Multidisciplinary investigations of the German Task Force for Earthquakes related to the Izmit earthquake of August 17, 1999 and the Düzce earthquake of November 12, 1999

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Abstract

In the early morning of August 17, 1999, a disastrous M_w=7.4 earthquake occurred near Izmit in NW Turkey. Just 3 months later another M_w=7.1 earthquake destroyed the Düzce area. The focal mechanisms of both events were almost pure right-lateral strike-slip with observed horizontal surface displacements of up to 4.9 m in the first and 4.1 m in the second event. After both earthquakes temporary seismological networks containing up to 19 short period and broad band instruments, and 6 mobile GPS receivers were installed to study the aftershocks, and monitor crustal deformation. Civil engineers have analysed structural damages in order to discover different failure mechanisms. In addition, they carried out site response studies using 10 strong motion recorders. Earthquake related changes of thermal and mineral waters were mapped and significant (4 to 7 fold) CO_2 increases in thermal and mineral waters were observed over large areas after the Düzce event. INSAR results and seismological findings agree upon a cumulative seismic moment of 2-2.6 x10^{20} Nm for the Izmit event, but not on the directivity mode of rupture propagation.

Introduction

The German Task Force for Earthquakes was founded in 1993, jointly by earth scientists, structural experts, sociologists, search and rescue experts and insurers. Its purpose is to co-ordinate the rapid deployment of interdisciplinary scientific-technical teams of experts to earthquake disasters. In Turkey, the M_S=6.8 Erzincan earthquake of March 13, 1992 (Grosser et al., 1998), the M_S=6.1 Dinar earthquake of October 1, 1995 (Woith et al., 1999), and the Adana event of June 27, 1998 had been investigated by teams of the German Task Force.
Upon invitation of the General Directorate of Disaster Affairs in Ankara, part of the German Task Force for Earthquakes arrived in Turkey within 24 hours after the first event to study 1) aftershocks with strong motion recorders, 2) crustal deformation with 6 mobile GPS receivers, and 3) possible earthquake related changes of thermal and mineral waters. Two days later a second team of seismologists and civil engineers arrived in the epicentral area to 4) install a temporary seismological network and 5) investigate structural damages. Two days after the Düzce earthquake seismologists and civil engineers began to re-install the mobile seismic network and to investigate damaged buildings. Thermal and mineral waters have been re-investigated during November 23-29, 1999. This paper gives an overview of the multidisciplinary activities of the Task Force related to the Izmit and Düzce earthquakes of 1999. Aims have been to a) derive the mode and extend of co-seismic subsurface faulting, b) approximate the distribution of strains and study co-seismic redistribution of strains and stresses, c) compare geodetic surface information with seismic information, d) provide indirect evidence of the directivity of co-seismic rupture propagation, e) understand the

response of crustal fluids to strong earthquakes, f) investigate the structural damage in relation to the ground response, and g) provide input parameters for modelling of improved scenarios in order to better assess damage caused by future events.

Earthquake History

The Izmit M_w=7.4 earthquake of August 17, 1999 ruptured a western section of the North Anatolian Fault (NAF), a 1500 km long fault separating the Anatolian block from the Eurasian plate. Only 87 days after this devastating event, a M_w=7.1 earthquake occurred near Düzce. According to Ambraseys and Finkel (1995) a similar "earthquake couple" happened in 1766 in the Marmara Sea area: On May 22, 1766 the first event hit the area between Tekirdag and Izmit whereas 75 days later the area west of Tekirdag was affected by a second major quake. Between 1939 and 1967 seven earthquakes above M=6.8 happened along the NAF indicating westward migration of Eq. starting in Erzincan (Stein et al., 1997; Toksöz et al., 1979). The last event of this series affected the Mudurnu valley fault, a branch of the NAF located in the area west of Bolu, in 1967 (Ambraseys and Zatopek, 1969). Using data from GPS surveys in the Marmara area during 1990 through 1996 Straub et al. (1997) obtained a movement rate of the Anatolian block of the order of 22 ± 3 mm/year relative to Eurasia and concluded "that the most active zone of dextral shear follows a line along Mudurnu Valley, the northern Marmara Sea and the Saros Trough...". Based on temporal and spatial b-value variations Westerhaus et al. (this volume) depicted a small circle at 30.1°E and 40.7°N to be the most likely location for a major earthquake along this section of the NAF. This location is near to the epicentre of the Izmit earthquake (29.97°E, 40.76°N). In 1878 a strong earthquake took place probably near to the epicentre of the recent Izmit event (Toksöz et al., 1979). The time interval of 120 years and an average horizontal displacement of 3 m combines to a slip rate of 2.5 cm/year assuming that no creep occurred along the Izmit fault segment. This value fits to the recent plate motion of 2.5 cm/year determined from GPS measurements (Reilinger et al., 1997).

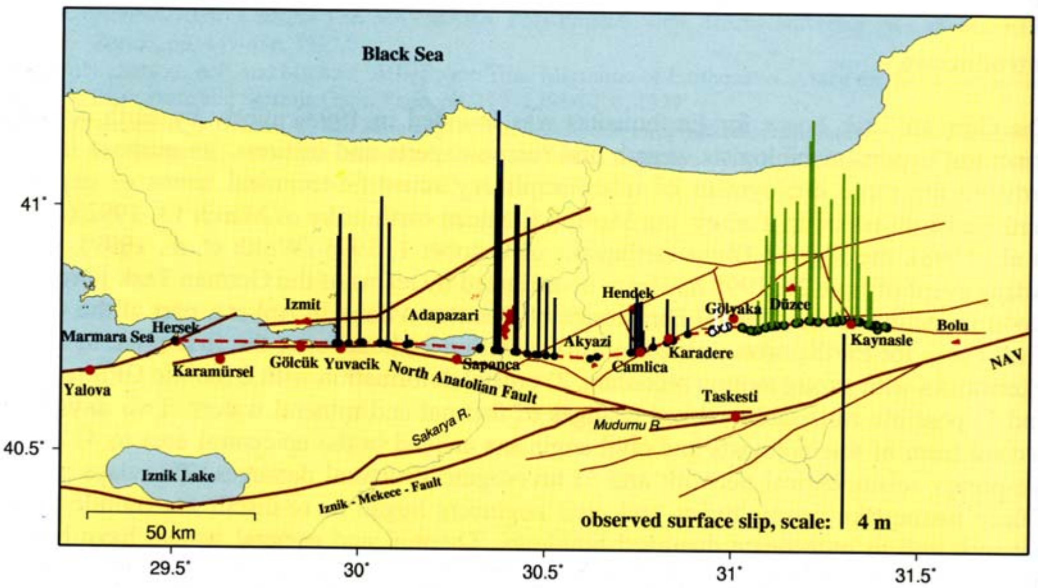


Figure 1 *Surface ruptures mapped after the Izmit (blue) and Düzce (green) earthquakes with contributions by E. Günter and Ü. Dikmen. White symbols depict sites which were affected by both events. Fault lines from Barka and Kadinsky-Cade (1988) and Michel (1994).*

Surface Ruptures

The Izmit and Düzce earthquakes ruptured segments of the North Anatolian Fault west and north of the area where the 1967 Mudurnu valley earthquake occurred. Surface ruptures of the August 17, 1999 Izmit earthquake were traced for 127 km from Karamürsel, a town on the southern shore of the Izmit bay about 30 km W of Izmit, to Gölyaka, a small town about 15 km SW of Düzce. The ruptures are dominantly of dextral strike-slip character with a maximum horizontal displacement of 4.9 m near Adapazari (Fig. 1). According to the different data sets discussed below, the Eq.-fault may be divided into 3 segments: The westernmost segment was traced between the Izmit bay and the western end of the Sapanca lake. Surface breaks suggest a maximum displacement of 3 m. The epicentre of the Izmit Eq. is located on this segment. The second segment can be traced from south of Adapazari to Akyazi. Surface ruptures are of the largest magnitude there. Displacements below 1 m are typical for the easternmost segment between Akyazi and Gölyaka. Within this segment, the general direction of the fault trace changes from E-W to nearly 80°.
The total length of the surface ruptures related to the November 12, 1999 Düzce earthquake amounted to 43 km. Again, surface ruptures indicated right-lateral Eq.-motion. Contrary to the Izmit rupture, slip is continuous with a maximum displacement of 4.1 m at the centre of the rupture SE of Düzce.

Earthquake Mechanisms

The focal mechanisms of both events were almost pure right-lateral strike-slip (Bock et al., this volume). Relevant seismological parameters are summarised in Table 1. The epicentre of the first event is located SW of Izmit. From there, the rupture propagated (only a few fault km were ruptured to the West) unilaterally to the East. Assuming a depth of 18 km, an average horizontal displacement of 3m, a shear modulus of $3\ 10^{10}$ Nm, and a seismic moment of $2.1\ 10^{20}$ Nm, a total rupture length of 130 km is obtained, which is near to the mapped length of the surface ruptures of 127 km. With the given parameters the stress drop calculates to 4.3 MPa.

Table 1 *Parameters of the 1999 Izmit and Düzce earthquakes compiled from the following sources: USGS US Geological Survey, HVD Harvard University; KO Kandilli Observatory (Toksöz et al., 1999), Istanbul; ERD Earthquake Research Department, AFET, Ankara; GFZ GeoForschungsZentrum Postdam (Bock et al., this volume); SABO SABOnet (Milkereit et al., this volume).*

source	°E	°N	depth km	M_w	strike °	dip °	rake °	moment Nm
				Izmit 17.08.1999 00:01:37				
USGS	29.83	40.64	15.0	7.4	91	76	179	$1.4\ 10^{20}$
HVD	30.08	40.81	16.6	7.5	268	84	180	$2.1\ 10^{20}$
KO	29.97	40.76	18.0					
ERD	29.91	40.70	15.9	7.4				
GFZ				7.4	270	87	178	$1.52\ 10^{20}$
				Düzce 12.11.1999 16:57:19				
USGS	31.148	40.768	14	7.1	276	59	167	$4.5\ 10^{19}$
HVD	31.29	40.56	15.0	7.1	265	65	158	$6.5\ 10^{19}$
ERD	31.21	40.79	11.0	7.2				
GFZ				7.1	264	64	184	$0.46\ 10^{20}$
SABO	31.198	40.818	12.5					

The epicentre of the Düzce event has been located by the SABOnet near to the city of Düzce approximately in the middle of the mapped surface ruptures. Thus the rupture propagation seems to be bilateral for this event. Assuming a depth of 12.5 km, an average horizontal displacement of 3 m, a shear modulus of $3\ 10^{10}$ Nm, and a seismic moment of $6.5\ 10^{19}$ Nm, a total rupture length of 58 km is obtained, which is 15 km above the value indicated by surface ruptures. Using a rupture length of 58 km, a stress drop of 6.3 MPa was estimated for the Düzce event.

Aftershocks

A permanent seismic network - called SABOnet - was installed in the area between the Sapanca lake and the city of Bolu in 1996 within the frame of the Turkish-German project on earthquake research (Zschau et al., 1982). After the Izmit earthquake 19 mobile stations were installed by the Task Force group within a few days in the area to the west of SABOnet. The temporary "Izmit" net operated until October 21, 1999. Three days after the Düzce earthquake the mobile stations were re-installed to the East, again partially overlapping the SABOnet. This temporary "Düzce" net operated until December 13, 1999. During the first day after the Izmit event about 2000 earthquakes were detected by the SABOnet; after 2 months still more than 200 events were recorded per day. The preliminary manual analysis of the aftershocks of one day in August showed clustering of the earthquakes in two distinct areas located between Adapazari and Akyazi, and between Karadere and Düzce (Milkereit et al. this volume).

Ground Response and Structural Damage

With a total death toll of about 19,000 plus 30,000 people missing the Izmit and Düzce earthquakes of 1999 belong to the most disastrous of the last century. Within an area of roughly 200 km by 10 km more than 60,000 buildings were heavily damaged, leaving 300,000 people homeless (Toksöz et al., 1999). The financial loss is estimated at 12.5 billion US$, about 1 billion US$ being insured property (Berz, 2000).
After the strong earthquakes in August and November 1999, a network of strong-motion accelerographs had been installed in the disaster-struck area in order to investigate local ground response to seismic waves. The decision upon the different sites depended on geological and topographical conditions as well as on the extent and concentration of building damage. The positions of the strong-motion recorders during the mission after the Kocaeli mainshock in August 1999 are shown in Figure 2. Due to the fact, that the effects of the Düzce earthquake in November 1999 were mostly concentrated on the town of Düzce and its surrounding villages, the installation of strong-motion equipment had been restricted to the urban area of Düzce.

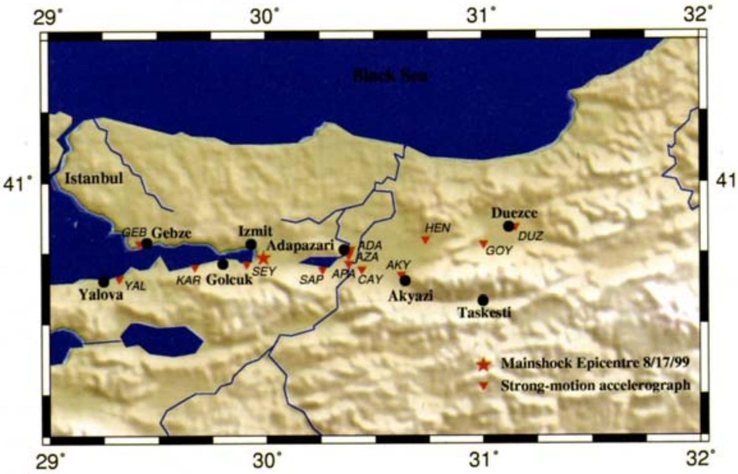


Figure 2 Temporal strong-motion network of German Task Force.

A maximum peak ground acceleration (PGA) of the Kocaeli mainshock reaching 0.41g was observed at a station in Adapazari (epicentral distance approx. 35 km; Kandilli Observatory Istanbul, 1999). Figure 3 illustrates the time-histories of a $M_b = 4.2$ aftershock from August 29, 1999, recorded at the stations Düzce (DUZ) and Gölyaka (GOY), respectively. The corresponding response spectra are shown in the Figures 4. During the entire recording period from August to November 1999, hundreds of different aftershock events were recorded by the 10 strong-motion accellerographs of the German Task Force, of which 50 events had a magnitude above M_L=3. The strongest aftershock occured on September 13, 1999 (UTC 11:55:28.18) with a moment magnitude M_w=5.9 (USGS).

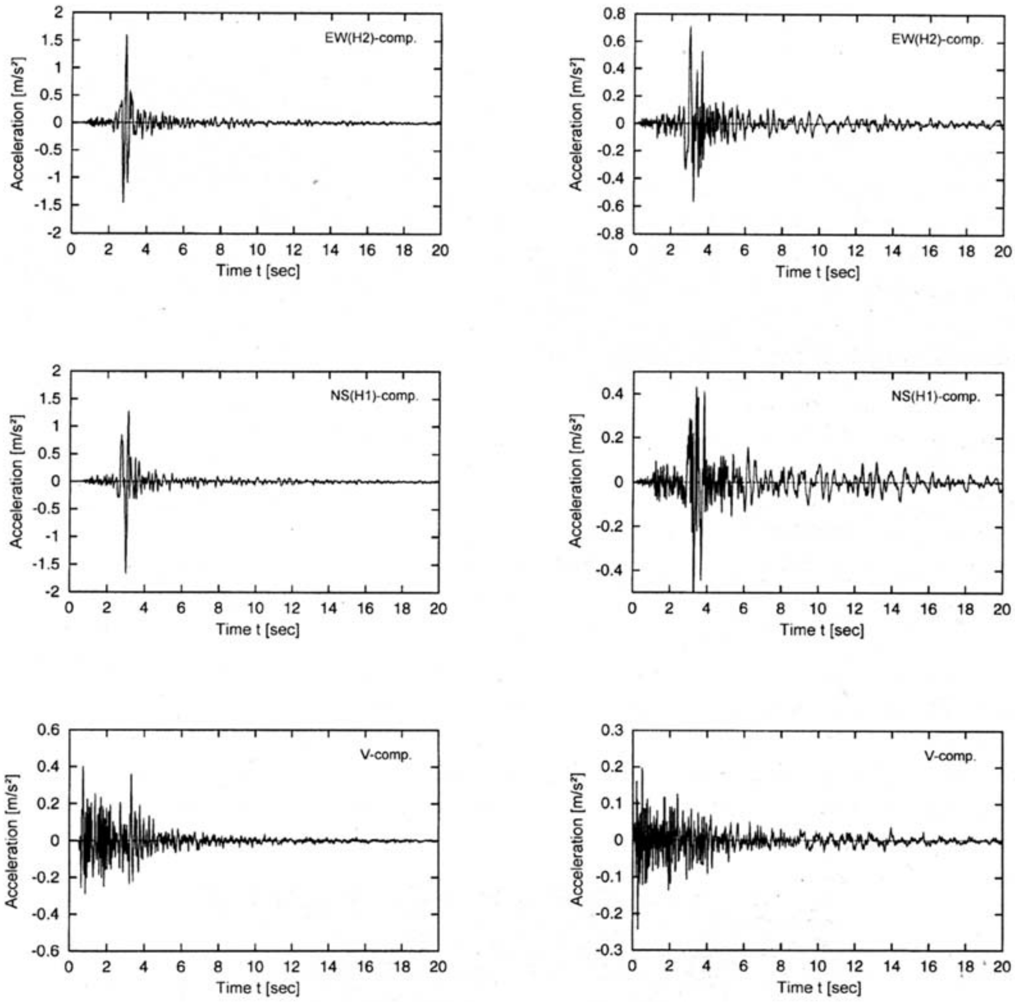


***Figure 3** Time-histories of a recorded aftershock event (M_b = 4.2) at station Düzce (left) and station Gölyaka (right)*

Furthermore, the investigation of structural damage had been carried out by two different approaches. Macroseismic investigations had been worked out for several urban areas by regarding the different building types and grades of damage. Additionally, a microregion in Düzce was studied after both earthquakes in August and November 1999, elaborating the effects of damage progression. Selected damage cases (Figure 5) were analysed in more detail in order to determine the vibrational characteristics of predominant structural systems by varying the number of stories, stiffening systems as well as the grade of interaction between reinforced concrete frames and non-structural masonry infills.

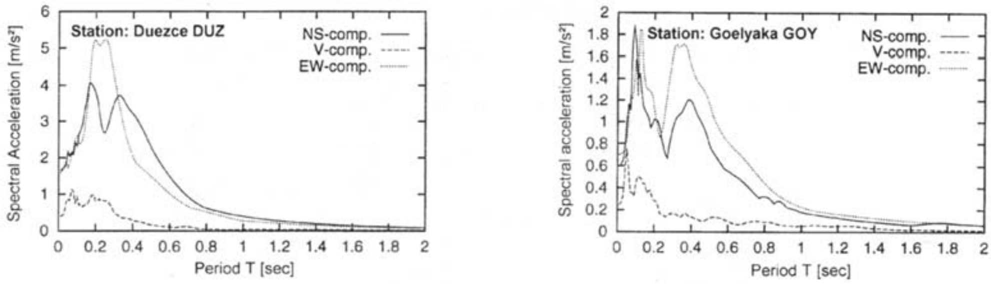


Figure 4 Response spectra at station Düzce (left) and station Gölyaka (right)

Figure 5 *Damage of a hotel-building in Düzce provoked by posterior addition of building parts (left). Damaged 3-storey RC-frame building in Gölyaka (right). Plastic hinges in the joints were caused by defects in design, material quality and reinforcement detailing. (Photos: Lang/Raschke)*

It is of special importance for engineering analysis to compare the results of aftershock measurements with the observed damage pattern in order to elaborate the local site amplification potential as well as to identify predominant building types, mainly affected by seismic excitation (Schwarz et al., 2000a; Schwarz et al., 2000b).

Post-seismic Deformation Derived from GPS

Immediately after the Izmit and Düzce earthquakes GPS-receivers were installed in the vicinity of the surface ruptures for continuous monitoring of aseismic after-slip and aftershock-induced deformation. 6 GPS-receivers were placed north and south of the surface rupture generated by the Izmit earthquake. Installation started at August 18 and was completed within 3 days. The receivers (2-frequency, Trimble 4000SSE) were set to continuous recording and remained in the field until October 15, 1999. After the Düzce Earthquake, 5 GPS-receivers were placed and worked in continuous mode until November 29, thereafter, recording was changed to repeated measurements every 5 days until December 15, 1999. The net configuration was different for both events. After the Izmit earthquake, the stations were installed to cover a large segment of the surface rupture (approx. 100km). For the Düzce event, the receivers were placed forming a transect across the rupture zone at aproxx. 31°E (Fig. 6). Both nets have one common point, TAS. The station KOP was nearly at the place, but unfortunately the marker of the Izmit campaign was destroyed when we re-installed the station after the Düzce Earthquake.

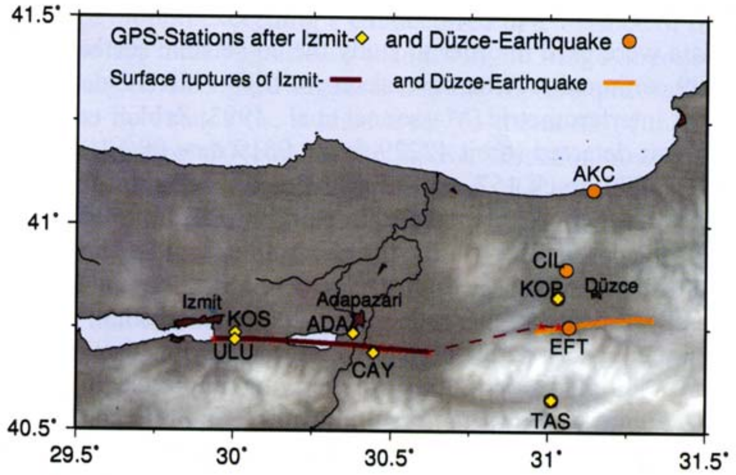


Figure 6 Station distribution for the GPS campaigns after the Izmit- and Düzce-earthquakes.

Preliminary processing of the data from the Izmit campaign was carried out using the commercial software GPSurvey. Precise ephemerides provided by the International GPS Service for Geodynamics (IGS) were used. In a first step, the initial station positions were determined using data from permanent IGS stations. Then, for the investigation of temporal changes, several blocks of 24 hours of observation were analysed to obtain distance vectors between the stations and its components (north-south- (dn), east-west- (de) and height (dz) differences). The results of this first processing for the Izmit earthquake observations indicate ongoing right-lateral E-W directed movement along or adjacent to the Eq.- rupture zone. Horizontal post-Eq.-movements reached values of 8 cm in 6 weeks. Changes in NS direction were below the significance level (see fig. 7).

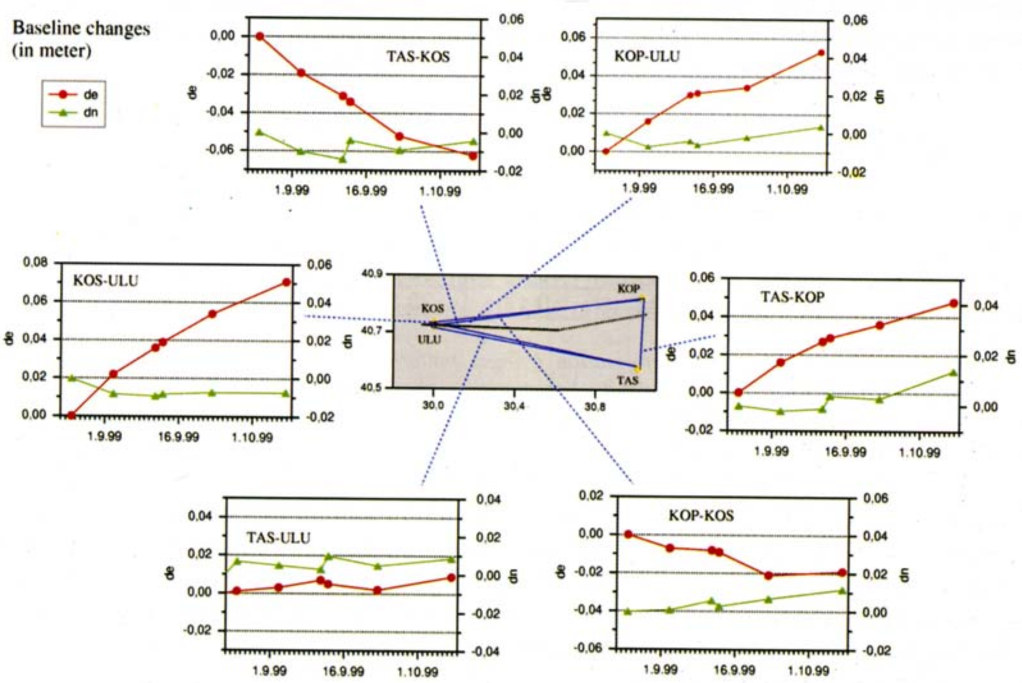
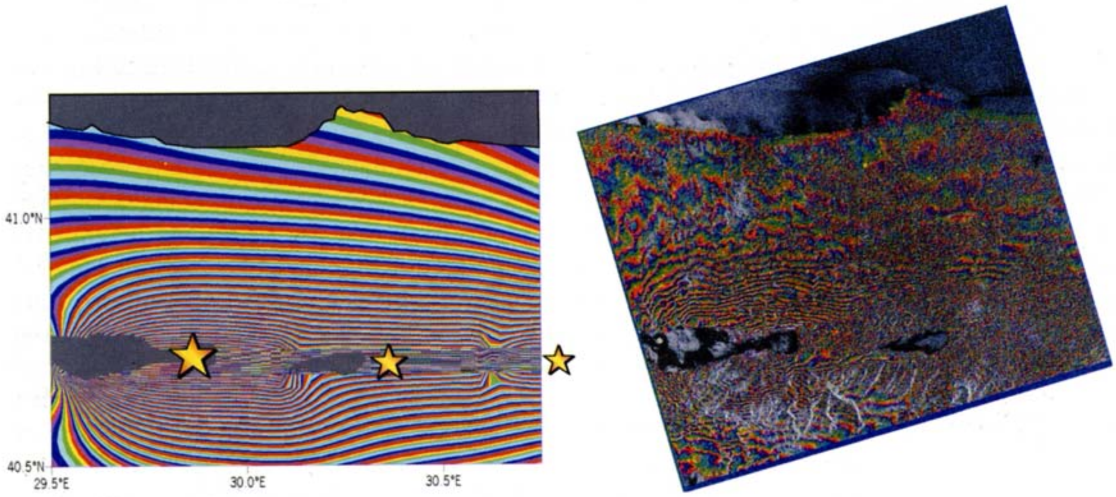


Figure 7 Temporal development of EW (red) - and NS (green) - distances for selected baselines. The blue lines in the map (middle of figure) show the baselines, the black line marks the observed surface rupture.

Co-seismic Deformation Detection of the Izmit Earthquake with INSAR

ERS-1 and ERS-2 data were used in order to study the co-seismic surface deformation of the Izmit August 17, 1999 earthquake. After several sets of ERS-1/ERS-2 data had been checked, a pair suitable for SAR interferometric (Massonnet et al., 1993; Zebker et al., 1994; Reigber et al., 1997) processing was detected (orbit 42229 frame 0819 date 08/12/1999 and orbit 42730 frame 0819 date 09/16/1999, track 157, ascending). Due to ERS-orbit manoeuvring that was conducted by the ESA after the earthquake, this pair provided very small baselines and a special opportunity to approximate surface deformation almost unaffected by ground topography. The orbit manoeuvre caused an apparent relative shift in the orbits of the two scenes used and re-adjustment of the scenes had to be conducted before applying the interferometric technique. Precise orbit products of the GFZ Potsdam were applied. These products provided an additional opportunity for deriving improved highly precise surface deformation patterns. Figure 8 shows the resulting interferogram each fringe (color cycle) each corresponding to a ground displacement of 2.8 cm in satellite's viewing direction (slant range).



displ. [cm]	length [km]	depth [km]	long. [°]	lat. [°]
420	49	0-17	29.80	40.7
300	41	0-17	30.35	40.7
300	45	0-17	30.88	40.7

Figure 8 *Right: Apparent co-seismic deformation (fringe) pattern derived using SAR interferometry. Left: Results from dislocation modelling with fault characteristics shown in the table. The area covered by the interferogram extends from the Hersek peninsula in the west, to the area of Hendek to the east. The major North-Anatolian Fault (NAF) trace is approximated by a virtual axis that connects the eastern elongation of the Marmara Sea (Izmit Bay) with the Sapanca Lake located east of it.*

Fringes are distributed fairly homogeneously within the area studied, suggesting that surface deformation is dominated by elastic co-seismic strain release. Phase gradients to the north of the NAF point towards the fault whereas they point away from the fault to its south. Along with a considerable increase in fringe density in the vicinity of the fault, this suggests that the fault had ruptured the surface during the earthquake. Assuming that deformation was purely (or at least dominantly) strike slip, results indicate that the area to the north of the NAF was shifted (relatively) to the east whereas the area south of the fault was shifted to the west indicating dextral motion along a roughly E-W trending fault in concert with teleseismic results. The distribution of fringes suggests that an area larger than the area shown in the figure has significantly been affected by co-seismic elastic surface deformation. This indicates that co-seismic surface motion exceeding 1 cm occurred in a distance of the order of 70 km in the direction normal to the fault. Significant changes in the fringe directions towards the fault at the western boundary of the figure suggests that the rupture terminated there. The eastern termination appears to lie outside the studied area. To the north of the fault, 25 ± 2 fringes were counted, approximating 70 cm of slip in the direction towards the satellite. This approximates 180 cm of eastward directed horizontal displacement along this side of the fault if purely horizontal motion is assumed. Only a fraction of the deformation zone is covered by the more limited data to the south of the fault. However the very steeply dipping fault and the roughly two dimensional solution approximated by the teleseismic data (Bock et al., this volume) suggest that deformation and slip might be comparable along both fault sides. This suggests that seismic slip was of the order of 3.6 m.

Forward dislocation modelling (Okada, 1985) was applied in order to approximate the surface deformation pattern provided by the SAR interferometry. This was done using different solutions assuming uniform slip along one fault or several sub-faults. The depicted solution was derived taking into account a) the distribution and amount of surface rupturing (Fig. 1), b) approximate seismic moments and location of sub-events derived from teleseismic body wave records (Bock et al., this volume) and c) by carefully examining the distribution and continuation of fringes in the interferogram. Although the area adjacent to the fault is rather difficult to examine using the SAR data, slight changes in the continuation of fringes west of the Sapanca Lake suggest a change in the continuation of the rupture there. This coincides with a minimum in the amount of surface rupturing observed in the field and with the findings of Bock et al. (this volume) that suggest sub-events that are located east of the main shock. Taking into account the dimensions shown in figure 8, a cumulative seismic moment of 2.4 10^{20}Nm was derived. This coincides with the moment indicated by the teleseimic solutions (Bock et al., this volume). Significant changes in the orientation of the causative faults of the sub-events were tested. Results suggest that none of these sub-events covered by the studied area constitute a trace that deviates significantly from that of the main shock. Assuming that pure strike-slip motion accounts for the studied fringes, an overall co-seismic displacement of 3.6 ± 0.14 m was approximated. Due to the rather steep satellite's viewing direction (23° to nadir), slightly oblique motion might however result in significantly smaller horizontal displacement.

According to Bock et al. (this volume) the nucleation point of the main shock is situated at the eastern apex of the Izmit bay. As opposed to their result, that suggests an unilateral rupture-propagation mode, the distribution of fringes clearly indicates an extend of the rupture zone west of their nucleation point and towards 29.5°E (Hersek penisula). This suggests bilateral rupture propagation.

Response of Thermal and Mineral Waters to the Earthquakes

Temporal variations of the physico-chemical properties of thermal and mineral waters have been investigated after both events. Water samples from more than 40 sites within an area of about 350 km by 120 km were analysed (Fig. 9). About one third of the springs had been investigated before the earthquakes in the frame of the Turkish-German project on earthquake research (Woith, 1996) and within the READINESS project (Woith et al., 1998). For the springs located on the Armutlu peninsula and in the Bursa area pre-earthquake data were collected by colleagues from the ETH Zurich (Eisenlohr, 1995; Greber, 1992; Imbach, 1992). Some locations had been re-visited by the Swiss colleagues a few weeks before the Izmit earthquake (pers. comm. Balderer, ETH Zürich).

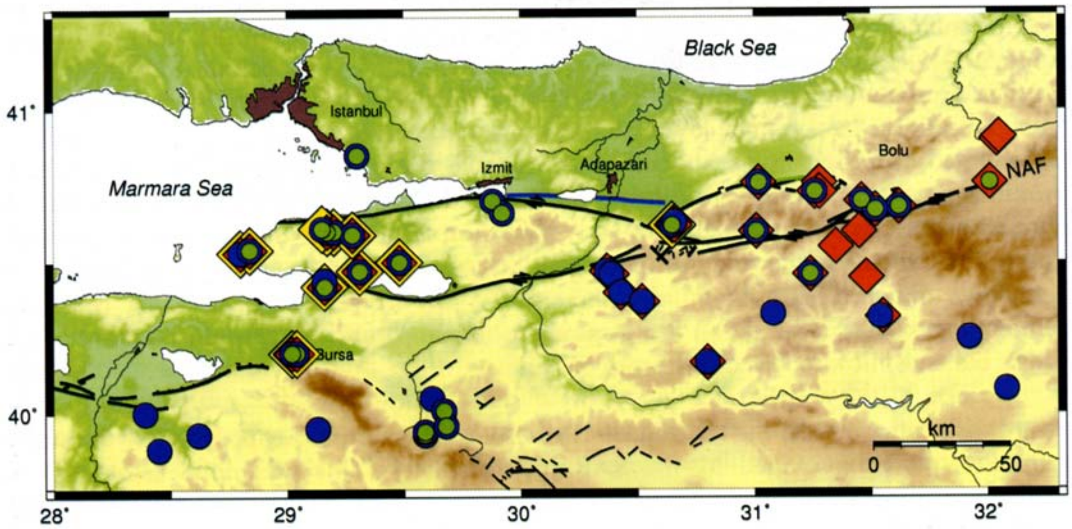


Figure 9 *Location of thermal and mineral waters in NW Turkey. Water samples were taken in the time interval August 19-30, 1999 (blue circles), and November 23-29, 1999 (green circles). Pre-Izmit data are available for sites marked with red (gfz potsdam) and yellow (eth zurich) diamonds. Active faults according to (Saroglu et al., 1992).*

Significant co- and post-seismic changes of the water discharge were reported from several locations at distances from the epicentres of up to 200 km and confirmed by our own measurements. At the thermal springs of Yalova, a new hot spring was detected two weeks before the Izmit earthquake. This has been documented by a letter written by the district head to the university of Istanbul on August 3, 1999. The new spring still existed after the earthquakes. The spring is located in the bed of a creek, a few meters north of a very old natural spring called "Göz Su". On August 25, 1999 the following parameters were determined in the field: At a discharge of 24 ltr/min and 53.6°C a fluid with a specific electrical conductivity of 1755 µS/cm, a pH of 7.34, a redox potential on –78 mV_{SHE}, and an oxygen content of 1.1 mg/l emerges from a crack. Its chemistry (Na-Ca-SO_4 type) is very similar to the chemistry of the other springs within this thermal field.

Based on the available data, the physico-chemical properties of the investigated thermal and mineral waters did not show any significant changes after the Eq. with respect to temperature, specific electrical conductivity, and the main anions and cations. The most striking changes were observed in the CO_2 concentration of the thermal and mineral waters. After the first event, a 4 to 7 fold increase in CO_2 was observed in a mineral water spring near the town of Geyve (S of Adapazari) (Fig. 10a). After the second event, almost all springs – for which pre-Izmit data are available by now – show a significant increase in the CO_2 content (Fig. 10b). At the thermal bath of Efteni (SW of Düzce) extraordinarily strong gas bubbling was observed - and reported to the local authorities - two days before the Düzce earthquake happened. Assuming that these reports are reliable, the increased CO_2 degassing could be related to a seismic swarm activity on the Karadere fault segment (SW of Düzce) which started 2 days before the Düzce main shock (Seeber, pers. comm.).

Conclusions

Results from multidisciplinary investigations covering the areas of the Izmit and Düzce earthquakes, indicate that

- The extent of surface ruptures mapped in the field of 127 km are in good agreement with seismological estimates of 130 km for the Izmit event. The maximum horizontal displacement was found to be 4.9 m south of Adapazari.

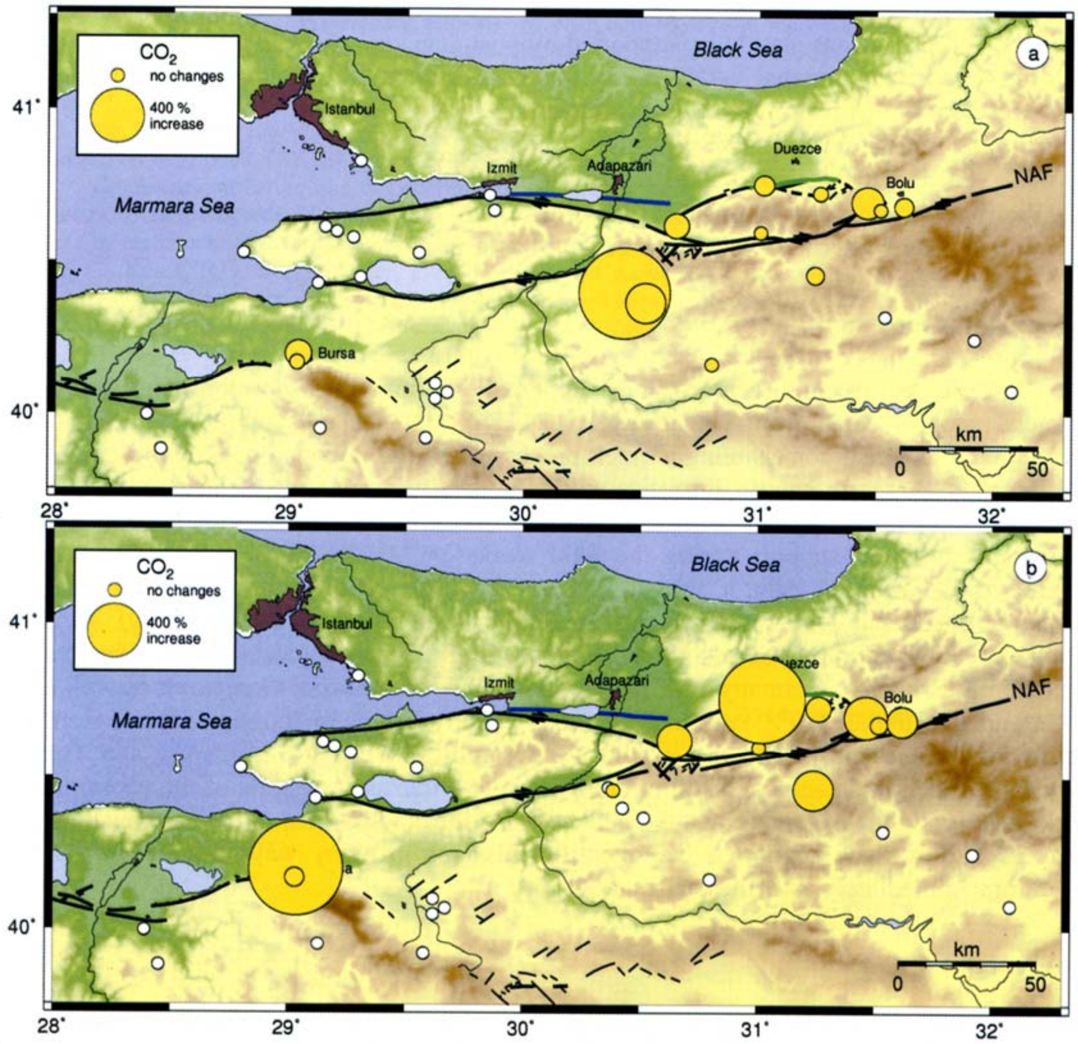


Figure 10 Increase of CO_2 concentration in mineral and thermal waters after the Izmit (below) and after the Düzce (above) earthquake. Shown are relative changes as ratios "before/after" the event.

- For the Düzce earthquake a discrepancy of 15 km remains between the ruptures observed at the surface (43 km) and the seismologically estimated rupture length of 58 km. Near to the epicentre the largest surface slip was observed with 4.1 m.
- Whereas seismological data indicate unilateral rupture propagation to the E for the Izmit event, INSAR results suggest that the rupture propagated to the E and W.
- Aftershocks do occur in well-defined clusters. The rate decreased from 2000 events per day to about 100 events per day within 3 months.
- GPS data show post-seismic right-lateral shear in the order 8 cm in 6 weeks.
- From INSAR studies an overall co-seismic displacement of 3.6 ± 0.14 m was approximated. Slight changes in the continuation of fringes coincide with results from seismologic data and surface ruptures mapped in the field. They suggest three sub-events.
- Acumulative seismic moment of 2.-2.6 10^{20} Nm was approximated using seismological and INSAR data.

- Engineering analysis of damage can be successfully supported by aftershock measurements and site response investigations.
- The reinterpretation of selected damage cases requires the detailed knowledge of structural layout and system and the recognition of force transmission path within the structural system, which cannot be performed by external view of damage pattern alone.
- Task Force missions should be supported by post-event missions in order to consider site effects and their regional variation. By this way different site response techniques could be tested at sites of strong-motion instruments.
- Co- and postseismic changes in the discharge of thermal and mineral waters were observed at distances up to 200 km from the epicentres.
- (Pre-?), co-, and post-seismic CO_2 increases (4 to 7 fold) were observed in thermal and mineral waters after the Düzce earthquake over large areas.

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