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Seismotectonics of the Southeastern Area of Muğla Province, SW Anatolia, Türkiye

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Abstract
This study aimed to investigate the seismotectonics of a region encompassing both continental and marine areas, forming the southeast of Muğla Province in SW Turkey. The main tectonic element of the study area is the active subduction zone that forms the boundary between the Anatolian and African plates. Furthermore, numerous strike-slip and normal faults are present both onshore and offshore. This study examines the focal mechanisms of 21 earthquakes with magnitudes greater than M 3.5, spanning the period 1987-2023. Based on the common inversions of these earthquakes, two distinct tectonic regimes were identified. Deep-focus earthquakes located near the subduction zone were found to be associated with compressional activity, directed approximately N-S. Earthquakes with focal depths less than 30 km, located primarily in continental areas, and extending approximately E-W were determined to be the product of an extensional regime, striking approximately N-S. This suggests that the subduction process between the Anatolian and African plates along the Hellenic arc continues to operate via a roll-back mechanism.

Keywords: *Seismotectonic, Earthquake, Inversion, Focal Mechanism, Muğla, SW Anatolia*

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I. INTRODUCTION

This study covers both terrestrial and marine areas to the southeast of Muğla Province, located in the extreme southwestern part of Turkey (Figure 1). This study utilizes the focal mechanisms of earthquakes greater than M:3.5 that occurred in this region over the last century, particularly between 1987 and 2023, to reveal the current state of the regional stress regime.

The study area is located in a geodynamically important location. While located within the Anatolian plate, it also forms its outermost portion. The African plate is subducting beneath the Anatolian plate here (Figure 1).

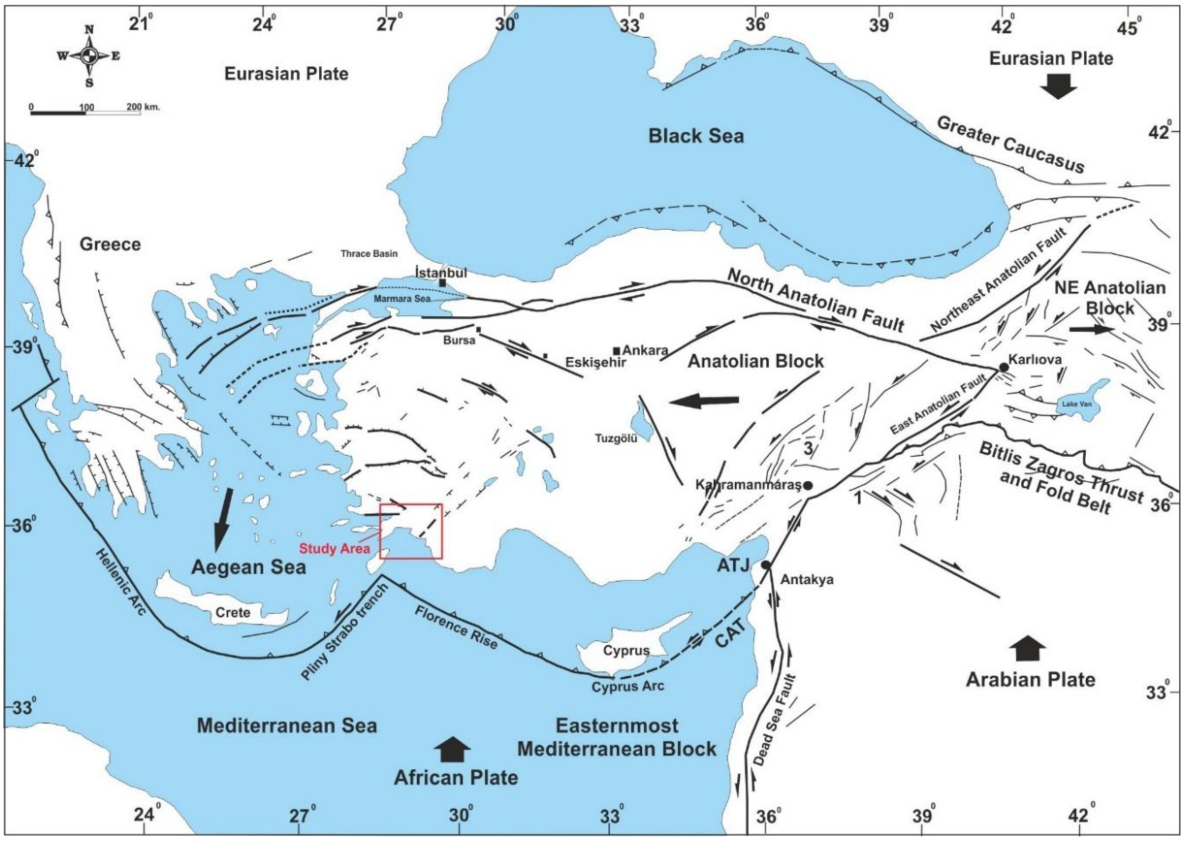

Figure 1: Study area within the simplified tectonic framework of the eastern Mediterranean region (modified from Barka, 1992). CAT: Cyprus-Antakya Transform Fault. ATJ: Antakya Triple Junction. Black arrows show the GPS velocity vectors from McClusky et al. (2000).

This subduction zone, which develops northward along the Hellenic and Cyprus arcs, is represented by a thrust fault. The Anatolian plate, which overlies the African plate, is spreading with an approximately N-S extension at a rate of 40 mm/year (Mc Clusky et al., 2000). The subduction zone is shaped by the Plino-Strabo trench on one side and the Florence Uplift on the other, forming an elbow (Figure 1). The formation of this structure has been explained by a rupture occurring deep within the African plate (Faccenna et al., 2004). Numerous active fault segments exist within the Anatolian plate. These are represented by the approximately NW-SE-trending Milas Fault, the Yatağan Fault, the Muğla Fault, and the E-W-trending Ula-Ören Fault, which borders the Gulf of Gökova to the north, and are shown as active on the Active Fault Map of Turkey. In the northeast of the study area, normal fault systems extend from Çameli and Acıpayam towards Fethiye. Similar fault systems also exist in marine areas (Figure 2).

In order to reveal the seismotectonics of this region, where a large number of earthquakes have occurred, focal mechanism inversion solutions of 21 earthquakes were considered.

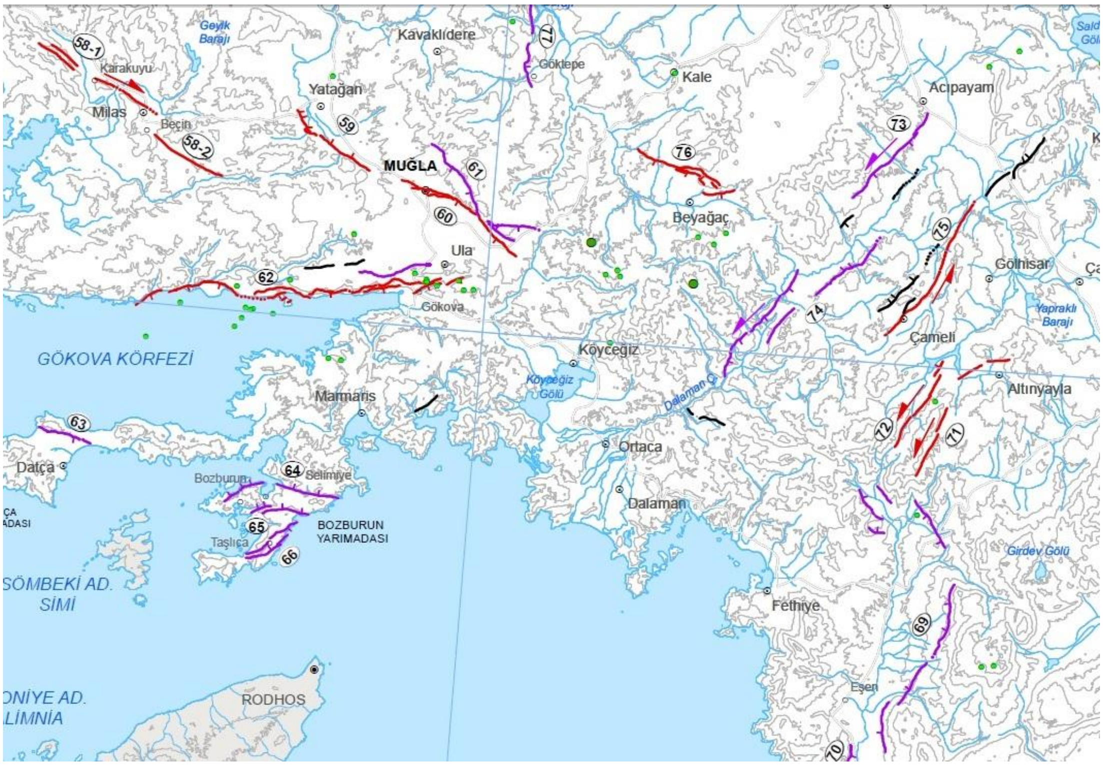

Figure 2: Active faults of the study area and its immediate surroundings (Emre et al., 2013)

II. RESULT AND DISCUSSION

II.1. Methodology

II.1.1. Focal Mechanism Solutions

In order to gain valuable insights into the regional deformation process, analyzing the full waveform is essential for determining focal mechanisms accurately. We used three-component broadband data from Türkiye's regional network operated by the Kandilli Observatory and Earthquake Research Institute (KOERI). Our approach to determining earthquake mechanisms involves employing the iterative deconvolution method of Kikuchi and Kanamori (1991) via ISOLA software (Sokos and Zahradnik, 2008) for 4 events with magnitudes between 3.9 and 4.7. Synthetic seismograms were generated using Green's functions within the Fortran code of ISOLA, employing the discrete wavenumber method (Bouchon, 1981).

II.1.2. Kinematic Analysis of Focal Mechanism Solutions: Inversion

The method used in this study is a computer-aided numerical analysis method first developed by Carey (1979) and later developed by Carey-Gailhardis & Mercier (1987). This method can be applied to focal mechanism solutions for selected seismic fault planes (Carey-Gailhardis & Mercier, 1987). In fact, the genuine fault plane, which carries the slip vector and corresponds to the principal stress orientations, can be determined using Bott's (1959) model and is one of the two nodal planes identified in the earthquake focal analysis. The calculated stress ratio [$(R=(\sigma 2-\sigma 1)/(\sigma 3-\sigma 1)$] should be between 0 and 1, and the seismic shear vector must be compatible with the stress tensor. While the auxiliary plane does not meet this requirement, the seismic plane from the nodal plane does if both planes do not contact one another along a primary stress vector (Carey, 1979). In this study, joint inversion solutions of seismic fault planes selected from 21 earthquake data were performed.

II.2. Seismotectonics of the Region

It is known that approximately 420 earthquakes with magnitudes greater than M=4.0 occurred in the SE of Muğla Province in SW Anatolia during the instrumental period (1900-2023), and that this activity is still ongoing. Intense seismic activity in the area, especially around the Datça Peninsula, Marmaris, and Dalaman, is quite remarkable. Furthermore, it is known that approximately 65 earthquakes with magnitudes greater than M=5.0 occurred in the study area and its surroundings during the instrumental period (1900-2023), and that this activity is still ongoing. Additionally, one M:6.0 earthquake occurred in the region in 1941, two M:7.3 earthquakes in 1957, one M:6.4 earthquake in 1961, one M:6.0 earthquake in 2012, and one M:6.6 earthquake in 2017 (Figure 3).

Figure 3: Distribution of earthquakes greater than M:5 in the study area from 1900 to the present (USGS).

However, focal mechanism solutions for some earthquakes greater than 3.5 magnitude for the period between 1987 and 2023 are included here (Table 1).

Table 1: Earthquakes greater than M=3.5 that occurred in the project area and its surroundings between 1970 and 2023 (USGS Catalog). Bold characters indicate seismic planes.

No	Date	Time (UTC)	Lat N (Degree)	Long E (Degree)	NP1 (Strike/Dip/Rake)	NP2 (Strike/Dip/Rake)	Magnitude	Depth (km)	Ref
1	19.06.1987	18.45:41	36.791	28.193	316/54/137	**75/57/45**	5.3	79.5	USGS
2	19.02.1989	14.28:46	37.009	28.226	93/32/-85	**267/58/-93**	5.4	10,0	USGS
3	27.04.1989	23:06:52	37.027	28.180	277/54/-87	**92/36/-94**	5.5	13.9	USGS
4	28.04.1989	13:30:19	37.004	28.139	284/50/-81	**90/41/-101**	5.6	16.9	USGS
5	05.10.1999	00:53:28	36.730	28.240	**275/52/-34**	28/64/-136	5.2	33.0	USGS
6	20.12.2004	23.02:12	37.042	28.206	**105/45/-70**	257/48/-109	5.4	5.0	USGS
7	10.06.2012	12:44:16	36.420	28.880	203/75/-11	**295/79/-165**	6.0	35.0	USGS
8	10.11.2014	06:16	37.138	28.785	120/52/-94	**307/38/-84**	4.8	12.9	USGS
9	13.04.2017	16:22:16	37.125	28.691	**273/50/-52**	42/53/-127	5.0	10.0	USGS
10	07.11.2017	02:40:32	36.283	28.418	293/40/153	**45/73/53**	4.9	67.7	USGS
11	22.11.2017	20:22:53	37.051	28.643	**306/66/-68**	82/32/-130	5.1	10.0	USGS
12	24.11.2017	21:49:15	37.085	28.622	106/43/-85	**279/47/-95**	5.2	5.2	USGS
13	03.10.2019	04:44:56	36.277	28.572	226/31/81	**56/60/95**	5.1	17.8	USGS
14	24.10.2019	21:06:47	36.462	28.674	**9/57/101**	171/35/74	4.6	10.0	USGS
15	28.06.2020	17:43:28	36.748	28.248	**329/56/149**	78/64/38	5.4	63.0	USGS
16	29.06.2020	04:06:24	36.727	28.206	296/50/141	**53/61/48**	4.6	67.0	USGS
17	28.09.2021	06:01:05	36.430	28.410	**283/34/-70**	79/58/-103	3.9	30.0	This study
18	16.01.2022	22:16:17	36.570	28.520	179/35/47	**47/65/115**	4.7	26.0	This study
19	05.09.2022	13:45:54	37.100	28.510	**291/79/-174**	200/84/-11	3.5	6.0	This study
20	02.10.2022	10:58:04	37.074	28.924	**78/53/-72**	230/41/-113	4.6	10.0	USGS
21	18.11.2022	04:26:35	37.080	28.450	208/29/-153	**94/78/-64**	4.2	10.0	This study

When these earthquakes are examined, it can be seen that earthquakes 2, 3, 4, 6, and 21 are located on the E-W-trending Ula-Ören Fault, which borders the Gökova Gulf to the north. These earthquakes developed under a N-S-oriented regional extensional regime (Table 1, Figure 4).

Earthquakes numbered 1, 15 and 16 are reverse faults that developed under a compression regime with approximately N-S direction just to the north of the Bozburun Peninsula and represent a local compression (Table 1, Figure 4).

Earthquakes No. 8, 9, 11, 12, and 20 occurred along the southeastward continuation of the Muğla Fault and were associated with a regional extensional regime trending approximately N-S (NNW-SSE and NNE-SSW). They exhibit normal faulting. Among these earthquakes, earthquake No. 19 was a right-lateral strike-slip (transtensional) event, indicating a strike-slip component at the far end of the Muğla Fault (Table 1, Figure 4).

Earthquake number 5 is associated with the Bozburun Fault and is a normal fault that developed under the NNE-SSW extension regime (Table 1, Figure 4).

Earthquakes 7, 10, 13, 14, 17, and 18 occurred within the Mediterranean Sea to the south of the study area. These earthquakes (except 17) appear to be reverse and strike-subduction faulting, developing mostly under a NW-SE compressional regime. This region corresponds to the boundary between the Anatolian and African Plates and is close to the Plino-Strabo Trench region. Earthquake 17 appears to be a normal faulting earthquake located within this trench system (Table 1, Figure 4).

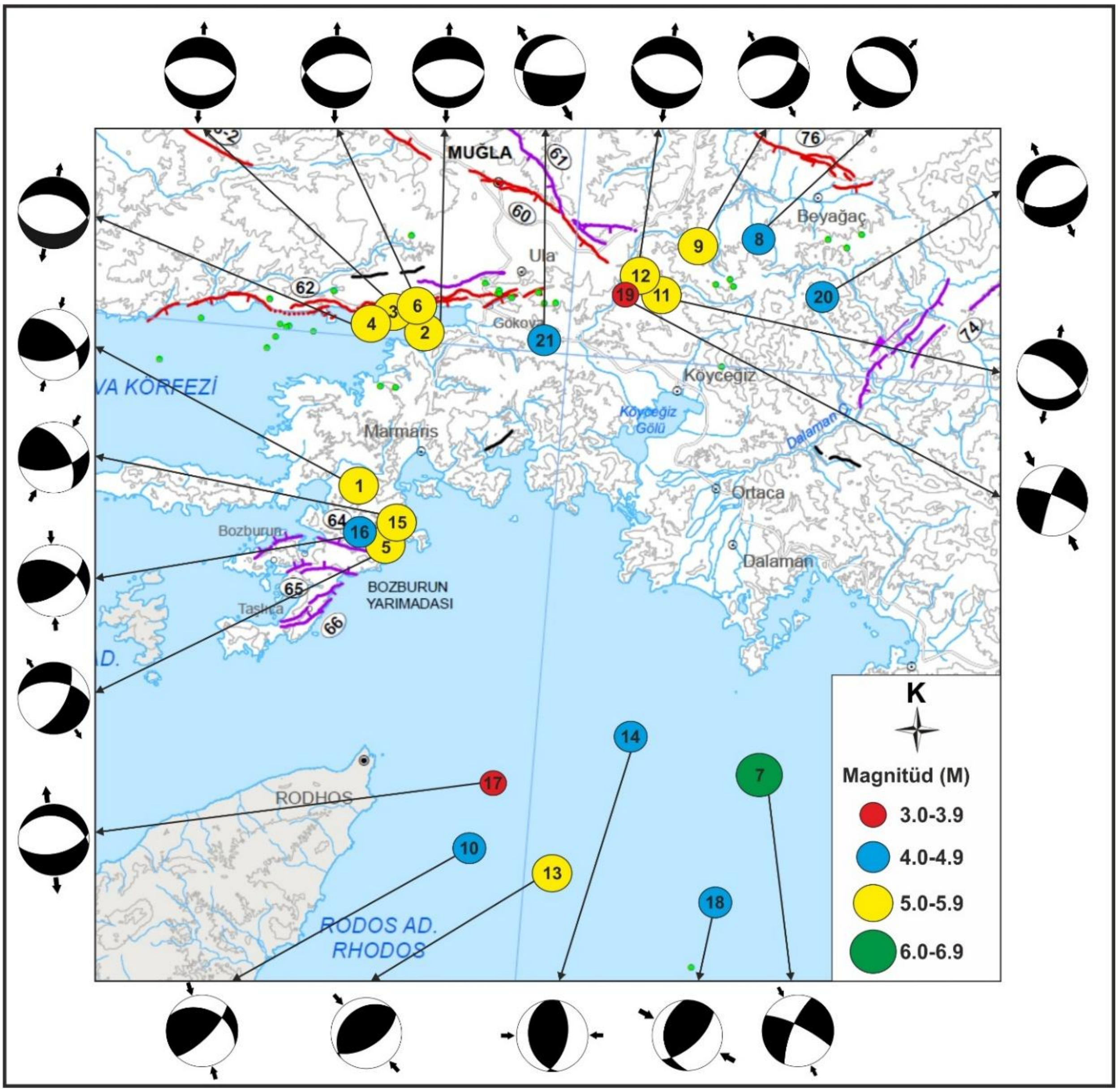

Figure 4: Epicenters and focal mechanism inversion representations of earthquakes greater than M=3.5 (21) that occurred between 1987 and 2023 in the study area and its immediate vicinity.

Kinematic analysis of the focal mechanism solutions of the earthquakes was carried out using a computer-aided numerical analysis method developed by Carey (1979) and Carey-Gailhardis & Mercier (1987) (Figure 5).

Accordingly, the combined solution of nine reverse-component earthquakes (Figure 5, comp) yields a NNW-SSE compressional regime with the largest principal stress axis horizontal and in the outer arc (Sigma 1: 168/26) and the smallest principal stress axis vertical and in the center (Sigma 3: 287/46). This current compressional regime is generally characterized by earthquakes with depths greater than 30 km, corresponding to the compressional regime in the subduction zone, and represented by reverse and strike-slip faults (Figure 6).

The joint inversion of 12 normal component earthquakes (Figure 5, ext) yields a N-S extensional regime with the largest principal stress axis vertical and central (Sigma 1: 351/86) and the smallest principal stress axis horizontal and in the outer arc (Sigma 3: 170/4). These earthquakes appear to have shallower foci, less than 30 km deep, and are the product of the N-S rapid extensional regime in the present-day SW Anatolia region, with approximately E-W-trending normal faulting (Figure 6).

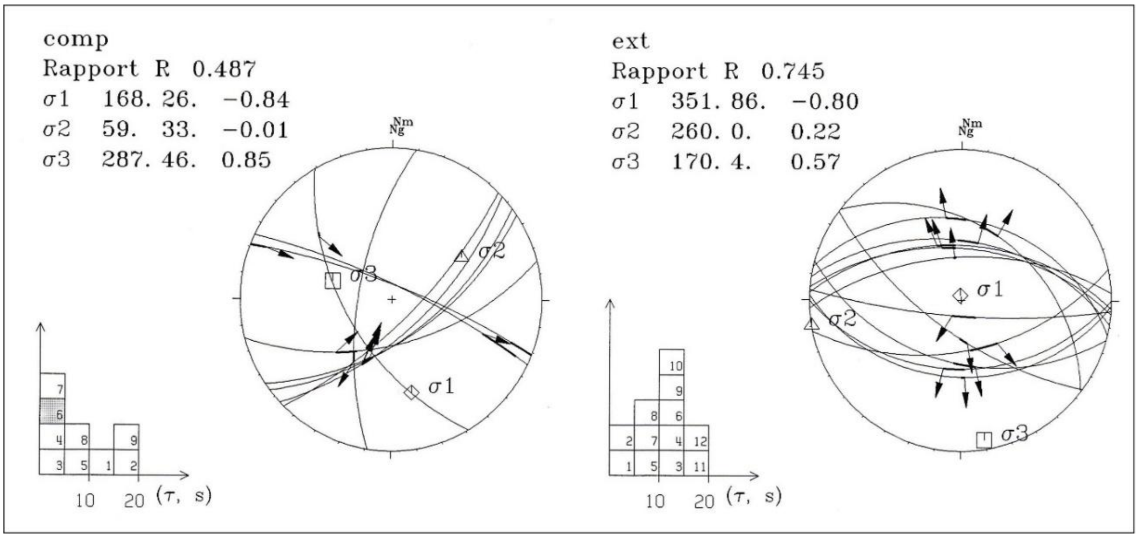

Figure 5. Common inverse solutions of the focal mechanism of the earthquakes in Table 1 (two common solutions for the comp: compression and ext: extension regimes)

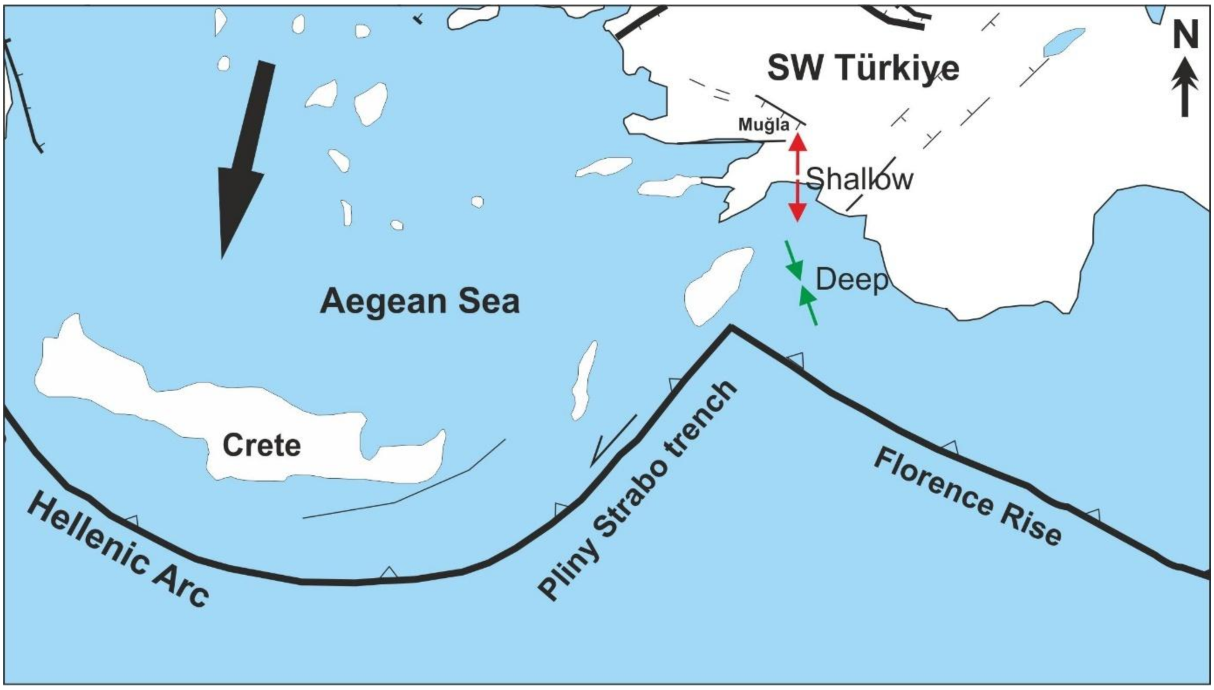

Figure 6: Distribution of current stress directions in the study area. The compression regime effective in deep structures is shown with green arrows, and the extension regime effective in shallow structures is shown with red arrows

III. CONCLUSION

In this study, the seismotectonics of the area located in the SE of Muğla province in SW Anatolia were interpreted based on the focal mechanism solutions of 21 earthquakes.

The results indicate that the study area, located at the edge of the Anatolian Plate, is influenced by the Western Anatolian extensional regime (N-S oriented) in the areas near the plate boundary. The earthquakes occurring within the Mediterranean Sea are represented by reverse and strike-slip faulting associated with the complex subduction process between the Anatolian/African Plate and predominantly compressional regime (N-S oriented) (Figure 6). Particularly along the Hellenic Arc, the African Plate is rapidly pulling the Anatolian Plate towards itself in a rollback mechanism, causing the region to undergo N-S extension. The data evaluated in this study also support this mechanism.

ACKNOWLEDGMENTS

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