The devastating earthquake in Kobe

Tamao Sato

A devastating earthquake rocked the Japanese city of Kobe on 17 January 1995. The present paper describes the damage caused by this earthquake, and the tectonics of the region in and around the epicentral area. Comparisons are also made with the 1993 Latur earthquake, which was also an intra-continental event.

A disastrous earthquake (M 7.2) with its epicentre near Kobe struck the Hansin metropolitan area in the Hyogo Prefecture (district) of western Japan (Figure 1) on 17 January 1995 at 05:46 a.m. This earthquake devastated an elegant harbour city in one terrible convulsion, and wreaked havoc over a large area including Kobe, nearly 30 km away, and other neighbouring cities. It killed about 5400 people, injured 27,000 and left more than 300,000 destitute. This earthquake was the most disastrous to hit Japan since the Great Kanto earthquake of 1923. Strong ground shaking caused by this earthquake was observed to last for about 10 s, which destroyed about 110,000 buildings and sections of freeways (Figure 2), twisted railway lines (Figure 3), disrupted water supply systems, ruptured gas pipelines, and ignited more than two hundred fires that raged on for days, consuming an area of 1 km^2. Preliminary estimates of property damage are about ten thousand billion yens (about Rs 3000 billion), nearly triple that inflicted by the 1994 Los Angeles earthquake. The seismic intensity VII assigned to the severely damaged area on the JMA scale (Japan Meteorological Agency 0–VII intensity scale) is the highest so far to have been experienced since the introduction of this intensity scale in Japan in 1949.

The devastating earthquake measured 7.2 on the JMA magnitude scale, the US Geological Survey (USGS) estimate being $m_b = 6.0$ and $M_s = 6.8$. The seismic moment of this event determined by the Harvard group is 2.5×10^{26} dyne cm ($M_w = 6.9$), and that determined by USGS 1.8×10^{26} dyne cm ($M_w = 6.8$). The JMA epicentre was located in the Akashi strait that runs between Kobe and the Awaji-shima island (Figure 4). The focal depth was estimated to be about 14 km. Aftershocks were distributed from Awaji-shima to Kobe, along a zone running for about 40 km along northeast–southwest (NE–SW) (Figure 5). The focal depths of aftershocks were less than 15 km and aligned almost vertically. The focal mechanism solutions determined by the Harvard group and USGS are almost similar, indicating a strike-slip faulting with maximum compression in the east–west direction. Thus, it is inferred that the earthquake was caused by right-lateral faulting on a nearly vertical plane striking along the NE–SW direction. The coseismic crustal movement measured by global positioning system (GPS) receivers is consistent with right-lateral motion on the NE–SW-trending fault (Figure 6). If the aftershock area is taken to be 40×15 km^2, the average slip on the fault is estimated to lie between 2 and 3 m. Since the epicentre is located near the centre of the aftershock zone, it seems likely that the rupture nucleated near the centre and propagated towards northeast and southwest bilaterally. The result of inversion of the teleseismic body waves suggests that the earthquake

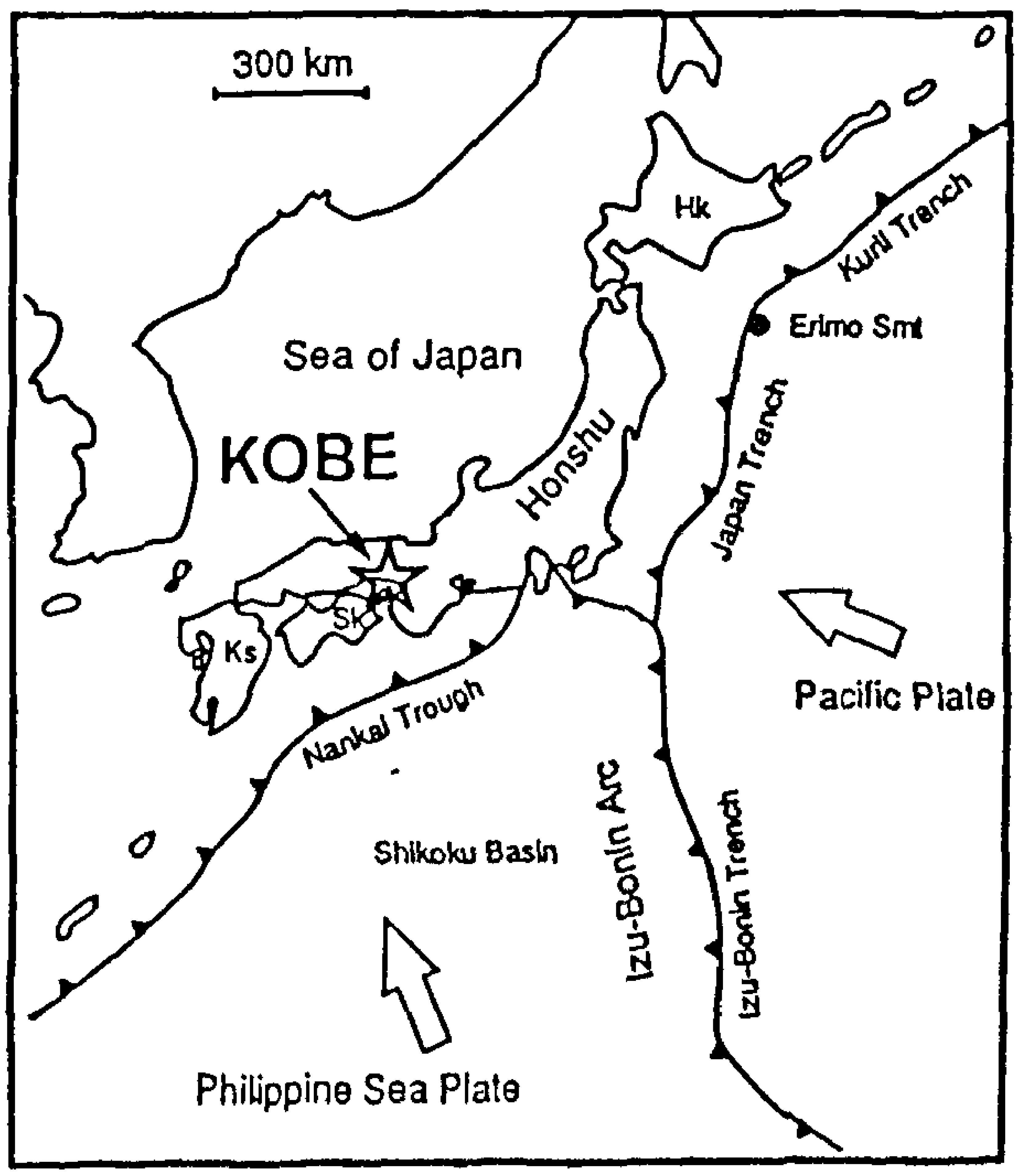

Figure 1. Present framework of the arc-trench system around the Japanese islands. Abbreviations: Hk, Hokkaido; Sk, Shikoku; Ks, Kyushu

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Figure 2. Failure of freeway (courtesy of the *Asahi Shinbun* newspaper)

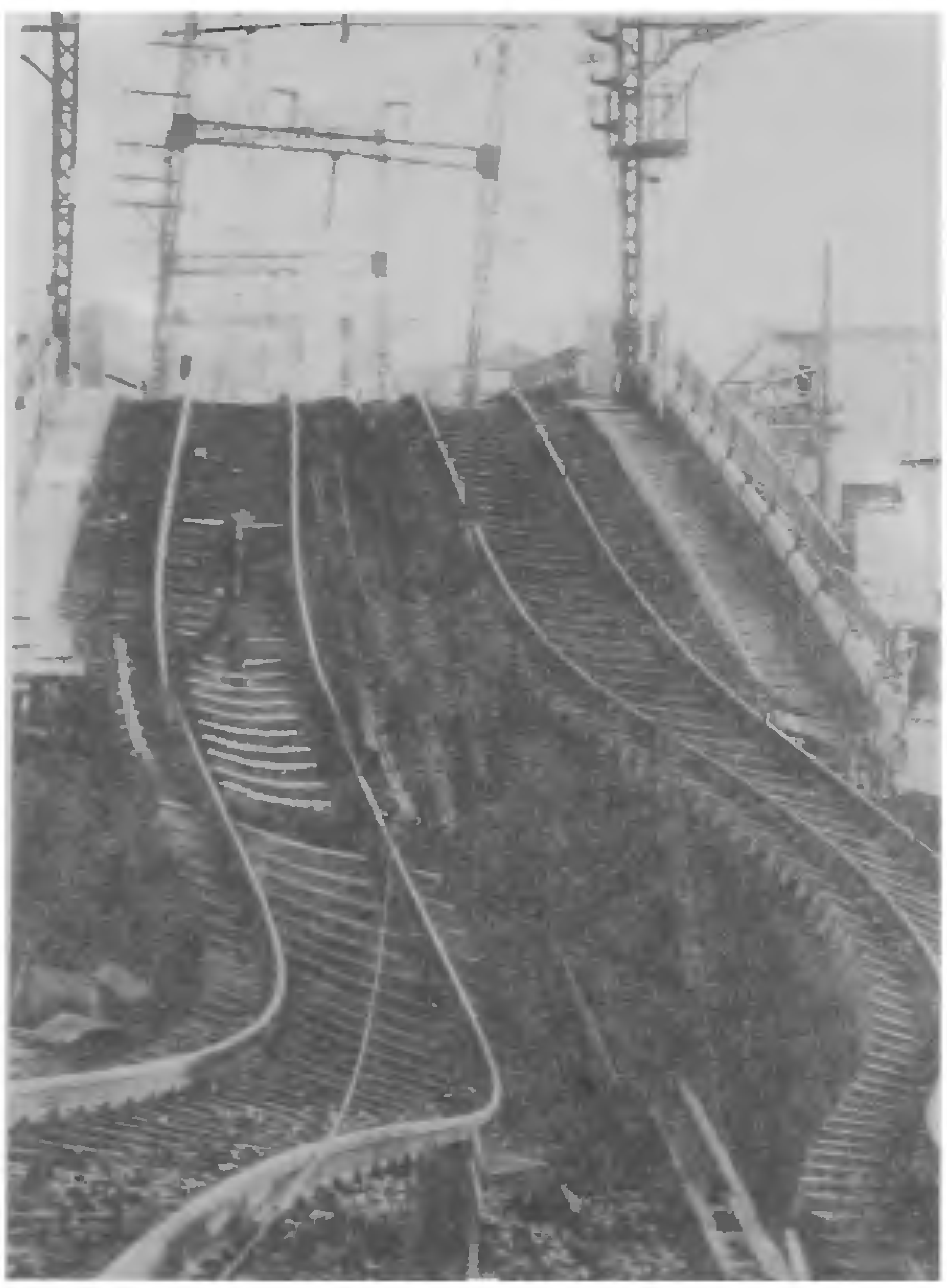

Figure 3. Damage of railway track (courtesy of the *Asahi Shinbun* newspaper).

consisted of three major subevents[1] and the entire rupture took 11 s to complete.

Primary surface rupture

After the earthquake, clear surface ruptures were observed in the Awaji-shima island[2]. These were traced along the Nojima fault and the Asano fault (Figure 4), which show evidence of repeated movements in recent geological times[3]. The ruptures show right-lateral offsets of about 1–2 m, the vertical offsets being about one-fourth of the horizontal offsets. From the amount of offset, these ruptures appear to be primary surface ruptures that released a substantial amount of seismic energy during the Kobe earthquake. For, although abundant ground cracks and fissures were found in Kobe, these are considered to be secondary features of the ground deformation created by strong ground shaking. Immediately after the main shock, many temporary seismographs were deployed in and around the epicentral area for precise determination of aftershocks' hypocentres. Most of these aftershocks determined from the dense seismograph network are concentrated on pre-existing active faults to the north of Kobe (Figure 7), indicating that the main rupture propagated along the active faults in Kobe.

A levelling survey in the epicentral area revealed an abrupt change in the vertical displacement across the Suma fault in Kobe[4], strongly suggesting that the Kobe earthquake ruptured the Suma fault. The Suma fault does not extend from the Nojima fault, as shown in Figure 4. The two faults are offset near the Akashi strait where the rupture initiated. It seems likely that the rupture shifted from one fault to the other at an early stage of the earthquake. The western part uplifted relative to the eastern part across the Suma fault[4] and the eastern side moved upward relative to the western side across the Nojima fault in the Awaji-shima island[2]. The sense of relative displacement is opposite to each other. In each case, however, the sense of relative vertical movement is consistent with the topographic highs and lows across the fault. The topographic feature in the epicentral area thus appears to be formed by repeated occurrences of similar earthquakes in the past.

Narrow belt of severe damage

The maximum accelerations and velocities observed in Kobe and surrounding areas are shown in Figure 8. In Kobe, the observed maximum accelerations range from 0.5 to 1.0g, more than double the acceleration recorded in Tokyo during the great Kanto earthquake of 1923. The maximum velocities are nearly 50 cm/s. Figure 9 shows the accelerogram recorded at a site very close to the ruptured fault. A maximum acceleration of 0.8g was recorded on the north–south component. It is seen that the duration of large accelerations ($\geq 0.3g$) is short, being only about 5 s for the horizontal components.

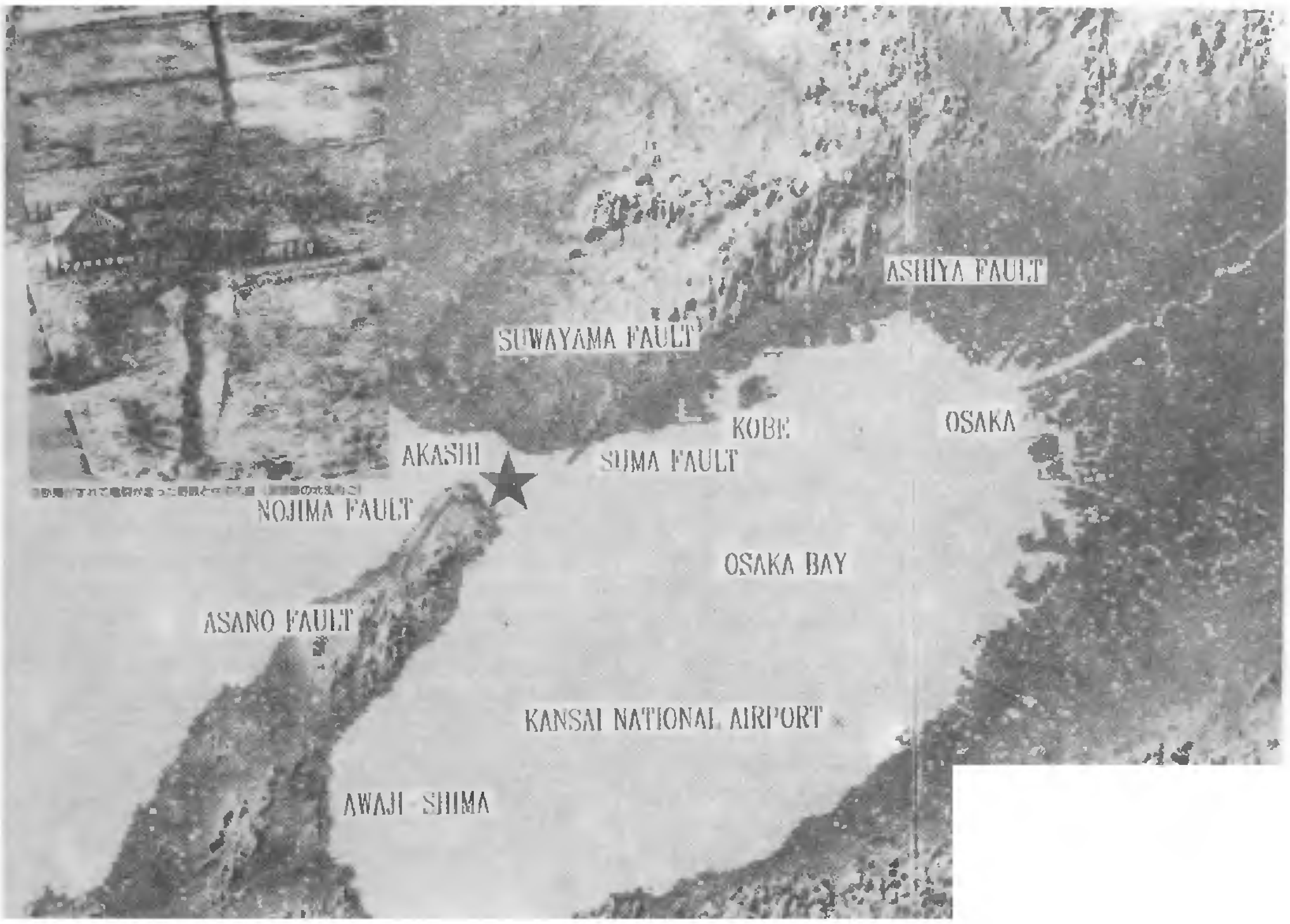

Figure 4. Map of the epicentral area The star indicates the epicentre of the Kobe earthquake (officially, first named as the 1995 Hyogo-ken Nanbu earthquake, and later renamed as the 1995 Hanshin Awaji-shima earthquake) that occurred at 05 46 a m on 17 January 1995 The lines denote the active faults that ruptured this time. The inset picture shows a primary surface rupture cutting through the field and the garden in front of the houses, found in the Awaji-shima island (Photo courtesy of the *Mainichi Shinbun* newspaper)

In Japan, the earthquake resistance standard was revised in 1981. Most of the buildings constructed according to the latest building code were apparently unscathed. According to a survey carried out by a construction company, for evaluating the safety of office and apartment buildings that suffered serious damage (pillars, foundations, etc.), 36% of the pre-1981 buildings were found to be severely damaged, but only 6% of those built after 1981. Strong vertical motion during the earthquake was also felt by many people in the damaged area. However, the seismograms did not indicate that the vertical motion was any greater than the horizontal motion[5]. On an average, the amplitude of vertical motion was found to be about half that of the horizontal motion, which is consistent with the result of near-field observations made in California. Still, some architects hold the view that serious damage to buildings and roadways was caused by an exceptionally large vertical motion.

The areas of highest damage in Kobe and nearby cities accounting for most building collapses were found to form a 25 km long narrow (1–2 km wide) belt[6] (Figure 7). This narrow belt lies to the south of the active faults that are thought to have ruptured during the main shock. At first, it was suspected that another primary rupture was buried just beneath the damaged belt, but this was soon discounted as few aftershocks were located beneath the belt (Figure 7). Ground cracks and fissures in the damaged belt are thus interpreted as being the result of secondary deformations of the ground. Later, as the results of detailed site investigations came, it became clear that the damaged belt was underlain by an unconsolidated soil deposit which had strongly amplified the ground motion. Further studies of aftershocks records revealed that ground motion within the damaged belt was ten times greater than that observed outside the region[7]. These observations support the idea that the narrow belt of high damage was primarily the result of site amplification. The southern boundary of the damaged belt also appears to mark the boundary of reclaimed lands. The latter apparently absorbed the seismic wave energy in the frequency range most sensitive to the structural responses of the buildings. Lique-

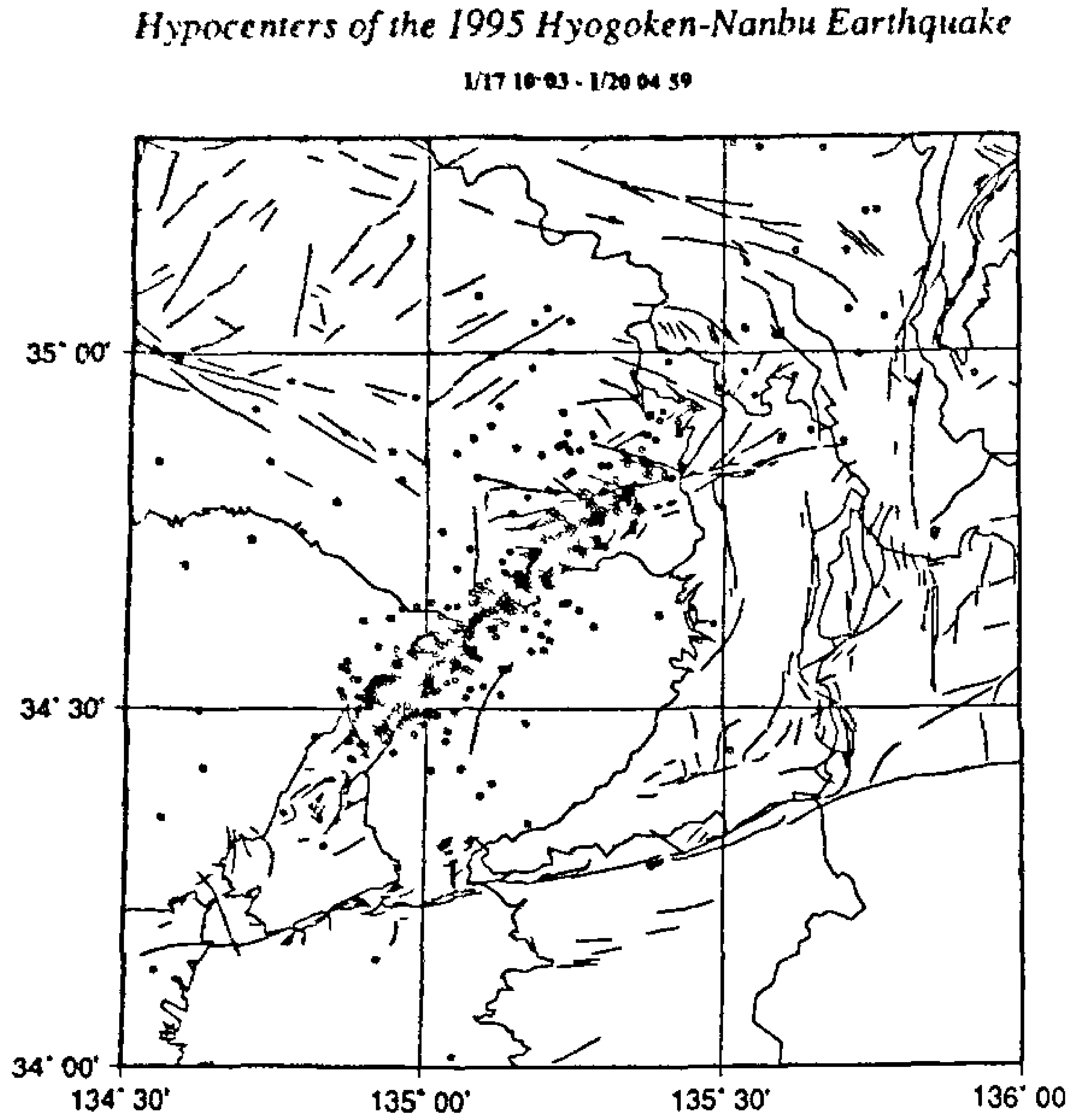

Figure 5. Aftershocks in the time period from 10 a m January 17 to 5 p m January 20, 1995 These hypocentres are determined by the automatic hypocentre location system at the Abuyama Observatory, Disaster Prevention Research Institute, Kyoto University, based on the seismic networks of Disaster Prevention Research Institute Kyoto University, Wakayama Observatory, Earthquake Research Institute, University of Tokyo and School of Science, Nagoya University The lines denote active faults in this area Anonymous FTP on ftp eri u-tokyo ac jp

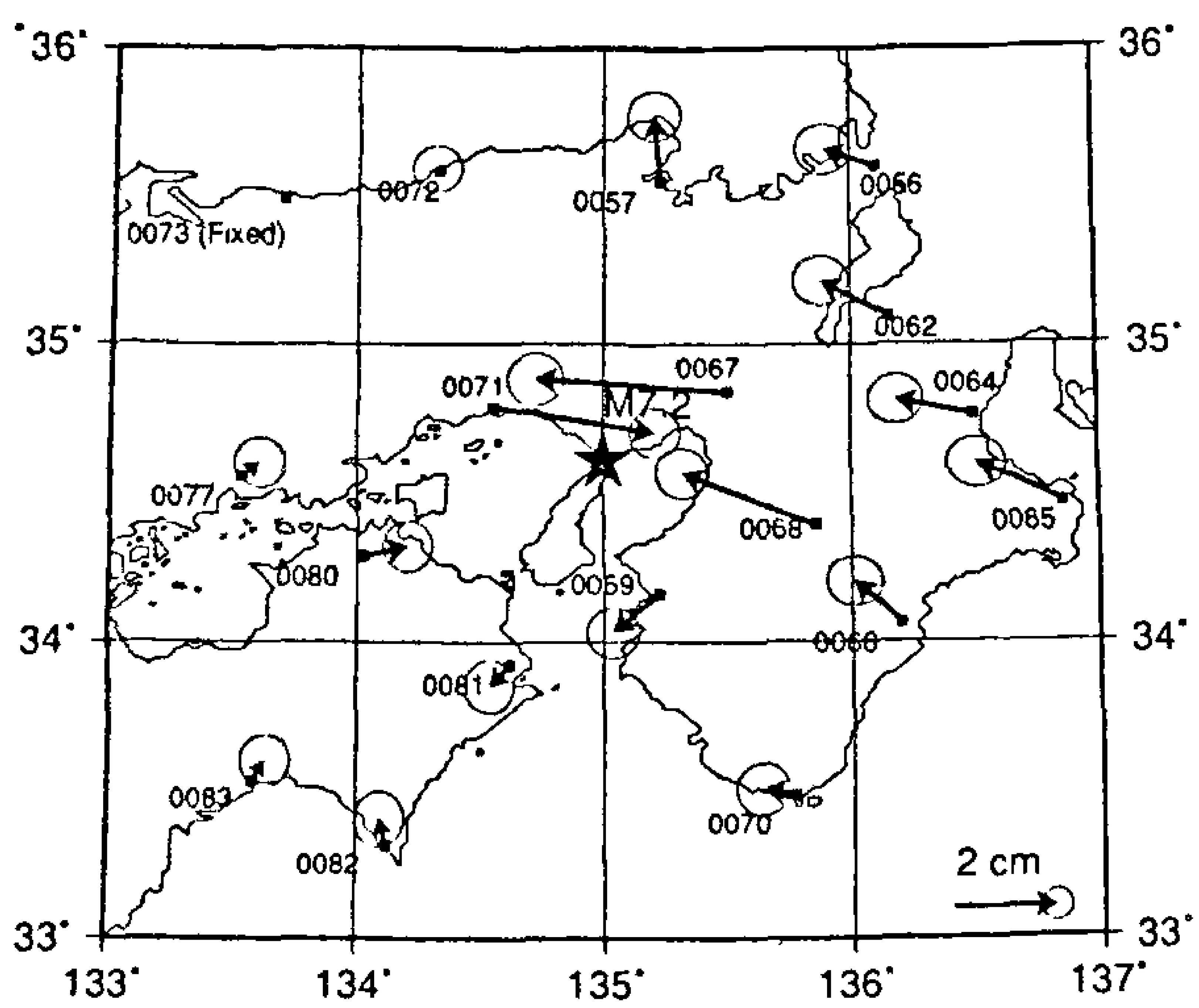

Figure 6. A preliminary result on GPS site displacements associated with the 1995 Kobe earthquake Arrows indicate horizontal displacement vectors calculated from 24-hour data on 14 and 17 January 1995. The error ellipses represent 99% confidence regions The star denotes the epicentre By courtesy of Tsuji, H and Hatanaka, Y., the Geographical Survey Institute, Japan Anonymous FTP on terras gsi-mc go jp

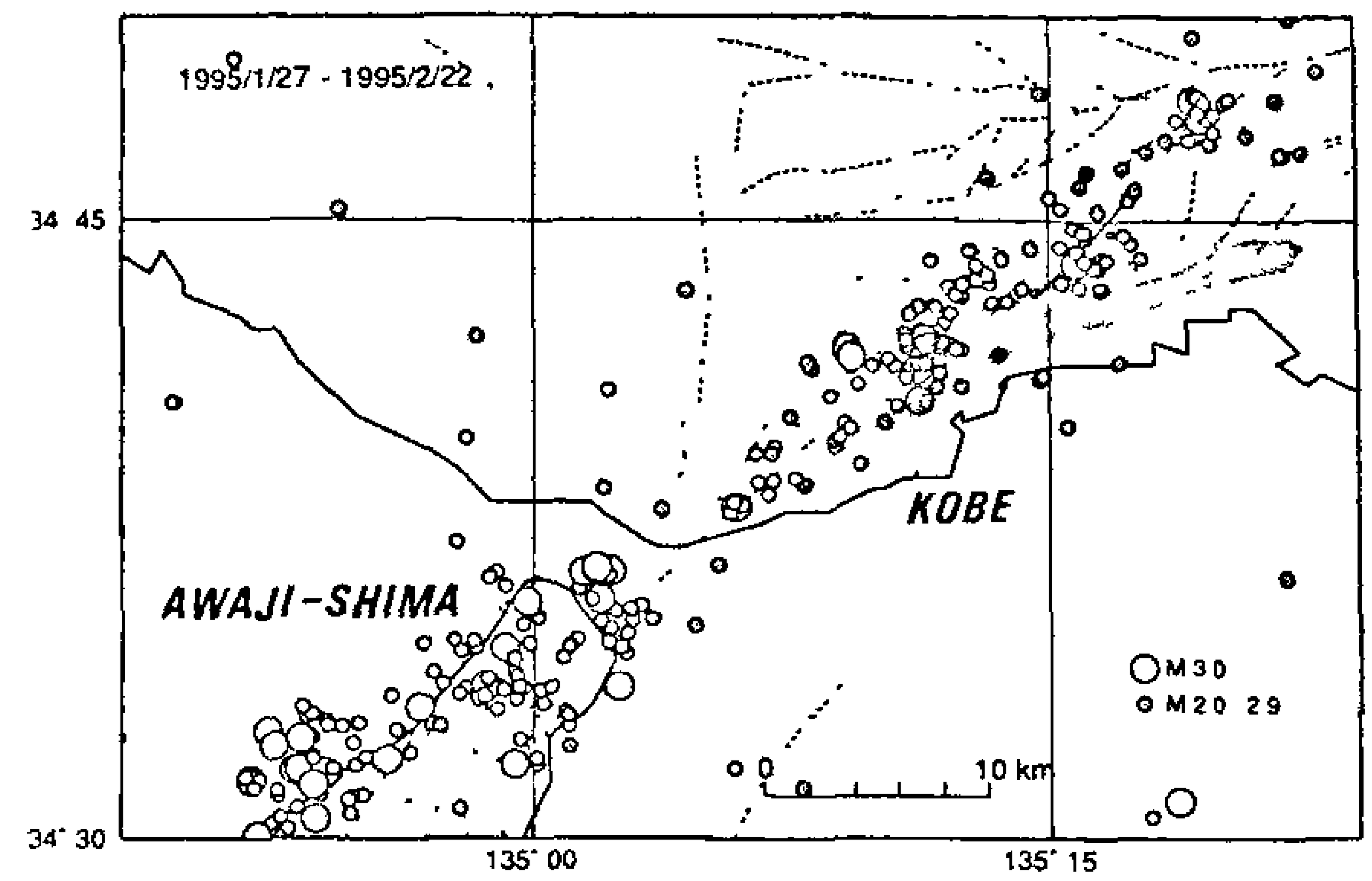

Figure 7. Aftershocks determined by the Japanese University Group of Urgent Observation for the 1995 Hyogo-ken Nanbu earthquake The dotted lines indicate the active faults in this area The hatched zone indicates the belt of severe damage (courtesy of T. Yoshii, Earthquake Research Institute, University of Tokyo Anonymous FTP on ftp eri u-tokyo ac jp)

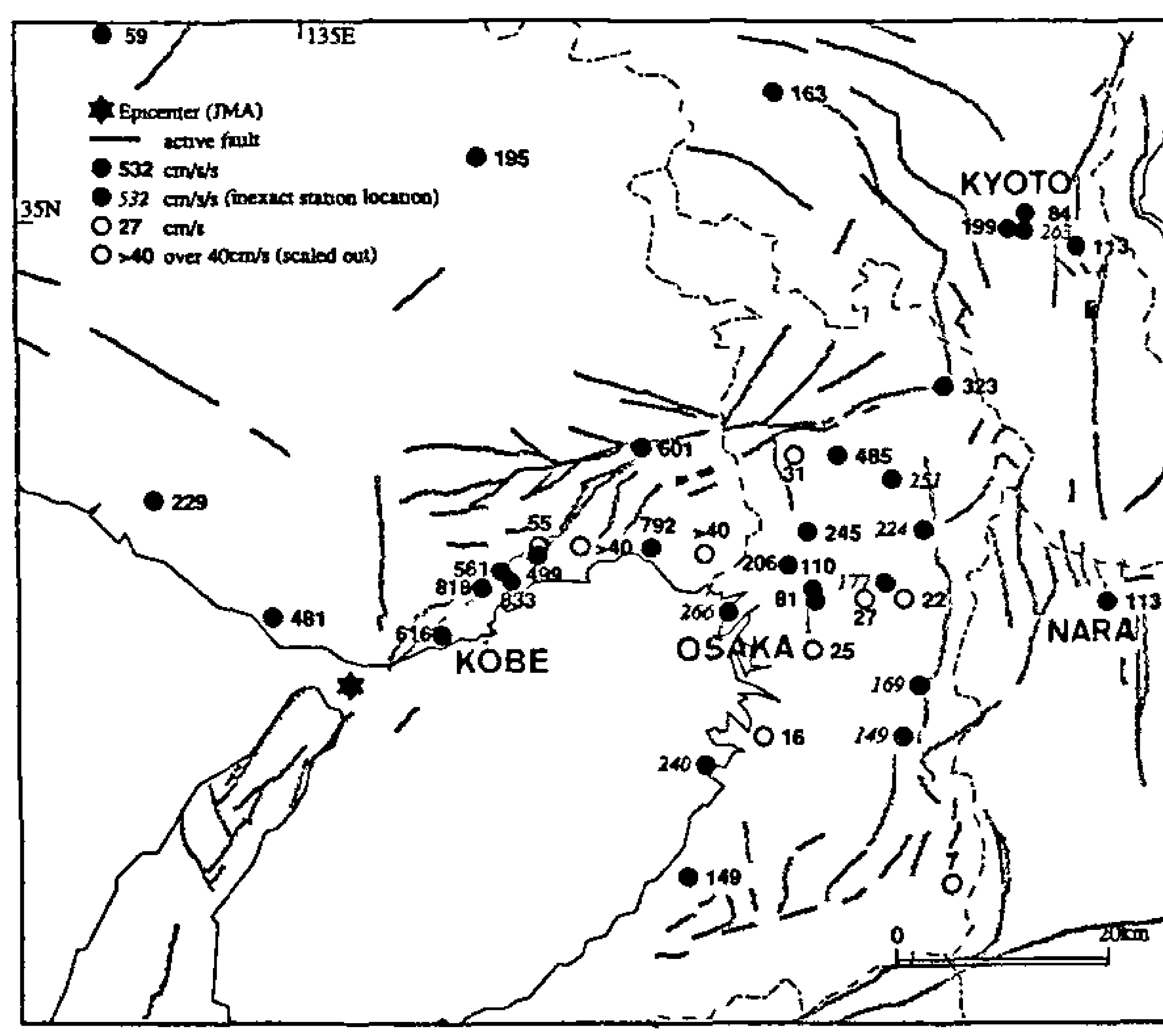

Figure 8. Maximum accelerations and velocities observed in and around the epicentral area of the Kobe earthquake The lines denote active faults and the star indicates the epicentre The solid circle accompanied by the numeral 818 indicates the site of the Kobe Marine Observatory of the Japan Meteorological Agency (courtesy of K. Koketsu, Earthquake Research Institute, University of Tokyo Anonymous FTP on ftp eri u-tokyo ac jp).

faction too was observed to have occurred over a vast area covering the reclaimed land along the shore, causing severe damage to the bank and port facilities.

Active faults

The Kobe region has been outside the danger zone of earthquakes. The historical earthquake catalogue

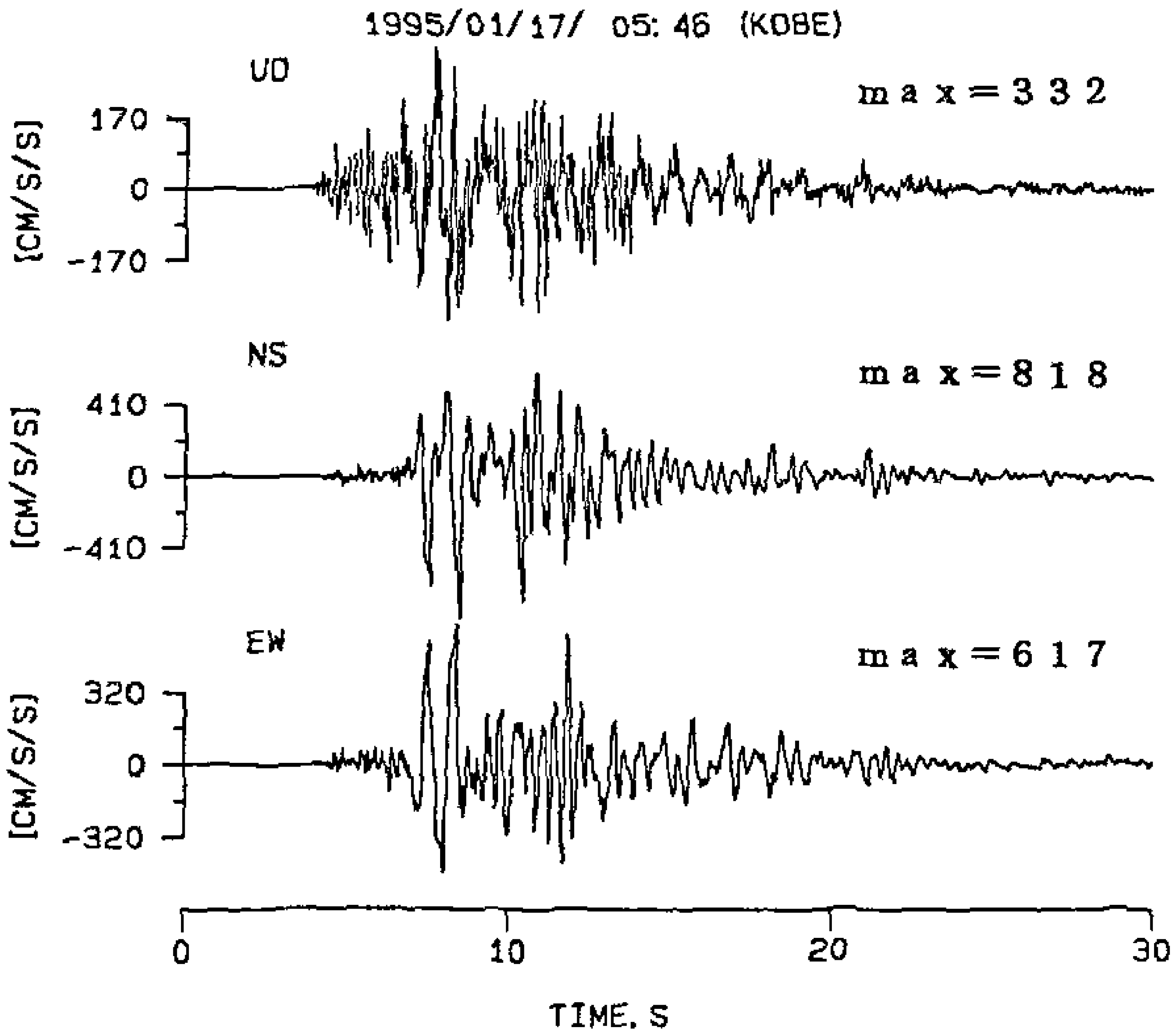

Figure 9. The ground acceleration recorded at the Kobe Marine Observatory of the Japan Meteorological Agency. The observatory is located very close to the rupture that caused the Kobe earthquake

contains many damaging earthquakes near Kyoto and Osaka, but reports only one event[8] (M 6.1) near Kobe, that killed one person in 1916. Seismic activity over a much longer period can, however, be estimated from the geologic record. The density of active faults in and around Kobe is probably among the highest in the circum-Pacific region, with many active faults showing evidence of prehistoric earthquakes[3]. The degree of fault activity is estimated in terms of the long-term slip rate during the late Quaternary (0.2 Ma to present). For example, the long-term slip rate[9] of the Nojima fault in the Awaji-shima island is rated as being 0.1–1.0 m/1000 yr, and nearby faults have most likely similar long-term slip rates. If the fault is assumed to slip 2 m at a time, then the recurrence interval is estimated to be 2000–20,000 years. It is no wonder, therefore, that very few historical earthquakes are known to be associated with the active faults near Kobe. About 80% of the inland damaging earthquakes in the last 130 years in Japan have occurred along active faults[10] or very close to them. However, even if we believe that active faults are the only potential sources of inland earthquakes, it is still very difficult to specify the location of a future inland earthquake. Indeed, historical record of repeated damaging earthquakes on the same fault is extremely rare, as most of the active faults in Japan have apparently recurrence intervals[11] of greater than 1000 years. The only exception is the Tanna fault, on which destructive earthquakes occurred in 841 and 1930. The former, reported in an old document from Izu Province, was actually verified by means of fault trenching. More than 40 excavations of active faults have been conducted in Japan since the late 1970s in order to extend the historical record backwards in time and thereby obtain reliable recurrence intervals of faulting during the late Quaternary as well as the time elapsed since the last event. But there are about 40 times more active faults whose past activities still remain to be unravelled. Under such circumstances, the seismic gap theory cannot be advantageously used to predict the site of a future earthquake. The unexpected occurrence of the Kobe earthquake demonstrated this basic difficulty of predicting inland earthquakes in the interior of Japan.

Premonitory phenomena

In the last two years (1993–1994), four large earthquakes have occurred in northern Japan of magnitudes 7.5–8.1. The epicentre of one of these lay in the Japan Sea, while the other three events occurred in the Pacific Ocean. The damage caused by these was not so severe as compared to that caused by the Kobe earthquake, as the epicentres of these earthquakes were far from populated areas. The Kobe earthquake occurred about three weeks after the latest of these events in northern Japan. Most seismologists do not believe any relation to exist between the recent seismic activity in northern Japan and the Kobe earthquake, simply because the northern and western parts of Japan lie in different seismotectonic settings.

The historic record indicates that 50 years before the occurrence of a great interplate earthquake in the Nankai trough, where the Phillippine Sea plate subducts beneath the Eurasian plate[12], the seismic activity in western Japan increases. The large interplate earthquakes tend to occur periodically at a time interval of 80–120 years. Nearly 50 years of quiescence have passed since the occurrence of a large event (the M 8.0 Nankai earthquake of 1946) in the Nankai trough and some seismologists expected that the seismic activity in western Japan may now increase from the quiet stage to an active one. In this light, western Japan was long overdue for a major earthquake.

Some hours before the Kobe earthquake, several small earthquakes occurred near the epicentre, which could be regarded as foreshocks. But there are good reasons why seismologists could not tell that these events represented the forerunner of an impending disaster. For, they well know that this level of high activity can happen anywhere at anytime and a method to discriminate the premonitory activity from the normal activity has yet to be established. An approach based solely on the level of seismic activity is thus not likely to be of much help. It was also reported that a peculiar migration pattern of seismic activity appeared on a regional scale before the Kobe earthquake, the zone of high seismic activity moving from north to south towards the epicentre of the main event. However, this observation too could not be confidently treated as a warning signal. We still need to develop more reliable diagnostics to assess the probability of a large earthquake in the future.

The experience gained in the wake of the recent Kobe earthquake has, however, given some insight to pursue a few alternative approaches to predicting a large earthquake. The Geographical Survey Institute (GSI), from the studies of crustal deformation prior to the Kobe earthquake, based on triangulation survey data (1975–1985), showed that during 1975–1985 some parts of the epicentral area suffered a north–south extensional deformation of 2×10^{-6}, in contrast to a contractional deformation in the surrounding area. This complex pattern of crustal deformation may have been associated with a change in the seismogenic environment at depth. In this respect, continuous monitoring of crustal deformation using GPS receivers could most likely prove quite illuminating. From 1994, the GSI started a programme of continuous measurement of crustal movements deploying more than 200 GPS stations all over Japan. In the southern Kanto and Tokai districts, these measurements are being closely monitored to predict the next seismic gap earthquake; in these areas GPS stations have been distributed at intervals of 15 km, to form a dense enough network of GPS stations that could possibly detect anomalous crustal movements preparatory to a major earthquake.

The Latur event

The disaster of Kobe reminds us of the Latur (Khillari) earthquake that occurred in the Maharashtra state of India on 30 September 1993. It killed about 10,000 people in Khillari and nearby villages. Almost all deaths were caused indoors as people were trapped under collapsed roofs of houses made from stones loosely bonded with mud. People had no time to get out of these houses before they collapsed. Deaths caused by the Kobe earthquake were almost in a similar situation. More than 80% were buried under the collapsed houses. The strong motion seismographs operating near the damaged areas near Kobe show details of the ground motion that destroyed many houses. The strong ground acceleration exceeding $0.3g$ started within a few seconds of the initial tremor, and lasted for only about 5 s (Figure 9). Accounts from Khillari show a similar time history of the ground motion: the onset was sudden and the strong vibration was very impulsive. For an observer immediately above the rupture surface the strong ground motion arrives without any early warning by weaker vibration, giving little time to take shelter under a safe space, to put off fires, or to get out of collapsing buildings. The estimated fault length of the Latur earthquake (about 10 km) is about one-fourth of the fault length of the Kobe earthquake; the duration of the strong motion may have been even shorter than that of the Kobe earthquake. It is difficult to say whether the maximum acceleration in Khillari was smaller than that in Kobe. The maximum acceleration near the rupture, however, depends on the dynamic stress and the rupture kinematics of the fault segment close to the observer, being insensitive to the entire fault dimension. These inferences cannot be proved because no strong motion seismograph was operating around Khillari when the earthquake struck.

The seismic intensity in the area most affected by the Latur earthquake is reported to be VIII–IX on the Modified Mercalli (MM) scale. The seismic intensity assigned for the area of severe damage in Kobe was VII on the JMA intensity scale. Based on the maximum accelerations observed in the damaged area (0.5–1g), the JMA intensity VII corresponds to an intensity X on the MM scale. Thus, the ground motion in Khillari seems to have been weaker than in Kobe[13]. Although the death toll of 5400 in Kobe was considered to be high, the percentage of fatalities suffered was much less than in Khillari, where about one in four people were killed. This may be ascribed to the difference in the percentage of the collapsed houses in the epicentral area. In Khillari and nearby villages, almost all houses were destroyed. In Kobe, many houses and buildings were still standing besides the collapsed ones, which were old, wooden houses of pre-1981 vintage. In order to construct earthquake-resistant buildings, a thorough investigation of the damage is now being made by many engineers.

According to the USGS, the magnitude of the Latur earthquake was 6.3 on both M_s and m_b scales, and 6.1 on the seismic moment magnitude (M_w) scale. The corresponding magnitudes of the Kobe earthquake are $M_s = 6.8$, $m_b = 6.0$ and $M_w = 6.8$. The m_b versus M_w plot of the Latur event is contrasted with that of the Kobe earthquake. The Latur event has a higher m_b value than that of the Kobe earthquake, while its M_w is much smaller in comparison. The value of m_b is proportional to the amplitudes at higher frequencies whereas that of M_w is proportional to the amplitudes at lower frequencies. It is inferred, therefore, that the Latur event generated higher-frequency waves more efficiently than the Kobe earthquake did. This could be caused by the Latur event yielding a higher stress drop than the Kobe earthquake. Since no evidence of pre-existing fault is found in the exposed rock near the epicentre, the Latur event may have ruptured previously unfractured rock as far down as the brittle ductile boundary[14], thus yielding a higher stress drop. It would indeed be instructive to estimate the stress drop of the Latur event as it may indicate the state of stress in the southwestern Indian shield.

If large earthquakes in the Indian shield area are generated by many and ubiquitous faults that show no significant slip nor any evidence of regularly repeating ruptures, their prediction may be even more difficult than that of Japan's inland earthquakes. In India, at least one-third of the damaging earthquakes in the 1980s seem to have been triggered by artificially created lakes. Systematic measurement programmes to monitor various geophysical signals near water reservoirs may help in identifying precursors of damaging earthquakes.

It is possible to study various precursory phenomena in order to predict an earthquake. However, an accurate earthquake prediction still seems to be a complicated task unless we have a good understanding of all the physical processes involved. The most valuable lesson learnt in the aftermath of the Kobe earthquake is that Japan is not so earthquake-resistant as had been believed. The numerous public facilities in the Kobe region, such as office buildings, freeways, railways and so on, were severely damaged. If the death toll had not been so high, we may not have regarded this earthquake as being so devastating, but destruction of many residential houses caused a large number of fatalities. In order to mitigate the loss of lives and property in the next large earthquake, as yet an unpredictable natural phenomenon, it is therefore imperative that we design and construct buildings with all the knowledge and insight so far gained from worldwide experience so that they can withstand the strong ground motion expected to occur in a region.

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ACKNOWLEDGMENTS In writing this article, I have greatly benefited from an Internet forum, hyogo@eri u-tokyo ac jp, which was opened soon after the occurrence of the Kobe earthquake We are thankful to the administrative staff of the forum and many researchers who have contributed valuable information on the Kobe earthquake through the Internet forum Finally, we are grateful to Ramesh P Singh for his comments and suggestions which have helped improve an earlier version of the manuscript

Kobe earthquake: An urban disaster

Paul Somerville

The 17 January 1995 Hyogo-ken Nanbu earthquake was the most damaging to strike Japan since the great Kanto earthquake destroyed large areas of Tokyo and Yokohama and killed 143,000 people in 1923. As of 30 January, the toll from the earthquake in Kobe and adjacent cities had reached 5096 dead, 13 missing, and 26,797 injured. One-fifth of the city's 1.5 million population was left homeless and more than 103,521 buildings were destroyed. The Hyogo Prefectural Government estimated the cost of restoring basic functions to be about $100 billion; the total losses, including losses of privately owned property and reduction in business activity, may be twice this amount, which would be 10 times higher than losses resulting from the 1994 Northridge, California, earthquake.

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Earthquake mechanism

The hypocentre of the earthquake was located about 20 km southwest of downtown Kobe between the northeast tip of Awaji Island and the mainland (Figure 1). The earthquake was assigned a Japan Meteorological Agency (JMA) magnitude of 7.2. Seismological analyses indicate a strike-slip mechanism with a seismic moment of about 3×10^{26} dyne cm, corresponding to a moment magnitude of 6.9 (ref. 1). Teleseismic waveform