

Progress in Paleoseismology in Japan during the 1990s

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We review progress of geological and geomorphological approaches in paleoseismology in Japan during the this decade. We emphasize the growth of active fault studies since the 1995 Kobe earthquake. Two examples of intensive trenching studies, one on the Itoishizu-Tectonic Line in central Japan, and the other on the Miura Peninsula south of Tokyo, are briefly discussed with special reference to fault segmentation and the probability of large earthquakes. Studies of coastal morphology and deposits which are used for the reconstruction of paleoearthquakes are also reviewed. Japanese scientists have contributed much to paleoseismological studies overseas through collaborative international projects including identification of coseismic uplift, subsidence and tsunami deposits along the Pacific coasts as well as studies of inland faults.

Key Words : paleoseismology, late Quaternary, active fault, trenching survey, coseismic coastal deformation

I. Introduction

Knowledge of paleoearthquakes is fundamental to understanding future earthquakes and assessing earthquake hazards. Paleoearthquakes can be detected and their histories reconstructed from many kinds of evidence—the geology and geomorphology of offshore and onshore faults, coastal landforms and deposits, archaeology, and historic documents. Because Japan has several convergent plate boundaries, the study of paleoearthquakes is one of the important topics in Japanese Quaternary research. Recent comprehensive publications on Japanese paleoseismology include Hagiwara *et al.* (1995), Ota and Shimazaki (1995) and a Special Issue of Journal of the Seismological Society of Japan (Ishibashi *et al.*, 1998).

Here we briefly review some geomorphologic and geologic studies of paleoearthquakes along

onshore and offshore faults in Japan. First, we summarize studies of the past 10 years. The 1995 Hyogoken-nanbu (Kobe) earthquake, which caused enormous loss of life and property was a turning point in Japanese earthquake research. Then we review the rapid growth of active fault studies since the 1995 earthquake, especially progress in identifying and dating paleoearthquakes by means of trenches dug across onshore faults. Finally, we mention a few overseas paleoseismological studies involving Japanese scientists.

II. Paleoseismological studies during the last 10 years

Onshore faults : A major accomplishment of the early 1990s was the publication of the Revised Edition of Active Faults of Japan by The Research Group for Active Faults of Japan (1991). This comprehensive inventory of Japan's active faults supersedes the first edi-

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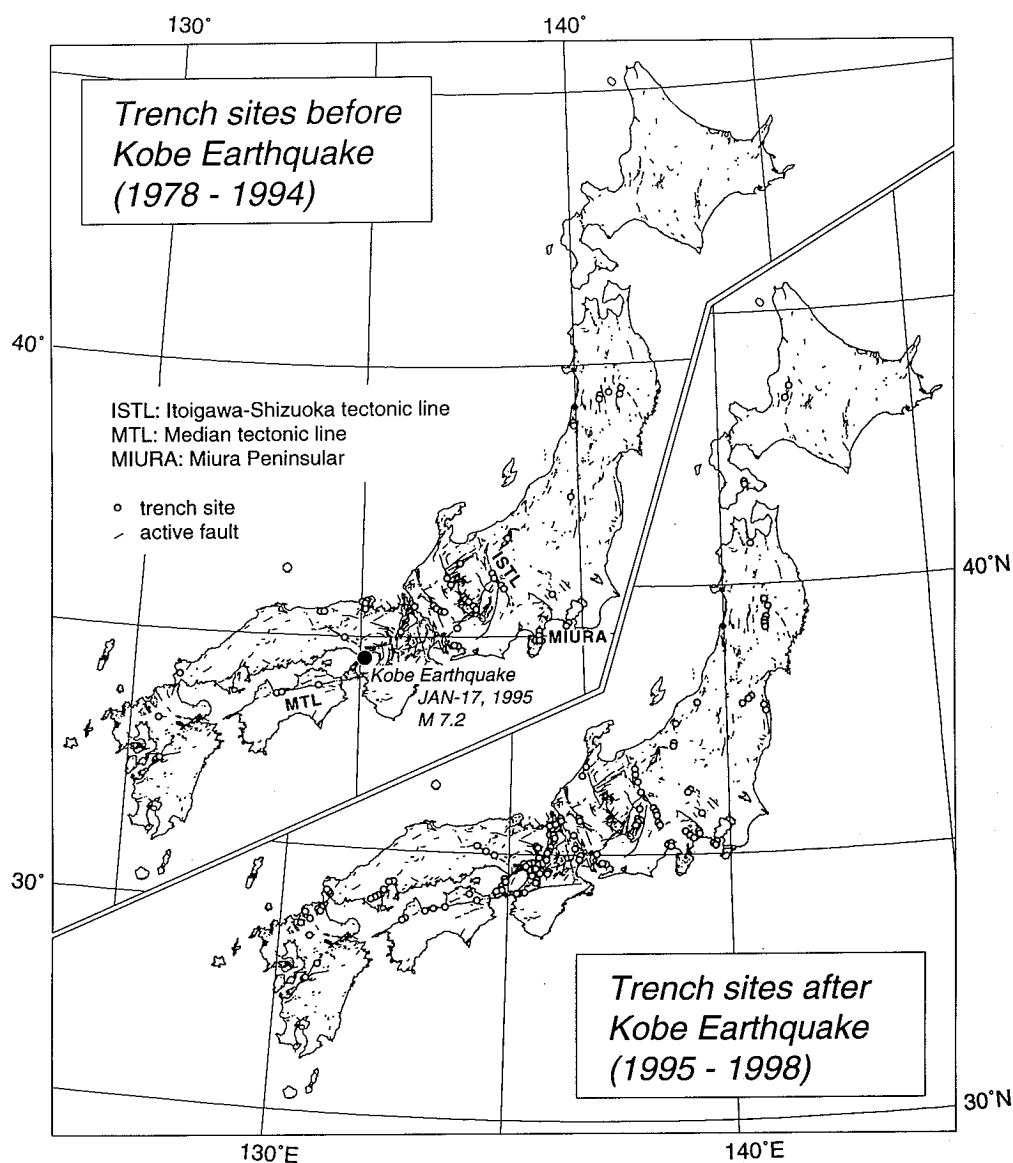


Fig. 1 Distribution of major active faults and trench sites in Japan

Active faults longer than 3 km are simplified from Research Group for Active Faults of Japan (1991). Trench sites are from various sources. Closely spaced sites are represented by a single circle.

tion published in 1980. Carefully defined, uniform criteria were used to identify and map faults repeatedly active in the Quaternary. The 1991 edition describes over 2,000 faults (Fig. 1). An abridged edition in English and Japanese was also published (The Research Group for Active Faults of Japan, 1992).

Although most active faults were included in the 1991 edition, new faults continue to be discovered. For example, Goto (1998) identified previously unknown fault strands from subtle topographic features along the Median Tectonic Line in Shikoku and presented a rupture history and a segmentation model for this fault

zone. These results are being compiled on new fault maps using a GIS (Geographic Information System). More recently, active faults with high slip rates and evidences of repeated Holocene events were identified at the Shinano River area of central Japan (Ota *et al.*, unpublished data).

Additional onshore highlights include:

- Matsuda (1990) divided the Japanese Islands into 14 regions with different expected maximum earthquake magnitudes, based on the mapping of major seismogenic active faults.
- Special attention is now paid to segmentation of long faults such as Median Tectonic Line in the southwestern Japan (Tsutsumi and Okada, 1996).
- Back tilting, range-facing scarplet, and flexural scarp and their progressive deformation were documented along reverse faults (Ota *et al.*, 1994), which are especially common in northern Japan.
- Timing of paleoearthquakes was estimated from faults and liquefaction features found at archeological sites. Sangawa (1992) used this method in the Kinki area of central Japan, where archaeological sites are abundant and well dated by artifacts.
- Reconstruction of onshore paleoearthquakes relies on trenching survey started in Japan in 1978. Recent examples are reviewed in section IV.

Offshore studies : Mapping of submarine faults has progressed rapidly in the past 10 years, especially in the Sea of Japan area off northern Honshu. Several active faults have been mapped on the sea floor and lake beds by means of newly developed high-frequency (4 to 10 kHz) sonic profiling techniques (*e.g.* Ogawa *et al.*, 1992).

Marine and lake sediments may provide a more complete record of paleoearthquakes than many onland records. Nakata and Shimazaki (1993) examined such records to help reevaluate their time-predictable model of earthquake recurrence (Shimazaki and Nakata, 1980).

Coastal uplift : Paleoearthquakes caused by offshore faulting have been inferred from uplifted marine terraces of Holocene age. Based on radiocarbon-dated Holocene emerged land-

forms and deposits, Maemoku (1992) inferred that peninsulas facing the Nankai Trough have been uplifted during intraplate as well as interplate earthquakes ; but also during intraplate earthquakes ; eastern Kyushu, by contrast, has been uplifted aseismically.

New work by Shishikura (1999) has renewed controversy about coseismic uplift of the Boso Peninsula. He proposed that a small coastal lowland on the Boso Peninsula was coseismically uplifted during a relatively small and frequent (Taisho type, as in 1923) earthquake, but that the lowland subsided during larger and less frequent (Genroku type, as in 1703) type earthquakes. This proposal challenges earlier idea (Matsuda *et al.*, 1978) that each of four major terraces was uplifted during Genroku-type earthquakes. More work is needed to fully understand the mechanism of terrace uplift.

Tsunamis : Tsunami deposits have received particular attention in the past decade. Minoura and Nakaya (1991) inferred that submarine earthquakes produced large tsunamis at intervals of 250–400 years at the Tsugaru Plain and about 800 years at the Sendai Plain. Tsunami deposits in a coastal sequence dated at 940 ± 80 yrs BP at the Masuda Plain, in southwestern Japan, probably resulted from a historically recorded tsunami in AD 1026 (Minoura and Nakata, 1994). On the Boso and Miura peninsulas around Tokyo Bay, Fujiwara *et al.* (1997, 1999) found several Holocene tsunami layers in outcrops and boreholes. Most of these layers are similar in age to the coseismic uplift events. Kawana and Nakata (1994) extended the known distribution of huge coralline blocks left on coral terraces of the Ryukyu Islands by a tsunami in 1771.

III. The 1995 Kobe earthquake and the Nojima earthquake fault

Tectonic surface rupture during the 1995 Kobe earthquake (M 7.2) was restricted to the Nojima fault. This fault previously displaced an alluvial fan 25,000 years old (Mizuno *et al.*, 1990). It strikes northeast to southwest along the coast separating mountains on the southeast from a narrow lowland on the west side of Awaji Island off Kobe. The 1995 rupture

followed pre-existing fault strands. Such coincidence of the latest with earlier faulting came as no surprise; surface ruptures during the 1891 Nobi, 1896 Rikuu, and 1930 Kitaizu earthquakes also followed pre-existing strands. What surprised many people was the enormity of disaster associated with slip on the Nojima fault, for this fault had no documented historical activity.

Many scientists studied the surface rupture along the Nojima fault in 1995 (e.g. Nakata *et al.*, 1995; Ota *et al.*, 1995). They found a maximum right-lateral offset of 1.8 m and a maximum vertical offset of 1.3 m. Awata and Mizuno (1998) compiled large-scale strip maps of the surface rupture. Much or all of the uplift of the upthrown side of the fault was probably absolute, as shown by emerged shorelines near the northern end of the fault. This coseismic coastal uplift, as great as 0.6 m, diminished southeastward and disappeared about 400 m from the fault (Ota *et al.*, 1997a).

Surface displacement produced a distinct scarp where Plio-Pleistocene siltstone is exposed at or near the surface. By contrast, in some alluvial lowlands flexural scarps were formed. The fault scarp degraded most rapidly where reverse slip had produced an overhanging scarp that rapidly collapsed. The scarps of such reverse faults degrade far more rapidly than the scarps of normal faults in arid climate such as in the western United States (Ota *et al.*, 1997a).

Toda *et al.* (1998) used Coulomb failure function analyses to estimate aftershock and future main shock probabilities on the Nojima fault. They treated the faults of the Kinki region as a dense network of active faults with complexity.

IV. Growth of active-fault studies since the 1995 Kobe earthquake

Before the 1995 Kobe earthquake, research on active faults in Japan was directed mainly towards mapping of faults and understanding their behavior. There was little public demand for active onland fault research. Instead, public and scientific attention was focused on the offshore plate boundary faults, particularly the Tokai segment of the Nankai

Trough. Long-term earthquake forecasting was commonly subordinated to short-term prediction, and hazard assessment and reduction were widely viewed as of low-scientific priority.

After rupture of the Nojima fault in 1995, the public became so anxious about the potential hazard from onshore earthquakes that the national government created new programs to assess onshore active faulting and its associated hazards. The Japanese Diet passed a Special Measure Law on Earthquake Disaster Prevention and placed the Headquarters of Earthquake Research Promotion in the Science and Technology Agency (STA). This new office is now responsible for planning and overseeing scientific research on active faults. In addition, the office must publicize the information gathered.

Because it occurred on a fault that lacked historical activity but had been identified as active, the 1995 Kobe earthquake vastly increased interest in active fault studies. Government agencies were exceptionally generous in their financial support of active fault studies, which could now be proposed by individual scientists as well as by university research groups and government agencies. The STA created an influential Earthquake Research Committee that includes several active-fault specialists. This speciality is also represented on the National Committee for Geodesy, a high-level advisory panel for the Ministry of Education, Culture, Science, and Sports (Monbusho). The committee named active-fault studies as one of high priority fields for earthquake research in Japan. The Geological Survey of Japan established a department devoted to the mapping and trenching of active faults. The Geographical Survey Institute of Japan has published 62 sheets of 1:25,000-scale maps of active faults in urban areas.

Much of Japan's active-fault research is now decentralized through STA grants to prefectures and large cities. This program, begun in 1996, allowed 98 major active faults to be evaluated by 1999. The faults were selected based on their slip rate, length, and the size of human population at risk. Principal field methods include trenching, seismic reflection,

and drilling. Results are reported annually in a national meeting that is attended not only by members of the active-fault study committees but also by public officials from the prefectures and cities.

Kumamoto (1998) recently estimated the conditional probability of ground shaking throughout Japan. He used methods similar to those of the Working Group on California Earthquake Probabilities (1995). Such probabilistic assessment of onshore active faults in Japan is complicated by long recurrence intervals (more than 1,000 yr) and by large uncertainties in dating paleoearthquakes.

A recent successful highlight in active fault research is a new soil sampling system called the geo-slicer (Nakata and Shimazaki, 1997). With this device one can obtain trench-like cross sections as much as 15 m deep with little

disturbance to the land surface or to sub-surface.

V. Examples of intensive trenching surveys and seismic hazard assessment of fault zones

The number of trenches across the active faults in Japan increased from 60 sites on 38 faults before the 1995 earthquake to 163 sites on 84 faults by 1998 (Fig. 1). The time of the last surface-rupturing earthquake has now been estimated at many of these sites (65%), and some of the paleoearthquakes inferred from trenching can be correlated with events in historical documents. However, only 10% of trench sites record more than three earthquakes, which makes it difficult to estimate recurrence intervals. Two trenching studies are summarized below :

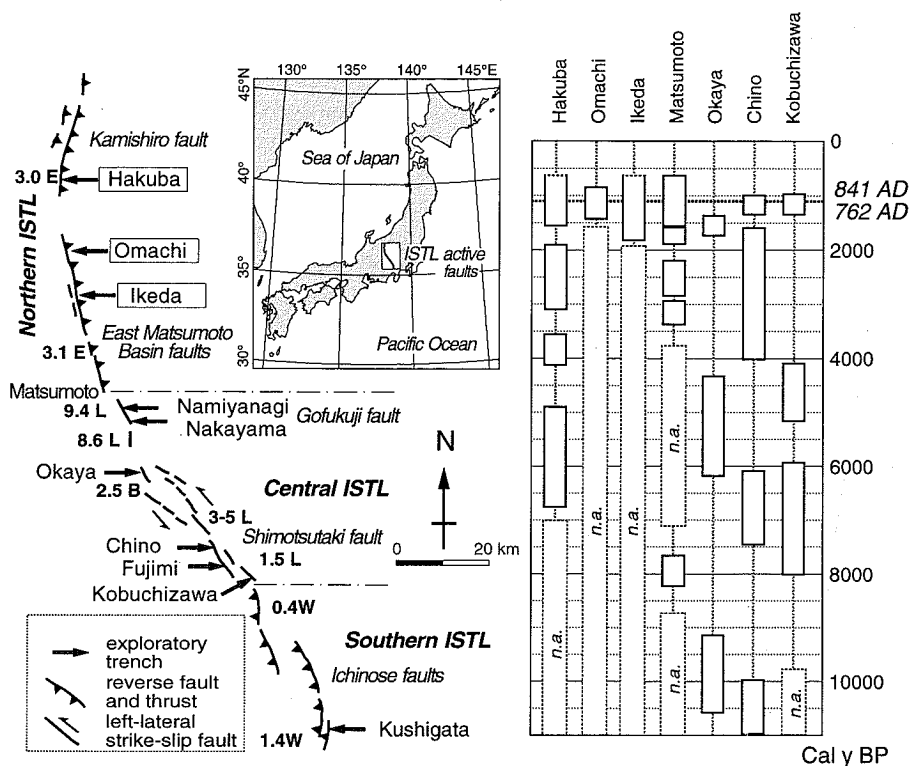


Fig. 2 Paleoseismicity of the Itoigawa-Shizuoka Tectonic Line (ISTL) Active Fault System, in central Japan (Okumura *et al.*, 1998)

Left : Northern and middle part of ISTL active fault system and sites of trenching survey. Numerals indicate average slip rate of the faults in m/1000 yrs. E : east-side up, W : west-side up, L : left-lateral, and B : subsidence of Suwa pull-apart basin. Right : Rupture history of the northern and middle portion of the ISTL active fault system. Each rectangular indicates an estimate of the timing of the seismic event.

Itoigawa Shizuoka (Itoshizu) Tectonic Line (ISTL), central Japan : The Itoigawa-Shizuoka Tectonic Line Active Fault System (Fig. 2) is one of the most intensively studied and fastest-moving onshore fault systems in Japan. The average slip rate in the central part of the system is 7 to 14 m/kyr (Ikeda and Yonekura, 1986; Fujimori, 1991; Okumura *et al.*, 1994a). The most recent earthquake on the system took place probably in AD 841 or 762 as judged from historic records (Usami, 1995) and trenching studies at 10 sites (Research Group for the Itoshizu Tectonic Line Active Faults, 1988; Okumura *et al.*, 1994a, 1998). The elapsed time since the last earthquake is more than 1,150 years, whereas the average recurrence time inferred from trench data near Matsumoto is probably less than 1,000 years (Okumura *et al.*, 1994a).

The most recent earthquake ruptured at least the northern and central parts of the ISTL; the rupture length was about 110 km. The slip during this event is estimated at 6 to 9 m near Matsumoto (Okumura *et al.*, 1994a). But slip in earlier events was not the same as during the last one. Moreover, recurrence intervals at other trenches are probably two or three times longer than at Matsumoto. Thus, results so far are not precise enough to estimate the exact location and size of the next earthquake.

Despite these uncertainties, paleoseismic results from the ISTL are the main basis for the first official warning of seismic risk on a specific active fault in Japan. The warning, announced by the Government of Japan in September 1996, states that the northern and central parts of the ISTL are likely to rupture within the next few hundred years and that the magnitude will probably be 8.0 to 8.5.

Active faults on Miura Peninsula : Five subparallel active faults, striking NWW to SEE, transect the densely populated Miura Peninsula, south of Tokyo. Most have right-lateral strike slip with a smaller vertical component. Despite their high slip rates (several meters/kyr), the faults are not held responsible for damaging historical earthquakes. Seismic risk has increased in their vicinity because of residential development.

Trenching or drilling have been done at many sites on the faults since the late 1980s. Especially following the Kobe earthquake, three of the faults, the Kinugasa, Kitatake and Takeyama faults from north to south have received special attention (*e.g.* Ota, in press). The age of the latest movement along 8 km of the Kitatake fault is estimated at 1,300–1,600 yrs BP at four trench sites and one drilling site. The most recent faulting probably occurred at the same time along the entire 8 km of the fault. A recurrence interval of 1,500–2,000 years has been estimated for the Kitatake fault from differences in the thickness of Holocene beds correlated across the fault (Ota *et al.*, 1991a).

Trenching on the Takeyama fault revealed three events in the past ca. 5,500 years with an average repeat time of about 2,000 years. The youngest event occurred at 2,000 to 2,100 yrs BP, slightly before the latest earthquake on the Kitatake fault. The history of the Kinugasa fault was formerly uncertain because landforms along its trace had been modified artificially. But trenching in 1998 showed that the Kinugasa fault has ruptured at least twice in the last 13,000 years. The latest earthquake probably occurred after ca. 2,000 yrs BP.

Although earthquakes on these three faults may have occurred at different times, most recent event on each of them probably occurred within the same several hundred years period. For this reason, the faults can be considered as a single fault zone. Grouping the faults into a zone implies that even though the average repeat time for each fault may be 1,500 years or longer, the repeat time for damaging earthquake shaking anywhere within the zone may be several centuries shorter.

VI. Overseas studies on paleoseismology by Japanese scientists

Japanese scientists have made paleoseismic studies around the Pacific Basin. Most of the works was carried out as collaborative projects with international colleagues, as illustrated below :

Onshore faults :

- In eastern Asia, active faults (*e.g.* Ulsan fault)

were discovered in southeastern Korea where no active faults has been previously been identified (*e.g.* Okada *et al.*, 1998).

- After the recognition of the surface rupture associated with the Neftegorsk earthquake in 1995, a Japanese—Russian joint project mapped the rupture and the active faults in the entire Sakhalin area through interpretation of aerial photographs and field surveys (*e.g.* Shimamoto *et al.*, 1996 ; Suzuki *et al.*, 1998).
 - The active faults along the north piedmont of the Liulengshan Range, Shanxi Rift System in China, have been investigated by a Chinese and Japanese joint team. Average Holocene vertical slip rates on these faults are in the range 0.43–0.55 mm/yr. The period of 12.8 to 7.6 ka is the most intensive phase of vertical faulting during the past 60 ka (Xu *et al.*, 1997).
 - Nakata *et al.* (1990) studied the 1990 Philippine earthquake in central Luzon. They found that the surface rupture coincides with a previous fault trace identified by Hirano *et al.* (1986).
 - Nakata *et al.* (1991) published an active fault map of Pakistan.
 - Trenching by several Japanese—Turkish teams identified historic earthquakes that occurred on the North Anatolian Fault in 1939, 1942, 1943, 1944, and 1967 (Ikeda *et al.*, 1991 ; Okumura *et al.*, 1994b).
 - Japanese researchers contributed to the study of the San Andreas fault and related faults in California (*e.g.* Schwartz *et al.*, 1998).
- Coastal areas and offshore faults :** Some international work has focused on coastal tectonic land level changes.
- New data on Holocene coseismic uplift was obtained during a joint project on the east coast of North Island, New Zealand, adjacent to an active plate boundary (Ota *et al.*, 1991b, 1992).
 - Holocene and late Pleistocene coseismic uplift was also identified by a international team working on the Huon Peninsula, Papua New Guinea, where very rapid late Quaternary uplift is recorded by a well-known flight of coral terraces (*e.g.* Ota *et al.*, 1993 ; Chappell *et al.*, 1996). Meter-scale, thousand-

year-interval coseismic uplift was inferred from marine terraces in both New Zealand and Huon Peninsula.

- Paleolandslides and debris flows disrupting or covering coral terraces at Huon Peninsula were used to identify paleoearthquakes (Ota *et al.*, 1997b).
- Repeated sudden subsidence at the Cascadia subductin zone was identified at several new intertidal marsh sites (Ota and Uimitsu, 1995 ; Nelson *et al.*, 1998).
- An AD 1700 tsunami recorded on the Pacific coast of Japan was correlated with the most recent prehistoric tsunami inferred from coastal geologic studies along the Cascadia subduction zone (Satake *et al.*, 1996). This correlation yielded the only written records of a great earthquake and associated at Cascadia.

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