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The travel time delay correction of seismic wave at CEORKA strong ground motion observation stations in the Osaka Basin

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Abstract

Arrival times of seismic waves at sites located over sedimentary basins show travel time delays due to the difference in seismic wave velocity between basement rocks and overlying sediments. This time delay leads to an error of the hypocenter determination. We determined the corrected values for the travel time delay at the 13 CEORKA sites distributed in the Osaka Basin. Using the heuristic search and empirical criteria, we could achieve an effective estimation for the travel time delay correction caused by the sedimentary cover. For earthquakes in and around the Osaka Basin, this correction method may improve the accuracy of the hypocenter determination using only seismograms acquired on sites over sediments.

Key-words : Travel time delay, CEORKA, Osaka Basin, sedimentary layer, arrival time.

1. Introduction

Seismograms acquired over sediments show travel time delays caused by the velocity difference of seismic waves in basement rocks and in sediments. This problem of the travel time delay induces an error in hypocenter determination using only seismograms acquired over sediments. These conditions are applicable to most sites which belong to the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA) on the Osaka Basin. In order to solve this problem, we need to calculate and remove the travel time delay caused by the sedimentary cover at each site.

There are specific phases that appear in seismograms acquired over the sediments. The most specific 2 phases are the Ps-wave that appears on the horizontal component after the P-wave arrival and the Sp-wave that appears on the vertical component before the S-wave arrival (Fig. 1). These converted waves are not observed on seismograms acquired over the basement because they are generated at the boundary between the sediments and the basement due to the difference in impedance. This is because there is a slight or no difference between P-Ps time interval and Sp-S time interval, the term P-Ps interval is used to specify both intervals in this study. We used the P-Ps interval as information of subsurface sediments to estimate values of the travel time delay correction (TTDC) at the 13 CEORKA sites on the Osaka Basin.

2. Data

We selected 5 earthquakes that occurred in the period between 1994 and 2001 in and around the Osaka Basin for picking the arrival times of P-, Ps- Sp-, and S-waves (Table 1). We also used seismograms of the 5 earthquakes obtained at the 13 CEORKA sites as well

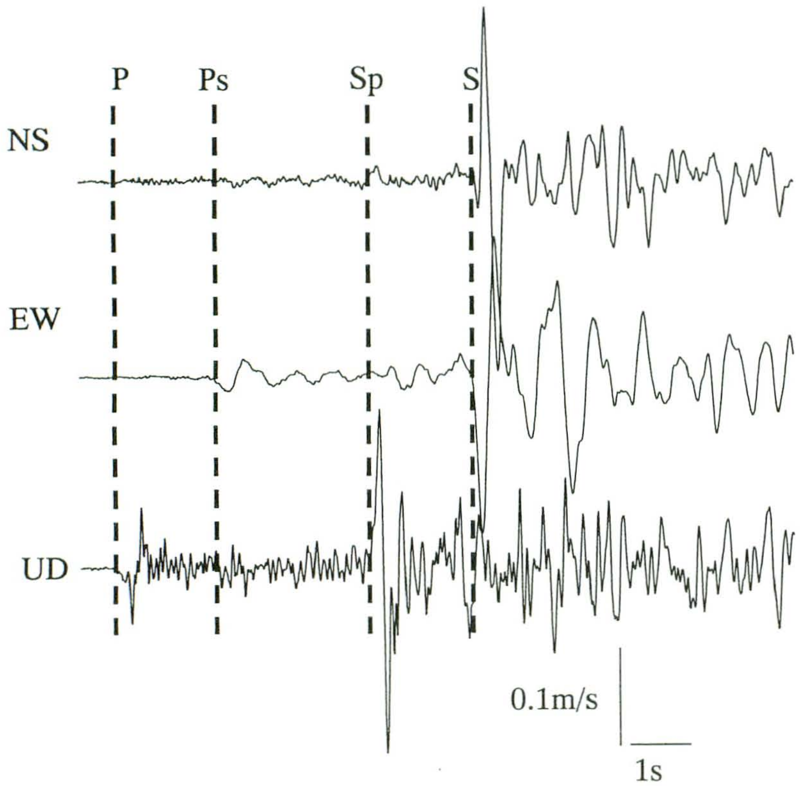

Fig. 1 Example of seismogram acquired over sedimentary layer. NS, EW, and UD indicates north-south component, east-west component, and vertical component, respectively.

Table 1 Parameters of hypocenters of the 5 earthquakes used in this study as determined by Japan Meteorological Agency (JMA).

No.	origin time (Y. M. D h: m: s)	Latitude (degree)	Longitude (degree)	Depth (km)	JMA magnitude
1	1995.02.02 16:19:27.8	34° 41.4'	135° 08.5'	18.0	4.1
2	1997.09.16 14:28:11.0	34° 40.4'	134° 47.5'	14.0	3.9
3	1999.08.02 04:58:14.4	34° 26.4'	135° 20.6'	14.0	3.9
4	2000.08.27 13:13:13.7	34° 31.9'	135° 39.0'	11.0	4.1
5	2001.08.25 22:21:25.2	35° 08.8'	135° 39.6'	10.0	5.1

as sites on the basement that belong to the Abuyama and Tottori observatories of the Disaster Prevention Research Institute, Kyoto University; the Wakayama Observatory of the Earthquake Research Institute, the University of Tokyo; the Japan Meteorological Agency (JMA); and the National Research Institute for Earth Science and Disaster Prevention (NIED). Site distribution is shown in Fig. 2.

3. Setting the TTDC values as search space

In the present study, we assumed a single converted phase and a vertical incidence of the wave because of the contrast between the basement rocks and the sedimentary cover. Based on these assumptions, values of the TTDC for the P-wave (*cp*) and the S-wave (*cs*) are expressed as follows:

$$cp = D/Vp, \quad cs = D/Vs \tag{1}$$

where D is depth to basement, Vp and Vs are the velocities of the P-wave and the S-wave in the sediments, respectively. Vp and Vs range from 1.5 to 2.5 km/s and from 0.3 to 1.4 km/s, respectively. These velocities were selected according to Horike *et al.* (1996) and Kagawa *et al.* (1998).

Depth to the basement is expressed by equation (2) based on Nemoto *et al.* (1997).

$$D = t^*(Vs^{-1} - Vp^{-1})^{-1}, \tag{2}$$

where t is the P-Ps interval at each site.

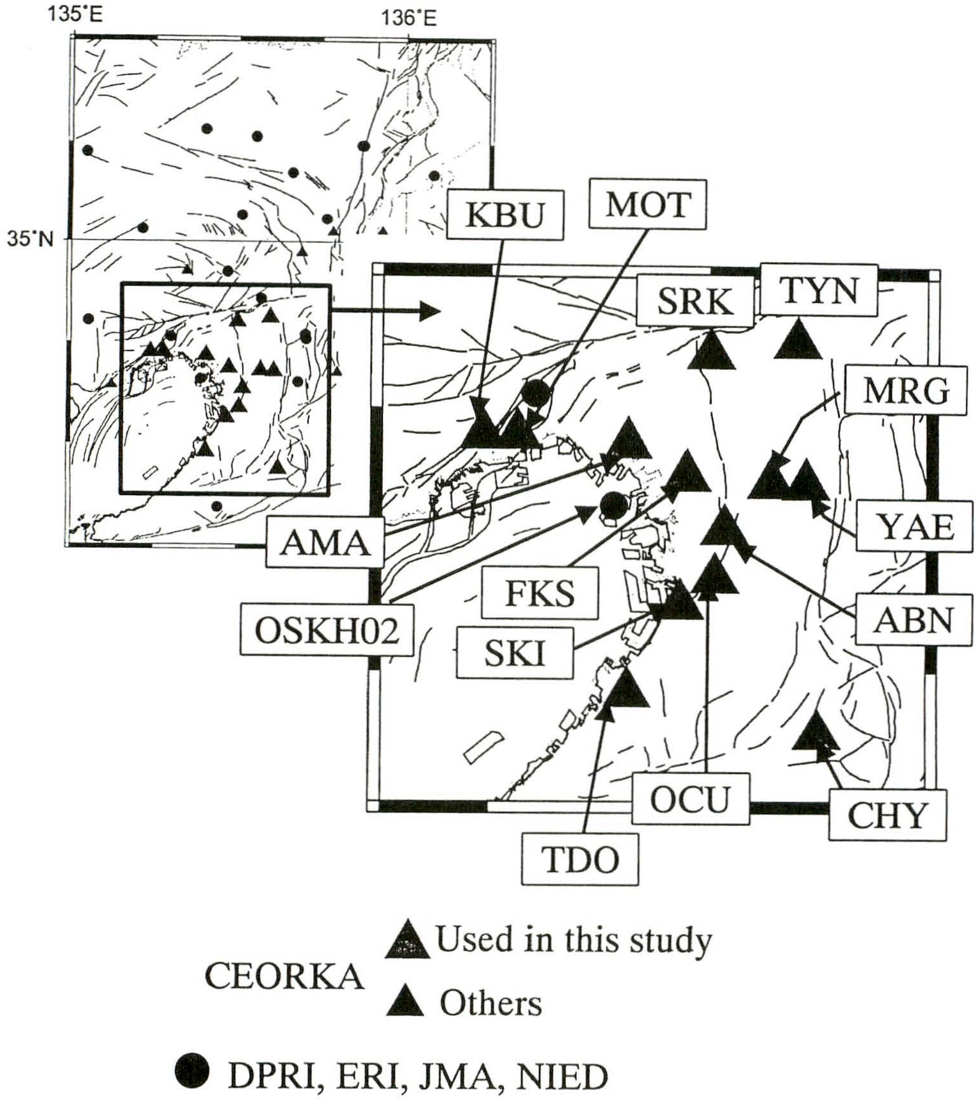

Fig. 2 Distribution of seismic observation sites in the Osaka Basin. The three capital alphabets indicate the name of the sites which belong to the Committee of Earthquake Observation and Research in the Kansai Area (CEORKA). "OSKH02" is the site belongs to KiK-net by the National Research Institute for Earth Science and Disaster Prevention (NIED)(2000) that was used in empirical criteria.

We picked about 10 P-Ps intervals at the 13 sites with an accuracy of 0.01 s (Table 2). Standard deviations of the P-Ps intervals at the 13 sites are shorter than 0.1 s, and relative errors are smaller than 8% at the 13 sites except for the three sites, CHY, KBU, and TYN (Fig. 1).

The travel time delay, which needs to be corrected by the TTDC, differs from one site to another. This is because of the violation of some assumptions and the uncertainty in event picking, and each value is represented by a range of time values (Table 3). The estimates of the TTDC values are obtained from a search space which contains about 30 trillion values of TTDC. These TTDC values satisfy equations (1) and (2), and the resultant ranges are shown in Table (3).

4. Heuristic search using empirical criteria

For an effective estimation of the TTDC values, we adopted the heuristic search using empirical criteria. The adopted empirical criteria are as follows:

(a) Absolute value of the residual arrival time at a site on the basement in the Osaka Basin.

(b) Accuracy of the hypocenter determination.

(c) Root mean square of residuals of the arrival times at all sites.

Table 2 Average, standard deviation, and number of pickings of the P-Ps interval.

Station Code	P-Ps interval Average(s)	STD(s)	Pick
ABN	1.22	0.07	10
AMA	1.55	0.03	10
CHY	0.26	0.08	7
FKS	1.52	0.07	9
KBU	0.12	0.06	10
MOT	1.10	0.09	10
MRG	1.34	0.05	9
OCU	1.14	0.07	10
SKI	1.26	0.06	10
SRK	0.73	0.05	10
TDO	1.18	0.03	10
TYN	0.27	0.07	10
YAE	1.34	0.07	10

STD.: Standard deviation
Pick: number of picking up

Table 3 Travel time delays at the 13 sites which belong to CEORKA.

Station Code	dp (s)	ds (s)
ABN	0.60 ± 0.27	1.73 ± 0.50
AMA	0.63 ± 0.22	2.17 ± 0.54
CHY	0.09 ± 0.40	0.39 ± 0.61
FKS	0.79 ± 0.26	2.31 ± 0.55
KBU	0.40 ± 0.40	0.94 ± 0.65
MOT	0.79 ± 0.75	2.29 ± 1.16
MRG	0.64 ± 0.20	2.00 ± 0.41
OCU	0.61 ± 0.31	1.79 ± 0.59
SKI	0.65 ± 0.35	2.04 ± 0.73
SRK	0.48 ± 0.14	1.31 ± 0.34
TDO	0.73 ± 0.69	2.09 ± 1.17
TYN	0.41 ± 0.17	0.84 ± 0.23
YAE	0.70 ± 0.27	2.05 ± 0.43

* dp and ds are travel time delay of P-wave and S-wave

For criterion (a), we used the residual at OSKH02, which belongs to KiK-net, NIED. The parameters of each hypocenter, their error values, and their residuals are used from each result of HYPOMH, which is the hypocenter determination program (Hirata and Matsu'ura, 1987). Input parameters for HYPOMH are the arrival time at each observation site, the values of TTDC, and P-wave velocity model in basement used by Kuroiso and Watanabe (1977). Hence, the S-wave velocity in basement is considered to be the P-wave velocity divided by $\sqrt{3}$ (Hirata and Matsu'ura, 1987).

Fig. 3 shows a schematic sketch of applying the empirical criteria in a situation of 20 TTDC combinations. Determinations of thresholds in the empirical criteria are as follows:

(A) The second best values for criterion (a), 0.04 s for P wave arrival and 0.52 s for S wave arrival, were selected as threshold, then, 11 TTDC combinations were omitted.

(B) The second best value for criterion (b), 0.72 km for hypocenter determination error, was selected as threshold, then, 4 TTDC combinations were omitted.

(C) The second best values for criterion (c), 0.12 s for P wave arrival and 0.32 s for S wave arrival, were selected as threshold, then, a TTDC combination was omitted. As a result, 4 TTDC combinations were adopted.

Fig. 4 shows a schematic sketch of the heuristic search in a situation of 4 TTDC combinations for each of 4 sites. A search space consists of 256 values of TTDC. The heuristic search using the empirical criteria in this study was done as follows:

(1) In case of 'ABN', firstly, the values of TTDC as one of the input parameters for HYPOMH are 'A_1', 'A_2', 'A_3' and 'A_4'. Secondly, the arrival times at 'ABN' in addition to sites on basement are given as inputs to HYPOMH (Fig. 4A). Finally, hypocenters are calculated using the HYPOMH program.

(2) Empirical criteria are applied to the results of hypocenter determination. In Fig. 4, 'A_1' and 'A_4' are adopted for 'ABN' (Fig. 4A). Similarly, 'O_2' and 'O_3' for 'OCU', 'M_3' and 'M_4' for 'MOT', and 'K_1' and 'K_2' for 'KBU' are adopted, respectively.

(3) In case of 'ABN & OCU', arrival times of both sites and values of TTDC named 'A_1 & O_2', 'A_1 & O_3', 'A_4 & O_2', and 'A_4 & O_3' are used in hypocenter calculations (Fig. 4B). The procedures applied to 'MOT & KBU' are the same as those applied to 'ABN & OCU'. At the end of this step, hypocenters are calculated using the HYPOMH program.

(4) The empirical criteria are applied to the result of hypocenter determinations. In Fig. 4, 'A_4 & O_2' and 'A_4 & O_3' are adopted for 'ABN & OCU' (Fig. 4B). 'M_3 & K_1' and 'M_4 & K_1' for 'MOT & KBU' are also adopted.

(5) The arrival times at 'ABN & OCU & MOT & KBU' and values of TTDC named 'A_4 & O_2 & M_3 & K_1', 'A_4 & O_2 & M_4 & K_1', 'A_4 & O_3 & M_3 & K_1', and 'A_4 & O_3 & M_4 & K_1' are given as inputs to HYPOMH (Fig. 4C). Hypocenters are

	Empirical criteria					
	(1)		(2)	(3)		
Comb.	OSKH02			RMS		
No.	P	S	Accuracy	P	S	
001	-0.05	-0.52	0.63	0.12	0.31	×
002	-0.05	-0.52	0.65	0.13	0.31	×
003	-0.04	-0.51	0.73	0.12	0.33	××
004	-0.04	-0.52	0.64	0.11	0.31	
005	-0.05	-0.52	0.63	0.12	0.31	×
006	-0.05	-0.52	0.65	0.12	0.31	×
007	-0.04	-0.51	0.72	0.12	0.32	
008	-0.04	-0.52	0.64	0.12	0.32	
009	-0.05	-0.52	0.63	0.12	0.31	×
010	-0.04	-0.51	0.73	0.12	0.33	××
011	-0.05	-0.52	0.65	0.12	0.32	×
012	-0.04	-0.52	0.73	0.12	0.32	××
013	-0.05	-0.52	0.65	0.13	0.31	×
014	-0.04	-0.52	0.64	0.12	0.32	
015	-0.05	-0.52	0.63	0.12	0.31	×
016	-0.04	-0.51	0.73	0.12	0.33	××
017	-0.04	-0.51	0.72	0.13	0.34	×××
018	-0.05	-0.52	0.65	0.12	0.32	×
019	-0.06	-0.52	0.65	0.12	0.32	×
020	-0.07	-0.52	0.65	0.12	0.32	×

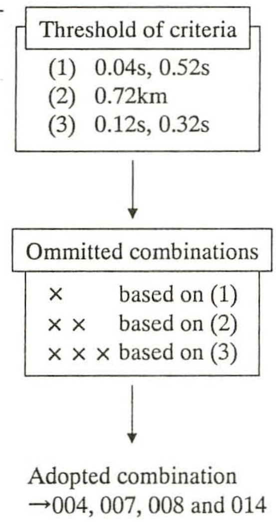

Fig. 3 Schematic sketch of applying the empirical criteria in a situation of 20 combinations of the travel time delay correction.

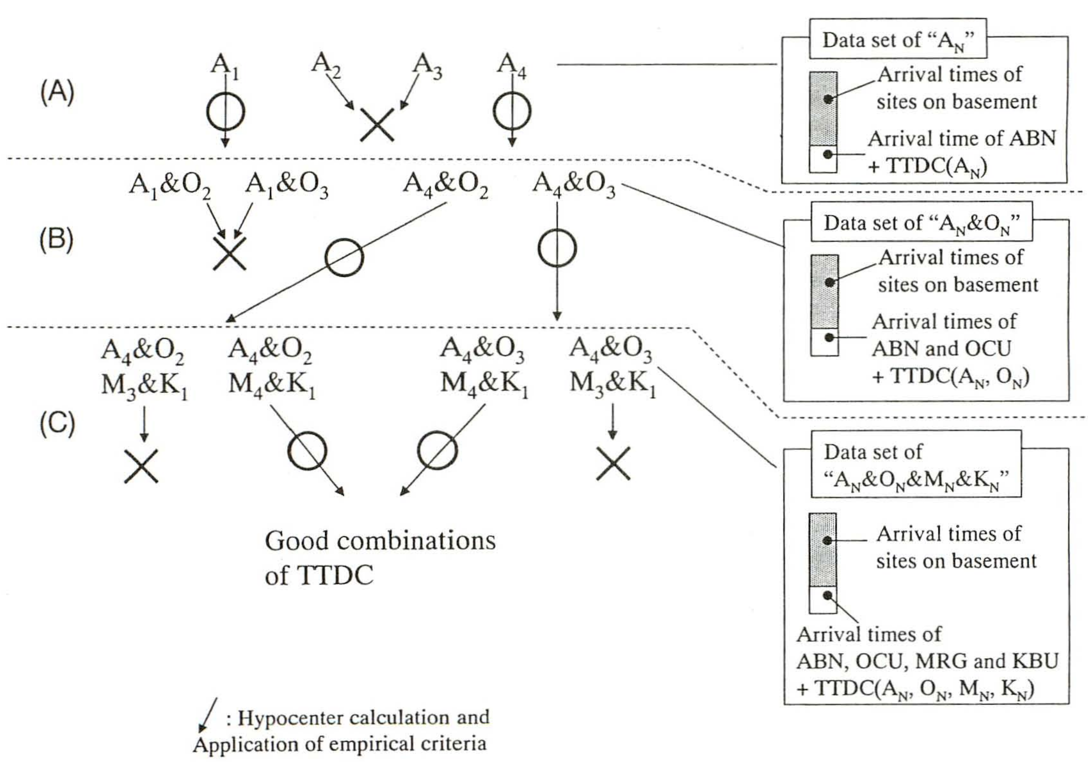

Fig. 4 Schematic sketch of the heuristic search in a situation of 4 values of the travel time delay correction at 4 stations.

Table 4 The values of TTDC at the 13 sites of CEORKA as estimated in this study.

Station Code	cp (s)	cs (s)
ABN	−0.70	−1.92
AMA	−0.78	−2.33
	−0.09	−0.35
CHY	−0.10	−0.36
	−0.11	−0.37
FKS	−0.72	−2.24
KBU	−0.20	−0.32
MOT	−0.60	−1.70
MRG	−0.55	−1.89
OCU	−0.61	−1.75
SKI	−0.42	−1.68
SRK	−0.39	−1.12
TDO	−0.49	−1.67
TYN	−0.29	−0.56
YAE	−0.61	−1.95

calculated using the HYPOMH program in this step as well.

(6) The empirical criteria are applied to the result of hypocenter determinations. The values of TTDC named 'A_4 & O_2 & M_4 & K_1' and 'A_4 & O_3 & M4 & K_1' are adopted as the best (Fig. 4C).

5. Results and discussion

We obtained values of TTDC at the 13 sites (Table 4). There is one value of TTDC at all sites except for CHY. At CHY, we obtained a probable solution $(cp, cs) = (-0.10\ \mathrm{s}, -0.36\ \mathrm{s})$ by averaging the obtained values.

For the hypocenter determination, it is important to precisely estimate the TTDC values. For this purpose,

Table 5 Hypocenter determination accuracy using raw seismograms and corrected data by CEORKA, and basement data. Numbers 1∼5 are the same as in Table 1.

	No.	Latitude (degree)	Longitude (degree)	Depth (km)	Error(km)		
					Latitude	Longitude	Depth
(a)	1	34.687	135.101	23.6	0.6	0.7	0.7
	2	34.690	136.014	14.2	0.5	0.6	0.8
	3	34.386	135.324	16.5	0.5	0.5	0.6
	4	34.503	135.689	12.7	0.3	0.4	0.5
	5	35.168	135.658	5.0	0.8	1.0	29.6
	e1	34.416	134.790	26.1	1.1	1.2	0.6
	e2	34.644	135.072	16.2	0.5	0.7	1.0
	e3	33.938	135.481	70.2	2.4	2.9	2.8

↓

	No.	Latitude (degree)	Longitude (degree)	Depth (km)	Error (km)		
					Latitude	Longitude	Depth
(b)	1	34.679	135.196	18.2	0.4	0.5	0.5
	2	34.674	135.936	17.0	0.4	0.5	0.6
	3	34.452	135.359	11.3	0.3	0.3	0.4
	4	34.536	135.637	4.8	0.1	0.2	0.2
	5	35.131	135.668	10.7	0.5	0.3	0.9
	e1	34.439	134.791	16.1	0.7	0.9	0.5
	e2	34.645	135.167	8.0	0.3	0.4	0.9
	e3	34.047	135.468	67.3	2.0	2.4	2.2
(c)	1	34.697	135.154	17.9	0.3	0.3	0.3
	2	34.689	135.965	12.4	0.2	0.3	0.8
	3	34.433	135.358	13.8	0.3	0.3	0.7
	4	34.530	135.657	4.9	0.2	0.2	0.3
	5	35.151	135.670	6.2	0.1	0.1	0.2
	e1	34.437	134.815	16.0	−	−	−
	e2	34.642	135.135	14.0	−	−	−
	e3	34.042	135.473	70.0	−	−	−

(a) Using raw data by CEORKA
(b) Using raw data by CEORKA after travel time delay correction
(c) Using data on basement, parameters of e1, e2 and e3 are by JMA

we need sites located over basement and over sediments. In this study, we adopted a method for applying TTDC to seismograms recorded over sediments. Using TTDC, the hypocenter determination should be more accurate when only seismograms over sedimentary layers are available. We validate TTDC values using the data of the 5 earthquakes as well as three other earthquakes (Table 5). The results for these earthquakes showed that the accuracy of the hypocenter determination is improved using only the arrival times over sedimentary layers by TTDC. This result suggests that TTDC values at the 13 sites used are useful for the hypocenter determination in and around the Osaka Basin.

6. Conclusion

We corrected the travel time delay at the 13 sites belonging to CEORKA with the heuristic search using the empirical criteria. The results of this study can be used to improve the hypocenter location determination for sites located over sedimentary layers and the determined times can be as credible as those recorded directly over basement rocks. This can improve the hypocenter determination for future earthquakes in and around the Osaka Basin as well as other sedimentary basins.

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