

Evaluation of spatial resolution and estimation error of seafloor displacement observation from vessel-based bathymetric survey by use of AUV-based bathymetric data

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Abstract A repeated bathymetric survey reveals seafloor displacement between before and after geodynamic events. We evaluated the less-known spatial resolution and estimation error of the seafloor displacement observation from a vessel-based multi-narrow beam bathymetric survey. In this evaluation, bathymetric data from vessel-based and near-seafloor high-resolution autonomous underwater vehicle (AUV)-based surveys in the same area were used. Simulated vessel-based bathymetric “before and after” data of the seafloor displacement were made using AUV-based bathymetric data. The displacement was verified by comparing these simulated data using the analysis conditions that no locational errors of beam sounding points exist, a footprint effect is uniform, depth accuracy is constant in the analysis area, and there are no depth offset between two data. As a result, we found that the smallest vertical seafloor displacement that can be detected occurs when the horizontal extent of the deformation is larger than several times the size of the footprint (area of the narrow sounding beam projected onto the seafloor) of the used vessel’s multi-narrow beam echo sounder, and in the situation that the amplitude of the depth difference is greater than the accuracy of the vessel-based depth measurement

(standard deviation of measuring error). When local slopes of the bathymetry are gentler than those of the artificial variation appeared in the depth differences between two data, the horizontal seafloor displacement seems to be difficult to resolve accurately. The local slope of the artificial depth variation is derived from the wavelength and the amplitude which are equivalent to $\sim 1\text{--}3$ times of the footprint size and the accuracy of the depth measurement, respectively.

Keywords Repeated bathymetric survey · Seafloor displacement · Spatial resolution · Estimation error · Iheya-north knoll · AUV *Urashima*

Introduction

Background and motivation

Bathymetry is basic information for any kind of seafloor observation, and therefore vessel-based multi-narrow beam bathymetric surveys are conducted quite often. In recent years, more bathymetric data of the most scientifically-important areas have become available from the previous survey. Therefore, repeated vessel-based bathymetric surveys revealed seafloor changes or displacement related to geodynamics, such as volcanic eruption, collapse of submarine volcanoes, or coseismic displacement of subduction zone earthquakes (e.g. Fox et al. 1992; Fujiwara et al. 2011; Watts et al. 2012). In the rupture zone of the 2011 Tohoku-oki earthquake (Mw 9.0), large seafloor elevation on a regional scale caused by the coseismic displacement was observed. Furthermore, quite large horizontal seafloor displacement caused by the earthquake was estimated (Fujiwara et al. 2011). This coseismic displacement was

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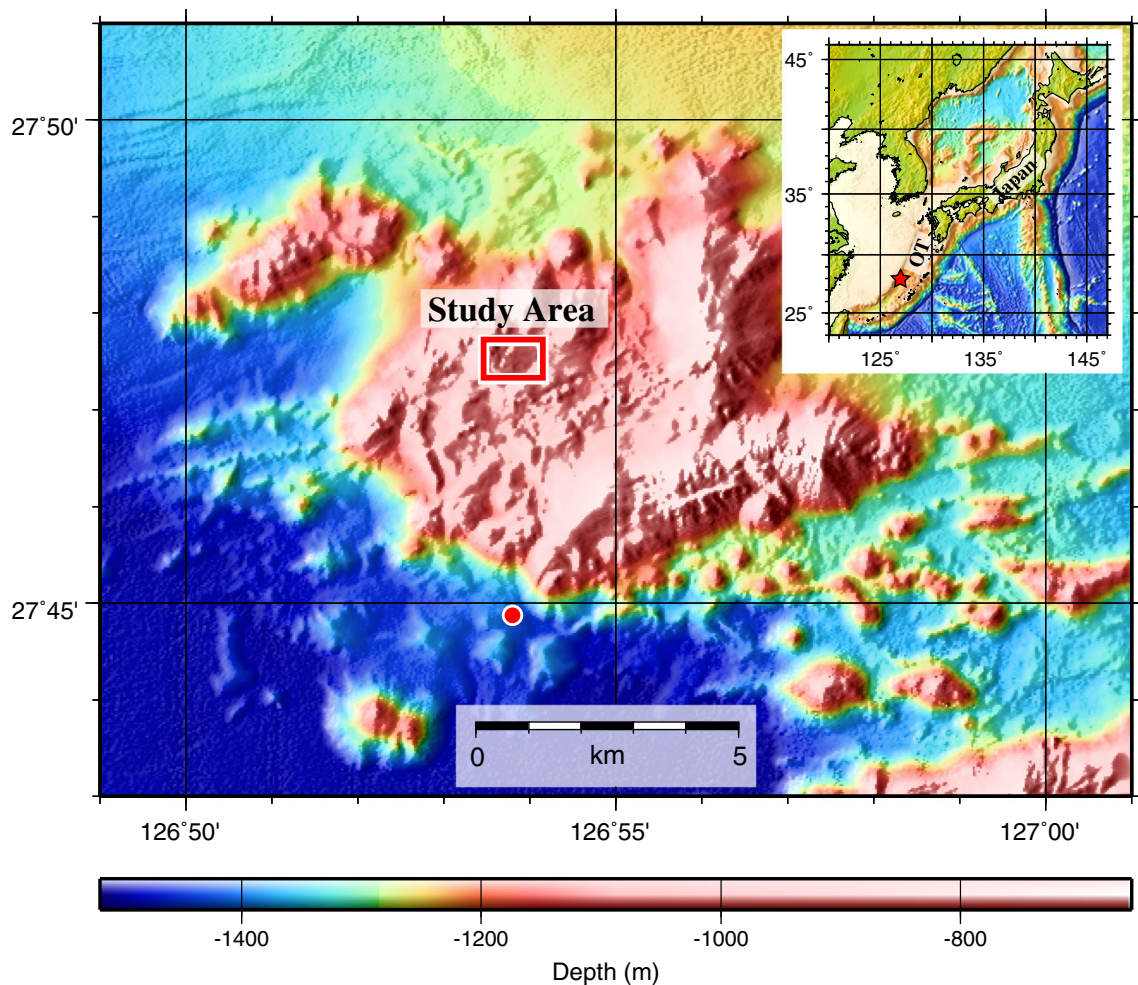


Fig. 1 Regional bathymetry of the Iheya-north knoll. The *red square* indicates an active hydrothermal and study area. The *red circle* shows an XBT observation point. The *inset* shows the location of the Iheya-north knoll in the Okinawa trough (OT) backarc basin (the *red star*)

likely an important factor contributing to the generation of the huge tsunami. Also, upward and downward changes in seafloor elevation on a local scale caused by thrust faulting was evident at the axial seafloor of the Japan trench (Kodaira et al. 2012; Strasser et al. 2013). Although no evidence was reported yet, occurrence of bathymetric change associated with the great earthquake even on a small scale is potential all over the trench slope in the rupture zone, because real-time turbidity current was observed and turbidite deposits were collected from the wide area (e.g. Arai et al. 2013).

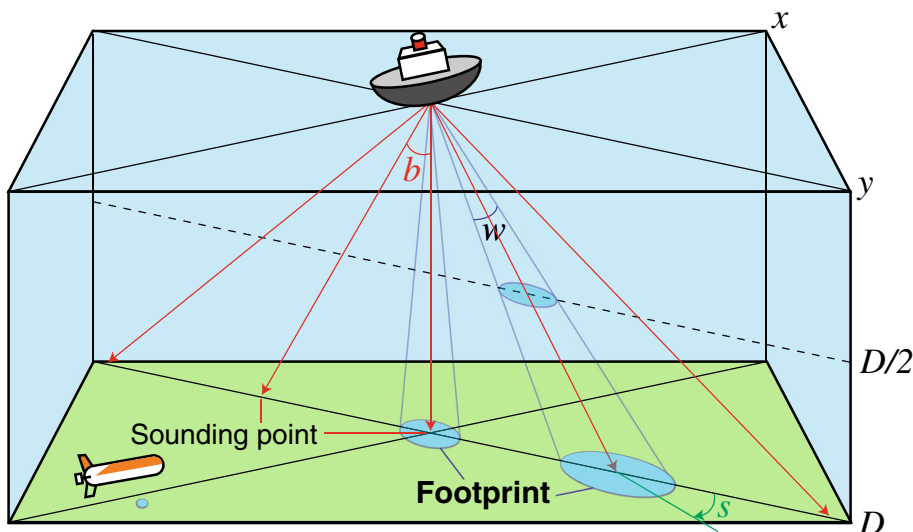
To investigate ability to resolve small change in the seafloor, it is important to verify the uncertainty of the data, however, the spatial resolution and estimation error of the seafloor displacement observation from the vessel-based survey are not exactly known. This is because the data comparison is usually done by using a pair of limited-resolution bathymetric data. Water depth degrades the

spatial resolution and accuracy of depth measurement from the vessel-based survey.

While on the other hand, a near-seafloor autonomous underwater vehicle (AUV)-based survey enables us to obtain high-resolution bathymetric data. In this paper, we evaluated the spatial resolution and the estimation error of the seafloor displacement observation from vessel-based bathymetric survey. In the evaluation, bathymetric data from vessel-based and AUV-based surveys in the same area were used.

A suitable dataset was collected in the Iheya-north knoll of the Okinawa trough. The knoll is a volcanic complex in a back-arc rifting system (Fig. 1). Since the discovery of hydrothermal activity in 1995 (Momma et al. 1996), many research cruises have been performed for multidisciplinary studies including deep-sea drilling (Integrated Ocean Drilling Program: IODP; Takai et al. 2011). Ordinary and high-resolution bathymetric surveys were conducted as a part of the study.

Fig. 2 Schematic illustration of footprints by echo-sounding beams. The footprint size relates to w beam width, b beam angle, s slope angle, D water depth



Footprint sizes for a flat seafloor

$$\text{fore-aft direction: } a_x = \frac{2D}{\cos b} \tan \frac{w}{2}$$

$$\text{athwart ships direction: } a_y = \frac{2D}{\cos^2 b} \tan \frac{w}{2}$$

$$\text{(in the presence of a slope) } a_y = \frac{2D}{\cos b \cos (b+s)} \tan \frac{w}{2}$$

Spatial resolution and depth precision accuracy due to water depth

Water depth, which means distance from the vessel’s echo sounder to the seafloor, is one of important factors in determining the spatial resolution and accuracy of the multi-narrow beam bathymetric measurement. The echo-beam spreads into a cone shape toward the seafloor, and an insonified area on the seafloor produces what is known as a ‘footprint’ (Fig. 2). The footprint size becomes large with the increasing water depth. As other factors, the large footprint size is caused by the wide beam width, the large beam angle formed by the vertical line and the outer echo-beam, and also the outward facing local slope angle at the insonified area (e.g. International Hydrographic Organization 2005; Lurton 2010). Measured bathymetry is spatially-smoothed as a function of the footprint, thus the large footprint degrades the spatial resolution. Sounding points (representative location of echo-beam) are distributed sparsely at greater depths associated with the echo-beam spreading, which results in low spatial resolution. The accuracy of depth measurement is known to fall inverse in proportion to the water depth as well.

In contrast, an AUV-based survey enables us to obtain high-resolution and high-accuracy bathymetric data. As a multi-narrow beam echo sounder with high-frequency

sound and narrow beam width can be applied to the near-seafloor AUV-based survey, the footprint size is small as well because of the distance from the seafloor.

Bathymetric data collection

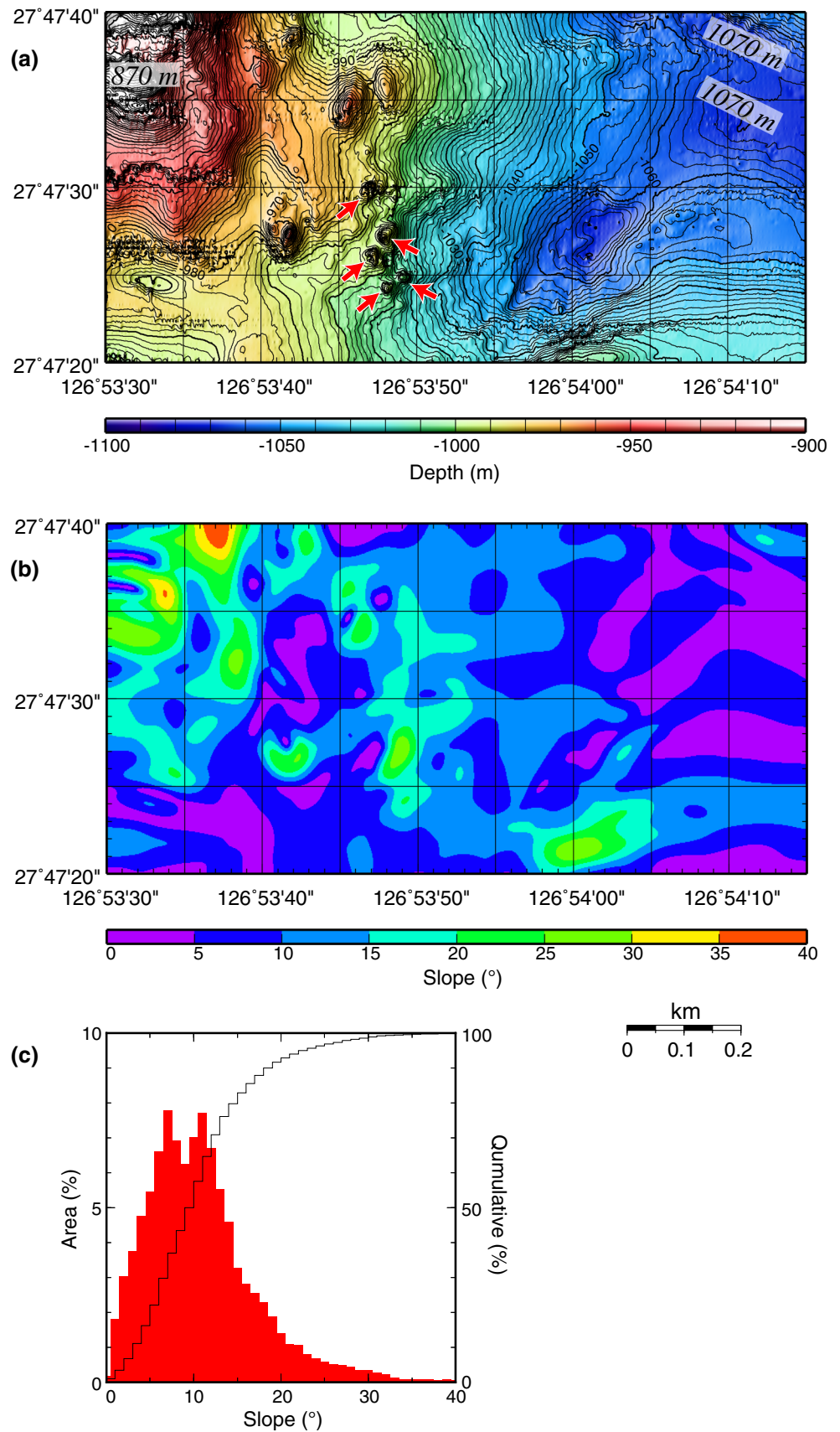
AUV Urashima survey

AUV *Urashima* bathymetric survey was conducted in JAMSTEC YK07-07 cruise aboard the R/V *Yokosuka* in May 2007 (Yamamoto et al. 2009). The applied multi-narrow beam echo sounder was a SEABAT 7125 [frequency 400 kHz, beam width $1.0^\circ \times 0.5^\circ$ (fore-aft \times athwart)]. The AUV survey tracks were aligned in the east–west direction with a spacing of 120 m. Survey

Table 1 Summary of R/V *Yokosuka* survey tracks

Survey track (date)	Ship speed (kt)	Track direction
718 (July 18)	8	South to North
720 (July 20)	3.5	West to East
721 (July 21)	4	South to North
723-1 (July 23, 1st)	3	East to West
723-2 (July 23, 2nd)	3	North to South
724 (July 24)	16	South to North

Fig. 3 **a** Swath bathymetry measured by the AUV *Urashima*'s multi-narrow beam echo sounder, contoured at 2 m. **b** Slope angle distribution of the AUV bathymetry. The slope angle was calculated after 'grdfilter' (width: 100 m) operation. **c** Histogram of frequency percent of the slope angle



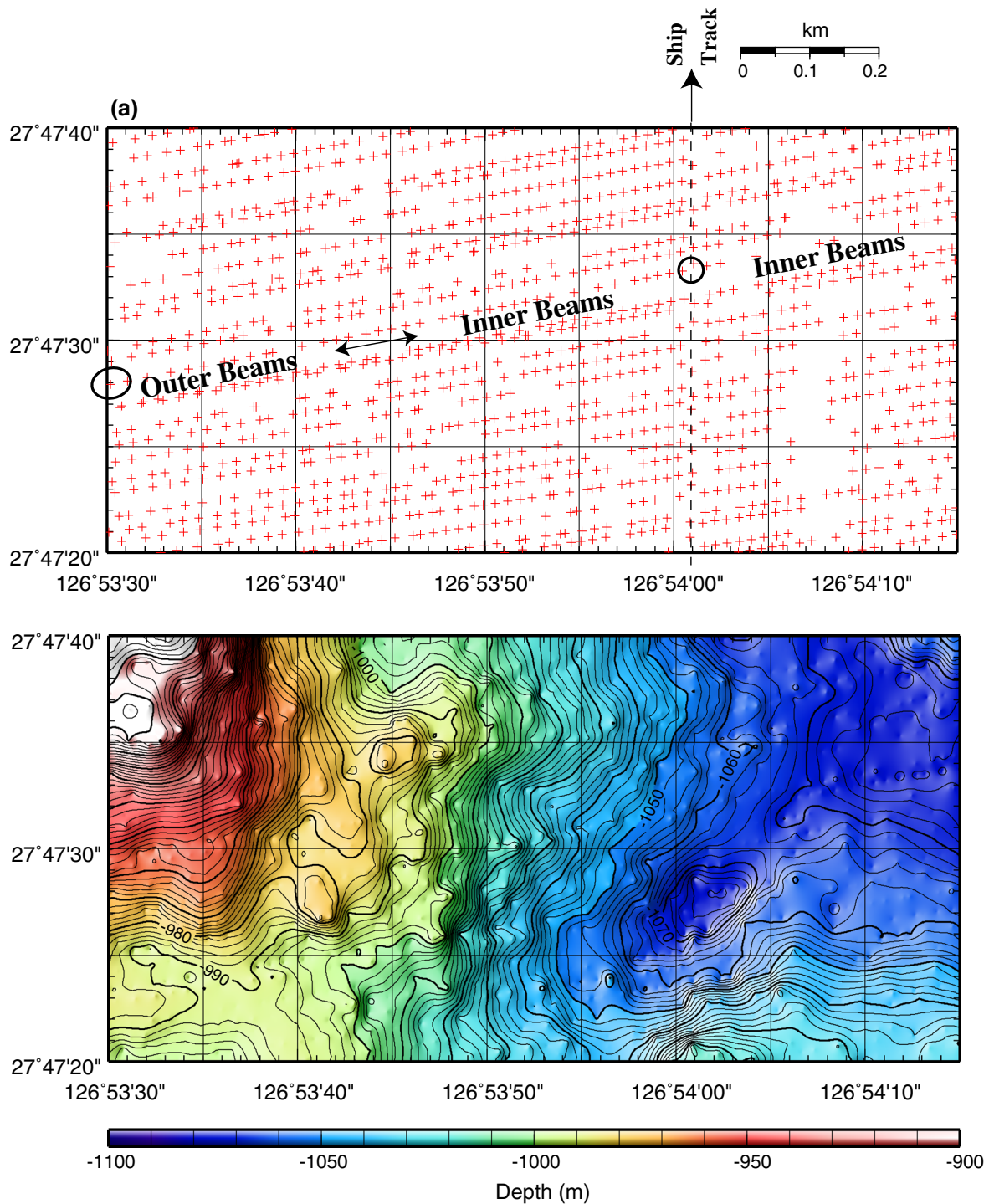


Fig. 4 In the upper figure, red crosses show sounding points of the R/V *Yokosuka*'s multi-narrow beam survey. The arrow and dashed line show the ship track and the traveling direction. Black ellipses in a are indications of the footprint sizes. The lower figure shows swath

bathymetry measured by the vessel-based survey. **a** Survey on July 18 (718), **b** first survey on July 23 (723-1), **c** second survey on July 23 (723-2), and **d** survey on July 24 (724)

altitude was kept to ~70–100 m. Water depth was determined by the sum of the vehicle's depth and measured values from the AUV. The near-seafloor sound velocity was calculated using measurements from an expendable

bathothermograph (XBT). Navigation was achieved by a combination of an inertial navigation system (INS) and super-short baseline positioning (SSBL). The positioning control was not in good condition and more or less 50 m of

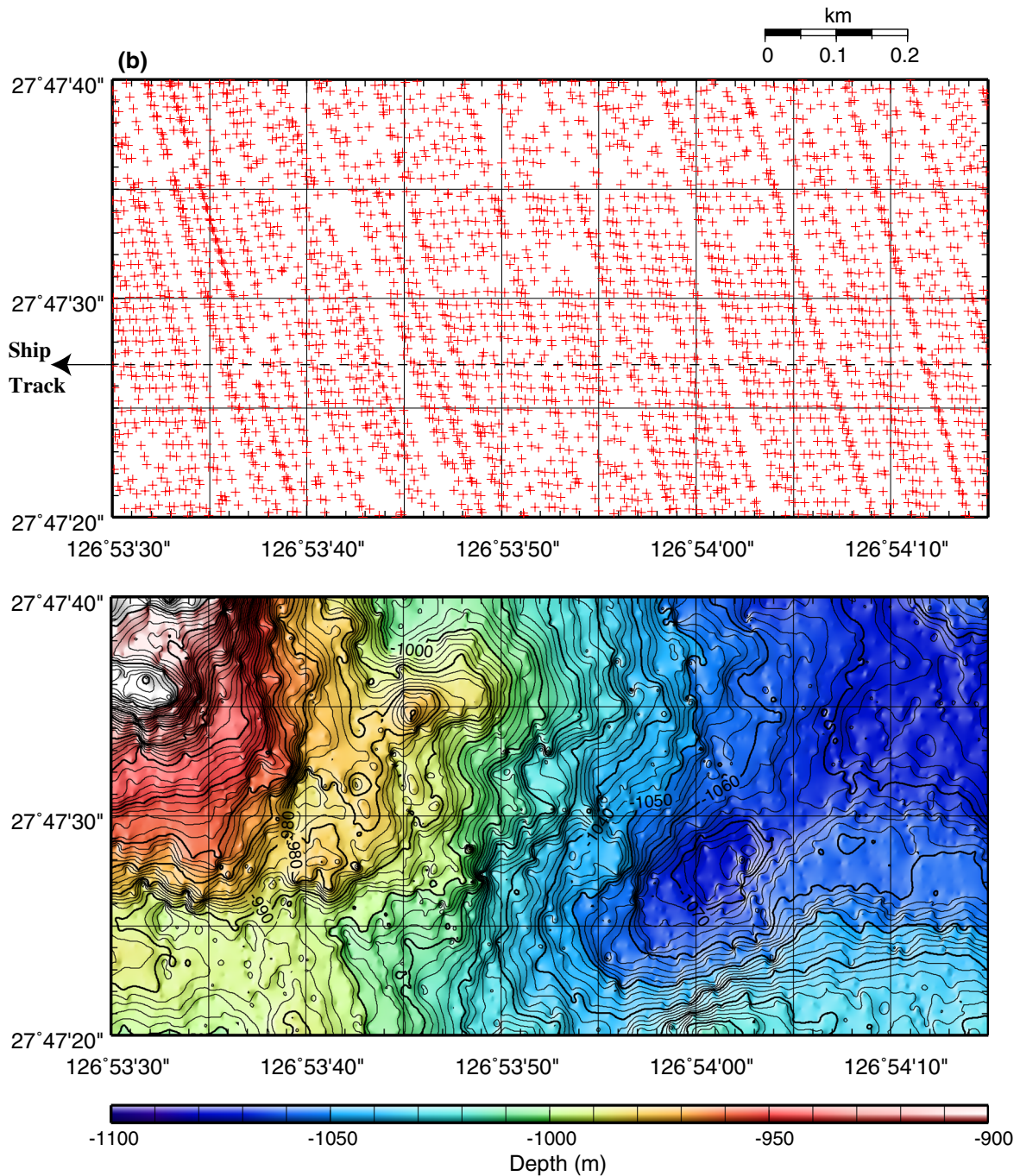


Fig. 4 continued

the positioning error was inferred. Finally, the horizontal positions were corrected to match the morphological features observed on overlapped tracks.

R/V *Yokosuka* survey

R/V *Yokosuka* bathymetric survey was performed using a SeaBeam 2112 echo sounder (12 kHz, $2^\circ \times 2^\circ$) in YK06-09 cruise from 18 to 24 July 2006 (Masaki et al. 2011). The

specifications of this echo sounder have been commonly used for deep-sea bathymetric surveys. The vessel passed over the survey area six times, each with a constant speed and obtained bathymetric data (Table 1). One survey track was treated as one's independent survey in this study. The beam angle was within 40° in the survey area. The XBT measurement for the sound velocity profile in the water column was conducted at $126^\circ53.86'E$, $27^\circ44.87'N$, ~ 5 km south of the survey area, on 18 July 2006.

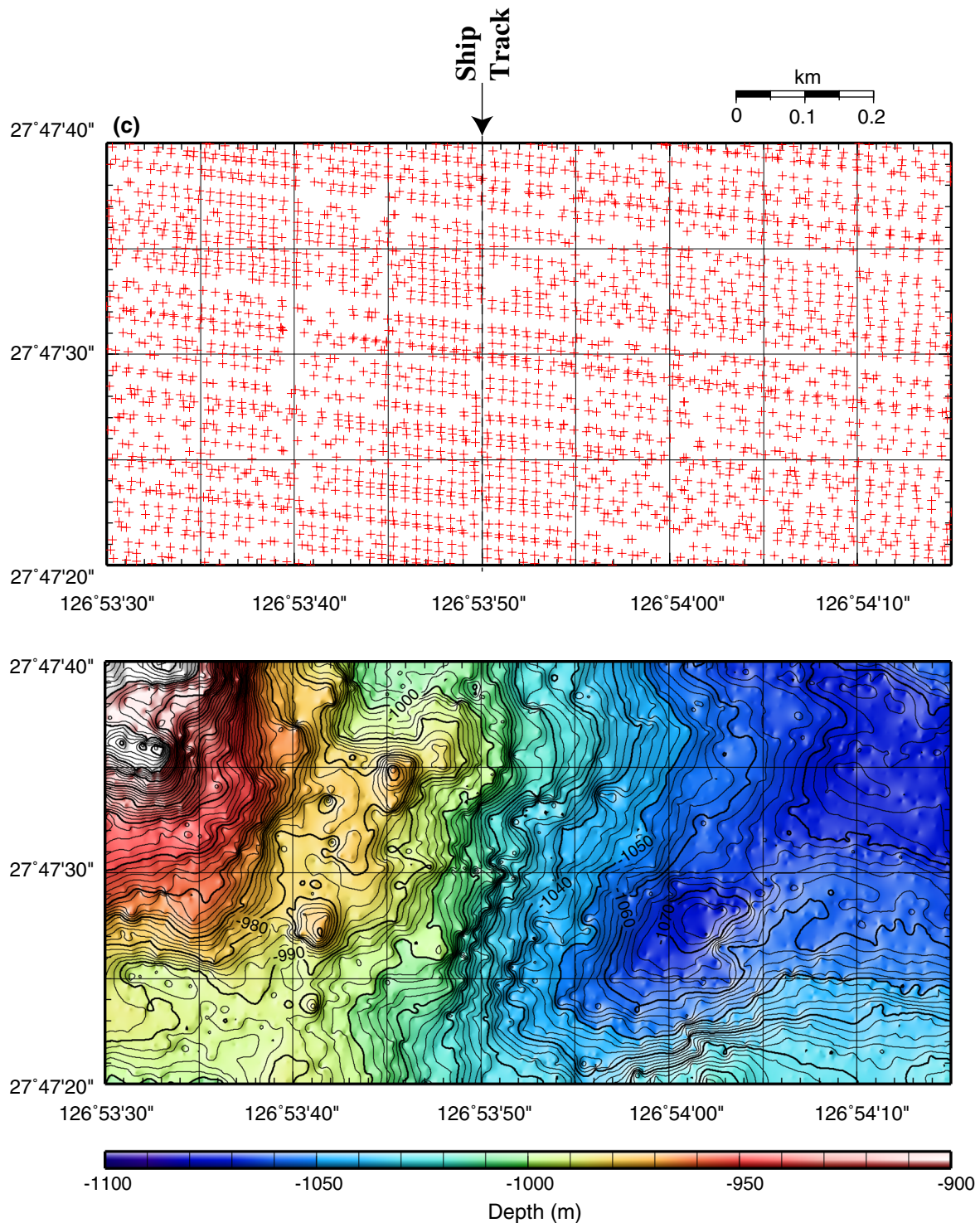


Fig. 4 continued

Comparison between AUV and vessel bathymetry

The Generic Mapping Tools (GMT) software (Wessel and Smith 1995) was used in the bathymetric data processing. Sounding points of the AUV *Urashima* survey were distributed uniformly because of the measurement at nearly

constant altitude, and the footprint size was $\sim 1.4 \times 0.7\text{--}1.8 \times 1.1$ m. Continuous curvature surface gridding algorithm ‘surface’ (tension: 0.35) and pre-processor filter ‘blockmedian’ were operated for the gridding. The data were gridded at a spacing of 0.05 arc-second (~ 1.5 m). The data are named ‘*Urashima* data’.

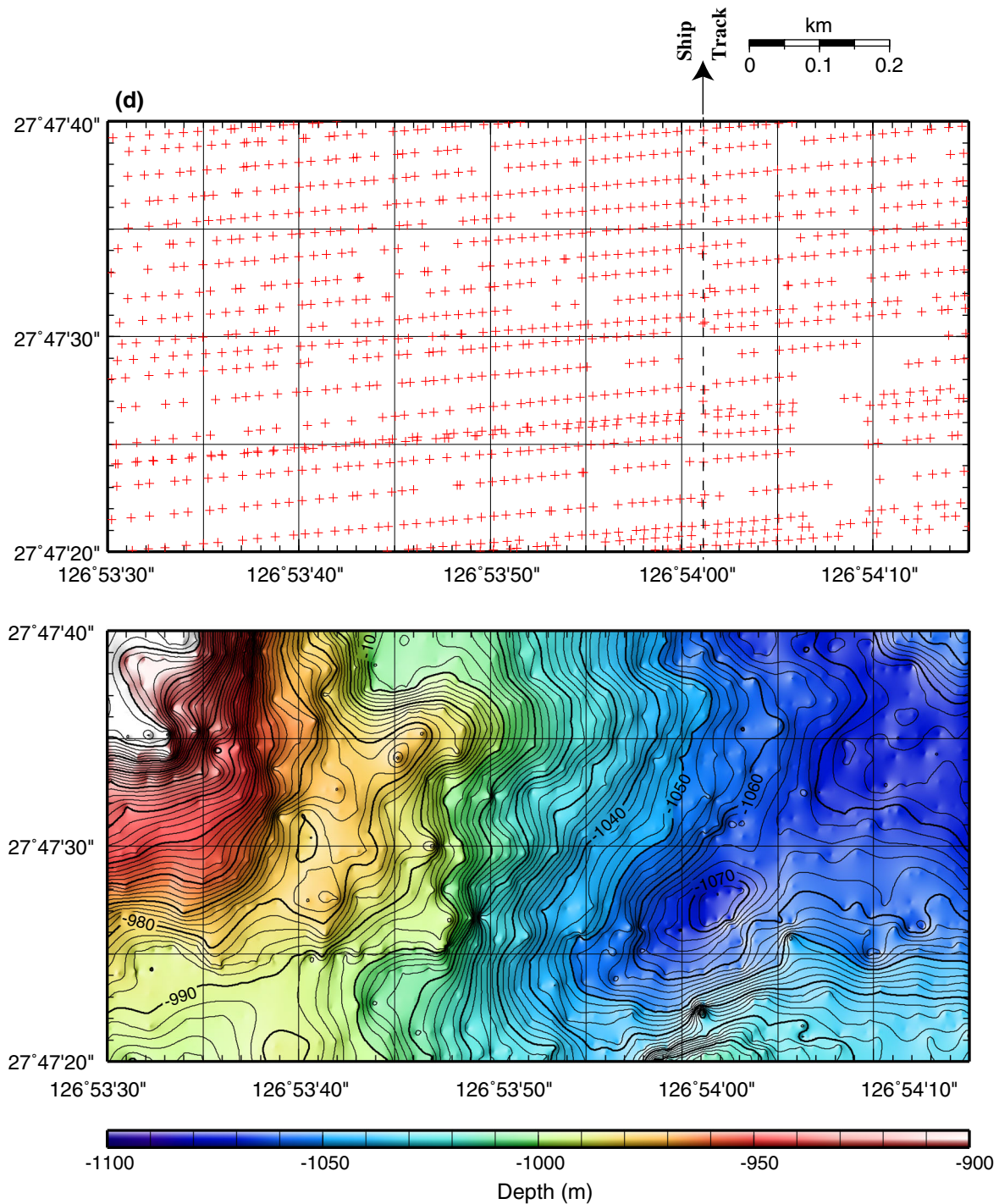


Fig. 4 continued

AUV bathymetry shows hills (the shallowest depth ~ 870 m) on the western side and basins (the deepest $\sim 1,070$ m) on the eastern side (Fig. 3a). The average/median depth is 1,010 m, approximately 1,000 m. Hydrothermal chimney mounds ~ 30 m in diameter and ~ 10 – 20 m in height were found on the hillside around $126^{\circ}53'45''$ – $50''$ E, $27^{\circ}47'24''$ – $30''$ N in the high-resolution

bathymetry. There are somewhat artifacts of small-scale depth discontinuities, with amplitude of ~ 2 – 4 m, on the overlapped tracks due to the uncertainties in AUV positioning. Slope angles of 0° – 20° are dominant and the mode value is $\sim 10^{\circ}$ in the survey area (Fig. 3b, c).

Vessel bathymetry is shown in Fig. 4. Each survey track was treated as an independent survey in this study. The

same parameters for the *Urashima* processing were used for the R/V *Yokosuka*'s. The grid spacing is finer than the mean spacing of the vessel's raw soundings, but it can avoid aliasing, thus the grid data can more directly reflect the measurement conditions such as distribution of sounding points and quality of measured values. The footprint size of the vessel-based survey is ~ 35 – 43 m at the depth of 1,000 m in ship's fore-aft direction. The footprint size in athwart ship's direction is estimated to vary from ~ 35 to ~ 80 m in consideration of the beam angle and the local slope. The footprint size of ~ 35 – 50 m covers 70 % of the survey area, and the footprint size within 80 m covers 95 % of the area. The maximum beam angle 37° is situated on the westernmost survey area in the July 18th (718) survey (Fig. 4a). Distribution of the sounding points is sparse and non-uniform. The vessel speed causes bathymetry low spatial resolution, especially in the July 24th (724) survey when the vessel went at 16 kt (29.632 km/h) high speed (Fig. 4d).

In the vessel bathymetry, geographical features which are smaller than the footprint size, for example, the hydrothermal chimney mounds cannot be recognized (Figs. 3, 4). Seafloor morphology is slightly different from each track survey due to inhomogeneous distribution of sounding points and measuring errors.

The high-resolution AUV bathymetry was assumed to be the "true" bathymetry. The *Urashima* data were smoothing-filtered by Gaussian type convolution 'grdfilter' in consideration of the footprint size. The filter width was examined by comparing filtered AUV-based data with observed vessel-based survey. The filtered data were sampled at sounding points of the vessel-based survey, and then depth differences between the AUV- and the vessel-based data were taken. As the result, when a filter width (that is six times the Gaussian sigma) of 100 m was applied, standard deviations of the depth differences were the smallest. In that case, the standard deviations (1σ) ranged from 2.64 m (723-2 survey) to 2.97 m (724 survey) (Fig. 5). Practically, locational errors in the sounding points are an additional effect on the depth differences. Uncertainties in positioning of the AUV, additionally, errors in water column sound velocity, roll, and pitch motions of the vessel are possible sources of the locational errors. Therefore the accuracy of the vessel-based depth measurement [standard deviation (1σ) of measuring error] is considered to be within ~ 0.2 – 0.3 % of water depth ($\sim 1,000$ m).

Evaluation tests of seafloor displacement detection and estimation

In our evaluation tests, simulated vessel-based bathymetric data, which were created from the AUV-based bathymetric

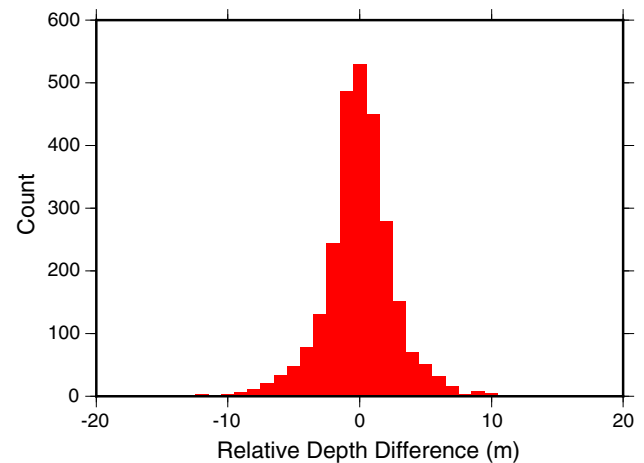


Fig. 5 Histogram of relative depth difference between AUV *Urashima* and R/V *Yokosuka* (723-2) data, the bias value of 6.46 m is removed. The standard deviation (1σ) of the distribution is 2.64 m

survey, were used. This data were assumed to be "before" the seafloor displacement. Then a variety of locational and convex/concave elevational changes were applied on the AUV-based bathymetric data, which was then treated to produce a simulative data of "after" the seafloor displacement. The displacement was then verified by comparing these "before" and "after" sets of data. Regarding analysis conditions, no locational errors of beam sounding points existed, depth accuracy was constant within the analysis area, and footprint effect was uniform in the analysis area. As the depth values were sampled from the same AUV-data, there was no depth offset between two data.

Estimation of horizontal seafloor displacement

Locations (longitude, latitude) of the *Urashima* data were shifted uniformly as the simulation of rigid horizontal seafloor displacement. We used the method of Fujiwara et al. (2011) to estimate the horizontal displacement. The evaluation test was performed according to the following procedure.

1. Filtered (Gaussian, width: 100 m) *Urashima* data values were sampled at sounding points of a *Yokosuka* survey. Normally-distributed random values ($1\sigma = 3$ m) as a simulation of depth accuracy were added to the sampling values. The simulated vessel-based bathymetric data was used as "before" the displacement (Data-1, e.g. Fig. 6a).
2. The *Urashima* data, of which the locations were shifted, were filtered and sampled at sounding points of other *Yokosuka* survey data. Normally-distributed random values ($1\sigma = 3$ m) were added to the sampling values as "after" the displacement vessel-based bathymetric data (Data-2, e.g. Fig. 6b).

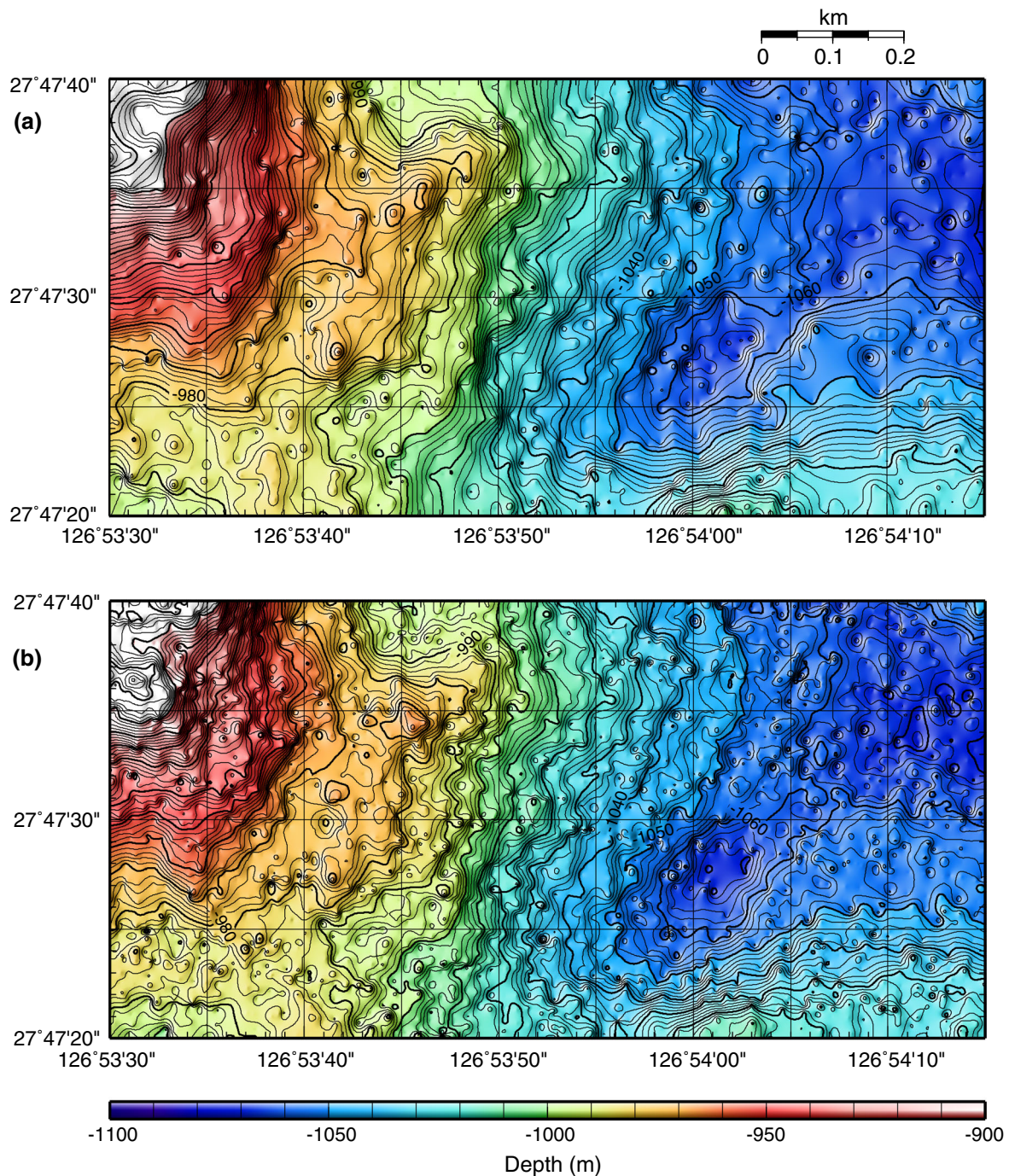


Fig. 6 Simulated vessel-based bathymetric data using the AUV *Urashima* data. The AUV data are sampled at sounding points of **a** 718 and **b** 723-2 surveys, then normally-distributed random values ($1\sigma = 3$ m) are added to the sampling values

3. “After” bathymetry (Data-2) was horizontally shifted to minimize the variance of depth differences from “before” bathymetry (Data-1) (to maximize the cross-correlation of the bathymetry).
 4. Horizontal displacement was estimated by the amount of horizontal shift, and dislocation from the given shift showed the error of estimation (Figs. 7, 8).
 5. The amounts of location shift were varied both in longitude and in latitude, and the procedures from 2 to 4 were repeated. The horizontal shift amount spans $\sim \pm 4.9$ m ($\pm 0.00005^\circ$) in longitude and $\sim \pm 5.6$ m ($\pm 0.00005^\circ$) in latitude.
- As the result, we found that the estimation error of the seafloor horizontal displacement is 0–3 m (Fig. 8). The

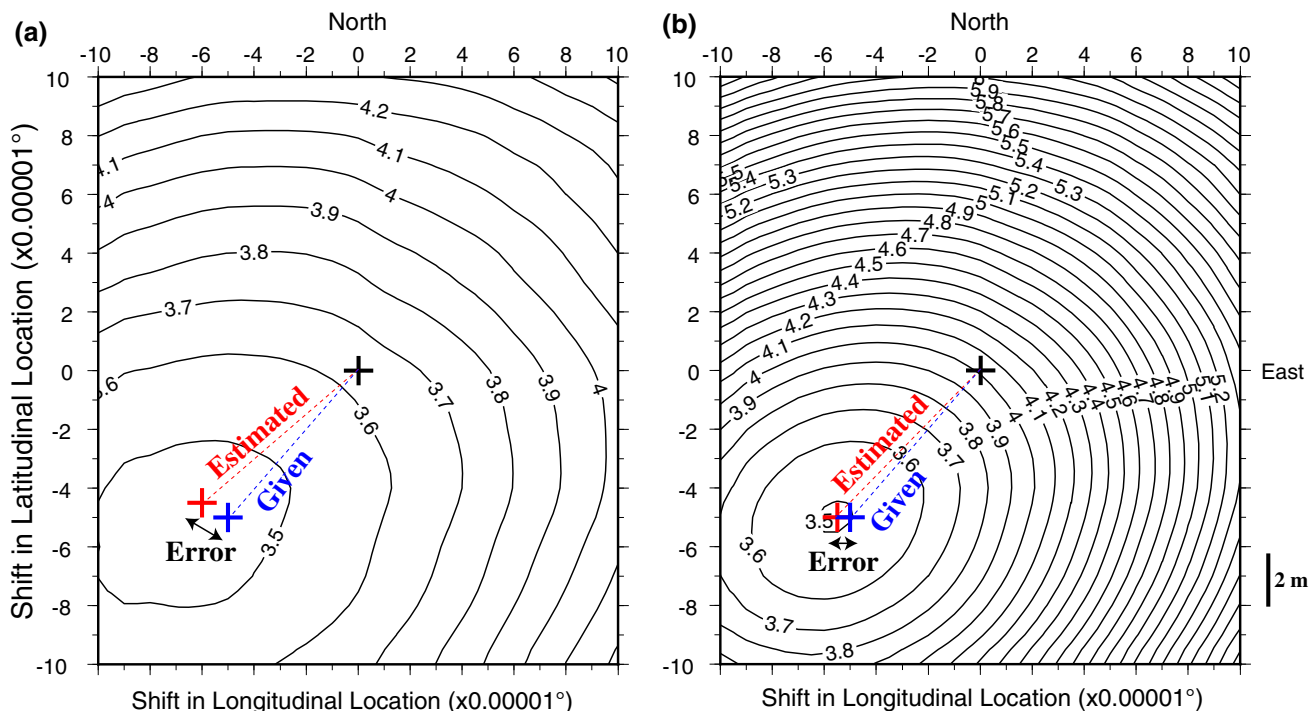
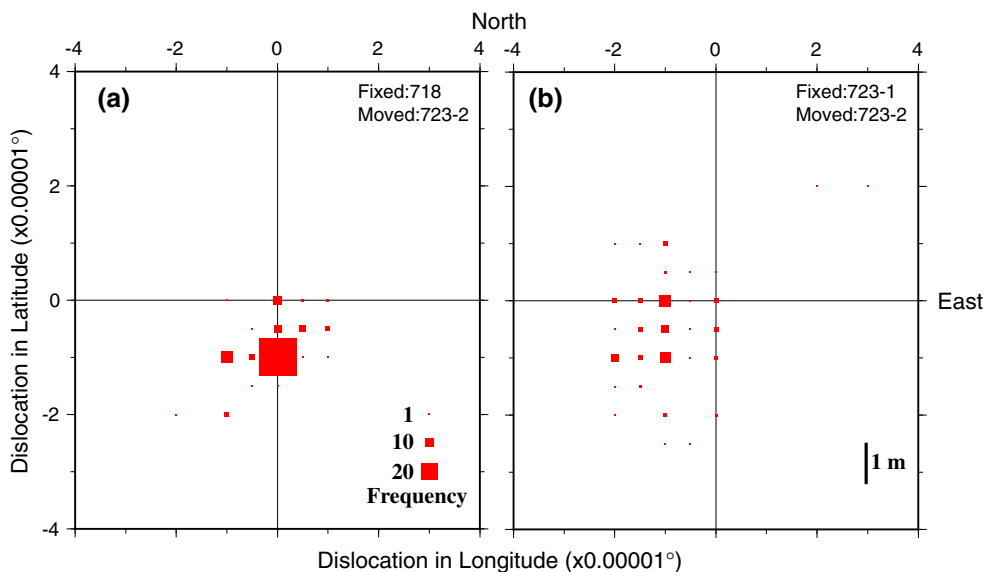


Fig. 7 Contours showing standard deviations of depth differences between two data. **a** The red cross at $(-6, -4.5)$ ($\times 0.00001^\circ$) indicates the location of the minimum value. The blue cross at $(-5, -5)$ points the given shifted location. The dislocation from the blue to

the red crosses $(-1, +0.5)$ is the error of estimation shown in Fig. 8. **b** Contours when using a high relief bathymetry model of which relative height was doubled

Fig. 8 Scatter plot of errors of estimated seafloor horizontal displacements. The sizes of red squares show occurrence frequency. **a** Comparison between simulated Data-1 using the sounding points of the R/V *Yokosuka* 718 survey and simulated Data-2 using the sounding points of 723-2 survey. **b** Comparison between simulated Data-1 and Data-2 using 723-1 and 723-2 surveys



distance of error was not dependent on the amount of given location shift. As shown in the contour map showing standard deviations of depth differences between two data of Fig. 7a, there is little difference in value between any points around the location of the minimum value, thus the location of the minimum likely to drift within distance of 0–3 m (for example, inside the 3.5 m contour in Fig. 7a).

The pattern of error distribution varied with a pair of *Yokosuka* surveys (Fig. 8) or a pattern of random values added, though, the error range didn't change. In trial runs using relatively dense distribution of the sounding points of 718 and 723-2, or dense distribution of 723-1 and 723-2 surveys, the error range didn't change. However, in trial runs using sparse distribution of the sounding points of 718

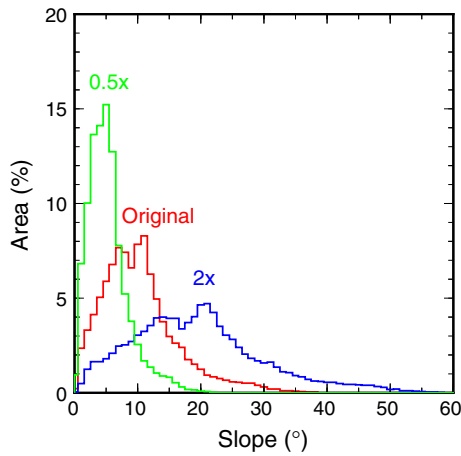


Fig. 9 Histogram of slope angles. The red, blue, and green lines show slope angle frequency percent of the original AUV bathymetry as shown in Fig. 3c, in addition, high, and low relief bathymetric models, respectively

and 724 surveys, the error range was doubled. Thus, we found that significant decline in spatial resolution due to the sparse distribution of sounding points causes large estimation error for horizontal displacement.

The estimation error depended on the standard deviation of random values given as the depth accuracy. In cases when no random values were added, the horizontal

displacements were accurately determined and the errors were within the range of 0–1 m.

We examined factors of bathymetric relief and steepness of the local slope. High relief bathymetry was emulated from the *Urashima* data of which relative height from the average depth was magnified up to two times. The average depth is 1,010 m and the same as the original data. Accordingly, the mode of the local slope angles became $\sim 20^\circ$ and slope angles ranged widely from 0° to larger than 40° (blue line in Fig. 9). The evaluation test was performed according to the same procedure. As shown in Fig. 7b, in trial runs using the high relief bathymetry, values greatly change across the distance and the minimum value is located within a narrow range of the bottom of the contour map (for example, inside the 3.5 m contour in Fig. 7b). Then, the horizontal displacements were accurately estimated, and the error range was within 0–1 m.

On the other hand, the evaluation test was also performed using low relief bathymetry. In these models, the relative height was changed down to a half of the original *Urashima* data, and then the local slope angles $<10^\circ$ were predominant, and the angle's mode value was $\sim 5^\circ$ (green line in Fig. 9). In these trial runs, the resultant error range extended up to 10 m, thus this method was no longer effective for the low relief bathymetry and rather monotonous morphology. The result suggests the bathymetric

Fig. 10 a Convex-concave up/down seafloor elevation placed on the hill slope of the study area (Model-A). **b** Cross-sections of up/down models along a latitude of $27^\circ 47' 30''$ N. Model-A's amplitude of the up/down is ± 7 m, horizontal width in the east–west direction is 400 m. Model-B has horizontal extent of 200 m and amplitude of ± 3.5 m, Model-C's dimension is 100 m and ± 7 m in horizontal and vertical directions, respectively

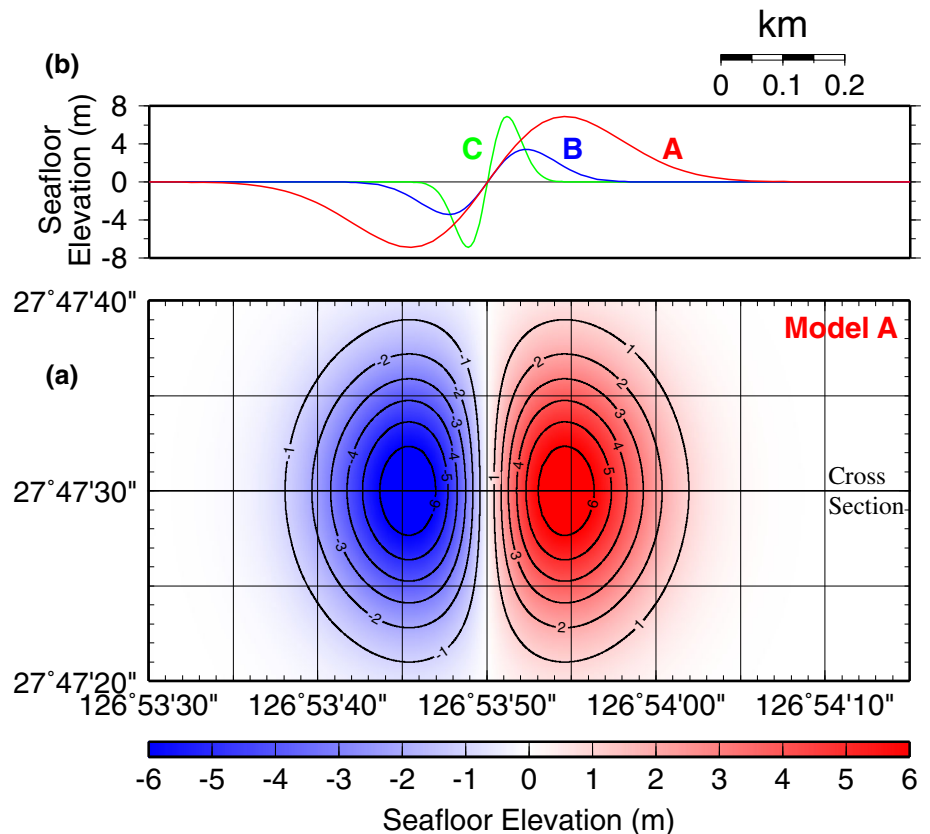
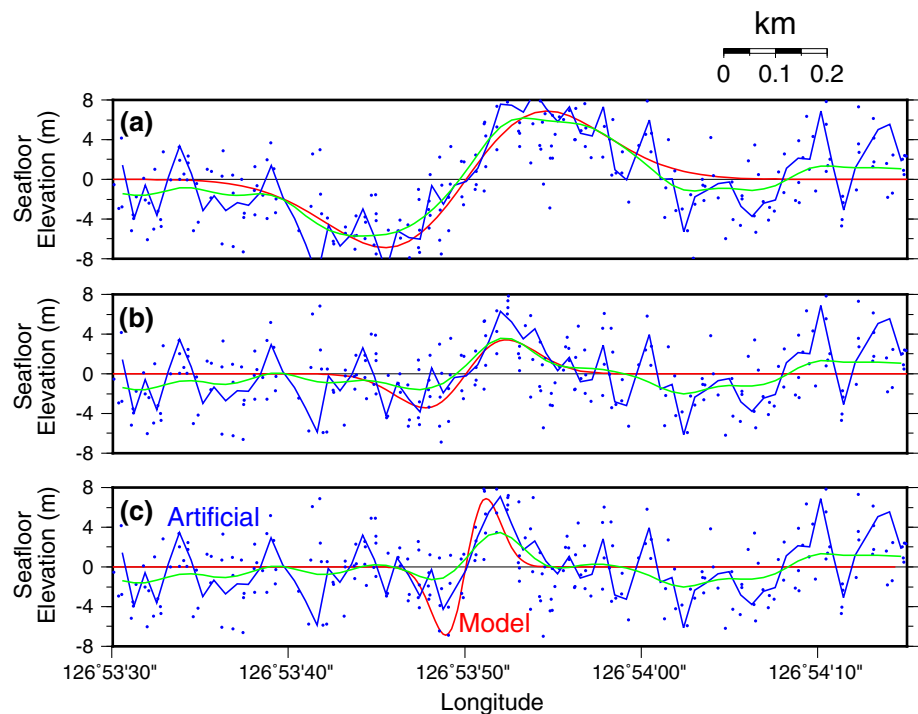


Fig. 11 Cross-sections along a latitude of $27^{\circ}47'30''\text{N}$. *Red lines* indicate the convex-concave up/down models, **a** Model-A, **b** Model-B, and **c** Model-C. *Blue dots* are depth differences sampled at 723-2 survey sounding points in the area between $27^{\circ}47'29''\text{N}$ and $27^{\circ}47'31''\text{N}$. *Blue lines* show depth differences along the latitude of $27^{\circ}47'30''\text{N}$. *Green lines* are filtered depth differences (Gaussian, width: 200 m) to suppress the artificial variation



relief and the steepness of the local slope are significant contributing factors.

Detection of vertical seafloor displacement

Convex-concave up/down seafloor elevation was added to the *Urashima* data as the simulation of vertical seafloor displacement on a local scale (Fig. 10) associated with horizontal seafloor displacement on a regional scale. The detection test was performed according to the following procedure.

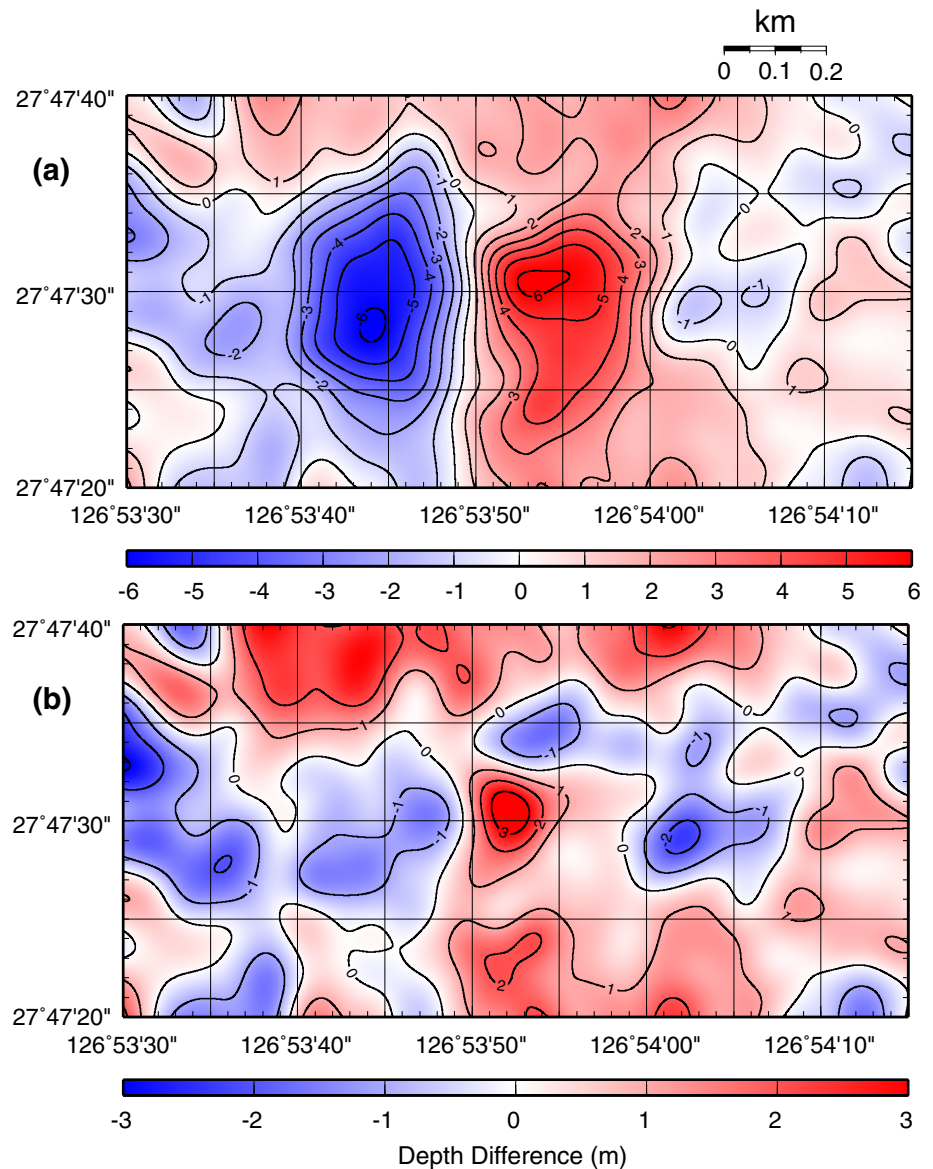
1. As shown in the last section, filtered (Gaussian, width: 100 m) *Urashima* data values were sampled at sounding points of a *Yokosuka* survey. Normally-distributed random values ($1\sigma = 3$ m) as a simulation of depth accuracy were added to the sampling values. The simulated vessel-based bathymetric data was used as “before” the displacement (Data-1).
2. Convex-concave up/down seafloor elevation was added to the *Urashima* data. In addition, locations (longitude, latitude) of the *Urashima* data were shifted with uniformly as horizontal displacement occurred concurrently. The filtered displacement data were sampled at sounding points of other *Yokosuka* survey data. Normally-distributed random values were added to the sampling values as “after” vessel-based bathymetric data (Data-2).

3. Water depth difference between “before” (Data-1) and “after” (Data-2) was taken.
4. The horizontal extent and amplitude of the up/down model were varied, and the procedures from 2 to 3 were repeated.

Artificial variation in the water depth difference beside the given depth difference occurred due to the inhomogeneous distribution of sounding points and the measuring errors (Fig. 11). The “fake” depth difference variation has a wavelength ~ 50 – 150 m in the trial run using a pair of dense distribution of the sounding points of 723-1 and 723-2 surveys. Amplitude of the variation shown in Fig. 11 is rather higher than ~ 3 m. The wavelength and the amplitude are equivalent to ~ 1 – 3 times of the footprint size and the standard deviation of the given random values as depth accuracy of this vessel-based survey, though the amplitude of the variation shown in Fig. 11 is rather higher than 3 m because of increasing variance of the depth differences by the added horizontal displacement. Therefore, displacement that can be detected occurs when the horizontal extent of the up/down model is larger than several times the footprint size, threefold is enough, and in the situation that the amplitude of the depth difference is greater than the given depth accuracy (Figs. 11a, b, 12).

In Figs. 11, 12, the resultant depth differences were filtered using longer lengths of filter-width to suppress the artificial variation (e.g. green lines in Fig. 11). The result suggests that the vertical seafloor displacement which has

Fig. 12 Color contour figure showing depth differences between two pieces of data, contoured at 0.5 m. Comparison between simulated Data-1 using the sounding points of the R/V *Yokosuka* 723-1 survey and simulated Data-2 using the sounding points of 723-2 survey. Convex-concave up/down seafloor elevation **a** Model-A, and **b** Model-B are added to Data-2. Then Data-2 are shifted the longitude and latitude to 0.00005°, 0.00005° (~ 4.9 , ~ 5.6 m) to simulate horizontal displacement. The depth difference data are low-pass filtered (Gaussian, width: 200 m)



long enough length of horizontal extent becomes detectable. In contrast, the vertical displacement in short horizontal extent is difficult to be distinguished from the false variation even in case of greater height difference was given (Fig. 11c).

Discussion

According to the results of this study, the footprint size and the accuracy of the depth measurement are suggested to be important factors for the seafloor displacement observation in the vessel-based bathymetric survey. In consideration of practical survey keeping with adequate survey vessel speed, and thus dense distribution of sounding points, as for

the smallest vertical seafloor displacement that can be detected, the criteria of threshold are that the horizontal extent of the deformation is larger than several times the size of the footprint, and in the situation that amplitude of the depth difference is greater than the depth accuracy.

As for the estimation of the horizontal seafloor displacement, slope angles of the artificial depth difference variation may be a contributing factor. The horizontal displacement was difficult to resolve when local slopes of the bathymetry were gentler than those of the artificial variation appeared in the depth differences. The slope angle of the artificial depth variation is derived from the wavelength and the amplitude which are equivalent to ~ 1 – 3 times of the footprint size and the accuracy of the depth measurement as shown in the last section. The slope

angles of the artificial variation is calculated to be $\sim 5^\circ$ – 10° . By contrast, the horizontal displacement should be accurately estimated in the area where high relief bathymetry has steep slopes and a variety of slope angles. In the case of moderate relief bathymetry, the estimation error depends on the magnitude of accuracy of the depth measurement. In this evaluation test, because slope steepness and variation changed concurrently, we could not figure out which factor is more significant.

To apply to practical seafloor displacement observation, criteria of the depth accuracy and the footprint size are interpreted with reference to water depth as a rough guide. By using a conventional multi-narrow beam echo sounder for deep-sea bathymetric surveys (sound frequency 12 kHz, beam width $2^\circ \times 2^\circ$), the accuracy is ~ 0.2 – 0.3 % of water depth and the footprint size is ~ 3 – 5 % of water depth.

Collection of high-accuracy bathymetric data must be considered for the seafloor displacement observation. Use of only the data obtained by inner beams near the nadir of the vessel is preferable to obtain small errors and reliable estimation, because these data have higher accuracy than that of outer beams. And in practical surveys, the data obtained by outer beams is problematic due to magnified local errors in accuracy of the depth values and location of the sounding points caused by effects of errors in water column sound velocity. And moreover, measuring errors due to ship's rolling motion are severe on outer beams. Therefore in the practical analysis, use of datasets collected along the same track is the best way because it enables a comparison between inner beams with a similar distribution pattern of sounding points as long as possible.

The vessel's navigation error and the sea surface height variation due to ocean tide, that is a possible error of the depth sounding, must be considered in practical surveys. To rectify the errors in the absolute depth values and location of the sounding points that are not called into account in this study, it is necessary to survey an area thought to have suffered from little change by seafloor displacement, which extends from an area of large displacements. This survey can reduce the apparent offsets considered to be of systematic errors existing in the whole area. The benchmarks are, for example, an off-axis ridge flank for volcanic eruption at the mid-ocean ridge (Fox et al. 1992), the foot of a submarine volcano for growth or collapse of the volcano (Watts et al. 2012), and a seaward trench slope for a subduction zone megathrust earthquake (Fujiwara et al. 2011).

We found that the bathymetric relief and steepness of the local slope are probably significant contributing factors for the horizontal displacement estimation. The evaluation in other areas, where seafloor morphology is different, is

essential to constrain how these influence the spatial resolution and the estimation error. To confirm the applicability to scientifically-interesting areas as in mid-ocean ridges, which have an average depth of $\sim 3,000$ m or trenches deeper than 5,000 m, the evaluation in areas at greater depths is also needed. For the future, there is room for verification in the modeling methods that are interpolation of gridding to compare different surveys with; random sounding point locations, optimum processing to emulate the footprint effect, and proxy for the measuring error.

Conclusion

In comparison with the AUV bathymetry, geographical features smaller than the footprint size cannot be recognized in the vessel bathymetry. Seafloor morphology is different from each track survey due to the inhomogeneous distribution of sounding points and measuring errors. The difference causes artificial variation in the depth difference, which hampers detection and estimation of the seafloor displacement. The wavelength and the amplitude of the artificial depth variation are equivalent to ~ 1 – 3 times of the footprint size and the accuracy of the vessel-based depth measurement, respectively. Thus, the smallest vertical seafloor displacement that can be detected occurs when the horizontal extent of the deformation is larger than several times the footprint size, and in the situation that the amplitude of the depth difference is greater than the depth accuracy.

Significant decline in spatial resolution due to the sparse distribution of sounding points causes large estimation error of horizontal seafloor displacement. When dense distribution of soundings is certified, estimation error of the horizontal displacement depends on the depth accuracy. Probably the bathymetric relief and the steepness of the local slope are significant contributing factors for the estimation of the horizontal seafloor displacement. A possible threshold is the slope angle of the artificial variation appeared in the depth difference. The horizontal displacement may be difficult to resolve when local slopes of the bathymetry are gentler than those of the artificial depth variation.

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