Numerical modeling of present-day stress field and deformation pattern in Anatolia

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Abstract

The present-day stress field in the Earth's crust is important and provides insights into mechanisms that drive plate motions. In this study, an elastic plane stress finite element modeling incorporating realistic rock parameters have been used to calculate the stress field, displacement field and deformation of the plate interactions in Anatolia. Modeled stress data for the African-Arabian-Anatolian plate interactions with fixed Eurasian platform correlate well with observed stress indicator from the world stress map (WSM) and focal mechanism of earthquakes; while displacement field agree qualitatively well with GPS vectors and sense of motion indicated by focal mechanisms for large crustal earthquakes (M>6) and plate motion models. Modeling result shows the direction of maximum horizontal compressive stress (σ_{Hmax}) toward the direction of absolute motion of these plates. Large perturbations in σ_{Hmax} orientations are shown to occur in and around tectonic boundaries between those plates. It is observed that, although the African plate acts mostly as indenter, which transmits the collisional motion from the Arabian plate to the Anatolian plate, in the current situation the far-field stress probably from the Hellenic subduction is needed to satisfy the present-day stress field in Anatolia.

1. Introduction

The Anatolia, which lies in the eastern Mediterranean region, is one of the most active and intensely deforming parts of Alpine-Himalayan orogenic belt, is best noted for its active tectonics (Fig.1) (McKenzie, 1970, 1972; Dewey et al., 1973; Sengor and Yilmaz, 1981; Jackson and McKenzie, 1984; Sengor et al., 1985; Dewey et al., 1986; Barka and Kadinsky-Cade, 1988; Yilmaz, 1993; Jackson, 1994; Westaway, 1994; Jackson et al., 1995; Kiratzi and Papazachos, 1995; Ambraseys and Jackson, 1998; Vidal et al., 2000; Hinsbergen et al., 2009). Geotectonic setting of the region is complicated due to kinematics of northward convergence of African and Arabian plates into the Eurasian plate. The most prominent geotectonic feature is the westward movement of the Anatolia away from the Arabia-Eurasia collisional zone. These movements have caused crustal shortening, uplift, extension and extrusion related deformation with generation of several fold and thrust belts, suture zones, strike-slip and normal faults and associated basins formation. Therefore, the region can be regarded as one of the modern natural laboratories for studying active tectonics as well as for the short-scale variation of stress field (e.g. McKenzie, 1972; Zoback, 1992; Heidbach et al., 2008). Anatolia may be regarded as a buoyant continental sliver being squeezed and driven away from the zone of maximum convergence as a consequence of collision between Arabian and Eurasian plates, which is being taken up by Aegean subduction at the Hellenic Arc (Tatar et al. 1996; Gursoy et al. 1997; Jaffey et al. 2004). The continued convergence of Arabia relative to Eurasia resulted in the development of the North Anatolian Fault Zone (NAFZ) and subsequently the East Anatolian Fault Zone (EAFZ). Later the Dead Sea Fault Zone (DSFZ) also developed and joined the EAFZ to form the Anatolian-Arabian-African triple junction. The development of these fault

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systems contributed the tectonic escape of the Anatolian crustal block toward the Aegean arc system (McKenzie, 1972; Dewey et al., 1986; Sengor, 1979; Barka and Kadinsky-Cade, 1988; Taymaz et al., 1991; Westaway, 1994; McClusky et al. 2000; Sengor et al., 2005; Reilinger et al. 2006; Hubert-Ferrari et al., 2002; Hubert-Ferrari et al., 2009).

Modeling crustal stress field is the key to understanding physical processes acting within the Earth's crust. Maximum horizontal compressive stress (σ_{Hmax}) can be sparse and sporadic over large extents of the continent and also over a geological time-span; modeling of present-day stress field becomes imperative in analyzing a regional stress field. In spite of the motion of the African, Arabian and Anatolian plates being well established from geological, seismological and geodetic observations (DeMets et al., 1990, 1994; Chu and Gordon, 1998; McClusky et al., 2000; Nyst and Thatcher, 2004; Reilinger et al., 2006), their contribution to the origin of stress field in Anatolia is still under discussion (Rebai et al., 1992; Meijer and Wortel, 1996, 1997; Cianetti et al., 2001; Fischer, 2006). Processes that have been proposed in order to form the driving mechanism and deformation of the observed kinematics for the westward motion of the Anatolia can be summarized into: (1) 'push forces' due to northward convergence of Arabian plate over Eurasia (Taymaz et al., 1991; Le Pichon et al., 1995; Cianetti et al., 2001; Nyst and Thatcher, 2004), (2) mantle flow and gravitational collapse in Anatolia (Lundgren et al., 1998; Fischer, 2006), or by (3) pull forces induced by slab-roll-back of Aegean subduction in the Hellenic arc (Le Pichon and Angelier, 1979; Jackson, 1994; Meijer and Wortel, 1996; Wortel and Spakman, 2000; Doutsos and Kokkalas, 2001). In this context, it seems reasonable to reconstruct the tectonic stress field of eastern Mediterranean region by means of FE models using various tectonic boundary conditions and highlight the possible reasons for the origin of present-day stress field in Anatolia. Here, I will calculate the horizontal pattern of stress and displacement field that are associated with various force distributions for the active deformation of the region. The modeling results will be tested and verified with geological, seismological and geodetic data particularly from WSM, focal mechanism solution of earthquakes, and GPS observations.

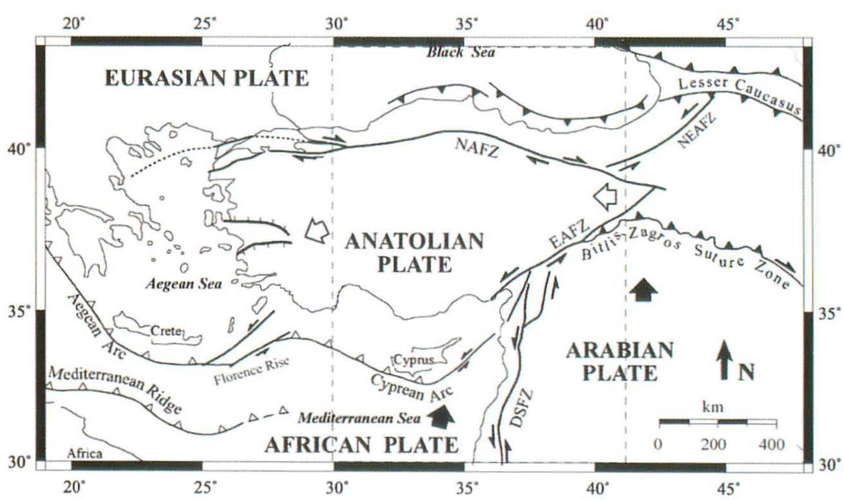

Fig.1. The main tectonic features of the eastern Mediterranean region. Anatolia-Aegean block escapes westward from Arabia-Eurasia collision zone, toward Hellenic subduction zone. Dotted box outlines the study area. NAFZ-North Anatolian Fault Zone, EAFZ-East Anatolian Fault Zone, NEAFZ-Northeast Anatolian Fault Zone, DSFZ-Dead Sea Fault Zone. Arrows show relative plate motions (not to scale; after McCluskey et al., 2000)

2. Tectonic framework

The active tectonics of the eastern Mediterranean is evidenced by the large number of damaging earthquakes (M > 6.0) due to apparent collision between African, Arabian and Eurasian plates (Fig.2). The northward movement of Africa and Arabia at different rates and their collisional shortening with

Eurasia has caused crustal thickening, uplift extension and lateral extrusion in Anatolia (McKenzie, 1972, 1976; Dewey et al., 1986; Yilmaz, 1993; Ambraseys and Jackson, 1998; McClusky et al., 2000). The timing of escape tectonics in Anatolia is consistent with the commencement of sea floor spreading in the southern Red Sea and in the Gulf of Aden (Hempton, 1987). McKenzie (1972) explained the westward movement of Anatolia as a response of the continental lithosphere moving laterally away (tectonic escape) from zones of compression, to minimize topographic relief and to avoid subduction of buoyant continental material. Major faults bounding the Anatolian block are: the left lateral Dead Sea Fault Zone (DSFZ) and the East Anatolian Fault Zone (EAFZ), and the right-lateral North Anatolian Fault Zone (NAFZ). These faults are, in fact, assumed to be formed by the consequences of compression of African and Arabian plate over Eurasia and it is believed that these faults have accommodated most of the plate motion to allow westward expulsion of the Anatolia (Barka and Kadinsky-Cade, 1988; Barka, 1992; Westaway, 1994; Bozkurt, 2001; Doutsos and Kokkalas, 2001). Geological, geophysical, neotectonic, seismic, and recent geodetic observations have shown that these faults are active for less than 5 Myr and are contributing for the westward expulsion of the Anatolia (McKenzie, 1972; Scordilis et al., 1985; Westaway, 1994; Armijo et al., 1999; Papazachos, 1999; McClusky et al., 2000; Vidal et al., 2000; Hubert-Ferrari et al., 2002; Sengor et al., 2005; Hubert-Ferrari et al., 2009). Geodetic observations have also shown that Arabian plate is moving faster than the African plate because of the movement along these NAFZ and EAFZ (DeMets et al., 1990, 1994; Reilinger et al., 1997; McClusky et al., 2000; Reilinger et al., 2006)

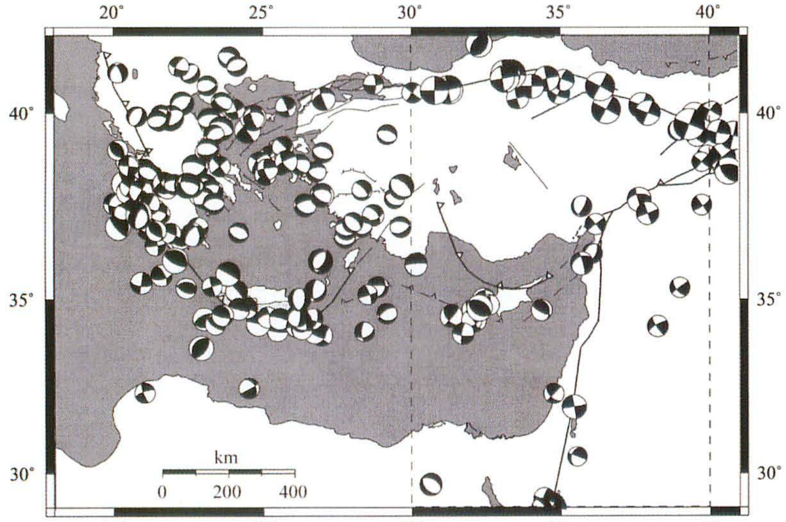

Fig.2. Focal mechanism solutions for some selected major earthquakes in the eastern Mediterranean region (after McKenzie, 1972; McCluskey et al., 2000)

On the basis of seismicity and active structures, Anatolia can be divided into three parts, eastern, central and western. Interior of Anatolia is topographically flat and aseismic (Fig.2) (McKenzie, 1972; Jackson, 1994) and its southern plate margin cannot be determined (Vidal et al., 2000). Throughout the area, faults show dominantly north-south extension with fault planes running approximately east to west (Fig.3) (Jackson, 1994; McClusky et al., 2000). Distribution of seismicity shows the number of events increase significantly from western Anatolia to Aegean and finally into Hellenic arc, a subduction zone where African plate converges with Aegean. Aegean, on the other hand, shows a large number of normal faults due to back arc expansion of the crust. Hellenic subduction zone terminates at the Florence Rise, a submarine ridge that marks the beginning of the Cyprean arc. The area between Hellenic arc and Cyprean arc shows transpressional deformation associated with strike-slip faulting, while transtensional deformation is dominant to the east of Cyprean arc (Kempler and Garfunkel, 1994; Wortel and Spakman, 2000; Zitter et al., 2000). The historical and instrumental earthquake records show that eastern Anatolia is seismically less active (Ambraseys and Jackson, 1998). Central Anatolia on the other hand is dominated by strike-slip tectonic regime. In contrast, western Anatolia is dominated by a series of NE-SW and NW-SE trending cross-graben and horst structures bounded by active, oblique-slip normal faults with strike-slip sense (Fig.3). This region forms a transitional zone between the Anatolia and Aegean. The existence of two sets of normal faults indicates that western Anatolia is extending biaxially, with both NE-SW and NW-SE components of extension (Westaway, 1994; Bozkurt, 2001).

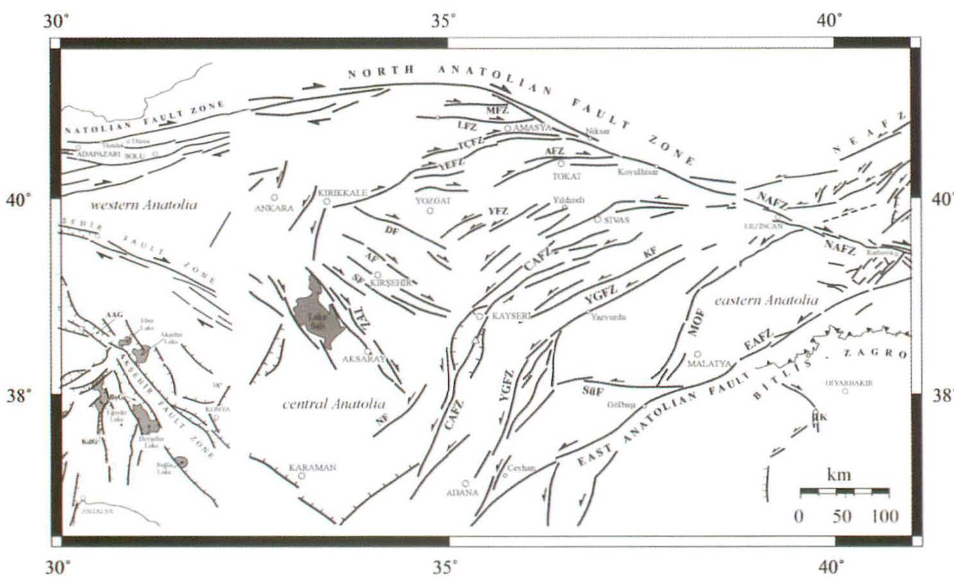

Fig.3. Map showing major structural elements of the Anatolia (modified after Bozkurt, 2001). Heavy lines with half arrows are strike-slip faults with arrows showing relative sense of movement. The heavy lines with hachures show normal faults: hachures indicate downthrown side. Central Anatolian Fault Zone (CAFZ), Malatya-Ovacik Fault Zone (MOF), Tuzgolu Fault Zone (TFZ) and Eskisehir fault zones form the major neotectonic structures in Central Anatolia, while Western Anatolia is characterized by several extensional basins

3. Tectonic Structures

3.1 Dead Sea Fault Zone (DSFZ)

The DSFZ is the continental transform boundary between African and Arabian plates, which is accommodating the differential motion of those plates as they converge and collide with Eurasia (Le Pichon and Gaulier, 1988). This NNE-SSW trending left lateral strike-slip fault zone contains number of elongate structural depressions, and joins the EAFZ in the north and Red Sea, Gulf of Suez and Gulf of Aqaba in the south (Garfunkel, 1981) (Fig.1). Plate tectonic models and recent GPS observations show that the present-day relative motion between the African and Arabian plates is about 4-8 mm/yr (Joffe and Garfunkel, 1987; Chu and Gordon 1998; McClusky et al., 2000). This range of slip rates is consistent with results from field studies along the DSFZ (Klinger et al., 2000; Gomez et al., 2003). There is a general agreement that movement on the DSFZ has comprised two distinct episodes, although there are debates about the precise timing (Quennell, 1984; Hempton, 1987). The first probably occurred during the Middle and Late Miocene (~14-5 Ma), with ~60 km of left-lateral displacement along the southern DSFZ. The second episode of motion began in the early Pliocene, with ~20-45 km of displacement along the northern DSFZ, probably corresponding with the ridge push from the onset of sea-floor spreading in the Red Sea (Hempton, 1987) and this tectonic system persists through recent times. The total geologic offset along DSFZ since Miocene, is amounted to be about 105 km (Joffe and Garfunkel, 1987; Garfunkel and Ben-Avraham, 1996). The difference in total offsets of ~20-45 km for second episode in the northern part of DSFZ corresponds with crustal shortening of up to 20 km along Palmyride fold belt during Arabia-Eurasia convergence (Chaimov et al., 1990).

3.2 North Anatolian Fault Zone (NAFZ)

NAFZ is approximately 2200 km-long, broad arc-shaped, right-lateral strike-slip fault system that extends from eastern Turkey to Greece and makes the northern boundary of the Anatolia with Eurasia (McKenzie, 1972; Sengor, 1979; Dewey et al., 1986; Kiratzi, 1993; Sengor et al., 2005). Along much of its length, NAFZ consists of a few shorter subparallel fault strands that sometimes display an anastomosing pattern (Fig.3). The age of dextral motion along NAFZ is controversial, either in the Middle Miocene (McKenzie, 1970; Sengör, 1979), or Early Pliocene (Arpat and Sarogulu, 1972; Barka, and Kadinsky-Cade, 1988; Bozkurt and Kocyigit, 1996; Barka et al., 2000). The dextral motion commenced due to westward motion of Anatolia during the late phase of collision between Arabia and Eurasia (McKenzie, 1972; Sengor, 1979; Sengor et al., 1985; Dewey et al., 1986; Barka, 1992; McQuarrie et al., 2003; Sengor et al., 2005; Hubert-Ferrari et al., 2009) resulting the uplift of Anatolian plateau and the onset of volcanism in eastern Anatolia (Yilmaz et al., 1987). At present, NAFZ has a nearly uniform total displacement of about 85 ± 5 km along most of the fault (Sengor, 1979; Westaway, 1994; Barka, 1992; Armijo et al., 1999; Barka et al., 2000; Hubert-Ferrari et al., 2002; Sengor et al., 2005). The rate of motion on the NAFZ from analysis of geological data suggests that it is about 5-10 mm/yr (Barka, 1992), or 17 ± 2 mm/yr (Westaway, 1994), or 18.5 ± 3.5 mm/yr (Hubert-Ferrari et al., 2002), while the plate motions and seismological data suggest rates of 30-40 mm/yr (Taymaz et al., 1991) (see Table 1). This discrepancy arises from the exaggerated slip rate by treating the intense seismicity on the NAFZ. On the other hand, recent GPS data indicate present-day rates of about 15-30 mm/yr (Reilinger et al., 1997; McClusky et al., 2000; Reilinger et al., 2006). The extrapolation of recent rates to Early Pliocene yields a total displacement of 75-125 km, which is in close agreement with the estimate of 85 ± 5 km.

Table 1. Velocities of tectonic plates derived from geologic and geodetic data in the study area

Plates/plate boundaries	Velocity range (mm/yr)	Direction of movement	Velocity taken for the modeling (mm/yr)	References
African plate	5-12	N to NW	10	10-12 mm/yr: DeMets et al. 1990 (NUVEL-1A) 4-8 mm/yr: Kahle et al. (1998), Reilinger et al. (2006), Kreemer et al. (2003) < 10mm/yr: McQuarrie et al. (2003), Reilinger et al., 1997; Chu and Gordan, 1998; McCluskey et al., 2000
Arabian plate	20-30	NE to N	20	20-25 mm/yr: DeMets et al. (1990) (NUVEL-1A), Chu and Gordan (1998) 20-30 mm/yr: Le Pichon et al. (1995), Reilinger et al. (1997), McCluskey et al. (2000), Reilinger et al. (2006)
Anatolian plate	10-30	E-W	15, 30	10-20 mm/yr: Barka et al. (1992), Barka and Cadinsky-Cade (1988), Westaway (1994), Hubert-Ferrari et al. (2002) 15-30 mm/yr: Jackson and McKenzie (1988), Reilinger et al. (1997), McClusky et al. (2000), Reilinger et al. (2006)
Aegean plate	30-40	E-W to SW	-	30-40 mm/yr: Le Pichon et al. (1995), Reilinger et al. (1997), Kahle et al. (1999), Kahle et al. (1998)
Red Sea rift	10-20	NE-SW	-	10-16 mm/yr: Chu and Gordon (1998) 17-20 mm/yr: McCluskey et al. (2003)
Gulf of Aqaba-Dead Sea transform	5-9	E-W to NE-SW	-	8-9 mm/yr: Le Pichon and Gaulier (1988), Girdler (1991) 7.5 mm/yr: Westawy (1994) 4-6 mm/yr: Reilinger et al. (2006), Wdowinski et al. (2004), Heidbach and Ben-Avraham (2007)

3.3 East Anatolian Fault Zone (EAFZ)

The East Anatolian Fault Zone (EAFZ) is a 2–3 km wide, active strike slip fault extending from Antakya in the west to Karliova in the NE, where it meets the eastern termination of the North Anatolian Fault Zone (NAFZ) (Fig.1). Its total length is about 560 km on ground surface and must extend beneath the sea. As recognized by earthquake focal mechanism solutions, this is a left-lateral strike-slip fault, the movement along which aids the westward movement of Anatolia (McKenzie, 1970, 76; Taymaz et al., 1991; Jackson, 1994). Compared to NAFZ and DSFZ, EAFZ has a lower slip rate, i.e. 4-7 mm/yr (e.g. Arpat and Sarogulu, 1972; Dewey et al., 1986), and fewer earthquakes (Toksoz et al., 1979).

3.4 Cyprean Arc

The Cyprean Arc is an area of the convergence of African plate into Anatolian plate in eastern Mediterranean. This arc is represented by subduction boundary in the west and transform boundary in the east (McKenzie, 1972; Kempler and Garfunkel, 1994). This arc links with the Florence rise and Hellenic trench in the west. The eastern prolongation of the Cyprean arc is, however, controversial because of the complexity of deformation between African, Arabian and Anatolian plates. Cyprean arc is reasonably well defined by narrow bands of seismicity and well imaged down beneath the lithosphere (Wortel and Spakman, 2000). In this area the deformation is partitioned along strike-slip fault systems forming sets of positive flower structures, distributed over a wide zone, rather than forming a sharp plate boundary (Vidal et al., 2000).

4. Observed deformation, seismicity, active faults and stress field: constraints for modeling

4.1 GPS velocities

Plate tectonic models, kinematic and spatial geodetic measurements (DeMets et al., 1990, 1994; Jackson, 1994; Le Pichon et al., 1995; Reilinger et al., 1997; Kahle et al., 1995; McClusky et al., 2000; McClusky et al., 2003; Nyst and Thatcher, 2004; Reilinger et al., 2006) have provided better understanding of the present-day plate motions and tectonics of eastern Mediterranean (Fig.4; Table 1). Previous studies indicate that the Arabian plate is moving N-NNW direction relative to Eurasia at a rate between 20-25 mm/yr, while the African plate is moving NW at a rate between 6 and 10 mm/yr. The left lateral motion along the DSFZ adjusted the differential motion between the African and Arabian plates. Towards the Aegean Sea the Anatolia reaches to a value ~30 mm/yr. Plate motion models by DeMets et al. (1990, 1994) and Chu and Gordon (1998) suggest that African and Arabian plate are slowing down as they move south to north and collide with Eurasia, while the velocity of the Anatolia is increasing progressively from east to west and SW towards Aegean subduction in Hellenic arc (McClusky et al., 2000; McClusky et al., 2003). Kinematic studies have shown that Anatolia is moving towards west, relative to Eurasia, with an average velocity of ~ 37 mm/yr (McKenzie, 1972; Jackson, 1994) and with total seismic deformation in the order of ~ 22 mm/yr (Papazachos and Kiratzi, 1996, Papazachos, 1999).

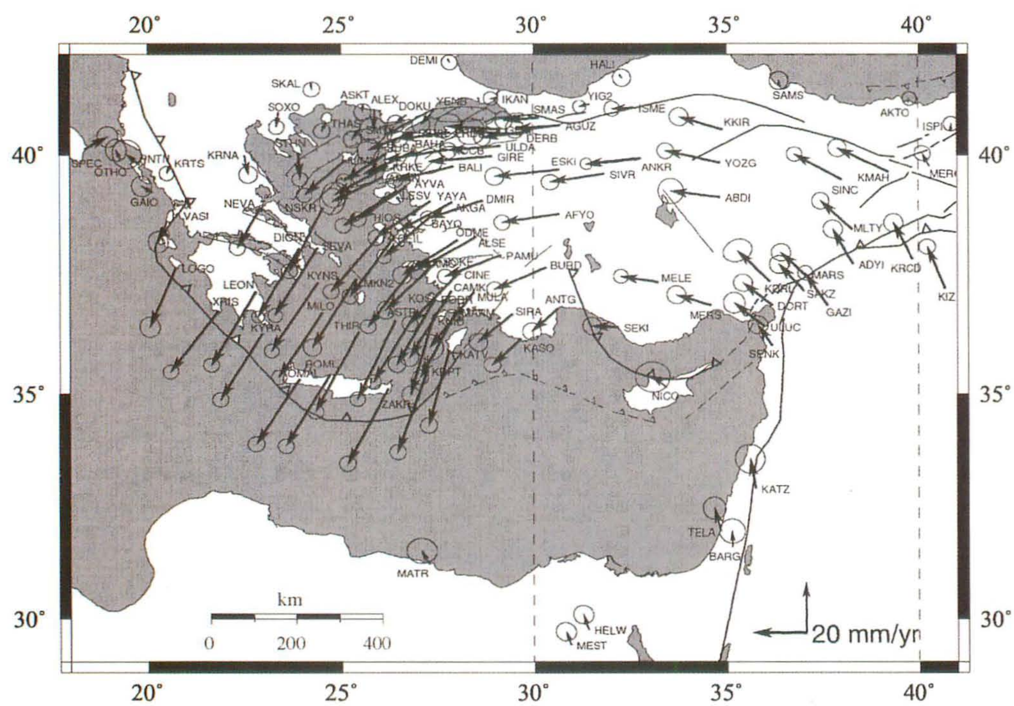

Fig.4. GPS velocity vectors relative to stable Eurasia for the period between 1988-1997 (after McCluskey et al., 2000)

4.2 Seismicity and earthquake focal mechanism solutions (FMS)

The spatial distribution of earthquakes clearly reflects the associated deformation pattern in the eastern Mediterranean, (Fig.2). It shows the close spatial relation between earthquake faulting and sense of motion on active faults. DSFZ which concentrates most of the seismic moment released from the Africa-Arabia interaction indicates strike-slip movement on a fault plane directed approximately NNE-SSW. This plane is characterized by horizontal tensional stress. In the EAF, although there is few information about seismicity, most of the activity is related to NW-SW trending faults. For the case of NAFZ, the focal mechanism shows right lateral strike-slip faulting with compression trending NE-SW and extension in NW-SE direction. At its western termination, however, the line of earthquakes become more diffuse, and the NAFZ splinters into a series of parallel strike-slip faults oriented SW-NE. In general, FMS of moderate to large earthquakes affecting the eastern Mediterranean, show the tensional and compressional stress axes in NNE-SSW and NNW-SSE direction respectively. N-S directed normal faults are widespread on Aegean and western Anatolia while strike-slip faults are largely confined to NAFZ, EAFZ and DSFZ. Similarly, reverse faults are predominant along the Hellenic and Cyprean Arc.

4.3 Neotectonics and active faults

Field observations and analysis of neotectonic faults on different scales have provided a detailed view of deformational history in Anatolia (Bozkurt and Kocyigit, 1996; Tatar et al., 1996; Bozkurt, 2001). Orientations of fault planes and tectonic striation can be used in inversion schemes to obtain information about the associated state of stress (Angelier, 1979). The Anatolia is separated by numerous active seismogenic faults, mostly strike-slip and some normal and thrust-type (Fig.5). Neogene and Quaternary volcanism with varying composition are widespread and cover more than half of the Anatolia (Yilmaz et al., 1987; Yilmaz, 1993). Eastern Anatolia near the Karliova triple junction is characterized by N-S compressional tectonic regime. Conjugate strike-slip faults of dextral and sinistral sense of movement paralleling to NAFZ and EAFZ are dominant structural elements in this region. These faults are seismically active, and are the source for many earthquakes (Fig.2) (Bozkurt, 2001). Central Anatolia shows the generation of large number of structures or reactivation of older structures due to internal deformation of continental lithosphere (Fig.3) (Jackson, 1994; McClusky et al., 2000; Bozkurt, 2001). The region is affected by approximately N-S to NNE-SSW shortening, related to collisional processes between Anatolia and Africa along the EAFZ and Cyprian arc, while it is rotating anticlockwise. In this frame, the western Anatolia is deformed by a number of second-order faults. Notable faults of eastern Anatolia are Dumlu Fault Zone, Malatya-Ovacik Fault Zone, and Northeast Anatolian Fault Zone; central Anatolia are Central Anatolian Fault Zone, Delice Fault, Nigde Fault, Salanda Fault, Tuzgolu Fault Zone, Yagmurlu-Ezinepazari Fault Zone, and Yakapinar Goksun Fault Zone; western Anatolia are Aksehir Fault Zone and Eskisehir Fault Zone. As shown in Fig.3, many of these fault zones are splayed out from the NAFZ and run in SW direction across the Anatolia for hundreds of kilometers, and display distinct geometries. Most notable geological structure of western Anatolia are some extensional and variable sized pull-apart basins such as Aksehir Afyon Graben, Beysehir Graben, Burdur Graben, Dinar Graben , Kutahya Graben and Sandikli Graben, which are bounded by oblique-slip faults. These basins are important features since they contain valuable information on the evolution of Anatolia.

4.4 World Stress Map (WSM)

Stress indicators from WSM can be compared with the calculated stress field from which the direction of the largest horizontal stress (σ_{Hmax}) and most likely faulting regime can be deduced (Zoback, 1992; Heidbach et al., 2008; Yin and Ranalli, 1992). Eastern Mediterranean represents a region of complicated contemporaneous stress pattern and considerably more heterogeneous than in the stable areas of Eurasian plate (Fig.5). Most of these stresses are concentrated along the plate boundaries, and few are dispersed inside the plate. Along the entire length of DSF, σ_{Hmax} trend almost NW-SE with strike slip faulting. Most of these stress orientation show obliquity to the fault. In the eastern part of EAF and near the junction between EAFZ and DSFZ, σ_{Hmax} trend NE to SW whose orientation shows obliquity to the fault corresponding to strike-slip faulting. For the entire part of NAFZ, σ_{Hmax} trend NNE-SSW to NW-SE making obliquity to the fault corresponding to strike-slip faulting. In the interior of Anatolia, in its eastern part, σ_{Hmax} trend NE-SW. These stresses progressively rotate toward NW-SE in the western part of Anatolia where mostly normal type of faulting exist due to pull from Aegean extension. To the south of Cyprean arc, σ_{Hmax} trend almost E-W and parallel to the arc corresponding to thrust type of faulting due to compression. In other parts of region stress data are not available. In overall, present-day stress pattern for the eastern Mediterranean clearly shows σ_{Hmax} pattern in same direction with plate motions. The rotation of stress axis arises mostly along the plate boundaries.

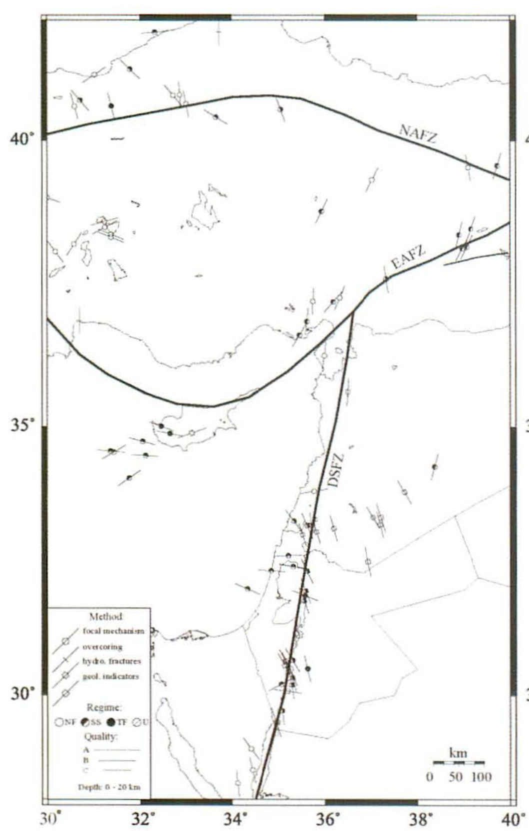

Fig.5. Present-day stress field from the World Stress Map (WSM) project in the study area (after Heidbach et al., 2008). The direction of the symbols indicates the direction of largest horizontal stress axis (σ_{Hmax}). Stress data is for 0-20 km depth interval.

5. Numerical modeling

In this study, by using the FE package (Hayashi, 2008), I tested the influence of tectonic boundary condition for the present-day stress field and deformation of Anatolia. Linear elastic rheology is assumed for the modeling and gravitational force is taken into account assuming that the crust is mechanically isotropic. This FE package which is being extensively used for the modeling of intraplate stress field (Otsubo and Hayashi, 2003; Chamlagain and Hayashi, 2008; Dwivedi and Hayashi, 2008; Dwivedi and Hayashi, 2009), is used in plane stress condition. This FE package requires specification of an initial condition, boundary condition and material property.

5.1 Definition of model parameters

On the basis of well-recognized tectonic boundaries (McKenzie, 1970, 1972; Sengor et al., 1985; Dewey et al., 1986; McClusky et al., 2000; Reilinger et al., 2006) , which is 950 km (EW) by 1625 km (NS), eastern Mediterranean region is divided into four discrete domains (Fig.6); (1) Africa (2) Arabia, (3) Anatolia, and (4) Eurasia, that are covered by finite element mesh containing 1012 triangular elements interconnected with 552 nodes. Plate boundary is treated as weak 'fault zone' of finite width that would fail by slip (strike-slip faulting) or separation (normal faulting). It is assumed that displacements on the fault zone are small with respect to the length and there is no ductile deformation of the material inside this zone. Each domain is assigned into elastic and strength parameters (Fig.7). The parameters, density (ρ) is adopted from Saleh et al. (2006) and Fischer (2006) while Young's modulus (E) of 70 GPa is taken for the whole model (Cloetingh and Wortel, 1986; Grunthal and Stromeyer, 1992; Bada et al., 1998; Jarosinski et al., 2006; Gölke and Coblentz, 1996) except 3 GPa for the weak zone (Homberg et al., 1987). Likewise, for Poisson's ratio (υ), 0.25 is taken for the overall model and 0.40 for the weak zone (Table 2).

Table 2. Boundary conditions and displacements used for the numerical models

Models	Boundary conditions tested	Depth (km)	Displacement (m) (a=Africa ~10 mm/yr, b=Arabia ~20 mm/yr, c=Anatolia ~15-30 mm/yr)
Single Domain model	BC-1 BC-2 BC-3	2, 20	(25,000 yrs) BC1: a=250, b=500 BC2: a=250, b=500, c=375 BC3: a=250, b=500, c=750
Four Domain model (model without fault zone)			
Five Domain model (model with fault zone)			
Single Domain model	BC-1 BC-2 BC-3	2, 20	(37,500 yrs) BC1: a=375, b=750 BC2: a=375, b=750, c=562.5 BC3: a=375, b=750, c=1125
Four Domain model (model without fault zone)			
Five Domain model (model with fault zone)			
Single Domain model	BC-1 BC-2 **BC-3***	2, **20***	(50,000 yrs) BC1: a=500, b=1000 BC2: a=500, b=1000, c=750 **BC3: a=500, b=1000, c=1500***
Four Domain model (model without fault zone)			
Five Domain model (model with fault zone)*			

** best-fit model*

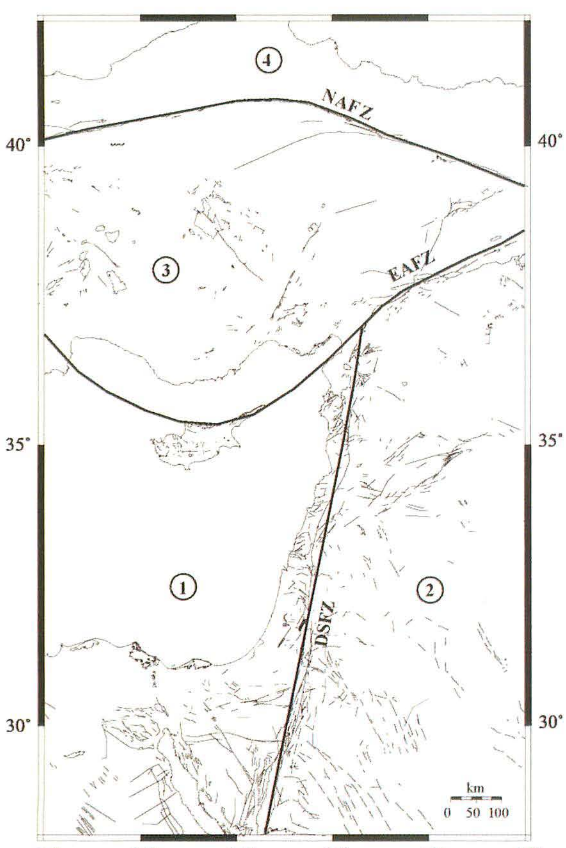

Fig.6. Model geometry and rock domains. (1) African plate (2) Arabian plate (3) Anatolian plate (4) Eurasian plate. Thick lines represent fault zones separating rock domains. Thin lines are active faults

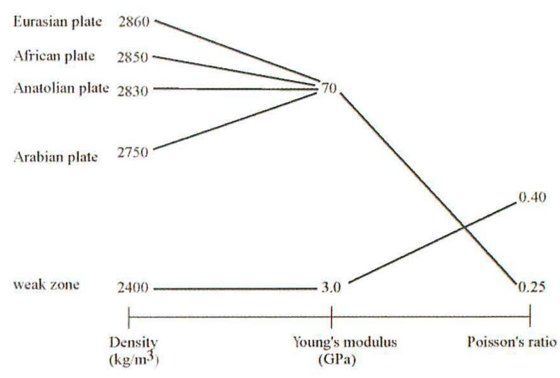

Fig.7. Rock domain parameters

5.2 Boundary Conditions

The large number of geodetic and geophysical data sets available for the eastern Mediterranean (Kahle et al., 1995; Le Pichon et al., 1995; Davies et al., 1997; Reilinger et al., 1997; McClusky et al., 2000; Reilinger et al., 2006) has allowed constraining suitable boundary condition in the FE models. It is generally accepted that (a) African and Arabian plates are driven by 'ridge-push force' acting from the Pacific Ocean, southwest Indian Ocean and Red Sea, (b) Anatolian plate is driven either by 'collisional force' acting due to indentation of Arabian plate into Eurasian plate or 'slab-pull force' acting due to subducting African plate over Aegean in Hellenic Arc. These forces act as primary or first-order sources of stress field in the eastern Mediterranean and are the driving forces for the FE model. We evaluate the relative contribution of the African, Arabian and Anatolian plate movement to the present-day stress field of the area with fixed a Eurasian platform. Displacements are applied on the lateral faces of the model in the direction of absolute plate motion, whose magnitude is proportional to the velocities of plates (Table 2). Considering the rate of plate motion, three set of displacements are calculated and tested for the corresponding years of 25000, 37500 and 50000 in the FE models.

To simulate the present-day stress field and plate motions, initially eight boundary conditions were tested, out of which three BC-1, BC-2 and BC-3 was taken as representative boundary conditions and were tested respectively under 2 km and 20 km crustal depth for three model geometries; Single Domain model, Four Domain model (model without fault zone) and Five Domain model (model with fault zone). BC-1 was used to evaluate the effect of boundary conditions representing Arabian push over Anatolian plate. BC-2 was used to evaluate the effect of Arabian push and the far-field effect of Aegean subduction (Aegean subduction < Arabian push), while BC-3 was used to evaluate the effect of Arabian push and the far-field effect of Aegean subduction (Aegean subduction > Arabian push). Details of tested boundary conditions are presented in Table 2. As shown in Fig.8, the triangle marks at the upper edge of the model indicate fixed points, where the displacement is set to zero both in x and y directions. The rollers on the edges indicate that the displacements normal to the edge are zero, but they are free to move parallel to the edge. Thin arrows indicate applied edge displacements. Edge without triangles, circles and arrow indicate free boundary (i.e. free to move in both x and y directions).

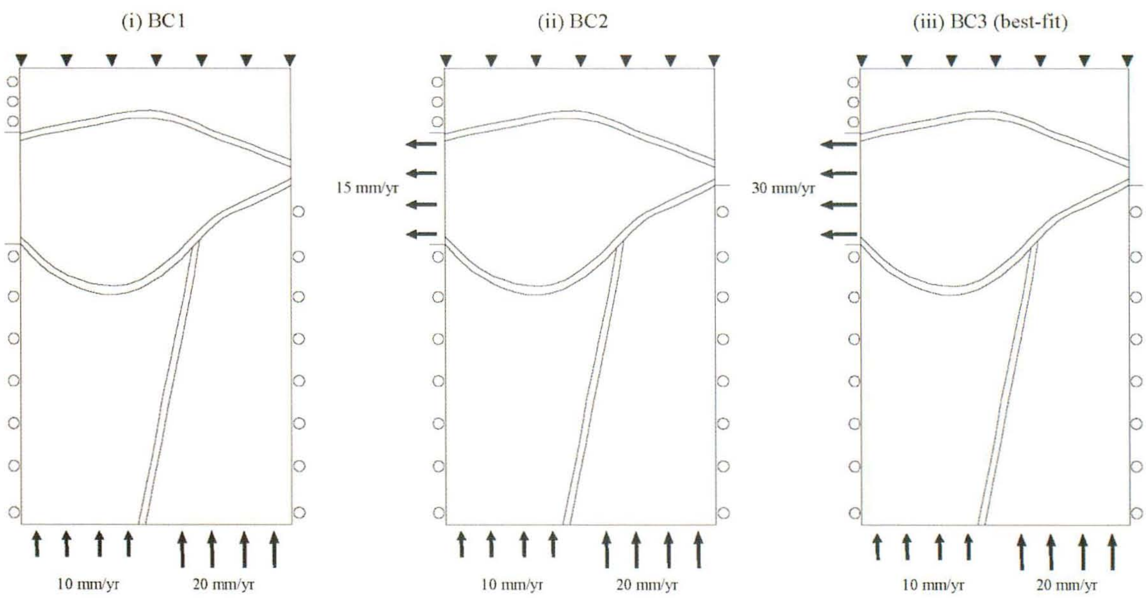

Fig.8. Boundary conditions. (i) BC1, effect of Arabian push (ii) BC2, effect of Arabian push and far-field effect of Aegean subduction (Aegean subduction < Arabian push) (iii) BC3, effect of Arabian push and far-field effect of Aegean subduction (Aegean subduction > Arabian push). See text for full description

6. Modeling results

Modeling results are presented on the basis of: (1) distribution, orientations, and magnitude of σ_{Hmax} and (2) horizontal displacement field. Since there is large number of tested models, here we present only for the case of 50,000 years (see Figs.9-14) with best-fit model described in detail.

6.1 Maximum horizontal stress (σ_{Hmax}) field

It is clearly indicated that the presence of fault zone on the present-day stress field of the study area (Fig.14, iii). σ_{Hmax} along the NAF, EAF and DSF makes obliquity to the fault. Left lateral movement along DSFZ is represented by NW-SE orientation of σ_{Hmax} along the fault. NW-SE orientation of σ_{Hmax} along NAF represents right lateral strike-slip movements while NE-SW orientation of σ_{Hmax} along EAF represents left lateral strike-slip movement along these faults. Few tensional N-S to NE-SW oriented σ_{Hmax} exist near the junction between NAF and EAF as well as near the junction between DSF and EAF. In addition, along the Cyprean arc σ_{Hmax} are almost E-W and are parallel to subduction front. Orientation of σ_{Hmax} from the Arabia to Africa shows anticlockwise rotation. At the Interior of the Anatolia, σ_{Hmax} are oriented NE-SW in its eastern part to NW-SW in the western part. Tensile σ_{Hmax} occur along the western corner of the model in Anatolia. In overall, modeling results show σ_{Hmax} trend NW-SE to NE-SW in Anatolia, N-S in Arabia and NW-SE to N-S in Africa. These directions yield satisfactory fit to the observed data from WSM (Fig.14, iii and Fig.5) as well as from structural analysis, active fault studies (Fig.3 and Fig.6) and earthquake focal mechanisms for the study area (Fig.2).

6.2 Horizontal displacement field

Horizontal displacement field obtained from the best-fit model is presented in Fig.15, iii. Modeling results are comparable to the GPS data from McClusky et al. (2000). In the Arabian plate displacement vectors are uniformly directed northward decreasing in magnitude toward northern limit of the domain. Northwest of the Arabian margin, along the boundary between Anatolia and Arabia, the displacement field bend northwestward, with a corresponding decrease in magnitude. Close to the western boundary of Anatolian, the direction of the displacement field changes towards west with magnitude increasing towards Aegean. Similarly, in the African plate displacement vectors are uniformly distributed and oriented toward northern limit of the domain. Near the Cyprean arc displacement field deviates towards northwest. These displacement vectors give the sense of motion and directions that correspond well with GPS velocity vectors (Fig.4) (McClusky et al., 2000) and focal mechanism solution of earthquakes (Fig.2).

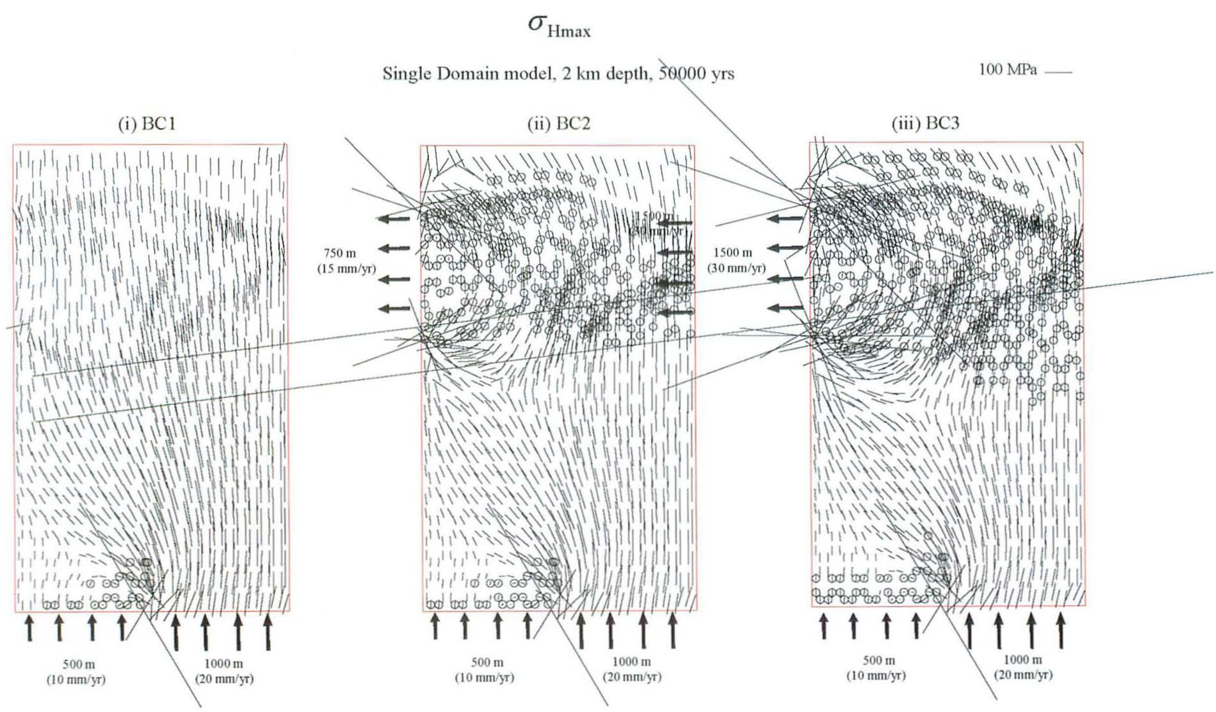

Fig.9. The calculated stress field for a Single Domain model, under 2 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3. Orientation of stress indicates the direction of largest horizontal stress axis (σ_{Hmax}), tensional stresses are represented by small black circles.

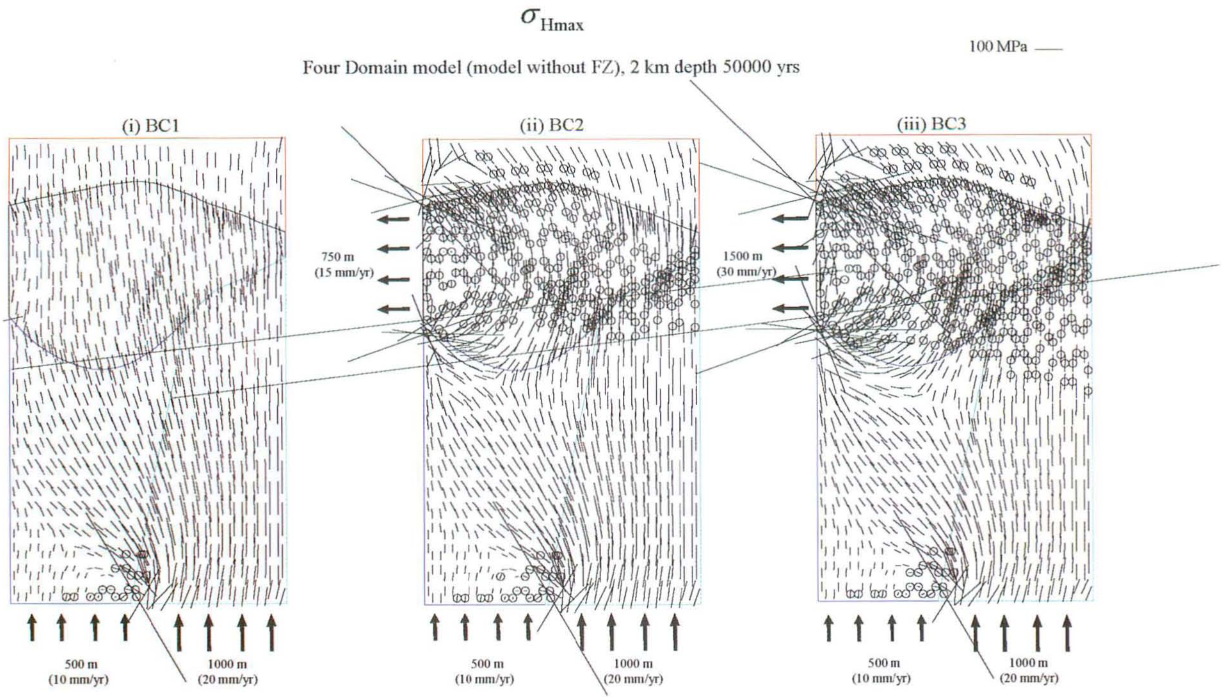

Fig.10. The calculated stress field for a Four Domain model (model without fault zone), under 2 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3. Symbols are same as in Fig.9

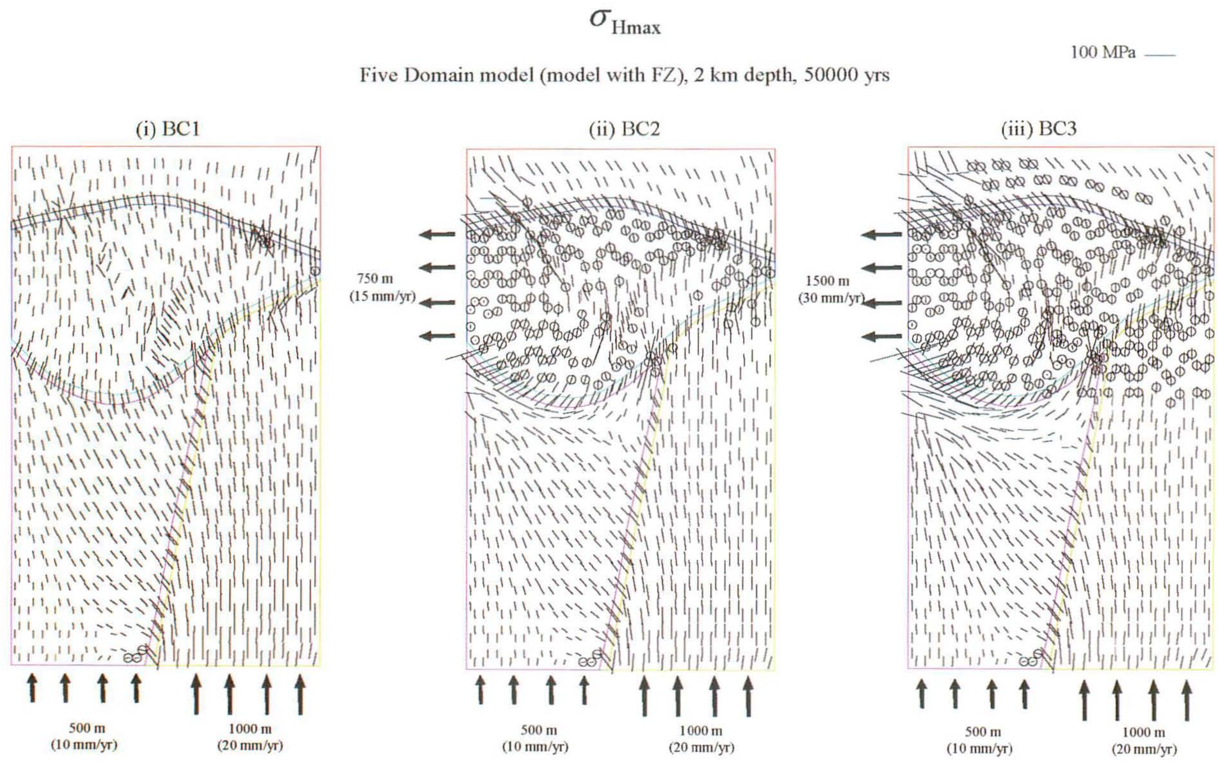

Fig.11. The calculated stress field for a Five Domain model (model with fault zone), under 2 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3. Symbols are same as in Fig.9

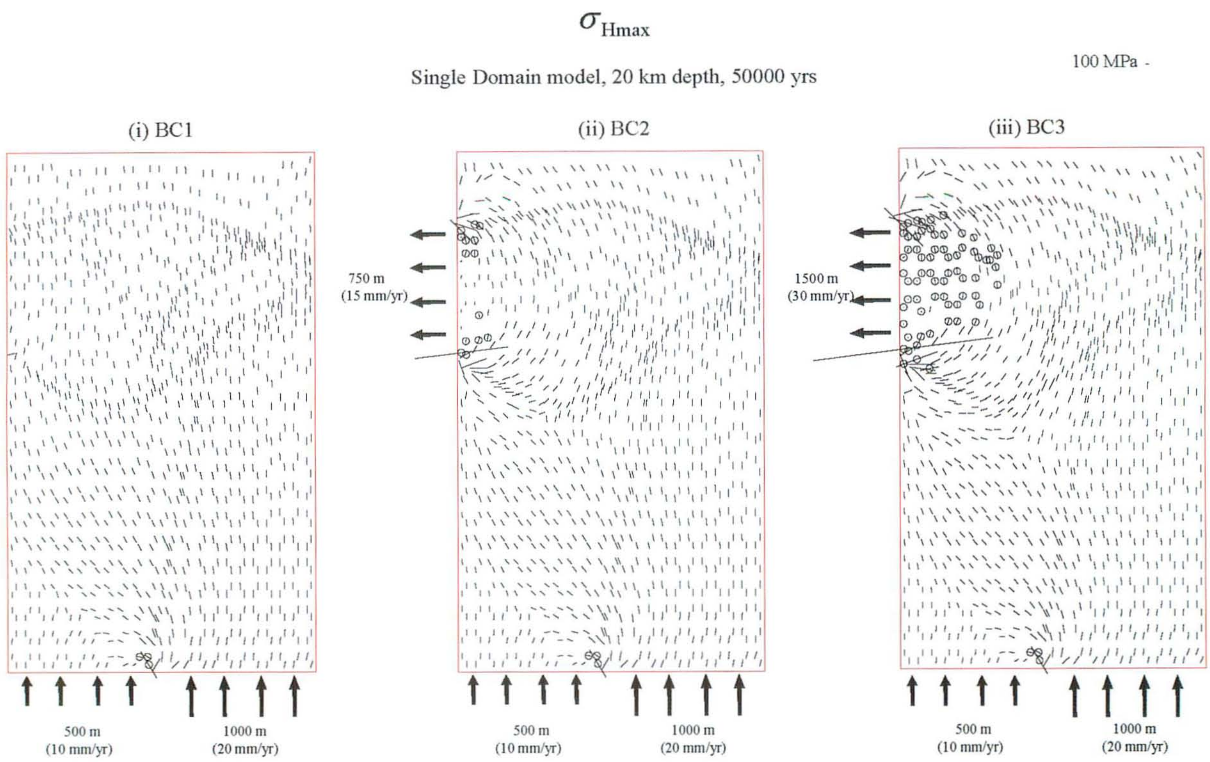

Fig.12. The calculated stress field for a Single Domain model, under 20 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3. Orientation of stress indicates the direction of largest horizontal stress axis (σ_{Hmax}), tensional stresses are represented by small black circles.

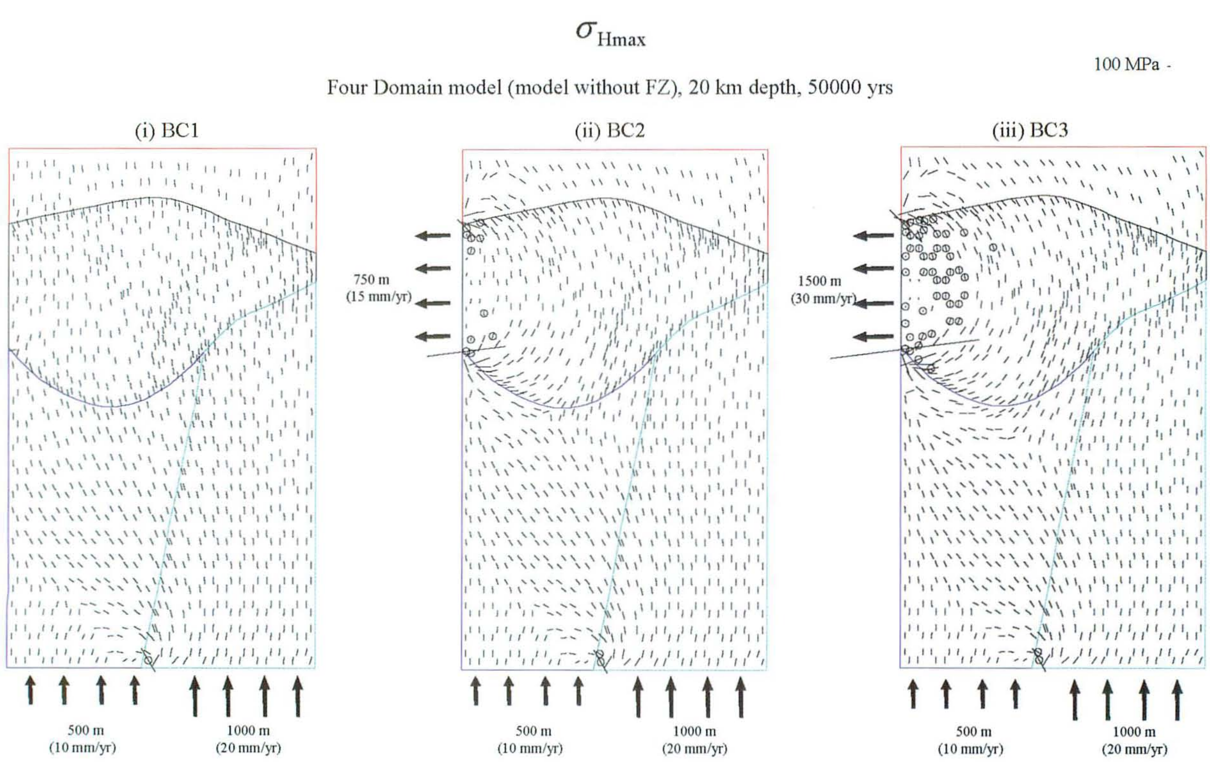

Fig.13. The calculated stress field for a Four Domain model (model without fault zone), under 20 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3. Symbols are same as in Fig.9

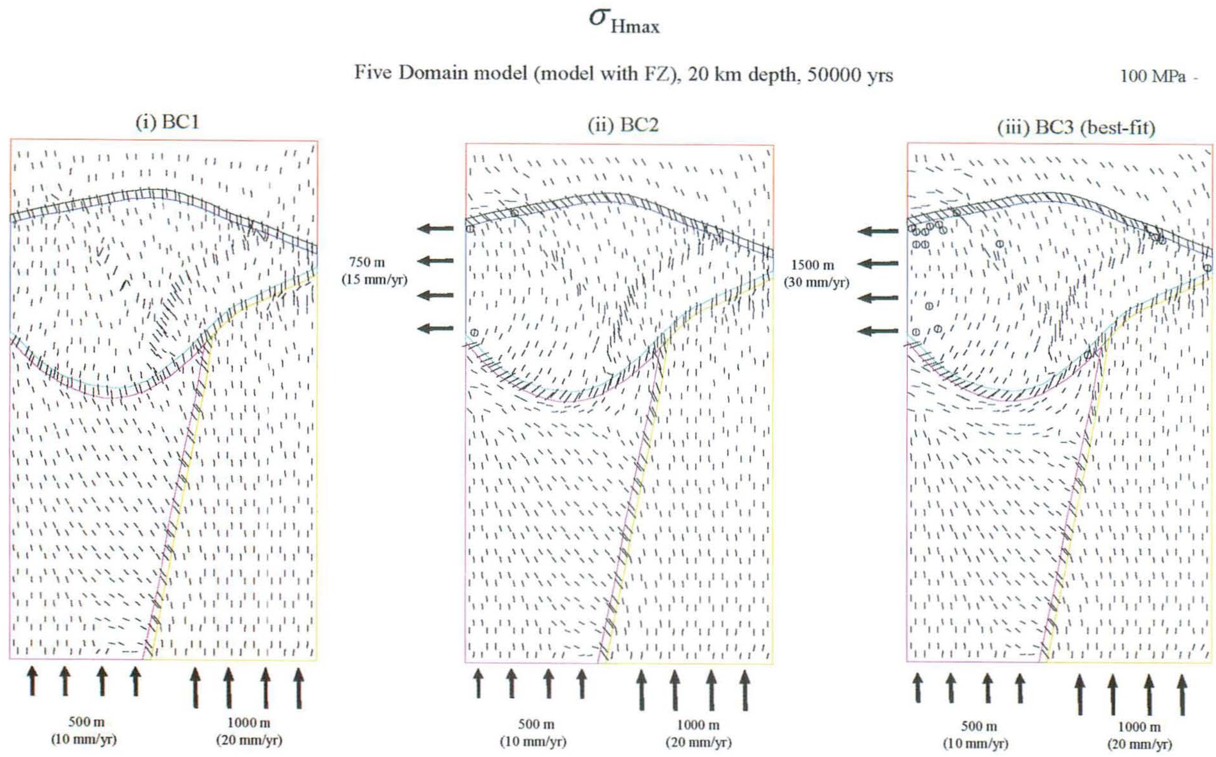

Fig.14. The calculated stress field for a Five Domain model (model with fault zone), under 20 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3 (best-fit model). Stress field from BC3 closely resembles with observed data. Symbols are same as in Fig.9

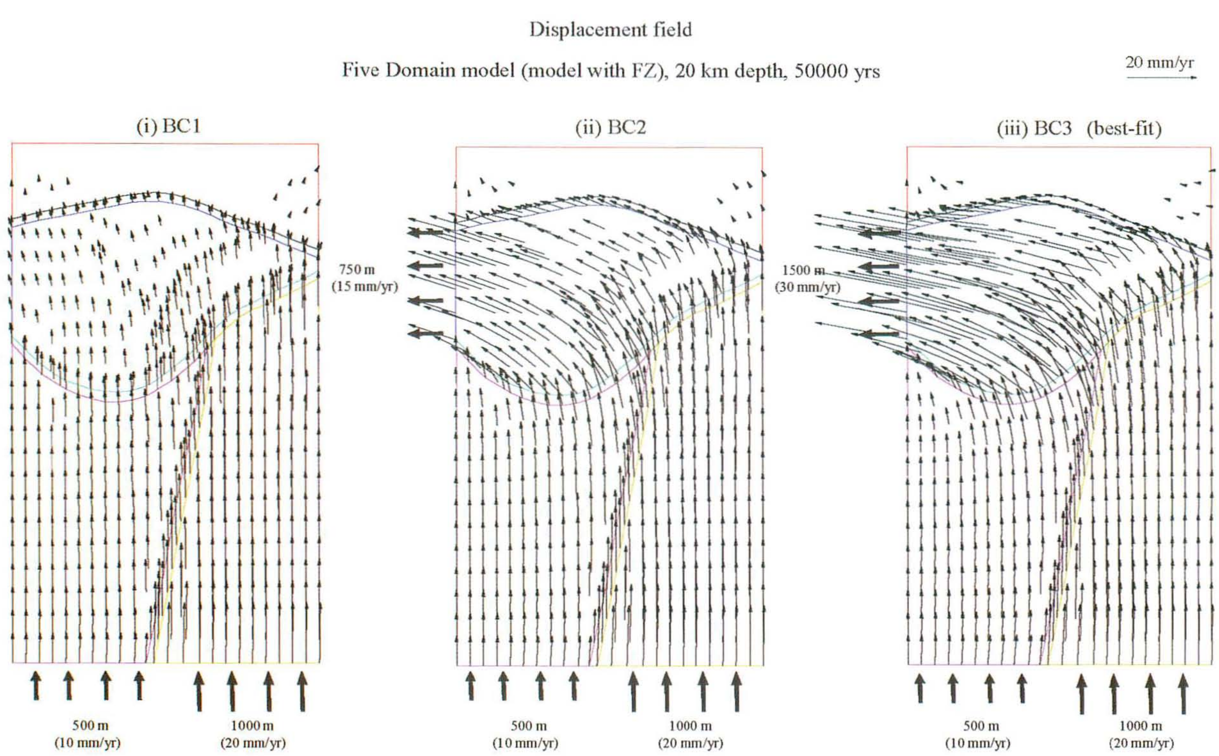

Fig.15. The calculated displacement field for Five Domain model (model with fault zone), under 20 km depth for 50,000 years. (i) BC1 (ii) BC2 (iii) BC3 (best-fit model). Displacement field from BC3 closely resembles with observed data

7. Discussions

7.1 Present-day Stress field of the eastern Mediterranean

Although stress data from WSM (Zoback, 1992; Heidbach et al., 2008) for eastern Mediterranean are very few and scattered, modeling results are almost close to these data set. For the present-day deformation and dynamics of Anatolia, we obtained the best-fit model for the Five Domain model (model with fault zone) under 20 km depth using boundary condition BC-3 for 50000 years (Fig.14, iii; Table 2). In the best fit-model, magnitude and orientation of simulated σ_{Hmax} is compatible with the compressional force acting due to northward movement of Afro-Arabian plate and westward expulsion of Anatolian plate (DeMets et al., 1990, 1994; Westaway, 1994; Kahle et al., 2000; McClusky et al., 2000). For most part of the African and Arabian plates, σ_{Hmax} trend N to NNW, that is compatible with African and Arabian drift direction. For the Anatolian plate, σ_{Hmax} trend NW to W that is compatible with the westward escape direction (Zoback, 1992; Rebai et al., 1992; Heidbach et al., 2008). This means, plate motions significantly control the pattern of first order stress field in this area. Large perturbations in σ_{Hmax} occur at the plate boundaries or fault zones showing the effect of relative plate motion. For the most part of DSFZ, except its northernmost part, σ_{Hmax} are oriented NW-SW making obliquity to the fault. This direction has also been confirmed by geological observations along this fault (Lyberis, 1988). On the other hand, NW-SE orientations of σ_{Hmax} along the southernmost part of Dead Sea are considered to be related to the opening of Suez and Aqaba rifts (Le Pichon and Gaulier, 1988; Steckler et al., 1988). In northernmost part of DSFZ, near the junction between EAFZ and DSFZ, σ_{Hmax} direction trend parallel to the fault. This is expected due to the northward indentation of Arabian plate over the Anatolia (Bozkurt, 2001; Hubert-Ferrari et al., 2009). Similarly, P-axis orientation along DSFZ agrees well with NW-SE orientation of σ_{Hmax}, which makes obliquity to the fault zone. Orientation of P-axis along the EAFZ is comparable to NE-SW σ_{Hmax} orientation while along the NAFZ it is comparable to NW to SE oriented σ_{Hmax} (Fig.2 and Fig.14, iii).

σ_{Hmax} along the Cyprean arc are oriented E-W corresponding to compression of African plate with Anatolia. Anatolia, on the other hand, is represented by both extensional and compressional state of deformation. The NE-SW trending σ_{Hmax} in eastern Anatolia is associated with northward convergence of Arabia with Eurasia, whereas the NW-SE oriented σ_{Hmax} in central and western Anatolia is associated with westward movement of Anatolia relative to Eurasia (Fig.14, iii) (McKenzie, 1972; Taymaz et al., 1991; Barka, 1992; Papazachos and Kiratzi, 1992; Kiratzi and Papazachos, 1995). When compared to Fig.3 the best-fit model corresponds most of the orientation of σ_{Hmax} directions to the structural elements of Anatolia and hence shows the effect of tectonic boundary condition over the formation of faults in this area. Pronounced N-S tension obtained in the western Anatolia gives acceptable agreement with observed data. Rebai et al. (1992) reported N-S oriented tensional stress in western Anatolia from large number of in-situ stress measurements. These stresses correspond to the presence of number of small scale graben features due to Aegean pull in Anatolia (Fig.3) (Bozkurt, 2001).

GPS data, on the other hand, show clear evidence of deformation pattern in the region (Fig.4) (Le Pichon et al., 1995; Reilinger et al., 1997; Kahle et al., 2000; McClusky et al., 2000; Reilinger et al., 2006). Horizontal displacement field for the best fit model (Fig.15, iii) shows the pattern of deformation that is qualitatively comparable with the GPS vectors (McClusky et al., 2000) and plate motion models (DeMets 1990, 1994). These results, hence, clarify the influence of tectonic boundaries for the plate motions and resulting active deformation in the eastern Mediterranean. The best-fit model is achieved for the higher rate of plate motion for Anatolia (~30 mm/yr) rather than low rates (~15 mm/yr) derived from geologic and geodetic studies. This shows that the Arabian push alone does not control Anatolian westward motion, and therefore the rest of the velocity must be aided to Anatolia from nearly source possibly from Aegean subduction.

7.2 Implications for continental deformation

We constructed the FE models to apply realistic material properties and boundary condition for the understanding the present-day dynamics of eastern Mediterranean region, with particular emphasis on Anatolia. To account for the observed partitioning of the deformation between the rock domains we have treated a boundary between plate domains as fault zones. The presence of fault zone, representing DSFZ, EAFZ and NAFZ, clearly reveals its influence over the stress field in Anatolia. The occurrence of large number of earthquakes along these fault zones manifests that these faults have accommodated partly the motion between the African, Arabian and Anatolian plates and aided for the westward movement of Anatolia. Modeling shows the presence of fault zone reduces the tensional stress field for the observed kinematics and stress data in Anatolia. Studies have shown that northward Arabian push alone does not explain the observed prevalence of stress field and deformation in the Anatolia (Rebai et al., 1992; Cianetti et al., 1997; Lundgren et al., 1998). In fact, the push of the Arabian plate, in terms of rates, is about half or less as compared to the movement of Anatolia (McClusky et al., 2000). Le Pichon and Angelier (1979) and Meijer and Wortel (1996) have suggested that slab-roll back of the subducting African plate and stretching of overriding Aegean plate has accounted the observed seismicity, spatial acceleration of motion and deformation in the Aegean-Anatolian region. Cianetti et al. (2001) have outlined that the high strength of the Aegean lithosphere is causing to generate pull along the Hellenic Arc and that force transfer directly to Anatolia. Similarly, recent GPS studies have suggested the evidence of pull forces acting from Hellenic subduction for the westward extrusion of Anatolia and the active deformation of the region (Reilinger et al., 1997; Kahle et al., 1995; McClusky et al., 2000; Reilinger et al., 2006). We find that in addition to the Arabian push, the model with outward pulling forces from the Aegean subduction (Aegean subduction > Arabian push) yield the observed pattern of deformation and stress field in Anatolia (Fig.14, iii). These results have interesting implications for the evaluation of active deformation and seismic hazard in Anatolia.

8. Conclusions

The state of present-day stress field of eastern Mediterranean is governed by various forces. Essentially, the northward convergence of Arabian plate into Eurasian plate, formation of the NAFZ and EAFZ, and the consequent westward extrusion of the Anatolian plate along these faults have resulted active tectonics, seismicity and deformation in the region. The deformation pattern has been largely influenced by lateral variations of lithospheric rheology as well as pre-existing structural discontinuities. This can be explained by elastic finite element modeling with realistic material properties and precise boundary condition based on the regional plate kinematics. In particular, when simulated the regional stress field incorporating the present-day tectonic boundary condition, the plate boundary forces remarkably control the intraplate stress pattern in the model. Average stress directions are parallel to the direction of absolute motion of these plates. Large perturbations in σ_{Hmax} occur at the plate boundaries or fault zones. We emphasize that despite the detailed complexity of continental deformation revealed by seismicity, active faulting and earthquake focal mechanism solution, simulated results are similar to the observations from WSM, seismicity and GPS data. Apart from African and Arabian plate movements, westward motion of Anatolian plate dominantly controls the magnitude and pattern of the first order stress field in the model. Hence, we infer that the present-day stress field of the eastern Mediterranean, particularly in Anatolia, is largely controlled by the regional plate tectonic stresses due to Arabian push and pull from Aegean subduction. These results have interesting implications for the evaluation of active deformation and seismic hazard in the area.

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