— Report —

Development of the off-Toyohashi seafloor cabled observatory

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The existence of fluid in seismogenic zones plays a key role in great earthquakes. Data on electrical conductivity structures obtained by electromagnetic surveys across the great earthquake zones show that the seismically locked zones correspond to low conductive zones. This low conductivity is possibly interpreted as relatively low fluid content in rock or sediment. For more discussion on the role of fluid in earthquake occurrence, we have recently started an electromagnetic and seismological monitoring project using long submarine cables off Toyohashi, in the southwest part of Japan's main island. The cables are located on the Tokai seismogenic zone, where both slow-slipping and locked zones are obvious by GPS observation. We constructed a seafloor observatory at the tip of the western cable, including a seismometer, pressure gauges, a magnetometer, voltmeters, and thermometers. These sensors measure and transfer data on the seafloor environment in real time. The data will be used for passive and active monitoring below the seafloor, including in the Tokai seismogenic zone.

Keywords : seafloor cable, earthquakes, electromagnetics, montoring, Toyohashi

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1. Introduction

The existence of fluid in seismogenic zones plays a key role in the occurrence of great earthquakes because high pore pressure in a fault zone allows sliding at low shear stress (e.g. Blanpied et al., 1992). In fact, Fujie et al. (2002) found in the Japan Trench region that large amplitude reflected waves generated at the subducting plate boundary were observed in a low seismicity region and vice versa. Sato et al. (2005) identified the upper surface of the Philippine Sea Plate below Tokyo Bay through the use of deep seismic reflection profiling, and recognized that the relatively high amplitude seismic reflector correlates with the transitional slip region surrounding the high-slip region (so-called “asperity”) of the 1923 Great Kanto Earthquake. These heterogeneous distributions of reflectors may be attributed to heterogeneous fluid distribution on the plate boundary, and may indicate the role of fluid in earthquake occurrence. However, other factors can explain such reflectors, so independent geophysical surveys sensitive to fluid are required for further discussion.

Electromagnetic surveys have revealed fluid distribution in seismogenic zones (e.g. Unsworth et al., 1999; Unsworth et al., 2000) because enhanced electrical conductivity at subsolidus temperatures is principally controlled by the presence of water. For example, the electrical conductivity structure was investigated across the central segment of the Atotsugawa Fault in Japan by using magnetotelluric soundings (Goto et al., 2005). The central segment shows lower seismicity than the other segments of the fault. Goto et al. (2005) indicate a shallow high-conductivity zone along the fault to a depth of less than 1 km, but also an underlying low conductive crust at a depth of about 5 km below the fault trace. Goto et al. (2005) concluded that the low conductive crust is a feature of a locked fault segment, possibly interpreted as a condition of less fluid. Thus, land-based electromagnetic surveys imply fluid playing a role around seismogenic zones. Such resistive features along the active fault are often reported from other EM imaging (e.g. Oshiman et al., 2002).

Marine magnetotelluric soundings around the seismogenic zones along megathrust faults also indicate a correlation between conductivity structure and earthquake occurrence. One field example was obtained in the Tonankai area. The 1944 Tonankai Earthquake (M 7.9) in the Kumano Basin and Nankai Trough, off the Kii Peninsula in southwest Japan, was typical of the megathrust earthquakes that recur along subduction zones. Land and marine magnetotelluric surveys in the Kii Peninsula, the Kumano Basin, and the Nankai Trough were carried out in 2002–2004. On the basis of the marine data, Goto et al. (2003) estimated an electrical conductivity model below the seafloor in which the Philippine Sea Plate has conductive oceanic crust before subduction. As the plate goes down the Kumano Basin, the conductivity becomes low at a depth of 10 km below the seafloor, which approximately coincides with the up-dip limit of the Nankai megaearthquake zone. Meanwhile, Kasaya et al. (2005) tried joint modeling using land and marine data, and their preliminary model shows that the Philippine Sea Plate becomes more conductive (with 0.1 S/m) again below a depth of 30 km, around the down-dip limit of the earthquake zone. In other words, the rupture zone of the 1944 Tonankai Earthquake corresponds to a less conductive zone than the shallower and deeper zones on the subducting plate. A similar result was obtained off the Tokai region in Japan (Sakata et al., 2007), discussed below.

Although seismic and electromagnetic surveys imply the possibility of less fluid conditions around seismically locked zones, there is no information on how fluid can act regarding the occurrence of great earthquakes: for example, whether highly pressurized deep fluid moves into seismically locked zones and reduces the strength of locked zones or not. One of the best ways to prove such a hypothesis is seismic and electromagnetic monitoring around seismically locked zones, together with monitoring crustal deformation, subseafloor temperatures, and so on. For monitoring the seismogenic zone and elucidating the role of fluid in earthquake occurrence, we have constructed a seafloor observatory at the tip of the off-Toyohashi cable, located on the Tokai seismogenic zone in Japan, and we are now continuously recording seafloor data. In this paper, we briefly introduce the observation purpose and results of the project, named Tokai-SCANNER: Tokai Submarine Cabled Network Observatories for Nowcast of Earthquake Recurrences.

2. Monitoring an offshore seismogenic zone with a submarine cable

In the Tokai region in the central part of Japan, a locked plate boundary on the subducting Philippine Sea Plate is clearly recognized (Sagiya, 1999). In addition, a slow slip on the plate boundary has recently been found (Ohta et al., 2004: Fig. 1). Such a slip creates a concentration of stress near the boundary between the locked and slipping zones, so that the boundary region has the potential for an initial

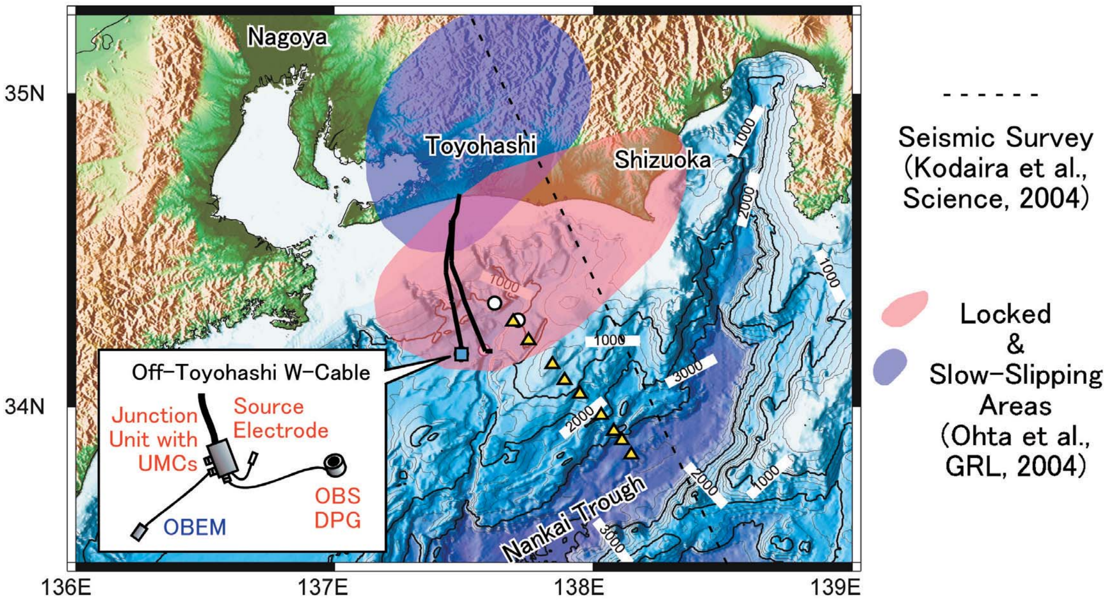


Fig. 1. Location of the off-Toyohashi cables (thick lines). Rectangle: location of the seafloor observatory. Blue and red areas: seismically locked and slow-slip areas (Ohta et al., 2004). Dashed line: seismic survey by Kodaira et al. (2004). Circles: location of Earth Field Observation Systems (EFOS). Triangles: self-pop-up OBEM/OBE sites. Details of OBEM, OBS, DPG, and so on at the end of the off-Toyohashi W-cable are summarized in Fig. 4.

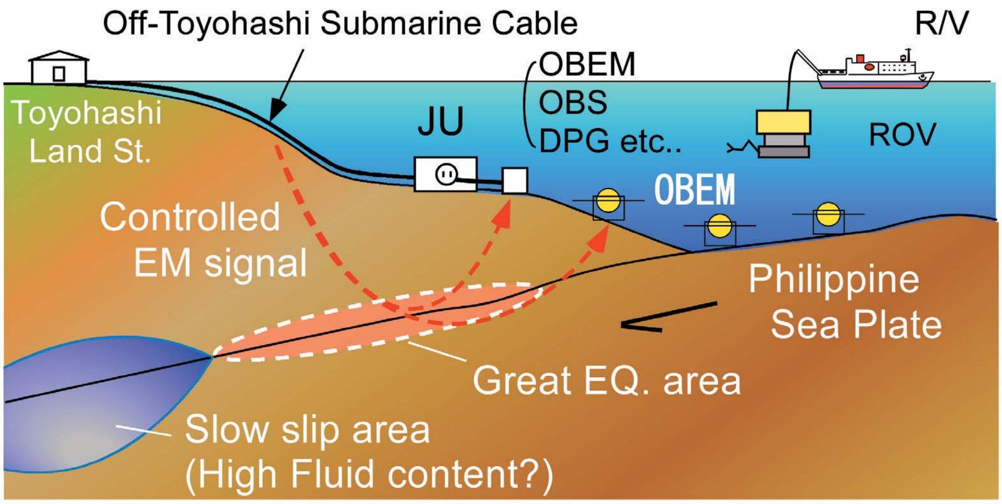


Fig. 2. Concept of Tokai-SCANNER and "mobile" OBEM surveys. Short-term OBEM arrays recording natural and controlled EM signals have higher spatial resolution and cover the Tokai-SCANNER with long-term observation. JU: junction unit; OBEM: ocean bottom EM meter; OBS: ocean-bottom seismometer; DPG: differential pressure gauge.

rupture in the next Tokai earthquake. The off-Toyohashi cables (Fig. 1) were originally part of JIH (the Japan Internet Highway) installed by KDDI for data transfer and telecommunications. Due to leakage trouble, these cables were retired and were transferred to JAMSTEC in 2006 for scientific use. The cables are located on both the locked and slipping zones of the Tokai region, so they can be used as the best facility to monitor the physical properties around the plate boundary. Therefore, we constructed a seafloor observatory connected to the western off-Toyohashi cable in April 2007 in the Tokai region of Japan (Fig. 2). A brief history of the off-Toyohashi cable, the seafloor observatory, and related events are summarized in Table 1. A similar ocean-bottom observatory based on repurposed submarine cable, called the VENUS project (Kasahara et al., 1998), was constructed off Okinawa, Japan. The project started in 1995, and observation started in August 1999, but unfortunately the project terminated in November 1999. Although the VENUS system was not operated successfully, all of the knowledge obtained has been used for the Tokai-SCANNER system.

Details of the scientific observations at Tokai-SCANNER are presented here. The observatory is used for active and passive geophysical monitoring. As an active method, controlled-source electromagnetic monitoring is conducted to detect conductivity variation, an indication of fluid migration, around the plate boundary. The off-Toyohashi W-cable is used as a transmitting dipole source with two electrodes located at 0 km (coastline) and 50 km (offshore) (Fig. 2). For the receivers, the off-Toyohashi E-cable is available. The cable has an electric leakage at 5

Table 1. History of the off-Toyohashi cabled observatory.

Apr. 1999	JIH constructed and put to use for communications.
Jun. 2006	The off-Toyohashi cables transferred to JAMSTEC.
Dec. 2006	Tank test for the junction unit (JU), OBEM, and OBS-DPG units (OCC Kita-Kyushu).
Jan. 2007	R/V *Natsushima* and ROV *Hyper-Dolphin* cruise (NT07-01: Fig. 8) - Short-term OBEMs deployed at six sites. - One EFOS deployed by the ROV, about 20 km east of the off-Toyohashi W-cable (Fig. 1). The dipole length for the receiver was 300 m. - Site survey of planned location of the junction unit (JU) and geophysical sensors. Seafloor video images, subseafloor temperatures, and bottom water currents were obtained near the end of the off-Toyohashi W-cable by using the ROV. - Testing a new measuring tool for shallow seafloor resistivity (MORSE, or mobile resistivity meter at seafloor environments) by ROV. Depth < 1 m.
Feb. 2007	R/V *Natsushima* cruise (NT07-03) - All of the short-term OBEMs recovered successfully.
Mar. 2007	Cable ship *KDD Pacific Link* (KPL-Mar: Figs. 3, 7) - Junction unit attached to the end of the off-Toyohashi W-cable.
Apr. 2007	R/V *Natsushima* and ROV *Hyper-Dolphin* cruise (NT07-06: Figs.3, 5, 6) - Two geophysical packages (OBEM and OBS-DPG) connected to the JU. Geophysical monitoring of the Tokai-SCANNER started. - Three OBEMs deployed for recording natural EM fluctuations. - One EFOS recovered and reinstalled. Another new EFOS deployed about 15 km east of the off-Toyohashi W-cable (Fig. 1). The dipole length of the new EFOS is 10 m.
Jul. 2007	R/V *Natsushima* cruise (NT07-14) - Three OBEMs recovered. At that time, OBEM (or OBE) data was obtained at nine sites (Fig. 1).
Apr. 2008	R/V *Natsushima* and ROV *Hyper-Dolphin* cruise (NT08-08) - Controlled source EM monitoring started: the electric current supplied to the JU through the off-Toyohashi W-cable is artificially varied with period of 120 sec., and the amplitude of potential variations generated at the sea earth of the JU was monitored on the seafloor. - Precise location measurements of each seafloor sensor using the ROV homing system - Measuring shallow seafloor resistivity with the DC resistivity method by using the ROV and MORSE. Depth = about 10 m. - Recovery of two EFOSs by ROV - Testing a new arm-folding system for a long-term OBEM (deployment and recovery) cf. The long-term OBEM and EFOSs records the artificial signal from the off-Toyohashi W-cable.

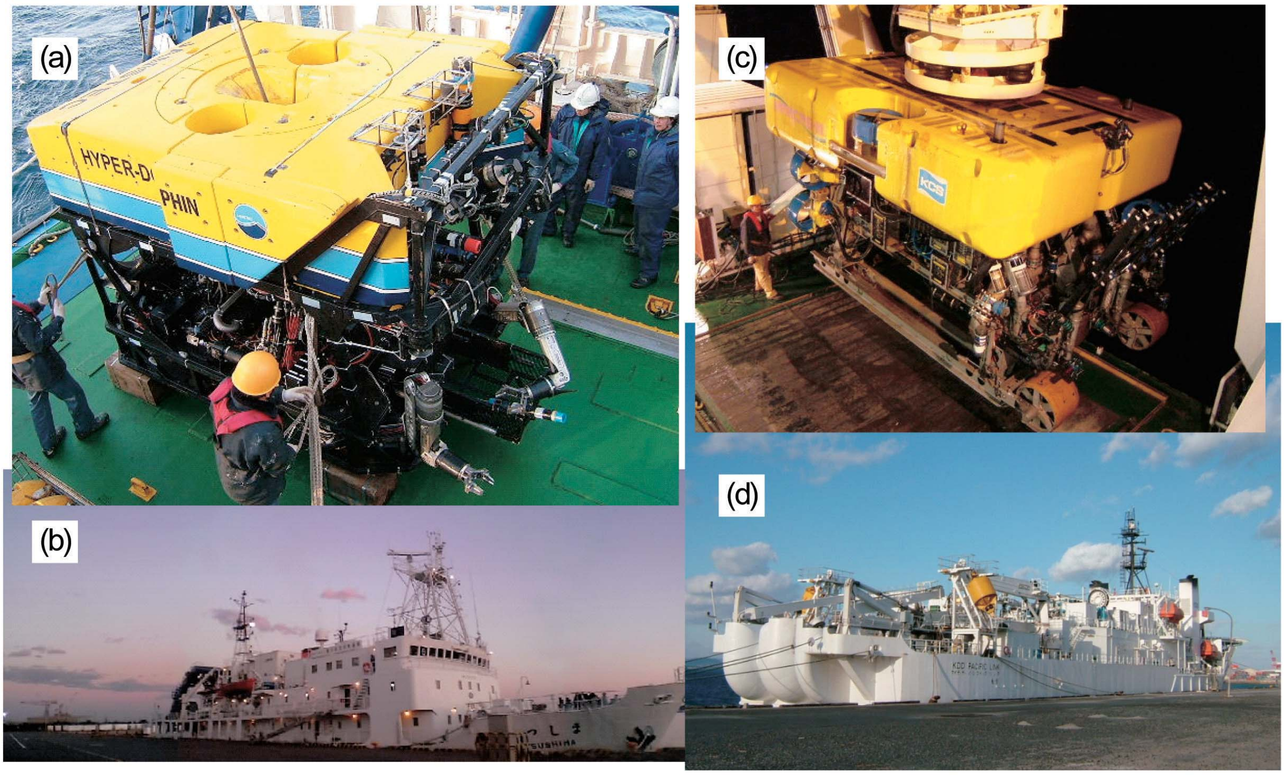


Fig. 3. ROVs and vessels used for our project. (a) ROV *Hyper-Dolphin* on (b) R/V *Natsushima*, JAMSTEC. (c) ROV *MARCAS-III* on (d) cable ship *KDD Pacific Link*, Kokusai Cable Ship Co. Ltd.

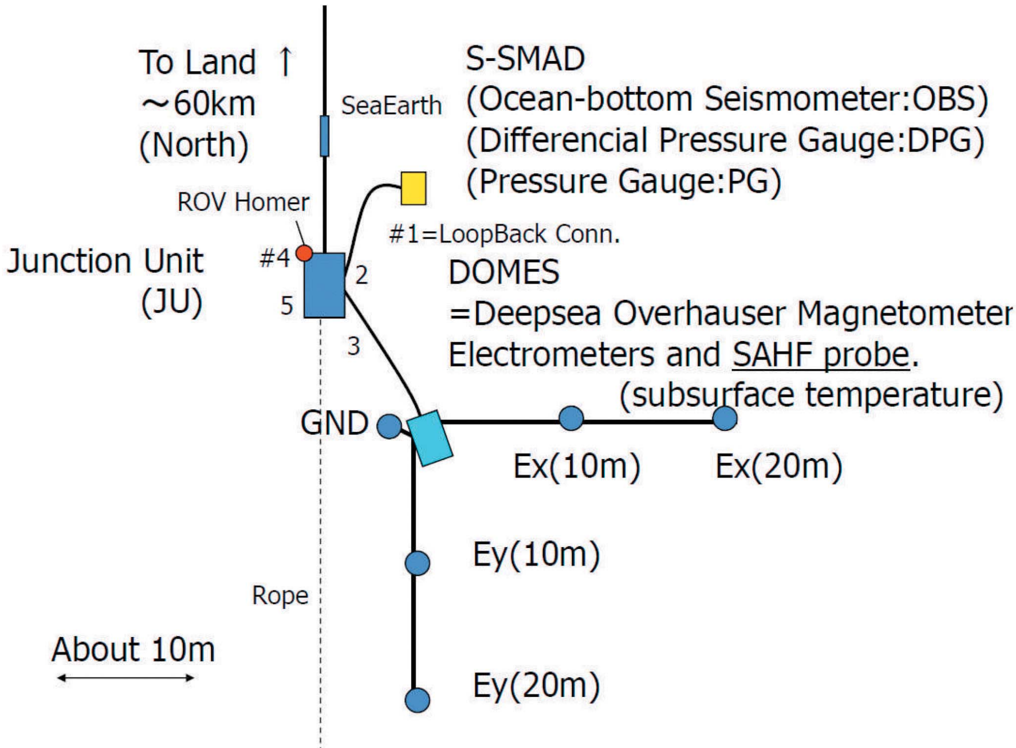


Fig. 4. Plane map of the off-Toyohashi submarine cabled observatory. The water depth of the observatory is 1310 m. The location of the JU is 34°10.466 N and 137°29.337 E. Five blue circles indicate potential electrodes for the measurement of the seafloor electric field. Note that the map is a schematic one. A more precise map will be updated in the near future.

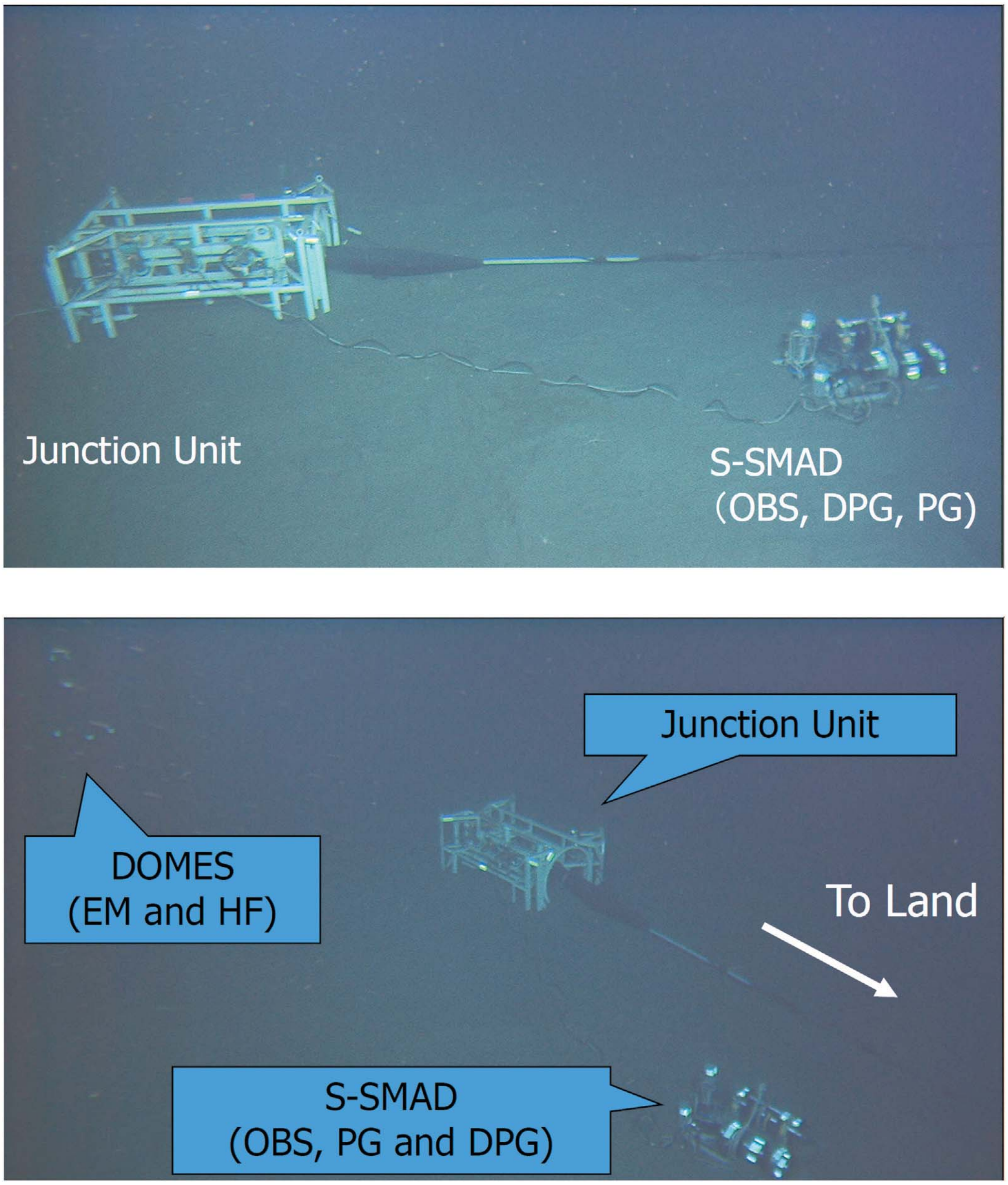
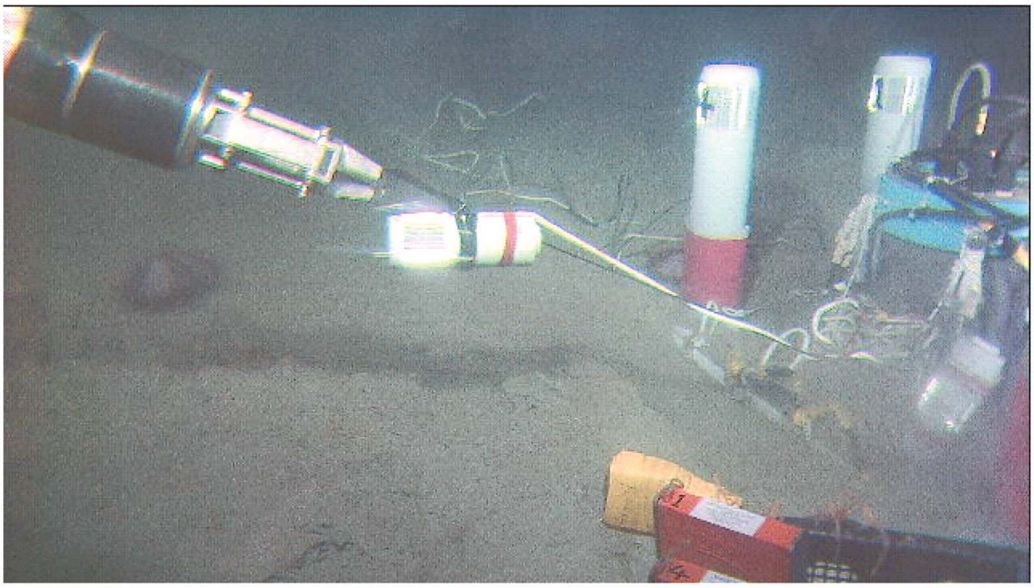


Fig. 5. Photographs of the off-Toyohashi cabled observatory obtained by ROV *Hyper-Dolphin* on the NT07-06 cruise. Top: overall view of the off-Toyohashi observatory. Bottom: the junction unit and the S-SMAD, a sensor package with three sensors: an ocean bottom seismometer (OBS), a differential pressure gauge (DPG), and a pressure gauge (PG). The JU and S-SMAD was connected with the underwater matable connector.



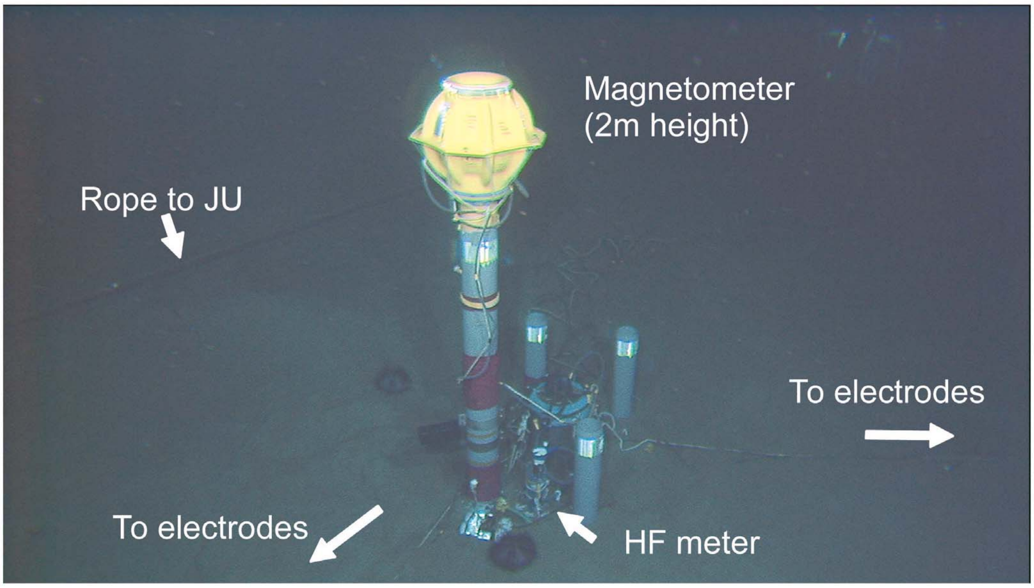


Fig. 6. Photographs of the DOMES (deep-sea Overhauser magnetometer, electrometers, and SAHF probe) taken by the ROV *Hyper-Dolphin* on the NT07-06 cruise. Top: central part of DOMES with the Overhauser magnetometer. HF means a heat-flow meter, a thermometer probe. Short cables (white arrows) run to each of the electrodes. Bottom: extension of the cable to the electrode at deployment. The cylinder-like sensor is an Ag-AgCl electrode.

km offshore. The electric leakage ends telecommunications, but it gives us a chance for electrical potential observation on the seafloor. Measurement of the voltage difference using the off-Toyohashi E-cable as a 5 km dipole started from 2004 and has been continued by Tokai University. The artificial electrical signal from the W-cable can be received by the E-cable. In addition, the long-term electric field observation system (EFOS), originally developed by the University of Tokyo, can act as a receiver. Although the EFOS is not connected to the submarine cables, it can record the seafloor electric field continuously for several years. Two EFOSs were installed in January 2007 by the JAMSTEC ROV *Hyper-Dolphin* with receiving dipoles with lengths of 10 m and 300 m (Fig. 1). Numerical calculations show us that apparent resistivity values obtained daily can change if the high conductive zone on the plate boundary is revealed. Therefore, the submarine cables are useful tools for monitoring resistivity variation and possibly fluid migration around the plate interface. When the EFOSs settled on the seafloor, an artificial signal was sent from the JU at the tip of the W-cable (Table 1), so the EFOSs should record the artificial potential field before their recovery. Both the data on the source current amplitude from the off-Toyohashi E-cable and the potential amplitude received by the EFOSs are now being analyzed.

As a method of passive monitoring, we connected various sensors to the tip of the off-Toyohashi W-cable: an ocean-bottom seismometer (OBS), a differential pressure gauge (DPG), and a pressure gauge (PG). The OBS, DPG, and PG are assembled into one package named S-SMAD (Fig. 5). The OBS, which is an accelerometer type, can measure high-frequency ground motion. The PG can measure the nearly static pressure variation on the seafloor. The DPG can also measure the pressure on the seafloor, but it has two pressure sensors in and out of a chamber. The pressure difference between the two sensors allows us to monitor low-frequency pressure variation with higher accuracy than the PG. The DPG can monitor micro–pressure waves created by low-frequency seafloor motion. As a result, these sensors attached to S-SMAD are sensitive to offshore microearthquakes, slow-slip events, seafloor upward/downward movements, tidal waves, and tsunamis.

We also connected an electromagnetometer to the off-Toyohashi W-cable. Our electromagnetic (EM) sensors are also packed into another package named DOMES: deep-sea Overhauser magnetometer, electrometers, and SAHF probe (Figs. 4 and 6). DOMES has three major sensors: an Overhauser magnetometer, voltmeters, and a heat-flow probe. The Overhauser magnetometer can measure the absolute geomagnetic field (amplitude) with a resolution of 0.01 nT. The voltmeters can measure the horizontal electric field on the seafloor. Four electrodes were set on the seafloor, and the voltage differences between each electrode and a GND electrode (Fig. 4) are recorded with resolution of 0.3 μV. The sampling rate is 8 Hz for electric field measurements, and 1 Hz for other sensors equipped in DOMES, respectively. The heat-flow probe consists of five thermometers installed in a vertical rod at intervals of 10 cm. The shallowest one measures water and other temperatures below the seafloor, with a sampling rate of 0.2 Hz. Also, the tilt of DOMES is monitored by tiltmeters. The targets of these sensors are geomagnetic variations associated with stress changes, self-potential variation with fluid pressure changes, and heat transportation with fluid flow. In addition, the resistivity structure can be monitored by DOMES, which is effective for monitoring fluid below the seafloor, as mentioned in the previous section. The natural electric fluctuations induced by geomagnetic field variations can be monitored by DOMES, used for deep crustal monitoring using the magnetotelluric method. Controlled EM signals generated from the sea earth (Figs. 2 and 4 and Table 1) can be recorded by the DOMES voltmeters, so that the shallow resistivity structure can be monitored using the DC resistivity method. Thus, together with results from the S-SMAD, monitoring results of deep and shallow resistivity by DOMES can give us a correlation among earthquakes, crustal deformation, and fluid migration.

For connecting multidisciplinary sensors, the junction unit (JU) with five underwater matable ROV connectors is attached to the off-Toyohashi W-cable (Figs. 1 and 7). These sensors are sensitive to offshore microearthquakes, slow-slip events, and seafloor upward/downward movements. Such a package of various geophysical sensors will help us to discuss the detailed process before, during, and after earthquakes. Multidisciplinary observation is especially useful for signal and noise estimation of phenomena related to earthquakes.

3. Electromagnetic survey in the Tokai region

One problem with using long cables—for example, about 50 km in the case of the off-Toyohashi cable—for monitoring is low spatial resolution. Before monitoring, we suggested a conventional electromagnetic survey with self-

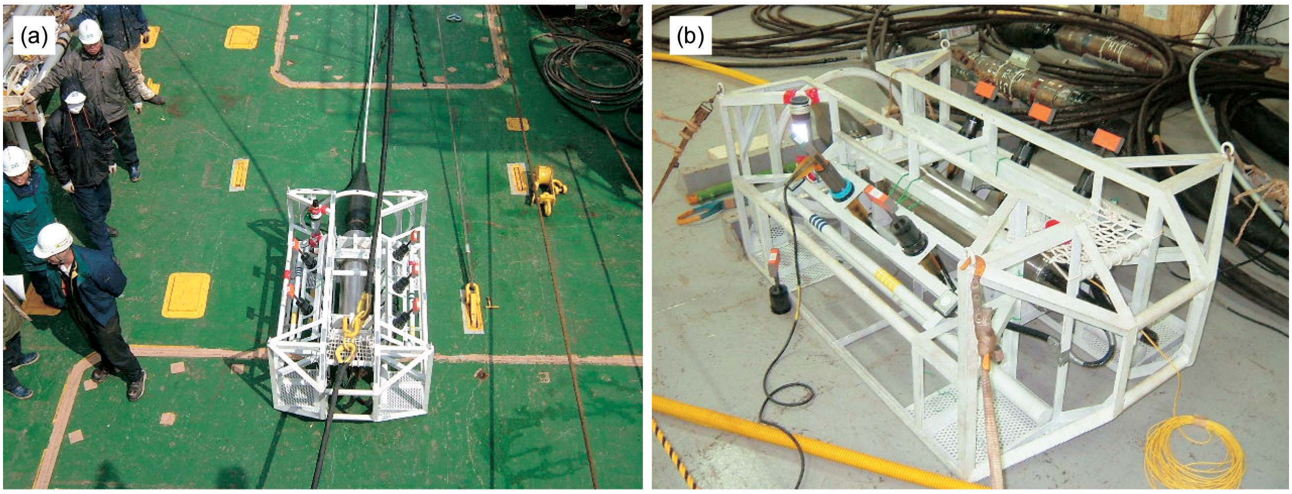


Fig. 7. Photographs of the junction unit (JU). (a) JU on board the *KDD Pacific Link* just before deployment. The white cable is the off-Toyohashi W-cable. (b) Close-up of the JU. Five ROV matable connectors are prepared for underwater connection. The JU is relatively smaller than the previous cabled JUs installed off Hatushima, Kushiro, and Muroto.

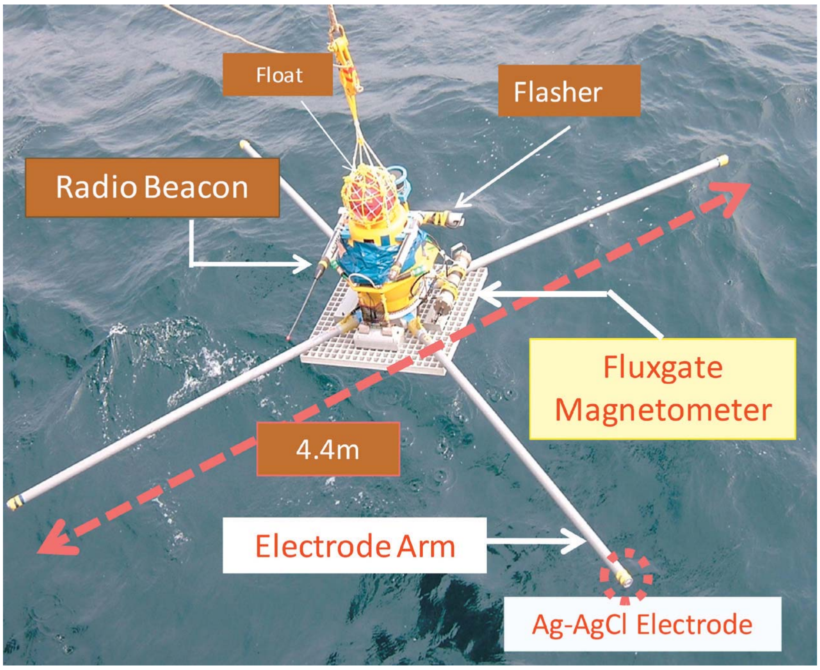


Fig. 8. Short-term OBEM. This photograph was taken at deployment on the NT07-01 cruise in January 2007.

pop-up ocean-bottom electromagnetometers (OBEMs). For imaging the crustal structure with higher resolution, we newly developed a small and short-term OBEM (Fig. 8). It consists of one deep-sea glass sphere, a three-component fluxgate magnetometer, voltmeters with Ag-AgCl electrodes, tiltmeters, and an acoustic release system common to the Japanese self-pop-up OBS. One feature of the OBEM is four long arms for electrodes. For speedy pop-up and easy recovery operations, these arms are folded when the OBEM is launched from the seafloor (detailed in Kasaya et al., 2006; and Kasaya and Goto, 2009). A number of the short-term OBEMs can be handled for an array observation even with a small fishing boat.

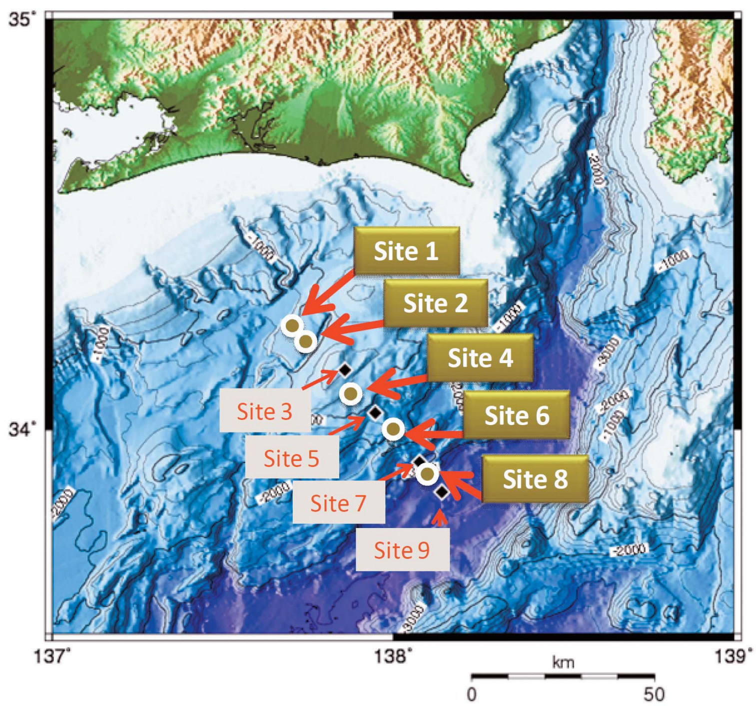
An electromagnetic survey of the Tokai seismogenic zone using the OBEMs was carried out in January 2007. Five OBEMs and four OBEs (without the magnetometer) were deployed and recovered on several research cruises by JAMSTEC's R/V *Natsushima* (see Table 1). The OBEM and OBE sites are shown in Figs. 1 and 9. After one month or longer of seafloor observation, all instruments were successfully recovered. The data obtained on fluctuations of natural electromagnetic fields can be analyzed with the magnetotelluric method and allow us to image the conductivity structure around the Tokai seismogenic zone, such as reported in Kasaya et al. (2005). The initial result by Sakata et al. (2007) shows similar features as in Goto et al. (2003). That is, the Philippine Sea Plate has a conductive oceanic crust before subduction, which becomes resistive as the plate runs down Japan's islands.

Although the OBEM survey shows us a snapshot of the crustal structure, it is useful for rough estimation of where anomalous conductivity variation will be located by the cables. Such information is quite useful if we acquire and interpret data on resistivity variations with Tokai-SCANNER. In addition, the OBEMs are expected to receive controlled electromagnetic signals from the off-Toyohashi W-cable in future. Although the lifetime of the short-term OBEMs on the seafloor is limited to less than three months, a combination of Tokai-SCANNER and a mobile OBEM survey is an effective tool for monitoring the seismogenic zone, as summarized in Fig. 2.

4. Seafloor em data obtained by Tokai-SCANNER

Since April 2008, seafloor monitoring data observed by Tokai-SCANNER has been stored continuously. The seafloor data is transferred to the Toyohashi land station, located on the coast, and also to the JAMSTEC submarine cable data center in Yokohama. Two typical examples of the seafloor electromagnetic data are shown as follows.

The first example is a self-potential variation



site	type	着底深度(m)
1	OBEM	1077
2	OBEM	953
3	OBE	536
4	OBEM	836
5	OBE	1405
6	OBEM	1773
7	OBE	2970
8	OBEM	3510
9	OBE	3603

Fig. 9. Location of short-term OBEM and OBE sites.

associated with earthquake shaking. On June 1, 2007, a small earthquake with a magnitude of 4.3 occurred along the coast of the Tokai area. The focal depth was 13 km, and the horizontal distance between the hypocenter and the off-Toyohashi observatory was about 50 km. Seismic waves (P, S, etc.) were observed by the seismometer in the S-SMAD. Simultaneously, abnormal voltage differences on the seafloor were observed by the voltmeters in the DOMES with an amplitude of about 20 μV. An example of the observed voltage difference is shown in Fig. 10. Large fluctuations are obvious, corresponding to the S-wave arrival of the M 4.3 earthquake. In addition, the DC levels of observed voltage differences show a gap before and after the S-wave arrival. The AC and DC potential changes are not observed without an earthquake. We conclude that the AC and DC potential changes are possibly due to earthquake shaking because these anomalous phenomena correspond to S-wave arrival, not to P-wave arrival. One of the mechanisms to generate

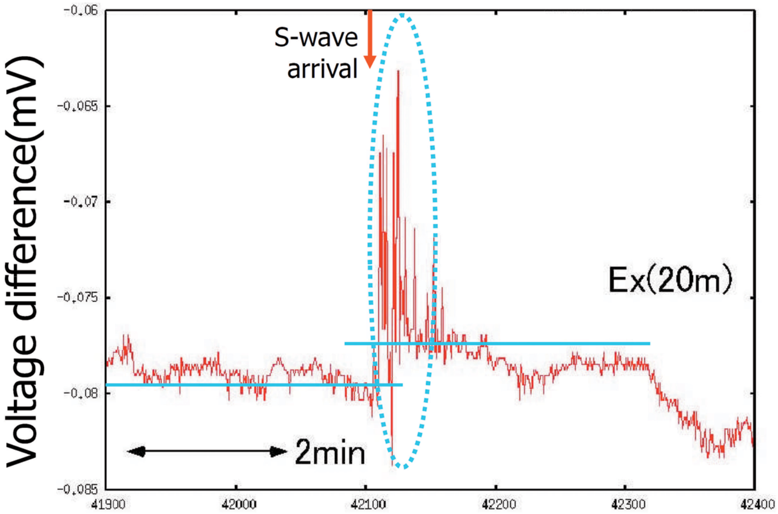


Fig. 10. An example of self-potential data. The voltage difference between electrode Ex (20 m) and GND in Fig. 4. The ellipse indicates large fluctuations associated with S-wave arrival of the M 4.3 earthquake on June 1, 2007. Solid bars indicate DC level before and after S-wave arrival.

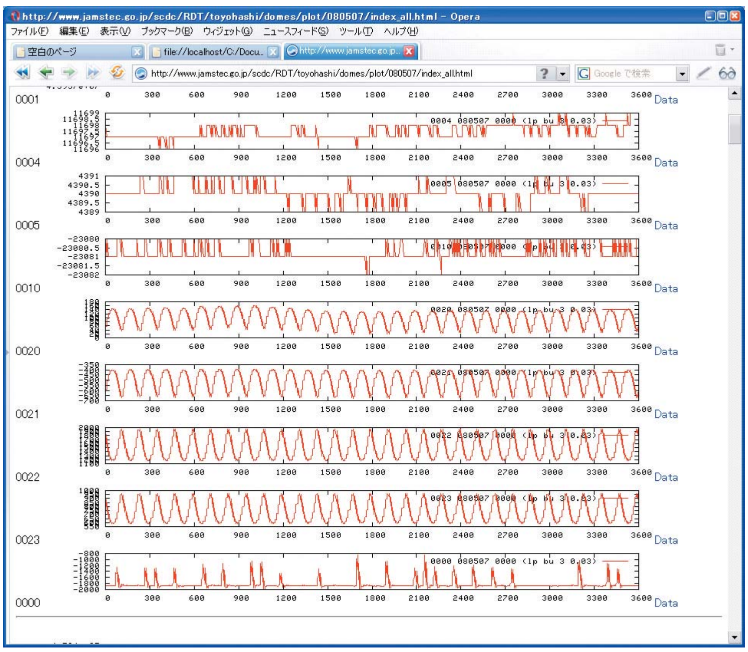


Fig. 11. An example of real-time data recorded at the off-Toyohashi cabled observatory. This plot was Web-based. We can get the time series of data from a Web site to check data in real time. The fourth to seventh waves are voltage differences measured by DOMES, including artificial semisinusoidal fluctuations created by the controlled electric current from the sea earth (Fig. 4). The Web database will be available in the near future.

both AC and DC potential changes is a conversion from a seismic wave to an electromagnetic field. If the subseafloor fluid is shaken by a seismic wave, AC-like electric potential fluctuations will be created due to electrokinetic phenomena. Also, strong shaking may change the path of subseafloor fluid after the earthquake. It results in a fluid pressure change and yields DC-like electric potential changes due to the same electrokinetic phenomena. By comparing the potential variations with the Ex (20 m) and Ex (10 m) electrodes (Fig. 4), we found that the potential variations are not generated regionally but locally (near the electrodes) because the parallel components of potential variations show different features. We conclude that the most likely possible candidate generating the seismic-electromagnetic wave conversion is shallow subseafloor water in the sediment below the electrode. Although further discussion and experiments are required for elucidating the cause of abnormal potential changes, we suggest the possibility that seafloor self-potential observation can monitor fluid flow below the seafloor.

The second example is an artificial controlled electric signal observed at the end of the off-Toyohashi W-cable. As described in section II, a controlled electric current is continuously transmitted through the off-Toyohashi W-cable. The source electrodes are located at 0 km (electrode at the coastline) and 50 km (offshore sea earth, Fig. 4), and therefore the off-Toyohashi W-cable itself is used as a large dipole. The wave shape of the transmitted source current is semisinusoidal with a period of 120 sec. Fig. 11 shows the voltage differences observed by DOMES. The artificial fluctuation of the voltage differences is obvious. Both the amplitude of the transmitted source current and received voltage differences allow us to monitor shallow seafloor resistivity continuously. On the basis of numerical study, the sounding depth (the depth range that can be resolved) is less than about 30 m. There is no previous research monitoring seafloor resistivity, so this experiment provides the first knowledge on how the seafloor environment, especially subseafloor fluid, is stable or changes over time. Also, the results of shallow resistivity research indicate that it is useful for monitoring the deep crust by using the magnetotelluric sounding method adopted for the off-Toyohashi OBEM data.

5. Conclusion

We successfully constructed a new seafloor observatory connected to a repurposed submarine cable off Toyohashi, Japan. We deployed multidisciplinary geophysical sensors, such as an electromagnetometer, a heat-flow meter, a seismometer, pressure gauges, and so on. Data have been collected since April 2008. Even now, fortunately, we are obtaining electromagnetic signals correlated to seismic waves. In addition, we have started continuous controlled-source electromagnetic sounding on the seafloor for monitoring electrical resistivity below the seafloor.

Tokai-SCANNER is a kind of frontier project for earthquake research using new technologies. Therefore, the project may not immediately contribute to predicting a Tokai earthquake. For example, if we detect a variation in the electromagnetic response function on the seafloor using a controlled signal, further observation with a short-term mobile OBEM array may be necessary to estimate the location and depth of the anomaly. Also, the EFOS, a receiver of the controlled signal, is not connected to the submarine cables. However, no one knows what kind of seafloor and subseafloor phenomena will be revealed before, during, and after a great earthquake. Multidisciplinary observation using active and passive methods seems to be a small spotlight on undiscovered seafloor phenomena. If our geophysical monitoring proves to be an effective tool for earthquake prediction, more “spotlights” will be attached to submarine cables.

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