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Simple, affordable and sustainable borehole observatories for complex monitoring objectives

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Abstract

Seafloor drill rigs are remotely operated systems that provide a cost effective means to recover sedimentary records of the upper sub-seafloor deposits. Recent increases in their payload included downhole logging tools or autoclave coring systems. We here report on another milestone in using seafloor rigs: the development and installation of shallow borehole observatories.

Three different systems have been developed for the MARUM-MeBo seafloor drill, which is operated by MARUM, University of Bremen, Germany. A simple design, the MeBoPLUG, separates the inner borehole from the overlying ocean by using o-ring seals at the conical threads of the drill pipe. The systems are self-contained and include data loggers, batteries, thermistors and a differential pressure sensor. A second design, the so-called MeBoCORK, is more sophisticated and also hosts an acoustic modem for data transfer and, if desired, fluid sampling capability using osmotic pumps. Of these MeBoCORKs, two systems have to be distinguished: the CORK-A (A = autonomous) can be installed by the MeBo alone and monitors pressure and temperature inside and above the borehole (the latter for reference). The CORK-B (B = bottom) has a higher payload and can additionally be equipped with geochemical, biological or other physical components. Owing to its larger size, it is installed by ROV and utilises a hotstab connection in the upper portion of the drill string. Either design relies on a hotstab connection from beneath which coiled tubing with a conical drop weight is lowered to couple to the formation. These tubes are fluid-saturated and either serve to transmit pore pressure signals or collect pore water in the osmo-sampler. The third design, the MeBoPUPPI (**P**op-**U**p **P**ore **P**ressure **I**nstrument), is similar to the MeBoCORK-A and monitors pore pressure and temperature in a self-contained manner. Instead of transferring data upon command using an acoustic modem, the MeBoPUPPI contains a pop-up telemetry with Iridium link. After a predefined period, the data unit with satellite link is released, ascends to the sea surface, and remains there for up to two weeks while sending the long-term data sets to shore.

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In summer 2012, two MeBoPLUGs, one MeBoCORK-A and one MeBoCORK-B were installed with MeBo on German RV *Sonne* in the Nankai Trough area, Japan. We have successfully downloaded data from the CORKs, attesting that coupling to the formation worked and pressure records were elevated relative to the seafloor reference. In the near future, we will further deploy the first two MeBoPUPPIs. Recovery of all monitoring systems by ROV is planned for 2016.

1 Introduction

Around 20 years ago, the scientific community started to use borehole observatories, so-called CORKs (**C**irculation **O**bviation **R**etrofit **K**its), which are installed inside submarine boreholes, and which allow the re-establishment and monitoring of in situ conditions (see summary in Davis and Becker, 2001). The key principle as well as the main objective is to provide a hydraulic seal between the borehole environment and the overlying ocean water body (Fig. 1). Based on this principle, various types of instruments with different capabilities have been developed over the past decades, the majority of those with scientific purposes within the Ocean Drilling Program (ODP) and the Integrated Ocean Drilling Program (IODP; see review by Becker and Davis, 2005).

From the first CORKs, which allowed only rudimentary fluid pressure and temperature measurements, the instruments evolved to multi-functional and multi-level subseafloor laboratories, including, for example, hydrologically isolated zones with casing screens (e.g. Davis et al., 2006), thermistor strings (e.g. Davis and Villinger, 2006), long-term fluid sampling devices (Evans et al., 2009), in situ microbiological experiments (Orcutt et al., 2010), or strainmeter (Kopf et al., 2011a). The advantages of long-term monitoring are the ability to obtain: (1) reliable measurement of ambient pore pressure (this measurement often requires significant time after drilling to re-equilibrate to original in situ conditions and usually cannot be obtained by downhole tools), (2) formation elastic and hydrologic properties determined from the response to tidal and seismic loading (e.g. Wang and Davis, 1996; Davis et al., 2004), (3) records of hydraulic transients associated with e.g. seismic and aseismic slip, fluid flow events, and possible precursory phenomena, over a wide range of timescales and rates (e.g. Davis et al., 2001, 2006), (4) temperature anomalies associated with fluid flow episodes (Davis and Villinger, 2006) or as precursors to earthquakes (Johnson et al., 2000); and (5) transient changes in chemical composition or seepage rate (Brown et al., 2005). The phenomena have in common that they are episodic in nature, and time series data are the only feasible way of increasing our understanding of them.

Nonetheless, most boreholes are still left uninstrumented, which is a major loss for the scientific community. Installation of CORKs usually requires a drillship, which is a major logistic and financial effort. Moreover, the increasing complexity of the CORK systems increased not only the expenses but led also to longer installation times and a higher sensitivity of the instruments to environmental constraints.

An affordable alternative to the drill ships is currently seen in the seafloor drills, which are tethered, remotely controlled devices that can be run from ships of opportunity provided they offer sufficient space and a strong enough A-frame. One such seafloor drill is the MARUM-MeBo (**Me**eresboden-**Bo**hrgerät), which has recently been developed at MARUM, University of Bremen (Germany) (see details in Freudenthal and Wefer, 2013). The MeBo70 can be operated from any research vessel and allows coring to a depth of 70 m in either push coring mode for soft sediments or rotary coring mode for hard rock drilling. A second device, MeBo200, is currently under implementation (sea trials anticipated in fall 2014) and will core to 200 m below seafloor with the majority of the other parameters similar to the first one.

In this manuscript we describe our main objectives in implementing observatories into MeBo boreholes. Foremost, this is the efficiency of a single round-trip of the seafloor drill and observatory unit (whereas drill ships always need a second round-trip by pipe or wire in order to deploy the borehole instrument). Secondly, the rather generic and modular design is a second objective so that a wealth of parameters may be monitored in a variety of settings. In the following, we present three types of miniature borehole observatories, which on one hand have evolved back to more simple systems when compared to ODP/IODP CORKs, but which on the other hand provide a wide range of possible in situ measurements. In addition to the technological concept, we report on the first installation of such MeBo observatories in the Nankai Trough area offshore Japan, this way providing a proof-of-concept.

2 State-of-the-Art: seafloor drills

Seafloor robotic drills bridge the gap between conventional seabed sampling techniques from multi-purpose research vessels (like gravity coring or dredging) and dedicated drilling vessels. Working from a stable platform at the seabed, which is not affected by ship movements due to wave heave or currents, ensures optimized control on the drilling process. As consequence of the increasing demand of core drillings in the range of 10–200 m for geotechnical site investigation, mineral ore exploration a variety of seabed drill rigs have been developed within the last decade (McGinnis, 2009). They are, however, more or less all in prototype status, with the MARUM MeBo being one of the most mature systems (see review in Freudenthal and Wefer, 2013).

The MeBo seafloor drill rig

MeBo (**Me**eresboden-**Bo**hrgerät, the German term for seafloor drill rig) is a robotic drill that is deployed on the seabed and remotely controlled from the vessel. The complete MeBo-system, including drill, winch, launch and recovery system, control unit, as well as workshop and spare drill tools is shipped within six 20′ containers (one of which carrying the MeBo drill itself; Fig. 2). A steel armoured umbilical with a diameter of 32 mm is used to lower the 10 t heavy device to the seabed where four legs are being armed out in order to increase the stability of the rig. Copper wires and fibre optic cables within the umbilical are used for energy supply from the vessel and for communication between the MeBo70 and the control unit on the deck of the vessel. The maximum deployment depth in the current configuration is 2000 m.

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The mast with the feeding system forms the central part of the drill rig. The drill head provides the required torque and rotary speed for rock drilling and is mounted on a guide carriage that moves up and down the mast with a maximum push force of 4 t. A water pump provides sea water for flushing the drill string for cooling of the drill bit and for removing the drill cuttings. Core barrels and rods are stored on two magazines on the drill rig. Wire-line core barrels (HQ) and hard metal drill bits with 55 mm core diameter (push coring) are usually used in soft marine deposits. The stroke length is 2.35 m each. With complete loading of the magazines a maximum coring depth of more than 70 m can be reached. Station time can reach more than 24 h per deployment. For a more detailed description of the MeBo70 see Freudenthal and Wefer (2009, 2013).

3 Methodology

3.1 Methodological objectives

Among the tasks we try to achieve with the MeBo borehole observatories, there are four fundamental ones:

1. seal the borehole,
2. collect data over long periods of time,
3. transfer data to the scientist/end user, and
4. increase capability by adding payload.

Our concept is very generic. Tasks 1 and 2 are mandatory and realised in all three MeBo observatory systems, whereas tasks 3 and 4 provide a suite of options that can be tailored to the needs of an individual campaign.

3.1.1 Borehole seal

The MeBo seafloor drill uses H-size HQ wireline coring tools. The outer diameter of the drill rods is 98 mm. During the routine drilling operations, these pipes are used to extend the drill string downhole, and are recovered once terminal depth of a given hole is reached (Freudenthal and Wefer, 2013). Each HQ rod has a male end with a conical thread at the base and a female conical thread at the top end.

If an observatory is to be set with MeBo, procedures change in the sense that some drill pipe (i.e. several of the 2.35 m-long rods) remain in the ground and serve as casing to stabilise the upper portion of the hole where the soft sediments would otherwise close in. The final, uppermost drill rod is then prepared to provide the borehole seal. In addition, this rod has a widened outer diameter to that it will facilitate seal at the seafloor where the drilling operation may have excavated the ground.

The two main principles to have a sealed upper rod are to screw in an instrumented plug having the shape of the conical thread and additional o-ring seals, or to prepare an entirely new instrumented rod of up to 2.35 m length with a hotstab seal in the middle. These two principles have been used in designs of the so-called MeBoPLUG and the MeBoCORK-A and -B, respectively (see Sect. 3.2 below).

3.1.2 Data mining

In addition to the borehole seal, data mining in the borehole and/or formation is a prerequisite for the instrumented drilling rods. If the inner volume of the "casing" (i.e. MeBo drill pipes in the ground) is the target, a simple plug with a data logger and transducers is sufficient to monitor e.g. the equilibration of the hole and ambient values thereafter. If, coupling to the formation is desired, a mechanism is needed that couples the transducers to the open hole formation. For this purpose, we designed a small device at the base of the instrumented uppermost drill rod that has a small coil with PVC tubing (1 mm inner diameter) which can be unrolled via an electrical motor upon command (acoustic signal or timer with preset date/time for lowering). At the tip of the tubing there is a stainless steel conical drop weight with a boring that will then provide access to the sediment at the base of the hole. The tubing may then serve to get ambient pore pressure readings, or extract pore water samples (in case an osmo-smpler is hooked to it at the seafloor). We have realised designs of both in the MeBoPLUG and the MeBoCORK-A and -B, respectively (see Sect. 3.2 below).

3.1.3 Data transfer

Retrieval of CORK data has always been a crucial issue in the past, with all ODP- and IODP-CORKs relying on ROV visits during regular 3rd party cruises in the years after deployment. This is a costly endeavour and further bears the difficulty of vagueness in planning because of dependency on weather, shiptime providers, etc. One of the key requirements in developing MeBo observatories was hence to start with a simple instrument to be recovered by ROV and then evolve to systems which make ROV visits or even visits of a vessel obsolete.

As a consequence, the MeBoCORK systems aimed at including acoustic modems so that the successful deployment and health of the system after the MeBo took off can be attested. Data transfer is moderately fast, so that practically, only limited data sets are to be downloaded that way while a final visit to recover the instruments by ROV seems still advisable. In case the deployments take place in an area where a return cruise is not anticipated for longer periods of time, it may be better to release a pop-up unit with a mirror data set of the main data logger as well as an iridium telemetry to transfer the data without the necessity to retrieve the instrument. If the latter is sufficiently cheap, net cost may be saved since ship time is also precious. We have realised designs of both in the MeBoCORK-A and -B and the MeBoPUPPI, respectively (see Sect. 3.2 below).

3.1.4 Increased payload

Given the wealth of critical parameters that govern seafloor processes, scientist desire to deploy multi-sensor instruments that often consume considerable energy. One main objective in MeBo-corking was hence to have a modular seafloor unit where space for additional devices and batteries play a minor role. Such a unit has to exchange the initial MeBoCORK instrument (with a limited lifetime) without affecting the borehole seal. This was achieved by a hotstab connector that can transport fluids, power, or both. At the seafloor end, capabilities may be increased by adding osmo-samplers with long tubing coils for fluid sampling over 24 months and longer, but also to provide power for energy-demanding systems such as geophones, etc. We have realised this by inventing the MeBoCORK-B (see Sect. 3.2 below).

In the next section we will introduce three general instruments of the MeBo observatory family: the PLUGs, CORKs and PUPPIs. Each of them is employing several (if not all) of the tasks listed above. In addition to those observatory instruments realised, many other combinations of transducers and data transfer principles, but also implementation of new transducers. This could be either in the instrumented drill pipe (if sufficiently slim) or inside the seafloor unit. With its generic and modular design MeBo observatories may become a versatile and affordable way to monitor hydrogeochemical and geological processes in the shallow sub-seafloor (< 200 m).

3.2 Implementation

3.2.1 MeBoPLUG borehole observatories

In regular-size industry boreholes, the casing of the upper portion on the well is a couple of decimeters, and re-entry into the hole is facilitated by a conical seafloor structure, often complemented by a platform to land a ROV. For the seafloor drill holes, all this is miniaturized and in case of MeBo a diameter of only 98–110 mm is available. Space is hence most seriously governing the design of the MeBo observatories, and re-entry

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is not feasible in such narrow drill pipes. In essence, the entire hole completion was initially designed as a stand-alone instrument, which does not differ from the geometry of a standard MeBo drill pipe (appx 235 cm long and 10 cm in diameter).

The name of the instrument is leaned from the SmartPlug and GeniusPlug observatories, which also represent simple types of CORKs designed as extension to mechanical bridge plugs, but IODP drillhole-sized (Kopf et al., 2001b). Instead of a bridge plug or CORK seal, we make use of the conical threads of the MeBo drill pipes and seal the pipe with a pair of additional o-rings (Fig. 3). The pressure housing is machined from a thermoplastic synthetic polymer, polyoxymethylene (POM), which tolerates moderate P and T and has successfully been used to 25 MPa confining pressure. At the top, a handle designed to specification of the ROV *MARUM-Quest* manipulator was added. In the borehole-facing section, a thermistor as well as the downward-looking P port are situated (Fig. 3, inset on right).

Inside the housing we hosted standard RBR data loggers with Keller differential pressure transducers for monitoring P transients in the boreholes (as a proxy for strain; Davis et al., 2006) relative to the seafloor P signal. With this approach we omit detiding of our data because all signals from wave action, etc. occur more or less simultaneously at the seafloor and in the shallow sub-seafloor formation. Given that only one thermistor was fitted into the so-called MeBoPLUGs, we are lacking a temperature record from the seafloor (i.e. upward-looking side of the MeBoPlug; see Fig. 3). In order to overcome this shortcoming, a simple self-contained device for seabottom T monitoring, a so-called MTL (Miniature Tempreture Logger by Antares; Pfender and Villinger, 2002) was deployed by ROV next to the MeBoPlug (see next section). The sampling rate of the MeBoPlugs was set to 10 s on the RBR data loggers, which is providing them with an estimated lifespan of about 4 years (anticipated end of recording is February 2016).

3.2.2 MeBoCORK borehole observatories

The two versions of the MeBoCORK, as seen in Figs. 4–7, are both self-contained with power, data logging, data transmission and transducers. They are recoverable at all times and hence minimize the risk of loosing the investment. In the following paragraphs, the deployment mechanism is explained in some detail. First, the MeBo hole has to be prepared for long-term instrumentation after coring is completed. This is achieved by leaving several pieces of MeBo outer drilling rods in the ground after wireline core retrieval. These rods, appx. 30–40 m in total length, act as a casing and stabilize the upper subseafloor portion where the deposits are poorly consolidated and otherwise may close in. Only the lowermost part of the hole is free of "casing" and provides direct access to the formation. The first prerequisite to keep the MeBoCORK simple follows the first hydrological observatory in ODP: only hydraulic tubing is lowered into the hole to access fluid pressure (or fluids) at depth (Wheat et al., 2011), and all electronics remain at the wellhead. For MeBo, a string of 2 armored PTFE tubes is coiled up in the lower part of the MeBo-set observatory unit (termed MeBoCORK-A, where A stands for "autonomous", i.e. MeBo by itself is capable of placing a stand-alone observatory), namely in the lower portion of the "adapter" hosting the receptacle for the hotstab. Once the drilling device has set this piece, the coil of tubing is unlocked and a dead weight favours the tubing's descent towards terminal depth where the hole is open. The upper end of the individual tubings connects to borings of the hotstab receptacle. The lower unit also hosts battery packs.

The upper portion of the MeBoCORK-A hosts the data transmission unit, data logger and transducers, the latter of which are connected to the borings of the male hotstab end (Figs. 4a and 5). The hotstab is mated with its female counterpart, and the two halves of CORK-A are further secured by a bayonet connector that allows coupling of the MeBo70 top drive and hence torque being transmitted (in clockwise direction only!). During installation MeBo fully srews in the entire CORK instrument, which in total is the exact length of a regular MeBo drill rod and which sits on the magazine with the other rods. Once this piece is properly set, MeBo pushes the unit to a depth so that only the titanium part (ca 70 cm long) sticks out of the seafloor and then takes off. In the initial design, this simple, MeBo-set CORK monitors pressure and temperature, which are both indicators for deep-seated fluid flow; pore pressure is additionally valuable as strain proxy (see above). Depending on the sampling rate, the batteries will allow monitoring for many months to a few years (in case of the system deployed during leg SO222A = 7 months).

If monitoring or parameters other than pressure and temperature is desired, the instrumented MeBo70 rod (CORK-A) is too small and an ROV dive is required to recover the CORK-A and deploy an external, more sophisticated observatory unit (Figs. 4b and 6). Since the ROV dives to the seafloor and connects a seafloor (= sea bottom) unit to the MeBo rod with Hotstab recepticle, this system was termed MeBoCORK-B (= bottom). The ROV is able to unlatch the bayonet connector in counter-clockwise direction and can transport the MeBo-set CORK back to the ship, because its weight is low and the diameter is suitable for the manipulator claw. Before this, a seafloor unit will be placed next to the MeBo drillsite (Fig. 6). This system contains of a pressure housing with an attached hood in which a male hotstab adapter plus the umbilical of armored tubing strings is coiled up. The ROV takes the hotstab and places it into the lower portion of the MeBoCORK, which is remaining connected to the outer drillstring at all times. This operation is straightforward and has been done in a similar way when pressure units from ODP or IODP CORKs got replaced. The pressure housing at the seafloor can be equipped to the mission's/scientists' specifications, and in the case of this proposal will host the P and T transducers (same as in the instrumented rod) plus an osmo-sampler (Fig. 7; see also Jannasch et al., 2003).

Both MeBoCORK instruments are programmed to measure the pressure for a period of 30 s and then record the average P value. Seafloor reference and borehole P are offset by 15 s, so that the data are written to the disk alternately.

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3.2.3 MeBoPUPPI borehole observatories

In a recent effort, we have taken the MeBo long-term borehole observatory science to the next level and build pop-up borehole instruments that can be released from the casing string after a predefined period. An underwater mateable connector further enables the user to also "manually" release the unit by ROV. Once the unit has ascended to sea level, the popup unit (Fig. 8) send their data via satellite link, rendering a second visit and additional shiptime unnecessary. Such instruments would in a first iteration monitor pressure and temperature, but could be equipped with geophones, seismometers and other components depending on the scientific demands of a given mission, the duration of monitoring, the amount of time series data, etc.

In contrast to the MeBoCORK systems, the MeBoPUPPIs do not rely on a hotstab connector and tubing that is lowered towards terminal depth of the borehole where direct access to the formation exists. Instead, the monitoring is restricted to P and T inside and outside of the borehole as well as tilt using a triaxial array of accelerometers. If desired, an additional unit that samples simultaneously one hydrophone and three geophone channels (type SM6, with 4.5 Hz lower frequency band, but no mechanical gimbaling system) can be mounted. Either sensing package has to remain in the borehole string for reasons of limited space and weight of the popup unit. This may be equally the case for part of the battery packs when very long monitoring periods are desired. In these cases, almost all of the total of 235 cm length of a MeBo70 drill rod segment, excluding a 53 cm-long adapter to protect the glass dome (Fig. 8, righthand side drawing) are available.

4 Results

During cruise SO222 on RV *Sonne*, the MeBo70 was deployed 6 times in water depth between 1900 and 2050 m. The main objective of this cruise was to install borehole observatories with the MeBo70, so holes were only drilled down to 35 m b.s.f. (meters below seafloor) or shallower. As explained before, the drilling procedure in observatory installations encompasses that only a few drill pipes are recovered to create open hole conditions at the base, and that a drill pipe that already included either a MeBoPLUG or a MeBoCORK-A is added to terminate the hole near the seafloor. Once that final rod was set the MeBo70 took of vertically while being assisted by the winch, and was then recovered on deck.

As explained in more detail in Kopf et al. (2013), a total of four observatories were set with MeBo70 during cruise SO222 with RV *Sonne*, and in case of MeBoCORK-B assisted by ROV. In general, operations were effortlessly carried out, in particular for MeBoPLUG #1 and MeBoCORK-A. Both systems were pre-installed on the uppermost, final drill rod, which was pushed down into the seafloor so that only appx. 70–80 cm stuck out into the water column. Figure 9a and b illustrates how the situation looked like before MeBo70 took off.

When installing MeBoPLUG #2 in the Kumano Basin, we encountered some problems with drilling progress when hitting several indurated sand layers at appx. 17 m b.s.f. Despite efforts to clean the hole with pressurised fluid, the string did not progress any deeper, so that the only option to install MeBoPlug #2 was to screw on the drill pipe section that hosted the MeBoPLUG and leave it sticking out of the seafloor by appx. 2.5 m. Despite this fragile pipe representing an obstacle, the MeBo70 take-off went well and the pipe was not bend or damaged.

The majority of the other installations were also successful, e.g. for the autonomous CORK-A (Fig. 9c), the CORK-B downhole assembly with endcap protecting the female hotstab end (Fig. 9b), as sighted later on by ROV. In particular the latter example demonstrates that the black end cap on the female hotstab connector (Fig. 9b) can easily replaced with a hotstab on an umbillical that is connected to P transducers and osmo-samplers (Fig. 7), which are hosted in a pressure housing together with the data logger, acoustic data transmission and other electronics (Fig. 9d).

During the installation of MeBoCORK-A at the crest of Kumano Basin mud volcano #4 (Kopf et al., 2013) we encountered no problems, and once the MeBo70 had taken

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off, we sent an acoustic signal to unlatch the drop weight and lower the coiled pore pressure tubing into the open bottom end of the otherwise cased drill hole. This process is controlled by an electrical motor which operates in either "command-mode" (triggered acoustically) or "timer-mode" (veering of tubing starts at a pre-programmed date and time). As can be seen from one of the first data sets downloaded from the CORK-A via acoustic communication by *develogic*, the borehole pressure shows appx. 18 m higher pressure values than its seafloor counterpart (Fig. 10), which is in good agreement with the terminal depth of appx. 19 m b.s.f. at this drill site. It can further be observed that the borehole temperature is appx. 1.1 °C warmer than the bottom water temperature (blue vs. turquoise data in Fig. 10).

At a neighbouring mud volcano, MV#3, we had at first no problem untangling the hotstab of the seafloor unit of MeBoCORK-B, take it to the MeBo70 drill rod, and plug the hotstab into its female counterpart (Fig. 9d). However, there was some uncertainty that the tubing got caught and pinched during this operation, so that we unplugged the hotstab again and pushed it back in more safely a second time. The P records of seafloor reference and downward-looking (= borehole) P are shown in Fig. 11. It can be seen that the differential pressures do not change much over the time of installation, which is unexpected given that the borehole terminates 33 m b.s.f. and the drop weight should sit near terminal depth of this hole. The only explanation for the P record measured is a leak somewhere inside the upper end of the female hotstab end of the drill string; all other sources of error, including the entire bottom unit, umbilical with tubes to hotstab and osmo-sampler, as well as the hotstab connector itself, are flawless.

5 Discussion, conclusions and outlook

In summary, the "MeBoCORK concept" with its three versions (MeBoPLUG, -CORK and -PUPPI) aimed at a smart approach where an observatory can either be set by MeBo alone, or in combination of MeBo70 and ROV. The designs represented a compromise scientifically since a limited set of parameters is monitored, however, this has

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not been any different when the first full-size ODP-CORKs were deployed (Becker and Davis, 2005). However, the three approaches taken appear extremely valuable at this stage and the future will likely provide opportunities for payload being added onto either observatory unit.

In the pilot study off Japan, we demonstrated that one MeBoCORK-A and one MeBoCORK-B as well as two MeBoPLUGs can successfully be deployed. This meant that 4 out of a total of 6 MeBo holes drilled during a 2-week expedition got instrumented. For the MeBoPUPPIs, we are currently in the phase of long-term performance tests in the pool before taking them into the natural environment.

Of course, the MARUM-MeBo borehole observatories are limited and high performance seismometers or strainmeters may turn out impossible to be installed because of both their size and energy consumption. However, it appears that future scientific ocean drilling may have to cope with such a mission-specific approach from ships of opportunity. In addition to it being most affordable, there are associated advantages such as absent heave on the system during installation (i.e. no danger of destroying the instruments). Future avenues to increase the payload of the MeBoPLUGs and -CORKs are miniaturisation of tranducers and optimisation of power consumption of the components, potentially combined with new ocean bottom fuel-cell technologies.

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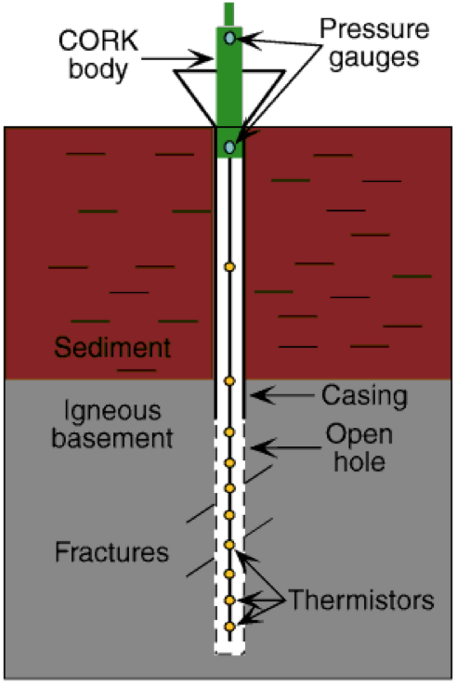

Figure 1. Schematic of a CORK observatory's main components: here an example in sediment-laden oceanic crust and a simple CORK head with seal and P transducers (green unit with light blue sensors) plus a thermistor string (self-contained; see yellow circles). From Becker and Davis (2005).

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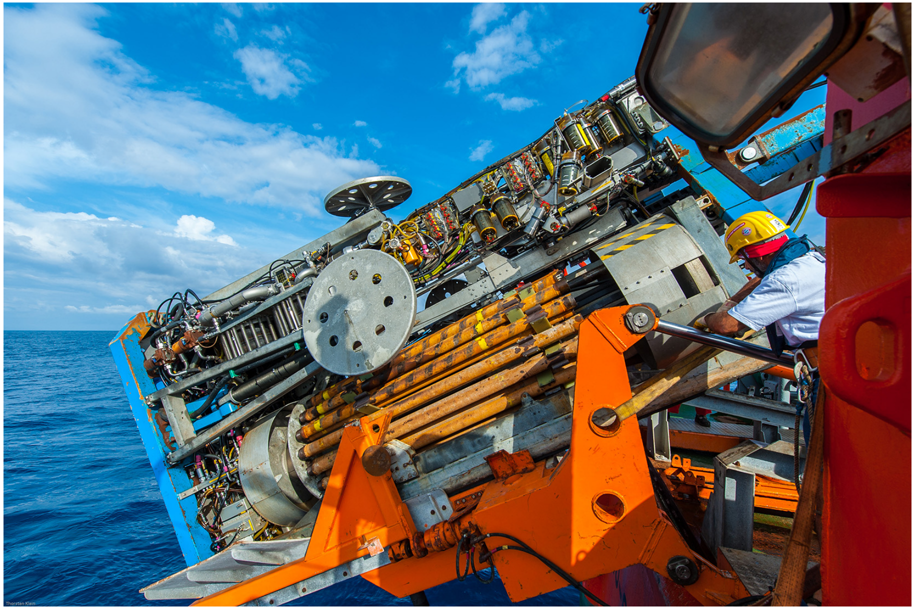

Figure 2. MARUM-MeBo70 drill rig during launch on the aft deck of RV *Sonne*.

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Figure 3. MeBoPlug prior to being screwed into a MeBo drill pipe (left); right photograph shows bottom view into the borehole with ports for P (hole at left) and T (little pin at right) monitoring. See text.

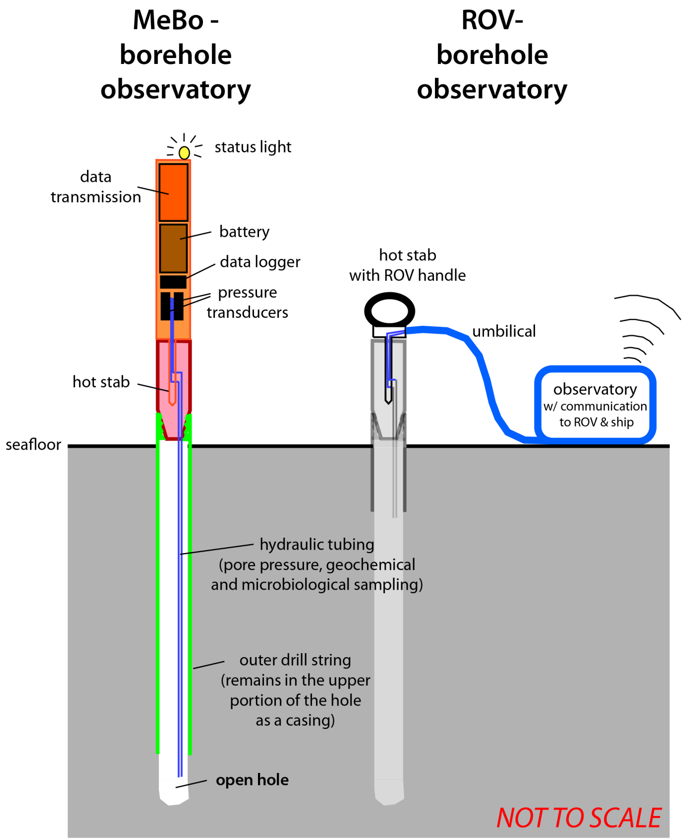

Figure 4. Schematic diagram of MeBoCORK-A (left) and MeBoCORK-B (right).

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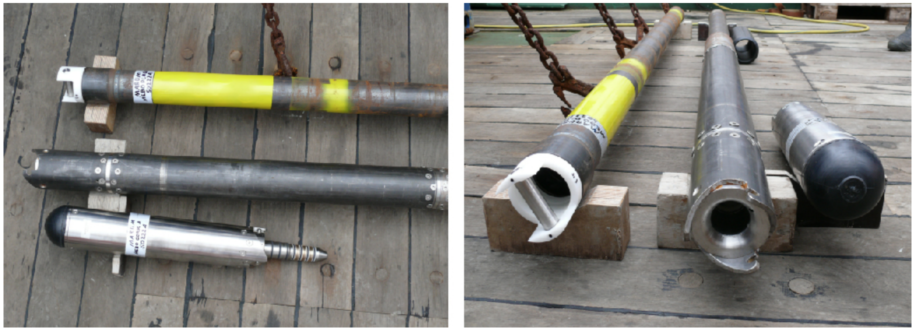

Figure 5. MeBoCORK A (= autonomous) as well as MeBoPlug for comparison. See text.

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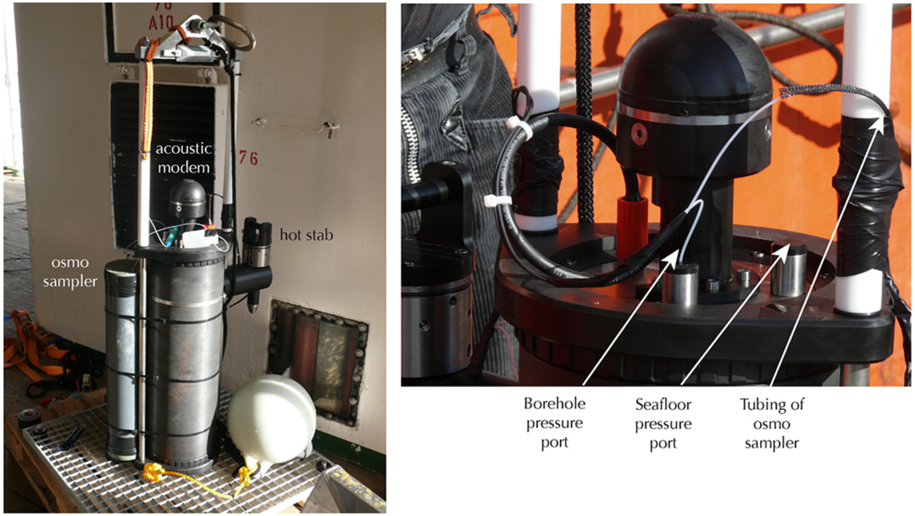

Figure 6. MeBoCORK B (= bottom) unit containing a pressure housing, acosutic modem, attached osmo-sampler, and the hot stab connector to couple to the drill pipe. Left photo shows overall unit, right photo contains detail with layout of tubings. See text.

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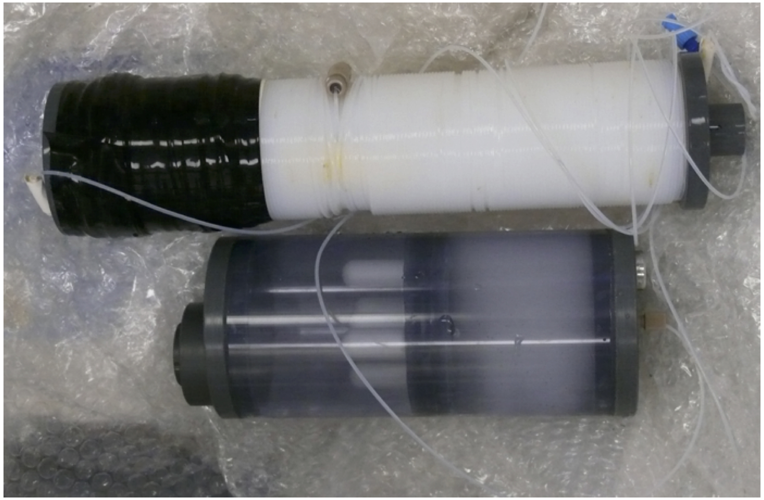

Figure 7. Osmo-sampler – tubing coil (top) and pumps (below) – that are hosted in a PVC tube attached to MeBoCORK-B.

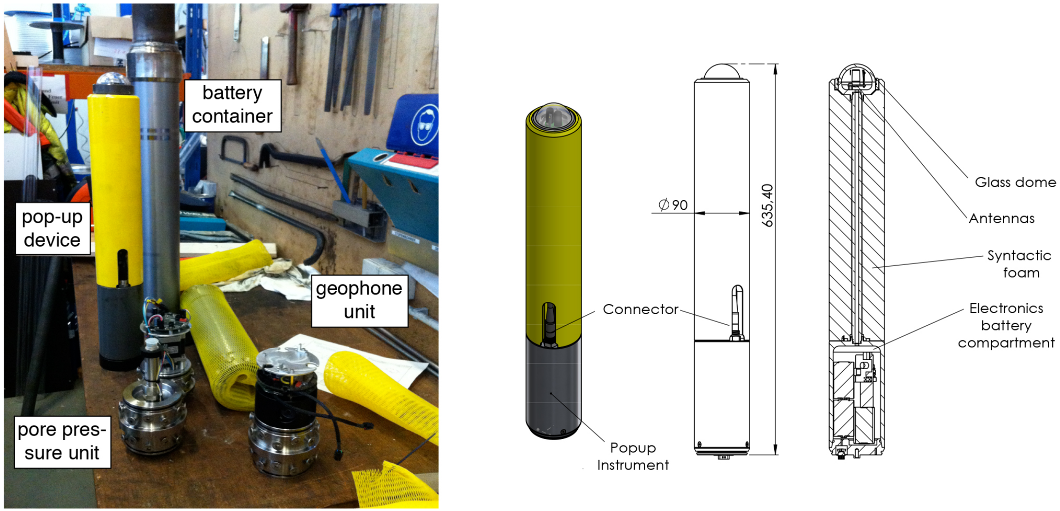

Figure 8. Schematic diagram (left panel) and photograph (right panel) of MeBoPUPPI observatory.

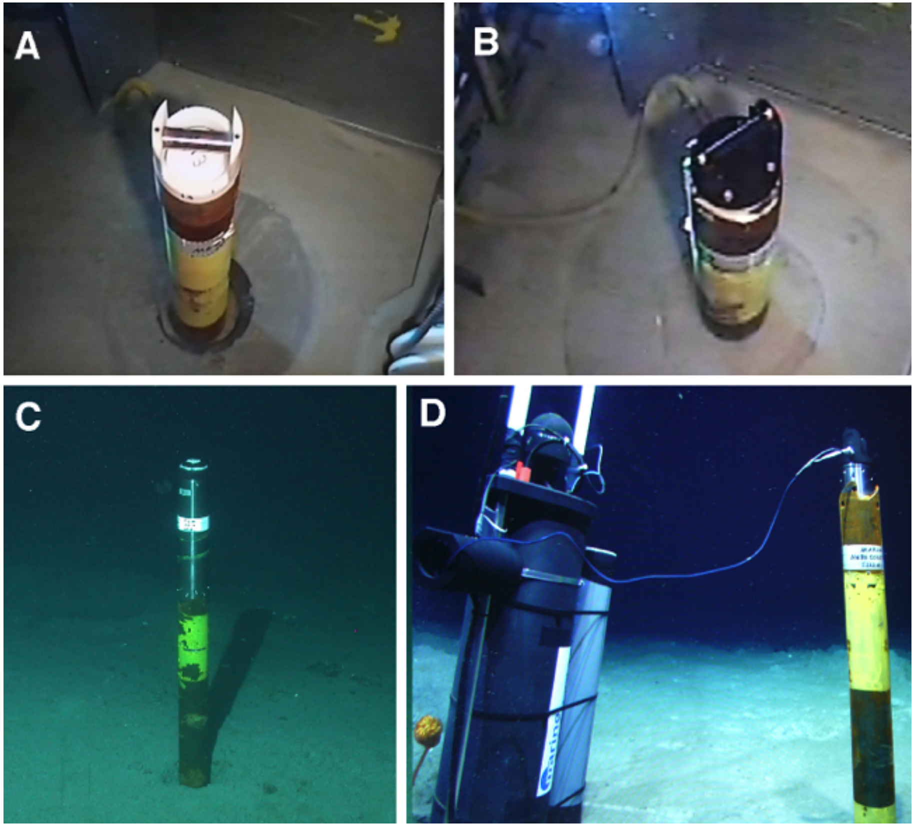

Figure 9. (a) MeBoPLUG and **(b)** MeBoCORK-B top hole assembly with black endcap after installation with MeBo70. Photos were taken immediately before the seafloor drill rig takes off the ground. **(c)** MeBoCORK-A and **(d)** MeBoCORK-B with seafloor unit. Photos were taken during subsequent ROV visits. See text.

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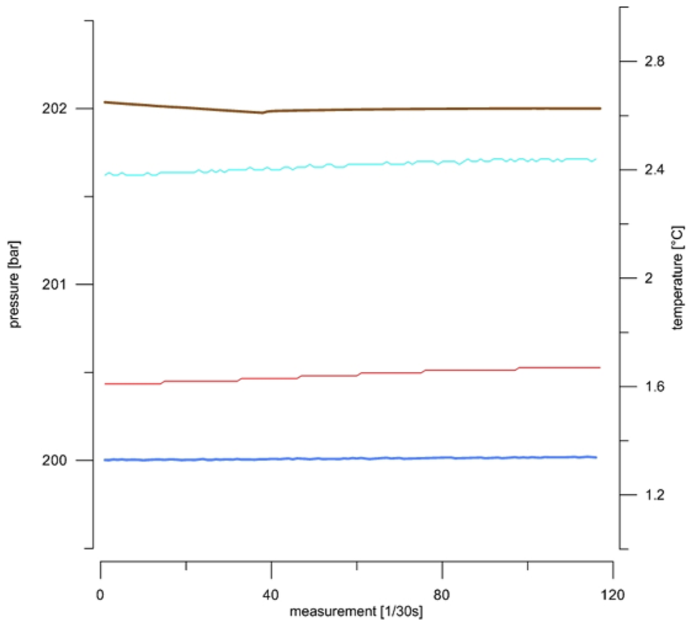

Figure 10. First data sets from MeBoCORK-A as recovered by acoustic data transmission. Pressure curves are blue/turquoise colours, T curves are red/brown colours (seafloor/borehole in either case). The *x* axis represents the time over 60 min, in which data are integrated over 30 s each. Note the offset in borehole vs. reference pressure, which attests the successful deployment of the drop weight and coiled tubing and access to the open hole formation.

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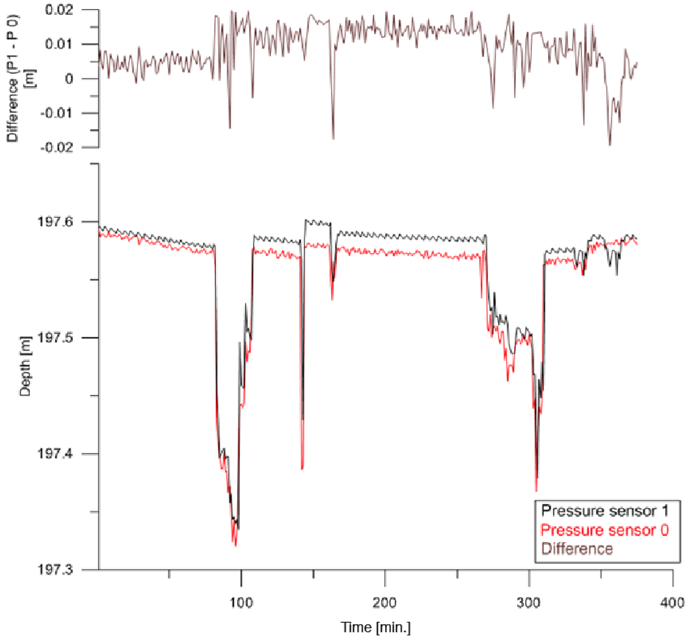

Figure 11. Data set covering the connection of MeBoCORK-B with ROV *Quest*. For reasons to be explored, the borehole pressure is not any higher than the seafloor reference, suggesting a problem with the hotstab connection. Note that the vertical scale is in $m \times 10^1$ and that the horizontal unit is min.