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Seismic Case Studies

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CHAPTER 6

The 26 July 2001 Skyros (north Aegean Sea, Greece) earthquake

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Abstract

On 26 July 2001 a strong earthquake of magnitude M_w=6.5 hit the central Aegean Sea at 00:21:39 GMT. The event took place off shore from Skyros Island, at a distance of 135 km NNE of Athens. A sequence of many aftershocks followed with the magnitude of the largest of them reaching Ms=5.4. The temporal and spatial characteristics of the aftershock sequence are investigated as well as the focal mechanism of the main shock and of the 47 largest aftershocks. The fault plane solution determined by the Institute of Geodynamics (National Observatory of Athens) implies that the main shock rupture is associated with sinistral strike slip faulting. In contrast to the general NE–SW strike of the principal planes of strong earthquakes in the North Aegean region, the strike of the Skyros earthquake rupture zone has a NW–SE direction, supported from the distribution and the fault plane solutions of the strongest aftershocks. Therefore, the rupture zone of the 26 July 2001 earthquake probably defines the western end of the North Anatolian Fault.

1 Introduction

On 26 July 2001 a strong earthquake of magnitude M_w=6.5 hit the north Aegean Sea at 00:21:39.1 GMT. The event, according to the Institute of Geodynamics, National Observatory of Athens (NOAGI), took place off shore from Skyros Island at a distance of 135 km NNE of Athens (39.046°N – 24.338°E, depth = 17 km; Figure 1). The epicentral region is situated at the westward extension of the

North Anatolian fault (NAF) into the Aegean Sea. This is an area of intense deformation, characterized by high seismicity with earthquake magnitudes up to about 7.5 (Papadopoulos *et al.* [1]). Strike-slip and normal faulting are predominant (Papazachos *et al.* [2], Taymaz *et al.* [3], Kiratzi and Papazachos [4]). The primary cause of the deformation is the motion of the Arabian plate in a NNW direction which causes the westward escape of Turkey (Anatolian plate) relative to Eurasia, towards the Aegean.

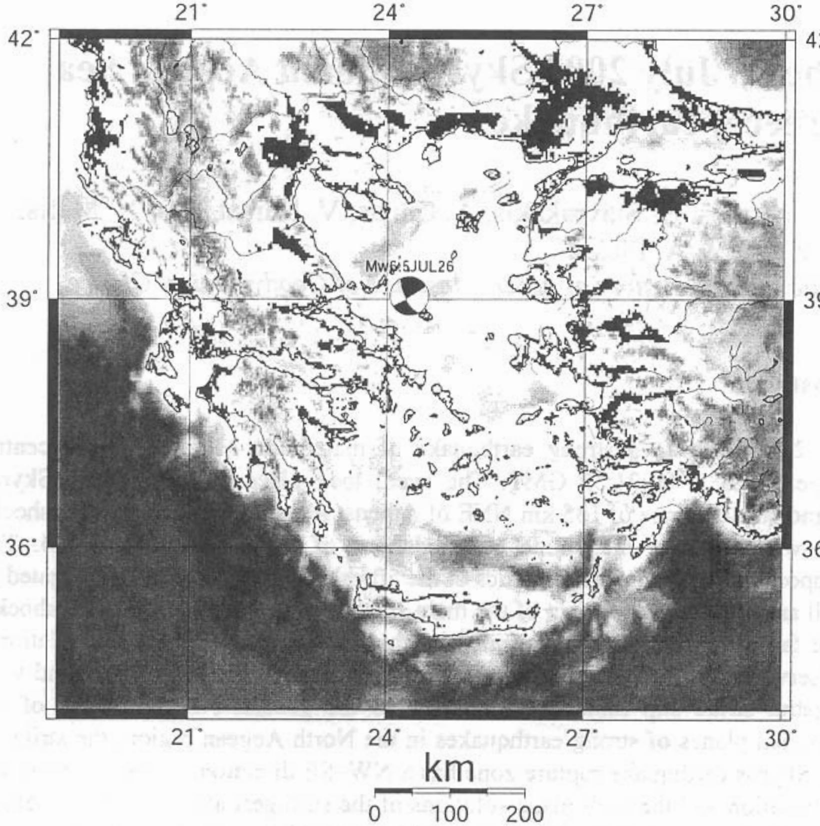

Figure 1: Tectonic setting of the Skyros earthquake. Background map is a raster digital elevation model of the Hellenic Arc and Back-arc areas. Thin lines are major rivers and political boundaries. Beach ball shows the focal mechanism solution according to several solutions (Table 1); black denotes compression quadrants.

It is important to note that the 26 July 2001 event was felt in a wide region (about 200 km radius) around the epicentral area. No severe damage was reported; however, almost 350 non-reinforced houses, mostly old traditional dwellings in the capital of Skyros, suffered minor damage. Among them, an almost 1000 year old monastery was badly damaged. The strong motion resulted in massive rock falls which crashed onto many parked cars beneath the steep hill of Skyros castle. The biggest effect to the population was the blockage of the spring which supplies the capital with water. The seismic intensity did not exceed I_{max}=VII (modified Mercalli) in Skyros town. Minor damage was reported on the islands of Skopelos and Alonissos, about 50 km to the north-west of the epicenter (Figure 2). An intense sequence of aftershocks followed, with the magnitude of the largest of them reaching M_s=5.3.

Table 1: Focal parameters and fault-plane solutions for the 26 July 2001 earthquake. Time is GMT. Capital phi and lambda are latitude and longitude coordinates, respectively. M is earthquake magnitude. Mo is seismic moment. Focal plane parameters are strike ξ, dip δ and rake λ.

Organization	Time	Φ (°N)	Λ (°E)	L (km)	M	M_0 (Nm)	ξ(°) NP1 NP2	δ(°) NP1 NP2	λ(°) NP1 NP2
NOA GI	00:21:39	39.046	24.338	19	Ms=5.8	$4x10^{18}$	150 60	70 85	5 160
ASPO	00:21:39	39.06	24.34	17	Mw=6.5	$4x10^{18}$	150	70	10
USGS	00:21:38	39.06	24.34	14	Mw=6.5 Mb=6.0 Ms=6.6	$5.4x10^{18}$	145 55	85 86	4 175
CSEM	00:21:37	39.07	24.14	10	Mw=6.4 Mb=5.8	$5.2x10^{18}$	128 37	81 84	6 171
SED	00:21:37	39.06	24.34	21	Mw=6.6	$8.7x10^{18}$	238 148	90 73	-163 0
HRV	00:21:44	38.93	24.30	15	Mw=6.5	$5.4x10^{18}$	148 238	71 89	1 -161
THE	00:21:38	38.99	24.38	14	M=6.4	—	—	—	—

The Skyros earthquake occurred two years after the Izmit earthquake (17 August 1999, Mw=7.4), in an area where several investigators had claimed that strong events should be expected as a result of NAF westward movement (Papazachos *et al.* [5]). In the present study, the focal mechanisms of the main shock, of the three foreshocks and of the forty-seven largest aftershocks as well as the spatial and temporal characteristics of the aftershock sequence are presented, in an attempt to illuminate the complicated seismotectonic regime of the region.

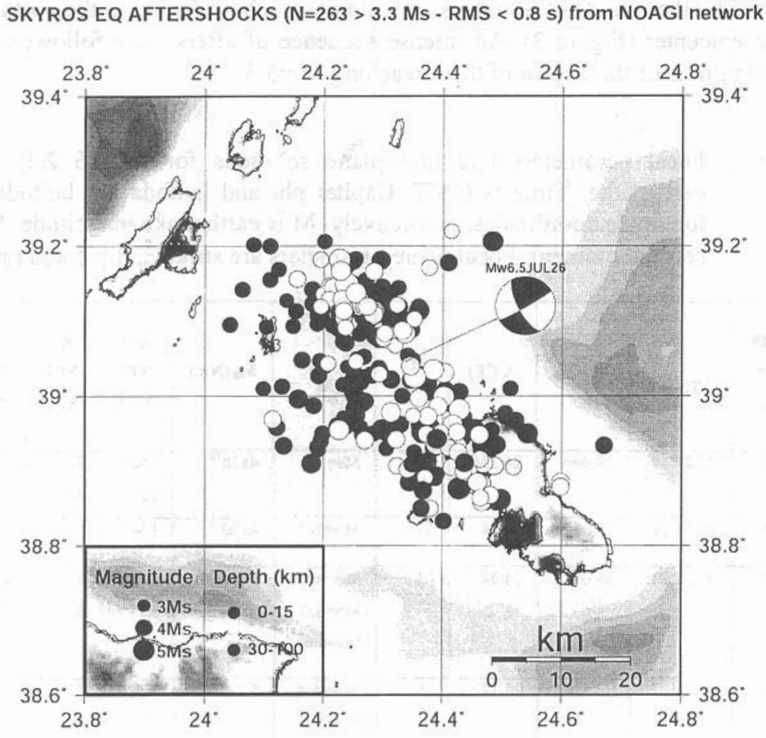

Figure 2: Map of aftershocks and focal mechanism solution of the Skyros 26 July 2001 earthquake. The aftershock colours and sizes follow depth and magnitude distribution, respectively.

2 Data: instrumental seismicity - foreshock activity

The fault-plane solution for the main shock that was determined from NOAGI, when plotted together with the aftershock sequence, implies that the main shock rupture is associated with strike-slip faulting (Figure 2). The solution was determined using 17 broadband NOAGI stations (at 20 s) and provides strike=150°, dip=70° and rake=5° (Figure 2). The scalar moment is $Mo=4x10^{18}$ Nm. In addition, a detailed study of the focal properties of the main event has been done by NOAGI (Melis *et al.* [6]). Using the ASPO method (Zahradnik *et al.* [7]), based on amplitude spectra of complete three-component waveforms and first motion polarities, they calculated strike=150°, dip=70°, rake=10° and Mo=4.1×10^{18} Nm. Both solutions are in agreement with those announced by USGS and other research centers (e.g. Benetatos *et al.* [8]). Table 1 summarizes the focal parameters, the magnitude and the fault-plane solutions according to different organizations. The main shock was preceded by three significant foreshocks (Table 2; Figure 3), which occurred on 21 July (M_L=4.1 and M_L=4.6) and on 25 July 2001 (M_L=4.2), very close to the epicenter of the main shock.

The largest event, closer to the epicenter of the 26 July earthquake, occurred on 4 March 1967 (17:58:09 GMT, M=6.8), almost 30 km to the East (Delibasis and Drakopoulos [9]). According to the NOAGI seismicity catalog, during the past 3.5 years seismicity has been very low in the region (Chouliaras and Stavrakakis [10]). Therefore, seismic quiescence was detected before the Skyros earthquake, concerning large events as well as small events.

2.1 The aftershock sequence – aftershocks focal mechanism

The Skyros earthquake was followed by intense aftershock activity. After careful examination of the digital records we processed 263 events, of which 47 are presented in Table 2. At least six P-wave and S-wave phases for each event, recorded by the digital array of NOAGI, were used to locate the aftershock sequence using the HYPOINVERSE algorithm. For the Greek seismicity catalog the M_L=3.2 is proposed by Drakatos and Latoussakis [11] as the minimum magnitude (threshold magnitude). But in the investigated region the detectability of the NOAGI network reaches smaller magnitudes (Chouliaras and Stavrakakis [10]). We note that the aftershock distribution (Figure 2) implies a bilateral rupture, with the major axis of the aftershock area striking in a NW-SE direction. The above mentioned direction becomes quite clear from the epicenter distribution of the aftershocks with determined focal plane solutions (Figure 3). In general, the aftershocks are well defined in a relatively narrow zone along the fault as can also be shown in the aftershock distribution with respect to depth (Figure 2). We suggest that the processed, largest aftershocks define the rupture zone of the Skyros earthquake (Figure 3). Their strike, NW–SE, coincides with that of the main shock nodal plane. Within the first day (26 July 2001) the rupture zone was defined with the long axis trending NW–SE and extending for almost 28 km. At the end of the aftershock sequence (end of October 2001) the long axis of the rupture zone extended for about 45 km (Figure 4 bottom).

The cross sections drawn both parallel and perpendicular to the fault strike show several events reaching depths of 30 km, which is deeper than the main shock hypocenter depth (17 km). These events define a narrow zone of earthquake occurrence in the lower crust beneath the main shock hypocenter. We note that crustal thickness around Skyros is estimated as 30 km (Tsokas and Hansen, [12]).

Table 2: Focal plane solution (preferred plane) of the 50 well-determined shocks of the Skyros earthquake sequence (3 foreshocks – 47 aftershocks). MAG is surface magnitude.

DATE	LAT	LONG	DEPTH	STRIKE	DIP	RAKE	MAG
721	39.071	24.318	20.89	135	40	-20	4.6
721	39.065	24.387	3.50	130	60	0	5.1
725	39.082	24.349	7.32	245	75	-170	4.7
726	39.025	24.359	13.79	155	75	-30	5.3
726	39.107	24.309	9.55	100	55	-50	4.8
726	38.965	24.431	7.87	0	60	50	4.9
726	39.112	24.283	19.47	100	70	-50	4.9
726	39.078	24.308	29.34	135	85	10	5.0
726	38.949	24.412	28.58	55	90	-140	5.2
726	38.929	24.470	11.87	230	85	170	5.3
726	39.035	24.384	17.85	300	85	0	4.7
726	38.999	24.402	17.75	125	85	-30	4.7
726	38.937	24.391	28.28	60	85	-160	5.1
726	38.907	24.487	21.29	125	55	110	4.2
726	38.986	24.392	27.95	325	90	10	4.3
726	39.010	24.514	10.63	15	30	20	4.2
726	39.067	24.320	29.75	240	55	170	4.1
726	39.076	24.293	6.20	245	60	180	4.3
726	38.944	24.404	26.07	325	85	0	4.8
726	38.943	24.390	30.20	55	90	-140	4.6
726	39.025	24.353	27.16	55	90	-140	5.1
726	39.111	24.284	18.97	130	40	0	4.3
726	39.018	24.373	6.09	60	90	-150	4.5
726	39.083	24.336	19.10	220	85	-170	4.5
726	39.125	24.258	16.19	115	70	-30	5.1
726	38.962	24.417	25.23	60	90	-160	4.5
726	38.910	24.469	26.27	330	90	30	4.4
727	38.862	24.498	6.39	50	85	-140	4.8
728	38.901	24.440	29.95	60	90	-130	5.1
730	39.126	24.244	19.68	140	85	-70	4.4
730	39.119	24.233	22.11	110	85	0	4.3
730	39.181	24.295	13.65	325	80	-50	4.4
730	39.114	24.360	9.11	160	70	-30	4.8
731	38.876	24.425	32.50	170	60	-30	4.3
8 2	39.206	24.483	7.41	120	65	30	4.8
8 3	38.996	24.157	7.95	90	80	120	4.4
8 3	39.117	24.268	14.89	330	90	30	4.4
8 3	39.098	24.272	13.93	150	85	-50	4.0
8 8	38.931	24.478	12.52	50	70	-140	4.9
810	38.991	24.263	10.33	145	75	30	4.6
812	38.999	24.253	6.64	150	75	-30	4.4
827	39.137	24.253	21.93	45	75	-150	4.8
9 4	38.941	24.269	18.66	315	85	-10	4.0
9 7	38.955	24.226	24.87	325	85	0	4.5
910	38.960	24.223	12.26	330	90	30	4.1
919	38.949	24.459	13.89	345	70	60	4.3
10 7	38.953	24.443	13.23	110	65	-70	4.0
1012	39.176	24.239	13.87	320	80	10	4.3
1029	38.877	24.428	13.70	75	75	-150	5.3
1029	38.874	24.367	33.30	85	85	-140	4.2

3 Discussion and conclusions

The primary cause of the deformation in the investigated region is the motion of the Arabian plate in a NNW direction which causes the westward escape of Turkey (Anatolian plate) relative to Eurasia, towards the Aegean (e.g. Taymaz *et al.* [3]).

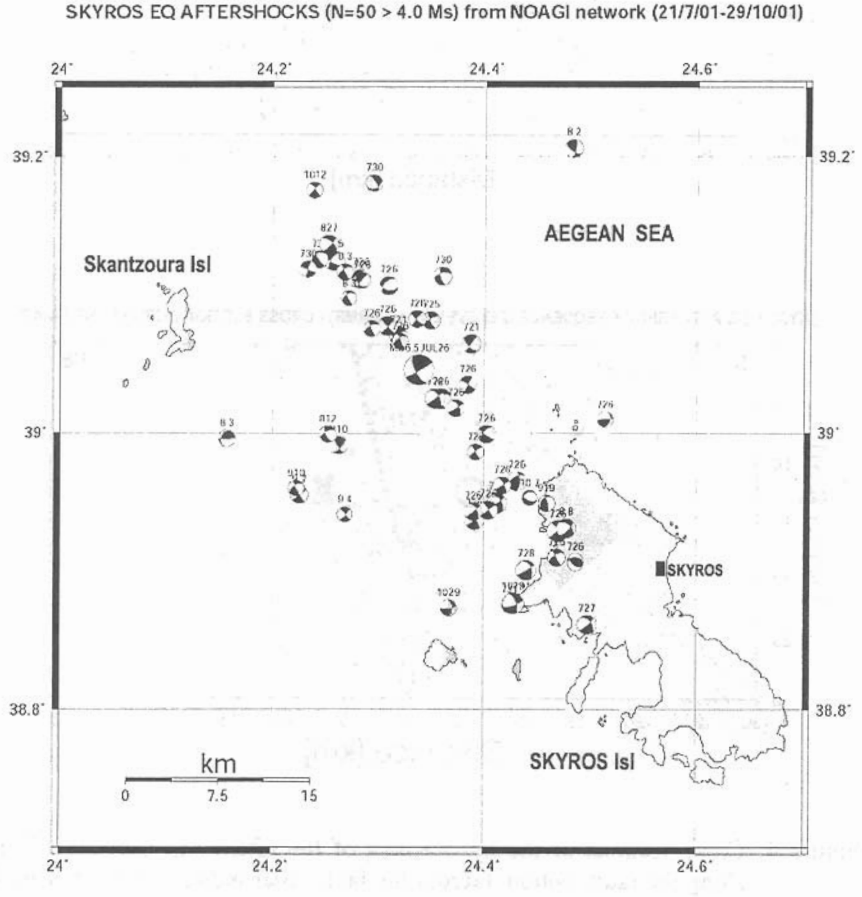

Figure 3: Map of focal plane solutions of major aftershocks of the Skyros 26 July, 2001 earthquake. Black denotes compression quadrants. Large, black beachball indicates solution for the main event. Shaded rectangle indicates extent of rupture zone and possible location of the seismic fault.

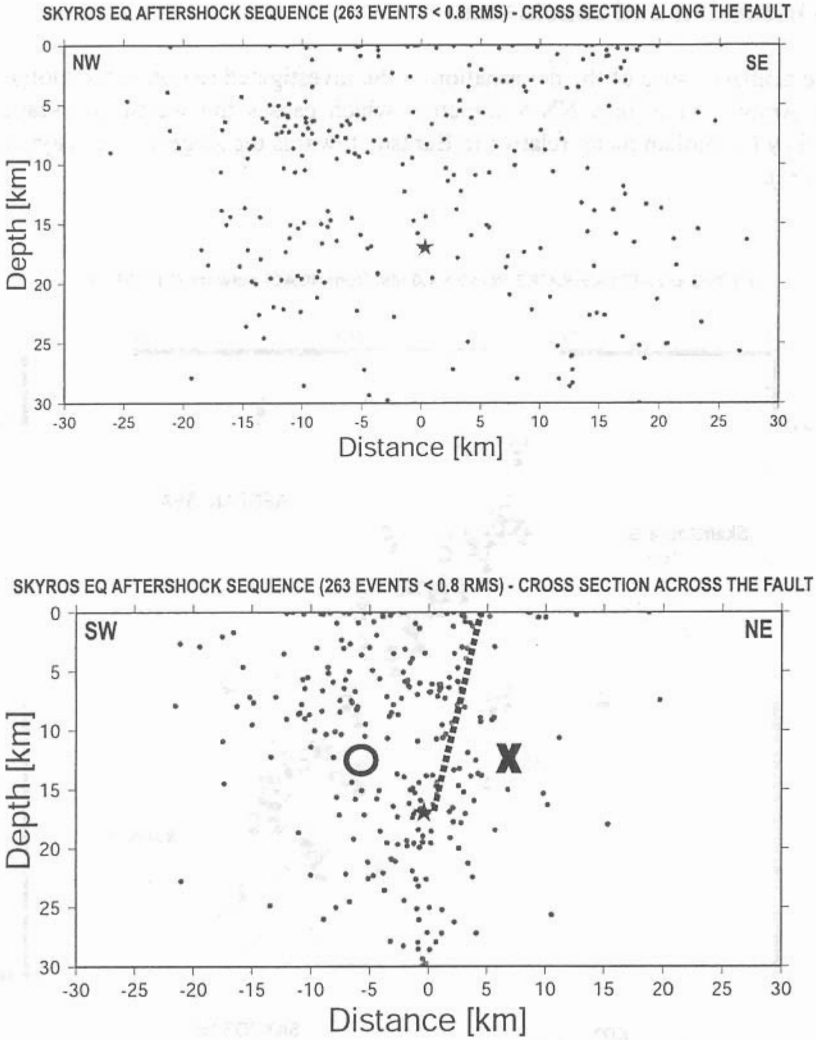

Figure 4: Cross sections of the hypocenters of the aftershock sequence. Top: along the fault, bottom (across the fault). Star indicates the mainshock hypocenter. Dashed line indicates geometry of the seismic fault. X indicates motion away from the observer.

The North East Anatolian strike-slip Fault accommodates this escape (Sengor *et al.* [13]). In turn, the counter-clockwise rotation of Anatolia causes an extensional stress field in the Aegean area (Pavlides and Tranos [14]). In its western termination, the NAF splits into two main branches. The northern branch is predominant in the region of the north Aegean Sea. The southern branch is less clear in the sea bottom morphology (Figure 1). It crosses north-western Asia Minor, and then it turns south-west and reaches the Skyros Basin, where the epicentral area of the Skyros earthquake (26 July 2001) is located. However, the extension of the NAF to the west (Greek mainland) is not well defined. The geological data suggest that this area is deformed primarily by normal faulting (e.g. Roberts and Ganas [15]). It is supposed that its continuation ends at the Cephallonia Transform Fault (CFT), which is considered as a triple junction of the Aegean, Eurasian and Adriatic plates (King *et al.* [16]).

On the contrary, our fault-plane solutions of the Skyros main shock show strike-slip faulting striking NW–SE with a small, thrust component (see also Melis *et al.* [6], Benetatos *et al.* [8]). These results document the existence of a major, left-lateral strike-slip fault in the area between Skyros Island and the Sporades basin (Figure 2). This fault appears to accommodate deformation between central Greece (to the west) and the Skyros basin (to the east). In addition, it should be mentioned that the fault-plane solution of the 4 March 1967 event (the largest in the vicinity of the epicentral region) indicates normal faulting (Delibasis and Drakopoulos [9]), striking NW–SE, as well.

This strong earthquake ends a long period of seismic quiescence in this region, since the previous strong event, of Ms=6.8, took place on 4 March 1967 at a distance of about 30 km from the epicenter of 26 July 2001 earthquake. Moreover, the strike of the seismic fault (NW–SE) is not optimally oriented to the general trend of the NAF. In this point, the critical question to be answered is whether the Skyros earthquake was an expected or an unexpected event. The progressive failure of NAF during the second half of the twentieth century has triggered strong earthquakes in the Aegean Sea, as supported by several investigators (Stein *et al.* [17], Nalbant *et al.* [18]). Therefore, from this point of view this event was an expected one. But its focal mechanism suggests that the activated rupture zone may define the western end of the NAF inside the Aegean Sea; and from this point of view the Skyros earthquake was an unexpected event.

References

[1] Papadopoulos, G.A., Ganas, A. & Plessa, A., The Skyros earthquake (Mw 6.5) of 26 July 2001 and precursory seismicity patterns in the North Aegean Sea. *BSSA,* **92(3)**, pp. 1141–1145, 2002.

[2] Papazachos, B.C., Kiratzi, A. & Papadimitriou, E., Regional focal mechanisms for earthquakes in the Aegean Sea. *PAGEOPH,* **136(4)**, pp. 405–420, 1991.

[3] Taymaz, T., Jackson, J. & McKenzie, D., Active tectonics of the north and central Aegean Sea. *Geophys. J. Int.,* **106**, pp. 433–490, 1991.

[4] Kiratzi, A. & Papazachos, C.B., Active crustal from the Azores triple junction to the Middle East. *J. Geodynamics,* **19(1)**, pp. 65–78, 1995.

[5] Papazachos, B.C., Karakaisis, G.F., Papazachos, C.B. & Scordilis, E.M., Earthquake triggering in the North and East Aegean plate boundaries due

to the Anatolia westward motion. *Geophys. Res. Lett.*, **27**, pp. 3957–3960, 2000.

[6] Melis, N.S., Stavrakakis, G.N. & Zahradnik, J., Focal properties of the Mw=6.5 Skyros, Aegean Sea, earthquake. *ORFEUS Newsletter*, **3(2)**, 2002.

[7] Zahradnik, J., Jansky. & Papatsimpa, N., Focal mechanisms of weak earthquakes from amplitudes spectra and polarities. *PAGEOPH*, **158**, pp. 647–655, 2001.

[8] Benetatos, C., Roumelioti, Z., Kiratzi, A. & Melis, N., Source parameters of the M 6.5 Skyros island (North Aegean Sea) earthquake of 26 July, 2001. *Annali di Geofisica*, **45(3/4)**, pp. 513–526, 2002.

[9] Delibasis. N. & Drakopoulos, J., Focal mechanism of earthquakes in the north Aegean Sea, 1965–1968 and related problems. *Geophys. Prospecting*, **N10**, pp. 149–167, 1974.

[10] Chouliaras, G. & Stavrakakis, G.N., Current seismic quiescence in Greece: Implications for seismic hazard. *Journal of Seismology*, **5**, pp. 595–608, 2001.

[11] Drakatos, G. & Latoussakis, J., Some features of Aftershock Patterns in Greece. *Geophys. J. Int.*, **126**, pp. 123–134, 1996.

[12] Tsokas, G.N. & Hansen, R.O., Study of the crustal thickness and the subducting lithosphere in Greece from gravity data. *Journal of Geophysical Research*, **102 (B9)**, pp. 20585–20597, 1997.

[13] Sengor, A., Gorur, N. & Saroglou, F., Strike-slip faulting and related basin formation in zones of tectonic escapes:Turkey as a case study, *Strike slip formation, basin formation and sedimentation. Soc. Economic Paleontologist and mineralogists*. eds. K.T. Biddle & N. Christ-Blick, Special Publ., **37**, pp. 227–265, 1985.

[14] Pavlides, S.B. & Tranos, M.D., Structural characteristics of two strong earthquakes in the North Aegean: Ierissos (1932) and Agios Efstratios (1968). *Journal of Structural Geology*, **13(2)**, pp. 205–214.

[15] Roberts, G. P. & Ganas, A. Fault-slip directions in central and southern Greece measured from striated and corrugated fault planes: comparison with focal mechanism and geodetic data. *Journal of Geophysical Research*, **105(B10)**, pp. 23443-23462, 2000.

[16] King, G., Sturdy, D. & Whitney, J. Landscape geometry and active tectonics of northwestern Greece. *Geol. Soc. Am. Bull.*, **105**, pp. 137–161, 1993.

[17] Stein, R.S., Barka, A. & Dieterich, J.H., Progressive failure of the North Anatolian fault since 1939 by earthquake stress triggering. *Geophys. J. Int.*, **128**, pp. 594–604, 1997.

[18] Nalbant, S., Hubert, A. & King, C.P., Stress coupling between earthquakes in northwest Turkey and the north Aegean Sea. *J. Geophys. Res.*, **103(B10)**, pp. 24469–24486, 1998.