GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.12, PAGES 2241-2244, JUNE 15, 1998

# Plate tectonic framework for the October 9, 1996, Cyprus earthquake

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**Abstract.**
We determine the centroid depths for the $M_W$=6.8, October 9, 1996, Cyprus earthquake and its largest aftershock to 32 and 27 km, respectively, by modeling P and SH waveforms. These depths are consistent with shallow subduction as the African plate, west of Cyprus, penetrates beneath the Anatolian plate. We calculate the pole of rotation between Anatolia and Africa and determine their relative motion. The result indicates that, along the Cyprean Arc, convergence between the African and Anatolian plate, in agreement with the observed seismicity, decreases from west to east. The northeasterly striking nodal plane is suggested as the plane on which the Cyprus earthquake ruptured since its strike agrees well with the derived plate motion vector. The faulting geometry suggests the emergence of a strike-slip tear fault within the African plate separating the continental Eratosthenes seamount south of Cyprus from the oceanic African lithosphere that subducts west of Cyprus.

## Introduction

The October 9, 1996, $M_W$=6.8, Cyprus earthquake was the largest earthquake to occur in the eastern Mediterranean since the 1981, $M_W$=6.7, Gulf of Corinth event. The earthquake was located in the Cyprean Arc off the west coast of Cyprus (Figure 1). The Harvard centroid-moment tensor (CMT) solution [*Dziewonski et al.*, 1997] shows a strike-slip mechanism, which is unusual for a subduction zone earthquake.

The Cyprean Arc is a tectonically complex region. It is divided into three distinct segments [*Ben-Avraham et al.*, 1988]. In the western segment normal subduction takes place. The relative plate motion is almost perpendicular to the arc and the oceanic lithosphere of the eastern Mediterranean is subducting beneath the arc [*Makris et al.*, 1988]. Currently, subduction northwest of Cyprus in the Antalya basin and below southern Turkey is apparent from the distribution of deep earthquakes [*Jackson and McKenzie*, 1984; *Ben-Avraham et al.*, 1988; *Ambraseys and Adams*, 1993] and from deformation of shallow sediments along the western arc segment [*Wong et al.*, 1971; *Anastasakis and Kelling*, 1991]. In the central segment, a collision between the Eratosthenes seamount [*Ben-Avraham et al.*, 1976] and the Cyprean Arc takes place. This region is characterized by intensive shallow deformation [*Leg 160 Scien-*

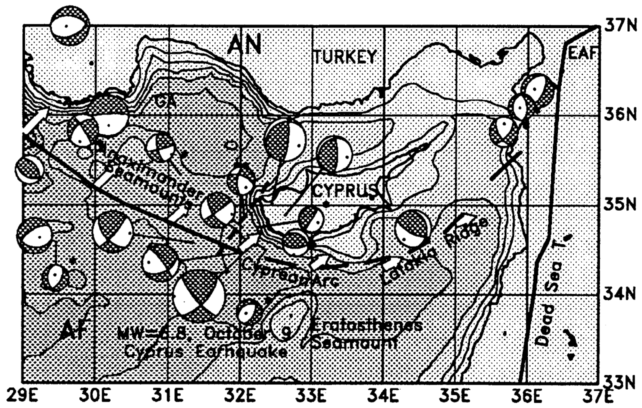


**Figure 1.** Map of Cyprus and eastern Mediterranean showing Harvard CMT solutions for earthquakes occurring in the period 1976–1996 and with depth less than 50 km. Arrows show the relative plate motion calculated from the An–Af pole (Table 1). Symbols: * — small surface wave CMT; ** — February 24, 1995, $M_W$=4.6, small surface wave CMT event; GA - Gulf of Antalya; AF - African plate; AN - Anatolian plate.



Paper number 98GL01547.
0094-8534/98/98GL-01547$05.00

*tific Party*, 1996]. In the eastern segment the arc forms a wide zone of wrench faulting [*Ben Avraham et al.*, 1995]. The most prominent element in the region is the Latakia Ridge, which extends from the bathymetric escarpment south of Cyprus northeastward to the Syrian coast near Latakia.

Traditionally, the Cyprean Arc was viewed as a segment of the plate boundary between Eurasia and Africa [*McKenzie*,1970]. However, in a more recent perspective, Cyprus may now be viewed as a part of the Anatolian block which is bordered by Arabia along the East-Anatolian fault in the southeast, Africa along the Cyprean and Hellenic arcs in the south and Eurasia along the North-Anatolian fault in the north. The convergence west of Cyprus is accommodated by oceanic-continental subduction, whereas south of Cyprus it has been described as a continental collision between Cyprus and the Eratosthenes seamount [*Ben-Avraham*, 1989]. The seamount is of continental origin and is embedded in the African plate [*Makris et al.*, 1983]. Careful relocations of earthquakes show no large deep earthquakes ($M_S$>4.3) beneath Cyprus [*Ambraseys and Adams*, 1993]. Thus, it is not clear if there is active subduction zone south of Cyprus.

The aim of this study is to determine how the 1996 Cyprus earthquake is related to the tectonics of the Cyprean Arc. We determine the focal depths of the October earthquakes, and examine the geometry of faulting in the regional context. We make use of recent geodetic estimates of block and plate motions in the eastern Mediterranean to estimate a pole of rotation between Anatolia and Africa. This provides a new tectonic framework in which to analyze the seismic activity along the Cyprean Arc.

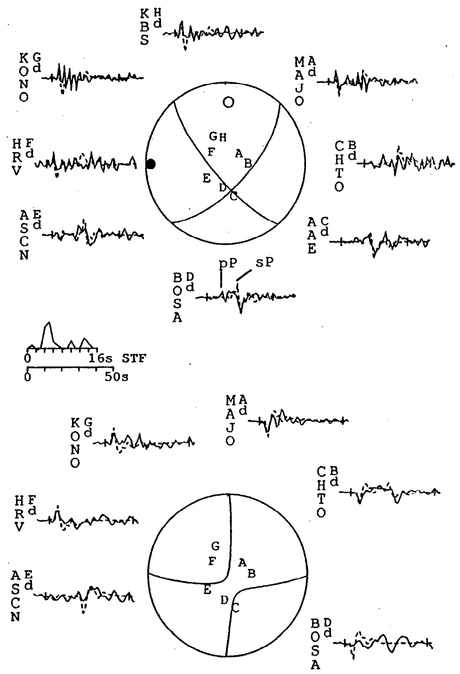


**Figure 2.** Inversion of *P* waves (top) and *SH* waves (bottom) for the centroid depth of the October 9, 1992, $M_W$=6.8, Cyprus earthquake. STF — source time function, 50 s — time scale for seismograms. Solid lines — observed seismograms; dotted lines — inverted synthetic seismograms. Letters A, B, etc., show location of station in the projection. d – down going P first motion. Also shown are *P*-wave radiation pattern of the *P*-wave radiation pattern (top) and *SH* wave radiation pattern for the Harvard CMT mechanism (lower hemisphere projections). Open and closed circles in the projection show locations of T and P axes. Velocity model modified from *Makris et al.* [1983] (water layer: thickness=2 km; layer 1: thickness=8 km, $V_P$=4.5 km s$^{-1}$, $V_S$=2.6 km s$^{-1}$, $\rho$=2400 kg m$^{-3}$; layer 2: $V_P$=6.5 km s$^{-1}$, $V_S$=3.7 km s$^{-1}$, $\rho$=2900 kg m$^{-3}$.

## Earthquake Source Parameters

We used the well known methodology of inverting *P* and *SH* waves [*Nabelek*, 1984; *McCaffrey et al.*, 1991] to derive source parameters for the October 9, 1996, Cyprus earthquake and its largest ($M_W$=5.8) aftershock on October 10. We inverted for the source time functions and centroid depths of the mainshock and aftershock. The focal mechanism was constrained to the best double couple as given by the Harvard CMT solution [*Dziewonski et al*, 1997]. The resulting centroid depths for the mainshock and aftershock lie at 32 and 27 km, respectively. The depths are well constrained as seen from the fit (Figure 2) of observed *pP*, *sP*, and *sS* surface reflections by the synthetic seismograms derived in the inversion. The reflected phases are clearly separated from the direct waves, allowing a stable derivation of depth.

A few additional focal mechanisms for earthquakes which occurred before the 1996 Cyprus earthquake were derived by the so called surface-wave CMT method [*Ekström, et al.*, 1995; *Arvidsson and Ekström*, 1997]. This method allows determination of centroid-moment tensors for earthquakes as small as $M_W$=4.5. These results are shown in Figure 1 together with the main shock and previous Harvard CMT solutions [*Dziewonski et al.*, 1997]. We note that one of these small earthquakes, February 24, 1995, $M_W$=4.6, occurred near the location of the 1996 Cyprus earthquake with a centroid depth at 42 km, which is in the same depth range as the 1996 Cyprus earthquakes.

We also applied joint-hypocenter determination (JHD) [*Dewey*, 1971] to all aftershocks with magnitudes greater than 4.5 which occurred in October using the phase data collected by the National Earthquake Information Center (NEIC). The JHD procedure is designed to reduce the effects of systematic and unmodeled errors in the travel time calculations used in event location algorithms, and provides good relative locations for earthquakes in clusters. The large geographical scatter of the aftershocks seen in the standard NEIC catalog is, however, not significantly reduced after JHD relocation (Figure 3). Therefore, while we believe there is some suggestion the aftershock locations that the NE striking

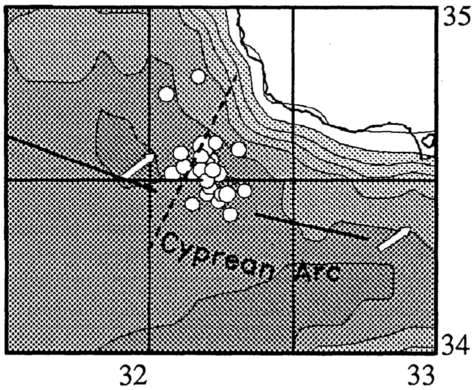


**Figure 3.** Map showing the epicenters of aftershocks determined using the JHD algorithm. Only events with magnitudes greater than 4.5 are shown.

plane is the fault plane, the observation is not conclusive.

## Pole of rotation between Anatolia and Africa

In order to clarify the expected tectonic motion expected in the hypocentral region, we computed the pole of rotation between Anatolia and Africa using the known poles for Africa–Eurasia from NUVEL-1A [*DeMets et al.*, 1994], and for Anatolia–Eurasia from recent geodetic results [*Reilinger et al.*, 1997] (Table 1). The computed plate motion direction at the boundary between Africa and Anatolia changes from north-northeast at 30°E to northeast at 32°E to nearly east at about 35°–36°E. The rate of motion decreases from about 23 mm $yr^{-1}$ to 14 mm $yr^{-1}$ (Figure 1) going from from 29°E to 34°E. This agrees with the observed decrease of seismicity from west to east.

Using the earlier estimate of *Le-Pichon et al.* [1994] for the Anatolia–Eurasia pole changes the Anatolia–Africa pole location to 32.6°N, 35.5°E, and the angular rate to $\omega$=0.026° $Myr^{-1}$. However, the rates and directions of plate motion along the boundary do not change substantially. By comparison, older determinations of the pole for Anatolia–Africa relative motion have given varied results with the pole situated northwest of Greece [*Le Pichon and Angelier*, 1979] and in southern Ethiopia [*Jackson and McKenzie*, 1984].

## Discussion and Conclusions

The centroid depths of the mainshock and the largest aftershock, at 32 and 27 km, are too large for ordinary crustal strike-slip earthquakes in tectonically active regions. They are, however, compatible with a shallow subduction zone environment like that of the Cyprean Arc. Although the differences in depth between the earthquakes discussed here are too small to be conclusive, we note that the shallowest earthquakes, the October 9 and October 10, 1996 earthquakes occured closer to the trench and that the deepest earthquake, the February 24, 1995 (Figure 1), event, occurred farther away from the trench, as expected for earthquakes in a subducting slab. The strike-slip mechanisms, on the other hand, are unusual in a trench environment. If we assume that the northeast striking plane is the fault plane, the slip vector for the 1996 Cyprus earthquake agree very well with the direction of relative plate motion between Africa and Anatolia. We propose that the earthquake occurred on a tear of the African plate caused by the slowing down or locking of the subduction of the African plate beneath Cyprus, east of the 1996 Cyprus earthquake [*Ben-Avraham*, 1988]. A slower subduction, eventually no subduction, south and east of the 1996 Cyprus earthquake would explain the lack of deep earthquakes [*Ambraseys and Adams*, 1993] beneath Cyprus. The plate motions we determined do not vanish south of Cyprus, as we would expect for a locked subduction zone, but they are much smaller there than to the west. The motion east of Cyprus is nearly parallel to the trend of the arc which would predict that for an undulating boundary, where any relative motion from convergence to divergence may be observed, any type of faulting can be found. Among the few events east of Cyprus (Figure 1), both thrust faulting and normal faulting is observed. However strike-slip faulting should dominate due to the overall differential motion between Africa and Anatolia. This agrees with observed strike-slip faulting [*Ben-Avraham et al.*, 1995].

If, on the other hand, the rupture occurred on the northwest striking nodal plane, the fault motion would be perpendicular to the direction of the computed plate motion. This would imply that the local stress either deviates significantly from the plate motion stresses, or the poles of motion are not accurate enough to describe the plate motions for this part of the Cyprean arc. The JHD aftershock locations (Figure 3) are, however, more in support of a tear fault as they are not traced parallel to the trench axis.

In conclusion, the plate motion that we calculated along the Cyprus trench explains the decrease of seismicity from west to the east. The convergence rate close to Cyprus is only half (An–Af; Table 1) of that

TABLE 1. Poles of rotation

| Pole | Latitude | Longitude | Angular vel. ° $Myr^{-1}$ | Reference |
|---|---|---|---|---|
| Af–Eu | 21.0°N | 20.6°W | 0.13 | *DeMets et al.* [1994] |
| An–Eu | 29.2°N | 32.9°E | 1.3 | *Reilinger et al.* [1997] |
| An–Af | 28.8°N | 37.7°E | 1.2 | This study |

near 29°E. Our preferred explanation for the October 1996 earthquake is that it occurred on a tear fault in the African plate related to the change in convergent style from subduction west of Cyprus to continental collision south of Cyprus. Our analysis indicates that relative plate motions and style of deformation along the Cyprean Arc are affected by crustal structure in the African plate, specifically the Eratosthenes seamount. In the complex environment of the eastern Mediterranean, plate motions result from a combination of the collision south of Cyprus and the anticlockwise rotation of Anatolia, and the sinking African plate further to the west beneath the Hellenic arc.

**Acknowledgments.** R. Arvidsson was partly supported by the Swedish Foundation for International Cooperation in Research and Higher Education by Swedish Natural Science Foundation (NFR) contract Dnr 720 22/95, and NFR contract G-AA/GU03164-318. Additional support was provided by NSF grant EAR-92-19361.

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(Received October 14, 1997; revised February 24, 1998; accepted March 23, 1998.)