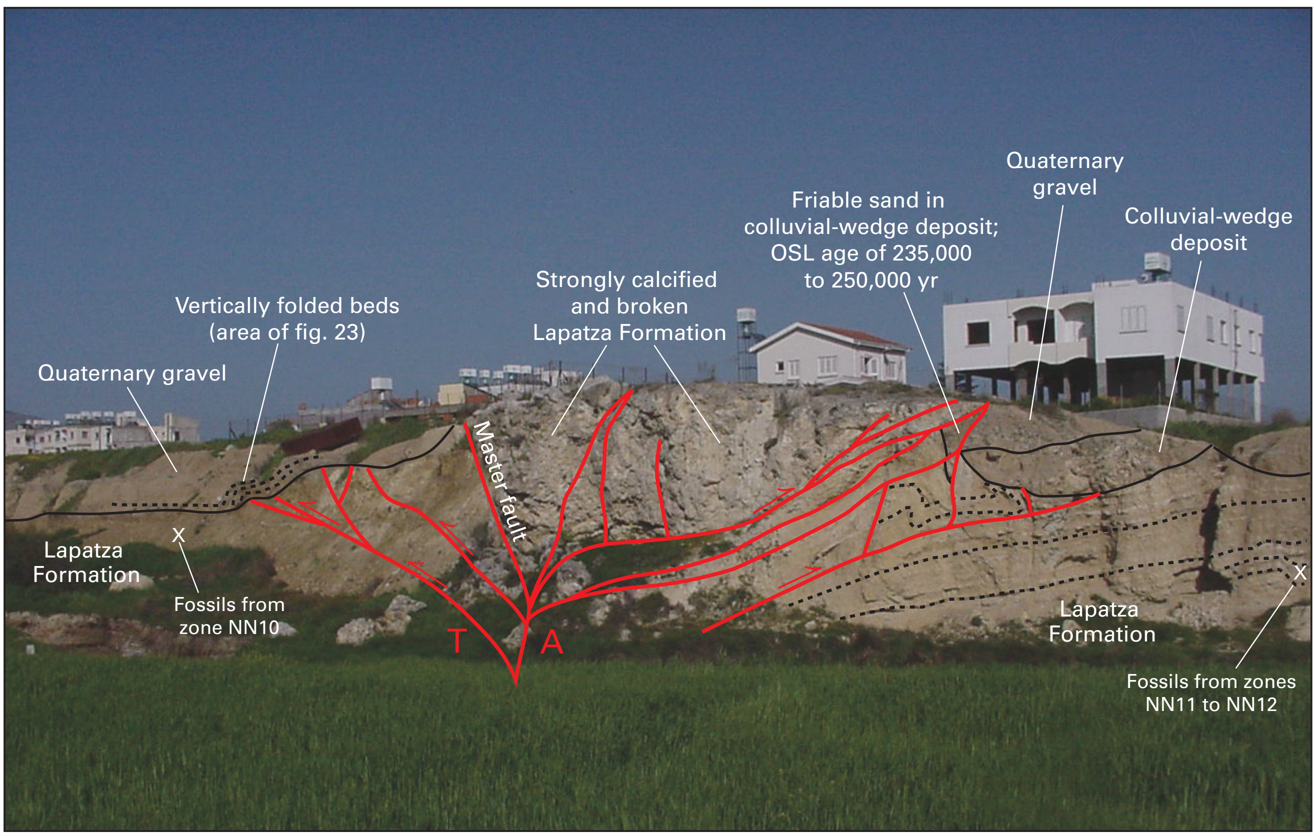
Prepared in cooperation with the Cyprus Geological Survey Department

# Bedrock Geologic Map of the Greater Lefkosia Area, Cyprus

By Richard Harrison, Wayne Newell, Ioannis Panayides, Byron Stone, Efthymios Tsiolakis, Mehmet Necdet, Hilmi Batihanli, Ayse Ozhur, Alan Lord, Okan Berksoy, Zomenia Zomeni, and J. Stephen Schindler

*Pamphlet to accompany*
Scientific Investigations Map 3046

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**Cover:** Positive flower structure on the Skali fault in cutbanks of the Pediaios River in northern metropolitan Lefkosia near Mandres village at approximate UTM coordinates of 3896300 m north and 533700 m east. View is towards the northeast.

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# Conversion Factors

Inch/Pound to SI

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| inch (in.) | 2.54 | centimeter (cm) |
| inch (in.) | 25.4 | millimeter (mm) |
| foot (ft) | 0.3048 | meter (m) |
| mile (mi) | 1.609 | kilometer (km) |
| | Area | |
| acre | 0.4047 | hectare (ha) |
| square mile ($mi^2$) | 2.590 | square kilometer ($km^2$) |

SI to Inch/Pound

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |

# Bedrock Geologic Map of the Greater Lefkosia Area, Cyprus

By Richard Harrison,[1] Wayne Newell,[1] Ioannis Panayides,[2] Byron Stone,[1] Efthymios Tsiolakis,[2] Mehmet Necdet,[3] Hilmi Batihanli,[3] Ayse Ozhur,[3] Alan Lord,[4] Okan Berksoy,[3] Zomenia Zomeni,[2] and J. Stephen Schindler[1]

## Introduction

The island of Cyprus has a long historical record of earthquakes that have damaged pre-Roman to modern human settlements. Because the recurrent damaging earthquakes can have a significant economic and social impact on Cyprus, this project was initiated to develop a seismic-hazard assessment for a roughly 400 square kilometer ($km^2$) area centered on Cyprus' capital and largest city, whose European name is Nicosia and whose local name is Lefkosia. In addition, geologic and seismotectonic evaluations for the project extended beyond the perimeter of the geologic map. Additional structural, stratigraphic, and paleontological data were collected island-wide as well as data from literature research throughout the eastern Mediterranean region, in order to accurately place the geology and seismic hazards of the Lefkosia area in a regional tectonic framework.

The project consisted of several elements: (1) geological studies of faulting with emphasis on the identification of active fault areas, (2) synthesis of the surficial geology in the Lefkosia area with existing knowledge and hazard assessment, (3) evaluation of the earthquake ground-motion amplification in the Lefkosia area on the basis of geophysical refraction surveys, the logging of seismic shear wave velocities in holes drilled to depths of 30 meters (m), and the extrapolation of the shear wave data to the entire 400-$km^2$ area by using a three-dimensional model of the surficial geology developed in the project, (4) determination of expected future earthquake ground shaking throughout the island, (5) evaluation of future possible economic losses resulting from earthquakes, and (6) the development of GIS capability (and the supply of equipment) which serves as an additional element to the project. This report is a product of element no. 1.

An unpublished report (edited by DeCoster and others, 2004) on all elements of the project is available on CD-ROM from the Cyprus Geological Survey Department, Lefkosia, Cyprus. Some of the geologic data and interpretations from this project were published previously by Harrison and others (2002, 2004). This report presents the detailed 1:25,000-scale bedrock geologic map and much of the data that went into its preparation; it also presents some of the regional interpretations and data that are considered significant to the geologic evolution, principally neotectonics and tectonic history, of the Lefkosia area.

## Overview of Cyprus and Its Geologic Terranes

Cyprus is the easternmost island in the Mediterranean Sea and one of the sea's largest with a surface area of 9,251 $km^2$. It lies in the northeastern corner of the Mediterranean Sea, approximately centered on latitude 35° N. and longitude 33° E. Its shape above sea level is very irregular and resembles a barbed club (fig. 1) with a narrow handle extending to the northeast. When topography and bathymetry are viewed together (fig. 2), it appears that the club has left a trail scarred into the ocean floor to the east. As discussed later in this report, these ocean-floor scars and the sharp angular peninsulas of Cyprus owe their shape to numerous faults and fault zones, many of which are active. Two mountain ranges occur on the island, the relatively large and high Troodos Range in the south, and the narrow, steep-sided, and curved Pentadaktylos Range along the northern coast. The saddle area between these two ranges is the Mesaoria Plain, which is where Lefkosia has been built. The entire geologic map of Lefkosia lies within the Mesaoria Plain.

The island is broadly divisible into four geologic terranes (Cyprus Geological Survey Department, 1995): Kyrenia terrane, the circum Troodos sedimentary succession, Troodos terrane (Troodos ophiolite), and Mamonia terrane (fig. 1). Geologic elements of each terrane are unique, because each terrane is the product of different tectonically controlled environments of deposition. The Lefkosia map area is almost equally divided between the Kyrenia terrane and the circum Troodos sedimentary succession at the surface. Ophiolitic rocks of the Troodos terrane are known to lie in the subsurface (see cross section *A–A′* on map sheet). The boundary between

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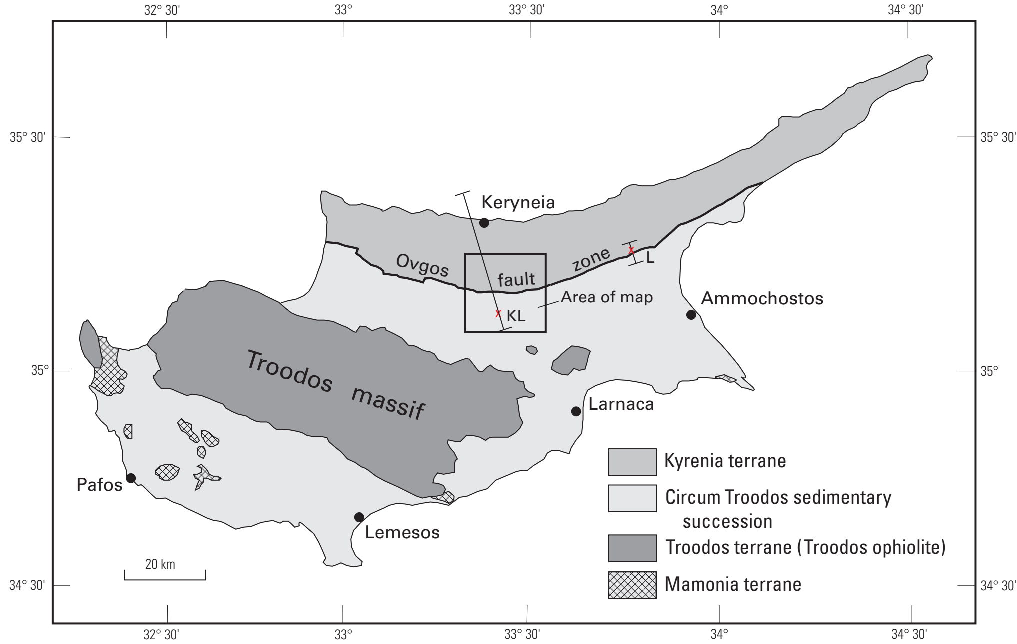



**Figure 1.** Map of the four major tectonic-stratigraphic terranes on Cyprus after the geologic map of Cyprus (Cyprus Geological Survey Department, 1995). Box is the approximate boundary of the Lefkosia geologic map. L, location of Lefkoniko borehole (x) and cross section shown in figure 5; KL, location of Kato Lakatameia borehole (x) and line of section shown in figure 4.

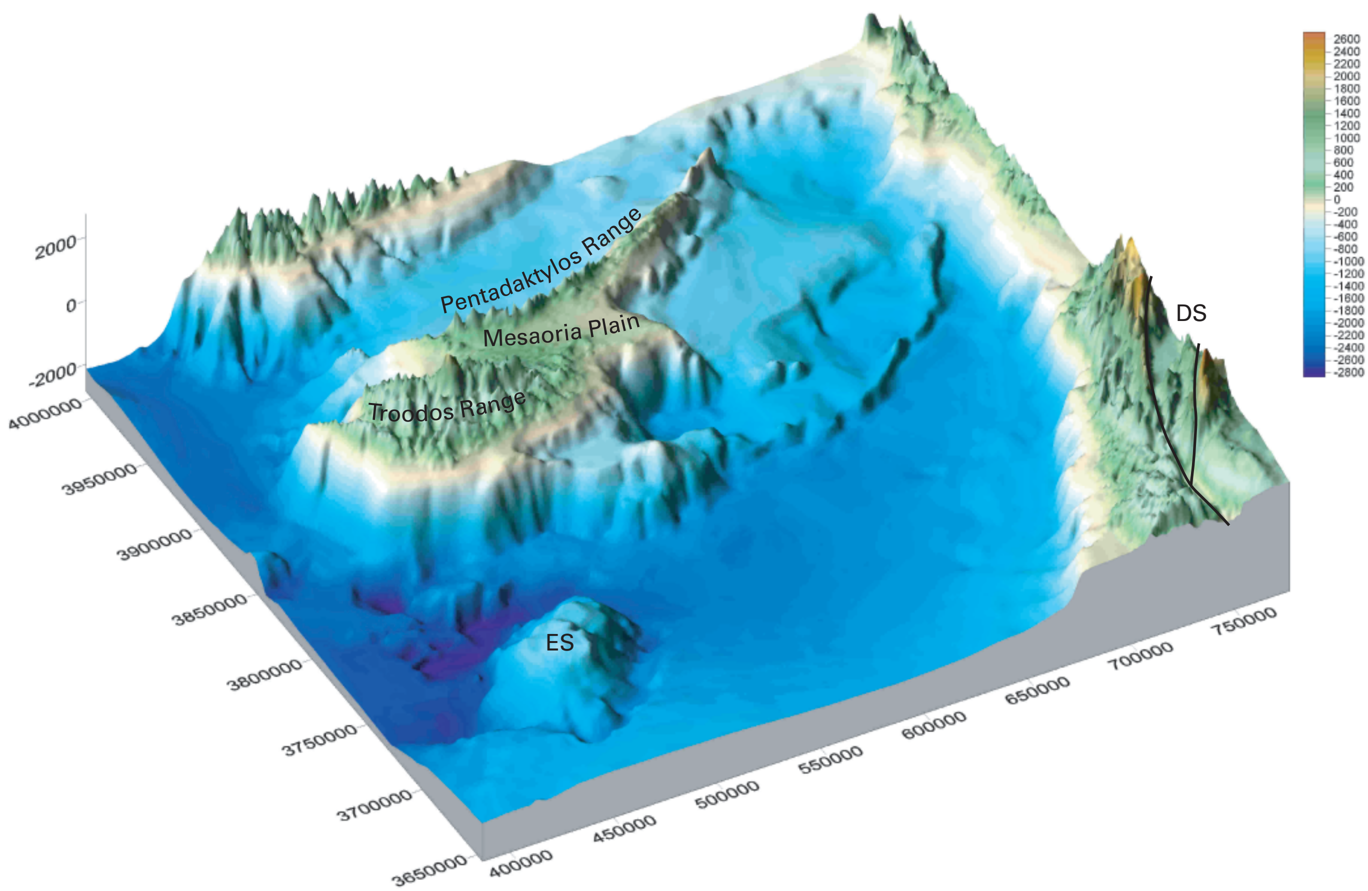



**Figure 2.** Digital elevation model (DEM) of the eastern Mediterranean region combining bathymetry (in meters) and topography. The narrow, curved mountain belt on northern Cyprus is the Pentadaktylos Range. The large mountainous area in southern Cyprus is the Troodos Range. The low-lying saddle area between these two mountain ranges is the Mesaoria Plain. The geologic map of Lefkosia lies entirely within the Mesaoria Plain; the Ovgos fault zone runs down the middle of the Mesaoria Plain. In the southeastern corner of the DEM, a section of the Dead Sea transform (DS) is visible. The mountainous area north of Cyprus is the Anatolian part of southern Turkey. The Eratosthenes Seamount (ES) is in the southwestern corner of the image.

the Kyrenia terrane and the circum Troodos sedimentary succession is the Ovgos fault zone, which is described in detail below and in Harrison and others (2004); the Ovgos fault zone is also interpreted to be the boundary between the Kyrenia and Troodos terranes at depth.

## Kyrenia Terrane

The Kyrenia terrane is a structurally complex assemblage of late Paleozoic to Recent sedimentary and minor metamorphic and igneous rocks. This terrane has an allochthonous Carboniferous and Mesozoic stratigraphic sequence of thickly bedded limestones that has been thrust southward over younger sediments, predominantly clastics and chalks, of Late Cretaceous to Miocene age (Baroz, 1979). In part, the older limestones are imbricated with the younger sediments. The oldest allochthonous rocks are Permian, and perhaps Carboniferous, massive limestones of the Kantara Formation; these rocks are very resistant, fine grained, dense, and locally recrystallized. Spectacular outcrops of these limestones are found in the eastern part of the Kyrenia terrane as variously sized blocks (olistoliths) in the younger sediments. The three major allochthonous limestone units in the Kyrenia terrane are the Hilarion, Sykhari, and Dhikomo Formations, all of Mesozoic age. None of the allochthonous units are present in the Lefkosia map area. From oldest to youngest, the younger formations of the Kyrenia terrane are the Lapithos Formation, the Kalogrea-Ardana Formation, the Kythrea Group (including the Lapatza Formation), the Kalavasos Formation, and the Nicosia Formation; of these units, Lapithos, Kalogrea-Ardana, and Kythrea are unique to the Kyrenia terrane; the Lapatza Formation is identical in lithology, fossil content, and age to the upper part of the Pakhna Formation of the circum Troodos sedimentary succession; and the Kalavasos and the Nicosia Formations are recognized also as part of the circum Troodos sedimentary succession, under which they will be discussed. A correlation diagram comparing geologic units of the Kyrenia terrane with those of the circum Troodos sedimentary succession is shown in figure 3.

The Lapithos Formation is of Maastrichtian to Eocene age (Cyprus Geological Survey Department, 1995) and consists of pelagic pinkish marls and white chalks with cherts; these rocks occur as strongly faulted, schistose and penetratively cleaved beds containing contemporaneous lava flows and breccias of basaltic and rhyolitic composition. The Kalogrea-Ardana Formation (previously known as the Bellapais Formation) is a turbidite, or flysch, unit composed of sands, silts, and marls. It rests with pronounced unconformity

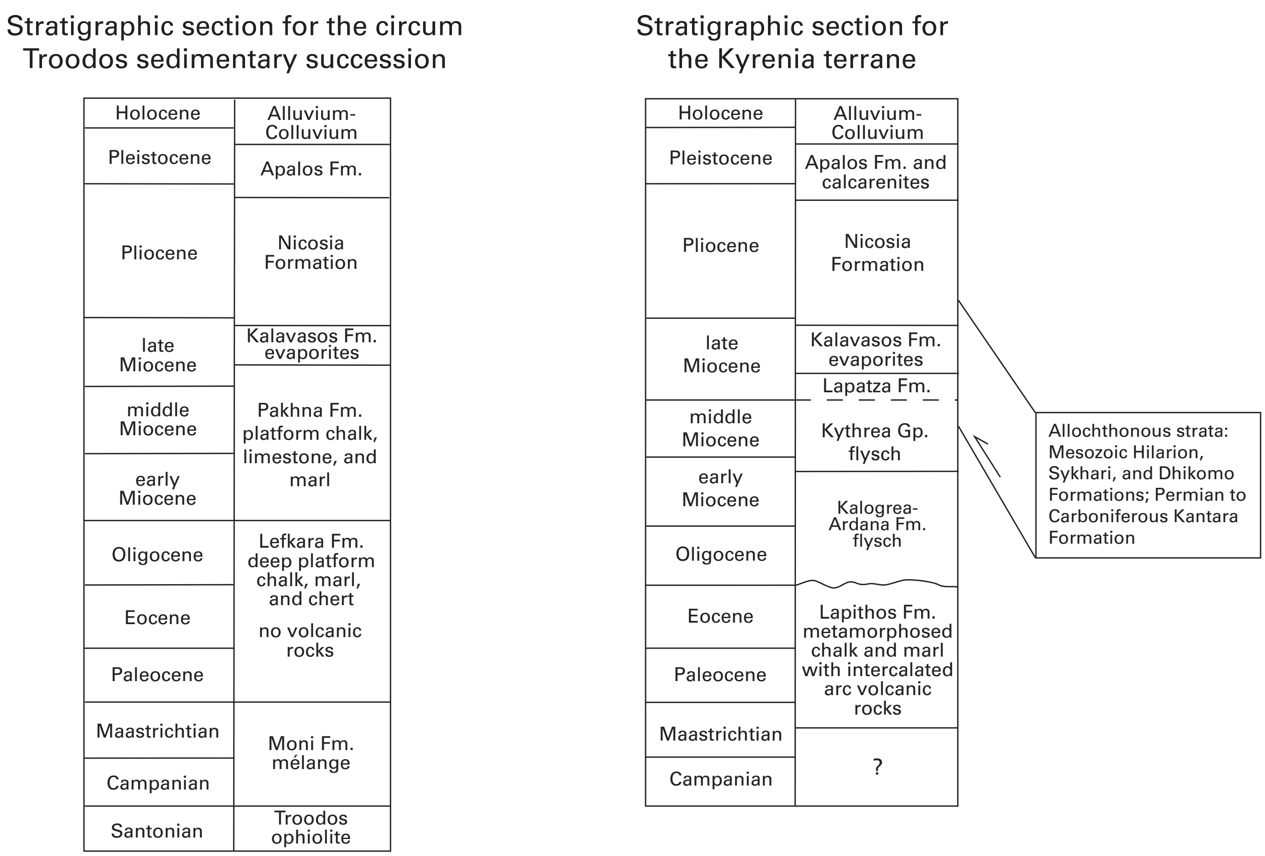



**Figure 3.** Comparative stratigraphic sections for the circum Troodos sedimentary succession and the Kyrenia terrane. Based on field data collected for this report and two deep boreholes at Kato Lakatameia and Lefkoniko (see figure 1 for locations and figures 4 and 5 for sections).

on highly deformed Lapithos and older formations, and is Oligocene to early Miocene in age (Cyprus Geological Survey Department, 1995).

The Kythrea Group, parts of which are referred to as the Kythrea Flysch (Weiler, 1965), is a thick and much-folded sequence of thin- to thick-bedded sandstones, siltstones, and marls. Most beds in this formation are poorly fossiliferous, and thus the exact age range of deposition is unknown. The geologic map of Cyprus (Cyprus Geological Survey Department, 1995) indicates a middle Miocene age, but included in this formation is the overlying Lapatza Formation. Others (Weiler, 1965; Ducloz, 1965, 1972; Baroz, 1979) have considered the Kythrea as middle to late Miocene in age. Paleontological data in this report indicate a late Miocene (Tortonian, zones N14–N16) age for some Kythrea beds in the northwestern quarter of the map area and an age range of sometime in the early or middle Miocene (Burdigalian or Langhian, zones N7–N9), for flysch beds occurring near the bottom of drill hole SHN11, which is located near the center of the geologic map (see table 1 on map sheet). Flysch of the Kythrea Group crops out on both sides of the Pentadaktylos Range, the thin, elongated northern mountain belt on Cyprus (see figure 2). The southernmost extent of the Kythrea Group is the Ovgos fault zone (see figures 4 and 5; and cross section *A–A′* on map sheet). Flysch deposits of the Kalogrea-Ardana Formation,

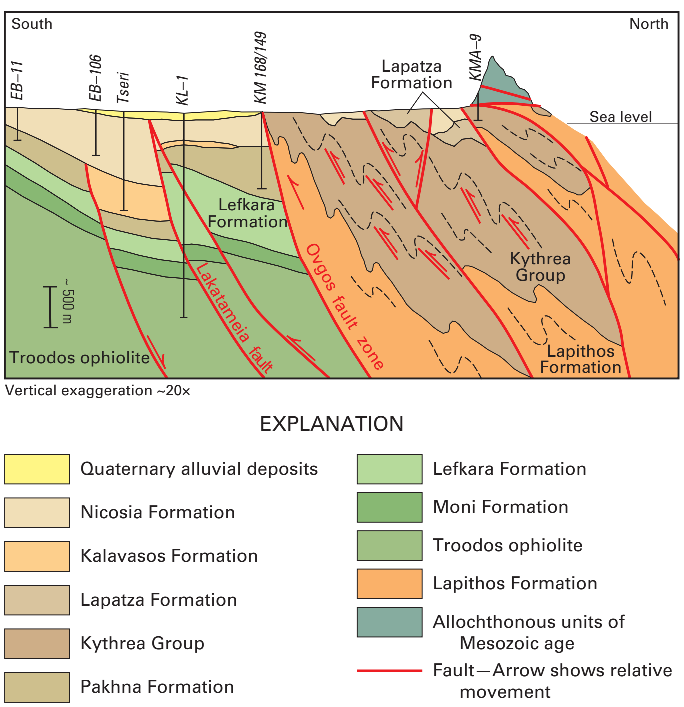



**Figure 4.** Schematic cross section extending from the circum Troodos sedimentary succession across the Kyrenia terrane to off the northern coast of Cyprus (see figure 1 for location). The cross section is based on geologic mapping and age dates from this report; several deep drill holes, including the Kato Lakatameia hole (KL–1); and an interpretation of a seismic-reflection dip log by Forest Oil Company, used with permission.

Oligocene to early Miocene in age, probably represent older fill in the same deep basin as that in which the Kythrea was deposited. At Lefkoniko (see figure 1 for location), the thickness of folded Kythrea sediments is approximately 2.1 km (fig. 5).

On the geologic map of Lefkosia, the Lapatza Formation overlies the Kythrea Group and is itself overlain by either the Kalavasos or Nicosia Formations. On the geologic map of Cyprus (Cyprus Geological Survey Department, 1995), the Lapatza Formation is undivided from the Kythrea Group. The Lapatza Formation is predominantly marl, laminated mudstone, sandstone, and chalk, with lesser amounts of limestone and clayey limestone; limestone beds in this unit appear to be more prevalent in the vicinity of the Ovgos fault zone and the South Mandres fault. Locally, the Lapatza Formation is intensely silicified; this is commonly true in limestone beds adjacent to mapped faults. Paleontological work presented in this report indicates that the Lapatza Formation is identical in fossil content to the upper part of the Pakhna Formation in the circum Troodos sedimentary succession; field mapping and drill core analyses for this report further indicate that the lithologies and depositional styles of the Lapatza and uppermost Pakhna are the same. This indicates that by the Messinian, deposition was relatively uniform across all of northern Cyprus. Paleontological analyses for this report typically found the Lapatza Formation to be barren of foraminifera fossils; however, some nannofossils were extracted from this formation that indicate an age range from Tortonian to Zanclean (zones NN10–NN12). The Kalavasos, Nicosia, and Apalos Formations are represented in both the Kyrenia terrane and the circum Troodos sedimentary succession and are described below.

## Circum Troodos Sedimentary Succession

The circum Troodos sedimentary succession is a sequence of sediments that was deposited upon the Troodos terrane (Troodos ophiolite). Uplift and erosion have produced a circular outcrop pattern for the sediments surrounding the extensive exposure of the ophiolite in the Troodos Range (fig. 1). The base of the circum Troodos sedimentary succession is marked by the Kannaviou Formation, which is exposed extensively in southwestern and southeastern Cyprus. The Kannaviou deposits are composed of volcaniclastic sandstones, siltstones, and bentonitic clays that have been dated as Campanian to mid-Maastrichtian on the basis of diagnostic foraminifera and radiolaria (Lord and others, 2000). In some areas of the island, the Kannaviou is strongly deformed, brecciated, and mixed with various exotic blocks of older rocks; such occurrences are referred to as the Moni Formation, or Moni Mélange (Lord and others, 2000). The only deep borehole in the Lefkosia map area at Kato Lakatameia (see figure 1 for location and figure 4 for generalized stratigraphy) penetrated rocks of the Moni Formation. Two intervals of Moni Formation, one on either side of a thrust fault, were drilled

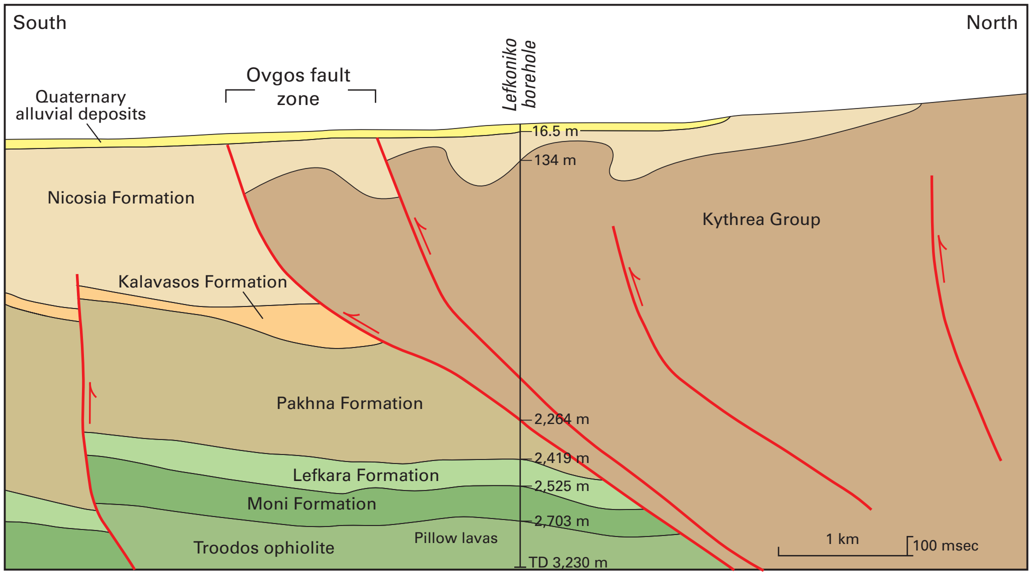



**Figure 5.** Lefkoniko borehole and schematic cross section across the boundary (Ovgos fault zone) between the circum Troodos sedimentary succession and the Kyrenia terrane near the village of Lefkoniko, east of the map area (see figure 1 for location). Cross section is adapted from an interpretation of a seismic-reflection dip log by Forest Oil Company, used with permission. Near vertical dips observed at the surface do not show on the seismic-reflection log. Also note that vertical distance is variable because the vertical scale is seismic traveltime; true depths of contacts are shown for the borehole. The Quaternary is undivided and consists of alluvial and colluvial deposits. TD, total depth. See figure 4 for explanation.

at Kato Lakatameia; these intervals were approximately 105 m thick in the hanging wall and 150 m thick in the footwall (fig. 4).

In southern Cyprus, the Kannaviou Formation is overlain by the Lefkara Formation, which typically consists of pelagic marl and white chalk, with or without chert. Four lithologic units have been identified for the Lefkara Formation (Lord and others, 2000). In ascending order, they are a lower marl unit, a chalk and chert unit, a chalk unit, and an upper marl unit. The lower marl unit is gray or pinkish-brown, thin-bedded marls with pink to brown nodular or lenticular cherts and marly chalks toward the top; maximum thickness estimates vary between 25 and 100 m. The overlying chalk and chert unit consists of well-bedded pure-white chalks, grayish marly chalks, minor gray marls, and silicified strata. The silicified strata show all gradations of silica replacement and alteration, from silicified chalk to granular chert to vitreous chert. The maximum thickness of this unit is approximately 300 m (Lord and others, 2000). The chalk unit is a chert-free sequence of sediments that is characterized by lateral bedding variations across the island. In some areas, its lower part is composed of massive chalks, while in other areas, it is composed of well-bedded chalks. It has a variable thickness between 70 and 250 m. The upper marl unit consists of typically gray-colored massive marls. The Lefkara Formation does not crop out in the Lefkosia map area, but the borehole at Kato Lakatameia (fig. 4) penetrated approximately 980 m in the subsurface.

The Pakhna Formation overlies the Lefkara Formation. Typically, Pakhna sediments are cream to buff-brown chalks and marls, which contrast sharply with the bright white chalks of the underlying Lefkara Formation. Another characteristic feature of this formation is the occurrence of thin to thick beds of calcarenite, as well as local conglomerates, which in the upper part of the formation contain rock fragments derived from the Troodos ophiolite. These fragments are evidence of exhumation of the Troodos ophiolite during the Miocene, indicative of initial emergence of the island from the sea. Two reef limestone members of the Pakhna occur locally on Cyprus; the Terra Member near the base and the Koronia Member near the top (Lord and others, 2000). Neither of these limestone members is known to occur in the Lefkosia map area; however, exposures of chalk belonging to the Pakhna Formation occur along the western margin of the map area. Approximately 375 m of Pakhna was penetrated by the Kato Lakatameia borehole (fig. 4). As mentioned previously, the upper parts of the Pakhna Formation are identical in lithology, fossil content, and age (Messinian) to the Lapatza Formation that occurs in the Kyrenia terrane. It appears that by the Messinian, all of northern Cyprus was at a relatively uniform water depth and was experiencing uniform sedimentation. This uniform state existed across the Ovgos fault zone, a feature that previously had separated different depocenters at differing water depths and sedimentary provenance. Prior to the Messinian, the Ovgos fault zone was a shelf margin (fig. 6).

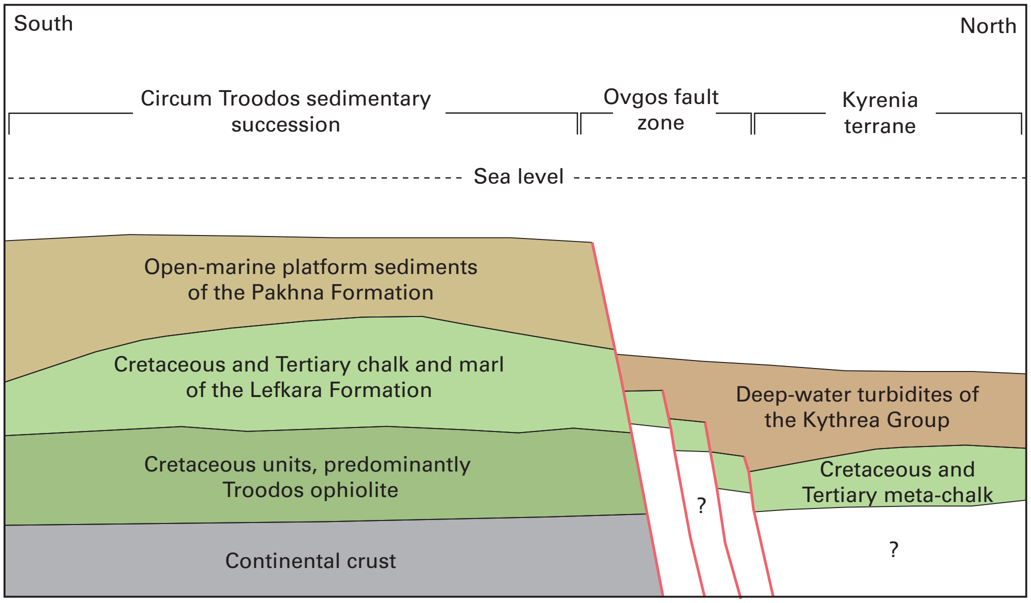



**Figure 6.** Schematic diagram of the shelf margin that existed in northern Cyprus during the middle Miocene. Deposits of the circum Troodos sedimentary succession were separated from sediments of the Kyrenia terrane by the Ovgos fault zone.

During the late Miocene marine regression, known in the Mediterranean region as the “Messinian salinity crisis,” the Kalavasos Formation was deposited in basins across northern Cyprus (Necdet and Anil, 2006). The Kalavasos Formation consists of gypsum and gypsiferous marls, which were deposited in restricted, structurally controlled basins (Robertson and others, 1995a; Harrison and others, 2004). In the circum Troodos sedimentary succession, the Kalavasos Formation overlies the Pakhna Formation; in the Kyrenia terrane, the Kalavasos Formation overlies the Lapatza Formation.

Quickly following the Messinian crisis, open-marine conditions were re-established in Cyprus, as elsewhere in the Mediterranean. Paleontological data acquired for this report demonstrate that the transition was rapid and happened in the late Miocene (late Messinian, zone N18). Subsequent sedimentary deposition records the Neogene uplift history of Cyprus.

The Nicosia Formation is a complex assemblage of predominantly clastic, marine depositional facies that vary both temporally and spatially. The Nicosia Formation occurs extensively throughout the southern half of the Lefkosia map area and at various locations in the northern part. Field mapping and paleontological work for this report developed a three-dimensional framework of six interfingering and transitional facies in the Nicosia Formation. Treated as members, these are basal conglomerate member, marl member, Kephales member, Athalassa member, lithic sand member, Aspropamboulos oolite member, and marine littoral member. Additional descriptions of these members can be found in the Description of Map Units on the map sheet. The basal conglomerate member (Tnbc) was mapped in one small area within the Ovgos fault zone, along the western margin of the map area; it consists of gravel, cobbles, and coarse-sand deposits that are matrix supported and nonfossiliferous. The position of this member at the base of the Nicosia Formation was established in reconnaissance mapping by the authors to the west of the Lefkosia map area; however, its exact age is unknown. The dominant facies in the Nicosia Formation is the marl member (Tnm), which is composed of massive to thick-bedded, green-gray to dark-brown, calcareous, fossiliferous, clayey silt and silty clay that typically is devoid of sedimentary features. Locally and generally adjacent to major faults, limestone beds occur within the marl member. These limestone beds are relatively thin and are not extensive enough to map separately. An example is the limestone beds found in proximity to the Vounari fault described below. The Kephales (Tnk) and Athalassa (Tna) members were previously termed Kakkaristra and Athalassa Formations, respectively, and both had been considered Pleistocene (Poole and Robertson, 1998). Those names were changed when it was discovered during the field mapping for this study that in several places both Kephales and Athalassa members were overlain by facies of the marl member that yielded diagnostic Pliocene microfossils. Subsequently, two samples from thin marl beds in the Kephales yielded nannofossils of zone NN15, indicative of a Pliocene (Zanclean) age (see map). The Kephales member is a high-energy, “Gilbert-type” marine delta facies that consists of a series of crossbedded conglomerates, fine-grained sands with conglomeratic intercalations, and siltstones. Kephales facies fills channels cut into other Nicosia facies of soft marl and sandy marl. Paleoflow indicators (mostly crossbeds) show a predominant flow direction towards the north and northeast, with some flow direction to the northwest. The Athalassa member consists of massive beds of fossiliferous, medium- to coarse-grained, crossbedded calcarenites, interbedded with lesser thin beds of sandy fossiliferous marl; age constraints provided by paleontological data indicate that the scattered occurrences of calcarenite facies were deposited at different times in the Pliocene. Paleoflow indicators (mostly crossbeds) show a dominant towards-the-south direction. The marine littoral member (Tnml) is composed of gravel, sand, and silt; typically, it is crossbedded and contains flat, rounded “beach” pebbles and some oolitic sand. The Aspropamboulos oolite member (Tnas) crops out in a small area of a few hectares at the "Aspropamboulos" locality, approximately 6 km south of the village of Lakkia. This member is an almost pure fine-grained oolite with planar crossbeds. Overall, the Nicosia Formation has a maximum thickness of up to 900 m.

The Nicosia Formation is considered a time transgressive sequence of detrital (lithoclastic and bioclastic), marine sediments derived largely from older units. It was deposited on the northern flank of the emerging Troodos Range. The wide range of ages for the Nicosia Formation at the surface suggests the presence of significant intraformational unconformities. Some of the lower beds of the Nicosia Formation are correlative with the Myrtou Marl mapped elsewhere in northern Cyprus (Moore, 1960).

The youngest bedrock unit in the circum Troodos sedimentary succession is the Apalos Formation, which is composed of near-horizontal, reddish, fluvial muds and silts with conglomerate intervals. The terrestrial Apalos sediments are a nonmarine continuation of deposition on the northern slope of the uplifting Troodos Range. These deposits reach a maximum thickness of 60 m in the Lefkosia map area and are generally considered Pliocene to Pleistocene in age. The youngest known rocks that they overlie are rocks of the marl member of the Nicosia Formation of Pliocene age (Piacenzian or Gelasian, zone N21).

## Troodos Terrane (Troodos Ophiolite)

The Troodos terrane is composed of Upper Cretaceous (upper Cenomanian to lower Campanian) oceanic crust and mantle material that was obducted onto continental crust during the Cretaceous (Gass and Masson-Smith, 1963). All components of a classical ophiolitic sequence are present in the Troodos terrane, but most significantly these rocks have not been disturbed from their original relative positions nor have they undergone any alteration other than serpentinization. The Troodos ophiolite is characterized by the following sequence of rocks, in ascending order:

- ultramafic complex consisting mainly of harzburgite;
- plutonic ultramafic and mafic rocks;
- sheeted dike complex consisting of 100 percent dikes, mainly of basaltic composition;
- mafic volcanic sequence of mostly pillowed lava flows;
- iron- and manganese-rich hydrothermal sediments, or umbers, of the Perapedhi Formation.

The ultramafic complex consists of about 90 percent harzburgite (80 percent olivine, 20 percent orthopyroxene) and about 10 percent dunite. The plutonic sequence constitutes an assemblage of dunites, werhlites, pyroxenites, gabbros, and plagiogranites, which are the products of fractional crystallization and magmatic differentiation of a basaltic magma. Rocks of the sheeted dike complex are fine- to medium-grained, generally aphyric basalt that occurs in a swarm of multigenerations of subparallel steeply dipping dikes. The dikes represent the infilling of fissures that opened along divergent boundaries as two adjoining plates moved away from each other. The mafic volcanic sequence consists of pillowed and non-pillowed lava flows that are the top of the igneous oceanic crust. The Perapedhi Formation is a sequence of umbers and radiolarian shales that were the first sediments to be deposited on the ocean floor, commonly filling voids on the lava surface.

From the Kato Lakatameia drill hole (fig. 4 and cross section *A–A′*), the Troodos ophiolite is known to exist in the subsurface beneath the Lefkosia map area. Although there are no known detailed descriptions of lithology and texture of the Troodos penetrated by the Kato Lakatameia drill hole, almost certainly, the subsurface Troodos beneath Lefkosia is similar to that of the Troodos Range.

## Mamonia Terrane

Rocks belonging to the Mamonia terrane are exposed across western and southwestern Cyprus. Small occurrences are exposed in the southeastern part of the island. Lithologies of the Mamonia terrane consist of various igneous, sedimentary, and very minor metamorphic rock types. Deformation within these rocks is extremely intense as they have been severely sheared, broken, and folded. The deformational style found throughout the Mamonia terrane is characterized as that of a left-lateral strike-slip fault zone (Swarbrick, 1993). Locally, Mamonia rocks are thrust over the southern leading edge of the Troodos ophiolite and juxtaposed against bentonitic clays of the Kannaviou Formation; this indicates a transpressive nature to the strike-slip faulting. Three major lithologic groups are recognized: the predominantly sedimentary Ayios Photios Group, the mostly igneous Dhiarizos Group, and the metamorphic Ayia Varvara Formation.

The Ayios Photios Group constitutes Middle Triassic to Upper Cretaceous quartz sandstones with fossil plant remains, siltstones, fossiliferous calcilutites, radiolarian-bearing mudstones, and calcarenites (Cyprus Geological Survey Department, 1995). The Dhiarizos Group constitutes pillow lavas, pyroclastic tuffs, and volcaniclastic conglomerates (Cyprus Geological Survey Department, 1995). Large blocks of reef limestone accompany the volcanic rocks. Many volcanic rocks in the Dhiarizos Group have been altered to serpentinite, particularly those occurring near intensely sheared areas. The Ayia Varvara Formation constitutes amphibolite-grade metavolcanics, metacherts, and marble (Cyprus Geological Survey Department, 1995).

The cataclasis, shearing, and mixing of such varying lithologies as those found in the Mamonia terrane can only be interpreted as indicative of a major tectonic zone of crustal scale. The proximity of the Mamonia terrane to a submarine zone of deformation and present-day seismicity, which has long been regarded as the principal boundary between the African plate and the Anatolian microplate (fig. 7), leads to the supposition that there is a close interrelation between the Mamonia terrane and the plate boundary. Onshore, there is no known southern boundary for Mamonia rocks and shearing on Cyprus.

## Paleontological Analyses

For the Seismic Hazard and Risk Assessment of the Greater Nicosia [Lefkosia] Area Project, 177 samples were collected for micropaleontological analyses. These samples were collected from outcrops and drill core/cuttings for the purpose of geologic map preparation, structural framework development, correlation of geologic units, and age and paleoenvironment determinations of stratigraphic units. These analyses were an integral part of the geologic study of the Lefkosia and surrounding area; without these analyses, the scope of this investigation would have been extremely limited. Most of the samples were analyzed for their foraminifera content; 28 samples were analyzed for calcareous nannofossils. On the basis of identified species, the samples were placed in universally accepted foraminifera and nannoplankton zones (Gradstein and others, 2004); these zones are shown on the Neogene time scale on the map sheet. Because of similarities in sedimentary facies in different geologic units, the age constraints provided by these data were critical in understanding the depositional history and timing of deformational events, which were required for interpreting the local and regional tectonic history, as well as the paleoseismic history of the Lefkosia area. The main uncertainty of the paleontological data is in evaluating the component of reworked fossils present in clastic deposits. In particular, the proximal offshore, shallow depositional environment of the Nicosia Formation was prime for reworking older fossiliferous material derived from the emerging Troodos Range.

A new understanding of the ages of sedimentary deposits found in the Lefkosia area, particularly of the Nicosia Formation, came out of the paleontological analyses for this study. Previously, upper and lower contacts for this formation were considered as occurring at Epoch boundaries; however, the paleontological data acquired for this report indicate that this is not the case. The lower contact of the Nicosia Formation, which was previously considered to lie at the Miocene-Pliocene boundary, is now known to be Messinian (late Miocene) in age. The upper contact of the Nicosia Formation with the Apalos Formation, which was previously considered to be at the Pliocene-Quaternary boundary, is most probably within the Pliocene. This is because no foram zones younger than N21 were determined for any sample collected from the Nicosia Formation.

## Unmapped Surficial Deposits

Extensive areas of Quaternary surficial deposits are not shown on the geologic map. These deposits will be shown in detail on a surficial map of the same area.

## Description of Geologic Structures

The principal purpose for undertaking the geologic investigations that are reported here was to better understand

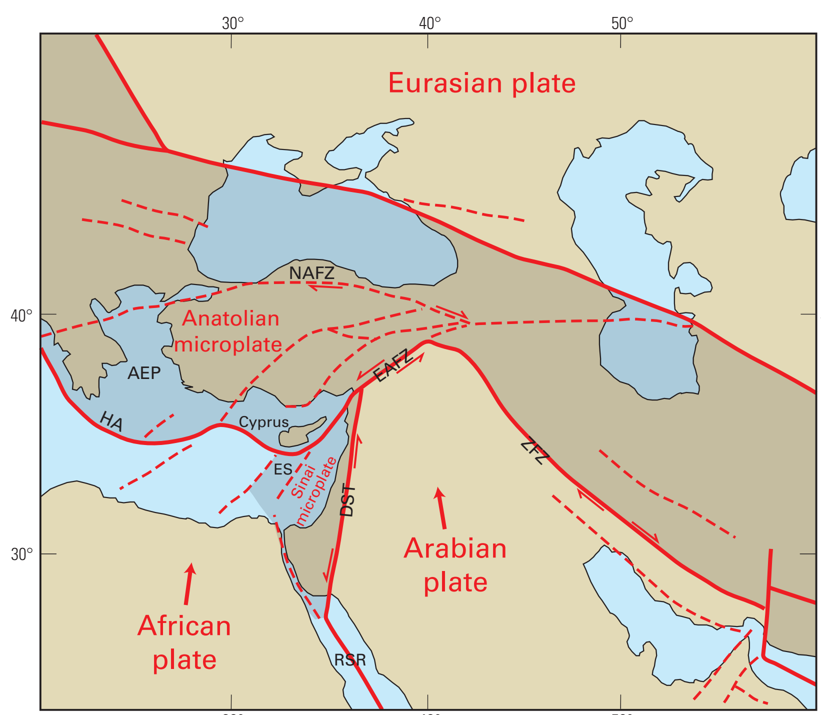



**Figure 7.** Generalized map showing the location of Cyprus in the plate tectonic setting of the eastern Mediterranean, Middle East, and central Eurasia (after Jackson and McKenzie, 1988). Shaded area represents belt of smaller, fragmented tectonic microplates. Large red arrows indicate motions of the African and Arabian plates relative to the Eurasian plate (after McClusky and others, 2000); red half arrows show relative movement of major plate-bounding transform faults that are shown as solid red lines. Dashed red lines are major intraplate structures. Abbreviations are as follows: AEP, Aegean extensional province; DST, Dead Sea transform; EAFZ, eastern Anatolian fault zone; ES, Eratosthenes Seamount; HA, Hellenic arc; NAFZ, northern Anatolian fault zone; RSR, Red Sea rift; ZFZ, Zagros fault zone.

the seismic hazard imposed on Lefkosia by both local and regional sources. Therefore, we first present a detailed description of the structural (deformational) nature and history of the Lefkosia area, and then take a look at the tectonic framework and evolution of the eastern Mediterranean region. Some of our conclusions were presented in Harrison and others (2004) and Harrison and Panayides (2004).

Structurally, the Lefkosia area is complex. Numerous faults of differing styles cut the area along multiple trends. The deformation is not uniform; rather, rocks in the approximate northern third of the map area are intensely folded and broken by a high density of thrust and strike-slip faults; rocks in the southern two-thirds of the map area are virtually unfolded and are cut by only a few, although very significant, faults. The boundary between these areas of intense and less-intense deformation is the Ovgos fault zone, which has had episodes of both strike-slip and contractional movement. Many thrust faults and fold belts parallel to the Ovgos trend are mapped to the north of the Ovgos fault zone; only a few paralleling thrust faults were mapped to the south. Rocks north of the Ovgos fault zone are cut by a strong and well-developed conjugate set of north-northwest- and north-northeast-trending strike-slip faults; to the south, rocks are deformed by only a few of the major strike-slip structures that cross the Ovgos fault zone.

## Ovgos Fault Zone

The Ovgos fault zone is a major tectonic boundary (fig. 1). In the Lefkosia map area, it has a slightly curved, east-west trend and separates the Kyrenia terrane to the north from the circum Troodos sedimentary succession to the south. The fault zone consists of multiple strands of predominantly southward-verging thrust or high-angle reverse faults. The fault zone is fairly well exposed west of Old Lefkosia (within the Venetian wall) and is poorly to not exposed beneath and to the east of Old Lefkosia, where its mapped continuation is based on subsurface data.

West of Old Lefkosia, west-northwest-striking thrust or high-angle reverse faults across a 0.6- to 0.8-km-wide zone define the Ovgos fault zone. Individual structures are most commonly thrust faults that dip to the north and place deep-water flysch deposits of the Kythrea Group adjacent to the marl member of the Nicosia Formation (fig. 8). The principal fault in the zone is herein defined as the southernmost-bounding structure for the Kythrea Group (see cross section *A–A′* and figures 4, 5, 8). Subparallel, subsidiary back thrusts occur locally; folded strata in and adjacent to the Ovgos fault zone typically dip parallel to the trend of the structure. However, an exception to this parallelism occurs west of the village of Gerolakkos along the western margin of the map area. There, northwest- and northeast-trending thrust faults and northwest-dipping strata are mapped between strands of the Ovgos fault zone. Kinematic indicators (slickenside striations and mullions) on the thrust faults reveal orthogonal motions on these structures.

Centered at approximate UTM coordinates of 3892925 m north and 527460 m east is a small patch of gravel of the Apalos Formation (fig. 8), which overlies a strand of the Ovgos fault zone. The gravel is subhorizontal and unconformably overlies steeply dipping (76° NE.) beds of the marl member of the Nicosia Formation. Several small faults with both normal and reverse offsets (fig. 9) cut the Apalos Formation indicating a probable Quaternary age of movement. These small faults are parallel to and directly overlie a major strand of the Ovgos fault zone, suggesting that they are coeval back thrusts along the Ovgos fault zone. A sample of the steeply dipping marl member in the hanging wall of the underlying thrust fault yielded forams of zone N18 (late Messinian). One sample of the marl member in the footwall of the underlying thrust fault yielded forams of zone N21 (middle to late Piacenzian or Gelasian), and two other samples yielded forams of zone N20 (early Piacenzian). From these data, it is inferred that compression along the Ovgos fault zone persisted throughout most of the Pliocene and that there has been subsequent reactivation during the Pleistocene.

Trenching and drilling along the Ovgos fault zone in the Agios Dometios area (~3,800 m east of the Apalos outcrop described above) confirmed the age constraints of the main compressional event. An exploration trench was excavated along the crest of a prominent hill in this area. The trench (fig. 10) exposed strata of the Nicosia Formation dipping approximately 60° to 90° (fig. 11). Micropaleontological analyses of samples collected from the trench confirmed the strata as part of the Nicosia Formation. The location of the trench between strands of the Ovgos fault zone indicates that the observed deformation is attributable to this structure.

East of Agios Dometios, most of the Ovgos fault zone in the Lefkosia area is covered by Quaternary deposits that are not shown on the geologic map. The easternmost surface exposure of the Ovgos fault zone is the Ledra Palace fault strand (see geologic map), which can be seen in the banks of the Pediaios River. There, the Pediaios River makes an abrupt “dogleg” to a N. 75° W. trend around a bedrock high and then bends sharply back to its northward trend. Exposed in the bedrock high are east-trending thrust faults and steep north-dipping strata. A sample from this strata was barren of forams; however, approximately 100 m to the south, another sample from similar strata exposed in an excavation along the banks of the Pediaios River yielded forams of middle to late Miocene age and also contained forams of Eocene age, suggesting reworking of older Eocene material during deposition. These strata are interpreted as part of the Lapatza Formation. Along the projection of the “dogleg” to the west in Holocene alluvial deposits is a gentle south-facing topographic scarp, which also trends N. 75° W. This topographic scarp is interpreted as a probable fault scarp. The scarp occurs in alluvial deposits that Ducloz (1965) called the Xeri (called “Tseri” on the map) alluvium, to which he assigned a post-glacial Holocene age. A Holocene age for these deposits is substantiated by a $^{14}C$ age of 4,665±35 years before present (yr B.P.) obtained on terrestrial snail shells collected from Xeri alluvium at the

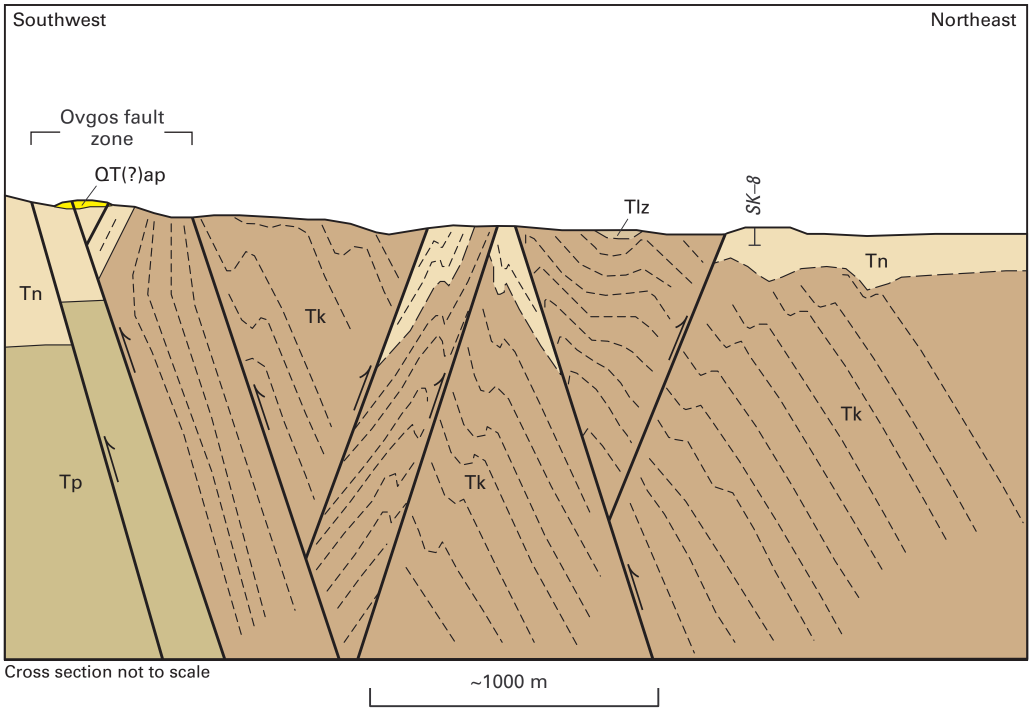



**Figure 8.** Generalized cross section through the Ovgos fault zone west of Old Lefkosia (see geologic map for approximate location). The strike of all thrust faults in this area is N. 75°–80° W. QT(?)ap, Apalos Formation (Pliocene? and Pleistocene); Tn, Nicosia Formation (late Miocene and Pliocene); Tlz, Lapatza Formation (middle to late Miocene); Tk, Kythrea Group (middle Miocene); Tp, Pakhna Formation (Miocene). Dashed lines represent approximate dips of bedding. Undivided Nicosia Formation is shown here.

nearby excavation for the new Cyprus Supreme Court building. Experience in dating terrestrial snail shells in the Lefkosia area (Harrison and others, 2004) and elsewhere in the arid Middle East region (Goodfriend and Hood, 1983; Goodfriend, 1987; Brennan and Quade, 1997) have shown that these snails commonly yield $^{14}C$ ages that are from 2,500 to 3,000 years too old. Preservation of a topographic scarp in such young deposits strongly suggests movement during the Holocene. However, because the scarp has not been trenched, its true nature is unknown, and thus the suggested age of movement must be considered tentative.

East of the Pediaios River in the area of the Lefkosia geologic map, there are no other exposures of any strand of the Ovgos fault zone because it is overlain by a relatively thick (typically >10 m) layer of unconsolidated alluvial material that is not shown on the geologic map. The fault trace portrayed on the geologic map is controlled by subsurface data for approximately 4 km east of the Venetian wall of Old Lefkosia. Beyond that, the trace is projected to the next known location for the structure that is just south of the village of Lefkoniko (see cross section in figure 5), more than 20 km to the east.

Beneath the Venetian wall of Old Lefkosia, the Ovgos fault zone appears to have an east-northeast-striking trend, which is slightly different from the north-northwest-striking trend to the west. North of the Ovgos fault zone in the area of transition in strike, there is a major rhomb-shaped graben that underlies most of northern metropolitan Lefkosia. The graben is bound by the northernmost fault of the Ovgos fault zone on the south, the East Lefkosia Basin fault on the east, the South Mandres fault of the Kanli-Gonyeli-Ortakoy-Mandres (KGOM) fault zone on the north, and the Skali fault on the west. The graben contains a relatively thick section of the late Miocene (Messinian) Kalavasos Formation (fig. 12), which does not occur immediately outside of the graben. In order to produce such a large pull-apart graben, there must have been a significant left step in strain along a left-lateral strike-slip system, from the Ovgos fault zone to the South Mandres fault, located approximately 4,000 m to the north. The age of this left-lateral transtensional movement along the Ovgos fault zone is constrained as Messinian because of the deposition of the syntectonic Kalavasos Formation and as early Pliocene because of the presence of an angular unconformity in the lowermost Nicosia Formation that separates strongly rotated beds from overlying relatively flat beds (fig. 12).

The complex nature of the Ovgos fault zone beneath the Venetian wall of Old Lefkosia is revealed by comparing the subsurface geology of drill holes along an approximately north-south line (cross section *A–A′* and fig. 12). Three of the holes on this section (SHN11, SHN10, and EPW 1) were logged in detail for this report, and samples collected from key intervals were analyzed for their fossil content (see table 1). Drill hole SHN11 penetrated about 75 m of Quaternary

**Figure 9.** Reverse offset in the Apalos Formation along the Ovgos fault zone, west of Old Lefkosia and north of the old Nicosia International Airport. Geologists are pointing to the same bed on either side of the fault.

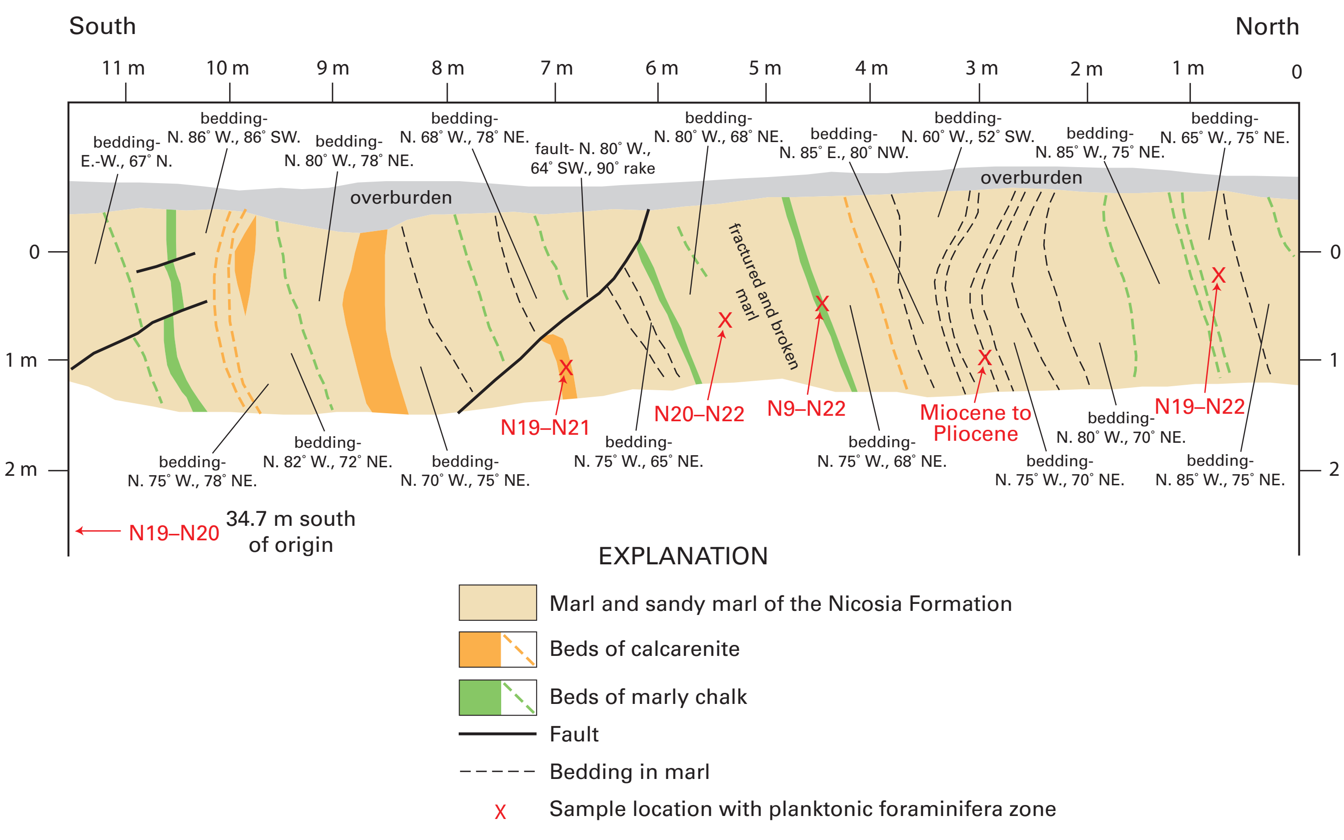



**Figure 10.** Schematic log for the Agios Dometios trench. Analyses of foraminifera in samples collected from this trench indicate that all material is of Pliocene age and, therefore, part of the Nicosia Formation.

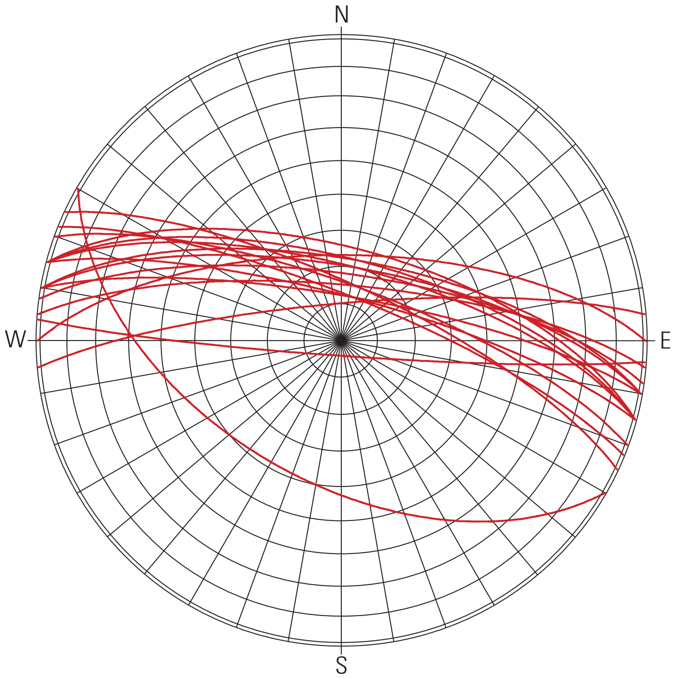



**Figure 11.** Lower hemisphere stereonet projection of bedding planes in the Agios Dometios trench.

alluvium and a relatively normal section of marl member of the Nicosia Formation that was moderately rotated (~30°); four samples analyzed for forams from this section indicate a late Messinian age (zones N17–N18). Below the Nicosia and separated by a fault is a section of moderately dipping flysch deposits (sand, silt, and clay) of the Kythrea Group that yielded forams of Langhian to Tortonian age (zones N9–N14) and forams of Burdigalian to Langhian age (zones N7–N9). Marls of the Nicosia Formation in drill hole SHN10 yielded forams of latest Messinian through Zanclean age (zone N19), indicating that the age of the Nicosia beds in SHN10 is much younger than the age of the Nicosia beds in SHN11. In addition, SHN10 penetrated an angular unconformity in the Nicosia Formation that was not present in SHN11. These subsurface data strongly indicate the presence of a fault between SHN10 and SHN11; this fault is interpreted to be normal in displacement and down to the north, with movement into the pull-apart graben described above. Drill hole EPW 1 was drilled on the northern side of the Ovgos fault zone and just inside the margin of the pull-apart graben. The section it encountered was very different from both SHN10 and SHN11 (fig. 12). Beneath a relatively thick interval of alluvial material, EPW 1 penetrated the late Messinian (zones N17–N18) marl member of the Nicosia Formation, then gypsum-rich deposits of the Kalavasos Formation, and finally flysch deposits of the Kythrea Group that yielded forams of Langhian to Serravallian age (zones N9–N11). Core inspection identified strong low-angle shearing in the Nicosia section and a fault contact between the Kalavasos and Kythrea sections (fig. 12). Coupled with additional drill-hole data to the north (fig. 12), the Ovgos fault zone is shown to have had a complex structural history of extension and compression at different times.

To the east, the last subsurface control on the location of the Ovgos fault zone is along the line of drill holes SHN14, SHN12, and SHN13. The first two holes penetrated marl member of the Nicosia Formation, while the northernmost hole, SHN13, penetrated limestone and sandy limestone of the Lapatza Formation overlying flysch of the Kythrea Group that yielded forams of Burdigalian to Langhian age (zones N7–N8). These data, plus a nearby small outcrop of limestone of the Lapatza Formation underlying the Kephales member of the Nicosia Formation, constrain the location of the Ovgos fault zone. The apparent lack of fault deformation in the Kephales member in the vicinity of drill holes SHN14, SHN12, and SHN13 suggests that the Ovgos fault zone in this area has not been active since deposition of the Kephales member in the Pliocene; the closest sample yielded nannofossils of Zanclean age (zone NN15).

Our data disagree with much of McCallum and Robertson's (1990) interpretations regarding the Ovgos fault zone, particularly in their pre-Pliocene and Pliocene portrayal of the structure. McCallum and Robertson (1990, their figure 3) did not recognize the existence of the Ovgos fault zone during the pre-Pliocene. Our detailed mapping and field investigations along the Ovgos fault zone indicate that it was the major boundary between the circum Troodos sedimentary succession and the Kyrenia terrane during the Miocene; a boundary that McCallum and Robertson (1990) placed much farther to the south. A second major disagreement between our data and the interpretations of McCallum and Robertson (1990) lies in their depiction of the Ovgos fault zone as a south-dipping normal fault during the early to middle Pliocene. The majority of all fault surfaces observed along the Ovgos fault zone in the Lefkosia map area dip to the north; this is also true for the Ovgos fault zone both east and west of Lefkosia all the way to the Mediterranean Sea in both directions (Harrison and others, 2004). The only documented normal faulting along the Ovgos trend lies beneath the Venetian wall of Old Lefkosia. Faulting here is clearly down to the north along north-dipping surfaces that bound the evaporite-filled basin described above.

## Thrust Faults and Folds Parallel to the Ovgos Fault Zone

There are numerous contractional structures, thrust faults, and folds shown on the geologic map that closely parallel the Ovgos fault zone. Thrust faults occur on both sides of the Ovgos fault zone, but are much more numerous to the north than they are to the south. Major folds with axes parallel to the Ovgos fault zone only occur to the north and are best described as fault-propagation folds, typically with anticlines forming in the hanging walls and synclines forming in the footwalls of thrust faults. As with the Ovgos fault zone, the trend of these parallel structures changes from west-northwest to east-northeast from west to east across the map area.

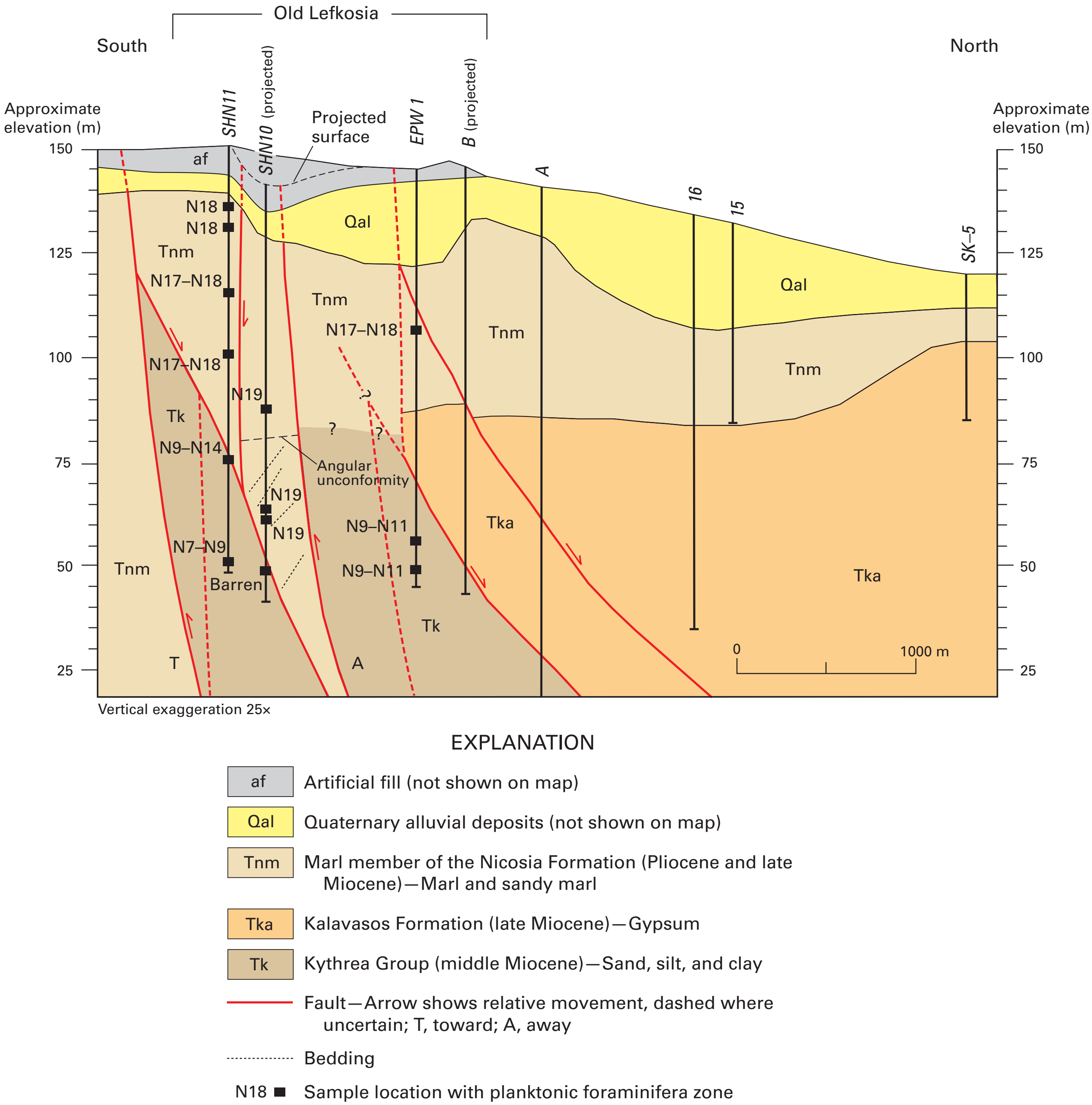



**Figure 12.** Generalized north-south-trending cross section through the northern part of metropolitan Lefkosia showing the complexity of subsurface stratigraphy and deformation along the Ovgos fault zone. This section is a vertically exaggerated version of cross section *A–A′*, shown on the geologic map. Drill hole SHN10 is projected into the line of section. Planktonic foraminifera zones determined from drill-hole samples are shown (see table 1). Strong rotation (65°–90°) of bedding was observed in the lowermost Nicosia Formation in core from drill hole SHN10 and is depicted on the figure.

Following are detailed descriptions of some of the more significant areas on the map sheet where characteristic contractional deformation parallel to the Ovgos fault zone has occurred. Examination of deformation in these areas provides insight into the style and timing of compressional deformation in the Lefkosia area.

## Spitoudia Area

About 4,000 m west-northwest of the Venetian wall of Old Lefkosia is an area designated as Spitoudia on the 1:5,000-scale topographic map 21/XX (see index map on map sheet). This area is centered at UTM coordinates 3894500 m north and

528200 m east. In the Spitoudia area, there is a series of relatively closely spaced thrust faults and fault-propagation folds that deform strata of the Kythrea Group and Nicosia Formation (fig. 13). Thrust faults and fold axes in the Spitoudia area trend N. 75° W., parallel to the Ovgos fault zone, which is located approximately 1,300 m to the south. Vergence on the Spitoudia fault is to the south (fig. 13*A*), similar to that of the Ovgos fault zone. However, a back thrust (fig. 13*B*), antithetic to the main thrust direction in this area, has a vergence direction to the north and places flysch sediments of the Kythrea Group to the south against marl member of the Nicosia Formation to the north. Two surface samples collected from the marl member yielded forams of late Messinian to Zanclean age (zones N18–N19), confirming the field interpretation of Nicosia Formation. These samples also indicate that the main phase of compression in the Lefkosia area was post-early Pliocene.

## Kanli-Gonyeli-Ortakoy-Mandres (KGOM) Fault Zone

At a distance of about 3 to 4 km north of the Ovgos fault zone, there is a zone of thrust faults that is approximately 2 km wide and crosses the entire Lefkosia map area. Named after small villages on the northern side of metropolitan Lefkosia, we refer to this zone as the Kanli-Gonyeli-Ortakoy-Mandres (KGOM) fault zone. Characteristically, this zone is the northernmost extent of both Kalavasos and Nicosia Formations in the Lefkosia area; north of this belt, only Kythrea Group crops out in the map area.

Exposures of fault surfaces in this zone are rare; fault traces are defined typically by the juxtaposition of different formations and steeply dipping strata folded into anticline-syncline pairs characteristic of fault-propagation folds, similar to those previously described for the Spitoudia area. The Vounari fault is an exception, in that it is well exposed at approximate UTM coordinates of 3895400 m north and 532300 m east, in the south bank of the Pediaios River. There, excellent exposures of the south-verging Vounari fault (fig. 14) and associated hanging wall and footwall folds (fig. 15) can be seen. The Vounari fault strikes from N. 80° W. to east-west and dips about 75° to the north. The fault places limestone and marl beds of the Lapatza Formation over the marl member of the Nicosia Formation. Analysis of nannofossils from the Lapatza Formation in the hanging wall yielded an age of early Pliocene to late Miocene (zone NN11b–NN12). Foram analysis of a marl bed in the footwall yielded a Zanclean age (zone N19) and confirms that the strata are part of the Nicosia Formation. Facies within the Nicosia Formation include deep-water deposits of marl and sandy marl, and shallow-water to intertidal limestone. The limestone facies was deposited in shallow-water banks in the photic zone that were isolated from deposition of clastic material. These banks consist of algal mats and intercalated indigenous biofragmental calcilutite, and calcarenite. Angular unconformities (fig. 16) present within folded strata of the Nicosia Formation indicate that tectonic deformation was syndepositional. The existence of these structures within the zone of deformation of the Vounari fault suggests uplift of the sea floor along this structure and active compressional tectonics during the early Pliocene.

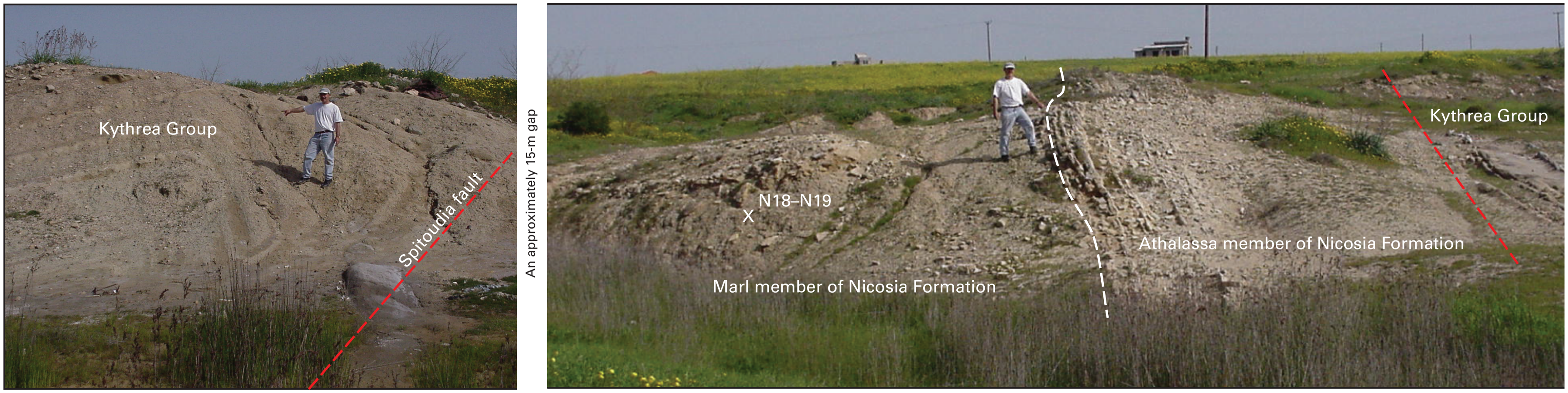
Most thrust faults in the KGOM fault zone dip to the north and have displacements sympathetic to the Ovgos fault zone. However, there are at least two areas where back thrusts that dip southward and have an up-to-the-south sense of displacement have been mapped. One such area is just south of the village of Kanli in the western part of the map area. There, a pair of opposing thrust faults occurs and between them a tight syncline has formed. South-dipping thrust faults also have been mapped in the bank of the Pediaios River, about 0.5 km north of the Vounari fault. Between two opposing thrusts at this locality, beds of the Lapatza Formation have been rotated to near vertical.

Within the Lefkosia map area, strands of the KGOM fault zone served as bounding structures for grabens in which evaporites of the Kalavasos Formation accumulated. The relatively large graben beneath northern metropolitan Lefkosia (see cross section *A–A′*) has a fault strand of the KGOM fault zone (South Mandres fault) along its northern boundary; this graben is bound on the south by the northernmost fault of the Ovgos fault zone (see discussion in previous section). Another graben that contains a thick Kalavasos sequence has been mapped in the northeastern quarter of the Lefkosia map; two strands of the KGOM fault zone, the North Mandres fault and the South Mandres fault, bound this graben; private drill-hole data indicate that the Kalavasos Formation there is greater than 50 m thick. Outside the map area, the distribution of other grabens containing Kalavasos Formation in northern Cyprus (Necdet and Anil, 2006) indicates a close association between them and extensions of the KGOM fault zone both to the east and west of the Lefkosia area. Conclusions drawn from these occurrences is that the KGOM fault zone was very active in the late Messinian and that deformation was probably transpressive in nature in order to produce graben structures in an otherwise contractional tectonic setting.

There is evidence that parts of the KGOM fault zone have had a Quaternary history of movement. In the vicinity of the villages of Mandres and Mia Milea, a south-facing, topographic scarp exists along the trace of the South Mandres fault strand. On the northern side of the scarp, the base of Quaternary alluvial-fan deposits (not shown on the geologic map) is 3 to 5 m higher than that on the southern side, suggesting possible fault offset. Unfortunately, the exact age of these gravels is unknown. Similar south-facing topographic scarps, in similar Quaternary deposits, occur along the mapped trace of the nearby, parallel North Mandres fault and along the mapped trace of the northernmost strand of the KGOM fault zone in the northwestern quarter of the Lefkosia map area.

## Thrust Faults and Folds North of the KGOM Fault Zone

Across the entire northern part of the geologic map, numerous thrust faults and folds that are parallel to the Ovgos and KGOM fault zones occur in the Kythrea Group. Observed




*A* *B*

**Figure 13.** *A*, Fault-propagation fold in the hanging wall of the Spitoudia fault, which is to the left of the geologist; fold is in flysch of the Kythrea Group. Fold axis trends N. 75° W., parallel to the Spitoudia fault and the Ovgos fault zone. *B*, Geologist is standing on the marl member of the Nicosia Formation and is pointing to steeply dipping beds of the Athalassa member of the Nicosia Formation, which are in fault contact with flysch deposits of the Kythrea Group at the far right of the photograph. Micropaleontological sampling of the marl member of the Nicosia Formation yielded forams of late Messinian to Zanclean age (zones N18–N19).

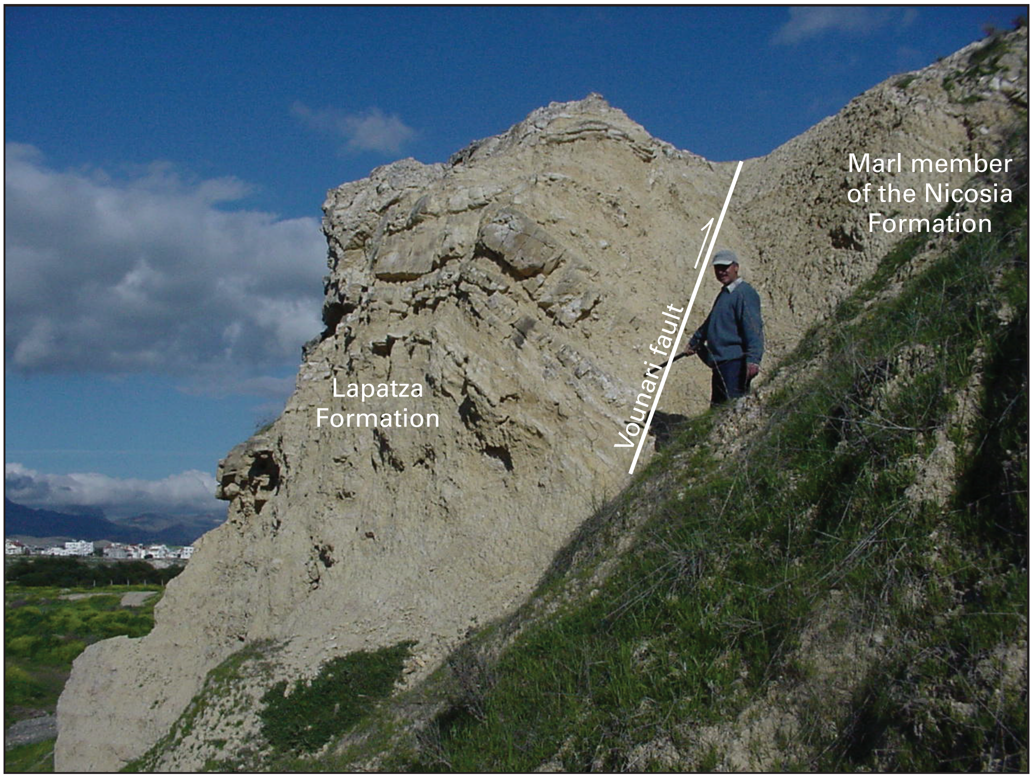



**Figure 14.** View is towards the east, looking along strike of the Vounari fault, which is a south-verging thrust fault that places the Lapatza Formation over the marl member of the Nicosia Formation. Location is in a cutbank on the south bank of the Pediaios River in northern metropolitan Lefkosia. Geologist is pointing at thrust fault surface, which strikes approximately N. 85° W. at this location and dips about 70° to 75° to the north.


**Figure 15.** Syncline in the footwall of the Vounari fault. View is towards the east along the approximately east-west-trending trough line that runs beneath the field pack. Beds are composed of limestone and sandy marl and lie within the marl member of the Nicosia Formation. The limestone facies was deposited in shallow-water banks in the photic zone that were isolated from deposition of clastic material. The existence of limestone beds within the zone of deformation of the Vounari fault suggests uplift of the sea floor along this structure in the early Pliocene.

**Figure 16.** Angular unconformity (directly below the compass) in the Nicosia Formation in the footwall of the Vounari fault. View is towards the east. Massive resistant beds are limestone; less resistant beds are sandy marl. This unconformity and the existence of limestone beds with the marl member of the Nicosia Formation is indicative of syndepositional movement on the Vounari fault.

thrust faults always dip to the north at 75° or more. Many of the fault surfaces are along bedding planes. Folds are abundant and occur as fault-propagation folds such as those at the Spitoudia area described previously, broad open folds that plunge east-west, and tight (almost isoclinal) folds (fig. 17).

## Lakatameia Fault

The Lakatameia fault is the only thrust fault known to exist south of the Ovgos fault zone in the Lefkosia map area. It dips to the north and is subparallel to the Ovgos trend. The Lakatameia fault is best known from an unpublished seismic-reflection dip log acquired by the Forest Oil Company in the 1960s. The data from this dip log were used to prepare cross section *A–A′* and the regional cross section shown in figure 4. The Lakatameia fault was penetrated by exploration hole KL–1, which was drilled by the Forest Oil Company in the 1960s; this drill hole is shown in cross section *A–A′* and the regional cross section shown in figure 4. In drill hole KL–1, the Lefkara and Moni Formations are both repeated across the Lakatameia fault (see cross section *A–A′*). Due to extensive cover by surficial deposits, the mapped trace of the Lakatameia fault is poorly constrained and its actual location is inferred beneath the Pediaios River valley. West of the Pediaios River valley, a normal fault that offsets the Apalos-Nicosia contact may represent a continuation of the Lakatameia fault that has experienced reactivation. A continuation of the Lakatameia fault for approximately 2 km to the east of the Pediaios River valley is inferred, based on anomalous surface drainage patterns and topography; any projection of this structure farther to the east is highly speculative.

The seismic-reflection dip log indicates that a graben structure filled with Kalavasos Formation exists south of and is bound by the Lakatameia fault (see cross section *A–A′* and figure 4). The Tseri drill hole (see geologic map, cross section *A–A′*, and figure 4) confirms the existence of a thick Kalavasos section in this area. As such, this graben appears to be similar to the previously described graben beneath northern metropolitan Lefkosia in that it is bound by east-west-trending thrust faults and by north-northeast-trending strike-slip faults.

## Conjugate North-Northeast and North-Northwest Strike-Slip Faults

There is an extensive set of conjugate north-northeast- and north-northwest-trending strike-slip faults in the Lefkosia map area. These strike-slip faults (fig. 18) occur throughout northern Cyprus and crosscut all other structural trends (Harrison and others, 2004). The north-northeast-trending faults are left-lateral, and the north-northwest-trending faults are right-lateral. Where these strike-slip faults faults cut the steeply dipping and relatively thinly layered flysch deposits of the Kythrea Group, they form a crisscrossed pattern on the landscape (fig. 19). The five most significant north-northeast-trending structures (Archangelos, Pediaios, Skali, Tseri, and Lakkia faults) and the two most significant north-northwest-trending structures (Mia Milea and Sehere Bakan faults) are described in more detail in the following sections.

**Figure 17.** Tight fold in the Kythrea Group in the northern part of the Lefkosia map area. Photographer is standing on the crest of an anticline looking east at the same crest on the opposite side of the reservoir.

**Figure 18.** Horizontal slickenside striations and mullions along an unnamed strike-slip fault in the Kythrea Group exposed at approximate UTM coordinates of 3897450 m north and 531450 m east. Many such exposures of strike-slip faults are seen in the northernmost part of the Lefkosia map area.

**Figure 19.** Conjugate strike-slip faults cutting steeply dipping flysch deposits in the Kythrea Group. Right-lateral offsets are along north-northwest-trending faults and left-lateral offsets are along north-northeast-trending faults. View is towards the west at approximate UTM coordinates of 3899700 m north and 529200 m east.

## Archangelos Fault

The Archangelos fault is named after an area shown in the southeastern corner of the 1:5,000-scale topographic map 21/XXVII (see index map on map sheet). In this area, the best expressions of the Archangelos fault are brecciation and shearing in the Apalos Formation. Some of the shearing (fig. 20) occurs as Reidel shears (northwest-striking, left-lateral strike-slip faults) that are sympathetic to the principal zone of displacement, which strikes N. 15° E. and is left lateral. Deformation of the Apalos Formation indicates that this fault has a Quaternary history of movement.

Much of the mapped strike length of the Archangelos fault is covered by Pleistocene alluvial deposits. The mostly covered segments are inferred from subsurface data (from drill holes SK–4, EPW 4, and EPW 5), as well as scattered outcrops that indicate a juxtaposition of Kythrea Group (middle Miocene) and Nicosia Formation (late Miocene and Pliocene) deposits across segments of the fault. As mapped, this fault has a strike length in excess of 17 km. Approximately 0.2 km of left-lateral movement is suggested by offset of the Ovgos fault zone by the Archangelos fault; however because of poor exposure and lack of precise control on the Ovgos offset, this amount of movement must be considered as inferred.

## Pediaios Fault and West Pediaios Fault

The Pediaios fault is a major north-northeast-striking, left-lateral strike-slip structure exposed north of the Venetian wall of Old Lefkosia. From the northern boundary of the map area southward, its trace is mapped continuously for approximately 7 km to its intersection with the KGOM fault zone. From this intersection southward, the Pediaios fault is covered by unmapped alluvium of the Pediaios River valley. The intersection of the Pediaios fault and KGOM fault zone coincides with a 90° bend in the course of the Pediaios River and is also the confluence of all drainages in the northwestern quarter of the Lefkosia map area and the Pediaios River. This confluence and bend in the river are interpreted as indicating a tectonic influence on surface drainage. Although piercing points have yet to be identified, intense deformation and rotation of bedding adjacent to the Pediaios fault suggest tens to hundreds of meters of offset. A splay of the Pediaios fault, the West Pediaios fault, is inferred from trenching in the Agios Dometios area, where the Kythrea Group and the Lapatza Formation are juxtaposed. Also, the West Pediaios fault is inferred to be located along a topographic scarp that coincides with a linear margin where the Apalos Formation crops out in the Egkomi area. The geologic map of Lefkosia shows a merging of the Pediaios and West Pediaios faults in the Kato Lakatameia area, which is based solely on the convergence of projected strikes for these structures and is unsubstantiated in the field. In actuality, multiple fault strands possibly could continue southward.

Between the West Pediaios fault and the Archangelos fault in the vicinity of UTM coordinates 3890000 to 3894000 m north and 529000 to 529300 m east, a set of northwest-striking, right-lateral strike-slip faults is exposed in the banks of a small north-south-trending hill that is capped by alluvial deposits of the Apalos Formation. The set consists of anastomosing fault surfaces with both steep (>75°) and low-angle

*A*

*B*

**Figure 20.** *A*, Brecciation and shearing along the Archangelos fault. *B,* Geologist is pointing at horizontal striations on a north-northwest-striking Reidel shear to the Archangelos fault.

(<45°) dips; all observed kinematic indicators, such as slickenside striations and mullions, suggest horizontal movement of a few meters or less. These structures deform strata as young as the Apalos Formation and are interpreted as subordinate Reidel shears related to the principal zones of displacement along the West Pediaios and Archangelos faults.

## Skali Fault

The Skali fault is named for exposures in a small cliff along the southern banks of the Pediaios River near Mandres village at approximate UTM coordinates of 3896300 m north and 533700 m east (figs. 21–23). From this locality northward, the Skali fault is traced continuously for more than 7 km along an overall strike of approximately N. 30° E. (parallel to the Pediaios and Archangelos faults) to the northern boundary of the Lefkosia map area. To the south of this locality, the Skali fault is covered by unmapped alluvial deposits of the Pediaios River and its location is inferred from the juxtaposition of different formations, apparent offset of the Ovgos fault zone, and linear topographic slopes and troughs in the alluvial fill of the Pediaios River. The Skali fault is the western boundary of the Kalavasos-filled graben that occurs beneath the northern part of metropolitan Lefkosia; it is interpreted as the eastern boundary of the Kalavasos-filled graben that occurs in the subsurface south of Kato Lakatameia (see cross section *A–A′*). The change in strike along the Ovgos fault zone that was discussed previously occurs principally at its intersection with the Skali fault. An actual amount of horizontal movement along the Skali fault is not accurately known; offsets of the Ovgos and KGOM fault zones portrayed on the geologic map are inferred only.

At the locality for which the Skali fault is named, there is an excellent exposure of a positive flower structure along a left-lateral strike-slip fault (fig. 21). This flower structure formed at a restraining bend along the strike of the fault as it curved from N. 15° E. to N. 40° E. and back again to N. 15° E. Characteristically, a right step in a left-lateral system produces splaying thrust faults that branch away from both sides of the principal zone of displacement, resembling the v-shaped pattern of flower petals and limbs coming off a main trunk. On the southeastern side of the master fault (see figure 21) of the Skali flower structure, calcified rock and fault breccia are thrust eastward over colluvial-wedge deposits shed off a fault scarp and Quaternary alluvial material in a set of anastomosing low-angle thrust faults (fig. 22). Thrust surfaces on the east side of the master fault strike from N. 80° E. to east-west and dip from 30° to the north to near vertical.

On the northwestern side, several southeast-dipping, low-angle thrust faults cut beds of the Lapatza Formation; strikes range from east-west to N. 25° E., and observed dips range from about 42° to vertical. Observed rakes of slickenside striations and mullions are typically from 70° to 80° to the southwest. A small fault-propagation fold occurs at the tip of one of these thrusts; Quaternary gravel beds are folded to about 85° to the northwest (fig. 23), and many rounded clasts derived from them are intermixed with marl from the Lapatza Formation in the crest of the fold, which strikes N. 80° E. There is approximately 2 m of elevation change in the Quaternary gravel-Lapatza contact across the fold. In contrast, some thrust faults on this side of the master fault do not deform overlying and truncating Quaternary gravel beds. This contrast indicates multiple episodes of displacement using different fault surfaces.

The master fault of the Skali positive flower structure lies on the northwestern side of the highly calcified zone (see figure 21) and is a sheared zone that is as much as 1 m thick. The master fault strikes N. 40° E.; dips of slip surfaces are from vertical to 64° to the southeast; and observed slickenside

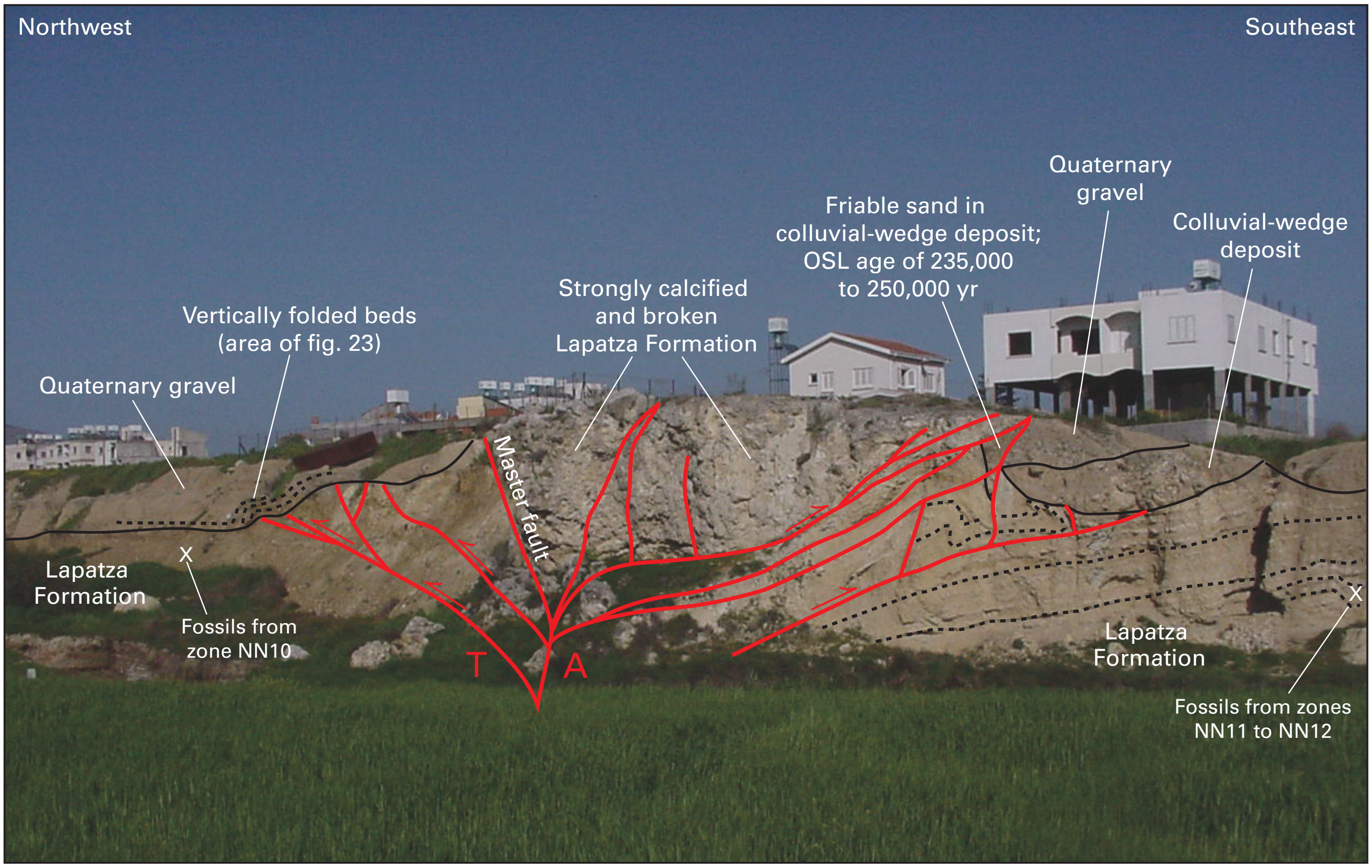



**Figure 21.** Positive flower structure on the Skali fault in cutbanks of the Pediaios River in northern metropolitan Lefkosia near Mandres village at approximate UTM coordinates of 3896300 m north and 533700 m east. View is towards the northeast. Contact between the Lapatza Formation and Quaternary gravels shown as solid line; dashed lines indicate some prominent bedding planes. Abbreviations are as follows: T, toward; A, away; OSL, optically stimulated luminescence.

striations rake ~42° to the southwest. On both sides of the master fault, there are several near vertical shear surfaces that are subparallel to the master fault with strikes ranging from N. 25° to 45° E. Slickenside striations on these shear surfaces demonstrate complex oblique movements and probable block rotations. For example, within a diameter of about 0.67 m on one vertical surface striking N. 25° E., slickenside rakes of 47° SW., 35° SW., 65° SW., 31° SW., and 84° NE. were measured. On another vertical surface striking N. 45° E., approximately 3 m from the previous, rakes of 22° SW., 65° SW., and 86° SW. were measured within 1 m of each other. Another indication of the complexity of deformation in the Skali flower structure is that relative movement of the earth on either side of the structure as shown by fault slickenside striations differs from that shown by the ages of the juxtaposed formations; left-lateral oblique slip suggested by the striations would result in the southeast block moving up; while the ages from nannofossils indicate that the southeast block is younger than the northwest block and therefore relatively downthrown. Such complexities are typical of strike-slip faults (Sylvester, 1988).

The accumulative deformation on the Skali positive flower structure is interpreted to be at least tens of meters, based on the intensity of deformation. As portrayed on the geologic map, the magnitude of offset of the Ovgos fault zone by the Skali fault is inferred and poorly constrained. Episodic movement on the Skali fault is indicated by the thrusting of breccia deposits over older colluvial-wedge deposits and by the different relations between thrust fault splays and Quaternary gravel; some thrusts predate and some postdate the deposition of these younger beds.

## Tseri Fault

The Tseri fault is named for exposures first identified by Ducloz (1965) on the eastern outskirts of Tseri at approximate UTM coordinates of 3881100 m north and 530400 m east. There, the fault strikes N. 30° E., dips approximately 80° to the northwest, and is solely within beds of the marl member of the Nicosia Formation. Within 50 m of the structure, the strike of bedding is orthogonal to the fault, and dips are less than 10° to the north. Immediately adjacent to the fault, bedding dips as much as 25° into the fault and the strike of bedding is parallel to the fault. There are no apparent marker beds in the area; therefore, the sense of displacement is problematic, but the structure has characteristics consistent with strike-slip movement.

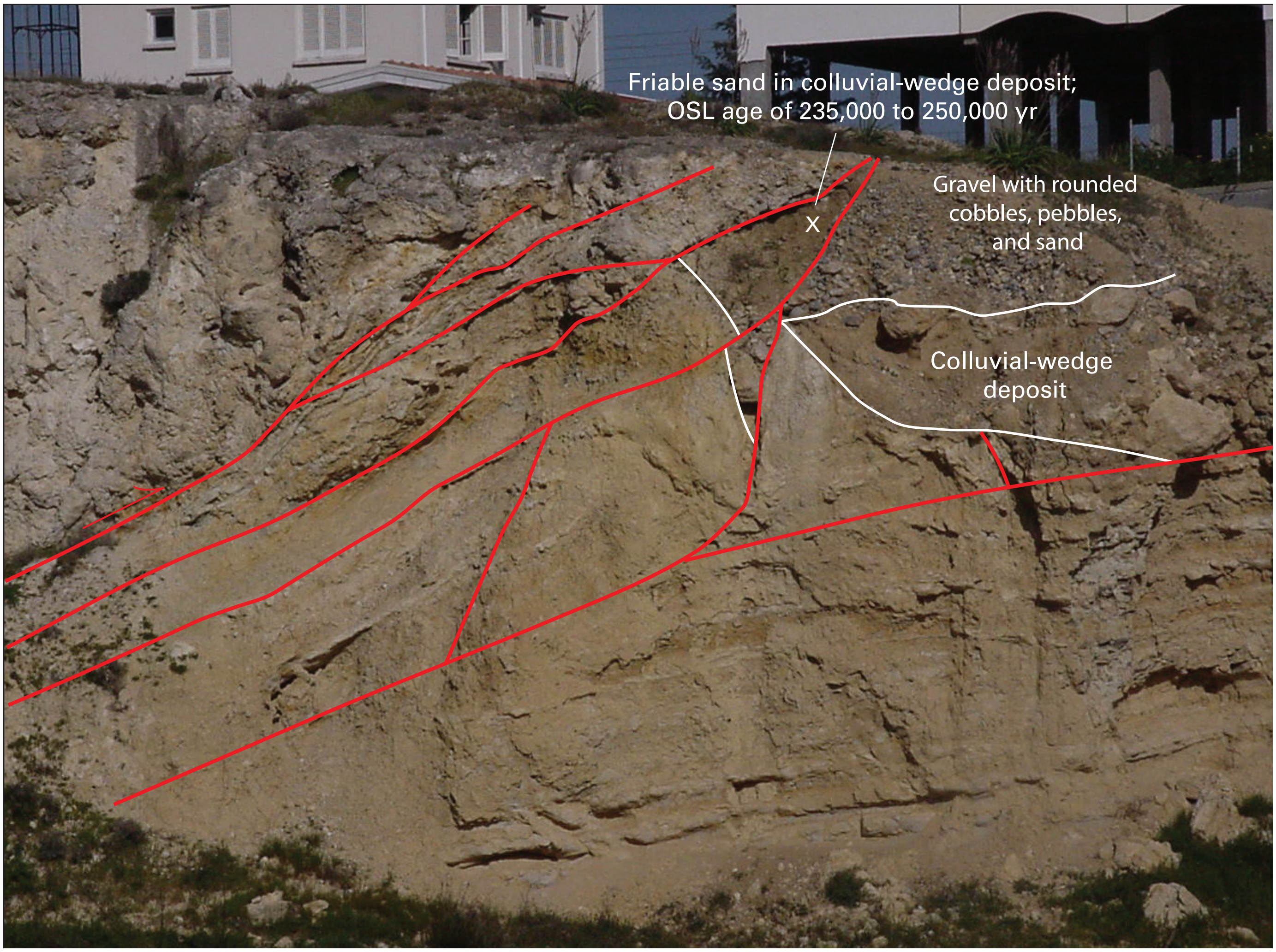



**Figure 22.** View of the northeastern part of the positive flower structure on the Skali fault showing low-angle thrust faults and relations of calcified breccia, colluvial-wedge, and Quaternary alluvial deposits. OSL, optically stimulated luminescence.

On the geologic map, the mapped extension of the Tseri fault to the northeast of the location described above is largely inferred from alignment of stream valleys and other evidence. The inferred extension corresponds to the western boundary of a large outcrop of Apalos Formation, suggesting a structural control on either deposition or subsequent erosion. Locally, outcrops of the Kephales member of the Nicosia Formation occur at about 20 m higher elevation on the southeastern side of the inferred Tseri fault than on the northwestern side, suggesting offset across the structure. The Tseri fault truncates the Lakatameia fault and an unnamed normal fault (see map).

## Lakkia Fault

The Lakkia fault was first identified by Ducloz (1965) at a site located at the southern boundary of the map area at approximate UTM coordinates of 3880700 m north and 531700 m east. At this site (fig. 24), the fault strikes N. 30° E. and dips 75° to 90° to the northwest, similar to the strike and dip of the Tseri fault. Coarse-grained marine gravels of the Kephales member of the Nicosia Formation occur in the hanging wall; massive, sandy marl of the marl member of the Nicosia Formation occurs in the footwall. All beds have been rotated to vertical in a zone that is a few meters wide, but a few meters away, these same beds gently dip less than 5°.

To the northeast of this exposure, on-strike projection of the Lakkia fault corresponds approximately to the eastern margin of the same large outcrop of Apalos Formation that is bound on the western side by the Tseri fault. These relations suggest that these two bounding structures had an influence on either deposition or subsequent erosion. Further projection of the Lakkia fault to the northeast is inferred from the juxtaposition of different facies within the Nicosia Formation (see geologic map). In the Lakkia area, for which the fault is named, massive friable sands of the lithic sand member are juxtaposed against massive marls of the marl member; and farther to the northeast, facies of the lithic sand member are juxtaposed against calcarenite of the Athalassa member. The

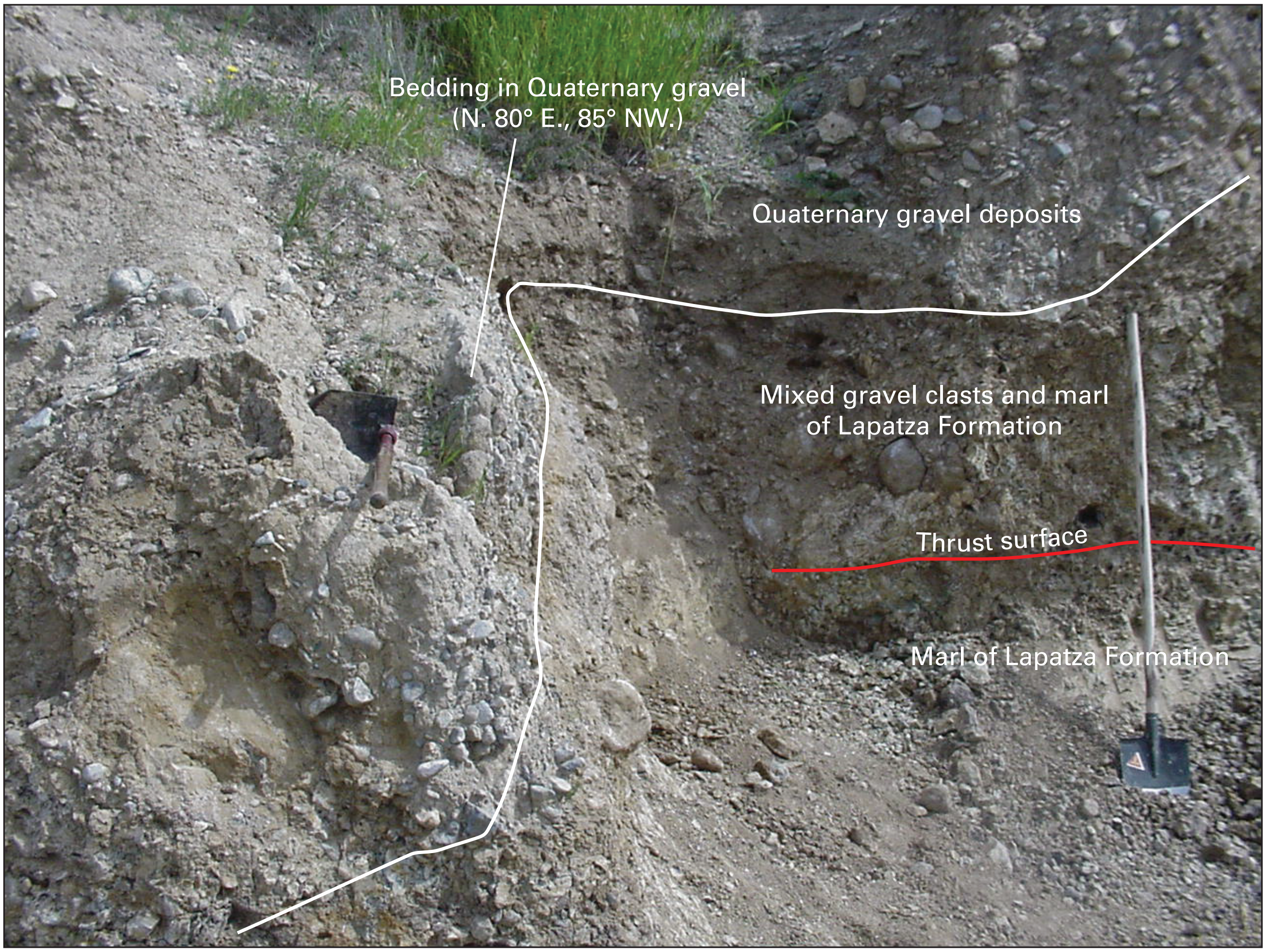



**Figure 23.** View of the northwestern part of the positive flower structure on the Skali fault showing folded Quaternary alluvial beds.

Lakkia and Tseri faults are thought to merge along strike to the northeast. Fault continuation along strike beyond the inferred merger is inferred by the juxtaposition of the Kalavasos Formation against the marl member of the Nicosia Formation in the northeastern corner of the map area. As such, the Lakkia fault is inferred to crosscut the Ovgos fault zone; however, this was not confirmed in the field due to thick cover of unmapped Quaternary alluvium.

## Mia Milia Fault

The Mia Milia fault is an overall N. 30° W.-trending series of en echelon right-lateral strike-slip faults that occurs to the northeast of the Venetian wall of Old Lefkosia and cuts through the Mia Milia village area. Eleven meters of dextral offset is evident from offset of near-vertical beds in the Kythrea Group near the northern boundary of the map. As shown on the geologic map, right steps in the en echelon pattern have produced at least four small pull-apart grabens.

The pull-apart graben immediately northwest of the village of Mia Milia is the best studied of these grabens; detailed lithologic descriptions and a graphic log (fig. 25) were first provided by Harrison and others (2004). Like other pull-apart grabens (see Sylvester, 1988), this one is thought to be rhombohedra shaped, but only the northeastern side of the rhomb has been excavated for investigation. Revealed in the excavations (fig. 26) is a principal fault (PF) that strikes N. 30° W., is near vertical, and has slickenside striations that rake 8° to the northwest. The principal fault juxtaposes a sequence of gravel, sand, and clay beds to the northeast against massive silt horizons that are overlain and underlain by gravel, sand, and clay beds to the southwest. There is no correlation between strata on either side of the fault (Harrison and others, 2004) across the fault. Two other faults were identified by Harrison and others (2004); both are northeast of the principal fault and are truncated upward by an angular unconformity. Harrison and others (2004) determined a $^{14}C$ age of 10,274±83 yr B.P. for a broken and disrupted layer of calcrete above the unconformity

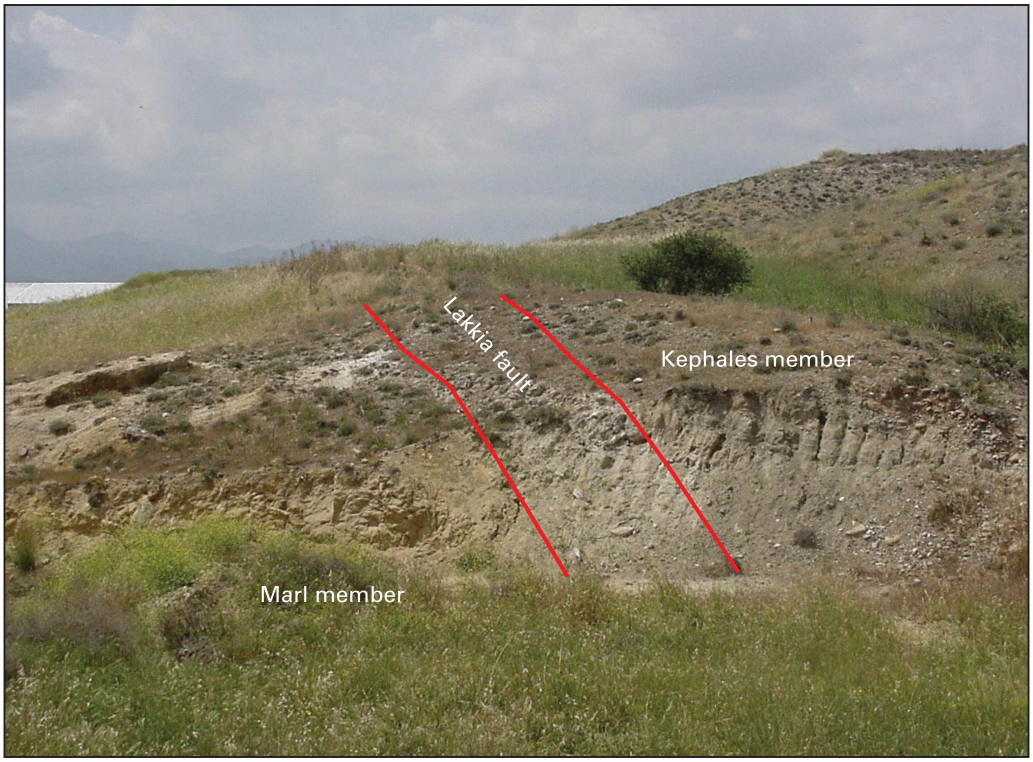



**Figure 24.** View of the Lakkia fault at approximate UTM coordinates of 3880700 m north and 531700 m east showing the juxtaposition of the marl and Kephales members of the Nicosia Formation. At this location, the fault strikes N. 30° E. and dips 75° to 90° to the northwest.

and near the surface. It is widely accepted that such an age on calcrete probably antedates the true age of the rock because of incorporation of older carbon (Williams and Polach, 1971; Chen and Polach, 1986). Harrison and others (2004) describe the uppermost unit southwest of the principal fault as poorly bedded to massive, largely matrix-supported gravel in a matrix of sand and clay. There are many low-angle slip surfaces in this gravel, as well as traces of red silty clay reworked from a nearby paleosol (terra rosa), which had been eroded from the upthrown side of the fault. This gravel overlies the upper silt horizon, a massive, very dense silt and minor fine-grained sand. Several low-angle slip surfaces also occur in this unit. The upper silt horizon overlies the lower silt horizon, from which it is separated by a thin pebble line. The lower silt horizon also consists of massive, very dense silt and minor fine-grained sand. It contains many clay and caliche-filled fractures, which are rotated out of vertical to approximately 75° adjacent to the principal fault. The lower silt horizon overlies massive, nonbedded matrix-supported gravel, which overlies deformed sand and massive clay beds. Overlying everything, including the principal fault, with angular unconformity is a thin (<0.5 m) layer of unfaulted and tilled overburden. A blue-light OSL (optically stimulated luminescence) age of 41,220±6,890 yr B.P. was determined by Harrison and others (2004) for a sample from the upper silt horizon and blue-light OSL ages of 70,240±7,390 yr B.P. and 73,650±3,210 yr B.P. were determined for samples from the lower silt horizon (see figure 25 for locations). Fossil land snails from the overburden deposit yielded a $^{14}C$ age of 4,077±148 yr B.P. (Harrison and others, 2004). Unfortunately, land snails commonly yield $^{14}C$ ages that are too old (Brennan and Quade, 1997); the maximum error is approximately 3,000 yr, and deviations correlate positively with the size of the land snails (Goodfriend and Hood, 1983; Goodfriend, 1987). Harrison and others (2004) report that the sampled snails from the exploration trench on the Mia Milia fault were rather large, as much as 2 cm in diameter; they also report that modern snails of the same species yielded a $^{14}C$ age of 2,975±35 yr B.P. Thus, Harrison and others (2004) concluded that the true age of the snails is probably about 1,000 yr B.P. This provides a youngest age constraint on timing of fault movements at this location.

Two episodes of movement are documented in the trench profile. The $^{14}C$ age on the calcrete loosely constrains the oldest movement as older than early Holocene. Harrison and others (2004) interpreted the lower gravel southwest of the principal fault as a colluvial-wedge deposit shed off a deteriorating fault scarp produced by the oldest episode of movement. If true, then the oldest faulting is older than 73,650 yr B.P., the age of the overlying lower silt horizon. Both silt horizons were downdropped into the pull-apart graben during the youngest episode of faulting, and the upper gravel is interpreted as a remnant of a colluvial-wedge deposit shed from the resulting fault scarp. This youngest episode is constrained as younger than the calcrete age and older than the age of the snails (in other words, the youngest movement is roughly constrained between 10,000 and 1,000 yr B.P). Therefore, Harrison and others (2004) concluded that this fault has a Holocene history of movement and that recurrence intervals are probably on the order of several tens of thousands of years.

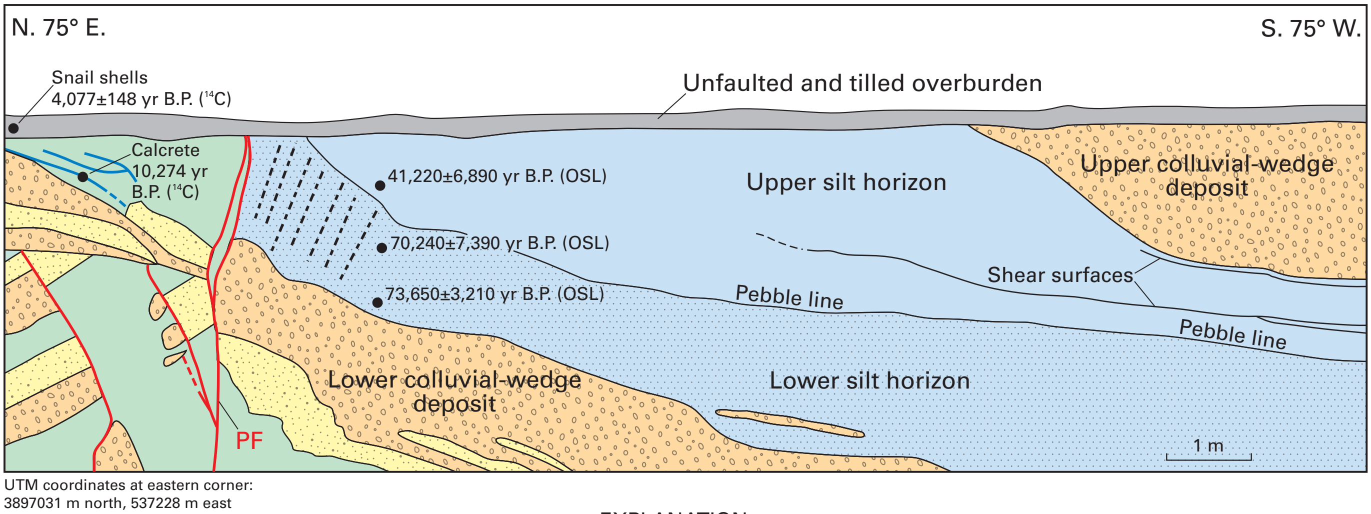



**Figure 25.** Trench log for excavations on the Mia Milia fault northeast of the village of Mia Milia and approximately 6 km northeast of the Venetian wall of Lefkosia (after Harrison and others, 2004). Abbreviations are as follows: OSL, optically stimulated luminescence; PF, principal fault; yr B.P., years before present.

Although it is inferred that the Mia Milia fault offsets the Skali and Pediaios faults, and the Ovgos and KGOM fault zones, and is truncated against the Lakkia fault, these relations were not observed directly in the field; rather they are interpreted from apparent topographic offsets. Also, our portrayal of the Mia Milia fault as the youngest structural feature on the geologic map is influenced by its known young age. To show other faults offsetting the Mia Milia fault would imply that they are also late Pleistocene in age and although that is not known, it is a possibility and we think that other strike-slip faults have almost certainly moved in the late Pleistocene and Holocene. Much of the seismic hazard report of the Lefkosia area (DeCoster and others, 2004) evaluates the risk for movement on one of these structures that occurs within the map area.

### Sehere Bakan Fault

A N. 25° W.-striking, right-lateral strike-slip fault cuts steeply dipping beds of the Kythrea Group down a narrow valley incised by the Sehere Bakan River. Approximately 50 m of horizontal offset was measured at one locality along the fault (approximate UTM coordinates of 3898610 m north and 529420 m east). The Sehere Bakan fault has a traceable strike length in excess of 5 km; an additional 4 km is inferred beneath unmapped Quaternary alluvium in the Pediaios River valley. Thus, it is considered one of the most significant faults in the Lefkosia map area. Because of the extensive cover by Quaternary alluvium in the Pediaios River valley, crosscutting relations between the Sehere Bakan fault and the other north-northeast-trending strike-slip faults described previously are not known. The portrayal shown on the geologic map is only one possible interpretation; it is preferred by the authors when considering the existing data. In our interpretation, the Sehere Bakan fault terminates against the Skali fault. We acknowledge that the Sehere Bakan fault could continue farther to the southeast and even cut the Ovgos fault zone. These and other possibilities remain unresolved.

## Synthesis of Structural Data and History

Through field observations and interpretations based on the interplay between crustal stresses and the complex pattern of faulting found in the Lefkosia area, Harrison and others (2004) developed a tectonic history for the late Miocene to the present day. The rocks exposed and in the near subsurface of this area do not allow for going back any farther in time. Following is a synthesis of this Neogene tectonic history.

There are no major angular unconformities in the depositional sequence of the Kythrea Group and Lapatza Formation, which extends from middle Miocene (Burdigalian to Tortonian) to late Miocene (Messinian) time in the Lefkosia map area. Outside the map area to the west, the Ovgos fault zone was active as a strike-slip structure during the middle Miocene (Harrison and others, 2004). The assumption is made that this strike-slip structure probably was active in the Lefkosia

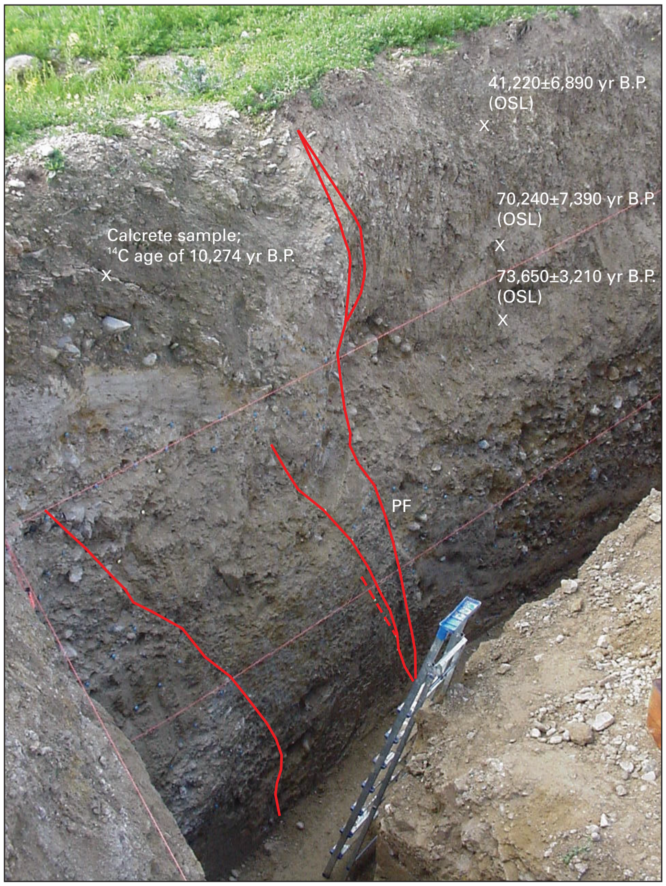



**Figure 26.** View of the major structural features in the Mia Milia fault excavation site. Abbreviations are as follows: OSL, optically stimulated luminescence; PF, principal fault; yr B.P., years before present.

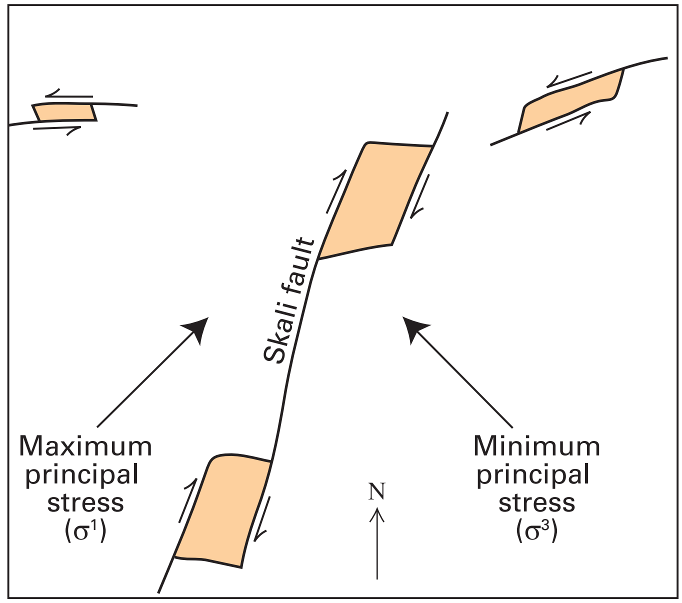



**Figure 27.** Schematic drawing of Kalavasos-filled, Messinian-age pull-apart grabens in the Lefkosia map area and interpretations of fault movements and responsible principal stress directions.

area as well during the Miocene. The formation of pull-apart grabens in which evaporitic rocks of the Kalavasos Formation were deposited is interpreted as syndepositional, therefore faulting was active in the Messinian. Strong rotation of bedding and a pronounced angular unconformity found in the marl member of the Nicosia Formation in drill hole SHN10 suggests that graben formation continued into the early Pliocene. The configuration of Kalavasos-filled grabens in the map area (fig. 27) is suggestive of: (1) a left step in an east-west-trending, left-lateral strike-slip fault zone and (2) right steps in north-northeast-trending, right-lateral strike-slip faults. A northeast-southwest-oriented, maximum principal stress direction ($\sigma^1$) coupled with a horizontal and orthogonal minimum principal stress ($\sigma^3$) and a vertical intermediate principal stress ($\sigma^2$) would be necessary to produce those structural features (fig. 27). The configuration of Messinian-age grabens in the Lefkosia area is similar to that of other known Messinian-age grabens throughout northern Cyprus (Necdet and Anil, 2006).

A change in tectonic regime from that of predominantly strike slip in the Messinian from one of northeast-southwest contraction to north-south contraction began in the late Miocene as indicated by the presence of limestone beds and the angular unconformity in the marl member of the Nicosia Formation along the Vounari fault. The youngest known beds that are deformed by this contraction (along the Ovgos fault zone in the Agios Dometios area) contain benthic forams diagnostic of zones N20 to N22, indicating a middle Pliocene to possibly Quaternary age. As indicated by paleontological data from many locations, early Pliocene (Zanclean) beds of the marl member of the Nicosia Formation are strongly folded and cut by thrust faults of the Ovgos and KGOM fault zones. Regional north-south-oriented maximum principal stress ($\sigma^1$) and east-west-oriented intermediate principal stress ($\sigma^2$) has been interpreted by Harrison and others (2004) as responsible for the contractional strain. Because the north-northeast- and north-northwest-trending strike-slip faults were apparently in existence and active in the Messinian, there is no reason to believe that they would not also be active during this late Miocene-Pliocene contractional event. They would function as tear faults that would accommodate differential shortening along the various east-west-trending thrust faults. Evidence supporting this interpretation lies in the relatively undeformed Kalavasos-filled basin beneath northern metropolitan Lefkosia, which from existing subsurface data appears to be relatively unfolded (see cross section *A–A′*). All existing drill-hole data (including more than 15 drill holes not shown on the map) examined for this investigation show a uniform stratigraphic sequence of the marl member of the Nicosia overlying the Kalavasos Formation, implying a relatively flat, low-dipping geologic contact; this is in stark contrast to geologic contacts on the opposite side of Skali fault, which is the western boundary fault of the Kalavasos-filled graben.

The youngest style of deformation observed in the Lefkosia map area is one of strike-slip faulting along the conjugate sets of left-lateral north-northeast-trending and right-lateral north-northwest-trending vertical faults. These strike-slip faults crosscut all other geologic structures. This deformation is interpreted as the result of horizontal $\sigma^1$ and $\sigma^3$ stress directions oriented approximately north-south and east-west, respectively (Harrison and others, 2004). The only change in principal stress orientations between this phase of dominant strike-slip faulting versus the older phase of contractional faulting and folding is that $\sigma^2$ and $\sigma^3$ have swapped positions. In essence, the vertical force of gravity increased relative to east-west horizontal stress, while $\sigma^1$ retained its orientation. This stress change was brought about by the uplift of Cyprus (Harrison and others, 2004). The timing of stress change and accompanying change in deformational style is loosely constrained as late Pliocene to early Quaternary (Harrison and others, 2004). Geologic evidence from the Mia Milia fault shows that deformation driven by this last stress field is ongoing in the Holocene.

The strike-slip faults that exist beneath the metropolitan area are of particular importance to seismic-hazard analysis of the Lefkosia area. The significance of these faults lies in the fact that they are properly oriented in the present-day stress field for reactivation and that they are part of a set of faults that have documented Holocene and late Pleistocene histories (Harrison and others, 2004; this report). Because mapped strike lengths range from a few to a few tens of kilometers, movement along these faults is probably capable of generating only moderate earthquakes of moment magnitude (**M**) ~5.5 to 6.5 (dePolo and Slemmons, 1990; Wells and Coppersmith, 1994; Pavlides and others, 2000). However, their proximity to an urbanized area increases its hazard potential.

## Evaluation of Regional Tectonics of the Eastern Mediterranean

In studying the structures and stratigraphy of the Lefkosia area, it became apparent that field observations and interpretations there did not fit the predominant regional tectonic models of either the present-day setting or the tectonic history back into the Miocene. A broader investigation into the scientific literature of the eastern Mediterranean led Harrison and others (2004) and Harrison and Panayides (2004) to suggest a new tectonic model that emphasizes the role of strike-slip, or transform, faults in accommodating relative horizontal movement between major tectonic plates. Following is a summary and further development of this model.

One could ask: Why is knowledge of plate interactions important? The answer is that plate tectonics is one of Earth's most important dynamic systems in regards to its impact on man and civilization. Seismic, volcanic, and tsunami hazards are all directly influenced by plate movements; the location and genesis of economic mineral deposits, as well as energy resources, are also governed by the various hydrothermal, deformational, and depositional environments associated with past and present plate interactions. A better understanding of present-day settings and the dynamic history of plate interactions are critical to man's future.

## Regional Tectonic Setting

Rifting, subduction, obduction, continent-continent collision, and transform faulting along the boundary between the Eurasian and African plates since the early Mesozoic has produced a collage of fragmented tectonic terranes, which includes the Anatolian and Sinai microplates, the Hellenic arc, the Aegean extensional province, and ocean basins of the Neotethys (Dewey and others, 1973; Dewey and Şengör, 1979; Robertson and Dixon, 1984; Şengör and others, 1985; Dercourt and others, 1986; Gealey, 1988; Anastasakis and Kelling, 1991; Robertson and others, 1991; Papazachos and Papaioannou, 1999). The island of Cyprus is located on the southern margin of the Anatolian microplate, adjacent to its boundary with the African plate (fig. 7); this boundary was first suggested by Dewey and Şengör (1979) and later verified by seismic evidence (Kempler and Ben-Avraham, 1987; Anastasakis and Kelling, 1991; Krasheninnikov and others, 1994) and drilling during the Ocean Drilling Program Leg 160 (Kempler, 1998; Robertson, 1998).

During the past 5 million years (m.y.), plate tectonics in the eastern Mediterranean-Middle East region have been dominated by strike-slip faulting along major plate and microplate boundaries (Şengör and others, 1985; Westaway, 1994). During this period, Cyprus has experienced continuous uplift (Robertson, 2000; Harrison and others, 2004), which has been greatest in the southwestern part of the island. The Eratosthenes Seamount to the south of Cyprus (see figure 7 for location) also has been uplifted and arched in the past 5 m.y. (Dolson and others, 2001, 2002).

The area between Cyprus and the Eratosthenes Seamount is a seismically active zone (Jackson and McKenzie, 1988; Ambraseys and Adams, 1993; Makris and others, 2000) that is commonly referred to as the "Cyprean arc" or the Cyprus arc. Its tectonic nature, however, is controversial. In our opinion, this area does not fit the definition of an arc; we prefer to call it the Cypriot transform fault after Harrison (2007). Many researchers (Woodside, 1977; Robertson, 1990, 2000; Robertson and others, 1995a; Garfunkel, 1998; Payne and Robertson, 2000) have interpreted the Cyprean arc as a subduction zone, thought to be the driving force for the neotectonic uplift of Cyprus.

An alternative idea is that strike-slip tectonics dominates the region and no "classical" subduction zone exists beneath Cyprus. Makris and others (2000) suggest that the area of concentrated seismicity between Cyprus and the Eratosthenes Seamount is part of a left-lateral strike-slip fault zone (their Eratosthenes shear), which is compatible with the regional tectonic model of Kempler and Garfunkel (1994). Neev and others (1985), Makris and others (2000), and Aal and others (2001) suggest that both the western and southeastern margins of the Eratosthenes Seamount are bound by left-lateral strike-slip faults; their existence has been substantiated by seismic-reflection imaging of structures possessing transpressive strike-slip characteristics (positive flower structures) southeast of Cyprus (Vidal and others, 2000a; Aal and others, 2001).

Neev (1977), Neev and Hall (1982), and Neev and others (1985) related the northeast-trending structures in the eastern Mediterranean Sea to a left-lateral transcontinental shear system, the Pelusium system, which extends across northern and central Africa. Neev and Hall (1982) and Neev and others (1985) considered the Pelusium system to be ancient and responsible for the counterclockwise rotation of Cyprus during the Cretaceous that has been documented by Moores and Vine (1971), Lauer (1984), and Clube and others (1985), as well as the counterclockwise rotation of the Eratosthenes Seamount suggested by Ben-Avraham and others (1976). Counterclockwise rotation is consistent with the kinematics of a left-lateral simple shear couple (Freund, 1974; Rotstein, 1984; Ron and Eyal, 1985). The existence of a restraining bend along a major left-lateral strike-slip fault zone between Cyprus and the Eratosthenes Seamount has been proposed by Harrison and others (2004) and Harrison and Panayides (2004).

## Problems and Inconsistencies With Subduction-Zone Models

For the past three decades, the dominant theory for the neotectonic setting and Neogene uplift of Cyprus has been that a north-dipping subduction zone exists beneath the island (Woodside, 1977; Robertson, 1990, 2000; Robertson and others, 1995a; Garfunkel, 1998; Payne and Robertson, 2000). There are, however, several problems and inconsistencies with subduction-zone models. One problem, which alone precludes the existence of a "classical" subduction zone, is the absence of volcanism in the vicinity of Cyprus at any time during the middle and late Cenozoic. Another problem is the absence of a north-dipping Benioff zone beneath Cyprus. A tabulation and plot of the best-constrained recorded seismic events by Algermissen and Rogers (2004) reveals a vertical zone of seismicity that extends to depths of greater than 60 km (fig. 28) at the location of the Cypriot transform fault.

In addition, focal mechanisms calculated for larger earthquakes in the Cypriot transform fault indicate a mixture of faulting styles but are predominantly strike slip (Arvidsson and others, 1998; Papazachos and Papaioannou, 1999; Pinar and Kalafat, 1999; Makris and others, 2000; Kahle and others, 2000). Mixtures of faulting styles are characteristic of strike-slip fault zones (Sylvester, 1988) and not characteristic of subduction zones. Seismicity in the vicinity of Cyprus occurs along north-northwest and north-northeast linear trends (Makris and others, 2000; Algermissen and Rogers, 2004) and is not concentrated directly between Cyprus and the Eratosthenes Seamount, as would be expected in a subduction-zone setting; rather, seismicity occurs predominantly to the northwest of the Eratosthenes Seamount and on the island of Cyprus. Also, known onshore Quaternary faults are a combination of strike-slip and transpressive structures along the north-northwest and north-northeast seismic trends (J.P. Soulas, Geologie-Tectonique-Environnement et Risques, written commun., 1999; Harrison and others, 2002, 2004).

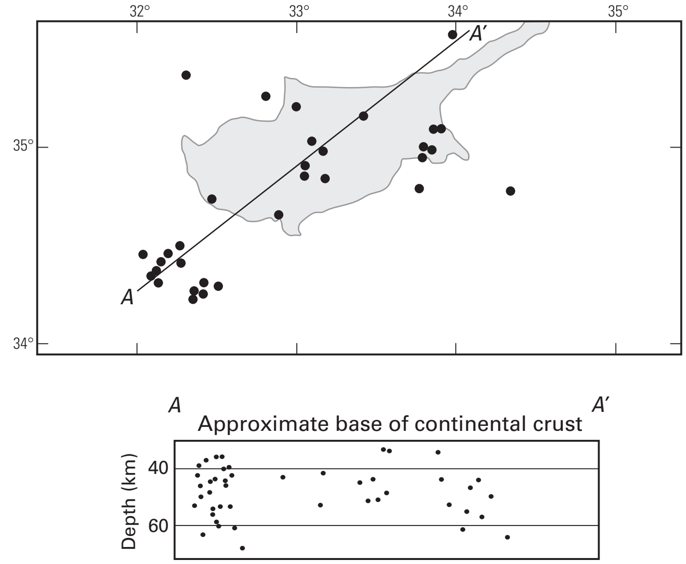



**Figure 28.** Locations of the best-constrained, recorded deep earthquake epicenters in the Cyprus area (after Algermissen and Rogers, 2004). Cross section *A–A′* shows hypocenters projected to the line of section. Note that the top of the cross section is at about 30 km—the approximate base of the crust. Focal mechanisms calculated for larger earthquakes along the Cypriot transform fault indicate a mixture of faulting styles but are predominantly strike-slip (Jackson and McKenzie, 1988; Arvidsson and others, 1998; Pinar and Kalafat, 1999; Makris and others, 2000). Strike-slip fault zones typically have mixing of faulting styles; subduction zones do not. If the vertical zone of seismicity southwest of Cyprus is a steeply dipping Benioff zone, then the uplift of Cyprus is unexplained, and there should be a volcanic arc in the vicinity (Mariana-type subduction zone).

Furthermore, geophysical gravity investigations (Gass and Masson-Smith, 1963; Makris and others, 1983) show that Cyprus is underlain by approximately 35 km of continental crust and that the Eratosthenes Seamount is underlain by approximately 28 km of continental crust; seismic-refraction measurements support this interpretation (Aal and others, 2001; Ben-Avraham and others, 2002). Thus, the Cypriot transform fault is a continent-continent interface. Continuous seismic-reflection profiles across the Cyprus-Eratosthenes Seamount boundary (Udintsev and others, 1994) reveal a complex pattern of horsts and grabens that is more characteristic of a transpressive positive flower structure than a subduction complex. Also, global positioning system (GPS) results (McClusky and others, 2000) show that Cyprus is moving to the west, orthogonal to the motion of the African plate (fig. 29). This movement direction is viewed as inconsistent with subduction-zone models, but very consistent with a model based on escape tectonics and strike-slip faulting where north-south compression is driving lateral motion, similar to a seed being squeezed between two fingers.

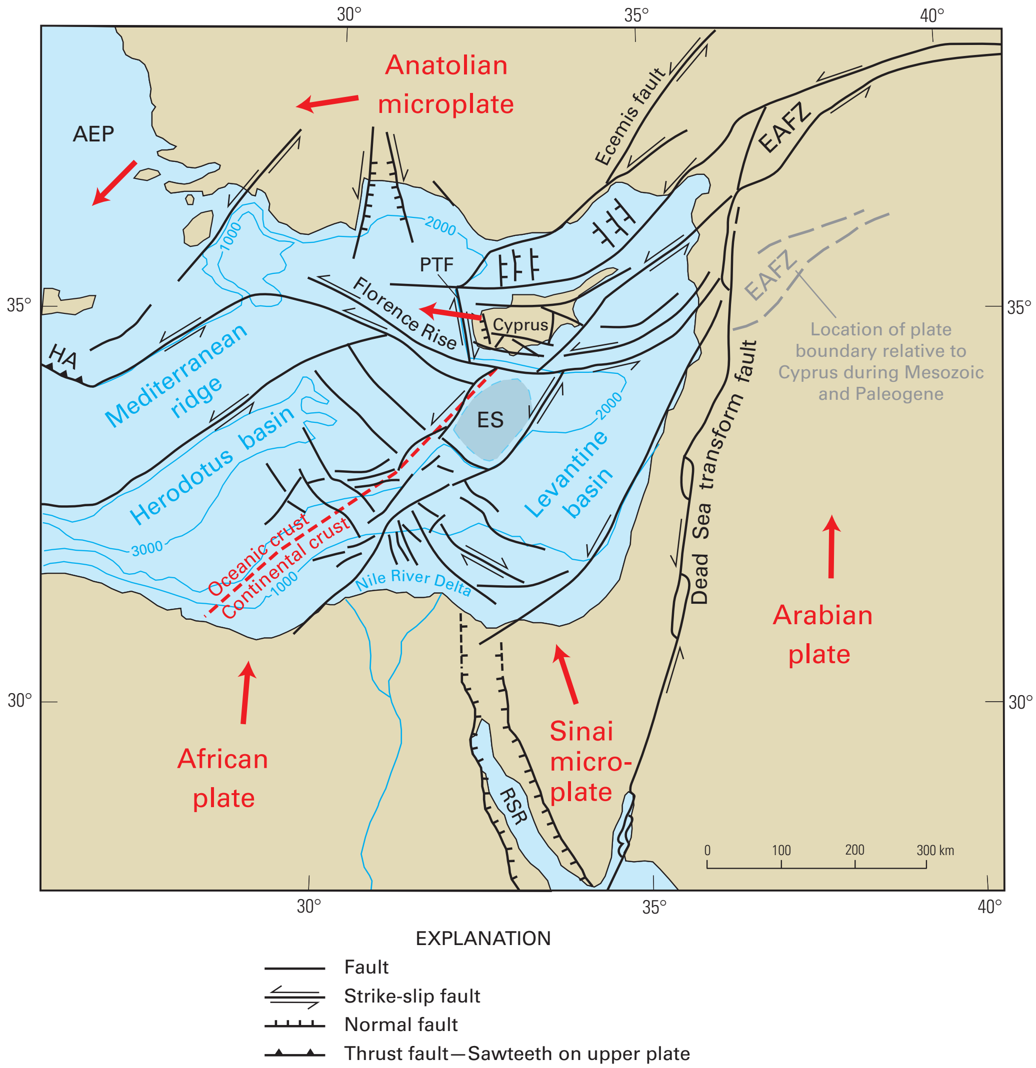



**Figure 29.** Present-day tectonic map of the eastern Mediterranean region (after Robertson and Grasso, 1995; Robertson and others, 1995b; Garfunkel, 1998; Glover and Robertson, 1998; Mascle and others, 2000; Vidal and others, 2000a,b; Aal and others, 2001; Dolson and others, 2001; Harrison and others, 2004). The Florence Rise occurs along a left-lateral strike-slip structure (ten Veen and others, 2004a,b). During the Mesozoic and Paleogene, prior to opening of the Red Sea rift, the eastern Anatolian fault zone was located south of the present-day fault zone and is shown in the figure. The approximate boundary between oceanic and continental crust is from Dolson and others (2002). Large red arrows represent relative plate motions (after Jackson and McKenzie, 1988; McClusky and others, 2000). The fault system between Cyprus and the Eratosthenes Seamount is the Cypriot transform fault (previously referred to as the Cyprean or Cyprus arc), which marks the northern African plate boundary. Abbreviations are as follows: AEP, Aegean extensional province; EAFZ, eastern Anatolian fault zone; ES, Eratosthenes Seamount; HA, Hellenic arc; PTF, Pafos transform fault of Papazachos and Papaioannou (1999); RSR, Red Sea rift. Bathymetry is in meters.

## Restraining-Bend Model

We have compiled a present-day tectonic map (after Robertson and Grasso, 1995; Robertson and others, 1995b; Garfunkel, 1998; Glover and Robertson, 1998; Mascle and others, 2000; Vidal and others, 2000a,b; Aal and others, 2001; Dolson and others, 2001; Harrison and others, 2004) of the eastern Mediterranean-Middle East region that is presented in figure 29. Current geophysical data (Gardosh and Druckman, 2006) indicate that the Levantine basin, southeast of Cyprus, is filled with 12 to 14 km of Phanerozoic sediment, which overlies highly attenuated continental crust. These data, coupled with the knowledge that (1) the Eratosthenes Seamount is composed of continental crust (Gass and Masson-Smith, 1963; Robertson and others, 1995a; Ben-Avraham and others, 2002); (2) an oceanic-continental margin exists along the eastern side of the Herodotus basin (Aal and others, 2001; Dolson and others, 2001, 2002); and (3) on the basis of seismic velocity, gravity, and magnetic profiles, Aal and others (2001) indicate that continental crust lies beneath the Nile River Delta and the Moho occurs at 25 to 30 km depth, suggest that the easternmost part of the Mediterranean Sea is composed entirely of continental crust. The presence of only continental crust has major ramifications for any paleotectonic interpretations that call for the existence of oceanic crust in this region of the Earth, especially considering that there are no volcanic arcs indicating subduction and destruction of oceanic crust. In essence, there is no evidence that any oceanic basin ever existed in the eastern Mediterranean, other than the Troodos ophiolite on Cyprus. An interpretation of the Levantine basin that best fits with our regional tectonic setting is one of a transtensional basin controlled by a partial stepover in strike-slip crustal movement from the Dead Sea transform fault to transform structures that bound the Eratosthenes Seamount (fig. 29). The Levantine basin is a rhomb-shaped structure and is bound by major strike-slip faults; it has all the characteristics of a large pull-apart graben. Offshore seismic-reflection profiles (Udintsev and others, 1994; Mascle and others, 2000; Vidal and others, 2000a; Aal and others, 2001; Woodside and others, 2002; Zitter and others, 2003) show an abundance of positive and negative flower structures, which have developed along major northeast-trending strike-slip fault zones in the northern part of the Levantine basin.

Left-lateral strike-slip faulting along northeast-trending structures has also been postulated along the Florence Rise (see figure 29 for location) to the west of Cyprus (Kahle and others, 2000; Woodside and others, 2002; ten Veen and others, 2004a,b) and in the Nile River Delta area (see figure 29 for location) (Aal and others, 2001). Papazachos and Papaioannou (1999) proposed the existence of a north-trending structure immediately west of Cyprus that they referred to as the Pafos transform fault; from focal mechanism analyses they identified right-lateral strike slip motion along this structure. From seismic-reflection data, north-northwest-trending structures, also with strike-slip characteristics, have been recognized by Woodside and others (2002), Zitter and others (2003), and ten Veen and others (2004a,b) along the western branch of the Cypriot transform fault.

The restraining-bend model for neotectonism in the Cyprus region is based on a generic model (fig. 30*A*) by Mitchell and Reading (1986), derived from Kingma (1958), Wilcox and others (1973), and Crowell (1974); it is independent of scale. In this model, the most important factor that controls uplift and subsidence along a strike-slip fault is the curvature geometry of the fault surface relative to its slip vector (Sylvester, 1988). Where strike-slip movement is impeded by restraining bends, transpression occurs in association with crustal shortening and uplift (Sylvester, 1988). Restraining bends located along plate boundary zones, such as the setting for Cyprus, result in topographic uplifts of area measured in thousands of square kilometers (Mann and others, 1984). The Transverse Ranges

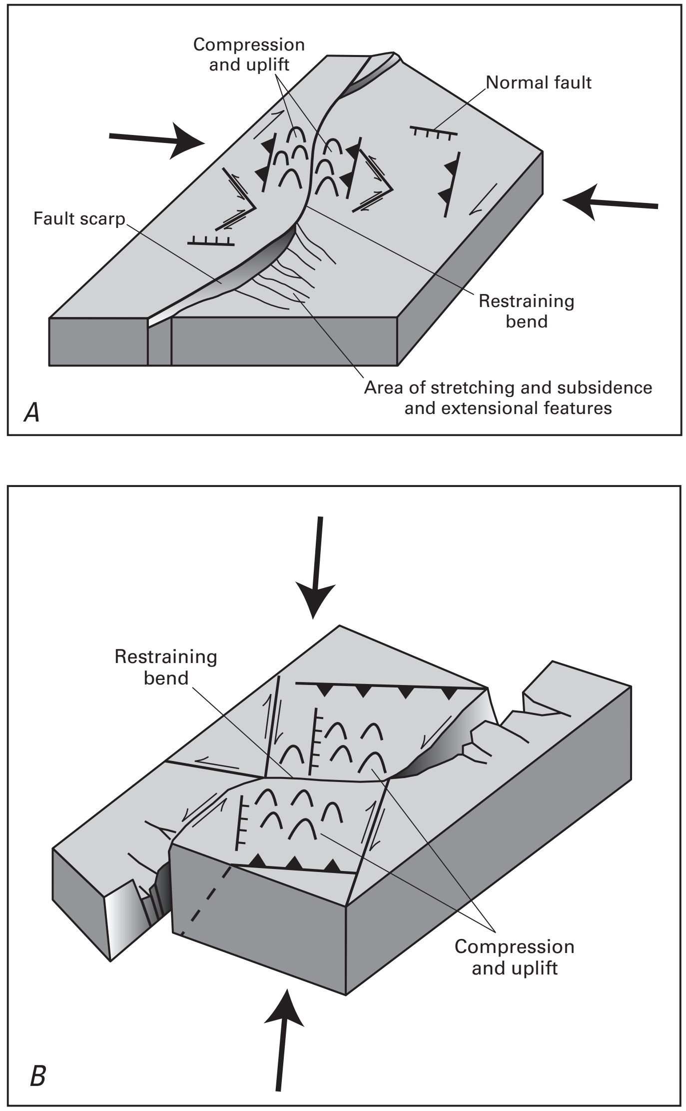



**Figure 30.** *A,* Generic model illustrating how the curvature of a strike-slip fault may produce closely adjacent basins and uplifts with superimposed tectonic pattern (after Mitchell and Reading, 1986, fig. 14.48), derived from Kingma (1958), Wilcox and others (1973), and Crowell (1974). Uplift and compression occur on both sides of the restraining bend. *B,* Generic model inverted to convert from right-lateral displacement to left-lateral displacement. Note that in both models, the compressional axis is orthogonal to the fault segment in the restraining bend, but overall block movement is oblique to the compressional axis.

in southern California, the Southern Alps of New Zealand, and the Lebanon Ranges of Lebanon are examples of uplifts along major restraining bends (fault separations of approximately 100 km or more) within continental lithosphere. The island of Hispaniola occurs along a major restraining bend within island arc lithosphere (Mann and others, 1984).

The generic model shown in figure 30*A* was developed for right-lateral displacements associated with the San Andreas transform fault in California. In order to apply this model to the left-lateral displacements observed in the Cyprus area, an inverted (mirror) image (fig. 30*B*) must be generated. When the elements of the inverted generic restraining-bend model (fig. 30*B*) are overlain on the Cyprus-Cypriot transform fault-Eratosthenes Seamount region (fig. 31), similarities emerge. The uplifted areas of Cyprus and the Eratosthenes Seamount are in the proper positions, as are the locations of left-lateral strike-slip faulting to the southeast of Cyprus and along the Florence Rise, and the right-lateral strike-slip faulting on north-trending structures (including the Pafos transform fault) to the west of Cyprus.

## Summary of the Present-Day Tectonic Setting

The restraining-bend model that we propose explains all details of neotectonism documented in the northern part of Cyprus by Harrison and others (2004) and in the southern part of Cyprus by J.P. Soulas (Geologie-Tectonique-Environnement et Risques, written commun., 1999) and Robertson (2000). The model also is compatible with all regional geologic, seismologic, and geophysical data. Uplift of Cyprus and the Eratosthenes Seamount is predicted by our model. The absence of magmatism and a north-dipping Benioff zone beneath Cyprus, the vertical linear arrays of seismicity (with predominantly strike-slip focal mechanisms) in the vicinity of Cyprus, and the thrust (transpressive) faults along the southern coast of Cyprus are all compatible with our restraining-bend model. Our model also is compatible with the abundance of strike-slip structures (positive and negative flower structures) identified offshore by geophysical methods (Udintsev and others, 1994; Vidal and others, 2000a,b; Aal and others, 2001).

We envision Cyprus as being squeezed westward, accommodated by strike-slip faulting, as part of the escape tecton-

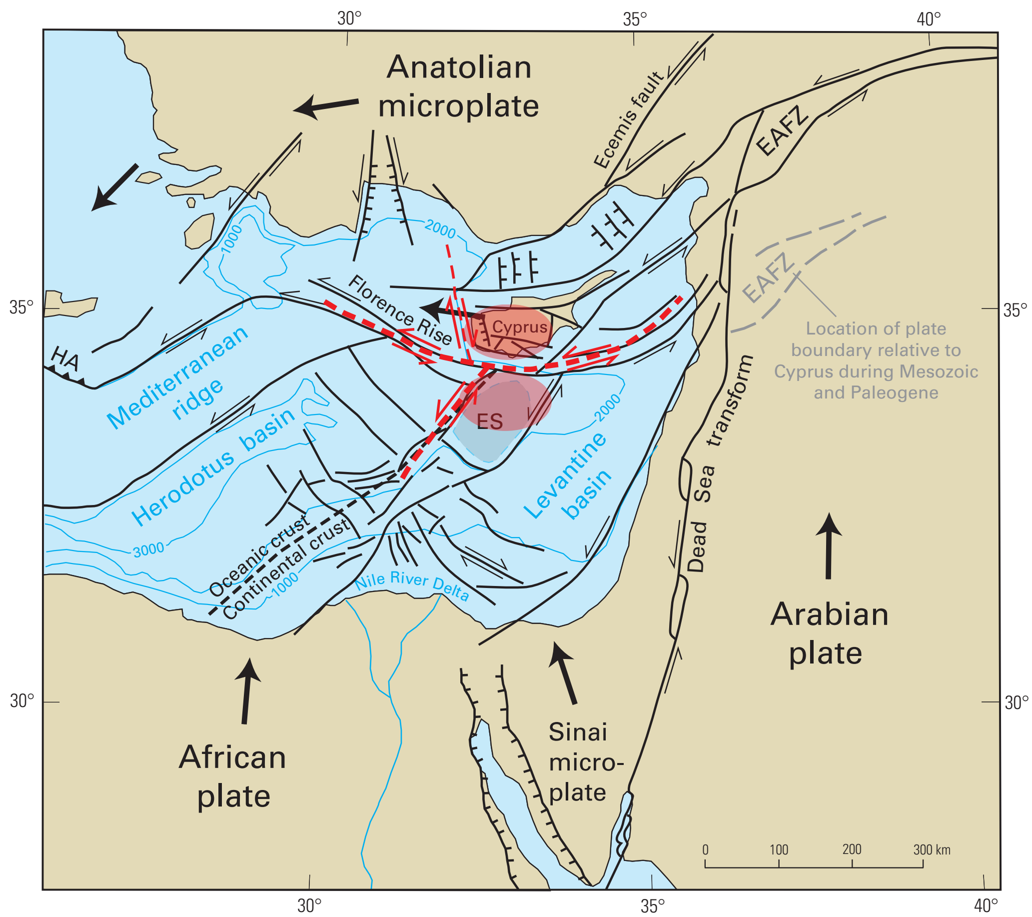



**Figure 31.** Overlay of the inverted generic model (fig. 30*B*) on the tectonic map of the eastern Mediterranean-Middle East region (fig. 29). Red-shaded areas are regions of predicted uplift; thick red-dashed lines represent the main traces of curved fault zones; thin red-dashed line is a subsidiary structure. Note that the uplifted areas of Cyprus and the Eratosthenes Seamount are in the proper positions, as are the locations of left-lateral strike-slip faulting to the southeast of Cyprus and along the Florence Rise and the right-lateral strike-slip faulting on north-trending structures to the west of Cyprus. Abbreviations are as follows: EAFZ, eastern Anatolian fault zone; ES, Eratosthenes Seamount; HA, Hellenic arc. Bathymetry is in meters. See figure 29 for explanation of symbols.

ics that are driving the Anatolian microplate westward. It is important to remember that plate kinematics and dynamics in the eastern Mediterranean-Middle East region are principally controlled by the relatively rapid northward movement of the Arabian plate, which is “pushing” the Anatolian microplate towards the west. In essence, the African plate is sliding against the southern margin of the Anatolian microplate, producing uplift, deformation, and seismicity on and surrounding Cyprus.

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