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# An experimental multidisciplinary observatory (VENUS) at the Ryukyu Trench using the Guam-Okinawa Geophysical Submarine Cable

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**Abstract**
A MultiDisciplinary Ocean Bottom Observatory (MDOBO) was installed on VENUS (Versatile Eco-monitoring Network by Undersea-cable System) at a depth of 2170 m on the slope of the Ryukyu Trench. In this context, «Eco-»refers to both economic (*e.g.*, earthquake hazard mitigation) and ecological motivation. The first step in this instillation was to insert a telemetry/power system into the submarine coaxial cable; this system could then service the MDOBO, which consists of seven major bottom sensor packages. During August-September 1999, using a deep-towed unit and both manned and unmanned submersibles coupled with precise ship navigation, the MDOBO system and its attendant cables were deployed over a range of distances from 80 m to 1 km from the telemetry system, with several meters allowance for navigational uncertainty in positioning. The unmanned submersible then extended the multi-conductor extension cables from the instrument units toward the telemetry system and connected them to undersea mateable connectors on a junction box installed on the submarine cable. The MDOBO collected one and half months of continuous records. Several kinds of useful data were collected after installation, including an aftershock ($M_s = 6.1$) of the 1999 Chi-Chi earthquake ($M_s = 7.7$) in Taiwan.

**Key words** *decommissioned submarine cables – ocean bottom observatory – real-time telemetry – ecological monitoring – junction box – OBS*

## 1. Introduction

During the last several decades, intense geophysical and geochemical investigations on the seafloor have been carried out in regions such as subduction zones, mid-ocean ridges, and abyssal areas away from plate boundaries, and results from these studies have greatly improved the details of our geophysical understanding of the Earth. However, very few investigations of temporal changes in these geophysical/geochemical phenomena have been carried

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out. It has been widely recognized that such temporal investigations are of great importance, since geophysical and geochemical phenomena have episodic natures and some phenomena such as earthquakes, landslides, or submarine volcanic eruptions require real-time observation.

Several subduction zones surround the Japanese Archipelago. Subduction of the Pacific and Philippine Sea plates beneath the Japanese archipelago generates destructive earthquakes along the plate boundaries beneath the forearc slopes. To minimize casualties and damage to buildings caused by large earthquakes, it is important to study both the nature of these earthquakes and the seismic structures along subduction zones. Real-time seismic observation on the deep-seafloor has been proposed from the viewpoint of understanding these earthquake hazards. In addition to hazards, real-time monitoring of earthquakes is very important to understand ongoing movements along subduction zones. Environmental measurements on the deep-seafloor are important from the viewpoint of monitoring of ecological changes due to the disposal of chemical materials in the sea and/or accidents involving nuclear submarines. Thus, long-term and real-time geophysical/geochemical observations are essential for understanding earthquake hazards and environmental changes in the deep-sea.

One of the best methods currently available for collecting and transmitting real-time observations is the use of submarine cables, which have long histories of technological development and proven field use in telecommunication. Although fiber-optic submarine cables use very advanced and reliable technology, using new fiber-optic submarine cables is extremely costly. Another kind of submarine cable is the coaxial cable, which can provide electrical power and real-time telemetry similar to fiber-optic cables (Submarine Cable Association, 2003). Due to the rapid growth of fiber-optic technology and large demands for global telecommunication, a number of fiber-optic submarine cables with Giga-to-Tera bit capacity have been deployed. Although many submarine cable OBSs have been deployed around the Japanese coast during the past two decades (*e.g.*, Mikada *et al.*, 2003), each system required a huge investment. Construction of similar systems far from the shore is both more difficult and more expensive. For example, a submarine cable OBS along the Izu-Bonin arc would require much longer cables and using a fiber-optic system is neither practical nor economical. With the installation of fiber-optic systems, the older TPC-1 (Trans Pacific Cable-1) and TPC-2 (Trans Pacific Cable-2) coaxial submarine cables were removed from commercial service in 1990 and 1994 after 26 and 18 years of near-continuous use, respectively. TPC-1 (KDD, 1964) was the first Japan-US submarine cable, constructed in 1964, and TPC-2 (KDD, 1976) was the second, constructed in 1976. By reusing such resources, real-time geophysical observatories on the deep-seafloor can be installed and implemented with high reliability and at reasonable cost (Nagumo and Walker, 1989; Kasahara *et al.*, 1995; Kasahara, 2002). Sections of the TPC-1, between Ninomiya, Japan and Guam Island, and the TPC-2 between Okinawa Island, Japan and Guam Island were donated to the ERI (Earthquake Research Institute) and the Incorporated Research Institutions for Seismology (IRIS) in 1990, and to the ERI in 1996, respectively. Both cables cross geophysically important regions (fig. 1). TPC-1 is routed from Guam, along the Mariana-Bonin-Izu Trenches to Sagami Bay (KDD, 1964). TPC-2 is routed from the Mariana Trough across the mid-Philippine Sea plate to the Ryukyu Trench (KDD, 1976). These areas contain very seismically active subduction zones, many active volcanoes, and a rifting backarc basin.

We developed two cabled ocean bottom observatory systems using decommissioned submarine cables, the first is called GeO-TOC (Geophysical and Oceanographical Trans Ocean Cable using TPC-1 cable; Kasahara *et al.*, 1995) and the second VENUS; we describe the latter in this paper.

In 1997, an OBS (IZU-OBS; Kasahara *et al.*, 1995) using the GeO-TOC was deployed at 2800 m depth on the forearc slope of the Izu-Bonin Trench (fig. 1). It consisted of three-component accelerometers with 24-bit A/D resolution, a hydrophone, and quartz temperature-

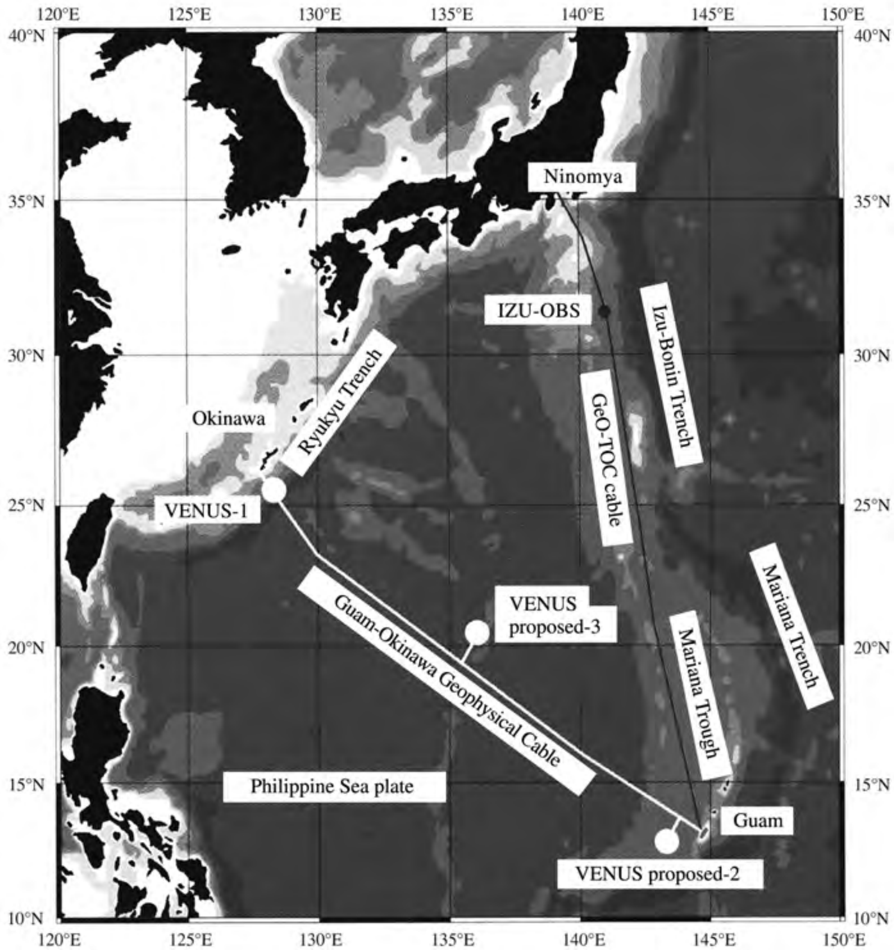


**Fig. 1.** Cable routes of the GeO-TOC and GOGC submarine cables, and locations of the IZU-OBS and the VENUS-MDOBO.

pressure sensors. It transmitted uninterrupted seismic and pressure-temperature data to Tokyo for more than 5 and a half years, an exceptional record for any seismometer, let alone one on the seafloor far from Japan. Data transmission was abruptly terminated on October 1, 2002 just after a large typhoon passed above the shore station in Ninomiya, Japan. The cause of termination was found to be cable faults located 9 km from the shore station, probably related to turbidity currents caused by flooding of the nearby Hayakawa River. In fall, 2003, we decided to use only off-shore segments of TPC-1 for a new installation of sea-Earth at 400 km distance from Tokyo, because of heavy cable crossings by commercial telecommunication lines ~9 km from the coastal region of Japan. These crossings make it impossible to repair the cable faults.

The TPC-2 submarine cable was used to develop multidisciplinary ocean bottom observatory (VENUS project). In this paper, we describe the outline of the VENUS system and show examples of the data obtained by this system.

## 2. VENUS-GOGC observation system

In contrast to the GeO-TOC OBS, the VENUS project (1995-1999) was intended to develop new technologies for using decommissioned submarine cables for environmental measurements at the ocean bottom. In the fall of 1999 a multidisciplinary observatory using the GOGC cable (Kasahara *et al.*, 2000) was installed at a depth of 2200 m on the forearc slope of the Ryukyu Trench, ~50 km from Okinawa Island (fig. 1). The objectives of the VENUS project (Kasahara *et al.*, 2000, 2001) were to develop a multidisciplinary station to study deep-sea environmental changes due to the subduction of the Philippine Sea plate at the Ryukyu Trench. Eight Japanese institutions cooperated on this project.

The cable length of the GOGC is 2400 km. The system uses a so-called SFsystem with 1.5 inch-diameter coaxial cables (KDD, 1976; Submarine Cable Association, 2003). The former TPC-2 system had 845 voice channels. Although +1.080V DC from Okinawa and −1.080V DC from Guam were supplied to the cables at a constant current during commercial use, the electric power supply for the VENUS project was modified to use a single 3.000V DC source from Okinawa. The observatory system comprises seven ocean bottom sensor units (Kasahara *et al.*, 2000, 2001), an ocean bottom telemetry system, and several coaxial cables for connection to the submarine cable. The land system comprises a shore station and a data center. The total power dissipation caused by the bottom units (see fig. 2) was approximately 53.5 W (Kasahara *et al.*, 2000; Kojima *et al.*, 2000). The telemetry system in the data telemetry unit used 20 W, and the sensor packages used the rest. To minimize corrosion during the long observation period, all pressure cases and the major parts of frames for the bot-

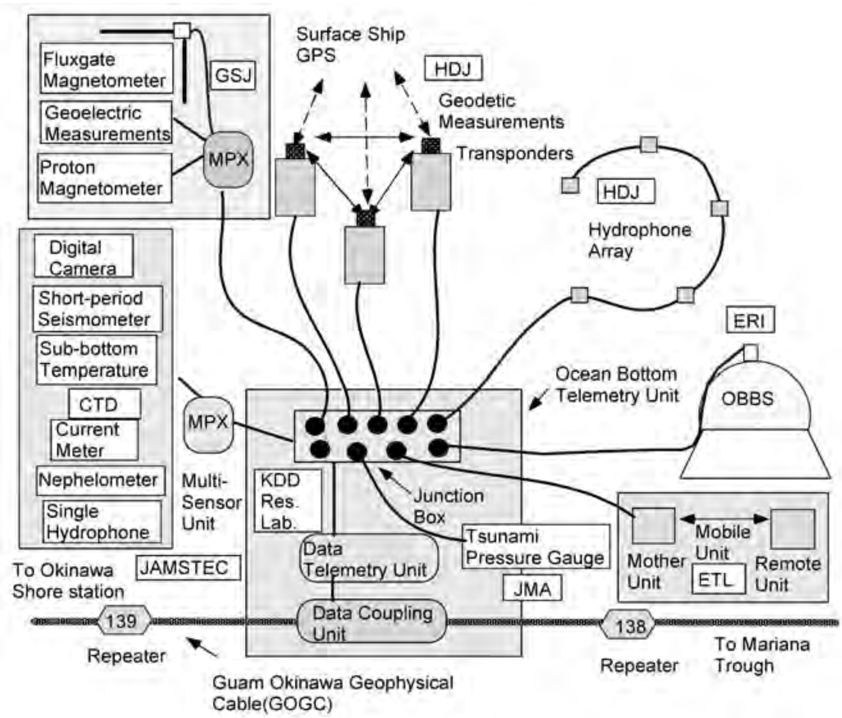


**Fig. 2.** Instruments and telemetry system configuration for the VENUS-MDOBO.

tom units were made of titanium and plastic. Plastic insulators protected titanium and stainless steel interfaces.

The sensor units comprise Ocean Bottom Broadband Seismometers (OBBS), a tsunami pressure sensor, a hydrophone array, a multi-sensor unit, geodetic instruments, geoelectric-geomagnetic instruments, and a mobile unit (fig. 2) (Kasahara, 2000; Kasahara *et al.*, 2000, 2001). The OBBS uses gimbal-mounted «Guralp CMG-1T» tri-axial broadband seismometers with response bands between 300 and 0.05 s. OBBS outputs are digitized at 24-bit resolution and 100 Hz sampling. The tsunami gauge uses a quartz pressure sensor and the resolution for sea-level change is 0.5 mm (Katsumata *et al.*, 2000). The multi-sensor unit comprises short-period seismometers, a hydrophone, a digital camera, a CTD sensor, a current meter, a light transmission meter, and sub-bottom temperature probes (Iwase *et al.*, 2000). The hydrophone array is composed of five hydrophones with 700 m spacing (wider than optimum due to budgetary limitations) (Watanabe, 2000). During the experiment, sixteen-bit data were transmitted to shore. The geodetic changes were acoustically determined by precise baseline measurements between two transponders (Nagaya, 2000). Three units were placed in a triangular formation and the distance between two units was approximately 1 km. The estimated accuracy of geodetic measurements is a few cm/yr, which is estimated to be less than the expected precursory crustal deformation near the trench if a *M* 7 or greater earthquake occurs just beneath the site (Kasahara *et al.*, 1998a,b). The geoelectric-geomagnetic unit comprises a proton magnetometer, flux-gate magnetometers, and orthogonal geo-potentiometers, 20 m long each (Nakatsuka *et al.*, 2000). The mobile unit consists of an acoustic communication unit and a remote instrument (Iidaka *et al.*, 2000). A separate report describes the details of each sensor (Kasahara, 2000; Kasahara *et al.*, 2000, 2001).

The bottom telemetry system comprises a data-coupling unit, a data-telemetry unit and a junction box (fig. 2) (Kasahara *et al.*, 2000; Kojima *et al.*, 2000). The first DC-DC converter in the data-coupling unit creates 100 V DC power using 880 V DC extracted from 136 mA constant cable current, and then the second DC-DC converter in the data-telemetry units does 24 V DC using 100 V DC for the sensor packages. The power separation filter in the data-coupling unit separate the high-voltage DC component from the high-frequency carriers, and later re-mix the high-frequency carrier with the DC component. The data-telemetry unit multiplexes the data and sends them to shore using a 240-kHz-carrier bandwidth. The transmission rate for the multiplexed data is 96 kbps. Each instrument, however, uses a unique transmission rate, *e.g.*, 19.2 kbps for the OBBS. Hydrophone data uses another 240-kHz bandwidth. If an instrument does not operate correctly, users can shut it down remotely from the land base. The junction box has nine so-called ROV (Remotely Operated Vehicle) undersea mateable connectors (fig. 3). The ROV connector has 8 conductor pins: two pins for 24 V DC, three for data from sensors to telemetry, and three for command signals to sensor. The extension cables between sensor packages and the junction box have 8 conductors with OD 17 mm filled inside by jelly-like insulating material and jacketed by plastic. The ROV connectors allow different units to be switched in or out of the sensor array on the ocean floor using either submersibles or ROV.

The route of the GOGC cables was identified on the ocean floor (under a few centimetres sediment cover) using a deep-tow camera on the R/V Yokosuka in February 1998. Usually, submarine cables shallower than 1500-200 m depths are buried to minimize any damage from fishery activities. In the TPC-2 VENUS cable, the cables near the test site were not buried in the sediment because of the depth. In March 1998, the manned submersible Shinkai 6500 (Dive # 411/YK98-02-Leg3) cut the GOGC at 25°44′N, 12°02.5′E at a water depth of 2200 m using a newly developed cable cutter. Three major operational legs were carried out by the M/S Kuroshio-Maru, the R/V Kaiyo, and the R/V Karei/ROV-Kaiko for deployment of the telemetry system, deployment of instruments, and extension-connection of cables, respectively. Instruments were confined to an area within an approximately 1-km radius around the junction box. The data-coupling unit was spliced into the main cable on the deck of the M/S Kuroshio-Maru in August 1999. The M/S Kuroshio-Maru installed the bottom telemetry

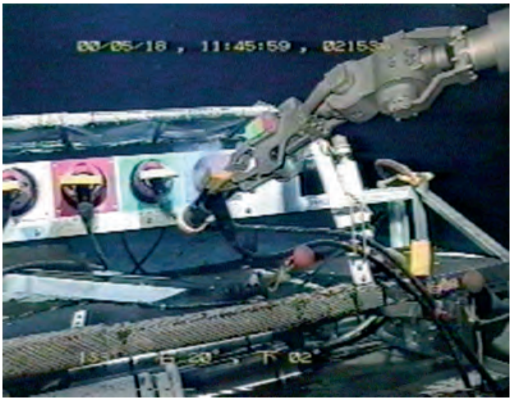


**Fig. 3.** Junction box and ROV Kaiko manipulator during installation operations on the ocean floor.

**Fig. 4.** VENUS Broadband Seismometer (photo taken from ROV Kaiko).

system with the tsunami sensor and the hydrophone array on the ocean floor. The location of the telemetry system is 25°44.53′N and 128°03.52′E (WGS84) at a water depth of 2.157 m. The mother ships used GPS system for navigation, and the submersibles (Shinkai 6500 and ROV Kaiko) and the deep-tow unit used by LBL systems based the GPS navigation. The deep-tow equipment on the R/V Kaiyo was used to install five instrument units on the ocean floor in September and October 1999. The ROV-Kaiko coupled each male termination of the ROV connectors on the extension cables of nine instruments to the corresponding female connectors on the junction box installed on the main cable October 1999 (fig. 3). The OBBS was placed ~80 m north of the bottom telemetry system at a water depth of 2154-m (fig. 4). The OBBS was not buried in sediment, as there was no shovel installed on the ROV-Kaiko. Instead of burial, 80 kg weights were placed on the OBBS frame to anchor it to the ocean floor; however, this method does not seem to be sufficient to reduce low frequency noise caused by infra-gravity waves (Kasahara and Sato, 2000; Kasahara *et al.*, 2001).

The VENUS specific equipment was installed in the KDD Okinawa shore station. Some shore equipment was obtained from the previous station used by the TPC-2 system. The shore-receiving unit demodulated signals and sent them to Yokosuka, Japan, using two 64-kbps lines, and supplied 3100 V to the cable. Data from ocean bottom instruments were archived in the data storage unit at JAMSTEC (Japan Marine Science and Technology Center).

## 3. Data obtained by VENUS system

Some of the results obtained by the VENUS experiment are presented in this section. The

**Fig. 5.** Photo taken by a digital camera incorporated in the multi-sensor system. A fish is passing near the sub-bottom temperature probe.

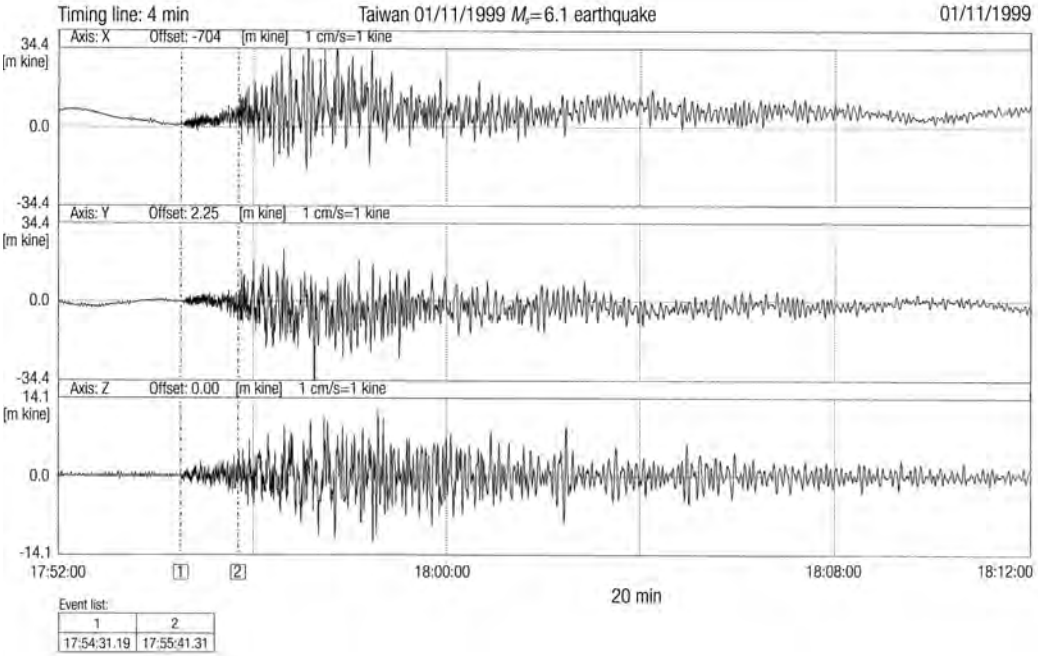
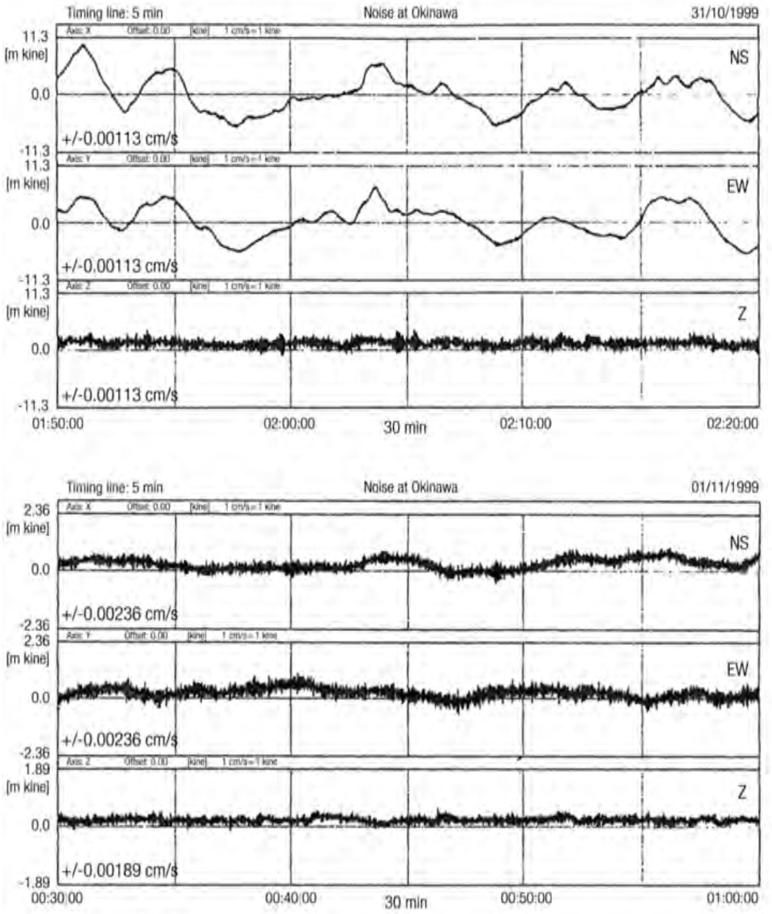


**Fig. 6.** $M_S = 6.1$ earthquake, November 1, 1999, which occurred off Taiwan. NS ($34.4 \times 10^{-5}$ m/s full scale), EW (the same scale as NS) and Z ($14.1 \times 10^{-5}$ m/s). Horizontal axis: 20 min record.

multi-sensor system had a digital camera and transmitted photo images to land every hour. Figure 5 shows a fish passing near the sub-bottom temperature probe.

A number of earthquakes, including two large events in Southern California ($M_S = 7.3$) on October 16 and the Taiwan earthquake ($M_S = 6.1$) of November 1, 1999, were observed (fig. 6) (Kasahara and Sato, 2000). The Taiwan event was one of the aftershocks of the September 21, 1999 Chi-Chi (Taiwan) Earthquake ($M_S = 7.7$). The noise levels in data obtained from the broadband seismometers seem to be extremely high (*e.g.*, $\cong 5$ $\mu$m/s at 300 s for horizontal components) (fig. 7). The change in amplitudes with time is several tens of times higher on the horizontal components than on the vertical components. The reason for large noise amplitudes on the horizontal components is partly because the OBBS was not buried in ocean-bottom sediments (Kasahara and Sato, 2000; Kasahara *et al.*, 2001). Another reason is related to tilting caused by infra-gravity waves (approximately, 100-200 s) (Webb, 1998).

The data obtained by the multi-sensor system are shown in fig. 8a-c. The water temperature data (fig. 8a) exhibit nearly identical variations with the electrical conductivity data in time, showing both 15-day and diurnal cycles. The salinity is almost constant except for spikes, which seems to be caused by heat convection generated by the electronics of data transmission unit attached under CTD sensor. The temperature measured by sub-bottom temperature probes (fig. 8c) shows similar variation with the water temperature. On the other hand, the east-west component of bottom current (fig. 8b) shows semi-diurnal change, although north-south component mostly shows diurnal change except for the spring tides. Vertical transfer of water with temperature gradient of the water column mainly causes the water temperature change. Diurnal change in both water temperature and north-south component of water current



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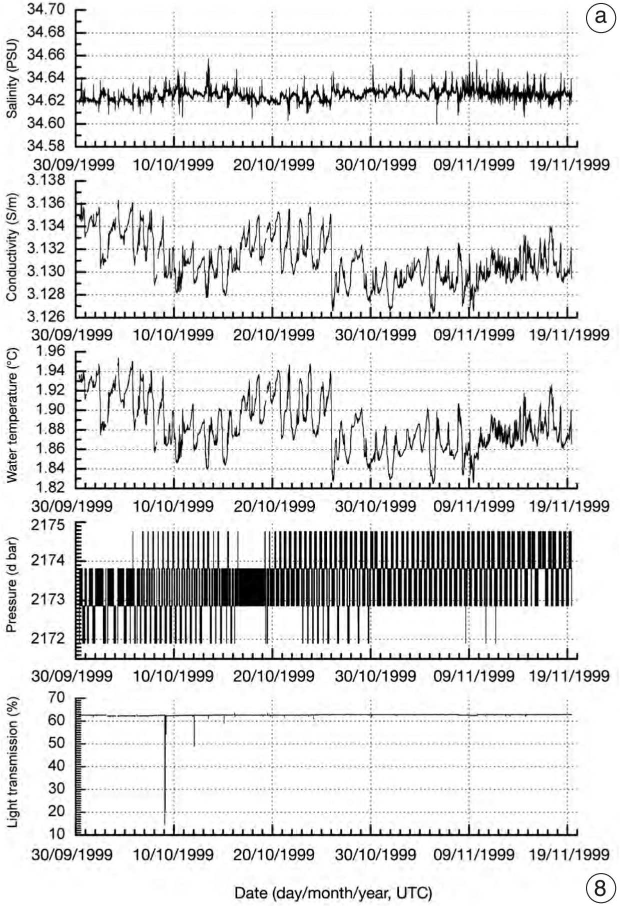

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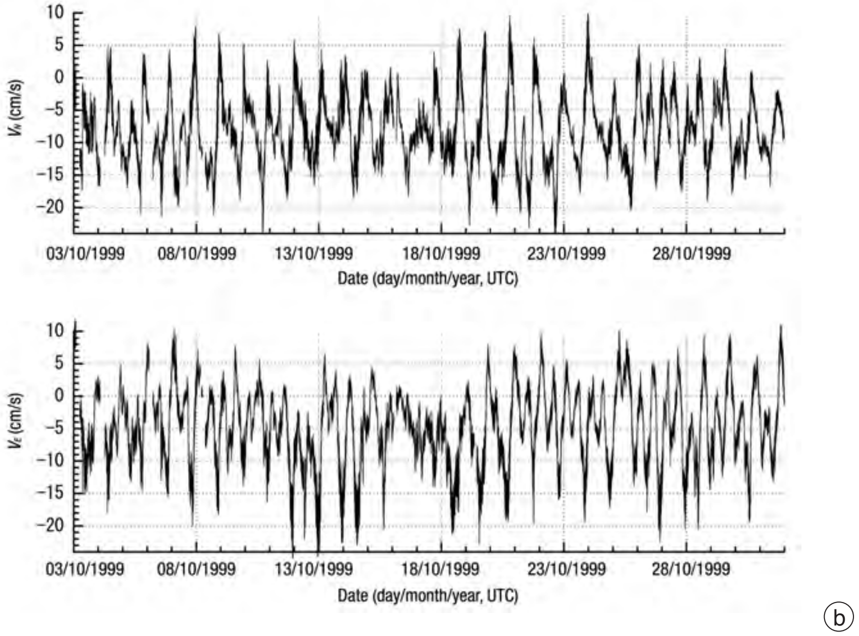
**Fig. 7.** Example of ocean bottom noise observed by OBBS. 30-min records. Top three records: vertical scale in $\pm 1.3 \times 10^{-2}$ cm/s. Bottom three records: vertical scale in $\pm 2.36 \times 10^{-3}$ cm/s for NS and EW components, and $\pm 1.89 \times 10^{-3}$ cm/s for *Z* component.

**Fig. 8a.** Records obtained by the multi-sensor system (from top to bottom): salinity, electrical conductivity, water temperature, water pressure, light transmission through water.



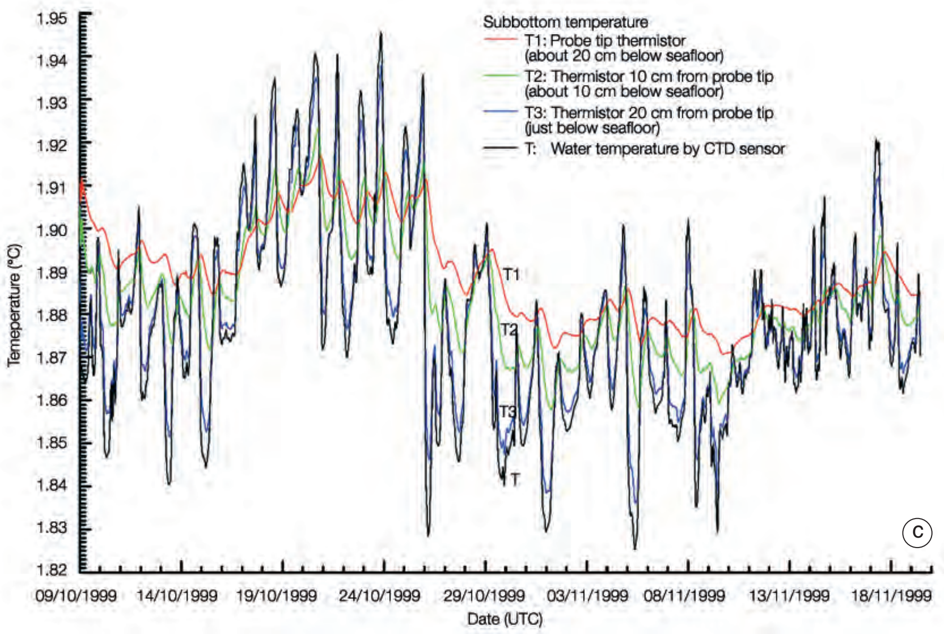


**Fig. 8b,c.** Records obtained by the multi-sensor system. b) Sea-water bottom current estimated by measurements collected using the NS and EW components of an electromagnetic current meter. Note: there are some offsets due to lack of absolute level calibration. c) Sub-bottom temperature measurements from three probes at 0 cm, 10 cm and 20 cm below the ocean floor compared to CTD temperature.

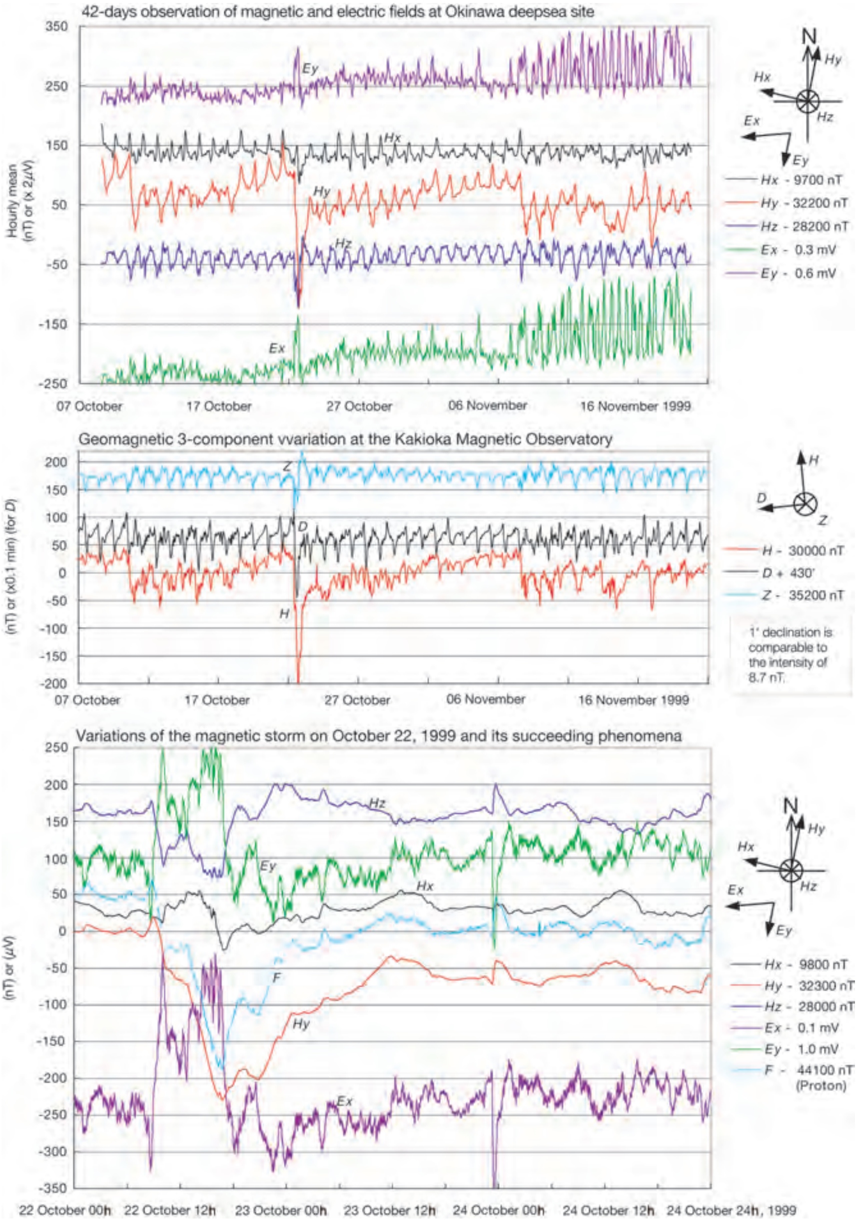


**Fig. 9.** Records obtained by the geoelectric-geomagnetic unit. 42-days observation at the Okinawa deep-sea site (top) and data from Kakioka Magnetic Observatory (middle) are well-correlated, with slight differences due to the difference in latitude. Variations related to a magnetic storm took place on October 22, 1999 (JST), and subsequent electro-magnetic phenomena are shown on the bottom graph. Electric field data are represented as the voltage between two electrodes separated by about 20 m. The disturbances in the electric field data became much larger after November 06, which might indicate some unknown process related to the progress to the stop of whole observation system.

is probably due to the regional topography of southeastward or south-south-eastward slope, although more regional observation is necessary to confirm the result.

The geoelectric-geomagnetic unit was operated continuously for 42 days (fig. 9), until system failure occurred as an unfortunate result of water leakage in that sensor's telemetry unit (Kojima, 2003). The continuous geomagnetic observation data exhibit field variations similar in pattern, but different in absolute values, from those observed at the Kakioka Magnetic Observatory in central Japan, which is quite reasonable as the VENUS deep-sea site is about 1.600 km SW of Kakioka. During this period of observation, a remarkable magnetic storm took place on October 22, 1999. The fine-scale 3-day variations of electric and magnetic fields subsequent to this event are illustrated in fig. 9. Our observations clearly detected electro-magnetic variations related to this storm and subsequent phenomena, which could be the subject of further investigations. Electric field data have a somewhat noisy character, probably due to the effects of bottom currents. We consider that electric field data express both the induction of magnetic field variation such as magnetic storm and the electro-motive force from the bottom current in the geomagnetic field, though there is a somewhat noisy character in it. The electric field disturbances became larger after November 06. This increase in noise levels may be related to some unknown process, or alternatively may be related to the progressive breakdown of the observation system due to water leakage.

## 4. Conclusion and future plans

A multidisciplinary ocean bottom observatory was specifically developed with the aim of utilizing decommissioned submarine cables: the VENUS multidisciplinary station using the GOGC cable at the Ryukyu Trench. The GeO-TOC-IZU OBS used digital data acquisition, but it borrowed many methods, techniques and technologies from traditional submarine cable technology. In contrast, the VENUS system is more sophisticated than GeO-TOC, and was deployed by manned and unmanned submersibles, deep-tow equipment, and cable ships. Many new technologies have been developed for both OBS systems. The VENUS system comprises six major bottom observatory stations, and one land based observation-recording-transmitting station. Some of the results are presented here. The OBBS records from the VENUS Observatory highlight the necessity of installing or burying seismometers in sediments to reduce noise (*e.g.*, Webb, 1998). The VENUS system proved the usefulness of decommissioned submarine cables for multidisciplinary measurements on the deep-seafloor. However, it also reveals the difficulties in deployment, long-term observation recording and monitoring, and methods of instrument installation and maintenance.

The submarine cable between Okinawa and Ninomiya (Okinawa Cable) will be used to monitor future large earthquakes along the Nankai Trough. The AREANA (Advanced Real-time EArth monitoring Network in the Area) plan is another potential use of these cables to monitor deep-sea environmental change in areas surrounding the Japanese Archipelago (Kasahara *et al.*, 2003; Shirakaki *et al.*, 2003). The NEPTUNE project in the Western U.S.A. and Canada will install a submarine cable network off Seattle and Vancouver Island to observe temporal changes in a wide array of multidisciplinary phenomena. Real-time, long-term measurement will remain a major objective for future geophysical/geochemical ocean bottom observatories, and the (re)utilization of submarine cables will continue to be a crucial technology for both installation and monitoring of these systems.

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