A Model for the Plate Tectonic Evolution of the Eastern Mediterranean Region that Emphasizes the Role of Transform (Strike-Slip) Structures

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Abstract: - A model for the tectonic evolution of the Eastern Mediterranean region from Mesozoic to Present is developed from geological, geophysical, and seismological data on and surrounding the island of Cyprus. This model emphasizes the role of major transform structures in accommodating horizontal plate motions, driven from the west by spreading along the Atlantic-Arctic mid-ocean-ridge system and from the east by escape tectonics related to the movement of the Arabian plate. In particular, this model interprets the African-Anatolian plate boundary as a system of left-lateral transform structures, >75 km wide, that has been active since the early Mesozoic. In this model, Neotethys spreading and closure (subduction and obduction) occurred north of the transform system. Geophysical data indicates that the Troodos ophiolite dips northward; suggesting that subduction was to the north beneath the Anatolian plate. Southward obduction of the Troodos ophiolite was facilitated by contemporaneous left-lateral horizontal shear. The northward sequence of 1) a wide zone of shear containing ophiolites; 2) contracted trench and accretionary prism rocks; and 3) a north-dipping subduction zone is similar to the sequence described across the Arabia-Anatolian plate boundary, indicating commonality in tectonic evolution.

Key Words: Eastern Mediterranean, Plate tectonics, African plate, Mesozoic, Cenozoic, Cyprus, Troodos

1 Introduction

Plate tectonics is one of the 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.

The Eastern Mediterranean region has had a complex tectonic history since the early Mesozoic breakup of Gondwana. Between the major plates of Africa and Eurasia, there is a > 1,500-km-wide intervening collage of differing tectonic terranes that is the product of shearing, rifting, subduction, obduction, and contraction over the past 200 Ma. The dynamics of plate interactions is recorded in the assembly of this collage. The E. Med. region encompasses the southern portion of the collage and includes its margin with the African plate. The early Mesozoic opening of the Atlantic basin instigated left-lateral shear along the northern margin of the African plate, as Africa moved eastward relative to the Eurasian plate [1,2]. Neotethys rifting and creation of subduction zones characterizes much of the Mesozoic in the E. Med. region [1,2,3,4]. As Atlantic rifting expanded northward into the N. Atlantic and Arctic, relative motion between these two plates became more convergent and regional stresses along the African plate margin became more transpressive [1,2]. Two other global-scale tectonic events have significantly impacted the E. Med. First, the Eocene collision of the Indian plate with Eurasia enhanced left-lateral movement of Eurasia relative to Africa. And second, the Miocene separation of the Arabia plate from Africa along the Dead Sea transform produced a northward impingement of Arabia into the intervening collage of terranes, in particular the Anatolian microplate; this event initiated escape tectonics of Anatolia [1,2]. Thus, plate tectonics in E. Med. region over the past 5 Ma has been influenced by the westward escape of the Anatolian microplate; this has been accommodated by strike-slip movement along generally NE-SW- to E-W trending faults along the African-Anatolian and Arabian-Anatolian boundaries [2,3,5,6]. Cyprus is located on the southern margin of the Anatolian microplate (Fig. 1), adjacent to the African plate boundary [1]. Understanding the tectonic evolution of Cyprus is critical to a better understanding of the tectonic evolution of the entire Eastern Mediterranean region.

2 Problem: Competing Plate Tectonic Models for the Eastern Mediterranean Region

The tectonic evolution of the margin between the African and Anatolian plates is controversial [5,6,7], including the present-day tectonic setting (Fig. 1). Much of the controversy centers on (i) the nature of major structures offshore of Cyprus, (ii) the origin of the Troodos ophiolite and its obduction onto continental crust, and (iii) the nature of the crust under the Levantine basin (oceanic vs. attenuated continental). The two competing ideas on the nature of major structures offshore of Cyprus are: 1) that a northerly dipping subduction zone, which has consumed oceanic crust since the Late Cretaceous, exists south of Cyprus [8,9,10,11,12,13], or 2) that a complex system of left-lateral strike-slip faults exists south of Cyprus (Fig. 1) and that there has never been a subduction zone nor oceanic crust south of the island [5,6,7, 14,15,16, 17]. The two competing ideas for the obduction of Troodos are: 1) emplacement from the south after formation over a supra-subduction zone [8,9,10,11, 12,13]; and 2) obduction from the north [5,6,7,18] contemporaneous with left-lateral strike-slip tectonics [7,]. The two competing ideas on the crustal nature of the Eastern Mediterranean are: 1) Cyprus, Eratosthenes Seamount (ES), Nile Delta, and the Levantine basin are all underlain by continental crust, the latter two of which are highly attenuated [19], and 2) the Levantine basin is underlain by oceanic crust [20, 21]. The nature of the crust is beyond the scope of this paper; however, the geophysical evidence that the Levantine basin is highly attenuated continental crust [19] is accepted, otherwise the ES, which is underlain by ~28 km of continental crust [27, 28], becomes an unlikely protrusion off of the African plate.

2.1 Problems with Subduction Zone Models

For the past three decades, the dominant theory for the tectonic setting of Cyprus has been that a northerly dipping subduction zone exists beneath the island [8,9,12,29]. However, several problems exist with the

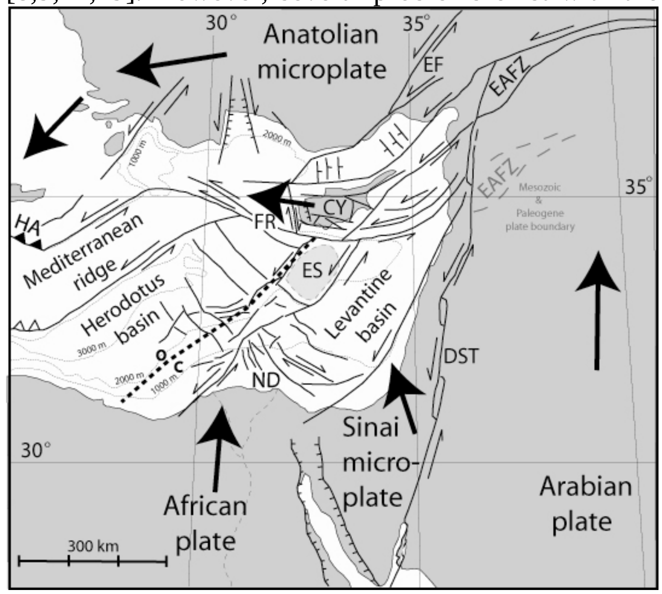

Figure 1. Present-day tectonic map of the Eastern Mediterranean region [after 5,6]. CY- Cyprus, ES- Eratosthenes Seamount, FR- Florence Ridge, which occurs along left-lateral strike-slip structure [22]; EF- Ecemis fault, EAFZ - Eastern Anatolian fault zone (paleo-location to the south during Mesozoic & Paleogene shown by ghost lettering) DST- Dead Sea transform, ND- Nile delta, HA- Hellenic arc; bold dashed line is approximate boundary between oceanic (O) and continental (C) crust [23,24]; large arrows represent relative plate motions [after 25,26]. The fault system between Cyprus and ES is the Cypriot transform, which marks the northern African plate boundary [1,2].

subduction-zone models [5,6,7]. Summarized, these are: **1)** absence of a volcanic arc in the vicinity of Cyprus; the nearest arc rocks are far to the north in the middle and northern parts of the Anatolian plate; **2)** the absence of a Benioff zone beneath Cyprus; rather, a tabulation and plot of the best-constrained recorded seismicity [30] reveals a clustered vertical zone of seismic events (Fig. 2) that extends to depths of greater than 60 km; **3)** known onshore Neogene faults are dominantly strike-slip and transpressive structures [5,6,7,36]; **4)** gravity investigations [27,28] show that Cyprus is underlain by ~35 km of continental crust and that the ES is underlain by ~28 km of continental crust; seismic-refraction measurements support this interpretation[38,39], thus, the plate boundary is a continent-continent interface; **5)** continuous seismic reflection profiles across the Cypriot transform [40] reveal a complex pattern of braided horst and graben structures that is more characteristic of a transpressive positive-flower structure than a subduction complex; **6)** GPS results [26] show that Cyprus is moving in a westerly direction (Fig. 1) that is orthogonal to the motion of the African plate; this is viewed as inconsistent with subduction-zone models, but is very consistent with a model based on escape tectonics and strike-slip faulting [2,5,6].

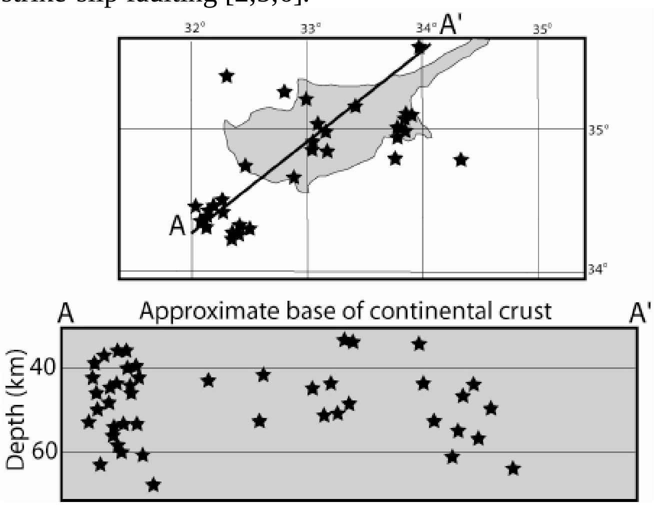

Figure 2. Locations of the best-constrained, recorded deep earthquake epicenters in the Cyprus area [after 30]. Cross section A-A' shows hypocenters projected to the line of section. Note that the top of the cross section is at about 30 km- the approximate base of the crust. Focal mechanisms calculated for larger earthquakes along the Cypriot transform indicate a mixture of faulting styles, but are dominantly of strike-slip faulting [3132,33,34]. Such mixtures of faulting styles are characteristic of strike-slip fault zones [35] and are atypical of subduction zones. If the vertical zone of seismicity offshore Cyprus is a steeply dipping Benioff zone, then the uplift of Cyprus is unexplained and there should be a close-lying volcanic arc (Mariana-type subduction zone).

3 Proposed Solution: A Model Emphasizing Strike-Slip Tectonics

All present-day geologic, geophysical, and seismological data and observations in the Eastern Mediterranean region can be attributed to strike-slip tectonics; active uplift and faulting on Cyprus are attributable to a restraining bend along the Cyprus transform [5,6,7]. One primary premise of this paper is that strike-slip tectonics has played an active role in the geologic history of the region since early in the Mesozoic. The second premise is that obduction of the Troodos ophiolite occurred from the north in concert with strike-slip tectonics.

3.1 Ancestry of Strike-slip Structures

In the vicinity of Cyprus, the northern African-plate margin consisted of parallel strike-slip fault zones in Mesozoic and Paleogene time (Fig. 3). Together with a complex system of associated R, R', and P shears, the Ovgos fault zone, Southern Troodos transform, and the Cypriot transform accommodated eastern movement of the Africa plate relative to Eurasian plate that began with the initial breakup of Gondwana [1]. This zone of strike-slip faulting is >75 km wide; left-lateral shear-coupling across the zone explains the counter-clockwise rotation of Cyprus [41,44,45] and the ES [21] during the Late Cretaceous to Eocene (see Fig. 3).

Across the Ovgos fault zone, differing geologic terranes of Mesozoic and Paleogene age are juxtaposed [6]. North of the Ovgos, accretionary prism and trench rocks, including metamorphosed sediments that contain blocks of pillow basalt and arc-like rhyolite, are overlain by strongly faulted and folded, deep-water turbidites (flysch). South of the Ovgos, platform sediments occur that are comprised of only slightly faulted and un-metamorphosed shallow-water chalk and carbonate rocks with no volcanic rocks [6]. The fact that there is a total mismatch of sedimentary and structural features across the Ovgos until Late Miocene deposition and deformation [5,6] suggests as much as a few hundred kms of transposition.

Beneath Cenozoic sedimentary cover, the entire southern portion of Cyprus is underlain by tectonic mélange and allothonous horizontally sheared rocks of Triassic to Cretaceous age [18,41,42]. Horizontal slip in this zone, the South Troodos transform, was left lateral [18,41,43]; strands of this zone are similarly active today [37]. Also, Late Cretaceous debris-flow deposits in SE Cyprus possess strong, non-penetrative, vertical, E-W-trending shear fabric. Shear was non-abrasive, as there is a total lack of slickenside surfaces, gouge, and other brittle deformation; it is interpreted as having occurred while the deposits were water saturated during deposition.

The Cypriot transform is considered the primary northern African plate boundary during the Mesozoic [1]; extensions to both east and west are known strike-slip crustal boundaries [14,16,22,40,46]. A good modern analogy for this structure in the Mesozoic is the San Andreas fault zone, which runs along the North American plate margin and is inboard to a sequence of allothonous continental crust and mélange, oceanic

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crust and spreading center (Pacific plate), and an opposite-facing subduction zone (western Pacific margin). A corollary of this is that the ES lay farther to the west, relative to Cyprus, in the Mesozoic (Fig. 3).

If Neogene motion along the Dead Sea transform is restored in an amount equal to the opening of the Red Sea, then the Eastern Anatolian fault zone at the Arabian-Anatolian plate boundary becomes aligned E-W with faults on and offshore Cyprus described above (see Fig. 1). This indicates a common ancestry, which is also implied by the similar in tectonic packages and history between Arabian-Anatolian boundary [47,48] and the African-Anatolian boundary presented here.

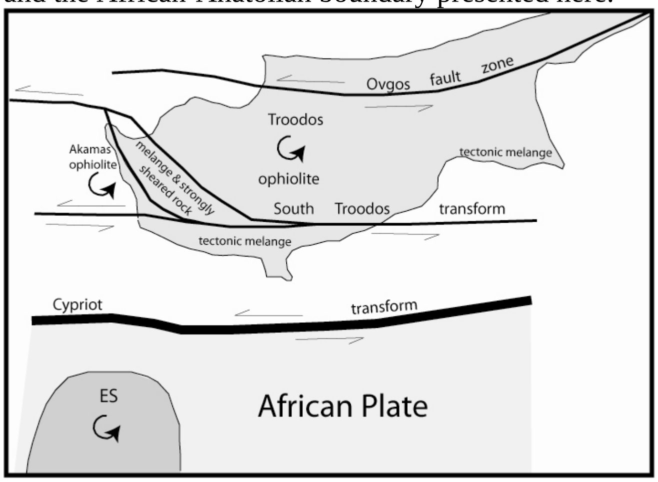

Figure 3. Schematic diagram showing major Mesozoic and Paleogene transform structures along the African plate boundary in vicinity of Cyprus and the Eratosthenes Seamount (ES); in part adapted after [21]. Counter-clockwise rotations after [21,41,43,44].

3.2 Troodos Obduction

Gravity data [18,27] indicate that mantle rocks and oceanic crust dip northward away from the exposed Troodos ophiolite; suggesting a southward-vergence for its obduction in the late Mesozoic (Fig. 4). It is proposed that obduction was facilitated by oblique low-angle slip in a transpressive strike-slip setting (Fig. 5); the same kinematics that produced CCW rotation. A corollary is that the Southern Neotethys becomes a simple uniform sea along the northern margin of the African-Arabia plate, defined by the continuous ophiolite belt from Cyprus eastward.

4 Conclusions:

1) All regional geologic, geophysical, and seismological data are explained through a model that invokes a leading role of strike-slip tectonics along the northern plate margin of Africa. 2) Crustal obduction, 90° CCW rotation of crust, left-lateral shearing, and localized Neogene uplift have occurred across a >75-km-wide tectonic system north of the African plate margin. 3) Neotethys spreading and the creation of oceanic crust (Troodos) occurred north of this strike-slip system. 4) The Troodos ophiolite was obducted from the north, driven by low-angle transpressive stress. 5) Trench, fore-deep, and accretionary prism rocks were over-thrusted from the north by transpressive stress in the Neogene. 6) The northern margins of African and Arabian plates shared a common tectonic evolution prior to Neogene separation along the Dead Sea transform.

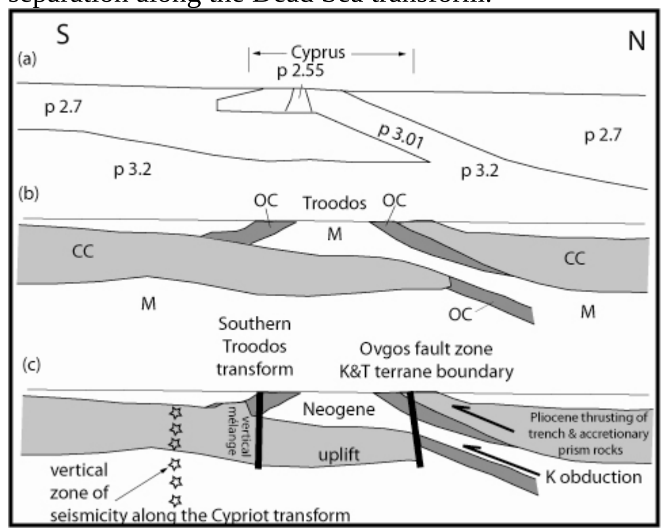

Figure 4. N-S crustal cross sections through Cyprus. (a) Model of gravity data showing rock densities [after 27]. (b) Interpretation of crustal material [after 27]; CC- continental crust, OC- oceanic crust, m- mantle material. (c) Location of seismicity along the Cypriot transform, Also depicted are Neogene uplift do to a restraining bend along the Cypriot transform [5.6] and the direction of Neogene thrusting of trench and accretionary prism rocks [6].

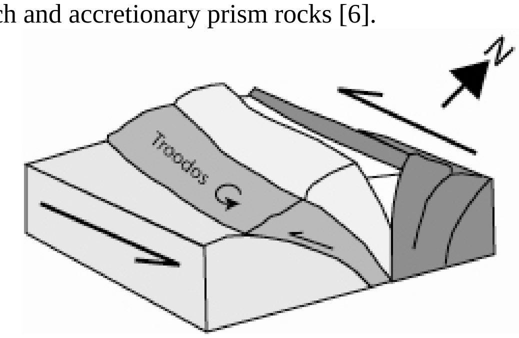

Figure 5. Schematic of Troodos obduction contemporaneous with left-lateral strike-slip faulting, modeled after deformation along the San Andreas transform [35].

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