OD21 Science Advisory Committee
Downhole Measurement/Monitoring Working Group
Interim Report

March 6, 2002
May 17, 2002, Revised
June 11, 2002, Drilling and Measurement Panel approved
August 21, 2002, Revised, 2nd version
December 20, 2002, Revised

Contents

1. Introduction 1

2. Previous long-term downhole observations 2

3. Objectives and specifications of downhole measurement/monitoring in seismogenic zones 3

3-1. Objectives of downhole measurement/monitoring in seismogenic zones 3

3-2. Study regions of downhole measurement/monitoring in seismogenic zones 4

3-3. Specifications of downhole measurement/monitoring in seismogenic zones 4

4. Downhole measurement/monitoring plan for seismogenic zones -- from scientific aspects -- 7

4-1. Geophysical long-term monitoring (seismic, geodetic, temperature, pressure, electromagnetic field) 7

4-2. Water sampling and organisms 15

4-3. Downhole logging 17

5. Discussion 18

6. Recommendations: Scenario for technology development in IODP downhole measurement/monitoring 21

7. Reference 23

(Chairperson)

Masanao Shinohara	University of Tokyo, Earthquake Research Institute

(Members)

Eiichiro Araki	Japan Marine Science and Technology Center, Deep Sea Research Department
Masahiro Kamata	Schlumberger K.K., Fuchinobe Technology Center
Masataka Kinoshita	Japan Marine Science and Technology Center, Deep Sea Research Department
Masanori Kyo	Japan Marine Science and Technology Center, OD21 Program Department
Kazushi Kuroki	Japan Marine Science and Technology Center, OD21 Program Department
Yoshinori Kosuge	Schlumberger K.K., Nagaoka Branch
Teruaki Kobayashi	Japan Marine Science and Technology Center, OD21 Program Department
Sunao Konno	Telnite, Co. Ltd., Technology Department
Tadanori Goto	Japan Marine Science and Technology Center, Deep Sea Research Department
Saneatsu Saito	Japan Marine Science and Technology Center, Deep Sea Research Department
Masayoshi Suzuki	Geophysical Surveying Co. Ltd
Toru Takahashi	OYO Corporation, Tsukuba Technical R&D Center
Keiichi Tadokoro	Nagoya University, Graduate School of Environmental Studies, Research Center for Seismology and Volcanology
Urumu Tsunogai	Hokkaido University, Graduate School of Science, Division of Earth and Planetary Sciences
Kazuhiko Tezuka	Japan Petroleum Exploration Co., Ltd., Technology Research Institute
Kenji Namba	University of Tokyo, Graduate School of Agricultural and Life Sciences
Shori Nishi	Schlumberger K.K, Analysis and Consulting Department
Ryota Hino	Tohoku University, Graduate School of Science, Research Center for prediction of Earthquakes and Volcanic Eruptions
Hitoshi Mikada	Japan Marine Science and Technology Center, Deep Sea Research Department
Nobuo Morita	Waseda University, Faculty of Science and Engineering, Department of Resources and Environmental Engineering
Chikao Yoshida	Japan Petroleum Exploration Co., Ltd., Development Headquarters, Development III Section, Ocean Development Group

(Observers)

Hisao Ito	National Institute of Advanced Industrial Science and Technology, Institute of Geosience
Nobuhisa Eguchi	iSAS Office
Tatsuya Murayama	Japan Marine Science and Technology Center, OD21 Program Department

(Secretariat)

Yasuo Yamada	Japan Marine Science and Technology Center, OD21 Program Department

Yoshihisa Kawamura	Japan Marine Science and Technology Center, OD21 Program Department
Hideaki Machiyama	Japan Marine Science and Technology Center, OD21 Program Department
Yusuke Yano	Japan Marine Science and Technology Center, OD21 Program Department
Tetsushi Komatsu	Japan Marine Science and Technology Center, OD21 Program Department

(Previous meeting dates)

The first meeting	November 9 (Friday), 2001
The second meeting	January 8 (Thursday), 2002
The third meeting	February 20 (Wednesday), 2002
The fourth meeting	March 6 (Wednesday), 2002
The fifth meeting	May 17 (Friday), 2002
The sixth meeting	December 20 (Friday), 2002

1. Introduction

The Downhole Measurement/Monitoring Working Group was started at the request of IODP National Scientific Drilling Promotion Committee's Drilling and Measurement Study Panel. Its scope of study is downhole measurement/monitoring in general, such as downhole logging in drilling operation and subsequent long-term downhole measurement (including related drilling techniques). The Group is conducted in cooperation with Analysis, Core, Data Study Panel and other relevant Panels. The focus of study is on drilling hole completion techniques, downhole sensors, and new logging techniques. Results of study will be summarized into a report to Drilling and Measurement Study Panel. Some of the proposals submitted to Support System lack consideration from the technical viewpoint of drilling or measuring/monitoring. In order to make them become feasible proposals, the group will give advice to the proponents in collaboration with Drilling and Measurement Study Panel.

This Working Group had three meetings for discussion until March 2002. In particular, drilling and downhole measurement/monitoring in seismogenic zones, for which proposals have already been submitted, demands a high degree of technology development. Therefore, we decided to take the downhole measurement/monitoring in a seismogenic zone as a case to study specific technical challenges that are necessary to carry out downhole measurement/monitoring. For this, information on what to measure and how to measure is necessary. For a start, we decided to present objectives of downhole measurement/monitoring in seismogenic zones and specifications of measurement, in terms of the following six items: Seismic and geodetic monitoring, Temperature and pressure measurement, Electromagnetic field monitoring, Water sampling, Organisms, and Downhole logging. After that, we will discuss feasibility of measurement/monitoring from technical aspects. At present, we report the result of study on scientific measurements for technical study.

At the fourth and fifth meetings of the Working Group, up-to-date drilling and measurement techniques were presented for better understanding of the current status, and decided to give recommendations to IODP National Scientific Drilling Promotion Committee's Drilling and Measurement Study Panel, toward future activities. We complemented the recommendations and the scope of studies at the sixth meeting. A system for technical development of downhole measurements, especially for feasible study, was also discussed.

2. Previous long-term downhole observations

This section briefly summarizes the long-term downhole seismic and geodetic observations and temperature, pressure monitoring and water sampling conducted by ODP, to study possibility of deep drilling and long-term downhole observations in seismogenic zones.

1. Seismic and geodetic observations

ODP has conducted many downhole seismic observations using drill holes (*e.g.* Stephen *et al.*, 1983; Jacobson *et al.*, 1984; Duennebire *et al.,* 1987). However there are a few long-term observations:
- Observation at ODP Hole 794D hole in the Japan Sea (Suyehiro *et al.*, 1929),
- Experiment at ODP Hole 396B hole in the Atlantic Ocean (Montager *et al.,* 1994), and
- Observation at ODP Hole 843B hole off Hawaii in the Pacific Ocean (Stephen *et al.*, 1999).

These observations used broadband sensors and their goal is to operate as a seismic station in the global seismic network. However the longest observation period was 115 days for offshore Hawaii (Stephen *et al.*, 1999). After those observations, broadband geophysical sensors were installed in four seafloor drill holes at three sites around Japan during 1999 - 2001, and long-term observations have been started (Sacks *et al.*, 2000; Kanazawa *et al.*, 2001; and Salisbury *et al.*, 2002). In particular, holes ODP Holes 1150D and 1151B in the slope on the landward slope of the Japan Trench have tiltmeters and volumetric strainmeters for the first time (Sacks *et al.,* 2000). ODP Hole 1179E where broadband seismometers were installed has the seismic record more than one year (421 days) in total as of August 2002.

2. Temperature, pressure and water sampling (CORK)

Since 1990, observations have been performed with CORK (Circulation Obviation Retrofit Kit) to measure the flow of interstitial water beneath the seafloor. CORK puts a lid to close a hole and deploys thermometer, pressure gauge and water sampling string in the hole. The data is retrieved by submersibles (Davis et al, 1992). CORKs have been installed during ODP Leg139, 164, 168, 174B. Furthermore, A-CORK (Advanced CORK) has developed and being used. A-CORK separates the inside of a hole with packers, and obtains information from particular places (faults, etc.). The latest installation is conducted at ODP Hole 1173B in Nankai Trough during ODP Leg 196 (Mikada *et al*, 2002).

3. Objectives and specifications of downhole measurement/monitoring in seismogenic zones

We decided to consider drilling in seismogenic zones for a case study of downhole measurement/monitoring in deep drilling. One of the objectives for downhole measurement/monitoring in seismogenic zones is "to obtain a physical model of earthquake occurring in a trench axis area". For this scientific objectives, seismic and geodetic observations, temperature and pressure measurement, electromagnetic measurement, water sampling, organisms, and downhole logging will give useful information. For these measurement/monitoring, we have studied their objectives and specifications.

3-1. Objectives of downhole measurement/monitoring in seismogenic zones

Seismic and geodetic observation

To obtain spatial and temporal processes of strain accumulation and release in seismic zones of a plate boundary area, and their relation with the structure (physical properties, fluid). For this, we need to carry out downhole geophysical observation to know physical conditions of seismic field and to know strain accumulation and release processes in a seismic cycle in terms of space and time. Specifically, energy of earthquake (spectrum), source mechanism (how breaking spreads over a fault plane), and the distribution of scatterers around the fault must be studied. In geodetic observation, we have to estimate stress accumulation in a seismic zone, time series of release, and places of stress accumulation.

Temperature and pressure monitoring

Temperature and pressure are important parameters to define the physics of earthquake occurring. To know thermal and hydraulic structures of a seismic zone, we must measure in-situ temperatures and pressures in the seismic zone and their temporal changes. Distributions of temperatures and pressures up to the seismic zone should be studied. The role of water (particularly free water) during a coseismic slip could be estimated by measuring fluid pressures in layers. The relation between flow of fluid beneath sea floor and cold seep on seafloor and temperature, pressure conditions in seismic zone and BSR are also objectives for the monitoring.

Electromagnetic observation

Pore fluid pressure is an important parameter to discuss process of earthquake generation. Change in pore pressure can accompanies fluid flow, which is detectable by electromagnetic observations as well as pressure and heat observations. Electromagnetic phenomena related to fluid movement include variations of potential field and change in electric conductivity. Average velocity of fluid flow is obtained from changes in magnetic and electric fields in a borehole related to the natural potential field. Amount of fluid can be estimated from change in electric conductivity around a borehole. Also, stress field can be estimated by detecting geomagnetic total field variations with crustal movement.

Water sampling

It is possible to estimate environmental change such as the movement of pore water and material balance in seismogenic zones from chemical composition and temporal change of water obtained in the seismic zone.

Organisms

Measurement of biomass, community of microorganisms, and microbial activities is useful for estimating environments of seismogenic zones and their changes.

Downhole logging

We characterize physical properties of seismic zones by downhole logging. We also obtain depth profiles of physical properties from a seafloor to a seismic zone. Downhole logging is essential to identify and characterize the seismogenic zone for determining the positions of geophysical sensors for long-term monitoring. From deep downhole logging, a physical property profile, existence and amount of fluid, and hydraulic permeability can be estimated.

3-2. Study regions of downhole measurement/monitoring in seismogenic zones

For the objectives of downhole measurement/monitoring in seismogenic zones, it is most important to carry out observations as close to seismogenic zone as possible. Therefore, drilling should at least reach "the seismogenic fault in the plate boundary plane", and measurement/monitoring must be performed near the boundary. It is also important that the measurement/monitoring is carried out across several faults that have different characteristics. In our study case of seismogenic zones, we should carry out measurement in the following three regions: a plate boundary with few slip during large earthquakes, a branch fault separating from the plate boundary, and a plate boundary with large slip at great earthquakes (Figure 1).

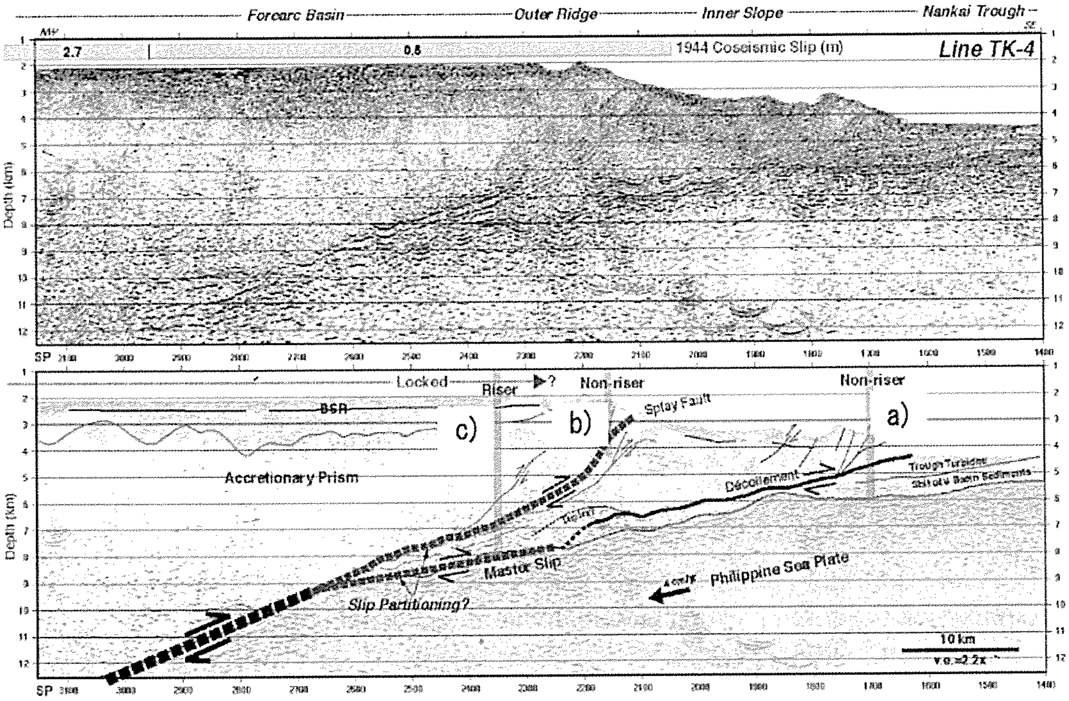


Figure 1. Drill hole positions in a seismogenic zone for downhole measurement/monitoring. a) Decollement near the trough (plate boundary), b) Splay fault (branch fault), c) Up-dip limit of the seismogenic zone (plate boundary)

3-3. Specifications of downhole measurement/monitoring in seismogenic zones

Seismic observation

We need to cover microearthquakes to great earthquakes that occur at plate boundaries, which requires a wide dynamic range (120 db or more) and a wide frequency band (0.5 Hz - 1,000 Hz). And sensitivity of sensor should be at least 10^{-7} (m/s^2), because low seismic noise is expected in downhole seismic observation (Figure 2).

In order to determine the focal mechanism of earthquakes, it is necessary to deploy ocean bottom seismometers. Deployment of vertical seismometer arrays in drilling holes is also necessary, because the vertical array improves accuracies of focal depths and focal mechanisms of earthquakes. In this case, arrays with several-meter intervals are necessary it the vicinity of faults, and arrays with several-hundred-meter intervals are enough for other regions.

Geodetic observation

Plate convergence with a rate of cm/year is occurring over a region with 100 km scale, which means strain velocity is 100 nstrain/year on average. Therefore, 1nstrain/day of change in strain has to be detectable. Precisions of 10^{-12} in volumetric strain observation and 1nrad in tilt observation are expected. For geodetic observation, strain and tilt are measured at several points near the earthquake fault, because largest strain and tilt are expected near the fault. One-second interval measurement is required. It should be noted that effective coupling with crust is necessary.

Temperature monitoring

To obtain a temperature field, it is necessary to measure the entire downhole. Measurement should be taken at every 1m in the vicinity of a fault, and at every 100 m in other places. Measurement at every 1 minute is sufficient. But, long-term stability is required. For measurement of temperature, necessary accuracies are 1mK in relative measurement and 1K in absolute value.

Pressure monitoring

It is necessary to measure both absolute pressure and pressure variation. To obtain the movement of fluid during earthquake, it is required to be able to detect a pressure change of 10^4 Pa within 12-hour to 24-hour, and a change of 10 Pa within 100 second. Absolute pressure should be measured with accuracy of 10^6 Pa. Measurement should be performed with time interval of 1 minute, spatial interval of 1m near faults, and about 100m in other regions.

Electromagnetic observation

Electric fields should be measured with accuracy of 0.01 μ V near a fault and 1 μ V in other regions. Magnetic fields should be measured with resolution of 0.001 nT. These also need long-term stability. An electric field should observe spatially, therefore it is desirable to install instruments, not only in the vertical direction in a downhole, but also in horizontal directions in branch holes. Also, measurement has to be performed at few hundred-meter intervals near a fault, and at 1 km intervals in other places, with every one-minute sampling. Several electric sensors are needed in the vicinity of a fault. For the magnetic filed, 200 m observation intervals below and above the fault is effective to detect fluid flow, and a reference sensor is necessary in the shallow part of the downhole.

Water sampling and organisms

If we could obtain water in the crust near a fault, we can measure chemicals and microorganisms. Variety of measurement depends on amount of sampled water. The more water we can sample, the more items we can measure. Downhole sensors might be possible, but at present, development of measuring equipment is necessary.

Downhole logging

We conduct the best possible measurement currently available from the seafloor to the fault. Natural gamma ray, gamma ray density, neutron porosity, electric resistivity, geophysics, sonic velocity, resistivity imaging, acoustic imaging, nuclear magnetic resonance logging, temperature, etc. are measured. Precision of measurement should be, for example, $\pm 0.01\%$ for water content, $\pm 0.01 g/cm^3$ for density, ± 0.01 km/s for velocity, and ± 0.001℃ for temperature.

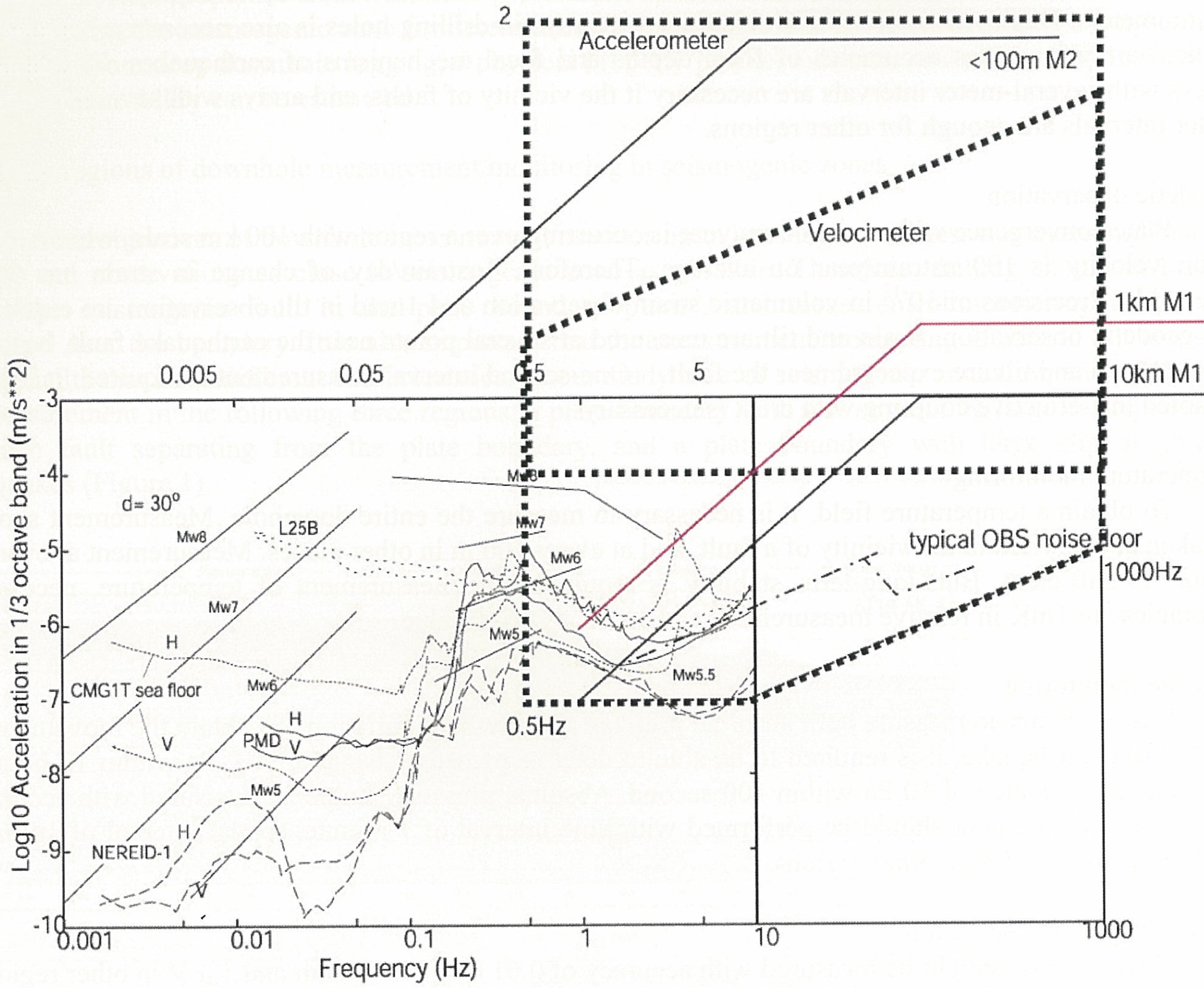


Figure 2. Relation between frequency band and sensitivity in earthquake observation.

4. Downhole measurement/monitoring plan for seismic zones -- from scientific aspects --

We have made an ideal installation plan for observation system based on the necessary specifications on measurement/monitoring that we discussed in the previous section. Items of geophysical long-term measurement are related to each other and arrangement of devices can be integrated. Thus we put seismic/geodetic observation, temperature/pressure measurement and electromagnetic observation together into one installation plan, and discuss water sampling/organism and downhole logging separately.

4-1. Geophysical long-term measurement (seismic observation, geodetic observation, temperature monitoring, pressure monitoring, electromagnetic observation)

A) Arrangement of sensors

To research a seismic zone, it would be necessary to carry out measurement/monitoring in three places: drilling with a non-riser into the decollement near trench (plate boundary); drilling into a branch fault (Splay fault); and drilling with a riser into a fault in the seismogenic zone (plate boundary). Instruments should be arranged densely in the vicinity of these faults (positions must be studied and determined before installation, based on the results of logging), and rather dispersively in other places. In non-riser drill holes (shallower than 2 km) around the decollement, measurement is performed densely for strain, tilt, fluid pressure and temperature, in a similar manner to those in the vicinity of faults in a seismogenic zone, but earthquakes are measured with dispersed arrays, with horizontal coverage by sea floor observations.

B) Data transmission and recording

Continuous recording for long time is desired. Event-triggered recording is not suitable. Downhole transmission should not cause a cross talk of records. Optical fibers or metal cables should be used for measurements. Analog transmission or digital transmission is also considerable. A/D conversion needs a resolution of 24 bits. It is also necessary to consider a balance between high sampling rate and power consumption in seismic observation. The position of an A/D converter may have to be below the well head in a riser hole, because it seems difficult to draw out many wire lines from the well head. Deployment of a data recorder that is replaced by a submersible replaces the recorder or a cable connects to the land for data retrieval must be considered. Cable connection to the land has two methods: One is by optical thin cable, which cannot send electric power, and the other can supply the electric power. The former has to find a way to supply the electric power.

C) Specification of downhole sensors

Since sensors are placed in a high temperature and a pressure near faults, the sensors and the data transmission have to be adaptive for this condition. Either optical fiber or metal cable needs evaluation for long-term reliability.

C-1) Seismic observation

- Sensor arrangement

With arrays of seismometers and strong motion meters, we observe the rupture process during earthquake and the scattering process in its surrounding medium. In the vicinity of a fault, a sub-array consisting of about ten seismometers and about ten strong motion meters with an aperture of about 10m are placed at intervals of 100 m-200 m. In other regions, combinations of a seismometer and a strong motion seismometer are installed at intervals of about 200 m (Figures 3, 4, 5, and 6)

- Installation

Both seismometers and strong motion meters must be cemented with casing and coupled well with the crust. Cementing in open hole is best, but cementing to the inside of the casing seems to be also good.

It is necessary that a shock during the installation never reduce the performance of a sensor.

- Size

Cylinder. Diameter less than 3.5", length less than 50 cm. Not a doughnut shape.

- Cautions

It is required that three-component ground motions can be measured accurately within the inclination of the drill hole. Evaluation of influence of drill hole casing (surrounding medium, scattering at casing) is needed. It is also necessary to examine observational frequencies for scientifically meaningful observation.
Coupling, response and other problems may be solved if hydrophones are used instead of seismometers. In the case that the highest frequency for observation is 1 kHz, sampling frequency of 4 kHz or higher is necessary. With a large density array, way to draw signals from the hole may become a problem.

- Calibration

We need to study calibration of sensitivity for sensors after installation to a drill hole. It is also necessary to evaluate an aging problem caused by high temperatures and high pressures.

(Seismometer)

- Velocity meter
- Noise floor: 10^{-7} (m/s^2) at 10 Hz is necessary.
- Dynamic range: Better than 120 dB.
- Frequency band: From 0.5 Hz to 1000 Hz. It may be difficult to observe this frequency band with single sensor.
- Durability: Sensor's performance has to be maintained for a long time even under a condition where the largest acceleration is 10 G.
- As for sensor's principles, moving coil and optical fiber are considered. With a mechanically fixed sensor measuring momentum, the effective band is empirically 250-300 Hz. Accelerometers may be realistic to use, when considering the shock of installation. Observation with a low frequency (less than 0.5 Hz) should be considered.
- Fixing seismometer vessels to a casing pipe is necessary in any case

(Strong motion meter)

- accelerometer
- Noise floor: 10^{-4} (m/s^2) at 10 Hz
- Dynamic range: Better than 120 dB (maximum acceleration reaches 100 G)
- Frequency band: From 0.5 Hz to 1000 Hz
- Observation with wide dynamic range is possible by combination of seismometer and strong motion meter.

C-2) Strain

We measure three-component strain or volume strain at several places in the neighborhood of a fault (plate boundary). Depth of installation, particularly in the neighborhood of a fault, must be considered by using information from site survey data and downhole logging.

- Method: Hydraulic system and optical fiber cable system are suitable for high temperature.
- Sensitivity: About 10^{-12} for volumetric strain is best sensitivity. Smaller sensitivity may be enough near earthquake faults (Dynamic range of measurement must be considered).
- Dynamic range: It is necessary that no error (such as offset not by strain) is caused by earthquake motions of M4 or smaller which are expected to occur frequently in the vicinity during the observation.
- -Installation: A strainmeter needs to be homogeneously coupled with the crust outside the casing, so

sensors can not be installed inside casing pipes. It is necessary that the sensor is installed outside the casing or the casing itself must be a strainmeter (Figures 3, 4, 5 and 6). Strainmeter vessel can have a doughnut-shaped structure (Vessel has inner wall and outer wall). But it is not desirable if fluid stays in inner wall (Inside of inner wall must be filled with cement). Strainmeter might work as a pressure gauge.

- Size: At present, 8" in diameter and 500cm in length. It can be made about 5" in diameter, if sensitivity is sacrificed.

C-3) Tilt

We measure deformation of crust at more than ten depths from the bottom of the hole (plate boundary) to the seafloor. Depth of installation, particularly in the neighborhood of a fault, must be considered by using information from site survey data and downhole logging.

- Sensitivity: About 1nrad.
- Dynamic range: It is necessary that no error (such as offset not by strain) is caused by earthquake motions of M4 or smaller which are expected to occur frequently in the vicinity during observation.
- Size: At present, for example, Applied Geomechanics tiltmeter is 3" in diameter and 120 cm in length. Laser tiltmeter is estimated to have about 7" in diameter and about 100cm in length, and an outer diameter of 5". Doughnut shape is impossible.
- Installation: Must be fixed to the casing (Figures 3, 4, 5 and 6). The casing should be coupled with the surrounding crust by cementing.
- Function: It is necessary that sensors are leveled in borehole. Leveling mechanism must be considered for high temperature and high pressure.

C-4) Pressure

We measure absolute pressures and differential pressures at several depths in the downhole.

- Installation: To measure pressures, it is necessary to prepare several holes on the casing and the cement layer outside the casing to measure pressure. To estimate a movement of fluid, it is important to measure a differential pressure between two points. To measure pressures at any depth, a casing-embedded pressure gauge should be considered. For installation of pressure gauges, the pressure gauge must not be cemented by using of packers or others (Figures 3, 4, 5 and 6). The gauges are sealed with cement rather than packers.
- Sensitivity: We want to detect pressure change caused by fluid movement accompanied with an earthquake. Pressure changes by tides are about 10^4 Pa (1 day, 1/2 day), and changes by surface gravitational waves have a number of 10 Pa (100 sec). These should be detected. We need to measure both absolute pressures and differential pressure changes. Accuracy in absolute pressure measurement should be better than 1 MPa. Long-term stability for absolute pressure must be considered.
- Sampling: About 1 minute, about 1m are enough around a fault. More than 100m intervals are enough for other depths.
- Size: Needs further study.

C-5) Temperature

- Potential sensors: Thermistor, thermocouples, platinum resistance temperature sensor, optical fiber, crystalline quartz thermometers. Optical fiber method is suitable for its size and heat resistance. Power supply and the size of laser light source may be problems.
- Data transmission method: Electric wire is drawn to the seafloor, signals are converted to digital form on the seafloor. Quartz thermometers need a pre-amplifier placed close to the sensor.
- Size: 5 mm or smaller is possible.
- Precision: Long-term stability is necessary. For relative measurement, 10 mK (detection of gas hydrate stability boundary), 100 mK (detection of pore fluid flow) accuracy is necessary. For absolute value, about 1 K is necessary.
- Installation: It may be possible to install together with seismometers or other geodetic sensors

(Figures 3, 4, 5 and 6).

C-6) Electromagnetic observation

(Electric observation)

- Method: Silver-silver chloride electrodes. High temperature is a problem. Evaluation of influence of metal casing is also necessary.
- Size: About 20 cm.
- Transmission method: Electric wire is drawn to the seafloor, and A/D and recording of potential difference between the electrodes are settled on seafloor. Combination of electrodes for voltage measurements is decided by a multiplexer on the seafloor.
- Precision: 0.01 μ V in the neighborhood of a fault, and 1 μ V in other places. Stability is the problem.
- Installation: Vertically, in downhole. Horizontally, in branch holes. May be installed with seismometers and other instruments (Figures 3, 4, 5 and 6).
- Sampling: About 1 second. Several points at intervals of 100-200 m vertically around a fault, and at intervals of about 1 km in other places.

(Magnetic observation)

- Method: Fluxgate type for places where the temperature is 80 degrees or lower. In higher temperatures, optical fiber type or induction coil type. The optical fiber type has a problem in precision.
- Size: About 1 m?
- Transmission method: For fluxgate type and coil type, sensors are attached in the downhole, and the recording part is settled on the seafloor. They are connected with electric wire. For optical fiber type, optical fiber is installed in the downhole, and the light source, the measuring part, and the recording part are placed on the seafloor.
- Precision: 0.001 nT.
- Installation: Fixed to the downhole with clamps. Non-metal casing should be partly used around the magnetic sensors (Figures 3, 4, 5 and 6).
- Sampling: About 1 second. Two units, 200 m apart, above and below the fault respectively. Other two units as reference in the shallow part.

In addition, we install transmission electrodes of electric current to measure electric conductivity.

- Method: Metal electrodes (same material as the casing)
- Size: About 50 cm.
- Transmission method: Current transmission part (current generator and controller) is placed on the seafloor. Transmission electrodes in the borehole are connected by electric wire.
- Installation: Vertically in downholes near a fault for transmission electrodes, and also on the seafloor.
- Sampling: Once a month, electric current is applied for 5 minutes and electric potential difference is measured with the silver-silver chloride electrodes, which is mentioned above (with 100 Hz sampling). The problem is a battery life. Or apply electric current from a ship by using ROV at maintenance.

Non-riser

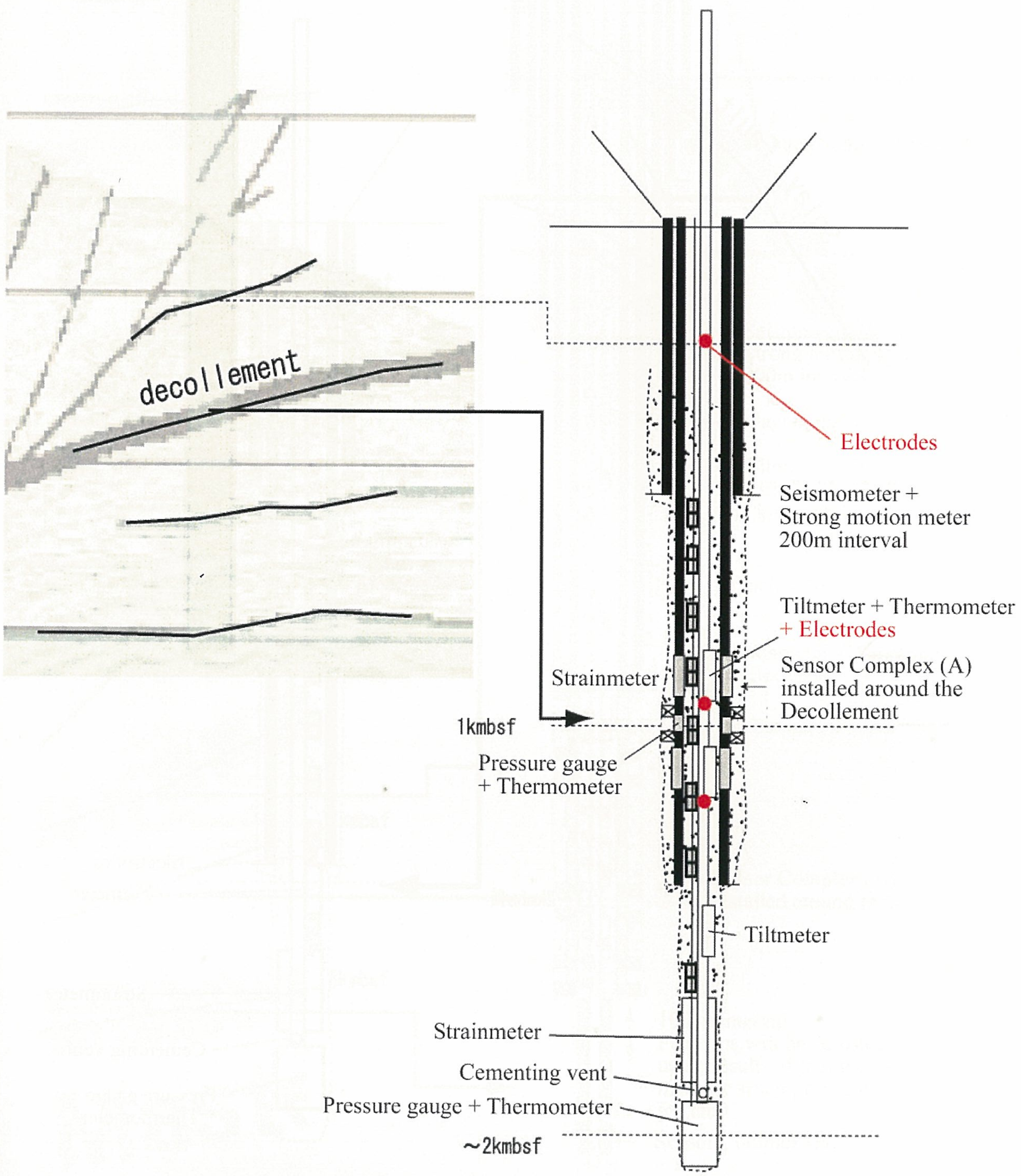


Figure 3. Installation plan for sensors in a drill hole near decollement around the trench axis

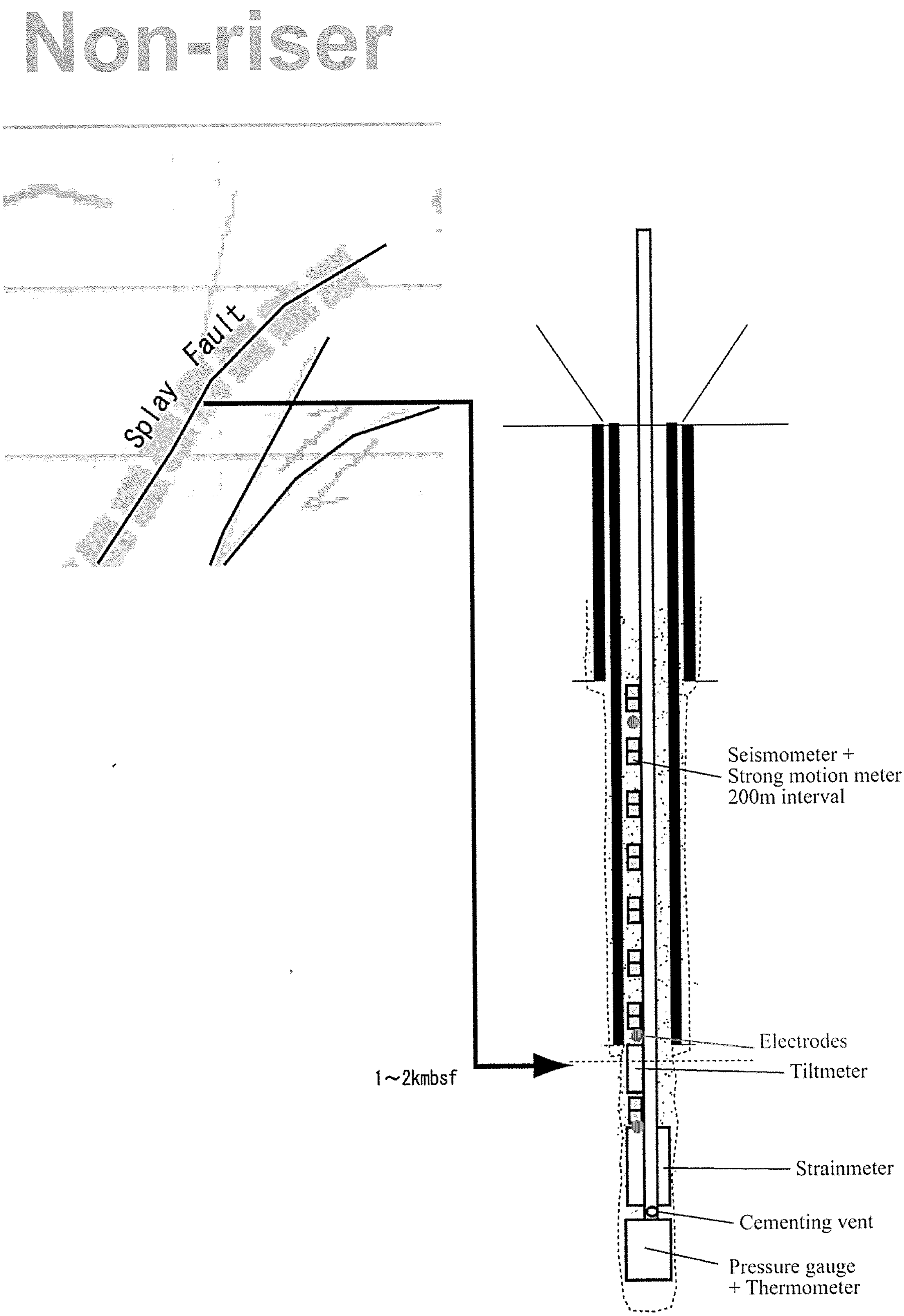


Figure 4. Installation plan for sensors in a drill hole near splay fault

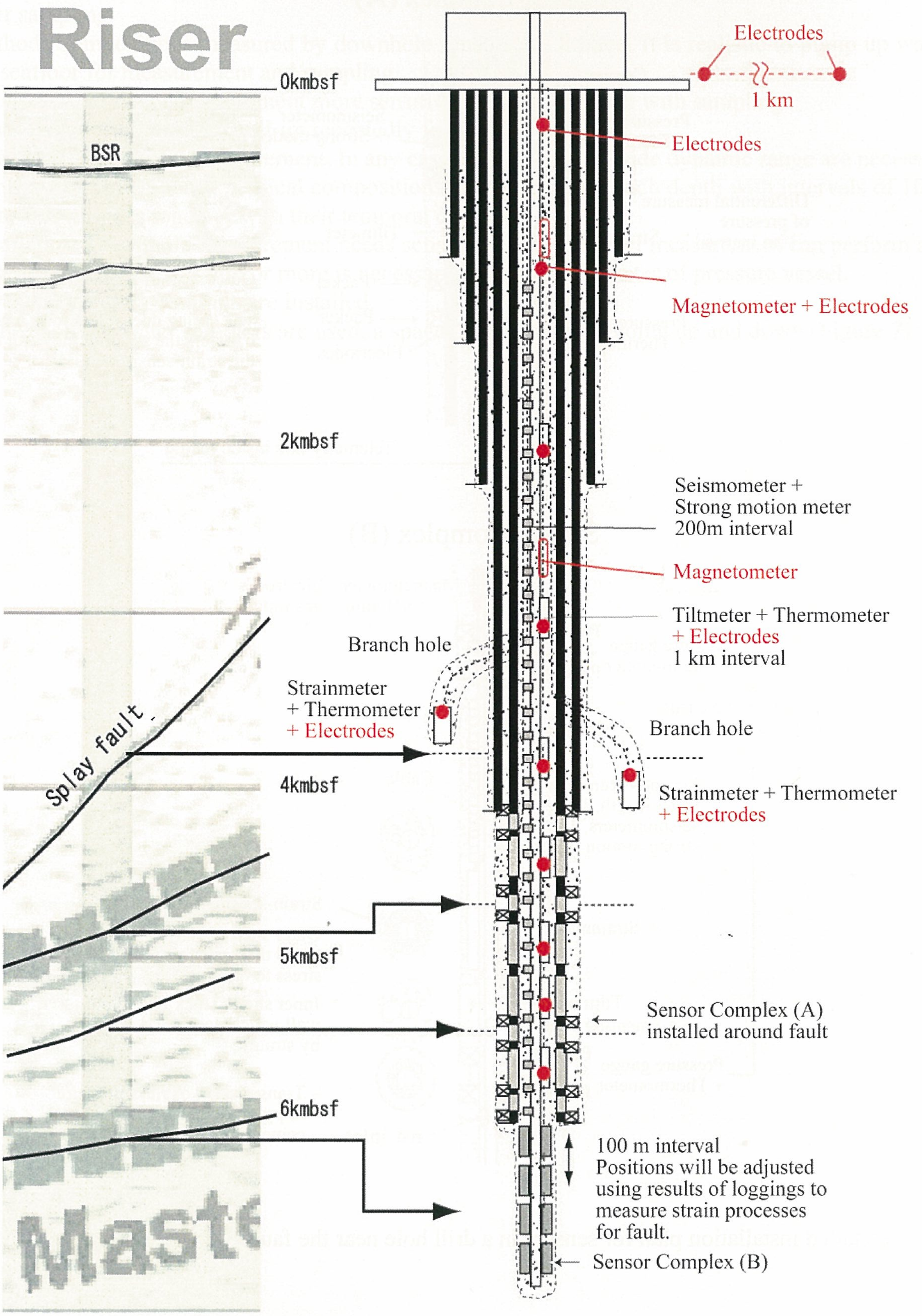
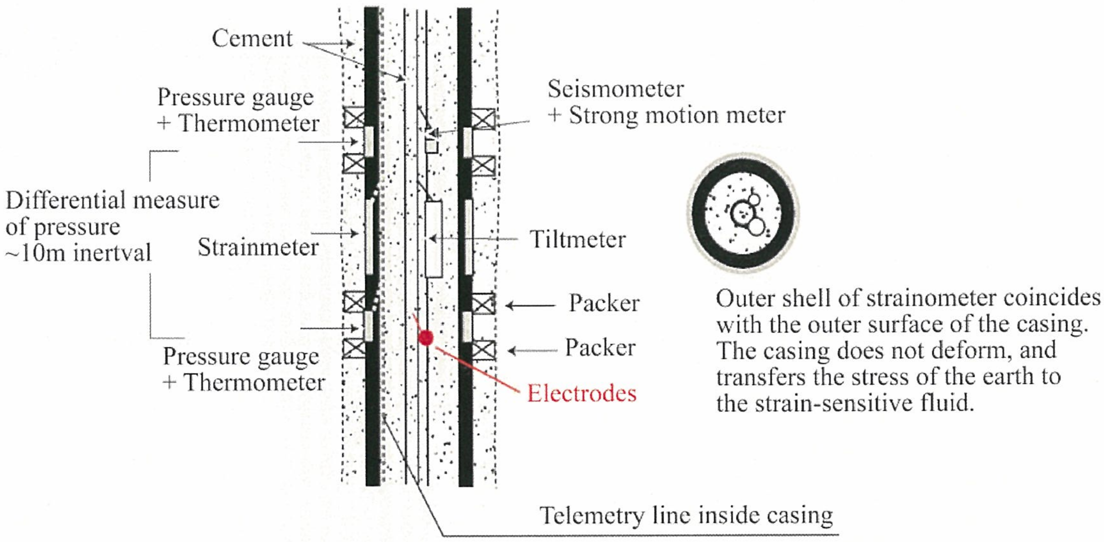


Figure 5. Installation plan for sensors in a drill hole near up-dip limit of seismogenic zone

Sensor Complex (A)



Sensor Complex (B)

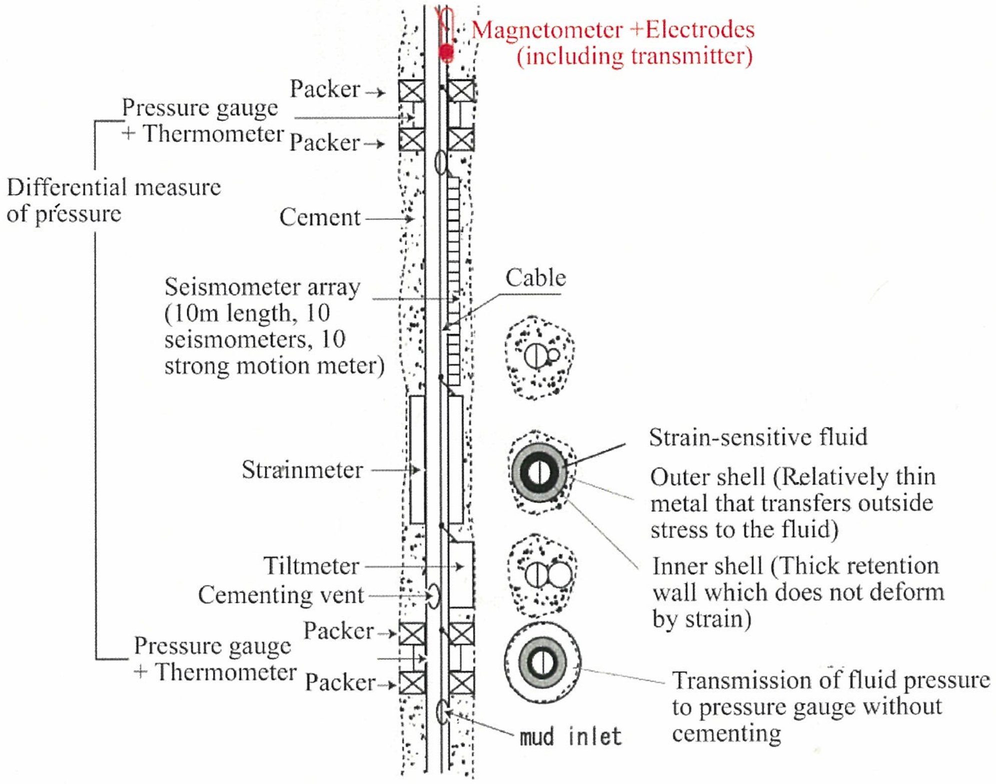


Figure 6. Detailed installation plan for sensors in a drill hole near the fault

4-2. Water sampling and organisms

A) Water sampling

- Method: Compositions measured by downhole sensors are limited. It is realistic to pump up water to the seafloor for measurement and sampling.
  Using packers make measurement more sensitive, but incompatible with sampling.
  Downhole sensors need to pull-up repeatedly for maintenance.
- Precision: Depends on measurement. In any case, sensitivity and wide dynamic range are necessary.
- Sampling: It is best that Chemical compositions are measured at each depth with intervals of 10 m in every one minutes together with their temporal changes.
- Installation: Downhole measurement needs sensors and loggers, but measurement can perform at any depth. It seems that 100 mm or more is necessary for outside diameter of pressure vessel.
  For pumping, only conduits are installed.
  In the case that water samplers are used, a space is necessary for going up and down (Figure 7).

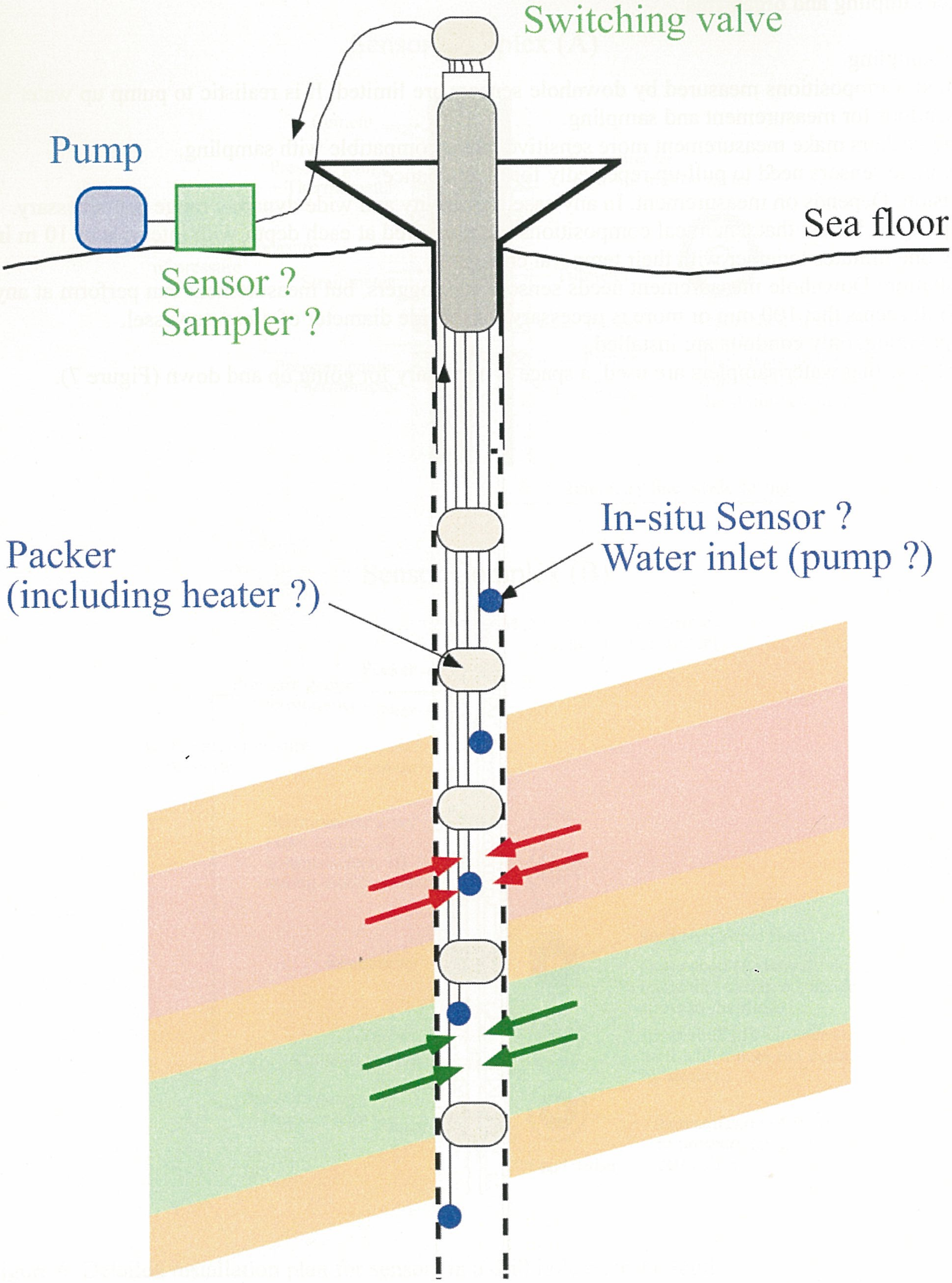


Figure 7. Water sampling system in a seismogenic zone

B) Organisms

Research of microorganisms is closely related with the chemical composition of water. Basically, if water sampling is possible, then analysis of microorganisms is also possible.

- Biomass: Measurement of how many microorganisms exist there.
- Community composition analysis: analysis of what kinds of microorganisms exist there.
- Activity: Survey of activities of microorganisms.

For these, we could think of several downhole sensors other than water sampling, but they need further technical development.

4-3. Downhole logging

By downhole logging in a seismic zone, we can identify and characterize the seismic zone, make a physical property profile, detect the existence and amount of fluid, and measure hydraulic permeability. These are useful in determining depths of sensors for long-term observation. For future measurement, we need to develop Logging-While-Coring (LWC) and Multi-sensor probe. LWC is necessary for reliable logging in deep drilling under conditions of low core recovery rates and unstable borehole walls. A multiple-probe sensor measures high spatial resolution temperatures.

- Measurement items: Best possible measurements available up to date should be applied to seismic zones.
  Natural gamma ray, gamma ray density, neutron porosity, electric resistivity, sonic velocity, resistivity imaging, acoustic imaging, nuclear magnetic resonance logging, temperatures, etc. are measured. Precision of measurement should be, for example, $\pm 0.01\%$ for water content, ± 0.01 g/cm^3 for density, ± 0.01 km/s for velocity, and ± 0.001℃ for temperature.
- Downhole experiment: MDT, determination of pore pressure by water injection experiment with multiple packers, hydraulic fracture experiment, high resolution VSP, borehole radar, cross hole tomography, etc.

5. Discussion

We are now finalizing discussion about what need to be measured in long-term borehole observatory in seismogenic zones. We will then discuss technical feasibility of the measurements and technical development needed for the instrumentation in detail.

At the fourth and fifth meetings, to consider necessary technical development we reported and proposed following existing technologies, particularly related to the measurements:

a. Outline of the hole entry device for riser drilling by "Chikyu",
b. Present status of pore pressure measurement (minimum pressure) in boreholes,
c. Proposal on water recovery from deep holes,
d. Seismic While Drilling,
e. Small and lightweight seismic sensors with flat frequency response in high frequencies,
f. Newly developed schemes for new drilling techniques,
g. Actual examples of system development for long-term downhole seismic observatory in ODP, and
h. Deterioration of optical fiber by hydrogen, and present techniques for replacing optical fiber.

The reports on present technologies provided important information in considering future downhole measurements, particularly development of measuring techniques in deep holes.

The topics of discussions in the last six meetings for downhole measurement in seismogenic zones are listed below. Further studies in detail are absolutely necessary.

1. Deep drilling

Since the riser holes are very deep, drilling itself is a challenge. The drilling objective cannot be achieved by the methods used in ODP. We need to study the installation of equipment in the riser holes. We need to make a plan throughout the process from drilling to completion of a hole by considering the downhole long-term observatory.

2. Sensors that withstand high temperatures and high pressures

We need to develop sensors that ensure a stable and long-term observation under the conditions of high temperatures (about 250 degree Celsius) and high pressures (about 150 MPa?) that are expected in a seismic zone, and we need to develop techniques to install these sensors in deep parts. We also need to study how to make direct contact between the rock bed outside and the sensors inside where multiple casings are installed, and how to bring the outside environment into the casing (perforation technique).

3. Formulation of casing programs

It is extremely important to make an appropriate casing program before drilling a deep hole, by simulating a drilling on the desktop, as is called the “Desktop Drilling”. At present, about seven sizes of casing from 7 to 42 inches are available. We need to set the mud density for drilling to be between the fracture pressure and the pore pressure. When the mud can no longer hold the pore pressure, a set of casing needs to be installed. Therefore, it is important to know the fracture pressure and pore pressure "beforehand". In practice, we need to know both values at least for sedimentary layers by drilling a pilot hole. The final hole diameter is likely to be 8-1/2 inches (7” final casing). We need to think about possibility of sensors in this hole size and consider a drilling plan accordingly.

4. Drilling and installation of casing

If casing itself is specially made, we need to consider whether there is any special requirement. We also need to consider the life expectancy of electronic components and sensors and classify the sensors into those for which maintenance is possible and those for which maintenance is not possible. These are closely related to hole completion.

5. Hole completion: installation of wellhead

In IODP drilling, it is required to prevent in-layer materials from leaking into the seawater. Therefore, we have to pay full attention to this requirement when installing sensors for long-term observation. One of the hole-sealing tools is a combination of wellhead + Christmas tree. Its specification depends on downhole pressure. We have to study whether we need such a device even when the hole is cemented for geodetic observation.

We also have to study how to retrieve signals from downhole sensors through the wellhead.

6. Accurate decision of depth for installation of sensors

We need to establish a technique to identify necessary intervals for sensor installation from downhole logging and coring. Since we will actually install the sensors after identifying the intervals, we will need sufficient time between decision of depth and installation of device.

7. Transmission of sensor signals to the seafloor

We have to study how to transmit signals to the seafloor, with what cable and connectors, under the conditions of high temperatures, multiple casings and multiple sensors. Since it is difficult to make electronic circuits work at high temperatures, we also consider analog signal transmission as an alternative method.

8. Water sampling from deep section

We should consider an additional plan in which cores are recovered while the downhole pressure is maintained by PTCS and the pore water is sampled on board.

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

Although development of LWC is considered to be feasible with current technologies, the following three problems need to be solved. They are the problems of space for a LWD, logging while drilling tool so that the core liner can go through.

(1) Electric power supply

LWC needs a space in the central part of a LWD so that the core liner can go through. Therefore it is difficult to install and operate a turbine to supply power to the system. We have to come up with some solution such as operating the LWD tool with large capacity batteries.

(2) Radioactive sources

Legally, the radioactive sources in logging tools must be retrievable when a trouble is encountered borehole. If the space in the central part of a logging tool is used for core liner passage, it becomes difficult to retrieve the radioactive source. We need either to invent some special retrieval technique or to consider introduction of some alternative measuring techniques that do not use radioactive sources.

(3) Data transmission

To preserve the space for core liners to go through, it becomes difficult to use a mud pulse telemetry system of MWD (measurement while drilling). We have to consider a system that does not use real time data transmission; data is to be stored in non-volatile memories and retrieved when core liner is retrieved.

10. Installation experiment on land

To do reliable long-term observation, it is indispensable to do an experimental installation on land and identify problems in the development stage.

11. Existing information

For further consideration of borehole instrumentation, we need to obtain information from existing deep wells.

6. Recommendations: Scenario for technology development in IODP downhole measurement/monitoring

This interim report is a summary of the result of preliminary survey on feasibility of technologies necessary for obtaining new scientific results by downhole measurement, which is one of the main components of IODP. It is indispensable to promote systematic technology development under a strong collaboration by Japanese and world scientists, to realize IODP downhole measurement and long term observation. We recommend the following scenario for future promotion based on specific ideas.

1. Scenario for future promotion

It is dispensable to search its feasibility, to achieve technology development for IODP measurement/monitoring. However, we need to concentrate on those items which satisfy the following during feasibility stage:

- Technologies that do not currently exist
- Technologies necessary to fulfill the specification to achieve scientific goals, and
- Technologies that are difficult to survey by scientists and need help from expertees in technology.

Items that satisfy these conditions include packer, high-temperature technologies, and data transmission. For these items, we aim to specify:

1) Current status of existing technologies,
2) Levels that can be achieved within 5 years and the necessary budget, and
3) Levels that can be achieved within 10 years and the necessary budget.

On the other hand, for those feasible with current technologies, it is enough to specify them in some detail, so that scientists can obtain information on them. Detailed study is done when it comes to a specific drilling plan.

2. Specific ideas for FS

1) Study on techniques to maintain downhole in-situ environment under high temperatures in great depth

To elucidate dynamics of the earth's interior such as stress conditions during earthquake preparation process, characteristics of hydrate phase boundary, and fluid circulation in earth crust, it is indispensable to monitor in-situ stress, pore water pressure, temperature, and chemistry etc., while removing as much disturbance caused by drilling operation as possible. It is necessary to "isolate" the intervals concerned (e.g. fault fracture zone) from the drill hole, wait for disturbance to be stabilized, and then carry out long-term monitoring. This FS aims at studying how to do "isolation" under very deep, high temperature and high pressure conditions. More specifically, we study the following:

- Performance and limit of packers against expected formation pressure and pore pressure, and
- Suitability of open-hole packers and casing packers.

2) Study on technologies under high temperatures

The most hostile condition expected is high temperature, in downhole environment. At present, we are considering drilling at temperatures as high as 250℃ in seismogenic zones and as 400℃ in hydrothermal zones. We need to study how high a temperature do sensors, pressure seals such as o-ring, connectors and cables withstand under such conditions, and their current availability and that in ten years. We estimate their budget sizes for those items which need technology developments.

3) Study on data transmission techniques

In a very deep borehole the cable for power supply or data/information transfer is also quite long, which causes problems such as attenuation of signals. Also, increasing the number of sensors requires denser data transfer, by multiplexing using the optical fiber cable. This theme is studied with the high-temperature environment problem.

3. Toward realization

It is obvious that feasibility studies mentioned above are beyond the range of what individual researchers and engineers can do on a voluntary basis. Scientists need to recognize this, and should place their efforts on getting the budget for FS or development.

If a FS on technology development is required when making a proposal for drilling, it has to be conducted, in principle, by the proponents themselves, and the results of FS has to be attached to the proposal. Then, if such proposals are evaluated as scientifically important, IODP TAP (Technology Advice Panel) /SciMP (Scientific Measurements Panel) will study their feasibility of necessary technological developments, and submit a report with a budget plan to IODP SPC (Science Planning Committee). IODP will make a final decision, taking the budget size into consideration.

In IODP, the method and scientific products have to be clearly differentiated from those of ODP and other survey techniques. Japanese scientific community, while appealing advantages of riser method as much as possible, should try their best to obtain secure and new results that were not possible through any existing techniques. It is important to establish a system that can answer ever-increasing demands from scientists, by aggressive technological developments not only for core retrieval at great depth but also for downhole measurements/monitoring.

7. Reference

Davis, E.E., Becker, K., Pettigrew, T., Carson, B., and MacDonald, R., CORK: a hydrologic seal and downhole observatory for deep-ocean boreholes. *In* Davis, E.E., Mottl, M.J., Fisher, A.T., et al., *Proc. ODP, Init. Repts,* **139**: College Station, TX (Ocean Drilling Program), 43-53, 1992.

Duennebire, F. K., B. Lienert, R. Cessaro, P. Anderson and S. Mallick, Controlled-source seismic experiment at Hole 581C, *Init. Repts. DSDP*, **88**, 105-125, 1987.

Jacobson, R. S., R. Adair and J. Orcutt, Preliminary seismic refraction results using a birehole seismometer in Deep Sea Drilling Project Hole 395A, *Init. Repts. DSDP*, **78B**, 783-792, 1984.

Kanazawa, T., Sager, W.W., Escutia, C., et al., 2001. *Proc. ODP, Init. Repts.,* **191** [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Mikada, H, Becker, K., Klaus, A., et al., 2002. *Proc. ODP, Init. Repts.,* **196** [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Montagner, J. P. et al., The French pilot experiment OFM-SISMOBS: first scientific results on noise level and event detection, *Phys. Earth Planet. Inter.*, **84**, 321-336, 1994.

Suyehiro, K., T. Kanazawa, N. Hirata M. Shinohara and H. Kinoshita, Broadband downhole digital seismometer experiment at Site 794: A technical paper, *Proceedings of the Ocean Drilling Program Scientific Results*, **127/128**, Part 2, 1061-1073, 1992.

Sacks, I.S., Suyehiro, K., Acton, G.D., et al., 2000. *Proc. ODP, Init. Repts.,* **186** [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Salisbury, M. H., Shinohara, M., Richter, C., et al., 2002. *Proc. ODP, Init. Repts.,* **195** [CD-ROM]. Available from: Ocean Drilling Program, Texas A&M University, College Station TX 77845-9547, USA.

Stephen, R.A., S. Johnson and B. Lewis, The Oblique seismic experiment on Deep Sea Drilling Project Leg 65, *Init. Repts. DSDP*, **65**, 319-327, 1983.

Stephen, R. A., J. A. Collins , K. R. Peal, J. A. Hildebrand, J. A. Orcutt, F. N. Spiess and F. L. Vernon, Seafloor seismic stations perform well in study, *Eos*, **80**, 592, 1999.

Published by

OD21 Program Department
Japan Marine Science and Technology Center
2-15 Natsushima-cho, Yokosuka 237-0061 JAPAN
url: http://www.jamstec.go.jp
e-mail: od21@jamstec.go.jp

Downhole Measurement/Monitoring Working Group
Interim Report

OD21 Science Advisory Committee
December 2002