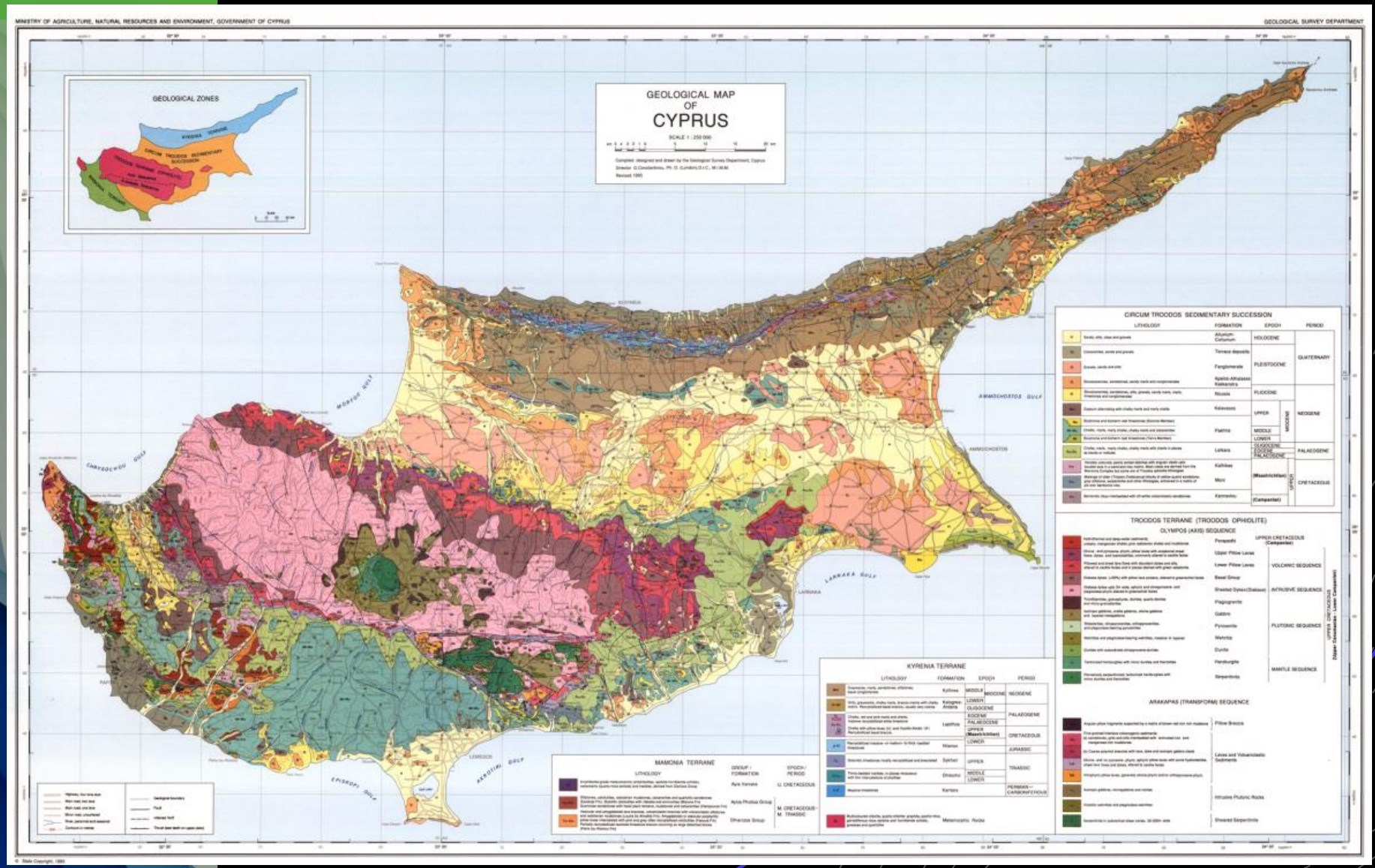
Overview of the Geology of Cyprus



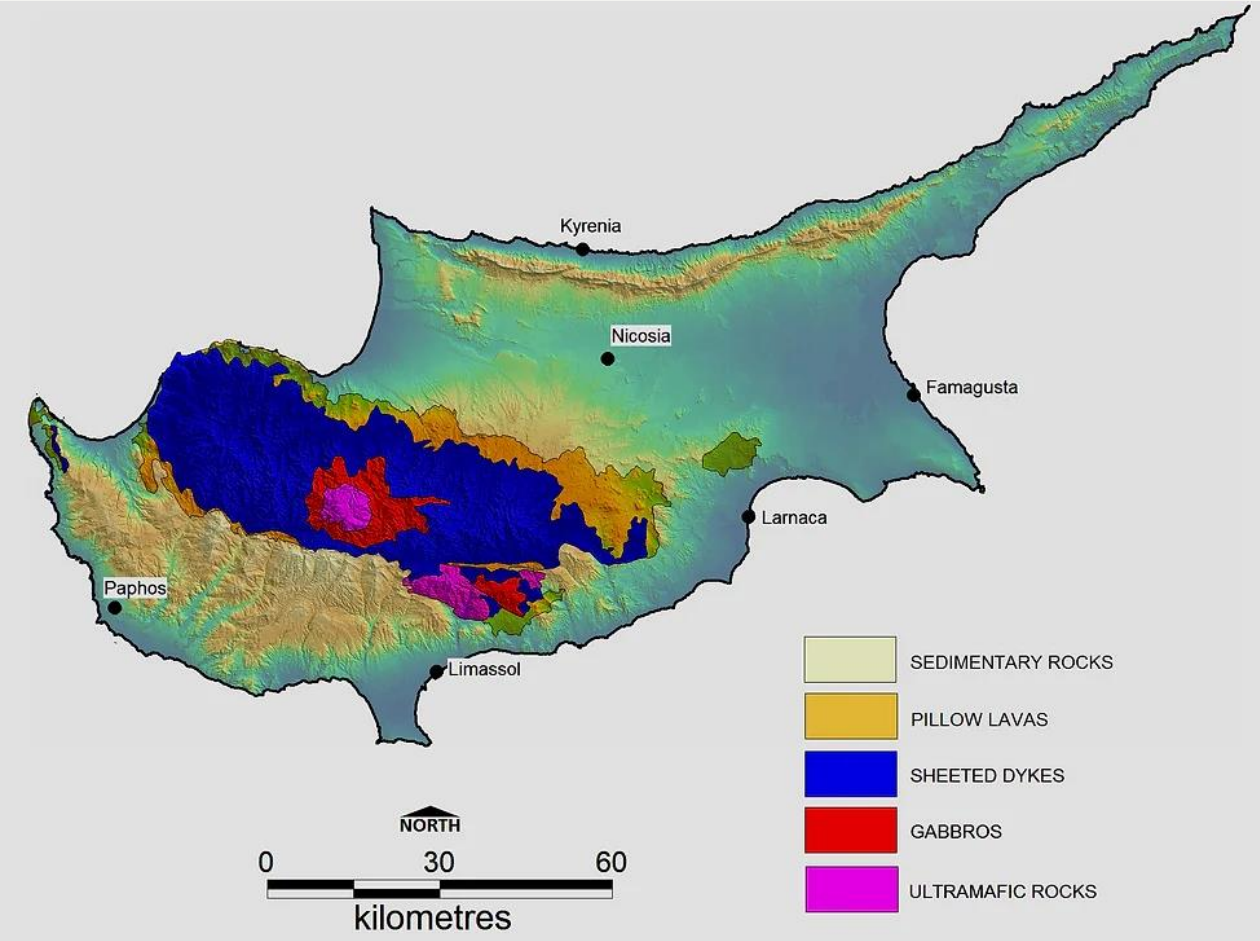
East Tennessee Geological Society

January 8, 2024

Brian Murray PG

Presentation Topics

- Island of Cyprus
- Tectonic Setting Overview
- Geologic Terranes
- Regional Tectonic History - Troodos Ophiolite Formation
- Ongoing Uplift Theories
- Copper and Chrysotile Mining



The author is solely responsible for any errors, misrepresentations, and/or misstatements that occur in this presentation.

- Topography - central plain with mountains to the north and central; scattered but significant plains along the southern coast
- 140 miles long with a max. width of 60 miles
- Area: 2,762 sq miles, 400 miles of coastline
- Climate: temperate, hot dry summers, cool winters
- Natural resources: copper, pyrites, asbestos, gypsum, salt, marble, clay, earth pigment

- Former British colony, Cyprus became independent in 1960 following years of resistance to British rule
- Invasion by Turkish troops (1974) resulted in a partition of the island and establishment of a Turkish Cypriot state (1983)
- Tensions between the Greek Cypriot majority and Turkish Cypriot minority communities continue
- Leaders of the two communities resumed formal discussions under UN auspices in 2014, aimed at reuniting the divided island

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Population: ~1.3 million
Greek Cypriot = 73%
Turkish Cypriot = 27%

Kourion Ancient Amphitheater

Kourion beach – SW Cyprus

City of Kourion was built cliffside and overlooked the fertile river valley of Kouris; destroyed in a severe earthquake in 365 AD

Acoustics of the Kourion Amphitheatre are said to be among the best of any external theatre in the world

Polis coast – looking north and west, very western end of island in distance

Polis coast – N. Cyprus

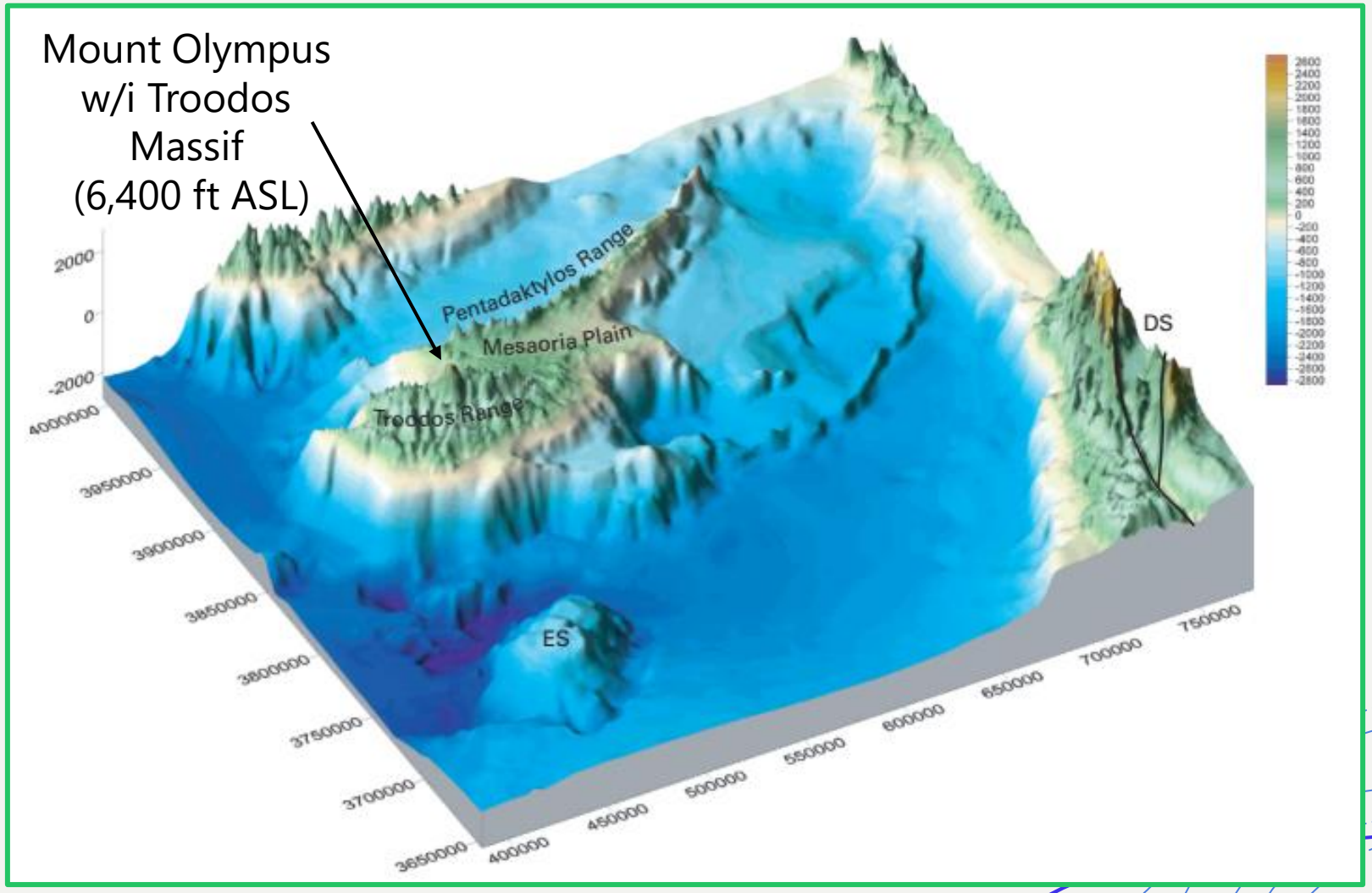
Primary References (Abbreviated)

Title	Date	Organization (Lead Author)
The Uplift of Troodos Massif, Cyprus	2019	Department of Geological Sciences, Stockholm University, Sweden
Longitudinal and Temporal Evolution of the Tectonic Style Along the Cypress Arc System, Assessed Through 2-D Reflection Seismic Interpretation	2018	Universite Pierre et Marie Curie, Geosciences Division, Paris, France
Copper and Copper Mines in Cyprus	2017	Cyprus Geological Survey Economic Geology Section
From ocean depths to mountain tops: Uplift of the Troodos ophiolite (Cyprus) constrained by low-temperature thermochronology and geomorphic analysis	2016	Department of Geological and Environmental Sciences, Ben-Gurion University of the Negev, Israel
Dynamics of intraoceanic subduction initiation: 2. Suprasubduction zone ophiolite formation and metamorphic sole exhumation in context of absolute plate motions	2015	Department of Earth Sciences, University of Utrecht, Utrecht, Netherlands
Late Pleistocene and Holocene uplift history of Cyprus: implications for active tectonics along the southern margin of the Anatolian microplate	2013	Geological Society, London, Special Publication 2013, v.372 (authors from US Geological Survey, Geological Survey Department of Cyprus, Senckenberg Forschungsinstitu und Naturmuseum,)
Minerals Yearbooks	2013 to 2019	U.S. Geological Survey, Virginia
Bedrock Geologic Map of the Greater Lefkosia Area, Cyprus	2008	U.S. Geological Survey, Virginia
Geological Map of Cyprus *Geology of Cyprus*	Revised 1995 2016	Government of Cyprus Ministry of Agriculture, Natural Resources and Environment, Geological Survey Department

Tectonic Setting Overview

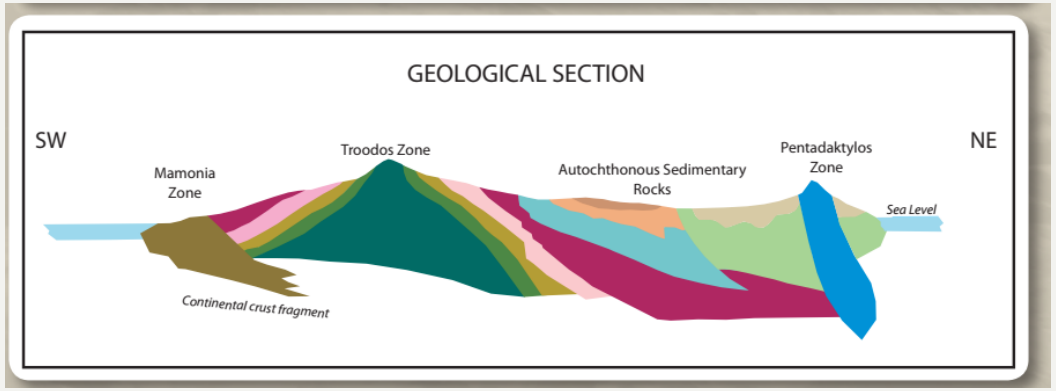
Cyprus Topography & Eratosthenes Seamount

Emergence of the island of Cyprus is directly connected with the subduction and collision of the African Continental plate with the Eurasian Continental plate



Ophiolite

- *Ophiolite* refers to an intact on-land section of oceanic lithosphere that has been thrust onto a continental margin (obduction); ophiolite belts occur in many mountain ranges
- *Obduction* – a process whereby denser oceanic crust (even upper mantle) is scraped off a descending ocean plate at a convergent plate boundary and thrust on top of an adjacent plate
- Typical sequence (termed a Penrose sequence) of oceanic lithosphere consists of assemblage of deep-marine cover sediments (chert, limestone, clastic sediments), volcanic rocks (pillow lavas, volcanic glass, volcanic ash, sheeted dykes and gabbros) and harzburgitic peridotite (upper mantle)

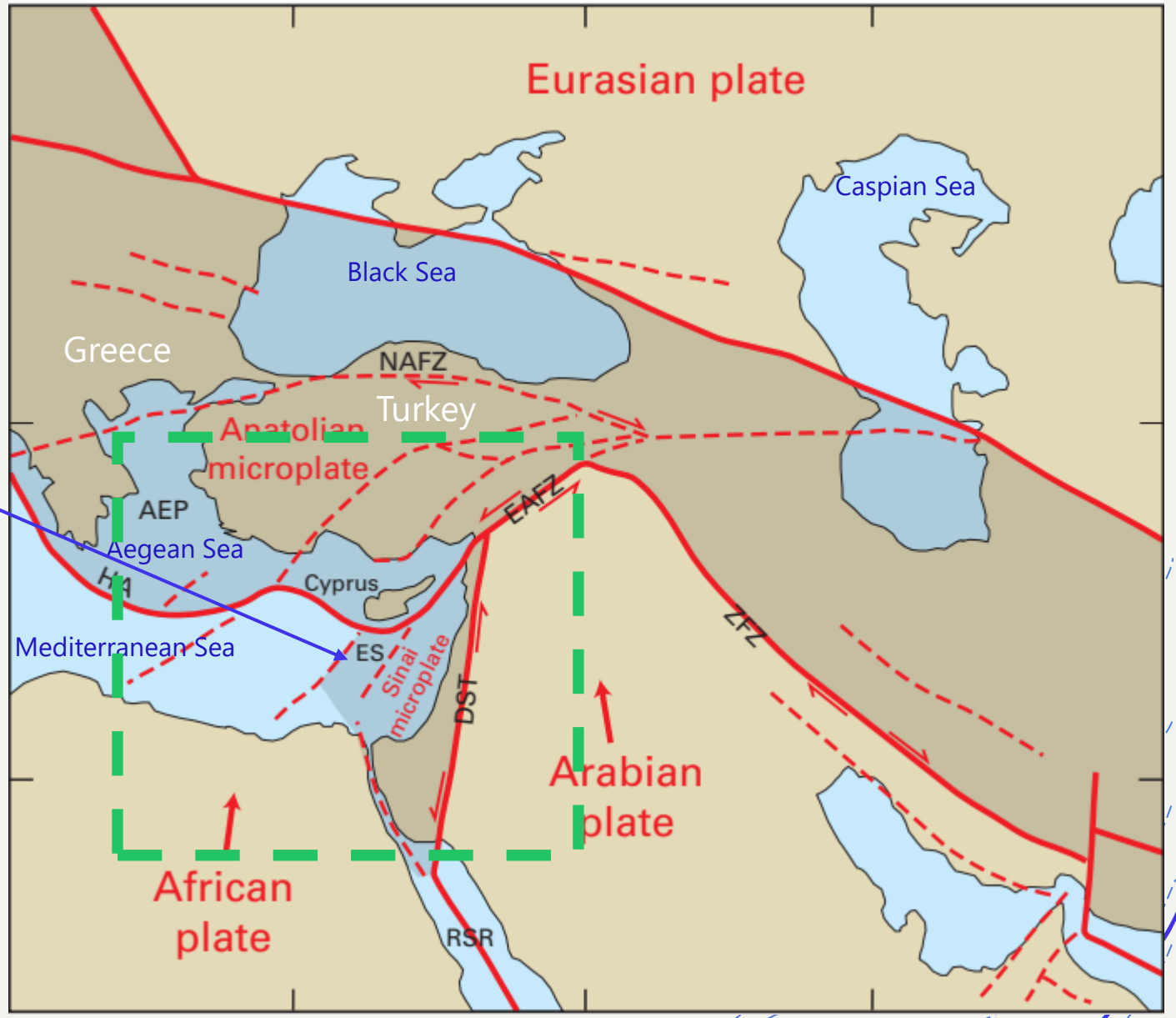


Troodos Ophiolite

- Formed 90-92 Ma in depths of NeoTethys Ocean by seafloor spreading above a suprasubduction-zone
- Suprasubduction-zone ophiolites – require the formation of a spreading center immediately adjacent to a subduction zone (i.e., in a highly convergent setting)
- Formation is restricted to first ~ 10 Myr of a subduction zone's lifetime (i.e., during subduction initiation) as such, ophiolites are considered the best geological archive of the subduction initiation process

Regional Plate Setting

- Cyprus is located near the triple junction of three major plates
- Cyprus forms the upper plate of a subduction zone for the collision of Africa and Eurasian plates
- To the east, the Sinai-microplate and the Arabian plate are moving northwards in tandem with the African plate
- Eratosthenes Seamount (ES) is an Early Cretaceous (K) carbonate platform that formed on a rifted continental fragment with episodes of submergence, subaerial exposure (Miocene), and resubmergence (late Pleistocene)
- Rifting, subduction, obduction, continent-continent collision, and transform faulting along the boundary between the Eurasian and African plates since the early Mesozoic that has produced a collage of fragmented tectonic terranes

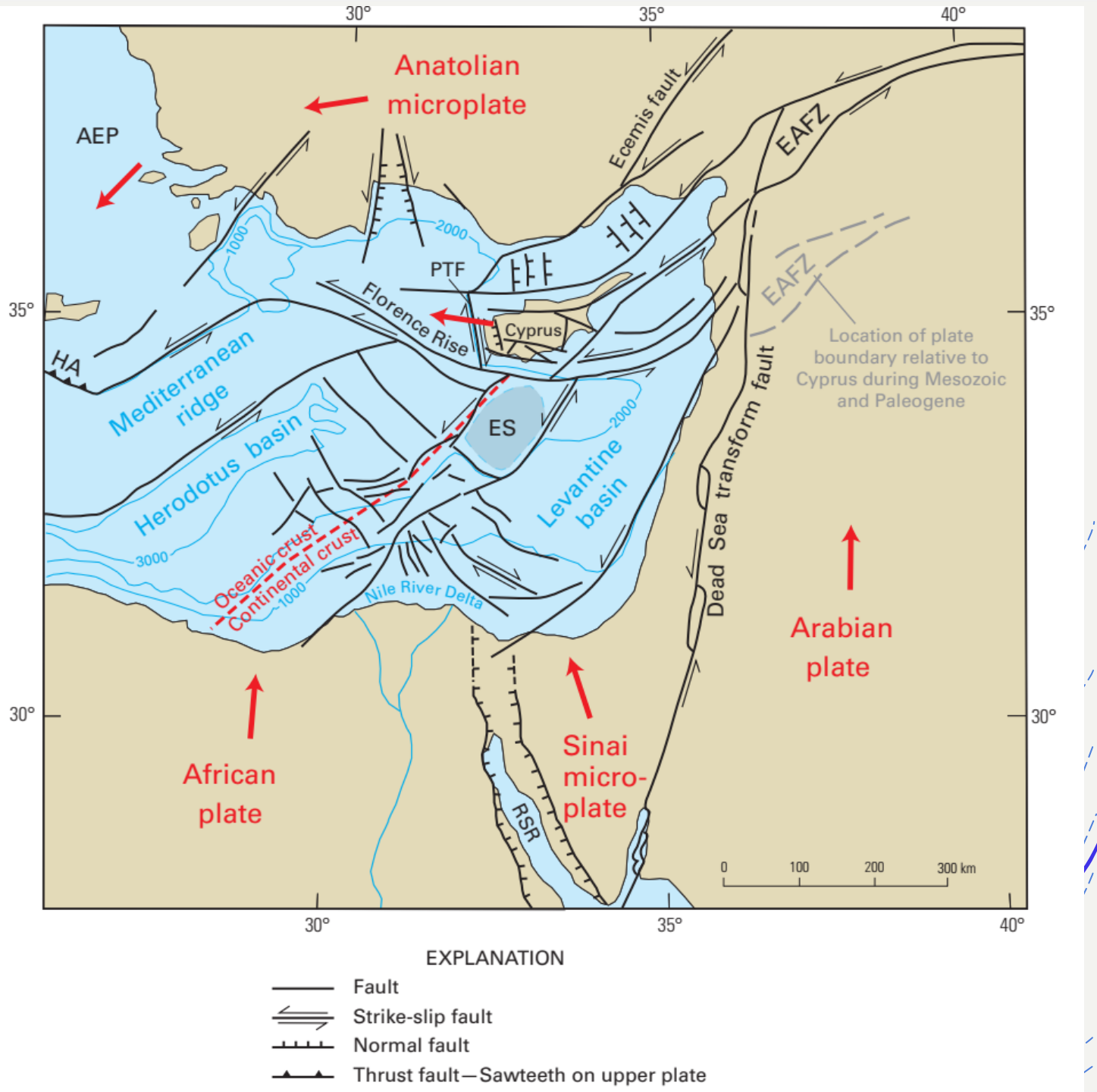


EAFZ – eastern Anatolian fault zone
ES – Eratosthenes seamount
HA – Hellenic arc, subduction trench area of African plate
NAFZ – northern Anatolian fault zone

(Fig. 7, USGS 2008)

- Red arrows - motion of African and Arabian plates relative to Eurasian plate
- Half arrows - relative movement of major plate-bounding transform faults (solid red lines)
- Shaded area - belt of smaller, fragmented tectonic microplates
- Dashed red lines – major intraplate structures

- Continuous movement of the African and Arabian Continental plates towards the north, and more specifically the collision of the Arabian plate with the Anatolian Microplate (position of Turkey today), resulted in the westward escape of the Anatolian Microplate along two major strike-slip faults (North Anatolian and East Anatolian faults)
- Cyprus is like “a seed being squeezed between two fingers” in extremely slow-motion
- The island is considered a ‘seismically active zone’
- In past 30 days (as of 12/31/2023), Cyprus had 64 earthquakes: 1 at M3.3, 15 between M2 and M3, and 48 below M2



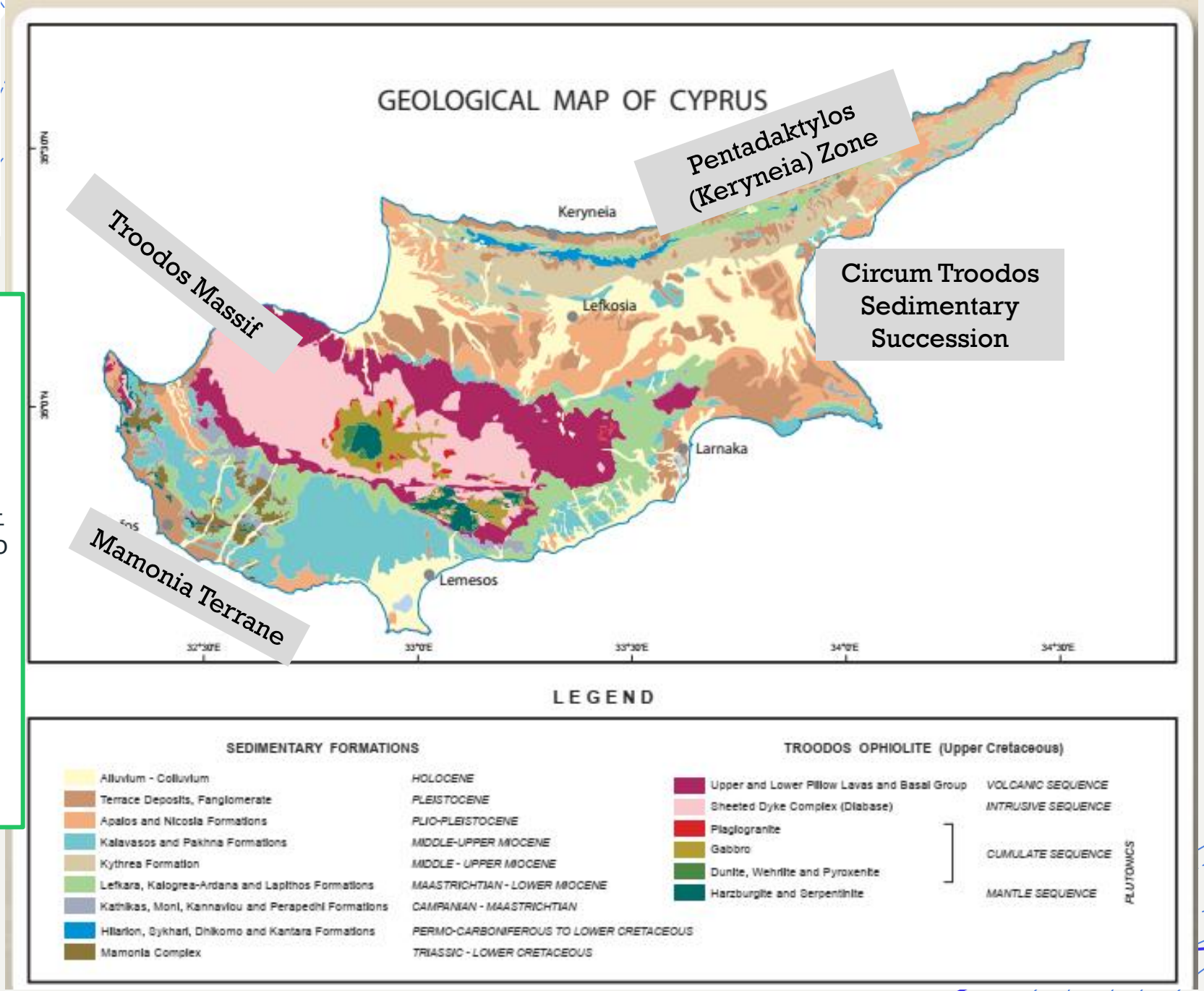
Geologic Terranes

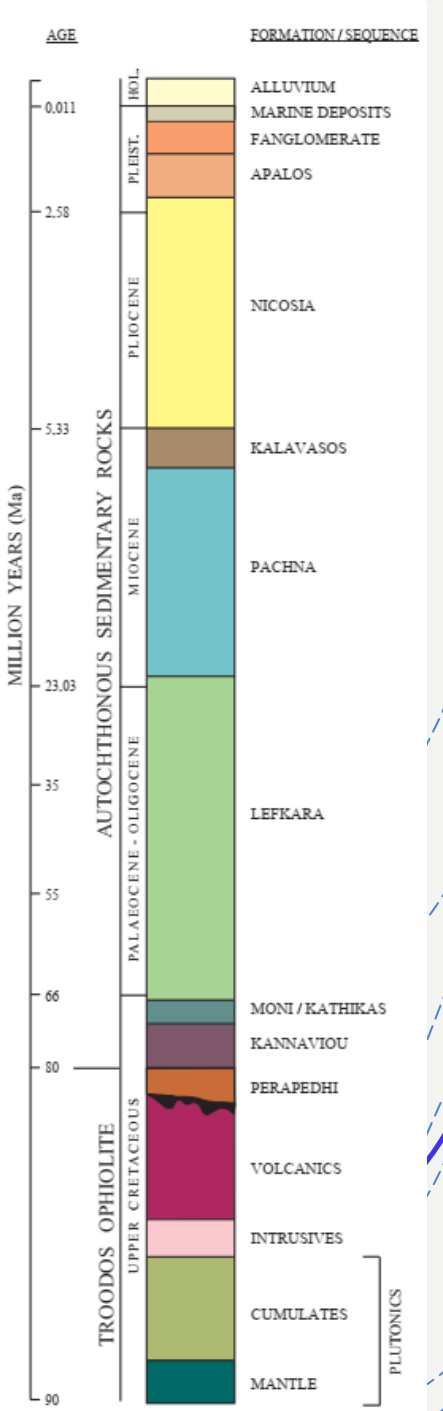
Four geologic terranes – each is the product of a different tectonically controlled environment(s) of deposition

+ Troodos Massif - a slice of late Cretaceous Neo-Tethyan oceanic lithosphere

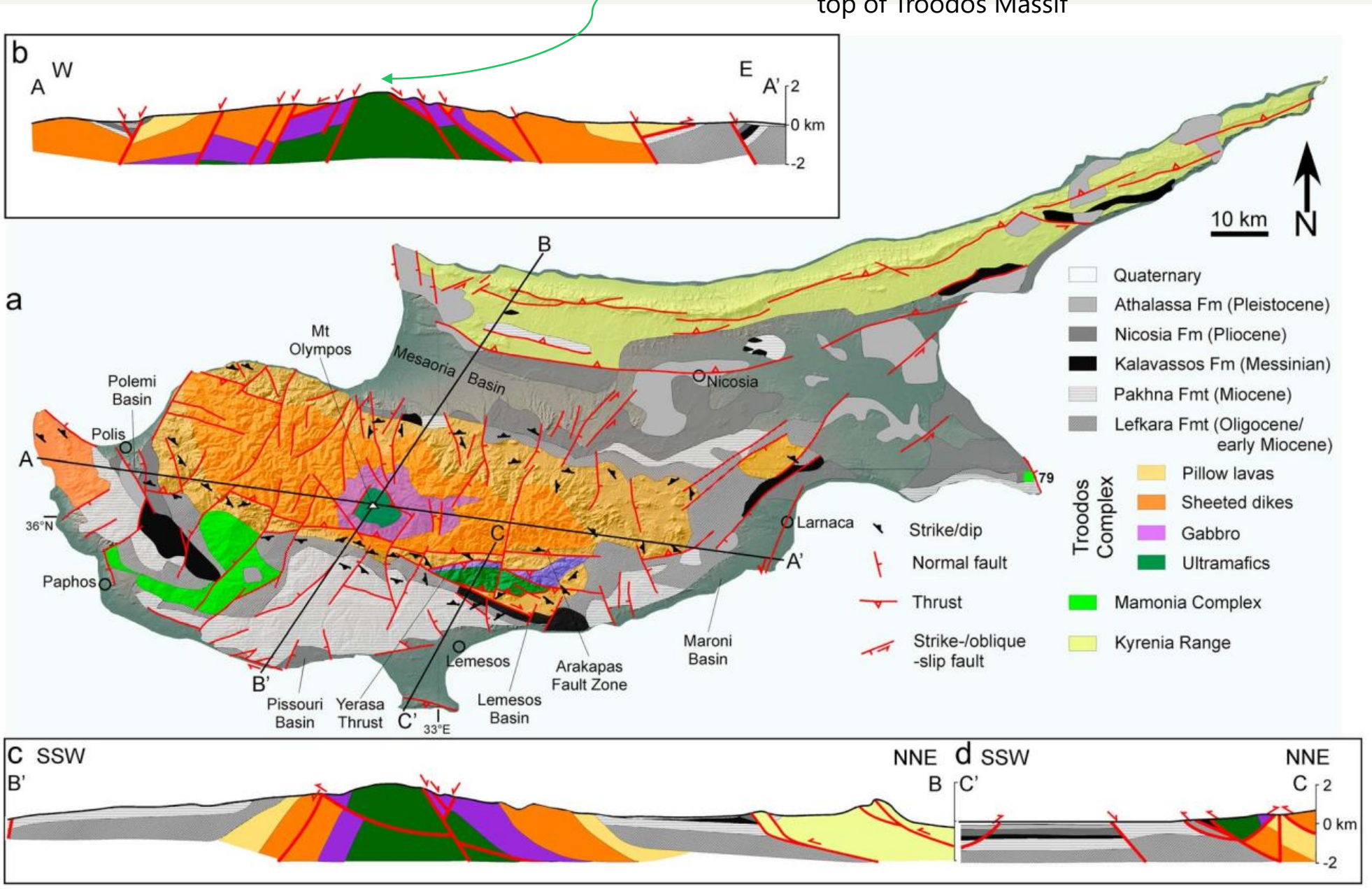
+ Mamonia Complex- deformed Triassic to Cretaceous passive margin sequence

+ Kyrenia Range - fold and thrust sequence of Late Paleozoic-Cenozoic sedimentary rocks

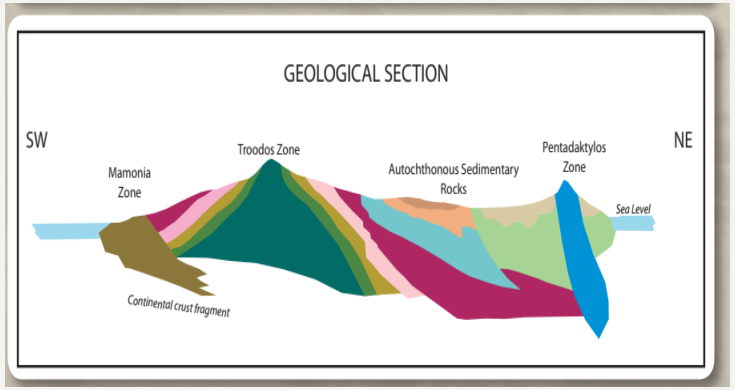




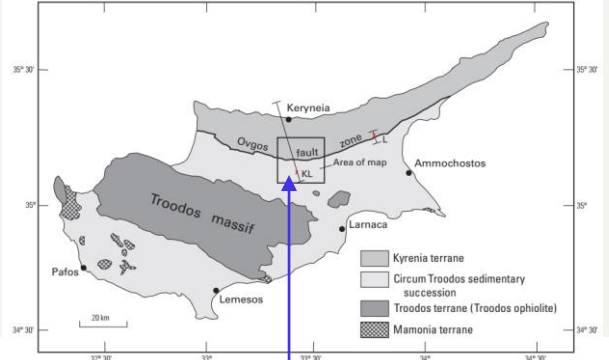
Geologic/tectonic map of basement units, Circum Troodos sedimentary sequence and major faults over digital elevation model



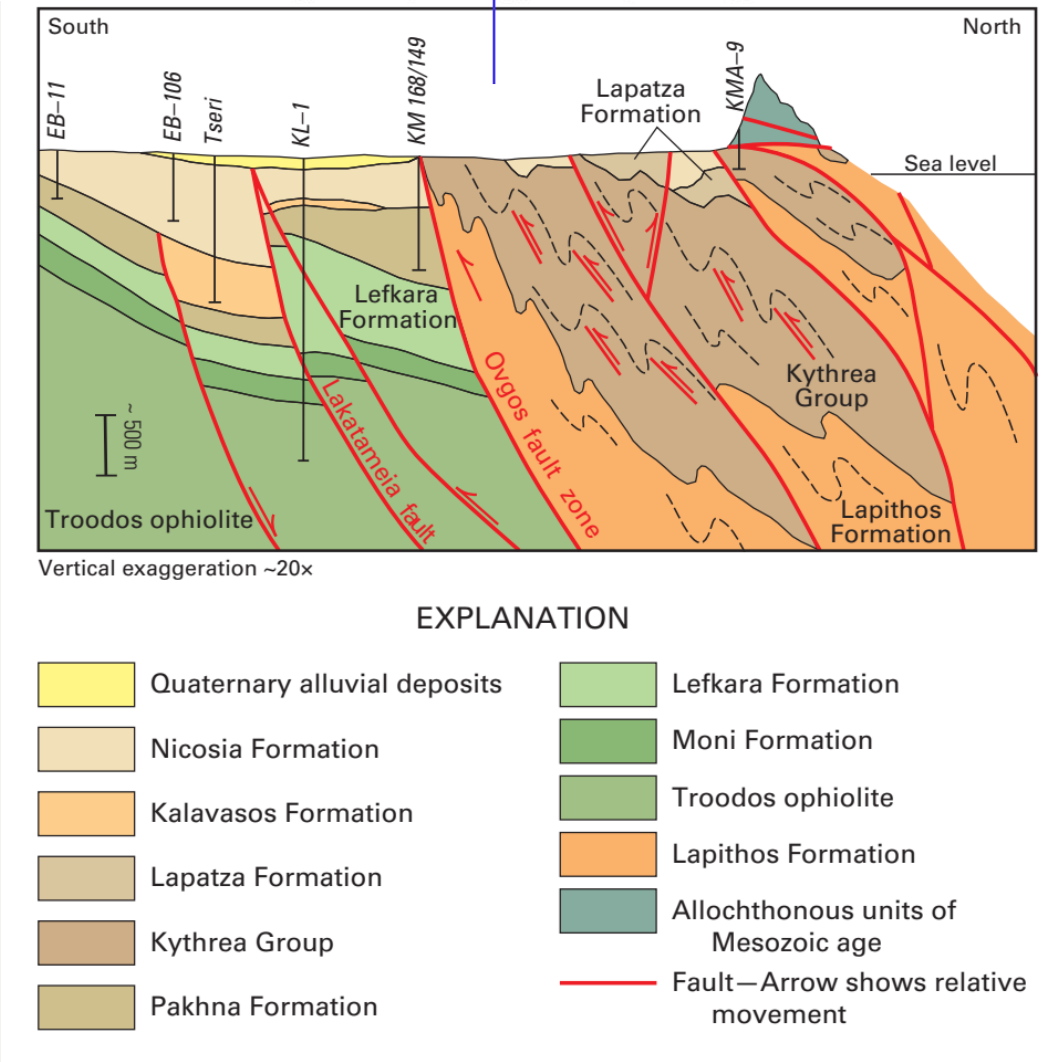
Pentadaktylos (Keryneia) Zone



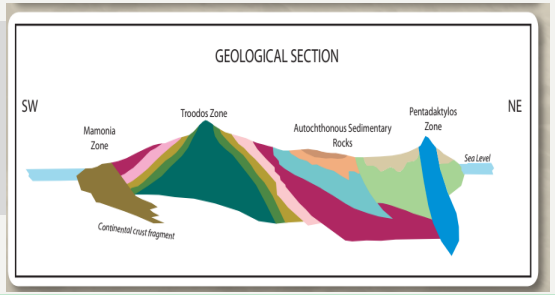

The Pentadaktylos mountain crest



- Kyrenia Range is comprised of a series of narrow, steep-sided mountains (2,300 to 3,400 ft AGL) along northern coast
- Range is separated from the sea by a 3-mile narrow terraced coastal plain, while to the south it is flanked by the broad lowland of the Mesaoria plain
- Mountain range is result of southward thrusting and collision (~6 Ma)
- Older allochthonous Permian-Carboniferous to Lower Cretaceous (350-135 Ma) stratigraphic sequence of massive and recrystallized ls, dolomites, and marbles that has been thrust southward over younger sediments, predominately clastics and chalks of Late Cretaceous to Middle Miocene (67-15 Ma)



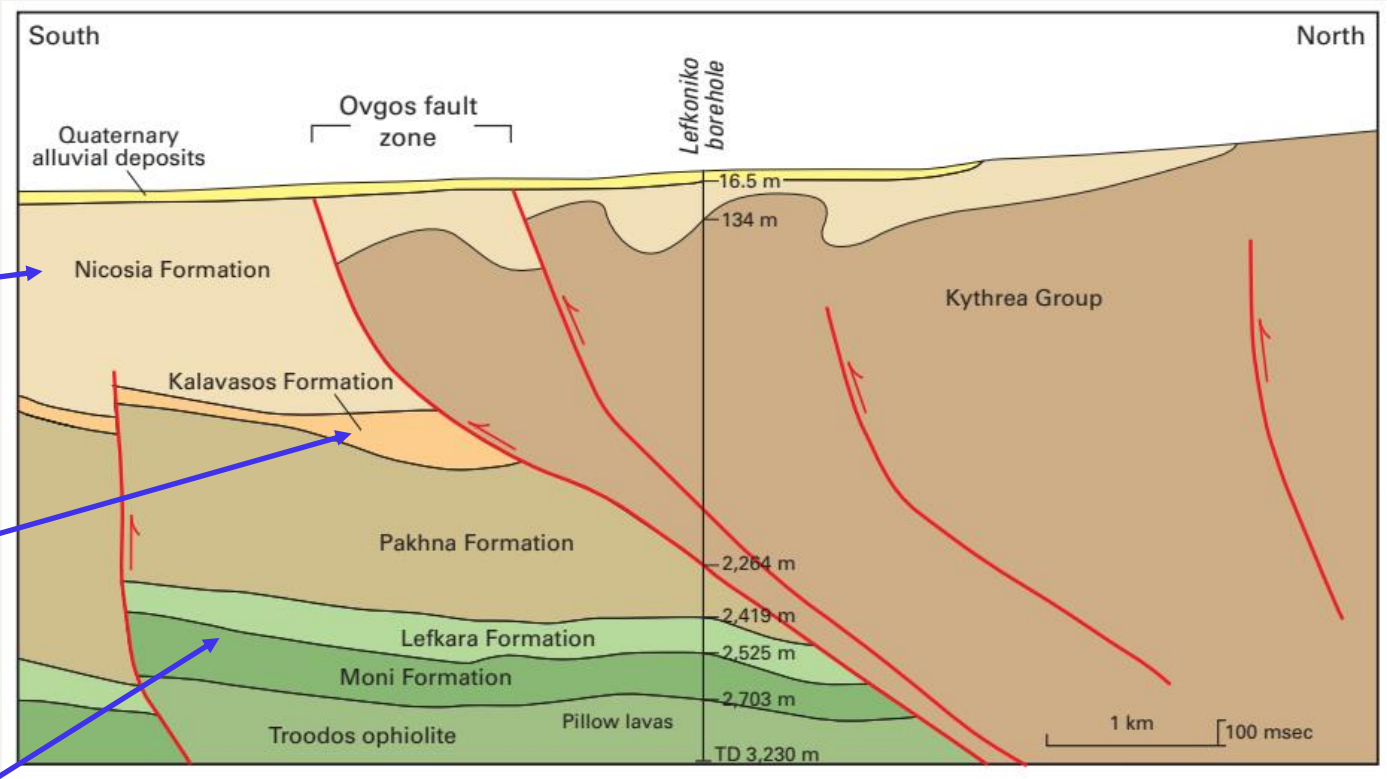
Circum Troodos Sedimentary Succession

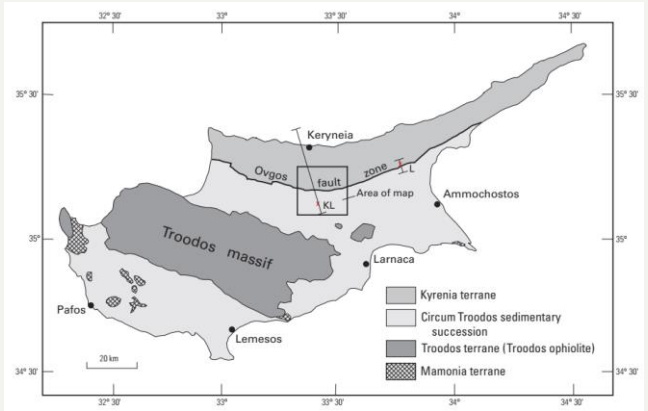


Reopening of Gibraltar Strait and reconnection of Mediterranean Sea with the Atlantic, the Nicosia Fm. (5-2 Ma) represents renewed sedimentation

Kalavasos Fm. (6 Ma) consists of evaporites resulting from isolation of Mediterranean Sea from Atlantic Ocean and subsequent evaporation of its waters

Moni Fm. to Pakhna Fm. are a sequence of sediments indicate shallowing of deposition depth with uplift of Troodos ophiolite





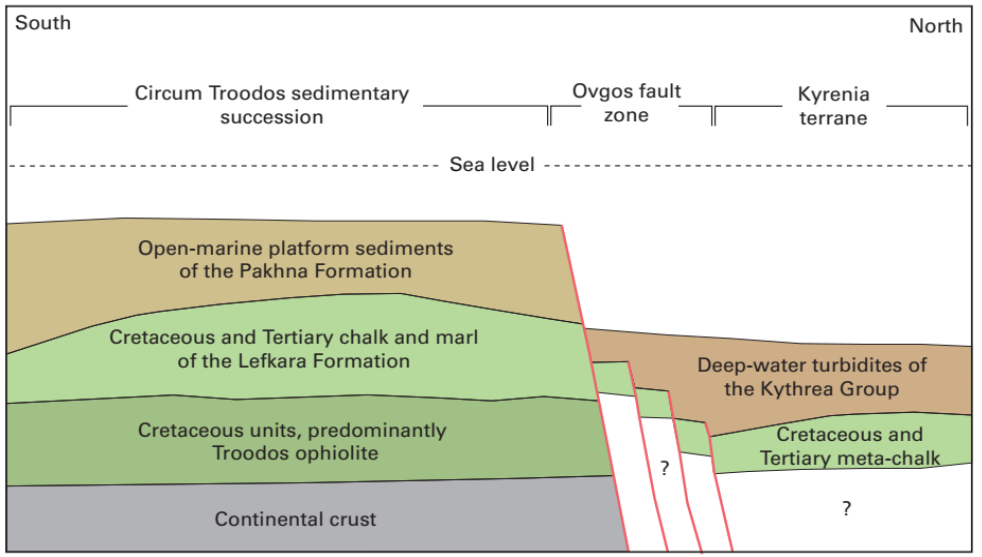
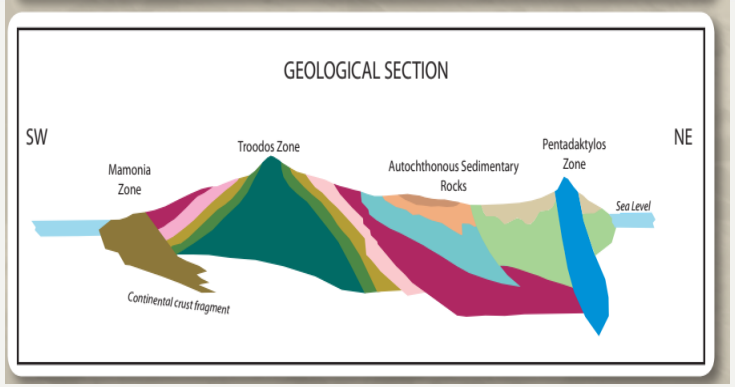


Figure 6. Schematic diagram of the shelf margin that existed in northern Cyprus during the middle Miocene. Deposits of the circum Troodos sedimentary succession were separated from sediments of the Kyrenia terrane by the Ovgos fault zone.

Mamonia Terrane*



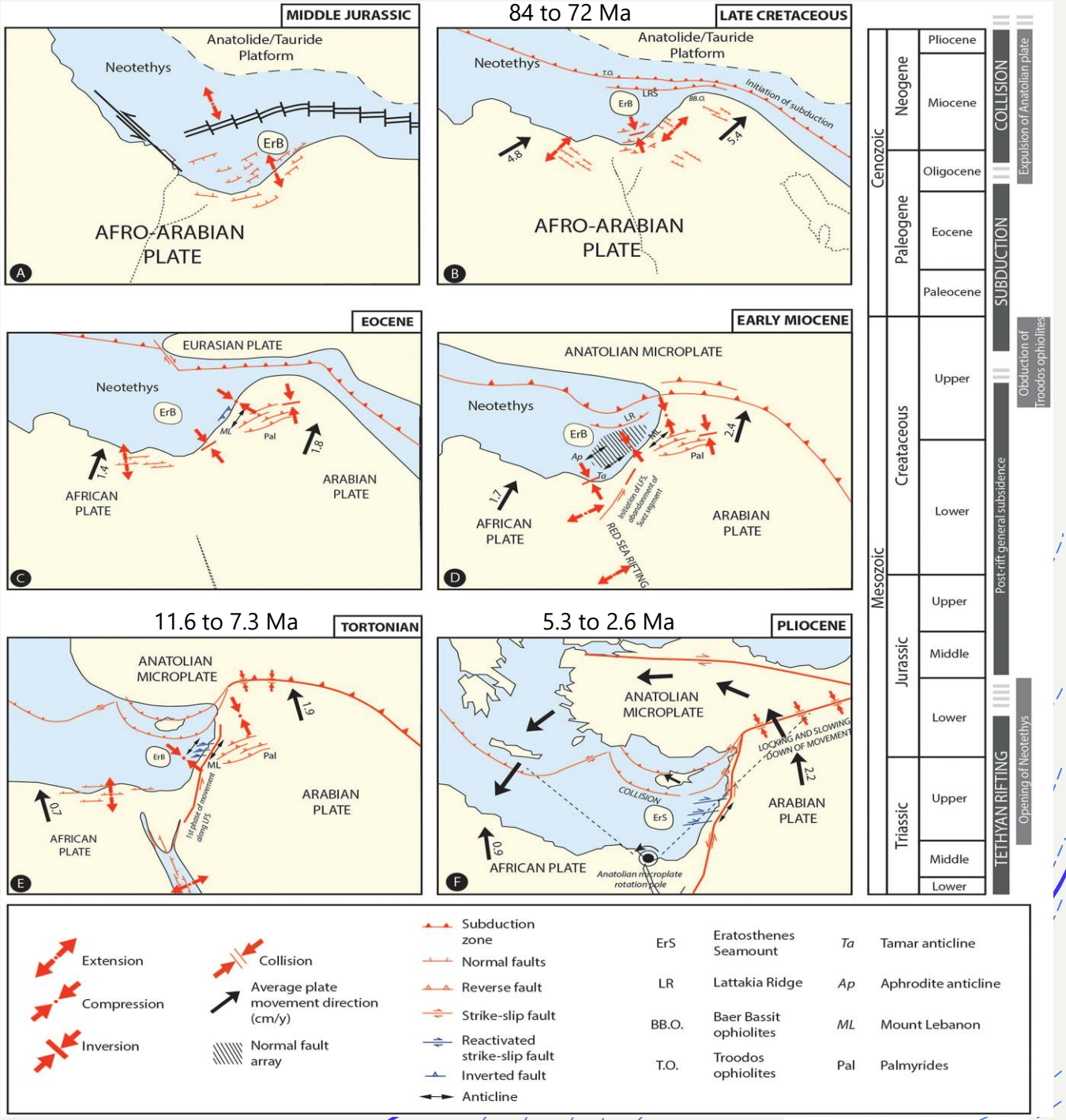
Folded strata of the Mamonia Zone. Folds are quite common in the Zone due to the high degree of deformation

- Exposed across western and southwestern Cyprus, Mamonia Complex comprises late Triassic to early Cretaceous sediments and late Triassic mafic igneous rocks with minor metamorphic rocks that predate the Troodos ophiolite
- Mamonia rocks were thrust over the southern leading edge of Troodos ophiolite during Late Cretaceous resulting in extreme deformation
- Complex is regarded as allochthonous (i.e., formed elsewhere) in relation to the overlying autochthonous (formed in place) carbonate successions and the Troodos ophiolite rocks
- Rocks of Mamonia complex have been intensely deformed (severely sheared, broken, and folded) and mixed with the Troodos ophiolite rocks forming extensive zones of melange
- Proximity of Mamonia terrane to a submarine zone of deformation and present-day seismicity is interpreted to be indicative of a plate boundary

*termed Mamonia Complex by Cyprus Geological Survey

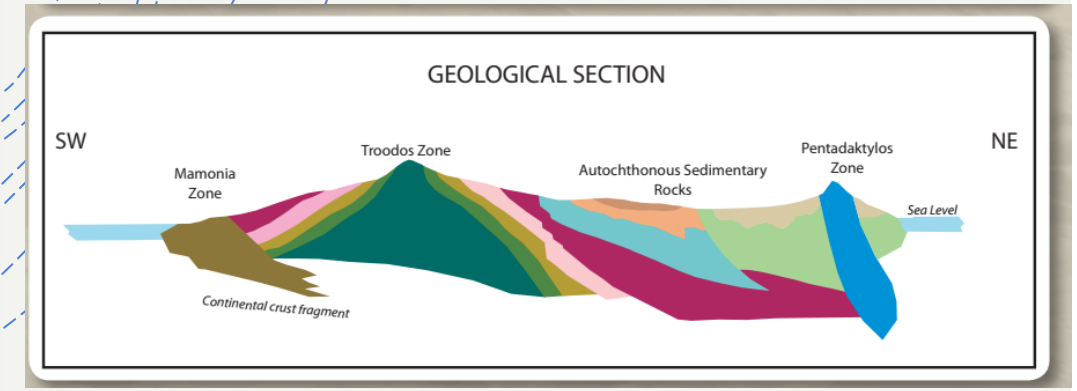
Regional Tectonic History - Troodos Ophiolite Formation

A	Mesozoic rifting phase, normal fault activity ceases by Middle Jurassic
B & C	Late Cretaceous – Eocene - start of convergence between African and Eurasian plates and initial closing stage of Neo-Tethys Ocean results in obduction of multiple ophiolites from Turkey to Cyprus to Oman (peri-Arabian ophiolitic crescent)
D	Early Miocene – initial folding along the Levant margin
E	Westward expulsion of the Anatolian microplate
F	Current tectonic regime
Not shown	Pleistocene – main phase of uplift of Troodos Massif (2.14 and 1.95 Ma) as a tectonic block is indicated by ophiolite-derived clastics in surrounding basins to the north and south

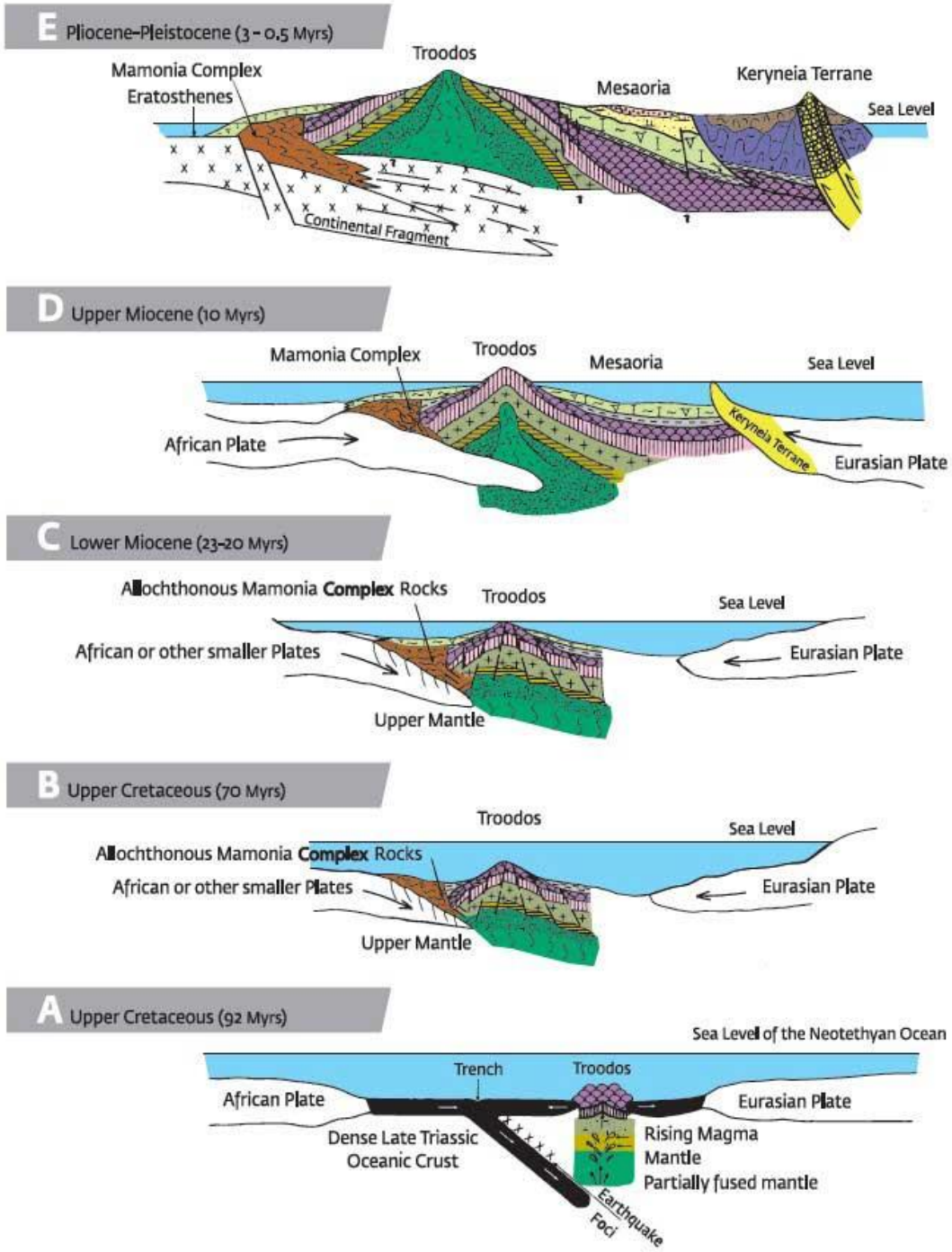


Primary reference: Universite Pierre et Marie Curie, Geosciences Division, Paris, France

Troodos Ophiolite Tectonic Origin



Massive sulphide, chromite, and asbestos mineral deposits are associated with different stratigraphic units (lavas, dunite, and harzburgite respectively) and came to the surface because of its uplift



Primary reference: Cyprus Geological Survey Department

Troodos Ophiolite

Simplified Stratigraphic Units (ascending order):

+ Plutonics and cumulates

- Mantle sequence consisting of residuals after partial melting of upper mantle and formation of basaltic magma. Composed of harzburgite and dunite with 50-80% of original minerals altered to serpentine and serpentinite
- Cumulates are product of crystallization and concentration of crystals at the floor of the magma chamber beneath spreading zone. Dunite, wehrlite, pyroxenite, gabbro, and plagiogranites.

+ Intrusives – solidification of magma chambers at the bottom of oceanic crust, feeding at same time the submarine extrusion of lava onto sea floor

+ Volcanics – two series of basaltic pillow lavas and flows; between intrusives and pillow lavas, a transitional zone termed Basal Group, dominated by a sheet dyke complex

+ Hydrothermal and deep-water sediments – first sediment deposited over the ophiolite rocks as a result of hydrothermal activity and sedimentation on seafloor

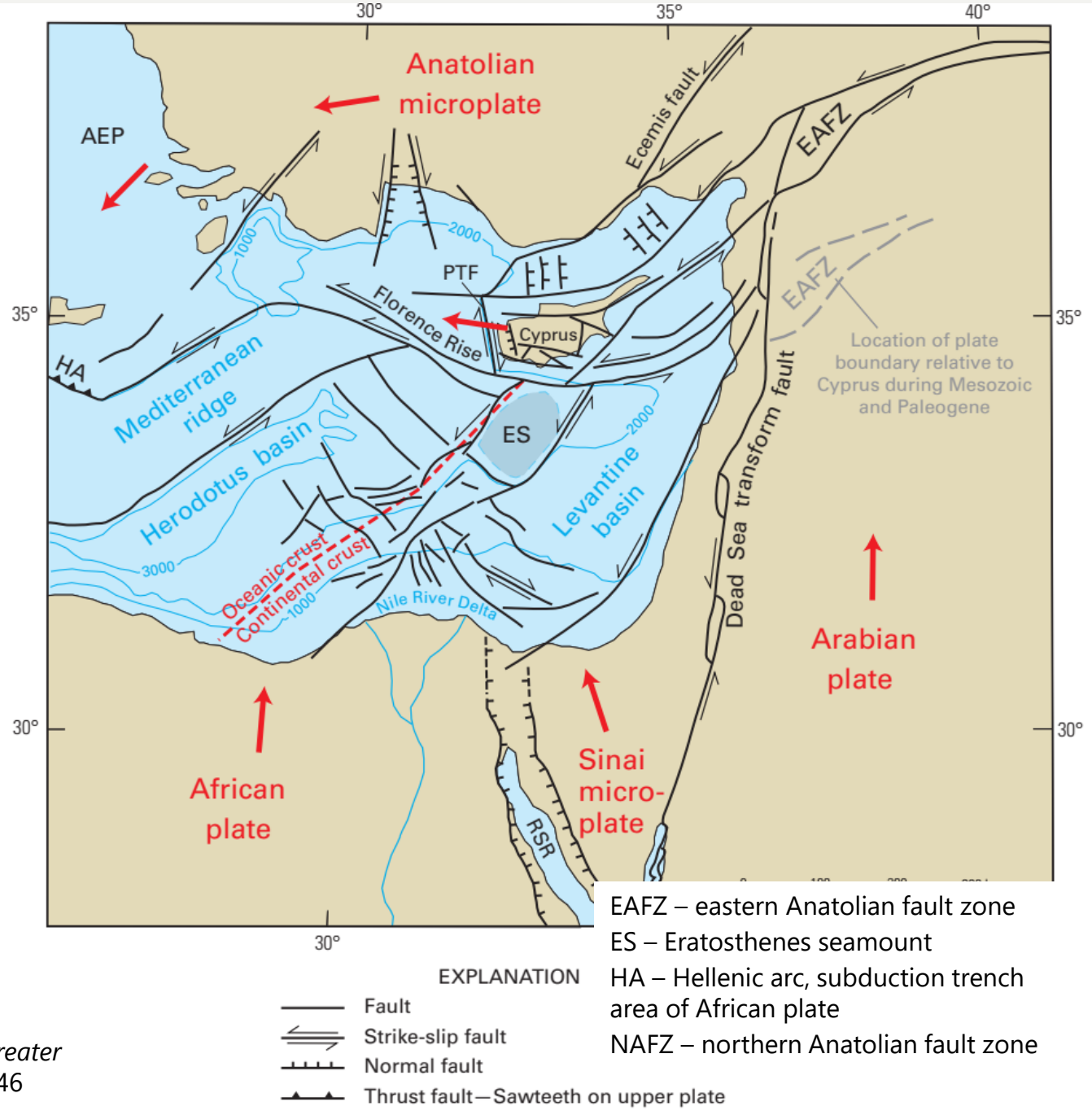
Perapedhi Fm.	First sediments deposited
Upper Pillow Lavas	Volcanic Sequence
Lower Pillow Lavas	
Basal Group	
Sheeted Dikes (diabase)	Intrusive Sequence
Plagiogranite	Plutonic Sequence
Gabbro	
Pyroxenite	
Wehrlite	
Dunite	
Harzburgite	Mantle Sequence
Serpentinite	

Late Cretaceous

Ongoing Uplift Theories

Figure 29. Present-day tectonic map of the eastern Mediterranean region (Harrison R. et al, (2008)

- The Florence Rise occurs along a left-lateral strike-slip structure
- 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
- 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



EAFZ – eastern Anatolian fault zone
ES – Eratosthenes seamount
HA – Hellenic arc, subduction trench area of African plate
NAFZ – northern Anatolian fault zone

Primary reference: Harrison, R. W., et al, (2008) *Bedrock geologic map of the greater Lefkosia area, Cyprus*: U.S. Geological Survey Scientific Investigations Map 3046

Ongoing Uplifting Mechanism – multiple hypotheses in literature

+ In addition to a westward migration, multiple lines of evidence indicate that since the Middle Pliocene much of the island has been above sea level and has been episodically rising
+ One reference paper (V. Symeou et al., 2018) summarized the different scenarios attempting to describe the tectonic evolution of the region:

  a) "long-lived collision scenario: depicting continuous thrusting and folding onshore and offshore Cyprus from Eocene until recent as a result of the continent-continent collision between the African and Eurasian plates"

  b) "strike-slip scenario, supported by the absence of a volcanic arc and a Benioff zone offshore Cyprus, in addition to the recognition of strike-slip structures onshore, which suggests that the emplacement of the ophiolites and the creation of the Cenozoic basins and Recent structures are associated with a left-lateral strike-slip regime since Late Cretaceous"

  c) "Pliocene collision scenario: where the Pliocene compressional tectonics followed a succession of compressional (from Late Cretaceous to Paleogene) and extensional regimes (Miocene time due to slab roll-back of the northward subducting African plate). This last scenario rests on the recent uplift of Cyprus and the change in sedimentation from Miocene hemi-pelagic carbonates to Pliocene clastics as a result of the continent-continent collision between the Eratosthenes microcontinent and the Eurasian plate in Pliocene."

+ One author proposes serpentinite diapirism

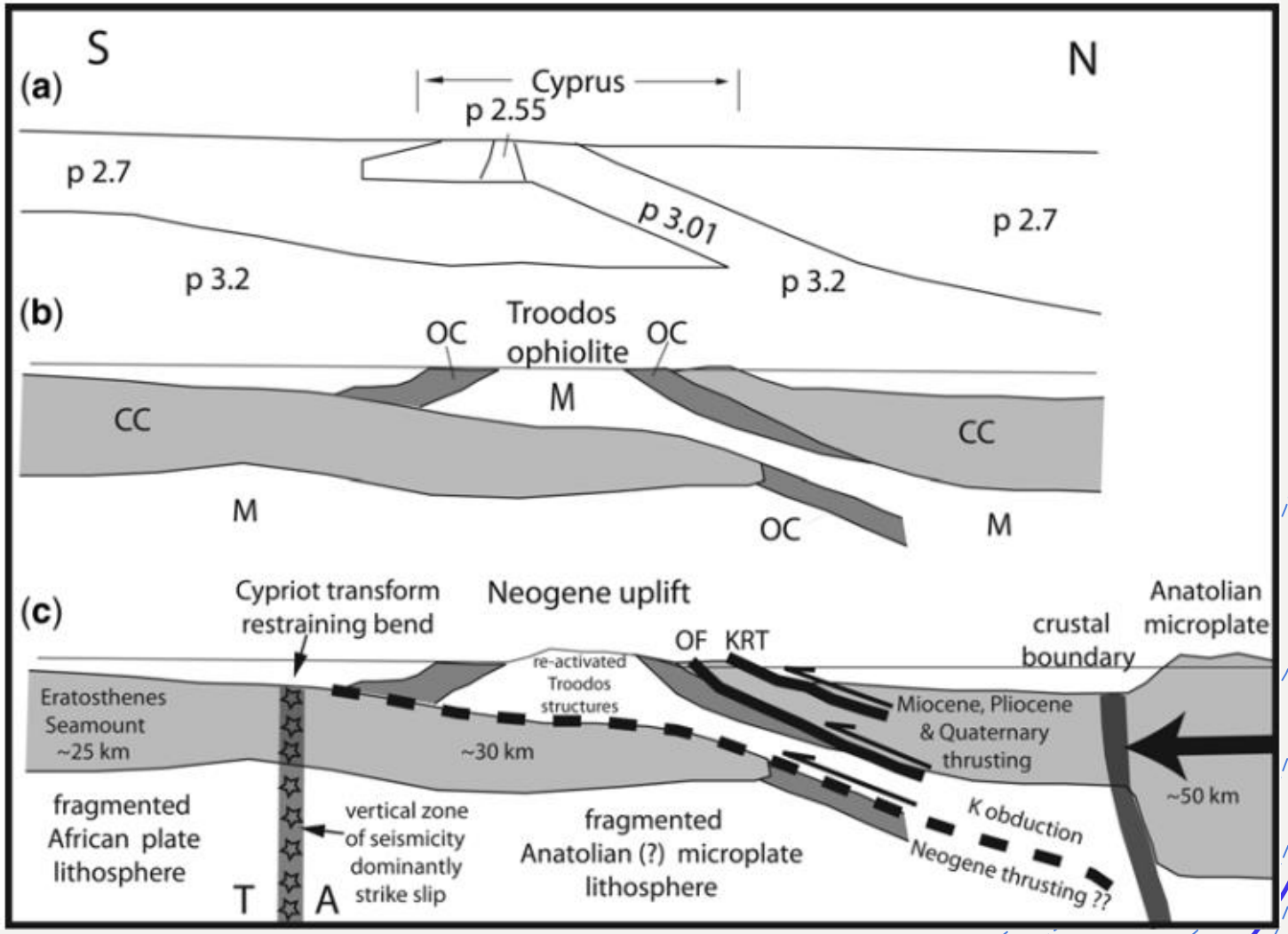
Uplifting Mechanism – Tectonic wedging at a plate boundary with a restraining bend mechanism

- Under thrusting from the south of a continental crustal block beneath Cyprus, re-activation of the basal detachment fault has contributed to portioning of strain and uplift of the Troodos Ophiolite in the form of a tectonic wedge
- A tectonic wedge is being driven S and SW over continental thrust that is restrained from southward movement by the Cyprus-restraining bend section of the transform plate boundary

a) Model of gravity data showing rock densities, base of TO is a low-angle, northward dipping surface

b) Interpretation of crustal material based on gravity data

c) Location of seismicity along Cypriot transform; area of Neogene uplift along margins of Troodos Ophiolite; interpretation of north-dipping structures that accommodate lithospheric contraction



M – mantle
OC – oceanic crust
KRT – Kyrenia Range thrust system (Neogene)
OF – Ovgos fault zone
T – towards; A - away

Primary reference: Harrison, R.W., Tsiolakis, E., Stone, B.D., Lord, A., McGeehin, J.P., Mahan, S.A., and Chirico, P. (2013) *Late Pleistocene and Holocene Uplift History of Cyprus; implications for active tectonics along the southern margin of the Anatolian microplate* in Geological Development of Anatolia and the Easternmost Region, Geological Society, London Special Publications, 372, 561-584

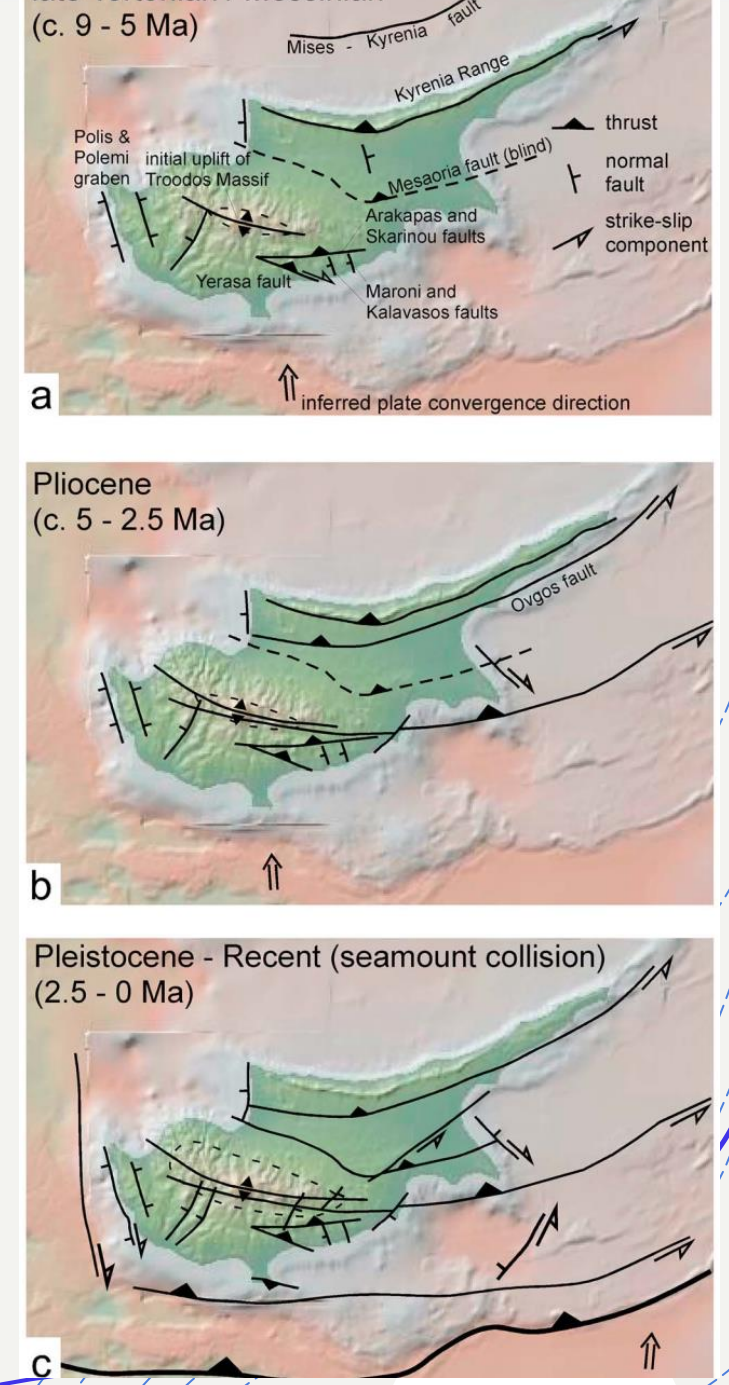
Uplifting Mechanism – ES Movement

- Pleistocene uplift of Troodos Massif took place when Erastosthenes Seamount entered the southern subduction zone
- Surface uplift of Cyprus, accompanied subsidence of the northern under-thrusting of the Erastosthenes Seamount
- Architecture of the Troodos Massif was controlled by a growing anticline that gradually became doubly plunging due to shortening
- The center of developing doubly-plunging Troodos anticline above the Erastosthenes Seamount resulted in a focused uplift

a) Late Miocene deformation of KR; initial development of Troodos anticline

b) Structures continued to grow and deformation in N. Cyprus propagated into Mesaoria Basin and Ovgos fault forms

c) Under thrusting of ES at ~2 Ma caused differential shortening across Troodos Massif and formation of doubly-plunging Troodos anticline, latter amplified by normal faulting along ~N-S striking faults

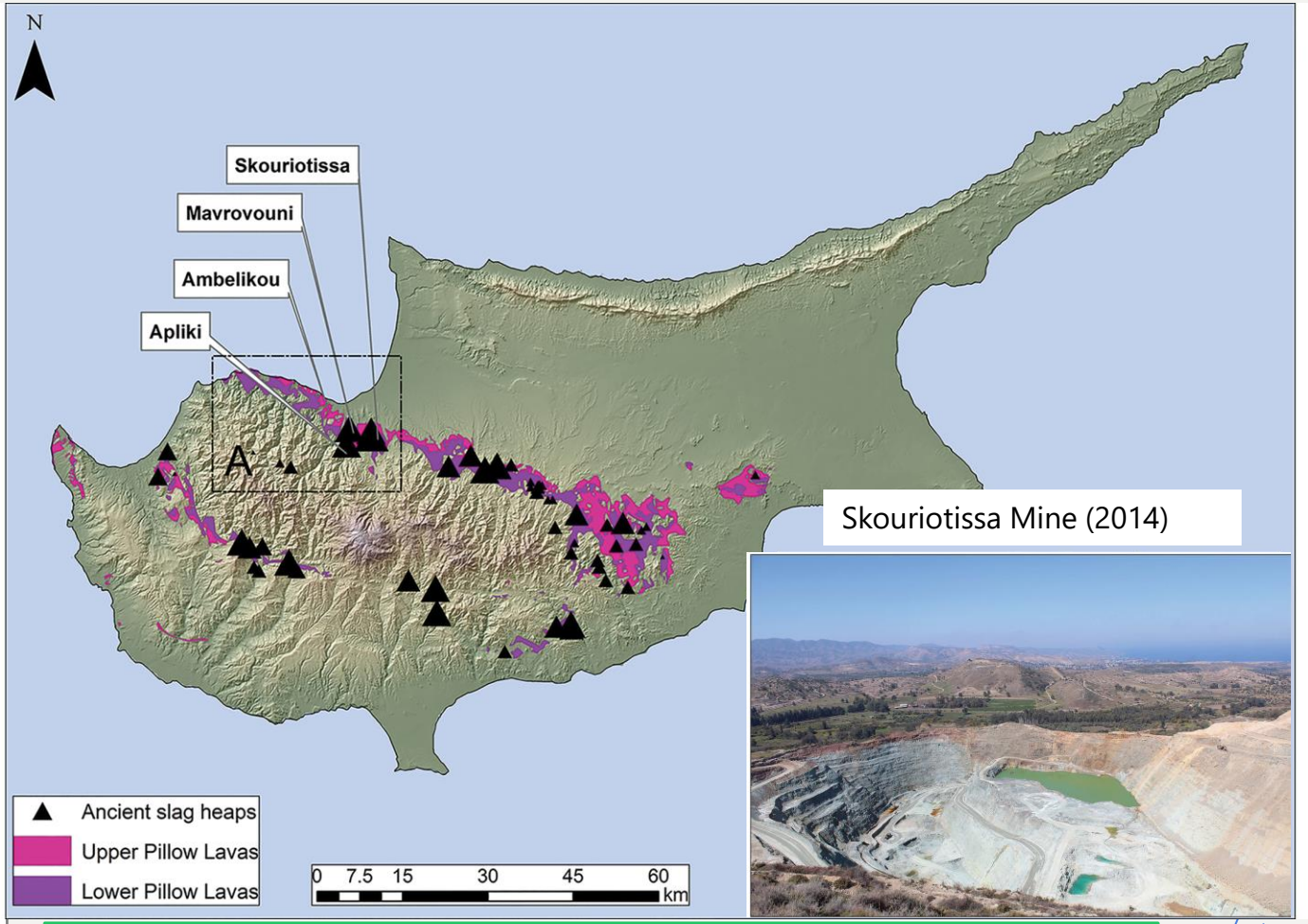


Primary reference: Symeou, V., Homberg, C., Nader, F. H., Darnault, R., Lecomte, J.-C., & Papadimitriou, N. (2018) *Longitudinal and temporal evolution of the tectonic style along the Cyprus Arc system, assessed through 2-D reflection seismic interpretation*. Tectonics, *37*, 30–47.

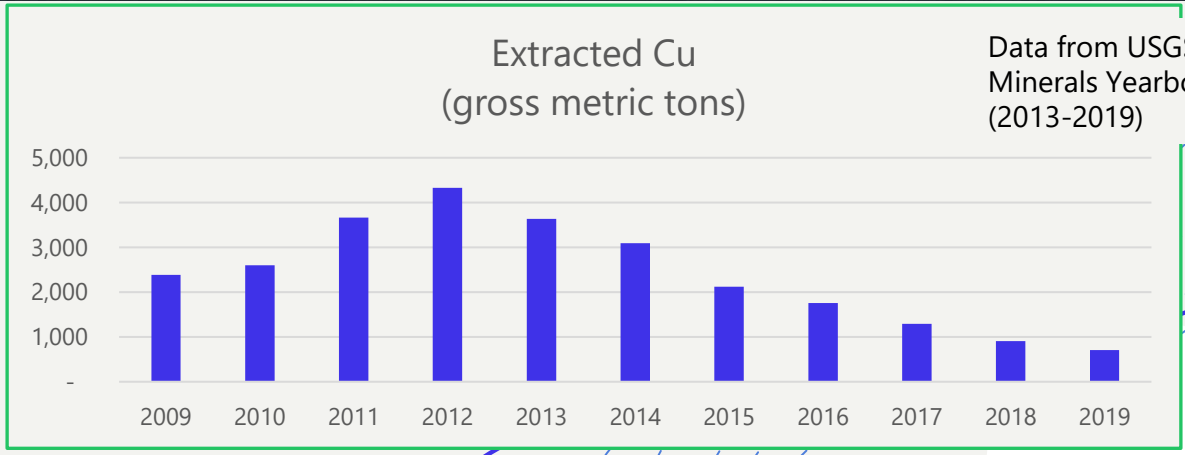
Copper and Chrysotile (Asbestos) Mining

Copper Mining

- Cyprus was famous in antiquity for its copper resources - the word *copper* is derived from the Greek name for the island, *Kupros*
- Cyprus is considered to be one of the five richest countries in copper per surface area in the world
- Troodos mountain range includes all of the economically-significant mineral deposits
- All copper deposits identified as of 2013 were volcanic-associated massive sulfide (VMS*) deposits that were under shallow cover rock
- These massive copper deposits, mainly composed of pyrite and chalcopyrite, are located in the periphery pillow lavas formations
- Skouriotissa Mine is considered to be the world's longest producing copper mine (~3,000 years)



Skouriotissa Mine (2014)

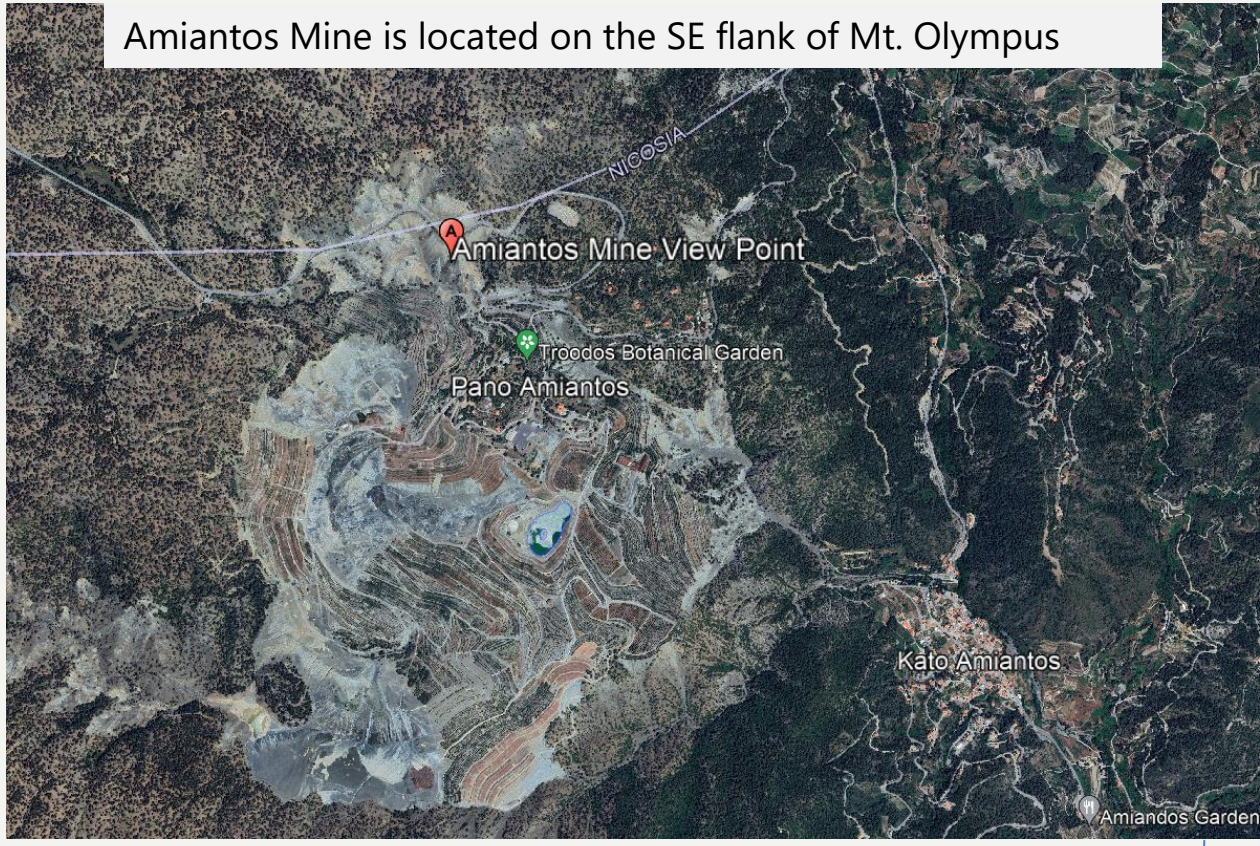


* VMS/Cyprus type: small, medium-grade deposits rich in copper and zinc / generally lens or mound shaped accumulations of massive pyrite developed in ophiolite-related, extrusive basalt sequence (e.g., Skouriotissa) (USGS 1986)

Chrysotile Mining

- Chrysotile (white asbestos) is a soft, fibrous hydrous magnesium sheet silicate in the serpentine group of phyllosilicates ($Mg_3(Si_2O_5)(OH_4)$)
- Chrysotile fibers are found as veins in serpentines, in serpentinized ultramafic rocks, and in serpentinized dolomitic marbles
- Genesis of chrysotile is associated with the serpentinization of harzburgite (basal unit of ophiolite)
- Serpentization occurs by hydrothermal alteration of ultrabasic rocks such as dunite, peridotite, and pyroxenite infiltrated by water low in carbon dioxide (subduction zones)
- Amiantos Mine was an open pit mine (area of 5 mi^2) with abundant white asbestos, employing thousands of workers at one time when manual mining was common (prior to 1950s)
- Asbestos was mined from 1904 until 1998 when the market collapsed due to health concerns associated with asbestos
- The mine produced approx. 1 million tons of asbestos from 130 million tons of rock removed during its 84 years of operation
- The last major mine owner was a Danish company – they abandoned the mine in 1986 when Denmark prohibited the usage of asbestos the same year
- Rehabilitation of the site began in 1996 and is expected to continue to 2035

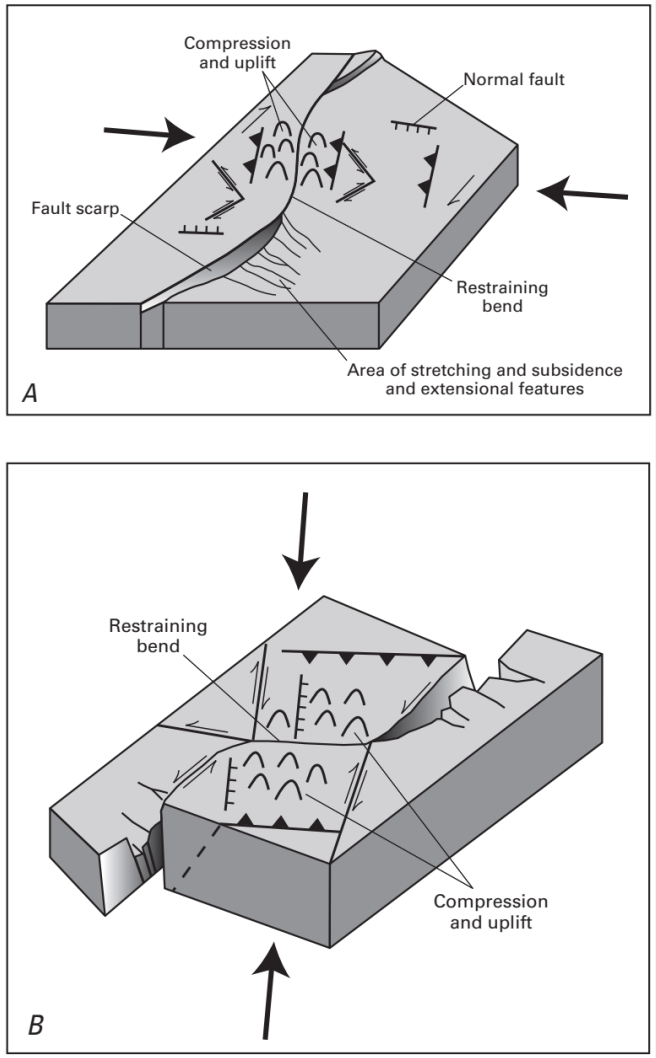
Amiantos Mine is located on the SE flank of Mt. Olympus



The major difference between chrysotile and amphiboles is related to its chemical composition, its acid-resistant properties and its effects on health. In contrast with amphiboles, chrysotile does not persist in the lungs after inhalation; it is quickly eliminated by the body. A prolonged exposure to high concentrations of chrysotile fibers is required for a clinical manifestation of pulmonary damage to appear. Amphiboles because of their toxicity and their high biopersistence, are mainly responsible for mesothelioma and pulmonary diseases even caused after a short or moderate exposure.

Note: amphibole asbestos fibers are formed as solid rods/fibers. The structure of an amphibole is a double chain of silicate tetrahedral which makes it very strong and durable. The external surface of the crystal structures of the amphiboles is quartz-like and has the chemical resistance of quartz. The amphibole fibers have negligible solubility at any pH that might be encountered.]
https://chrysotileassociation.com/chrysotile/overview/default.php

Questions?



Harrison, R. W., et al (2008) *Bedrock geologic map of the greater Lefkosia area, Cyprus*: U.S. Geological Survey Scientific Investigations Map 3046

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. 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.

Harrison, R.W., et al (2013) *Late Pleistocene and Holocene Uplift History of Cyprus; implications for active tectonics along the southern margin of the Anatolian microplate* in Geological Development of Anatolia and the Easternmost Region, Geological Society, London Special Publications 372

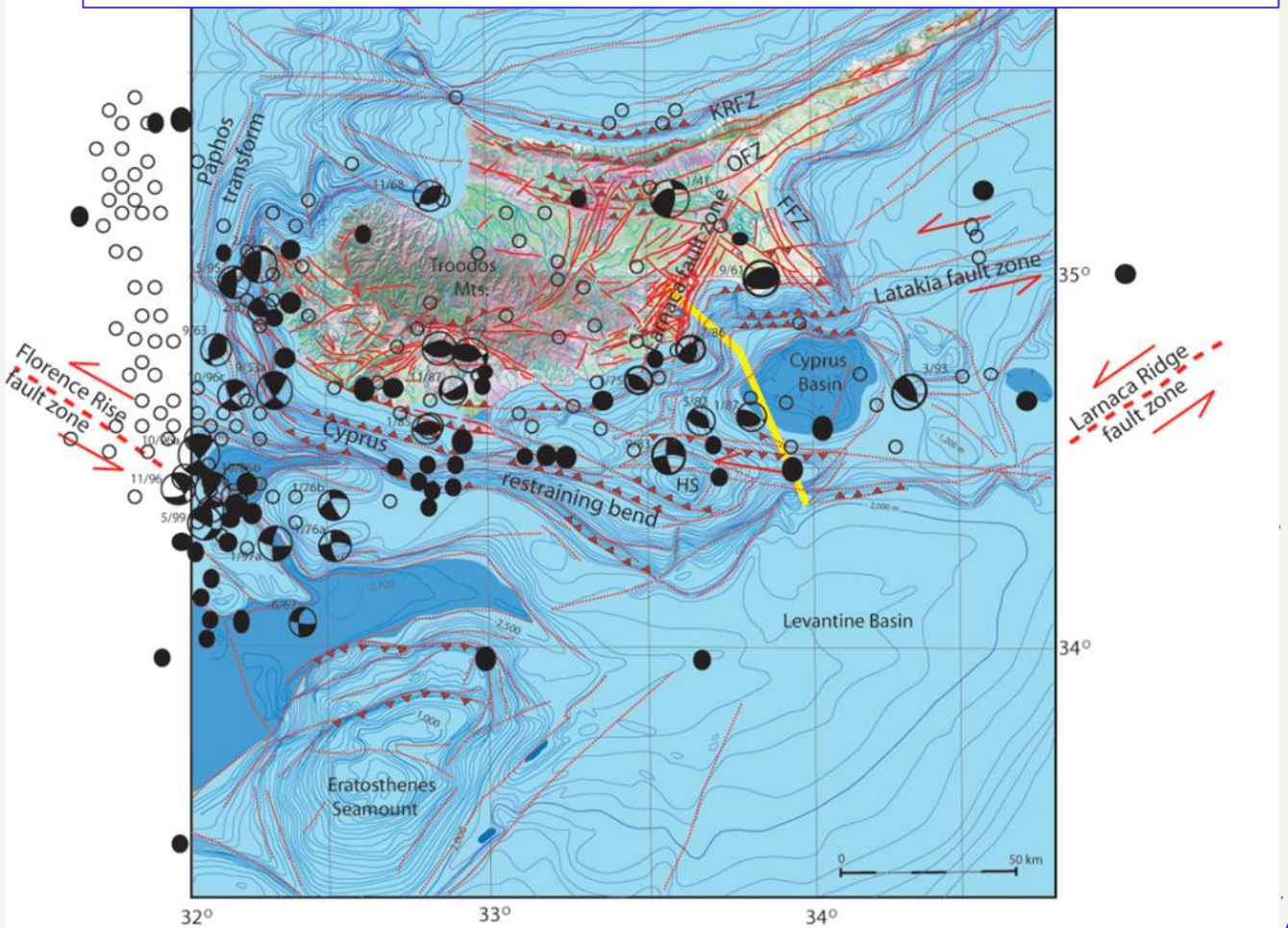


Fig. 11. (a) Map of neotectonic faults on and surrounding Cyprus. Onshore faults are from reconnaissance mapping by authors, Harrison et al. (2008), and GEOTER (2005). Offshore faults are interpreted from sea-floor relief and linear features. Beach-ball symbols show focal mechanisms for events M5.5 (dark areas are compressional quadrants) and filled-black circles are M4 events; open circles are epicenters for the period April 1997 to January 1998.
KRFZ, Kyrenia Range fault zone; OFZ, Ovgos fault zone; FFZ, Famagusta fault zone; HS, Herodotus Seamount.

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