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Long-Term Monitoring Using Deep Seafloor Boreholes Penetrating the Seismogenic Zone

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Abstract

Large earthquakes occur frequently in subduction zones. Most earthquakes are generated in the seismogenic zone, a fairly limited area confined to the shallower regions of the subduction plate boundary. To understand the processes of earthquake generation, it is essential to monitor the physical and mechanical properties of the seismogenic zone over long periods. At present, there are no deep borehole observations of the seismogenic zone more than 3 km below seafloor, because it has, until now, been impossible to penetrate to such depths below the sea floor. The Integrated Ocean Drilling Program (IODP), scheduled to begin in 2003, plans to drill boreholes beneath the ocean floor using a multiple-drilling platform operation. The IODP riser-quipped drilling ship (Chikyu) enables the emplacement of boreholes up to 6 km beneath the ocean floor, and will provide opportunities to conduct long-term deep borehole observations in the seismogenic zone. Long-term borehole observations in the seismogenic zone are expected to require the development of advanced sampling, monitoring, and recording technology. Here, we discuss the scientific objectives, engineering and technical challenges, and experimental design for a deep borehole, long-term deep-borehole monitoring system aimed at understanding the processes of earthquake generation in the seismogenic zone of subduction plate boundaries. We focus specifically on the relationships between environmental conditions in the deep subsurface, details of monitoring and recording, and design and implementation of scientific tools and programs.

Key words: seismogenic zone, long-term monitoring, logging, borehole, IODP

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1. Introduction

The majority of the earth's seismic activity occurs in subduction zones. Studies on the seismic characters of subduction zones are critically important from both practical and scientific perspectives. Large earthquakes and associated tsunami generated in subduction areas have caused significant damage to population centers and civil infrastructure, and understanding earthquake generation in these areas could mitigate damage and allow preparation, design, and engineering of appropriate responses and structures. In addition, clarifying subduction zone tectonics is important for our overall understanding of earth processes. Most earthquakes are generated in the seismogenic zone, which is a limited portion of subduction zones confined to specific temperature, pressure, and hydration regimes along the plate boundary. In the seismogenic zone, strain accumulates due to the strong coupling between subducting and overriding plates, and is eventually released as a large earthquake. To understand this process and to potentially predict a large earthquake, many methods of observation and experiment are applied, mainly in subareal installations and investigations. From the results of these observations, the modern understanding of the tectonics of subduction has made significant progress. However, our understanding of the mechanics of plate boundary faulting in seismogenic zones is still limited due to a lack of information from observations and experiments close to plate boundaries.

Geophysical and geochemical (hydrothermal) long-term monitoring using seafloor boreholes is useful to reveal the processes of plate dynamics. The Ocean Drilling Program (ODP) has conducted several long-term downhole seismic and geodetic observation programs, coupled with temperature and pressure monitoring, and water sampling to further expand our understanding of subduction tectonics. ODP has conducted many downhole seismic observations using boreholes (e.g. Stephen *et al*., 1983; Jacobson *et al*., 1984; Duennebire *et al*., 1987). However, there were only a few long-term observations until 1999: observation at ODP794D hole in the Japan Sea (Suyehiro *et al*., 1992), experiment at ODP396B hole in the Atlantic Ocean (Montagner *et al*., 1994), and observation at ODP843B hole off Hawaii in the Pacific Ocean (Stephen *et al*., 1999). These observations used broadband sensors and the installations aimed at the eventual construction of a permanent seismic station for the global seismic network. Among them, the longest observation period was 115 days for the observations off Hawaii. Geophysical sensors including broadband seismometers were installed in four seafloor drill holes at three sites around Japan from 1999 to 2001, and long-term observations have begun to be collected (Sacks *et al*., 2000; Kanazawa *et al*., 2001; Salisbury *et al*., 2002). Specifically, observation systems installed at holes ODP1150D and 1151B holes (station names are JT-1 and JT-2, respectively) on the slope of the landward side of the Japan Trench have, for the first time, included tiltmeters and volumetric strainmeters (Sacks *et al*., 2000). A seismic record of more than one year (421 days in total) was recovered from the WP-2 station, which has broadband seismometers installed in ODP hole 1179E, in August 2002 (Shinohara *et al*., 2002).

For temperature and pressure long-term monitoring and water sampling, the Circulation Obviation Retrofit Kit (CORK) observation system was developed in 1990. The CORK system monitors temperature, pressure, and water chemistry in the borehole. One of the objectives of the CORK system is to estimate the flow of water beneath the seafloor. CORK puts a lid on the top of a hole and deploys downhole temperature sensors, pressure gauge, and water sampler/analyzer. The data are retrieved by submersibles (Davis *et al*., 1992). Several CORKs were installed during ODP Legs. Recently, the A-CORK (Advanced CORK) system, which separates a borehole into partitions with packers to obtain information from particular places (such as faults), was developed and has been installed in ODP holes 808I and 1173B in the Nankai Trough during ODP Leg 196 (Mikada *et al*, 2002). However, there are no deep borehole observations of the seismogenic zone more than 3 km below the seafloor, because it has been impossible to penetrate to such depths.

A new riser-equipped, dynamically positioned drilling vessel, Chikyu, is being constructed and will be operational in the near future. Chikyu has the capability to drill to depths of up to 6 km beneath the sea floor. This capability will enable penetration of the plate boundary in subduction zones such as the Nankai Trough. Riser drilling provides opportunities both to obtain samples from the plate boundary zone and to conduct long-term observations at or near a plate boundary. Data sets revealing spatial and temporal changes in the geophysical and geochemical properties of the plate boundary and associated fluids and fluxes are important factors for understanding the tectonics of subduction. Long-term monitoring and downhole measurements are the only ways to acquire such data. Long-term downhole monitoring and measurements in seismogenic zones using deep boreholes requires the development of new technologies for measuring, recording, and relaying data. In this paper, we present the objectives of long-term monitoring and downhole measurements in seismogenic zones, and discuss some of the specific goals of downhole seismic and geodetic observation, temperature and pressure monitoring, electromagnetic field monitoring, water sampling, biological sampling, and downhole logging. We also discuss the feasibility and challenges presented by downhole measurement and monitoring from a technological perspective. This paper is based on the interim report of the downhole measurement/monitoring working group, OD21 science advisory committee, available through the OD21 Program Department (od21@jamstec.go.jp)

2. Objectives and specifications of long-term monitoring and downhole measurements in seismogenic zones

One of the objectives of long-term monitoring and downhole measurements in seismogenic zones is to construct a physical model of earthquakes occurring along a subduction plate boundary. For this purpose, seismic and geodetic observations, temperature and pressure measurement, electromagnetic measurement, water sampling, samples of living organisms, and downhole logging give useful information. Below, we discuss the program objectives and technical specifications for these monitoring and measurement initiatives.

2.1. Objectives of downhole measurement and monitoring in seismogenic zones

2.1.1. Seismic and geodetic observation

Downhole geodetic observations are necessary to estimate the physical conditions of the seismogenic zone and to understand spatial and temporal variations of strain accumulation and release in seismogenic zones. From geodetic observations, we can estimate stress accumulation in the seismic zone, obtain time series strain release data, and pinpoint locations of stress and strain accumulation. In addition, downhole seismic observations will be useful for measuring the radiated energy of earthquakes (spectrum), source mechanisms (direction and rate of rupture propagation along a fault plane), and the distribution of wave scatterers around the fault.

2.1.2. Temperature and pressure monitoring

Temperature and pressure are important parameters used to estimate the physics of earthquake rupture, stress and strain accumulation, and the physical character of fault zones. Measurements of temperatures and pressures, as well as documenting temporal changes of temperature and pressure within a deep borehole in the seismogenic zone are essential for estimating overall temperature and pressure conditions within subduction zones. These observations will be combined with depth variations of temperature and pressure down to the seismogenic zone to explore the role of water in earthquake generation, and the relationships between the subsurface fluid flow and the discharge volume at cold seeps on the seafloor.

2.1.3. Electromagnetic observations

Pore fluid pressure is an important variable in any discussion of the processes of earthquake generation. Changes in pore pressure often accompany fluid flow events, which are detectable by electromagnetic observations, as well as pressure and temperature observations. Electromagnetic phenomena related to fluid movement include variations in the spontaneous potential field and changes in electrical conductivity. The average velocity of fluid flow in (or through fractures in walls of) a borehole is obtained from changes in magnetic and electric fields related to the spontaneous potential field. According to numerical estimations (Segawa and Toh, 1992; Jouniaux *et al*., 1999), changes in magnetic and electric fields in the vertical direction due to fluid flow are larger than those in the horizontal direction. Therefore, a vertical array of sensors is ideal for detecting fluid flow, and can be constructed using a borehole. The amount of fluid can be estimated from changes in electrical conductivity around a borehole. In addition, the stress field can be estimated by relating geomagnetic total field variations with strain measurements that record tectono-magnetic effects on local crustal material.

2.1.4. Water sampling and organisms

It is important to estimate the mode of movement and the source regions of pore water, as well as environmental changes, in seismogenic zones from chemical composition and temporal geochemical variations in water obtained from borehole sampling. It is possible to estimate the chemical and thermal environment, and variations in these parameters, of a seismogenic zone from biomass volume, microorganism community structure, and microbial activities.

2.1.5. Downhole logging

The physical properties of seismogenic zones are characterized by downhole logging. We will also make depth profiles of physical properties from the seafloor to the seismogenic zone. Downhole logging down to and within the seismogenic zone enables identification and characterization of the seismogenic zone, physical property profiling, estimation of pore fluid characteristics, volume, flow rate, source, and hydraulic permeability, all of which are critical information used for determining where and what kind of sensors for long-term observation should be installed.

2.2. Study areas of downhole measurement and monitoring in seismogenic zones

To meet the objectives of downhole measurement and monitoring in seismogenic zones discussed above, it is critical to carry out observations and collect data in or near sections of the plate boundary, the décollement and subsidiary (splay) faults. Therefore, drilling should at least reach the seismically active portion of the plate boundary (or décollement), and measurement and monitoring are required along or near these fault segments. It is also important that measurement and monitoring are carried out across several fault segments that have different structural characteristics and tectonic histories. In seismogenic zones such as the Nankai Trough, measurements in the following three regions are suitable and practicable: a segment of the décollement with a small estimated slip during recorded or historic large earthquakes, a splay fault plane branching off from the plate boundary, and a segment of the plate boundary with large estimated slip during recorded or historic large earthquakes (Fig. 1).

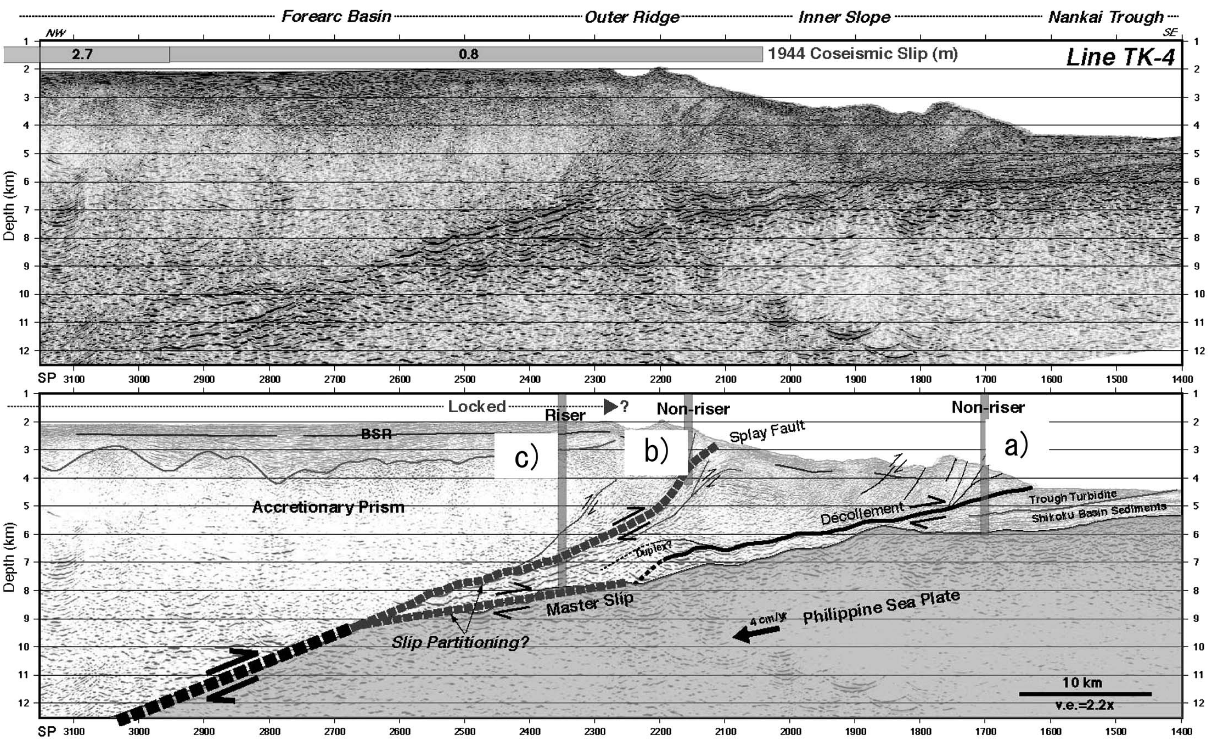

Fig. 1. Borehole positions in a seismogenic zone for downhole measurement and monitoring (from Park *et al.,* 2002). a) Décollement near the trough (plate boundary), b) Splay fault (branch fault), c) Up-dip limit of the seismogenic zone (plate boundary). Three positions for drilling are suitable for long-term monitoring to clarify the process of plate subduction.

2.3. Specifications of downhole measurement and monitoring in seismogenic zones

2.3.1. Seismic observations

Seismic observations need to cover the entire range of seismic activity from microearthquakes to great earthquakes that occur at plate boundaries. Such seismic observations require a wide dynamic range (120 dB or more) and a wide frequency band (0.5 Hz–1,000 Hz). Observation sensitivity should be at least 10^{-7} (m/s^2); such a high sensitivity is possible and desirable because low seismic noise is expected in deep boreholes (Fig. 2). Deployment of vertical seismometer arrays in boreholes is also necessary to significantly improve the determinations of focal depths and focal mechanisms of recorded earthquakes. In this case, arrays with several-meter intervals are necessary for individual fault segments, and arrays with several-hundred-meter intervals are sufficient for other regions. A small span seismometer array near faults will be useful for observing fault zone waves such as fault zone head wave, direct wave propagating in fault zone, and seismic trapped waves to understand fault zone properties (e.g. Ben-Zion and Malin, 1991; Hough *et al.*, 1994; Li *et al*, 1994).

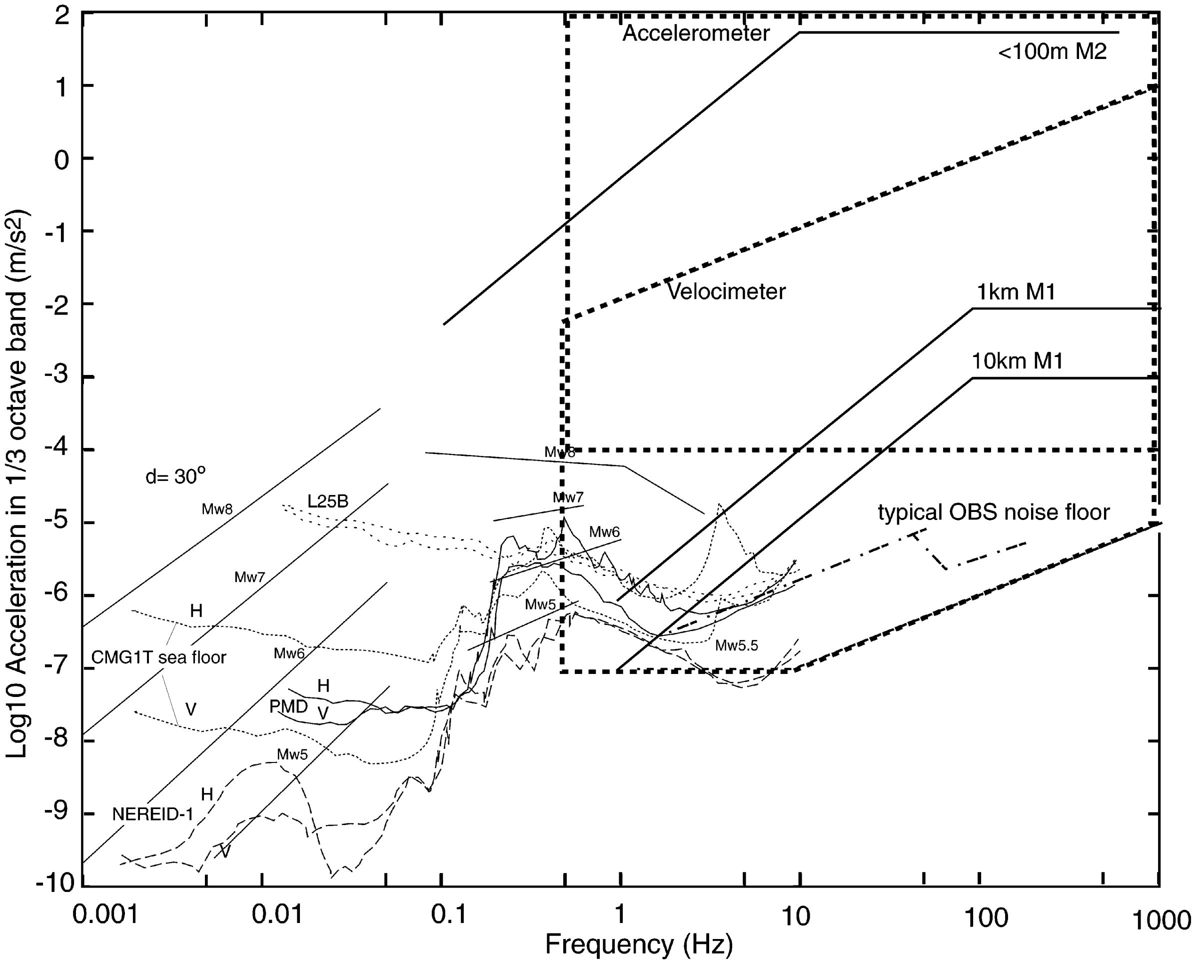

Fig. 2. Relation between frequency band and sensitivity in earthquake observation. Typical ambient noise spectra from broadband borehole seismometer in the Japan Trench (NEREID-1), broadband seismometer on the sea floor off Sanriku (CMG1T), and intermediate period seismometer on the sea floor (PMD) are plotted. Typical noise spectrum of a conventional OBS with short-period seismometer is also shown (L25B). H and V indicate vertical component and horizontal component of seismometer, respectively. The accelerations expected from earthquakes of different magnitudes at various epicentral distances are also shown by solid lines (Agnew *et al.*, 1986). Polygons with thick dash lines indicate frequency band and dynamic range of velocimeter and accelerometer for microearthquake observation in a deep borehole. Note that the noise level from sea floor borehole seismometer (denoted by NEREID-1) is lowest with a frequency band from 0.01 Hz to 10 Hz.

2.3.2. Geodetic observations

We estimate strain and tilt fields associated with subduction (modeled with and without slow slip on the plate boundary and associated splay faults) using a calculation based on the work of Savage (1983), Okada (1992), and Nakanishi *et al.* (2002). The objectives of the numerical calculation are to estimate the possibility of detecting temporal variations in strains and tilts associated with subduction, both with a locked plate boundary and with slow slip along the splay fault and a plate boundary, using existing sensors at suitable positions to monitor strain and tilt.

We used a program developed by Okada (1992) for the calculation. The program calculates internal deformation fields due to shear faults in a half-space for rectangular sources. First, we estimated deformation around the borehole using the back-slip model (Savage, 1983). The locked zone along the plate boundary is assumed to be from 9 km deep to 23 km deep along the plate boundary, based on the results of a seismic survey using ocean bottom seismometers (Nakanishi *et al.*, 2002). The top of the locked zone is assumed to be relatively deep for estimating the possibility of detection. This situation gives small values for strain and tilt at the borehole positions. The length of the locked zone is 85 km. The magnitude of displacement of the subducting plate along the plate boundary is 4 cm. This corresponds to a period of one year from the start of monitoring. Fig. 3 shows the calculated strain and tilt fields. The strain and tilt are concentrated at the termination of the locked zone. The order of strain and tilt near the proposed borehole positions are 10^{-7} strain and 10^{-6} radian, respectively. Variations of strain and tilt with depth are clearly seen. These results indicate that long-term monitoring of strain and tilt in boreholes can locate the transition zone between locked zones and unlocked stretches of the plate boundary.

Second, we calculated strain and tilt using the assumption that instead of a locked plate boundary, a slow slip occurs along the plate boundary and associated splay faults. The total amount of slow slip was assumed to be 1 cm. The slipping region consists of a section of the plate boundary with a length of 30 km and a splay fault with a length of 28 km. The edge of the slow slip region reaches the sea floor. Fig. 4 shows the results of the calculations. Calculated strains and tilts have large values at the edge of the slow slip area, especially in the region of the footwall directly below the emergent tip of the slow slipping fault. This indicates that vertical arrays in deep boreholes are useful to detect slow slip on plate boundaries and/or splay faults. Consequently, the strain and tilt associated with subduction, with either a locked plate boundary or with slow slip on the plate boundary and splay faults, can be detected using existing sensors. Vertical arrays of strainmeters and tiltmeters in deep riser holes are essential to estimate the positions of transition zones between locked and unlocked portions of the plate boundary. The vertical arrays are needed to determine regions of slow slip. Penetrating a slow slip fault (e.g. a splay fault) is necessary to observe strain along these structures.

According to the numerical calculation, strain and tilt should be measured at several points with intervals of a few kilometers above and below faults in a borehole to estimate the coupling of the plate boundary. Data collected with one-second measurement intervals over an extended observation period (more than one year) are ideal. It should be noted that effective coupling with the crust is necessary.

2.3.3. Temperature monitoring

Downhole measurements of the temperature field and heat flow require collection of sensor data along the entire length of the borehole. Measurements should be taken at intervals of 1 m in the vicinity of faults, and every 100 m at other places. A sampling rate of 1 minute is sufficient, as long as data are collected over a long period with a measurement precision of ~1 mK for relative values and ~1 K for absolute values.

2.3.4. Pressure monitoring

It is necessary to measure both absolute pressure and changes in pressure. Detecting fluid movements associated with earthquakes requires that measurements are sensitive enough to record pressure changes of 10^4 Pa over a 12- to 24-hour period, and changes of 10 Pa over a period of ~100 seconds. Sensors must be able to record absolute pressure with a precision of 10^6 Pa. Data should be collected over temporal intervals of about 1 minute and over a spatial scale of 1 m around faults, and about 100 m in other regions.

2.3.5. Electromagnetic observations

Jouniaux *et al.*, (1999) showed that magnitude of

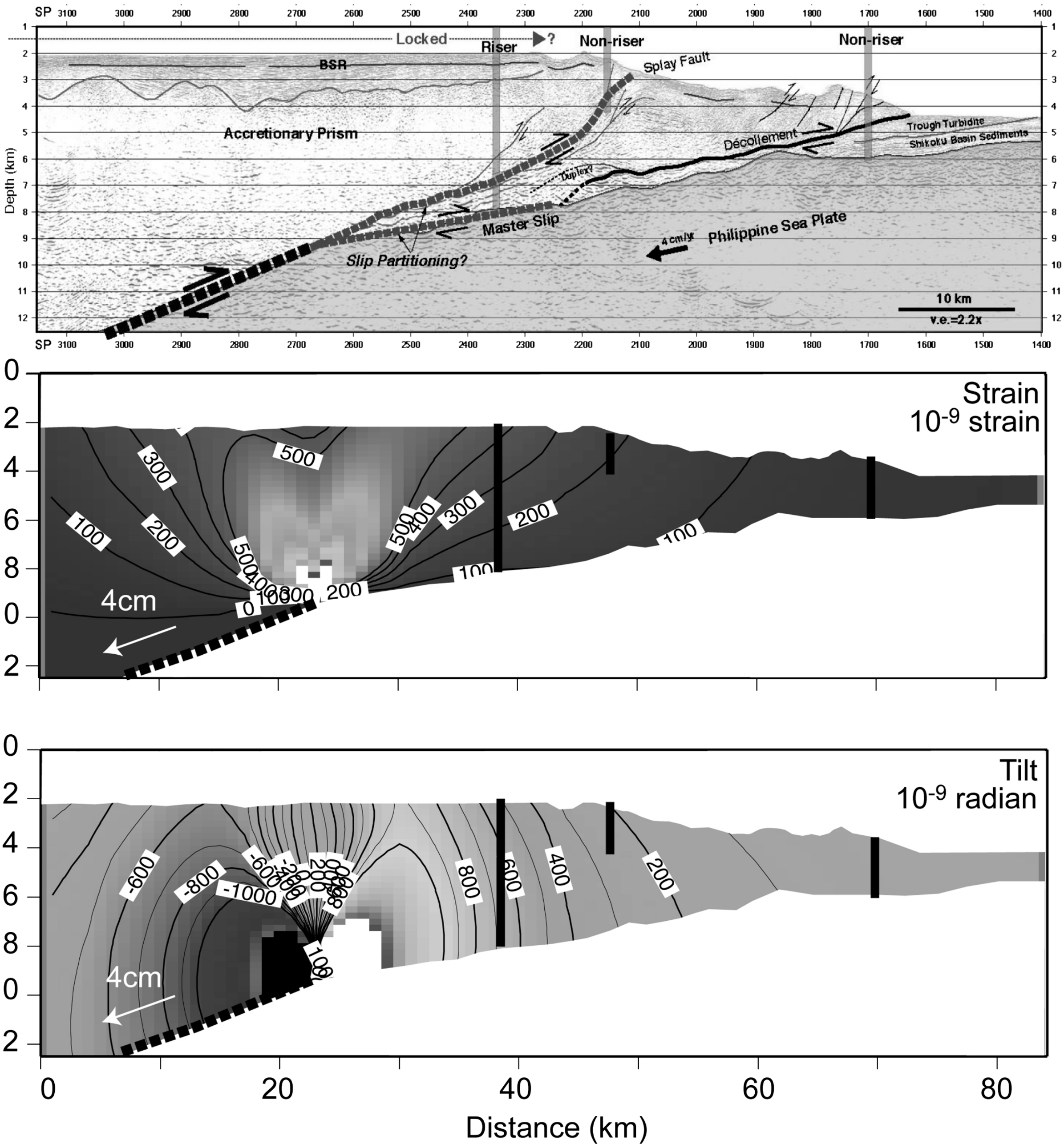

Fig. 3. Strain and tilt field calculated by method of Okada (1992) associated with the plate subduction. Top: Depth migrated MCS section. Thick dashed lines indicate the locked area on the plate boundary. Black bars denote boreholes. A displacement of the subduction plate of 4 cm is assumed. Middle: Calculated strain field. Strain parallel to the profile is plotted. Bottom: Calculated tilt field. Tilt parallel to the profile is plotted.

an electric field anomaly for fluid flow is 10–50 mV/km for the vertical direction and the size of an anomaly is a few hundreds meters for the vertical direction. When the variation of fluid flow is 0.1%, the magnitude of electric field anomaly is 10–50 μV/km. Therefore, electric fields should be measured with a precision of 0.01 μV near faults and 1 μV at other places. Jouniaux *et al.*, (1999) also estimated that the magnetic field anomaly is 0.005–0.015 nT/km for a 0.1% variation of fluid flow. Magnetic fields should be measured with a precision of 0.001 nT. These measurements also require long-term stability. High-quality observations of the electric fields require extended spatial coverage, so it is desirable to install instruments not only in the downhole vertical direction, but also in horizontal directions in branch holes.

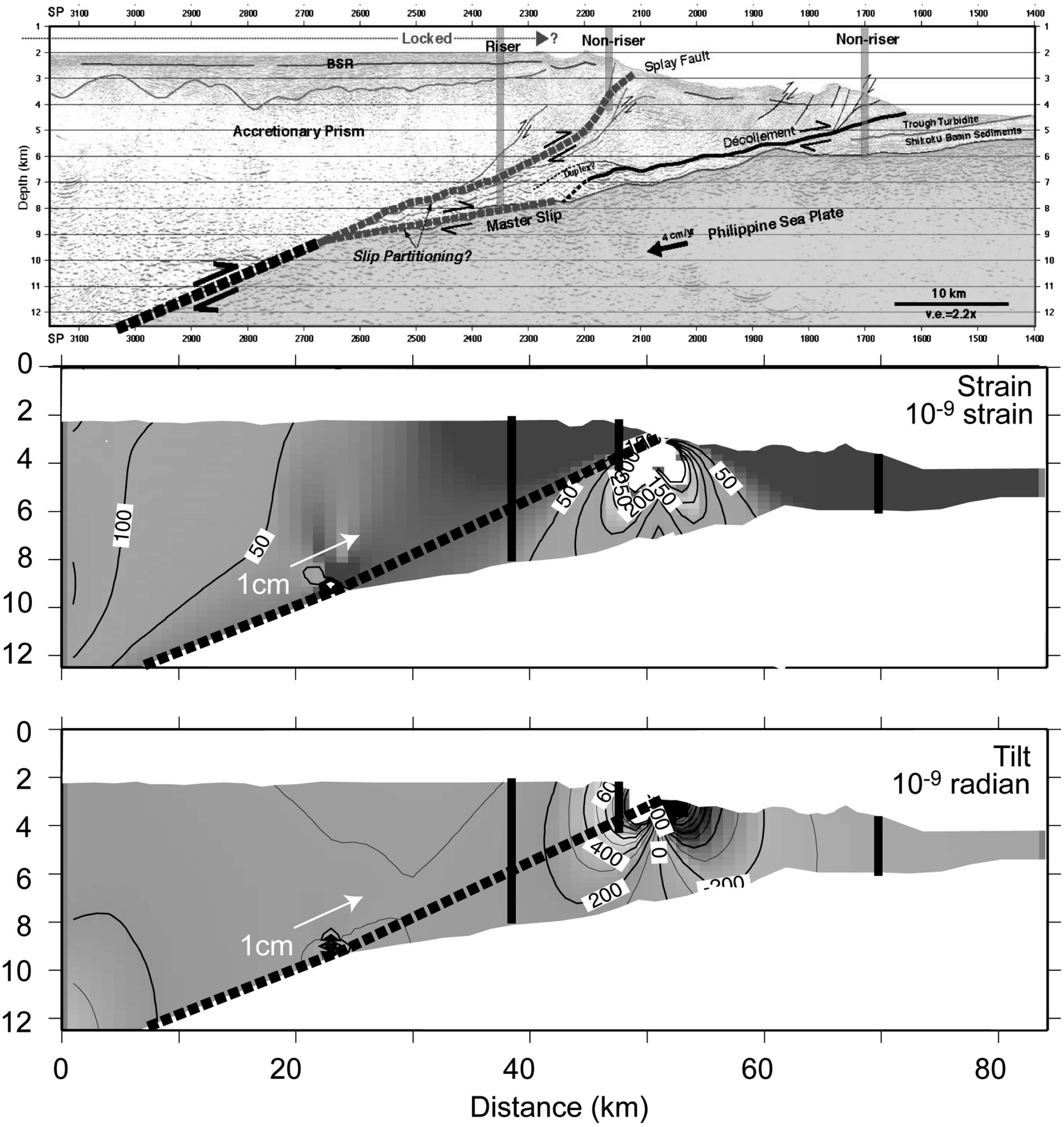

Fig. 4. The same as Fig. 3, but for a slow slip on the plate boundary and the splay fault. The magnitude of the slow slip is assumed to be 1 cm. Note that the landward plate motion is in the opposite direction to that of Fig. 3, because a slow slip is assumed.

Also, data should be collected at several points (at 100–200-meter intervals near faults, and at 1 km intervals at other places) with sampling rates of about 1 minute. For magnetic field measurements, observation intervals of ∼200 m below and above faults are effective to monitor fluid flow, and a reference station is required in the shallow part of a borehole.

2.3.6. Water sampling and microorganisms

If pore water in the crust near a fault can be sampled, we can measure various chemicals and microorganisms. The more pore water we can sample, the more we can measure. Downhole sensors may be able to measure some of the properties we hope to record, but, at present, development of a downhole sampling device is necessary. In addition, contamination of samples during drilling or measurement must be avoided.

2.3.7. Downhole logging

We will conduct downhole logging from the seafloor to the décollement using the most modern array of tools available. Natural gamma ray, gamma ray density, neutron porosity, electric resistivity, sonic velocity, resistivity imaging, acoustic imaging, nuclear magnetic resonance logging, temperature, etc. will be measured. Measurement precision will reflect the capabilities of current tools.

3. Downhole measurement and monitoring plan for seismic zones: Technical and scientific aspects

Here, we address the technical and scientific aspects of the ideal installation plan for an observation system based on the necessary specifications for measurement and monitoring discussed in the previous section. Because of the integrated nature of the site- and target-specific, long-term geophysical measurements we aim to collect, sensors and tools (and possibly the drilling and casing process itself) can be integrated. Seismic and geodetic observations, temperature and pressure measurements, and electromagnetic observations are combined into one installation plan, while water and organism sampling and downhole logging are discussed separately.

Installation plans for long-term geophysical measurements (seismic observation, geodetic observation, temperature monitoring, pressure monitoring, electromagnetic observation) for three areas are considered: non-riser drilling into the décollement near a trench (plate boundary) (Fig. 5); drilling into a branch fault (splay fault) (Fig. 6); and/or riser drilling into an earthquake fault in the seismogenic zone (plate boundary) (Fig. 7). Sensors must be closely spaced at the parts of the borehole adjacent to the drilled faults. Sensor positions should be determined before installation using logging results. In other regions, sensors can be placed in more loosely spaced configurations. In non-riser drill holes (shallower than 2 km) down to and through the décollement, densely spaced sensors are suitable for strain, tilt, fluid pressure, and temperature measurements. If the borehole is inclined, some of the sensors must be mounted on a gimbaled mechanism. The influence of drill hole casing must be also considered for seismic and electromagnetic observations, and some kinds of sensor need to be strongly coupled with the earth's crust outside the casing (Figs. 5, 6 and 7). We need to study how to calibrate the sensitivity of sensors within a drill hole. It is also necessary to evaluate the aging of sensors under high temperatures and high pressures.

For water and organism sampling, compositions and populations that can be measured by downhole sensors are limited. It is realistic to pump water up to the seafloor. Packers enable more sensitive measurement due to the prevention of contamination from other sections, but are incompatible with sampling. For downhole monitoring, newer, more sensitive downhole sensors with a broader range of measurable chemical species must be developed. For pumping, only a duct must be installed, however, if water samplers are used, a conduit for transporting water samplers up- and downhole is necessary.

Downhole logging enables us detect the existence and the volume of a fluid, and to measure hydraulic permeability. The results of deep logging will be helpful for determining a plan to position sensors for long-term observations. For future measurements, we probably need to develop Logging-While-Coring (LWC), as well as new multi-sensor probes, to complement existing Logging-While-Drilling (LWD) packages. LWC is necessary for reliable logging in deep drilling under conditions of lower core recovery rates and unstable borehole walls. A multi-sensor probe will measure temperatures and physical characteristics with a higher spatial resolution than is presently available.

4. Discussions

4.1. Deep drilling

Because the riser holes are very deep, drilling itself is a challenge. Reaching deeper portions of the crust is difficult with the existing ODP method. We need to study and carefully plan the installation of both existing and new equipment packages in the riser holes. A plan for drilling and hole completion considering the downhole long-term observatory is required.

4.2. Sensors for high temperatures and high pressures

New sensors must be developed to ensure stable, long-term data collection and monitoring under high temperatures (about 200 degrees Celsius) estimated from heat flow measurements on the sea floor and

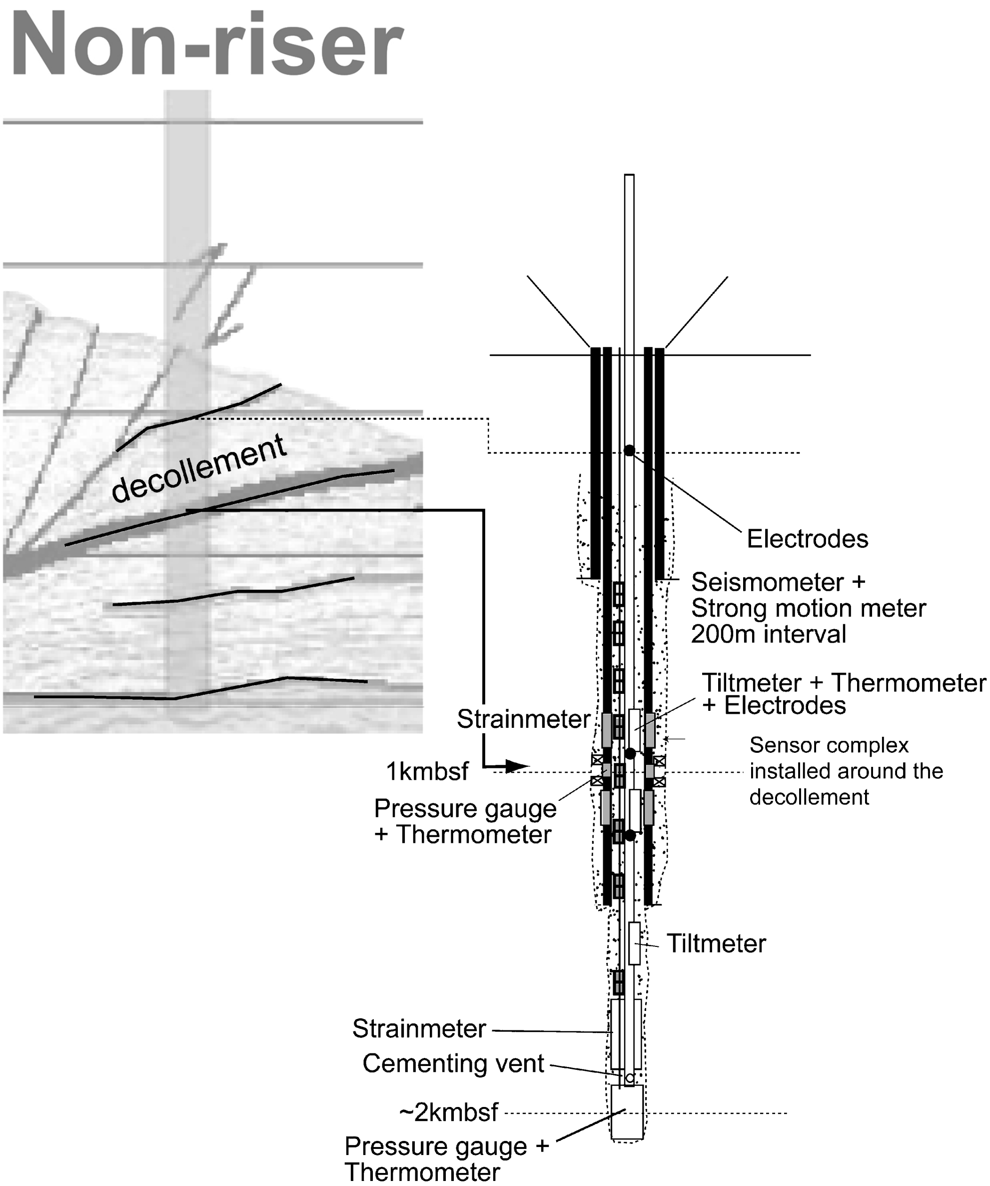

Fig. 5. Installation plan for sensors in a borehole near the décollement around the trench axis. Because crustal movement and fluid flow are expected near the décollement, the sensors should be deployed densely around the décollement.

high-pressure (about 150 MPa) conditions. We must also develop techniques to install these sensors in deep holes. Methods for ensuring direct contact and coupling between the sensors and surrounding rock formations, especially where multiple casings are installed, must be established. Additional techniques for measuring environmental parameters outside the borehole casing (some form of perforation or remote method) must be developed.

4.3. Establishment of casing programs

It is extremely important to design an appropriate casing program before drilling a deep hole, and this is best accomplished by simulating drilling operations. At present, about seven sizes of casing from 7 to 42 inches are available. For drilling, circulation of mud is needed for cooling drilling bits etc. The density of the mud is important for preventing collapse of a borehole in deep region. The mud density for drilling should be determined by estimating modeling closure pressure on fractures and pores by modeling and directly measuring ambient deviatoric and non-deviatoric stresses at depth in the borehole. In practice, we will require a pilot hole to be drilled to obtain these data. The final hole diameter is esti-

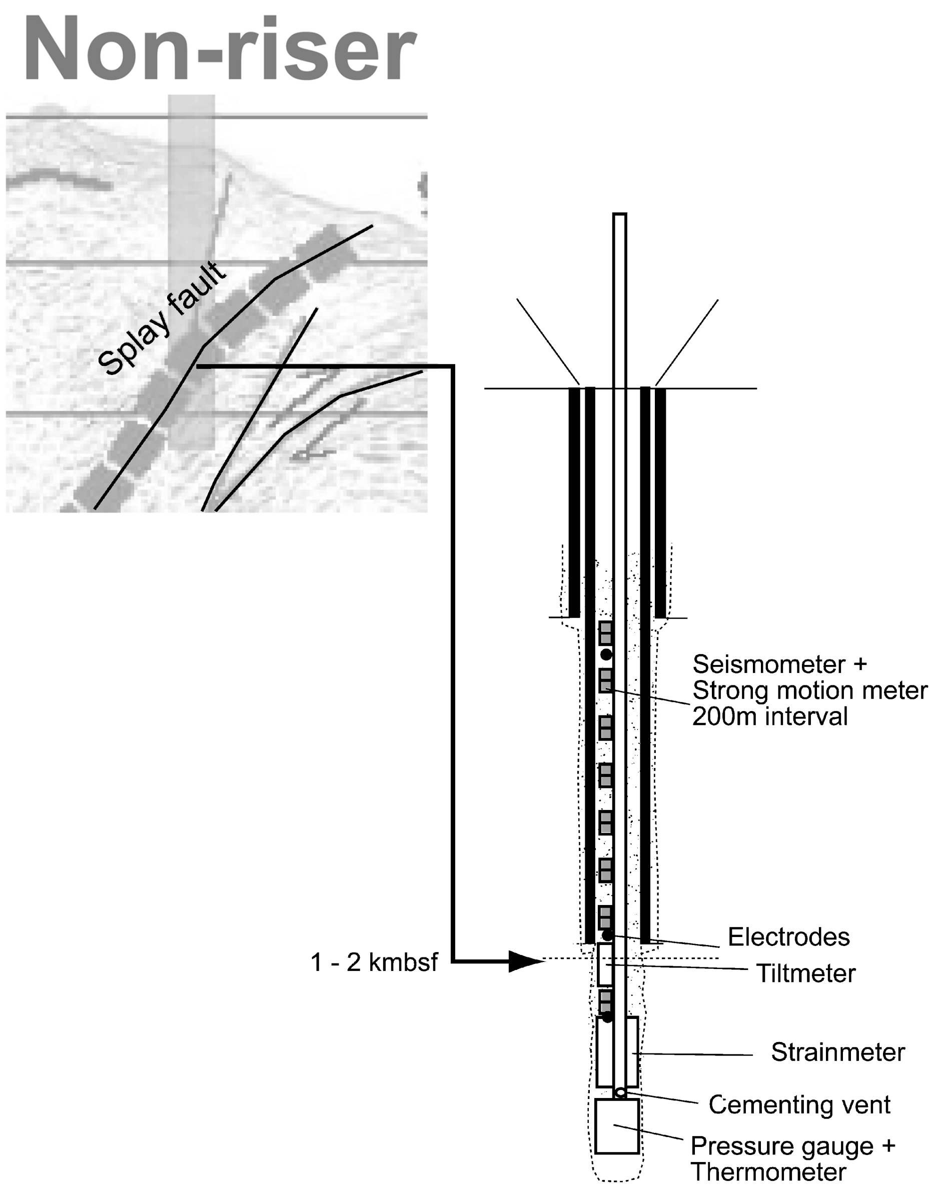

Fig. 6. Installation plan for sensors in a borehole near the splay fault. Strainmeter and tiltmeter near the splay fault will be useful for detecting displacement of the splay fault. Pressure measurements at the splay fault zone are important to monitor fluid flow along the splay fault.

mated to be 8-1/2 inches (7″ final casing). The dimensions of sensor packages must comply with this final hole diameter.

4.4. Drilling and installation of casing

If the casing itself has a special function, for example, if sensors are integrated into a casing, new methods of casing installation must be considered. We also need to estimate the life spans of electronic components and sensors. These considerations are related to hole completion.

4.5. Hole completion: installation of hole-sealing tools

During IODP drilling, it will be required to prevent materials (fluids and particulates) from leaking into the seawater. Therefore, we need hole-sealing tools (wellhead) on the sea floor, even if sensors for long-term observation are installed. The technical specifications of these tools depend on downhole pressure. We also have to study how to retrieve signals from downhole sensors through the wellhead.

4.6. Accurate determination of installation depth of sensors

A technique to identify target regions for sensor installation from downhole logging and coring must

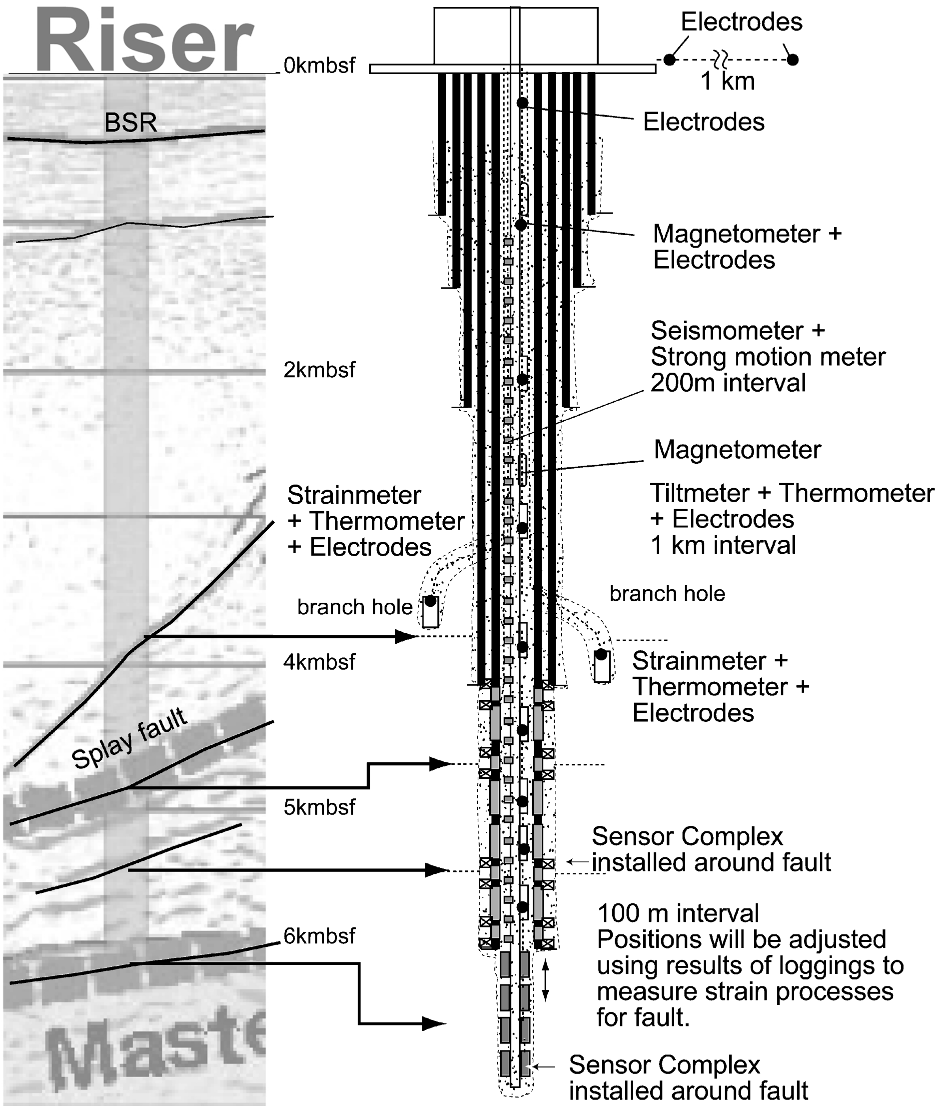

Fig. 7. Installation plan for sensors in a borehole near the up-dip limit of the seismogenic zone. Due to the depth of the plate boundary, riser technology is needed for drilling. A vertical array of strainmeter and tiltmeter is useful to understand the dynamics of plate subduction. Dense emplacement of sensors near the plate boundary and associated faults is suitable.

be established. Since installation of sensors will be carried out after determining the target regions, we will need enough time for depth determination and sensor package installation.

4.7. Transmission of sensor signals to the seafloor

A method of transmitting signals to the seafloor under conditions of high temperature, with multiple casings and multiple sensors must be developed. Cables and connectors for data transmission are important components in this effort. Because it is difficult to use electronic circuits due to high temperatures, we will also consider analog signal transmission as an alternative method.

4.8. Water sampling from deep sections

We will also consider an additional plan to recover cores from deeper sections of the borehole, while simultaneously maintaining ambient high pressures using PTCS (Pressure Temperature Core Sampler: a tool for recovering samples at near in-situ pressures and temperatures in the sub-seafloor) and to conduct on-board pore-water sampling.

4.9. Problems in developing Logging-While-Coring (LWC)

Although development of LWC is considered to be feasible using current technologies, some problems remain to be solved. LWC requires a space in the central part of the logging tool so that the core liner can pass through the tool, making it difficult to equip the tool with a power supply system. Legally, radioactive sources in logging tools must be retrievable if a problem is encountered in a borehole. If there is a space in the central part of the logging tool, it would be more difficult to retrieve the radioactive source. In addition, a central space or conduit through the logging tool will create difficulties in using the mud pulse telemetry system required for Measurement While Drilling (MWD).

4.10. Installation experiment on land

One factor that is indispensable for developing a reliable long-term observation program is implementation of an experimental installation on land to explore and identify problems at the development stage.

4.11. Existing information

For further consideration of borehole instrumentation and downhole monitoring techniques, we will obtain information, results, and techniques from existing deep wells and ongoing or past deep-borehole monitoring programs.

5. Conclusions

This paper summarizes the results of a preliminary survey on the feasibility of technologies necessary for obtaining new scientific results by downhole measurement and monitoring in the seismogenic zone. Deep borehole logging and long-term monitoring in active fault zones will reveal important information required to understand the process of earthquake generation at a subduction plate boundary. During the course of this survey, we recognized several technological challenges facing long-term monitoring in deep boreholes. Some of these challenges have not been encountered during previous long-term observation programs undertaken during ODP operations. We feel that such initiatives are indispensable for the promotion and the development of the systematic technological programs necessary to obtain quality data from measurements and long-term observations in deep boreholes in the seismogenic zone. It is critical to develop new technologies, not only for core retrieval at great depths, but also for instituting a comprehensive downhole measurement and monitoring program.

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