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The 10 June 2012 Fethiye M_w 6.0 aftershock sequence and its relation to the 24–25 April 1957 M_s 6.9–7.1 earthquakes in SW Anatolia, Turkey

Ethem Görgün^{a,*}, Arno Zang^{b,1}, Doğan Kalafat^{c,2}, Kivanç Kekovalı^{c,2}

^a Department of Geophysical Engineering, Istanbul University, 34320 Avcılar, Istanbul, Turkey

^b German Research Center for Geosciences GFZ, Section 2.6: Seismic Hazard and Stress Field, Telegrafenberg, 14473 Potsdam, Germany

^c Boğaziçi University, Kandilli Observatory and Earthquake Research Institute, National Earthquake Monitoring Center, 34684 Çengelköy, Istanbul, Turkey

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ABSTRACT

The 10 June 2012 M_w 6.0 aftershock sequence in southwestern Anatolia is examined. Centroid moment tensors for 23 earthquakes with moment magnitudes (M_w) between 3.7 and 6.0 are determined by applying a waveform inversion method. The mainshock is a shallow focus strike-slip with reverse component event at a depth of 30 km. The seismic moment (M_0) of the mainshock is estimated as 1.28×10^{18} Nm and rupture duration of the Fethiye mainshock is 38 s. The focal mechanisms of the aftershocks are mainly strike-slip faulting with a reverse component. The geometry of the focal mechanisms reveals a strike-slip faulting regime with NE–SW trending direction of T -axis in the entire activated region. A stress tensor inversion of focal mechanism data is performed to obtain a more accurate picture of the Fethiye earthquake stress field. The stress tensor inversion results indicate a predominant strike-slip stress regime with a NW–SE oriented maximum horizontal compressive stress (S_H). According to variance of the stress tensor inversion, to first order, the Fethiye earthquake area is characterized by a homogeneous interplate stress field. The Coulomb stress change associated with the mainshock and the largest aftershock are also investigated to evaluate any significant enhancement of stresses along the Gulf of Fethiye and surrounding region. Positive lobes with stress more than 0.4 bars are obtained, indicating that these values are large enough to increase the Coulomb stress failure towards NNW–SSE and E–W directions.

1. Introduction

The Fethiye earthquake (EQ) occurred at 12:44:16.9 GMT on 2012 June 10. The mainshock was a moderate size ($M_w = 6.0$) event at a depth of 30 km. The Fethiye EQ is located along the Fethiye-Burdur Fault Zone (FBFZ) of the western Anatolia extensional system (Fig. 1). The mainshock is revealed by a strike-slip motion with a reverse component. Fault rupture zone of an earthquake of this size extends typically from 8 to 20 km length. This region is one of the most seismically active parts of the western Anatolia extensional tectonic regime. The western Anatolia is characterized by very uniform (in magnitude and orientation) plate velocity vectors from Global Positioning System (GPS) indicating SW motion at about 30–40 mm/yr (Fig. 1, McClusky et al., 2000; Reilinger et al., 2006, 2010). It is dominated by a series of graben and horst structures bounded by normal or oblique faults (Taymaz et al., 1991; Koçyiğit et al., 2000; Bozkurt, 2001). The main tectonic structures of the eastern Mediterranean region are the Aegean and Cyprus arcs that compose convergent plate boundaries where the African plate (AF) to the south is subducting beneath the Anatolian (AT) and Aegean Sea plates (AS) to the north (inset in Fig. 1). Subduction in the eastern Aegean arc has traditionally been interpreted as occurring along the Pliny and Strabo trenches. Compressional motion is transformed into strike-slip on the Pliny and Strabo trenches (McClusky et al., 2003; Gürer et al., 2004; Nyst and Thatcher, 2004;

ten Veen et al., 2004). A line with a projection of the Pliny trench along the Rhodes Island and southwest Turkey is interpreted as the Rhodes Transform Fault (RTF) and Fethiye-Burdur Fault Zone (FBFZ) (see Fig. 1; McClusky et al., 2003; Gürer et al., 2004; Nyst and Thatcher, 2004; Reilinger et al., 2010; Çevikbilen and Taymaz, 2012). Bathymetric trends associated with the Pliny trench in the Rhodes basin link with N70°E striking faults in the Turkish continental slope. This basin is the continuation of the Pliny trench. This interpretation, strongly supported by marine geophysical data (ten Veen et al., 2004), precludes an alternative interpretation in which the Pliny trench is related to the hypothetical FBFZ, a correlation previously suggested by several authors (Taymaz and Price, 1992; Barka et al., 1997; Temiz et al., 1997; ten Veen et al., 2004). The FBFZ and RTF are evaluated as a wide left lateral fault zone with a large component of extension and well-defined seismicity (Taymaz et al., 1991; Taymaz and Price, 1992; McClusky et al., 2000, 2003; Gürer et al., 2004; Nyst and Thatcher, 2004; Reilinger et al., 2010; Çevikbilen and Taymaz, 2012). Magnetotelluric studies in south-west Anatolia revealed that the depth of the crust/upper mantle boundary varies between 30 and 50 km (Gürer et al., 2004). On the basis of S receiver functions, the lithosphere–asthenosphere boundary of the subducting AF is at 100 km depth beneath the southwestern part of Anatolia and dips beneath the volcanic arc to a depth of about 225 km and therefore implies a thickness of 60–65 km for the subducted African lithosphere (Sodoudi et al., 2006).

In this study, a stress tensor inversion of earthquake focal mechanism data is performed to obtain a more accurate picture of the Fethiye EQ stress field. For this purpose, seismic waveforms at local and regional distances are used to calculate source parameters of 23 events ($3.7 \leq M_w \leq 6.0$) of the Fethiye M_w 6.0 EQ seismic sequence using the waveform inversion method (Nakano

* Corresponding author. Fax: +90 212 4737180.

E-mail addresses: ethem.gorgun@istanbul.edu.tr (E. Görgün), zang@gfz-potsdam.de (A. Zang), kalafato@boun.edu.tr (D. Kalafat), kekovalı@boun.edu.tr (K. Kekovalı).

¹ Fax: +49 331 2881127.

² Fax: +90 216 3083061.

Figure 1. Tectonic map of western Turkey showing GPS velocities with respect to Eurasia and 95% confidence ellipses for western Anatolia (McClusky et al., 2000; Reilinger et al., 2006). Seismically active faults are shown by red lines (Şaroğlu et al., 1992). Blue, black and red triangles with station codes depict locations of the KOERI, AFAD and NOA broadband seismic stations, respectively. The epicenter of the 2012 Fethiye EQ is indicated by the red star. For reference, focal mechanisms of the previous significant earthquakes are plotted (Tan et al., 2008; Kalafat et al., 2009). FBFZ and RTF stand for Fethiye–Burdur Fault Zone and Rhodes Transform Fault, respectively. Two closely spaced black and red single arrows display shear sense of major faults. Black and white circles on beach-balls exhibit *P* and *T*-axes, respectively. The inset in the above left shows whole Turkey. Boundaries (heavy colored red lines) of the Aegean Sea (AS) and Anatolian (AT) plates, which are surrounded by the African (AF), Arabian (AR) and Eurasian (EU) plates (Bird, 2003). The solid black rectangle shows the study area, which is enlarged in Fig. 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

et al., 2008). This provides additional information on the stress field that may improve kinematic models for the FBFZ and thus develop the understanding of the local and regional tectonics. Furthermore, the Coulomb stress analysis is applied to determine the expanded spatial distribution of the Fethiye EQ seismic sequence. Determination of accurate source parameters, especially source locations, using data from the local and regional seismic network are crucial for investigations of the seismotectonics in and around Turkey.

2. Data and waveform inversion method

Fig. 1 displays the distribution of the Kandilli Observatory and Earthquake Research Institute (KOERI), Disaster and Emergency Management Presidency Earthquake Department (AFAD) and the National Observatory of Athens (NOA) broadband seismic stations used in this study. We use seismic records obtained from 8 KOERI stations, 3 AFAD stations and 2 NOA stations in this study (see Fig. 1).

Centroid moment tensor (CMT) solutions of earthquakes along the FBFZ are computed using the waveform inversion method developed by Nakano et al. (2008). In this approach, if the location yielding a minimum residual lies at the edge of a search area, the grid is extended to surround the location of the minimum residual. When the location of minimum residual lies within a search area, a new search is performed around the location using a reduced grid spacing to find a detailed source location. The seismic moment and rupture duration are estimated from the deconvolved form of the moment function (Nakano et al., 2008, 2010).

Three-component seismograms are used for the inversion of Simav EQ seismic sequence. Seismograms with good data quality are selected. The average number of waveforms used for the CMT analysis is 10. The observed velocity seismograms are corrected for instrument response and then integrated in time to obtain the displacement seismograms. Waveforms are bandpass filtered between 50 and 100 s and decimated to a sampling frequency of 0.5 Hz. A total data length of 512 s (256 data points in each channel) is used for the inversion. Green's

Table 1

Crustal model used to estimate the source parameters of the mainshock and its aftershocks. V_p and H are P -wave velocity and thickness of the layers, respectively.

V_p (kms ⁻¹)	H (km)
4.73	0.0–1.5
5.06	1.5–3.0
5.84	3.0–5.0
6.00	5.0–15.0
6.25	15.0–21.0
6.43	21.0–29.0
7.80	29.0–

functions are generated using the discrete wavenumber method (Bouchon, 1979), assuming the crustal structure model of Akyol et al. (2006) for the calculation. The synthetics are calculated for a horizontally layered structure given in Table 1. Green's functions are computed for every 10 km of epicentral distance up to 1500 km. At each of these radius steps, three-component displacements are calculated at every 1° in azimuth for each basis of moment tensor. Green's functions are calculated at every 5 km for source depths shallower than 100 km. For spatial grid search, hypocenter locations estimated by KOERI are used as an initial location. Adaptive grid spacings, in which the grid spacings are gradually decreased in each step of the search, are also applied. Spatial grid search is started with a horizontal grid spacing of 0.5° and a vertical grid spacing of 10 km. In the next step, the grid spacing is reduced to 0.2° horizontally and 5 km vertically. Finally, the horizontal grid spacing is reduced to 0.1°. At each grid point, the fault and slip orientation parameters (strike, dip and rake angles) are searched in 5° steps. For each combination of source location, fault and slip orientation parameters, the waveform inversion is carried out to estimate the best-fitting source parameters (see Nakano et al., 2008, 2010 for details).

The CMT solutions are obtained using data only from

stations in Turkey, and therefore azimuthal coverage is sufficient. The inversion method of Nakano et al. (2008) uses the double-couple constraint, which stabilizes the inversion solution and reduces the trade-off between source location and non-double-couple components (see Nakano et al., 2008, for details). Furthermore, all stations used are only located in Anatolia thus; possible effects of the structural contrast may be minimized.

3. Stress tensor inversion

The stress tensor has six unknown, either three principal stresses and orientations, or three normal and three shear stress components (e.g., Zang and Stephansson, 2010). Four of the unknown are resolved by the inversion of the stress tensor, the fifth unknown is calculated by the assumption that slip occurs in the direction of maximum shear stress (Wallace–Bott hypothesis), and the sixth unknown is usually resolved using the assumption that the stress tensor is homogeneous and constant in the binning region throughout the time interval of interest.

In this study, the technique of Michael (1984, 1987) is applied to the selected 23 events. The Michael-approach provides a more appropriate estimate of uncertainty (Hardebeck and Hauksson, 2001). The algorithm uses the statistical method of bootstrap re-sampling and allows determining the orientation of the three principal stresses (σ_1 = maximum principal compressive stress, σ_2 = intermediate and σ_3 = minimum) as well as the stress ratio $\phi = (\sigma_2 - \sigma_3)/(\sigma_1 - \sigma_3)$, also called relative stress magnitude (Bott, 1959). The ϕ is defined using the standard geologic/geophysical notation with compressive stress positive and $\sigma_1 > \sigma_2 > \sigma_3$ (Zoback, 1992). The stress ratio ϕ ranges from 0 to 1. Values of $\phi < 0.5$ and $\phi > 0.5$ indicate a transpressional and transtensional regime, respectively. All parameters are determined by finding the best fitting stress tensor to the observed focal mechanisms. Assump-

Table 2

Locations and source parameters of the 10 June 2012 Fethiye EQ and its sequence. H is depth, M_w is moment magnitude, Str is strike angle and R is the normalized residual of waveform fitting.

No	Date	Time (GMT)	Lat (°N)	Lon (°E)	H (km)	M_w	Str (°)	Dip (°)	Rake (°)	R
1	10.06.2012	12:44:16.9	36.445	28.909	30	6.0	262	69	49	0.06
2	10.06.2012	15:02:40.9	36.463	28.898	29	4.0	240	30	15	0.04
3	10.06.2012	15:11:00.8	36.466	28.919	30	3.9	277	69	-131	0.02
4	10.06.2012	18:28:33.7	36.454	28.942	33	4.0	225	60	15	0.04
5	10.06.2012	18:42:29.7	36.443	28.929	23	3.7	280	60	125	0.07
6	10.06.2012	22:31:45.6	36.414	28.914	25	3.7	30	90	-45	0.08
7	11.06.2012	02:06:35.3	36.393	28.966	35	3.8	330	45	-30	0.02
8	11.06.2012	06:58:50.8	36.431	28.935	40	3.8	210	90	-30	0.03
9	11.06.2012	14:00:18.6	36.410	28.977	22	4.1	310	60	125	0.05
10	11.06.2012	17:35:38.6	36.394	28.984	30	3.9	195	60	45	0.03
11	11.06.2012	19:51:06.7	36.428	28.971	27	3.8	195	75	0	0.04
12	12.06.2012	21:58:12.6	36.433	28.930	30	4.5	285	45	75	0.06
13	13.06.2012	08:59:07.9	36.450	28.922	25	4.1	240	30	45	0.07
14	14.06.2012	16:46:07.5	36.383	29.051	36	4.8	45	60	15	0.04
15	14.06.2012	20:41:28.1	36.429	28.915	33	4.1	90	75	180	0.05
16	23.06.2012	04:26:06.5	36.444	28.919	28	3.7	251	76	164	0.07
17	25.06.2012	13:05:29.7	36.445	28.951	34	5.0	179	64	-34	0.03
18	25.06.2012	14:33:30.7	36.454	28.934	29	4.5	225	75	45	0.02
19	09.07.2012	13:54:58.2	35.511	28.983	50	5.4	210	90	0	0.06
20	31.07.2012	08:26:14.9	36.275	28.925	40	3.9	195	75	0	0.08
21	07.08.2012	11:05:01.3	36.395	28.719	55	4.1	210	90	-15	0.07
22	20.10.2012	01:09:40.7	36.552	28.232	35	4.1	30	30	-15	0.02
23	13.11.2012	18:25:49.7	36.521	28.223	30	4.1	255	75	30	0.05

Figure 2. (a) Topographic map view of CMT solutions obtained by the waveform inversion method developed by Nakano *et al.* (2008). Focal mechanisms are projected on the lower hemisphere and scaled with magnitude. Black and white circles on beach-balls exhibit *P* and *T*-axes, respectively. (b) Epicenter distribution of the Fethiye aftershocks along the mainshock region. Red circle represents the Fethiye mainshock. A-A' is the depth cross-section profile. Cross-section is perpendicular to the strike of the fault rupture. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

tions that must be fulfilled by the input data are: (1) stress is uniform in the area of interest during the observed time interval, (2) earthquakes are shear-dislocations on pre-existing faults, (3) similar shear stress magnitude are present on each fault and (4) slip occurs in the direction of the resolved shear stress on the fault plane.

To quantify the misfit between the best stress tensor and the data, the angle between the calculated slip vector from stress tensor inversion and observed slip vector from fault plane solutions is used. This angle is referred to as β . The angle $\bar{\beta}$ refers to the mean value of β for the data in a single inversion (Michael, 1987). A synthetic control study showed that the amount of heterogeneity in the stress field could be characterized by the average misfit between the observed and predicted slip directions ($\bar{\beta}$) (Michael *et al.*, 1990). If $\bar{\beta} \leq 33^\circ$, stress tensors are spatially uniform. If $\bar{\beta} > 33^\circ$, the inversion result is interpreted in terms of a spatially heterogeneous state of stress (Michael, 1991). Heterogeneity of the stress field is documented in the average misfit level of the inversion. For each stress inversion, 2000 bootstrap iterations are performed.

4. Results

The waveform inversion of earthquakes is carried out with local magnitudes (M_L) ≥ 3.5 determined by KOERI. CMT solutions are computed for 23 earthquakes in the period between 2012 June 10 and November 13 (Fig. 2a and Table 2). The moment magnitudes (M_w) range from

3.7 to 6.0. Fig. 2a shows 23 fault plane solutions in lower hemisphere equal-area/angle projection in map view. The along strike dimension of the activated zone is approximately ~ 30 km and its width is ~ 20 km, in accordance with the magnitude of the largest event of the sequence ($M_w = 6.0$). Most of the aftershock focal mechanisms depict left-lateral strike-slip faulting with reverse component. Based on the focal mechanisms and aftershock distribution, the NNW-SSE trending planes are the fault planes (Fig. 2a and b). A number of aftershocks are located off the main aftershock cluster. This observation is also indicated in the cross-section perpendicular to the strike of the fault rupture (Fig. 2b). The best constrained focal depths from CMT solutions show that the sequence is mainly confined in the crust ($20 \leq H \leq 40$ km) and is reaching in the approximate depth range from 20 to 55 km. The main aftershock cluster (Fig. 3) is clearly depicted in the ~ 20 km width narrow vertical zone of the cross-section.

4.1. June 10, 2012, $M_w = 6.0$ Fethiye earthquake (mainshock)

First, the source centroid location and focal mechanism of the mainshock are estimated. Waveforms recorded by six stations (AYDB, BODT, FETY, KARP, MLSB and YER; Fig. 4a, blue triangles), which are located at epicentral distances ranging from approximately 25 to 190 km are used. Fig. 4a shows the horizontal residual distribution around the best fitting source location obtained from the waveform inversion. The best fitting source location is at 28.909°E , 36.445°N at a depth of 30 km (Fig. 4a). Using

Figure 3. Cross-section profile for A-A' in Fig. 2b. This is a zooming for the narrower region along the mainshock area. The aftershock sequence operates in the depth range from 20 to 40 km for $M_w \geq 3.7$ events. Orientation of aftershocks trends NNW-SSE. The main aftershock cluster is clearly depicted in the ~20 km width vertical zone of the cross-section.

the hypocenter location determined by KOERI as an initial source location, the waveform inversion searched for the best-fitting source parameters. Revised source locations vary in average 4 km horizontally and 5 km vertically with respect to the initial locations of KOERI, but this variation does not change the general pattern in seismicity. Location differences depend on velocity model, station coverage and number of stations participated in finding the hypocenter. The observed velocity waveforms are corrected for instrument response, and then they are integrated in time to obtain the displacement seismograms. The focal mechanism of the mainshock obtained at the best fitting source location is related to strike-slip with reverse component motion (Fig. 4b), characterized

by a nodal plane with strike, dip and rake 262° , 69° and 49° , respectively. The seismic moment of the mainshock is estimated as $M_0 = 1.28 \times 10^{18}$ Nm, and the corresponding moment magnitude is $M_w = 6.0$.

The seismic moment function obtained from the waveform inversion is shown in Fig. 5a. The rupture duration estimated from the moment function is 38 s (Fig. 5a). Waveform fits between observed and synthetic seismograms calculated for the best fitting source parameters are shown in Fig. 4c (Nakano et al., 2008 for details on the approach). Waveform fits are in good agreement with a normalized residual (R) of 0.06 (Fig. 4c). The residuals are calculated for each focal mechanism solution in this study. Fig. 6 shows a histogram of residuals for all focal mechanism solutions.

4.2. The 2012 Fethiye seismic sequence

In this section, the two largest aftershocks of the Fethiye seismic sequence are presented. Some specific large size events are chosen as an example. It would be interesting to present these large size aftershocks whose focal mechanisms differ from the one of the mainshock since the majority of the data are small size aftershocks. These events are representative of the aftershock data set. The results of the representative events are given in Table 2 and Figs. 7 and 8.

The 25 June 2012 M_w 5.0 event is investigated (event #17, Table 2 and Fig. 7). Waveforms recorded by five stations are used (ANTB, AYDB, BODT, DALY, KORT; Fig. 7a, blue triangles), which are located at epicentral distances ranging from 50 to 190 km. The observed velocity waveforms are corrected for instrument response, and then integrated in time to obtain the displacement seis-

Figure 4. June 10, 2012, $M_w = 6.0$ Fethiye mainshock. (a) Map showing the source centroid locations and contour plots of the horizontal residual distribution around the best-fitting source (red star). Blue and red triangles with station codes indicate locations of the KOERI and NOA broadband stations, respectively. (b) Estimated focal mechanism and source parameters of the event. (c) Waveform fittings obtained from the waveform inversion. Black and red lines represent the observed and synthesized seismograms, respectively. The station code and component of motions are indicated at the upper right of each seismogram. Maximum and minimum displacements are shown at the upper right of each seismogram. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 5. Comparison of the moment functions (m^f , red line) and the functions m_d^f (green line) obtained from the waveform inversion of the Fethiye mainshock (a) and the two large aftershocks (b and c). Blue line represents the deconvolved form of the moment function (m_d). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mograms. Fig. 7a shows the horizontal residual distribution. A well-defined global minimum residual is found, which is at 28.951°E , 36.445°N at a depth of 34 km. This aftershock is located at the same location as the mainshock. The estimated focal mechanism is indicated in Fig. 7b; a nodal plane corresponds to (strike, dip and rake) = $(179^\circ, 64^\circ \text{ and } -34^\circ)$. The focal mechanism of this event is strike-slip faulting with normal component. This indicates that the aftershock does not have the similar focal mechanism as the mainshock. The compressional axis is NE–SW. The rupture duration estimated from the moment function is 20 s (Fig. 5b). The fits between observed and synthesized seismograms are shown in Fig. 7c. The small residual ($R = 0.03$) indicates that the observed seismograms are in good agreement with the synthetic ones (Fig. 7c).

The second sample of event occurred 125 km south of

Figure 6. A histogram of residuals for all focal mechanism solutions.

the main-shock on 2012 July 9 (Fig. 8 and Table 2, event #19). The wave-forms observed at stations ARG, BODT, FETY, KARP, TURN and YER are used. These stations are located at epicentral distances ranging from approximately 110 to 228 km. The focal mechanism of this event is a pure strike-slip motion. The compressional axis is directed ENE–WSW (Fig. 8b). Waveform fits between observed and synthesized seismograms are displayed in Fig. 8c. A small residual is calculated ($R = 0.06$). A well-defined global minimum residual is found, which is at 28.983°E , 35.511°N at a depth of 50 km. The M_0 and M_w for the event are estimated as 1.78×10^{17} Nm and 5.4, respectively. The rupture duration estimated from the moment function is 32 s (Fig. 5c).

4.3. Analysis of stress tensors

The results of the stress tensor inversion are presented in Fig. 9 and Table 3. The measure of the misfit values is evaluated by the areas of 95% confidence limit (see Fig. 9). Stress tensor inversion of the Fethiye EQ aftershocks reveals a low level of non-uniform stress for the entire catalog ($\bar{\beta} = 39^\circ$) according to Michael (1991). The maximum principal stress, σ_1 , trends $\text{N}16^\circ\text{W}$ with a plunge of 5° and the minimum principal stress, σ_3 , trends $\text{N}76^\circ\text{E}$ with a plunge of 18° (Fig. 9). The resulting stress tensor corresponds to a transpressional regime ($\phi = 0.35$). The orientation of maximum horizontal compressive stress (S_H) is NW–SE and strike-slip stress regime is found for the study region.

Low variance (0.17, Table 3) indicates a good fit of homogeneous stress tensor to the observed focal mechanism, and shows low heterogeneity of the stress field (Michael et al., 1990; Lu et al., 1997; Wiemer et al., 2002; Bohnhoff et al., 2006; Görgün et al., 2010). The results from the stress tensor inversions based on 23 focal mechanisms are shown in map view in Fig. 10. The directions of the maximum principal stress (σ_1) are plotted along the Fethiye EQ region (Fig. 10, blue bars). The alignment of σ_1 is NNW–SSE. Deformation regimes obtained from the stress tensor inversion indicate the predominant strike-slip stress regime in the mainshock area in Fig. 10 (blue bars). Wiemer et al. (2002) concluded that a low degree of heterogeneity in stress field (variance < 0.2) indicates uniformity. There is no significant variance in stress tensor orientations (variance < 0.2). Thus, to first order, the Fethiye EQ region is characterized by a homogeneous interplate stress field.

Figure 8. June 25, 2012, $M_w = 5.0$ aftershock following the Fethiye mainshock. The same as Fig. 4. Blue and black triangles with station codes indicate locations of the KOERI and AFAD broadband stations, respectively. Other details are similar to those of Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 8. July 9, 2012, $M_w = 5.4$ aftershock following the Fethiye mainshock. The same as Fig. 4. Blue, black and red triangles with station codes indicate locations of the KOERI, AFAD and NOA broadband stations, respectively. Other details are similar to those of Fig. 4. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

4.4. Calculation of the Coulomb stress change

The static Coulomb stress change caused by a mainshock has been widely applied to assess areas of subsequent off-fault aftershocks (Reasenber and Simpson, 1992; Toda et al., 2008; Toda et al., 2011). The Coulomb stress change is defined as $\Delta CFF = \Delta\tau + \mu\Delta\sigma$, where τ is the shear stress on the fault (positive in the inferred direction of slip), σ is the normal stress (positive for fault unclamping) and μ is the apparent friction coefficient. Failure is promoted if ΔCFF is positive and inhibited if negative; both increased shear and unclamping of faults are taken to promote failure, with the influence of unclamping controlled by fault friction (Toda et al., 2011). After the occurrence of an earthquake, the areas with

positive values of ΔCFF are loaded with stress. To resolve the Coulomb stress change on a ‘receiver fault’ (fault receiving stress from a mainshock) requires a source model of the earthquake fault slip, as well as the geometry and slip direction on the receiver (Toda et al., 2011). It is assumed that the receiver faults share the same strike, dip and rake as the mainshock source fault, and we can resolve stress on a major fault of known geometry (McCloskey et al., 2003). We can also find the receiver faults at every point that maximize the Coulomb stress increase given the earthquake stress change and the tectonic stress (King et al., 1994), termed the ‘optimally-oriented’ Coulomb stress change (Toda et al., 2011).

The source parameters deduced from waveform modelling are used to calculate the Coulomb stress change

Figure 9. The best stress model is represented by the square (σ_1), the triangle (σ_2) and the circle (σ_3). The contours around the best model define the 95% confidence region of each stress axis. Histogram of ϕ values versus frequency is shown at the bottom. The β obtained from this inversion is 39° . Relative stress magnitude (ϕ) is found to be 0.35. This value indicates that the study region is described by transpressional stress regime.

(Table 2). The stress tensor principal axes are also used to compute the spatial distribution of the Coulomb stress change (Table 3). The stress changes are resolved at 30 km depth based on the estimated geometry of major active faults. Increased shear stress in the rake direction and unclamping on surrounding “receiver” faults are interpreted to promote failure (Toda et al., 2008). The Coulomb 3.3 software (www.coulombstress.org) is used to project strike-slip faulting mechanism at a depth of 30 km with a strike/dip/rake of $262^\circ/69^\circ/49^\circ$ and a friction coefficient $\mu = 0.4$ in an elastic half space with uniform isotropic elastic properties (Lin and Stein, 2004; Toda et al., 2005, 2008, 2011).

The spatial distribution of the Coulomb stress change due to the occurrence of the 2012 $M_w = 6.0$ Fethiye EQ is presented in Fig. 11. Stress increase regions close to failure are represented by the red lobes. Positive Coulomb stress change is observed in NW–SE and E–W directions

Figure 10. Significant features (FBFZ: Fethiye-Burdur Fault Zone; RTF: Rhodes Transform Fault) of the seismotectonic setting of the study region. Orientations of the trend of S_H (blue bars) in the Fethiye EQ area from stress tensor analysis in region. Stress regime obtained in this study is represented by blue colored bars as strike-slip regime. Green and black bars display the maximum horizontal compressional stress (S_H) from the World Stress Map (Heidbach et al., 2008). Green and black bars represent strike-slip and thrust faulting stress regime, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the rupture zone. The eastern and western ends of the Fethiye EQ rupture are brought to 0.2–0.5 bars closer to failure. Stress changes of ≥ 0.1 bars are generally observed to influence seismicity rates (King et al., 1994).

We also examine the picture of the largest aftershock Coulomb stress change located 125 km south of the mainshock. This aftershock occurred one month after the mainshock (see Table 2 for parameters). Fig. 11 presents the cumulative picture after the 2012 June 10 M_w 6.0 event. In this case, for the receiver fault we adopt the geometry of the typical strike-slip faults for the region. The Coulomb stress change for the largest aftershock is less pronounced than the mainshock (Fig. 11). Positive stress values (red lobes) are observed at a NE–SW direction. Taking into account both events in the study region, we prefer to regard the post 2012 pattern to indicatively show a number of regions where stresses are increased.

To further compare the Coulomb stress change between the mainshock and the largest aftershock, two cross-sections are presented in Fig. 12. We find that the spatial and depth distribution of aftershocks and their focal mechanisms are consistent with the calculated Coulomb stress changes imparted by the coseismic rupture. Most of the aftershocks lie in the Fethiye EQ region (Fig. 2b) for which the Coulomb stress decreased (mainshock energy released) by ≤ -0.5 bars, and there is a stress drop between 15 and 40 km depths (Fig. 12a). Taking into account both earthquakes, the dimension of the activated area can be explained on the basis of the Coulomb failure criterion because of stress transfer loading. Thus, the post-seismic stress changes affect the production of aftershocks, as evaluated by spatial and depth

Table 3

Results of stress tensor inversion for the entire set of 23 focal mechanisms at Fethiye EQ area.

Volume	No. Fps	σ_1 (tr)	σ_1 (pl)	σ_2 (tr)	σ_2 (pl)	σ_3 (tr)	σ_3 (pl)	Misfit	ϕ	Var.
FE	23	-16	5	-121	71	76	18	39	0.35	0.17

FEA represents Fethiye EQ area. Results contain number of fault plane solutions within the relevant volume, directions for the three principal stress- σ_{1-3} in terms of trend and plunge, average misfit (β), relative stress magnitude (ϕ) and variance.

Figure 12. Coulomb stress change, taking into account the 2012 Fethiye mainshock and the largest aftershock. Color palette of Coulomb stress values is leveled in the range $-0.5/+0.5$ bar. Red color represents positive stress changes, while blue negative. Red and yellow stars indicate the Fethiye mainshock and the largest aftershock, respectively. Black circles show epicenter distribution of the Fethiye aftershocks along the mainshock region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Figure 12. Two cross-sections of the Coulomb stress change associated with two profiles (A–B and C–D) marked on Fig. 11. Red lines show the coseismic rupture based on the calculated focal mechanisms (Table 2). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

distributions of focal mechanisms (Figs. 2 and 3).

5. Discussion and conclusions

We study the spatio-temporal source characteristics of the 2012 June 10 $M_w = 6.0$ Fethiye EQ seismic sequence, which occurred 30 km SW of Fethiye Gulf in the eastern Mediterranean. The distribution of epicenters and the focal mechanisms clearly indicate the activation of N76°E trending left lateral strike-slip fault with reverse component. The stress tensor inversion results reveal a predominant strike-slip stress regime with a NNW–SSE oriented maximum horizontal compressive stress (S_H). The entire study region is rather homogeneous according to the stress tensor inversion results (variance < 0.2 , Table 3). The relative stress magnitude (ϕ) is estimated to be 3.5

(transpressional stress regime) for the Fethiye EQ region. Therefore, to first order, the Fethiye EQ region is characterized by a homogeneous interplate stress field as far as the orientation of stress is concerned (Fig. 9 and Table 3). This result can be explained by an influence of western Anatolia extensional regime between the African, Aegean Sea and Anatolian plates' interaction.

The World Stress Map (WSM) 2008 (Heidbach et al., 2008) reported strike-slip and thrust faulting with S_H oriented in NE–SW at the northern margin and in NNW–SSE at the southern margin of our study region, respectively. Since the Fethiye Gulf region shows a strike-slip regime with S_H oriented in NNW–SSE directions, there is a significant change of regime especially at the northern margin. This is presumably due to the increasing influence of the active FBFZ that is also apparent in the region northeast of the Rhodes Island (Fig. 10). Along the FBFZ and on faults perpendicular to its NE–SW striking structure we observe strike-slip faulting mechanisms. The incorporation of focal mechanisms from the WSM to the stress inversion results in a counter-clockwise rotation of S_H towards E–W orientation (Fig. 10).

The 2012 Fethiye EQ occurred in the Fethiye Gulf along the FBFZ, a region which previously accommodated strong earthquakes (Fig. 1). In a broad context, the region of eastern Mediterranean is a domain characterized by diffused deformation, which is influenced by both Aegean arc extension (Pliny trench), approximately NE–SW, and by the shear transferred from the North, due to the operation of the Fethiye–Burdur Fault Zone (FBFZ) combination with Rhodes Transform Fault (RTF) (Gürer et al., 2004; Nyst and Thatcher, 2004; ten Veen et al., 2004; Çevikbilen and Taymaz, 2012). Left lateral strike-slip or oblique motions prevail in the Fethiye EQ region (Fig. 1), which form fault zones, that can be considered as segments of the FBFZ and probably follow zones of weakness inherited from the past (ten Veen et al., 2009). These left lateral fault zones terminate in well-defined compressional trenches (Pliny and Strabo), which are in turn controlled by NW–SE trending reverse faults, or pure strike-slip faults exhibiting left-lateral motions. The most prominent example for the former case comes from the 1957 Fethiye EQ sequence (1957 April 24 $M_b = 6.9$ and April 25 $M_b = 7.1$), which was connected with the rupture of a left lateral strike-slip fault (Tan et al., 2008; Kalafat et al., 2009). The 1957 Fethiye events (Fig. 1) are example of a NW–SE trending left lateral strike-slip fault. This type of strike-slip faulting was also observed in south of Karpathos Island further to the SW (Çevikbilen and Taymaz, 2012). The sequence studied here is a typical example of strike-slip motions along specifically off-shore extension of the FBFZ, which is now better defined. It is worth noting that the causative fault could be connected with a segment of a previously mapped ~ 300 km fault (Fig. 1, Nyst and Thatcher, 2004; Çevikbilen and Taymaz, 2012).

Another question that arises refers to the connection of the 2012 Fethiye sequence with the FBFZ (Fig. 10) which terminates off-shore, SW Fethiye (Çevikbilen and Taymaz, 2012). This zone was next to the epicenter of 1957 April 24 $M_b = 6.9$ and April 25 $M_b = 7.1$ earthquakes. The 2012 Fethiye sequence is connected with the off-shore segment of the FBFZ. It is located approximately 30 km to the southwest of on-shore part of the FBFZ. The

Coulomb stress change associated with the mainshock is also examined in order to evaluate any significant increase of stresses for specific target faults with similar orientation as the rupture of the 1957 Fethiye earthquakes. The Coulomb stress analysis exhibits that the regions of positive static stress changes (i.e. more prone to seismic triggering) reached epicenters of 1957 Fethiye events.

The coseismic Coulomb stress changes are correlated with the distribution of aftershocks in map view (Fig. 11). Considering the location of the Fethiye mainshock, the zone with the negative stress values can reveal the expected dimension of the epicentral area (approximately 40 km). The intermediate area, which is characterized by negative stress values, contributed to the increase of seismicity, although at the same time the aseismic activity occurred in regions where positive stress values are observed. Taking into account these observations, the dimension of the activated region can be explained on the basis of the Coulomb failure criterion because of stress transfer loading. Both the upper crust (< 10 km depth) and the crust beneath the fault plane are brought closer to failure. Afterslip on the fault plane acts to reload the upper crust (Fig. 10). This type of strike-slip faults may tend to increase the failure stress in the upper crust coseismically, producing confined and low productive aftershock sequence.

Most of the earthquakes in Fethiye region are concentrated between depths of 20–40 km with a strike-slip mechanism. The main aftershock cluster is related to a fault plane trending NW–SE and dipping towards SE (Fig. 3b). These events occurred in the lower crust (Gürer et al., 2004). We evaluate that strike-slip faulting in the FBFZ has occurred as a result of basement reactivation due to transpressional stresses stimulated by an interaction between African, Anatolian and Aegean Sea plates.

The focal mechanism solutions of the Fethiye seismic sequence suggest that almost entire activated region displays strike-slip faulting with significant reverse component (i.e., event #12). The overall seismic activity shows not only strike-slip mechanisms but also reverse mechanisms. These reverse mechanisms may occur due to the local stress change in the activated region after the mainshock. Moreover, the aftershocks in the southern part of the main cluster indicate that several small secondary fault segments exist in this area. These fault segments may produce different faulting mechanisms (i.e., event #9, #10, #12).

In this study, all aftershocks are deeper than 20 km. Furthermore, similar findings were published by Gürer et al. (2004). Accordingly, it can be speculated that the thickness of brittle seismogenic crust in FBFZ region is about 50 km. This aftershock study also indicates that the majority of aftershocks occur in the crust shallower than 50 km with the exception of one event (event #21, Table 2) about 55 km. In addition to these findings, Tan et al. (2008) also noted that the 1957 Fethiye earthquakes in the Fethiye Gulf region (Fig. 1) are located in the crust with shallower than 55 km depth.

Consequently, the 10 June 2012 M_w 6.0 sequence that located in the Fethiye Gulf region is associated with active NW–SE trending strike-slip structures. These types of faults are wide-spread in the eastern Mediterranean and

are capable of causing larger earthquakes along the fault zones. The 2012 Fethiye EQ sequence imposes a tsunami-genic type of earthquake hazard to nearby islands and the coastal region of SW Turkey.

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