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Velocity Structure Survey in Beppu Bay Basin, Japan

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Abstract

Beppu Bay sedimentary basin is about 50 km x 30 km bell shaped basin with maximum sediments thickness is 4 km. Velocity structure of Beppu Bay basin, Kyushu, Japan, has been investigated with microtremor array survey and ambient noise interferometry survey. Microtremor array survey with array radius about 20 to 1000 m has been conducted at 21 sites around Beppu Bay using T=10s velocity seismometers to estimate subsurface S-wave velocity structure. S-wave velocity structures down to the seismic basement have been estimated by converting phase velocities analyzed with SPAC method and V method using empirical relation. Overall performance of published velocity structure, J-SHIS model, is good, but remarkable discrepancy in phase velocities are found at Beppu fan sites. Ambient noise interferometry has been conducted using year-long data obtained with 12 broadband seismometers deployed around the Beppu Bay to investigate S-wave velocity structure beneath the sea covered area. Group velocities of the Rayleigh and Love waves between station pairs have been successfully retrieved from CCFs. Group velocities along the paths through Beppu Bay are found to be systematically smaller than those calculated from J-SHIS model, indicating the S-wave velocity beneath the sea area of the Beppu Bay is slower than modeled.

Keywords: Microtremor array survey, ambient noise interferometry, phase velocity, group velocity, observation

1. Introduction: Velocity structure of Beppu Bay basin

Beppu Bay sedimentary basin is about 50 km x 30 km bell shaped basin trending E-W direction with its mouth open to the east. Pioneering seismic surveys of the Beppu Bay by Yusa et al.[1] revealed key topography of the sedimentary basin down to the bedrock. The deepest part of the basin is about 4,000 m and is located southwest of the basin. Beppu-Haneyama active faults run through the basin and they are possible source of inland earthquake.

Three-dimensional S-wave velocity structure models of the Beppu Bay basin [2-4] have been constructed for the purpose of ground motion prediction based on data from gravity anomalies [5], seismic surveys [1,6,7] and microtremor array surveys [8,9]. They are composed of layers each has uniform properties following velocity layer models proposed by microtremor array survey. Iwaki et al.[10] investigated performance of one of the velocity models by finite difference simulation of seismic waves generated by shallow earthquake occurred about 250 km northeast from the Beppu Bay, and found that the velocity model of the Beppu Bay should be modified to reproduce predominant period and wave packets of the surface waves generated in the basin.

2. Microtremor array survey in the Beppu Bay basin

2.1 Outline of the microtremor array measurement

We conducted large to small aperture (maximum radius about 1 km, smallest 20 m) microtremor array survey at 21 sites in the Beppu Bay basin (Fig.1, Table 1) to obtain deep to shallow velocity structure. Survey sites were chosen so that the surveys cover most of the lowlands of the basin. All the previous microtremor array studies had been done in the Oita plain, south of the Beppu Bay, and they were concentrated in the northern part of the plain. No observation had been conducted west and north of the Beppu Bay. So, our survey sites are distributed in the southern part of the Oita plain (OSO, OSG, OAK, OND, OMK, OMY, OHD), on the Beppu fan (BAK, BKT, BFJ, BIS, BSN), northern part of the Beppu Bay (HJI, HJO, KTK) and Yufuin basin (YUF), as well as at the gaps of previous survey sites in the highly populated northern Oita plain (OOT, OHT, OTR, OOZ, OSI).

Three component velocity seismometers (Tokyo Sokushin SE-321; 500V/m/s, T=10s.) were deployed connected with 24bit data logger (Hakusan DATAMARK LS-8800, GPS time calibration). Every microtremor array was consisted of four temporal stations composing of centered equilateral triangle array. At each observation site, two to three equilateral triangle arrays were simultaneously deployed; up to 12 seismometers were set. For arrays larger than M array (radius: r=290m), observation has been made for more than eight hours through the night, whereas for smaller arrays it has been made for about two hours in the daytime.

2.2 Results of microtremor measurement: observed phase velocity and estimated velocity structure

U-D component of the observed microtremor data are analyzed with SPAC-method [11] and V-method [12] using BIDO2.0 software [13]. Time series data are segmented to shorter length data (163.84s, 81.92s, 40.96s and 20.48s depending on array radius) and processed. Phase velocity is, at first, obtained by averaging analyzed phase velocities of every segment of a same size of array. Then, unified phase velocities (observed phase velocities) for a site are obtained by merging phase velocities of all the arrays after smoothing with Konno-Ohmachi filter [14], which has symmetric bandwidth with regard to the logarithmical frequency.

Characteristics of the obtained phase velocities (Fig.2) differ among sites, but, in general, it can be summarized as follows: For sites on the Oita plain, phase velocities are obtained between the frequency range of 0.2-5 Hz and velocities range between 0.2 to 2.5 km/s. For sites on Beppu fan, Yufuin basin, and north of the Beppu Bay, they are obtained in the frequency range of 0.5-5 Hz and the phase velocity reaches or excesses 2 km/s at frequency higher than 0.5 Hz. This reflects characteristics of the subsurface S-wave velocity structure at the site. Comparison of the obtained phase velocity and theoretical phase velocity calculated using published velocity structure models (J-SHIS [3,4] and JVM [15] models) are also shown in the Fig. 2. Theoretical phase velocity of J-SHIS model, overall, fit with the observed one better than those of the JVM model. Especially for sites in the north of the Beppu Bay (HJI, HJO, KTK) and south of the Beppu fan (BAK, BFJ), J-SHIS model succeeds in reproducing observed phase velocity whereas JVM model fails. This indicates J-SHIS model is better than the JVM model in this area.

S-wave velocity structure can be estimated from observed phase velocity. A lot of inversion techniques have been proposed for microtremor array survey, however, uncertainty of S-wave value and distribution remains. Since our purpose is modifying three dimensional S-wave velocity structure, 1-D profile beneath the site is not necessary our core concern. Still, it is of some use to show 1-D profile corresponding to the observed phase velocity. Here, observed phase velocities are converted to 1-D S-wave profile following the idea of Ballard [16] as the parameters for conversion is different. We assumed,

$$Vs\,(d) = 1.1\,Vr\,(L) \tag{1}$$

$$d = L/a \tag{2}$$

,where Vs (d) is the S-wave velocity at the depth d, Vr (L) is the phase velocity for a wave with wavelength L, and a is a dimensionless parameter we empirically found a=2.7 performed well when a layer boundary was set at the center depth between the two converted points.

Converted S-wave profiles are drawn in blue on the right panel of each box in Fig. 2. Phase velocity larger than 2 km/s is neglected in the conversion and Vs=3.2 km/s bedrock is added at the bottom in calculating theoretical phase velocity drawn on the left panel. P-wave velocity and density is defined as a function of the S-wave velocity after Ludwig et al.[17]. Converted S-wave profiles reproduce well the observed phase velocity. Now we have the idea of how to modify the velocity models from the comparison of the 1-D S-wave profiles.

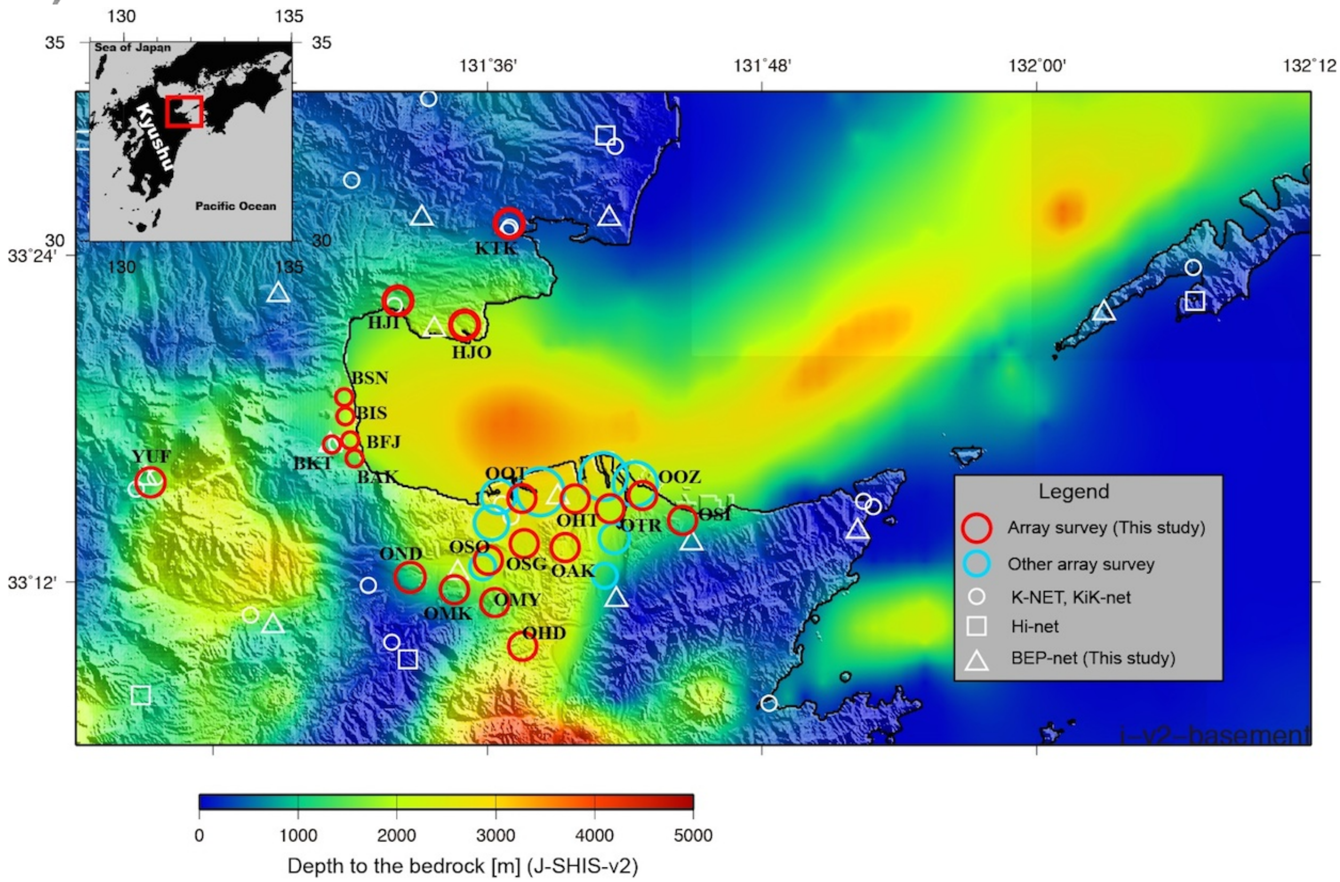

Fig. 1 - Locations of large aperture microtremor surveys in the Beppu Bay basin.

Table 1 – Array location and radius

name	Lat.	Lon.	radius	name	Lat.	Lon.	radius
OSI	33.2375	131.7426	LL,L,M,SM,S,SS	OND	33.2018	131.5446	LL,L,M,SM,S,SS
OOZ	33.2517	131.7137	XL, LL,L,M,SM,S,SS	BAK	33.2750	131.5021	L,M,SM,S,SS
OTR	33.2439	131.6888	XL, LL,L,M,SM,S,SS	BKT	33.2838	131.4858	L,M,SM,S,SS
OHT	33.2500	131.6647	LL,L,M,SM,S,SS	BFJ	33.2868	131.5005	L,M,SM,S,SS
OOT	33.2509	131.6245	LL,L,M,SM,S,SS	BIS	33.3007	131.4970	L,M,SM,S,SS
OAK	33.2209	131.6566	LL,L,M,SM,S,SS	BSN	33.3123	131.4955	L,M,SM,S,SS
OSG	33.2240	131.6260	LL,L,M,SM,S,SS	YUF	33.2608	131.3531	LL,L,M,SM,S,SS
OSO	33.2136	131.6007	LL,L,M,SM,S,SS	HJI	33.3712	131.5347	LL,L,M,SM,S,SS
OHD	33.1605	131.6253	LL,L,M,SM,S,SS	HJO	33.3570	131.5807	LL,L,M,SM,S,SS
OMY	33.1863	131.6043	LL,L,M,SM,S,SS	KTK	33.4190	131.6151	LL,L,M,SM,S,SS
OMK	33.1951	131.5749	LL,L,M,SM,S,SS				

XL: r=2200m, LL: r=980m, L: r=490 m, M: r=290 m, SM: r=94 m, S: r=47m, SS: r=21m

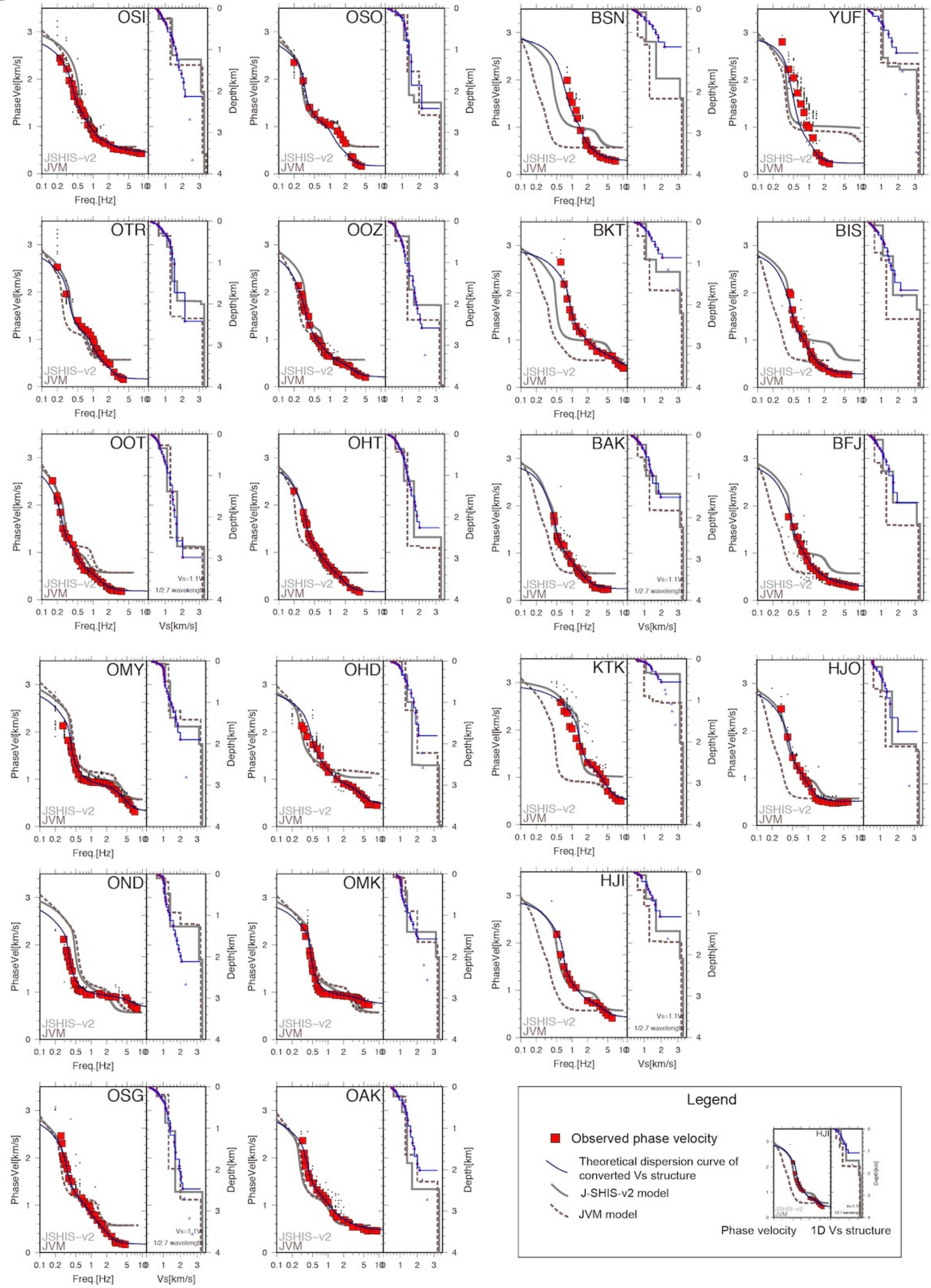

Fig.2 – Comparison of observed phase velocities and theoretical dispersion curves of published velocity models and converted velocity structure using empirical relation of phase velocity and S-wave structure.

3. Application of Seismic Interferometry to Continuous Microtremor Data

3.1 Continuous microtremor observations around the Beppu bay area

The deepest part of the Beppu Bay sedimentary basin is located beneath the center of the Beppu Bay (around 4000 m), indicating seismic wave propagation and amplification inside the bay strongly influence the characteristics of ground motions in the surrounding areas. However, there was no direct data of the S-wave velocity structure beneath the bay. Recently the seismic interferometry techniques using continuous microtremor (ambient noise) records are widely applied to investigate the characteristics of surface wave propagation inside sedimentary basin and the accuracy of shear wave velocity structure model [18, 19, 20]. Several studies demonstrated that the technique provides useful information on validation of S-wave velocity structure beneath bay areas [20, 21, 22].

We have deployed a dense temporary seismic array around the Beppu Bay area since late August 2014, to investigate seismic velocity structure of deep sedimentary basin in the bay. As of June 2016, twelve stations are in operation (Fig. 3). The seismic station consists of a three-component broadband seismometer (Nanometrics Trillium compact; 750 V/m/s, T=120s) set in a hole at about 30 cm depth, connected with a 24bit data logger (Hakusan DATAMARK LS-8800; sampling rate of 100 Hz). Each observation system is powered by a lead-acid battery, which is charged with a solar cell. There are 66 station-to-station pairs in the distance range from 6.4 km (BEP09-BEP10) to 65.2 km (BEP06-BEP12).

3.2 Cross-correlation functions of microtremor data between selected station pairs

We used hourly measured continuous microtremor data between September 2014 and December 2015 to extract Green's functions between two receivers (66 station pairs) for nine components (R-R, R-T, R-Z, T-T, T-R, T-Z, Z-R, Z-T, Z-Z; "R", "T", and "Z" indicate radial, transverse, vertical components, respectively). At first, running-absolute-mean normalization (Bensen et al. [23]) in the time domain is applied to the data in the frequency range of 0.2–2 Hz (0.5–5 s) to suppress the effects of earthquakes and then spectral whitening in the frequency domain is performed to enhance the contributions of low-level components. Although we used microtremor records from broadband stations, the data at frequency below 0.2 Hz were excluded since long-period volcanic signals from Mount Aso were frequently observed throughout the observation period. We obtained cross-correlation functions (CCFs) for N-N, N-E, N-Z, E-E, E-N, E-Z, Z-N, Z-E, and Z-Z components for all station pairs and converted them into the corresponding nine components based on the technique of Lin et al.[24]. The stacked CCFs show distinct wave trains for station pairs that across shallow-bedrock areas, whereas it is still difficult to visually confirm the wave trains for station pairs that across deep sedimentary basin (Fig.4).

3.3 Estimation of surface wave group velocities

As a first step to investigate and validate the present three-dimensional basin structure model, group velocities of surface waves between two stations are estimated using the multiple filtering technique (MFT) by Dziewonski et al.[25]. In the analysis, the stacked CCFs are folded at zero and group velocities are estimated dividing station-to-station distances by the peak times of filtered waveforms, only when the common wave trains are found between the causal (positive) and acausal (negative) parts. For the estimation of Rayleigh-wave group velocities, stacked CCFs in the (ZR-RZ)/2 component (composed of Z-R and R-Z components) are used in order to prevent the contamination of body waves in the CCFs (Takagi et al. [26]). On the other hand, CCFs in the T-T component are used for the estimation of Love-wave group velocities.

Figure 5 show spatial variations of Rayleigh- and Love-wave group velocities. The group velocities are not well estimated for some station pairs due to low signal-to-noise ratios, but the results indicate clear dispersive characteristics of surface waves in the sedimentary basin. The theoretical group velocities are also calculated by spatial integration of calculated group velocities from one-dimensional velocity structures beneath the path between two stations, using a velocity structure model of deep sedimentary layers (J-SHIS model). The estimated values indicate smaller group velocities in the Beppu Bay area than those in the surrounding areas and generally show good agreements with theoretical ones. On the other hand, the estimated values in Beppu Bay are systematically smaller than the theoretical ones, indicating S-wave velocity beneath the bay might be slower than those of the existing structure model.

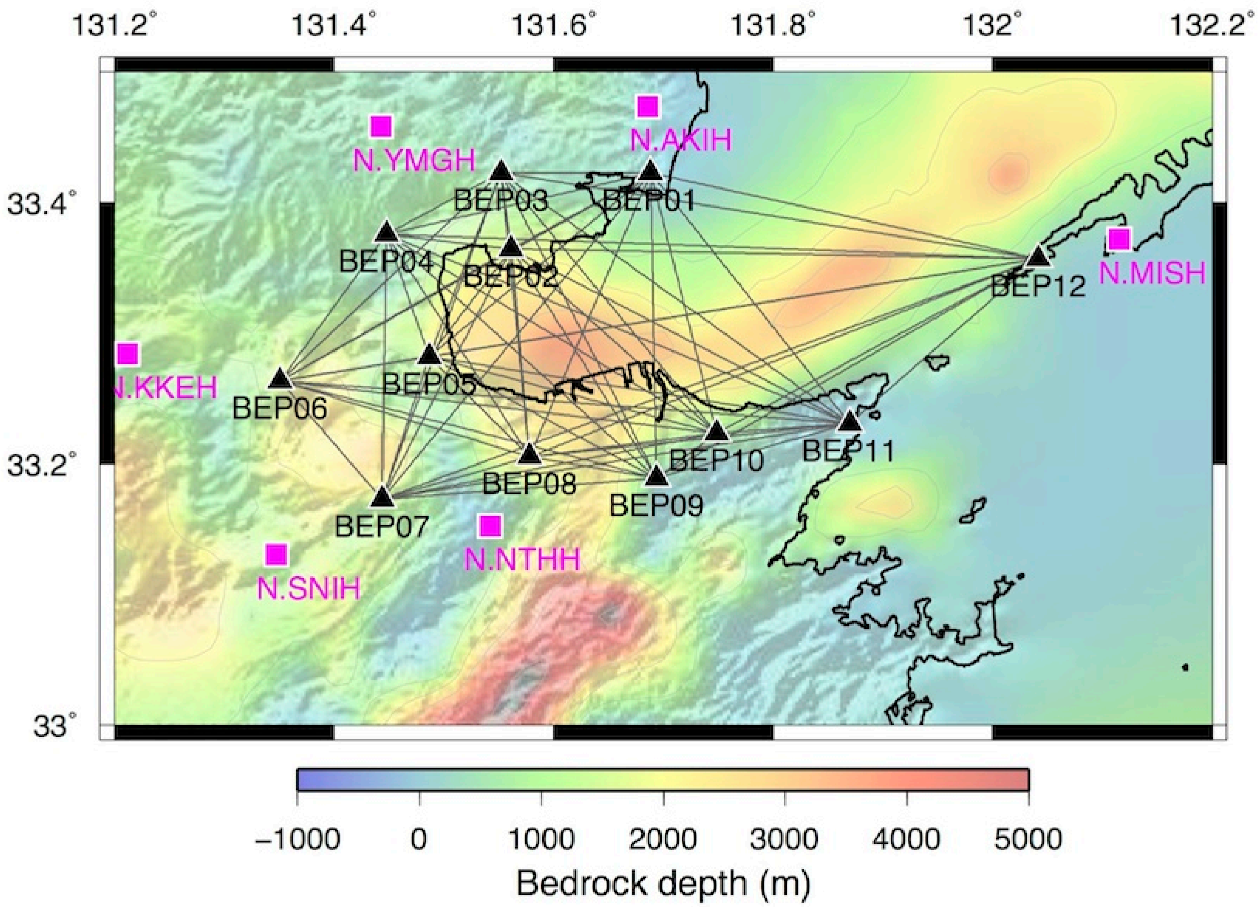

Figure 3. Broadband seismic observation stations in the Beppu bay area (triangles: BEP-net of our study, rectangles: Hi-net stations).

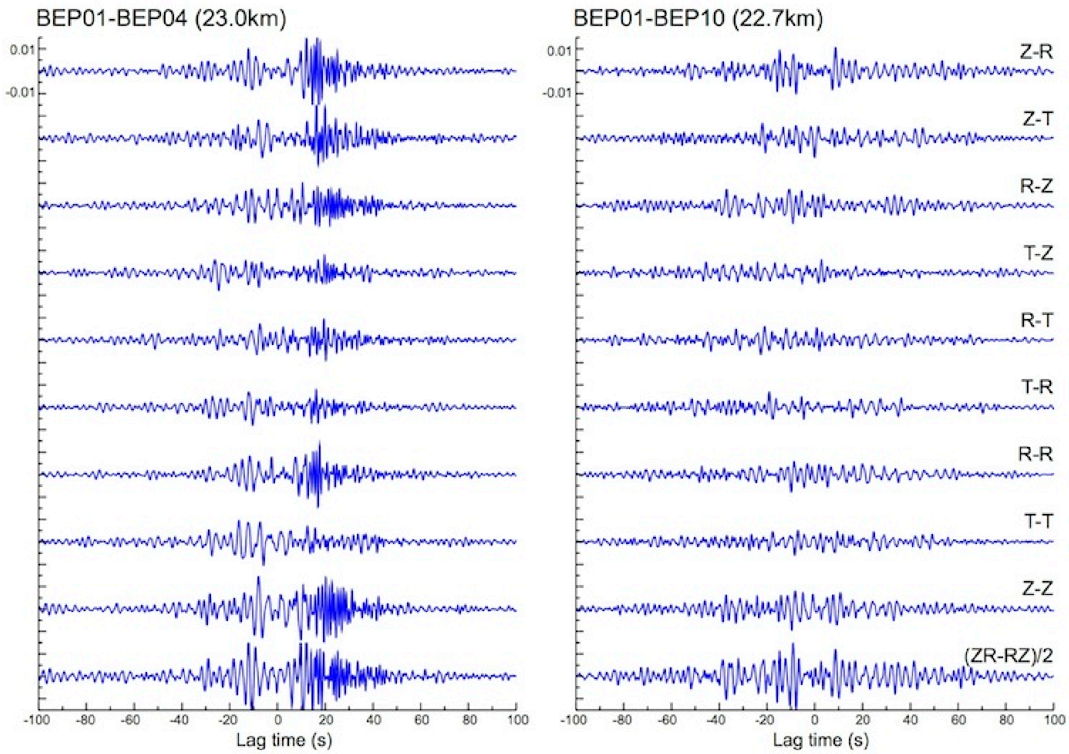

Figure 4. Examples of stacked cross-correlation functions (CCFs).

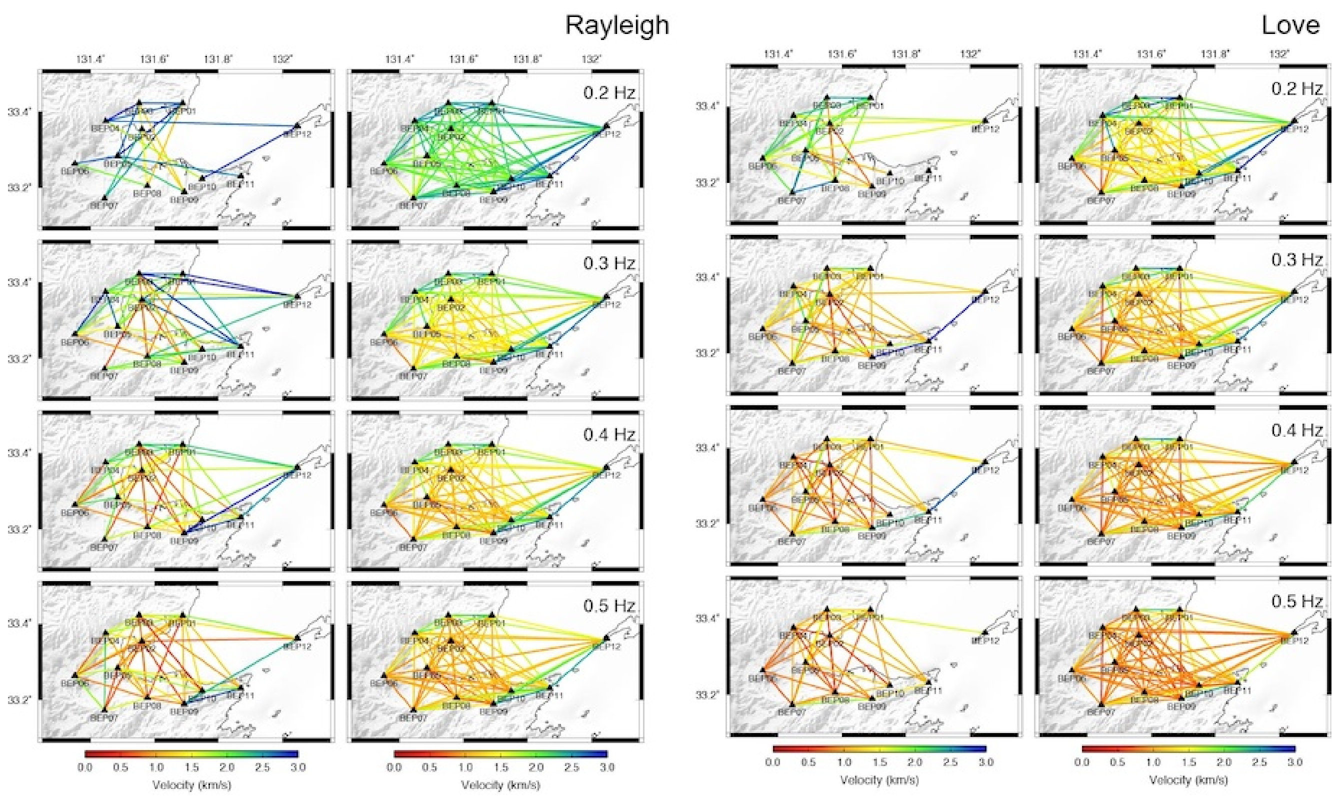

Figure 5. Comparisons between estimated (left) and calculated (right) group velocities of Rayleigh wave and Love wave.

5. Summary

Velocity structure of Beppu Bay basin, Kyushu, Japan, has been investigated with microtremor array survey and ambient noise interferometry survey. Microtremor array survey with array radius about 20 to 1000 m has been conducted at 21 sites around Beppu Bay using T=10s velocity seismometers to estimate subsurface S-wave velocity structure. S-wave velocity structures down to the seismic basement have been estimated by converting phase velocities analyzed with SPAC method and V method using empirical relation. Overall performance of published velocity structure, J-SHIS model, is good, but remarkable discrepancy in phase velocities are found at Beppu fan sites. Ambient noise interferometry has been conducted using year-long data obtained with 12 broadband seismometers deployed around the Beppu Bay to investigate S-wave velocity structure beneath the sea covered area. Group velocities of the Rayleigh and Love waves between station pairs have been successfully retrieved from CCFs. Group velocities along the paths through Beppu Bay are found to be systematically smaller than those calculated from J-SHIS model, indicating the S-wave velocity beneath the sea area of the Beppu Bay is slower than modeled.

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