline geological map of Cyprus showing the three areas to be visited (adapted from Gass, 1980)



## *Troodos Massif*

The overall stratigraphy of the main Troodos massif is relatively simple. Submarine volcanics overlie sheeted dykes that in turn overlie an upper plutonic unit composed principally of gabbros. This in turn overlies a unit of mantle peridotite. Sulphide deposits occur within the lava section and related deposits of umber overlie the lavas. The structure is dome-like so that the deepest parts of the stratigraphy occupy the central, topographically highest area (Fig. 1)

The **submarine volcanics** show a wide range of volcanic products (Schmincke and Bednarz, 1990).. These include pillow flows, sheet flows, breccias and hyaloclastites. Compositions range from basalts through to andesites, dacites and rhyolites, and include lavas allied to boninites (distinctive high-magnesium andesites otherwise found in intraoceanic forearcs). Individual lava flows can be identified and traced for several kilometres along strike. The lavas are cut by faults that displace the ocean floor only by tens of metres, but are associated in places with rotation of the dip of the lavas, which can be shown to have happened at the spreading axis. The thickness of the lavas is variable, but is typically about 1000 m.

Over much of its thickness, the **sheeted dyke** unit can be shown to be made up entirely of dykes intruding one another, a graphic demonstration of ocean floor spreading. The dykes range in width from narrow veins up to over ten metres, but the typical range of widths is from one to about five metres. Though some dykes intrude high into the lavas, the main transition from lavas to sheeted dykes happens over a vertical distance of only 100–200 m, as has been observed in oceanic drill holes, indicating crustal construction from a narrow zone of dyke injection (Kidd and Cann, 1974). Over much of the Troodos massif the dykes trend approximately north-south, indicating the orientation of the spreading axis during crustal construction. The direction of magma intrusion in the dykes varies from vertically upwards to horizontal, or sometimes even downwards (Staudigel et al., 1999). The dyke trend swings round to NE-SW and locally E-W towards the Arakapas Fault Belt. Palaeomagnetic data and cross-cutting dykes suggest that this is the result of clockwise rotation, soon after the dykes were formed, induced by dextral shear along the transform. The sheeted dyke complex is extensively deformed by brittle fracturing and generally metamorphosed in the greenschist facies.

Below the sheeted dykes, the **upper plutonics** are composed principally of layered and unlayered gabbro, with some ultramafic layers and veins of plagiogranite, apparently the result of extreme fractionation of basaltic magma. The plagiogranites are in places highly altered to epidote-quartz assemblages, apparently generated by magmatic fluids (Kelley and Malpas, 1992). The unit has a complex structure, with multiple intrusive relationships that can well be seen in the field (Malpas 1990).

At least three distinct relationships between dykes and gabbros have been described in the Troodos Massif. At some localities the transition is gradual over a few hundred metres, with vertical dykes separated by gabbro screens becoming thicker and coarser grained downwards, while still showing chilled margins. Elsewhere there is a sharp boundary, with the gabbros intruding and metamorphosing the dykes (Gillis and Coogan, 2002) (as described from ODP Hole 1256D). Finally there is an extensive area in the NW where dykes rotated to low angles are separated from gabbros by a low-angle brittle fault, the Kakopetria detachment. We will examine an outcrop of this type on field day 1. The hotel in Agros lies within the upper plutonics. Gabbros outcrop just beyond the hotel grounds. North of the hotel there is an excellent view of a gabbroic ridge capped by sheeted dykes (Fig. 2).

Fig. 2 Gabbro-dyke boundary above Agros

The **lower plutonics** are dominated by ultramafic and, to a lesser extent, gabbroic rocks, often layered. They grade downward into pyroxenites and massive dunites that form a thick crust-mantle transition zone.

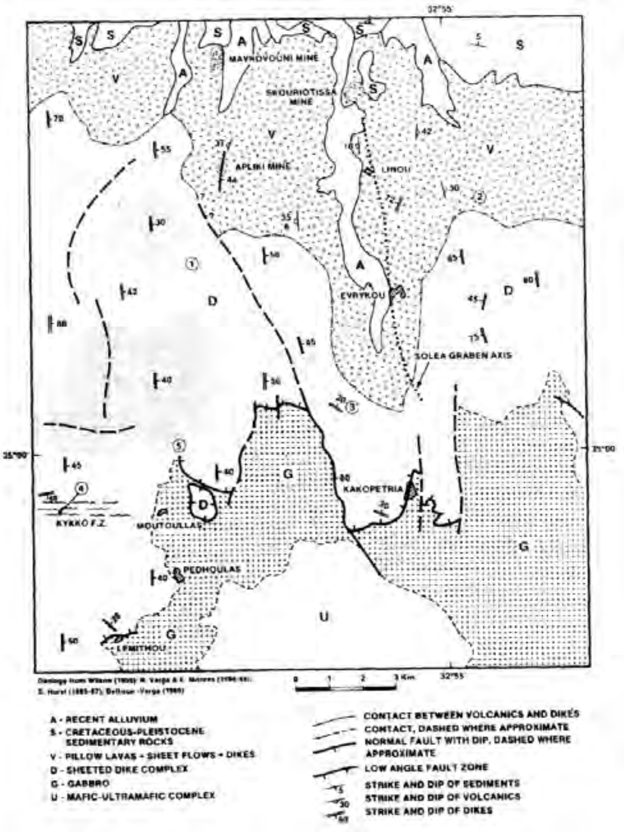
The **upper mantle**, composed of partially serpentinised harzburgite, dunite and pyroxenite, is exposed around the peak of Mount Olympus, and there are excellent localities showing evidence of percolation of magma through mantle harzburgites. Chromite was mined from the mantle section, and the relationships can be seen between chromite ore and host mantle. Peridotite pervasively altered to serpentinite forms a ’bullseye‘-shaped unit at the east side of the mantle massif. The formation of this unit is controversial. Its chromites have distinctly different compositions to all other Troodos peridotites. The circular outcrop is underlain by a large negative gravity anomaly, constraining the body to have a pipe-like form. It is conventionally regarded as being the result of doming during uplift of the ophiolite during the Neogene, probably linked to diapiric intrusion related to volume increase during hydration. However, it has recently been suggested that the steep reverse fault that bounds the east side of the serpentinite (the Amiandos Fault) was the steep part of an oceanic detachment fault formed during crustal construction, possibly connecting with the shallow Kakopetria Detachment (see below) between the dykes and the gabbros. We will visit an exposure of the Amiandos Fault on the first excursion. In places within massifs of serpentinite both here in the main Troodos area and in the Limassol Forest, there are springs of cool calcium-rich, alkaline fluids produced during continuing serpentinisation of the peridotite. These springs are analogous to the Blue Pool springs of Oman and the Lost City vents at 30°N on the Mid-Atlantic Ridge.

During crustal construction, **black smoker circulation** was common. Pyrite-rich exhalative sulphide deposits occur within the lavas at different levels, and were mined for copper and/or sulphur. Their exhalative nature can be demonstrated by associated sediments formed by seafloor weathering of the sulphides, and by the presence of fossil worm tubes and gastropods within the sulphides. We will get a view of the Skouriotissa sulphide deposit on the first excursion and you will have a chance to enter the Mavridhia pit of the Kalavasos mining district on one of the two Limassol Forest days. Beneath the sulphide deposits are alteration pipes that reach down to the top of the sheeted dyke unit through which hydrothermal solutions rose to the seafloor. Near the base of the sheeted dykes are extensive high-temperature hydrothermal reaction zones marked by development of epidosites (epidote-quartz rocks) within the dykes, and by depletion in Cu, Zn, and Mn (Richardson et al., 1987; Varga et al., 1999). The black smoker circulation took place very close to the ancient spreading axis, as can be shown by the burial of almost all of the sulphide deposits within the lava pile, by the close association of the hydrothermal reaction zones with the dyke-gabbro boundary, and by field evidence that dykes were being intruded while hydrothermal circulation was proceeding.

Iron and manganese-rich **hydrothermal sediments (umbers)** occur in many places on top of the lava sequence, and occasionally within it. Within hollows or in half-grabens their thickness may reach 35 metres, but most deposits are less than 10 metres thick. These sediments are interpreted as fallout from black smoker plumes, formed by oxidation of the iron sulphide black smoke particles in the water column and by adsorption of hydrothermal manganese from the diluted hydrothermal solutions onto the newly formed iron oxides. They subsequently accumulated on the seafloor and were preserved in hollows in the seabed. By analogy with modern systems, accumulation rates of the umbers were probably fastest close to the vents, and just beyond the limit reached by lava flows, though accumulation may have continued for several million years at ever-decreasing rates as the crust spread away from the spreading centre.

**Low-temperature circulation** continued for several tens of millions of years after crustal construction. This has been documented by K/Ar dating of low-temperature alteration minerals such as celadonite (Staudigel et al., 1986). In areas where the seafloor was not covered by sediment for a long time, low-temperature circulation produced oxidative alteration of the basalts with the development of orange palagonite and carbonates (Gillis and Robinson, 1990). Deeper in the section in these same areas, alteration becomes more reducing and less pervasive, so that fresh basaltic glass remains in pillow margins. As temperature of alteration increases with depth, it can be difficult to distinguish later alteration from early black smoker alteration once the sheeted dyke complex is reached.

Several **structural grabens** have been identified in the main Troodos massif, mainly by the rotation of dykes in the sheeted dyke complex. The most marked one of these is the Solea Graben that we will be visiting on the first day trip. On either side of this the dykes dip towards the graben axis, implying rotation in the hangingwall ‘bookshelf’, probably listric, faulting above a low-angle fault located at the gabbro-dyke boundary (Varga 1991, Hurst et al., 1994). This low-angle structure has been termed the **‘Kakopetria Detachment’**. The rotation is especially large on the west



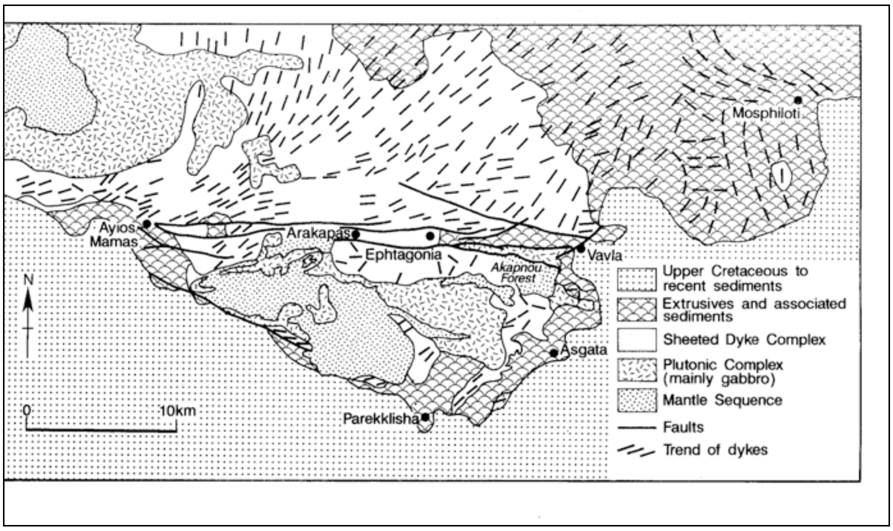
side of the graben axis, where the dykes may dip at less that 30° towards the east. This rotation can be shown to have happened very early in the history of the ophiolite, during the construction of the oceanic crust, but after the epidotisation that happened very soon after dykes were intruded. These and other structural observations have led the Solea graben to be interpreted as an extinct spreading axis within the ophiolite, though its overall morphology is rather different from extinct spreading axes in the oceans. It is clear that this region has seen major extension, and an important question is whether this extension is or is not related to detachment faulting of the type seen in the oceans. The lack of displacement of the uppermost lavas by the faults within the grabens, and the lack of significant mass wasting deposits in the lava sections, is hard to reconcile with the large rotations of the dykes. These relationships are apparently at odds with observations from slow spreading ridges, such as the Atlantic, where large fault-related rotations have been observed.

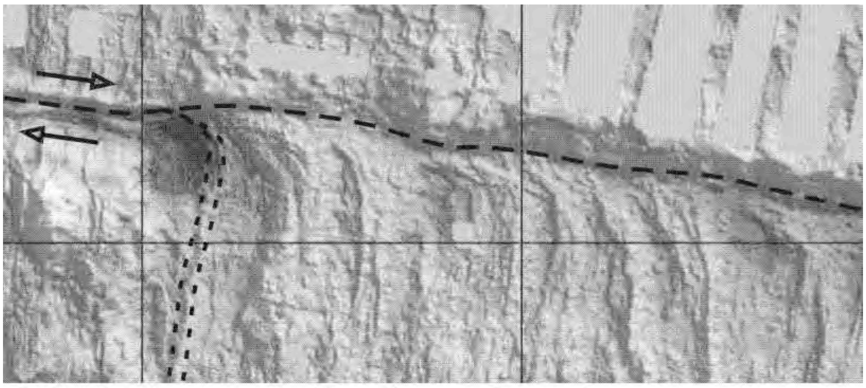
## *Arakapas Fault Belt*

The Arakapas Fault Belt runs east-west along the southern edge of the Troodos massif. It forms a prominent linear valley that is clearly visible today, on the ground or from space. The fault belt is about 1 kilometre wide and was identified as a **transform fault** by Moores and Vine (1971). It runs at right angles to the dyke trend and is blanketed by overlying pelagic sediments, so was clearly an ocean-floor structure. Soon after, Simonian and Gass (1978), showed that the fault belt formed a topographic trough at the time the ophiolite was forming. The basement of the fault zone is made of highly deformed and metamorphosed sheeted dykes. Part of the fill is of lavas, most of which belong to a geochemically distinctive boninitic lava series with highly depleted compositions and U-shaped rare-earth element profiles. These lavas are generally unaltered, with abundant fresh glass. The other component of the fill is sedimentary. The sediments are interbedded with the lavas and range from proximal coarse polymictic breccias to turbiditic sandstones and fine-grained sediment dominated by reworked umber. The breccias contain clasts of lava, diabase from the sheeted dykes and very rare fragments of microgabbro. These indicate considerable relief on the walls of the transform valley but not enough to expose mantle rocks or the main plutonic sequence. The fill of the trough is locally cut by fault strands, but is otherwise significantly less deformed than the basement.

At many modern transforms the trends of the volcanic ridges and faults created at the spreading axis curve progressively towards the opposite ridge crest as the fault is approached (the ridge offset being in the opposite sense to the slip direction on the transform fault). This swing in direction is usually taken to be caused by rotation of the stress field from extensional to strike slip as the fault is approached, and the formation of extensional faults and dykes in this rotated stress field.

In the Troodos Massif, the strikes of the dykes and faults swing progressively from north-south to NE-SW as the Arakapas Fault Belt is approached, on much the same scale as the deviation of abyssal hill trends in the oceans. By simple analogy with modern transform systems this dyke swing should therefore imply dextral offset of the ridges and sinistral slip along the Southern Troodos Transform Fault Zone. However, this analogy raises a conundrum, as steep serpentinite shear zones within the Limassol Forest Complex show kinematic indicators of dextral strike-slip movement.





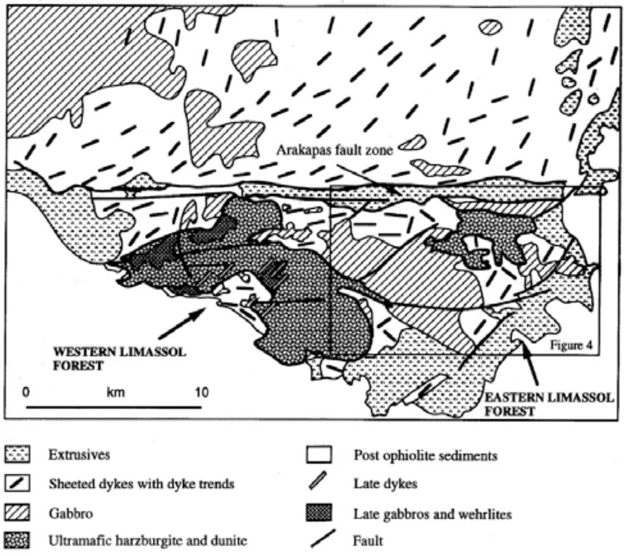
Volcanic ridges near the Kane Fracture Zone 0 ——— 10 km

Palaeomagnetic measurements from NNE- to NE- to ENE-trending dykes in the area of dyke swing in Troodos demonstrate clockwise rotations about vertical axes, clearly showing that the deviation of dyke trend was caused by the bodily rotation of dykes subsequent to their intrusion, rather than by intrusion of dykes into a rotated stress field (Bonhommet et al., 1988; Allerton and Vine, 1990; Morris et al., 1990). This, however, raises an interesting question: why should the swing of dyke trends in Cyprus be opposite to the sense normally seen in the oceans? Does this imply greater coupling across the Southern Troodos Transform Fault than at modern oceanic transforms? We cannot answer these questions definitively, but do note that in very rare cases at modern transform faults (e.g. Clipperton, Bullard) the block rotation sense of curvature is observed, i.e. abyssal hill fabrics swing inwards towards the (orthogonal) ridge-transform intersection.

## *Limassol Forest Complex*

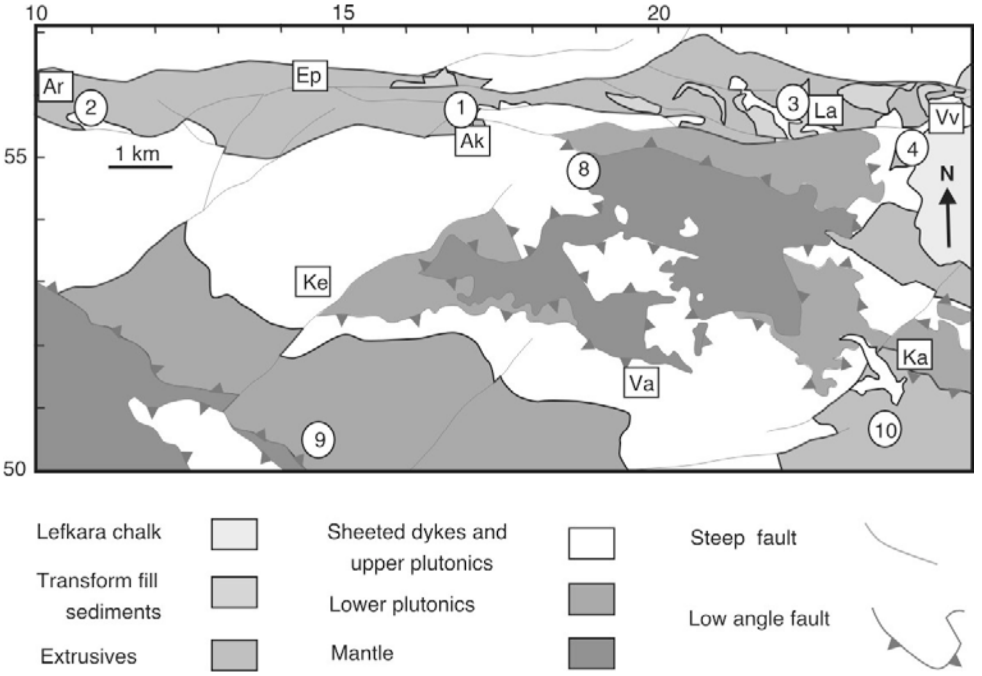
The Limassol Forest Complex lies south of the Arakapas Fault Belt. It contains the same lithological units as the Troodos Massif, but without the simple layered stratigraphy seen there; instead, the units are juxtaposed in a complex way, with very significant levels of brittle faulting. The area was first mapped (at 1: 5000 scale) and investigated in detail in the mid-1980s by Bram Murton and Chris MacLeod (both PhD students of Ian Gass), in the western and eastern halves of the region respectively. This work formed the basis of the Cyprus Geological Survey Department Memoir No. 9 (Gass et al., 1994) and accompanying 1: 25,000 scale geological maps.

Figure 3



In the eastern Limassol Forest a wide range of crustal units, ranging from lower crustal plutonics up to sheeted dykes and lavas, is in direct contact with serpentinite with large parts of the crustal section missing over much of the area. These gaps in the stratigraphy suggest the presence of large-scale extensional faulting. The northeastern Limassol Forest, centred on the Akapnou Forest region, shows the relationships particularly well. These can be simplified into a basement unit of serpentinised harzburgites and dunites overlain tectonically by overlapping, crustal blocks bounded by gently SW-dipping normal faults. The boundary between the serpentinites and the tilted crustal blocks is a low-angle extensional detachment fault, termed the **Akapnou Forest Décollement** by MacLeod.

This fault is gently domed and steepens to near-vertical as it approaches the Arakapas Fault Belt. It can be traced for more than 10 km and has accommodated a considerable amount (≥ 2-3 km) of extension with an apparent top to the SW transport direction. Lavas within the crustal blocks are tilted steeply, mostly dipping towards the northeast. These lavas include boninites, so that this structure was active subsequent to the extrusion of boninitic lavas but at the same time as the umbers were accumulating, i.e. immediately following the local cessation of volcanism. Palaeomagnetic results from the highly tilted hanging wall blocks demonstrate consistent NW-trending sub-horizontal rotation axes.



In the western Limassol Forest significant areas of serpentinised mantle rocks are exposed as a number of domes, elongated east-west, juxtaposed by extensional faults against disrupted remnants of a layered crustal sequence, including gabbros, sheeted dykes and in places lavas. Large parts of the crustal section are missing. Major vertical serpentinite shear zones trending predominantly east-west with dextral strike-slip shear indicators cut the serpentinite. Some of these are up to 500 m in width and may be traced along strike for more than 5 km. Ultramafic and mafic plutons, together with associated (usually NE-trending) dykes, cut the serpentinised mantle sequence and disrupted crustal blocks. Most of the dykes have been partly replaced by greenschist facies minerals and/or rodingitised. The plutons are composed of gabbro and wehrlite and have been much less serpentinised than the mantle harzburgite and dunite that form the basement. The dykes share the distinctive boninitic compositions with U-shaped rare-earth element patterns of the lavas erupted within the Arakapas Fault Belt. Because of their geochemical similarities with the lavas of the Arakapas Fault Belt, these were termed ‘Transform Sequence’ magmas by Murton, and interpreted by him as have been intruded syn-tectonically into the active domain of a broad **Southern Troodos Transform Fault Zone** that would stretch south from the Arakapas Fault Belt. The sequence and style of intrusion, and of alteration grade, is consistent with progressive cooling and uplift during the syn-tectonic magmatism in the western Limassol Forest. At the southern edge of the western Limassol Forest, clasts of serpentinite are found in sediments interbedded with lavas faulted against serpentinite. This indicates that serpentinite was already exposed at the sea floor at the time of the eruption of the lavas.

The western part of the Limassol Forest has mostly been eroded to deeper levels than in the east following Miocene uplift (see below), but there are places where we have recently identified a similar low-angle fault that separates serpentinite beneath from sheeted dykes above. The low-angle faults demonstrably postdate and truncate the steep serpentinite shear zones. We have not yet investigated the low-angle faulting in the western Limassol Forest in any detail, but it may well represent a previously unrecognised continuation of the Akapnou Forest Décollement.

In the eastern Limassol Forest, north of the Kalavasos Mines region, clastic sediments are interbedded with volcanics, though south of the Kalavasos Mines such interlava sediments disappear. Deformation of this southern area is also significantly less than anywhere else in the Limassol Forest Complex, such that the ~45km$^2$ area of volcanics and (NE-trending) sheeted dykes exposed in the southeastern corner of the Limassol Forest massif is similar in overall appearance to upper crustal sequences of the main Troodos Massif. These observations together led MacLeod to conclude that the volcanics and (NE-trending) sheeted dykes exposed in the southeastern Limassol Forest (and probably also those disrupted crustal blocks in the remainder of the Limassol Forest) were generated at an **'Anti-Troodos'** ridge axis, on the opposite side of the transform zone from the main Troodos Massif. Palaeomagnetic studies of the NE-trending dykes in this Anti-Troodos region are consistent with early clockwise rotations about steeply-plunging axes. These rotations may have been induced by drag adjacent to a dextral transform and, as such, to be directly analogous to the dyke swing north of the Arakapas Fault Belt.

Tectonic interpretation of ocean-floor processes in the Limassol Forest area is made (even!) more difficult by several later deformation episodes. WNW-trending extensional structures cut the Akapnou Forest Décollement and rotated crustal blocks in the eastern Limassol Forest, and were reactivated as dextral strike-slip faults in the south at the same time as the Troodos microplate was rotated anticlockwise in the Campanian-Maastrichtian. A WNW-trending Miocene fold and thrust belt – probably reactivating late Cretaceous lineaments – runs along the southwestern margin of the massif, and locally results in serpentinites being thrust over Palaeogene chalks. This deformation is associated with the first stages in the uplift of the ophiolite – which was initially centred on the Limassol Forest block – and post-dates crustal construction by over 60 million years. Though the effects of this Miocene deformation are most significant in the southwestern Limassol Forest, reverse faulting is also present around the periphery of the Akapnou Forest serpentinised peridotite massif in the northeastern Limassol Forest. The latest identifiable generation of faults – north-south trending extensional structures, some associated with gypsum – cut the Akapnou Forest Décollement and further complicate the geology of the Limassol Forest. Such structures also cut recent river terraces nearby and are present elsewhere in Cyprus (e.g. the Polis graben at the western end of the island), attesting to a phase of deformation that probably continues to the present day. The effects of all these later deformation episodes need to be carefully assessed and accounted for when attempting to interpret the ocean-floor tectonic processes operating here.

The interpretation of the tectonics in the Limassol Forest is controversial, and your field excursion leaders have very different views! The original mapping of the area was by Chris MacLeod and Bramley Murton. Their conclusions have evolved slightly since some of their earlier papers (e.g. Macleod and Murton, 1993). In essence Chris and Bram's current view (in brief) is that the Southern Troodos Transform Fault Zone became a transtensional structure, whilst in the active transform domain, thus focusing the boninitic magmatism there. This probably occurred in response to a change in regional spreading direction, as the latest sheeted dykes in the main Troodos Massif are NW-SE trending. They envisage the Akapnou Forest Décollement as forming very soon afterwards, immediately post-dating the (local) crustal construction of the ophiolite, in response to continued stretching that pulls the Troodos and Anti-Troodos domains apart. Critically, to them, the Akapnou Forest Décollement develops in response to NE-SW extension, and the rotated bookshelf faults that bound the klippe in the hanging wall are reactivated, originally *transform*-parallel structures.

The alternative view is that of Joe Cann and his colleagues (Cann et al., 2001) which has also evolved since publication. Currently his view (also in brief) is that the detachment faulting is related to the generation of oceanic core complexes by spreading-direction parallel extension *during* crustal construction, though the detachment faults may have been reactivated at a later date. The spreading-parallel faults in the west Limassol Forest would then be related to exhumation of core complexes and not to transform tectonics. The presence of serpentinite clasts in interlava sediments is evidence for early exposure of serpentinite at the sea floor, and hence for an early start to the tectonics of the area. This conclusion is supported by the metamorphism of dykes intruded into the serpentinite, indicating a host rock still hot from the mantle. The detachment faults would then have capped core complexes, though not all would have been exposed at the sea floor, and would, as in modern core complexes, have rolled over to steep dips close to transform faults. Later reactivation would explain many of the other observations.

This sets the stage for what may well turn into some intense discussion on the outcrop!

On the field days we will be examining a wide range of problems within the ophiolite. Although it is important to be cautious about making parallels between ophiolites and ocean crust, the opportunity to walk around far below the ocean floor gives crucial insights into processes taking place in the ocean crust. In the oceans these deeper crustal levels can be seen only in core from narrow drill holes, or through the porthole of a submersible on steep fault scarps half-covered with sediment. Whatever the nature of the ocean-floor processes that generated the complex tectonic structures of the Limassol Forest, and the Solea Graben, we have the opportunity to stand on, examine and debate the geological processes – at all scales – that are associated with a set of major extensional faults that can be clearly demonstrated to be oceanic in origin.

## Field Days

**Day 1 is in the Troodos main massif, north of the Arakapas Fault Belt, days 2 and 3 are in the Limassol Forest with a short visit to the Arakapas Fault Belt.**

### *Safety in the Field:*

As you know, AGU expects field trip participants to take personal responsibility for safety and you have all signed a waiver to this effect. Here are the main hazards you will encounter, with some basic advice we expect you to follow in the interests of both your own safety and that of the party. We will point out specific hazards at some localities.

1) The biggest risk is undoubtedly from road traffic. Cypriot drivers are supposed to drive on the left of the road but the middle is often favoured and they will not expect to see pedestrians. Please do not stand on the tarmac, and always keep an eye on traffic
2) Falling rocks – our advice is to look up before approaching any rock face and avoid anywhere with loose rocks above. Please do not climb up and dislodge rocks on people below
3) Rough ground – we will mostly work on road and tracks sections but there will be plenty of loose rocks underfoot and you should wear footwear with good grip and ankle support.
4) Weather - although it is normally dry in Cyprus in May, cold wet weather cannot be ruled out, and neither can hot sun. Come prepared with warm clothes, a hat and sunscreen, and take plenty of fluid with you in the field
5) Hammering – please do not hammer the outcrops, especially in key locations. If you want to collect specimens, loose rocks are always available, and please take great care not to hammer near other people
6) Animals – there are some poisonous snakes. Dogs can be vicious. Avoid the wildlife.
7) Plants – also vicious! Most of the vegetation is sharp and thorny. If you wear shorts and want to get up close and personal with the outcrops then expect to get scratched. Note also that oleander bushes, which are poisonous, are common. Avoid contact with them. The field course leaders will point them out to you if we come across them.

If you are injured or feel unwell, please tell the leaders immediately and we will summon help. If you have any pre-existing conditions that may affect your safety or that of others, please let us know

***Note:*** Somewhat inconveniently, Cyprus uses the European 1950 datum with UTM for all its base maps, including your geological maps. This grid is offset 35m to the east and 173m to the north with respect to WGS84, which is the most widely used datum and the typical default setting on a GPS receiver. The difference is sufficient on the 1: 25,000 Limassol Forest maps at least to be confusing. In this guide we quote all grid references first in WGS84 (for your GPS) and then *[Euro 1950] (for your maps)*, in the format (eastings, northings). All positions are relative to Zone 36 of the UTM Spheroid; hence, for simplicity, the figure '36' is omitted from the grid references given below.

## *Day 1: Main Troodos massif north of the Arakapas Fault*

Aims: (a) To introduce the field relations within the ophiolite north of the Arakapas transform fault, demonstrating the overall layer-cake structure of lavas over dykes over gabbro over mantle, and the processes that shaped it. (b) To show that the ophiolite has been very little deformed or heated since it was formed on the ocean floor, 91 million years ago. (c) To investigate the area of the Solea Graben where there is good evidence for very early major rotation of sheeted dykes on low angle faults during crustal construction, and where there is a possible extinct spreading axis. (d) To see one of the calcium-rich, alkaline (Lost City/Blue Pool type) springs indicative of active serpentinisation.

***A.*** *If you have the time, walk down to the entrance to the hotel car park and look at the exposure of gabbro by the roadside there. Look north from the hotel to the ridge of sheeted dykes. Can you see the fabric of the dykes towards the top of the ridge? The break in slope towards the foot of the ridge corresponds to the boundary between the dykes and the upper plutonics.*

***B.*** *Drive from Agros through gabbro, then through sheeted dykes, past Alona, then down the road towards Platanistasa and Nicosia.*

**Stop 1a.** About 1 km beyond Alona, stop at an outcrop of the gabbro-dyke contact in a new road cut (0503866, 3866245 WGS 84 *[0503901, 3866418 Euro 1950 – map]*). The contact here, as in many other places, is clearly intrusive, with the sheeted dykes metamorphosed by the gabbro and truncated by it. The field relations are not easy to see at a glance. The sheeted dykes here have been rotated to dip at a shallow angle (350°/55°E). They have a granular, hornfelsic texture and the chilled margins of the dykes are recrystallised. Farther down the road towards Platanistasa the dykes are more extensively recrystallised and cut by veins of plagiogranites that may be partial melts of the hydrous metabasalt. These contain angular fragments of the dykes. Nearby are outcrops of coarse-grained gabbro.

***C.*** *Drive down through Platanistasa towards Nicosia. Pass a road junction (to the left towards Polystipos) and continue down into the forest towards Nicosia.*

**Stop 1b.** About 5 km beyond the road junction, stop at a tall east-west road cut deep in the sheeted dykes (0505822, 3871448 *[0505857, 3871621]*). This is a very good place to examine sheeted dykes and understand how they form. Start at the west end of the roadcut. Here the sheeted dykes are very well-developed and relatively undeformed. First, examine the rocks closely to recognise the chilled margins of the dykes (many of the vertical cracks in the outcrop are not chilled margins, but joints). Now follow the outcrop to east or west, checking the chilled margins as you go. You should be able to demonstrate: (a) that all of the outcrop is made of dykes with chilled margins, and none of gabbro or lavas; and (b) that most of the dykes have both chilled margins present, even when they have been cut by a later dyke. Prolonged examination of this and other localities shows that about 10% of the dykes only have one chilled margin present, with the other part of the dyke rifted away, perhaps to the other side of the spreading axis.

Now cross to the other side of the road and walk eastwards along the road cut. The dykes are not exactly parallel, but cut across one another. Can you identify a relative intrusive chronology? If so, are steeper dykes are later than shallower dykes, or vice versa? Some dykes are green. These have been hydrothermally altered to epidote-quartz rocks (epidosites) by solutions flowing through the rock at black-smoker temperatures. Note that the alteration is confined to single dykes. What might this mean?

At the east end of the outcrop a major fault cuts through the dykes, running parallel to the dykes (and thus not obviously listric). The dykes on either side are shattered and cut by quartz- pyrite veins with some epidote, indicating that the fault had channelled hot hydrothermal fluid.

***D.** Drive about 9 km farther down the road to a road junction to the left signposted to Ayia Marina. This is very close to the village of Kato Moni.*

**Stop 2.** The outcrop is the road cut on the north side of the Ayia Marina road just W of the junction (0507743, 3879194 *[0507778, 38793667]*). Take care – the road is busy and the traffic drives fast (remember – look left!). Please don't try to climb up the road cut sides. You an see best from the road and all the units come down to the road side somewhere.

This stop demonstrates the variety of volcanic products formed by submarine eruptions in the Troodos ophiolite. At the road junction is a unit of gently-dipping pillow lavas, with the dip shown clearly by the shape of the pillows and their relation to each other. Although it is difficult to measure the dip and strike of a section of pillow lavas precisely, note how the general attitude can be determined, especially in '3-D' outcrops such as this.

Farther west the pillow unit contains a single columnar-jointed sheet flow. This is moulded over the tops of the pillows, showing that it is not a sill. Continuing west, the pillows become brecciated and oxidised in a wide damage zone in the hanging wall of a major E-dipping fault. The fault dips to the east and the fabric in the fault zone shows that it is a normal fault. The oxidation of its hanging wall shows that it has been a conduit for low-temperature fluid flow. Beyond the fault is a very different unit of volcanics. Much of this is made up of columnar-jointed sheet flows set in a matrix of volcanic breccia, a style of submarine volcanism very different from the normal pillows. At the far west end of the road cut is a unit of hyaloclastite, a sandy sediment composed of clasts of volcanic glass, perhaps formed by submarine fire-fountaining, perhaps by the successive fragmentation of a slowly flowing, highly viscous (probably siliceous) lava. The sheet flow unit is cut by a sill, almost parallel to the sheet flows, and also columnar-jointed. It can be demonstrated to be a sill by its cross-cutting nature and by its sharp chilled margins at top and bottom.

***E.*** *Drive on down towards Nicosia to the B9 near Peristerona, Turn left on the B9 towards Astromeritis and Troodos, and branch right onto the E908 towards Linou and the Marathasa Valley. Continue to the Flasiana viewpoint on the right opposite a café of the same name.*

**Stop 3.** Flasiana viewpoint (0488349, 3881070 *[0488384, 3881244]*). This stop introduces the Solea Graben and provides an overview of the graben and its contents. In the roadcut opposite the café and in outcrops beside the path up to the viewpoint are outcrops of dykes cutting lavas. The dykes are dipping at about 45-60°NE while the lavas dip at about 30°W. This locality is on the west flank of the Solea Graben. In roadcuts 5 km east of here, on the other side of the graben axis, the dykes dip west and the lavas dip east.

Walk up to the viewpoint. The contact between the lavas and the overlying sediments lies about 5 km north from here, in a region that is not currently accessible for political reasons. There is no morphological graben at the contact; the outcrop of the uppermost lavas continues straight across the graben axis. To the northeast are the dumps of the Skouriotissa opencast copper mine. The sulphides of this mine lie close to the top of the lava section. To the southeast a topographic valley follows close to the graben axis, and here the lavas extend much deeper into the section than on either flank. At these structural levels the dykes are highly rotated to low dips. The dykes and lavas at the Flasiana viewpoint have been rotated to a lesser extent. Clearly the graben evolved as the construction of the crust proceeded.

***F.*** *Drive up the Marathasa valley. Note that the sheeted dykes in the roadcuts have been rotated to low angles and that alteration to epidosite is widely developed. Drive to Pedhoulas, then west towards Kykkos, and turn south towards Lemithou and Tries Elies. Drive towards Lemithou, again noting highly rotated and epidotised dykes by the roadside. Park at the bottom end of the village (0482436, 38567553 [0482471, 38567726]).*

**Stop 4.** Kakopetria detachment. This stop demonstrates a low-angle fault beneath highly rotated sheeted dykes on the west flank of the Solea Graben. Walk from the bus up the road into the village. Along the way are good outcrops of gabbro, coarsely crystalline with patches of much coarser pegmatitic gabbro, probably the result of segregation of water within the magma as it crystallised. Turn sharp left up a concrete track and walk along until the detachment comes into view towards the right (0482550, 3867644 *[0482585, 3867817]*). The detachment separates sheeted dykes above from gabbro below. It dips from E to W across the outcrop. The gabbro is similar to the outcrops in the village. The sheeted dykes have been rotated to very low angles and are striped with pale yellow-green epidosite. The rotation probably originates in the hangingwall of a listric fault. Be very careful here. The outcrop is very unstable, and it is easy to knock blocks onto people standing below. It is not easy to determine the sense of slip on the fault (which ought to be top to the east). Close to the track the fault divides around a big block of gabbro. Varga and Moores (1990) map the detachment as continuing at the gabbro-dyke boundary for more than 10 km to the west from here.

***G.** Return to Pedhoulas, then up to Prodromos and left up to Troodos village. Here turn towards Platres and drive downhill for about 1 km to an outcrop of layered plutonics on the right (0487948, 3863176 [0487983, 3863349]). Be very careful here. Traffic comes very fast and very determinedly.*

**Stop 5a:** The layered plutonics here are deep in the crust, deeper than any gabbro seen elsewhere. The dark and light layering arises from alternations of cumulate wehrlite and gabbro. Though the outcrop appears undeformed at first sight, the layers contain a variety of deformation features including tight recumbent isoclinal folds.

***H.** Walk downhill for 500m, past a fault that is covered by debris to outcrops of brown peridotite near an old bridge at a bend in the road (0487290, 3863225 [0487325, 3863398]).*

**Stop 5b:** The peridotite here is mostly harzburgite, with a matrix of brown-weathering olivine, protruding grey crystals of orthopyroxene and small black specks of chromite. A weak deformation fabric can be seen in the rock. The harzburgite is cut by a body of dunite, without the pyroxene crystals of the harzburgite, but with larger, euhedral chromite grains, and by smaller dunite veins that can be shown to be replacing the harzburgite by melt-rock reaction. Both harzburgite and dunite are cut by veins of pyroxenite and gabbro. The relationships between these rock types arise from the complex processes that take place during mantle melting beneath the spreading axis. The mantle is sheared as it rises and melts. Magma is removed from the rock, and also rises through the rock from the mantle beneath that has already started to melt. Dunite is generated by reaction between melt and the wall rock, and from olivine precipitated from the rising magma. The pyroxenite veins are characteristically and straight-sided – they postdate the fabric in the harzburgite but are cut by dunite veins.

***I.** Return to Troodos village and take the road down towards Nicosia. Pass the Olympos Café and stop at the Chrysovrysi Spring (0493098, 3865627 [0493133, 3865800]), a few hundred metres downhill from it.*

**Stop 6:** This stop is in a large body of serpentinite forming the eastern part of the ultramafic massif at the top of the Troodos Mountains. The harzburgite forming most of the massif, including that at stop 5b, is about 25% serpentinised, while the serpentinite body is almost entirely serpentinised. Across the road is the large Pano Amiandos pit of the disused asbestos mine worked for many years here, and now in process of reclamation. The roadside outcrops show many of the typical features of serpentinite, including slickensided joint surfaces and fibrous veins of serpentine minerals. The Chrysovrysi Spring emerges near the roadside. Just below the spring, on the same side of the road, is another spring that precipitates a cloudy white precipitate as it emerges. This spring is of an alkaline, calcium-rich water, and the precipitate is calcite produced by absorption of carbon dioxide from the atmosphere. Such fluids are formed during the serpentinisation of peridotite, and can be seen emerging from the summit of the Atlantis core complex at 30°N in the Atlantic Ocean, forming the Lost City vent field, and also at the Blue Pools in the Oman ophiolite. The biological communities around Lost City are supported by microbial oxidation of hydrogen and methane dissolved in the fluids.

***J.*** *Walk down the road for a few hundred metres to find a fault zone separating serpentinite from gabbro. This is the Amiandos Fault.*

**Stop 7:** The Amiandos Fault runs approximately N-S along the eastern border of the serpentinite body. Its significance in the evolution of the ophiolite is not clear. It has conventionally been interpreted as an uplift-related structure, formed in the Neogene as the ophiolite started to undergo rapid uplift and was exhumed. Gravity studies show that a 150mgal negative anomaly exists beneath the summit area of Mount Olympus, almost certainly due to a diapir of serpentinite beneath. Serpentinisation of mantle peridotite, probably at depth, caused a volume increase and hence a decrease in density, leading to formation of a serpentinite diapir that drove the uplift. The Amiandos Fault is seen as the eastern edge of this diapir, accommodating the differential uplift of the serpentinite plug. However, in a recent model Nuriel et al. (2009) reinterpret the Amiandos Fault as the steep section of a large-offset fault associated with a core complex, and formed during oceanic crustal construction in the Cretaceous. This fault would have rooted at a spreading axis in the Solea Graben. In this model, the Kakopetria Detachment might be a low-angle section of the same fault, though this would be in conflict with the mapping of the detachment by Varga and Moores (1990). In addition the sense of rotation above the Kakopetria Detachment implies a concave upwards fault plane rather than one concave downwards.

***K.*** *Return to Agros.*

## *Day 2: Eastern Limassol Forest Complex*

Aims: (a) To gain an understanding of the overall structure of the eastern Limassol Forest area, in which the effects of detachment faulting predominate. (b) To demonstrate steeply dipping lavas and interpillow sediments in the hanging wall of a detachment. (c) To examine outcrops of two low-angle faults, one a 'bookshelf' fault that separates tilted fault blocks above the main detachment, and the other of the main detachment itself, the Akapnou Forest Décollement, separating lavas from serpentinite. (d) To investigate the open cast pit of the Mavridhia copper deposit, itself also tilted steeply.

***A.** Drive from Agros to Limassol, then along the A1 to Kalavasos. Drive past Kalavasos village along the Vasilikos river valley and up to the Kalavasos Dam. Park on the southwest abutment of the dam (0523719, 3850849 [0523754, 3851023]), overlooking the Vasilikos Reservoir to the north and Kalavasos Mines to the south. Walk 200 m back down road to junction.*

**Stop 1.** One of the most obvious differences between the extrusive section of the eastern Limassol Forest and that of the main Troodos massif is that the lavas here are very steeply tilted. Along the roadside outcrops here pillow lavas dip 60-65° towards the northeast. This orientation is very consistent and is typical of the whole Kalavasos Mines area, and southwest to Asgata and beyond. The pillows here are grey, generally aphyric mafic lavas. Minor quantities of discontinuous, fine reddish hydrothermal sediment may be present in between the pillows, which are pink stained. These lavas are typical of those from the upper part of the extrusive sequence in the area.

***B.** Walk along the track south into the disused mine.*

**Stop 2.** (0523693, 3850225 *[0523728, 3850398]*). This disused sulphide mine is the Mavridhia opencast pit, part of the Kalavasos mining district. In the 1980s the area was part of a military base and not accessible for study. Much of what is known of the geology of the mine itself therefore comes from the work of mine geologist Nick Adamides (Adamides, 1980).

Approximately 400,000 tons of ore, predominantly pyrite and chalcopyrite, was mined from the Mavridhia deposit between 1971 and 1977, and it is estimated that 200,000 tons remain. It is one of thirteen sulphide bodies in this district, from which six million tons of ore was extracted in the 20th century, and probably much more again in ancient times. The Kalavasos Mines deposits overall are highly dismembered by the faulting that affects the whole eastern Limassol Forest, but appear to have been typical 'Cyprus-type' volcanic massive sulphide mineralisation prior to the disruption. Massive sulphide lies between altered 'lower' and slightly later (unmineralised) 'upper' lava sequences and accumulated on the seafloor, as shown by the presence of fossil vent faunas in some deposits. Beneath the deposits are alteration pipes through which the hydrothermal fluid flowed. These “stockworks” are composed of highly altered lavas cut by veins of pyrite and quartz. In Kalavasos the stockworks all lie along NE-SW trending (dyke- and hence ridge-parallel) faults, localised where these structures meet the gently south-dipping Mavridhia Fault, which we will view and discuss at stop 3.

As you enter the Mavridhia opencast pit note the post-mineralisation pillow lavas dipping steeply northeast high up on the right-hand wall. These overlie a thick massive flow that itself overlies and caps the ore body. Fresh sulphide rubble at ground level marks the top of the deposit. Vent fossils have been found in similar material at other Cyprus deposits. The stockwork zone, exposed further into the pit, is formed of hydrothermally altered basalt originally veined by quartz and pyrite, now intensely weathered to an iron oxide stained rock and an array of sulphates and other minerals including the bright yellow-orange jarosite (hydrous sulphate of K and Fe). Some at least of the replacement of the stockwork lavas is likely to have been a result of recent acid mine drainage.

***C.*** *Walk back to the car park on the southwest abutment.*

**Stop 3.** In the section exposed in the cutting for the overflow sluice gate a sequence of glassy pillows and hyaloclastites is cut by numerous thin dykes and sills. The dykes trend NE and dip moderately to steeply SE. These lavas are typical of those from the lower part of the extrusive section and are silica-rich; some have $SiO_2$ contents in excess of 70%. They are cut by minor NE-trending faults that have oxidation and alteration along them. In the section exposed in the car park itself an indistinct band of oxidation traverses the top of the outcrop, and separates the Si-rich lavas beneath from the grey pillows from Stop 1. This unprepossessing feature is the Mavridhia Fault. It dips 100°/28°S, perpendicular to the lavas, and has been traced continuously across the entire Kalavasos Mines area, underground also. Adamides showed that it is the key structural feature that controls the location of the ore bodies here: that mineralisation is primarily concentrated along the NE-trending faults where they intersect with the Mavridhia Fault.

***D.*** *Walk/drive over to the northeast abutment of the dam.*

**Stop 4.** Pillow lavas are again exposed on the tarmac road that winds down from the NE abutment of the dam (0524131, 3851281 *[0524166, 3851455]*). These are olivine-phyric boninitic lavas with distinctive U-shaped rare-earth element profiles. They dip ~65° NE and lie conformably on the Si-rich lavas by the sluice gate. A 6-8 m thick unit of lava breccia lies beneath the olivine-phyric flows, and on top of another olivine-phyric unit that has flat rare-earth profiles. This coarse unsorted breccia is a debris flow deposit typical of the interlava sediment that is found in the Arakapas Fault Belt and in the northern outcrops of the Limassol Forest Complex. To the south of here such sediments are absent, whereas just to the north, near Dhrapia (stop 6), they thicken markedly, with an estimated thickness of more than 250 m of coarse lava and dyke breccia.

***E.*** *Walk back up to the house on the northeast abutment of the dam and then ~200 m along the dirt track to the north.*

**Stop 5.** Low, khaki-coloured outcrops of the lava seen at stop 4 are abruptly replaced by white, degraded material on the track. The white rock is highly altered gabbro. The contact between the lava and gabbro is exposed amongst the scrub in a low outcrop

50m to the west of the track. This is the Vasilikos Reservoir Fault. It is a clear faulted contact, with a prominent white planar surface dipping ~290°/25°S. XRD analyses of the white material show it to be poorly crystalline silica, with some calcite and lime. Gabbros and ultramafic cumulates, with steep NE-dipping layering visible nearby, form the footwall, and the NE-dipping olivine-phyric lavas the hanging wall. This structure is parallel to the nearby Mavridhia Fault. Both are orthogonal to the lavas and must have been originally vertical, and probably near E-W in strike. Unlike the Mavridhia Fault the Vasilikos Reservoir Fault has accommodated an extensional offset of the order of ~3 km. It is interpreted by MacLeod as having been a transform-parallel structure (stepping down to the north, hence responsible for the thickening of inter-lava sediments at Dhrapia) that was reactivated as a 'bookshelf' fault, accommodating both tilting and extension during a post-volcanic phase of stretching.

***F.** Return to the car park. Drive back towards Kalavasos, turning left across the Vasilikos River and along the dirt road to Dhrapia.*

**Stop 6.** Chocolate-brown umber is exposed in a small pit at the side of the dirt road at the southern end of the abandoned village of Dhrapia (0525584, 3850920 *[0525619 3851094]*). The deposit was originally about 10 m in thickness. It dips 25-35° northeast and lies upon massive lava and dyke breccia debris flow deposit. Stepping back to the road, a much larger umber deposit can just be discerned in the distance, above the village a kilometre to the northeast. This umber is 35 m thick, contains blocks of lava breccia up to 4 m in diameter, and shows a systematic change in dip from 36°NE at its base to <10°NE at its top, parallel to conformably overlying radiolarian sediments. The angular relationships here, considered in conjunction with the underlying crustal section, led MacLeod to suggest that the tilting and stretching of the ophiolite section in the eastern Limassol Forest occurred immediately after end of volcanism and during umber accumulation.

**G.** *Drive along gravel road northwards towards Lageia (Layia). Alternatively, if the condition of the dirt road is too bad, return to Kalavasos and the main highway, and approach on the tarmac road via Khirokitia, Vavla and Lageia). Park by the power lines and gate at 0523341, 3854847 [0523376 3855021]. Walk down the track downhill on the right-hand side of the stream ~750 m, beyond a house on the right. Continue approximately 200 m farther southwest beyond the beehives.*

**Stop 7a.** (0522966, 3854067 *[0523001, 3854241]*) Low outcrops here to the right of the track are typical of the serpentinised dunites and harzburgites that characterise the Akapnou Forest. Serpentinisation here is virtually pervasive. Dark specks of Cr-spinel are visible in the dunites; small-scale prospects 2 km to the west have revealed a few small pods of chromitite. Some white veins of crystalline calcite are present locally in the serpentinites.

Turn around to look back to the northeast, and note that the hill top behind the beehives and the hill with the house on top to the right (south) of it have a distinct reddish-brown hue. This colouration ends abruptly at the bases of the hills. As we will see at the next outcrop, these hill tops are composed of lava and dyke rock, and they lie with near horizontal contact upon the serpentinised peridotites on which we are standing here. This relationship is observed across much of the Akapnou Forest region to the west: slightly oxidised, orange sheeted dykes forming the hill tops, and silvery grey serpentinites the valleys.

***H.*** *Walk back along the track to the beehives, and then right (eastwards) through a small gulley immediately below them (0523125, 3854198 [0523160 3854372]).*

**Stop 7b.** This is the type locality of the Akapnou Forest Décollement, the major controlling detachment fault that extends across the entire eastern Limassol Forest Complex (and, we now suggest, probably the western Limassol Forest too).

Pale grey, bleached-looking lava and dyke-rock here lies directly on top of silvery blue-grey serpentinite. The contact here is sub-horizontal and clearly tectonic. Schistose serpentinite with a low-angle fabric passes across a sharp, planar contact into pale grey mafic material, the lowermost few centimetres of which is composed of extremely fine-grained (ultra-) cataclasite with thin partings parallel to the contact. XRD analyses reveal chlorite and actinolite in the cataclasite, and that the serpentinite immediately beneath is chrysotile. White veins of calcite are abundant in the mafic hanging wall here, but do not extend into the serpentinite of the footwall. Rare slickenside lineations are visible in a few places on the detachment fault surface itself and, according to MacLeod, have predominantly NE or SW azimuths. Lineations in the schistose serpentinite in the tens of centimetres below the contact tend to be less regular. The shear sense in the schistose serpentinite demonstrates a top to the SW or W sense of motion.

*Drive back up to main road and then west through Lageia (Layia) to the road cut just to the west of the village.*

**Stop 8 (*time permitting*).** (0522364, 3856137 *[0522399, 3856311]*) This classic locality preserves a >30 m thick, east-dipping section of ocean-floor sediments that were deposited onto faulted igneous basement within the Arakapas Fault Belt. The lowest part of the sequence is composed of massive units of coarse, poorly-sorted sedimentary breccia. Clasts range in size from centimetres to metres. They are dominated by blocks of lava, with some dyke rock, very rare microgabbro, and clasts of pre-existing clastic sediment. Two prominent flat rafts of finer grained clastic sediment that occur within the coarser breccias display grading that fines downwards, and may therefore be megaclasts that were turned upside down when they were incorporated into the breccia deposit. The main breccia horizon passes up into repeated fining-upward sequences of grey grits and sands alternating with fine red-purple mudstones. These are in turn overlain by a brown lava flow or sill.

Sedimentary sections such as this within the Arakapas Fault Belt are highly localised and variable. The coarse breccias are debris flow deposits, almost certainly derived from nearby fault scarps within the transform valley. The finer units are turbidites, and the red mudstone layers probably ferromanganoan sediments deposited between and/or caught up by turbidite flows. That a lava flow was extruded on top of these sediments neatly demonstrates the ocean-floor origin of the sedimentation.

The absence of serpentinite or coarse-grained gabbro or ultramafic cumulate clasts here, or anywhere else in the Arakapas Fault Belt, shows that the relief in the transform valley was not sufficient to expose deep levels of the crust or lithospheric mantle on the seafloor here. One sole outcrop of sedimentary breccia in the very south of the Limassol Forest (near Akrounda: 0507077, 3848143 *[0507112, 3848143]*) does contain serpentinite clasts.

Although fine-grained sediments and local talus breccias are occasionally observed within the extrusive section of the main Troodos massif, none are on anything approaching the scale of the debris flow deposits observed here. The presence of similar sediments at the Kalavasos Mines and Dhrapia (stops 4 and 6) is evidence that the bathymetric depression may have extended further south than the present-day Arakapas valley, and into the Limassol Forest Complex. These inter-lava sediments disappear to the south of the Kalavasos Mines, indicating a N-S width to the bathymetric depression of 5-6 km. The extrusive stratigraphy of the 'Anti-Troodos' lavas of the southeast Limassol Forest presumably therefore had a subdued seafloor relief much more similar to that of the main Troodos massif.

*Return to Agros via Limassol or via Arakapas.*

## *Day 3: Western Limassol Forest Complex*

Aims: (a) To investigate an area of the Limassol Forest that shows a very different set of features from that seen in the eastern area. (b) To see outcrops of a low-angle detachment fault separating hanging wall sheeted dykes from footwall serpentinite. (c) To examine late igneous bodies (dykes and plutons) intruding both the footwall serpentinite and the hanging wall blocks. (d) To investigate the evolution of the deformation of the footwall serpentinite. (e) To see veins of calcite in serpentinite deposited from calcic spring waters. (f) To determine an overall chronology of deformation, magmatic activity and hydrothermal alteration/metamorphism in this area.

This field day is an essentially north-south transect through the structures and lithologies of the west end of the Limassol Forest.

***A.*** *Drive from Agros to the village of Akrounta in the southern Limassol Forest, and north towards Arakapas to a parking place at 0507918, 3850194 [0507953, 3850367] by a serpentinite shear zone. Walk down the road for about 500m to a high roadcut showing dykes intruding serpentinite. Do not stop along the way! There will be chances to do that on the way back.*

**Stop 1:** At this locality the relations between the grey dykes and purple serpentinised harzburgite are clear. Close to the road the serpentinite contains a small intrusion of gabbro. This has been altered to rodingite, a rock made up of the calcium-aluminium minerals prehnite, pectolite and hydrogarnet. Alteration of this type shows that the gabbro was altered at the same time as the harzburgite was being serpentinised, and must have been emplaced earlier. By contrast the dykes are chilled against the serpentinite (with very sharp chilled margins) and scarcely deformed. They have been altered at greenschist facies (black smoker) temperatures, but after most of the serpentinisation was complete. The dykes strike NE-SW, a similar orientation to the sheeted dykes north of the Arakapas Fault zone. The dykes are truncated by a late, low-angle fault about half way up the outcrop. The dykes must have been intruded into the serpentinite when it was still warm, but nearly completely serpentinised.

***B.*** *Walk back up the road to the parking place. Along the way are more dykes intruding serpentinite. One or two of them are brown rather than grey. This indicates that they were not metamorphosed, and must have been intruded after serpentinisation was complete. The serpentinite becomes increasingly deformed by a near-vertical east-west sheared fabric. The grey dykes have been deformed by this shearing.*

**Stop 2:** Just south of the parking area take a close look at this serpentinite shear zone in the road cut. This is part of a steep, E-W trending shear zone that can be traced for ~3km along strike. It is one of a number of such shear zones present in the mantle sequence of the Limassol Forest that are interpreted by Murton and MacLeod as transform fault-related structures. As is typical with deformed serpentinite, the fabric is not totally penetrative, but is deflected by lozenges (phacoids) of unsheared serpentinite. On top of the outcrop of this shear zone, it is possible to demonstrate that the sense of shear is broadly strike slip and dextral, though slickenline lineations on the surfaces of the phacoids do not show a consistent orientation. Such complexity is common in deformed serpentinite.

**Stop 3:** Now cross the road to see small outcrops of brown rock in the scrub. These outcrops are of coarse wehrlite, with brown olivine weathered down and pale green clinopyroxene standing proud of the weathered surface. The cleavage surfaces of the large clinopyroxene crystals show small rounded inclusions of olivine. These textures are typical igneous features; there is no sign of deformation in the rock. The brown colour of the olivine shows that at least some of it has not been serpentinised. This body of rock is a late intrusion into the serpentinite, apparently after most of the deformation was complete

***C.** Drive about 1.5 km north along road towards Arakapas to an inside bend at 0507824, 3851795 [0507859, 3851968].*

**Stop 4:** In road cuts on either side of the apex of the inside bend are exposures of gabbro. This is another late intrusion into the serpentinised harzburgite. Its intrusive nature is shown by xenoliths of harzburgite and wehrlite. The gabbro contains coarse pegmatitic patches. Its position in the sequence of events is shown by the lack of any cross-cutting dykes, by the presence of veins of rodingite and a quartz vein cutting the gabbro. If you climb up the stream, taking the left hand branch (a route only for those who enjoy a thorny scramble) you will reach the contact of the gabbro with the surrounding serpentinite. The gabbro and serpentinite are deformed together at the contact.

***D.** Drive about another 2 km farther north along road to park by a long NW trending road cut (0508674, 3852967 [0508709, 3853140]). This road cut and its extensions contain four stops all reached by walking along this section of road. At these stops it will be possible to examine the relations between serpentinite and overlying sheeted dykes, the nature of structures within the serpentinite and sheeted dykes, the timing of dyke intrusions into the serpentinite and sheeted dykes, and the geometry of a low-angle detachment fault.*

**Stop 5:** Walk back along road from the parking place to a corner where the road bends sharply south. Examine the road cut on the inside of this bend. The serpentinite here shows a well-developed low-angle fabric. This is cut by a late dyke. Close to the bend is a good place to see veins of calcite precipitated from calcic/alkaline Lost City/Blue Pool spring waters produced during serpentinisation of peridotite.

**Stop 6:** Walk back to the parking place and look at the section there, with a strong fabric in the serpentinite and a lens of brown material at the top of the road cut. This outcrop is not easy to unravel. Several of the oblique structures can be seen to be dykes truncated by a schistose shear zone below the brown material. There is a strong localised schistose fabric in some of the serpentinite. The brown material is a block of sheeted dykes, so the contact zone is a large-offset extensional fault separating serpentinite from sheeted dykes.

***E.** It would be hard to be convinced by a single outcrop like this, spectacular though it is. But we can do better than that. Walk farther NW along the road for about 200m. Look down into the stream on your R. The far bank of the stream is made up of sheeted dykes, the near bank mostly of serpentinite.*

**Stop 7:** At 0508685, 3853143 *[0508720, 3853316]* you will see on the left an outcrop of brown material stretching for about 100m along the road cut. This is an outcrop of sheeted dyke, as closer examination will show. Serpentinite underlies it. The contact between the two units can be traced very conveniently and dips at about 20° to the NE. If you scramble around on the slope below the road, it seems that the contact steepens in this direction. At the small church of Profitis Elias, about a kilometre west of here, the contact can be seen again, and is close to horizontal.

***F.** Now walk farther along the road, around a sharp bend to the right, and up a hill. As you walk up the hill, the road cut on the left is a good outcrop of sheeted dykes, with well-defined chilled margins. At the top of the hill the road turns left, and straight ahead is a quarry turned into a parking/turning place. Walk into this area.*

**Stop 8:** This area is backed by an excellent outcrop of sheeted dykes with the dykes striking east-west. These are in the hanging wall of the detachment fault. The sheeted dykes can be seen to be cut by isolated dykes running NE-SW, the same orientation as the dykes at Stop 1 above. While the sheeted dykes have been metamorphosed as sheeted dykes are over most of the ophiolite, these late dykes are brown and unmetamorphosed. The faulted relationship between the sheeted dykes and the serpentinite was established early in the tectonic history of this area. Both units were later cut by the post-serpentinisation dykes and plutons that we have been seeing along this transect. Look north from here across the valley of the Arakapas Fault Belt to the main Troodos Massif in the distance.

***G.** Drive through the village of Dhierona to Arakapas and then west along the road towards Kalokhorio. Stop at a road cut about 3 km to the west of Arakapas.*

**Stop 9:** This stop is within the Arakapas Fault Zone. The fault occupies an east-west topographic trough, just as it did on the sea floor, though of course not as deep as it was then. There are few exposures of the basement of the fault zone, which is made up of deformed and metamorphosed sheeted dykes. Above this basement is a fill of clastic sediments and lavas that has been scarcely deformed at all, and certainly far less deformed than the Limassol Forest area through which we have been travelling. The clastic sediments here are breccias of sheeted dykes and lavas shed from the walls of the transform trough. Interbedded with these are lava flows of boninitic affinity.No serpentinite clasts have been reported from the breccias, so serpentinite cannot have been exposed nearby at the sea floor at the time the trough was being filled to this horizon. In contrast, on the southern edge of the western Limassol Forest, fragments of serpentinite can be seen in sediment between lava flows, showing that close to there serpentinite was already exposed at the sea floor while magmatism was still in progress.

***H.*** *Return to Agros.*

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