Abstract  An accurate aftershock distribution of the 1999 İzmit, Turkey, earthquake was obtained by using the data from a local seismic network, IZINET, and 10 temporary seismic stations. More than 2000 aftershocks were relocated for the period of about 2 months following the mainshock. From this aftershock distribution we obtained several pieces of information on the characteristics of the mainshock. First, the mainshock initiated fault rupture from a place adjacent to an active swarm area where many microearthquakes had been occurring for more than 20 yr prior to the mainshock. Second, the aftershock region extended in the east–west direction along the North Anatolian Fault Zone (NAFZ). This confirms that the mainshock was caused by a slip on the NAFZ. Third, the western end of the rupture caused by the mainshock is likely to have reached up to about 29.2° E in the İzmit Bay, and hence the total length of the fault rupture caused by the mainshock amounts to about 150 km, as long as the estimate of the fault rupture length is based on the aftershock distribution. This information is important for the discussion on the possibility of future large earthquakes in the west of the source region of the İzmit earthquake. We also found a clear tendency that aftershocks occur in clusters, which implies strong heterogeneity in both the rupture process and the medium along the fault zone.

Introduction

On 17 August 1999, a disastrous earthquake with a moment magnitude of $M_w$ 7.4 (Kandilli Observatory, Boğaziçi University; U.S. Geological Survey) took place near İzmit City in the northwestern part of Turkey. The surface rupture that appeared with the mainshock followed the North Anatolian Fault Zone (NAFZ) from the eastern end of İzmit Bay to about 31° E (Barka et al., 1999). The source region of this earthquake has been well known as a seismic gap; in fact, large earthquakes have occurred successively along the NAFZ from the east to the west (Toksoz et al., 1979). In this sense, this earthquake is the one that many seismologists have been afraid of for a long time.

The NAFZ is an extremely active tectonic line, and its tectonics and geology had been well investigated prior to the 1999 İzmit earthquake (Allen, 1969; Ambraseys, 1970; Barka, 1996; Ikeda, 1988). Large and medium earthquakes have also been studied (Dewey, 1976; Jackson and McKenzie, 1988). We have also undertaken multidisciplinary research in the western part of the NAFZ since 1981 in order to increase our understanding of this seismic gap (Honkura and İşikara, 1991). Seismological observations, however, have not been sufficient for monitoring microearthquake activity in the seismic gap region. Although the Kandilli Observatory, Boğaziçi University, has established the MAR-NET seismic network for microearthquake observations (Üçer et al., 1985), this network could not cover the whole seismic gap region. According to previous studies, microearthquake activity in the seismic gap region has been very low in general, except for some swarm areas (Crampin et al., 1985; Evans et al., 1987; Tsukuda et al., 1988; Lovell et al., 1989; Nishigami et al., 1990; Iio et al., 1991), but detailed characteristics have not been very clear without a dense network covering the seismic gap region.

In view of this, we have attempted, since 1992, to install a routine seismic network, IZINET, in the westernmost part of the NAFZ. IZINET was the only local seismic network in operation when the 1999 İzmit earthquake occurred, and it recorded the aftershock sequence following the mainshock. In this article, we present detailed features of the aftershock activity associated with the 1999 İzmit earthquake, as revealed from microearthquake observations.

Microearthquake Observations in the Western Part of the NAFZ

Two major branches have been identified in the westernmost part of the NAFZ. One is the southern branch, named the Iznik–Mekece Fault, which extends to the south-
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Figure 1. Distribution of the seismic observation stations in the westernmost part of the NAFZ. Solid squares represent the seismic stations of İZINET and solid triangles the temporary observation stations. Open circles show some major cities referred to in the text. Solid lines with a tick are active faults suggested by Barka (1992, 1997).

Table 1

Velocity Structure Model Used in the Present Study*

<table>
<thead>
<tr>
<th>Layer</th>
<th>$R - r_0$</th>
<th>$V_p$</th>
<th>$V_s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crust</td>
<td>0 km</td>
<td>5.40 km/sec</td>
<td>40.0</td>
</tr>
<tr>
<td>Mantle</td>
<td>39</td>
<td>8.00</td>
<td>2.3</td>
</tr>
</tbody>
</table>

*The seismic velocity is represented by $V(r) = V_0(r/r_0)^{-\zeta}$, where $V(r)$ is the seismic velocity at the radial distance $r$, $r_0$ is the radius of the top of each layer, and $V_0$ is the seismic velocity at $r = r_0$. In the table, $R$ represents the curvature radius of the earth at the latitude of 40°, that is 6361.1 km.
tral, and the eastern parts, and determined appropriate station corrections for each part in order to avoid large residuals. The average root mean square (rms) of residuals decreased to 0.09 sec when this procedure was used, whereas it was larger than 0.2 sec without these station corrections.

We also attempted to obtain a three-dimensional P-wave velocity structure in and around the source region of the İzmit earthquake using data from IZINET, temporary observations, and other temporary network installed by Ito et al. (2002) and Nakamura et al. (2002). Although we obtained more accurate hypocenter distribution by applying the three-dimensional velocity structure, the effect of the three-dimensional velocity structure on the hypocenter relocation was not significant. This is natural because we already took the effect of the lateral heterogeneity of the medium into account by using different station corrections in the three regions of the source area. In this article, we use hypocenter locations obtained by the procedure mentioned previously for the simple calculation.

The events we refer to hereafter show an rms of arrival-time residuals of 0.05 sec typically; in the worst case it is 0.3 sec. This means that the typical hypocenter error is 0.9 km, horizontally, and 1.5 km, vertically. By means of this higher accuracy of hypocenter locations compared with those of teleseismic studies, we can obtain detailed information about the seismicity before and after the 1999 İzmit earthquake.

Seismic Activity Prior to the Mainshock

Figure 2 shows the distribution of microearthquakes in the westernmost part of the NAFZ, as derived from IZINET during 7 yr prior to the 1999 İzmit earthquake. Generally speaking, the seismicity in this area has been low as mentioned previously, and the number of events for which hypocenters could be determined by IZINET is about 600 for the 7-yr period. Figure 2 shows three areas of high microearthquake activity in this region. The most active area is recognized near İzmit in the northern branch of the NAFZ. This region has been known as an active swarm area since 1975 (Crampin and Ücer, 1975; Crampin et al., 1985; Ücer et al., 1985; Evans et al., 1987). We can also recognize another swarm activity near Gemlik. Although this swarm is not as active as the İzmit swarm, it is noteworthy because it is located by the southern branch of NAFZ. On the other hand, rather scattered seismic activity can be seen in the south of the İzink–Mektece Fault. In this area, a large earthquake with a magnitude of $M_s$ 5.0 occurred on 21 October 1983 (Barsş et al., 2002). This would suggest the existence of another active tectonic line.

Figure 3 shows a space–time plot of the microearthquakes for the region shown in Figure 2. Some quiescence is apparent in Figure 3; this is obviously artificial and is caused by a system-down of IZINET. In this figure, we can clearly see that the swarm activity recognized in Figure 2 near the hypocenter of the 1999 İzmit earthquake has been taking place rather continuously for a long time. Although the activity is enhanced, for example in February and March of 1997, it is hard to say from this figure whether there were anomalous changes in the microearthquake activity prior to the İzmit earthquake.

Precise Locations of the Mainshock and Aftershocks

When the 1999 İzmit earthquake occurred, a group from our project happened to be carrying out magnetotelluric measurements just across the source region of the mainshock (Honkura et al., 2000). Their magnetometers and electric sensors recorded large signals caused by strong ground motion of the mainshock. Unfortunately, IZINET did not record the mainshock itself because the system happened to be on the stored records transfer mode. Instead, we could determine the precise hypocenter of the mainshock by using the electromagnetic signals recorded by our group together with the routine data of the Kandilli Observatory.

The hypocenter was thus relocated at the end of the İzmit Bay, as shown by an open star in Figure 2. Parameters of the hypocenter are also listed in Table 2. The location of this hypocenter is almost the same as that given in the announcement urgently issued by the Kandilli Observatory. The uncertainty of the hypocenter is about 2 km horizontally and 3 km vertically. Although the location of the hypocenter depends on the velocity structure assumed, it does not deviate by more than 5 km even if we use another velocity structure model. We can see from Figure 2 that the 1999 İzmit earthquake initiated fault rupture from a place adjacent to the İzmit swarm area, as mentioned in the section Seismic Activity Prior to the Mainshock. This would be one important piece of information on the potential risk assessment of large earthquakes that may occur in the future.

Although IZINET missed the recording of the mainshock, it successfully recorded the aftershock sequence from 10 min after the mainshock. Figure 4 shows the aftershock distribution until the end of September 1999. The number of aftershocks for which the hypocenters were determined during this period is about 2200. The aftershocks took place approximately linearly along the NAFZ. This clearly indicates that the 1999 İzmit earthquake was caused by the slip of the NAFZ. Aftershocks occurred in an approximately 170-km-long zone from about 29.2° E to 31° E in longitude. Most of the aftershocks occurred at depths less than 20 km. The lower limit of the focal depths is deeper in the eastern part. Figure 5 shows the space-time plot of the aftershocks projected on the east–west cross section. As shown in Figure 5, there are some portions where the aftershock data are lacking, because of the malfunctioning of the acquisition system. However, we could record the aftershock sequence continuously for the first 36 hr after the mainshock.

Temporal Changes of Aftershock Activity

The distribution of the aftershocks shows a very simple strike-slip faulting in the east–west direction. In detail, how-
Figure 2. Distribution of the microearthquakes observed by IZINET for the period from 1993 to the occurrence of the 1999 İzmit earthquake. The star represents the hypocenter of the 1999 İzmit earthquake obtained from the magnetotelluric data, together with seismic data provided by the Kandilli Observatory (Honkura et al., 2000).

Figure 3. Space–time plot of microearthquakes in the area shown in Figure 2 during the period from 1993 to 1999. Horizontal bars represent periods when IZINET was down for more than 1 month continuously.
Table 2
The Hypocenter of the 1999 İzmit Earthquake Obtained from the Magnetotelluric Data and the Routine Seismic Data at the Kandilli Observatory

<table>
<thead>
<tr>
<th>Origin Time (UTC) (dd/mm/yy)</th>
<th>Latitude (°)</th>
<th>Longitude (°)</th>
<th>Depth (km)</th>
<th>RMS* (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>17/08/99 0 hr 1 min</td>
<td>38.37 ± 0.53 sec</td>
<td>40.745 ± 0.023</td>
<td>29.961 ± 0.029</td>
<td>17.1 ± 3.4</td>
</tr>
</tbody>
</table>

*RMS is the root mean square of the arrival-time residuals.

Figure 4. Hypocenters of the aftershocks obtained by the end of September 1999. The solid line represents the surface trace of fault rupture that appeared in association with the mainshock.

However, we can recognize several significant features in the distribution of the aftershocks. The most marked feature is that the aftershocks tend to occur in clusters. In order to clarify the distribution of the aftershock in more detail, we have shown the epicenter distribution for five periods in Figure 6.

Period I represents the first 12 hr after the mainshock. Aftershocks occurred mainly in four regions during this period, between (a) 29.2° E and 29.5° E, (b) 29.6° E and 29.8° E, (c) 29.9° E and 30.1° E, and (d) 30.2° E and 30.7° E in longitude. Hereafter we will refer to these regions as (a), (b), (c), and (d), respectively. In regions (a) and (b), aftershocks occurred along a very narrow vertical plane. In region (c), however, aftershocks were not distributed along a simple east–west plane, but they rather seemed to align in the northeast–southwest direction. Among these three active areas there lay clear gaps where seismicity was very low. Such a feature suggests strong heterogeneity in the rupture process of the mainshock.

For region (d), we must note that both the resolution and detectability are not sufficient, as there were no observation stations in the eastern part during this period. In fact, temporary observations had not yet started, and the easternmost İZINET station, GÜL (see Fig. 1), was not in a proper state of operation during the periods I and II because of power cut in the earthquake area. Nonetheless, the characteristics of the aftershocks that occurred in region (d) were quite different from those in regions (a)–(c). Aftershocks did not occur along the surface rupture but were scattered widely. Period II corresponds to 1 day reckoned from 12 a.m. of 17 August. The characteristics of the aftershock that occurred were very similar to those of period I.
Figure 5. Space–time plot of the aftershocks of the 1999 Izmit earthquake. Horizontal bars represent periods when IZINET was down for more than 1 day.

Period III consists of 2 days from 20 August. During this period, a swarm activity started in the southwest of region (a). Hereafter we will refer to this swarm area as region (e). Thereafter the number of aftershocks in regions (a) and (b) decreased very quickly. In region (d), the center of activity seems to have migrated to the south and the number of events along the surface rupture trace decreased as in regions (a) and (b). We may therefore claim that aftershocks did not take place along the surface rupture in region (d), but were rather aligned to a preexistent active fault that was broken by the 1967 Mudurnu earthquake (Ambraseys and Zatopek, 1969). It should be noted here that the detectability and the resolution in region (d) increased during this period because the easternmost observation point, GUL, was resumed on 20 August. In this context, the aftershock distribution in region (d) must be considered carefully.

As the temporary observation stations were installed at the beginning of period IV, the accuracy in the determination of the hypocenters of the aftershocks, especially in region (d), became much higher in period IV than in the previous periods. The detectability of the aftershocks, however, changed very little even during this period, as we analyzed only the aftershocks that were detected by IZINET. Therefore, the number of events in region (d) actually increased, compared with other regions. In region (d), the tendency of the aftershocks to concentrate along a linear trend extending in the southeast direction became clearer in period V than in period IV.

From these temporal changes in the aftershock activity, we can conclude that the western end of the rupture caused by the mainshock was at the longitude of about 29.2° E in the Izmit Bay. The remarkable activity that appeared in region (e) is considered as a swarm activity triggered by the mainshock, because the activity started more than 2 days after the commencement of the mainshock. We suggest that the southern portion of region (d) was also activated by the mainshock.

Figure 7 shows a space–time plot of microearthquakes that occurred from the beginning of 1998 in a region including both the northern and southern branches of the NAFZ. This clearly shows that the activity of the microearthquakes along the southern branch also increased after the 1999 Izmit earthquake.

Discussion and Conclusions

The size of the aftershock area within a few days after a large earthquake is generally considered to correspond to the dimension of the rupture zone, and then the aftershock area expands with time (Utsu, 1969; Tajima and Kanamori, 1985). As IZINET was established several years prior to the 1999 Izmit earthquake and had been in operation when it occurred, we could obtain aftershock data within a critical period of a few days after the mainshock. The aftershock distribution is the information essential to estimate the western end of the rupture zone, because we cannot, at present, confirm the surface rupture under the sea. From the aftershock distribution obtained in our study, we concluded that the western end of the rupture is at the longitude of about 29.2° E. On the other hand, the eastern end of the rupture would be at about 31.0° E, as inferred from both of the aftershock distribution and the surface rupture that appeared in association with the mainshock. Therefore, the total length of the rupture zone of the 1999 Izmit earthquake would be about 150 km.

This estimate of the rupture length is quite different from the solutions of waveform inversion as discussed by Yagi and Kikuchi (2000). The point up to which the rupture
of the main shock extended is an important issue for estimating the risk of future disastrous earthquakes. From the physical point of view, for the estimation of the rupture area, the result of the waveform inversion would be more reliable than the aftershock distribution because we do not know exactly what the aftershock occurrences represent. However, such a claim holds good only when we have sufficient knowledge about the detailed underground structure, but in reality, there is some ambiguity about the underground structure. For example, several fault models were proposed from various points of view, based on a variety of data sets, and the results are somewhat different from each other (for instance, Toksöz et al., 1999; Yagi and Kikuchi, 2000; Sekiguchi and Iwata, 2002). In this sense, the distribution of the aftershocks is still an important piece of information, because the aftershock distribution is based only on the velocity structure. Moreover, the velocity structure has little affect on the result of our present study.

Aftershocks were distributed sharply along a narrow vertical zone in regions (a) and (b), as shown in Figure 6. They occurred immediately after the mainshock and decayed rapidly, which may indicate a small amount of energy re-
lease in these segments during the mainshock. We can see from Figures 4 and 6 that the active and the inactive parts are in clear contrast to each other. Such a contrast indicates that the source region is separated into several segments. Furthermore, aftershocks have tended to occur not in the east–west direction as expected, but with a linear trend in the northeast–southwest direction near the hypocenter of the mainshock. These features of aftershock occurrences imply a complex rupture process of the mainshock; it is quite possible that the slip in regions (a) and (b) along the segment in the İzmit Bay was rather smooth without strong asperities, so that no strong seismic waves were radiated from there.

In the eastern part of the source region, most of the aftershocks did not occur along the surface rupture. As shown in Figure 6, the center of activity in region (d) moved southwards 1 day after the mainshock, which suggests that the occurrence of the mainshock increased the stress along the fault of the 1967 Mudurnu earthquake, especially at the deeper portion of the fault. A similar mechanism might have been operative in the western part of the source region. In fact, an earthquake with a magnitude of $M_{6.3}$ occurred near region (a) in 1963 (Toksoz et al., 1979), and hence the swarm activity in region (e) might be related to this past event.

It is very important to note that the 1999 İzmit earthquake initiated the rupture in the area adjacent to the active swarm area. Generally speaking, there is no clear relation between the swarm activity of the microearthquakes and the occurrence of a large earthquake. Although Michael and Toksoz (1982) showed statistically that many swarm activities in western Turkey are an aftermath of large earthquakes, the distances between the swarms and the corresponding earthquakes were very large in most cases. The 1999 İzmit earthquake is the first large earthquake in the western part of the NAFZ since a modern seismic observation network has become available. This earthquake demonstrated the possibility that the swarm activity of microearthquakes might be related to the occurrence of a large earthquake in the NAFZ. Although we cannot derive any definitive conclusions and we need more examples, we should pay more attention to the swarm activities along the NAFZ.

On 12 November, another large event with $M_w 7.1$ occurred near Düzce. Milkereit et al. (1999) showed that the source region of this November event is adjacent to that of the İzmit earthquake. Therefore, we should pay more attention to the west of the source region of the İzmit earthquake that could perhaps be the region where the next large earthquakes may occur, because the İzmit earthquake is likely to have increased the stress accumulation in the western area (Parsons et al., 2000). At the same time, we should also take care of the southern branch of the NAFZ, the Iznik–Mektece Fault, because we do not know to what extent the stress accumulation in the seismic gap area suggested by Toksoz et al. (1979) was released by the İzmit earthquake. In fact, the activity of the microearthquakes along the southern branch increased remarkably after the İzmit earthquake as shown in Figure 7, in spite of the decrease in the Coulomb failure stress (Parsons et al., 2000). In any case, we should intensify seismic observations as soon as possible for monitoring the microearthquake activity possibly related to earthquakes that may perhaps occur in the future in northwestern Turkey.
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