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Water-Level Changes in Shallow Wells Before and After the 1999 İzmit and Düzce Earthquakes and Comparison with Long-Term Water-Level Observations (1999–2004), NW Turkey

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Abstract: It is well known that earthquakes cause hydrological changes, such as drying or flooding of water wells, fluctuations in ground-water levels in wells, changes in water quality, and formation of new springs. Significant drops in ground-water levels in wells were recorded during recent earthquakes in NW Turkey on August 17, 1999 in İzmit and on November 12, 1999 in Düzce. The İzmit earthquake (Ms 7.4) caused pre-seismic water-level changes in wells at Eskişehir, located 118–216 km away from the epicentre. Well-level changes in the Eskişehir, Sakarya, Bursa, Yalova, Yenişehir and İnegöl basins were recorded prior to and after the Düzce earthquake (Ms 7.2) as well. These changes are due to strain on the southern Marmara segments of the Thrace-Eskişehir Fault Zone (TEFZ), which is affected by deformation of the North Anatolian Fault Zone (NAFZ). Ground-water-level changes in wells prior to and after the earthquake away from the epicentre and the position of Eastern Marmara-Eskişehir region indicate a possible connection between well-level changes that respond to compressive and tensile stresses and shear strain away from active strike-slip faults. The wells, located in basins having an angular connection with the earthquake-producing main faults, completely activate only during major earthquakes. The wells showing anomalies prior to earthquakes are generally found near epicentres or in basins having an angular connection as stated above. The data collected after the 1999 anomalies up to September 2004 indicate that the 1999 anomalies are unique to that year. It was not difficult to separate the seasonal fluctuations of the water levels from the earthquake anomalies. In this context, it is concluded that the 1999 water level anomalies prior to the earthquake were the fast- and short-period signature of slow but long-term deformations that occurred over a large area.

Key Words: ground-water well-level changes, earthquake forecast, continental deformation, North Anatolian Fault Zone, Thrace-Eskişehir Fault Zone, 1999 İzmit-Düzce earthquakes

Sığ Su Kuyularında 1999 İzmit ve Düzce Depremleri Öncesi ve Sonrası Değişimler ve Uzun Dönem Su Seviyesi Değişimlerinin Karşılaştırılması (1999–2004), KB Türkiye

Özet: Deprem öncesi ve sonrasında su kaynaklarında ve kuyularda bir çok hidrolojik değişiklik oluşur. Su kaynaklarında kuruma veya yeni kaynakların oluşumu, su kuyularında salınımlar, su bileşiminde ve kalitesinde değişimler en bilinenleridir. 17 Agustos 1999 ve 12 Kasım 1999 depremleri öncesinden başlayarak suyu kuyularında (DSİ Eskişehir, Bursa) seviye değişimleri kaydedildi. İzmit depremi (Ms 7.4) öncesinde 118–216 km arasında uzaklıklardaki Eskişehir kuyularında sismik aktivite öncesinden başlayan kayıtlar alındı. Kuyulardaki seviye deşimleri Eskişehir, Sakarya, Bursa, Yalova, Yenişehir ve İnegöl havzalarında Düzce depremi (Ms 7.2) öncesi ve sonrasında da kaydedildi. Bu değişimler, Kuzey Anadolu Fay Kuşağı'nın güney Marmara'da bulunan reaktif Trakya-Eskişehir Fay Kuşağını etkilemesi ile ortaya çıkan düşük hızlı deformasyonun sonucudur. Güney Marmara-Eskişehir bölgelerindeki kuyu seviyelerindeki deprem öncesi ve sonrası deprem merkez üssünden uzakta meydana gelen değişimler, doğrultu atımlı faylarla ilişkili makaslama yamulmasından kaynaklanan sıkışma ve gerilme rejimlerine bağlı olarak genç yapıların etkilenmesinden kaynaklanır. Deprem olan ana fayla ilişkili, faya açılı sistemlerinin üzerine yerleşen havzalardaki kuyular, sadece büyük depremlerde tümüyle aktive olmaktadır. Bu kuyular ayrıca yerel olarak gerçekleşen depremler, aynı havzada, kuyu merkez üssüne yakın ise veya açılı bir sistemde deprem var ise, deprem öncesi tekil veya havza bazında grup olarak deprem öncesi değişimleri göstermektedir. 1999 değişimlerinden sonra 2004 yılının Eylül ayına kadar toplanan veriler, kuyulardaki 1999 değişimlerinin tamamen deprem olan yıla özel karakteristikleri olduğunu gösterir. Sürdürülen kuyu gözlemlerinde kuyularda mevsimsel değişimler kolaylıkla ayırt edilmiştir. Bu çerçevede DSİ kuyularında meydana gelen 1999 anomalileri, 17 Agustos ve 12 Kasım depremleri öncesinde başlayan, geniş bir alanda oluşan düşük hızlı deformasyonun, önce uzun periyotlu, kırılma öncesine yakın bir zamandaki kısa periyotlu imzasıdır.

Anahtar Sözcükler: kuyu yeraltısuyu seviyesi değişimi, deprem tahmini, kıta içi deformasyon, Kuzey Anadolu Fay Kuşağı, Trakya-Eskişehir Fay Kuşağı, 1999 İzmit-Düzce depremleri

Introduction

The North Anatolian Fault Zone (NAFZ) is the most prominent active fault system in Turkey and has been the source of numerous historical earthquakes (Ambraseys & Finkel 1995; Şengör *et al.* 2005). Two devastating earthquakes, 86 days apart, resulted from recent movements on the NAFZ in western Turkey (the Marmara region). The first earthquake, of magnitude 7.4, occurred in İzmit on August 17, 1999 at 03:02 local time (00:02 GMT). This earthquake originated at a depth of about 15.9 km with an epicentre at N40° 70´, E29° 91´ (Figure 1a). The earthquake damaged a large area covering almost the whole Marmara Region. The number of buildings that collapsed or were heavily damaged reached around 41,000 and the death toll was around 24,000. The Düzce earthquake (Ms 7.2) occurred on November 12, 1999 at 18:57 local time (16:57 GMT). The epicentre was at N40° 79´, E31° 07´ at a depth of 10 km. The death toll was 893, and the most significant damage occurred between Düzce and Bolu (Figure 1a).

Westward migrating activity on the NAFZ, which caused these two earthquakes, appears to threaten the Marmara region. In particular, İstanbul, the largest city of Turkey, is under threat of an M>7 earthquake, expected within 2 to 20 years (Le Pichon *et al.* 1999; Parsons *et al.* 2000; Ambraseys & Jackson 2000).

The arc-shaped NAFZ is 1500-km long, from eastern Anatolia to the northern Aegean region in northwestern Anatolia. The strike-slip nature of the NAFZ was first recognized by Ketin (1948) and numerous studies of it have been carried (e.g., Şengör *et al.* 1985, 2005 and references therein) (Figure1b). The fault zone consists of a single strand for most of its length and then splits into three approximately E–W-striking strands to the east of the Sea of Marmara: a northern segment (NAFNS), a middle segment (NAFMS), and asouthern segment (NAFSS) (e.g., Koçyiğit 1988; Yaltırak 2002; Figure 1a).

The Thrace-Eskişehir Fault Zone (TEFZ), an older right-lateral strike-slip fault, is now an active normal fault. It strikes NW–SE through the Marmara region and has been displaced by the three strands of the NAFZ (Figure 1). While the relationship between the NAFZ and TEFZ is not well understood, preliminary arguments have been recently set forth by Yaltırak *et al.* (1998) and Sakınç *et al.* (1999). In an earlier study, Perinçek (1991) interpreted the TFZ (Thrace Fault Zone; Thracian part of the TEFZ) as a part of the NAFZ by using seismic sections in Thrace. However, Yaltırak (1996) and Tapırdamaz & Yaltırak (1997) disagreed, on the basis of structural and palaeomagnetic data, with the Perinçek (1991) study and interpreted the TFZ as a different strike-slip system formed before the NAFZ. Following the idea of Yaltırak *et al.* (1998) that the TFZ has a similar age and position as the Eskişehir fault, Sakınç *et al.* (1999) named this fault the Thrace-Eskişehir Fault Zone (TEFZ), which is older than the NAFZ; the TEFZ is a dextral strike-slip fault extending from Eskişehir across eastern Thrace (Turkey) to western Thrace (Greece). At present, the different parts of this fault are characterized by low seismic activity and normal character, presumably due to dextral shear strain of the NAFZ (Yaltırak 2002).

Numerous Miocene–Quaternary basins resulting from the interactions of these two fault zones have been recognised recently. Although the hydrogeological properties of these basins have been investigated previously, their relationship to regional tectonics has not been adequately researched.

Pre-earthquake turbidity and temperature changes in thermal waters around these tectonically-formed basins have been reported (Şimşek & Yıldırım 2000) in connection with both of the 1999 earthquakes. However, after the İzmit and Düzce earthquakes there were insufficient measurements to indicate ground-water and well-level changes that occurred in response to these tectonic activities. Earthquake-related well-level changes have been reported in other locations (Yaltırak *et al.* 2001; Yüce *et al.* 2001, 2004; Yüce & Uğurluoğlu 2003), and some authors have discussed the reasons from a tectonic point of view (Cotta *et al.* 1860; Gordon 1970; Coe 1971; Wakita 1975; Rikitake 1976; Lomnitz &Lomnitz 1978; Nayak *et al.* 1983; Oki & Hiraga 1988;

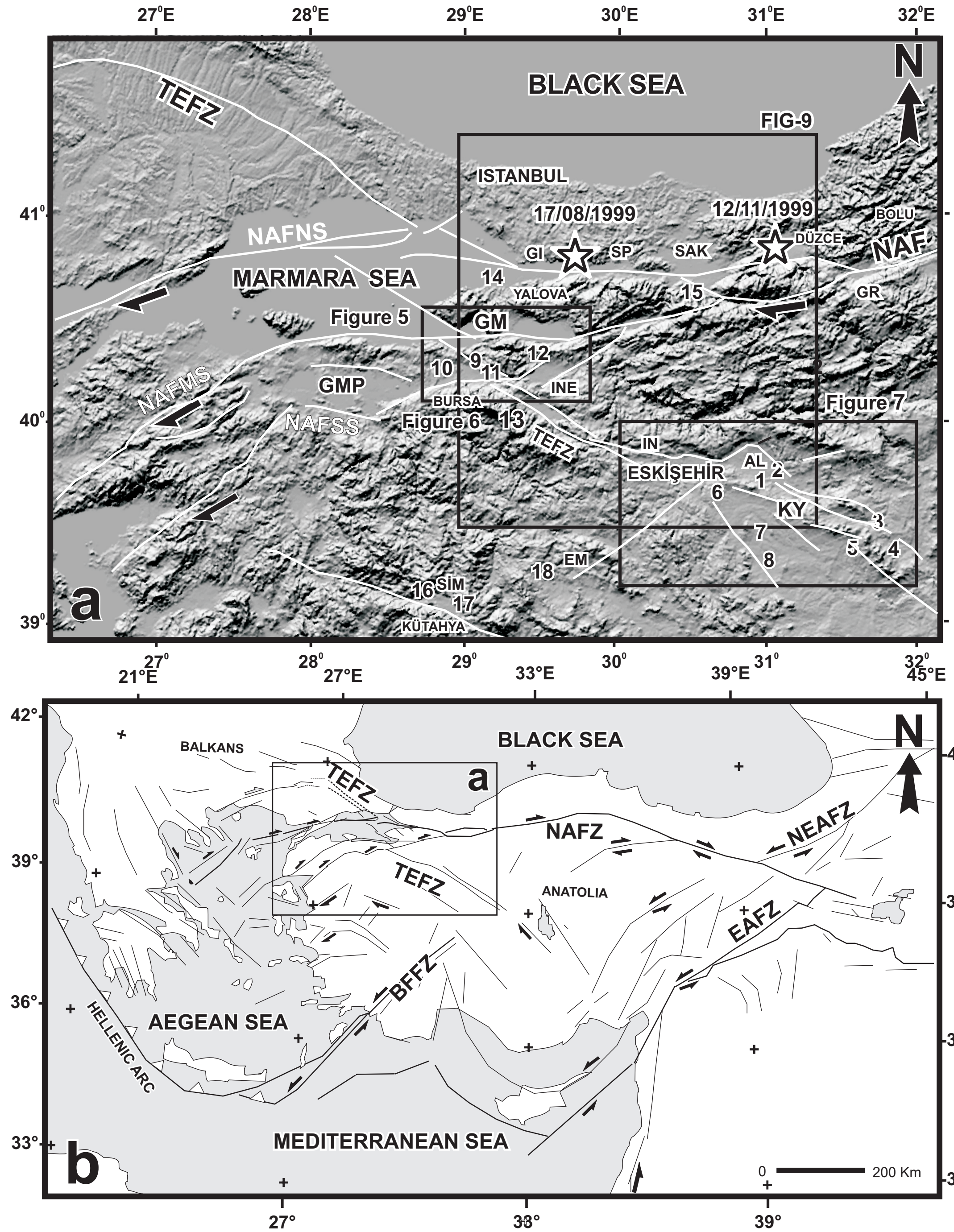

Figure 1. (a) Branches of the North Anatolian Fault and Thrace-Eskişehir Fault zones, and important localities. TEFZ – Thrace-Eskişehir Fault Zone, NAF – North Anatolian Fault, NAFNS – NAF north segment, NAFMS – NAF middle segment, NAFSS – NAF south segment, SAK – Sakarya, GR – Gerede, SP – Sapanca, GM – Gemlik, GI – Gulf of İzmit, GMP – Gönen-Manyas Plain, AL– Alpu; INE – İnegöl, IN – İnönü, KY – Kaymaz; EM – Emet, SİM – Simav. Branches of the North Anatolian Fault Zone in the Sea of Marmara re-interpreted after Yaltırak (2002) and Bozkurt (2001). Stars show earthquake epicentres and dates. Numbers show observation wells. (b) Map of the Neogene-Recent tectonic lines of Turkey; TEFZ – Thrace-Eskişehir Fault Zone, BFFZ – Burdur Fethiye Fault Zone, NAFZ – North Anatolian Fault Zone, EAFZ – East Anatolian Fault Zone, NEAFZ – Northeast Anatolian Fault Zone (compiled from Şengör *et al.* 1985; Yaltırak *et al.* 1998; Bozkurt 2001).

Astreadis & Livieratos 1989; Lomnitz 1994; Roeloffs & Langbein 1994; Roeloffs 1996, 2000; Kissin *et al.* 1996; Ohno *et al.* 1997; King *et al.* 1999; Grecksch *et al.* 1999; Gavrilenko *et al.* 2000; Arabelos *et al.* 2001; Woith *et al.* 2003). This paper presents data on well-level variations in DSİ (State Hydraulic Works) wells – used for monitoring long-term ground-water-level changes in young basins – located in Eskişehir (recorded during both earthquakes), Bursa, Sakarya, Yalova, Gediz, Emet (recorded after the İzmit earthquake), and evaluates their relationship to regional tectonics (Figure 1a).

Earthquakes and Well-Level Changes

Method and Data

The DSİ (State Hydraulic Works) wells used in this study were installed to observe seasonal water-level changes around irrigated plains. Previously, mechanical water recorders were used in these wells, and water levels were plotted on paper drums. Since 1999, DSİ replaced these recorders with semi-electronic instruments in particular for the convenience they provide at remote wells.

Before the İzmit earthquake, data from nine wells were recorded, stored and transferred to a computer. There were 18 wells recording before the Düzce earthquake (Table 1). Eleven of these located in the Eskişehir region continued recording in 2000 and 2004 and experienced the anomalies before the Düzce event (Table 1).

Method of Water-Level Recording

EKH-LHD5-61 hybrid-type water-level recorders manufactured by Akım Elektronik Company were used. This apparatus is capable of recording for 24 hours. The recorded data by DSİ are the maximum and minimum levels for each day (24 h); hence each apparatus was adjusted by DSİ technicians to store only these two data points. By doing this, the memory of the apparatus would be able to store several months of data.

The apparatus records all water-level changes greater than 1 cm within 24 h. At 00:00 (12:00 midnight), only the maximum and minimum water levels (in cm) and times (in h and min) are kept in the memory while the rest of the data are removed. Data transfer from recorders is done by technicians. A computer is connected to the data-logger of the recorder by using cables, and special software is run in order to enable an automatic transfer. During the transfer procedure, the time is automatically checked and set to the GMT+02:00 Athens, İstanbul, and Minsk time zone by Akım Elektronik Company before dispatch. The data logger has 32 KB static, low consumption C-MOS RAM (ring memory) powered by lithium batteries which have a 4-yr life. The sensitivity of the clock is annually max ±3 min per year. However, this error is minimised by adjusted data transfer at a maximum of every 6 months.

The float and reel of the water-level recorder is designed to record at a maximum speed of 0.256 ms^{-1}. The wells using this kind of water-level recorders are installed away from residential and agricultural areas in order to obtain reliable data.

In case of power failure, the water-level recording system goes on working, automatically connecting itself to the lithium battery. The recording happens by movement of a reel activating the LED sensor. Piezoelectric changes in the air and ground do not affect the system. The setting of time in all recorders is done by the same computer and technician, so the times of all recorders should be identical, enabling us to correlate their times. Even if the time is set incorrectly by accident, this error would appear in all recorders. In this case, the surface wave generated by an earthquake would be observed in recorders at 1-minute intervals as a function of distance from the epicentre.

Classification of Recorded Data Types

Changes Preceding an Earthquake. Pre-earthquake records and changes can be classified in two ways. One is the daily two extreme levels measured 1 minute prior to an earthquake (Figure 2a). Daylong measured levels, which are between the extreme values, are deleted by filtering and only the changes occurring in 1 minute are observed as pre-earthquake recorded values (Figure 2b). We call such records type A. Type-A records were seen in the Mahmudiye, İstiklal, Atlas, Güneli and Koçaş wells during the İzmit earthquake, and in the Bozan, Güneli and Atlas wells during the Düzce earthquake (Figure 3). Only the Bursa-Deliçay well recorded type-A changes at the eve of the Düzce earthquake.

The second type of change has only one extreme value prior to an earthquake (Figure 2c), which we call Type B. One of the extreme values is deleted due to filtering

Table 1. List and properties of observation wells.

well number	well name	Period of record	name of basin	depth well (m)	distance to İzmit earthquake (km)	distance to Düzce earthquake (km)	formation thickness (m)	lithology	aquifer type
1	*Güneli*	May 11, 1999 Nov 09, 2001	Alpu	200	136	118	10-250	soil - marl-limestone-marl-sand-claystone	semiconfined
2	*Bozan*	May 11, 1999 Nov 23, 2001	Alpu	175	138	111	10-250	soil -caliche- clay pebble-clay-sandypebble	unconfined
3	*Koçaş*	Oct 02, 1998 Sep 09, 2001	Sivrihisar	210	197	149	10-250	marl pebble-sand	semiconfined
4	*Atlas*	May 12, 1999 May 31, 2001	Sivrihisar	131	216	167	100-300	alluvium - conglomerate sand -conglm.	unconfined
5	*İstiklal*	Dec 11, 1998 Nov 19, 2001	Sivrihisar	205	197	156	100-300	conglomerate sand-conglm.	unconfined
6	*Yenikent*	Dec 18, 1998 Nov 08, 2001	Eskisehir	55	121	126	100-300	soil -limestone sandy clay c lay pebbles	unconfined
7	*Mahmudiye*	Oct 01, 1998 Nov 08, 2001	Mahmudiye	144	162	149	5-350	soil -tuff-marl tuff - aglom.	semiconfined
8	*Çifteler*	Oct 02,1998 Nov 15, 2000	Mahmudiye	306	171	156	5-350	soil -clay-sand-marl-clay -marl	unconfined
9	*Dudaklı*	Oct 27, 1999 Dec 12, 1999	Bursa	135.5	87	171	80-200	alluvium sand -pebble	unconfined
10	*Çayırköy*	Oct 27, 1999 Dec 19, 1999	Bursa	189.4	109	188	80-200	alluvium sand -pebble	unconfined
11	*Dudaklı*	Oct 27, 1999 Dec 19, 1999	Bursa	142	91	176	80-200	alluvium sand-Pebble	unconfined
12	*Karasıl*	Nov 3, 1999 Dec 13, 1999	Yenişehir	90	67	143	30-50	alluvium sand -pebble	unconfined
13	*Yenice*	Nov 3, 1999 Dec 12, 1999	İnegöl	184	90	162	2-100	alluvium sand -pebble	unconfined
14	*Yalova*	Nov 5, 1999 Dec 10, 1999	Yalova	36	52	147	2-50	soil -sand - pebble	unconfined
15	*Reşitbey*	Nov 7, 1999 Nov 22, 2001	Sakarya	30	43	53	2-40	pebbles	unconfined
16	*Hisarbey*	May 17,1999 Nov 02,2001	Simav	152	201	265	100-200	alluvium sand -pebble	semiconfined
17	*Gölköy*	Sep 02, 1999 May 18, 2001	Simav	103	198	259	100-200	alluvium sand -pebble	unconfined
18	*Örencik*	Sep 02, 1999 Nov 07, 2001	Emet	297	164	214	50-400	sand -pebble-limestone	confined

whereas the second extreme value is recorded after an earthquake (Figure 2d). Type-B records were observed in the Çifteler and Bozan wells during the İzmit earthquake, and in the Çifteler, Mahmudiye, Koçaş, Bursa and Dudaklı wells during the Düzce earthquake (Figures 3 & 4). The Sakarya-Reşitbey well recorded a short maximum and minimum type-B changes on the eve of the Düzce earthquake (Figures 3 & 4).

Water-Level Changes Recorded During and After Earthquakes. These types of records were observed in wells located near the epicentre or in areas close to the strands of the NAFZ, such as Yalova, Yenişehir-Karasıl, İnegöl-Yenice and Bursa-Deliçay (Figure 4). The extreme values recorded in these wells after the earthquake should be greater than pre-earthquake ones, so only the greater values are kept in the memory.

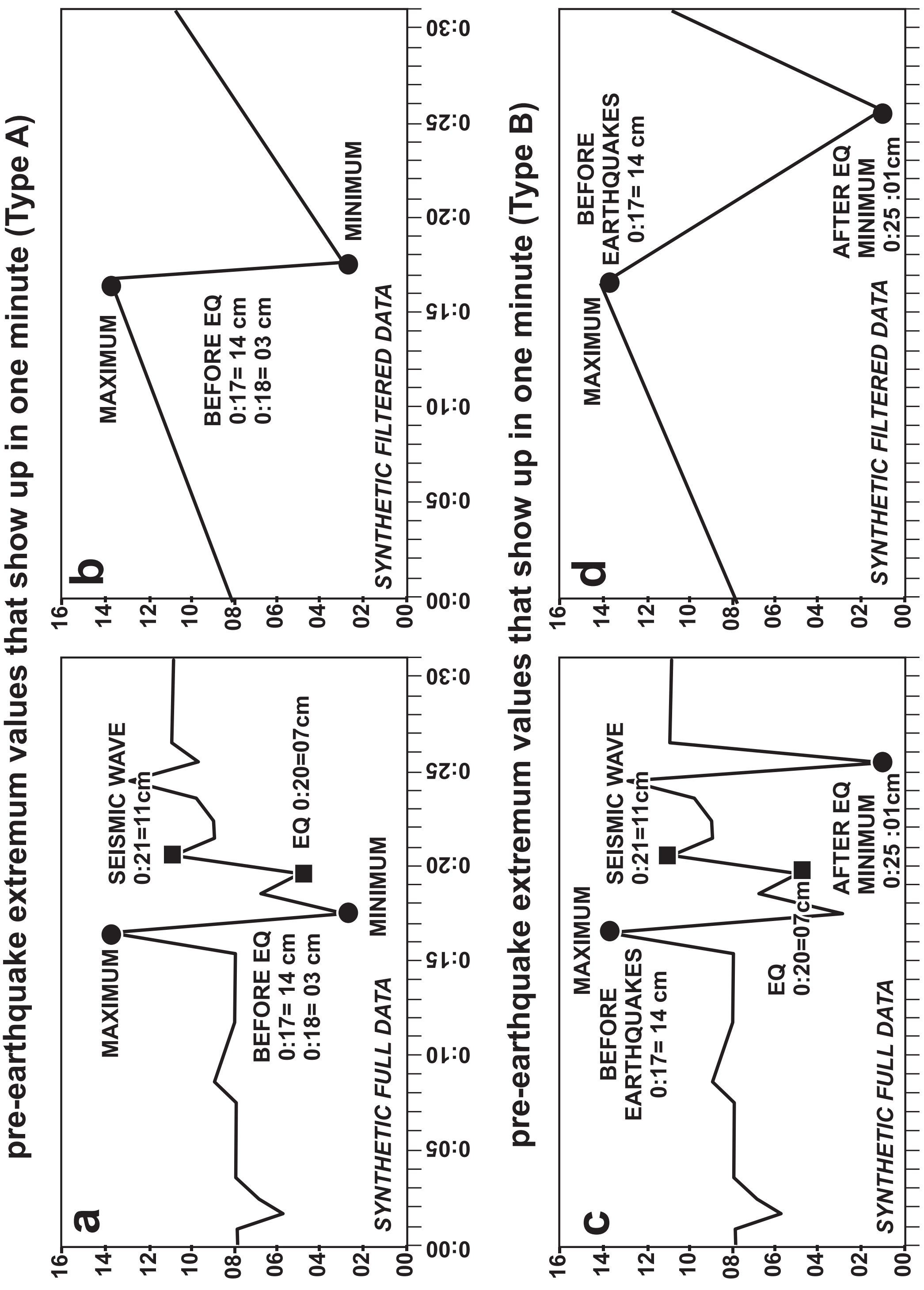

Figure 2. Synthetic curve examples showing anomalies recorded by wells recorded before and after filtration: (a) is between maximum and minimum values prior to earthquake; (b) comprises the changes that occurred only 1 minute prior to the earthquake after filtration; (c) contains the maximum value prior to the earthquake and minimum value after the earthquake (from memory) as a result of filtration; (d) only has records of one level value and one time value prior to the earthquake after filtration.

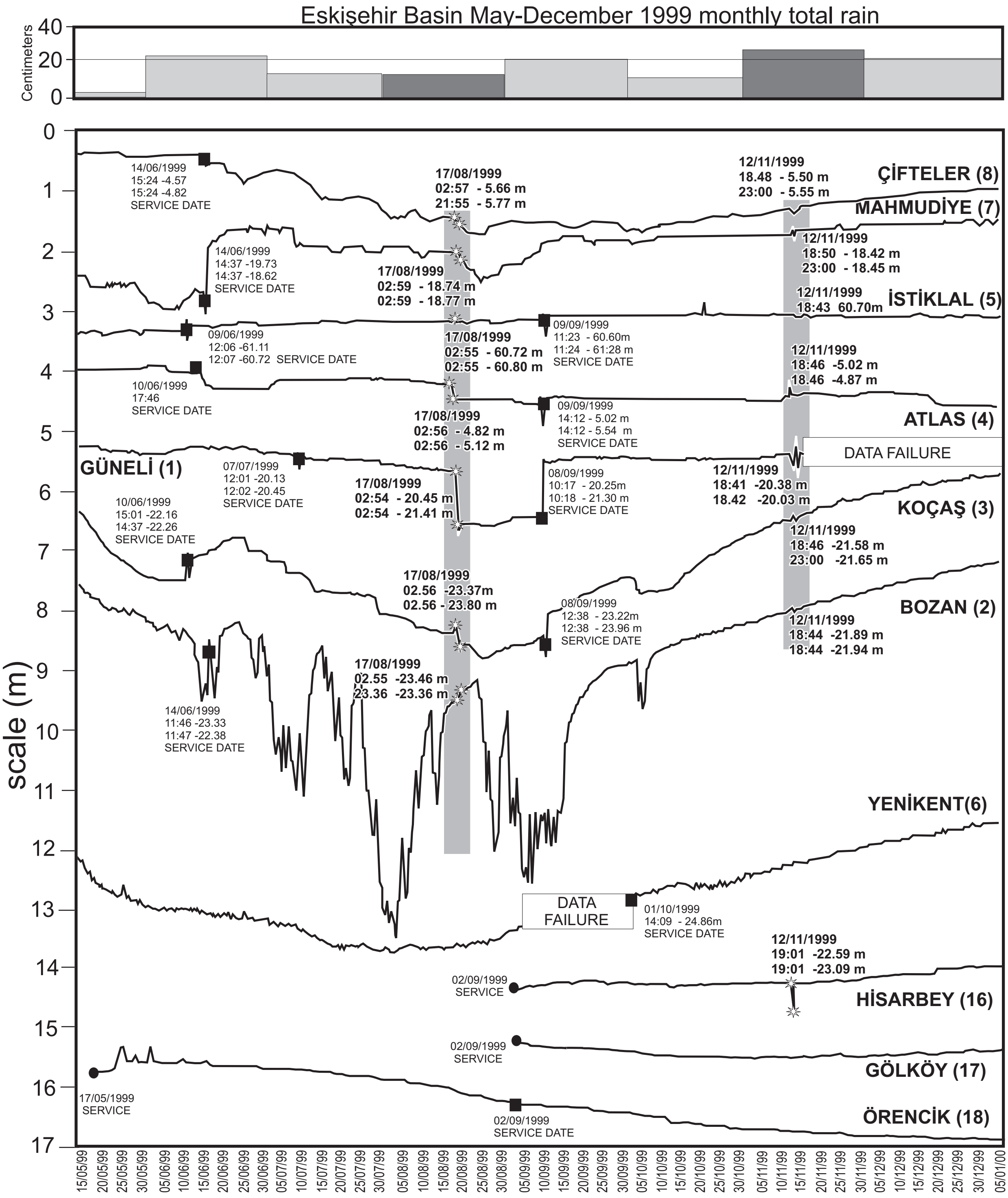

Figure 3. Water-level changes in the wells of the Eskişehir region prior to and after the 17 August 1999 and 12 November 1999 earthquakes. The service dates of technicians are indicated by black squares. Grey-banded areas show instantaneous changes as time and level. Maximum and minimum recordings are plotted for each day. The upper part of the figure shows the total rain for May–December 1999.

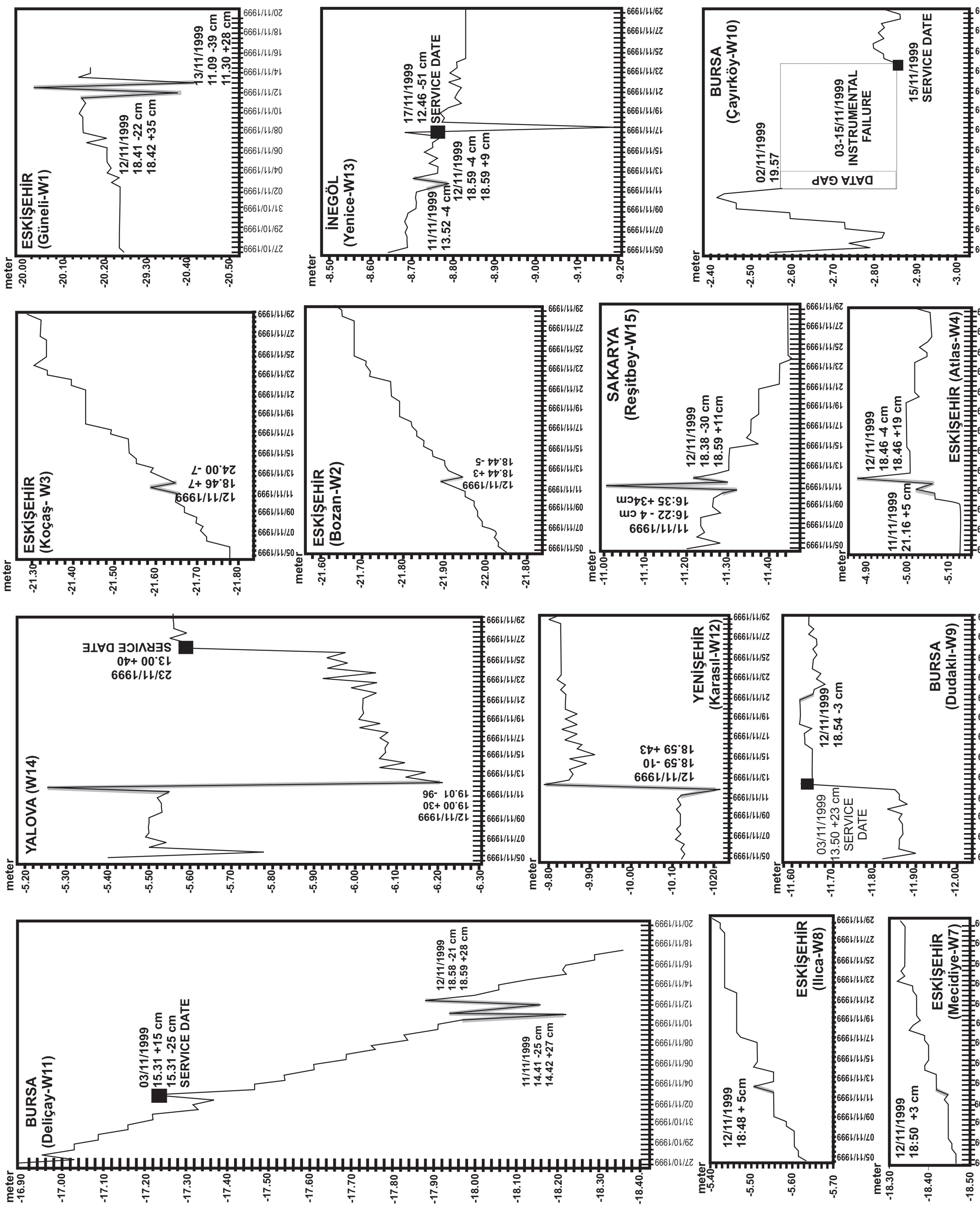

Figure 4. Plot of changes in the Eskişehir and Bursa wells prior to and after the 12 November 1999 earthquake. All the graphics have the same scale. Water levels for each well are indicated at the right side of the figure. Maximum and minimum recordings are plotted for one day.

Wells Showing No Water-Level Changes Related to Earthquakes. Wells located outside the areas affected by the NAFZ showed no water-level changes during the earthquakes. The purpose in presenting the data from these wells is to show the difference between the areas affected and unaffected by the NAFZ and TEFZ. These wells are the Yenikent and Örencik (Figure 1 & Table 1) wells that began recording prior to the İzmit earthquake. The other two wells are the Hisarbey and Gölköy (Figure 1 & Table 1), which have been recording water-level changes since 09 February 1999 (Figure 3). The water-level changes are generally seasonal and differ from earthquake-related anomalies. Only the Hisarbey well recorded the surface waves 1 minute after the earthquake, probably because it is located in a tectonically active basin (Figure 3).

1999 Anomalies Recorded from the DSİ Wells

Eskişehir Wells. There are recorders installed on water wells (Güneli, Bozan, Kocaş, Atlas, and İstiklal, Yenikent, Mahmudiye, Çifteler, Hisarbey, Örencik and Gölköy) in the Eskişehir region that recorded well levels one year before and four years after the earthquakes (Table 1). These wells responded differently during the two earthquakes because of their distances from the epicentres and their positions relative to the tectonic pattern. The discrepancies in anomalies in the wells are also related to surrounding formations. As an example, the Bozan well showed the highest daily well-level difference (Figure 3). The presence of conglomerate between the two thick clay layers affected this result. However, the anomalies in the Güneli well, south of the Bozan well, were different and small in magnitude. The well is drilled in fractured limestone, and sand and marl alternations (Table 1). The Koçaş well had another of the anomalies and was drilled in gravel, and sand and clay alternations, and the presence of weakly cemented porous material was an important factor in varying anomalies (Table 1). To the south of the Kocaş well, the Atlas well, drilled in sand, gravel and conglomerate, also played an important role in reflecting the pre-earthquake strains. Anomalies were observed in the İstiklal well, which is close to the TEFZ and drilled in conglomerate and sand. However, the Yenikent and Örencik wells, which are out of the system, recorded no anomalies (Figure 3), and were drilled in clay and silt. The Çifteler and Mahmudiye wells, which are located in a secondary basin at 45° angles to the TEFZ, showed weak water-level variations during both earthquakes (Figures 1 & 3). The lithologies of these wells are alternations of various units; they have high porosities and show that the young basins were affected by strain.

All of the wells, except for the Yenikent and Örencik wells, showed anomalies prior to the İzmit earthquake (Figures 3 & 4). Some of them showed fluctuations that began a few months before the earthquake and that increased with time; but some showed small magnitude fluctuations. The Bozan, Koçaş, Mahmudiye, Çifteler, Atlas, Güneli and İstiklal wells started fluctuations from mid-May 1999 (Figure 2). The common characteristic of all of these wells is a relative decrease in water level compared to the winter period. This decrease became an increase in water levels after the August 17, 1999 earthquake.

It is also possible to observe some man-made signals due to static water-level calibration by technicians. The dates and times of this kind of anomalies are indicated on recordings by the technicians (Figure 3).

The anomalies related to the İzmit and Düzce earthquakes were recognised afterwards during data evaluation. The most noticeable feature of these anomalies was their time of occurrence; the sudden (within a minute) anomalies were 5 to 9 minutes prior to the İzmit earthquake, and 4 to 15 minutes prior to the Düzce earthquake (Table 2).

The drop in water level of the Koçaş well was 43 cm, 6 minutes prior to the İzmit earthquake (at 02.56) (Figure 3). At Düzce, the same well began rising by 7 cm before the earthquake, and lasted until 12 minutes prior to the occurrence of the earthquake, followed by a 3 cm drop (Figure 4 & Table 2).

The Bozan well recorded large-magnitude continuous fluctuations between 5 May and 7 September 1999, unlike the other wells (Figure 3), reaching its lowest level on 4 August 1999. Since that day it raised with fluctuations continuously until 7 October 1999. The signal of 17 August 1999 was weak with in these large-magnitude level variations. Water levels were recorded at 02:55 (23.44 m) and 23:53 (23.36 m) on 17 August 1999; however, other levels could not be seen in the memory due to their type-B behaviour (Table 2). In this well only, the minimum level was recorded 8 minutes prior to the earthquake. The water level of the same well

Table 2. Ground-water and water-level fluctuations in wells during and after the 17 August and 12 November 1999 earthquakes. Bold characters show water-level changes prior to and after the earthquake. Level 1 is the first value of the day that was saved in memory, and Level 2 is a second record.

date	time/level-1 hour/meter	time/level-2 hour/meter	*date*	time/level-1 hour/meter	time/level-2 hour/meter
Eskişehir Bozan	*prior to earthquake*		*Eskişehir Bozan*	*prior to earthquake*	
15/08/1999	00:00= -23.54	19:54= -23.51	10/11/1999	00:00= -21.97	12:35= -21.95
16/08/1999	00:00= -23.52	20:00= -23.44	11/11/1999	00:00= -21.95	23: 53= -21.92
17/08/1999	**02.55= -23.44**	23:53= -23.36	12/11/1999	**18:44= -21.89**	**18:44= -21:94**
18/08/1999	00:00= -23.36	23:32= -23.25	13/11/1999	00:00= -21.91	07: 13= -21.90
19/08/1999	00:00= -23.26	16:00= -23.24	14/11/1999	00:00= -21.90	19:13= -21:87
Eskişehir Güneli	*prior to earthquake*		*Eskişehir Güneli*	*prior to earthquake*	
15/08/1999	04:00= -20.44	16:00= -20.46	10/11/1999	04:19= -20.16	23:49= -20.17
16/08/1999	00.00= -20.46	00.00= -20.46	11/11/1999	00:49= -20.17	16:26= -20.16
17/08/1999	**02:53= -20.45**	**02.54= -21.41**	12/11/1999	**18:41= -20.38**	**18.42= -20.03**
18/08/1999	00:00= -21.34	16:00= -21.35	13/11/1999	11:09= -20.42	11:30= -20.14
19/08/1999	04:00= -21.35	00.00= -21.35	14/11/1999	00:00= -20.17	23:00= -20.17
Eskişehir Koçaş	*prior to earthquake*		*Eskişehir Koçaş*	*prior to earthquake*	
15/08/1999	00:00= -23.54	20:00= -23.53	10/11/1999	05:00= -21.65	23:00= -21 65
16/08/1999	00:00= -23.53	20:00= -23.52	11/11/1999	00:00= -21.65	23:00= -21.65
17/08/1999	**02:56= -23.37**	**02:56= -23.80**	12/11/1999	**18:46= -21.58**	23:00= -21.61
18/08/1999	00:00= -23.73	24:00= -23.73	13/11/1999	13.55= -21.59	23:00= -21.59
19/08/1999	00:00= -23.73	24:00= -23.73	14/11/1999	15.32= -21.55	23:00= -21.55
Eskişehir Atlas	*prior to earthquake*		*Eskişehir Atlas*	*prior to earthquake*	
15/08/1999	00:00= -4.83	20:00= -4.84	10/11/1999	00:00= -5.12	17:16= -5.07
16/08/1999	00:00= -4.82	24:00= -4.82	11/11/1999	00:00= -5.07	21:16= -5.02
17/08/1999	**02:56= -4.82**	**02:56= -5.12**	12/11/1999	**18:46= -5.06**	**18:46= -4.87**
18/08/1999	08:00= -5.08	24:00= -5.09	13/11/1999	13:29= -5.00	23:00= -5.00
19/08/1999	04:00= -5.08	24:00= -5.08	14/11/1999	00:00= -5.00	23:00= -5.00
Eskişehir İstiklal	*prior to earthquake*		*Eskişehir İstiklal*	*prior to earthquake*	
15/08/1999	00:00= -60:78	24:00= -60:78	10/11/1999	00:00= -60.68	23:00= -60.68
16/08/1999	00:00= -60:78	24:00= -60:78	11/11/1999	00:00= -60.68	23:18= -60.69
17/08/1999	**02:55= -60.72**	**02:55= -60.80**	12/11/1999	00:00= -60.69	**18:43= -60.70**
18/08/1999	00:00= -60:79	24:00= -60:79	13/11/1999	08:15= -60.70	23:00= -60.70
19/08/1999	00:00= -60:79	12:00= -60:80	14/11/1999	13:39= -60.68	23:00= -60.70
Eskişehir Mahmudiye	*prior to earthquake*		*Eskişehir. Mahmudiye*	*prior to earthquake*	
15/08/1999	04: 00= -18.76	24: 00= -18:77	10/11/1999	00:00= -18.45	23:00= -18.45
16/08/1999	16: 00= -18.74	24: 00= -18:76	11/11/1999	17:29= -18.44	23:00= -18.45
17/08/1999	**02:59= -18:74**	**02: 59= -18:77**	12/11/1999	00:00= -18.45	**18:50= -18.42**
18/08/1999	04: 00= -18:76	16: 00= -18.80	13/11/1999	00:00= -18.42	23:00= -18.42
19/08/1999	00: 00= -18.80	21: 48= -18:93	14/11/1999	12:33= -18.42	23:00= -18.42
Eskişehir Çifteler	*prior to and after earthquake*		*Sakarya Reşitbey*	*prior to earthquake*	
15/08/1999	00: 00= -5.66	24: 00= -5.66	10/11/1999	00: 00= -11.27	09: 45= -11.29
16/08/1999	00: 00= -5.66	21: 55= -5.70	11/11/1999	**16: 22= - 11.33**	**16: 35= - 11.01**
17/08/1999	**02: 57= -5.66**	21: 51= -5.77	12/11/1999	**18: 38= - 11.31**	**18: 49= -11.22**
18/08/1999	00: 00= -5.77	20: 00= -5.85	13/11/1999	00: 00= - 11.27	16: 15= -11.31
19/08/1999	00: 00= -5.85	08: 18= -5..91	14/11/1999	00: 00= -11.31	23: 00= -11.31
Bursa Deliçay	*prior to and after earthquake*		*Bursa Yenice*	*prior to and after earthquake*	
10/11/1999	00:00= -17.91	11:14= -17.97	10/11/1999	00:00= -8.71	04:00= -8.71
11/11/1999	**14:41= -18.22**	**14.42= -18.02**	11/11/1999	00:00= -8.71	**13:52= -8.75**
12/11/1999	**18.58= -18.16**	**18:59= -18.07**	12/11/1999	**18:59= -8.79**	**18:59= -8.70**
13/11/1999	00:00= -18.00	11.03= -18.06	13/11/1999	00:00= -8.76	24:00= -8.76
14/11/1999	00:00= -18.06	20:04= -18.13	14/11/1999	00:00= -8.76	16:00= -8.74
Bursa Dudaklı	*prior to earthquake*		*Yenişehir Karasıl*	*after earthquake*	
10/11/1999	00:00= -1162	00:00= -11.62	10/11/1999	00:00= -10.12	08:00= -10.10
11/11/1999	04:00= -1162	00:00= -11.62	11/11/1999	00:00= -10.12	12:00= -10.12
12/11/1999	**18:54= -1165**	00:00= -11.62	12/11/1999	**18:59=-10.22**	**18:59= -9.79**
13/11/1999	10:11= -1168	00:00= -11.65	13/11/1999	00:00= -9.86	20:00= -9.85
14/11/1999	08:00= -1166	00:00= -11.67	14/11/1999	04:00= -9.85	15:32= -9.89

dropped 5 cm in a minute, 14 minutes prior to the earthquake at 18:44 on 12 November 1999 (Figure 4 & Table 2). The water level in the Güneli well dropped 96 cm between 02:53–02:54, 8 minutes prior to the 17 August 1999 earthquake (Figure 3 & Table 2). The water level of the same well dropped 12 cm from 16:26 (16 November 1999) until 17 minutes prior to the 17 November 1999, and went up 35 cm between 18:41–18:42 (Figure 4 & Table 2). The water level in the Atlas well dropped 30 cm at 02:56, six minutes prior to the 17 August 1999 earthquake (Figure 3 & Table 2). The same well rose by 19 cm 11 minutes prior to the 12 November 1999 earthquake (Figure 4 & Table 2).

The water level of the İstiklal well began to drop from the eve of the earthquake continuously until 02:55 on 17 August 1999, at this time the level rose 6 cm and then dropped 2 cm in a minute (Figure 3 &Table 2). The same well dropped 1 cm (at 18:43) 12 minutes prior to the 12 November 1999 earthquake (Figure 4 & Table 2). The well level dropped 3 cm suddenly at 02:59, three minutes prior to the 17 August 1999 event (Figure 2 &Table 2). This well had its highest level of 12 November 1999 at 18:50, 8 minutes prior to the earthquake (Figure 4 & Table 2). The Çifteler well dropped 4 cm on 16 August 1999 at 21:55, 4 cm again at 02:57 on 17 August 1999 (5 minutes prior to earthquake), and another 4 cm after the earthquake at 21:51 (Figure 2 & Table 2). On 12 November 1999, this well recorded a 5 cm rise between 0:00 and 18:48 (10 minutes prior to the earthquake) (Figure 4).

Another well in the Eskişehir region that began water-level recording before the 12 November 1999 earthquake is the Sakarya Reşitbey well (Figure 1 & Table 1). It recorded a 32 cm rise between 16:22 and 16:35 on the eve of the Düzce earthquake (Table 2). 20 minutes prior to the earthquake, at 18:38, the water level fell 30 cm and rose again (11 cm) between 18:38 and 18:48 (Figure 4 & Table 2).

Bursa Wells. In the Bursa region, water-level recorders were installed in wells after the 17 August 1999 earthquake. These recorders worked during the year 1999. The wells of this region were in fluvial sediments comprising loose sand and gravel intercalations. There are six wells, namely the Deliçay, Dudaklı, Çayırköy, Yenice Karasıl and Yalova wells. The float wire was broken in the Çayırköy well at 22.07 due to a sudden drop in water level, 1267 minutes before the Deliçay well drop (Figure 4). The technicians became aware of this failure on 15 November 1999. The drop in the water level in the well should have been faster than 3 m $(min)^{-1}$. The ground-water-level difference between pre-failure measurement and after repair is 30 cm. The Yalova well was calibrated by technicians after the 12 November 1999 earthquake. The technicians realised that the earthquake impaired the float-counterbalance system (Figure 4).

The Bursa-Deliçay well fell 75 cm at 14:41, and suddenly rose 20 cm in one minute between 14:41 and 14:42 on the eve of the 12 November 1999 earthquake (Table 2). Following this record, the water level fell 14 cm at 18:58; there was 9 cm rise between 18:58 and 18:59 (Figure 4 & Table 2). The fall in the water level of the Dudaklı well prior to the 12 November 1999 earthquake was 4 cm at 18:54 when compared to the previous day (Figure 3 & Table 2).

The water level of the Yenice well dropped 4 cm between 0:00 and 13:52, another 4 cm drop and then a 9 cm rise occurred at 18:59 prior to the 12 November 1999 earthquake (Figure 4 & Table 2). The Karasıl and Yalova wells show co-seismic water-level fluctuations (12 November 1999). The Karasıl well's water level dropped 43 cm at 18:59 whereas the Yalova well's water level dropped 96 cm between 19:00 and 19:01.

2000–2004 Anomalies Recorded from the DSİ Wells

In the first stage of the observations, the water-level measurements were taken from the earthquake date to year 2000; there were no such anomalies in the wells within this period. However, the brevity of the observation time has been criticized by the referees of earlier versions of this paper. Taking into consideration these criticisms, the observation time were extended until 2004. Within this time span, the anomalies of 1999 have not been repeated except for some minor local effects (Figure 5). One of these local anomalies was observed in the Yenikent-Mahmudiye-Çifteler well groups. Beginning on 4 May 2000, water-level drops (65–110 cm) were recorded in a 20-day period, which ended with an earthquake that occurred just a few kilometres from the Yenikent well (M= 3.3, location N39° 51′ – E30° 22′, Figure 5). Following the earthquake, water levels rose back to their original levels. Due to the very low seismicity

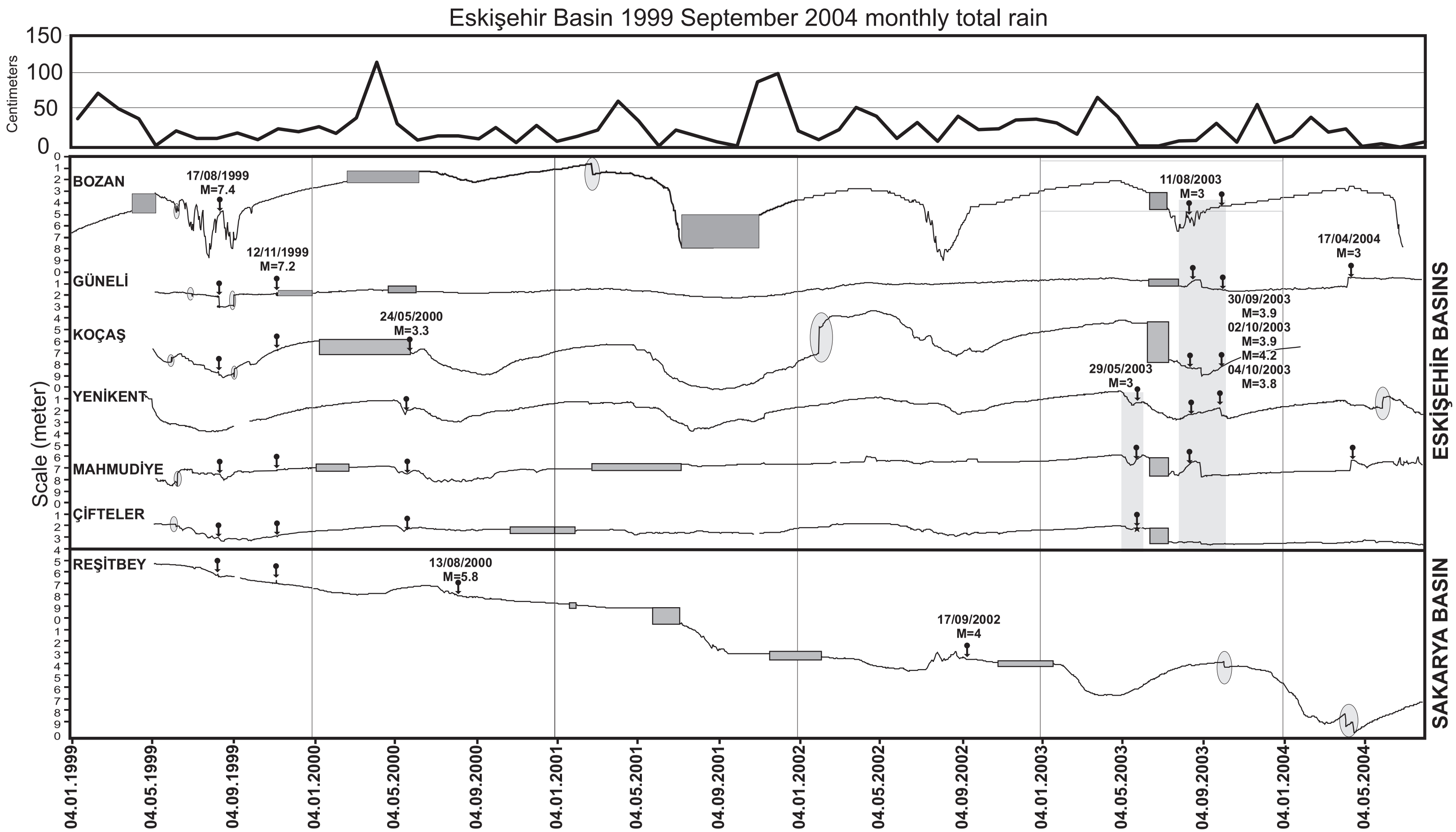

Figure 5. Water-level changes in the wells of Eskişehir region, January 2000 to December 2004. The modification dates of technicians are indicated by ellipses. Grey rectangles show memory failure.

(M < 3.0) in the Eskişehir basin until 2003, no anomalies were observed in the 2001–2003 time interval. Then again, water levels in the aforementioned wells began to fall in May 2003, which was followed by an earthquake on 29 May 2003 to the SW of the wells (M= 3.0, location N39° 90´ – E30° 31´, Figure 5). Following the earthquake, the water levels again rose back to original levels within 7–12 days. Another anomaly was observed in July in the Bozan-Güneli-Mahmudiye-Yenikent wells: a sudden water-level rise was followed by an earthquake on 11 August 2003 (M= 3.0, location N39° 90´ – E30° 31´, Figure 5). Following this earthquake, fluctuations occurred in the same wells, as soon as the fluctuations ceased, four earthquakes occurred between 2 and 4 October 2003 (M= 3.9, location N39° 88´ – E30° 61´; M= 3.9, location N39° 80´ – E30° 51´; M= 4.2, location N39° 83´ – E30° 55´; M= 3.8, location N39° 84´ – E30° 50´, Figure 5). Similar changes in water levels subsequent to an earthquake in 2004 occurred in the Güneli and Mahmudiye wells, before the 17 April 2004 event (M=3, location N39° 50´ – E31° 07´; Figure 5).

There were also some local anomalies in the Reşitbey well, which is outside of the Eskişehir Basin but connected to the NAFZ by a normal fault near this well (Figure 1a). Fluctuation in this well began on 7 July 2004, and the water level dropped up to 50 cm. During these fluctuations, an earthquake occurred on 28 August 2004 along the Düzce strand of the NAFZ, causing a 146 cm rise and then a 70 cm drop. Similar fluctuations were observed before an earthquake on 17 September 2004 (M=4, location N40° 74´ – E30° 58´). There were no anomalies in the Reşitbey well for M< 4 events.

Miocene-Quaternary Basins

There are three groups of young basins in NW Turkey. The first group includes the Düzce, Adapazarı, Sapanca, İzmit, Geyve and İznik basins, all of which have formed along the NAFZ (Figure 1a). The second group includes the Yenişehir and Bursa basins, which were formed by the complex effects of the NAFZ on older faults. The third group of basins includes the İnegöl, İnönü, Eskişehir and Alpu basins, formed by the reactivation of older faults consequent to activity on the NAFZ (Figure 1a). The first group of basins formed along the NAFZ were not examined in this study.

The Bursa Basin

The Bursa Basin occurs on the south segment of the NAFZ and the Mudanya-Dudaklı part of the TEFZ (Yaltırak 2002) (Figure 6). The basin has a right-triangular shape; it is 17 km long and 7 km wide. The surface area of the adjacent Bursa plain is 208 km^2. The Çayırköy plain, with a surface area of 40 km^2, is connected to the Bursa plain via the Nilüfer River. To the north of the Uluabat fault, the thickness of the basin fill is between 30 and 50 m (Göçmen *et al.* 1973). Alluvial fans extend to the Bursa plain from the north, where the city of Bursa is located. The alluvium comprises coarse gravel and boulders at its margins, with conglomerate, and sand and silt intercalations proximal to the Nilüfer River. The thickness of the alluvium varies between 80 and 200 m in the Bursa plain (Göçmen *et al.* 1973). The dominant tectonic structure of the basin is the southern strand of the NAFZ (Yenişehir-Uluabat) overlain by alluvial fans (Figure 6). There are a number of hot springs (35–85°C) emerging on this fault segment, some of which have produced travertine deposits.

The Yenişehir Basin

The Yenişehir Basin is a rhombohedral pull-apart basin bounded by normal faults to the NW and SE (Figure 6); it developed above a post-Neogene area due to the effect of the southernmost strand of the NAFZ (Yaltırak 2002). The contact between the Neogene formations and alluvium to the north is a normal fault. The basin is 20 km long and 12 km wide, and the surface area of the adjacent Yenişehir plain is 240 km^2. The thickness of the alluvium varies between 30 and 50 m, and the northwestern and southeastern parts comprise sand and gravel and the central parts silt and sand. The basin becomes swampy where the ground-water level is close to surface.

The İnegöl Basin

The İnegöl Basin is an alluvial basin bordered by faults along its southwestern flank (Figure 6). Its surface area, length and width are 185 km^2, 26 km and 7 km, respectively. Alluvium overlies the Miocene and pre-Neogene formations, and comprises intercalations of mudstone, sand and gravel, with a thickness varying between 2 and 38 m at its western edge and 60–100 m

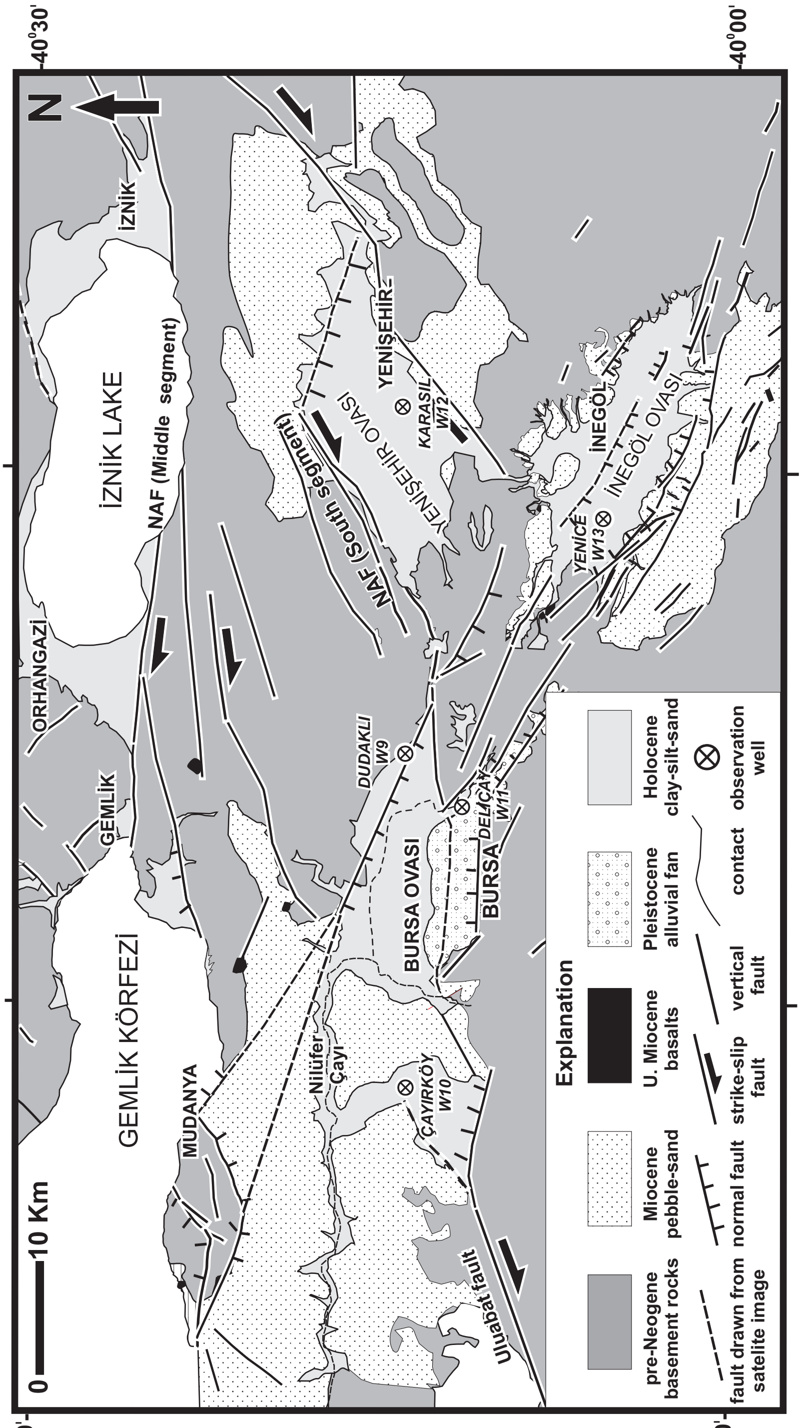

Figure 6. Geological map of the Bursa, İnegöl and Yenişehir area. (modified from Yaltırak & Alpar 2002a).

at its eastern margin. Field evidence suggests that the margin-bounding faults of the İnegöl Basin are normal faults reactivated via the tectonic influence of the NAFZ (Yaltırak 2002). The recent predominant tectonic activity is a NE–SW-trending extensional regime, as suggested by the structural data from faults parallel to the TEFZ; they border the unconsolidated Miocene formations and the metamorphic basement (Kaymakçı 1991; Yaltırak 2002). The reason for this regime is rotational extension created by the NAFZ where it intersects the TEFZ.

The Eskişehir Basin

This basin consists of three alluvial plains, namely the İnönü, Eskişehir and Alpu plains, bounded by faults along their northern and southern margins (Figure 7). The lengths and widths of the plains are as follows: 7 km x 4 km for the İnönü Plain, 32 km x 12 km for the Eskişehir Plain and 23 km x 12 km for the Alpu Plain, with a total surface area for the plains being 639 km^2. Pleistocene conglomerates, sands and gravels intercalated with mudstone and caliche have a thickness of about 200 m, and unconformably overlie the Miocene and pre-Neogene formations. Pleistocene sediments are overlain by 10–90-m-thick Holocene alluvium that comprises loose sand and gravel laid down by the Porsuk River (Esen *et al.* 1975). Altunel & Barka (1998) observed many young normal faults at places affected by the TEFZ (Figure 7). Gözler *et al.* (1985) indicated that the Thrace-Eskişehir Fault Zone, buried by unconsolidated Miocene formations, was a right lateral strike-slip fault prior to the Quaternary. This NW–SE-trending dextral strike-slip system was transformed into an extensional regime via the effects of the NAFZ during the Plio–Quaternary. It may be concluded that the main tectonic activity is a NE–SW-trending stress regime even though the activity of the faults that border the Eskişehir Basin is quite limited.

Tectonic Outline

The NAFZ occurs essentially as a single strand from Varto to Bolu; this zone proceeds westward along the Bolu-Mudurnu River, and ruptured in 1957 and 1967 near Gerede. From there, the NAFZ follows the Sapanca-İzmit line (ruptured by the İzmit earthquake) and extends to the Sea of Marmara (Figure 1). The first branch of the NAFZ occurs somewhere near Gerede. Thus, the northern strand of the NAFZ is the Bolu-Gulf of İzmit line and the southern strand is the Gerede-Gemlik line (Figure 1). The southern strand may also be considered as the line that goes through Bursa. The WNW–ESE-trending fault segment, extending to Sapanca, is included in the system that ruptured during the 1967 Adapazarı earthquake. Thus, the most prominent characteristic of the NAFZ in the Marmara area is its splitting into strands. Before reaching Geyve, the NAFZ has a westward-propagating character (Ketin 1948), but this aspect is lost once the NAFZ splits.

Another important aspect of the NAFZ is its intersection with NW–SE-trending faults (Figures 1 & 6). The intersection of the NAFZ and TEFZ controlled the formation of small Quaternary basins (Tapırdamaz & Yaltırak 1997; Yaltırak *et al.* 1998; Sakınç *et al.* 1999; Yaltırak 2002). Where the three strands of the NAFZ cross the TEFZ, the TEFZ is divided into the 200-km-long Kestel-Alpu and the 40-km-long Mudanya-Kestel sections, respectively (Figures 1, 5 & 7). The activity of the TEFZ ceased when the NAFZ reached the Marmara region 3.7–3.4 million years ago (Yaltırak *et al.* 2000; Yaltırak & Alpar 2002a; Yaltırak 2002). The TEFZ became less active 10–40-km-long normal-fault segments under the tectonic influence of the NAFZ. However, the section between the Gemlik and Bursa strands of the NAFZ is partially active (Yaltırak 2002). The activity of the TEFZ from İnegöl to Eskişehir is particularly well-known; there it is cut by the southern strand of the NAFZ around Kestel (Figure 6). It is well known that the TEFZ is active as a normal fault where it is cut by the southern segment of the NAFZ at Kestel (Figures 6 & 7) (Gözler *et al.* 1985; Kaymakçı 1991; Altunel & Barka 1998).

Tectonic Model

The kinematic relationship, from the points of view of the seismicity and deformation of the TEFZ, which is cut by the NAFZ at three points, can explain the deformation of NW–SE-striking normal faults oblique to an E–W-striking dextral strike slip fault. The formation of young basins in the Marmara region is due to the direction of the maximum tensile stress perpendicular to the dextral shear stress. The tensile stress also exhibits an appropriate direction to the propagation of deformation (Figure 8a). According to the this model, changes in GPS velocities (from north to south) and in block-bounding faults can be attributed to the actual reflection of dextral shear stress

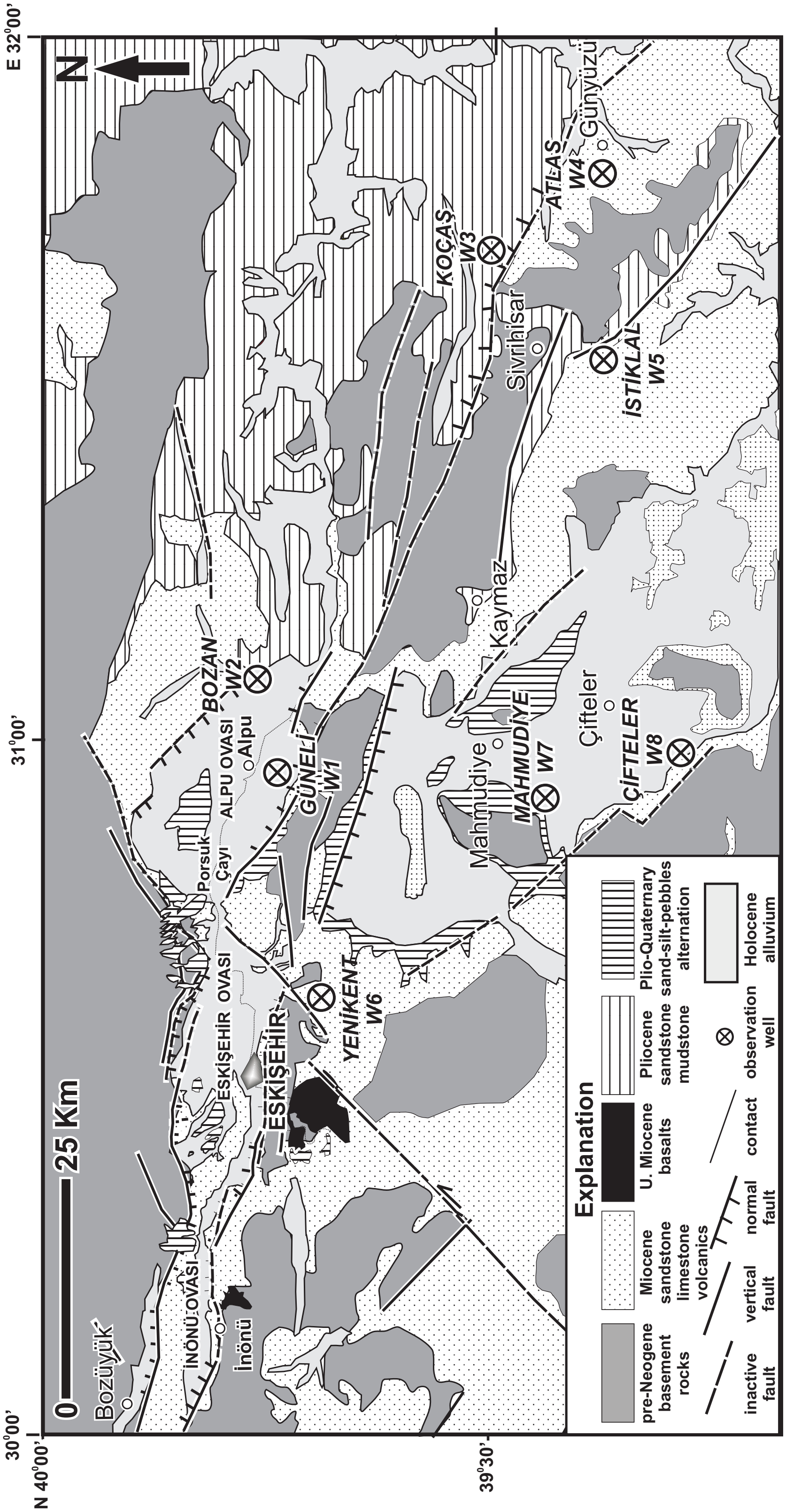

Figure 7. Geological map of the Eskişehir area (compiled after Esen *et al.* 1975; Altunel & Barka 1998; Gözler *et al.* 1985 and field observations from this study).

(Figure 8b; Straub *et al.* 1997). Furthermore, the parallelism of GPS vectors to the NAFZ and velocity differences between the blocks within the regional fault pattern indicate the displacement of the TEFZ by the NAFZ (Fig. 8b). Using GPS, Straub *et al.* (1997) measured 0.16 μ strain/year extension on the TEFZ (Figure 8c). This situation indicates that the strain of the TEFZ originates from the NAFZ (in Figure 8). For this reason, the slowing of velocities near the fault boundaries may be observed easily; this is the clearest evidence of deformation. In this case, it is possible to find ideal areas for observation of water-level changes in shallow wells prior to earthquakes by searching fault patterns and shear strain (as seen by comparison of Figures 1, 6, 7 & 8). A list of wells, their reaction to earthquake(s), the stress regimes of the plains, and the dominant fault(s) that create stress are given in Table 3.

Global Examples of Ground-Water-Level Changes Prior to Earthquakes and Relationships to Tectonic Patterns

There are numerous published studies concerning shallow deformation occurring prior to and after earthquakes. Some of these studies reported observations of ground-water changes in wells that took place long before earthquakes. The first example dealt with ground-water level drops in shallow wells in Bordeaux (France) prior to the 1 November 1755 Lisbon earthquake (Cotta *et al.* 1860). This locality, which is 900 km away from the epicentre – reportedly in the Azores (Davison 1936) – has a special tectonic position. The wells are located on the eastern edge of the Bay of Biscay, which was formed by the separation of Spain from the French coast by rotation due to the effect of the strike-slip faults (Williams 1975). The age of the system is Cenozoic to Recent (Ries 1978). Another important reason for the rotation of Spain is transform faults, extending from the Azores to Gibraltar. While the Spanish block separated from the French coast like a fan due to the effect of these faults, the Bordeaux Basin formed to the south of this fan. In so far as this earthquake affected an area extending to the Alps, the deformation of the Bordeaux Basin should be related to stress resulting from the tectonic pattern. Another example was reported by Kissin *et al.* (1996), who tried to predict earthquakes along the NWW–SEE-striking Ashgabat Fault (Turkmenistan) on the eastern margin of the Caspian Sea. They observed water-level changes in 23 wells. The water levels in 22 wells located near this fault changed during and after the earthquake, but the level of well '3r', located 140 km from the epicentre, dropped on the eve of the 16 September 1989 M> 6.5 earthquake. The location of well 3r, according to the map of Lyberis & Manby (1999), is on a normal fault oriented 45° to the dextral Ashgabat Fault. In this case, it was possible to establish a relationship between the fault pattern and

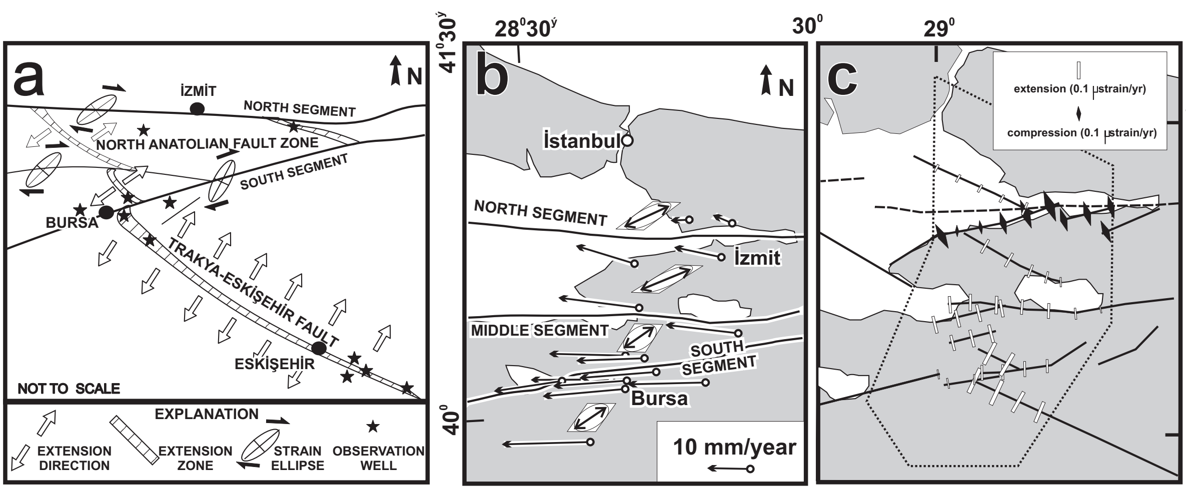

Figure 8. (a) Model of deformation in relationship to the North Anatolian Fault Zone (NAFZ) and Thrace-Eskişehir Fault Zone (TEFZ); (b) position of GPS vectors and distribution of the velocities of blocks bounded by the NAFZ in the Bursa area (correlated with Figure 6) (after Straub *et al.* 1997); (c) the GPS velocities on the branches of the NAFZ in the Bursa area are given relative to Istanbul (after Straub *et al.* 1997).

Table 3. Wells, their reaction to earthquake(s), stress regimes of the plains and dominant fault(s) creating stress; TEFZ – Thrace-Eskişehir Fault Zone, NAFZ – North Anatolian Fault Zone.

	NAFZ	TEFZ	extension	extension + compression	compression	prior to earthquake	after earthquake
Dudaklı	+	+	-	+	-	+	-
Çayırköy	+	+	-	+	-	+?	-
Deliçay	-	+	+	-	-	+	+
Güneli	-	+	+	-	-	+	-
Koçaş	-	+	+	-	-	+	-
Bozan	-	+	+	-	-	+	-
Atlas	-	+	+	-	-	+	-
İstiklal	-	+	+	-	-	+	-
Mecidiye	-	+	+	-	-	+	-
Yenice	-	+	+	-	-	+	+
Karasıl	+	-	-	+	-	no data	+
Yalova	+	-	-	-	+	no data	+
Reşitbey	+	-	+	-	-	+	-
Yenikent	-	-	-	-	-	no response	no response
Hisarbey	-	-	+	-	-	no data	+
Gölköy	-	-	+	-	-	no data	no response
Örencik	-	-	-	-	-	no response	no response

water-level changes prior to the earthquake in wells far from the earthquake epicentre. Three other examples include the W. İzu-Oshima 1978 (M= 7.0), Miyagi 1978 (M= 7.4), and E. İzu-Oshima 1980 earthquakes. A group of amateurs observed water-level changes in shallow wells 14 days prior to the W. İzu Oshima 1978 earthquake, located 50–150 km away from the epicentre (Oki & Hiraga 1988). Similar phenomena were also observed for the two other earthquakes. It is well-known that the earthquakes in this region occur on dextral fault extending from the Oshima Islands to the İzu Peninsula (Sacks *et al.* 1981; Lomnitz 1994). All of the observation wells are near the fault, which is angular to the seismogenic fault. Therefore, this is another good example of the relationship between seismogenic and angular faults. There are many other examples of water-level changes in shallow wells away from epicentres (Coble 1967; Gordon 1970; Coe 1971; Wakita 1975; Lomnitz & Lomnitz 1978; Deng *et al.* 1981; Nayak *et al.* 1983; Wang *et al.* 1984; Oki & Hiraga 1988; Ekstrom *et al.* 1992; Roeloffs 1996; Roeloffs & Quilty 1997; Kissin *et al.* 1996; Grecksch *et al.* 1999; King *et al.* 1999; Gavrilenko *et al.* 2000; Arabelos *et al.* 2001). However, these studies did not establish a relationship between tectonic pattern and shallow deformation, and this is simply due to the general belief that pre-earthquake deformation occurs near faults. For this reason, most researchers have a tendency to select observation sites near or on faults. Similarly, in Turkey, deformation and water-level measurements have been carried out along faults (Umutlu 2000). The most meaningful well with regard to water-level changes is the EDY well, located on the Izu Peninsula in Japan, as reported by Wakita (1996); it reacted prior to the Hokkaido-Toho-Oki (4 October 1994; M 8.1), Sanriku (28 December 1994; M 7.5), and S Hyogo (17 January 1995; M 7.2) earthquakes (Wakita 1996). The distances from the earthquake epicentres to the EDY well were 1190 km, 730 km and 380 km, respectively. The common point of these earthquakes was their epicentres, which were located on strike-slip faults created by the Japanese trench systems. Discontinuities in the Izu Peninsula are kinematically related to seismogenic structures.

Two recent studies have also given examples of water-level changes in shallow wells prior to earthquakes. Grecksch *et al.* (1999) observed water-level changes in shallow wells prior to the 1992 Roermond earthquake to the west of Bonn, Germany. This earthquake occurred on NNW–SEE-striking faults via stress developed perpendicular to the faults. Another example is the anomaly of the Lisi well (Georgia), which behaved differently during earthquakes that occurred in Georgia and Armenia (Gavrilenko *et al.* 2000). This well recorded an anomaly during the 1988 Spitak (Armenia) earthquake but not during the 1991 Racha (Georgia) earthquake. One should carefully examine the detailed tectonic maps of the region to elucidate a correlation between the locations of epicentres and basins, with the goal of discerning a reason(s) for these different behaviours during earthquakes.

Similar patterns accompanied the 1975 Haicheng (Deng *et al.* 1981), 1976 Thangsan (Lomnitz & Lomnitz 1978; Wang *et al.* 1984; Chu *et al.* 1996), and 1978 Sungpan Pingvu (Wallace & Teng 1980) earthquakes. In conclusion, wells sensitive to deformation are located in areas proximal to seismogenic faults.

The Nature of Ground-Water-Level Changes in Wells and the Relationship of these Changes to Deformation

Previous work, which has not addressed the issue of measurements of deformation related to regional tectonic patterns responsible for ground-water-level changes, can be divided into two groups. One includes studies on co-seismic poroelastic changes in water wells, the other shear-wave splitting in stress-aligned cracks. These two groups of works provide the basic arguments for shallow deformations.

Poroelastic Changes in Shallow Wells

Research and observations on water-level changes resulting from earthquakes and the origins of these changes in shallow wells were mainly carried out over the last quarter of the 20th century (Wakita 1981; Roeloffs 1988; Rojstaczer 1988; Roeloffs *et al.* 1989; Astreadis & Livieratos 1989; Kumpel 1992; Muir-Wood & King 1993; Rojstaczer *et al.* 1995; Roeloffs & Quilty 1997; Grecksch *et al.* 1999; Gavrilenko *et al.* 2000). All of these studies concentrated on the nature of water-level changes in wells. These changes were interpreted as due to: (1) seismic waves (Cooper *et al.* 1965; Lui *et al.* 1989), (2) fault creep (Wesson 1981; Roeloffs *et al.* 1989), or (3) atmospheric loading (Rojstaczer 1988). Roeloffs (1988) initially indicated a relationship between co-seismic changes and crustal strain by taking into account various factors. She concluded that crustal deformation caused of volumetric strain in shallow wells, in relationship to earthquakes. However, Roeloffs *et al.* (1989) indicated a relationship between water-level changes and episodic fault creep. Kumpel (1992) explained, in the framework of mathematical modelling, the relationship between strain change in wells and stress. Roeloffs (1996) reported that earthquake-related stress changes around wells are due to poroelastic changes. Roeloffs & Quilty (1997) reported water-level rises beginning three days before the Kettleman Hills earthquake in 1985. Quilty & Roeloffs (1997) analysed co-seismic changes of water levels in wells near Parkfield; their data showed that co-seismic water-level changes in many wells were proportional to volumetric strain. All of these studies clearly set forth a common opinion – that water-level changes occur due to increase in porosity preceding earthquakes generated by crustal strain. Similar changes were observed and modelled by Grecksch *et al.* (1999) and Gavrilenko *et al.* (2000). Many papers dealing with the reasons for water-level changes evaluate the kinematic relationship between fault rupture and well locations (e.g., Igarashi *et al.* 1995; Kissin *et al.* 1996; Grecksch *et al.* 1999; Gavrilenko *et al.* 2000; Arabelos *et al.* 2001). These studies also point to crustal strain as the cause of water-level changes, even in inhomogeneous media.

Relationship between SHEAR-Wave Splitting and Shallow Deformation Preceding Earthquakes

Another group of studies have concentrated on the investigation of poroelastic changes created by shallow deformation that affects ground water (Crampin 1999a; Crampin *et al.* 1999). The studies of Stuart Crampin and colleagues provide us with key points for understanding the nature of ground-water-level changes (Crampin 1978, 1998, 1999a, b, 2001; Crampin *et al.* 1999). The basic points are summarized here:

1. The build-up of stress before earthquakes increases crack aspect ratios (crack swelling) until fracturing occurs.
2. Rock is weak toward tensile stress, so the effects of the stress build-up before earthquakes are pervasive over large volumes of the crust.
3. The response of fluid-saturated rock to changing conditions, prior to fracturing, can be calculated.
4. The parameters that control changes to microcrack geometry also control the splitting of shear waves.

5. Split shear waves travel at different velocities and their signatures can be observed on three-component digital seismometers.
6. The changing conditions in fluid-saturated rocks increase aspect ratio.
7. If stress accumulates in a small volume, the build-up is rapid, but the resulting earthquake is small, whereas if stress accumulates over a larger volume, the increase is slower but the eventual earthquake is larger (Crampin 1999, p. 512; Crampin *et al.* 1999, p. F2).

All of these arguments are based on field studies of shear waves and, on the basis of the data examined in this study, we hope to show a correlation between the Crampin arguments and the results from the young basins examined in this paper.

1. Pre-earthquake stress before rupture increases porosity (Roeloffs 1988, 1996) in extensional basins angular to the main fault.
2. Tensile stress becomes greatest in young basins controlled by faults. Even though pre-earthquake stress may be observed over wide areas, ideal sites should be chosen on the basis of tectonic pattern. For example, Straub *et al.* (1997) calculated the maximum stress field in young basins located at the axes of the TEFZ; these basins are bounded by normal faults belonging to an E–W dextral strike-slip system, suggesting NW–SE extension.
3. It is possible to find pre-rupture changes in saturated unconsolidated sediments that are similar to rocks. Roeloffs (1988, 1996) indicated this type of changes; Grecksch *et al.* (1999) and Arabelos *et al.* (2001) observed such changes in wells located in loose sediments.
4. Conditions in saturated young basins also change the volumes of saturated pores (Roeloffs 1988; Kumpel 1992).
5. If the stress accumulation is rapid and limited to confined plains, then the resulting earthquake is small. If the stress accumulation is slower with sudden impulses in all basins over a selected tectonic pattern, then the eventual earthquake is large and affects a large area.

The measurement of these properties can be done by SHEAR-wave analysis, but requires continuous seismic activity (Crampin *et al.* 1999). These conditions were not valid before the 17 August 1999 earthquake. Nevertheless, the Eskişehir wells were sensitive to changes at both earthquakes, similar to the aforementioned EDY well (Wakita 1996). Some other randomly-installed wells also recorded anomalies following the first earthquake. The locations of these wells are within young basins of a similar tectonic pattern. A co-seismic interferometry map (Wright *et al.* 2001; Çakır *et al.* 2003) produced from satellite data shows elevation differences that occurred in response to the first earthquake. This map, combined with regional morphology and tectonics (Figure 9), indicates that deformation reached the Eskişehir well localities; moreover, it also shows that the young basins formed on the TEFZ are in the same deformation zone.

Discussion

Discussion of the relationship between earthquakes and shallow deformation is based on strain measurements. Taking into consideration that deformation change depends on regional heterogeneity, the compulsion of measuring minute values will not easily yield pre-earthquake indications. Thus, studies of site selection and determinations dependent on tectonic pattern should gain importance. Priority should be given to understanding the nature of water-level changes, since we know that these changes extend back some 245 years. The questions of where and why such changes occur should be answered in the first place. The reason for water-level changes in shallow wells is directly related to the nature of the anisotropic 60-m depths from the surface described using shear waves (Crampin *et al.* 1999). The slow-down of shear waves in this weathered and fractured zone is due to the opening of micro-cracks, which correspond to porosity increases in alluvial plains. The maximum value of this increase is expected to be parallel to the maximum tensile stress (Roeloffs 1988, 1996, 1998). As a matter of fact, faults will form following the occurrence of fractures developed perpendicular to maximum tensile stress. Regional deformation will accumulate in young basins composed of granular, porous and elastic material formed in such areas. It is easier to obtain reliable data if there is kinematic interaction between such plains and seismogenic faults. Even though it is possible to measure many parameters, the measurement of two types of effects related to shallow deformation may yield more

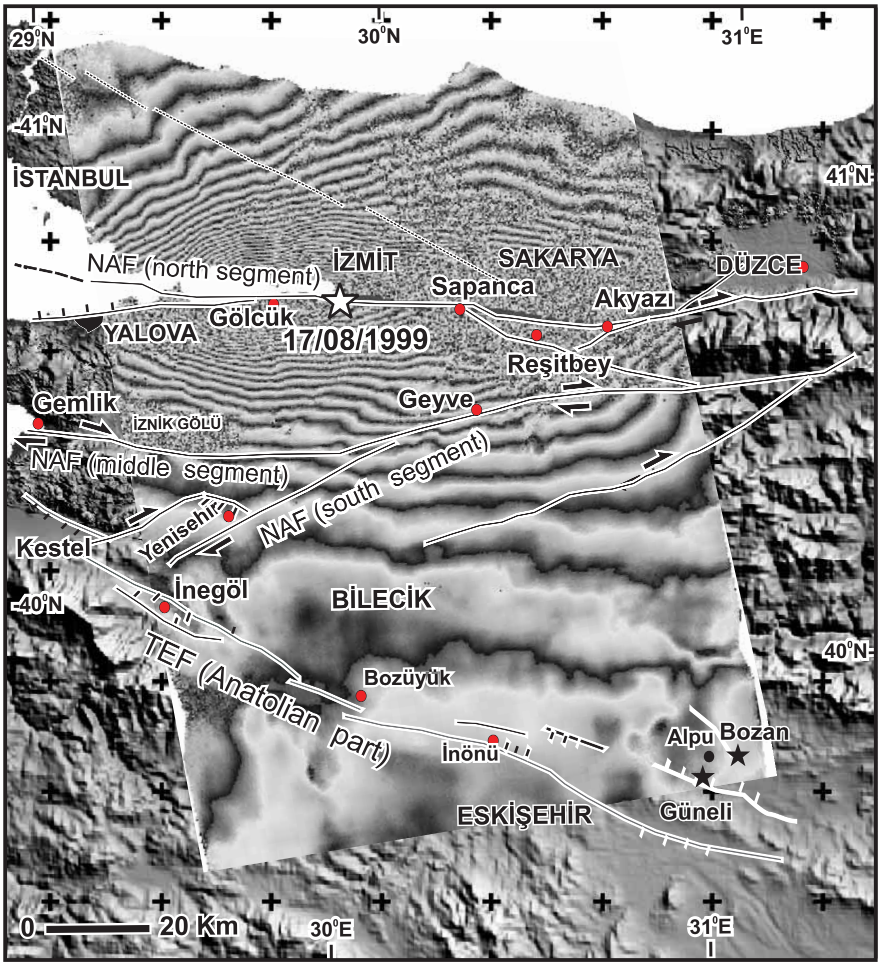

Figure 9. Superimposed digital elevation map and co-seismic deformation map of the August 17 1999 İzmit earthquake (images from Wright *et al.* 2001). This map shows earthquake deformation effects on the Eskişehir area.

reliable results. One of them is shear-wave analysis (Crampin 1978). The other is the observation of groundwater and water-level changes in wells in stressed basins developed relative to the regional fault pattern (Wakita 1975, 1981; Roeloffs 1988; Rojstaczer 1988; Roeloffs *et al.* 1989; Kumpel 1992; Muir-Wood & King 1993; Rojstaczer *et al.* 1995; Roeloffs & Quilty 1997; Gavrilenko *et al.* 2000; Arabelos *et al.* 2001). Ground water and drops in wells will be observed in stressed basins due to porosity increases. Poroelastic changes in sediments due to tensile stress will cause sudden groundwater level anomalies in wells.

These studies contain a number of points that readers might dwell on. They concentrate on the relationship between the types of records and earthquakes. The setting of time in well recorders by a common computer shows whether the changes are due to pre-earthquake deformation or surface waves. This type of time setting also provides ease of correlation. All the recorders were set to Turkey (GMT +02.00 Athens, Ankara, Minsk) mean time. The setting of time based on GPS would not cause considerable shift because the wells and the epicentres of both earthquakes were located between 28ºE–32Eº (in UTM zone 35–36).

Another example that may be used to prove the reliability of the clocks is the surface-wave record in the Hisarbey well, located 265 km away from epicentre, during the 12 November 1999 earthquake (Figures 1 &

3). When the observed time differences are considered, it is seen that the same well reacted at different times to both earthquakes (Table 4). Such major time differences cannot simply be explained by clock malfunction (Tables 2 & 4). For instance, the Güneli well, located 136 km away from epicentre, recorded type-A sudden changes 9 minutes prior to the first earthquake (Figures 2 & 3). The Mahmudiye well, 162 km away from epicentre, recorded type-A sudden changes only 4 minutes prior to the earthquake. Careful examination of Figure 1 and Table 4 reveals that the interval of the reaction time in wells increases when they are close to NAFZ junction points. For example, the wells [Deliçay (5 km), Yenice (27 km) and Reşitbey (25 km)] are located only short distances from the intersection of the NAFZ and obliquely oriented (45º) normal faults. In order to understand the magnitude of water-level changes in wells between extreme values prior to earthquakes, one should have momentary recordings. In this stage, momentary pre-earthquake changes prove that the wells in the basins recorded poroelastic changes that resulted from crustal strain.

It may be suggested that water-level changes in the DSİ wells occurred due to surface waves. However, this is not a realistic explanation in that there should have been time differences on the order of 10 seconds among the wells, proportional to their distances from the epicentres. Assuming that the recorders clocks are correct, the arrival of surface wave to the Güneli and Mahmudiye wells (located 82 km apart) would take 4 minutes, but this is impossible. Thus, this proposal cannot be considered reasonable. Only the Yalova and Yenişehir wells, located on the NAFZ, recorded co-seismic water-level changes. For example, the Hisarbey well, located 265 km from the epicentre and having the same time site as the Eskişehir wells, recorded surface waves from the 12 November 1999 earthquake (Figure 1 & Table 4).

Some of wells that recorded only one-time-add one-extramum value may be interpreted as wells that lack earthquake anomaly records. In those wells, one of the two pre-earthquake extramum values was overlapped by changes that occurred after the earthquake, where type-B record was observed (?) (Figure 2c & d). In the present study, even single extreme records preceding the earthquake were classified as a pre-earthquake anomalies.

It is obvious from Figure 3 that all of the Eskişehir wells recorded the fluctuations related to the 1999 earthquakes. On the other hand, drastic differences between Figures 3 and 5 are notable; Figure 5 comprises

Table 4. Distance of wells to epicentres, and short-period time variations prior (-) to and after (+) earthquakes.

August 17, 1999 earthquake			November 12, 1999 earthquake		
well name/number	distance (km)	time (minute)	well name/number	distance (km)	time (minute)
Bozan W2	138	-7	Güneli W1	118	-15
Güneli W1	136	-9	Bozan W2	111	-13
İstiklal W5	197	-7	Koçaş W3	149	-11
Koçaş W3	197	-6	Atlas W4	167	-11
Atlas W4	216	-6	istiklal W5	156	-14
Çifteler W8	171	-6	Mahmudiye W7	149	-7
Mahmudiye W7	162	-5	Çifteler W8	156	-10
Yenikent W6	121	no response	Dudaklı W9	171	-4
Örencik W18	164	no response	Deliçay W11	176	-1697
			Yenice W13	162	-1746
			Reşitbey W15	53	-1583
			Karasıl W12	143	+1
			Yalova W14	147	0
			Hisarbey W16	265	+1
			Çayırköy W10	188	?
			Yenikent W8	126	no response
			Gölköy W10	259	no response
			Örencik W18	214	no response

the records of 2000 and 2004. Major fluctuations in Figure 3 cannot be observed in Figure 5 where fluctuations in the latter are only seasonal effects, consistent with rainy and dry periods.

Another interesting anomaly was recorded in the Bozan well (Figure 3). There have been no anomalies observed in this well since 1999. One may think that these water-well changes are due to pumping from nearby well(s). The water-level change between 15 June 1999 and 08 August 1999 was 5 m. The well nearest the Bozan observation well is 276 m away. The maximum calculated drawdown is 82.5 cm for unconfined aquifer conditions and 210 cm for confined aquifer conditions by continuous 27 l/s discharge (optimum capacity) from the nearest well at the end of 53 days. Another well, 512 m from the Bozan well, has a maximum drawdown (with the same optimum capacity) of around 260 cm. The addition (or interference) of these two wells is less than 5 m. In light of this information, it is significant that 5 m of water-level change were not observed in 2000 and 2002. A similar change was only observed in 2003 prior to low-magnitude earthquakes in Eskişehir; this is interesting and makes it difficult to propose a possible relationship between pumping and water-level changes. Thus, it is possible that pre-earthquake poroelastic changes caused these fluctuations. Superimposed effects of pumping and fluctuations may cause such an anomaly. The anomaly of the Bozan well should be taken into consideration within this framework.

The earthquakes that occurred between 2000 and 2004 in the basins where the Eskişehir wells are located produced anomalies before earthquakes. The anomalies – in addition to the aforementioned ones – can only be observed in wells directly related to earthquake-producing faults. Local anomalies prior to earthquakes of M> 3 are possible if there is a connection between earthquake-producing faults and wells. This phenomenon has been clearly observed in the Yenişehir-Mahmudiye-Çifteler wells during the 24 May 2000 earthquake. The responsible fault (near the epicentre) is a sinistral strike-slip structure; it is not very active and intersects with the normal fault associated with the basin near Yenikent. Accordingly, the largest anomaly can be observed in the Yenikent well, which is the well nearest the intersection point (Figures 5 & 10). Another earthquake occurred on 29 May 2003 on the fault that borders the basin to the west, and caused anomalies in Yenişehir-Mahmudiye-Çifteler wells (Figures 5 & 10). An earthquake that occurred on 17 April 2004, just 1–2 km away from the Mahmudiye well (and not known to be located on a fault), caused fluctuations. Some anomalies were recorded in the Reşitbey well (Sakarya) prior to two earthquakes of M>4 (Figures 5 & 10). The relationships among wells, basins and bounding faults, and the anomalies of 2000–2004 (in addition to those of 1999), indicate that they are random anomalies and that water-level changes between 1999 and 2004 can be described as regional for earthquakes of M> 7, and local for those of M<6.

Some may insist that barometric pressure is the cause of fluctuations. However, it has been proven that such major differences cannot be corrected by removal of barometric pressure (Quilty & Roeloffs 1991). Moreover, such an enormous barometric-pressure change would not be expected in August 1999 during hot (29º C), stable, and clear atmospheric conditions. The possible inaccuracy of recording times of pre-earthquake water-level changes in the wells was the first possibility that occurred to someone, but this situation is only possible if three errors come together. The time can be wrong if the computer's, recorder's and technician's clocks are all wrong and it is still possible. If a time error has occurred, this can be checked while testing our hypothesis in future. However, the changes in water levels were a result of earthquakes but, indeed, the correctness of the time is truly important if these changes occurred prior to earthquakes.

Conclusions

In this study, it has been determined that middle-term (monthly) and short-term (hour-minute) ground-water-level fluctuations occurred prior to earthquakes in water wells of the Bursa and Eskişehir regions. These anomalies took place in close proximity to faults that control the young basins which developed on the TEFZ. The water-level fluctuations in wells that preceded the 1999 earthquakes were functions of sediment successions, depths of wells, and distances to epicentres: 5–9 minutes prior to the 17 August 1999 earthquake and 4–15 minutes prior to the 12 November 1999 event. There is generally no direct relationship between the distance to epicentres and the time of fluctuation. As an exception, water-level changes in the Reşitbey, Deliçay and Yenice wells, which are located on faults oriented obliquely (45°) to the NAFZ, began on the eve of the 12 November 1999

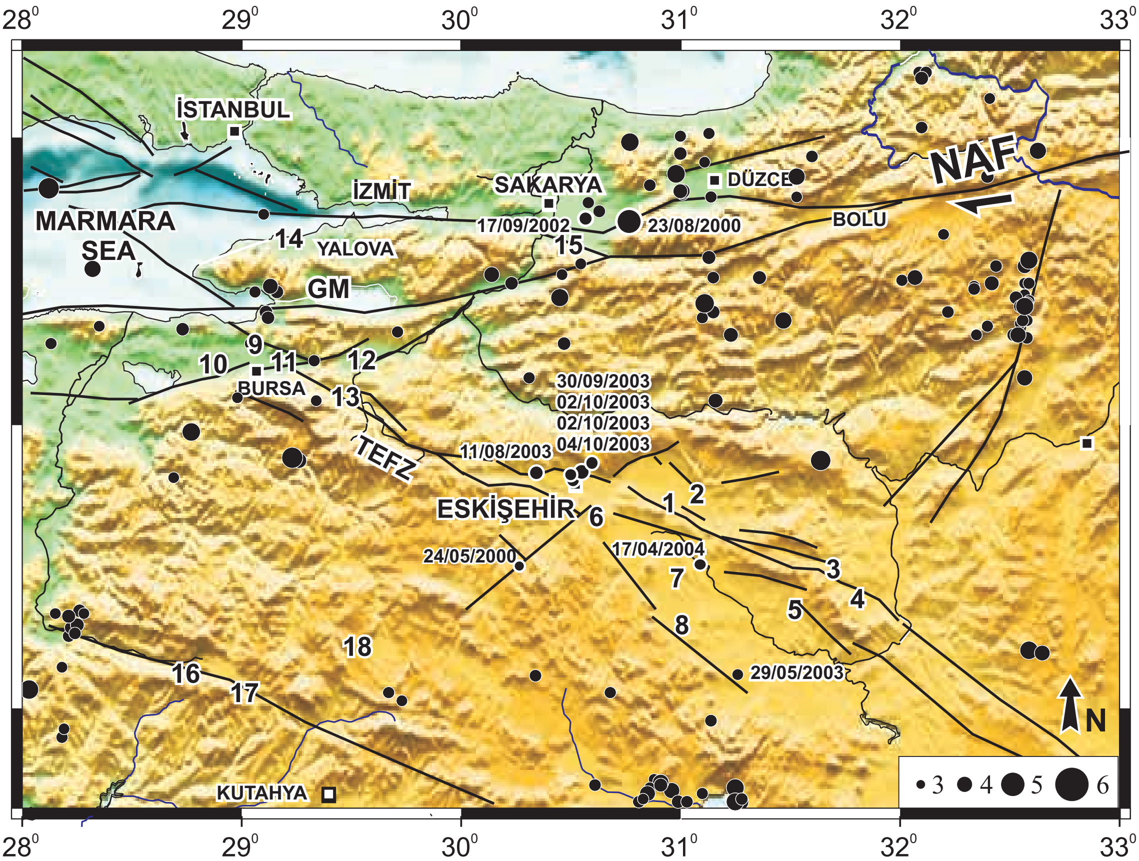

Figure 10. Seismotectonic map of the study area and vicinity. Seismic data from the Kandilli Observatory and Earthquake Research Institute database. Topographic data is from 30-second sampling NASA-SRTM (http://www2.jpl.nasa.gov/srtm) and figure is drawn by GMT 3.4.

earthquake. Indications of the 12 November 1999 earthquake in the Eskişehir wells were weak. The reason for this weakness is the remoteness of the epicentre relative to the junction of the TEFZ and the eastern Marmara fault system. A region close to the eastern Marmara faults, located between a point south of Eskişehir and the NAFZ-TEFZ junction, was affected by the 17 August 1999 earthquake months before; this was due to its nearness to the epicentre. For the 12 November 1999 earthquake, the time of water-level changes preceding the earthquake increased while the magnitude of water-level changes diminished with increasing distance of the well from the epicentre.

Water-level fluctuations in these wells cannot be due to surface waves after the shock because of the differences in arrival times to wells located at the same distance from the epicentre (the Koçaş and İstiklal wells, Tables 1, 2 & 4). Furthermore, some wells at different distances from the epicentre showed water-level changes at similar times (the Bozan, Atlas, Koçaş and İstiklal wells). Consequently, water-level changes preceding the earthquake were due to porosity changes. This conclusion resembles those of previous studies on shear waves and co-seismic water-level changes in wells (Wakita 1975; Crampin 1978, 1998, 1999a, b; Crampin *et al.* 1999; Roeloffs 1988; Rojstaczer 1988; Roeloffs *et al.* 1989; Kumpel 1992; Muir-Wood & King 1993; Rojstaczer *et al.* 1995; Roeloffs & Quilty 1997; Grecksch *et al.* 1999; Gavrilenko *et al.* 2000).

Although the data sets obtained in this study were not intended for earthquake forecast, a simple and reliable system installed by DSİ for water-level observations in plains fortunately yielded nearly ideal results. The anomalies in the data were noticed months after the earthquakes. However, most of the sceptic scientists consulted by DSİ had no interest in the records because of their prejudices, namely that earthquakes cannot be forecasted. The data was assumed redundant without considering the tectonic setting of the region; moreover, the recording system was criticised, without support, and the anomalies were attributed to various factors – such as surface waves, power failure, change in instrument calibration prior to the earthquakes, and/or clock problems. The present researchers decided to use these data sets, after determining their reliability, in order to investigate the reasons for the anomalies that preceded both earthquakes. The literature is replete with unexplained water-level changes in shallow wells preceding earthquakes. In this study, we compared examples from both within and outside of Turkey, and tried to explain anomalies by considering the relationship between wells and seismogenic-fault locations. Consequently, all data sets were evaluated in the framework of a clearly testable model that takes into account the relationship between the NAFZ and the development of the basins. The model is based on the relationship between seismogenic normal faults produced by angular stress vectors conformable with seismogenic faults. For instance, stress reaches a maximum prior to earthquakes in the NW–SE-oriented low activity basins (TEFZ basins) located at 45º to the E–W dextral strike-slip seismogenic faults, such as the NAFZ. Poroelastic changes in loose sediments surrounding the shallow wells show anomalies due to maximum stress prior to earthquakes. The drastic differences between the 1999 and 2000–2004 data sets indicate that this model should be considered.

An ideal earthquake-forecast area can be found if one can establish a kinematic relationship between seismogenic faults and maximum stress areas, even when they are far from each other. Ideal places might be as follows: local grabens, ramp basins in front of thrust faults, basins bounded by stretching normal faults oriented obliquely (45°) to strike-slip faults, low activity basins developed parallel to normal faults, and basins developed on transform faults perpendicular to normal faults or thrust faults.

This study suggests that the nature of ground-water-level changes in wells may be used as an earthquake forecasting method in the Marmara region of Turkey:

a. Areas with young basins and older normal faults, which have a N45ºW position on the dextral E–W-trending NAFZ, are subject to maximum deformation prior to earthquakes if they are concordant with the stress vector.
b. The water-level changes in wells in these young basins occur as a result of pre-earthquake deformation, and are observed at different times with varying levels of change due to the heterogeneity of the basins.
c. It is understood that the accumulated strain on faults between Yalova and Bolu affected the area extending 103 to 293 km from the earthquake epicentres.
d. Under these conditions, the Eskişehir, İnönü, Alpu, İnegöl, Bursa, Çayırköy and Yenişehir basins may be considered to be appropriate for pre- and post-earthquake water-level changes in wells. Similar properties can be seen in Plio–Quaternary sedimentary basins along the TEFZ in Thrace and the NAFZ.
e. At the western side of the study area, rises in ground-water levels in wells can be expected on the Manyas and Gönen plains, which are bordered by faults concordant with the compressional vector.

Regarding their belief that ‘earthquakes cannot be predicted today’, other researchers should be asked if it is acceptable to reject scientific and reliable data concerning real phenomena and set forth unsupported arguments. If the answer is ‘yes’, then scientific research becomes routine and the work of technicians (Kuhn 1962). Thus, whoever sees that a project is a danger to his/her study fails to take into account the basics of science, such as testing and falsification (Popper 1935). The hypothesis presented in this study, however, is highly subject to testing. Studies of earthquake prediction may also bring political and economic problems, as pointed out by Sneider & van Eck (1997), especially if a possible earthquake threatens a high-population area. Speculation sometimes causes more economic damage than do earthquakes in free-market economies of democratic regimes; however, the effects are less in regimes such as China. Even in the present case, the Marmara region provides an ideal natural laboratory for forecasting studies, and is a geopolitically strategic area with profound economic power – approximately half of Turkey's total.

The Marmara region, at the intersection of the NAFZ and TEFZ (Yaltırak 2002), has sites for measurements of surface deformation (on land and the sea floor) preceding an earthquake of Mw 7.4–7.7 (Yaltırak & Alpar 2002b; Yaltırak *et al.* 2003). We suggest observation sites located in areas and on structures that are oriented oblique to fault systems, with seismogenic faults that are capable of creating maximum surface deformation prior to an earthquake. Relative shore-level measuring systems, shear-wave measurements, tilting measurements, piezoelectrical studies together with on-line, shallow-well water-level recording systems located on basins associated with the TEFZ in Turkey, will reveal if the suggested hypothesis works or not.

Consequently, this study proposes the following hypothesis: If (1) an earthquake occurs without any changes in the water levels of wells, our hypothesis will be proven false; (2) changes occur in the water levels of wells without an earthquake, our hypothesis will be proven false; (3) both changes in the water levels of wells (similar to 1999) and earthquake occur, our hypothesis should be deemed valid at least until another test; (4) in order to predict the next earthquake, continuous measurements of water-level record changes only during and after an earthquake, it will be seen that the times used in this paper are wrong and the hypothesis concerning deformation proposed by us for earthquake forecasting will be proven false.

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