New ways for research and development using a deep-sea hydrothermal vent system in the Okinawa Trough

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***Abstract* —** JAMSTEC has an international patent for the environmentally-friendly cultivation system of offshore hydrothermal chimneys as the accessory product of scientific drilling program in the Okinawa Trough at deep water of 1,100 mbsl. This cultivation system was inspired by rapid growth of precipitated minerals (sulfide chimney) on the drilled hole. We introduce in this paper, the achievement from the riserlesss drilling campaign in Iheya North field in 2010 as IODP Exp. 331 and in 2014 as SIP Okinawa.

After the IODP Exp. 331, the major findings were the massive continuous hydrothermal fluid supply from the drilled hole and the rapid growth of the precipitated minerals (sulfide chimney). The flow rate estimated from the installed producer is around 300 - 500 liter per minute through 3.5 inch pipe in diameter. The Cu-Pb-Zn-rich sulfide chimney having average concentrations of 4.5 wt% Cu, 6.9 wt% Pb, 30.3 wt% Zn and 8.7 wt% Fe at the outlet of the drilled hole was rapidly grown to be from 2 m to 8 m in 6 months.

In Exp. 331 two temporary wells are and 5-1/2" tubing pipe were installed and those are producing the hydrothermal fluid. JAMSTEC are planning to install two new monitoring wells in Feb 2016 at Iheya North field and at Noho field. Those wells are sensing and logging flow rate, temperature and pressure. It can capture the precipitated minerals from hydrothermal fluid and those data by retrieving monitoring cell by ROV. The system was built and tested in March 2015.

LWD operation was performed in 2014 as a part of SIP program. 7 wells are drilled with LWD for the depth of 200 - 350 mbsf in only 9 days in riserless drilling throughout the risk of 350 deg.C thermal fluid by applying continuous circulation system. The continuous circulation system successfully suppresses the hydrothermal fluid pressure by the circulation back pressure and the maximum downhole temperature recorded at LWD was only 85 deg.C in a short period.

At the last our future plan is discussed focusing on our present concerns.

Keywords* — *Black Ore Cultivation; Hydrothermal Vent; Okinawa

I. Introduction

A. IODP Exp. 331

In the Expedition 331 of the Integrated Ocean Drilling Program (IODP), numerous core holes were drilled for the biological research called as "deep hot biosphere" (*Fig. 1*) (Takai et al., 2011). Discharge of the hydrothermal fluid was observed at the all drilled wells around 30 - 40 meters below seafloor (mbsf) (Kawagucci et al., 2013). The maximum temperature of this hydrothermal fluid during the drilling operation was estimated to be around 300 degree C measured by a thermo tape on the core barrel.

All drilling operations were performed without a riser pipe and BOP (blowout preventer). Among all the drilled wells, three wells were equipped with a base structure composed of tripod-shaped and 5-1/2" production tubing (25% Chrome). Out of these three wells, the Hole C0016F was not completed with 5-1/2" production tubing due to the limited operation days. Thus, the other two drilled wells, the Holes C0013E and C0014G, are the suitable candidates for the black ore cultivation test. The hydrothermal discharge of the Hole C0013E has been waning for 2 years from the drilling operation and now completely ceased. On the other hand, the hydrothermal discharge from the Hole C0014G is still vigorous and maintained the similar flow rate for 3 years.

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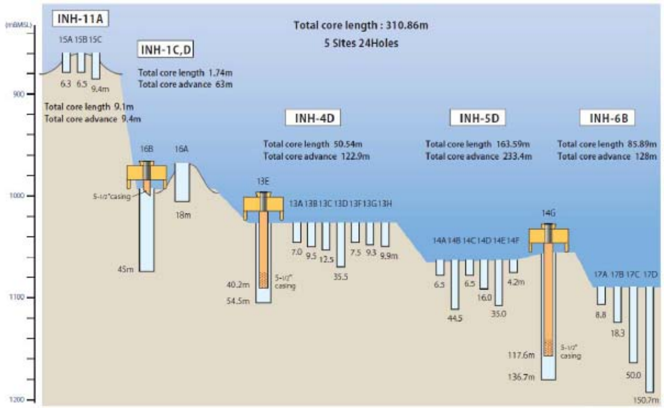


Fig. 1 Summary of the drilling and coring operation (Exp.331)

Fig. 2 Hydrothermal fluid flow from riserless wellhead

B. Zero-age Chimney (IODP Exp.331)

At the site C0016, one well (Hole C0016A) was drilled at the top of the mound structure. The high temperature hydrothermal fluid emerged when we drilled a few meters below the seafloor. Although the industrial coring system was applied for this coring, the core barrels were twisted off due to the hydrogen embrittlement effect. Thus, we could not recover a core sample at this site.

The high temperature hydrothermal fluid (~310 degree C) was observed at the Hole C0016A during the ROV dive 11 month later from the drilling operation (Kawagucci et al., 2013). The new and very infant chimney (hereafter called as zero-age chimney) has grown rapidly to be 8 m in height as shown in Fig. 3 although the chimney was purposely broken by ROV for the hydrothermal fluid sampling.

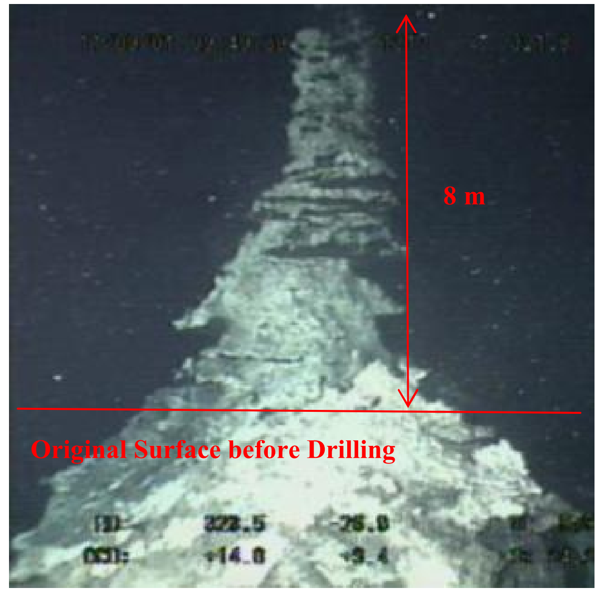


Fig. 3 Rapid growth of Zero-age Chimney

C. Metal Grade of Zero-age Chimney Sample

Under the microscope, the zero-age chimney exhibits a porous structure whose porosity is 10 to 20% and is dominated by chalcopyrite, sphalerite and galena, which has a dendritic texture. Inner and outer parts of dendrites are composed of chalcopyrite and sphalerite, respectively. Galena and minor pyrite fill spaces of these crystals. Based on the results of XRD analysis, the peak of wurtzite which hardly occur in the Kuroko-type VMS deposits on land was frequently observed. In the outermost part, spherical pyrite crystal which has a zonal structure of density and Pb-Sb-As-Ag-S minerals were also found by electron probe microanalysis. The whole-rock geochemical composition determined by ICP-QMS analyses is similar to that of high-grade kuroko ore. The Zn, Cu and Pb concentrations are 24 - 36, 1.9 - 7.2 and 0.9 - 7.6 wt%, respectively, together with several hundred ppm of Ag, As, Cd and Sb (Fig. 5) (Nozaki et al., 2013; Nozaki et al., *in revision*).

Fig. 4 Hand specimen of the Sulfide-rich Zero-age Chimney (Black Ore)

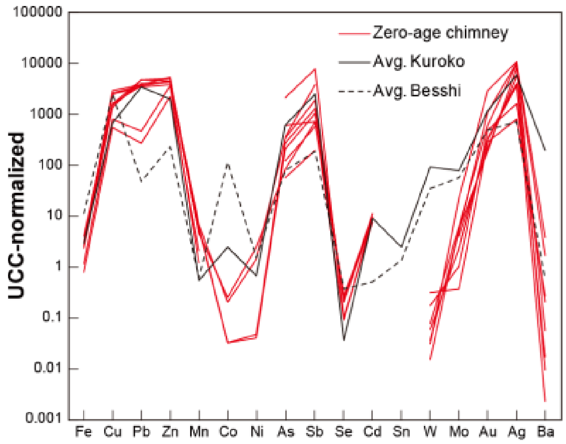


Fig. 5 UCC-normalized Element Patterns of the Zero-age Chimney (UCC = Upper Continental Crust)

D. *Hydrothermal fluid production*

The high temperature hydrothermal fluid started to flow when the drilling operation approached 45 - 50 mbsf in Hole C0014H and 35 mbsf in Hole C0013E, respectively. The production of the hydrothermal fluid from the tubing has continued for several months (*Fig. 6*). Since the flow rate of hydrothermal fluid was too high, only the top part of the tubing pipe was sealed with calcium sulfate minerals caused by the quenching of hydrothermal fluid with cold sea water. Even if the top part of the corrosion cap was plugged, this hydrothermal flow resurged when the ROV broke the sealing plug (*Fig. 7*).

Fig. 6 Hydrothermal Fluid Flow from the Top of tubing

Fig. 7 Removing the Plug of Calcium Sulfate Minerals from top of tubing by ROV manipulator

II. Black Ore Genesis Monitoring System

A. *Concept of the Black Ore Genesis Monitoring System*

The concept was inspired from all aforementioned findings during the coring and drilling operation at the IODP Exp. 331.

a. Rapid growth rate of the zero-age chimney
b. High metal grade of the zero-age chimney
c. Continuous high flow rate of the hydrothermal fluid from the existing tripod well.

In addition to these findings, following advantages are expected:

a. Isolated cooling system of hydrothermal fluid without contamination of sea water to suppress calcium sulfate formation which leads improvement of metal grade of black ore.
b. Limited environmental impact on the biological system
c. Semi-permanent monitoring system
d. No power supply required for the ore cultivation
e. Shallow riseless drilling with simplified wellhead

The feed-back from the system is expected to clear the genesis of black ore field and the possibility of the cultivation. Based on this conceptual idea (*Fig. 8*), the experimental test and feasibility study of the black ore cultivation system using an artificial hydrothermal vent was started in 2010, with the ultimate goal of developing a new mining method with the least environmental impact and pollution.

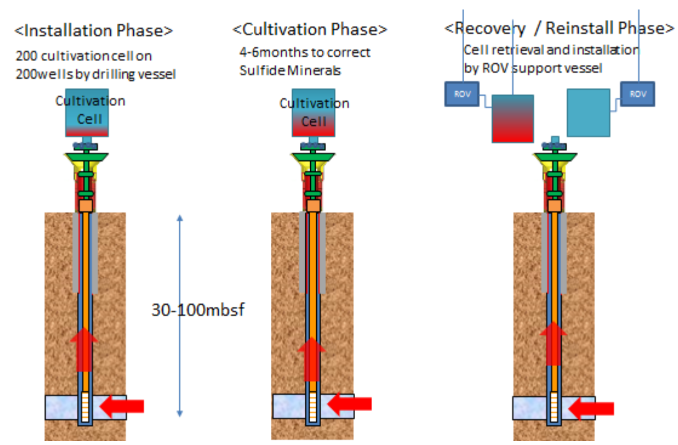


Fig. 8 Conceptual Diagram of the Black Ore Cultivation System

B. *1st Development of Black Ore Genesis Monitoring System*

The 1st prototype cultivation cell was developed to accomplish the following three objectives.

a. Cooling down the hydrothermal fluid by 4 - 5 degC ambient seawater at 1,100 mWD without direct mixture of hydrothermal fluid and seawater.

b. Measuring hydrothermal fluid temperature, pressure and flow rate.

c. ROV intervention interface for manifold valve operation and, cell installation and retrieval.

d. Cell and manifold install on the existing production well.

The 1st prototype cell was built with the valve manifold in Jan 2014, tested and ready to install on top of the tubing of the existing producers. However the plan was changed to install a new well and a new system in two hydrothermal field in Okinawa; Iheya North and Noho in Feb 2016.

Fig. 9 Flow Testing of 1st Generation System

III. LWD DRILLING APPLICATION IN JULY 2014

A. Riserless Drilling Operation in Hydrothermal Vent

The riserless drilling is very cost effective drilling method for shallow water target in deep water, since time consuming BOP and riser running are not required. On the other hand the riserless drilling does not allow the well control which can stop the hydrothermal fluid invasion into the well bore. Once the hydrothermal fluid starts flow into the well, the well keep flowing at all the time.

In Exp. 331 the rubber seals and plastic materials were melted in a minutes once hydrothermal fluid layer is passed especially the circulation is reduced or stopped for wireline operation and pipe connection. A bitumen core liner of 9.5 m in the length was melted and shrink down to 0.7 m.

Fig. 10 Melted Core Liner (0.7 m, originally 9.5 m) in Exp.331

B. Logging While Drilling (LWD)

A basic LWD tool consists of gamma ray, resistivity measurement device for the geology information and temperature sensors for the hydrothermal fluid detection.

If logging while drilling (LWD) is applied, the major risk is high temperature environment. For the pipe connection, the circulation needs to be stopped to insert the additional piping on the drilling assembly since the drilling fluid circulation is through its piping down to the bit.

The temperature limit of LWD tool in the market is rated for 150 deg.C while the hydrothermal fluid temperature is ranged from 300 - 350 deg.C. It is significant risk to apply LWD tool in the hydrothermal field in riserless option which does not allow well control. In such environment, LWD will be fully exposed to 300-350deg.C and be damaged in a few minutes.

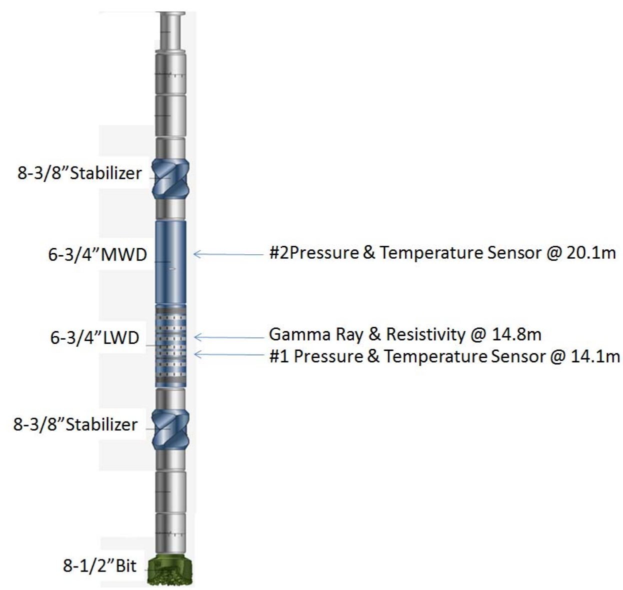


Fig.11 Sensor Location on LWD

C. Continuous Circulation System for LWD operation

Continuous circulation system allow us to continuous circulation using the side entry sub while the pipe connection. The LWD will be protected while the drilling down and tripping out from the hole. While the pumping seawater or environmental-free drilling fluid, the pumped seawater will be mixed with hydrothermal fluid and reduce the temperature of hydrothermal fluid below the working temperature of 150 deg.C. To countermeasure the double failures of side entry sub, the side entry subs were installed on every connection of top side drill pipe to cover up the drilling distance

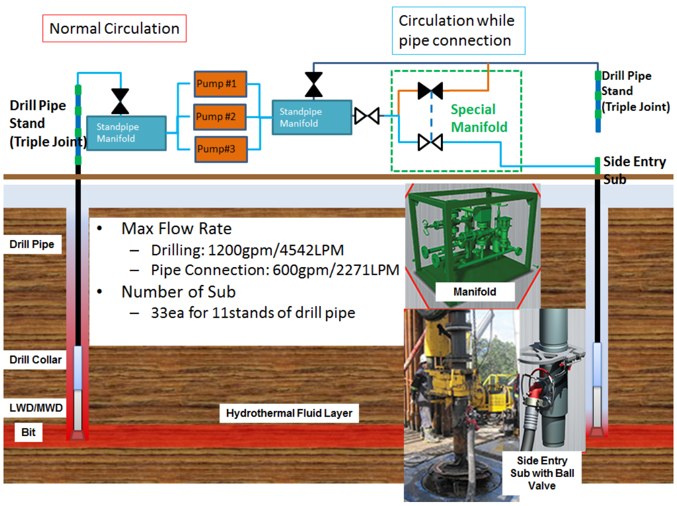


Fig. 12 Continuous Circulation System

D. LWD results

In Exp. 907 carried out in July 2014, 7 LWD holes were drilled in the depth range of 16.9 - 341.5 mbsf in the water depth range of 886.5 - 1,132 mbsf. The maximum temperature recorded was 85 deg.C. The continuous circulation effectively reduced the risk of heat from hydrothermal fluid.

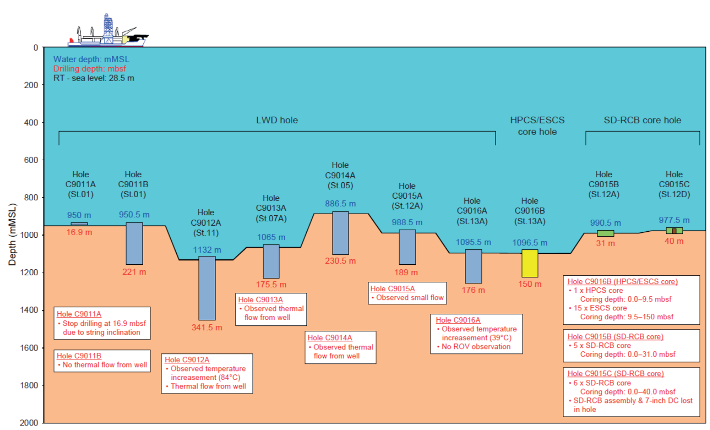


Fig. 13 Summary of LWD holes in Expedition 907

E. Comparison between Core and LWD results

We obtained Gamma-ray and electrical resistivity data with temperature and pressure within the drill hole by using LWD. The Gamma-ray and resistivity data have several patterns as follows; (1) high Gamma-ray and low resistivity layer corresponds to the neutral hydrothermally altered clay layer, (2) low Gamma-ray and low resistivity layer is equivalent to the sulfide mineral-rich layer and (3) low Gamma-ray and high resistivity layer corresponds to altered volcanoclastics. Based on the comparison with actual core samples, acid hydrothermally altered clay layer baring low Gamma-ray and low resistivity was also detected. This layer is difficult to distinguish from the sulfide mineral-rich layer based on only Gamma-ray and electrical resistivity data. The detailed results of the comparison between actual core observation and LWD data will be reported elsewhere (Saito et al., *in prep*).

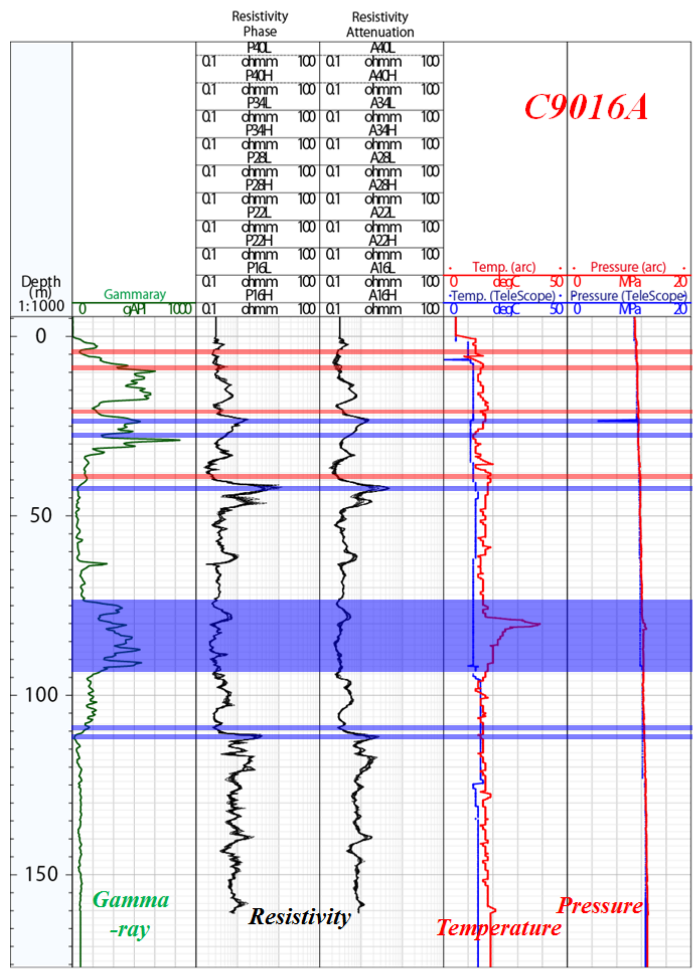


Fig. 14 Comparison of Core and LWD results of Hole C9016

IV. New Approaches in Feb 2016

A. 2nd Generation System for Installion in Feb. 2016

2nd generation cell and system was developed to focus on:

a. Independent cell installation and recovery by ROV (light weight cell).

b. More sensing devices (2 sets x pressure / temperature transducers and loggers, 1 set x flowmeter and loggers, 1 set x load cell and loggers)

c. Three ways manifold for alternative devices.

2nd generation cell systems are designed more for the hydrothermal fluid monitoring adding more sensors and enhance the ROV installation and recovery capability. The cell size is one third of 1st generation cell. The manifold for the 2nd generation system equipped 3way outlets to accept three devices so the 1st generation cell and 2nd generation cell both will be installed on the manifold system at the time.

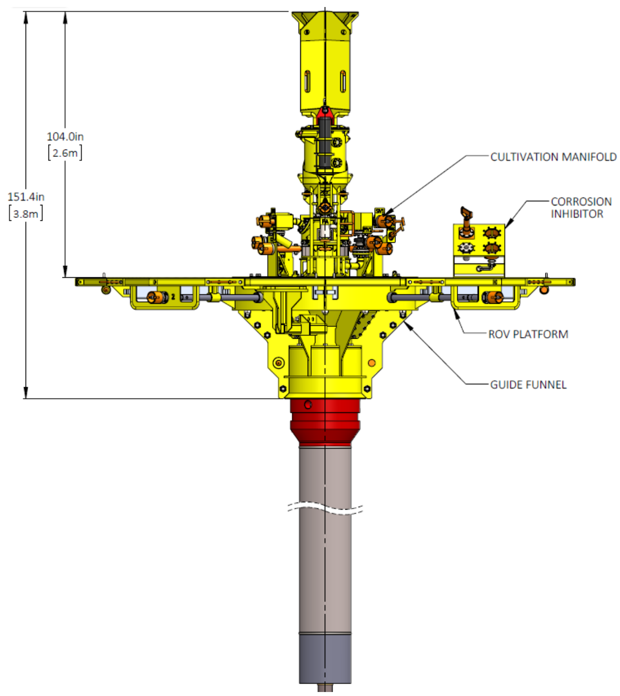


Fig. 15 General Overview of 2nd Generation System

B. Temporary Flowmeter for 2nd generation system.

Even though the 2nd generation cell was light and enhanced for ROV recovery, the recovery operation still requires the assist of floatation devices and the data retrieval will be 3 - 5 months after the installation for the mineral precipitation period. For on time data recovery, a temporary flowmeter is designed. This device allows to read out the analogue temperature, pressure and flow rate of hydrothermal fluid in real time and to log the digital pressure and temperature data of the hydrothermal fluid. The digital pressure temperature data will be logged while the coring in the offset wells, in order to investigate the impact of coring into the producers.

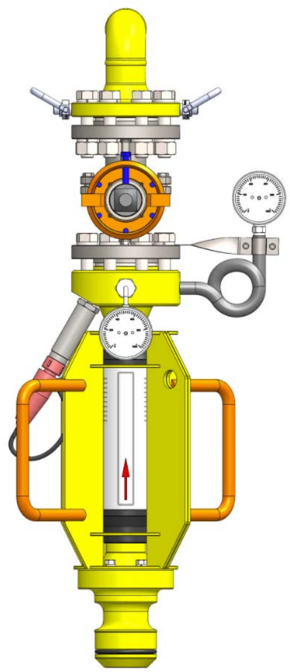


Fig. 16 ROV Deployable Temporary Flowmeter

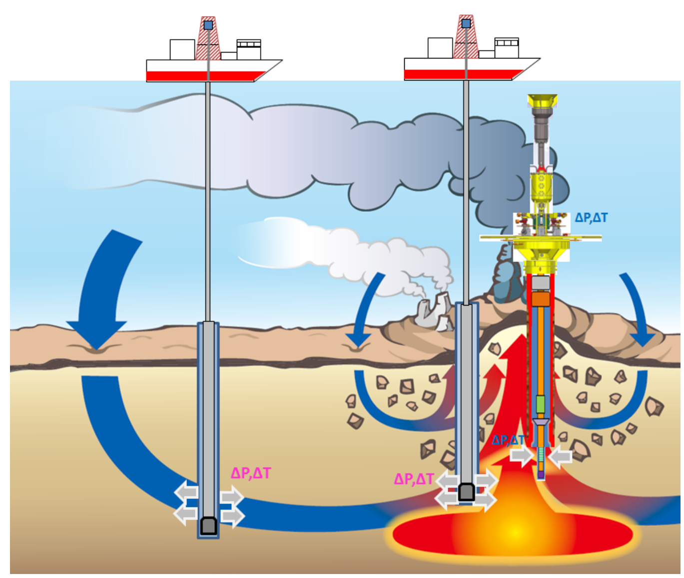


Fig. 17 Offset Well Coring Impact Measurement using Temporary Flowmeter

C. Wireline Temperature Gauge and Flowmeter Application for Detection of Hydrothermal Vent Layer

As described the details above, Logging While Drilling (LWD) was applied to the riserless drilling into the hydrothermal vent as the world's first successful attempt in July 2014. It enables to capture the geological information by gamma ray and resistivity in a real time. However it will suppress the ingress of hydrothermal flow into the hole by the circulation back pressure which protects LWD from the aggressive heat from hydrothermal fluid. So the detection of active source of hydrothermal fluid is very difficult.

The wireline coring operation repeats the low flow conditions while the recovery of the core inner barrel. While Exp. 331, the massive flow had been confirmed in many of coring wells.

Two systems are currently developed to suite for the existing wireline retrieval system. One is JAMSTEC owned temperature gauge which can be directly thrown form drill floor and latch inside the outer barrel. The retrieval will be done by the wireline. The other option is a flowmeter with P/T sensors which is generally used in geothermal wells. This system requires wireline operation in deployment and installation.

This system enables us to immediate and efficient detection of production layer just after the coring operation.

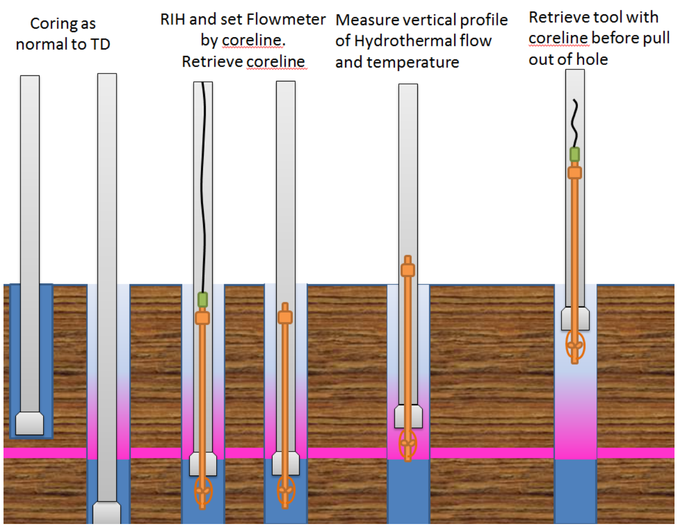


Fig. 18 General Overview of Wireline Temperature Gauge

D. Universal ROV intervension tool development and Testing

Following ROV devices are newly developed in parallel of manufacturing 2nd generation systems to operate the special tools for 2nd generation system with multiple ROV candidates.

a. Universal Independent hydraulic power unit (IHPU) for multiple ROV operation
b. Torque Tool for Valve Operation
c. ROV drill for Precipitation Removal
d. Hydraulic Jack for Cell Removal
e. Hot-stab Hydrraulic Supply for Drill String Deployed Running Tools

The independent HPU has the electric and hydraulic supply and controls for all the tools. Vehicle side is protected from the direct impact of the emergency case like tool oil contamination by hose burst or black out situation by isolating the hydraulic / electric supply.

By mounting IHPU on any ROV candidates to use for Okinawa project, all the required tools becomes possible to use, since the tools are operated by IHPU.

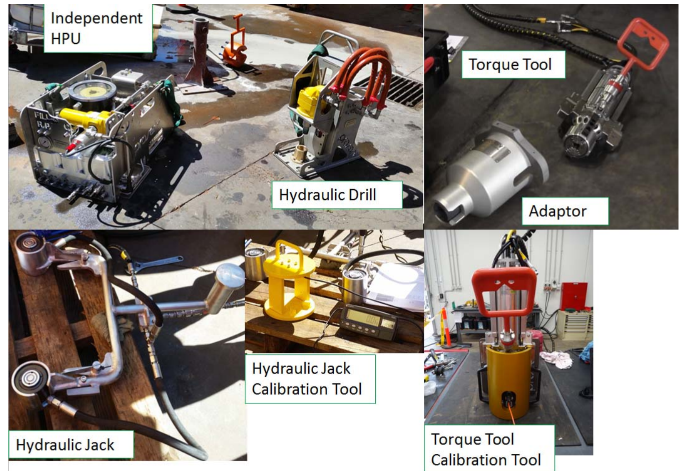


Fig. 19 Newly developed ROV tools for 2nd generation systems.

V. Testing of As build Equipment

A. 2nd Generation System Stack up Test

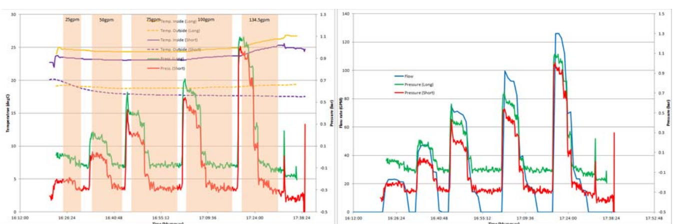
2nd generation system were built and stack up testing was carried out in early 2015 to simulate the actual installation into the deep water. Some modification were carried out based on the results of the stack up to improve the operation feasibility.

Fig. 20 Stack up Testing of 2nd Generation System

B. Flow Test on 2nd Generation System

As a part of SIT, flow test was carried out through the manifold and cell with water flow of 600 liters per minutes into the system. The sensor feed backs on digital flowmeter, pressure and temperature transducers were also confirmed with output reading of analogue gauge readings.

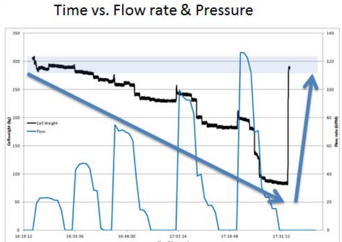
Fig. 21 Flow Testing of 2nd Generation System



Time vs. Temperature & Pressure

Time vs. Flow rate & Pressure

	Sensor S/N	Logger S/N	Demister:
P/T sensor (Long)	302225	O-0020	5%
P/T sensor (Short)	297450	O-0013	
Lord cell	1420293	SLL-0016	
Flow meter	159700	151501	



Time vs. Weight & Flow rate

Fig.22 Output of Sensors from the flow test.

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