Ultra-High-Resolution Seismic Surveys: 3D Sea Trial at Beppu Bay

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Chapter

Ultra-High-Resolution Seismic Surveys: 3D Sea Trial at Beppu Bay

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Abstract

A 3D high-resolution seismic (3D-HRS) survey was conducted to clearly reveal and map faults and fractures in a shallow-water region of Beppu Bay, Japan. The 3D-HRS was conducted using a dense array of six short streamer cables combined with a single GI gun, which generate the primary pulse and create the main bubble with generator and collapse the main bubble with injector. This high-frequency seismic source and high-density seismic source/receiver point distribution achieved a significant improvement in seismic imaging resolution. Because the 3D-HRS system is compact and lightweight and can be operated by small vessels, its effectiveness and necessity have been demonstrated, especially in shallow coastal waters, where conventional seismic survey using large ships and long streamer cables is difficult. For seismic data processing, pre-stack noise attenuation, de-ghosting, multiple removal, and acquisition footprint removal had essential roles in enhancing seismic imaging quality. Compared to existing 2D seismic survey technology, the 3D-HRS achieved much higher resolution and delineated highly detailed features of the seafloor and subsurface. Following the seismic processing sequence, similarity and thinned fault likelihood attribute workflows were applied to detect and visualize faults and fractures within the 3D-HRS volume. These seismic attributes revealed a network of broadly distributed faults and fractures along an active fault system in Beppu Bay.

Keywords: high-resolution seismic, shallow water, seismic data acquisition, seismic data processing, seismic attribute

1. Introduction

In recent years, the importance of geotechnical surveys to identify and evaluate geological risks related to seafloor topography and seafloor characteristics in shallow coastal waters has been increasing. Recently, the development of offshore wind power generation projects has been promoted by the public and private sectors, and the establishment of techniques to properly identify, evaluate, and manage geological seabed risks for the structural foundations of wind turbines has become an urgent issue (e.g., [1]). Because Japan exists in a variable zone where plate boundaries exist, it has unique geohazards different from those of other areas, such as Europe. Therefore, it is necessary to take appropriate responses to deal with the geological risks, especially in coastal waters, of active faults, earthquakes, submarine landslides, volcanoes, shallow gases, and sediment fills in old river channels.

Seismic surveys have been applied not only to marine resource surveys but also to active fault surveys, geohazard surveys, and monitoring surveys. In recent years, the development of high-resolution seismic (HRS) survey technology, which consists of high-frequency seismic sources and short streamer cables with a high-density channel arrangement, has progressed with the aim of understanding the detailed subsurface structure in shallow areas below the seafloor. These HRS techniques use a seismic source frequency of 200 to 400 Hz, and ultra-high-resolution seismic (UHRS) surveys use a seismic source frequency of 2 to 3 kHz. The HRS/UHRS technology has been put into practical use and achieved a significant improvement in vertical and horizontal resolution by using high-frequency seismic sources and high-density seismic source and receiver point distributions. Because the HRS/UHRS system is compact and lightweight and can be operated by small vessels, its effectiveness and necessity have been demonstrated, especially in coastal shallow waters where conventional seismic surveys using large ships and long streamer cables are difficult (e.g., [2, 3]). The vertical resolution and detection depth range in offshore seismic reflections largely depend on the frequency band of the seismic source used, with higher-frequency sources having higher vertical resolution but lower penetration due to greater energy attenuation during seismic wave propagation. Due to this trade-off between vertical resolution and detection depth range in HRS/UHRS systems, they are often used in different ways depending on the survey target. Suda et al. [4] reported improvements of vertical resolution and detection depth range by multi-scale exploration using multiple seismic sources with different frequency bands simultaneously.

JGI, Inc., has developed lightweight short streamer cables to make improvements by reducing cable towing noise, improving real-time positioning accuracy, and controlling cable position. After the 3D UHRS survey in the Yatsushiro Sea in Kumamoto Prefecture [3], which was conducted as part of the comprehensive active fault survey by the Japan Ministry of Education, Culture, Sports, Science and Technology in 2016, the HRS/UHRS system with independent recording type streamer cables (i.e., an autonomous cable system) is now commercially available. In this chapter, we show the results of a demonstration test conducted in Beppu Bay in an effort to understand the depth and shape of an engineered foundation, which is important for offshore wind power generation projects, and to visualize and extract geohazard factors such as faults, shallow gas, and soft layers. Then, we discuss the utility of high-resolution 3D seismic surveys in shallow coastal waters using the HRS/UHRS system.

2. 3D high-resolution seismic survey data acquisition system

The 3D-HRS data acquisition system is a compact system developed to obtain a detailed understanding of the geological structure of the shallow subsurface below the seabed. The system consists of short streamer cables, small high-frequency seismic sources, and onboard equipment. The system configuration and main technical specifications of the 3D-HRS data acquisition system are shown in **Figure 1** and **Table 1**, respectively. Closely spaced shot points and receivers allow high-density

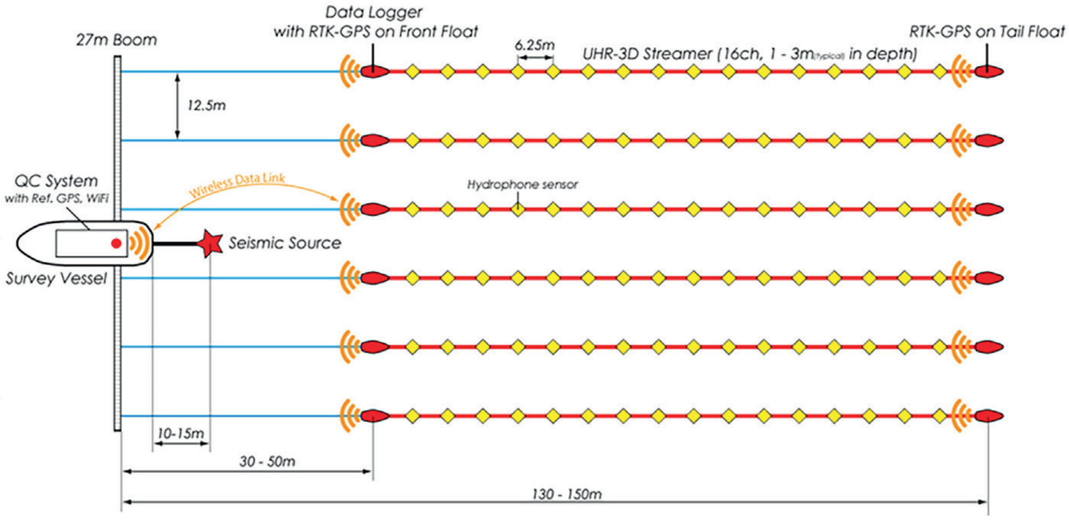


Figure 1.
Schematic configuration of 3D-HRS data acquisition system.

Streamer cable	**ACS (JGI, Inc.)**
Number of channels/line	16 ch
Channel spacing	6.25 m
Total length of streamer	100 m
Outer diameter	20 mm
Sensitivity of hydrophone	−201 dB re: 1 V/uPa
Frequency response	5 Hz–10 kHz (±3 dB)
Autonomous data recording system	**JGI-HR3D-2019 (JGI, Inc.)**
Number of input channels	16 ch
A/D converter	24 bit ΔΣ
Sampling frequency	1 kHz/4 kHz/10 kHz
Dynamic range	109 dB
Preamplifier gain (selectable)	xl/x4/x8/xl6
Navigation system	**vNAV (JGI, Inc.)**
Navigation	D-GPS, RTK-GPS
Shooting interval	Constant distance intervals/constant time intervals

Table 1.
Specifications of the 3D-HRS system.

seismic records to be acquired around the seismic spread, providing a high-resolution, accurate understanding of the 3D subsurface structure.

A high-resolution 3D seismic survey was conducted using the 3D-HRS data acquisition system with a small vessel having a gross tonnage of approximately 300 tons. Several short streamer cables around 100 m long were deployed using crane booms installed on either side near the stern of the vessel. The system was designed to efficiently perform high-resolution 3D seismic surveys over a range of several kilometers to several tens of kilometers at low cost. The main features of this system are described below.

2.1 Autonomous cable system

The autonomous cable system is an analog streamer cable with 16 highly sensitive hydrophone sensors placed at 6.25-m intervals. The cable is thin (20 mm in diameter) and lightweight, allowing it to be deployed and retrieved manually (no streamer winch required) and requiring only a small deck space on the survey vessel.

2.2 Cable towing system using crane booms

In areas with heavy vessel traffic, such as bays and coastal areas, it is necessary to conduct surveys in a maneuverable manner. Therefore, instead of using large paravanes, as commonly used in marine 3D seismic surveys, the streamer cables are towed from crane booms (less than 30 m long) extending from both sides of the stern of the vessel. The system has a very small turning radius (300–400 m) and can successfully tow multiple short streamer cables in a row, even when currents and winds prevent the vessel from maintaining a prescribed speed.

2.3 Cable depth and position control

The streamer cables are designed to have neutral buoyancy in seawater, and the towing depth is set by depth control devices located under the front and tail floats. The towing depth is observed with a depth gauge attached near the middle of each cable, and the weight of the cable is adjusted to maintain the specified towing depth as much as possible. This system does not use any active towing depth control device, such as a bird, to reduce cable towing noise. The steering control devices are mounted on the tail floats that try to maintain the streamer cables in certain positions. GPS devices are mounted on all floats to measure the exact positions of the receivers and the seismic source. It is also the role of the GPS devices to provide accurate time synchronization of all observation systems.

2.4 Data communication between the cables and survey vessel

A data logger is mounted on the front float of each cable, and signals from the hydrophone sensors and cable depth gauge are converted from analog to digital and stored in the data logger. Seismic data and GPS positioning information stored in the data logger and control signals to the steering control device on the tail float are transmitted *via* Wi-Fi in real time to and from the observation room on the survey vessel.

2.5 Quality control of seismic records

The onboard equipment consists of the 3D-HRS recording system developed by JGI, Inc., which collects and displays seismic data transmitted from the data loggers *via* Wi-Fi. A quality control (QC) system manages the quality of seismic records and the navigation system (vNAV system developed by JGI, Inc.), which navigates the survey vessel and controls the shot-timing of the seismic source. The real-time QC of seismic records and the position of the seismic spread is performed in the observation room to detect anomalies in each system and makes corrections to meet survey requirements by clients and/or survey designers.

3. Sea trial evaluation of the 3D-HRS survey

3.1 Survey area

We conducted a sea trial of the 3D-HRS survey system in Beppu Bay, Oita Prefecture, which is located at the western end of the Median Tectonic Line (MTL) and has many active fault systems that are a mixture of strike-slip faults and normal faults (e.g., [5]). To evaluate the activity of this fault zone, it is important to precisely understand the fault locations, distribution geometry, and displacement in the upper part of the Holocene deposits. In this 3D-HRS trial, data acquisition specifications were designed to obtain seismic records that contribute to the evaluation of the activity of subsurface active faults, with a vertical resolution of approximately 2 m and a maximum investigation depth of 300 m or more below the seafloor. The water depth in the survey area was 30 to 50 m.

A marine 2D seismic survey (9 survey lines with a total length of 138 km) was conducted by the Faculty of Science, Kyoto University, in 1989 to investigate the deep subsurface structure of Beppu Bay, and Yusa et al. [6] obtained groundbreaking insights into the geometry and tectonic motion of the MTL and the formation process of Beppu Bay, as well as the deep subsurface structure. Subsequently, in a 3-year national project starting in fiscal year 2014, new survey data were acquired for highly accurate strong-motion prediction of this fault zone and a comprehensive study, including the existing data, was carried out to update the fault distribution and deep structure from the coastal sea to land areas around Beppu Bay [7, 8]. However, deformation of the sedimentary layer due to fault movement diffuses and bifurcates near the ground surface and the seafloor. Therefore, the development of 3D high-resolution seismic survey technology has been identified as necessary for advanced evaluation of long-term earthquake prediction.

3.2 Data acquisition

The 3D-HRS sea trial was conducted in March 2020 in the southeastern part of Beppu Bay, the gateway to Beppu Port, Oita Port, and the steel and oil refinery complexes located in the Oita coastal industrial zone. The survey area was a rectangle of 6 km by 3 km (18 km^2), as shown in **Figure 2**. The area is an important marine traffic route for passenger vessels, iron ore and other raw material vessels, oil tankers, LNG carriers, and other vessels and is also a good fishing ground. Many ships, including pleasure boats and fishing boats, pass through this area day and night throughout the year in the survey area. Therefore, a highly maneuverable offshore 3D seismic survey system was required to facilitate the survey. The inline direction in this seismic survey was set to be orthogonal to the MTL (north-northwest to south-southeast) to facilitate comparison with the existing 2D seismic surveys (inline direction: long axis direction of the rectangular survey area). **Table 2** shows the data acquisition specifications.

In this survey, six short streamer cables approximately 100 m long were towed at 12.5-m intervals. Because there was only one seismic source in the survey, the common midpoint distribution area (swath width) in the crossline direction (orthogonal to the inline direction) obtained with a single survey line was 37.5 m, and the bin size was 3.125 m (inline) by 6.25 m (crossline). The width of the survey area in the crossline direction was 3 km, so the number of planned seismic survey lines was 81.

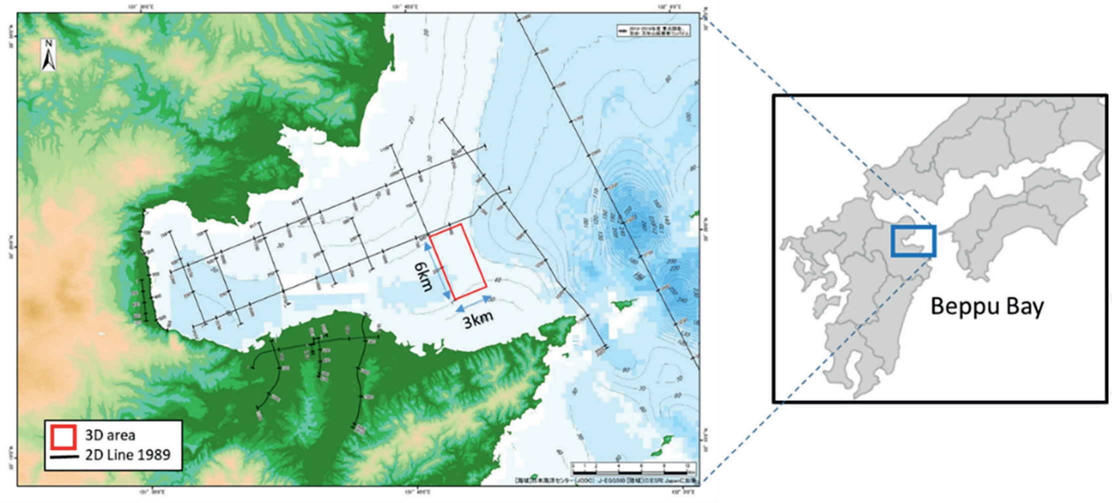


Figure 2.
Map of the survey area. The red square indicates the area of the 3D-HRS survey. The total area is approximately 18 km^2. Black lines indicate the lines of the seismic survey conducted by Kyoto University in 1989. All lines were reprocessed with state-of-the-art techniques [7].

Streamer cable	**ACS (JGI, Inc.)**
No. of streamers	6
Line spacing	12.5 m
Streamer depth	1.5 m
Total number of channels	96 ch
Channel spacing	6.25 m
Seismic source	**GI-Gun (Sercel)**
Capacity	150 cu.in. (45 + 105)
Shooting interval	6.25 m
Source depth	3.0 m
Recording system	**JGI-HR3D-2019 (JGI, Inc.)**
Sampling rate	0.25 ms
Record length	3.0 s
Bin size (Inline × Xline)	3.125 m × 6.25 m
Nominal number of folds	8

Table 2.
Specifications of the data acquisition trial in Beppu Bay.

The coordinates of shot points of the seismic source were directly measured with high precision by the GPS device mounted on the source float. The coordinates of the receiving points were calculated by interpolating the highly accurate positions measured by the GPS devices mounted on the front and tail floats attached to both ends of the streamer cables.

During seismic data acquisition, feathering of the streamer cables (deviations of the towing streamers from the planned positions) was observed in real time and the streamer spread was automatically optimized by the steering devices mounted on

Figure 3.
Photo of towed streamers taken from the sky.

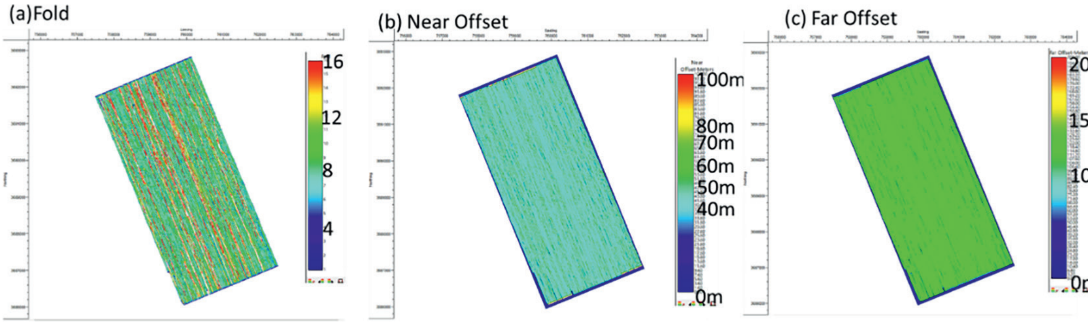


Figure 4.
Fold and offset distribution. (a) Number of folds for each bin (3.125 m inline, 6.25 m crossline). (b) Near-offset (40–50 m) distribution for each bin. (c) Far-offset (100–120 m) distribution for each bin. Both near- and far-offset data were uniformly acquired.

the tail floats of the streamer cables so as to maintain the specified towing interval for the streamer cables (**Figure 3**). The spatial distributions of the number of folds, the near offsets, and the far offsets for each bin obtained in the survey are shown in **Figure 4**.

The onboard QC of the survey data included real-time monitoring and confirmation of seismic records, amplitude spectra, near-trace records, fold maps, and noise levels (noise RMS amplitude values for every channel) at each seismic line, as well as checking the quality and consistency of the source waveforms acquired by the hydrophone sensor installed near the seismic source (**Figure 5**). The actual distribution of reflection points was found to be slightly spread out from the planned positions due to deflection of the towed streamers from the planned survey lines caused by sea conditions, obstructions at sea, and currents. Because missing reflection points in the acquisition coverage can contribute to significant compromise of the imaging quality of the seismic records, the onboard QC checked the number of stacking folds in each bin in real time during data acquisition, and if a certain number of zero-fold bins were found in the crossline direction due to deviations of the reflection point distribution, survey lines (infill seismic survey lines) were added to fill the gaps. The final number of survey lines was 112, of which 81 were planned and 31 were infill. It

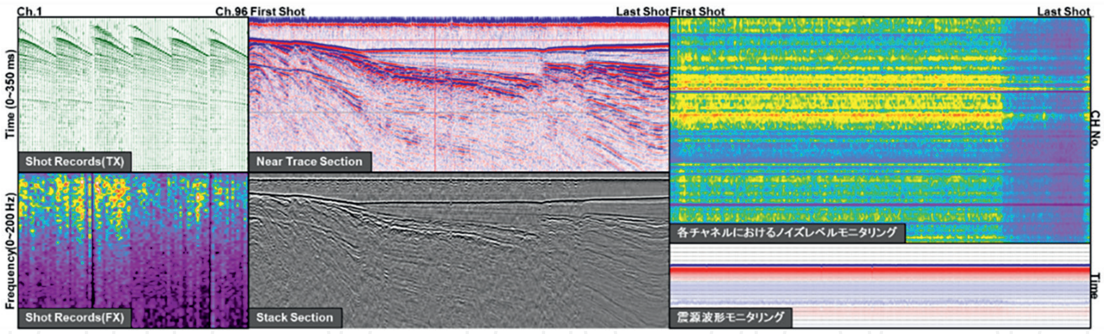


Figure 5.
Examples of onboard QC. Clear reflection events were observed in shot records, near trace sections, and in stack sections. Background noise and near-field source wavelets were monitored and used for system error detection in the survey.

Figure 6.
Flow chart of 3D-HRS data processing.

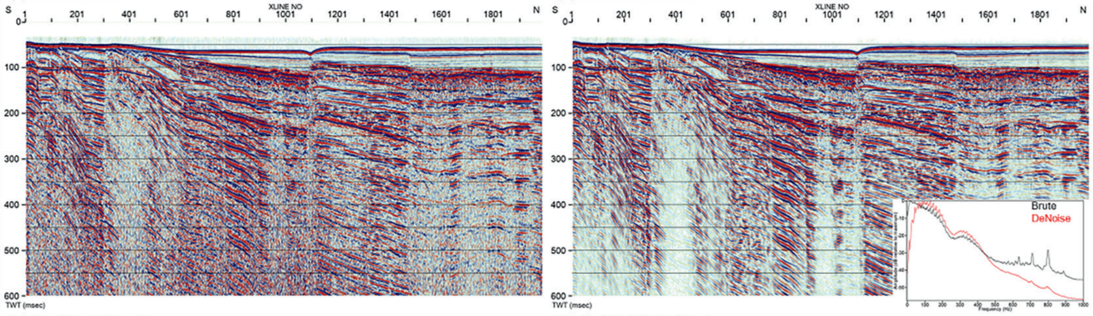
took approximately 1.5 hours to observe one survey line of 6 km and a total of 9 days to complete the survey, including weather standby and infill surveys.

4. Data processing

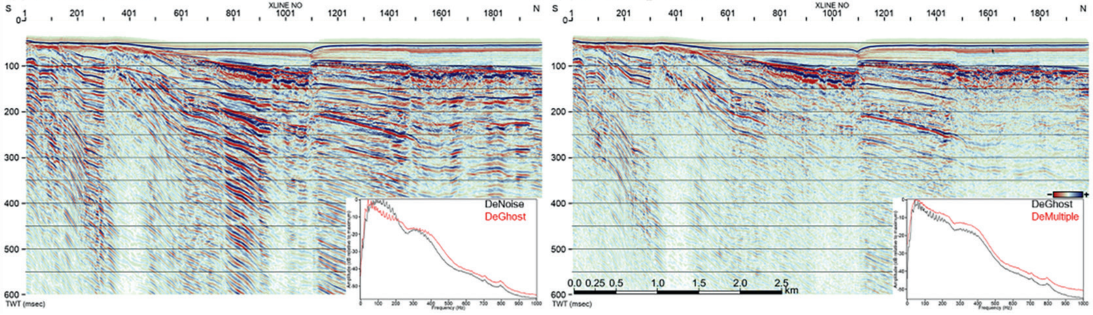
The 3D-HRS data, which have enhanced resolution and improved imaging accuracy, require an adaptive seismic processing sequence with attention to detail in order to maintain the higher frequencies in the original seismic field records. Especially for 3D-HRS in shallow waters, short-period multiples and strong swell noise due to shallowly towed streamers are critical issues in processing. Positioning errors, varying tide, and wave conditions or velocity changes in the water column cause imaging artifacts due to severe static shifts. Here, we focus on these issues and introduce the seismic processing sequence summarized in **Figure 6**. The main seismic processing steps are described below.

4.1 Pre-stack noise attenuation

The acquired seismic data contained various types of noise, such as sudden strong amplitude noise, coherent noise that may have been caused by surrounding vessels, and noise that may have been generated by the survey vessel or front and tail floats. Therefore, we applied a noise suppression process that combines various methods in consideration of the noise characteristics. The applied noise suppression techniques are an FX (frequency vs. space) edit filter (burst noise suppression), FX prediction filter (random noise suppression), and velocity filter (linear noise suppression), which are applied in both the shot and channel domains. **Figure 7a** and **b** show seismic stack sections and amplitude spectra before and after the noise suppression process. These figures show that the noise components on the seismic stack section were effectively suppressed, improving the quality of the stack section.



(a) Brute Stack **(b) DeNoise Stack**



(c) DeGhost Stack **(d) DeMultiple Stack**

Figure 7.
Examples of seismic data processing along a 2D inline section and their frequency amplitude spectra. (a) Brute stack. (b) De-noised stack. (c) De-ghosted stack. (d) De-multipled stack. The pre-stack noise attenuation reduced several sources of noise and enhanced laterally continuous events. In addition, the zero-offset de-multiple method effectively suppressed the apparent reverberation below the seafloor reflection.

4.2 Multiple removal

Because water depths within the survey area ranged from 30 to 50 m, short-period multiple reflections dominated the seismic section and interfered with the primary reflections. The 3D-HRS system has a short maximum offset, which limits the effectiveness of surface-related multiple elimination and high-resolution parabolic Radon transform methods, which are typical multiple suppression methods used in conventional marine seismic surveys. To process the Beppu data, therefore, a zero-offset de-multiple (ZOD) technique based on approximate 1D modeling of multiple components was implemented. The ZOD was conducted in three steps. The first step applied time-shifts to seismic traces using the two-way travel time of the seafloor reflection for modeling and suppressing water-layer-related multiples. The second step was an auto-convolution of each trace for modeling and suppressing other long-period free-surface multiples. The third step was a long-gap deconvolution with the water depth as the gap distance to suppress residual multiples. **Figure 7c** and **d** show seismic stack sections and amplitude spectra before and after the ZOD process. These figures show that the quality of stack sections was improved by effectively suppressing multiples. The ripples in the amplitude spectrum caused by multiples were also reduced.

4.3 Velocity analysis

Generally, velocity analysis is difficult with 3D-HRS data due to the limitation of the maximum offset. However, because water depths within the survey area were shallow (from 30 to 50 m), there was sufficient variation in the angle of incidence to reflection surfaces up to about 200 ms below the seafloor. Consequently, the velocity analysis was possible up to about 150 m below the seafloor. Velocity analysis examples with a constant velocity stack, normal moveout common midpoint gather, and velocity semblance are shown in **Figure 8**. The velocity trend in the deeper than 150 m was estimated from other seismic data acquired by ocean-bottom nodes.

4.4 Footprint suppression

In the time slice shown in **Figure 9a**, significant acquisition footprints and missing traces along the sail line direction are observed. In addition to residual tidal changes after tidal correction, water column statics and irregular changes in cable depth caused

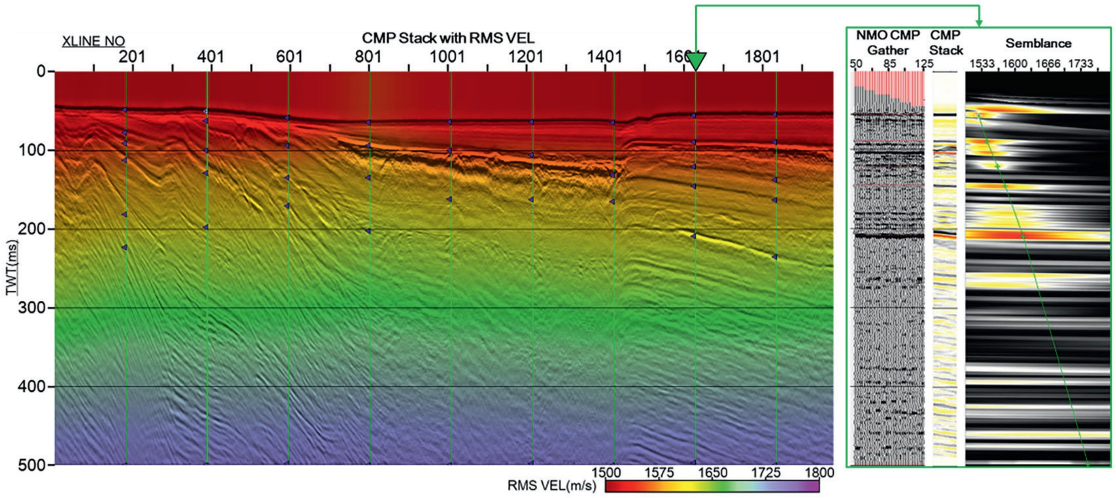


Figure 8.
Examples of the seismic velocity analysis. The velocity semblance spectrum indicates velocity trends until 300 ms, even though the offset range is limited to about 30–150 m.

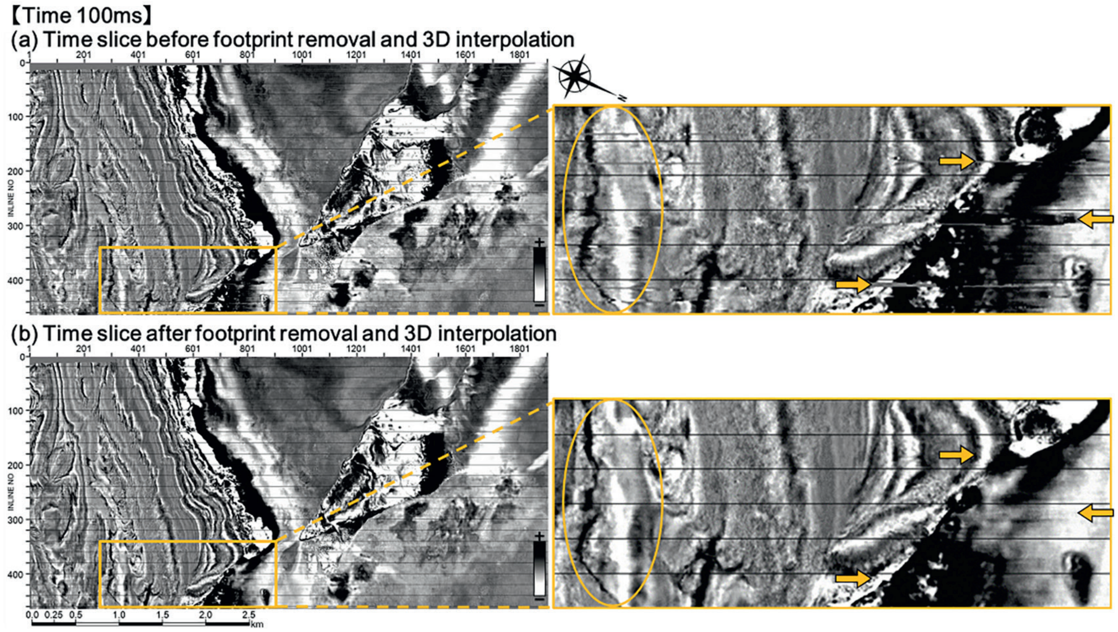


Figure 9.
(a) Enlargement of original time slice (time = 100 ms). The yellow circle and arrows indicate, respectively, acquisition footprints and missing traces. (b) The same slice after footprint suppression and 3D interpolation. These processes are shown to be effective for enhancing seismic images.

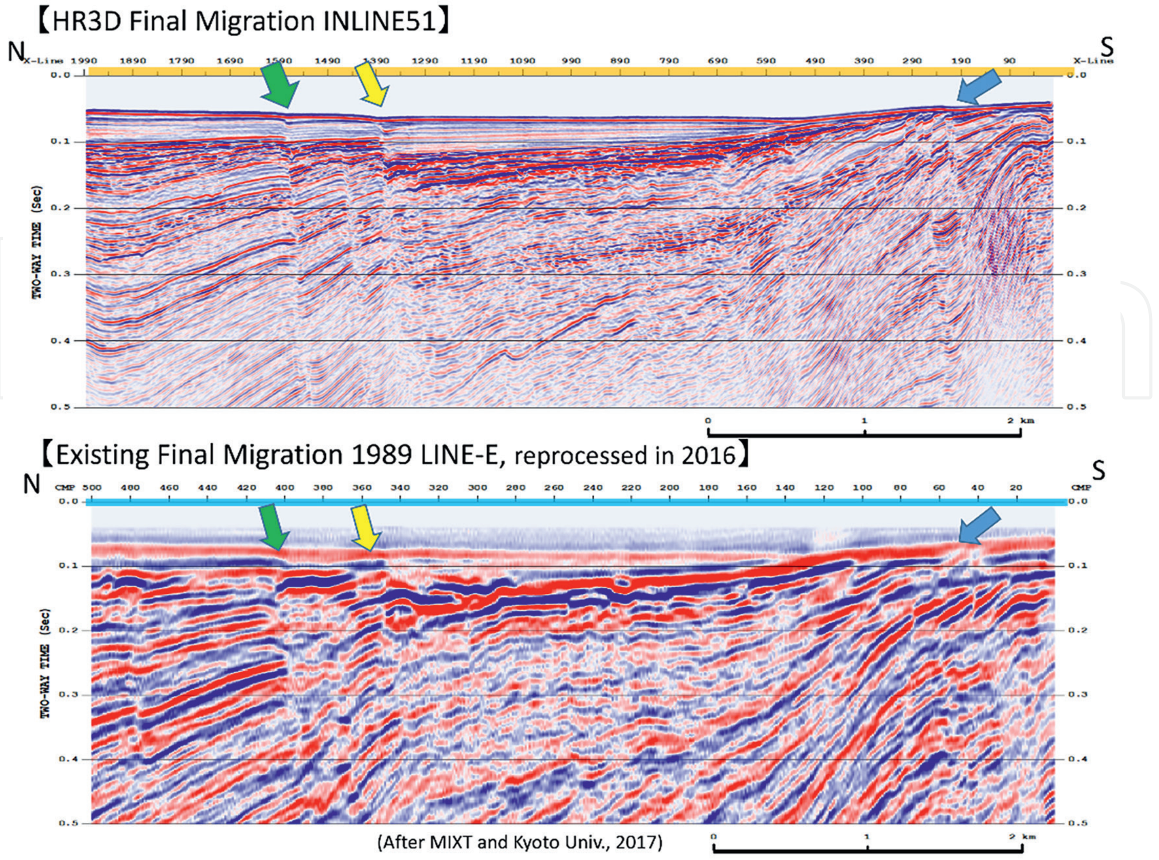


Figure 10.
(Top) Inline section of the final 3D-HRS dataset. (Bottom) Section of the existing 2D seismic record re-processed in 2016. Colored arrows indicate typical subsurface discontinuities highlighted in the 3D-HRS section.

severe static shifts. Such footprints become more pronounced as the vertical resolution of the seismic data improves, so footprint suppression is an important processing step for high-resolution surveys. Footprint suppression was applied to compensate for differences in reflection travel time due to the above factors and to suppress small spatial discontinuities in the reflection events. The footprint suppression included residual statics correction, trim statics, and smoothing of the seafloor reflections. After the footprint suppression, a structure dip-based 3D trace interpolation was conducted to correct irregular distributions of folds and offsets. **Figure 9a** and **b** show time slices before and after footprint suppression. The **Figure 9b** shows that the irregular changes in reflection events at **Figure 9a** were suppressed, and the continuity of reflection events was greatly improved. In addition, small gaps in acquisition coverage were successfully filled in (**Figure 9b**).

The vertical resolution in the shallow subsurface of the final migrated 3D-HRS volume was approximately 2.5 m based on the dominant frequency (150 Hz) and estimated P-wave velocity (1500 m/s). Compared to existing 2D seismic sections, 3D-HRS has much higher resolution. In particular, 3D-HRS can be seen to effectively extract spatial discontinuities, such as faults and fractures (**Figure 10**). The 3D view of the final migration results (**Figure 11**) shows the detailed subsurface shallow 3D structure with seafloor topography. In the vertical section and time slices, a spatially continuous fault distribution is clearly observed. This suggests that the 3D fault plane tracking using the 3D-HRS migration volume is more reliable than a 2D seismic survey.

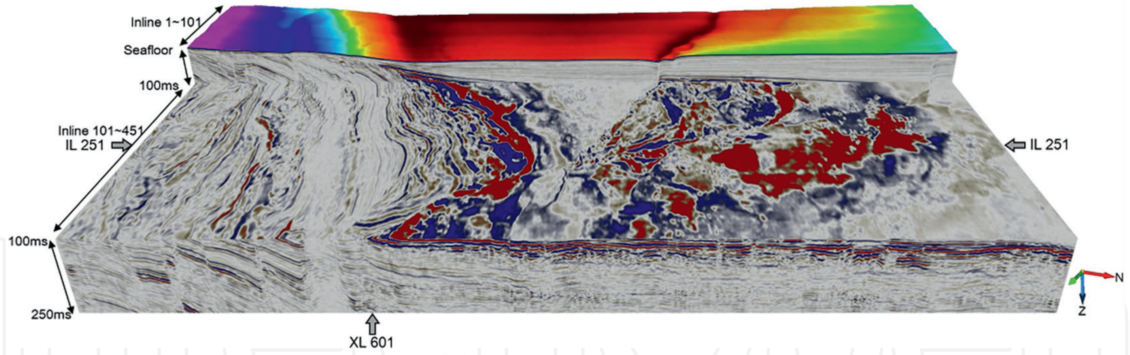


Figure 11.
3D-HRS post-stack time migration volume. In addition to the detailed 3D subsurface structure, the seafloor topography is also mapped with high accuracy. A spatially continuous fault distribution is clearly observed, indicating that 3D fault plane tracking using the 3D-HRS migration volume is more reliable than 2D seismic surveys.

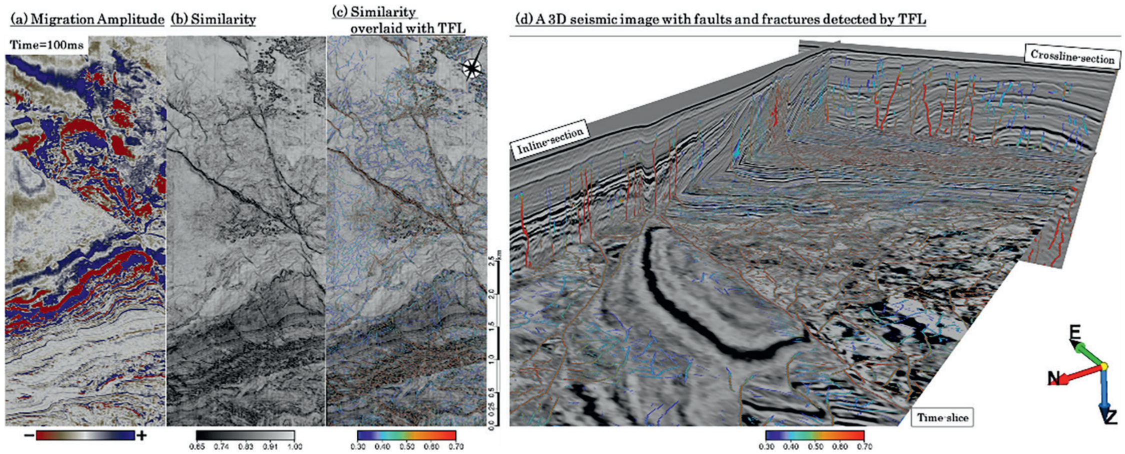


Figure 12.
Time slices at 100 ms of (a) input migrated volume, (b) similarity, and (c) similarity overlaid with TFL. The similarity attribute represents the discontinuous features of structural and stratigraphic trends. The TFL effectively highlights the fractures and faults within the similarity image. (d) 3D seismic image displayed with the faults and fractures detected by TFL. TFL successfully detects complicated subsurface 3D faults and fractures.

5. Seismic attribute analysis

Seismic attribute calculations are essential steps in the 3D seismic interpretation workflow. Seismic attributes can accelerate and provide quantitative justification for the interpretation of geologic features. We calculated the similarity and thinned fault likelihood (TFL) attributes of the post-stack time-migrated 3D-HRS volume for mapping of faults and fractures.

5.1 Similarity

Similarity is an attribute that indicates spatial coherency, with a value between 0 (discontinuity) and 1 (continuity). It is an indicator of structural continuity and directionality and is particularly useful for extracting spatial discontinuities such as faults and fractures.

5.2 Thinned fault likelihood

The TFL is likewise a useful attribute for fault and fracture extraction and is expected to indicate the probability of their presence, as well as provide highly accurate fault and fracture imaging [9]. **Figure 12a-c** show time-slice examples at 100 ms of input-migrated volume (**Figure 12a**), similarity (**Figure 12b**), and similarity overlaid with TFL (**Figure 12c**). The similarity attribute effectively delineates the subsurface discontinuities. It also highlights the major and thick discontinuities in the survey area. The TFL result describes major faults in the center of the survey area as having a high likelihood of being larger and longer. Additionally, the TFL values in the southern area show the presence of relatively more fractures on a small scale. The subsurface features from the similarity and TFL attributes show good consistency, but the TFL attribute delineates minor discontinuities that are difficult to detect with the similarity attribute. Furthermore, the TFL attribute provides a more intuitive illustration of subsurface discontinuities and examination of probable fault images (**Figure 12d**).

6. Discussion and summary

A 3D-HRS survey was conducted to clearly reveal and map faults and fractures in a shallow-water region of Beppu Bay, Oita Prefecture, Japan. The high-frequency seismic source, densely distributed layout of seismic source and receiver points, precise positioning system, and data processing focused on noise and footprint suppression achieved high-resolution and high-precision imaging.

The 3D-HRS system, which is lightweight, easy to deploy and retrieve, and fits on a small vessel, realizes highly cost-effective data acquisition in shallow coastal waters, where data acquisition is difficult with conventional seismic survey methods using large vessels. Our results confirm that the 3D-HRS system can visualize subsurface structures down to depths of about 300 m below the seafloor surface at high resolution and that it is an effective tool for providing detailed information on complex systems of faults or fractures.

The 3D-HRS technique can be used to interpret the geological structure with a 3D seismic cube having various attributes and to understand the details of the faulting history based on the accumulation of fault displacements in the Holocene and upper Pleistocene deposits, which will greatly contribute to the evaluation of faulting activity in areas where trenching is not feasible. The evaluation of spatial characteristics of the subsurface geological structure and fault distribution using the 3D-HRS system is an extremely effective method for active fault investigations, including lateral strike-slip fault systems, and is considered to produce valuable data for regional earthquake disaster prevention.

Future work is expected to include more precise attribute and seismic facies analyses focusing on geological risks, such as fault fracture zones, shallow gas, submarine landslide deposits, and buried channel fill sediments. In addition, the importance of understanding the 3D subsurface structure with high precision is expected to increase in a wide range of fields, including geotechnical investigations for offshore wind power generation; site risk assessment of facilities; investigation of offshore resources such as oil and natural gas, methane hydrate, and seafloor minerals; and carbon dioxide capture and storage. The 3D-HRS system is expected to play an important role as a fundamental technology.

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References

[1] Kawamura K, Nomura H. Off-shore wind power farms and marine geological risks. Journal of Japan Geotechnical Society. 2021;**69**(9):35-38

[2] Murakami F, Furuya M, Kochi E, Maruyama K, Hatakeyama K, Takeda N, et al. Development of the high-resolution three-dimensional seismic survey system for shallow water and the survey of active fault in the nearshore waters of the northern Suruga Bay using the system. Active Fault Research. 2016;**44**:29-40

[3] Ino S, Suda S, Kikuchi H, Okawa S, Abe S. Ultra-high-resolution 3D (UHR3D) seismic survey – application to Hinagu fault zone, Yatsushiro Sea, Kyushu, Japan – 2018. Butsuri-Tansa. 2018;**71**:33-42

[4] Suda S, Kozawa T, Murakami F, Sato N, Tsukahara H, Konno K. Trial survey of dual source UHR2D seismic system. In: Proceedings of the 143rd SEGJ Conference. Tokyo; 2020. pp. 131-134

[5] Takahashi K, Ikeda M, Sato T, Adachi K, Nishizaka N, Onishi K, et al. Distribution and activity of Median Tectonic Line in the Iyo-Nada Sea off northwestern Shikoku based on seismic survey. Active Fault Research. 2020;**53**:13-32

[6] Yusa Y, Takemura K, Kitaoka K, Kamiyama K, Horie S, Nakagawa I, et al. Subsurface structure of Beppu Bay (Kyushu, Japan) by seismic reflection and gravity survey. Zisin (Bulletin of Seismological Society of Japan). 1992;**45**:199-212

[7] MEXT (Ministry of Education, Culture, Sports, Science and Technology, Japan), Graduate School of Science at Kyoto University. Comprehensive Research and Survey for the Beppu-Haneyama Fault System (Oita Plain – Eastern Part of Yufuin Fault), Heisei 26-28 Fiscal Year Report. Kyoto: Graduate School of Science at Kyoto University; 2017. Available from: https://www.jishin.go.jp/database/project_report/beppu_haneyama/

[8] Itoh Y, Kusumoto S, Takemura K. Evolutionary process of Beppu Bay in Central Kyushu, Japan: A quantitative study of the basin-forming process controlled by plate convergence modes. Earth, Planets and Space. 2014;**66**:74. Available from: http://www.earth-planets-space.com/content/66/1/74

[9] Hale D. Methods to compute fault images, extract fault surfaces, and estimate fault throws from 3D seismic images. Geophysics. 2013;**78**:33-43