PRELIMINARY PALEOEARTHQUAKE INVESTIGATIONS OF ACTIVE FAULTS ON AWAJI ISLAND, JAPAN, IN RELATION TO THE 1995 GREAT HANSHIN (KOBE) EARTHQUAKE

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ABSTRACT

Approximately one year after the Great Hanshin (Kobe) Earthquake, two New Zealand geologists were invited to help with the Geological Survey of Japan's paleoearthquake/active fault studies in the Kobe/Awaji area. Trenches excavated across the Nojima fault, which ruptured during the Great Hanshin Earthquake, showed evidence of past surface rupture earthquakes, with the age of the penultimate earthquake estimated at approximately 2000 years. A trench across the Higashiura fault, located 3-4 km southeast of the Nojima fault, revealed at least two past surface rupture earthquakes. The timing of the older earthquakes is not yet known, but pottery fragments found in the trench constrain the timing of the most recent earthquake at less than 500-600 years. Historical records for this part of Japan suggest that within the last 700 years there has been only one regionally felt earthquake prior to the 1995 Great Hanshin Earthquake, and this was the AD 1596 Keicho Earthquake. It thus seems reasonable to suggest that the Higashiura fault was, at least in part, the source of the AD 1596 Keicho Earthquake.

INTRODUCTION

On 17 January 1995, the Great Hanshin Earthquake (Mw 6.9) struck near Kobe, Japan (Figure 1). This was a major strike-slip earthquake that impacted a modern city, and tragically it claimed the lives of over 5,500 people and left about 300,000 people homeless. From a New Zealand perspective, the consequences of this earthquake, and the lessons that can be learned regarding disaster response, lifelines, and earthquake engineering in general have been covered in several papers published by the New Zealand National Society for Earthquake Engineering [e.g. Billings 1995, Park et al. 1995, Brunsdon et al. 1996].

In direct response to the Great Hanshin Earthquake, the Japanese government made available significant sums of money for the study and research of seismic hazards in this part of Japan. One of the research projects initiated by the Geological Survey of Japan was a paleoearthquake investigation of the active faults on Awaji Island, including the Nojima fault which ruptured in the Great Hanshin Earthquake. In early December, 1995, the first two authors were invited to participate in these studies. While in Japan, John and I were hosted by the Geological Survey of Japan, and assisted with Awata-san's research into the paleoearthquake history of the Nojima and Higashiura faults. This paper reports on some preliminary findings related to trenching studies on the Nojima and Higashiura faults, and touches on some additional earth science-related aspects of the Great Hanshin Earthquake that are relevant to New Zealand.

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GEOLOGIC SETTING OF THE GREAT HANSHIN EARTHQUAKE

The Kobe/Awaji region, severely damaged by the Great Hanshin Earthquake, is located at the easternmost part of the east-west trending Setouchi shear zone. This shear zone is 80-100 km wide, is bound to the south by the Median Tectonic Line, and is characterised by a number of obliquely-trending basins and uplifted islands resulting from right-lateral shear within the zone. Awaji Island is a horst-like structure within the shear zone, and is bounded on both sides by active faults (Figure 1). The northern part of the island is bounded to the northeast by the Nojima fault, and, in part, to the southwest by the Higashiura fault [Mizuno et al. 1990]. The structural high represented by Awaji Island extends northeastward across Akashi Strait as the Rokko Mountains immediately north of Kobe. Active faults along the Awaji/Rokko structural high are predominantly high-angle, right-lateral strike slip faults with a component of reverse dip-slip displacement; these are the faults that ruptured in the Great Hanshin Earthquake. Geologic, seismic, and geodetic data suggest that fault rupture during the Great Hanshin Earthquake extended for some 60-70 km from Awaji Island northeastward under Kobe and the Rokko Mountains. Only south of Akashi Strait did fault rupture reach the ground surface on the steeply southeast-dipping Nojima fault; north of Akashi Strait, rupture appears to be confined to the subsurface on a steeply northwest-dipping fault(s) that underlies the Rokko Mountains [e.g. Hirata 1995, Sugiyama et al. 1995, Wald 1995, Yoshida et al. 1995].

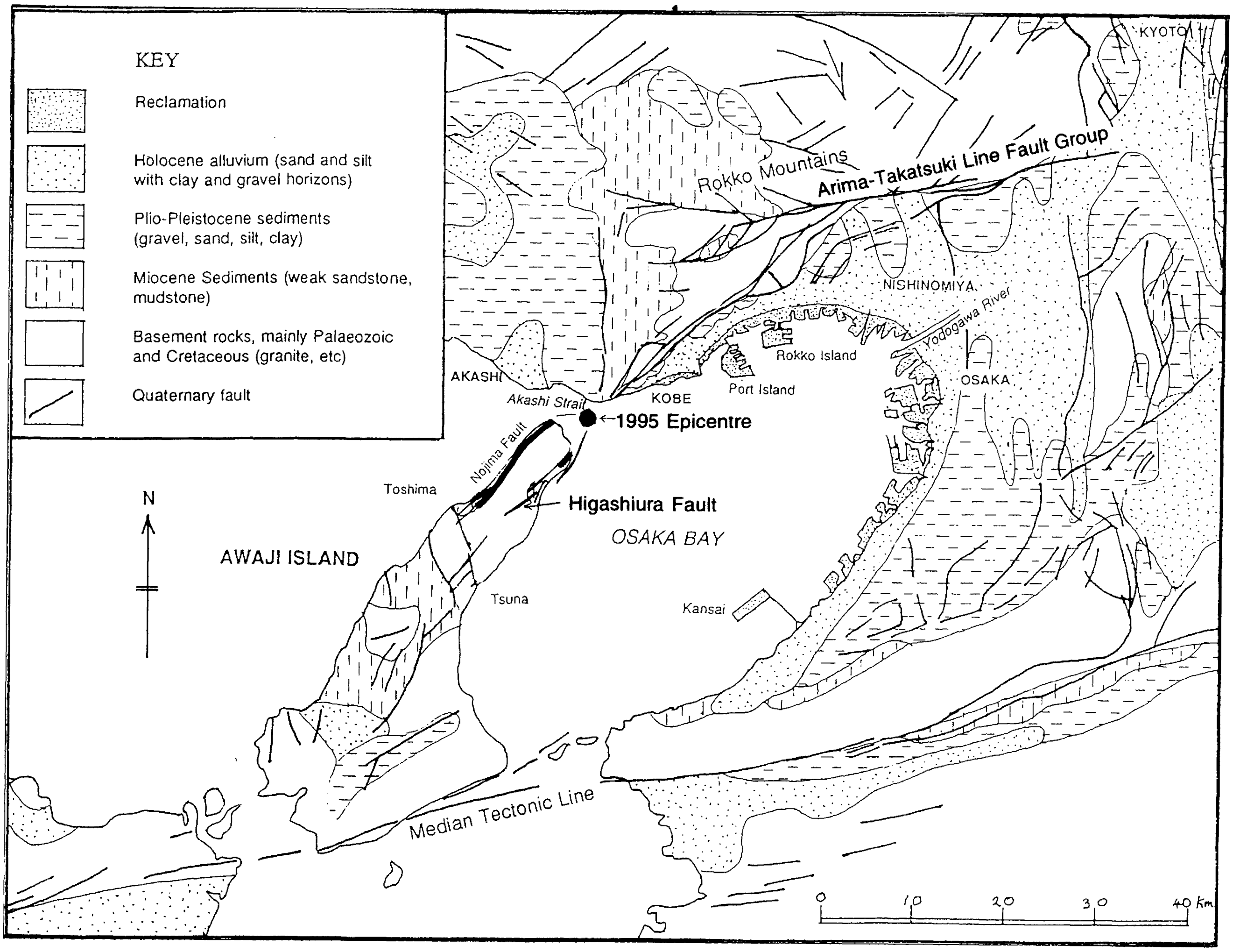

FIGURE 1. Generalised geology of Kobe/Awaji region, Japan [after Figure 2.1 of Park et al. 1995]. Bold lines denote surface fault rupture on Awaji Island resulting from the 1995 Great Hanshin Earthquake, the epicentre of which is shown as a solid circle.

NOJIMA FAULT

The Nojima fault ruptured during the Great Hanshin (Kobe) Earthquake; it has a northeast trend, extends along the northwest side of Awaji Island (Figure 1), and, prior to the earthquake, had already been identified as an active fault capable of generating large magnitude earthquakes. The sense of displacement along the fault during the earthquake was right-lateral with a high-angle reverse component, predominantly southeast side up. Coseismic displacement ranged from 1.2 to 2.1 m right-lateral and 0.4 to 1.3 m vertical, with an average net displacement of roughly 1.6 m (Figure 2). There was at least 10.5 km of coseismic surface rupture. Towards the southwest, rupture appears to die-out near Toshima. However, towards the northeast, surface rupture extends at least to the coast of Awaji Island, where surface fault displacement is greater than 1 m and coastal uplift occurred on the southeast side of the fault [Y. Ota pers. com 1996], but it is not known how far surface rupture extends into Akashi Strait. No surface rupture has been identified north of Akashi Strait in the severely damaged Kobe area. The Nojima fault has a long-term slip rate of approximately 1 mm/yr, and if the coseismic displacements resulting from the Great Hanshin (Kobe) Earthquake are representative of the size of past surface rupture displacements on the fault, then a 1000-2000 year recurrence interval for surface rupture earthquakes can be inferred for the Nojima fault [Awata et al. 1995, 1996].

The two New Zealand authors had the good fortune of being able to observe eight trenches across the 1995 surface rupture of the Great Hanshin (Kobe) Earthquake. They were able to see the effects of recent fault rupture both at the ground surface and in the shallow sub-surface. In many of the trenches there was evidence of past surface rupture earthquakes. Preliminary results suggest that the penultimate surface rupture on the Nojima fault occurred about 2000 years ago [Suzuki et al. 1995]. Most of the trenches were sited on flat rice fields. The upper metre or so of exposure in the tenches was a cultivated soil composed of a massive, gritty, sandy silt. It was very difficult to identify and located the shearing/faulting that must have extended through these deposits as a result of the Great Hanshin (Kobe) Earthquake. In fact, had the trenches not been located across known metre-scale displacements, it would have been difficult/impossible to definitively interpret these deposits as being faulted. This is a sobering thought when trying to interpret a trench exposure across a fault whose past surface-rupture history is not known.

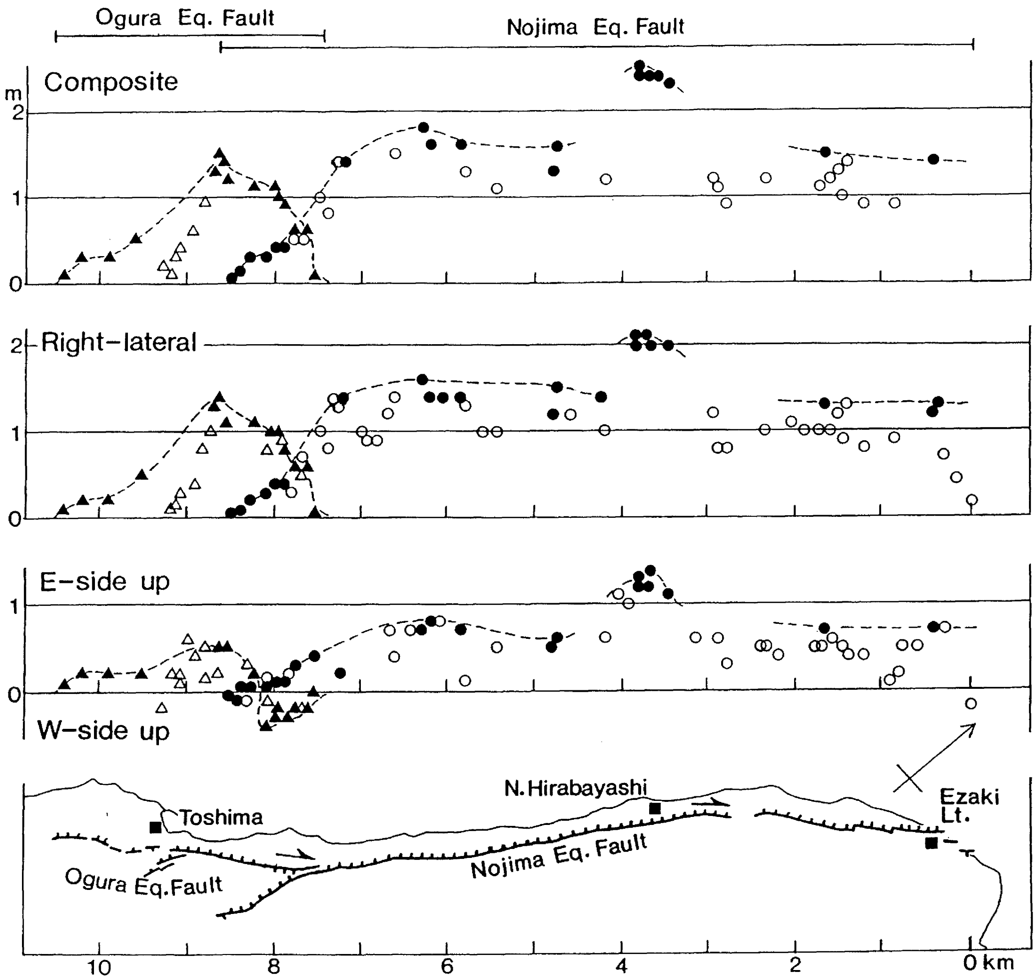

FIGURE 2. Distribution of slip along the surface rupture of the Great Hanshin Earthquake [from Figure 6 of Awata et al. 1996]. Solid symbols indicate localities where total displacement could be measured; open symbols indicate localities where only partial displacement could be measured.

POSSIBLE TRIGGERED SLIP DURING GREAT HANSHIN EARTHQUAKE

The 100 million cubic metres of fill used in the construction of the artificial Kansai Island, now home of Kansai International Airport, largely came from a quarry on the eastern-most portion of Awaji Island. During the Great Hanshin (Kobe) Earthquake, the only known surface rupture on the eastern side of Awaji Island coincided with the area of most extensive quarrying [Awata et al. 1996]. Surface rupture displacements on this fault were centimetre-scale, and were possibly triggered as a result of the combination of strong earthquake shaking and reduced overburden pressure.

HIGASHIURA FAULT

The majority of the first two authors' time in Japan was spent assisting with the logging and interpretation of a trench across the Higashiura fault which is located 3-4 km southeast of the Nojima fault, on the opposite side of Awaji Island. The fault strikes slightly more easterly than the Nojima fault (Figure 1), and presumably dips steeply to the northwest. Prior to this study, there were no data available on the earthquake history of the Higashiura fault.

The Baba trench, as it was called, was excavated on a flat rice paddy. Centuries of cultivation had long since removed any surface trace of the fault; shallow boreholes were used to constrain the position of the fault at the bedrock surface at c. 10 m depth, and help site the trench. A sketch of the faulted portion of the trench exposure is shown in Figure 3. The exposure can be mapped into four general units. A sequence of anthropic soils comprise units 1 and 2; unit 2 is faulted, unit 1 is not. Units 3 and 4 are both composed of alluvial gravel and sand, and a major unconformity separates the two units. Both units 3 and 4 are faulted with the fault zone being much wider below the unconformity than immediately above the unconformity in unit 3.

At least two faulting events can be recognised in this trench. The fault zone, as noted above, is wider below the major unconformity than it is immediately above. The unconformity truncates all but the northwestern margin of the fault zone in unit 4. It is clear from this relation that prior to the unconformity, and deposition of unit 3, there was a c. 30 cm wide fault zone in unit 4, and subsequent to the unconformity, only the northwestern margin of the fault zone in unit 4 has been active. Unit 4 has thus experienced more faulting than units above. Unfortunately, the number of additional faulting events that unit 4 has experienced, relative to unit 3, is not known, nor is the age of unit 4 known.

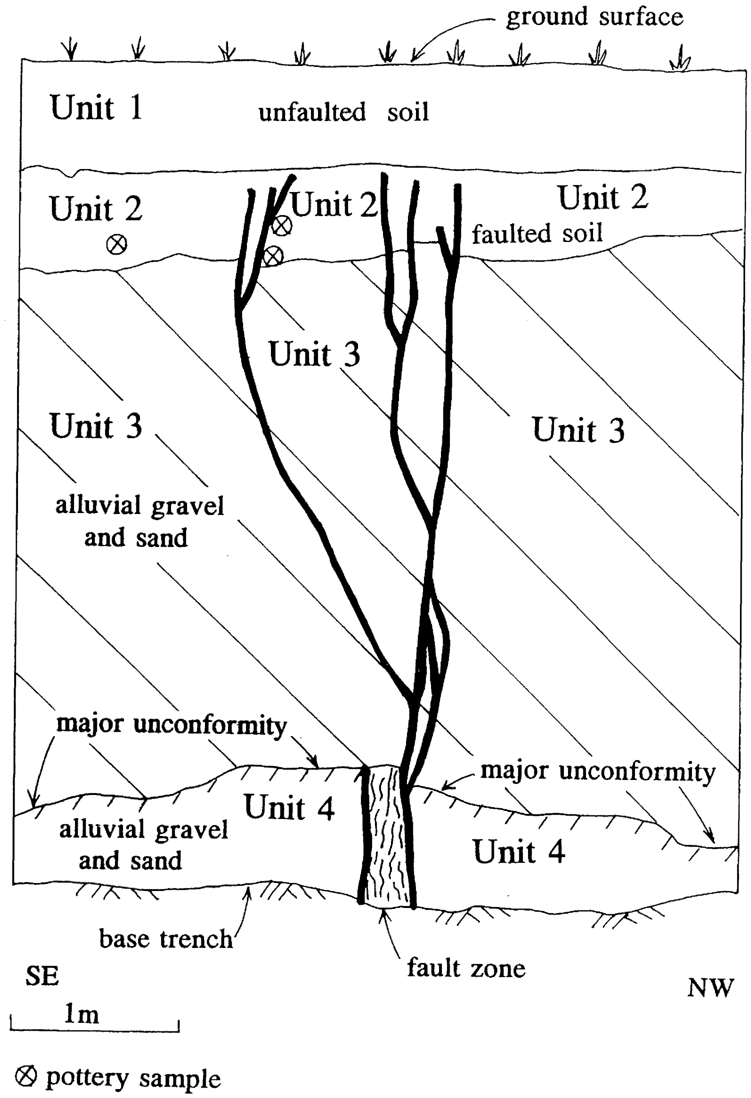

FIGURE 3. Sketch of a trench exposure of the Higashiura fault, southwest wall of Baba trench (no vertical exaggeration).

Above the unconformity, all the faults that cut units 2 and 3 terminate within the same horizon of unit 2. Also, vertical displacement of horizons within units 2 and 3 are similar. Both these observations suggest that only one faulting event disrupts units 2 and 3. This event is younger than unit 2, and older than the base of unit 1. As noted on the trench log (Figure 3), pottery fragments were found within unit 2. One of these fragments was identified as dating from the fifteenth century. Thus the most recent surface-rupture on the Higashiura fault occurred within the last 500-600 years. This is the first documented Holocene movement on this fault, and perhaps more importantly is its possible relation to the AD 1596 Keicho Earthquake (see below).

KEICHO EARTHQUAKE (AD 1596) AND ITS POSSIBLE RELATION TO THE HIGASHIURA FAULT

Historical records from this part of Japan suggest that prior to the AD 1995 Great Hanshin (Kobe) Earthquake there has been only one earthquake within the last 700 years that has generated regionally extensive ground shaking. This was the AD 1596 Keicho Earthquake. The Keicho Earthquake is thought to have been larger in magnitude than the Great Hanshin Earthquake because of its greater/wider distribution of felt effects. Until recently, the source of the Keicho Earthquake was not known.

It is reasonable to assume that a surface-rupture earthquake on the Higashiura fault would be of a large magnitude, and would result in regionally felt shaking. Based on the above trenching study, the most recent surface-rupture on the Higashiura fault occurred within the last 500-600 years, and the historical earthquake record suggests that within the last 700 years there has been only one regionally felt earthquake prior to the 1995 Great Hanshin (Kobe) Earthquake, and this was the AD 1596 Keicho Earthquake. It thus seams reasonable to suggest that the Higashiura fault is, at least in part, the source of the AD 1596 Keicho Earthquake.

Results from trenching studies on a group of faults (Arima-Takatsuki Line Fault Group) located approximately 60 km northeast of the Higashiura fault suggests that some of these faults may have also ruptured in the Keicho Earthquake. This would imply a surface-rupture length of 60+ km for the Keicho Earthquake. This infered longer surface rupture length for the Keicho Earthquake, relative to that of the Great Hanshin Earthquake, rupture length of 10+ km, is consistent with its inferred larger magnitude (estimated to be approximately M 7.5).

MISCELLANEOUS THOUGHTS RELATED TO THE GREAT HANSHIN EARTHQUAKE AND THE VISIT TO JAPAN

Two images that remain with the authors attest to the long-term effects of the Great Hanshin Earthquake on the day-to-day lives of the people of the Kobe/Awaji area. Looking down on central Toshima from our hotel room, the number of vacant sections was immediately apparent (some blocks were 80% bare), but a day or two passed before it sunk in that, prior to the earthquake, these were the sites of family homes and businesses. Our visit to Japan was about a year after the earthquake, and many citizens of central Toshima remain displaced - living with friends or relatives, or in one of a number emergency "temporary" housing camps.

The second image comes from Kobe where, a year before the earthquake, Van Dissen attended a conference on recent crustal movements. It was curiosity that motivated us to detour one day into downtown Kobe to see if the multi-storeyed hotel stayed in during the conference was still standing. It was - and it appeared as if business continued as usual. The building next door was also still standing. The difference being that it was now condemned and vacant. As we walked back to the train station, we were conscious of the number of other buildings in a similar state - condemned, vacant, yet still standing.

The geologic similarities between Kobe and Wellington, New Zealand, have been touched on by Park et al. [1995], and Brunsdon et al. [1996]. Notably strike-slip faulting predominates near Kobe, as it does for much of central New Zealand. The Great Hanshin Earthquake, primarily a strike-slip earthquake, produced measurable directivity effects, with long period ground motions oriented perpendicular to the trace of the Nojima fault measuring stronger than similar period motions oriented parallel to the fault's trace [Sommerville 1995]. Strike-slip faults in central New Zealand have a general northeast-southwest trend. Is it of value to consider the possibility that long period ground motions resulting from large earthquakes on these faults may be stronger in the northwest-southeast direction than in the northeast-southwest direction?

A more notable feature of the earthquake was a narrow zone of intense damage (1-2 km wide, 20-25 km long) that extended through Kobe and diverged eastward from the earthquake's aftershock zone (see figures 2.2 & 2.3 of Park et al. [1995]). It appears that this zone of intense damage was the result of two conspiring factors [Motosaka & Nagano 1995, Iwata et al. 1995]; a) amplification of ground motion due to near-surface, low velocity sediments, and b) amplification due to the focusing of motion caused by subsurface "topography".

In summary, the trip to Japan was a success. It afforded the valuable opportunity to see the effects of recent fault rupture both at the ground surface and in the shallow sub-surface, and will thus assist in deciphering the paleoearthquake record of active faults in New Zealand, and elsewhere. The New Zealand authors were able to assist their hosts in documenting repeated earthquake activity on the Higashiura fault, and, in doing so, helped to piece together evidence for the source and rupture characteristics of the 1596 Keicho Earthquake. Finally, both groups of geologists benefited from the sharing and interchange of ideas on how earth scientists from each country approach the common goal of understanding earthquake history and hazards posed by active faults.

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REFERENCES

Awata, Y., Mizuno, K., Sugiyama, Y., Imura, R., Shimokawa, K., Okumura, K., Tsukuda, E., Kimura, K. 1996. Surface fault ruptures on the northwest coast of the Awaji Island, associated with the Hyogo-ken Nanbu Earthquake of 1995, Japan. *Journal of Seismological Society of Japan.*.

Awata, Y., Mizuno, K., Sugiyama, Y., Imura, R., Shimokawa, K., Okumura, K., Kimura, K., Tsukuda, E. 1995. Surface fault ruptures associated with the Hyogo-Ken Nanbu (Kobe) Earthquake of 1995, Japan. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F372.

Billings, I.J. 1995. Restoration of road and rail transportation following the Great Hanshin Earthquake of 17 January 1995. *Bulletin of the New Zealand National Society for Earthquake Engineering*, v. 28, n. 4, p. 311-334.

Brunsdon., Britton, N.R., Carter, R.J., Crimp, R.F., Gates, E.F., Gordon, M.A., Hughson, G.J., Lamb, A.J.W., Leslie, P.D., Wabnitz, G., Watson, A.C. 1996. Lessons for New Zealand lifelines organisations from the 17 January 1995 Great Hanshin Earthquake. *Bulletin of the New Zealand National Society for Earthquake Engineering*, v. 29, n. 1, p. 1-55.

Hirata, N. 1995. Fault system of the 1995 Hyogo-Ken Nanbu (Kobe), Japan, Earthquake deduced by aftershock observations and the Trans-Awaji seismic profiling (TASP). *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F377.

Iwata, T., Hatayama, K., Pitarka, A., Kawase, H., Irikura, K. 1995. Site amplification effects of underground structure on ground motions during aftershocks of the 1995 Hyogoken-Nambu earthquake in severely damaged zone - array observation of ground motion at Higashinada Ward, Kobe City, Japan. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F377.

Mizuno, K., Hittori, H., Sangawa, A., Takahashi, Y. 1990. Geological sheet map 1:50,000 "Akashi". Geological Survey of Japan.

Motosaka, M., Nagano, M. 1995. Effects of deep irregular underground structure and shallow surface geology on the amplification characteristics of ground motions in Kobe City during the 1995 Hyogo-ken Nanbu earthquake - analytical study on interpretation of the heavily damaged belt zone. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F372.

Park, R., Billings, I.J., Clifton, G.C., Cousins, J., Filliatrault, A., Jennings, D.N., Jones, L.C.P., Perrin, N.D., Rooney, S.L., Sinclair, J., Spurr, D.D., Tanaka, H., Walker, G. 1995. The Hyogo-ken Nanbu Earthquake of 17 January 1995. *Bulletin of the New Zealand National Society for Earthquake Engineering*, v. 28, n. 1, p. 1-98.

Sommerville, P.G. 1995. Rupture directivity effects in Kobe strong motions. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F372.

Sugiyama, Y., Endo, H., Kinugasa, Y. 1995. Geological background of the 1995 Hyogo-Ken Nanbu (Kobe) Earthquake. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F371.

Suzuki, Y., Nakata, T., Watanabe, M., Sawa, H., Imaizumi, T., Matsuda, T. 1995. Preliminary report on the excavation study of the Nojima fault. *Proceedings of the 5th Symposium on Geo-Environments and Geo-technics*. p. 75-80.

Wald, D.J. 1995. A dislocation model of the 1995 Kobe, Japan, Earthquake determined from strong motion, teleseismic, and geodetic data. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F378.

Yoshida, S., Koketsu, K., Kato, T., Shibazaki, B., Sagiya, T., Yoshida, Y. 1995. Joint inversion of near- and far-field waveforms and geodetic data for the rupture process of the 1995 Kobe Earthquake. *EOS*, Transactions, American Geophysical Union, v. 76, n. 46 (supplement). p. F378.