

Acoustic images of the submarine fan system of the northern Kumano Basin obtained during the experimental dives of the Deep Sea AUV URASHIMA

Takafumi Kasaya^{1,3} Toshiya Kanamatsu¹ Takao Sawa² Masataka Kinoshita¹ Satoshi Tukioka²
Fujio Yamamoto²

¹Institute for Research on Earth Evolution, Japan Agency for Marine–Earth Science and Technology (JAMSTEC), 2-15, Natsushima, Yokosuka, Kanagawa 237-0061, Japan.

²Marine Technology Center, Japan Agency for Marine–Earth Science and Technology (JAMSTEC) 2-15, Natsushima, Yokosuka, Kanagawa 237-0061, Japan.

³Corresponding author. Email: tkasa@jamstec.go.jp

Abstract. Autonomous underwater vehicles (AUVs) present the important advantage of being able to approach the seafloor more closely than surface vessel surveys can. To collect bathymetric data, bottom material information, and sub-surface images, multibeam echosounder, sidescan sonar (SSS) and subbottom profiler (SBP) equipment mounted on an AUV are powerful tools. The 3000 m class AUV URASHIMA was developed by the Japan Agency for Marine–Earth Science and Technology (JAMSTEC). After finishing the engineering development and examination phase of a fuel-cell system used for the vehicle's power supply system, a renovated lithium-ion battery power system was installed in URASHIMA. The AUV was redeployed from its prior engineering tasks to scientific use. Various scientific instruments were loaded on the vehicle, and experimental dives for science-oriented missions conducted from 2006. During the experimental cruise of 2007, high-resolution acoustic images were obtained by SSS and SBP on the URASHIMA around the northern Kumano Basin off Japan's Kii Peninsula. The map of backscatter intensity data revealed many debris objects, and SBP images revealed the subsurface structure around the north-eastern end of our study area. These features suggest a structure related to the formation of the latest submarine fan. However, a strong reflection layer exists below ~20 m below the seafloor in the south-western area, which we interpret as a denudation feature, now covered with younger surface sediments. We continue to improve the vehicle's performance, and expect that many fruitful results will be obtained using URASHIMA.

Key words: autonomous underwater vehicle (AUV), debris deposit, sidescan sonar, subbottom profiler, submarine fan.

Introduction

Autonomous underwater vehicles (AUVs) are characterised by their independent operation by computers in the vehicle, which can maintain the vehicle's stable attitude near the seafloor. This feature provides scientists with the opportunity to carry out various investigations related to earth science fields in the deep sea. Several AUVs have been developed and evaluated throughout the world recently. Typically consisting of a cylinder shaped body, they are operated by their own onboard computers. In general, after deployment from the mother ship, they dive and carry out surveys with a dive schedule that is programmed beforehand. The vehicle's attitude and position in the water are derived from an inertial navigation system (INS). An acoustic long-baseline (LBL) or super short-baseline (SSBL) acoustic navigation system is also used in many cases to check and monitor the absolute position of the vehicle.

An AUV carries various instruments, such as a digital still camera, a conductivity-temperature-depth profiler (CTD), and acoustic geophysical instruments to meet the numerous requirements for scientific investigations. Acoustic survey instruments are especially basic tools for many earth science related purposes. Their data provide important information about the deep sea environment. In general, surface survey vessels have a multibeam echosounder (MBES), a sidescan

sonar (SSS), and a subbottom profiler (SBP). They are usually used over wide areas to collect bathymetric data, to collect information about seafloor materials, and to investigate the subbottom structure. High-frequency acoustic sonar data are effective for elucidating details. However, acoustical attenuation presents a severe problem for high-frequency acoustic sonar; remotely operated vehicles (ROV) and deep-towed systems are better able to carry out surveys near the sea bottom than surface survey vessels because they can conduct high-resolution surveys with high-frequency signals. However, their abilities are limited by the tow cable motion and the ship's motion. In contrast, an AUV can carry out self-controlled survey operations while maintaining a stable vehicle attitude at low altitude above the seafloor. Because of these advantages, AUVs have attracted attention for use in scientific missions and natural resource surveys.

In the United States, the Autonomous Benthic Explorer (ABE), developed by Woods Hole Oceanographic Institution (WHOI), has obtained many remarkable results (Kelley et al., 2005). Its characteristic shape consists of three cylindrical bodies. It has a still camera and some sensors. Yoerger et al. (2007) summarised ABE research operations around hydrothermal areas. In fact, WHOI has developed other types of AUV, and has conducted a field survey (Newman et al., 2008). The

Monterey Bay Aquarium Research Institute also has an AUV, called the Mapping AUV. Their vehicle is designed to gather bathymetric information and to perform subsurface surveys. Paull et al. (2008), using their vehicle, conducted an acoustic mapping survey around the Santa Monica Basin off California. Scientific AUVs have been developed in other science communities. Bluefin Robotics in the USA, for example, market three different sizes of AUV for commercial purposes. In Japan, the URASHIMA (Figure 1) and the r2D4 are representative of scientific AUVs that can accommodate many scientific instruments. They have been used in some areas for experimental scientific operations (e.g. Ura et al., 2004; Kasaya et al., 2007).

An AUV can more closely approach the seafloor than a survey conducted from a surface vessel, and can keep its attitude more stable than a ROV and deep-tow system. This characteristic is advantageous for scientific surveys, resource exploration, and other missions. In this paper, we introduce some details of the AUV URASHIMA, and present acoustic survey results obtained during experimental dives around a submarine fan.

AUV URASHIMA

The 3000 m class AUV URASHIMA (Figure 1) was developed by JAMSTEC in 1998. The URASHIMA is ~10 m long and cylindrical, and was originally optimised for long-distance

cruising. In its first engineering tests, the URASHIMA used a lithium-ion rechargeable battery system, and reached a maximum dive depth of 3518 m. In a subsequent phase, URASHIMA used a fuel-cell system as the vehicle's power supply system to achieve good long-distance cruising performance. In this form, the URASHIMA set a new maximum continuous dive record of 317 km (Tsukioka et al., 2005a). After these achievements, a renovated lithium-ion battery power system was installed in the URASHIMA. The deployment of the AUV was shifted from its previous engineering purposes to scientific tasks (Tsukioka et al., 2005b). Table 1 presents recent specifications of the AUV URASHIMA. Various scientific instruments (e.g. MBES, SSS, SBP, and CTD) were loaded; then several experimental survey cruises were conducted.

Table 1. Specification of URASHIMA.

Specifications	
Max. depth	3500 m
Max. cruising distance	130 km (Li-ion cell)
Speed	0–2.5 kn
Length	10 m
Width	1.3 m
Height	1.5 m
Weight in the air	6.5 tonnes
Power system	Rechargeable Li-ion cell



Fig. 1. Photograph of AUV 'URASHIMA'.

Table 2. Specifications of acoustic survey systems of URASHIMA.

Seabat7125 system	
Frequency	400 kHz
Swath width	128 degree
Beam width (Along-track × Across-track)	1.0 × 0.54 degree
Range	Max 200 m
Edgetech 2200 system Sidescan sonar	
Frequency	120 kHz
Beam width (Along-track)	0.9 degree
Range	Max 300 m
Range resolution	6.25 cm
Subbottom profiler	
Frequency	1–6 kHz (Chirp)
Beam width	28–36 degree
Resolution	15–25 cm

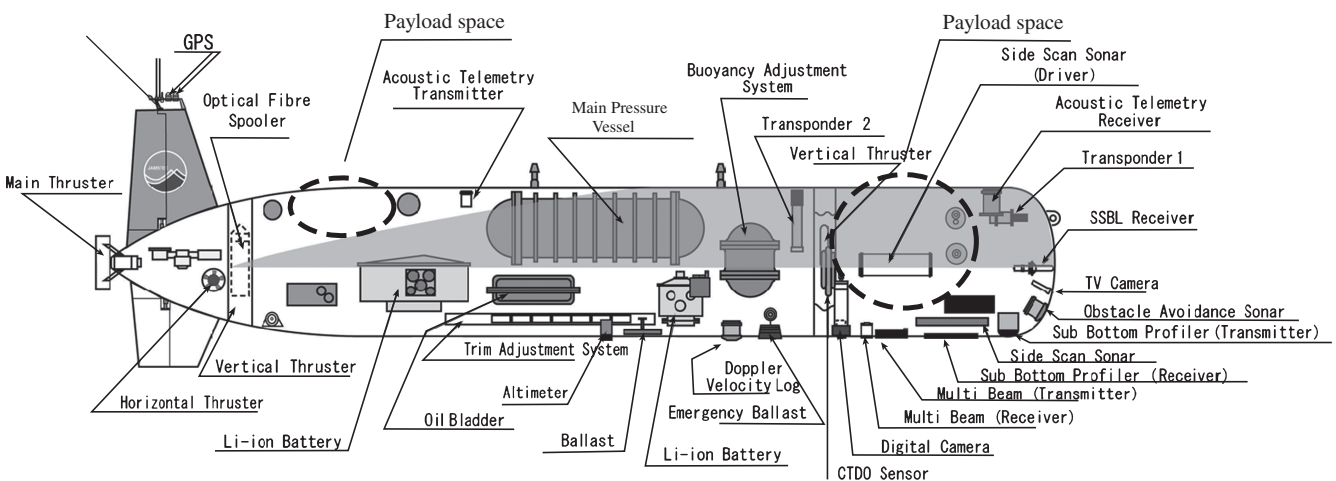


Fig. 2. General arrangement map of AUV Urashima. Two dashed circles show the payload space available for additional instruments.

The current MBES, SSS, and SBP systems were installed in 2006, when we conducted a test survey cruise around off Hatsushima Island, Sagami Bay. The SSS mosaic images obtained during this cruise revealed some irregular patches around a mudflow area (Kasaya et al., 2007), which were subsequently interpreted as debris generated by earthquakes. In fact, a mudflow event was observed by the many instruments of the Hatsushima cable observatory in 2006 (Kasaya et al., 2009). After additional experimental surveys, the latest specifications of each acoustic survey system installed are shown in Table 2. A CTD sensor (SBE-9 plus) is also installed on the AUV.

The vehicle position is a very important parameter for observational instruments. The URASHIMA usually uses a high-accuracy INS system, which is initialised using GPS before a dive. To improve the precision of its positioning in the water, the INS system is compensated using the Doppler Velocity Log. If the need arises, the absolute position of vehicle can be calibrated using SSBL data.

Figure 2 presents a recent general arrangement map. URASHIMA can accommodate additional payload instruments in the fore and aft areas of the vehicle (Figure 2) and operate various instruments simultaneously. Moreover, URASHIMA can supply real-time output of vehicle navigation data, and provide DC power to instruments installed in the payload space. Navigation data for the user are in the National Marine Electronics Association-compatible format. Table 3 presents a list of navigation data. The maximum DC power

Table 3. List of output navigation data.

NMEA, National Marine Electronics Association; UTC, Coordinated Universal Time

No.	Navigation data output	Output rate	Record format
1	Clock time (UTC)	1 Hz	NMEA compatible
2	Latitude	1 Hz	NMEA compatible
3	Longitude	1 Hz	NMEA compatible
4	Depth	1 Hz	NMEA compatible
5	Height	1 Hz	NMEA compatible
6	Roll	10 Hz	NMEA compatible
7	Pitch	10 Hz	NMEA compatible
8	Heading	10 Hz	NMEA compatible
9	Velocity	1 Hz	NMEA compatible

supply capacity for a payload instrument is 6 A at 24 V DC through the underwater electric cable from the main battery.

Field test results around the northern Kumano Basin off the Kii Peninsula

We present experimental data obtained at a depth of ~2000 m in the northern Kumano Basin off the Kii Peninsula (Figure 3). Saeki et al. (2006) carried out a 3D reflection seismic survey with a sampling rate of 2 ms and 12.5 m CDP bin size in this area. They reported the existence of two large submarine fan systems (grey areas in Figure 3) and discussed their formative history. They reported that each submarine fan was detected as a strong

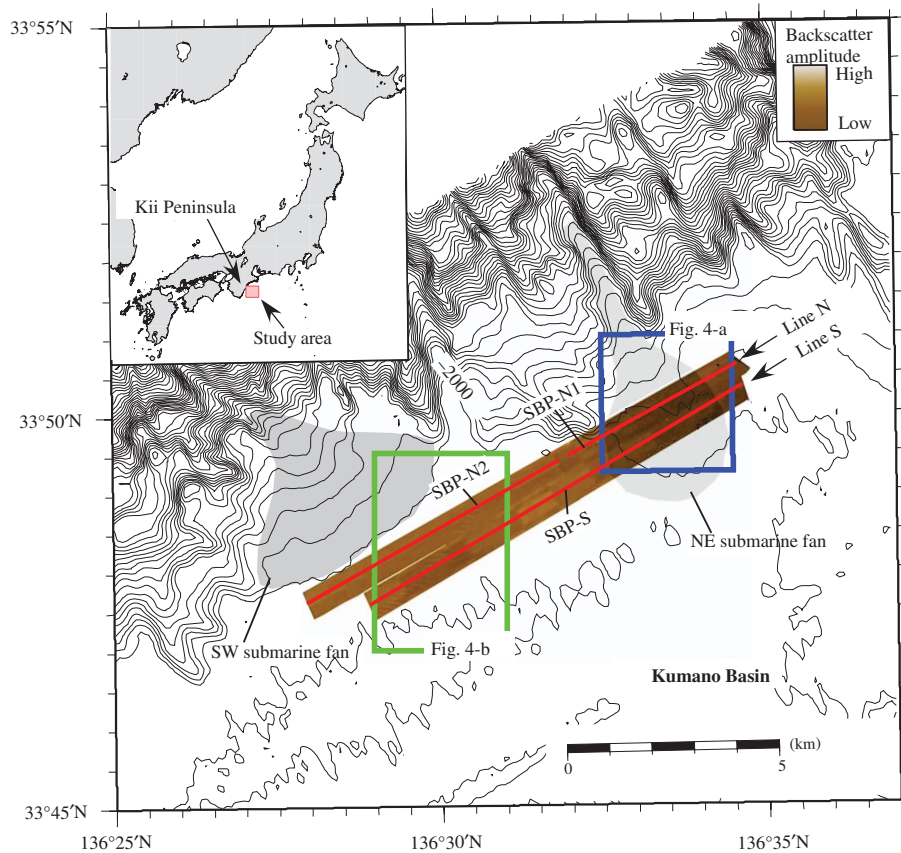


Fig. 3. Study area map of the northern Kumano Basin. The backscatter intensity map deduced using a sidescan sonar of AUV Urashima is also shown. The contours show the bathymetry collected by the 12 kHz SeaBeam system of the JAMSTEC vessels. The contour interval is 10 m. Two grey shaded areas show a submarine fan area pointed out by Saeki et al. (2006). A mosaic image obtained by SSS along the survey lines is also shown. The bright colour shows high-backscatter amplitude. Blue and green squares show the areas covered by Figure 4a and b, respectively.

reflection from the seafloor in the area of Figure 3, and that the sedimentation cycle had occurred at least three times. We conducted an acoustic survey using SSS and SBP on two survey lines that passed through the toe of the north-eastern submarine fan. During these experimental dives, we were unable to use the MBES data because of technical problems. Because those problems have been resolved after this cruise, we will be able to obtain the high-accuracy bathymetry data.

Figure 4a presents details of the SSS mosaic image of the north-eastern area. There are many mound structures, which are

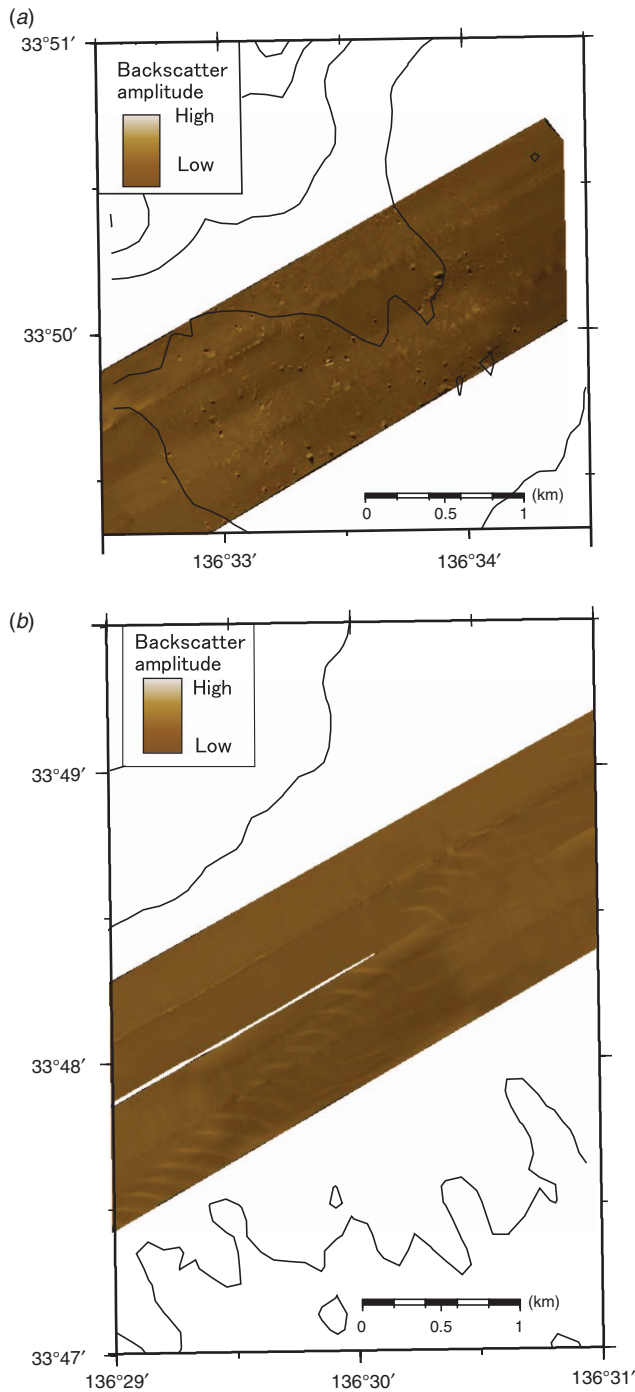


Fig. 4. (a) Intensity map of backscatter with bathymetry around the submarine fan in the north-eastern end of study area; there is much debris. The 12 kHz bathymetric data were obtained by JASMTEC vessels. (b) Intensity map of backscatter with bathymetry data around the south-western end of study area. The 12 kHz bathymetric data were obtained by JASMTEC vessels.

imaged as high-backscatter patches. Some of the largest high-backscatter patches are ~100 m diameter. Small patch structures are also apparent in some places. However, Figure 4b shows that the seafloor surface is almost flat, with many dune-like structures in the south-western part of our survey area. This survey area does not include the south-western submarine fan detected by Saeki et al. (2006).

A subbottom profiling survey with a sampling rate of 0.046 ms was also conducted in this survey. The SBP data has 15 cm (~0.2 ms) resolution and provides images of sub-surface sediments up to 20–30 m depth. In general, we must apply water-depth corrections for these data obtained by an AUV in a different way from data obtained using shipborne instruments, because the vehicle's depth is not constant throughout the duration of a survey. In fact, the main purpose of these dives was an engineering test. For that reason, the vehicle's depth changed frequently to confirm the vehicle's performance (see the vehicle's track in Figure 5a and b). Therefore, we calculated water-depth corrections using the vehicle's navigation and attitude data. For this calculation, an average acoustic velocity of 1500 m/s was assumed. Figure 5a and b show the corrected SBP sub-surface images along each survey line. The vertical axis shows the two-way travel time (TWT) from the sea surface, in milliseconds. The corrected TWT of the seafloor agrees with the first reflection event in the 3D seismic data (Figure 6). This result shows that our water-depth correction is effective for use with the AUV data. A data gap exists around the middle of Figure 5a because of an emergency ascent caused by the failure of the acoustic navigation system.

In the north-eastern area (NE submarine fan), an acoustic transparent zone is apparent immediately beneath high-backscatter patches detected on the seafloor (red circles in Figure 5a and b). The SBP sea bottom reflection shows a very rough feature. These characteristic features appear in both survey lines. The maximum layer thickness is ~20 ms (~15 m). These detailed sub-surface images detected by SBP data were not necessarily clear from the 3D seismic data shown in Figure 6. In the south-western area, the SSS image shows that the seafloor is almost flat. However, the seafloor geometry in Line N forms a gradual mound (Figure 5a) and a strong reflection layer exists at ~20 ms below the seafloor. A mound structure is not seen in Figure 5b, but a similar reflection layer is evident below the seafloor. Results also show dome-shaped structures in the middle of the northern survey line (blue circle with dashed line in Figure 5a). A layered structure is observed inside the domes. One dome crops out at the seafloor; the others lie under the sedimentary layers.

Geological interpretation and discussion

NE submarine fan

The north-eastern area has many mounds, which are imaged as high-backscatter patches (Figure 4a). Some of the largest of these patches are ~100 m diameter. The SBP seafloor reflection also shows very rough features and reveals some smaller mounds (a few milliseconds height). There is also an acoustic transparent zone immediately beneath the seafloor of this area on both survey lines (Figure 5a and b). This structure extends laterally and becomes thin at each end. The maximum thickness of this lenticular shape structure is ~20 ms (~15 m). In the 3D reflection seismic results (Figure 6), the high-amplitude reflection on the seafloor was detected, and was interpreted as a denudation surface. However, this data could not resolve the subsurface acoustic transparent zone. Normark et al. (2004) conducted a high-resolution seismic-reflection survey off southern California,

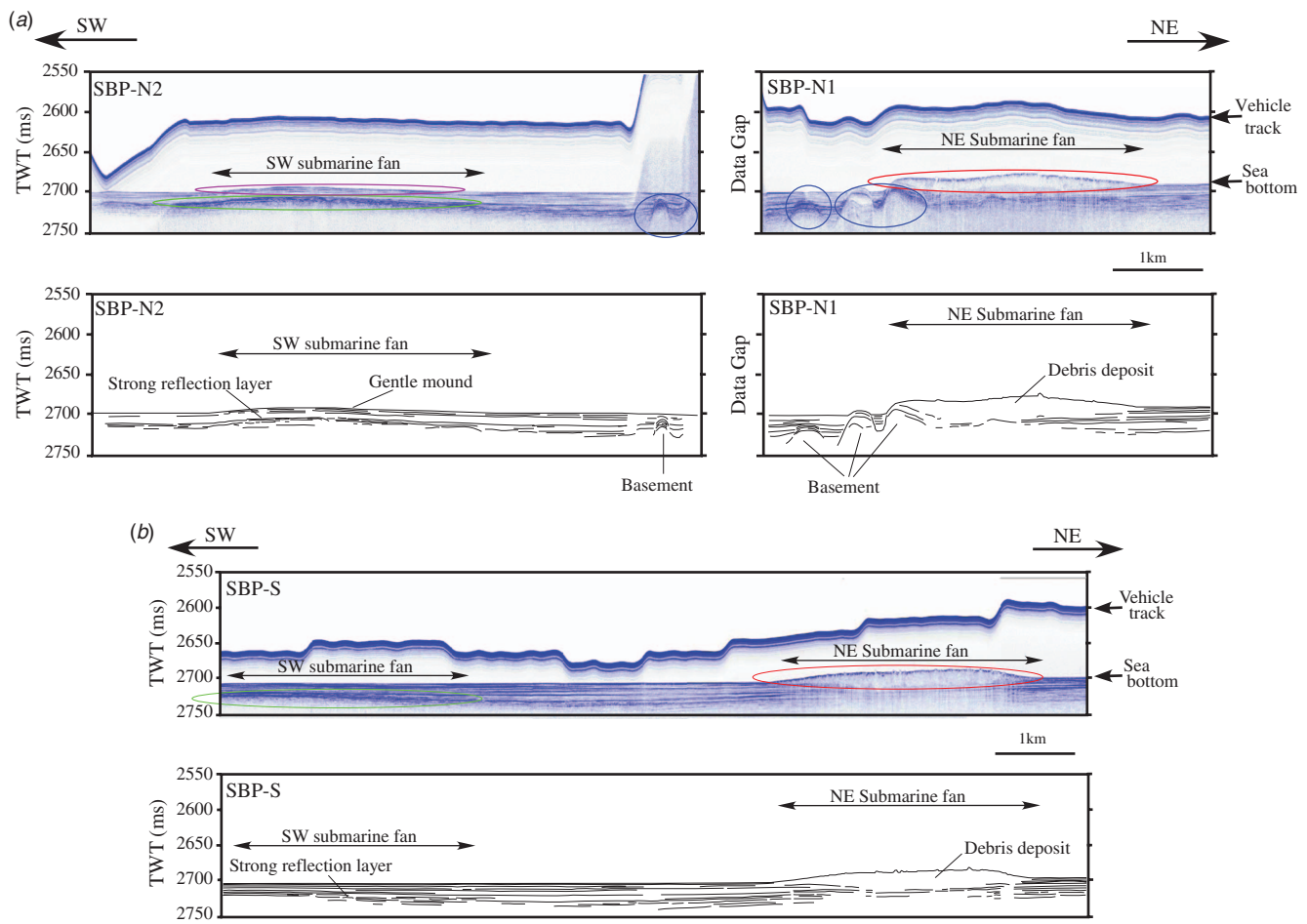


Fig. 5. (a) The SBP profile and interpreted section of Line N. The vertical axis shows two-way travel time in milliseconds from the sea surface. A data gap exists on the middle of Line N because of an emergency ascent executed after failure of the acoustic navigation system. Each coloured circle shows a characteristic structure (see the main text for details). (b) The SBP profile and interpreted section of Line S. The vertical axis shows the two-way travel time in milliseconds. Each coloured circle shows a characteristic structure (see the main text for details).

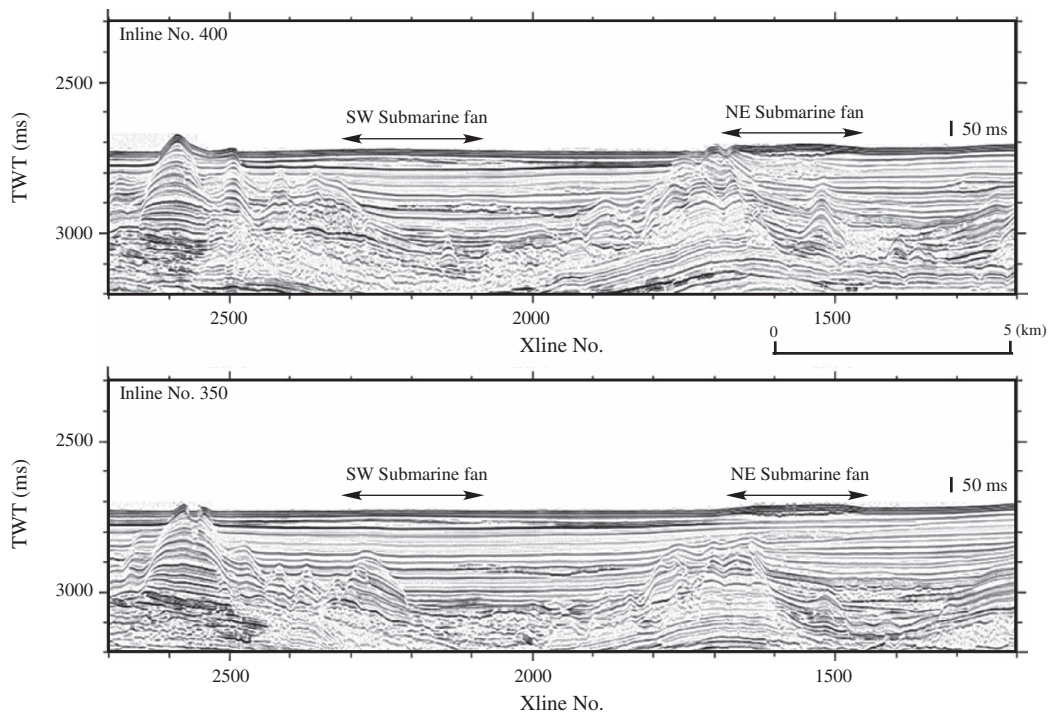


Fig. 6. Two 3D seismic sections from Saeki et al. (2006). Each section almost corresponds to Line N and Line S, respectively. Vertical axis shows the two-way travel time in milliseconds.

using a deep-tow seismic system with a boomer seismic source. There they detected a submarine debris avalanche, imaged as an acoustic transparent zone with a rough surface. Moreover, many debris structures were found in the debris avalanche zone. Their results resemble the characteristic features of our acoustic images. We infer that the results obtained using the SSS and SBP data are consistent with debris deposits related to the submarine fan formation.

SW submarine fan

The backscatter data (Figure 4b) and bathymetry data collected by the JAMSTEC vessel show that the seafloor feature in the south-western area is almost flat. Only aligned dune-like structures are apparent in Figure 4b. These have two trends, NE–SW and N–S. The seafloor material is almost entirely muddy sediment, as revealed by a deep-tow camera (Sakuma, 2007). A core sample in this area shows a layer of almost silt-sized material (Arita and Kinoshita, 1988). In the SBP image, the seafloor geometry (see purple circle in Figure 5a) forms a gentle mound, with a strong reflection layer ~20 ms below the seafloor. Each reflector shape is very similar and parallel. However, no mound structure is apparent on the southern line, but a strong reflection layer was revealed below the seafloor (Figure 5b). This second reflection layer also shows similar convex shape. Upstream of our survey lines, the 3D seismic data detected the denudation surface related to the SW submarine fan (Saeki et al., 2006), but no strongly reflecting feature was detected at the seafloor around the southern part of our survey area. The denudation structure is probably covered with younger surface sediments in this area.

Dome-shaped structures

We found dome-shaped structures in the middle of the northern survey line (blue circle in Figure 5a). A layered structure is observed in their upper parts; the upper parts of the domes have similar reflection characteristics to the strong subsurface reflections below the SW submarine fan area. The 3D reflection seismic data also detected some similar dome-shaped structures (Figure 6) and these structures could be traced to a submarine ridge upstream (see figure 5 of Saeki et al., 2006). This result implies that these dome-shaped structures were buried by the younger surface sediments. These might constitute the basement present before the submarine fans' formation.

Summary and conclusions

We have described common characteristics of AUVs and those of our deep sea AUV URASHIMA specifically. The greatest advantage of AUVs is their autonomous operation maintaining a stable vehicle attitude near the seafloor. AUV URASHIMA was equipped with MBES, SSS, and SBP instruments for acquiring basic information about the seafloor and subsurface structures. Moreover, it has large payload spaces fore and aft within the vehicle. The supply of navigation data and DC power to the users' instruments also constitutes a noteworthy function.

High-resolution acoustic images were obtained by SSS and SBP onboard AUV URASHIMA during an engineering cruise. The SSS images revealed numerous debris objects. Furthermore, SBP images showed an acoustically transparent structure related to the debris deposit in the north-eastern part of our study area. These features suggest that the structure is related to the formation of the latest submarine fan. Around the south-western submarine fan, the SBP images revealed a strong reflection layer ~20 ms below the seafloor. This contrast implies the subsequent formation of the SW submarine fan. Moreover, four dome-shaped structures in the middle area of Line N were identified from SBP

images; these are interpreted as a basement surface buried by the younger sediment. These detailed surface and sub-surface images detected by the AUV were clearer than comparable surface 3D seismic data because the SBP data was recorded with a sampling rate of 0.046 ms and the AUV approached the seafloor more closely than a survey conducted from a surface vessel. This result also suggests that the depth resolution of SBP data can be comparable with core data.

These conventional acoustic instruments are very useful for scientific surveys in support of investigations of marine land slide research related with the mega-thrust earthquake activity. Moreover, two science parties have carried out two cruises using the URASHIMA in 2009. Conventional acoustic surveys were conducted during cruises, along with various surveys using instruments loaded on the payload space. For natural resource surveys, a new survey style in which various instruments are loaded and used simultaneously is effective to estimate the amount of resource deposits. We have sought to improve the vehicle's performance. It is expected that many fruitful results will be obtained using URASHIMA.

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深海巡航 AUV「うらしま」で得られた熊野灘北縁海底扇状地の音響イメージ

笠谷貴史¹・金松敏也¹・澤 隆雄²・木下正高¹・月岡 哲²・山本富士夫²

1 海洋研究開発機構 地球内部ダイナミクス領域

2 海洋研究開発機構 海洋工学センター

要 旨： 自律潜航のできる AUV(Autonomous Underwater Vehicle)は、一般的な船舶では不可能な海底に近づいて探査が可能である。特に地形、表層地質、表層下構造を得るための、マルチナロー測深器(MNBES)、サイドスキャンソナー(SSS)、サブボトムプロファイラー(SBP)といった音響機器にとって、それは大きなアドバンテージである。海洋研究開発機構で開発された 3000m 級の深海巡航 AUV「うらしま」は、燃料電池による長距離連続潜航の記録を打ち立て、その技術開発の終了とともに、リチウムイオン電池へ換装され、科学目的の利用へとその軸足を移した。「うらしま」には、MNBES、SSS、SBP の音響機器などの多くの観測機器が搭載され、2006 年からそれらを使用した試験観測が行われている。2007 年の試験航海では、紀伊半島沖熊野灘北縁の二つの海底扇状地を含む海域において SSS と SBP を用いた調査潜航が実施された。北東側に位置する海底扇状地では、SSS からは砕屑物と思われるパッチ状の高散乱強度分布が得られ、SBP による表層下構造では、砕屑物のあるエリアの下部が音響的に透明になっており、最も新しい時代に形成された海底扇状地であることが分かった。一方で、南西側に位置する海底扇状地では、後方散乱強度分布に大きな特徴は見られなかったものの、海底面から 20 ms 下に強い反射面が見られることが明らかになった。これは扇状地形成後に堆積物に覆われたことを示している。試験航海を通して AUV はその機能を徐々に向上させており、地すべり探査や資源探査など、多くの科学的成果が得られることが期待されている。

キーワード： 自律型無人潜水機 (AUV), 砕屑物, サイドスキャンソナー, サブボトムプロファイラー, 海底扇状地

심해 자율무인잠수정 우라시마의 잠항시험에서 취득된 북 구마노 분지 해저 선상지 시스템의 음향 영상

Takafumi Kasaya¹, Toshiya Kanamatsu¹, Takao Sawa², Masataka Kinoshita¹, Satoshi Tukioka², Fujio Yamamoto²

1 해양연구개발기구 지구내부다이나믹영역

2 해양연구개발기구 해양공학센터

요 약： 자율무인잠수정은 해수면탐사선에 비해 해저면에 더 가까이 접근할 수 있는 장점을 제공한다. 수심자료, 해저면 물질 정보와 해저면 하부 영상을 얻기 위해서는 자율무인잠수정에 탑재된 다중빔음향측심기, 해저면영상탐사기 및 천부지층탐사기 등이 유용하게 사용된다. 일본해양연구개발기구는 3000m급 자율무인잠수정 우라시마를 개발하였다. 잠수정의 전력공급용 연료전지시스템의 공학적 개발과 시험과정을 거쳐 우라시마에는 신형 리튬이온전지 시스템이 설치되었다. 잠수정은 초기 공학적인 업무에서 과학적 사용 목적으로 개량되었다. 다양한 과학장비들이 추가되었고 2006년부터 과학적인 목적의 임무수행을 위한 잠항시험이 수행되었다. 2007년 시험운항에서 일본 기이반도 해역 북 구마노분지 부근에서 우라시마의 해저면영상탐사기와 천부지층탐사기를 이용하여 고해상 음향영상자료를 획득하였다. 후방산란강도 도면에서는 많은 암설류가 확인되었고, 천부지층탐사단면에서 연구해역의 북동쪽 끝 부근의 하부구조가 확인되었다. 이러한 특징은 최신 선상지의 형성과 관련된 구조를 암시한다. 그러나 남서 해역에서는 해저면 하부 ~20 ms 부근에서 강한 반사층이 존재하는데, 이는 삭박특징으로 해석되며 현재는 더 얇은 해저 퇴적물로 덮여있다. 잠수정의 성능은 지속적으로 향상되고, 우라시마를 활용하여 많은 유용한 결과가 얻어질 것으로 기대된다.

주요어： 자율무인잠수정, 암설 퇴적물, 해저면영상탐사기, 천부지층탐사기, 해저 선상지