IDENTIFICATION OF THE BLOCK MOVEMENTS AND STRESS ZONES IN SOUTHWESTERN ANATOLIA THROUGH GNSS MEASUREMENTS, SEISMICITY, AND COULOMB STRESS DISTRIBUTION

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Abstract

This paper gives the early results of the evaluation of the GNSS data collected to identify the crustal movements and deformation anomalies around the faults in Southwestern Anatolia, and an identification of Coulomb stress accumulation and seismicity, and a definition of the seismic risk in the region. Southwestern Anatolia is located in a tectonically critical region. It incorporates Fethiye-Burdur fault zone, which is of transform nature, and divides two different tectonic regimes and various graben extension zones. Although several geologists acknowledge the extensional tectonism in the N-S direction, different models formulated for the mechanisms of extension in question are still controversial. Like many other parts of Turkey, the region of Southwestern Anatolia is located in a tectonically active region. The region has been a very active seismic zone throughout the historical and instrumental periods and the earthquakes in the region usually led to surface ruptures as well. With 33 earthquakes in the Aegean graben system and 13 earthquakes in the Hellenic-Cyprus trench during the last century, all of which were of M>5.5, the region constitutes one of the most seismic zones of Turkey. This study aims to clearly demonstrate and delineate the block model in Southwestern Anatolia through the GNSS points already located and to be located in the region. Previously sponsored and conducted studies 2003-2006 have made measurements at 16 points. To this end, through the measurement efforts, it designs an increase in the number of measurement points by 7-11, which would allow a detailed identification of the region's block model. After the three GPS campaigns the results will be examined in terms of seismicity. With the support of TUBITAK and with adding 7-11 points to previously measured points, GNSS measurements will be continued between 2009-2011 years.

Keywords: *Geodesy, GNSS, Crustal movement, Coulomb stress accumulation, seismic risk*

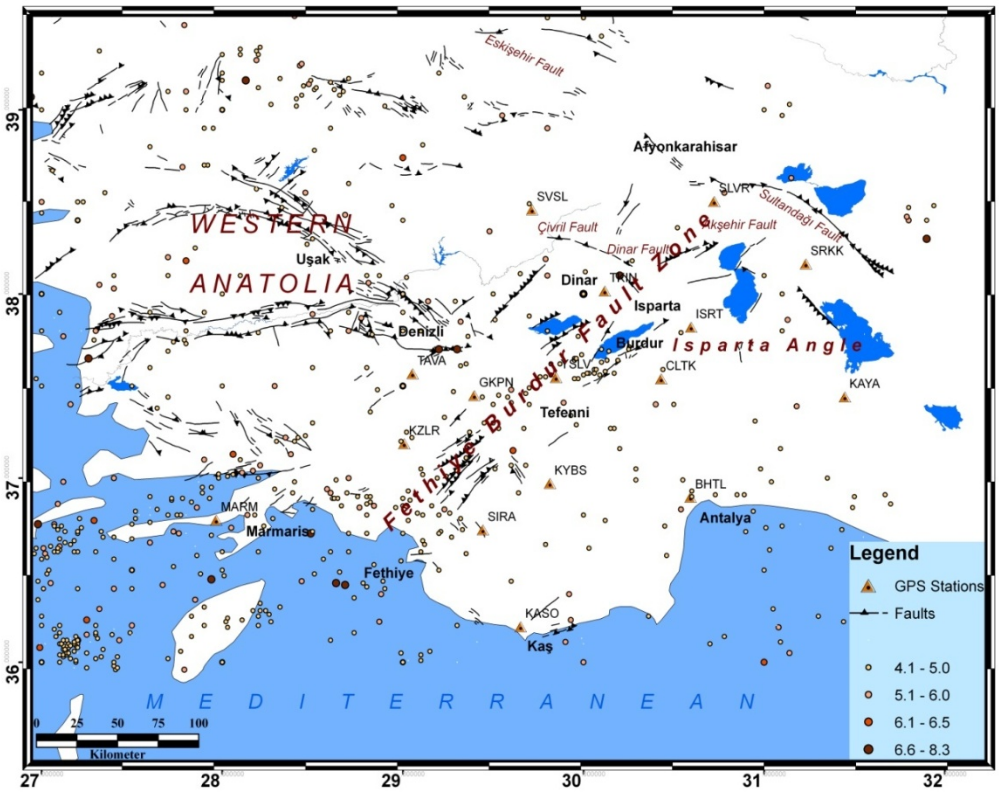
1. Introduction

Active crustal deformation within and around Turkey reflects the interaction between the Eurasian, African, Arabian, and Anatolia plates [1]. The North Anatolian, East Anatolian, Aegean, and Burdur-Fethiye fault zones point to the tectonic activity and diversity of Anatolia. An examination of the earthquakes that have occurred in Anatolia within the last 10 years reveals the importance of this region to geologists.

Since the mid 1980s, the Global Navigation Satellite System (GNSS) has provided earth scientists with new opportunities to estimate present-day surface motions and deformations directly [2, 3]. In the eastern Mediterranean, previous GNSS studies have helped quantify large-scale plate motions [4, 5], regional deformation in the zone of plate interaction [6, 7, 8] and deformations associated with the earthquake cycle [9]. GNSS studies conducted in recent years have demonstrated the presence of a recent expansion in Western Anatolia oriented in a NE-SW direction and developing with a speed of 30 mm/year towards the southwest [8].

Burdur-Fethiye fault zone is located in the southwest of Turkey in a tectonically active area [10]. The fault zone extending between Burdur and Fethiye is one of the most important zones and has produced many earthquakes in the recent past. Three important earthquakes of magnitudes ranging between 6.1 and 7.1 occurred in 1914, 1957, and 1971 in the region. Earthquakes that occurred in the region in the last century are shown on the tectonic map of Western Anatolia in Fig. 1.

Figure 1. Seismicity of the Western Anatolia in the last century with *M*s >4.



2. Tectonic Location of Southwestern Anatolia

Southwestern Anatolia is located in a tectonically critical region. The most active part of the region is Burdur-Fethiye fault zone. Burdur-Fethiye fault zone lies on the boundary between Fethiye gulf and Keçiborlu and extends northeast for 300 km (Fig. 1). The fault follows Senirkent and Hoyran Lake towards the northeast and intersects with the Akşehir-Simav faults in the Afyonkarahisar Çay region [11, 12, 13]. Meanwhile the Burdur and Akşehir-Simav faults form fracture lines, which limit the geological structure known as the Isparta Angle [14]. The Burdur fault line is the most important fault in the region, and events from Fethiye Gulf to Hoyran Lake strike to the northeast as an en-echelon shaped system [15].

In most places the fault zone is not one structural line but consists of short segments having discontinuous parallel lines. These segments are included in a zone which lies towards the northeast and has a width ranging between 3 and 10 km. Segments which extend to the northeast and are included in the zone are mostly limited by younger faults which are normal, direction pitched, and fully grown towards the north and northeast [15]. However, in the district located around the Çameli basin, the width of the tectonic zone reaches up to 30 km. Most of the faults located within the Burdur-Fethiye fault zone also carry the growth faults delimiting the neogene basins of the region [10]. The Cyprus and Hellenic Arc zones form an angle in the Fethiye Gulf shoreline. Formations of this angle have a geometric relationship with the Burdur fault's slip, which is to the left.

3. GNSS Observations

To determine the tectonic characteristics of region 5 campaigning GNSS measurements were performed. Between 2003 and 2006, two of the five campaigns were conducted for a period of six months with daily 12-hour sessions for each site. In the other three campaigns, the network was extended and measurements were conducted in three days with nine-hour sessions. Ashtech and Thales GNSS receivers were used in the sessions with a maximum elevation of 5^{o}. The register interval was chosen as 15 seconds. To provide the necessary relationships and to control internal measurement errors, which can occur in the network, the TKIN and KYBS sites were used as permanent sites in the first four campaigns and continuous measurements were made. In the last campaign, KYBS changed to BHTL because of logistical problems. Information obtained from campaigns was evaluated by GAMIT/GLOBK software. First, data obtained from the land were converted to RINEX format. Evaluations were made in three stages [16, 17]. In the first stage, a Linear Combination (LC) was formed for each day with GAMIT software. Using formed LC station coordinates, atmospheric delays for each station, and orbit information, and input values for analysis were obtained without giving weight to the parameters. In this stage of relating the local network to the IGS network using coordinates which are millimetric sensitive for calculating orbit information and earth rotation parameters, more accurate station points with respect to IGS networks were evaluated separately.

In the second stage, site coordinates, satellite coordinates, and covariance matrices were subjected to Kalman filtering without forcing to obtain accurate velocities and coordinates. To provide stabilization during this stage, local solutions and global IGS solutions edited by SOPAC were evaluated together [8]. In the third stage, a reference system (European frame) was defined for velocity estimations. Different site combinations were used for reference system definition. Horizontal velocities given by ITRF00 a-priori coordinates were minimized and a Eurasian reference system was defined [8]. Many datum stabilization attempts have been realized by means of different site selections related to the project. Site sets were formatted by different attempts and by extracting inappropriate sites. In a later stage, velocity values for different combinations were obtained using five periods' measurements (Fig. 2, table 1). With the support of TUBITAK and with adding 7-11 points to previously measured points, GNSS measurements will be continued between 2009-2011 years.

Figure 2. Horizontal velocity field in the Eurasia-fixed frame (ellipses are at 95% confidence level)

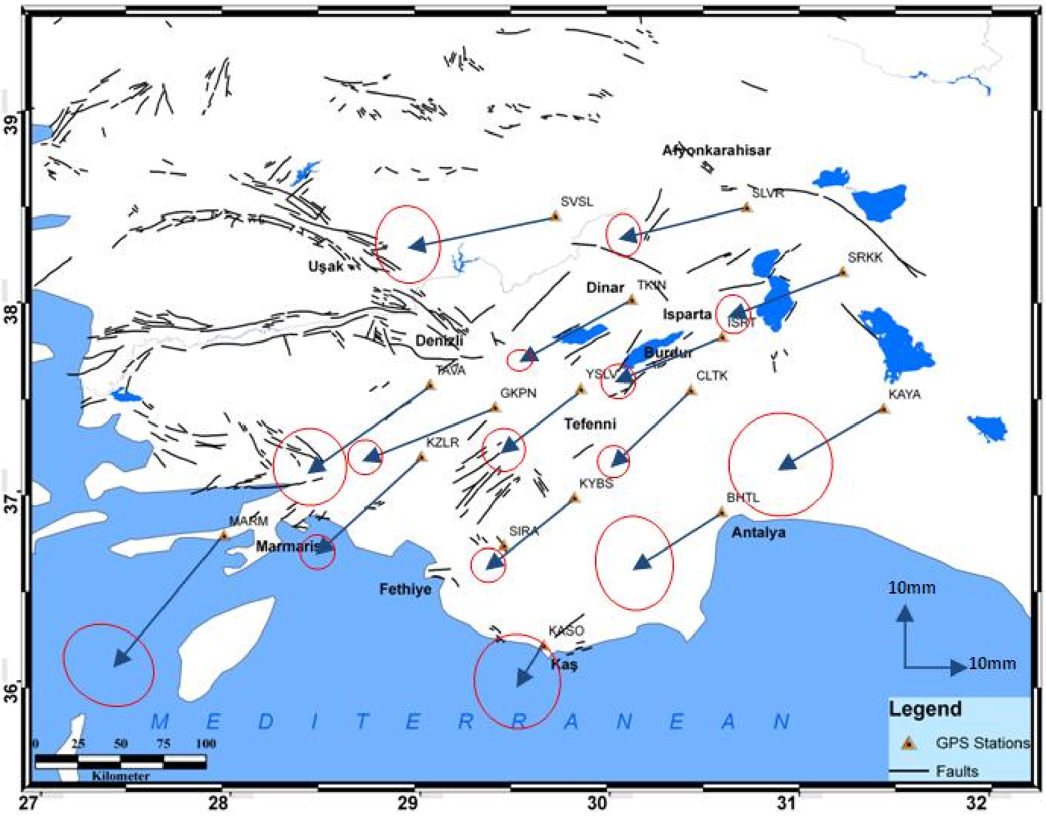


Table 1. Horizontal velocities and corresponding 1σ errors in Eurasia-fixed frame

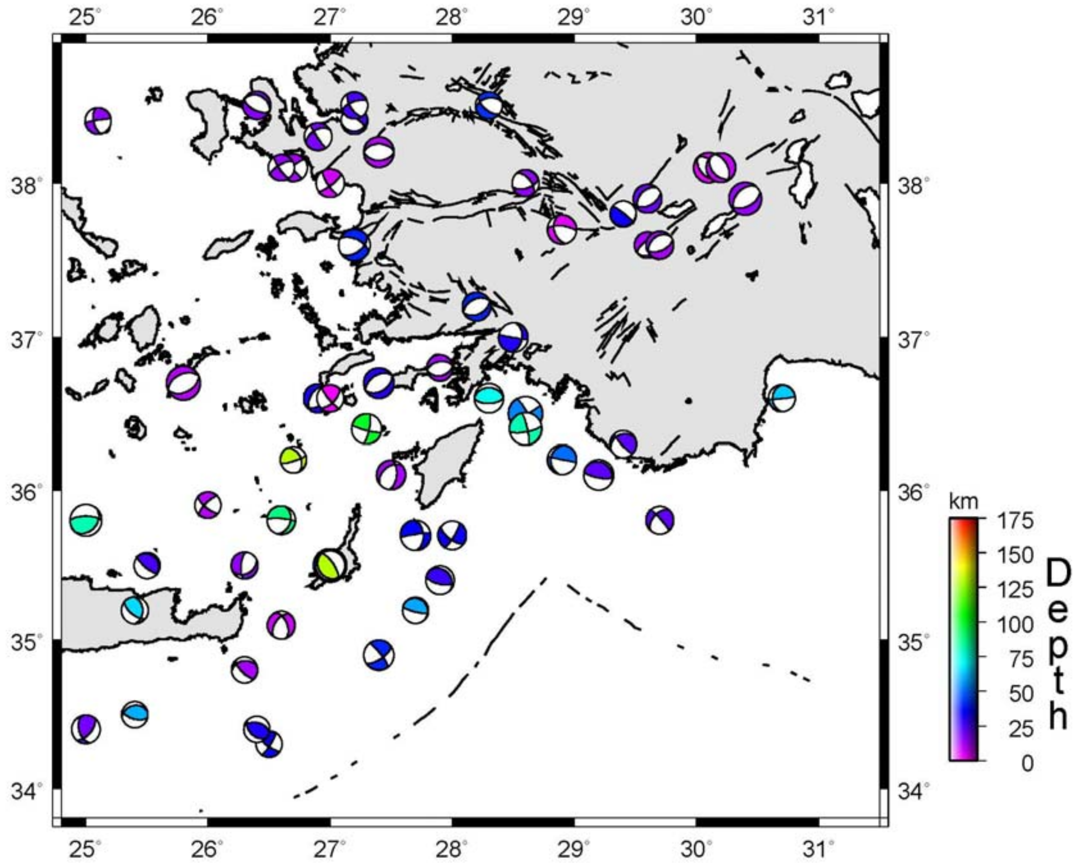
Site	Lat (°)	Lon (°)	V_E (mm)	V_N (mm)	σ_{VE} (mm)	σ_{VN} (mm)
BHTL	36.896	30.589	-13.45	-8.54	3.70	4.09
CLTK	37.53	30.427	-12.06	-11.45	1.47	1.55
GKPN	37.448	29.392	-20.15	-7.98	1.57	1.57
ISRT	37.82	30.592	-16.06	-6.92	1.51	1.61
KASO	36.194	29.648	-4.14	-5.95	3.97	4.24
KAYA	37.436	31.443	-15.9	-9.11	4.67	4.61
KYBS	36.971	29.81	-13.22	-11.14	1.52	1.47
KZLR	37.187	29.003	-15.92	-14.76	1.49	1.49
MARM	36.772	27.963	-16.55	-20	4.25	3.69
SLVR	38.503	30.72	-19.38	-4.82	1.69	1.90
SRKK	38.163	31.228	-16.91	-6.77	1.56	1.74
SVSL	38.458	29.711	-22.40	-4.67	3.10	3.36
TAVA	37.566	29.048	-18.13	-13.42	3.36	3.66
TKIN	38.016	30.114	-16.79	-8.93	1.13	1.01
YSLV	37.547	29.844	-11.43	-9.34	2.15	2.25

4. Seismicity and Seismic Risk Study

Statistical earthquake occurrence models have get more importance while amount of the available earthquake data increase. These models allow one to reduce the large data sets of earthquake occurrences to statistical parameters for any region. They can be used to predict earthquake occurrences, recurrence periods, maximum ground motions, and earthquake hazard at a given region [18].

150 seismic events with magnitudes of 4.0-7.1 took place in the Southwestern Anatolia and three main earthquakes occurred in the region in the last century of magnitudes ranging between 6.1 and 7.1 occurred in 1914, 1957, and 1971. The figure 3 illustrates the focal mechanisms of the earthquakes (M>5.5) that took place in SW Turkey and in the vicinity of NE Hellenic arc region. Most of the fault plane solutions of the events since 1977 are taken from Harvard Centroid Moment Tensor (CMT) catalogue. Also, the focal mechanisms of the 1914 Burdur earthquake (M=7.2) and the focal mechanisms of the 1957 Fethiye-Rhodos earthquake (M=7.2) are included. These are the largest two events that stroke the study region [19]

Figure 3 The focal mechanisms of the earthquakes in the Southwest Anatolia (M>5.5) [19].



The seismicity study will be carried out together with GNSS measurements with support of TUBITAK between 2009-2011 years. First of all, a seismicity study will be conducted in order to determine the earthquake risk associated with the region of interest. For this purpose, earthquakes of magnitude M≥ 4 which have taken place within approximately a 200-km radius of the city of Isparta since 1900 will be collected and clustered into two groups with respect to the year of occurrence: 1900-1964 and 1964-2007. The main region will be divided into sub-regions of dimension 25x25 km and for each sub-region; the parameters a and b in the equation Log N= a-bM [20] will be computed using the cumulative least-squares method, the maximum likelihood method, and the Kaltek method; and the parameter b, which is accepted to be the measure of seismicity, will be mapped for each of the three methods. The earthquake risk in the region, the highest possible earthquake magnitude, the period of rotation, the probability of occurrence and the fault systems that could potentially be involved in the occurrence will then be determined by manipulating this data through Poisson and Markov distributions and the Gumbel extreme values (1^{st} and 3^{rd} asymptotes). The amounts of acceleration that would affect the city center in the case of an earthquake driven by the identified fault systems will be calculated by means of the available empirical relations. After that, these acceleration values will be compared with those recorded in the region (recordings of the strong-motion seismographs we placed) and the relations for the region of interest will be either revised or improved.

In order to predict the effectiveness and the repetition period of future earthquakes, it is necessary to know the values of parameters associated with the past earthquakes such as occurrence time, epicenter coordinates, magnitude or strength and depth of focus. Researchers have focused on the determination of seismic risk by means of various statistical models, making also use of the above mentioned parameters. Of these models, the two most common are Poisson and Markov models. In a Markov model, future earthquake occurrences are dependent on the past occurrences. In a Poisson model, on the other hand, earthquake occurrences follow a Poisson process under the assumption that earthquake events are independent from each other. The two models have been observed to yield different results. The third statistical method to be used here is the Weibull distribution which is a special form of the Poisson model. According to this model, earthquake occurrences are thought of as being events that can be determined by the deformation statistics in the Earth's crust and seismic risk analyses are performed assuming that crustal tension increases linearly with time.

5. Strain analysis and Coulomb Stress Accumulation

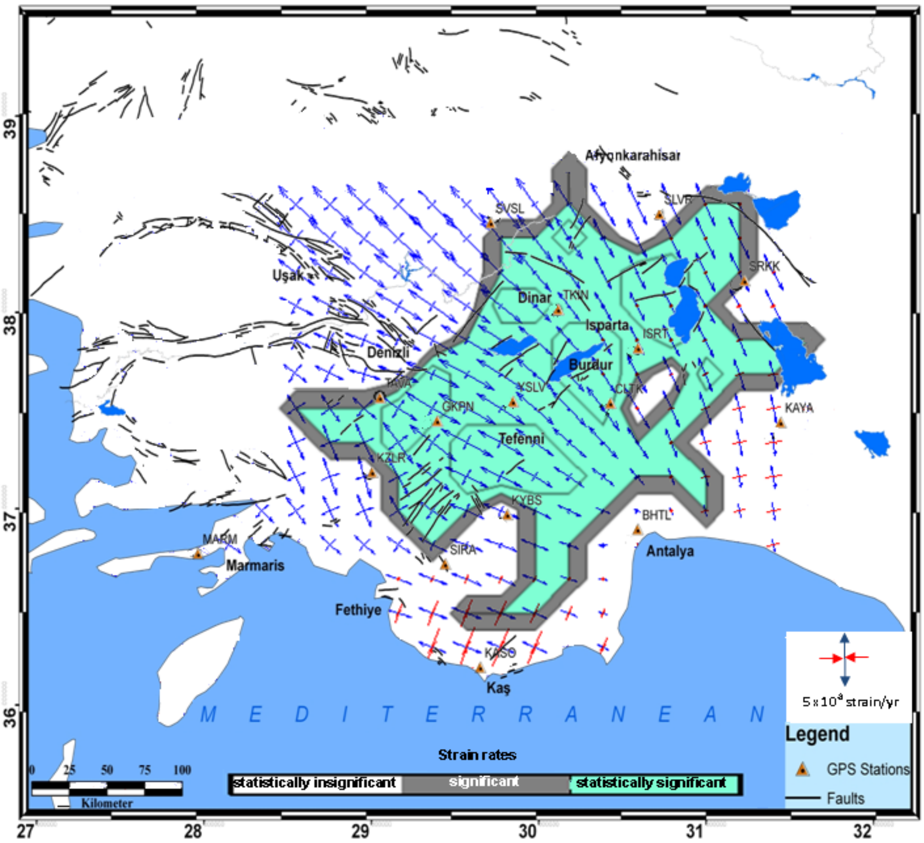
In view of velocity values gathered from GNSS measurements conducted between 2003-2006 years, analyzing of strain measurement points and strain analyses aimed at determination of block model, were made, Coulomb stress accumulation will be used for explain earthquake and faulting by up graded velocity data gathered from GNSS measurements.

The accuracy of the Coulomb stress changes due to an earthquake is directly related to the accuracy of the source parameters of that earthquake used in calculations. The more accurate the source parameters (i.e. the length, the width and the location of the fault rupture, as well as the distribution and the amount of slip thereon) are, the more reliable the calculated static stress changes will be. Therefore, very accurate extraction of the earthquake source parameters is highly important. Errors in the slip distribution and the fault geometry can lead to significant distortions in the Coulomb Stress accumulation.

Between 2003-2006 years, strain analysis sourced from GNSS measurement velocities was performed with grid_strain software. The problem was considered as two-dimensional. Because the GNSS measurements can only provide deformation rates on the earth's surface (x (EW) and y (NS) directions), and do not give any information on deformation rates in the radial direction (z).

The results of the strain computation on all the grid points are presented immediately after the conclusion of the iterations [21]. The eigenvectors are presented with their directions and two colors: if an eigenvalue is positive, (extension) the color is blue, whereas the color is red in the case in which the eigenvalue is negative (compression) (Fig 4).

Figure 4 Principal Strain rates. Blue and red arrows show maximum extension and compression, respectively in 10^{-7} strain/year



6. Results and Discussion

In this study it was found that the region is affected by a southwestern movement of 15-30 mm/yr. The most important findings of the study were velocity values for three years' measurements of the region. The TAVA, SVSL, MARM, KASO, BHTK, and KAYA stations show larger error ellipses than other sites. The main reason for this was that velocity values for these sites were calculated from three campaigns in two years, while the other sites velocity values were calculated from five campaigns in three years. Another reason was that measurement durations were long and repeated measurements were not made during the first and second periods [22]. It is considered that this phenomenon will be improvement with measurements that will be made in 2009-2011 years.

When the strain vectors between the SLVR and SRKK points were investigated there was found to be an extension in the region. Furthermore, when the fault plane solutions of the earthquake of Sultandağı considered, this extension structure is consistent with the velocity values too [23]. An examination of the ISRT, TKIN, and SVSL points revealed that the velocities were investigated consistent with the tectonic features of this region, and that the NW-SE extension is also active between TKIN and SVSL stations. The cause of the expansion can be addressed to Çivril fault. When the fault plane solutions of the earthquake of

Dinar (1995) examined (Fig 3) an NW-SE extension is shown controversy to the strain values of the region. This situation will be examined by GNSS measurements that will be made on the newly added GPS points at the 2009-2011 years. When the velocity vectors between the YSLV and CLTK points investigated these points located on the same zone. In fact, these two points are situated on the same block in the model of Reilinger et al. 2006 [3].

An extension movement was observed between the CLTK and TKIN points, which have been defined by Yağmurlu et al. 2005 [10]. The reason for these facts is the periodic formation of NW-SE directed attraction forces and the related formation of NE-SW oriented normal faults in the zone around Lake Burdur, since the Yeşilova peridotite mass to the south of this lake is of a nature that partially restrains the SW-directed slipping movement. As for the GKPN-KYBS and GKPN-YSLV points, an extension movement was visible. The NE-SW directed opening between the KZLR-TAVA and the KZLR-GKPN points suggest that the strike-slip moving the GKPN point is not located on the same block as the TAVA and KZLR points according to the model of Reilinger et al. 2006 [3].

An extension movement was observed between the CLTK and ISRT points, which has been defined by Yağmurlu et al. 1997 [14] as the "Antalya Fault Zone", and by Glover and Robertson (1998) as Kemer linearity. The expansion between the Antalya and Isparta shows that the fault system which parallel to the Eğirdir Kovada graben is active [24]. Consideration of the KAYA site demonstrates that directional pitched movements are effective in the region, and the Kirkkavak fault, which is right directional, is verified. Consideration of the SRKK, SLVR, YSLV, KYBS, KASO, and BHTL sites, which are shown in the same block by Reilinger et al. 2006 [2], and lie on the right-hand side of the Burdur fault zone, shows that these sites have a counterclockwise rotation. When the fault plane solution of the earthquake of 1957 Fethiye-Kaş earthquake examined, it was consistent with the compression in the Kaş region. This supports the movement, which was highlighted but was not noted clearly by McClusky et al. 2000 [8, 25].

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