CSIRO PUBLISHING
www.publish.csiro.au/journals/eg *Exploration Geophysics*, 2007, **38**, 37–43

Fusion of 3D seismic exploration and seafloor geochemical survey for methane hydrate exploration*

Sadao Nagakubo[1,2] Toshiaki Kobayashi[1] Tetsuya Fujii[1] Takao Inamori[1]

[1]Japan Oil, Gas and Metals National Corporation, 1-2-2, Hamada, Mihama-ku, Chiba city, Chiba 261-0025, Japan.
[2]Corresponding author. Email: nagakubo-sadao@jogmec.go.jp

Abstract. The MH21 Research Consortium has conducted a high-resolution 3D seismic survey and a seafloor geochemical survey, to explore methane hydrate reservoirs in the eastern Nankai Trough, offshore Japan. Excellent geological information about shallow formations was obtained from the high-resolution 3D seismic survey, which was designed to image the shallow formations where methane hydrates exist. The information is useful in constructing a geological and geochemical model, and especially to understand the complex geology of seafloor, including geochemical manifestations and the structure of migration conduits for methane gas or methane-bearing fluid.

By comparing methane seep sites observed by submersibles with seismic sections, some significant relationships between methane hydrate reservoirs, free gas accumulations below the seafloor, and seafloor manifestations are recognised. Bathymetric charts and seafloor reflection amplitude maps, constructed from seismic reflections from the seafloor, are also useful in understanding the relationships over a vast area. A new geochemical seafloor survey targeted by these maps is required.

The relationships between methane hydrate reservoirs and seafloor manifestations are becoming clearer from interpretation of high-resolution 3D seismic data. The MH21 Research Consortium will continue to conduct seafloor geochemical surveys based on the geological and geochemical model constructed from high-resolution 3D seismic data analysis.

In this paper, we introduce a basis for exploration of methane hydrate reservoirs in Japan by fusion of 3D seismic exploration and seafloor geochemical surveys.

Key words: BSR, seafloor geochemical survey, high-resolution 3D seismic survey, methane hydrate, Nankai Trough.

Introduction

Since 2001, the MH21 Research Consortium have been proceeding with Japan's Methane Hydrate Exploitation Program, for development of natural gas from methane hydrate reservoirs around Japan under the Ministry of Economy, Trade and Industry (METI). Japan's Methane Hydrate Exploitation Program consists of three phases, extending over 16 years. The purpose of Phase I (FY2001–2008) is an evaluation of methane hydrate reservoirs around offshore Japan. To achieve this goal, the MH21 Research Consortium has been conducting various marine surveys such as seismic surveys, seafloor geochemical surveys, and exploratory wells in the eastern Nankai Trough, which is a model area in the program. High-resolution 2D and 3D seismic surveys were conducted in FY2001 and FY2002 respectively. These surveys were designed to image shallow formations below the seafloor, where methane hydrates exist. Thus, more detailed information about the shallow formations was obtained, in comparison with using conventional seismic surveys. An exploratory drilling campaign named 'Tokai-oki to Kumano-nada' was carried out in FY2003 (Takahashi and Tsuji, 2005). The most impressive achievement in this campaign was that we recognised thick hydrate-bearing sand layers in turbidite sequences above BSRs (Bottom Simulating Reflectors; Tsuji et al., 2004). Consequently MH21 has decided to develop natural gas from methane hydrates preserved in thick sandy sediment derived from turbidites overlying above BSRs. Therefore 'methane hydrate reservoirs' are defined by 'thick sandy sediment, with pore-space methane hydrate, overlying above BSRs' in this paper.

It is expected that there will be some seafloor manifestations of methane hydrate reservoirs, because methane hydrates exist in formations that are shallow compared to conventional oil and natural gas reservoirs. Accordingly, since FY2002 the MH21 Research Consortium has conducted seafloor geochemical surveys as an auxiliary method for exploration of methane hydrate reservoirs (Nagakubo et al., 2005).

Recently, characteristics of methane hydrate reservoirs in the eastern Nankai Trough have been clarified by the surveys mentioned above. However, in most cases, the geological and geochemical settings where methane hydrates exist in shallow formations are unknown. The MH21 Research Consortium has attempted to construct a geological and geochemical model to understand the relationships between methane hydrate reservoirs and seafloor manifestations, using high-resolution 3D seismic data. The model would contribute to the design of a new seafloor geochemical survey procedure for exploration of methane hydrate reservoirs, and establish new survey methods for methane hydrate exploration by seafloor geochemical survey.

*Part of this paper was presented at the 8th SEGJ International Symposium, 2006.

10.1071/EG07005 0812-3985/07/010037

In this paper, we introduce a basis for exploration of methane hydrate reservoirs in Japan by fusion of 3D seismic exploration and seafloor geochemical surveys.

Although a huge amount of information was obtained by each survey, we provide only a part of the data with our interpretations in this preliminary paper.

Seafloor geochemical surveys in the eastern Nankai Trough

Methane hydrates exist in shallower formations than conventional oil and natural gas reservoirs. Thus it is expected that there will be some relationships between methane hydrate reservoirs and seafloor geological manifestations.

Various seafloor manifestations related to methane seepage activities were recognised on the seafloor in the eastern Nankai Trough. These included chemosynthetic biological communities, carbonate precipitations, pockmarks, and so forth (Figure 1). If some relationships between methane hydrate occurrences and these manifestations could be demonstrated, a seafloor geochemical survey could be an auxiliary method for exploration for methane hydrate reservoirs.

The MH21 Research Consortium conducted the following surveys to verify the effectiveness of seafloor geochemical surveys in FY2002–2004 (Figure 1):

(1) sediment sampling at the seafloor by piston corers or grab samplers;
(2) seawater chemistry measurement by CTD (Conductivity–Temperature–Depth profiler), methane sensors, and seawater sampling;
(3) seafloor visual observations by still and video cameras;
(4) analysis of seafloor conditions from side-scan sonar and sub-bottom profiler data.

The following analyses were conducted on the samples recovered:

(1) physical properties of sediment;
(2) chemical compositions of pore water in sediments and seawater;
(3) microbiological analyses in sediments;
(4) sedimentological analyses;
(5) carbon isotopic analyses.

At an early stage of the study, attention was focused on SMI (Sulfate–Methane Interface) depths measured in core samples recovered by piston corers. Borowski et al. (1996) have suggested that a relationship between methane hydrate

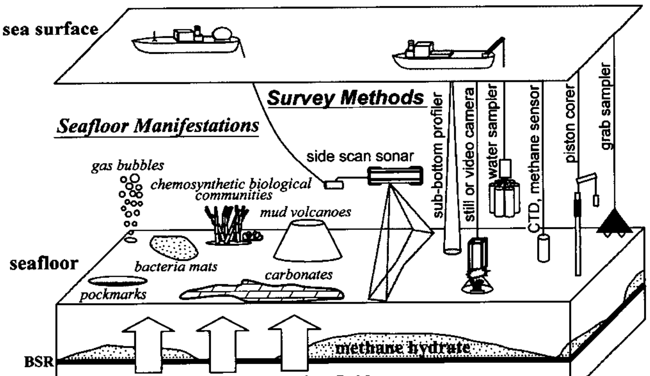

Fig. 1. Common seafloor manifestations accompanied with methane seepage activities, and methods of seafloor geochemical surveys conducted by the MH21 Research Consortium.

deposits below seafloor and methane fluxes at the seafloor could be estimated by SMI depths. Although 31 SMI depths were estimated from piston core samples from the eastern Nankai Trough, simple, distinctive relationships between SMI depths and BSR distribution were not recognised. Nagakubo et al. (2005) reasoned that this may be caused by complex geological settings in shallow formations in the eastern Nankai Trough, where permeable sandy sediments are widely distributed. Methane-bearing fluids might prefer migration through permeable sandy sediments to upward diffusion. Thus it is concluded that the methane flux at the seafloor does not apply directly to exploration of methane hydrate reservoirs in the eastern Nankai Trough. Other proxies for exploration of methane hydrate reservoirs by seafloor geochemical survey were required.

Geological and geochemical conditions in shallow formation where methane hydrates exist

Understanding the whole system, of geological setting and geochemical environment in shallow formations yielding methane hydrate, is important to the study of geochemical exploration indicator.

We know little about the geological settings of shallow formation in deep water. Sub-bottom profilers are the most common devices used for investigating geological conditions in shallow formation (e.g. for submarine cable or pipeline route surveys). However, the maximum penetration of sub-bottom profiler energy is usually 50–100 m at most. As conventional seismic surveys for oil and natural gas reservoirs are designed for deep formation exploration, the seismic resolution in shallow formations, where methane hydrates exist, is usually poor in such surveys. Although well data provides us with detailed information of geological conditions in shallow formations, it is limited only to specific sites. Thus the geological conditions in the shallow formations where methane hydrates exist were unknown over areas away from the boreholes.

Looking at methane hydrate from a geochemical point of view, the environment in which methane hydrates exist is extremely complex. Biological and chemical reactions such as anaerobic and aerobic methane oxidation, sulfate reduction, sulfur oxidation, and methane generation occur in shallow formations in deep water. These reactions also induce precipitation of secondary minerals (carbonates, sulfides, sulfates, etc.) according to chemical conditions.

From a physicochemical point of view, formation of methane hydrate is sensitive to changes of temperature and pressure. Methane hydrate easily forms and dissociates in response to changes of sea level and geothermal structure. Dissociation of methane hydrate can also be induced by invasion of methane-unsaturated fluids such as seawater into the methane hydrate-bearing sediments. Nagakubo et al. (2006a) reported that the changes of geothermal structure by seawater invasions in sediments might induce anomalies of BSR depths in the eastern Nankai Trough.

It is also well known that the following reactions occur when methane hydrate forms or dissociates:

(1) exclusion of ions from the methane hydrate crystal to pore water during formation;
(2) lowering of salinity of pore water by dissociation;
(3) exothermal/endothermal reactions during the formation/dissociation;
(4) fractionation of hydrocarbon components between the methane hydrate crystal and pore water during formation.

Thus, formation and dissociation of methane hydrate is influenced by the surrounding environment, and also impacts on that environment.

We interpreted high-resolution seismic data to give detailed geological images in shallow formations and at the seafloor, resulting in the suggestion of new indicators for seafloor geochemical surveys.

High-resolution seismic surveys

In FY1999, the first methane hydrate exploration well MITI 'Nankai Trough' was drilled in the eastern Nankai Trough. Methane hydrates were found in sediments overlying the BSR in this survey. These results encouraged the commencement of Japan's Methane Hydrate Exploitation Program. In FY2001, the 'Tokai-oki to Kumano-nada' high-resolution 2D seismic survey was conducted, to map the distribution of BSRs over wide areas in the eastern Nankai Trough. Based on the results of the 2D seismic survey, high-resolution 3D seismic surveys were carried out in three selected areas (Figure 2).

As the specifications of these seismic surveys were designed for methane hydrate exploration, we obtained excellent information about the shallow formations where methane hydrates exist. The detailed information about the surveys was summarised by Shimizu et al. (2003) and Tsuji et al. (2004).

Geophysicists and geologists have collaborated to detect methane hydrate reservoirs. In the process, useful data for analysis of geochemical conditions were obtained. Bathymetric and seafloor reflection amplitude maps (Figure 3), constructed using seismic waves reflected from the seafloor, contribute

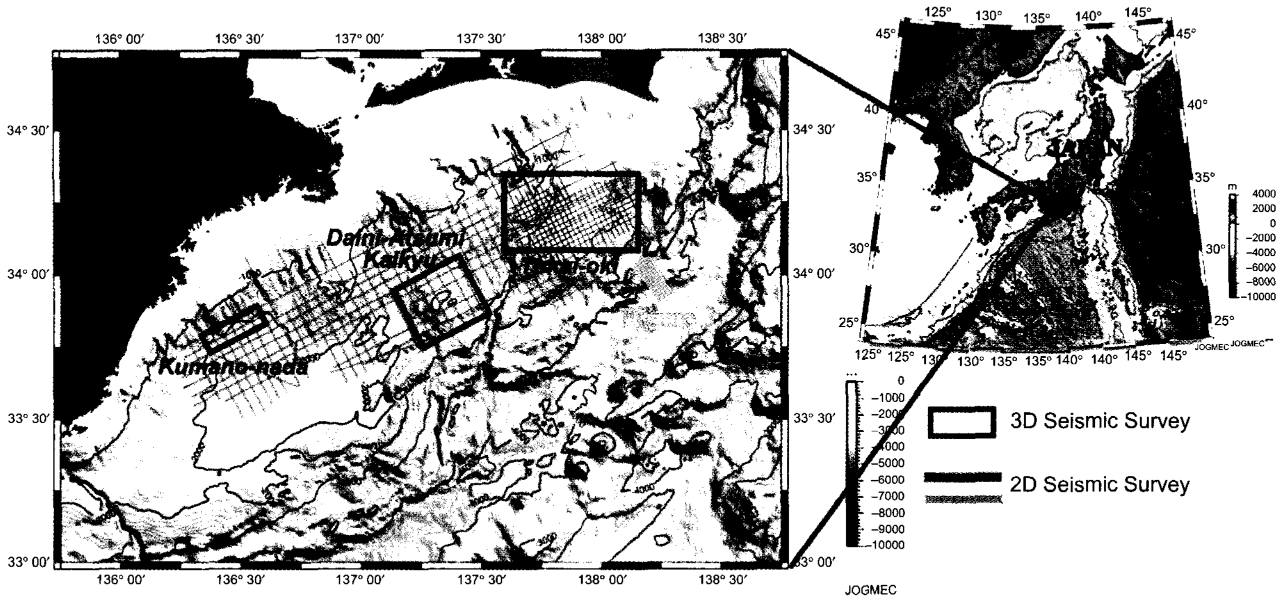

Fig. 2. Location maps for the eastern Nankai Trough, which is a model area in Japan's Methane Hydrate Exploitation Program.

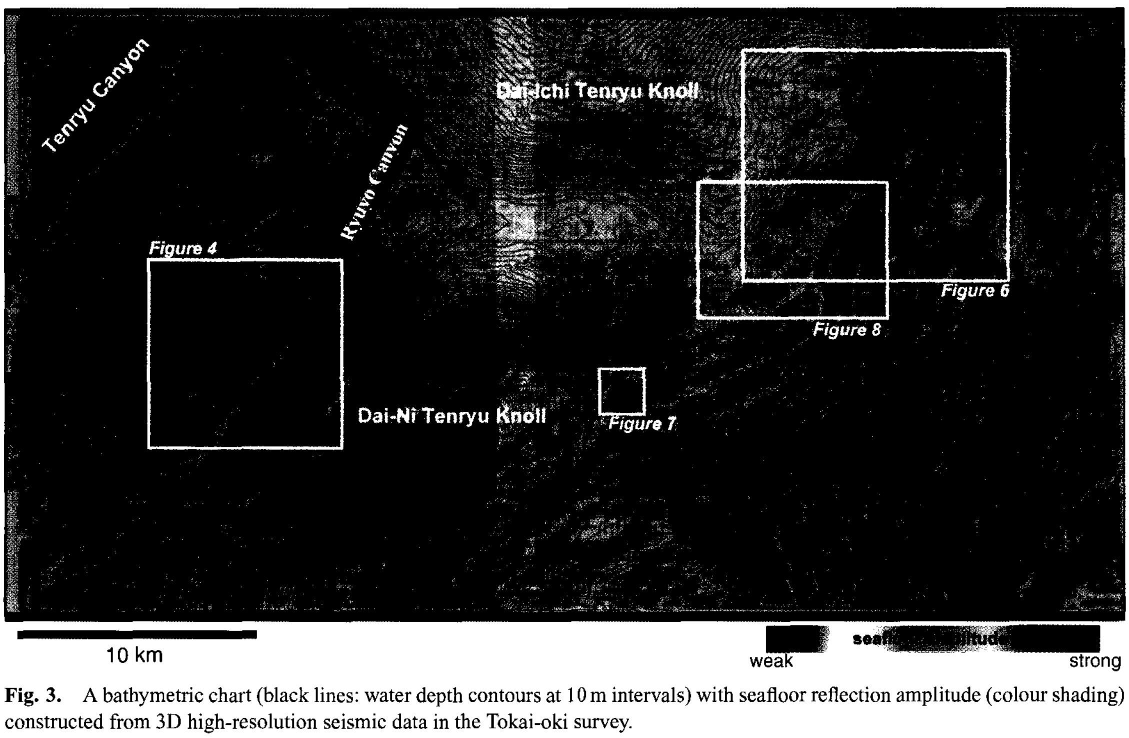

Fig. 3. A bathymetric chart (black lines: water depth contours at 10 m intervals) with seafloor reflection amplitude (colour shading) constructed from 3D high-resolution seismic data in the Tokai-oki survey.

effectively to our understanding of seafloor geological and geochemical manifestations over a vast area.

Seafloor features such as small canyons, pockmarks, landslides, and undulations are recognised in the eastern Nankai Trough (Nagakubo et al., 2006b).

Colour shading on Figure 3 shows the reflection amplitude of seafloor. Warmer colours show stronger seismic reflection amplitudes.

Seepage sites observed by submersible

We compared seismic sections with the following methane seep sites observed with the submersible 'Shinkai 2000' operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC).

Methane seep sites with biological colonies and bacteria mats were found on the western slope of the Ryuyo canyon (Figure 4). Pore water extracted from the sediments recovered by push corers at water depth of 1093–1094 m were found to be CH_4-enriched and Cl-depleted (Tsunogai et al., 1997, 2002). A seismic section (A–A′) crosses the observed methane seep site. The outcrop of a strong reflector (Reflector A) at the western wall of the Ryuyo canyon is recognised. The water depth at the outcrop calculated by two-way-time is ~1090 m (assuming a sound wave velocity in water of 1500 m/s). Reflector A extends to a strong reflector

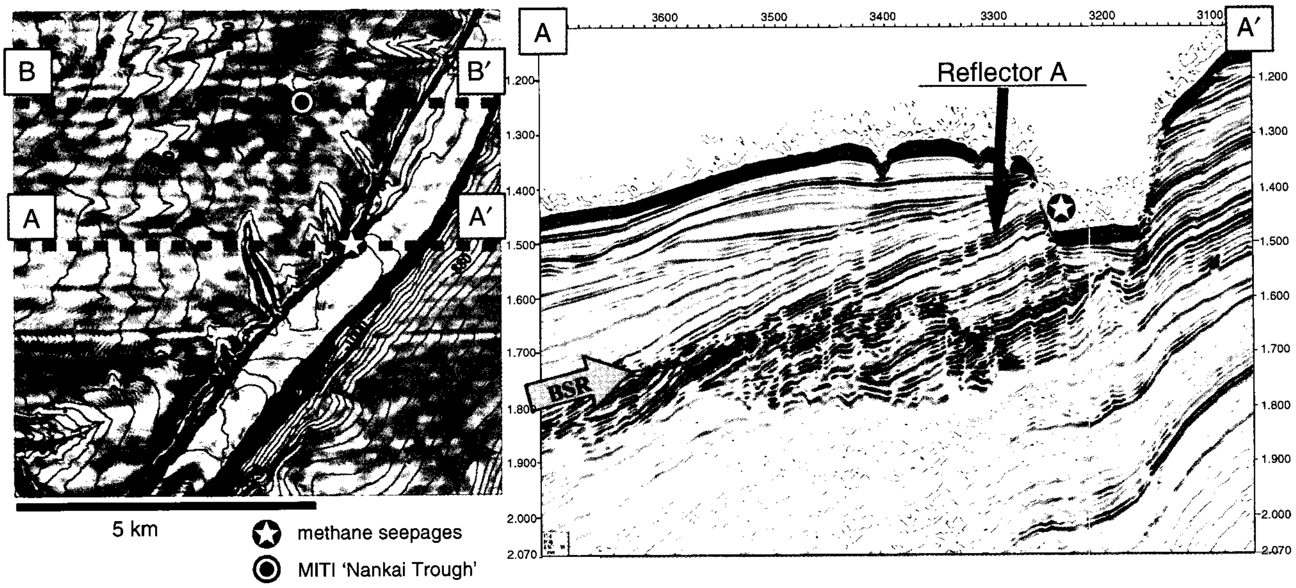

Fig. 4. A bathymetric chart with seafloor reflection amplitude (left) and a seismic section (right) around the western slope of the Ryuyo canyon.

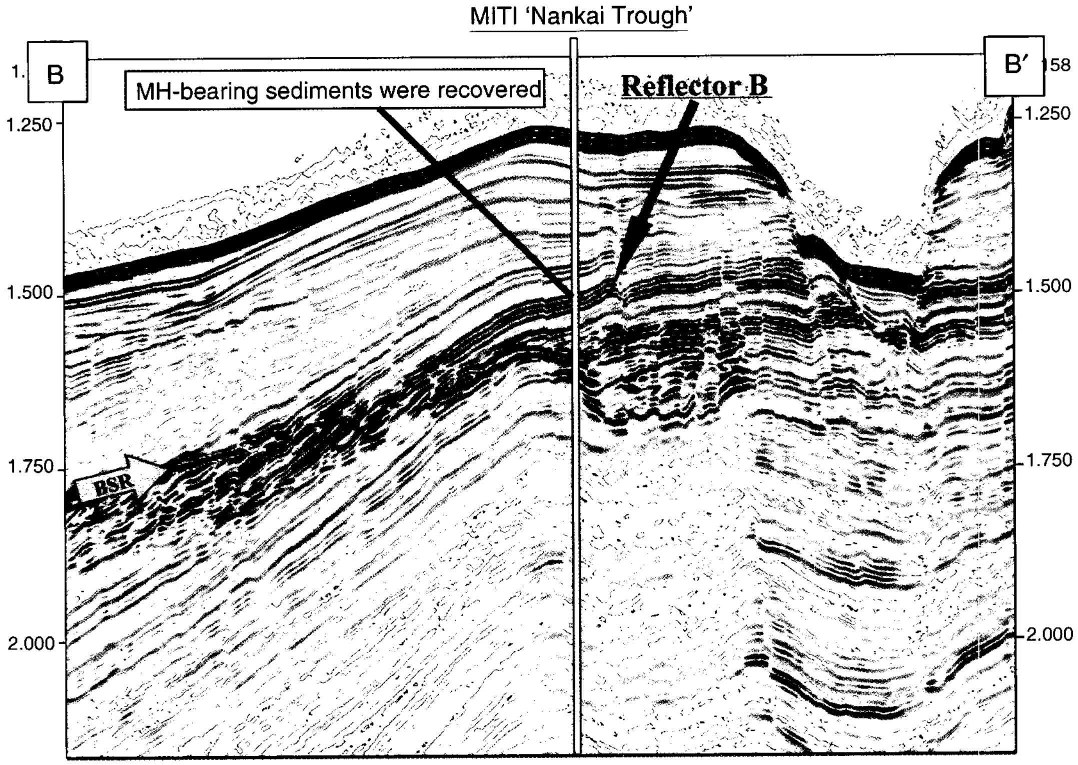

Fig. 5. A seismic section crossing Line B-B′ in Figure 4. Reflector A of the seismic section in Figure 4 extends to Reflector B. MITI 'Nankai Trough' is an exploratory well drilled in FY1999.

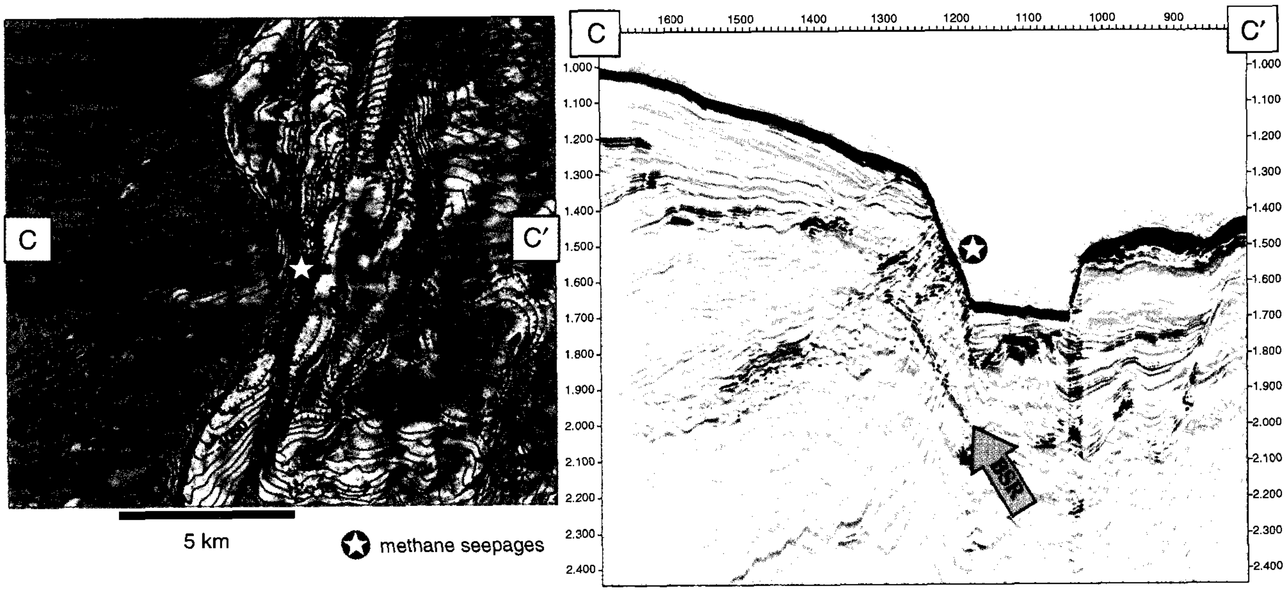

Fig. 6. A bathymetric chart with seafloor reflection amplitude (left) and a seismic section (right) around the western slope of a depression in an eastward direction from the Dai-Ichi Tenryu Knoll.

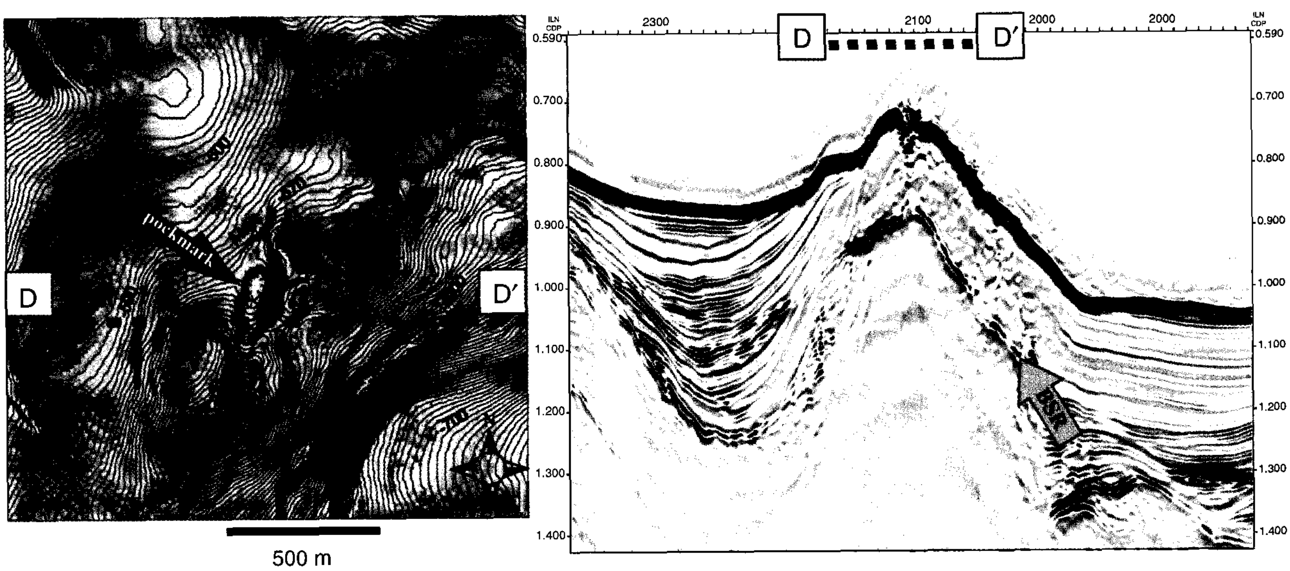

Fig. 7. A bathymetric chart with seafloor reflection amplitude (left) and a seismic section (right) around a small pockmark on a ridge extending to north-eastward from the Dai-Ni Tenryu Knoll.

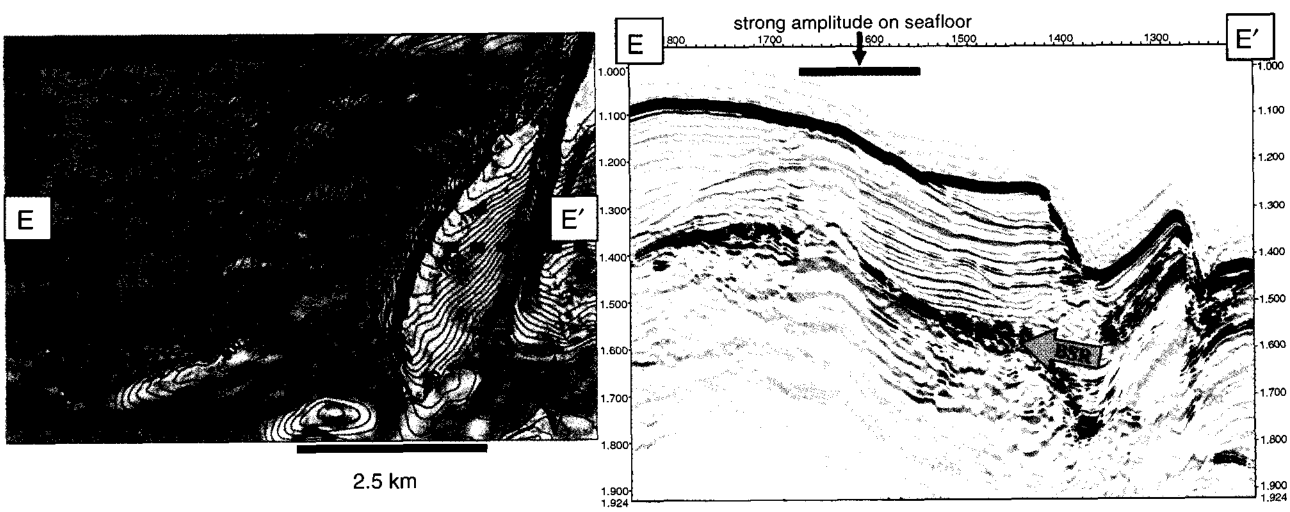

Fig. 8. A bathymetric chart with seafloor reflection amplitude (left) and a seismic section (right) around an area showing very high amplitude on seafloor.

(Reflector B in Figure 5) on the seismic section intersected by the exploration well MITI 'Nankai Trough'. Methane hydrate-bearing sandy sediments were recovered at the depth of the Reflector B. It is expected that Reflector A corresponds to methane hydrate-bearing sediments. Judging from the fact that dissociation of methane hydrate makes CH_4-enriched and Cl-depleted fluids, the methane seep sites at the western wall of the Ryuyo Canyon must be related to the existence of methane hydrates.

At the western slope of a depression east of the Dai-Ichi Tenryu Knoll (Figure 6), seepage sites, with dead clams and carbonates, were found by Ashi et al. (1995) with 'Shinkai 2000'. A seismic section in Figure 6 crosses the seepage site. A group of strong reflectors between the seafloor and the BSR can be recognised below the seepage sites, but it is not clear whether these reflectors correspond to methane hydrate-bearing sediments. The characteristic reflectors extend below the BSR, so it is concluded that the reflectors correspond to the formations in which free gas has accumulated; the gas may be accumulating along an unconformity. It is expected that the methane seepage sites at the western wall of the depression may be related to the existence of methane hydrates and free gases.

Seafloor manifestations expected by high-resolution 3D seismic data

Figure 7 shows a pockmark on a ridge extending north-eastward from the Dai-Ni Tenryu Knoll. A seismic section in Figure 7 crosses the pockmark. A velocity pull-up of the BSR and a strong reflector can be recognised just below the pockmark. Although it is not certain that the strong reflector and pull-up are caused by the existence of methane hydrate, there is no doubt that gas-bearing fluid near the BSR migrates upward to the seafloor. This must be caused by fluid migration, accompanied by hydraulic fracturing. Unfortunately, no seafloor geochemical survey has been conducted around the area as yet.

An area showing very strong amplitude in Figure 3 is shown in more detail in Figure 8. A seismic section in Figure 8 crosses the area. Faults in the shallow formation can be recognised, just below the area showing strong amplitude. This strong amplitude suggests the presence of seafloor carbonates, which precipitate from methane-bearing fluid supplied from below, migrating through faults. It is well known that carbonates precipitate near the seafloor at methane-bearing seepage sites as a result of anaerobic methane oxidation and mixing with seawater (Sassen et al., 2001). However, we have no ground-truth data on the seafloor at this site.

Conclusions

We have introduced a method to explore for methane hydrate reservoirs by fusion of 3D seismic exploration and seafloor geochemical surveys in the eastern Nankai Trough.

A 3D high-resolution seismic survey designed for methane hydrate exploration is useful for the interpretation of geological settings in shallow formations where methane hydrates may exist. Bathymetric and seafloor reflection amplitude maps, constructed from 3D high-resolution seismic data, provide valuable information about seafloor conditions over a vast area, and could be navigation maps for future seafloor geochemical surveys.

New findings about relationships between methane hydrate reservoir occurrence, observed in the seismic data, and seafloor geological and geochemical manifestations lead to the construction of a geological and geochemical model in shallow formation in the eastern Nankai Trough, and to the establishment of a comprehensive survey strategy combining geophysical and geochemical surveys for methane hydrate exploration.

Acknowledgments

The authors express special thanks to J. Ashi (University of Tokyo), U. Tsunogai (University of Hokkaido), M. Tanahashi (National Institute of Advanced Industrial Science and Technology), and R. Sassen (Texas A&M University) for valuable advice and suggestions throughout this study. We also express thanks to M. Nakamizu and T. Saeki (Japan Oil, Gas and Metals National Corporation) who have encouraged us to write this paper and to the Ministry of Economics, Trade and Industry (METI), the Research Consortium for Methane Hydrate Resources and the Japan Oil, Gas and Metals National Corporation which gave permission to publish this paper.

References

Ashi, J., Huchon, P., Segawa, J., Thoue, F., Kobayashi, K., 1995, Geological Structure and Cold Seepage at the Prism Slope Depression off Omaezaki: the 1994 KAIKO-TOKAI "Shinkai 2000" Dives: *JAMSTEC Journal of Deep-Sea Research* **11**, 189–195.

Borowski, W. S., Paull, C. K., Ussler, W., III, 1996, Marine pore-water sulfate profiles indicate in situ methane flux from underlying gas hydrate: *Geology* **24**, 655–658. doi: 10.1130/0091-7613(1996)024<0655:MPWSPI>2.3.CO;2

Nagakubo, S., Tanahashi, M., Ikehara, K., Fujii, T., 2005, Geochemical seafloor surveys for exploration of methane hydrates in the eastern Nankai Trough: *Chikyu* **27**, 954–959.

Nagakubo, S., Kobayashi, T., Inamori, T., and Fujii, T., 2006a, Anomaly of BSR depths at the Ryuyo area in the Eastern Nankai Trough: *Japan Geoscience Union Meeting 2006, Extended Abstracts*, G228–P001.

Nagakubo, S., Kobayashi, T., and Tanahashi, M., 2006b, Understandings of seafloor manifestations utilized by 3D seismic data around Tenryu knolls: *Japan Geoscience Union Meeting 2006, Extended Abstracts*, G228–003.

Sassen, R., Losh, S. L., Cathles, L., III, Roberts, H. H., Whelan, J. K., Milkov, A. V., Sweet, S. T., DeFreitas, D. A., 2001, Massive vein-filling gas hydrate: relation to ongoing gas migration from the deep subsurface in the Gulf of Mexico: *Marine and Petroleum Geology* **18**, 551–560. doi: 10.1016/S0264-8172(01)00014-9

Shimizu, S., Oikawa, N., Hayashi, M., Ochiai, K., and Nakamizu, M., 2003, The results of METI Geophysical explorations in FY2003 and 2004 – Methane Hydrate Exploration: *Proceedings of the 109th Conference, The Society of Exploration Geophysicists of Japan*, 1–3.

Takahashi, H., and Tsuji, Y., 2005, Multi-Well Exploration Program in 2004 for Natural Hydrate in the Nankai-Trough Offshore Japan: *Offshore Technology Conference*, 17162.

Tsuji, Y., Nonaka, Y., and METI, 2004, Multi-well drilling campaign METI "Tokai-Oki to Kumano-nada", *in* 2004 for methane hydrate evaluation in the Nankai Trough, off central Japan.: *Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards, AAPG Hedberg Research Conference, Extended Abstracts*, 1–2.

Tsunogai, U., Wakita, H., Ashi, J., Gamo, T., 1997, Fresh water seepage on the seafloor: Ryuyo Canyon, Nankai Trough: *JAMSTEC Journal of Deep-Sea Research* **13**, 503–508.

Tsunogai, U., Yoshida, N., Gamo, T., 2002, Carbon isotopic evidence of methane oxidation through sulfate reduction in sediment beneath seafloor cold seep vents on the seafloor at Nankai Trough: *Marine Geology* **187**, 145–160. doi: 10.1016/S0025-3227(02)00263-3

Manuscript received 29 November 2006; accepted 18 December 2006.

三次元地震探査と海底面地化学調査の融合によるメタンハイドレート探査

長久保 定雄・小林 稔明・藤井 哲哉・稲盛 隆穂

要　旨： 次世代エネルギー資源として期待され，日本周辺海域に相当量賦存していると考えられているメタンハイドレート（以下，MH）は，石油・天然ガスに比べて海底からの賦存深度が浅い（<500m）ため，MH 濃集層と海底面現象の間になんらかの関係が存在する可能性がある。メタンハイドレート資源開発研究コンソーシアム（略称：MH21 研究コンソーシアム）は東部南海トラフをモデル海域とし，地震探査，基礎試錐に加え，海底面地化学調査を MH 探査の補助調査として実施してきた。しかしながら，海底面地学調査の結果だけでは両者に顕著な関係を見出すことはできなかった。これは東部南海トラフの浅層地質環境の複雑性が原因と考えられ，東部南海トラフ浅層の「地質地化学モデル」構築が求められている。

MH21 研究コンソーシアムは，東部南海トラフにおいて実施された高分解能三次元地震探査データを利用した「地質地化学モデル」構築の試みを始めたところである。その中で，海洋研究開発機構（JAMSTEC）の深海潜水艇「しんかい 2000」による潜行調査結果と地震探査データの比較，および，地震探査データから作成した海底地形図および海底面反射強度図の解析により，MH 濃集層および海底面現象との関係が明らかになりつつある。

現在，MH21 研究コンソーシアムは，高分解能三次元地震探査データの利用によって構築される東部南海トラフ浅層の「地質地化学モデル」は，将来の海底面地化学調査による MH 探査の指標となるだろう。

本稿では，「三次元地震探査と海底面地化学調査の融合によるメタンハイドレート探査」に関する MH21 研究コンソーシアムの試みについて紹介する。

キーワード：メタンハイドレート，海底面地化学調査，南海トラフ，BSR，高分解能三次元地震探査

메탄 하이드레이트 탐사를 위한 3 차원 탄성파 탐사와 해저면 지구화학탐사의 융합 기술

Sadao Nagakubo, Toshiaki Kobayashi, Tetsuya Fujii, and Takao Inamori

요　약： MH21 연구 컨소시엄에서는 일본 난카이 트러프 동부의 메탄 하이드레이트 탐사를 위해 고분해능 3 차원 탄성파 탐사와 해저면 지구화학탐사를 수행해 왔다. 메탄 하이트레이트가 존재하는 천부지층을 영상화 하기 위해 수행된 고분해능 3 차원 탄성파탐사 결과, 천부 지층에 대한 훌륭한 지질 정보를 획득할 수 있었다. 이러한 정보들은 지질학적, 지구화학적 모델을 구축하는데 유용하며, 특히 메탄가스 또는 메탄을 포함하는 유체의 이동통로, 지구화학적 메탄 하이드레이트 지시자등을 포함하는 복잡한 해저면 지질구조를 이해하는데 유용하다.

수중잠수정을 이용해 확인된 메탄 유출 지점과 탄성파 단면의 비교 결과, 해저면 하부의 메탄가스층 및 메탄 하이드레이트 저류층과 해저면 메탄 하이드레이트 지시자 사이의 특징적인 관계가 확인되었다. 해저지형도와 해저면 반사파로부터 영상화된 해저면 반사파진폭 영상 역시 넓은 지역에 대한 이들 관계를 이해하는 유용하며, 이러한 자료에 기반한 새로운 지구화학적 해저면 탐사도 요구된다.

메탄 하이드레이트 저류층과 해저면 메탄 하이드레이트 지시자 사이의 관계는 고분해능 3 차원 탄성파탐사 자료의 해석을 통해 점점 더 분명해지고 있다. MH21 연구 컨소시엄은 향후 고분해능 3 차원 탄성파탐사로부터 구축된 지질학적, 지구화학적 모델에 기반하여 해저면 지구화학탐사를 수행할 것이다.

이 논문에서는 3 차원 탄성파 탐사와 해저면 지구화학탐사기술의 융합에 의한 일본에서의 메탄 하이트레이트 탐사에 대해 소개한다.

주요어： 메탄 하이트레이트, 해저면 지구화학탐사, 난카이 (Nankai) 트러프, 해저면 모방 반사면 (BSR), 고분해능 3 차원 탄성파탐사

（独）石油天然ガス・金属鉱物資源機構　　석유 천연가스·금속광물 자원 기구
〒261-0025　千葉県千葉市美浜区浜田 1 丁目 2 番 2 号