HOW TO INFER THE POSSIBLE MECHANISM AND CHARACTERISTICS OF EARTHQUAKES FROM THE STRIATIONS AND GROUND SURFACE TRACES OF EXISTING FAULTS

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The instrumented period for earthquakes is relatively short to understand their mechanism and characteristics in many countries. Even at present time, there are many areas in the world where seismic instruments are still insufficient. Therefore, it is very difficult to know the mechanism and the characteristics of future earthquakes in any place because of either the lack of instrumentation and/or the shortness of the instrumented period. In this article, the authors present a methodology for inferring the possible mechanism and characteristics of earthquakes from the ground surface traces and striations of existing faults. The methodology is then applied to the faults of certain locations in Turkey and compared with actual observations in order to see its validity and applicability.

Key Words: *acceleration, earthquake characteristics, fault, focal plane solutions, magnitude, striation*

1. INTRODUCTION

Earthquakes are known to be one of the natural disasters resulting in both the huge losses of human lives as well as of properties as experienced in the 1999 Kocaeli, Düzce, Chichi, and 1995 Kobe earthquakes. Since there is no way to prevent the occurrence of earthquakes from time to time in earthquake-prone countries such as Turkey, Japan, USA and Taiwan, the design of structures and residential and industrial developments must be done according to possible types of earthquakes. It is well known that the shaking characteristics and the possibility of surface fault breaks will depend upon the earthquake types. While many large earthquakes occur along the subduction zones which are far from the land and their effects appear as severe shaking, the large in-land earthquakes may occur just beneath or nearby urban and industrial zones as seen in the recent 1999 Kocaeli, Düzce, Chichi, and 1995 Kobe earthquakes. Some of the characteristics of faults, which are just a product of rupturing of the earth's crust associated with the earthquakes, may be inferred from their ground surface traces and paleo-seismological evidences. The striations and the sense of ground deformations along the ground surface traces of the faults may also indicate the type and mechanism of earthquakes and the associated source faults. In other words, the features of striations and/or the sense of dislocations of the surface faults may be interpreted as the indicators of possible mechanism and characteristics of earthquakes, which may be useful for the design and construction of structures, and the urban and industrial developments. In this article, the authors present some procedures how to infer the possible mechanism and characteristics of earthquakes from the ground surface traces and striations of existing faults. These procedures are applied to the faults of certain locations in Turkey and compared with actual observations in order to see their validity and applicability.

2. THE CHARACTERISTICS OF EARTHQUAKES ACCOMPANYING SURFACE RUPTURES

Turkey is one of the well-known earthquake-prone countries in the world and most of her large earthquakes involve ground surface rupturing. The data from the past and present earthquakes of Turkey as well as Japan, USA and Taiwan may be quite useful to establish and/or to revise empirical relations among the characteristics of earthquakes accompanying ground surface rupturing. The data compiled by the authors come from the Turkish earthquake data-base (TEDBAS) developed by the first author[4] and additional inputs from recent earthquakes[3-13,21]. The data for other countries are those compiled by Yeats et al. [23]. The following items are chosen as the characteristics of earthquakes:

a) Magnitude(surface wave magnitude, M_s)
b) Length of earthquake fault (L): L denotes the length of source fault or that estimated by the ground surface trace observed in the field.
c) Depth of earthquake hypocenter (D)
d) Rupture area (S): S denotes the ruptured area of the earthquake fault inferred from aftershock distribution or the multiplication of surface rupture length produced by the earthquake by its hypocenter depth with the assumption of a rectangular source area.
e) Net slip of the earthquake fault (U_{max}): U_{max} denotes the maximum slip along the slip direction[22]
f) Maximum ground acceleration (a_{max}) (hypocentre distance is mostly in the range of 15-25 km)
g) Rupture mode – striation orientation
h) Ratio of vertical maximum acceleration to the horizontal maximum acceleration (RVAHA)

Fig. 1 shows the plot of data for several parameters listed above. The horizontal axis of most of the plots is the surface magnitude of earthquakes. In the same figures some of empirical functions are also plotted. As seen from the figure, the data are quite scattered. Although it is possible to fit all data into a single function, it seems that it is better to fit the data of a given region or a country to specific relations relevant to each respective region or country in order to reduce scattering. Aydan and his co-workers[3,4,8] proposed various empirical relations among several parameters listed above for the Turkish earthquake data as follows:

$$L = 0.0014525 M_s e^{1.31 M_s} \text{ (km)} \quad (1)$$

$$S = 0.0032 M_s e^{1.66 M_s} \text{ (km}^2\text{)} \quad (2)$$

$$a_{\max} = 2.8 e^{-0.025R} (e^{0.9 M_s} - 1) \text{ (Gal)} \quad (3)$$

$$RVAHA = 0.217 + 0.046 M_s \quad (4)$$

$$U_{\max} = 0.0014525 M_s e^{1.31 M_s} \text{ (cm)} \quad (5)$$

where R is hypocenter distance (km), M_s: surface wave magnitude.

3. METHODOLOGY FOR INFERRING THE MECHANISM AND CHARACTERISTICS OF EARTHQUAKES FOR A GIVEN REGION

Many countries have developed their own maps of geology and faults in various scales. Furthermore, many countries have their own active fault maps, and each fault has its own stress history. The striations and internal structure of these faults are just evidences of what type of stress state caused them, and they may also indicate what type of earthquake they produced. Therefore, the data for the faults for a given region may be used to infer the possible mechanism and characteristics of earthquakes. For such a study, the young faults must be given priority. The methodology for the inference of the possible mechanism of the faults require data on dip, dip direction and striation orientation. The definition of striation orientation used by Aydan[5] follows the one suggested by Angellier[1,2]. **Fig. 2** shows an illustration of how striation angle is measured. Several examples of earthquake focal mechanism for striation measurements done on the fault breaks at Başiskele, Eskişehir, Neodani and Onoki along Abekawa River are depicted in **Fig. 3**.

The next step of the methodology is the determination of characteristics of earthquakes with the use of the ground trace length of the fault. Although the actual fault may be longer than the surface trace length of the fault, it may be useful for determining the earthquake characteristics. First the magnitude of earthquake is either obtained graphically or non-linear back analysis of Eq. (1). Once the magnitude of the earthquake is determined, then the other characteristics of the expected earthquakes can be obtained from the empirical relations similar to those given by Eqs.(2) to (5).

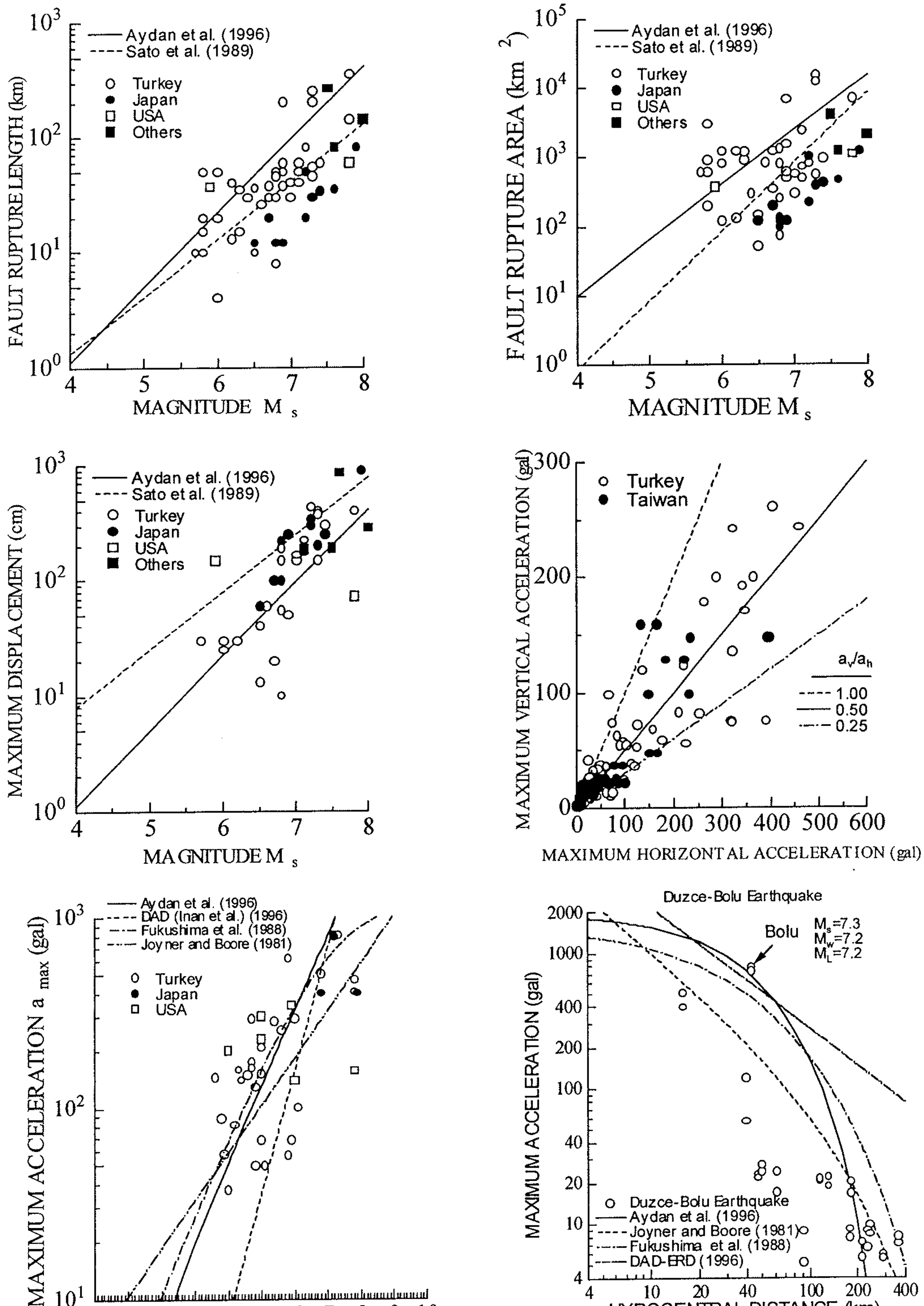

Fig. 1 Comparison of the seismic characteristics of the earthquakes from several countries with empirical relations proposed by Avdan et al. [9].

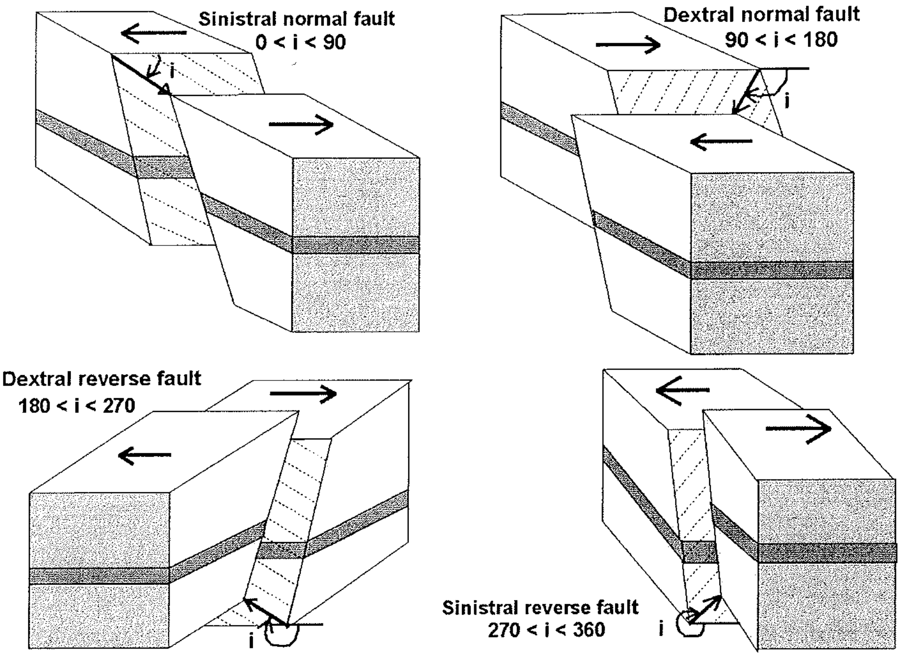

Fig. 2 Illustration of the definition of striation angle on a fault surface.

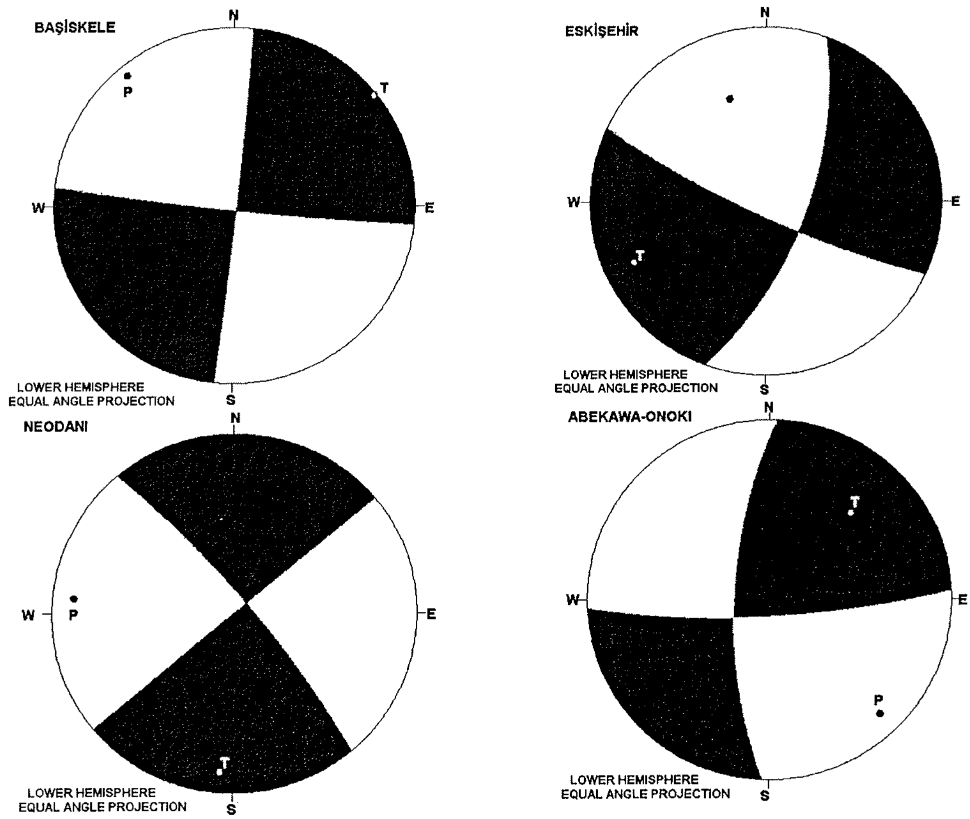

Fig. 3 Focal mechanism solutions for faults at Başiskele and Eskişehir (Turkey), and Neodani and Onoki along Abekawa River (Japan) from the orientation data of the faults and striations.

4. APPLICATIONS

(1) Back analysis of the recent earthquakes in Turkey

The proposed methodology is applied to the recent earthquakes in Turkey, which caused both structural damage and the loss of lives. In the analysis, the ground trace lengths of faults are used to infer the possible mechanism or the characteristics of the earthquakes, and the results are compared with the actual observations. Specifically; 1995 Dinar earthquake, 1998 Adana-Ceyhan earthquake, 1999 Kocaeli and Düzce-Bolu earthquakes are analysed. The parameters of the faults and the computed characteristics of the earthquakes are reported by Aydan & Kumsar[7] and Aydan et al. [10,12,13] and are given in **Tables 1-2**, respectively. **Fig. 4** illustrates the inferred faulting mechanism for each earthquake. From the comparison of the computed results with observations, it can be stated that it is possible to estimate the characteristics of earthquakes. Although some discrepancy exists between the computed and observed results, this problem can be solved if the faulting type is taken into account in the empirical relations. The inferred faulting mechanism of the earthquakes are quite similar to those reported by USGS, HARVARD, ERI, DAD/ERD and KOERI for each respective earthquake (Aydan et al. [7-12]).

(2) Applications to some possible future earthquakes

The methodology proposed in this study is applied to Denizli and Eskişehir regions in Turkey for possible earthquake scenarios, and the results of applications are described in the followings.

a) *Denizli region*

The Denizli region in the western Turkey, is a seismically very active region where Gediz and Büyük Menderes grabens join together. From the crustal deformation measurements by GPS and computations of mean stress variations, it is clarified that the region is undergoing a stretching strain regime. **Fig. 5** shows the mean stress distribution in the Western Turkey, in which the highest concentration occurs in the Denizli region (Aydan[5], Aydan et al.[5,13]). The seismic activity of this region is increasing at an alarming rate as seen from $\Sigma M\text{-}t$ relation and the frequency of earthquakes shown in **Fig. 6**. Earthquake data during 1973 and 1999 were obtained the data-base of National Earthquake Information Center of United States Geological Survey and denoted as NEIC[19] Data for year 2000 was obtained from Kandilli Earthquake Observatory and denoted as KOERI[18]. **Fig. 7** shows the magnitude versus frequency relation. The occurrence of an earthquake with a magnitude greater than 6 is almost imminent when the empirical relations presented in **Fig. 7** and the last two earthquakes with a magnitude of 6.4 in 1933 and a Mercalli intensity of IX in 1945 in this region are considered (Gençoğlu et al. [16]). Many small earthquakes occurred throughout 2000, and one of them had a magnitude of 5.2 on the Richter scale. The authors performed some site investigations on the striations of the faults and geological conditions. **Fig. 8** shows the fault traces and inferred focal mechanism solutions from the striations of the faults. The longest trace length of the investigated faults is about 35 km. For this fault trace length, it is expected that an earthquake with a magnitude of 6.3 may occur. Although no striation measurement is available for this fault, its faulting mechanism is likely to be similar to those shown for Sarayköy and Babadağ-1 (see **Fig. 8**). The characteristics of this possible earthquake along this fault trace can be computed from Eq.(2) to Eq.(5) as given in **Table 3**.

b) *Eskişehir region*

Although the recent seismic activity is quite sparse for this region, which is located in the northwest of Central Anatolia, it was shaken by an earthquake with a magnitude of 6.2 in 1956. The faults in the region are in the form of segments as shown in **Fig. 9**, and the longest fault trace is about 38 km. The Sultandere segment running from the south of Eskişehir city (see **Fig. 9**), is the most important fault which is a candidate to produce an earthquake in the region. The inferred magnitude of a future possible earthquake in the vicinity of Eskişehir is 6.35 for this fault segment. Based on this magnitude, the characteristics of an earthquake can be computed from Eq.(2) to Eq.(5) as given in **Table 4**.

Table 1 Parameters of the recent earthquake faults of Turkey.

Earthquake Name	Dip (°)	Dip Direction (°)	Striation Angle (°)	Length (km)
Dinar	52	234	101	20-25
Adana-Ceyhan	80	145	14	40-45
Kocaeli(average)	88	185	181	120-140
Düzce-Bolu(average)	88	188	164	45-50

Table 2 Comparison of the inferred and observed characteristics of the recent Turkish earthquakes.

Characteristics		Dinar	Adana-Ceyhan	Kocaeli	Düzce-Bolu
Magnitude, M_s	Computed	5.9-6.0	6.3-6.4	7.1-7.3	6.3-6.5
	Observed	6.0	6.2	7.8	7.3
Depth (km)	Computed	16.9-16.3	17.6-18.7	24.9-30.6	17.6-20.2
	Observed	24.0	14-17	15.0	14
Displacement (cm)	Computed	19.5-22.6	35.1-40.7	113-151	35.1-47.1
	Observed	51.0	-	450	420
Maximum acceleration (Gal)(R=25km)	Computed	303-332	435-477	900-1079	435-522
	Observed	320	274 (R=35km)	407 (R=46km)	513 (R=20km)
Vertical acceleration (Gal)(R=25km)	Computed	145-164	221-244	489-597	221-267
	Observed	135	87 (R=35km)	261 (R=46km)	340 (R=20km)

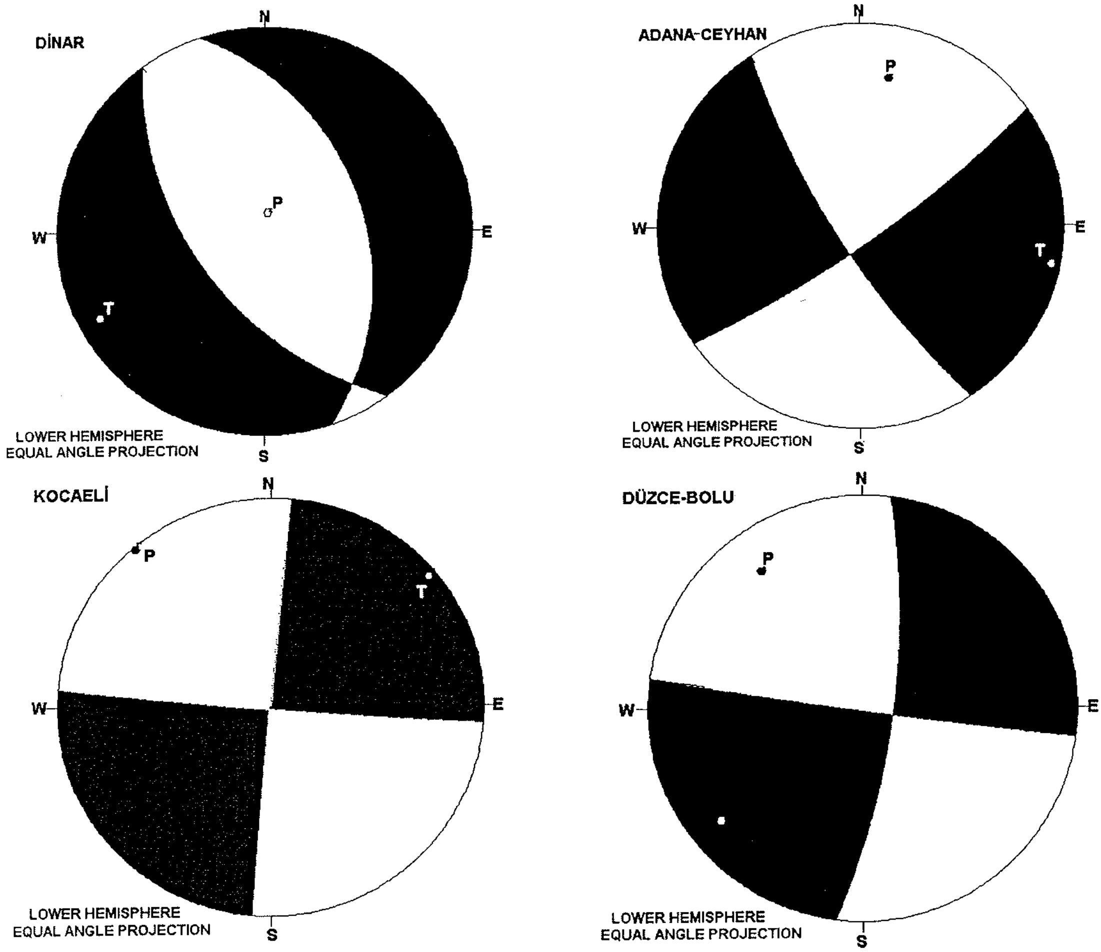

Fig. 4 Inferred focal plane solutions for 1995 Dinar earthquake, 1998 Adana-Ceyhan earthquake and 1999 Kocaeli and Düzce-Bolu earthquakes.

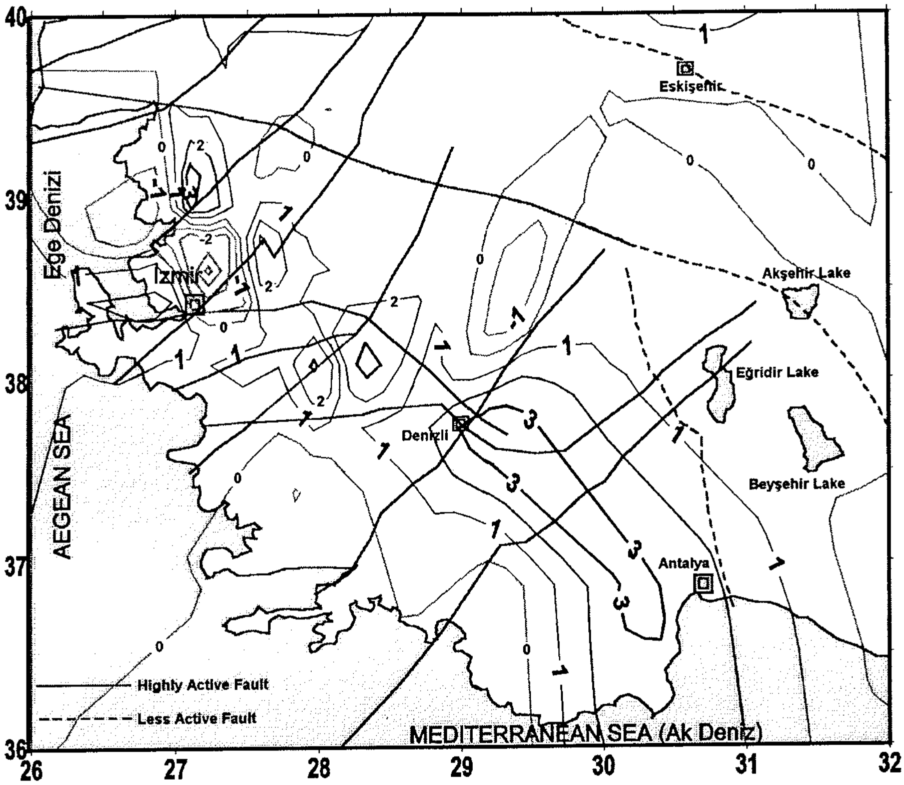

Fig. 5 Mean stress rate distributions computed from GPS measurements between 1988-1994 (Aydan et al. 2000b)(contours shows the mean stress rate value in kPa/year).

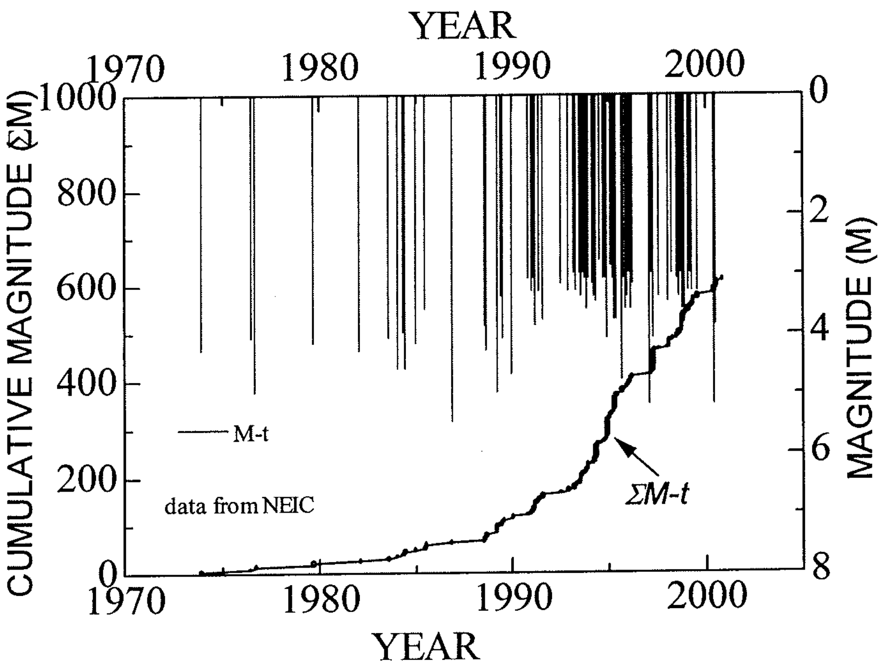

Fig. 6 Cumulative magnitude-time relation for the Denizli region between 1973-2000.

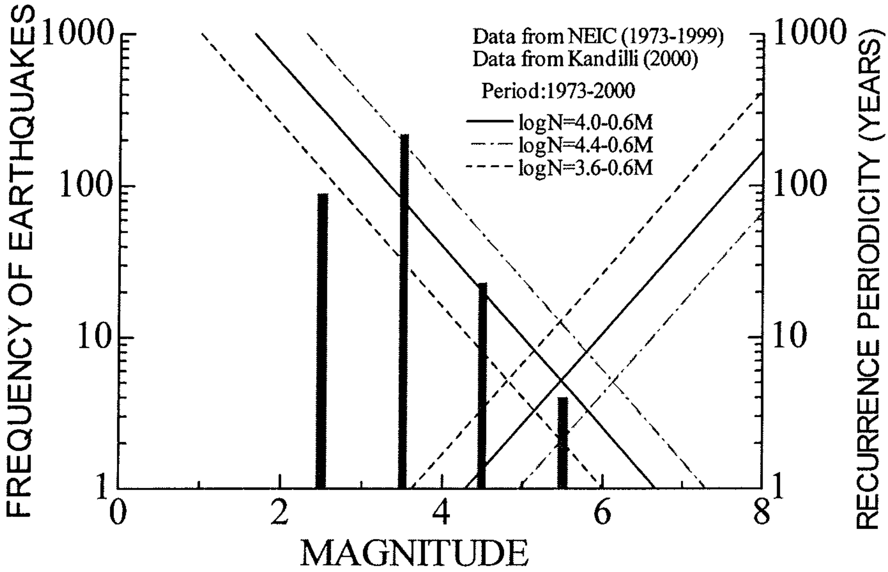

Fig. 7 Magnitude-frequency relation for the Denizli region between 1973-2000.

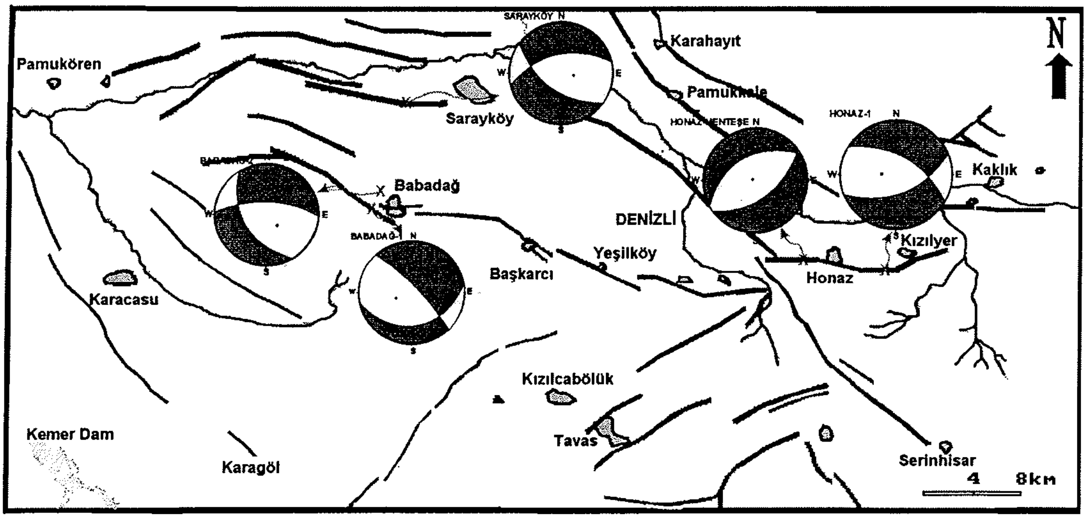

Fig. 8 Fault traces and inferred focal plane mechanism for the Denizli region.

Table 3 Comparison of the inferred characteristics of the earthquakes for the Denizli region.

Magnitude M_s	Depth (km)	Maximum acceleration (Gal) (R=25km)	Maximum vertical acceleration (Gal)	Displacement (cm)
6.30	19.96	432.2	219.0	35.00

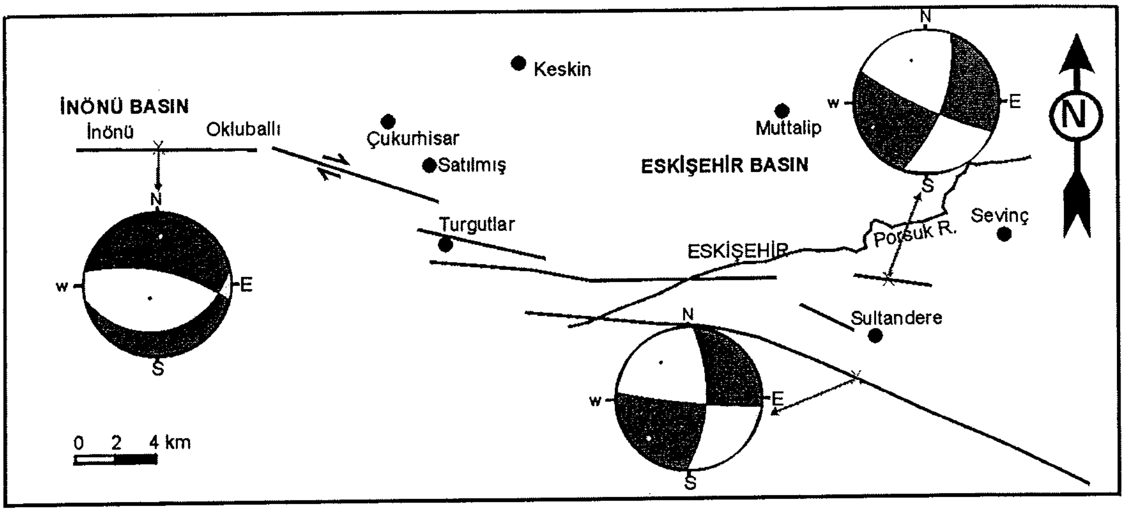

Fig. 9 Fault traces and inferred focal plane solutions for the Eskişehir region.

Table 4 Comparison of the inferred and observed characteristics of the earthquakes for the Eskişehir region.

Magnitude M_s	Depth (km)	Maximum acceleration (Gal) (R=25km)	Maximum vertical acceleration (Gal)	Displacement (cm)
6.35	20.36	454.6	231.5	38.00

5. CONCLUSIONS

The authors presented a methodology for inferring the possible mechanism and characteristics of earthquakes from the ground surface traces and striations of existing faults. The methodology is applied to the faults of certain locations in Turkey, and compared with actual observations in order to see its validity and applicability. From this study, the following conclusions may be drawn:

a) Empirical relations among several earthquake parameters suggest that it is better to fit the data region by region in order to achieve more representative values.
b) Comparison of the inferred and observed characteristics of the earthquakes occurred in Turkey shows a good coincidence and indicates that the methodology proposed for the focal plane solutions using the orientations of striations and the sense of surface fault dislocation yields considerably realistic results.
c) On the basis of the results of the analysis from two earthquake prone areas of Turkey, possible future earthquakes with magnitudes of about 6 seem to be possible.
d) The methodology proposed in this article may be useful for earthquake engineering design, particularly for preliminary assessments of the regions with a limited amount of information on their seismotectonic characteristics.
e) The applicability and performance of the methodology can be improved with further applications and comparisons at several places of the world with well-known seismotectonic characteristics.

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REFERENCES

1) Angellier, J.: Sur l'analyse de mesures recueillies dans des sites failles: l'utilité d'une confrontation entre les méthodes dynamiques et cinématiques, *C.R. Acad. Sci., Paris*, D281, pp.1805-1808, 1975.
2) Angellier, J.: Tectonic analysis of fault slip data sets, *J. Geophys. Res.*, Vol. 89(B7), pp.5834-5848, 1984.

3) Aydan, Ö.: Faulting and characteristics of earthquake waves in Hyogo-ken Nanbu Earthquake of January 17, 1995, *Jeoloji Mühendisliği*, No.48, pp.63-77 (in Turkish), 1996.
4) Aydan, Ö.: Seismic characteristics of Turkish earthquakes, *Turkish Earthquake Foundation*, TDV/TR 97-007, 1997.
5) Aydan, Ö.: A stress inference method based on GPS measurements for the directions and rate of stresses in the earth' crust and their variation with time, *Yerbilimleri*, No.22, pp.223-236, 2000.
6) Aydan, Ö. and Hamada, M.: The site investigation of the Erzincan (Turkey) Earthquake of March 13, 1992, *The 4th Japan-US Workshop on Earthquake Resistant Design of Lifeline Facilities and Countermeasures Against Soil Liquefaction*, pp.17-34, 1992.
7) Aydan, Ö. and Kumsar, H.: A site investigation of Oct. 1, 1995 Dinar Earthquake, *Turkish Earthquake Foundation*,TDV/DR 97-003, 1997.
8) Aydan, Ö. and Hasgür, Z.: Acceleration characteristics of Turkish earthquakes, *The 4th National Earthquake Engineering Conference*, pp.30-37, Ankara, 1997.
9) Aydan, Ö., Sezaki, M. and Yarar, R.: The seismic characteristics of Turkish Earthquakes, *The 11th World Conf. on Earthquake Eng.*, CD-2, Paper No:1270, 1996.
10)Aydan, Ö., Ulusay, R., Kumsar, H., Sönmez, H. and Tuncay, E.: A site investigation of Adana-Ceyhan Earthquake of June 27, 1998, *Turkish Earthquake Foundation*, TDV/DR 006-30, 1998.
11)Aydan, Ö., Ulusay, R., Hasgür, Z., and Taşkın, B.: A site investigation of Kocaeli Earthquake of August 17, 1999, *Turkish Earthquake Foundation*, TDV/DR 08-49, 1999.
12)Aydan, Ö., Ulusay, R., Kumsar, H. and Tuncay, E.: Site investigation and engineering evaluation of the Düzce-Bolu Earthquake of November 12, 1999, *Turkish Earthquake Foundation*, TDV/DR 095-51, 2000a.
13)Aydan, Ö., Ulusay, R. and Kumsar, H.: An approach for earthquake occurrences in Western Anatolia through GPS measurements, *The Symp. on Earthquake Potential of Western Anatolia*, pp.279-292, 2000b.
14)DAD-ERD: Catalogue of earthquakes between 1976-1996 with Acceleration Records,Edited by İnan, E., Çolakoğlu, Z., Koç, N., Bayülke, N. and Çoruh, E. Pub. of Earthquake Research Department, General Directorate of Disaster Affairs, Ministry of Public Works and Settlement, Ankara, 1996.
15)Fukushima, Y., Tanaka, T. and Kataoka, S.: A new attenuation relationship for peak ground acceleration derived from strong motion accelerograms., 9th WCEE, Tokyo, 1988.
16)Gençoğlu, S., İnan, I. and Güler, H.: Türkiyenin Deprem Tehlikesi. (Earthquake danger of Turkey) Pub. of the Chamber of Geophysical Engineers of Turkey, Ankara, 1990.
17)Joyner, W.B., and Boore, D.M.: Peak horizontal acceleration and velocity from strong motion records including records from the 1979 Imperial Valley, California, Earthquake. Bull.Seis.Soc.Amer.,Vol.71, No.6, pp.2011-2038, 1981.
18)KOERI: Kandilli Earthquake Observatory. http://www.koeri.boun.edu.tr/, 2000.
19)NEIC: National Earthquake Information Center of United States Geological Survey, http://neic.usgs.gov/, 1999.
20)Sato, R.: Handbook on Parameters of Earthquake Faults in Japan, Kajima Pub. Co., Tokyo, 1989.
21)Ulusay, R., Aydan, Ö., Kumsar, H. and Sönmez, H.: Engineering geological characteristics of the 1998 Adana-Ceyhan earthquake, with particular emphasis on liquefaction phenomena and the role of soil behaviour, *Bull. Eng. Geol. and Environment*, Vol.59, pp.99-118, 2000.
22)Whitten, D.G.A and Brooks, J.R.V.: A Dictionary of Geology, Penguin Books Ltd, Harmondsworth, Middlesex, England, 1972.
23)Yeats, R.S., Sieh, K. and Allen, C.R.: The Geology of Earthquakes , Oxford University Press, Oxford, Newyork, 1999.

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