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Some characteristic features of the Eastern Mediterranean Crust

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Abstract

The Eastern Mediterranean deformation is relevant to the deep tectonics but it is complicated. It is related to the collision between the passive margins of a major plate (Africa), locally acting as a continental indenter against the active margin of another plate (Europe). The Bouguer anomalies in the study area (Eastern Mediterranean region) are various between -40mGals at the southern margin of Turkey to 210 mGals (Herodotus Abyssal Plain).

The thickness of the crust varies approximately between 8 and 38 km. Thinner crustal thickness of about 8–14 km are found in the oceanic domains, namely, Herodotus Abyssal Plain.

The highest seismic strain rate release, S^{-1}, of order, 10^{-14}, is observed in Hellenic Arc. The lower strain rate release of, 10^{-25}, is observed in front of the Egyptian Coast (African Plate). The seismic strain release around Hellenic Arc, 10^{-14}, is relatively higher than the Cyprean Arc, 10^{-17}.

Key words: Eastern Mediterranean, Moho discontinuity, Seismic Strain, Density Model, Aegean Sea, Subduction.

INTRODUCTION

The Eastern Mediterranean Sea is an ideal location for study of crustal processes related to the collision of continental plates. The northern, passive margin of the African plate (Gondwana) rifted in the early Mesozoic, giving rise to an irregular pattern of embayment and promontories [1]. Africa and Eurasia converged in the late Mesozoic-early Tertiary, accommodated by subduction. By the Miocene, the seamount was located in the vicinity of the present convergent plate boundary, which extends across the Eastern Mediterranean Sea south of Crete, and then south of Cyprus to connect with the Tethys suture zone farther east. At the present time, the

Eastern Mediterranean Sea can be considered a remnant of the southerly Mesozoic Neotethys in its final stages of closure, associated with diachronous collision of the African and Eurasian plates. Alternative tectonic interpretations of the plate tectonic evolution of the easternmost Mediterranean Region as a whole are discussed in [2] and [3].

Oceanic crust was formed in the easternmost Mediterranean by the Late Triassic and is represented by "accreted" fragments in southwest Cyprus (Mamonia Complex), southwest Turkey (Antalya Complex), and northern Syria (Baer-Bassit). The easternmost Mediterranean represents the most southerly of several Mesozoic Netethyan oceanic basins, separated by continental slivers that were rifted from Gondwana, including the Tauride carbonate platforms of southern Turkey and the Pelagonian Zone in Greece. In the Cretaceous, the relative motion of the African and Eurasian plates became convergent [4].

The present study is aim to estimate the thickness variation of crustal structure and evaluate the major active tectonic processes in the Eastern Mediterranean. Also, it is aimed to evaluate the seismic strain between rigid blocks in the Eastern Mediterranean for better understanding of the complex geophysical structure and focuses on the deformation process in this important region.

Available Data

The bathymetric data of this study was revealed from the International Bathymetric Chart of the Mediterranean (IBCM) project for the compilation of a bathymetric chart [5]. The data is represented by a simplified bathymetric map (Fig. 2) which has on a 5x 5 km grid.

In this study, the digital data used from the Bouguer gravity sheet [6] and Bouguer anomaly map of the Eastern Mediterranean Sea [7]. Also, used the marine gravity data were digitized mainly from the profiles of the Cambridge Research Group [8] and from the OGS (Osservatorio Geofisico Sperimental, Trieste, Italy) profiles [9]. The digitize data have an accuracy that permits interpretation to 5 mGal isolines. The interpolated data from the map are used for geological interpretation.

The available data, on the Mantle material or on the deeper Crust in the Eastern Mediterranean, obtained from deep seismic reflection and refraction. The deep seismic reflection and refraction were carried out in 1971 by the Department of Geodesy and Geophysics University of Cambridge and [10] along the North Nile Cone, Southern Create and Southern Cyprus. Also, using 2-D density model [11] and [12] along the two seismic profiles, which has been further extended to 120 km offshore of northern Cyprus. According to these data, the Eastern Mediterranean Moho velocity could reach to 8.4 km/sec especially in North Nile Cone. The deep seismic indicates that the velocity of granitic layer in between 5.0 to 6.7 km/s.

The earthquake data have been compiled from the [13] for the period between 1903 and 2003. The collected earthquake data in the Eastern Mediterranean is about 214 seismic events with surface magnitude, *Ms*, in between 4 to 8.

METHODOLOGY

Estimation of Crustal Thickness

The empirical relation of estimated crustal thickness (in this study) was obtained from the correlation between the Bouguer anomaly and the depth to Moho discontinuity along the two seismic profiles in the Eastern Mediterranean. It was carried out by using regression analysis [14] and assuming a linear model of the subsurface medium. The wavelengths (λ) of the gravity anomalies, are equal to 5 and 10 (i.e. digitized each 5 & 10 km grid spacing, respectively). The corresponding values of crustal thickness is used for the two deep seismic refraction profiles; the first crosses from Cyprus to North Africa and the second located in the Southern Crete. These data along the two profiles were used for calculating the regression equation, standard deviation (SD) and correlation coefficients (r), by using Statgraph Program. The plot of the Bouguer anomalies versus the crustal thickness is shown in Figure (1). The estimated empirical relations between the Bouguer anomalies (Δg_B) and crustal thickness were found to be:

$$Hc = 27.5 - 0.083\ \Delta g_B \qquad (2)$$

For λ= 10 km, where: SD= 1.91, r= - 0.73, and

$$Hc = 28.2 - 0.081\ \Delta g_B \qquad (3)$$

For λ = 5 km, where: SD= 5.65, and r = - 0.62

The values of "SD" and "r" show that equation (2) is more reliable for detailed mapping of the relief to Mohorovicic boundary in the study area.

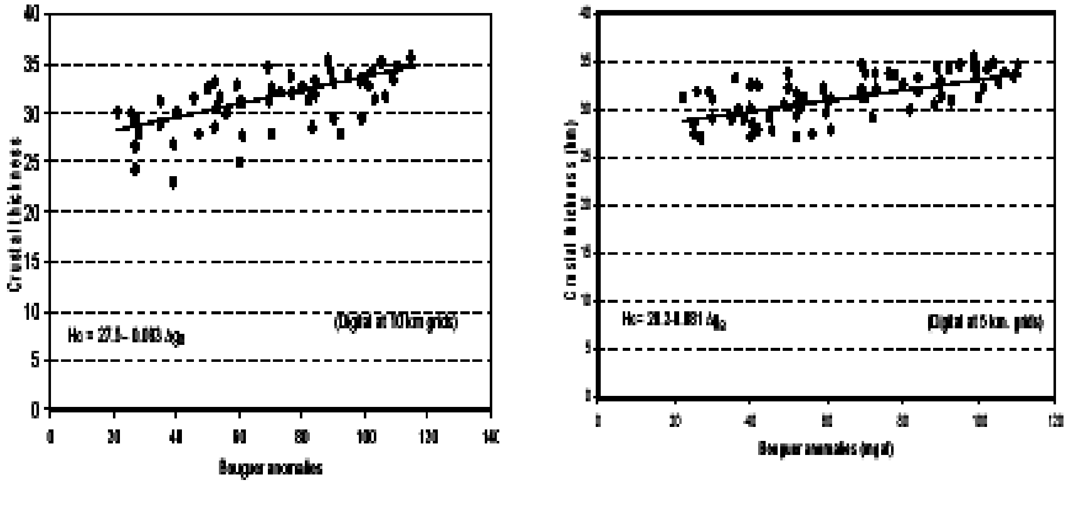

Figure 1: Relation between crustal thickness (Hc) and Bouguer anomalies (Δg_B) for the Eastern Mediterranean.

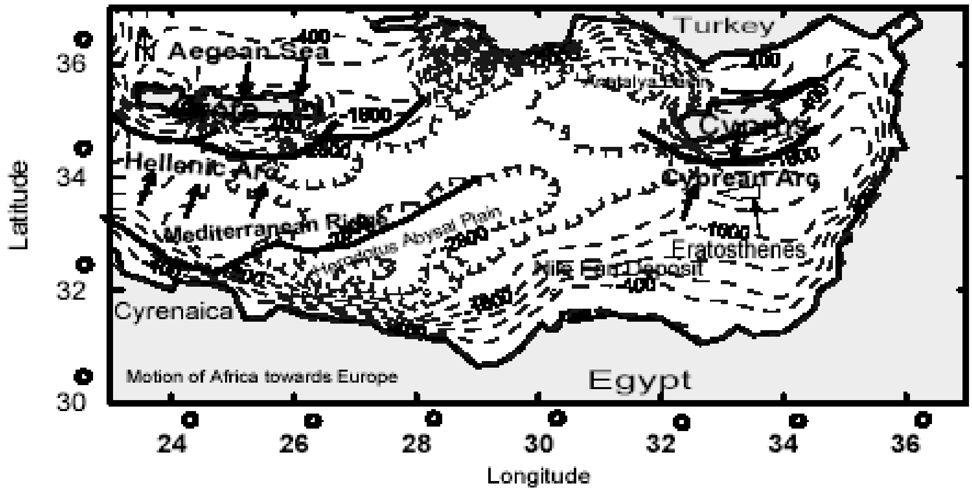

Figure 2: Simplified bathymetric map with major tectonic structure of the Eastern Mediterranean (contour interval is 400 m).

Two dimensional Modeling.

Gravity anomalies over the Eastern Mediterranean were modeled to determine the thickness of the low-density sedimentary section overlying the basement complex, and to understand the main structure variations of the upper crust [15]. The basic theory of the two dimensional modeling was first described by [16]. The following assumptions were taken into consideration:

i. The models are constrained by available geological data and seismic information.
ii. Formation densities are based on the available density types of the study area and taking the sea water density as 1.03 g/cm^3. Moreover, the value of basement density is considered to be 2.85 g/cm^3 as being estimated from the seismic velocity layer of seismic information. The density 2.9 g/cm^3 value for the lower crust is given by [17].
iii. The modeling technique is facilitated by using program developed and modified by [18].

Seismic Strain

The seismic strain rate has been calculated using the methodology described by [19] which give a measure of the brittle deformation according to:

$$Є = (1/ 2\mu v\, \Delta t) \sum_{n=1}^{N} M_0^n \quad (4)$$

Where, Є is the strain rate, v is the deforming volume, μ is the shear modulus, and

M_0 is the seismic moment of the nth earthquake from the N total earthquakes occurring during the time interval Δt. The seismic moment has been calculated according to [20] using the surface magnitude, Ms:

$$\text{Log } M_0 = \begin{cases} 19.24 + Ms & Ms < 5.3 \quad (5) \\ 30.2 - (92.45 - 11.4\, Ms)^{1/2} & 5.3 \leqslant Ms \leqslant 6.8 \quad (6) \\ 16.14 + 3/2\, Ms & Ms > 6.8 \quad (7) \end{cases}$$

RESULTS

Seafloor deformation

The seafloor deformation is relevant to the deep tectonic but is complicated by the occurrence of surficial deformation and gravitational gliding due to the presence of salt layer underneath. Rather than an active subduction zone, the compressive tectonic setting appears to have developed into a wrenching system along the Hellenic and Cyprus Arcs. The seafloor mapping reveals a large network of conjugated faults, mainly thrusts and strike-slip faulting, (Fig. 2). This figure shows that the seafloor level variation of the Eastern Mediterranean is related to tectonic deformation along the Mediterranean Ridge, Hellenic and Cyprean Arcs, and surrounding margins, including the Nile Fan Deposit. The Eastern Mediterranean Sea represents a unique opportunity for studying the beginning of such a collision between the passive margins of a major plate (Africa), locally acting as a continental indenter against the active margin of another plate (Europe). The maximum depth observed is about 3200 m in the Herodotus Abyssal Basin. The western side of Egypt to Cyrenaica is very steep slop may be related to the effect of the Mediterranean Ridge, but the steep slops in the southern of Cyprus and Crete may be related to the effect of Cyprean and Hellenic Arcs. Whereas; the gentle slop is located in front of Delta (Nile Fan Deposit) of Egypt.

The Mediterranean Ridge is itself a large accretionary prism between Africa and southern Europe. There are at least three recognizable main domains: the African continental slope to the south, the Southern Crete margin and bordering trench system to the north, and the Mediterranean Ridge in the middle. The data so far demonstrate clear differences in seafloor morphology and elevation and a strong contrast in structures.

Interpretation of Bouguer Map

Inspection of the Bouguer gravity map (Fig. 3), shows that Eastern Mediterranean has gravity anomaly varies between -40 (southern margin of Anatolian) to 210 mGals (Herodotus Abyssal Plain).

The slightly high gravity anomalies lies in Aegean Sea, Crete Sea and the North West Cyprus are nearly in between 140 to 180 mGals. This may indicate that the crust in these parts is probably thinner than others parts in the Eastern Mediterranean. Also, these parts are seemed to be highly active tectonics. Along the border of the continent (Africa, Asia, and European) the Bouguer anomaly changes to be of negative values. This indicates that there is a sort of deep structure along this area or/and highly crustal thickness. The clusters which have abrupt variations in the gravity anomalies may be related to changing in sediment thickness (i.e. in between Cyprus and Crete) in addition to the changing of the crustal thickness or/and may be related to abrupt changing from continental to oceanic type (i.e. Aegean Sea).

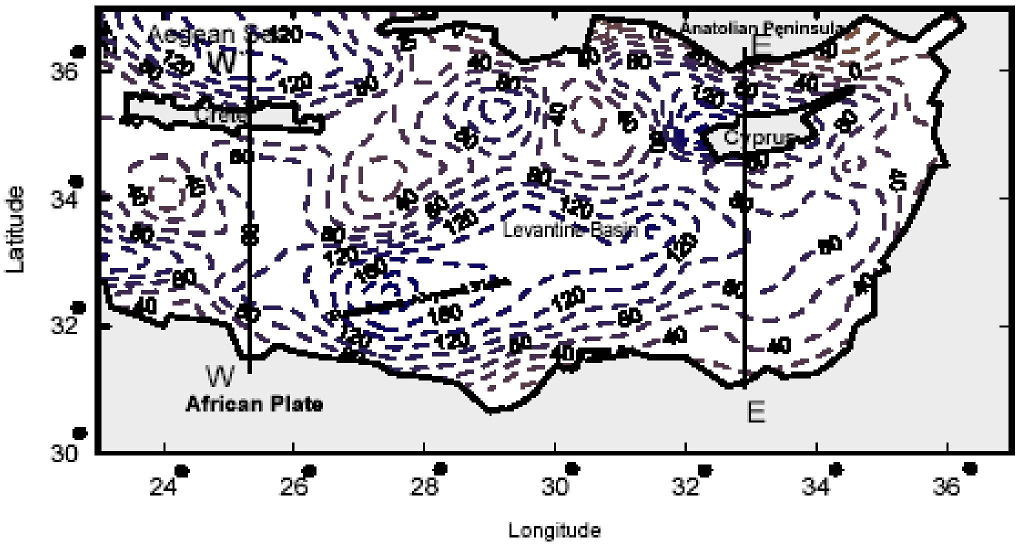

Figure 3: Bouguer gravity anomaly map of the Eastern Mediterranean Sea. Contour interval is 20 mgal.

Density Models

Figure (4) represents a composite 2 D crustal density models (EE` and WW`) along the eastern and western sides respectively, of the Eastern Mediterranean, across the trough of the Cyprean and Hellenic Arcs, respectively. This region consists of deep basins underlain with oceanic crust in the Eastern Mediterranean Sea. The 2 D density model cross sections eastern (EE`) and western (WW`) sides (Fig. 4) are affected by a set of major normal and reverse faults separated by alternative horsts and grabens. The 2 D crustal density models (EE` and WW`) show a difference of the sub-bottom structures between the eastern and western sides of the Eastern Mediterranean Region. The 2 D crustal density model cross the Hellenic Arc is more complicated structure than the Cyprean Arc. It may be related to the activity of compression force which is slightly higher in the Hellenic Arc.

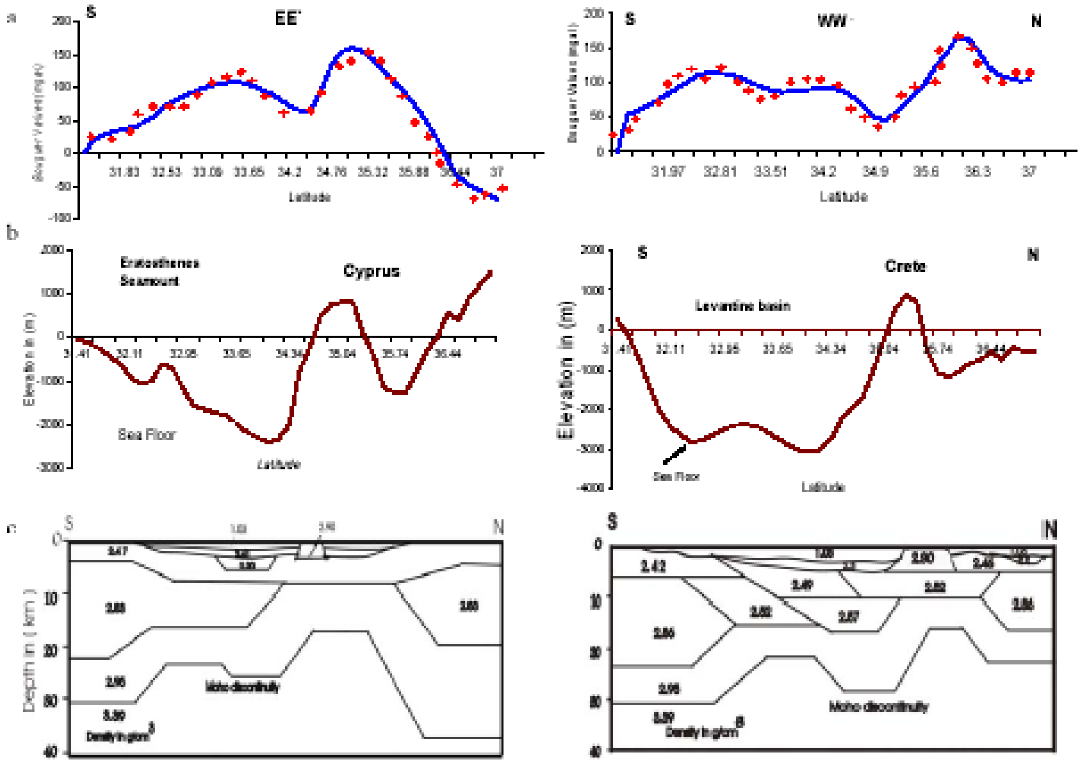

Figure 4: The 2 Longitudinal profiles, eastern (EE`) and western (WW`) sides, along the Cyprean and Hellenic Arcs respectively; (a) Bouguer anomaly curve, where + points = observed Bouguer values and curvature line is Δg``= computed and interpolated Bouguer values, (b) Topography (c) 2 D- crustal density model.

Figure (4) shows the upper unit corresponds to the sea water where its density is assumed to be 1.03 g/cm^3. The thickness of this unit varies from 0.1 to 2.8 km. The second unit corresponds to the sedimentary section where its density is assumed to be around 2.46 gm/cm^3. Sediment thicknesses are 0-8 km (along the continental slop/margin transition, 5.5-8 km sediments). The densities of granitic and basaltic layers are assumed to be 2.68 and 2.98 gm/cm^3, respectively. The crustal structure in the Eastern Mediterranean according to the obtained models consists of upper crust (granite) and lower crust (basalt). The highly positive Bouguer anomaly over Crete and Cyprus may be related to the obducted ophiolite which has average density 2.9 gm/cm^3, where the thickness of sediments varies from 5 to 15 km. The upper continental crust has density varies from 2.81 to 2.86 gm/cm^3, with varies thickness from about 15 km in the north (southern margin of Turkey) and south (northern Margin of Africa) to be about 4 km at Levantine Basin. The upper mantle has a density of 3.39 gm/cm^3. The Moho discontinuity has a maximum depth (about depth 38) at southern margin of Turkey (eastern profile EE`), while the maximum depth of Moho discontinuity along the western profile (WW`) is at the northern margin of

Africa. The average density of the oceanic crust is about 2.9 gm/cm^3 and the thickness is "between" 5-7 km. The crustal thickness under the Eratosthenes seamount (EE`) is about 25 km thick where is about 30 km at the northern margin of Egypt.

Crustal Thickness

Figure (5) shows the crustal thickness map of the Eastern Mediterranean. The crustal thickness varies approximately between 8 and 35 km. The thinner crustal thickness (about 8–12 km) is located in the oceanic domains, namely, Herodotus Abyssal Plain. The crust is thicker under the southern margin of Anatolian Peninsula and varies from 30 to 35 km (Figs. 5 and 6).

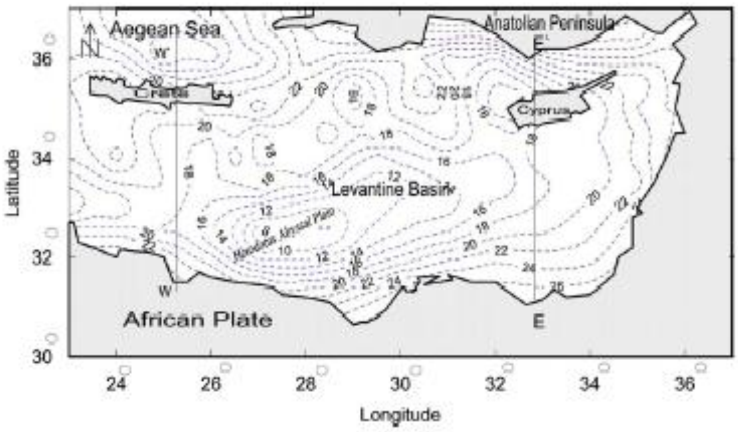

Figure 5: The crustal thickness of the Eastern Mediterranean Sea. Contour interval is 2 km.

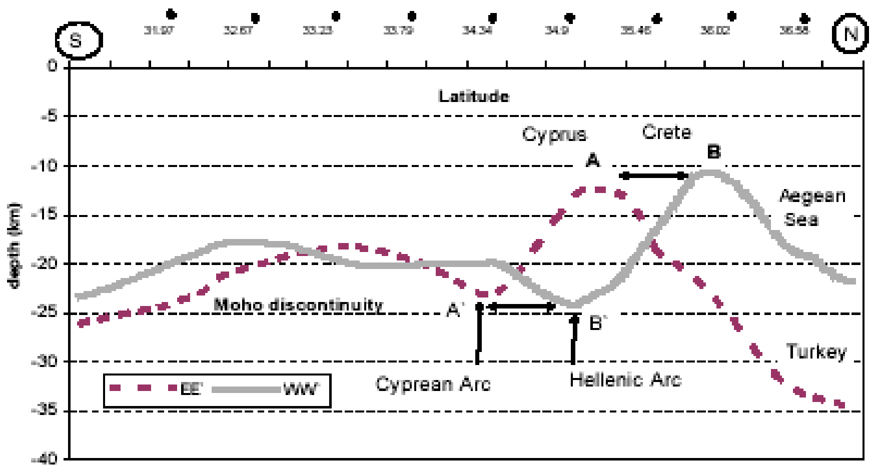

Figure 6: Correlation between the Moho discontinuities of the longitudinal profiles (NS direction) for the eastern and western sides of the Eastern Mediterranean Sea.

The Aegean Sea is characterized by a relatively thick crust (20-24 km) in spit of a long standing subduction, probably active at least since Cretaceous times (Fig. 6). The Aegean Sea is generally considered as a backarc basin due to the aforementioned subduction. The crust beneath the Sea of Crete and the Aegean Sea is continental and typically about 20-24 km thick.

Figure (6) shows the depth variation between Moho discontinuity (crustal thickness deformation) along the eastern (EE`) and western (WW`) sides, underneath the Eastern Mediterranean basin. It is noticed that the most deformed area (abrupt variation of the crustal thickness) lies nearly in between Latitude 34^o to 36.5^o N, where the trend of the main deformation affects and extend to the north. The highly deformed area (thinner crust) is located underneath the Cyprean and Hellenic Arcs, which characterized by tectonic activity. The variation in crustal thickness is not only observed along these profiles but also across them.

The asymmetry of crustal thickness along the two profiles of the eastern and western sides (EE` and WW`) of the Eastern Mediterranean could be attributed to the variation of the crustal movement (variation of compression forces) at each side (Cyprean and Hellenic Arcs). One of the fundamental problems is that the subduction occurs in NE-SW direction while, usually, it is suppose that the convergence between the African and Euro-Asiatic plates occurs along an approximately N-S direction [21].

In other words, we should rather analyze the Eastern Mediterranean plate tectonics in terms of both absolute motions, and relative motions of eastern and western parts (Hellenic and Cyprean Arcs) relative to Africa (Fig. 6). According to the model of [22] the major evidence on which these objection are based on the fact that the Aegean Arc is moving faster (roughly 30 mm/y) than the Anatolian block (roughly 24 mm/y). So, the movement variation between them is about 6 mm/y. If we suppose that the Hellenic and Cyprean Arcs move towards the same direction, the displacement distance between two deepest point (A` and B`) or shallow points (A and B) may equivalent to about 0.56^o (about 61.6 km). This displacement distance is assumed to be achieved in time period about 10 million years. So, the displacement distance may be related the different convergent rates at the two subduction zones (Hellenic and Cyprean Arcs). It is may related to differential velocities between hanging wall plates, since Greece is overriding Africa along the Hellenic Arc faster motion than Turkey along the Cyprus Arc. It is responsible for the extension in between two deepest point (A` and B`) or shallow points (A and B), (Fig. 6).

Seismic Strain

Figure (7) represents the resulting seismic strain rate in the Eastern Mediterranean Region, in units of S^{-1}, for a total 214 seismic events with *Ms* in between 4 to 8. It also represents the epicenters of the earthquakes included in these calculations. Africa, Greece, Anatolia, Eurasia and Arabia are the plates involved in the variation of the seismic strain of the eastern Mediterranean. Deformation is very active in the all area. In particular, it has been argued that this kind of strain rate mechanism cannot easily provide plausible explanations for a number of basic features.

The largest seismic strain rate release, S^{-1}, is of order (10^{-14}) observed in Hellenic Arc. The lower strain rate release of 10^{-25} is observed in the front of the Egyptian Cost (African Plate). The seismic stain release around Hellenic Arc (10^{-14}) is relatively higher than the Cyprean Arc (10^{-17}). The seismic strain release is abruptly increased starting from the Mediterranean Ridge towards the Aegean Sea where the maximum values located along the Hellenic Arc. Also, there are some clusters in the southern and northern Crete, which have high seismic strain release. It may be related to variation or relative motion between rigid blocks in this area. These variations of strain release may have relation to the forces which involved in deformation. On the other side, the abruptly increase is started directly in southern margin of Cyprus (Cyprean Arc).

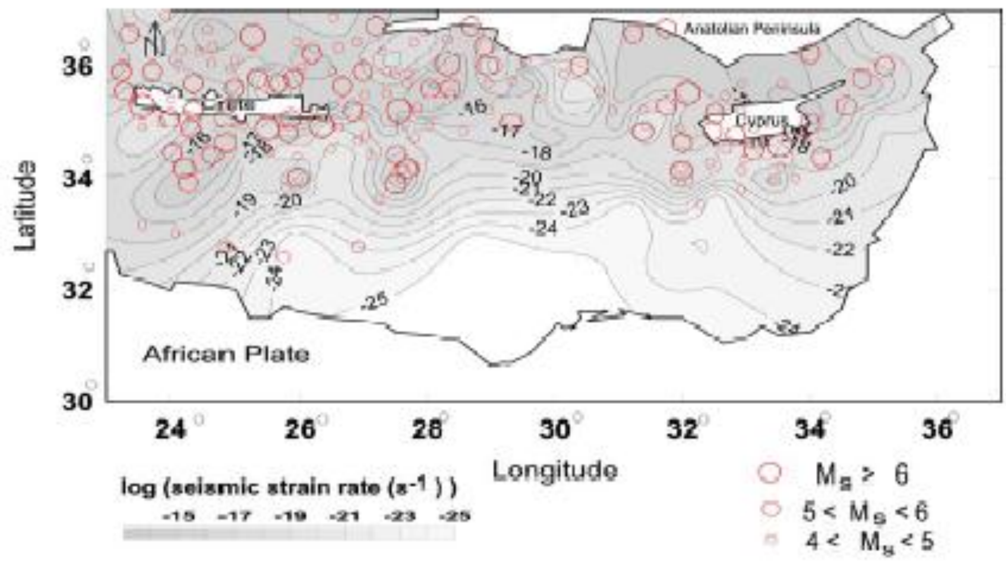

Figure 7: The Seismicity with Ms (NEIC catalog, 1903-2003) and calculated seismic strain rate in the Eastern Mediterranean Region.

DISCUSSIONS AND CONCLUSIONS

Earthquakes in the Eastern Mediterranean Region are not confined to a single fault, implying that the deformation in the region cannot be described simply by the relative motion between rigid blocks. However, in most continental areas the scale on which the active deformation and its consequent topographic features, such as mountain belts, plateaus, and basins, are distributed, makes it more practical to describe the overall characteristics of that deformation by a velocity field, rather than by the relative motions of rigid blocks. An important problem is then to obtain this velocity field and to understand its relation to the motions of the rigid plates that bound the deforming region and its relation to the forces involved in the deformation.

The Eastern Mediterranean has gravity anomaly varies between - 40 (Anatolian) to 210 mGals (Herodotus Abyssal Plain). The Aegean Sea and the North West Cyprus have gravity anomalies that range around 180 mGals. The clusters which have abrupt variation in the gravity anomalies may be related to changes in the sediment thickness (e.g. in the area between Cyprus and Crete), in addition to the changes in the crustal thickness and/or to abrupt variation from continental to oceanic types (e.g. the Aegean Sea).

The asymmetry of crustal thickness in between the eastern and western sides of the Eastern Mediterranean could be attributed to the variation of the crustal movement at each side (Cyprean and Hellenic Arcs). The most deformed area lies nearly in between 34^o to 36.5^o, around the Cyprean and Hellenic Arcs, where the main trend of deformation affects and extends to the north. The tectonic motions at the Eastern Mediterranean are terms of both absolute motions, and relative motions of eastern and western parts (Hellenic and Cyprean Arcs) relative to Africa. In fact, assuming Africa as a single plate, Greece is overriding Africa along the Hellenic trench faster than Turkey along the Cyprus Arc. The Greece along the Hellenic Arc is moving above Africa faster than Turkey towards the Cyprus Arc.

The highest seismic strain rate release, S^{-1}, is of order (10^{-14}) observed in Hellenic Arc. On contrast, the lower strain rate release of (10^{-25}) is observed in front of the Egyptian Cost (African Plate). The seismic strain release around Hellenic Arc (10^{-14}) is relatively higher than the Cyprean Arc (10^{-17}). The seismic strain release is abruptly increased starting from the Mediterranean Ridge towards the Aegean Sea where the maximum values located along the Hellenic Arc. Also, there are some clusters in the southern and northern Crete, which have relative high seismic strain release. It may be related to variations or relative motions between rigid blocks in this area. These variations of strain release may have relation to the forces which involved in deformation. On eastern side of the Eastern Mediterranean, the abruptly increase of seismic strain begins directly from the southern margin of Cyprus (Cyprean Arc).

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