Methods[1]

Expedition 332 Scientists[2]

Chapter contents

Introduction

This chapter documents the methods associated with borehole observatory recovery and deployment during Integrated Ocean Drilling Program (IODP) Expedition 332: the SmartPlug recovery and GeniusPlug deployment in IODP Hole C0010A and the long-term borehole monitoring system (LTBMS) permanent observatory deployment in IODP Hole C0002G. In addition, a suite of logging-while-drilling (LWD) and measurement-while-drilling (MWD) downhole measurements were performed in Hole C0002G in order to identify the best positioning of the LTBMS borehole instruments. Some of those components (tiltmeter, seismometer, and strainmeter) were tested at several stages during LTBMS deployment to confirm the integrity of the instruments and cable connections.

Reference depths

Depths of each measurement are reported relative to both the drilling vessel rig floor (rotary table) and to the seafloor. These depths are determined by drill pipe and correlated by the use of distinct reference points. Depths are reported as LWD depth below seafloor (LSF), core depth below seafloor (CSF), drilling depth below rig floor (DRF) and meters below seafloor (mbsf) (IODP Depth Scales, www.iodp.org/program-policies/).

Observatory deployment

Vortex-induced vibration (VIV) is a serious obstacle to deploying sensitive equipment by drill string through the Kuroshio Current, which can reach speeds of more than 5 kt across the entire Nankai Trough Seismogenic Zone Experiment (NanTroSEIZE) study area. The temporary and permanent observatories required a special design to resist VIV forces and protect the sensors and instruments, and modification of the drill string in certain sections (i.e., attachment of ropes) was also needed to reduce the effect of VIV forces.

Temporary observatory

A family of simple temporary borehole observatories was designed to be attached to a retrievable casing packer and provide rapid deployment and recovery. The SmartPlug is a temporary borehole observatory developed by the NanTroSEIZE Project

[1]Expedition 332 Scientists, 2011. Methods. *In* Kopf, A., Araki, E., Toczko, S., and the Expedition 332 Scientists, *Proc. IODP,* 332: Tokyo (Integrated Ocean Drilling Program Management International, Inc.).
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[2]Expedition 332 Scientists' addresses.

Management Team Observatory Team that was installed during IODP Expedition 319 and recovered during this expedition. Onboard data were collected after download in the laboratory. The GeniusPlug is an upgraded version of the SmartPlug that includes a limited suite of biological experiments and geochemical sampling over time.

LTBMS observatory

The LTBMS observatory is an expansion of the circulation obviation retrofit kit (CORK) design developed to link to a seafloor observatory network, transmitting real-time data to a monitoring station on land. A series of systems checks were performed on the data and electrical cables running from the strainmeter, seismometer, and tiltmeter during LTBMS assembly and installation. The separate pressure sensor unit, a self-contained unit attached to the CORK head, was tested before being attached to the CORK head and again after cementing operations were completed. In total, the downhole sensors were checked nine times:

1. After connection to the cables as the sensor carrier was run down,
2. Before the cables were run through the swellable packer,
3. After the cables were run through the swellable packer,
4. Before the cables were cut prior to termination with the Ocean Design, Inc. (ODI) underwater mateable connectors (UMCs),
5. After ODI termination was completed,
6. After mounting ODI connectors on the CORK head,
7. After the entire assembly was run into the water at ~350 m DRF,
8. When the CORK head reached final depth before being run into the wellhead, and
9. After the CORK was run into the borehole.

All tests were performed without encountering any problems.

Downhole measurements

During Expedition 332, LWD and MWD were conducted in Hole C0002G and used to confirm and correlate the location of lithologic boundaries identified through previous drilling of Hole C0002A during IODP Expedition 314. LWD technology has been successfully employed during multiple previous Ocean Drilling Program and IODP expeditions using several generations of tools to obtain measurements of bulk density, gamma radiation, resistivity, and sonic velocity (Mikada, Becker, Moore, Klaus, et al., 2002). In particular, Expedition 314 focused exclusively on in situ measurements using LWD and MWD tools to evaluate subseafloor physical properties, stress state, lithology, and geomechanics. During Expedition 332, we used a similar suite of logging tools to confirm the depth of lithologic boundaries anticipated from previous drilling and identify favorable conditions for placement of the LTBMS. Here we describe the technology used to obtain the geophysical measurements, as well as the methods used to interpret and analyze data included later in this report.

Logging while drilling

LWD and MWD in Hole C0002G were conducted under contract by Mantle Quest Japan, Inc., in conjunction with Schlumberger Drilling and Measurements Services. The tools included LWD and MWD capabilities to enable real-time measurement of drilling parameters (MWD PowerPulse/TeleScope) as well as storing data for retrieval when tools were recovered on the drill floor. Drilling parameters were monitored with the MWD PowerPulse/TeleScope, located on the main body of the arcVISION825 tool string. LWD measurements for Expedition 332 included only resistivity and natural gamma radiation, which were supplemented by previous logging in Hole C0002A, located 50 m east-northeast of Hole C0002G. LWD was used to identify the boundaries between lithologic Units I and IV, following the nomenclature used during Expedition 314 (Kinoshita, Tobin, Ashi, Kimura, Lallemant, Screaton, Curewitz, Masago, Moe, and the Expedition 314/315/316 Scientists, 2009). The Unit II/III boundary marks the transition from Quaternary lower forearc basin sediments to Pleistocene forearc basin sediments, and identification of this transition was critical to this expedition, as it determined the location of the casing shoe, the downhole casing plan, and the configuration of the LTBMS. Previous logging of this boundary indicates it is marked by a decrease in electrical resistivity fluctuations, decreasing gamma radiation, and high photoelectric absorption, and it was anticipated that this transition would be encountered at ~830 mbsf. The target depth for the strainmeter was proximal to the Unit III/IV boundary, or the top of the Miocene accretionary prism. In contrast to Unit III, this transition is marked by low natural gamma ray values and larger fluctuations in electrical resistivity, with an expected depth of ~935 mbsf.

Systems and tools

arcVISION825

The LWD tool used during Expedition 332 is the arcVISION Array Resistivity Compensated (ARC8) tool, developed by Schlumberger. The tool string was equipped with the ARC8 tool, which has a diameter of 6.75 inches (15.24 cm) with five transmitters and two receivers located along its antenna array (Fig. F1). The transmitters emit a magnetic field that travels through the formation and arrives at the receivers, which register a change in amplitude and phase. By varying the distance between the receivers and transmitter, multiple depths of investigation are accomplished; a larger distance between a transmitter and receiver increases the depth of investigation at the expense of lowering the resolution. The variable depth capability allows differentiation between anisotropy, borehole effects, shoulder beds, and invasion (i.e., mud entering the formation).

The arcVISION825 includes an array resistivity compensated tool based on propagation resistivity, meaning that it can make multiple borehole compensated phase-shift and attenuation resistivity measurements (**iodp.ldeo.columbia.edu/TOOLS_LABS/SPECIAL/lwd_arc.html**). Attenuation resistivity measurements have deeper penetration and are less affected by anisotropy than phase-shift resistivity measurements, but vertical resolution is poorer. Conversely, phase-shift measurements are more distorted by surrounding beds and apparent dip but less influenced by invasion. The two frequencies used for Expedition 332 are 2 MHz and 400 kHz, with the latter providing higher penetration depth but lower resolution. In addition, the usage of water-based mud, with a resistivity of ~1 Ωm, resulted in increased vertical resolution and decreased penetration depth.

In addition to the resistivity tools, the arcVISION825 provides nonazimuthal gamma ray measurements. Using a NaI detector, the naturally occurring gamma radiation emitted by rocks and sediment in different amounts is measured and used to identify changes in lithology. The gamma ray sensor has a measurement range of 0–250 gAPI, with an accuracy of 3% and a theoretical vertical resolution of ±2 gAPI at 100 ft/h (i.e., 31 m/h).

Depth tracking systems

LWD data interpretation requires specific and precise depth measurements that connect the logging data to lithologies in the subseafloor. Because LWD tools record data only as a function of time, an integrated drilling evaluation and logging surface system from Schlumberger, Ltd. is installed onboard the D/V *Chikyu* to record the time and depth of the drill string below the drill floor, as well as the rate of penetration (ROP).

Accurate and precise depth tracking requires independent measurements of the (1) position of the traveling block and top drive system in the derrick, (2) heave of the vessel because of wave action, swells, or tides, and (3) activity of the motion compensator. These measurements are automatically recorded during drilling, and the depth of the drill string and ROP are determined from the length of the bottom-hole assembly (BHA) and drill pipe and the position of the top drive in the derrick. The configuration of these components is illustrated in Figure F2.

Measurement while drilling (PowerPulse, updated TeleScope)

The arcVISION825 tool is integrated with an MWD PowerPulse/TeleScope and an annular pressure while drilling tool. MWD was critical to successful drilling during Expedition 332, as it provided real-time two-way communication between LWD tools and the surface and enabled scientists to monitor drilling operations and, if needed, stop drilling (e.g., when horizons selected for the casing shoe were reached). The data are transferred by fluid pulse telemetry through the fluid within the drill pipe. Continuous pressure waves are generated by a rotary valve, and analog information from the paired strain gauges, accelerometers, and lateral shock sensors near the base of the MWD collar are transformed into binary numbers and transmitted by the pressure waves as a series of "0s" and "1s." By changing the phase of the pressure wave signal, continuous transmission is obtained, which is sensed by a pressure transducer within the mud-flow line. In order to increase the amount of data and the speed of transmission, the TeleScope tool was used during Expedition 332, which is similar to the PowerPulse but allows data transfer to occur up to 4× faster by using the Orion telemetry platform.

The distance between the bottom of the drill bit and the logging bands for gamma ray and resistivity is typically several meters, which (during Expedition 314) translated to a 10–15 min recording delay before data were transferred into onboard memory. By comparison, Expedition 332 used fewer measurement sensors on the drill string, and the distance between the drill bit bottom and the logging ports was much shorter, so the rate of data updates was correspondingly shorter. Moreover, the ROP was slowed to provide higher data density than previously. The time after bit for gamma ray and resistivity data is 10–15 min if ROP is maintained at 30 m/h. This means that the bit was ~14 and 3.5 m ahead of the resistivity and gamma ray measurements on the monitoring screen in real time for the 12¼ and 10⅝ inch portions of the hole, respectively. Additional tool specifications appear in Figure F1.

Log characterization and lithologic characterization

LWD is commonly used to identify lithologic boundaries that reflect changes in the composition, texture, and structure of the rocks and pore fluids. During Expedition 332, the LWD logs were essential for identification of the boundaries targeted for casing planning and for LTBMS emplacement.

Data analysis

During Expedition 332, both resistivity and natural gamma ray measurements were employed to confirm the anticipated depths of lithologic boundaries identified during drilling of nearby Hole C0002A (Expedition 314). Changes in composition and texture were identified by variations in natural gamma ray values that coincided with amplitude changes in the electrical resistivity data. LWD data obtained from Hole C0002G were compared with data from Hole C0002A to confirm that both the depth and character of the transition were consistent with previous logging. In particular, a marked decrease in resistivity fluctuations coupled with an increase in natural gamma ray values defined the Unit II/III boundary. The lower boundary of Unit III was identified in the same manner in order to position the strainmeter in a relatively continuous zone of elevated gamma ray and resistivity values.

SmartPlug/GeniusPlug

Instrumented retrievable casing packer (temporary monitoring system)

As part of operations in Holes C0010A and C0002G, a mechanically set retrievable packer (Baker Hughes A3 Lok-Set) equipped with a small instrument package to monitor pore pressure and temperature was installed inside a 10⅝ inch casing string during Expedition 319 (see Saffer et al., 2009). This so-called SmartPlug was set at 374 mbsf immediately above a screened casing interval within the shallow megasplay fault zone. The instrument package includes a data logger, temperature sensor within the data logger housing, a self-contained temperature sensor, and two pressure gauges: one "upward-looking" and one "downward-looking." The pressure sensors monitor (1) below the packer seal in a screened interval that is open to the fault zone and (2) above the packer seal to serve as a hydrostatic reference open to the overlying water column. Both temperature sensors are just below the packer (Fig. F3). The SmartPlug instruments developed in 2009 can monitor formation pore pressure and temperature from the time the bridge plug is set until the instruments are retrieved at the beginning of permanent riserless observatory installation operations.

In 2010, an upgraded version of the SmartPlug, termed GeniusPlug, was developed. It relies on the SmartPlug design but replaces the end cap (the bullnose) with a second unit of the same diameter and adds 30 cm to the length of the plug (Fig. F4). The GeniusPlug hosts a continuous fluid sampler (OsmoSampler) (Jannasch et al., 2004) and a microbiological colonization experiment (flow-through osmo colonization system [FLOCS]) (Orcutt et al., 2010).

General description

The SmartPlug instruments built for Expedition 319 remain unchanged, given their robust design and uncomplicated handling, so the GeniusPlugs follow the same design. Structurally, each unit includes a hollow-bore 3.5 inch EU 8rd box-end threaded coupling at the upper end, which mates with the lower end of the Baker Hughes packer supplied by the Center for Deep Earth Exploration, and an outer O-ring sealed structural shell that is designed to withstand the loads encountered during hole reentry operations (Fig. F5). Housed inside are a high-precision pressure period counter with a 12.8 MHz real-time clock (RTC-PPC system, resolving ~10 parts per billion [ppb] of full-scale pressure, or ~0.7 Pa), a 24-bit/channel analog to digital (A/D) converter and data logger (designed and built by Bennest Enterprises, Ltd., Minerva Technologies, Ltd., and the Pacific Geoscience Centre, Geological Survey of Canada), two pressure sensors (Model 8B7000-2; Paroscientific, Inc., USA), and an independent miniature temperature logger (MTL) (Antares, Germany). Four independent temperature readings are made: (1) with the MTL, (2) with a platinum thermometer mounted on the primary data logger end cap, and (3) with each of the two pressure transducers. The inside of the structural shell is exposed to water in the cased borehole above through the internal open bore of the casing packer seal. One of the pressure sensors is connected to this volume to provide a hydrostatic reference, and the second sensor is connected to the sealed, screened borehole interval via hydraulic tubing that passes through the bottom end of the structural shell (Fig. F5). RS-422 communications with the main instrument for setting recording parameters and downloading data are conducted via a multisegment Seacon AWQ connector on the logger pressure case. Communications with the MTL are conducted through a special Antares interface and WinTemp software. The instrument frame is shock-mounted within the structural shell, and the pressure sensors are mounted with secondary shock pads within the frame (Fig. F3). Structural components are constructed with 4140 alloy steel, and pressure sensor housings and hydraulic tubing are constructed from 316 stainless steel.

The extension unit for the GeniusPlug configuration is made of the same material and further features a bulkhead to hydraulically separate the SmartPlug body from the OsmoSampler and FLOCS (Fig. F4). This way, only borehole fluid entering through the casing screens enters the lower portion of the instrument where the intakes for the OsmoSampler and FLOCS are located. These two experiments are constrained in a 7.15 inch high and 6.3 inch diameter space.

The OsmoSampler has two 2ML1 ALZET membranes that were attached to the housing with two-part epoxy (Hysol ES1902). The ends of the distilled water and saturated salt (noniodized table salt, NaCl) reservoirs are sealed with a single O-ring and held in place with a setscrew. This configuration will pump 73 mL/y at 20°C. The pump is attached to 150 m of small-bore polytetrafluoroethylene (PTFE) tubing that holds 170 mL (1.19 mm inside diameter [ID] and 2.0 mm outside diameter [OD]). The tubing was filled with 10% HCl for 5 days before it was rinsed with 18.2 MΩ water. Thus, this sampler can be deployed at 20°C for 2 y and maintain a continuous record for longer if the borehole temperature is cooler than 20°C.

The FLOCS experiment is attached to two pumps, each identical to the ones described above for the OsmoSampler. Both pumps are attached via a T-connection to double the pump rate (146 mL/y at 20°C). Likewise, these pumps are attached to 150 m of small-bore PTFE tubing that holds 170 mL and were prepared as above. At 20°C these pumps will fill the sample coil in 14 months. The pumps will continue to work because of the amount of excess salt in the pump but will only preserve the last 14 months of fluid within the sample coil. The loss of the early portion of the record was deemed acceptable because the FLOCS is filled with about 50 mL of sterile seawater that must pass through the coils before borehole fluids are collected within the coils. As this sterile seawater enters the distilled water portion of the pump, it will decrease the pump rate but only minimally, even for a 2 y deployment. The inlet was attached to a syringe filled with 18.2 MΩ water until just before deployment.

The FLOCS experiment consists of a single unit that has four chambers. All of the parts were sterilized and materials packed with sterile tools in a hood. The chamber closest to the inlet contained two grids with autoclaved rock chips (1–2 mm thick and 5 mm × 5 mm) mounted on them facing out. These two grids were separated by autoclaved glass wool and 5 mm borosilicate glass beads. Rock chips were attached to the plastic grids using "5 min epoxy." One grid has basalt glass in the bottom portion (AT11-20-4055-B6) and basalt above it (J2-246-R2). The other grid has basalt in the bottom portion (J2-244-R4) and olivine above it. Above the grids are three chambers filled with barite, olivine, and IODP Expedition 316 sediment (Section 316-C0004D-47R-2; ~357 mbsf), respectively. These materials were crushed from bulk rocks, sieved to <250 µm, and autoclaved. PTFE mesh screens were placed inside the cassette caps to prevent rock fragments from escaping the cassette. At sea, the FLOCS was filled with ~50 mL of sterile seawater with additional seawater added to remove air bubbles. During this process, some of the sediment from the end capsule escaped. The inlet was attached to a syringe with sterile seawater until just before deployment.

Settings

The SmartPlug instruments built in 2009 were set to begin recording data at the time they were shipped from the Pacific Geoscience Centre, Canada, to Shingu Port, Japan, on 11 April 2009, and stored in Shingu until they were transported to the *Chikyu* via supply boat for Expedition 319. Because one of them (Instrument 82) was not deployed during the cruise, it was shipped back to Shingu and stored in a warehouse until 2010. It was loaded onto the *Chikyu* during the preexpedition port call on 26 October 2010 and hence contained an 18 month record of data by the time Expedition 332 began. Logging intervals for the formation and hydrostatic pressure sensors and the internal platinum thermometer were set to 1 min; at this rate and with other operational parameters as set, battery power (provided by six Tadiran TL-5137 DD primary lithium cells) is the limiting factor for operational lifetime, which is roughly 7 y, including a de-rating factor of 75% applied to full power withdrawal. The instruments are equipped with 512 MB (low power) flash memory cards, which provide storage capacity until the year 2038 at a 1 min sampling rate. The independent MTL in Instrument 82 was set to sample temperature at 60 min intervals. The main logger clock was synchronized to Universal Time Coordinated (UTC) on 11 April 2009, and the MTL clocks were set on approximately the same date. The clock of the main logger was synchronized to UTC again on 7 August 2009 prior to deployment.

The second SmartPlug was fabricated in 2010 and followed an identical design. The main difference was the somewhat faster sampling rate of 30 s, resulting in storage capacity until the year 2033. This SmartPlug is meant to be used as a backup observatory in case operations in Hole C0002G are too slow to allow an in-time deployment of the LTBMS (see

"Long-term borehole monitoring system"). All configurations and potential damage during shipping were checked prior to deployment onboard the *Chikyu* (Fig. F5).

The GeniusPlug extension units were set up during the first weeks of Expedition 332. The first GeniusPlug was deployed only a few days after the OsmoSampler and FLOCS units were filled. For detailed set-up procedures, refer to the above text, Figure F6, and Kopf et al. (2011).

Implementation plan

During Expedition 332, it was first planned to retrieve the bridge plug/SmartPlug observatory that was installed in August 2009 (Fig. F7). Afterward, a GeniusPlug instrument was to replace the SmartPlug and monitor pressure, temperature, microbial activity, and fluid geochemical signatures in the screened interval in the shallow megasplay fault zone (Fig. F8).

Long-term borehole monitoring system

Strainmeter

A deep-sea borehole strainmeter was designed by Japan Agency for Marine-Earth Science and Technology (JAMSTEC) for deep-sea borehole installation (Fig. F9). The principle of the strainmeter is similar to the Sacks-Evertson type of volumetric strainmeter that measures the volume change of an oil-filled cylindrical strain-sensing volume that responds to ground deformation. Ground deformation is transmitted to the volume through the cement filling the annulus between the formation and the strainmeter. This type of strainmeter is widely used in land boreholes. For example, the Japan Meteorological Agency has deployed more than 10 volumetric strainmeters in land boreholes to monitor a possible precursor event for the Tokai anticipated earthquake.

The deep-sea strainmeter is installed in NanTroSEIZE Hole C0002G. For compatibility with IODP boreholes (targeting 9⅝ to 10¾ inch hole installation), the deep-sea strainmeter was designed to have a 168.3 mm diameter sensing volume, which is much larger than conventional land-based strainmeters (~75 mm). The length of the deep-sea strainmeter is ~10 m (Table T1), including digitizer electronics and transducer housing, chambers, joints, and the sensing volume (~1.7 m length). It also has a cement pass line through it so that cement can bypass the instrument and pour into the bottom of the borehole to cement the strainmeter and other seismic instruments.

The deep-sea borehole strainmeter is designed to withstand high ambient pressures up to the 70 MPa that the instrument experiences as it passes through the water column and into the borehole. The strainmeter is very sensitive to deformation of the sensing volume, achieved by measuring small volume changes of the sensing volume by the bellows connected to it (Fig. F10). The full-scale range of the volume change measured by the bellows is ~1 cm^3, corresponding to 3×10^{-5} strain change of the sensing volume. While lowering the instrument from the ship, it experiences much larger strain changes than it would tolerate within the full scale of measurement. Therefore, to protect the sensor, a valve bypassing the bellows is installed, and it is kept open while the instrument is deployed. After the instrument is cemented into position, the bypass valve is closed by a command from the CORK head on the seafloor to start strain measurements. The bypass valve is also opened when the instrument measures strain changes outside its full measurement range. By opening the valve, the bellows are recentered to zero to reset accumulated strain; the valve can then be closed to resume strain measurement. The bellows position (indicating strain change) is measured by a digitizer in the strainmeter, and the strain data are transmitted uphole by an electrical cable. A Paroscientific pressure gauge (8B7000-2) is also connected to the strain sensing volume, and its pressure reading is used to check the system status of components such as the bypass valve.

A controller inside the strainmeter controls the digitizing displacement of bellows and pressure and valve position (open and closed) and transmits data through an RS-422 serial link (57,600 bps) with the CORK head at the seafloor. The cable can also conduct power (24–30 V DC) to the strainmeter. The power consumption of the strainmeter is ~3 W during observation, which increases to ~4.5 W when operating the valve.

Broadband seismometer

A CMG3T borehole broadband seismometer (Guralp Systems, Ltd.) was installed in the instrument carrier to monitor broadband seismic signals in the borehole. The CMG3T seismometer measures ground velocity in three orthogonal axes in the frequency range between 1⁄360 and 50 Hz. Three separate sensors measuring ground motion for each axis are housed in a titanium pressure housing (Fig. F11). The seismometer is mounted near the bottom of the instrument carrier and is cemented in the hole to assure good coupling to the formation. Each sensor has a motorized leveling mechanism so that the sensors are functional within 4.5° of tilt.

In each sensor, a proof mass is supported on a pivot and suspended by a leaf spring during operation.

The pivot is purposely weakly designed to assure very high sensitivity to ground motion. To prevent the weak pivot from damage during transport, the proof mass must be motion-locked. Locking and unlocking the proof mass, leveling of each sensor, and digitizing the *x, y,* and *z* ground motion are performed by a DM24 digitizer, which is installed in the same pressure housing.

The three-component velocity seismic data along with the position of proof mass and inclination of sensor from the Micro-Electro-Mechanical Systems (MEMS) tiltmeter are encoded in a format called Guralp Compressed Format (GCF). The data are digitally uplinked through the borehole on a serial cable in RS-422 protocol. The three-component velocity data are digitized at 100 Hz in 24-bit resolution, whereas the mass position and tilt from the MEMS sensor are digitized at 4 samples/s.

Time synchronization of the data is governed by the DM24 digitizer. The DM24 receives a time reference through the RS-422 downlink on the serial cable in a format called Streamsync. The same downlink serial connection is also used to send commands to the DM24 to control the CMG3T seismometer (e.g., level the sensor, lock, unlock, center the proof mass, and sensor calibration).

Electric power for the CMG3T broadband seismometer is supplied by the same cable used for the data link. The nominal functional voltage range is 24–36 V DC, and power consumption of the seismometer ranges from 2 to 3 W, although it increases to 6 W when operating the onboard motor to level, unlock, and lock the sensors. Because the 1 km borehole cable dissipates power because of resistance (~32 Ω), higher voltages (~30 V) need to be applied to the end of borehole cable so that the seismometer can receive sufficient power to run the motor. Table T2 summarizes the specifications of the CMG3T borehole sensor for this long-term borehole observatory installation.

The CMG3T broadband seismometer for this installation was modified from the original in that the sensor has a better supporting mechanism to reduce the impact of severe vibration and shock the sensor may encounter during deployment and installation into the bottom of the borehole. During Expedition 319, a sensor dummy run test was conducted at Site C0010, which revealed the possibility that sensors may experience more than 2 g of acceleration while being lowered to the seafloor borehole because of VIV caused by strong sea current (see Fig. F14 in the “Site C0010” chapter [Expedition 332 Scientists, 2011b]). Therefore, design of the sensor and the sensor carrier was revisited to reduce movement (and therefore damage) of components from vibration-induced stress. The design revision was confirmed through a series of vibration tests for each sensor before all the components were assembled. After assembly, each component of the system was checked for noise performance in a vault, subjected to vibration, and rechecked for noise performance again to make sure that vibration does not affect the performance of the seismometer. Upon delivery of the seismometer to Japan, we noise tested it in the Matsushiro vault of the Japan Meteorological Agency. We compared the seismometer with the reference sensors in the vault (Figs. F12, F13), and the results suggest that a good performance can be expected from the new design.

Tilt combo

Specifications

The tilt combo is an integrated sensor module that combines sensors such as a tiltmeter, geophone, accelerometer, and stand-alone heat flow meter (SAHF) digitizer. A schematic diagram of the tilt combo is shown in Figure F14. The details are described as follows:

- The three-component geophone (4.5 Hz GS-11D, OYO Geospace), the three-component accelerometer (JA-5H200, JAE), electrical boards, a CPU board, an A/D conversion board, a power supply board, and internal batteries, are installed in the tilt logger titanium cylinder.
- Signal from the three-component geophones and accelerometers are digitized by the A/D converter (ADS1282, Texas Instruments) on the A/D conversion board at a 125 Hz sampling rate.
- The tiltmeter (LILY, Applied Geomechanics) and the thermometer digitizer (SAHF, Kaiyo Denshi Co., Ltd.) have their own A/D converters in separate titanium housings and are connected to the tilt logger cylinder through an electrical cable. The LILY has a 5 Hz sampling rate, and the SAHF has a 0.5 Hz sampling rate.
- All data from the sensors are merged and telemetered as RS-422 serial data to a recorder in the seafloor in WIN format. In stand-alone acquisition mode, all data may be stored to an SD memory card in the main tilt logger housing.
- The tiltmeter, thermometer digitizer, and accelerometer can individually be powered by switching electrical relays on the power supply board.
- Geophones may be calibrated by a circuit in the A/D board, which transmits an electrical pulse to the geophones.
- The clock time can be synchronized to a GPS 1 pulse per second signal through the RS-422 serial link.

- Power consumption is ~100 mA at 24.0 V when all the sensors are activated.

The tilt combo sensors were attached to the sensor carrier. We prepared at least two sets of each sensor for redundancy. Two geophone and accelerometer modules (1 and 2) were available. Three LILY tiltmeters (serial numbers N8035, N8068, and N8069) were also available, and two SAHF digitizers (1 and 2) were ready to be installed. Geophone and accelerometer Module 1, LILYN8068, LILY N8069, and SAHF Digitizer 1 were loaded on the *Chikyu* on 25 October 2010, whereas geophone and accelerometer Module 2, LILY N8035, and SAHF Digitizer 2 were loaded on the *Chikyu* during the Shimizu port call on 27 November 2010.

Performance test results

We conducted noise evaluation tests for the two sets of the tilt combo module at Matsushiro vault Seismological Observatory for confirming the noise level and long-term stability of the sensors. Matsushiro Seismological Observatory has an underground tunnel that is isolated from noise sources such as railroads, automobile traffic, and the sea coast. Temperature changes in the vault are small throughout the year. We also carried out a test at the JAMSTEC laboratory in Yokosuka, Japan, for performance in a noisy environment. An example of the time series data acquired in the Matsushiro tunnel is shown in Figure **F15.**

As a key result of the Matsushiro experiment, we obtained power spectral density (PSD) performance of the tilt combo sensors as shown in Figures **F16, F17,** and **F18.** Even in the low noise environment in Matsushiro, the microseism band peak of ~0.2 Hz can be clearly confirmed for the geophone, tiltmeter, and broadband seismometer as well as the reference broadband seismometer (CMG3T) deployed in the same Matsushiro vault.

The performance of the tilt combo sensors are summarized as follows:

1. The geophone has almost the same noise level as the CMG3T from 0.15 to 20 Hz after correction for geophone amplitude response (Fig. **F16**). The PSD of the CMG3T and the geophone have the same peak of –115 dB in reference to $(m/s^2)^2$/Hz in the microseism band. In the high-frequency band, from 20 to 50 Hz, the PSD of the geophone is much higher than that of the CMG3T. It was probably caused by the difference in installation conditions in the vault. We confirmed that the geophone has the same sensitivity as the CMG3T to ground motion from 0.15 to 20 Hz in this test.
2. The accelerometer PSD data presented in Figure **F17** do not show the microseisms peak. In Matsushiro vault, the ground motion in the microseism band is quieter than –115 dB from CMG3T data. It is lower than the accelerometer noise in the Matsushiro vault (–110 to –85 dB at a frequency range of 0.001–50 Hz). Because the accelerometer is adjusted for strong motion of more than ±6 g, low-level background noise in Matsushiro cannot be resolved. In the JAMSTEC laboratory data, the PSD of the accelerometer shows good correlation to that of the tiltmeter from 0.001 to 1 Hz and the geophone from 0.2 to 50 Hz.
3. The LILY tiltmeter has the same noise level in the microseism band from 0.13 to 1 Hz as the CMG3T (Fig. **F18**). From 0.01 to 0.13 Hz, the PSD of LILY data ranges from –140 to –120 dB and that of CMG3T data ranges from –180 to –140 dB. The difference is ~40 dB at 0.03 Hz. From 1 to 2.5 Hz, one of the LILY (N8068) sensors exhibits good noise level comparing to the CMG3T. However, the other LILY (N8069) sensor has a higher noise level than the CMG3T, showing 10 dB in this frequency band. Tiltmeters have different internal noise levels, especially at high frequencies. At 0.015 Hz, a remarkable peak is found in the LILY data record. This peak is probably caused by internal noise of the tiltmeter because this peak was found in the other tiltmeters in other tests and also appears in stand-alone acquisition by the LILY tiltmeter. The estimated noise level of the LILY tiltmeter is around –140 dB from 0.1 to 2.5 Hz in reference to ground acceleration ($[m/s^2]^2$/Hz).

Thermistor string

The thermistor string is designed for long-term monitoring temperature in the borehole. The string has five thermistors at different intervals along an electrical cable for array monitoring as shown in Figure **F19.** The electrical wires are covered by polyether-based material that has good hydrolytic stability. Thermistors and connectors are molded using the same material as the cable. The thermistor string is connected to the thermometer digitizer (Fig. **F14**). A/D converted data are merged to a WIN file on the CPU board in the main tilt combo cylinder. Thermistor cables were calibrated in a precise isothermal bath for temperatures ranging from 5° to 45°C. The calibration was conducted using the following empirical formula:

$$T = 1/\{A + B * \ln(R/2 - R0) + C * [\ln(R/2 - R0)]^2\} - 273.15,$$

where

T = temperature (degrees C) in the isothermal bath measured by high-precision quartz thermometer,

R = reading of the data logger (2× resistance in ohms),

$R0$ = resistance of lead cable (in this case up to 150 m two-way, depending on the position of the sensors), and

A, B, and C = coefficients determined for each thermistor.

Temperature differences between measured and calculated values (ΔT) were primarily attributed to actual temperature fluctuations in the isothermal bath. The absolute accuracy was estimated as ~10 mK. After calibration of the thermometer string, we conducted a continuous recording test in Matsushiro with other sensors of the tilt combo modules.

Temperature data from the Matsushiro experiment are shown in Figure **F20.** Two MTLs were deployed for comparison to the thermistor string data. In this experiment, the thermistor string was coiled and installed in almost the same position. We confirmed that MTLs and thermistors show the same trend and good correlation. However, there are some differences between thermistors and MTLs that reach 40 mK maximum, with the MTL delivering the higher values. It seems that the difference is caused by using the coefficients that have some margin of error due to limitation of precision of our isothermal bath used for the calibration. However, we confirmed that the thermistor string has a resolution of 1–2 mK. Afterward, two sets of thermistor strings were prepared for Expedition 332. One of them, String 1, was already adjusted to the total length of 150 m, whose thermometer sensor distribution was determined from the existing Expedition 314 LWD data set. String 1 was loaded on the *Chikyu* on 25 October 2010 after calibration and pressure tank testing. String 2 was prepared for an optimum length of 146 m after having obtained LWD data from Hole C0002G. Calibration and pressure tank tests of String 2 were conducted prior to loading it onto the *Chikyu* during the Shimizu port call on 27 November 2010.

Observatory hydrogeologic (pressure) unit

For the LTBMS deployed during Expedition 332, a pressure unit was developed for multilevel monitoring of pore pressure transients in the formation (as a proxy for strain) and comparison to seafloor reference pressure. The pressure unit was equipped with four Paroscientific Digiquartz pressure transducers, a RTC-PPC, a 24-bit/channel A/D converter and data logger, and associated "Paroscientific Intelligent Module" A/D converters. The Paroscientific gauges, which are also used in the temporary mini-CORKs (see **"SmartPlug/GeniusPlug"**), have proven to be accurate and very reliable, with accuracy within 0.01% of the full-scale range and pressure resolution to within 1 part per million of full scale (Becker and Davis, 2005). Each transducer connects to ¼ inch stainless tubing that terminates at three measurement points in the subseafloor, as well as a hydrostatic line at the seafloor. The three ⅛ inch hydraulic lines are housed in a urethane-coated flatpack umbilical that connects the monitored intervals to the CORK head (see Fig. **F9** in the "Site C0002" chapter [Expedition 332 Scientists, 2011a]). A swellable packer set at 746 mbsf inside the casing isolates the screened intervals to enable pore pressure monitoring of in situ formation pressures once the response to drilling and open hole operations has dissipated.

The lowermost monitoring interval is located in the accretionary prism (Unit IV) at the bottom of the open borehole, below the strainmeter (see Fig. **F9** in the "Site C0002" chapter [Expedition 332 Scientists, 2011a]). Pressure monitoring is achieved using three 1 inch diameter "miniscreens" plumbed to a single manifold that connects to a ⅛ inch stainless steel tube within the flatpack umbilical. This configuration maximizes azimuthal coverage of the borehole while minimizing the impact of screen obstruction. The second hydraulic line terminates within the cemented interval to act as a simple strainmeter, and the third monitors the screened interval from 757 to 780 mbsf, within the mudstones of the forearc basin fill.

When finally assembled, the pressure unit filled Bay 1 of the LTBMS CORK head (see Fig. **F21**). In its lower portion, a metal shield was mounted to facilitate remotely operated vehicle (ROV) operations and protect some delicate parts from collision or other damage. The data logger within the pressure unit can be accessed via an ODI Teledyne UMC with the same specifications as the set of three UMCs of the other CORK instruments mounted in Bay 2 (i.e., seismometer, strainmeter, and tilt combo; see **"CORK head"**). The ODI connector has a pin layout that is compatible to its three counterparts and hence allows the ROV pilot to use the same interface for communication and data download.

Instrument carrier

The broadband seismometer (CMG3T) and tilt combo, which consists of a geophone, accelerometer and tilt logger, SAHF digitizer, and a LILY tiltmeter, were mounted to the instrument carrier attached above the strainmeter. A H-beam shaped instrument carrier was newly developed to withstand the strong vibrations associated with high current and hold the high precision and sensitive sensors (see schematic drawing in Fig. F22). The instrument carrier secures borehole sensors, electrical cables, a thermistor string, and the hydraulic lines to the carrier and protects them from damage from contacting the casing and open hole walls while lowering the package into the hole. This instrument carrier was tested for safe operation under high-current velocities with dummy sensors during the March 2010 *Chikyu* CK10-01 cruise. The dimensions and weight of the instrument carrier as well as the sensors, which were housed in the instrument carrier, are summarized in Table T1.

A 190 mm diameter and 30 mm thick flange was adapted at both connection ends to ensure sufficient strength against bending and tension loading. Cables, thermistor string, and hydraulic lines pass through six slits. Six M16 high-tension bolts with self-locking nuts were used at each flange connection. Cement pipe with 48.6 mm OD and 34.4 mm ID was installed along the instrument carrier for cementing the sensors.

Before being loaded on the *Chikyu*, a test of sensor attachment and cable routing was performed on the instrument carrier to confirm the attachment procedures for the cables, thermistor string, and hydraulic line routing. Two instrument carriers (one for backup) were loaded onto the *Chikyu* on 27 October 2010 and stored in the Core Tech workshop and middle pipe rack.

The broadband seismometer, sensors consisting tilt combo (tilt logger, SAHF digitizer, tiltmeter) are installed on the instrument carrier using a band-type attachment tool. Isolation between sensor casings and instrument carrier was achieved with vinyl tape and fiberglass reinforced plastic. The electrical cables connected to the seismometer and tilt combo have a molded part (40 mm diameter). These were fastened inside the carrier (Fig. F23). The tiltmeter and thermometer digitizer were connected to the tilt-logger by the three-phase cable shown in Figure F24. The thermistor string was connected to the thermometer digitizer and placed on the top of the carrier. The electrical cable for the strainmeter and two ⅛ inch hydraulic lines were mounted and attached to the carrier in order to pass them through from bottom to top. These cables, lines, and strings were attached by cable ties and steel bands. Specifications of the sensors and instrument carrier are summarized in Figure F22. The orientation of the broadband seismometer, geophones, accelerometer, and the tiltmeter, all mounted on the instrument carrier, is illustrated in Figure F25.

Electrical cable

Three electrical cables of 21.3 mm diameter were connected to borehole sensors (tilt logger, broadband seismometer, and strainmeter) and placed in the BHA. The buoyancy of the cables was designed to be almost neutral to lower risks such as cable slack during long-term operation after installation. The weight of the cable in seawater is about –4.6 kg/km, and the minimum bending radius is 426 mm under tension. Seacon MINK-CCP connectors were molded at the bottom end of each cable before being loaded onto the *Chikyu* for sensor connections. A schematic drawing of the bottom ends are shown in Figure F23. These cables are attached by tie wraps and duct tape to 3½ inch tubing from the BHA to the CORK head, which is installed on the wellhead. The upper ends of the cables were terminated with ODI Teledyne UMCs on board the *Chikyu*.

3½ inch tubing and centralizers

The sensor tree mandrel used 3½ inch 12.7 lb/ft tubing. The CORK head was connected to the top joint of the tubing. Three electrical cables (21.3 mm diameter), a flatpack (12 mm × 28 mm, containing three strands of ⅛ inch diameter tubing), and a thermistor string (6 mm diameter) were attached tightly on 3½ inch tubing from the instrument carrier to the CORK head by cable ties and steel bands. Cable drums equipped with a compressed air braking system were used for the operation.

Two types of centralizers were used for accurate centralization and cable protection. Bowspring centralizers were attached below the strainmeter and above the cement port to allow uniform cement flow around the instruments. Further above, four rigid centralizers with cable protectors were attached to each joint of 3½ inch tubing to prevent cable and thermistor string damage caused by contact with the casing wall (Fig. F26). Cables and the thermistor string were secured by tie wraps and steel bands and were also protected by sheaths of rubber hose in areas where sharp edges or a change in diameter of the string was encountered.

Cementing equipment

Sensors installed at the bottom of the hole were cemented for coupling with the surrounding rock. The observatory system includes cementing system components that were embedded as a part of the hole completion operations. They consist of a plug landing collar, cement port, and top and bottom special combination plugs. A float collar was used as a landing point for the cementing plugs at the planned depth of the top of the cement column in Hole C0002G. The cement port was set to the planned depth of the bottom of the cement column at 937 mbsf. After the bottom plug was dropped, 39 bbl of cement was pumped downward using a rig floor pump. The top plug was behind the cement slurry. Seawater was pumped until plug bumping occurred at the collar. The bottom plug was bumped and ruptured with 2500 pounds per square inch (psi), whereas the top plug was bumped with 1000 psi.

Swellable packer

The swellable packer is a nonmechanical borehole seal that utilizes the swelling properties of rubber. The packer materials swell when in contact with water, which results in swelling of the element of up to 350% of its original volume (depending on pressure and temperature conditions).We installed a swellable packer from Haliburton at the target depth of 746 mbsf at Site C0002 to isolate a predefined section of the borehole for pore pressure measurements. A photograph of the swellable packer is shown in Figure **F27.** The initial OD is 7.89 inches and the active length is 1.5 m. The 9⅝ inch casing ID is 8.68 inches, so the initial clearance between the packer and the casing is 10 mm (20 mm total). The anti-extrusion end rings with the same OD as the packer were attached to each end of the packer. The end ring flaps expand radially against the casing ID, so that the packer seal elements are not able to come out over the end rings. The packer mandrel with 3½ inch OD and 4.5 m length was connected to the 3½ inch tubing, and the packer was covered with the diffusion barrier (type 8L), which is a material that slows water migration into the packer through reduced permeability. In the case of the 7.89 inch OD packer with diffusion barrier 8L, the OD is estimated as 8.09 inches after 1 week and 8.17 inches after 2 weeks at 4°C and also as 8.12 inches after 1 week and 8.19 inches after 2 weeks at 40°C by the swell simulation. From former laboratory test results at JAMSTEC, it was determined that the packer swelling rate is slightly lower at low temperatures.

In order to communicate with a series of sensors and perform the pore pressure measurements, the electrical cables (21.3 mm OD) and hydraulic flatpack (28 mm × 12 mm) were fed through the swellable packer on the working cart in the moonpool while lowering the sensor assembly. Cable installation tools for each electrical cable and the hydraulic flatpack were used for the operation. The clearance around the cable was set to be 2.5 mm (5 mm total). The clearance is needed to reduce the risk of cable damage due to the cable pull force and slack during lowering the packer into the borehole. The packer had to be cut four times along its length (each slit 90° apart) to allow for feed-though of the three electrical cables and the flatpack. After the cable installation, the anti-extrusion end rings with the cable slit cover were tightened, and the cables were fixed on the 3½ inch tubing independent of the packer.

CORK head

The CORK head (30 inch effective diameter and 24 ft, 2⅞ inch length) is the top of the sensor string mounted on a 9⅝ inch casing hanger inside the SG-5 riserless wellhead. Figure **F28** shows a photograph of the CORK head with the pressure unit being installed. The ODs of the inner and outer mandrels are 4½ inches and 9⅝ inches, respectively. Three bays are found in the central part of the CORK head (Fig. **F29**): Bay 1 for a pressure data logger and valves, Bay 2 with three ODI Teledyne UMCs for downhole sensors and cable coiling space, and Bay 3 for extra cable being attached.

The pressure data logger with four high-precision quartz pressure sensors (Paroscientific, Inc.) were installed on pressure monitoring Bay 1 and equipped with two-way and three-way valves to access the bottom hole pressure ports and an UMC attachment at the top of the pressure logger (Fig. **F28**). Three ¼ inch hydraulic lines from the bottom-hole pressure ports were connected to the valves. Additional protection was developed to shield the pressure data logger during ROV operations, and handles were added to assist the ROV in grabbing to stabilize while connecting to the UMCs. A pressure test of the hydraulic lines was performed to check for any leaks by hand pump and further modifications on valve indicators, pressure logger base plate, and the pressure logger recovering hook were made on the CORK head prior to deployment.

The top ends of the electrical cables were terminated and attached with UMCs on board the *Chikyu*. After the termination, the three electrical cables were securely attached to the split chain links welded on the bay panels and the outer mandrel using tie wraps and duct tape to prevent any damage during drifting through the high-current area and reentry. Three UMCs were mounted on the attachment plate. An UMC mounting plate was attached on Bay 2 using M16 bolts with self-locking nuts. The height of the mounting plate was set to be a minimum of 920 mm from the top of the ROV platform by considering the bending radius of the cable and allowing clearance for ROV operations. The attachment tools were designed to clear the valves and pressure logger installed in the next bay.

The ROV platform with 8 ft radius was attached for ROV access before lowering the CORK head into the moonpool. The final assembly, including the platform prior to launching it into the water, is shown in Figure **F30.**

Seafloor recording and submarine cable network connection

The long-term borehole observatory system has three separate cables for the downhole sensors: (1) strainmeter, (2) broadband seismometer, and (3) tilt combo (tiltmeter, geophones, accelerometer, and thermometer array). Pore fluid pressure through hydraulic lines from three different depths is recorded at the seafloor by the pressure recorder mounted on the CORK head. These sensors are all separate and can be regarded as four separate observatories sharing the same borehole. The electrical connection specifications are designed the same so as to give flexibility in a series of operations to connect to them.

ROV connection

During installation, the condition of the downhole sensors was inspected by cable connection to the connectors on the CORK head from an ROV. An interface circuit attached to the ROV *Magnum* on the *Chikyu* was used to switch power and RS-422 data connection (see Fig. **F21** in the "Site C0002" chapter [Expedition Scientists, 2011a]). By receiving 24 V power from the ROV, the interface circuit can supply 17, 24, or 30 V of power to the borehole instrument as well as measure supplied current and voltage to the borehole sensor. The interface circuit also converts the data format from the borehole sensors (RS-422) to a format supported by the ROV *Magnum* (RS-232C). The ROV *Magnum* supported up to 115,200 bps data speed in two-way communication to the surface. We used 57,600 bps as a standard speed to communicate with our borehole sensors.

Long-term observatory operation plans

During Expedition 332, we did not install a long-term data recorder on the CORK head, but we inspected the condition of the sensors installed and obtained the short period of initial data through the ROV connection. To start long-term observation with the borehole sensors, a recording system will be installed following a visit to the observatory in Hole C0002G by the ROV *Hyper Dolphin* deployed by the R/V *Kaiyo* (JAMSTEC). The recording system consists of a repeater and a data recorder with batteries and connects via UMCs to the borehole sensors (strainmeter, broadband seismometer, and tilt combo) as well to the data recorder. The repeater exchanges data between the data recorder and the borehole sensors as well controls the power supply to each borehole sensor. The data recorder houses lithium batteries and data memory to support up to 1 y of continuous operation of these borehole sensors. The data recorder has another underwater connector for control and online data recovery from a cable connection from the ROV. Time synchronization of the entire observatory is made through a GPS-referenced time signal sent from the ROV through the cable connection. The same ROV can also connect to the pressure recorder on the CORK head for pressure data recovery.

After a period of ~1 y, the long-term data recording system will be recovered for system evaluation, and a cable connection from land will be implemented by replacing the repeater with an interface box for a submarine cable network. This network, called the Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET), was laid out in this area during January–March 2010 (Fig. **F31**). The DONET junction point is within 10 km of the observatory. Upon connection to DONET, all the borehole sensors will receive power from the cable and the data will be received in real time on land. The timing of the borehole data will also be governed by precision time references from DONET.

Vortex-induced vibration measurements

In order to establish long-term borehole observatories in the NanTroSEIZE region, one of the primary challenges is to install high-precision sensitive sensors into the borehole without damaging them. In particular, strong vibration can damage sensors during lowering of the drill pipe through the water column and into the borehole, especially in areas of strong ocean currents such as the Nankai Trough where the Kuroshio Current prevails (see example in Fig. **F4** in the "Site C0010" chapter [Expedition 332 Scientists, 2011b]).

Given that strong vibrations during a dummy run test of the first-generation instrument carrier conducted during Expedition 319 (Saffer et al., 2009) caused severe damage to both sensors and the carrier itself, alternate installation methods have been explored to reduce VIV. A new H-beam type instrument carrier (i.e., 3½ or 5 inch tubing size) was developed for the sensor tree assembly, and drill collars to balance the weight were discussed. In addition, it was suggested that VIV reduction ropes be attached on the drill pipe. These countermeasures were tested and approved for operations during the CK10-01 shakedown cruise on the *Chikyu* in March 2010.

Acceleration measurements were carried out to monitor VIV on the drill pipe during SmartPlug retrieval at Site C0010 and long-term borehole monitoring system installation at Site C0002. These measurements had two main objectives: (1) to evaluate environmental conditions, such as VIV, shock, and acceleration during operations, and (2) to improve operational procedures for installing high-precision sensitive sensors into the borehole by avoiding VIV-induced damage by the strong Kuroshio Current.

A self-contained accelerometer (94 mm diameter and 760 mm length) equipped with a triaxial acceleration sensor, internal lithium batteries, and a data logger with 2 GB SD memory card was attached to the 5½ inch drill pipe through the attachment tool before running into the hole (Fig. F32). The device measures acceleration in three directions (x, y, and z) at a sampling rate of 250 Hz, where the z-axis corresponds to the downward direction of the drill pipe. The orientation of the three axes is shown in Figure F32.

An attachment tool was manufactured to secure the accelerometer to the drill pipe. A copper sheet was set between the attachment blocks and drill pipe to prevent sliding or rotation during deployment (Fig. F32). Self-locking nuts were used to tighten the bolts to prevent them from loosening from vibration. Figure F33 shows a photograph of the accelerometer instrument on the drill string.

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Figure F1. BHA schematic showing close up diagram of LWD/MWD tools. Drill strings for 12¼ and 10⅝ inch holes are sketched. Both configurations from bottom bit to arcVISION sensor, stabilizer, MWD, and drill collar are slightly different in length between bottom of bit to measurement points shown. DP = drill pipe, XO = crossover, NMDC = nonmagnetic drill collar, GR_MP = gamma ray measurement point, Res_MP = resistivity measurement point.

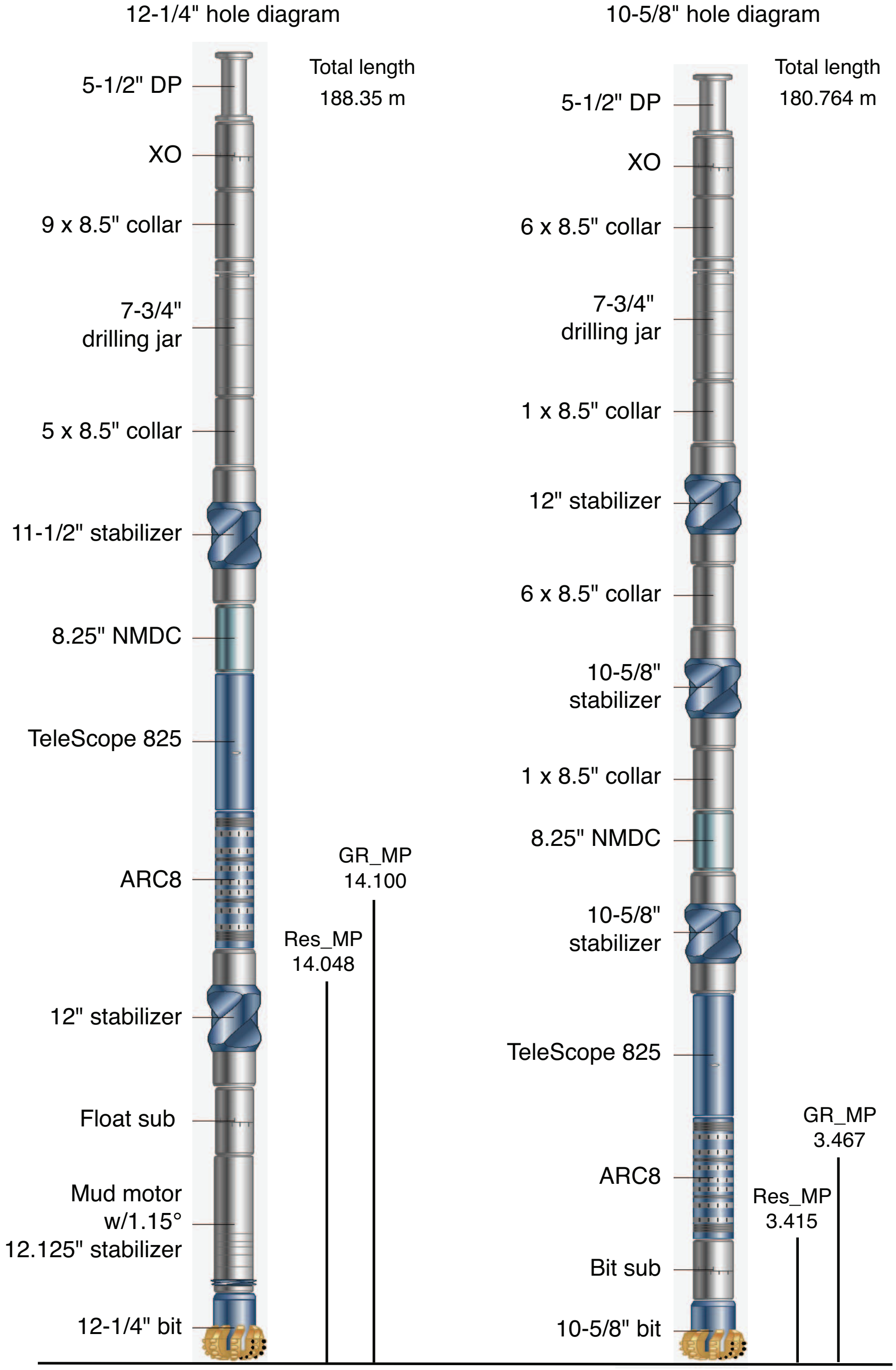

Figure F2. Schematic of rig instrumentation. Crown-mounted motion compensator increases accuracy of bit weight measurement and decreases heave influence on the drill string. MWD = measurement while drilling, LWD = logging while drilling.

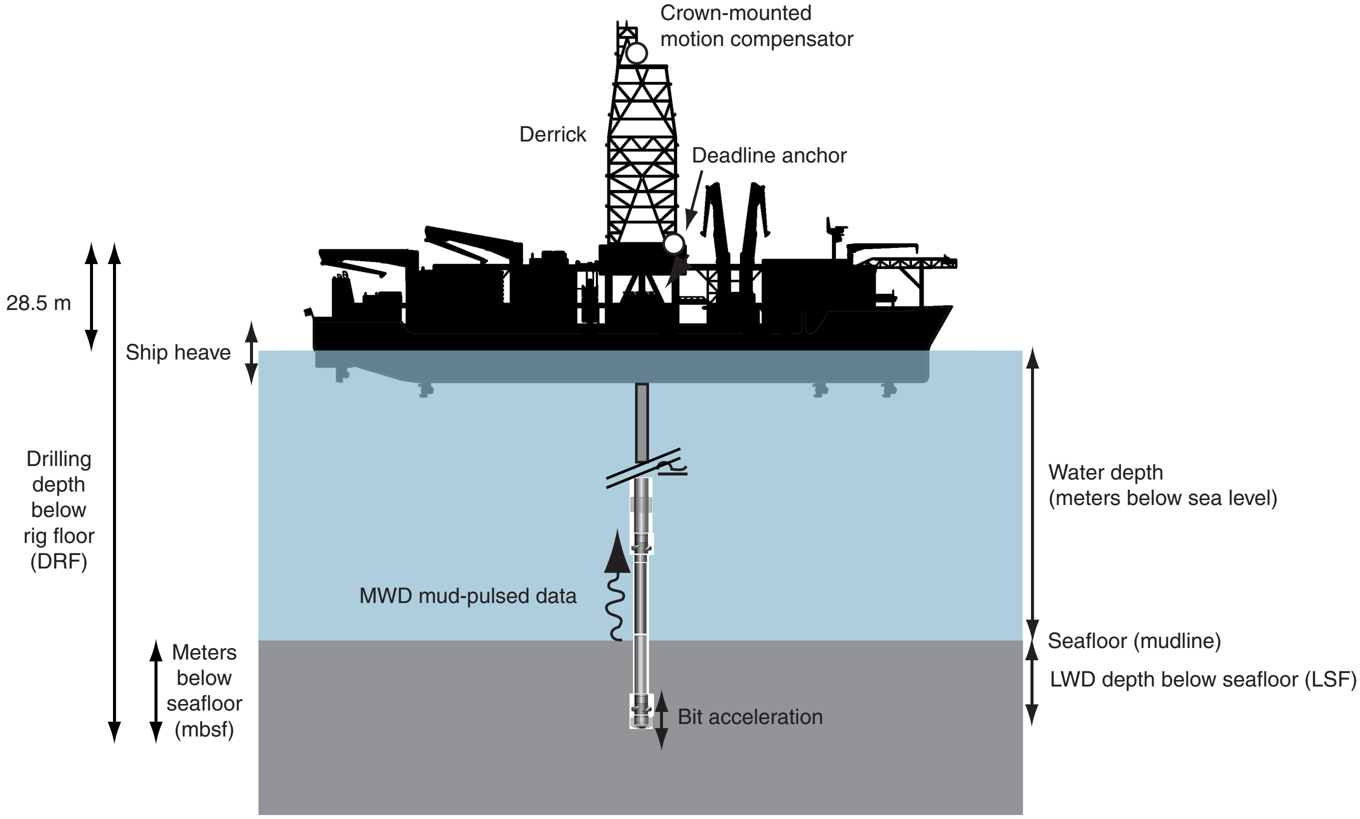

Figure F3. SmartPlug diagram. **A.** Side view. **B.** Cross-sectional top view with pressure period counter (PPC), battery pack (lithium thionyl chloride batteries, 7 y capacity at 1 min sampling rate), Paroscientific 8B 7000-2 pressure (P) transducers, and miniature temperature logger (MTL). Pressure case = 6 inch diameter, 8 inch outer diameter, flange-mounted end caps with high-pressure port feed through bulkheads leading to pressure sensors. Top end cap fabricated with 3.5 inch outer diameter EU 8rd thread for mounting to Baker Hughes retrievable casing packer.

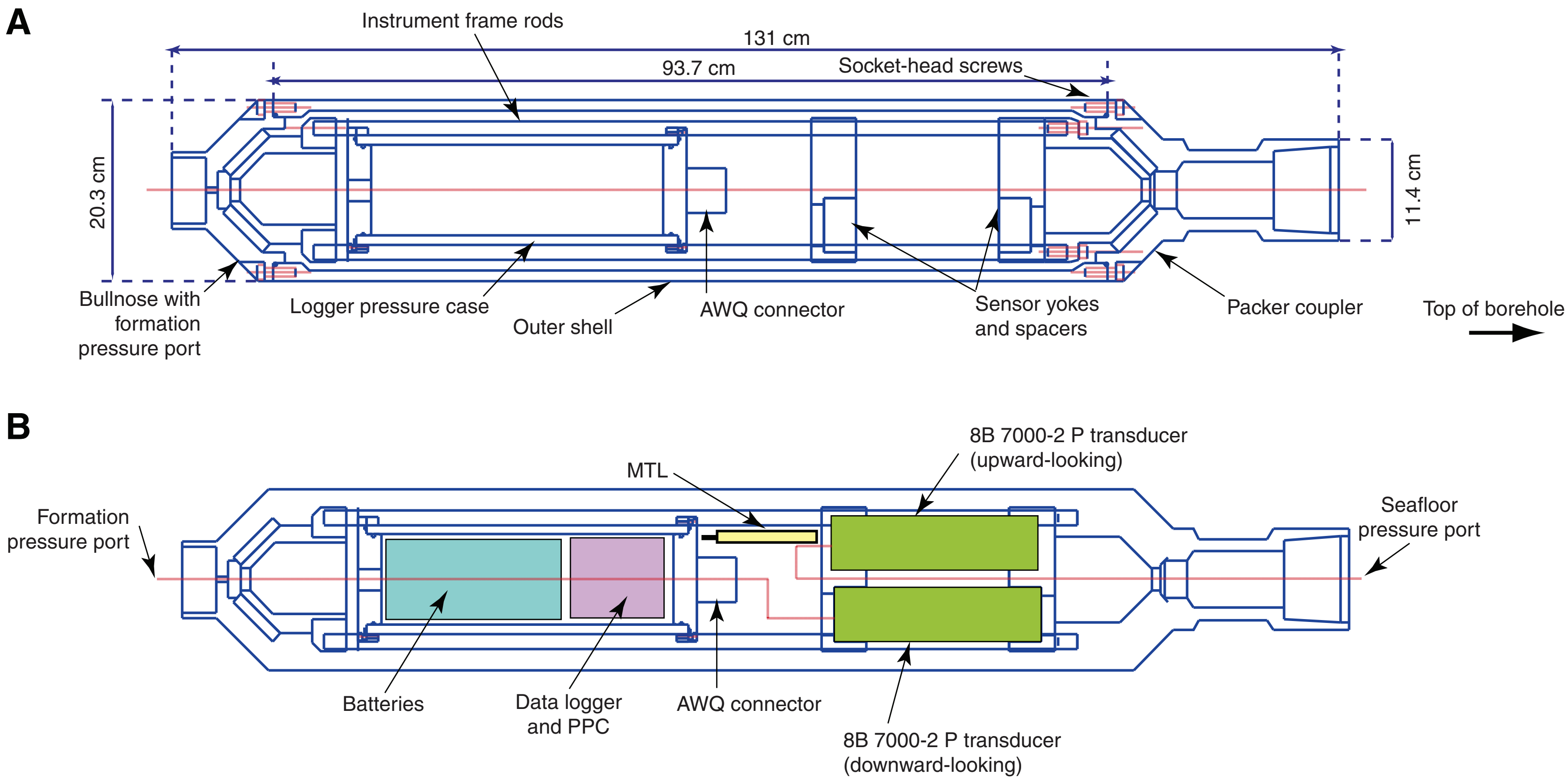

Figure F4. Diagram of GeniusPlug extension to SmartPlug including OsmoSampler geochemical observatory and FLOCS unit.

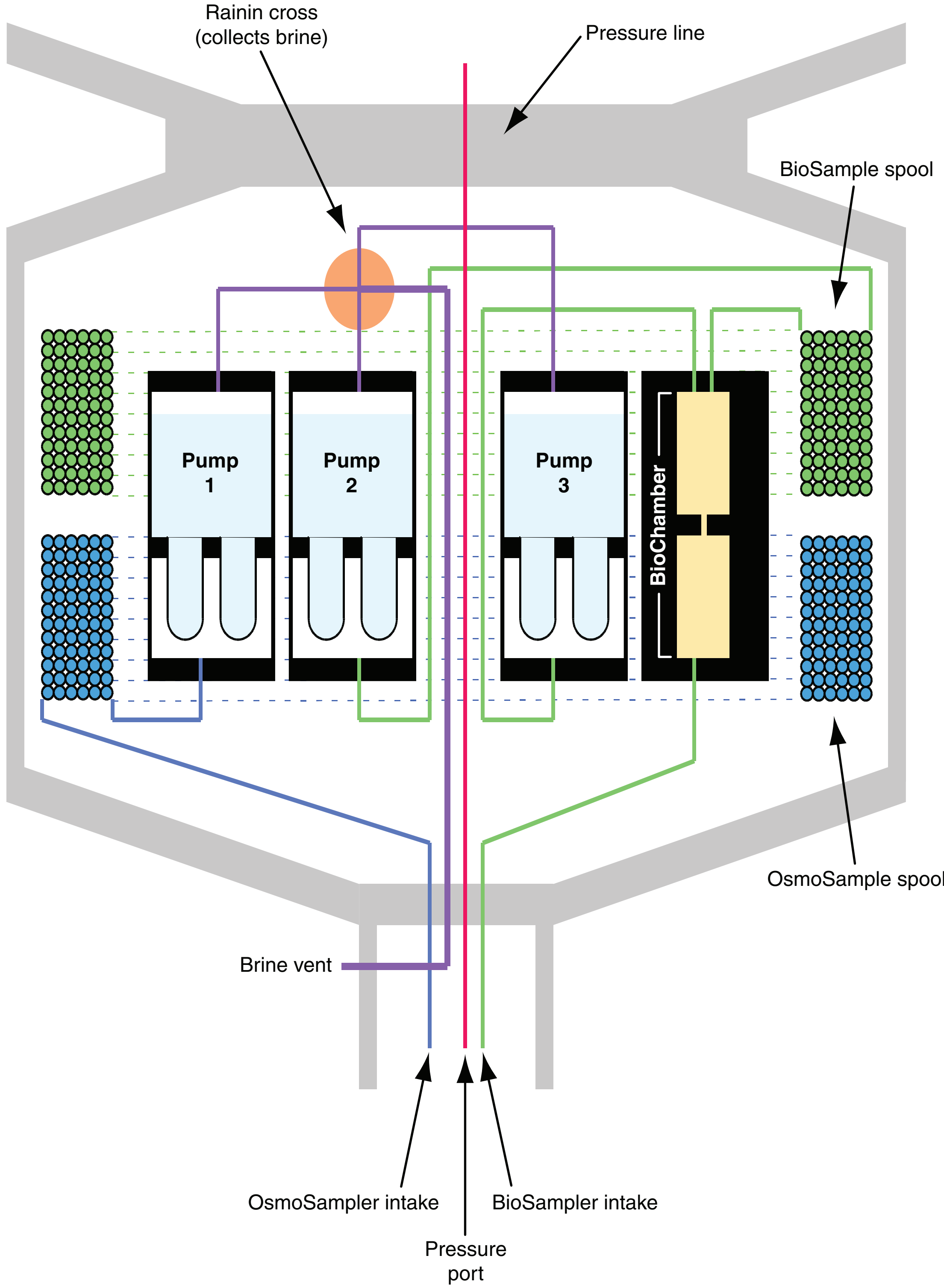

Figure F5. Photograph of SmartPlug instrument during final check prior to deployment. Note pressure transducers (left) and miniature temperature logger (MTL) and bottom tubing (right). RTC-PPC = real-time clock pressure period counter.

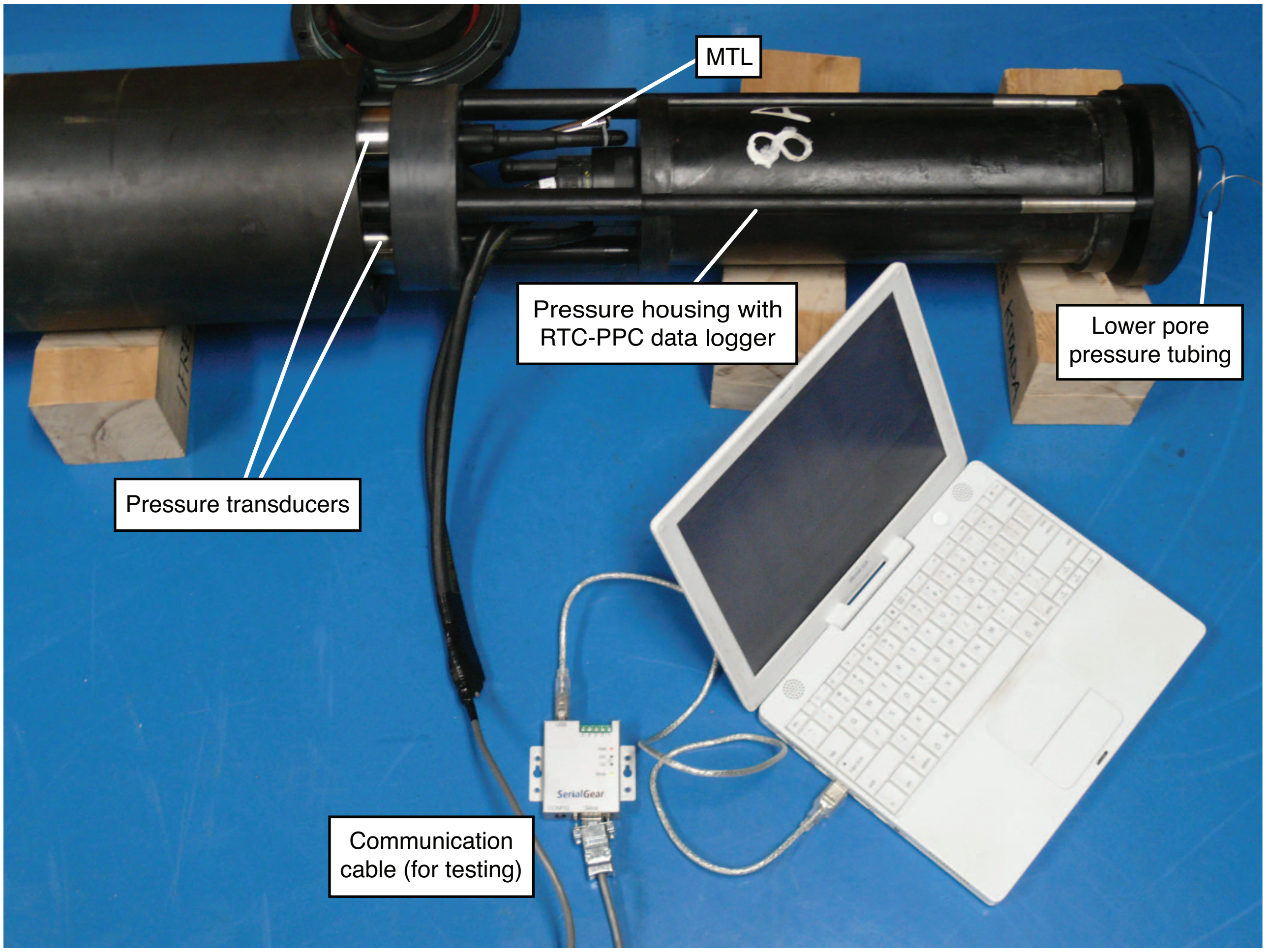

Figure F6. Photograph of GeniusPlug extension unit containing OsmoSampler and flow-through osmo colonization system (FLOCS) cylinder.

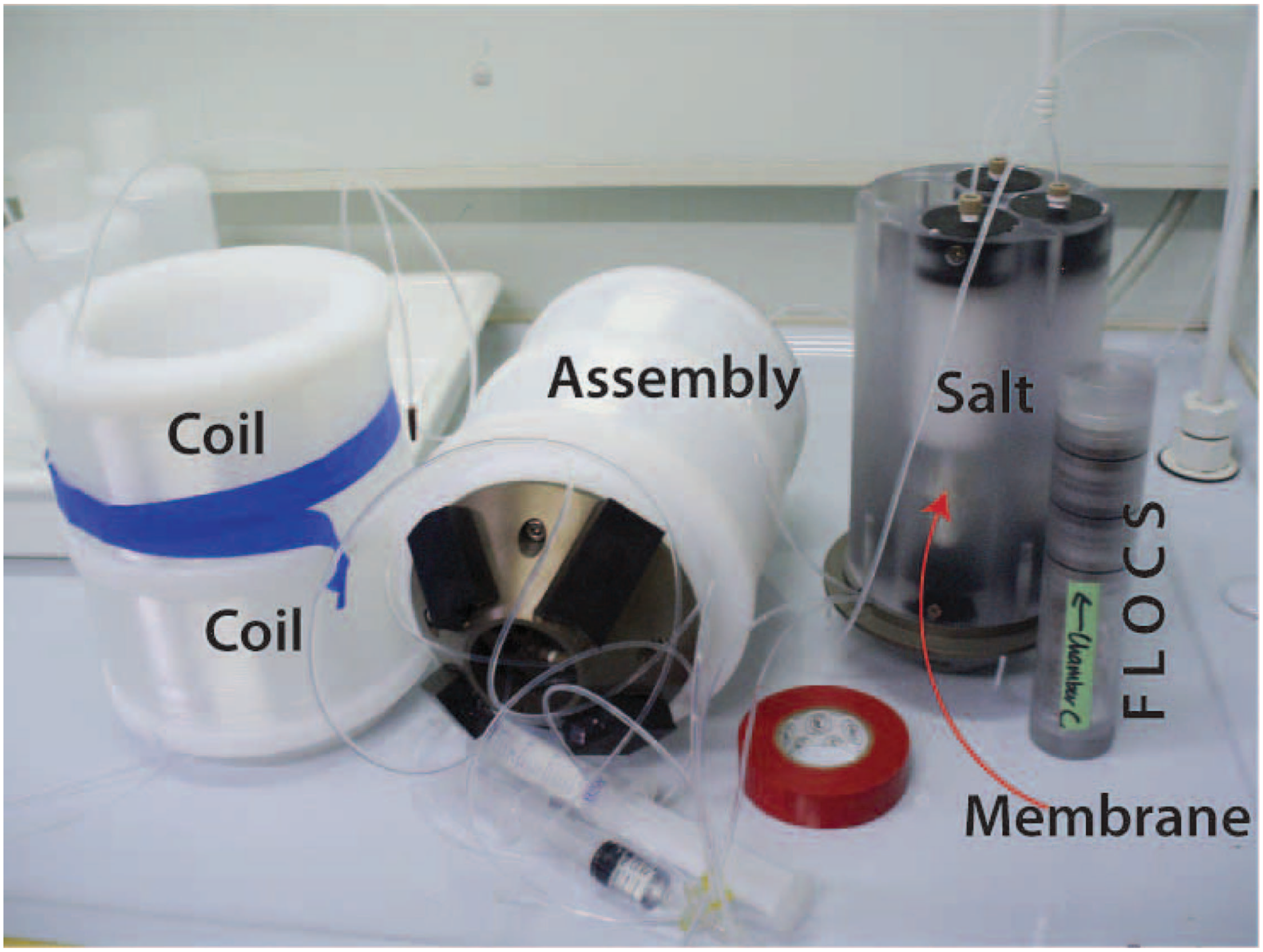

Figure F7. Photograph of SmartPlug Instrument 82 mounted to retrievable bridge plug prior to deployment during Expedition 319.

Figure F8. Diagram of borehole configuration for SmartPlug/GeniusPlug deployment, Hole C0010A. XO = crossover.

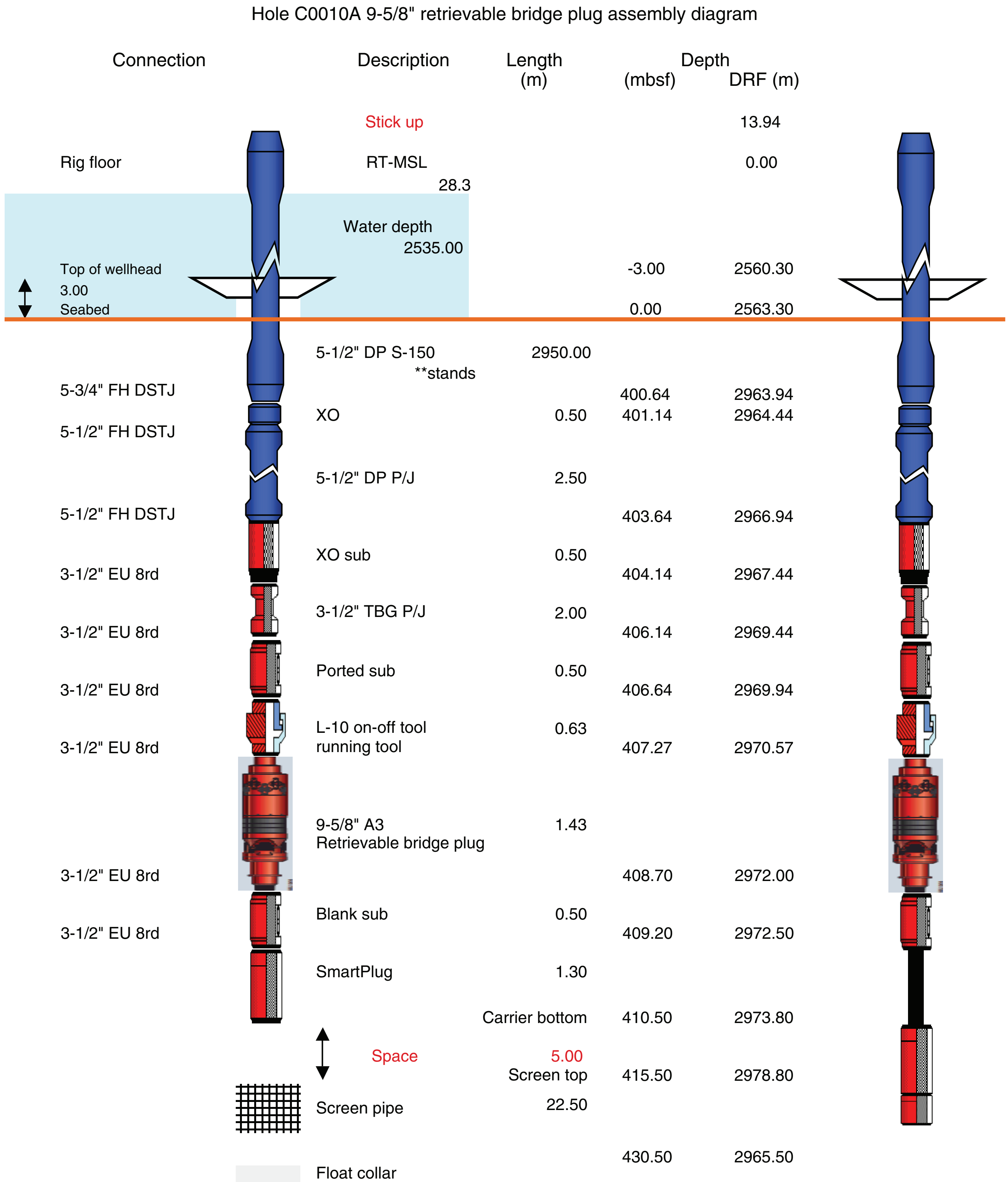

Figure F9. Schematic diagram of deep-sea borehole strainmeter. FCR = flange connector receptacle, XO = crossover, VAM = Vallourec and Mannesmann connection.

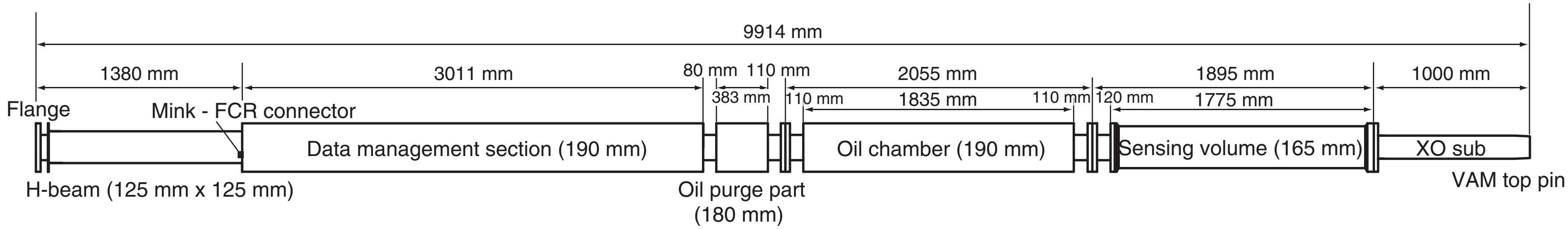

Figure F10. Schematic illustration of strainmeter functions during strain measurement.

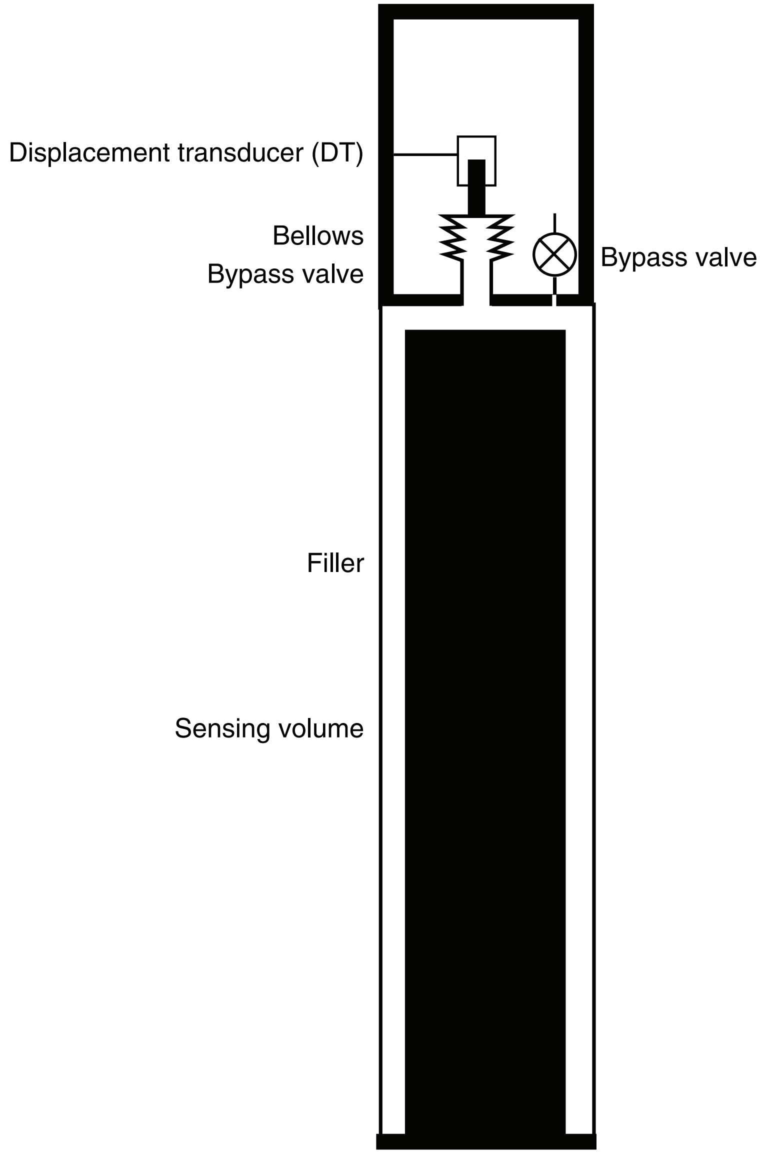

Figure F11. Schematic diagram of Guralp CMG3T broadband seismometer.

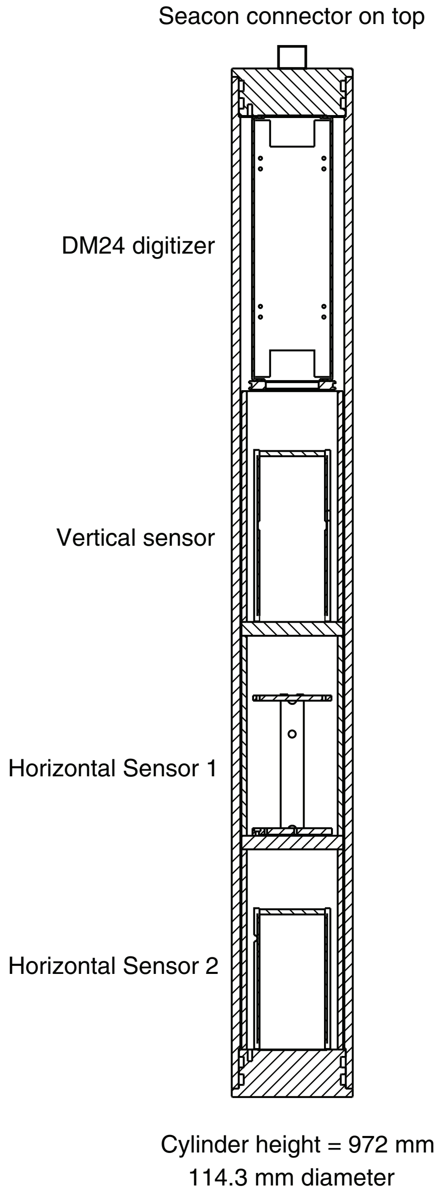

Figure F12. Noise spectra from CMG3T broadband seismometer in the Matsushiro tunnel for one horizontal (north–south) component. Red line = noise spectrum from installed CMG3T broadband sensor, blue dashed line = noise spectrum from reference sensor.

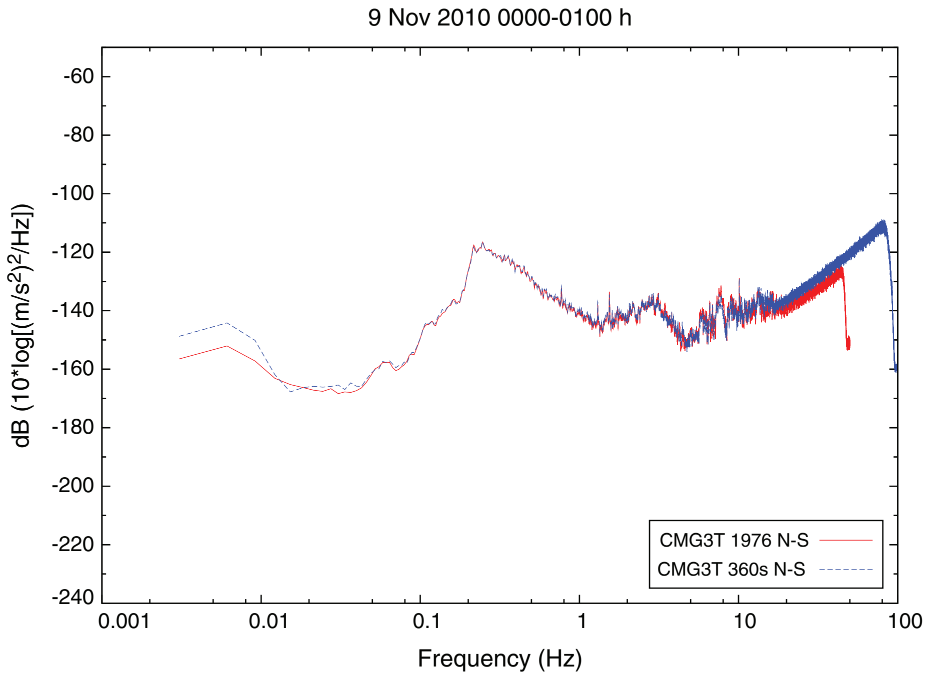

Figure F13. Noise spectra from CMG3T broadband seismometer in Matsushiro tunnel for the vertical component. Red line = noise spectrum from installed CMG3T broadband sensor, blue dashed line = noise spectrum from reference sensor.

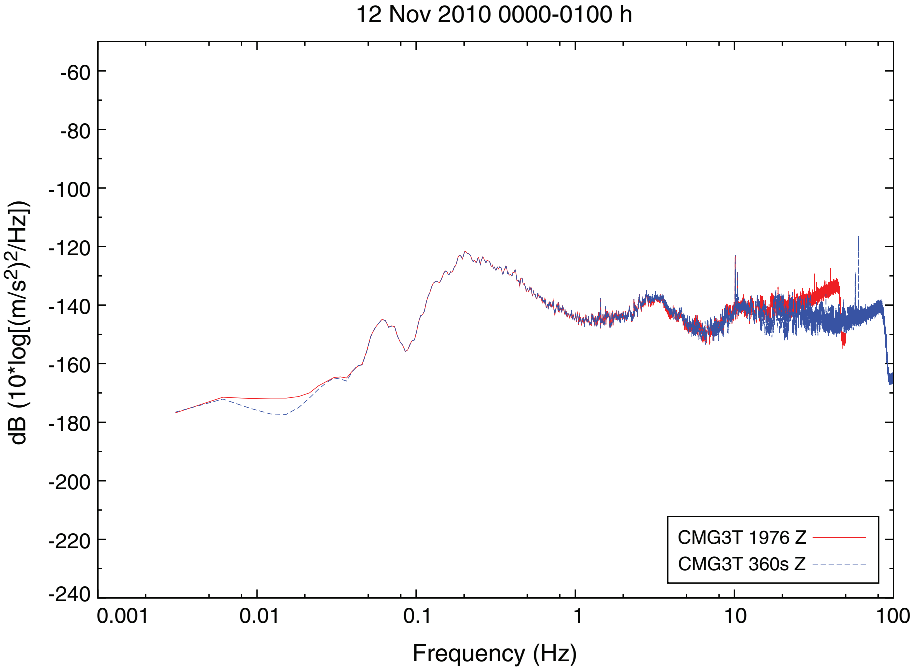

Figure F14. Schematic diagram of tilt combo module. Tilt combo has four different sensors: tiltmeter, geophone, accelerometer, and thermometer digitizer. Geophone (GS-11D, OYO Geospace), accelerometer (JA-5H200, JAE), and some electrical boards are on one titanium housing; LILY tiltmeter (Applied Geomechanics) and thermometer stand-alone heat flow meter (SAHF) digitizer (Kaiyo Denshi Co., Ltd.) have individual titanium housings. All three housings are connected by an electrical cable and will be fixed to a sensor carrier for borehole installation. PCB = printed circuit board, A/D = analog to digital.

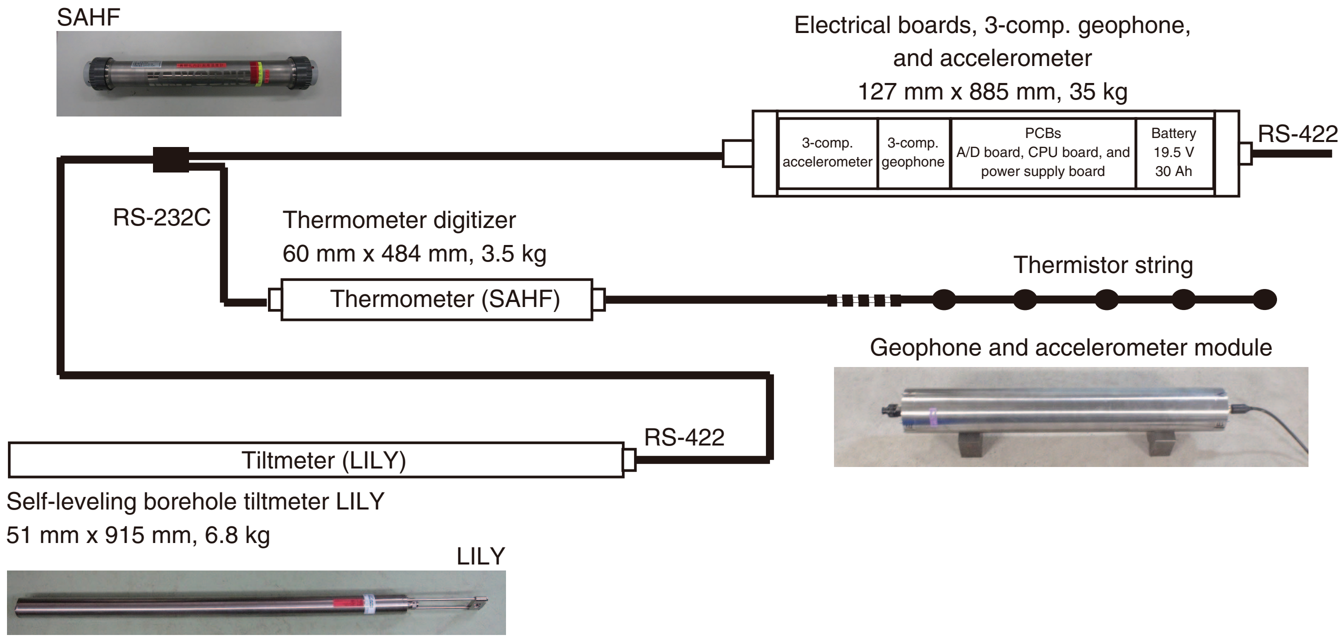

Figure F15. Test tilt combo records from Matsushiro vault Seismological Observatory. Geophone (GEO 1 and GEO 2), accelerometer (ACC 1 and ACC 2), tiltmeter (N8068 and N8069), and reference seismometers CMG3T (CMG3T 360s and CMG3T 120s) as reference seismometer were installed in Matsushiro Seismological Observatory. East–west component records for an hour of each sensors are shown.

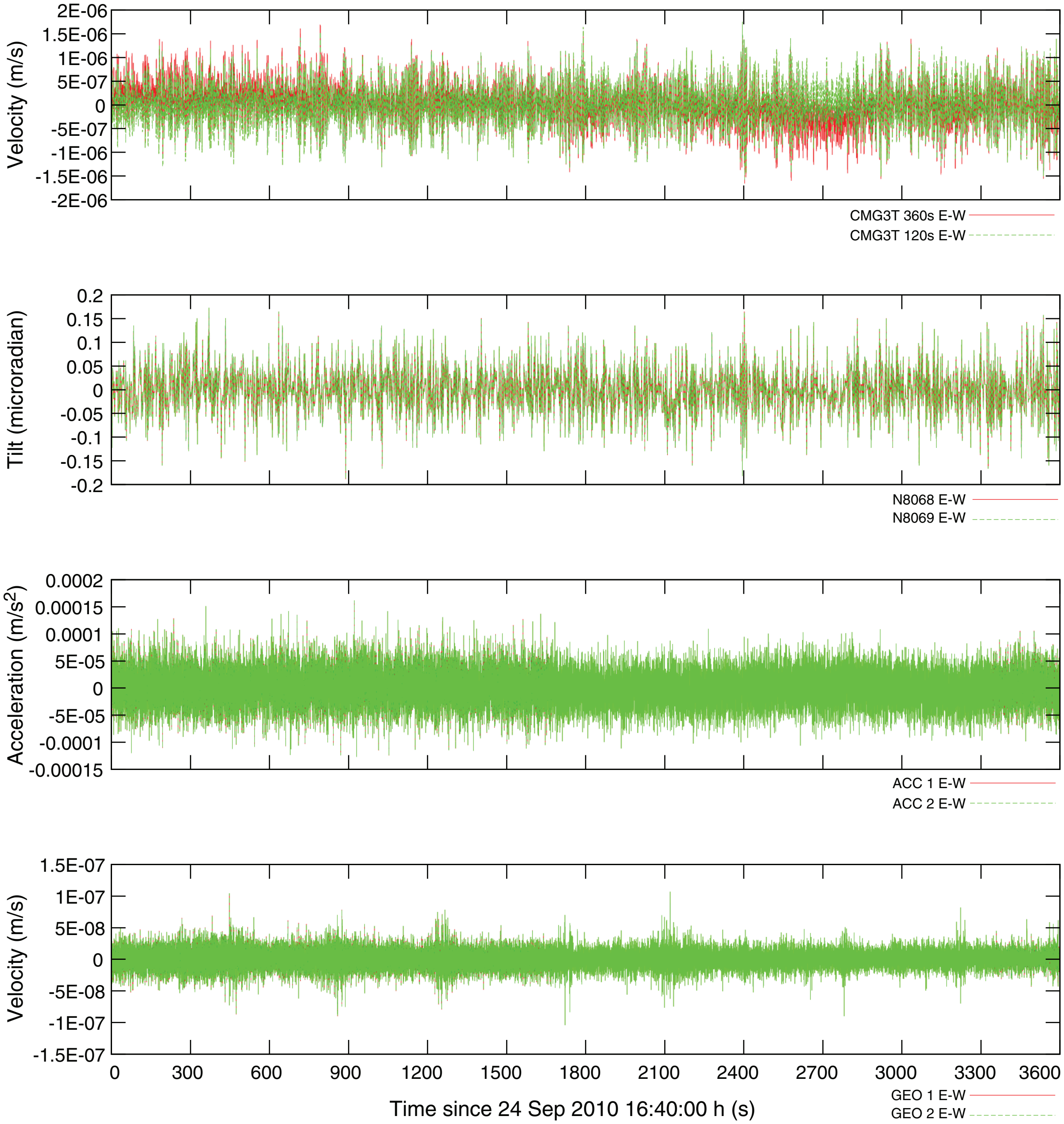

Figure F16. Acceleration power spectral density of geophones in the tilt combo in Matsushiro vault experiment compared with the reference seismometer Guralp CMG3T (CMG3T 360s). Results for all three components are shown. **A.** Module 1 (GEO 1). **B.** Module 2 (GEO 2).

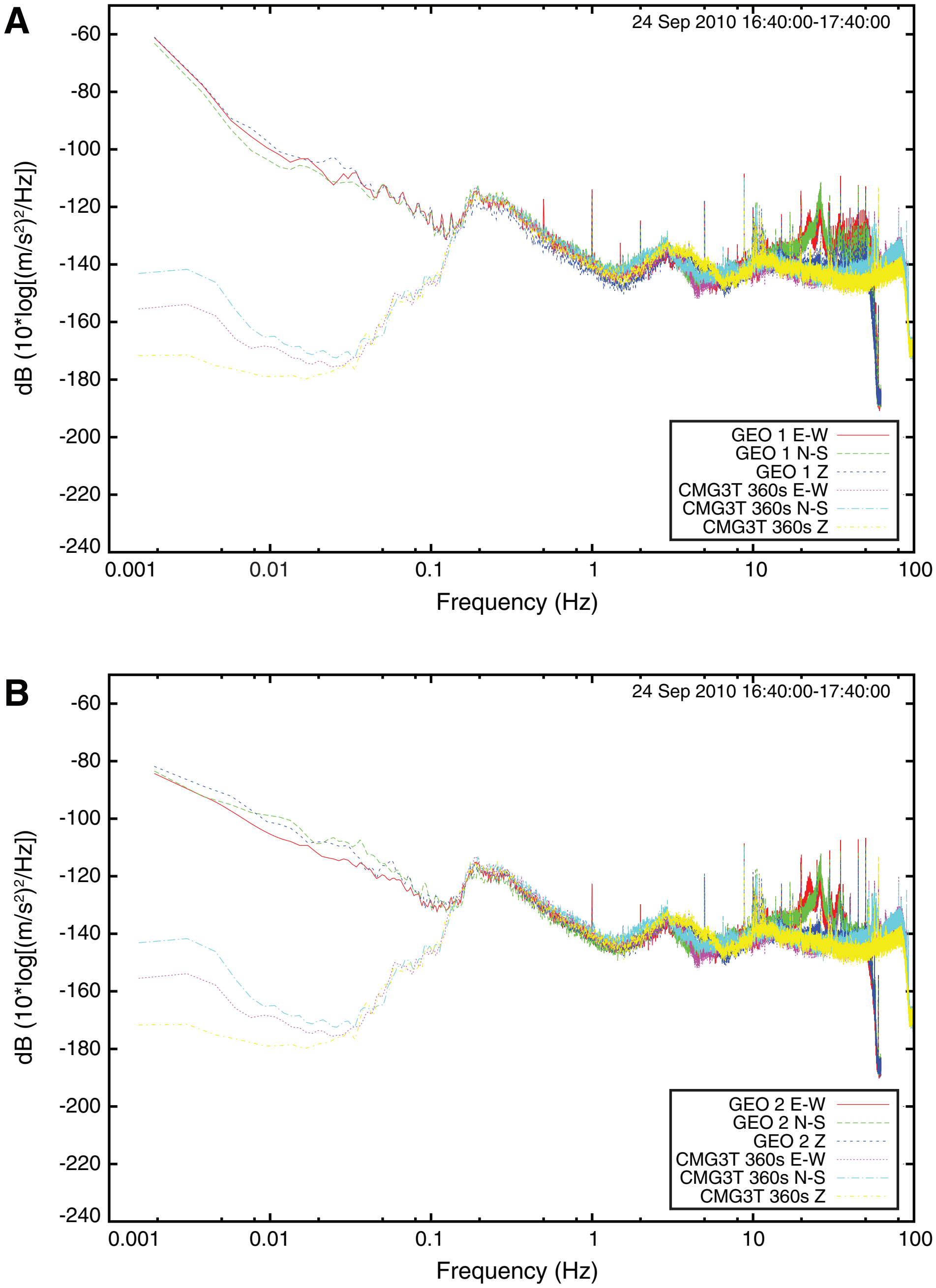

Figure F17. Acceleration power spectral density of accelerometers in the tilt combo in Matsushiro vault experiment compared with the reference seismometer Guralp CMG3T (CMG3T 360s). Results for all three components are shown. **A.** Module 1 (ACC 1). **B.** Module 2 (ACC 2).

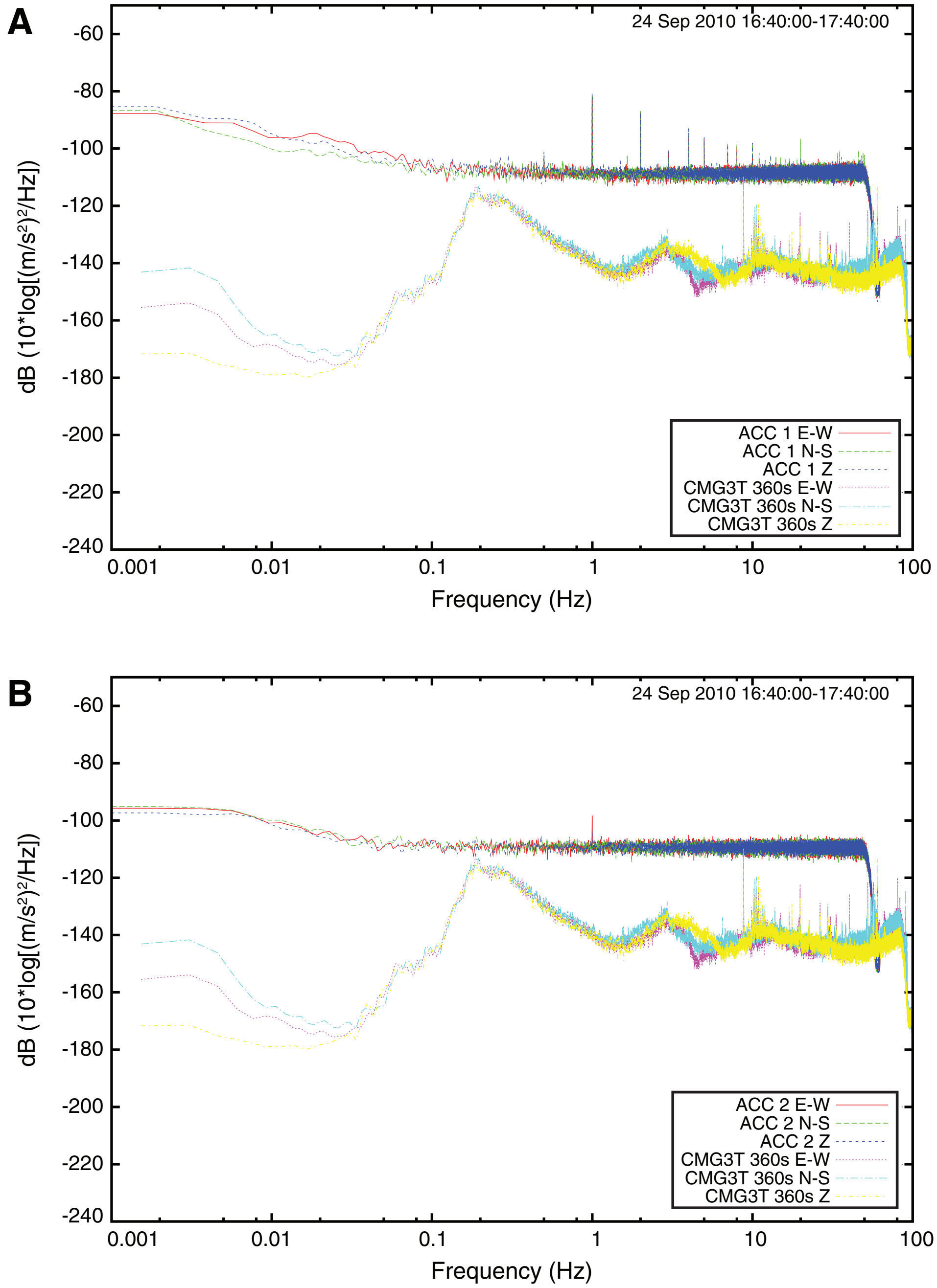

Figure F18. Acceleration power spectral density of tiltmeters in the tilt combo in Matsushiro vault experiment compared with the reference seismometer Guralp CMG3T (CMG3T 360s). Results for both east–west and north–south components are shown. **A.** Module 1 (N8069). **B.** Module 2 (N8068).

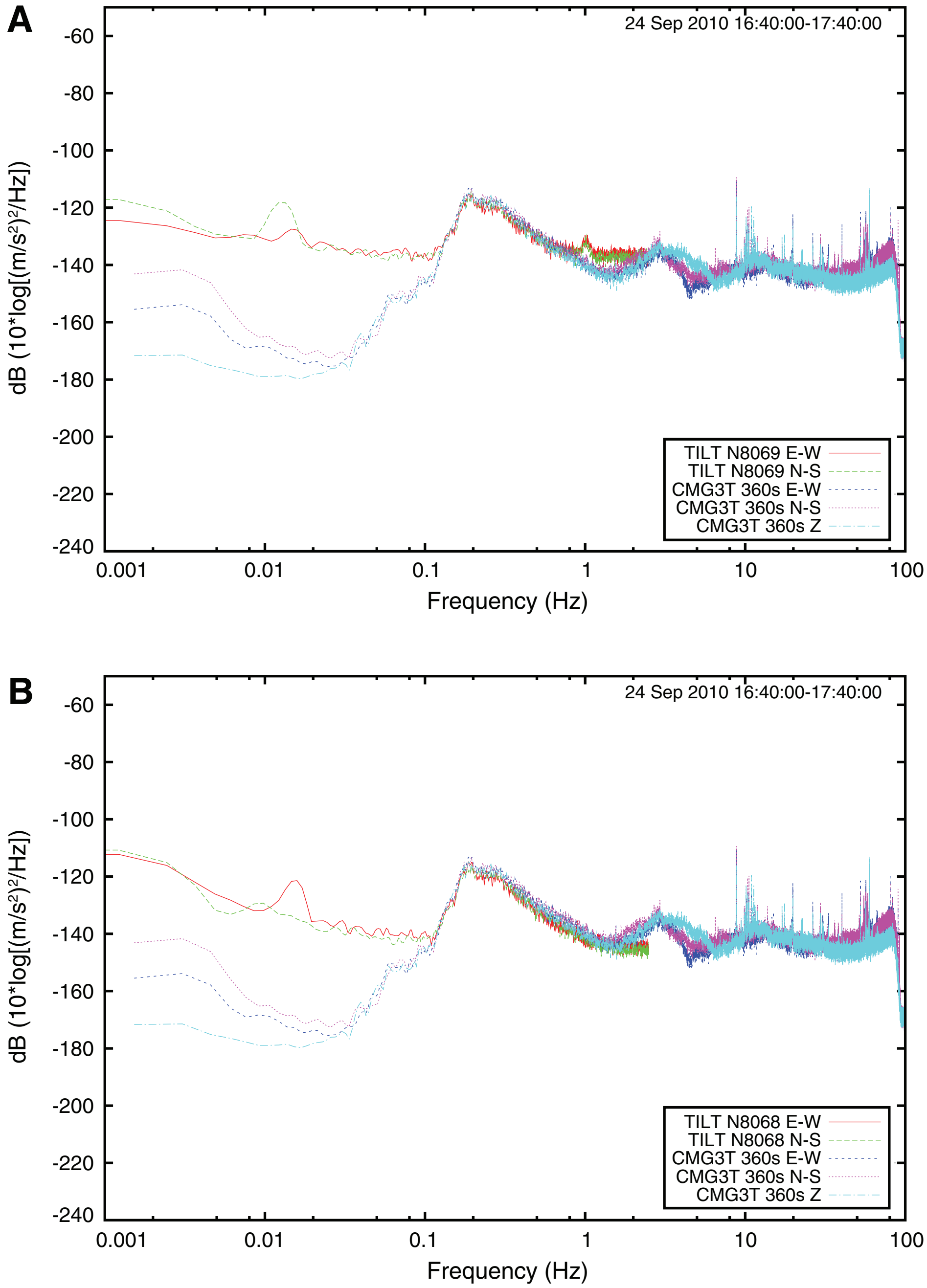

Figure F19. Schematic diagram of thermistor string shown for String 2. T1–T5 indicate position of thermistor modules. The difference between Strings 1 and 2 is the cable end length (L0). L0 of String 1 is 7 m, and L0 of String 2 is 3 m. Thus, total length of String 1 is 150 m, whereas total length of String 2 is 146 m. SAHF = stand-alone heat flow meter.

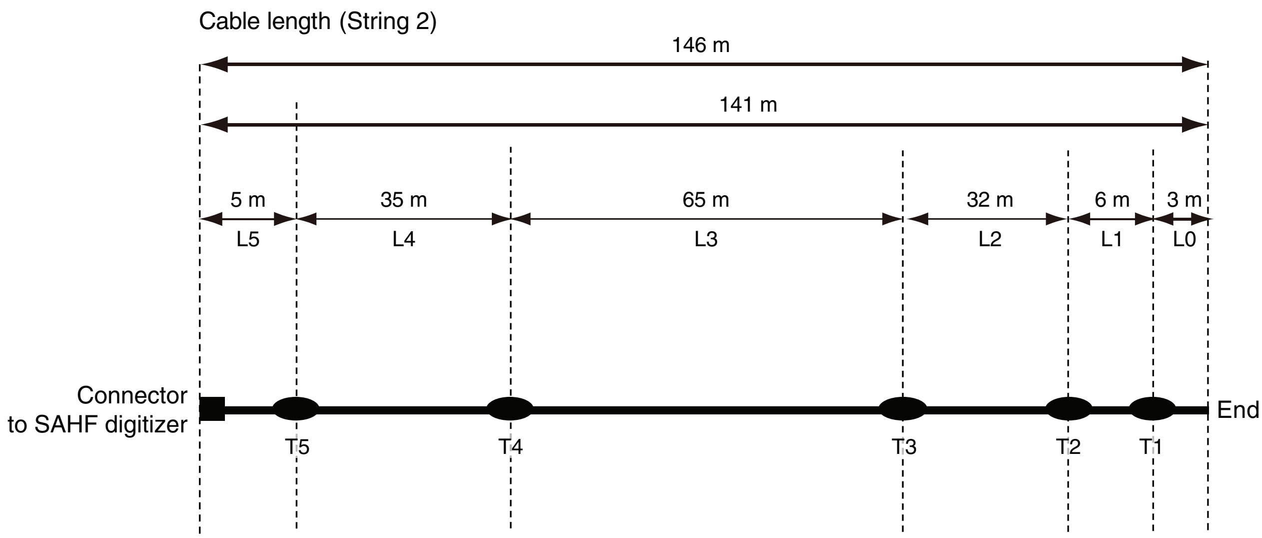

Figure F20. Time series data of thermistor string (stand-alone heat flow meter [SAHF] 1 CH1–CH5) in Matsushiro vault experiment. Miniature temperature loggers (MTL S/N 272 and S/N 301) are used as reference.

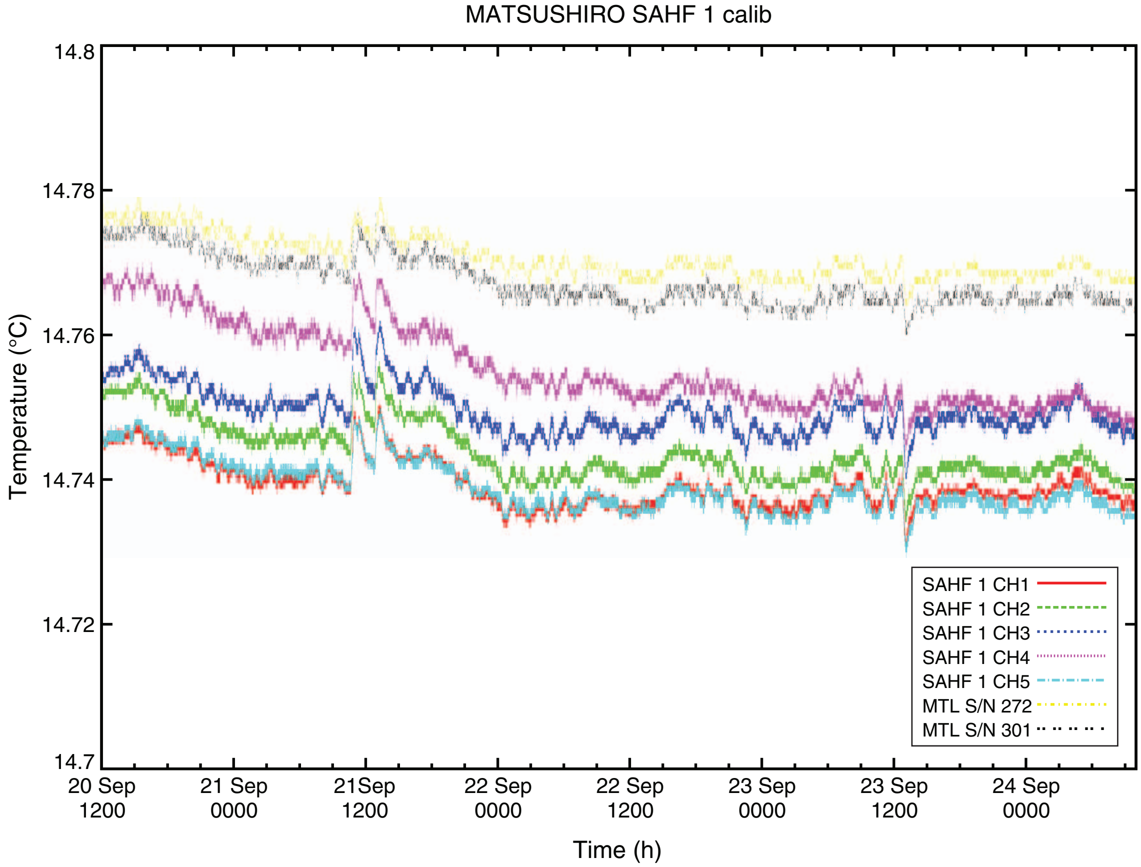

Figure F21. Photograph of pressure unit as well as valve handles within the CORK head "pressure bay" (Bay 1). Note the steel cover for protection and various lines for flushing the borehole tubing and connecting the pressure gauge to either the ocean or the downhole formation. See text.

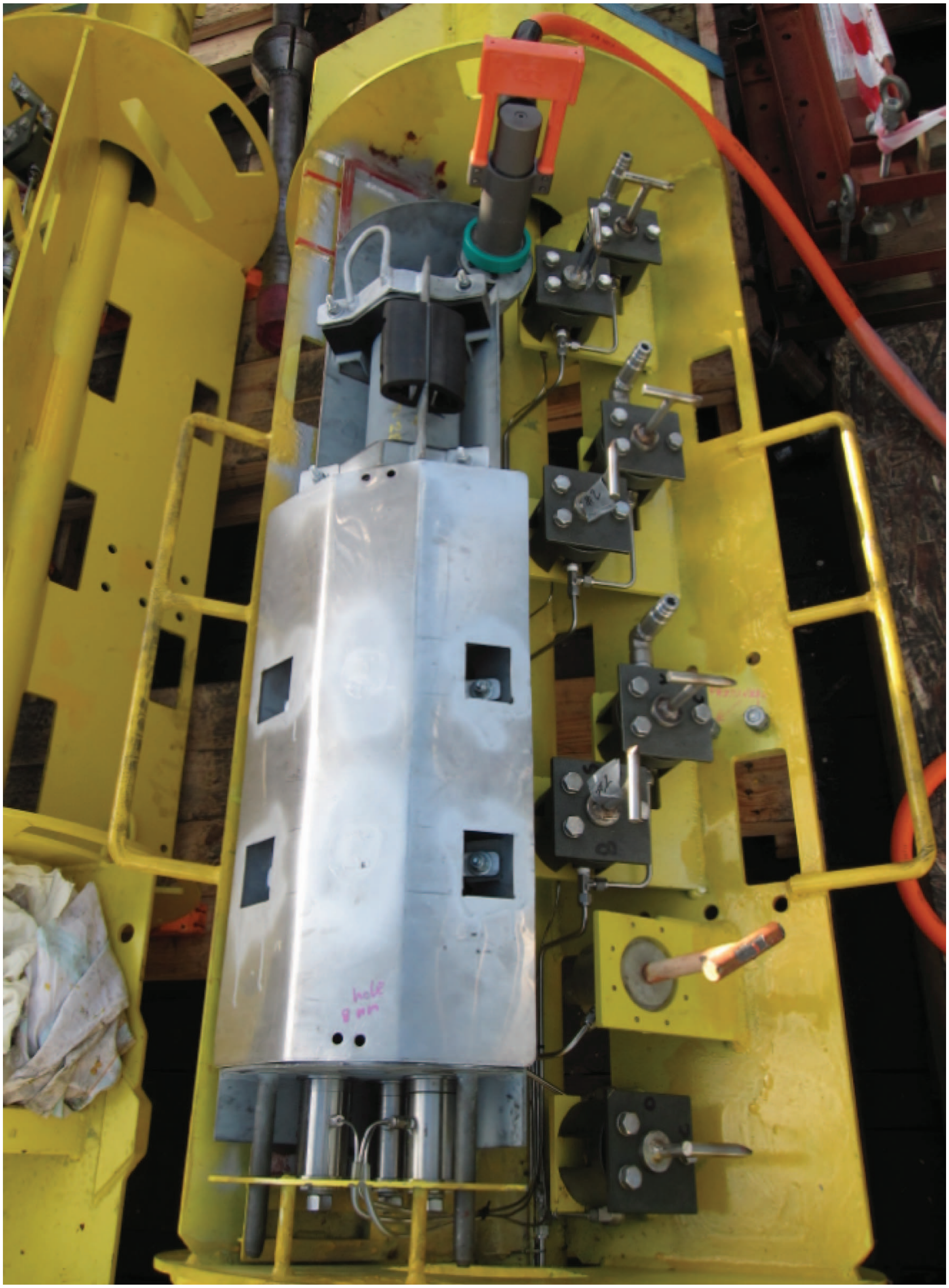

Figure F22. Schematic drawing of instrument carrier. Geophone, accelerometer (tilt logger), thermistor digitizer, tiltmeter, and broadband seismometer are attached on the instrument carrier. XO = crossover, VAM = Vallourec and Mannesmann, OD = outside diameter, ID = inside diameter.

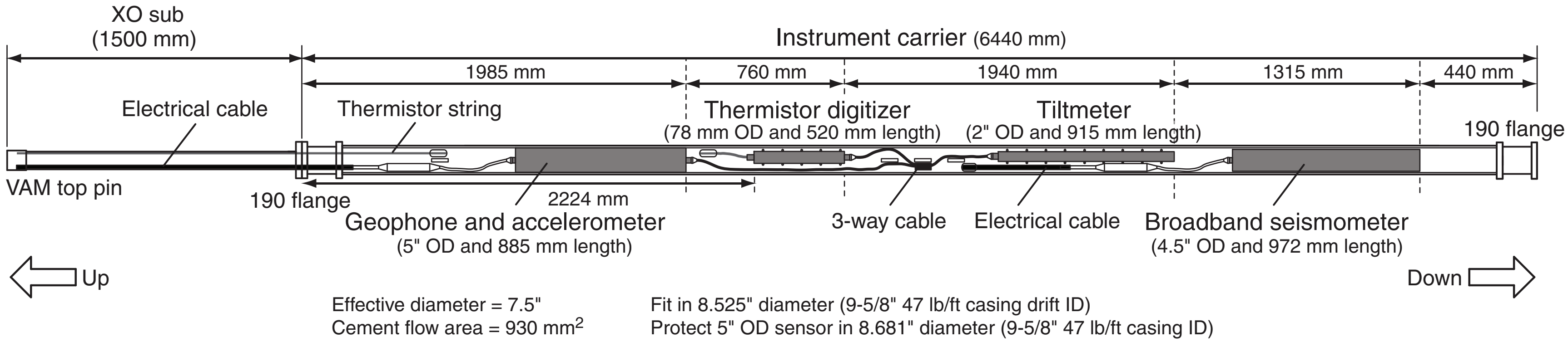

Figure F23. Schematic drawing of electrical cable end.

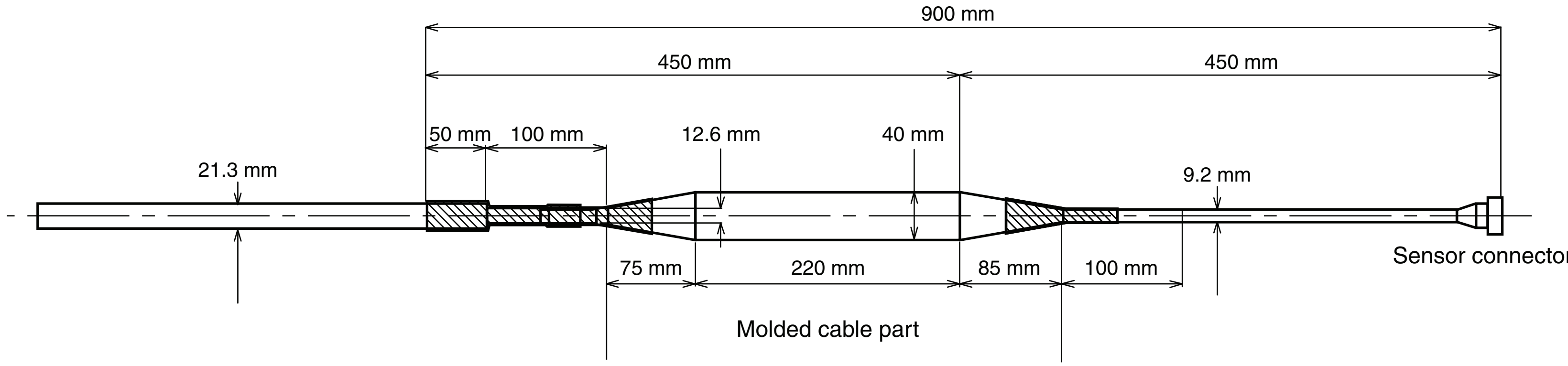

Figure F24. Schematic drawing of 3-phase cable used for connection between tilt logger, LILY tiltmeter, and thermistor digitizer (stand-alone heat flow meter [SAHF] digitizer).

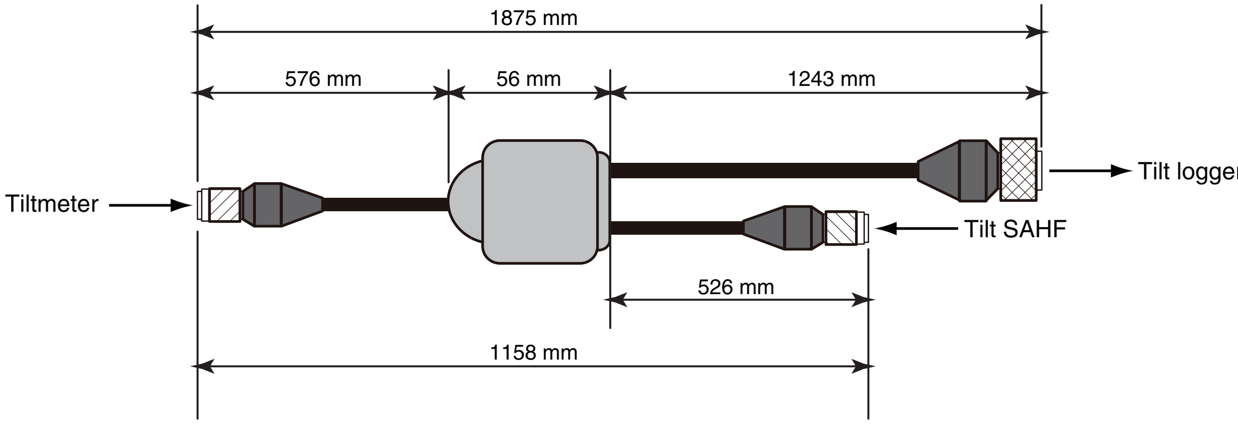

Figure F25. Cross sections at the top and bottom of instrument carrier with sensor orientation of the broadband seismometer, the geophone, the accelerometer, and the tiltmeter.

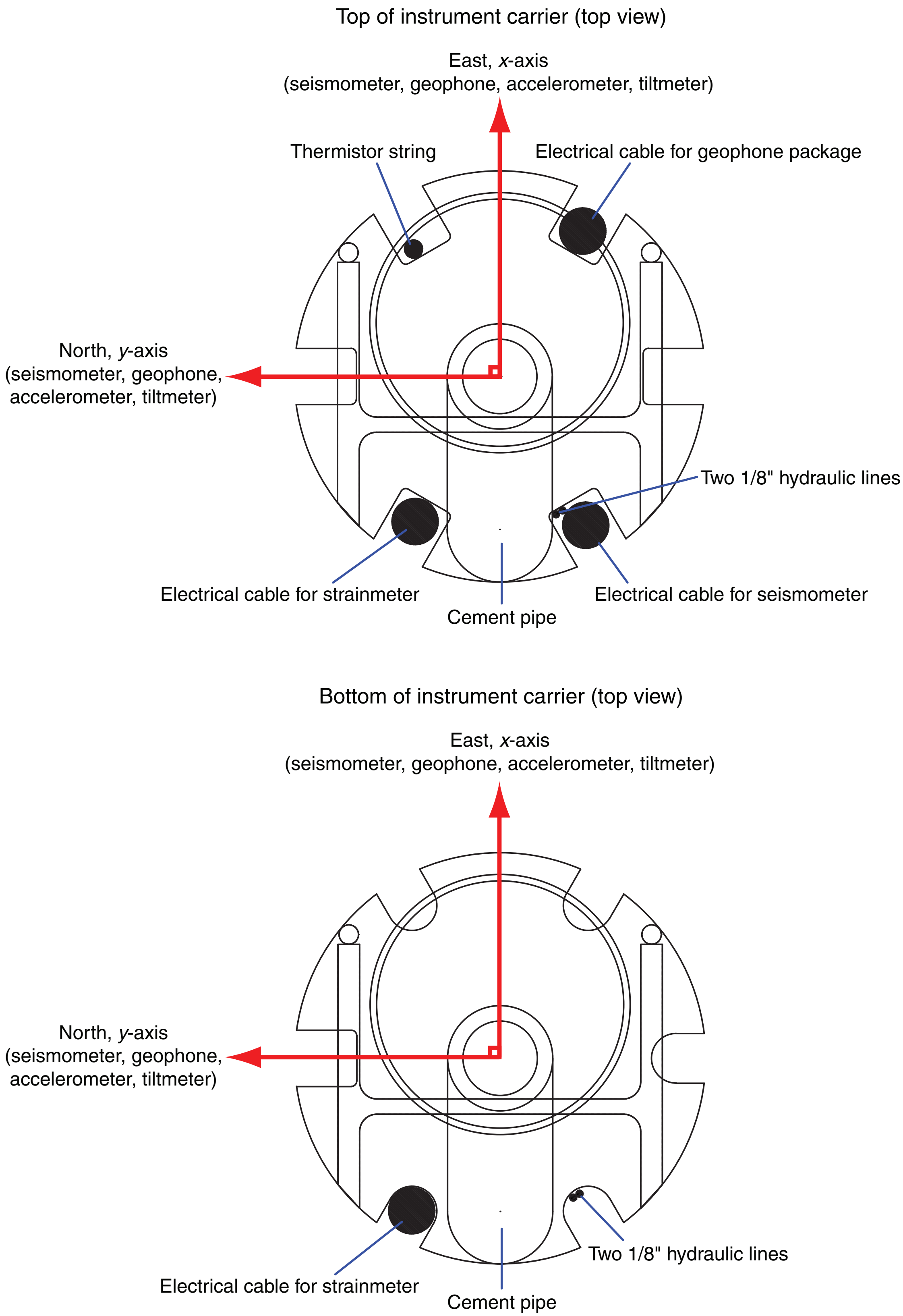

Figure F26. Photograph of centralizer and attachment of cables, thermistor, and flatpack using tie wraps and metal bands.

Figure F27. Photograph of the swellable packer attached to 3½ inch tubings and electrical cables.

Figure F28. Pressure data logger with four high-precision Digiquartz pressure sensors (Paroscientific, Inc.) and two-way and three-way valves. Note cylindrical pressure housing with data logger and pressure period counter unit. See text.

Figure F29. Photograph of CORK head where three ODI Teledyne underwater mateable connectors (UMCs) for the downhole instruments (seismometer, strainmeter, and tilt combo) are mounted.

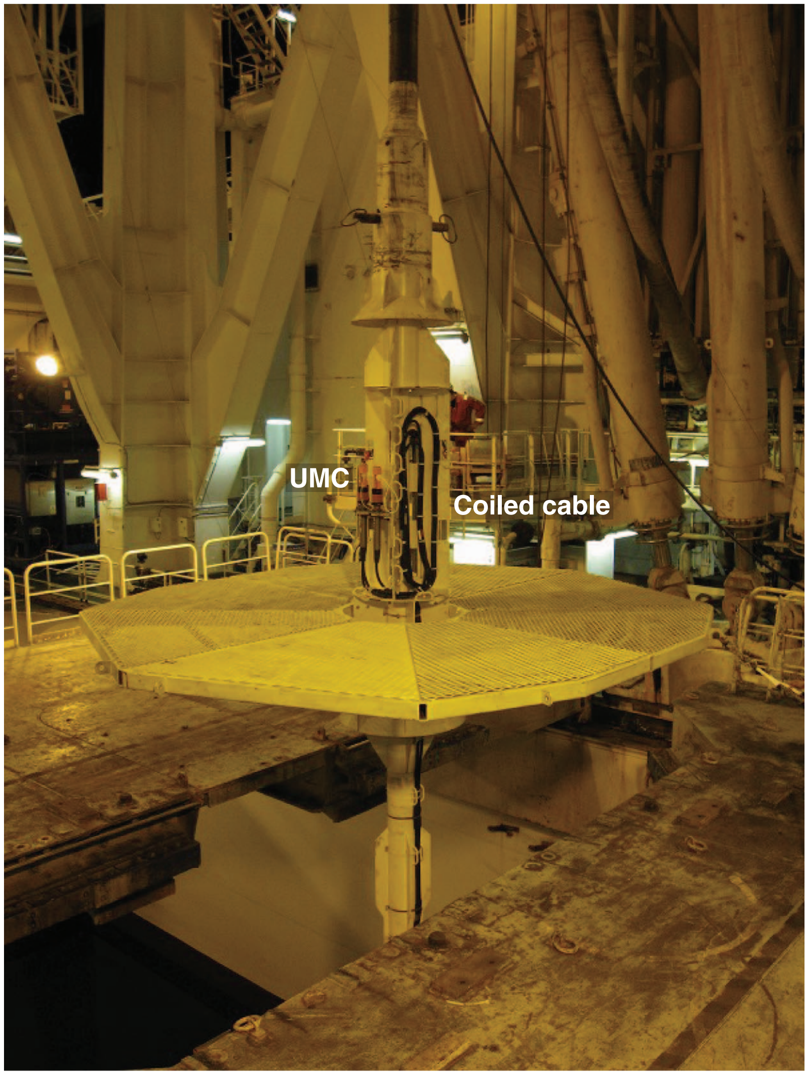

Figure F30. Photograph of assembled CORK head with ROV platform.

Figure F31. Location of observatory sites near IODP Sites C0002, C0010, and C0009 (planned). Red lines = Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) cable, red circles = seafloor observatories, gray = planned cable and observatories, green line = seismological observation cable of Japan Meteorological Agency. JAMSTEC = Japan Agency for Marine-Earth Science and Technology.

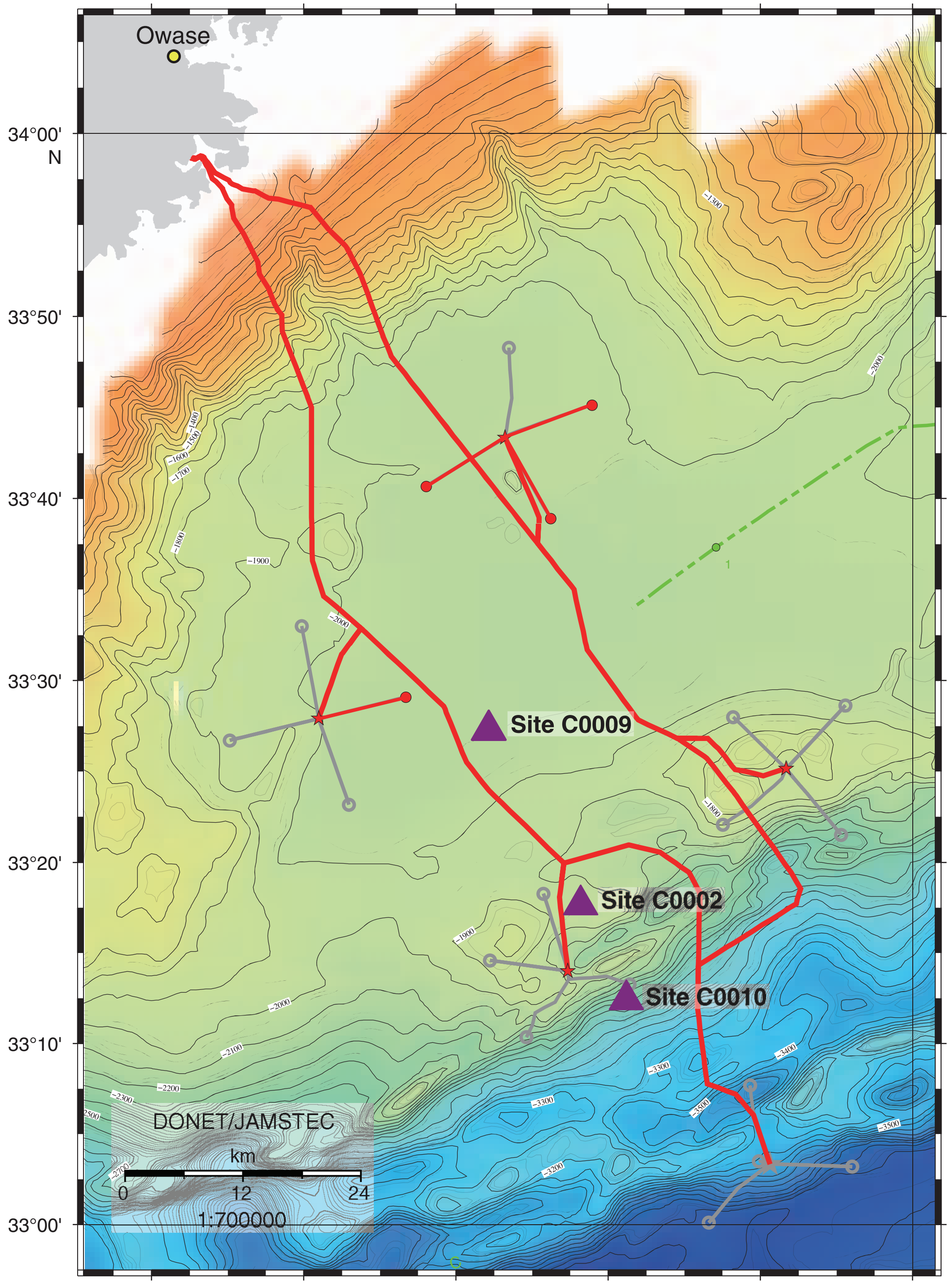

Figure F32. Schematic drawing of VIV measurement accelerometer on drill pipe, as used during SmartPlug retrieval at Site C0010 and LTBMS installation at Site C0002. BHA = bottom-hole assembly.

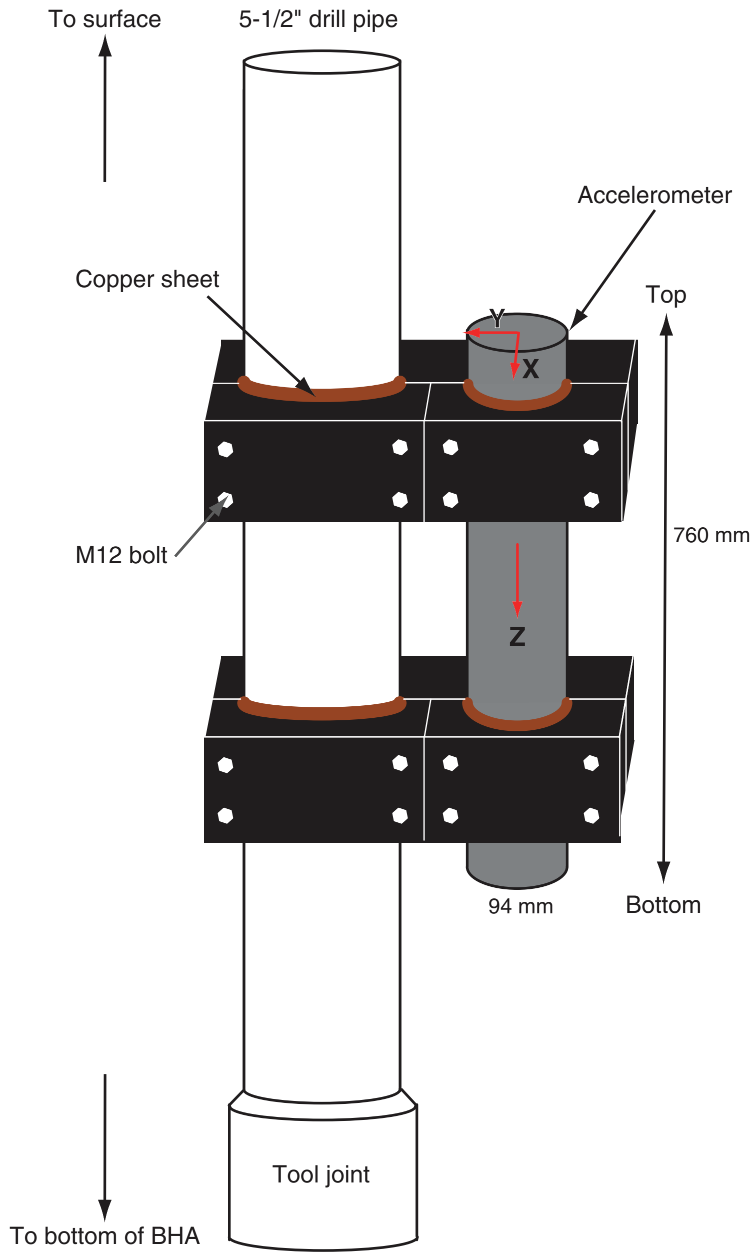

Figure F33. Photograph of accelerometer instrument attached to 5½ inch drill string.

Table T1. Instrument and sensor dimension list.

Instrument/Sensor	Length (mm)	Maximum outer diameter (mm)	Weight (kg)
Instrument carrier	6440	190.5	400
Seismometer	972	114.3	25
Tilt logger	885	127	35
SAHF digitizer	520	78	4
Tiltmeter	915	50.8	5
Strainmeter	9914	190	1000

SAHF = stand-alone heat flow meter.

Table T2. CMG3T broadband seismometer specifications.

Item	Specification
Dimensions	4.5 inch diameter 950 mm length
Pressure housing	Grade 5 titanium tested for 6000 m water depth
Measurement direction	Horizontal north/east and vertical
Output channels	Broadband velocity, mass position, tilt
Frequency response	Velocity response between 360 s and 50 Hz
Channel mapping	Vertical: Z2, north/south velocity: N2, east/west velocity: E2
	Vertical mass position: M8, north/south mass position: M9, east/west mass position: MA
	Calibration signal: X2
	East/west tilt: MF, north/south tilt: MC
Nominal sensitivity:	
Velocity channels	2 sensors: 750 V/m/s each, digitizer: 3.2 μV/count
Mass position	Sensor: 2500 V/m/s^2, digitizer: 290 μV/count (4 Hz), 1.13 μV/count (1 Hz)
Calibration	Digitizer: 3.2 μV/count, sensor calibration coil: 51 kΩ, 0.025 A/m/s^2
Tilt	Approximately 1200 counts for 1° tilt; MF channel positive for east tilt, MC channel negative for north tilt
Standard sampling frequencies	100 Hz (velocity), 4 Hz (mass position and tilt)
	1 Hz (decimated velocity)
Operational tilt range	Within 4.5° from vertical for velocity sensor
Sensor control	Leveling/Unlock/Lock/Centering/Calibration through command from serial communication line
Serial interface	RS-422, 57,600 bps, data transmission in GCF
Power requirement	24–36 V DC
	~6 W when unlocking, 2.8 W running
Connector	Seacon MINK-10-FCR 10 pin for power and serial communication
Time synchronization	Streamsync
	Synchronization status given by ASCII status block

bps = bits per second. GCF = Guralp Compressed Format.