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Study of blind thrust faults underlying Tokyo and Osaka urban areas using a combination of high-resolution seismic reflection profiling and continuous coring

Yuichi Sugiyama ([1]), **Kiyohide Mizuno** ([2]), **Futoshi Nanayama** ([1]), **Toshihiko Sugai** ([3]), **Hiroshi Yokota** ([4]), **Takashi Hosoya** ([5]), **Kenichiro Miura** ([6]), **Keiji Takemura** ([7]) **and Naoko Kitada** ([8])

([1]) *Active Fault Research Center, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan*
([2]) *Active Fault Research Center, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Osaka, Japan*
([3]) *Department of Natural Environmental Studies, University of Tokyo, Japan*
([4]) *Hanshin Consultants Co. Ltd., Osaka, Japan*
([5]) *Chuo Kaihatsu Corporation, Tokyo, Japan*
([6]) *Kiso-jiban Consultants Co. Ltd., Chiba, Japan*
([7]) *Institute for Geothermal Sciences, Kyoto University, Beppu, Japan*
([8]) *Geo-Research Institute, Osaka, Japan*

Abstract
We acquired high-resolution seismic reflection profiles and continuously cored boreholes to evaluate active flexures produced by major blind thrust fault systems within two densely populated Neogene-Quaternary sedimentary basins in Japan: the Fukaya Fault System near Tokyo in the Kanto Basin and the Uemachi Fault System in the Osaka Basin. The high-resolution seismic reflection survey made clear the length, geometry and growth history of fault-related folds, or flexures formed above the two blind thrusts. Continuously cored boreholes linked with high-resolution seismic profiles enabled us to estimate the uplift rate as defined by shallow stratigraphic horizons and constrain the age of the most recent growth of the flexures during earthquakes on the Fukaya and Uemachi fault systems. Even with the high quality of the data we collected, it is still not possible to exactly constrain the age of the most recent blind thrust earthquake recorded by flexure of these fault-related folds. Data presented in this paper form the basis for future efforts aimed at mechanical and kinematic models for fault growth to evaluate the activity of blind thrusts underlying urban areas.

Key words *blind thrust – fault-related fold – flexure – high-resolution seismic reflection profiling – continuous coring*

Mailing address: Dr. Yuichi Sugiyama, Active Fault Research Center, Geological Survey of Japan, National Institute of Advanced Industrial Science and Technology, Higashi 1-1-1, Tsukuba, 305-8567, Japan; e-mail: sugiyama-y@aist.go.jp

1. Introduction

In Japan several Neogene-Quaternary sedimentary basins have developed in close association with active faults along their margins. As the basins are composed of Plio-Pleistocene deposits more than one thousand meters thick, some of the active faults do not appear at the surface, but are expressed at the surface as a flexure or monocline usually one to several hundred meters wide. These flexures are commonly concealed beneath young Holocene deposits and show no geomorphic expression. High-resolution seismic reflection profiling is useful for studying this type of active blind fault with no topographic expression but with a wide subsurface deformation zone.

Continuously cored boreholes coupled with high-resolution seismic reflection profiles are especially useful for obtaining data on fault activity such as uplift rate. We applied this combination of methods to flexures that have grown in response to repeated earthquakes of two major blind thrust fault systems in the densely populated Kanto and Osaka basins, Japan.

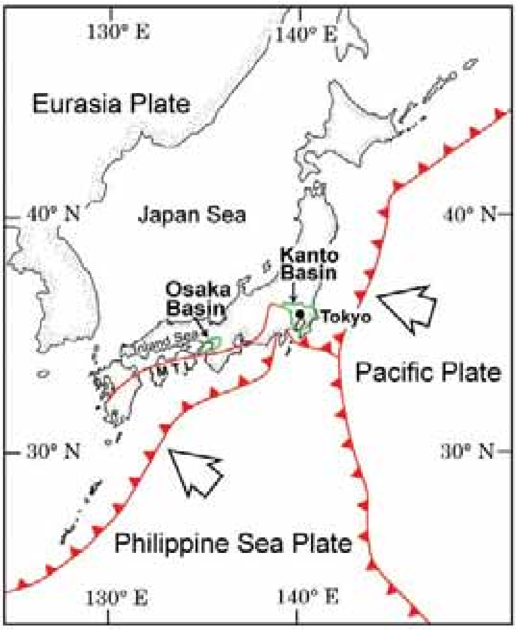

Fig. 1. Simplified tectonic setting of Japan and location of the Kanto and Osaka basins. MTL: Median Tectonic Line. Open arrows show relative convergence direction between Japan and the Pacific and Philippine Sea plates, respectively.

2. Fukaya Fault System in the Kanto Basin

2.1. *Kanto Basin*

The Kanto Basin is situated where the Pacific and Philippine Sea plates are subducted beneath Eastern Japan respectively from the east and south (fig. 1). The basin is approximately 150 km wide and 130 km long in E-W and N-S directions. Greater metropolitan Tokyo with a population of more than 30 million lies within this basin. Neogene-Quaternary deposits are 3000 m deep in the central and northwestern parts of the Kanto Basin. Active faults are recognized within the basin around its northwest and western peripheries. Geodetic surveys in the past 100 years show that the northwestern part of the basin is subject to compression in ENE-WSW direction and extension in NNW-SSE direction (*e.g.*, Geographical Survey Institute, 2002).

2.2. *Fukaya Fault*

The Fukaya Fault is located in the northwestern part of the Kanto Basin (fig. 2). This NW-trending west-side-up fault is identified by a 12 km long flexure or monocline, 4 to 14 m high and about 100 m wide, extending across Pleistocene terraces. NW-trending east-side-up back thrusts such as the Kushibiki and Hirai faults also exist as flexures on Pleistocene terraces about 5 to 10 km southwest of the Fukaya Fault (fig. 2). The long-term uplift rate is estimated to be 0.3-0.4 m/ky for the Fukaya Fault and around 0.1 m/ky for the Kushibiki and Hirai faults based on measured displacements and the inferred age of terrace surfaces (Yamazaki, 1984). Although a very shallow earthquake of magnitude 6.9 occurred in 1931 close to the Fukaya Fault, no surface rupture was recognized along the fault zone. The focal mechanism determined by Abe (1974) for the 1931 earthquake is consistent with NE-SW compression and left-lateral strike slip on an N70°W-trending nearly vertical source fault.

2.3. *High-resolution seismic reflection profiling*

Since the mid 1990's, the National Institute for Earth Science and Disaster Prevention (Ka-

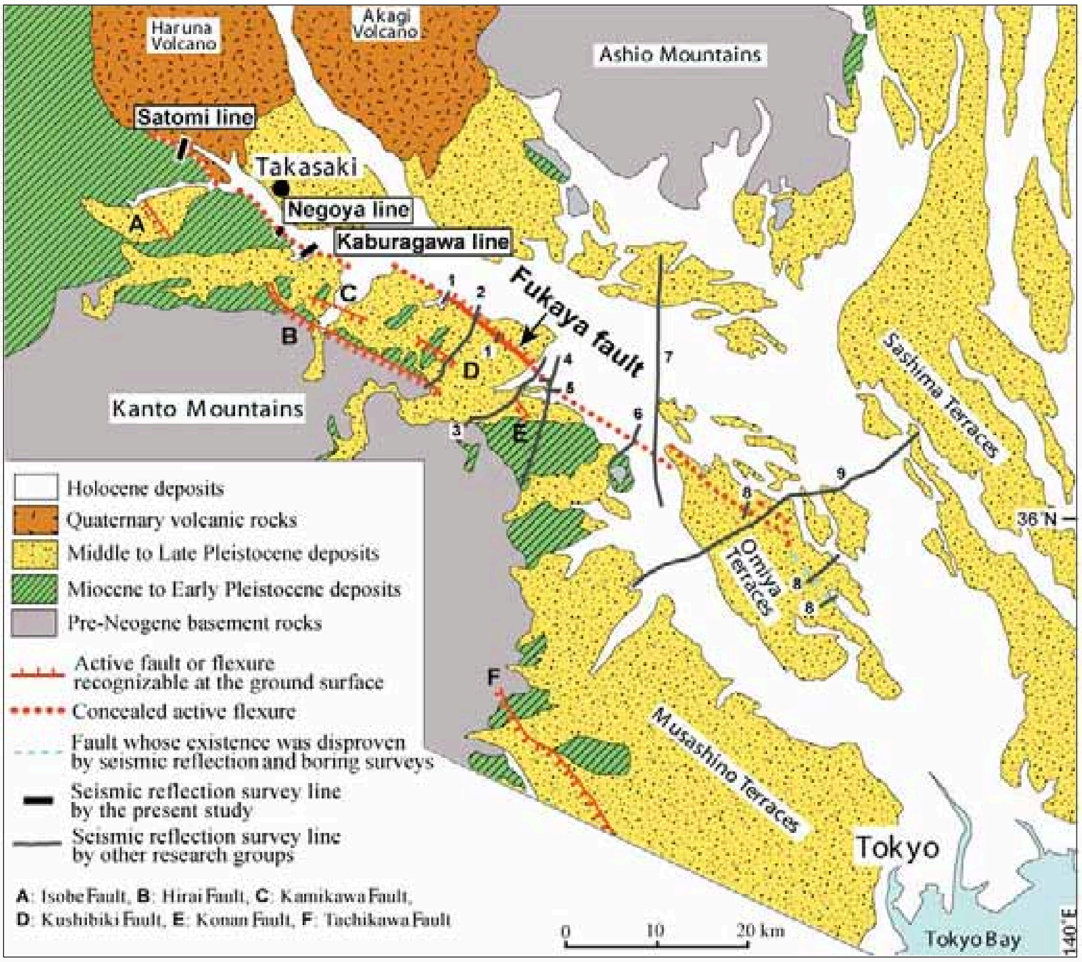

Fig. 2. Simplified geologic map of the central to northwestern part of the Kanto Basin. Simplified from Sugiyama *et al*. (1997). The basin is bounded by the Kanto and Ashio mountains on the west and north, respectively. Seismic reflection surveys shown by numbered survey lines were conducted by the following authors: 1 - Saitama Prefecture (1999); 2 - Yamaguchi *et al*. (1996); 3 - Yamaguchi et al. (2000); 4 - Ikawa *et al*. (1998); 5 - Inazaki *et al*. (1988); 6 - Yamaguchi *et al*. (1998); 7 - Kasahara (1996); 8 - Saitama Prefecture (1996); 9 - Kasahara *et al*. (1993).

sahara *et al*., 1993; Kasahara, 1996) and the Geological Survey of Japan (Yamaguchi *et al*., 1996, 1998, 2000) have carried out comprehensive seismic reflection surveys to reveal the subsurface structure of the Kanto Basin (fig. 2). Saitama Prefecture (1996, 1999) also undertook acquisition of seismic reflection profiles to evaluate the Fukaya Fault and its southeastern extension in the Omiya terraces (fig. 2). These studies revealed that the Fukaya Fault extends for about 35 km southeastwards as a blind thrust and is expressed in the shallow subsurface as a fault-related fold. No clear evidence was obtained, however, for its extension towards the northwest except for indi-

Table I. Main parameters for the seismic reflection survey of the Fukaya Fault System.

Seismic Source	Impactor (JMI-200)
Shot point interval	5 m
Standard times of shot at each shot point	10
Receiver	6-geophone array
Natural frequency	30 Hz
Receiving point interval	5 m
Standard receiving channels	120
Spread	End-on
Maximum offest	600 m
Standard CMP fold	60
CMP interval	2.5 m
Recording system	G·DAPS-4
Record lenght	2 s
Sampling interval	1 ms

rect geomorphic evidence such as lineaments along the mountain foots.

We conducted high-resolution *P*-wave seismic reflection surveys in the suburbs of Takasaki (fig. 2) to confirm whether the Fukaya Fault extended to the northwest. We acquired *P*-wave seismic profiles on 3 lines shown in fig. 2: Kaburagawa line (1700 m long), Negoya line (800 m long), and Satomi line (2150 m long). An oil hydraulic impactor was used as a seismic source, and both the shot points and receiving points were set at 5 m intervals for all the three lines. Main parameters for the seismic reflection survey are shown in table I.

Figures 3, 4 and 5 show depth-converted seismic reflection profiles of each survey line. A flexure or fault-related fold is clearly imaged on each profile. A concealed flexure in the Kaburagawa profile illustrates detailed stratigraphic

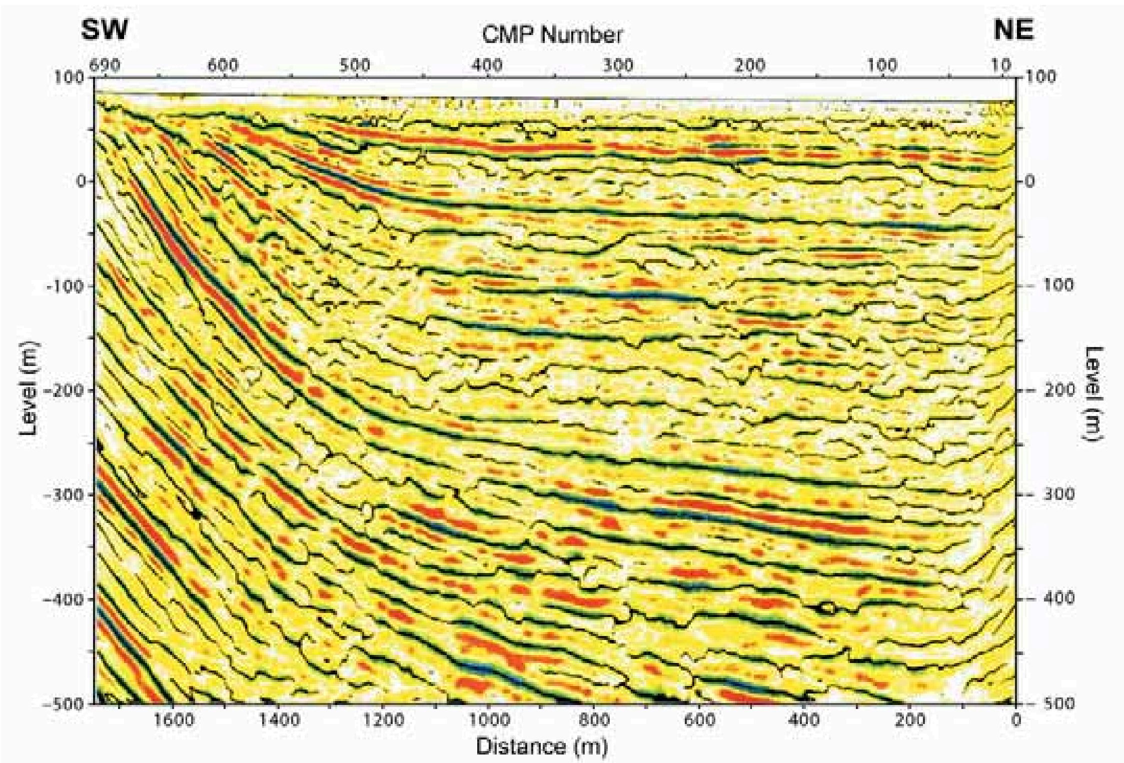

Fig. 3. Depth-converted seismic reflection profile for the Kaburagawa line to the south of Takasaki (vertical exaggeration × 2). See fig. 2 for the location of the survey line.

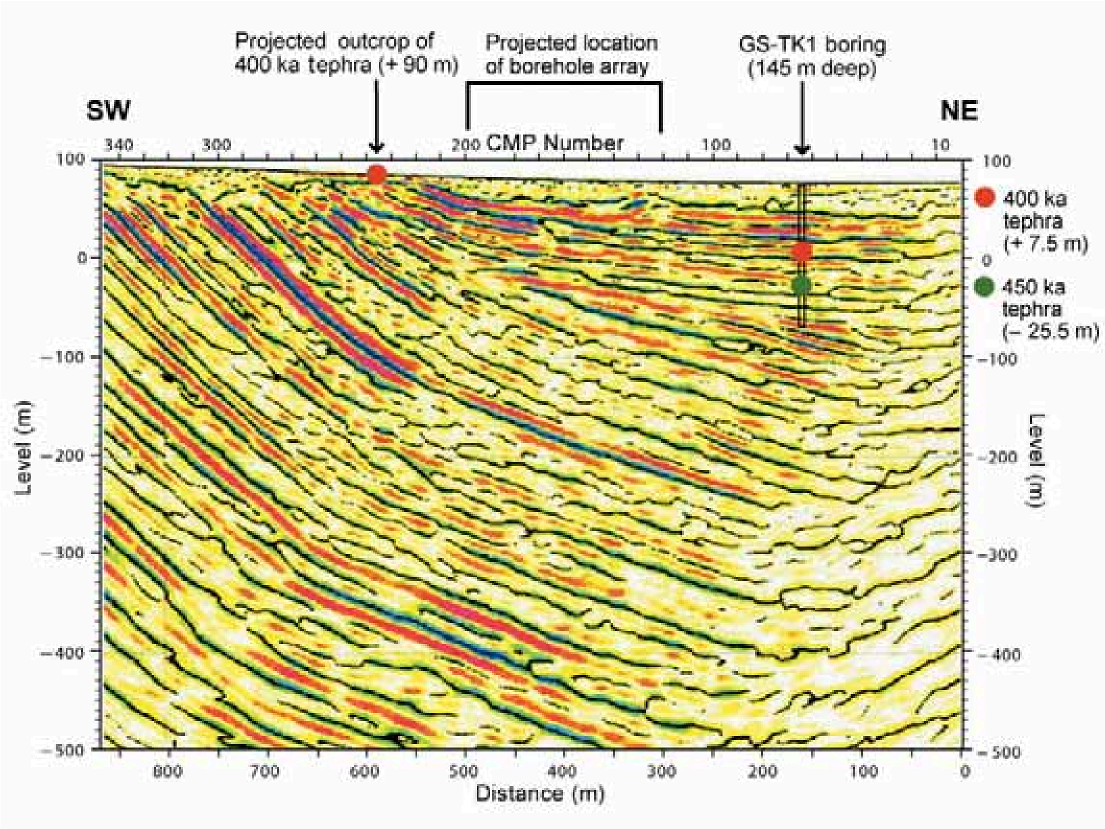

Fig. 4. Depth-converted seismic reflection profile for the Negoya line in Takasaki city (no vertical exaggeration). Both the location of borehole array and tephras recognized by 145 m deep boring and field survey are also projected. See fig. 2 for the location of the survey line.

growth architecture and cumulative deformation of the reflectors (fig. 3). The Negoya profile (fig. 4) is characterized by a kink fold with a hinge line dipping 50 to 60 degrees to the southwest. An angular unconformity is also clearly imaged in shallow strata (around 30 to 50 m below sea level) in the northeastern half of the profile. Although the Satomi profile (fig. 5) is rather low in resolution due to high traffic noise level in the study area, it extends across the entire monocline, which is around 600 m in width.

These results show that the Fukaya Fault extends for about 80 km in an N60°W direction, and forms a fault system, *the Fukaya Fault System*, which is composed of several left-stepping *en échelon* faults.

2.4. *Continuously cored boring*

2.4.1. 145 m long boring

We collected a 145 m long core (GS-TK1) from the downthrown side of the Fukaya Fault System in the Takasaki area. The borehole was located close to the CMP (Common Mid Point) number 65 of the Negoya seismic line (fig. 4). We identified two tephras named TE 5 (*ca.* 400 ka) and Ks 5 (*ca.* 450 ka), which are widespread in Central and Western Japan, at a depth of 70 m (+ 7.5 m in altitude) and 103 m (– 25.5 m in altitude), respectively (Sugai *et al.*, 2000). The TE 5 tephra also crops out on the hillside at about 90 to 96 m

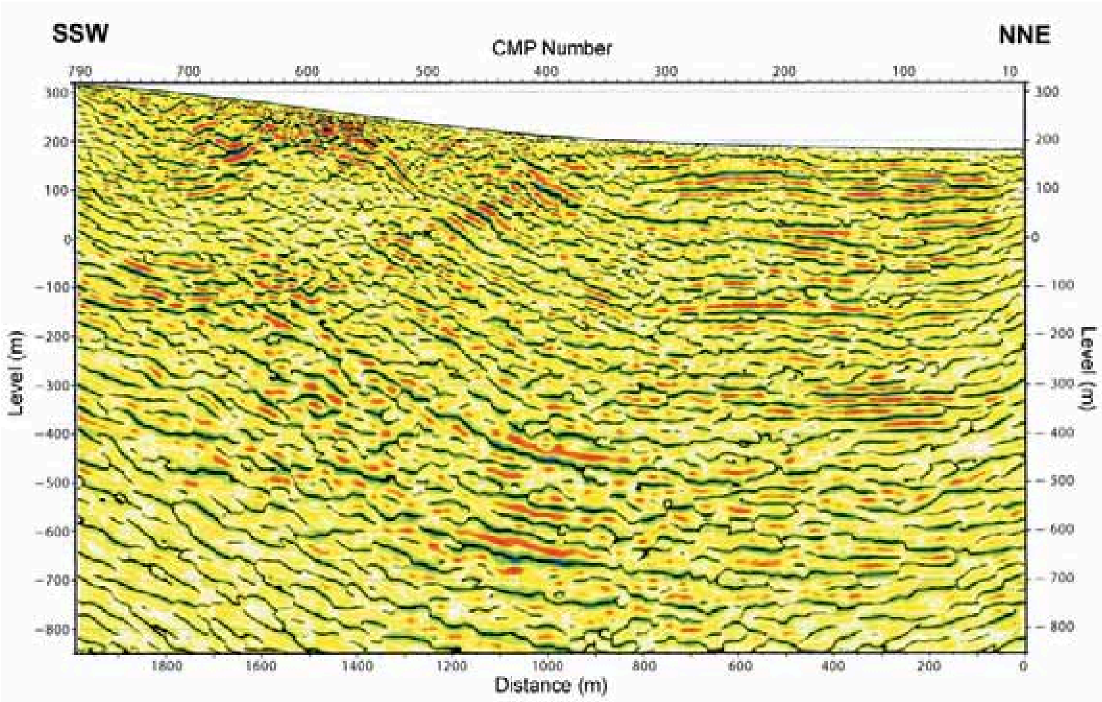

Fig. 5. Depth-converted seismic reflection profile for the Satomi line west of Takasaki (no vertical exaggeration). See fig. 2 for the location of the survey line.

in elevation on the upthrown side of the fault. On the Negoya profile, the exposure of the TE 5 tephra is projected just on the southwestward extension of the stratigraphic horizon where this tephra was found in the GS-TK1 core (fig. 4).

Based on the age of the TE 5 tephra and its measured vertical offset across the flexure, the long-term uplift rate of the Fukaya fault system in the Takasaki area is estimated to be more than 0.2 m/ky.

2.4.2. Boring array

We acquired an array of continuously cored boreholes to define the recency of displacement on the Fukaya Fault System. The 200 m long boring array was projected onto the flexure between CMP number 120 and 200 of the Negoya seismic profile (fig. 4). Figure 6 illustrates Late Quaternary strata defined by the boring array, which is composed of 13 (A-1 ~ A-13) cores ranging in length from 12 to 24 m. Both volcanic mudflow deposits (stratigraphic unit E in fig. 6) of around 50 ka and conformably overlying silt-rich formation (unit D) are deformed by the flexure. Vertical displacement of the unit E/D boundary is estimated at more than 10 m. This value is consistent with the long-term uplift rate (> 0.2 m/ky) across the Fukaya Fault System in the Takasaki area. The Holocene terrace deposits (units C and B) that unconformably overlie the units E and D, however, do not show evidence of deformation.

From these data, we conclude that the Fukaya Fault System in the Takasaki area was reactivated in the past 50 ky, although it remains uncertain whether the last faulting event occurred in Holocene time.

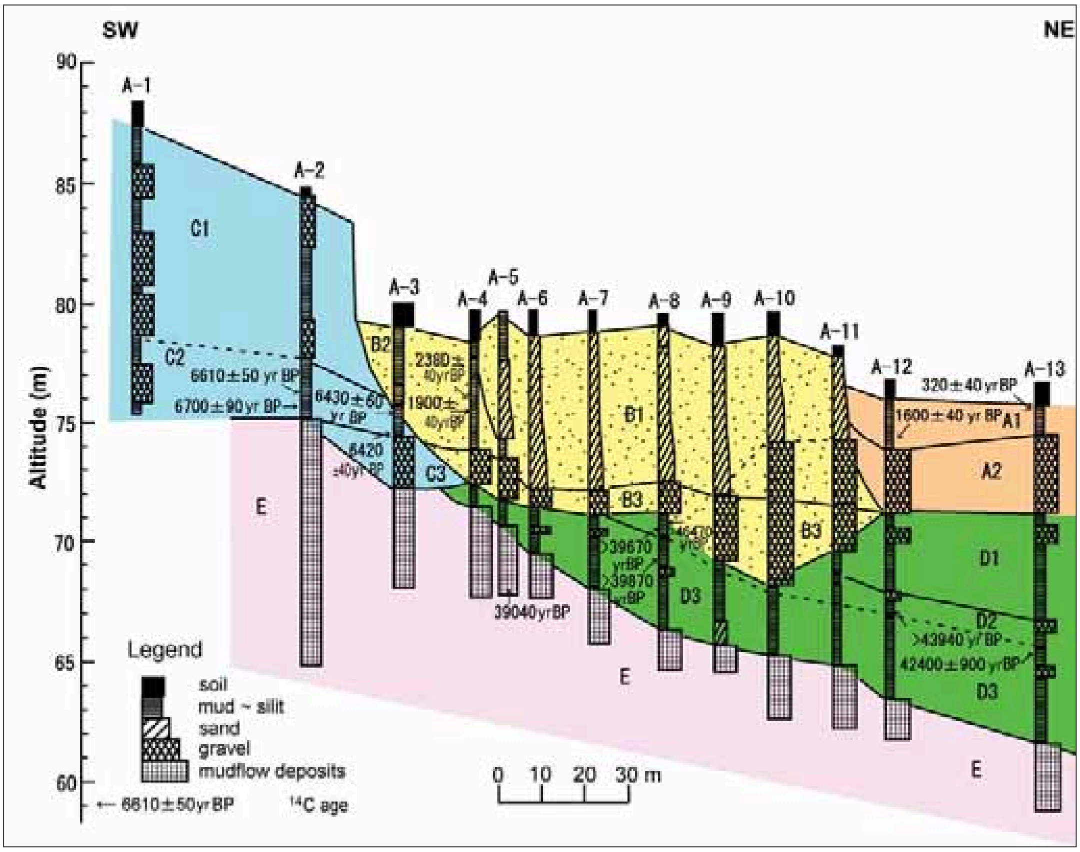

Fig. 6. Correlation of continuously cored boreholes within the flexure zone of the Fukaya Fault System in the Takasaki area. See fig. 4 for the projected location of the survey area. 5 stratigraphic units A-E are recognized, and each unit except for the unit E is divided into several subunits. After Mizuno *et al*. (2001).

3. Uemachi Fault System in the Osaka Basin

3.1. *Osaka Basin*

The Osaka Basin is situated in the easternmost part of the Seto Inland Sea immediate north of the E-W-striking Median Tectonic Line (MTL), which is here an active right-lateral fault system (figs. 1 and 7). The central and western parts of the basin are occupied by Osaka Bay (fig. 7). The northwestern margin of Osaka Bay is bounded by active faults extending from Awaji Island to the foot of the Rokko Mountains on the island of Honshu. The 1995 Kobe earthquake with over 6000 fatalities occurred on NE-striking faults in this region. The eastern onshore region of the basin is divided into the Kawachi Plain and coastal lowland by the N-S-trending Uemachi Fault System and adjoining Pleistocene Uemachi terrace. The Osaka metropolitan area with a population of more than 10 million is contained in the Eastern Osaka Basin. The basin is infilled with over 1000 m of Plio-Pleistocene deposits. Earthquake focal mechanisms, the strike of compressive folds and results of geodetic surveys indicate that the Osaka Basin is being actively shortened in an E-W to WNW-ESE direction.

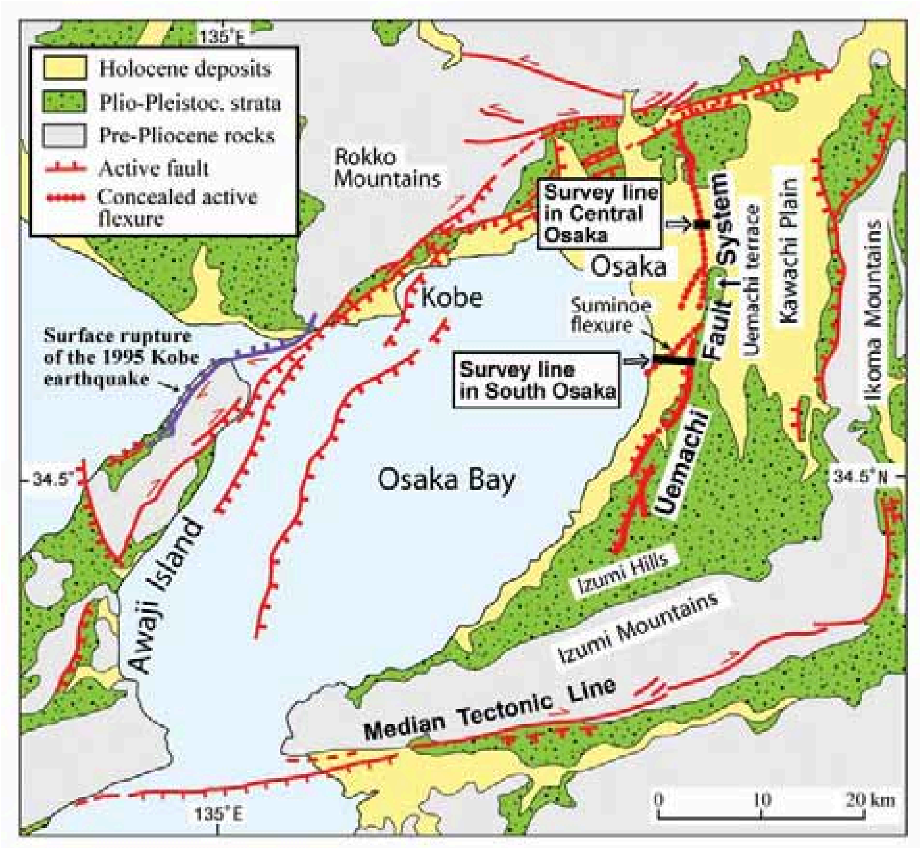

Fig. 7. Simplified geologic map of the Osaka Basin. The basin is bounded by Awaji Island on the west and the Rokko Mountains on the north. It is also bounded on the south by the Izumi Mountains along the Median Tectonic Line and by the Ikoma Mountains on the east.

3.2. *Uemachi Fault System*

Recent acquisition of seismic reflection profiles (*e.g*., Osaka City, 1996; Sugiyama, 1997) and mapping of deformed terrace deposits with air photos (*e.g*., Nakata *et al*., 1996; Okada *et al*., 1996) suggest that the Uemachi Fault System extends for about 45 km, and branches repeatedly towards the south (fig. 7). Along the southern part of the Uemachi Fault System, fluvial terraces of the Last Glacial Stage are vertically offset about 6 m in a fault-related fold formed above blind thrusts of the fault system. Based on borehole data, the long-term uplift rate since the Middle Pleistocene is estimated to be 0.3-0.4 m/ky for the central part of the fault system (*e.g*., Osaka Prefecture, 1999). The cumulative vertical displacement of pre-Neogene basement rocks by the Uemachi Fault System is more than 500 m.

3.3. *Combination survey of high-resolution* S-*wave reflection profiling and continuous coring for the Uemachi Fault in Central Osaka*

We conducted a combination survey of high-resolution *S*-wave reflection profiling and continuous coring across the Uemachi Fault in Central Osaka to constrain the rate and recency of move-

Table II. Main parameters for the seismic reflection surveys of the Uemachi Fault System.

Survey area	Central Osaka	South Osaka	South Osaka
Survey line length	790 m	4300 m	310 m
Applied seismic wave	*S*-wave	*P*-wave	*S*-wave
Seismic source	Plate hitter	Mini vibrator	Plate hitter
Shot point interval	1 m	10 m	1 m
Standard times of shot at each shot point	15 ~ 20	10 ~ 15	40 ~ 60
Receiver	3-geophone array	9-geophone array	3-geophone array
Natural frequency	30 Hz	27 Hz	30 Hz
Receiving point interval	1 m	10 m	1 m
Standard receiving channels	120	70	100
Spread	End-on	Off-end	End-on
Maximum offset	120 m	730 m	100 m
Standard CMP fold	60	35	50
CMP interval	0.5 m	5 m	0.5 m
Recording system	G·DAPS-4	Strata view 60	G·DAPS-4
Record length	2 s	2 s	1.5 s
Sampling interval	1 ms	1 ms	1 ms

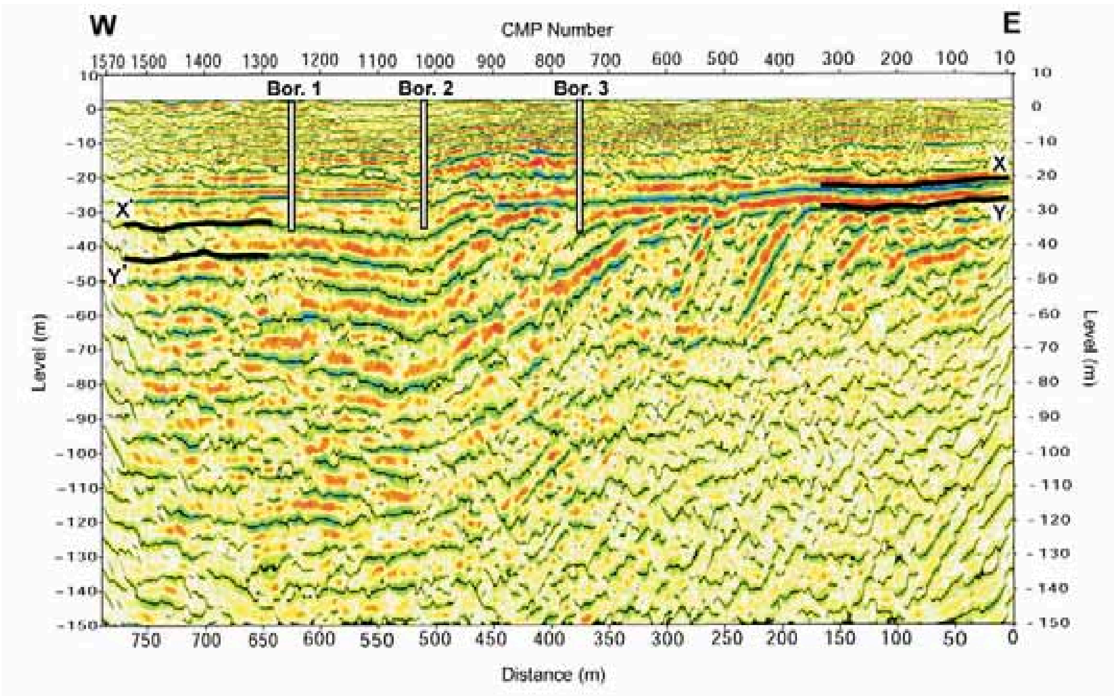

Fig. 8. Depth-converted *S*-wave reflection profile of the Uemachi Fault in Central Osaka (vertical exaggeration × 3). See fig. 7 for the location of the survey line. Reflection surfaces *X* and *X′* are correlative to the base of the Holocene Nanba Formation on the upthrown and downthrown sides of the fault, respectively. Reflection surface *Y* is probably correlated to the base of the Tenma Formation on the upthrown side, and *Y′* is supposed to be the equivalent horizon on the downthrown side. Locations of three continuously cored boreholes are also shown on the profile.

ment along it in Holocene time. A 790 m long survey line was located along the north bank of the Shin-Yodo River, where the Uemachi Fault had been previously identified by a *P*-wave seismic reflection profile (Yamamoto *et al*., 1992). Acquisition and processing parameters for the *S*-wave reflection survey are shown in table II.

The Uemachi Fault is clearly imaged as a flexure, or fault-related fault (fig. 8). A sharp angular unconformity shown by reflection surface *Y* was

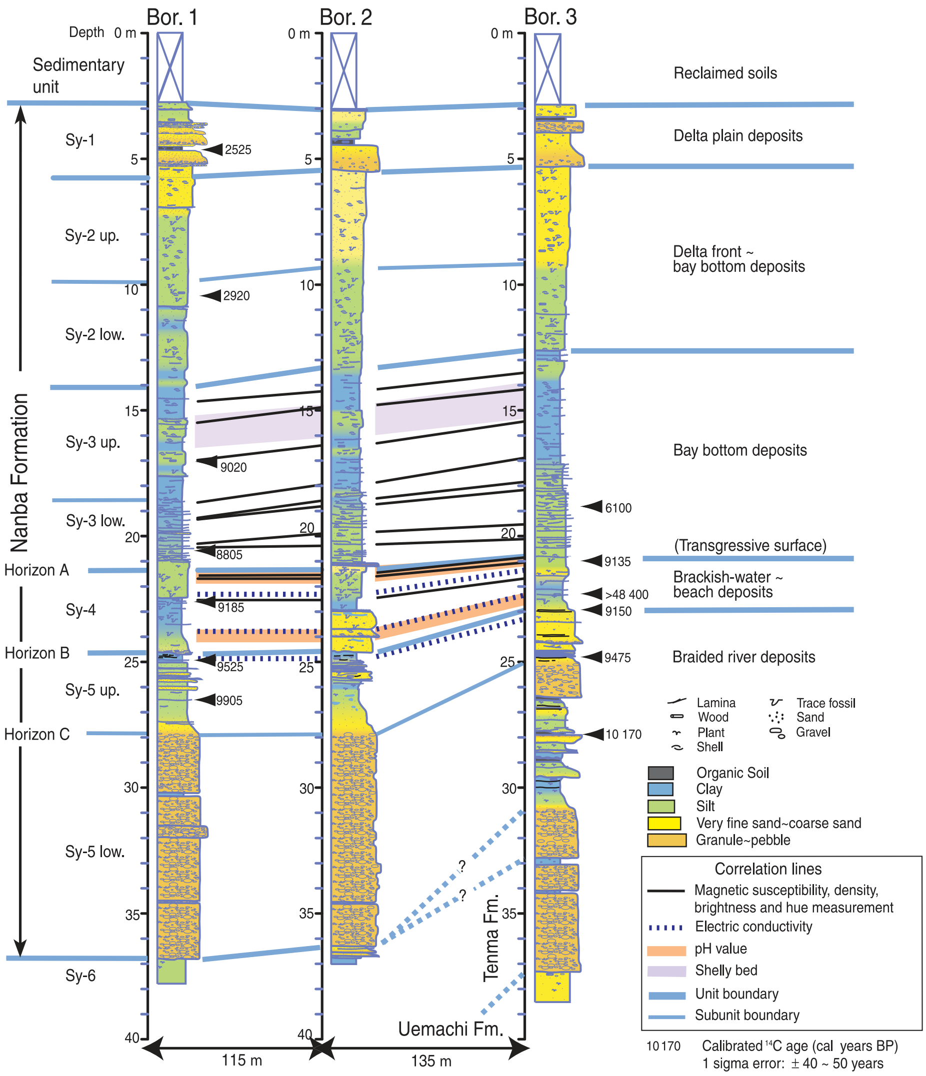

Fig. 9. Summarized stratigraphic correlation between boreholes 1, 2 and 3. The elevation of the three borehole sites is 2.5 m above the sea level. See fig. 8 for the location of each boring site. A clay bed intercalated at the depth of 33 m of borehole 3 is correlated to the Tenma Formation because it yields a pollen assemblage of the first half of the Last Glacial Stage. After Miura *et al*. (2002).

imaged in the eastern (right) part of the profile. Based on boring data, this unconformity is correlated with the boundary between the Uemachi Formation of the Last Interglacial Stage and the overlying Tenma Formation dated as *ca.* 50 to 25 ka. Although the flexure deformation is interpreted to reach the lower part of Holocene deposits (Nanba Formation), it is difficult to constrain the timing of the last faulting event only by the seismic reflection results.

We therefore acquired three continuous cores, all about 40 m long, from the downthrown side, the flexure foot, and the upthrown side (fig. 8). More than 15 correlative horizons were recognized in these cores by detailed analysis of sedimentary facies, pollen and volcanic ash as well as measurement of physical properties such as electric conductivity, *pH*, and magnetic susceptibility.

Correlation of shallow deposits (fig. 9) shows that the vertical separation of correlative horizons in the stratigraphic unit Sy-3 between boreholes 1 and 2 is nearly the same as that between boreholes 2 and 3 across the flexure. This result suggests that the difference in height between these correlative horizons in the three boreholes is of sedimentary origin, and that unit Sy-3 is not deformed by the flexure. Correlative horizons in units Sy-4 and Sy-5 were identified at nearly the same level between boreholes 1 and 2, while they show gradual upward decrease in height difference between boreholes 2 and 3 across the flexure. This gradual upward decrease in height difference across the flexure implies burial of a flexure scarp formed by a faulting event. Therefore we can point out a possibility that the latest faulting event occurred either around horizon C, or during the deposition of the under lying lower part of subunit Sy-5, although the ex act stratigraphic horizon of the latest event is not known because of the lack of correlative horizons within this subunit.

Based on the above seismic and boring survey results, we conclude that the most recent displacement of the blind Uemachi Fault occurred between about 9.5 ka and 25 ka, after deposition of the Tenma Formation, and before deposition of the stratigraphic unit Sy-4. The vertical surface displacement associated with the last faulting event might attain 3 m, assuming that the height diffe-

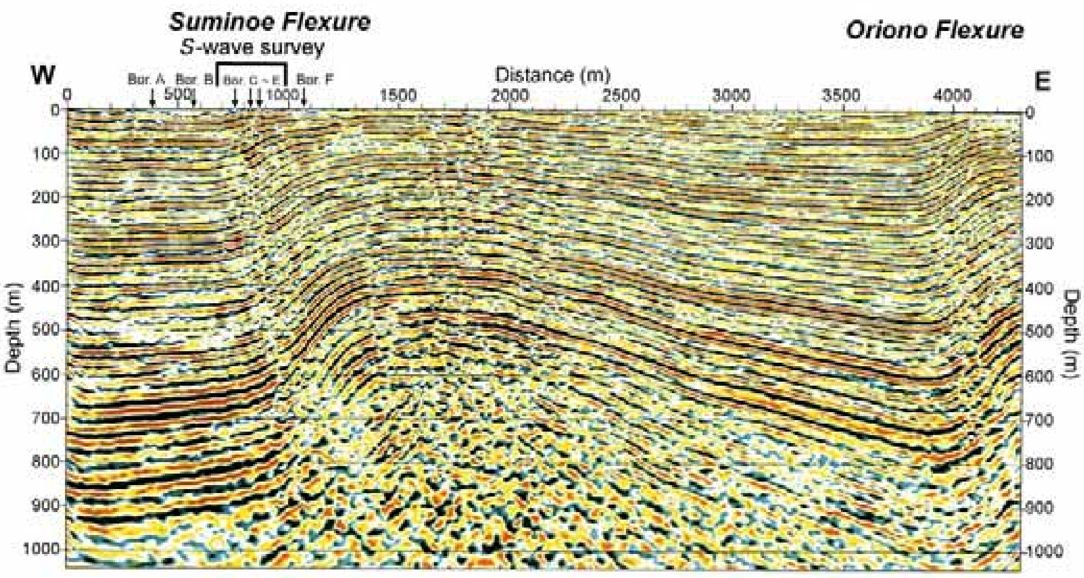

Fig. 10. Depth-converted *P*-wave seismic reflection profile across the Suminoe and Oriono flexures in south Osaka (vertical exaggeration × 2). See fig. 7 for the location of the survey line. Locations of *S*-wave reflection survey line and six boring sites are also shown on the profile.

rence of horizon C between boreholes 2 and 3 directly reflects the flexure deformation during the last faulting event. From the minimum elapsed time of 9.5 ky since the last faulting event and long-term uplift rate of 0.3 - 0.4 m/ky, about 3 m or more vertical surface displacement is expected for the next faulting event. This value is comparable to the above-discussed vertical displacement during the last event.

3.4. *Combination survey of high-resolution seismic reflection profiling and continuously cored borehole array for the Suminoe flexure in South Osaka*

We also studied the Suminoe flexure, a major component of the southern part of the Uemachi Fault System, using a combination of seismic reflection profiling (table II) and an array of con-

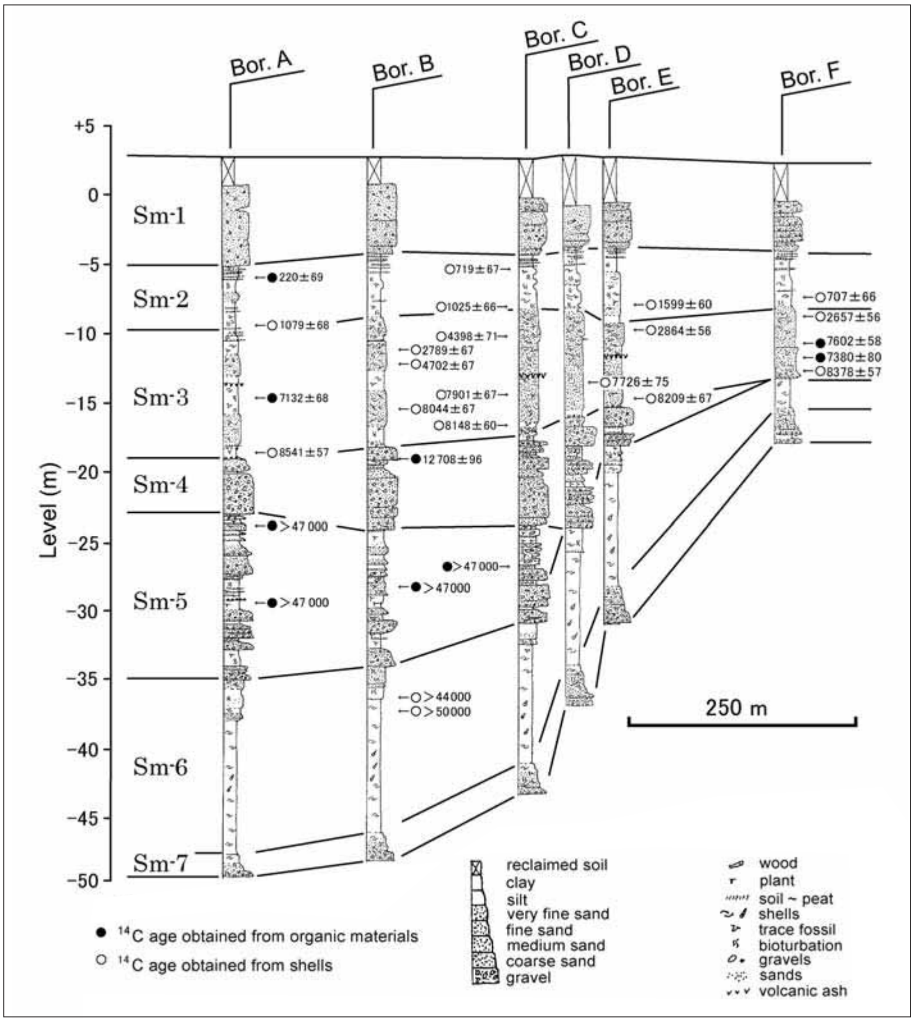

Fig. 11. Correlation of continuously cored boreholes across the Suminoe flexure in South Osaka. See fig. 10 for the location of each boring site. Modified from Nanayama *et al.* (2000a).

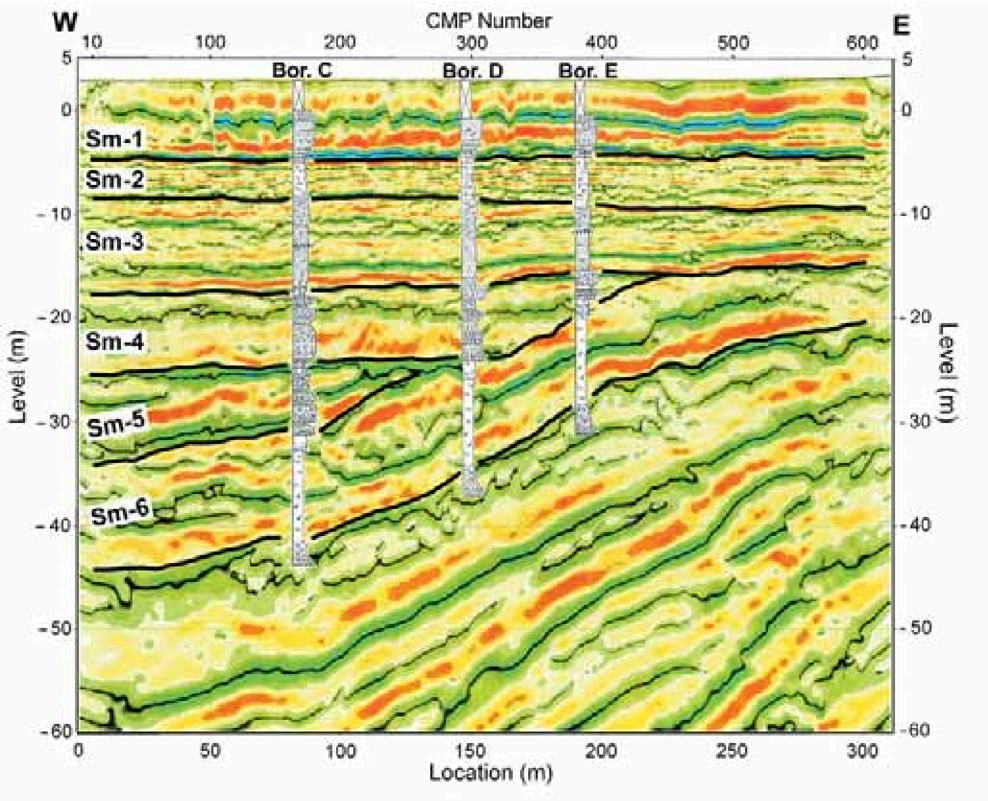

Fig. 12. Depth-converted *S*-wave seismic reflection profile across the Suminoe flexure combined with the boring survey result (vertical exaggeration × 4). See fig. 10 for the location of the survey line.

tinuously cored boreholes. We first acquired a 4300 m long *P*-wave seismic reflection profile (fig. 10) across both the locally named Oriono flexure along the western hillside of the Uemachi terrace and the Suminoe flexure, which is completely concealed beneath Holocene deposits in the coastal plain. The profile clearly imaged both the Oriono and Suminoe flexures as typical fault-propagation folds with compressive growth architecture (*e.g.*, Suppe *et al.*, 1992; Allmendinger, 1998). On the basis of the seismic profile and existing borehole data, the long-term uplift rates of the Oriono and Suminoe flexures were estimated to be 0.25 m/ky and 0.15 m/ky, respectively. In addition, Holocene deposits around the Suminoe flexure were inferred to be more than 15 m in thickness from existing borehole data. Consequently we chose the Suminoe flexure as the target fault for clarifying the recent activity by high-resolution *S*-wave seismic reflection profiling coupled with an array of continuously cored boreholes.

We acquired a 310 m long *S*-wave reflection profile across the Suminoe flexure and obtained six continuous cores ranging in length from 21 to 55 m. Correlation of Late Quaternary deposits among the six cores (fig. 11) is quite consistent with the *P*-wave and *S*-wave reflection profiles. The *S*-wave profile, coupled with the stratigraphy defined in the cores (fig. 12), shows that the stratigraphic unit Sm-4 unconformably overlies the tilted unit Sm-5, and onlaps the flexure scarp made up of the older unit Sm-6. It is also clearly shown that unit Sm-4 and overlying units are not involved in the deformation.

Based on our interpretation of the *S*-wave profile linked with the borehole array, we conclude that the most recent activity of the Suminoe flexure occurred after deposition of unit Sm-5 whose age is estimated at 70-50 ka based on its pollen assemblage (Nanayama *et al.*, 2001a), and before deposition of unit Sm-4 dated as 15-10 ka. Nanayama *et al.* (2001b) estimated an average uplift rate of 0.2 m/ky for the last 130 ky based on the assumption that the original depositional dip of the base of unit Sm-7 is the same as that of the base of unit Sm-3. This uplift rate, together with the minimum elapsed time of 15 ky since the last faulting event, implies that 3 m of vertical displacement has been stored on the Suminoe flexure.

4. Concluding remarks – problems and future research

Our work in the Kanto and Osaka basins has demonstrated the effectiveness of combining acquisition and analysis of high-resolution seismic profiles and continuously cored boreholes to assess the paleoseismic record of blind thrusts underlying densely populated and urbanized areas. It is, however, still difficult to constrain the exact timing of the most recent faulting event on blind thrusts because they are expressed at the surface as a wide deformation zone of flexure. This mainly stems from a difficulty in detecting differences between deformed layers and non-deformed beds, or differences between subtle tectonic tilting and primary depositional dip. Use of a newly developed device termed a Geoslicer (Nakata and Shimazaki, 1997; Atwater *et al.*, 2001) may improve paleoseismic records on blind thrusts by defining and dating liquefaction or subaqueous slides produced by paleoearthquakes.

We have focused on the slip rate as a target fault parameter in our blind fault study. It provides a basis for estimating moment release rates and constraining future earthquakes on blind faults (*e.g.*, Oskin *et al.*, 2000). It also can be coupled with structural models of fault-related fold growth (*e.g.*, Schneider *et al.*, 1996; Cannon *et al.*, 2001). Our estimates of slip rates for the Fukaya and Uemachi fault systems, however, are based only upon data obtained from the subsurface several tens to several hundreds meters deep. The slip rates in such a shallow part might be smaller than those at depths where seismic energy is substantially released (*e.g.*, Stein and King, 1984). The effect of compaction on thickness of deposits also must be taken into consideration for estimating slip rates (*e.g.*, Schneider *et al.*, 1996). We need to make further efforts to clarify the slip rate of the deeper part of these fault systems for acquiring more plausible earthquake scenarios for Tokyo and Osaka.

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