地 震 研 究 所 彙 報
Bull. Earthq. Res. Inst.
Univ. Tokyo
Vol. 81 (2006) pp. 239-245

Deep Seismic Surveys in the Kinki District : Shingu-Maizuru Line

Kiyoshi Ito[1)], Yasuhiro Umeda[1)], Hiroshi Sato[2)], Issei Hirose[1)], Naoshi Hirata[2)], Taku Kawanaka[3)] and Takeshi Ikawa[3)]

[1)] Disaster Prevention Research Institute, Kyoto University, Uji, 611-0011, Japan
[2)] Earthquake Research Institute, University of Tokyo, Tokyo, 113-0032, Japan
[3)] JGI, Inc, Tokyo, 112-0012, Japan.

Abstract

Seismic surveys of the crust and the upper mantle structure have been conducted under the Special Project for Earthquake Disaster Mitigation in Urban Areas (DAIDAITOKU). In 2004 deep seismic surveys were carried out in the Kinki district southwest Japan. Seismic refraction and wide-angle-reflection surveys were carried out along the Shingu-Maizuru line, which crosses Honshu Island from the Pacific side to the Japan Sea side nearly coincident with the direction of the subduction of the Philippine Sea plate (PHS). In the profile, 13 shots (100-700 kg) of dynamite and 3 multi-sweeps (a few hundreds of sweeps) with 4 vibroseis trucks were used as sources of the surveys. More than 2300 observation sites were set at intervals of 50-100 m all along the line. Clear first arrivals and reflections from PHS and from reflectors in the crust were obtained at almost all the stations. In particular, waves from dynamite were well recorded at all stations. As for the stacked data of multisweeps, waves can be recorded in the offset range of 30-40 km from the source. The multi-vibration method is particularly useful for the surveys in the urban areas, where dynamite cannot be used as a source. The reflections from PHS are very clear beneath Kii Peninsula and are still visible under the northern Kinki district at depth of about 50-70 km, where no earthquakes occur. The reflectors seem to indicate aseismic slab in the northern Kinki district. A clear two parallel reflectors dipping towards north associated with PHS are seen beneath Kii Peninsula. The lower reflector is coincident with the upper boundary of earthquake distribution in the mantle, which has been considered as the plate boundary. The boundary seems to be the oceanic Moho. The upper reflector is determined to be about 7-10 km shallower than the lower one and this is the plate boundary of the subducting plate. The layer between the two reflectors is thought to be the oceanic crust subducting in the mantle. Low frequency earthquakes and/or tremors occur at 30-40 km deep in the upper reflector, which is less distinct at the low frequency events. In the inland area, many clear reflections were obtained at depth of about 15 and 25 km. These reflectors decline towards north, which seem to relate with the large active faults. The reflector at depth of about 15km is well corresponded to the base of the seismogenic zone in the crust and seems to play an important role to the nucleation process of large inland earthquakes. Another reflector at depth of about 25 km may possibly be the impermeable layer, which may cause pre seismic slip for large inland earthquakes.

Key words : seismic velocity structure, controlled source seismology, active fault, Philippine Sea plate, strong motion evaluation

1. Introduction

A program was started by the Headquarters for Earthquake Research Promotion Japan in 2002 for the purpose of the reduction of seismic hazard in the metropolitan areas. As a part of this program, deep seismic profiling was begun in order to reveal the

* e-mail: ito@rcep.dpri.kyoto-u.ac.jp (Gokasyo, Uji, Kyoto 611-0011)

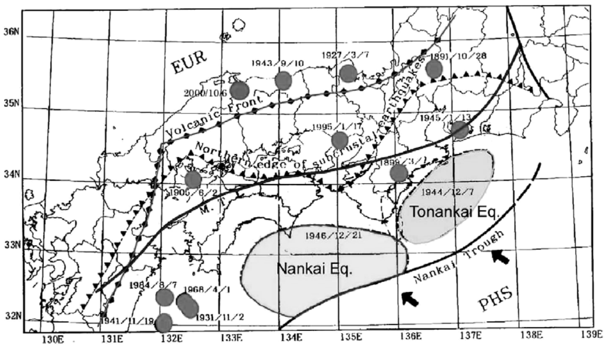

Fig. 1. Tectonic setting of Southwest Japan. The Philippine Sea plate (PHS) is subducting beneath the Eurasian Plate (EUR). Dots show large earthquakes with magnitude greater than 7 since 1885. MTL indicates the Median Tectonic Line.

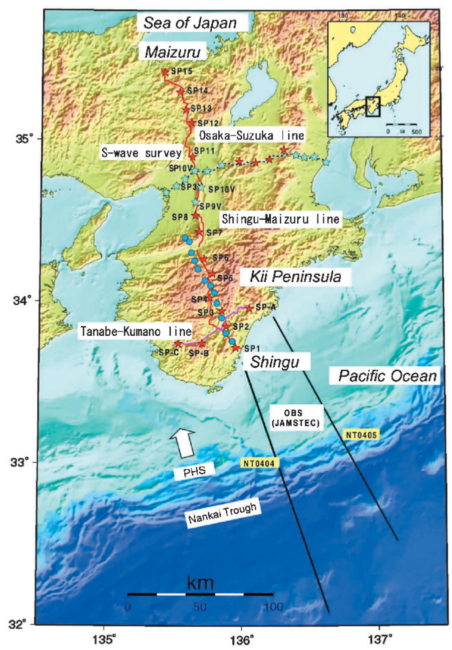

Fig. 2. Seismic survey lines in 2004 under the special project for earthquake disaster mitigation in urban areas (DAIDAITOKU I) in the Kinki district. Shoingu-Maizuru profile is reported in this paper. Osaka-Suzuka profile is conducted by ERI, University of Tokyo. Surveys in the sea were carried out by JAMSTEC under a different project but as cooperative with DAIDAITOKU project.

regional characterization of metropolitan areas as a five-year project. The final goal of the project is to produce a map of more reliable estimation of strong ground motions in the Kanto and Kinki areas. The surveys required for this project are accurate determinations of a source, a propagation path and a site

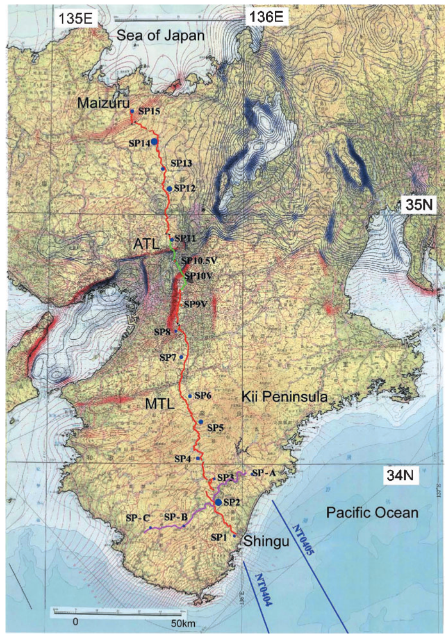

Fig. 3. The profile line with the Bouguere gravity anomaly (Gravity. Res. Group (2001). Shot points and observation lines are plotted in the figure. Dense contours of the gravity anomaly correspond to active faults, such as MTL (Median Tectonic Line) and ATL (Arima-Takatsuki Tectonic Line).

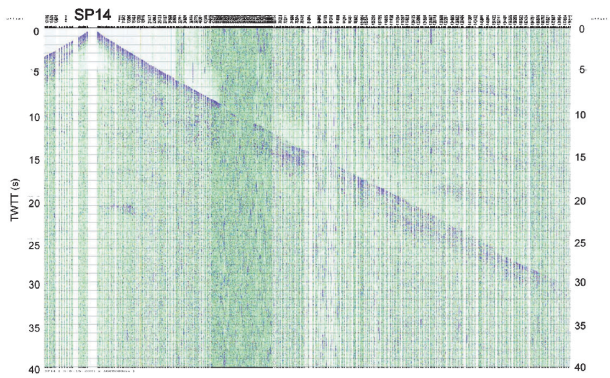

Fig. 4a. Record section for Sp14 of 700 kg dynamite at southern Kinki district.

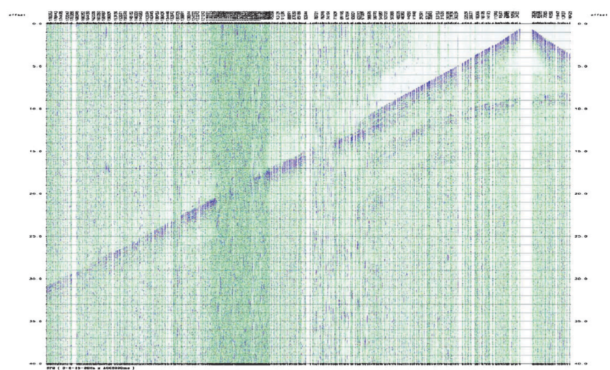

Fig. 4b. Record section for Sp2 of 700 kg dynamite in the northern Kii Peninsula.

response for earthquakes. More specifically, purposes of the surveys are to determine the accurate positions and geometry of source faults, subducting plates and mega-thrust faults, crustal structure, seismogenic zone, sedimentary basins, and 3D velocity structures. Reconstructions of source fault and velocity models lead to more realistic 3D estimation of strong motion seismic waves.

The surveys were conducted in the fiscal years of 2002–2003, in the Kanto area. Deep seismic surveys were extensively carried out along the 4 lines. In the fiscal year of 2004, the survey area was shifted to the Kinki area and surveys along two measure lines, Osaka-Suzuka (E-W) and Shingu-Maizuru (N-S) lines were conducted by ERI, University of Tokyo and DPRI, Kyoto University, respectively. This is a report for the Shingu-Maizuru (N-S) line, crossing Honshu Island from the Pacific side to Japan Sea side.

2. Outline of the surveys

Figure 1 shows the outline of the tectonic setting in southwest Japan. The Philippine Sea plate subducts towards northwest from the Nankai trough and great earthquakes such as the Tonankai and Nankai earthquakes have been repeated every about 100 years. Large earthquakes with M (magnitude) greater than 7 also occurred in the inland area.

Figure 2 shows the survey line with shot points. As shown in the previous paper (Ito *et al.,* 2004), the line is set to reveal the features of the Philippine Sea plate (PHS) nearly parallel to the subduction direction from the southern coast of Kii Peninsula to the northern coast of the Kinki district. As shown in Fig. 3, the line cut through the major fault systems of the Median Tectonic Line (MTL) and the Arima-Takatsuki Tectonic Line (ATL) trending about east-west direction. In addition, the line is located along the eastern margin of the Osaka-city area, crossing the dense active fault zone in the northern Kinki district.

Furthermore, the surveys were connected to those conducted by JAMSTC in the Pacific Ocean side at the same time (Fig. 2). The signals on land were recorded with ocean bottom seismometers and air-gun signals in the sea with recorders on land in the southern half of the measure line.

As shown in Fig. 3, 13 shots of dynamite (100–700 kg) and 3 multivibration (a few hundreds of sweeps) with 4 vibroseis trucks were used for refraction and wide-angle reflection surveys in the experiment. More than 2300 seismometer sites were deployed at intervals of 50–100 m all along the line. Each recorder of six channels were equipped with a GPS receiver which gives synchronized records within 1ms at all stations. All records, therefore, can be used for stacking of the reflection analyses.

Figures 4a and 4b show examples of the records from dynamite shots, sp14 and sp2, respectively. The charge sizes of the shots are 700kg. Clear first arrivals and reflections from PHS and the middle and lower crust were obtained all through the line as seen in Fig. 4. Although the records in Fig. 4 are obtained from 700 kg dynamite in charge size, all records of other shots of 100–400 kg charge were also clear at almost all stations.

3. Results of the wide-angle-reflection and refraction surveys

The obtained records were processed in the typical procedure of reflection seismology for wide-angle reflection sections. A migrated time section is shown in Fig. 5. Figure 6 shows depth section converted by use of the velocity analyses of the records for the measure line. Drawing of the apparent reflections and JMA (Japan Meteorological Agency) unified hypocenters are also shown in the Fig. 6. Besides, low frequency-earthquakes (LFE) are plotted in Fig. 6.

The clear image is obtained as a traverse of Japanese Islands. In particular, the reflections from PHS are very clear beneath Kii Peninsula. The subducting PHS is well determined as dual reflectors, which show the shape and structure of the plate as well as the location of the plate. Besides, the reflectors are still visible beneath the northern Kinki district at depth of about 50–70 km. Furthermore, the reflectors from the subducting PHS change their dip from 20 degrees to gentler angle at the middle of the Kinki district as shown in Figs. 5 and 6. No earthquakes in the mantle occur from there to inner zone.

At least two reflectors are clear beneath Kii Peninsula and the lower one roughly coincides with the upper limit of the earthquakes in the mantle. Therefore, the lower reflector is thought to be the oceanic Moho of the subducting plate. Thus, the depth of the plate boundary is shallower than those determined from the earthquake distribution by about 7–10 km. Plate boundaries determined by some methods are

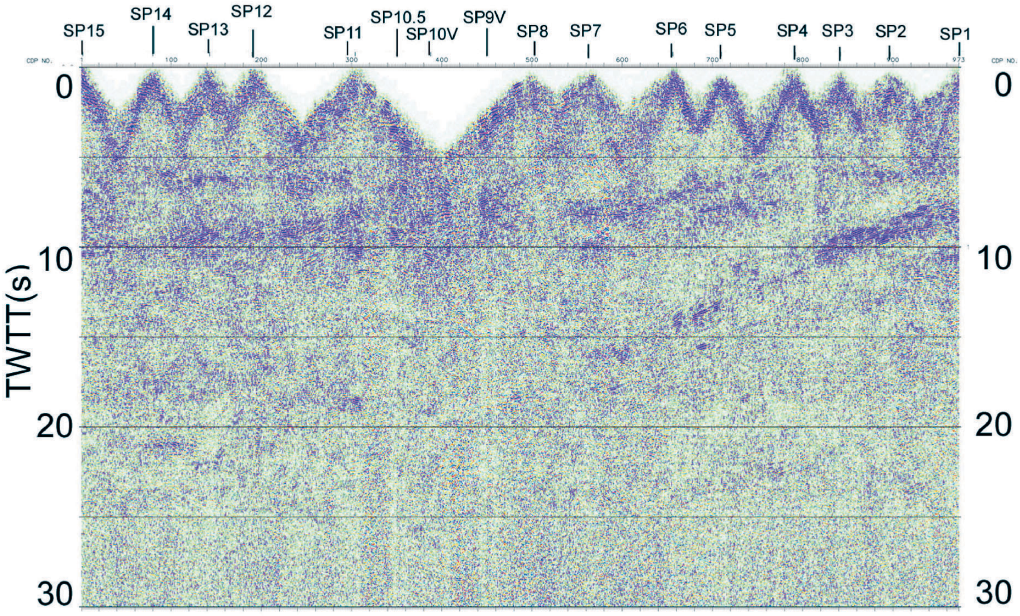

Fig. 5. Migration section of wide-angle reflection survey. Right side is the Pacific side and clear subduction of PHS is seen as double reflectors. Some reflections mostly dipping north are obtained in the middle to lower crust.

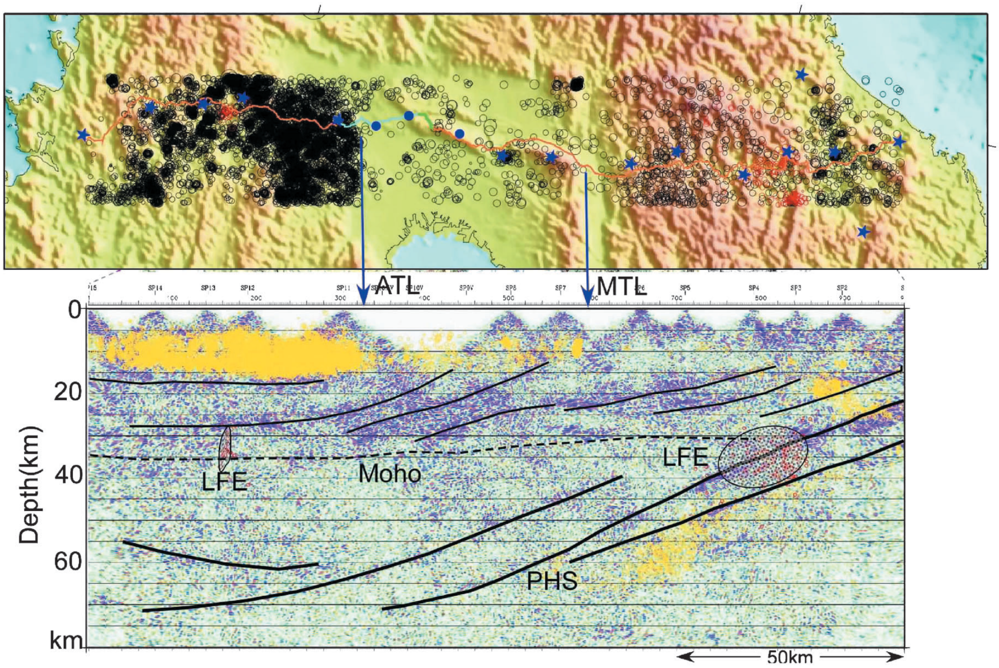

Fig. 6. Depth section of wide-angle reflection surveys (lower figure) along the Shingu-Maizuru line. Hypocenters (yellow dots) are plotted from the JMA unified hypocenters. Red dots show low-frequency earthquakes (LFE). Lines are eye-picked clear reflections.

shown in Fig. 7. Nakamura *et al.* (1997) determined the mean depth of earthquakes in the mantle by using the hypocenters of microearthquake data, collected from the Wakayama and Hiroshima Observatories of University of Tokyo, Kochi Observatory of Kochi University and Tokushima Observatory of Kyoto University. The contour map by Nakamura *et al.* (1997) is shown in Fig. 7. Yamauchi *et al.* (2003)

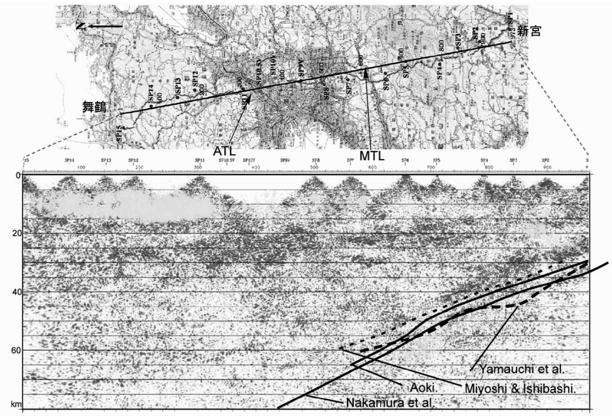

Fig. 7. Plate boundaries of PHS determined from other studies drawn in the reflection section in Fig. 6. See text for detail.

analyzed the Hi-net data by use of receiver function method and made a contour map of the plate boundary, which they thought to be the oceanic Moho. The contour map is nearly the same as that by Nakamura *et al.* (1997) shown in Fig. 8 and the boundary in the section of the profile is almost the same as that by Nakamura *et al.* (1997) as shown in Fig. 7. Aoki (2003) and Miyoshi and Ishibashi (2004) determined upper limit of the earthquakes in the mantle from the unified hypocenters by JMA. Results are almost the same as each other, of which boundaries in the profile are shown in Fig. 7. All these boundaries are deeper than the clear reflection obtained from seismic surveys as shown in Fig. 7.

Figure 9 shows focal mechanisms of the earthquakes deeper than 25 km. Most mechanisms of earthquakes in the area are strike-slip or normal fault types and no thrust-type events showing the plate subduction have been found in the mantle of this area. Tension axes of the events are nearly parallel to the Nankai trough. This suggests that the earthquakes are not inter-plate events but intra-plate ones. This shows that the events take place in the mantle under the oceanic Moho of the subducting plate.

Low frequency earthquakes (Obara, 2002) occur in the upper side of the lower reflector, between the two reflectors at depth of 30–45 km. The Moho reflections are not clear in Figs. 5 and 6, but it is supposed to be about 35 km from the travel times of refracted waves. Therefore, the low frequency earthquakes occur at the contact area of the Moho with the plate

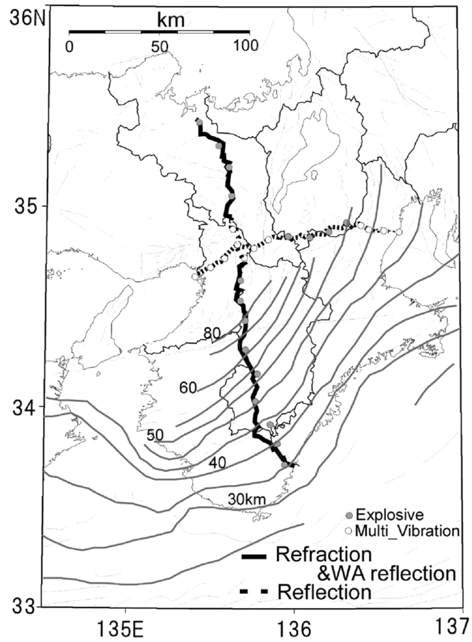

Fig. 8. Cantors of the mean depth of sub-crustal earthquakes showing subduction of the PHS. (Nakamura et al., 1997).

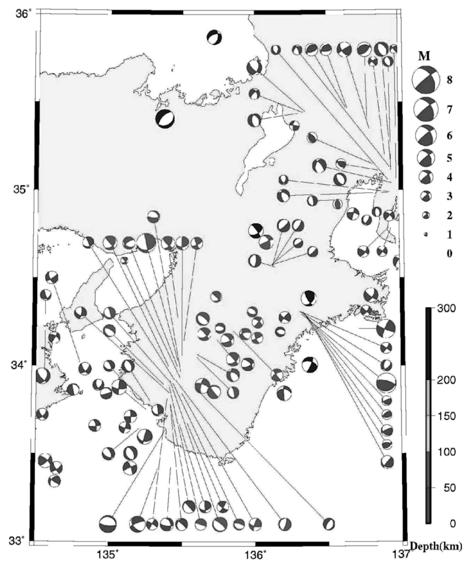

Fig. 9. Focal mechanisms of the earthquakes deeper than 25 km, in the mantle. They indicate strike-slip of normal fault types with the maximum tension axes perpendicular to the subduction of the plate.

boundary.

Reflections in the mantle beneath the northern Kinki district are thought to be related to the subduction of PHS, but no earthquakes were observed not only in the mantle but also in the lower crust in the middle of the northern Kinki district, except for low frequency earthquakes at depth of the Moho. Besides, the subduction angle seems to be gentle in the area of aseismic slab. The same kind of reflectors is found in western Tottori Prefecture, Chugoku district (Nishida *et al.,* 2001). This suggests that aseismic PHS possibly exists in the wide area of the northern Kinki and Chugoku districts.

Reflectors in the crust of the northern Kinki district are well distributed in two lines at depth of about 15–17 and 26–28 km. The former correspond to the base of the seismogenic layer in the crust. Since most of large inland earthquakes are likely to initiate near the cutoff of seismicity (Ito, 1992), the reflector is possibly be related to the source process of the large events in the crust as follows. High pressure or gas concentrated under the reflection layer flow up into the upper crust, when a part of the layer breaks. This fluid or gas reduces the strength of the fault in the upper crust, which cause the big earthquakes. The reflector at the base of the seismogenic layer is also distributed in the wide areas of the inland of Japanese Islands from other seismic survey results. The lower reflector may be another reservoir of the fluid or gas. The fluid or gas may come from the aseismic PHS benearth the Kinki district.

In the middle and the southern Kinki district there are clear reflectors dipping towards north. The reflections are distinct in the lower crust, but it is not clear how they continue to the upper crust and also to the active faults. In other words, it is not clear from this survey that the reflectors continue to active faults in the upper crust, since shot spacing is large as 10 to 15 km. However, the north dipping plane is well analyzed from the survey for the Median Tectonic Line (MTL). Although detailed survey was carried out for the Arima-Takatsuki Tectonic Line (ATL), the feature is still not clear.

4. Concluding remarks

From the seismic surveys along the Shingu-Maizuru line, the followings are obtaind :

1. Clear reflectors are detected at the cutoff of seismicity of 15–17 km deep in the northern Kinki district.

2. Another clear reflectors are found at depth of about 26–28 km in the northern Kinki district.

3. Clear double reflectors in the mantle dipping north are found in the middle to southern Kinki district. The reflectors show subduction of PHS.

4. The lower reflector of PHS corresponds to the upper boundary of the earthquakes in the mantle, which suggests the reflector is coincident with the oceanic Moho of the subducting plate.

5. Reflectors related to PHS continue to the northern Kinki district down to about 60–70 km deep.

6. Low frequency earthquakes occur between the upper and lower reflectors beneath Kii Peninnsula, where the Moho contacts with the plate at depth of 30–45 km.

Acknowledgments

We thank many stuff members of the local governments, such as Osaka, Kyoto, Shiga, Nara and Wakayama prefectures and related towns and villages for their assistance during the surveys. We also thank Dr. H. Kimura of Earthq. Res. Inst., Univ. of Tokyo for his critical reading of the manuscript. This workshop is sponsored by the Special Project for Earthquake Disaster Mitigation in Urban Areas from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

Aoki, H. (2003) Configuration of the subducting Philippine Sea plate and its continuity, Rep. Tono Res. Inst. Eq. Sci., 13, 43–50.

Gravity Research Groupin Southwest Japan, (Shichi R. and A. Yamamoto), 2001, Gravity database of Southwest Japan, (CD-ROM).

Ito, K., (1992), Cutoff depth of seismicity and large earthquakes near active volcanoes in Japan, Tectonophysics, 217, 11–21.

Miyoshi, T. and K. Ishibashi, (2004) Geometry of the Seismic Philippine Sea Slab beneath the Region from Ise Bay to Western Shikoku, Southwest Japan, Zisin (J. Seism. Soc. Jpn)2, 57, 139–152 (in Japanese with English abstract). Z

Nakamura, M, H.Watanabe, T.Konomi, S.Kimura and K. Miura, (1997) Characteristic activities of subcrustal earthquakes along the outer zone of Southwestern Japan, Annuals, Disaster Prev. Res. Inst. Kyoto Univ., 40, B-1, 1–20.

Nishida, R., N. Hirata, K. Ito, Y. Umeda and T. Ikawa, (2001) Underground structure investigation in western Tottori Prefecture (Part 1), Prog & Abst., Seis. Soc. Jpn., 2002, Fall Meeting, P062.

Obara, K., (2002) Nonvolcanic deep tremor associated with subduction in Southwest Japan. Science, 296, 1679–1681.

Ohmi, S., (2002) Deep low-frequency (DLF) earthquakes associated with active faults in Southwest Japan, Annuals, Disas.r Prev. Res. Inst. Kyoto Univ., 45, B, 545–553.

RGES (Research Group for Explosion Seismology), (1992), Explosion seismic observations on the Kii Peninsula, Southwestern Japan (Kawachinagano -Kiwa profile), Bull. Earthq. Res. Inst., Univ. Tokyo, 67, 37–56.

Yamauchi, M., K. Hirahara and T. Shibutani, 2003, High resolution receiver function imaging of the seismic velocity discontinuities in the crust and the uppermost mantle beneath southwest Japan, Earth Planets Space, 55, 59–64.

(Received December 1, 2005)
(Accepted December 4, 2006)