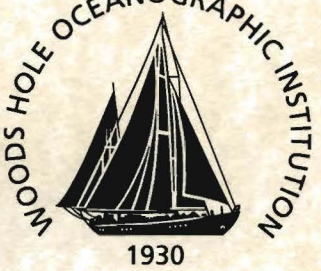
Technical Memorandum WHOI-01-2006

Woods Hole Oceanographic Institution



SeisCORK Meeting Report

by

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February 2006

Technical Memorandum

Funding was provided by the National Science Foundation under Grant No. OCE-0450318.

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SeisCORK Meeting Report

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November 15 and 16, 2004

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Summary

The purpose of this meeting was to explore design options to simultaneously acquire borehole seismic data and hydro-geological data (pressure, temperature, fluid sampling and microbiological sampling) on a single CORK system. The scientific focus was to add a seismic component to the Juan de Fuca Hydrogeology program. By permanently installing a sensor string in the borehole our goal was to enable: 1) time-lapse VSP's and offset VSP's with sufficient data quality to study amplitude versus offset, shear wave anisotropy, and lateral heterogeneity; 2) monitoring of micro- and nano- earthquake activity around the site for correlation with pressure transients. Because of the difficulty in ensuring adequate coupling through multiple casing strings we concluded that it was impractical to install the vertical seismic array with 10m spacing (50-60 nodes) that would be necessary for VSP's and time-lapse VSP's. We did describe a scenario for a vertical seismic array with approximately 100m spacing (5-6 nodes) that could be used for offset-VSP's and seismic monitoring. This uses some unique technology and involves two seismic strings: one in the annulus between the 4-1/2" and 10-3/4" casings and one in the middle of the 4-1/2" casing.

I. Introduction

The purpose of this meeting was to initiate the development of equipment to simultaneously acquire borehole seismic data and hydro-geological data (pressure, temperature, fluid sampling and microbiological sampling) on a single CORK (Circulation Obviation Retrofit Kit) system [*Davis et al.*, 1992; *Jannasch et al.*, 2003; *Shipboard_Scientific_Party*, 2002]. (The attendees and their contact information are given in Appendix A.) Such a capability could be used for a broad range of borehole geophysical experiments targeted at various geological and seismic processes, however the scientific focus of this effort is the Juan de Fuca Hydrogeology program (see Appendix B for notes on the hydrogeology science program). This program consists of two phases. The first phase, IODP Leg 301, was at sea on the Juan de Fuca Ridge in Summer 2004 (Figure 1)[*Shipboard Scientific Party*, 2004]. Planning for the second phase is based on the results of Leg 301 and is taking place in Fall 2004. The challenge is to formulate a drilling and instrumentation plan that can be implemented while the riserless drill ship is still in the Eastern Pacific in Summer 2006, 2007 or possibly 2008.

Permanently installed borehole seismometers would enable both active controlled source and passive monitoring experiments (see Appendix C for more notes on the scientific justification for borehole seismometers on CORKs). Seismic mapping of the lateral heterogeneity and anisotropy of the upper crust will be necessary in order to provide the framework for the hydro-geological results. This will best be accomplished by a combined OBS (ocean bottom seismometer) refraction and offset-VSP (vertical seismic profile) experiment. Given the logistical difficulties of coordinating the operations schedules of two vessels on the high seas, the best approach for the combined seismic experiment is to integrate the VLF (1-100Hz) borehole geophones with the CORK which will be installed in 2007 or 2008. The OBS experiment can then be carried out after the drill ship has left the site. The offset VSP data from the seismometers in the CORK can be acquired on the seafloor as in a conventional OBS.

The borehole sensors themselves can be considered expendable and will stay with the CORKs for the duration of the hydro-geological experiments. During this phase, which would last at least three years post drilling, the borehole geophones can record ambient nano- and micro-earthquake activity associated with the hydrothermal processes. The Juan de Fuca hydrogeology site is a proposed node ("ODP 1027") on the Neptune Canada seafloor cabled observatory network. As the cabled observatory infra-structure becomes available the borehole seismic data could be made available in real time to shore-based labs. (Tentative design goals for the Neptune Canada system are to have a least 9KWatts of power per node, to have 2-4Gigabit/sec ethernet at each node and to provide absolute time to within 10microsec.) Some notes on CORKs, the IODP drilling program and the OOI/ORION/NEPTUNE observatory program are given in Appendix D. A summary of various CORK and seismic observatory configurations used on DSDP, ODP and IODP is given in Appendix E.

The focus of this meeting was to develop SeisCORKs for IODP **non-riser** drilling on the **Juan de Fuca Ridge**. These holes will be only a few hundred meters deep through about 250m of soft sediments and penetrating about 200m to 350m into hard basalt. Beyond the focus of this meeting there are other applications for SeisCORKs in different geological environments. For example, systems similar to the Juan de Fuca Ridge program could be deployed in **non-riser** holes drilled for the Nankai Trough or Costa Rica Trench projects. Many of the problems and solutions discussed in this report have general applicability to a broad range of IODP drilling objectives.

II. Design Considerations

a) Not to interfere

Not to interfere with the existing and planned hydrological observations.

b) Node description

Each "node" should consist of a three component seismic sensor and a hydrophone.

c) Sensor specifications

System noise floor, sensitivity, THD, phase response, etc should be sufficient to faithfully acquire ground motion and pressure in the band 0.2-100Hz with system noise less than the quietest observed seafloor and sub-seafloor ambient noise spectra (Figure 2). (For a comparison of ambient seismometer and hydrophone noise levels in a borehole on the seafloor see Stephen et al, 1994 and 2003.)

d) Well configuration and depth

The focus here is on deployments in wells that are less than 2000m deep (typically 300-600m below sea floor) in water depths up to 5500m with sediment thickness of 250-300m. These holes are riserless (no BOP) and are generally left with a re-entry cone about 4m in diameter with 10-3/4" casing from the cone to upper basement and open hole below that. (The top of the IODP standard re-entry cone is actually an octagon inscribed inside a 12ft diameter circle.) Pressure housings, cables and connectors should be designed to operate to depths of 7500m (750atm or 11,250psi in water)

e) Sensor configuration

For VSP's you would want a sensor every 10m at most (up to 60 sensors in a 600m hole). For offset VSP's and passive monitoring a nominal sensor separation of 100m (6 sensors in a 600m hole) is sufficient. This will of course vary depending on the geology intersected by the well. The number of channels would vary from 240 (assuming 10m separation for VSP's) or to 24 or less (assuming 100m separation for offset VSP's and passive monitoring).

f) Field assembly

CORK bodies and sensor strings need to be made-up on board ship because the well dimensions are usually not known in advance. Plans change depending on drilling progress and flexibility is essential.

g) Sensor coupling

Good coupling to the formation is essential for quality seismic observations. This must be assured through some form of clamping mechanism, cement, glass beads, etc. Boreholes drilled for hydrologic observations typically have multiple casing strings with packers and seals in various locations. Only the center of the innermost casing is readily accessible and this can be separated from the formation by up to four casings. It is generally felt that the response of a sensor clamped to the innermost casing would be attenuated and distorted from the true formation motion. Historically tube waves, casing resonances and even clamping arm

resonances have been observed on borehole seismometers that are not adequately clamped to the formation.

h) Temperature

Typical temperatures in the upper basement at the Juan de Fuca sites are less than 70°C; the deepest hole so far in ocean crust (about 2km) had bottom hole temperatures of 200°C. A target design specification can be set at the military spec for solid state chips of 125°C.

i) Outside diameter

The available diameter through the center of a CORK varies depending on design. For the Juan de Fuca configurations gear that passes through the center of the 4.5" casing should have an OD of 3.5" or less. Gear that will be installed between casing strings should be 3.0" or less.

j) Power consumption

SeisCORKs will be operated in both autonomous and cabled observatory modes. In autonomous mode, at least one node should be acquired continuously for a year or more with only battery power supplies. The design goal is 2Watts per node including digitizing and recording. More nodes would be turned on for various experiments such as the offset VSPs and a reasonable power strategy needs to be defined.

k) Installation and maintenance

Most CORKs have been installed from the drill ship although two have been installed by wireline re-entry. Maintenance such as changing power supplies, retrieving data modules, or downloading data is usually carried out by ROV or submersible.

l) Data Acquisition and telemetry

All SeisCORK configurations must be able to acquire data for up to a year in autonomous recording mode as well as to interface with the cabled observatory infrastructure. Even under cabled observatory operation there needs to be a back-up capability for those periods when the cable is down.

m) Timing

In seismic refraction experiments absolute time, to an accuracy of one second, is required to obtain ranges and bearings from the navigation data of the shooting ship. Accurate relative times from the shot to the receivers, to an accuracy of 20ms, is required to measure meaningful velocities and depths for studying earth structure. Advanced array processing of the digital data requires extremely accurate, to with 50microsecs, relative times between samples on adjacent channels {Stephen, 1994 #7763}. The goal of seafloor networks such as Neptune Canada is to have absolute time available at the nodes to an accuracy of at most 10microsecs.

n) CORK configurations

Figure 3 shows the three CORK configurations deployed on Leg 301 in the summer of 2004. Planning for the next phase in 2006 or 2007 is based on installing CORKs similar to the ones in Holes 1301A and 1301B. A 20inch casing string is used to stabilize the hole just below the re-entry cone. 16inch casing is used through sediments and 10-3/4inch casing is used through the poorly consolidated rubble at the top of basalt.

o) Keep weight on the seals

As configured for the Juan de Fuca holes, the instrument string that runs down inside the 4.5" casing consists of two seals that must come to rest on seats in the casing. There must be sufficient weight below the bottom seal to pull the seals into place. This places constraints on systems which rely on "landing" a sensor in the bottom of the well.

Another option is to use latch-in seal plugs similar to the original Costa Rica installations. We had trouble extracting those plugs due to my error in having the seal nipples phosphate coated which increased the seal frication considerably. Using stainless steel seal nipples and lock mandrels (oil field terminology for the latching plug) dressed with low friction seals, I feel conficent that the lock mandrels can be extracted almost by hand. Note that the lock mandrels can be unlatched easily by hand.

There are two big advantages in using lock mandrels. First, once the lock mandrel is latched into the seal nipple it can not be pump of seat, acting like a check valve. Second, the lock mandrels are run on wireline using a special running tool. When the lock mandrel lands on the seal nipple it locks into the seal nipple profile. The running tool can only be released from the lock mandrel by jarring upward, shearing the release pin. This provides positive feed back that the lock mandrel is seated properly.

When deploying the "gravity" plugs, the wireline operator has to "sling" them off the wireline running tool, by picking up quite a ways above the seal nipple, spooling out slack in the wireline and then hard reversing the winch to whip running tool. If all goes well, the running tool shear fails, releasing the instrument string which falls down hole coming to rest in the seal

nipple. I reality the wireline has to be worked up and down several times to release the running tool, during which the instrument string is continuiously pulled up hole and dropped.

Quite frankly, I don't like deploying the gravity plugs that way. The instrument strings are usually so light that there isn't a clear indication on the wireline weight indicator that the string has been released. On occasion the wireline has been recovered only to find that the string is still attached.

Another option is to use the logging line with an electric release. Unfortunatley, my investigations into electric releases did not result in finding a suitable model. They all tend to leave large chunks of steel in the hole. This was not practical in the case of the Costa Rica installations since a rope attached to the instrument string was left suspended above the wellhead by floatation. The release had to go above the floatation and the weight of the release was such that it wasn't practical to add enough floatation to the line to float the release.

If we stick with the "gravity" plugs, I'd like to see a custom electric release fabricated. It doesn't have to be complex. It can be a simple mechanism like an acoustic release that is activated by energizing one of the condutors in the loging line.

We'll need to hash out the details of plugs and releases when we get down to the nitty gritty of designing the equipment.

p) In-situ check-out, recovery, and redeployment

Since borehole seismic systems often do not work correctly when first installed, it is prudent to have a system design that allows the sensor package to be checked-out in-situ and to be recovered and redeployed if necessary. Recovery is also a good idea if one wants to use the hole again for other measurements after the seismic work is done. For installation scenarios where this is not possible, extra effort must go into the design for reliability and redundancy.

q) Data acquisition

For adequate dynamic range the system should have 24bit D/A's. Data from the borehole array must be acquired on the seafloor in an autonomous, battery powered package which would be recovered and maintained annually.

For eventual use with the Neptune Canada cable, the cable interface will be Ethernet with TCP/IP. Some battery powered buffering will be necessary for periods when the cable power goes down.

r) Electrical connections through packers, seals and plugs

CORKs are designed to seal off sections of the hole for pressure measurements and sampling and this requires various combinations of packers, seals and plugs (Figure 4). Electrical pass-throughs are possible but they should be kept to a minimum in order to reduce failure modes and costs. Ideally the pass-throughs would be single coax.

s) Programmatic issues

The target date for the first SeisCORK installation from the drill ship would be Summer 2007 or summer 2008. There is a recovery cruise for the osmotic samplers in 2008 using either an ROV or submersible, but any seismic gear installed at that time would have to fit through the 4.5" casing.

t) Drill collars

Experience on Leg 301 suggested that drill collars should be added to the bottom of 4.5" casing to keep the casing in tension during deployment. The collars would have a larger OD but same ID as the 4.5" casing.

u) Casing ID's

The 4-1/2" casing has an ID of 4.052"; the 10-3/4" casing has an ID of 10.05"; and the 16" casing has an ID of 15-1/8".

III) Design Narrative

The two major design considerations in our discussions were sensor coupling and sensor outside diameter. Bottom cables exist with 240, 4-component nodes that could be configured into a 2.5"OD to lower into a well. All borehole seismic experience over the past 40 years suggests that this is not good enough. The seismic sensors must be coupled to the formation either directly in the open hole (for example by clamping or by burying in glass beads) or by clamping to the casing which is in turn coupled to the formation (by cement or by the natural compaction of the overburden). It is reasonable to assume that in soft sediments the sediments over time will collapse against the casing [*Stephen et al.*, 1994a, for example]. When a casing is installed in hard rock, enough cement is typically pumped into the well to rise up about 100m behind the casing (for the 16" and 10-3/4" casings in Figure 4 but not the 4-1/2"casing). (On the OSNPE for example the sensor was clamped in casing that had been cemented in the upper basement.)

Early in the meeting we concluded that a single string with sensors spaced every ten meters as conceived for time-lapse VSP's was impractical for the Juan de Fuca CORKs. (Similar systems are installed in tubing behind casing on land holes.) Even if a clamp were placed at each

node, the top 300m or so would be in "double-", "triple-", or "quadruple-casings" and seismic coupling through the annulus would be poor. Also pumping cement in behind casing to improve coupling would interfere with the hydrological measurements. So we focused on a multi-tier seismic sensor strategy:

1) Sediments

For the sediments, it is quite likely that the drilling will require two casing strings (16" to get to basement and 10-3/4" to get through the rubble zone at the top of basement) with an "annulus of silence". 1a) So for good coupling in the sediments we will need a separate SeisCORK that would be washed in. 1b) There is also on option to use a "dump bailer" arrangement designed by Tom Pettigrew (Figure 5) which could fill a short section in the annulus between casing strings with glass beads. This packing with glass beads may be sufficient to couple the inner casing with the formation. Given the potential pay-off of such a scheme it is probably worth testing it either on Juan de Fuca or during the MARS borehole tests. Then we could use a hydraulic clamp on the outside of the 4.5"casing to couple a sensor to the inside of the 10-3/4" casing at the depth of the bailer/basket.

Regarding the dump bailer, it can be made up to approximately 25 m long without hampering deployment from the ship. Hydraulic power to operate the dump bailer can be supplied via the packer inflation line or a separate dedicated hydraulic line. Note that when the dump bailer is actuated, no pressure pulse is introduced into the well bore. This is a good news/bad news situation. The good news is that the pressure meters and borehole proper will not see a pressure pulse from actuating the dump bailer other than the small change in volume created by the stroking action. Also, there will be small weep holes in the dump bailer to allow fluid to flow in and 1) equalize pressure during deployment, and 2) to account for the volume change during stroking and due to the glass beads draining out. The bad news is that the actuation volume change is so small that it will not be seen from the rig floor gauges. Thus the hydraulic lines will just have to be pressurized well above the shear pin setting and held for a period of time.

2) Upper basement above the packers

In the upper basement where there is just 10"casing next to the formation we could either 2a) use a hydraulic clamp on the outside of the 4.5" casing to couple a small sensor (about 3.0inch OD) to the wall of the 10"casing (Figure 6) or 2b) install a small sensor within a packer. Coupling between the 10" casing and the formation may not be good but this scenario (coupling to casing with clamping arms) was used on the OSNPE with apparently good results. Since this is above any packers it is relatively easy to bring lines to the surface. Note that all lines between the 4.5" and the 10" casing need to pass through the "well head seal". This will require a bulk head style connector with cable terminations on either side of the seal and to simplify this and reduce failure modes we recommend making this a coax connection. This means putting signal conditioning electronics, digitisers and multiplexors in housings in the annulus below the "well head seal".

Regarding the ability to attach a 3" diameter instrument to the outside of the 4-1/2" casing, this should be possible by using eccentric centralizers that push the 4-1/2" casing off center. With a 3" instrument attached, the apparent OD would be around 7-1/2". Given that the packer(s) are about 8" OD, the 3" instrument attached to the off center 4-1/2" casing, shouldn't pose any more of a restriction than the packer(s). However, please note that use of the eccentric centralizers will require that the instrument be place in the middle of a 3 or 4 joint section of 4-1/2" casing. This minimum length is required to 1) make a smooth transition in the curve, 2) minimize the restriction to long instruments deployed inside the 4-1/2" casing, and to not hamper insertion in the borehole. Thus the instrument cannot be deployed immediately above or below a packer, a screen, or other tools with their mandrels on center.

Regarding the hydraulic clamp, it can be placed almost anywhere in the 4-1/2" casing string. It will become an integral part of the 4-1/2" casing string. As with the dump bailer it can be tied into the packer inflation line, the dump bailer hydraulic line , or have it's own independent hydraulic line. Also like the dump bailer, the hydraulic clamp actuation will not show up on the rig floor gauges.

3) Between or below the packers

Between or below the packers we could use a hydraulic clamp but special care would be needed to get hydraulic and electrical lines to the surface through the packers.

4) Open hole

In the open hole below the 4" casing and below the osmo samplers we could use a traditional mechanical clamp or glass beads to couple a sensor. This could be lowered as 4a) a stinger on the 4.5"string and could be larger than the 3.75" ID or 4b) it could be lowered through the 4.5" casing if it were less than 3.75". In 4b) electrical lines could go through the inside of the 4.5" casing so running through packers would not be a problem. In 4a) all electrical lines would need to pass through all packers and the well head seal. Also in 4a) we would need screened/slotted casing above the seismic section to permit fluid flow into the osmo-samplers. Note that in 4b) if the seismometer provides the weight to pull the seal plugs into their seats then the seismometer cannot land in the bottom of the hole. Once the seal is in place, the weight of the seismometer can be relieved by clamping or glass beads. This means that sufficient glass beads need to be installed to fill the hole below the sensor as well as the annulus around the sensor. In this case a "wireline bailer" (similar in function to, but mechanically quite different from, the "dump bailer" in Figure 5), would be deployed on the cable, above the seismometer, and below the lowermost seal. Alternatively a sinker bar - soft tether arrangement could be configured. Or possibly combining both schemes where the wireline bailer could be used as a sinker bar and the seismometer could land in the bottom of the hole and also be surrounded by glass beads.

If lock mandrels are used, the weight to seat them is above the running tool. The instrument string would only have to weigh enough to prevent it from "floating" upward as the wireline is lowered. By controlling the lowering speed, very light instrument strings can be deployed. Use of lock mandrels would also allow for landing a seismometer in the bottom of the borehole.

Now also in 4b) the electrical wires are run up through the 4.5" casing to the drill ship. This has the advantage that during installation power can be provided to the sonde to extend the clamping arms, unlock the mass, level the sensor, and acquire test data. In order to make the connection to electronics at the well head the cable needs to be severed underwater. We propose a connector above the top plug/wellhead and approximately 10m up inside the drill pipe/BHA (ie several meters above the top of the re-entry cone). This connector would join the specialized electric cable in the well to the standard logging cable. When it comes time to disconnect, a burn wire can be activated at the connector. Just below the burn wire is a make/break underwater connector. Now most of the weight of the cables in the well will be supported at the well head by the top plug. Between the top plug and the burn wire connector the cable is made slightly positively buoyant either with floatation or a soft tether. After the burn wire release the logging cable is retrieved and the drill pipe is pulled off the floating cable. An ROV can then be used to plug the make/break underwater connector into the acquisition electronics on the well head.

In scenario 4b), the tops of the SeisCORKs should be reconfigured to enhance re-entry by wireline, ROV, or submersible assisted systems in subsequent rounds of instrumentation.

5) Separate seismic borehole

There is an obvious solution to go with a separate hole for the seismic work - but this would not be a "SeisCORK" and for now is not the focus of our discussions.

In the current design the CORK elements are mounted on a mechanical "Spectra Cable" which is lowered into the 4-1/2" casing. For SeisCORKS this would be replaced with electro-mechanical cable at least to the lowermost seismometer.

With respect to " In-situ Check-out, Recovery, and Redeployment", just about any system that places sensors on the casings will have at least two problems: a) Providing an electrical connection to the sensor from the drill ship will be difficult. Since the sensor is being lowered with the casing, it is awkward to maintain a cable connection while lowering the casing. (On Ngendie [*Adair et al.*, 1987] the sensor was in a "stinger" on the end of the drill pipe and electrical connectivity was maintained to the sensor by using a side-wall entry sub.) These systems usually bring electrical cables to plugs on the seafloor and clamping and quality control tests are carried out on a later ROV or submersible operation. b) With the possible exception of the 4-1/2" casing (which is like drill pipe), it is often a tricky task installing casing in open hole, and once installed no one would want to recover the casing just for a faulty sensor (even if it were technically possible). Also once the glass beads are released it will be difficult to get them back or to pull the sensor back out of the beads. (There is the possibility of deploying a

hydraulic vacuum for sucking the beads back out of the hole, but getting the beads back from between casings would not be possible). Only scenario 4b) - a wireline sensor deployed in open hole or clamped to the inside of the 4-1/2"casing, has the options of both in-situ check-out and conveniently recovering and redeploying the seismic sensor if it does not pass the tests

IV) SeisCORK Scenario for 2007/2008

Given the complexity of coupling a string of seismometers in multi-casing systems we do not recommend a single string with 10m node spacing for time-lapse VSP's on the Juan de Fuca project in 2007/2008. The best option for VSP's is to carry them out from the drill ship as a logging activity independent of the SeisCORK nodes, sequentially working the sections in which the casing at that time is the outermost or possibly even in open hole. For example, there is little point in doing a VSP in the 20"casing, but two VSP's could be done as follows: i) in the 16" casing (to get the sediment profile), ii) in the 10-3/4" casing (to get the upper, poorly consolidated, basalt layer) and in the open hole below the 10-3/4"casing before the 4-1/2" casing is installed (this should be in stable, open hole in consolidated basalt). Note that during this style of VSP the drill pipe is dangling and banging in the upper section of the hole reducing SNR. Some mechanism should be devised to clamp the drill pipe to reduce banging and other drill pipe related noise.

The drill pipe can easily be landed on top of the casing hangers in the throat of the reentry cone by making up the existing casing running tool in the BHA. Weight can then be set down on the casing hangers to compensate for heave. Assuming a new active heave compensator is available at the time of deployment (although the existing active heave compensator works pretty well when it is working), the weight fluctation on the casing hangers should be quite low. Perhaps in the 2000 – 3000 pound range. This should make things pretty quiet. It is also possible to attach rubber bumpers to the casing running tool such that there would be a cushion between the casing running tool and the top of the casing hanger if desired.

A borehole seismometer string with about 100m spacing could be installed using a staged approach. This string could be used for monitoring nano- and micro-earthquake activity, for offset VSP's with a shooting ship after the drill ship has left, and for time lapse offset VSP's. A SeisCORK scenario based on a CORK installation similar to Hole 1301B in Figure 7 is outlined in Table 1.

V) Acknowledgements

This work was supported by the National Science Foundation under Grant #OCE-0450318.

Table 1: Hypothetical SeisCORK installation in Hole 1301B

	mbrf	mbsf	msb
Seafloor	2668*	0	
Base of re-entry cone	2671*	3*	
Bottom of 20" casing	2710*	43*	
A - Mid-sediment Node (if necessary) (Tier 1b)	**2808**	**140**	
Basement	2933*	265*	0
Bottom of 16" casing	2939*	271*	6
B - Upper-basement Node (Tier 2a - clamped inside 10-3/4"casing)	**2948**	**280**	**15**
Bottom of 10-3/4" casing	3019*	351*	86
C – Node (Tier 2a - clamped to formation)	**3033**	**365**	**100**
D – Node (Tier 2b - inside the top packer)	**3098**	**430**	**165**
Top Packer	3098*	430*	165
E – Node (Tier 3 - between packers)	**3133**	**465**	**200**
Bottom Packer	3141*	478*	
Bottom of 4-1/2" casing	3177*	514	249
Bottom of CORK instrument string	3199*	536*	271
F - Bottom Node (Tier 4 - buried in glass beads)	**3233**	**565**	**300**
Bottom of Hole	3251**	583**	318**

(mbrf - meters below rig floor,
mbsf - meters below sea floor,
msb - meters sub-basement,
depths have been rounded to the nearest meter.
** - Depths in U1301B from page 67 [*Shipboard Scientific Party*, 2004],
* - Depths in U1301B from Figure 7
Depths in Hole U1301B are used as "typical" values, the CORKs installed in 2007/2008 would be installed in new holes in a similar setting.)

In the scenario in Table 1, the electrical lines for the mid-sediment and bottom nodes (A and F) would run through the inside of the 4-1/2" casing. These sensors would be lowered after the 4-1/2' casing was installed and the electromechanical cable would replace the "Spectra Cable" in the CORK instrument string. This cable would run through the upper and lower "seal plugs". Nodes A and F could have an OD up to 3.5". Node F could be buried in glass beads for improved coupling and reduced convection noise. It will be necessary to recover this string to retrieve the hydrothermal sensors. If glass beads are used for coupling we would need to think about how well the node would pull out of the beads. These sensors could be replaced if necessary.

Nodes B, C, D and E are mounted outside the 4-1/2' casing and are installed with the casing. The electrical and hydraulic lines for these nodes run in the annulus outside the 4-1/2" casing and must pass through the "well head seal". Since we would like this pass-through to be a single coax some conditioning electronics (preamps, digitisers, multiplexors, etc) would need to be installed in the annulus between the 4-1/2" and 10-3/4" casings and below the "well head seal". Lines from node E would need to run through the upper packer. These nodes can have an OD up to 3.5". They are permanently installed.

V) Frequently Asked Questions

Why not use the LFASE sondes?

The OD of the LFASE sondes is 4.39"(112mm) which is too big to fit through the ID of the 4.5"casing/pipe which is nominally 4.125" (3.5" recommended working ID, the OD of the borehole seismometers used on ODP and DSDP was 3.62").

Why not increase the size of the innermost casing string from 4.5" to something large enough to accomodate the LFASE and other large sensors?

Increasing the diameter of the innermost casing would "telescope-up" the whole casing design strategy.

It may be possible to use 5-1/2" casing which as mentioned above is 2.4 times as stiff as 4-1/2" casing. The increased stiffness would definetly aid in getting the string into the open hole section. However, any instruments that are deployed on wireline must pass through the drill pipe which has a minimum ID of 4.125 in. Typical maximum OD of any tool run through the drill pipe is 4.000". Also, there has to be a slight restriction to the ID of the wellhead to allow for landing the sealing plug on which is typically in the 3.875" diameter range. So, the drill string and sealing plug seats are actually the limiting factor determining instrument OD.

Why not use MEMS sensors?

MEMS sensors are OK for controlled source experiments such as VSP's but their system

noise floor is too high [about -127dB re: ((m/s^2)/sqrt(Hz))] for monitoring small earthquake signals in the band 1-100Hz where background earth noise levels are typically -160dB re: ((m/s^2)/sqrt(Hz)). One advantage of the MEMS is that they provide a 1-100Hz response in a 2.5"OD housing.

Will SeisCORKs replace dedicated ION-style ocean seismic observatories?

No. ION-style ocean seismic observatories are targeted to meet the specifications in bandwidth, noise floor and dynamic range of the Global Seismic Network. For example, the noise floor for ION observatory sensors is required to be less than the USGS low noise model for the frequency band from 0.001 to 10Hz. This requires relatively expensive "observatory quality" sensors which are typically large and which must be carefully installed in dedicated boreholes. For example the sensor on the OSN Pilot Experiment was about 10m long, 8"OD and cost over $80,000. For the controlled source and passive monitoring goals associated with hydrologic observatories, higher frequency, narrower band sensors are required (0.2-100Hz). These are similar to sensors used in petroleum exploration and are typically smaller and less expensive than broadband GSN style sensors. Furthermore there is very little overlap in the locations of boreholes for the ION-GSN network with the hydrological sites. For example the Juan de Fuca sites are close enough to GSN shore stations that they do not fill a significant gap in the global coverage.

Why not drill a separate hole for the seismic work associated with the hydrologic sites?

It is possible that the most cost effective approach (from the instrumentation perspective) is to install a seismometer string in a dedicated hole. Given drill ship costs, particularly for deep penetration holes, our goal is to maximize the scientific value of each hole. This meeting focused on installing seismometers in the same holes as the hydrologic sensors, although it was recognized many times that a dedicated seismic hole would be a lot easier. Note that for penetration into consolidated basement, a dedicated seismic hole would still require multiple casing strings and would have to address the coupling issues. A dedicated seismic hole would not have to contend with all of the plugs, seals and packers (but some packers might be necessary to block fluid flow). Also for a dedicated seismic hole a more concerted effort could be made at cementing the casing.

Why not configure the CORK top to facilitate wireline recovery of the central string and insertion of new strings?

This is a good idea that was only alluded to briefly in the report (last paragraph of Section III-4). A cone the diameter of the main body of the CORK would do, although the larger the quicker. That would assure that if the seismometer below the 4.5" casing (the most important in the installation) failed it could be replaced later by an ordinary research ship with only the CV (Control Vehicle). This would also allow for removal and replacement of the osmosamplers, second generation seismometer package installation or anything else one might want to install in the hole all without having to wait for availability of Alvin or the more complicated and expensive ROVs.

By redesigning the CORK running tool and top of the CORK for an "internal J" rather than the current "external J" a CORK reentry funnel of 32" max diameter can easily be incorporated into the CORK configuration. The "redesign" is straight forward and should be easy to carry out.

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Figure F1. Regional bathymetric map showing major tectonic features and the locations of IODP Expedition 301 drill sites and the ODP Leg 168 drilling transect. Bathymetry from Smith and Sandwell (1997). FR = First Ridge, SR = Second Ridge, DR = Deep Ridge.

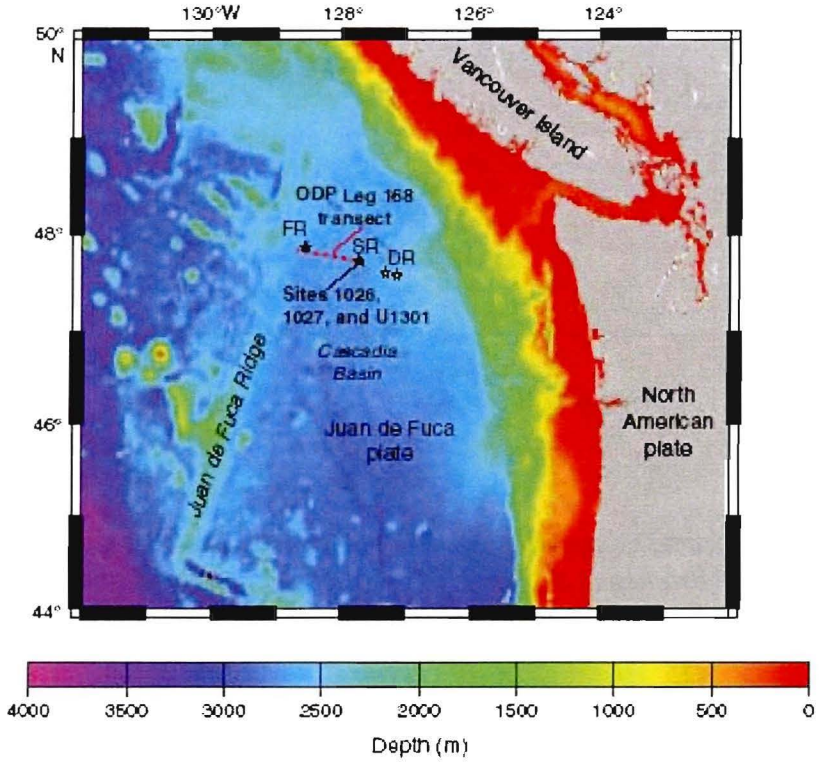

Figure 1: Location diagram of the Juan de Fuca hydrogeology drilling program (from [Shipboard Scientific Party, 2004])

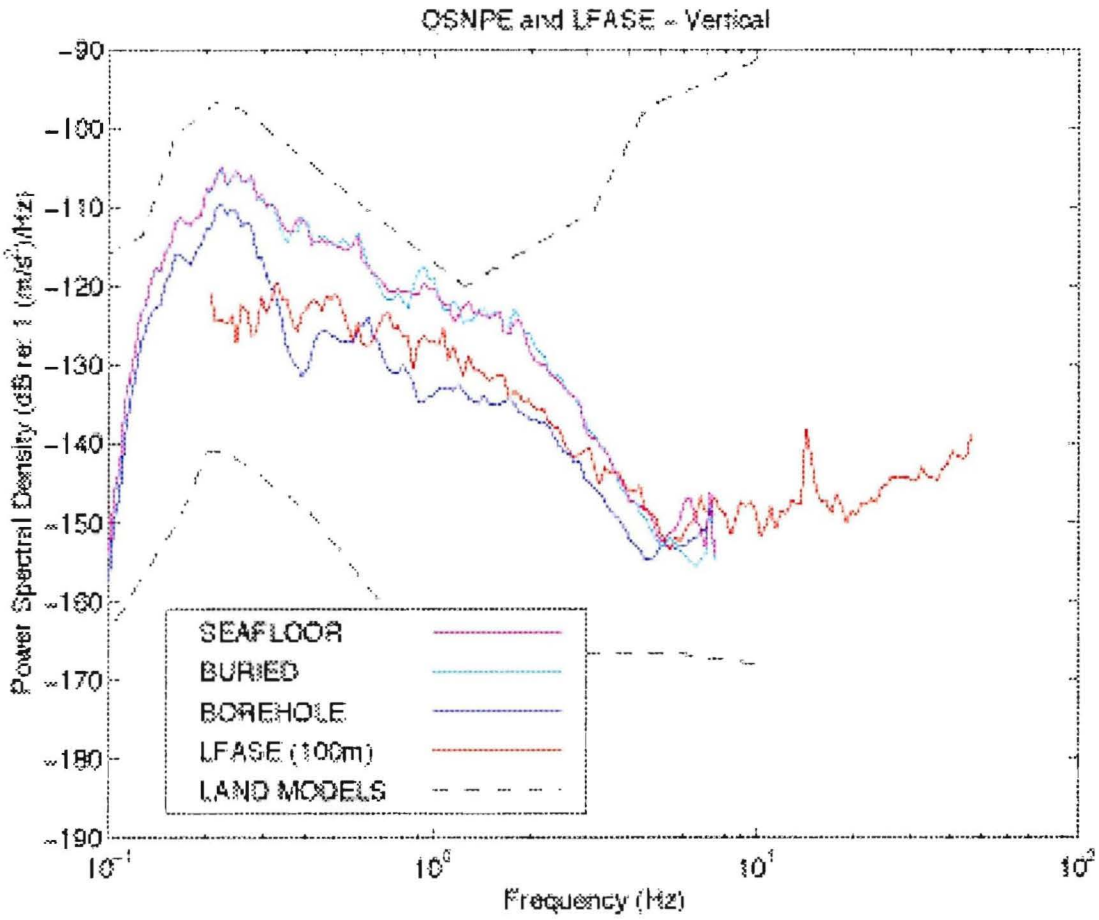

Figure 2: Power spectral densities of vertical component ambient noise in the band 0.1 to 60Hz for sensors on and beneath the seafloor [*Bradley et al.*, 1997; *Stephen et al.*, 1994b; *Stephen et al.*, 2003].

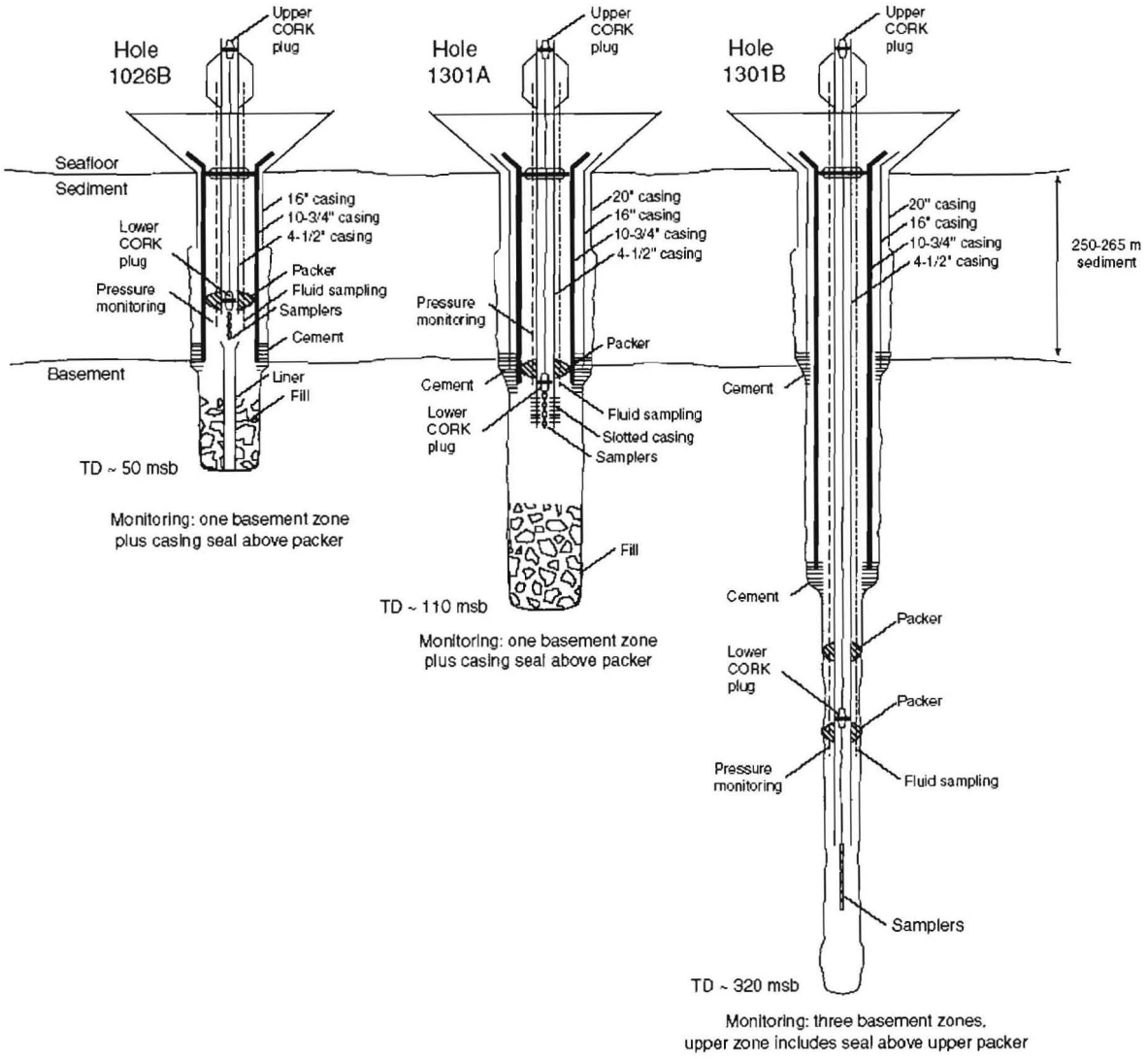

Figure 3: The three CORK installations made on IODP Leg 301 (from [*Shipboard Scientific Party*, 2004]. If a SeisCORK is deployed on the return program in 2006 or 2007 it would most likely be installed in a hole similar to U1301B.

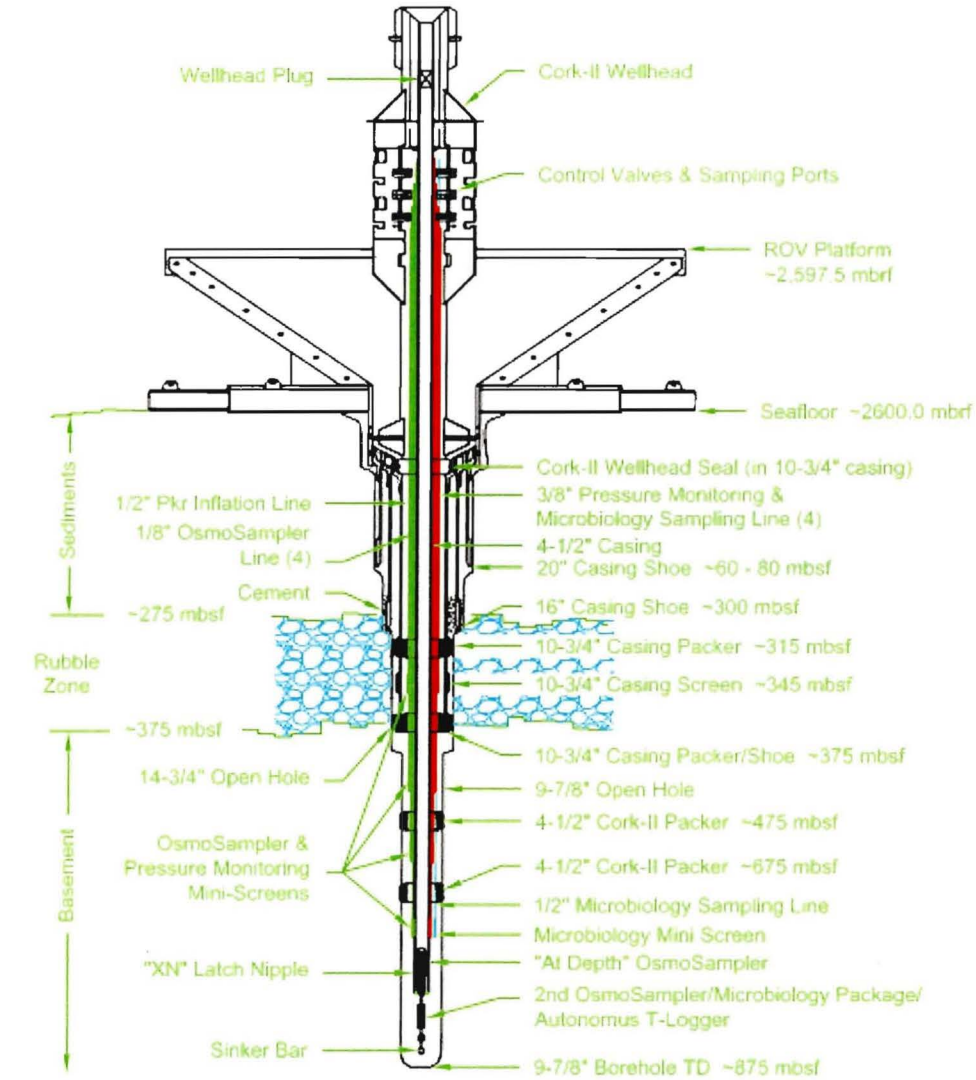

Figure 4: Schematic diagram of a typical CORK-II casing configuration.

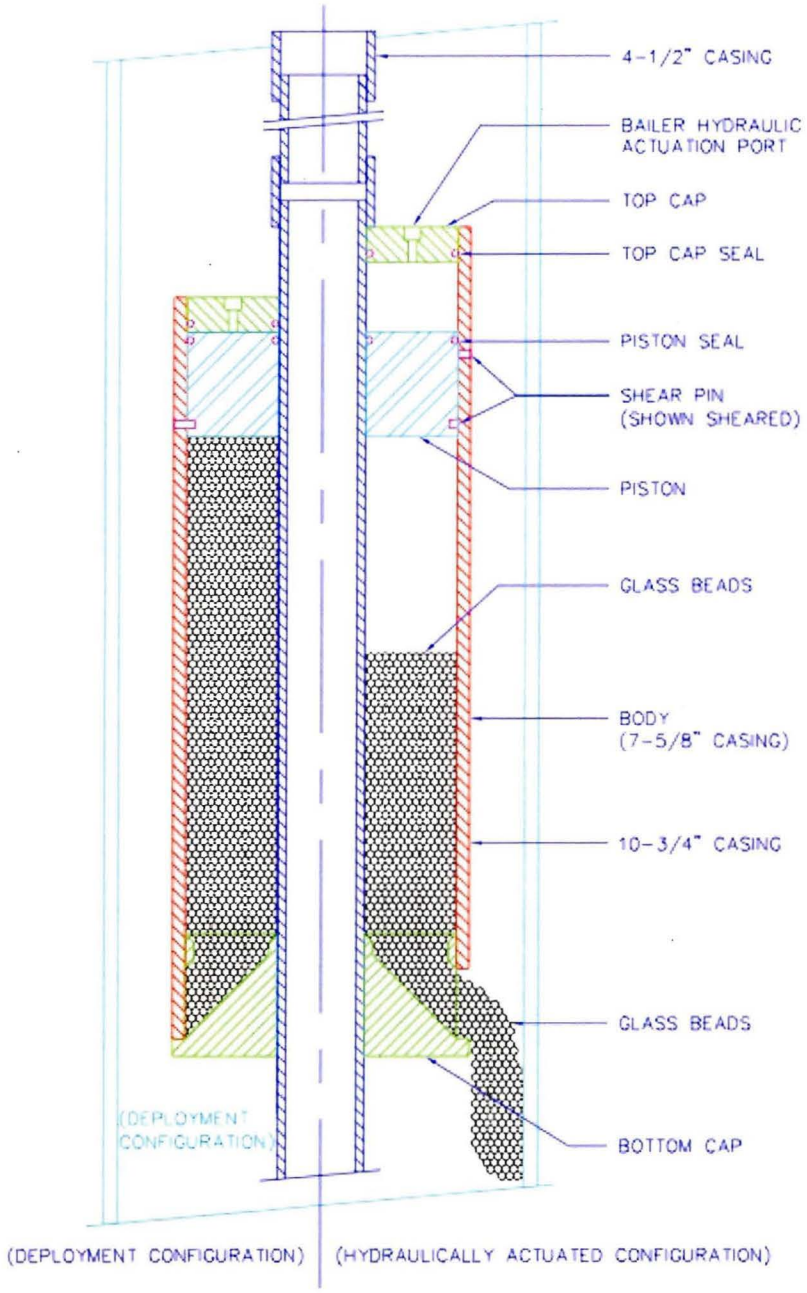

Figure 5. Hydraulically Actuated Bead Dump Bailer Concept.

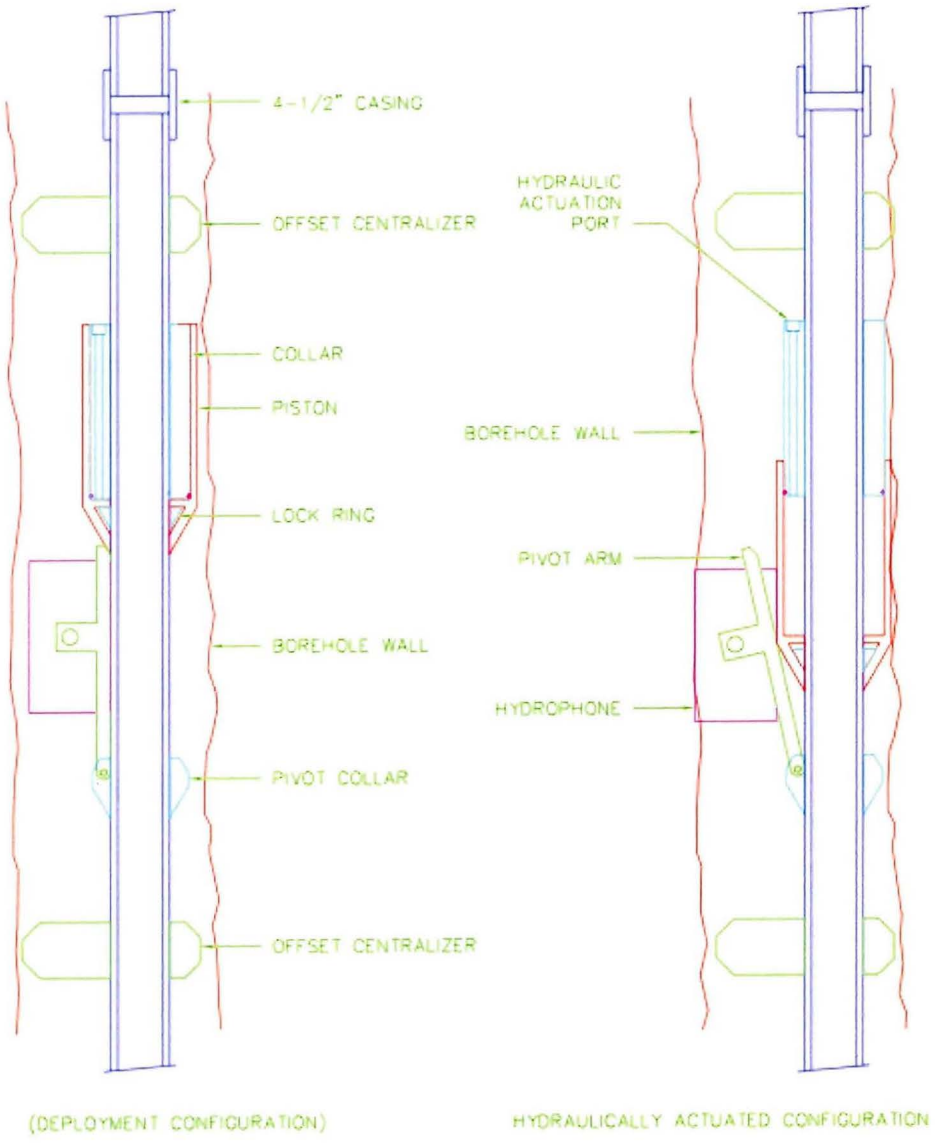

Figure 6. Hydraulically Actuated Hydrophone Clamp Concept.

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Figure F17. Schematic showing the Hole U1301B reentry cone and borehole casing (right), CORK borehole completion (center), and the instrument string deployed through the 4½ inch casing (left). ROV = remotely operated vehicle.

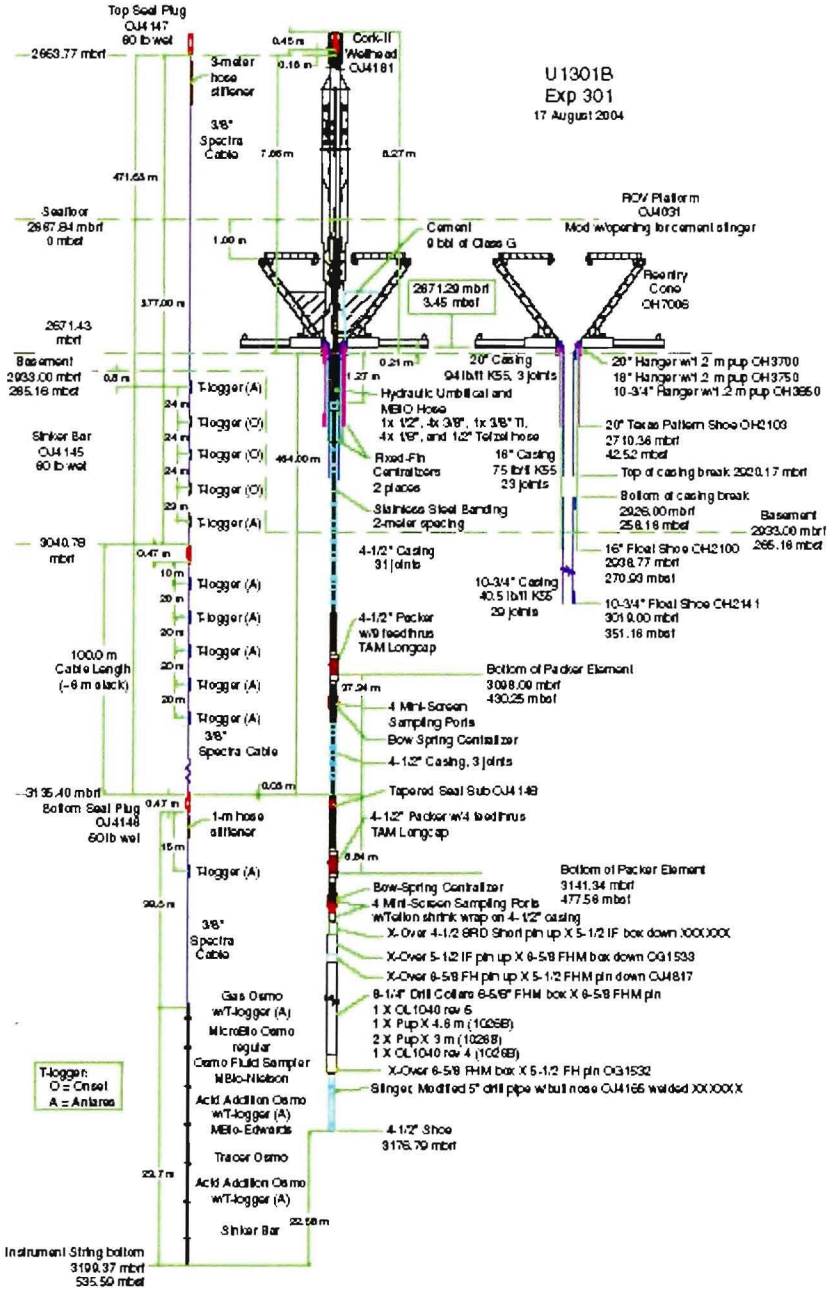

Figure 7: Detailed layout and dimensions of the CORK and casing strings used at Hole U1301B (from [*Shipboard Scientific Party*, 2004]).

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Appendix B: The Hydrogeologic Architecture of Basaltic Oceanic Crust

The investigation of the hydrologic architecture and deep biosphere of basaltic oceanic crust is an exciting initiative of the new Integrated Ocean Drilling Program (IODP)[*Integrated Ocean Drilling Program*, 2001, pages 18-33]. IODP has chosen to begin this investigation on the Juan de Fuca Ridge in the eastern Pacific Ocean. The goal of the first leg of IODP (Leg 301), which is at sea as this proposal is being written, is to study the compartmentalization, anisotropy, microbiology, and crustal-scale properties on the eastern flank of Juan de Fuca Ridge. A detailed prospectus of the scientific goals and drilling and instrumentation strategy is given in the Leg 301 Prospectus [*Fisher et al.*, 2004]. To provide some background for this proposal the Introduction of the Prospectus is repeated here:

"Thermally driven fluid circulation through oceanic lithosphere profoundly influences the physical, chemical, and biological evolution of the crust and ocean. Although much work over the last 30 years has focused on hot springs along mid-ocean ridges, global advective heat loss from ridge flanks (crust older than 1 Ma) is more than three times that at the axis [*Parsons and Sclater*, 1977; *Stein and Stein*, 1992] and the ridge-flank mass flux is at least ten times as large [*Elderfield and Schultz*, 1996; *Mottl and Wheat*, 1994]. Ridge-flank circulation generates enormous solute fluxes, profoundly alters basement rocks, supports a vast subseafloor biosphere, and continues right to the trench, influencing the thermal, mechanical, and chemical state of subducting plates [*Alt*, 1995; *Ranero et al.*, 2003, for example]. These processes crosscut all three primary themes motivating the Initial Science Plan for the IODP.

"Despite the importance of fluid-rock interaction in the crust, little is known about the distribution of hydrologic properties; the extent to which crustal compartments are well connected or isolated (laterally and with depth); linkages between ridge-flank circulation, alteration, and geomicrobial processes; or quantitative relations between seismic and hydrologic properties. **IODP Expedition 301 comprises the first part of a two-expedition experiment** to explore these processes and relations and to address topics of fundamental interest to a broad community of hydrogeologists working in heterogeneous water-rock systems: the nature and significance of scaling phenomena and the applicability of equivalent porous-medium representations of discrete fracture-flow processes. Expedition 301 benefits from operational and scientific achievements from Ocean Drilling Program (ODP) Leg 168 [*Davis et al.*, 1997], which focused on hydrothermal processes within uppermost basement rocks and sediments along an age transect across a young ridge flank. The primary goals of Expedition 301 include replacement of long-term observatories established in two reentry holes during Leg 168 and establishment of two new observatories, creating a three-dimensional observational network in upper oceanic basement. These observatories will be used to passively monitor thermal and pressure conditions in basement and to collect long-term chemical and microbiological samples. **During a later expedition, researchers will use these observatories for a series of multidisciplinary crustal-scale experiments.** Other primary goals of Expedition 301 include coring, sampling, and short-term downhole measurements. Secondary objectives include drilling, coring, and sampling one or more holes in a region of known hydrothermal seepage, where sediment thins above a buried basement ridge, and drilling, coring, and sampling a much thicker sediment section to the east, where basement temperatures and alteration should be more extreme."

Appendix C: Scientific Justification for Borehole Seismometers on CORKs

Borehole geophysics will play an important role on IODP. Experience on the previous drilling programs has indicated that there are three basic styles of borehole geophysical measurements: 1) conventional well logging, 2) two-ship borehole experiments (such as offset VSP's that require the drill ship to be on site) and 3) long-term borehole experiments (CORK's, strain installations, ION broadband seismometers, etc). All three categories apply to both riser and non-riser holes. In addition to enabling new styles of borehole geophysical studies, the new observatory infrastructure (ORION) can facilitate and expand the utility of some conventional borehole measurements that are usually made from the drill ship. Most of what follows is based on borehole seismic experiments of various kinds but other borehole geophysical measurements have similar issues.

Few question the wisdom of drilling a borehole to provide "ground-truth" to the analysis and geological interpretation of seismic and other data acquired at the surface or at the seafloor. Of course this is one of the primary motivations behind past, present and future ocean drilling programs. Because of the large differences in the scales of observation, however, the section intersected by the well (with observations from cores at horizontal scales less than 6cm and observations from well logs at horizontal scales less than a few meters) often does not correlate well with the seismic section (with horizontal scales of 100's of meters or more). For this reason, regardless of the geological scientific justification for drilling there is ample geophysical scientific justification for normal incidence Vertical Seismic Profiles (VSPs) [*Balch and Lee*, 1984; *Gal'perin*, 1974].

There have been many examples of the importance of normal incidence and offset VSP's on the DSDP and ODP programs including the origin of mid-sediment reflectors (from interference effects in thin layers) [*Bolmer et al.*, 1992], the nature of Layer 2/Layer 3 boundary in oceanic crust [*Detrick et al.*, 1994], and the investigations of gas hydrate deposits [*Holbrook et al.*, 1996]. In these cases and others it has been very useful to acquire VSP's using sources with similar bandwidth to the seismic sources in order to resolve the interference and multi-path effects that often affect the character of reflections on seismic record sections. The thorough ground-truth that boreholes and VSP's provides often demonstrates the importance of sophisticated seismic techniques such as true amplitude processing, amplitude versus offset (AVO) analysis, 3-D seismic, wave-form tomography, three-component seismics (with polarization analysis to study the effects of anisotropy) and pre-stack migration. Normal incidence VSP's provide a direct analog to the "normal incidence reflection profile" which is a common step in the multi-channel data analysis process. Offset and walkaway VSP's are often just as important as normal incidence VSP's in validating surface seismic because of shear waves (which are not usually excited at normal incidence but are frequently observed on offset profiles), other amplitude versus offset effects, and anisotropy.

Knowing how the seismic wave field correlates with the geological structure at the borehole gives more credibility to interpretations of the seismic data in the same region but away from the borehole [*Stephen*, 1988; *Stephen et al.*, 1980]. Significant lateral heterogeneity exists in the upper oceanic crust at the scale of a few kilometers or less (for example, see the drilling results from Sites 417 and 418 in the Western North Atlantic [*Salisbury et al.*, 1988; *Salisbury et*

al., 1979] or the seismically mapped lateral heterogenity at Site 504 [*Stephen*, 1988, Figure 18]) but it would be prohibitively expensive to drill an array of holes to directly sample this. There is no alternative but to use seismic sections to interpret the structure of the upper crust, so we should understand the evolution of the seismic wavefield at the few borehole locations that we can afford. Results from detailed studies at the borehole can then be extrapolated throughout the region.

The notion of "time lapse" seismology goes back at least 20 years when Aki proposed the method for analysis of hydrofracturing in petroleum and geothermal wells [*Aki et al.*, 1982]. The character of seismic arrivals from the upper crust can vary with time for at least three reasons: 1) when the state of stress varies with time a) as a result of an earthquake in the region which changes the regional stress pattern (Coulomb stresses, over days, months and years), or b) as a result of slow deformation (over tens of years); 2) when the drilling process itself changes the *in situ* pressure conditions on the fault by relieving whatever pressure anomaly may have originally existed (over hours to years); and 3) when the seismic acquisition system changes. Reasons 1) and 2) have significant geological consequences and will affect the application of seismic methods to understanding hydro-geological processes. Reason 3) is a common phenomenon. It is often very challenging to get similar seismic profiles from two different but similar surveys at the same place. There are a lot of reasons for this, including changes in small scale lateral heterogeneity and changes in frequency and wavenumber content of the observed field, but it is good practice in time lapse surveys to change as few aspects of the acquisition system as possible.

When we start to consider the necessary infrastructure for offset and time-lapse VSP's there are other spin-off scientific projects that could be carried out. The infrastructure for long-term borehole seismology is similar to that for CORK's and strain meters. Additional long-term borehole seismic experiments also fall into a number of categories:

a) Monitoring and locating micro-earthquakes

For time-lapse VSP, it would be best if we had a permanent array of closely spaced VLF (about 5-100Hz), three-component sensors either in the well or in the adjacent casing. Once the array is in place why only use it periodically for VSP's? It would make sense to record the data continuously to detect nano- and micro-earthquake events. The vertical array would help to improve the locations of events already being observed by seafloor seismometers, but also being closer to the fault and potentially in a lower noise environment, the vertical array may detect smaller events. Passive micro-earthquake monitoring would be a natural extension of the VSP infrastructure.

b) Cross-well tomography

Also with a permanent VSP array in place, there is the potential to carry out cross-well seismic tomography if a second hole is drilled near-by. In a tomography experiment seismic "volume" anomalies are detected using transmitted paths. Sharp discontinuities which are necessary to generate reflections from "surfaces", for multichannel surface seismic surveys for example, are not required for tomography. Although it is unlikely that a hole would be drilled just for cross-well tomography, it is possible that closely spaced holes may be drilled for other

cross-well experiments (water sampling, permeability, etc) or for sampling different sections along a fault (bright versus dull spots for example).

Appendix D: Background of CORKs, IODP and OOI/ORION/NEPTUNE

CORK's have been deployed for many years in boreholes drilled on the Ocean Drilling Program (ODP) (a good review of CORKs is Groschel's article in the Spring 2003 issue of JOIDES Journal which can be downloaded from http://poseidon.palaeoz.geomar.de/journal/) (see also http://www.brancker.ca/CORK.htm). All drilling on ODP was riserless and took place in environments where there was little risk of encountering hydrocarbons (except for some drilling into gas hydrates). The Ocean Drilling Program has recently been transformed into the Integrated Ocean Drilling Program (IODP - http://www.iodp.org/). IODP is based on three drilling strategies: the traditional **non-riser** drilling (operated by the US), **riser** drilling (operated by Japan), and mission specific drilling (operated by a European consortium).

Since there is considerable interest in long term measurements in seafloor boreholes there are natural links between IODP related projects and the new seafloor observatory programs OOI/ORION/NEPTUNE (http://www.coreocean.org/Dev2Go.web?id=249051&rnd=14255) which are aimed at establishing permanent observatories on the seafloor either through cables to shore or through permanent buoys (with satellite links to shore). (http://oceanusmag.whoi.edu/v42n1/becker.html) Given the projected importance of ROV's in observatory planning, it seems reasonable that SeisCORK installation and maintenance will require a combination of drill-ship and ROV capabilities.

The focus of this meeting is to develop SeisCORKs for IODP **non-riser** drilling on the **Juan de Fuca Ridge**. These holes will be only a few hundred meters deep through soft sediments penetrating a few tens of meters into hard basalt. As outlined below there is ample scientific justification to add seismometer strings to the usual hydrologic strings on CORKs. These sites may also be connected permanently to shore via the NEPTUNE Canada program (http://www.neptunecanada.ca/).

Beyond the focus of this meeting there are other applications for SeisCORKs. For example, systems similar to the Juan de Fuca Ridge program could be deployed in **non-riser** holes drilled for the Nankai Trough (NantroSEIZE - http://ees.nmt.edu/NanTroSEIZE/) project. There are plans for a 6km deep **riser** hole on NantroSEIZE and this hole ideally would also have SeisCORK components. Because of the additional length and technical complexity of riser holes (with multiple casing strings and the seafloor blow-out preventer, etc) it may be necessary to custom design the observatory components for this well.

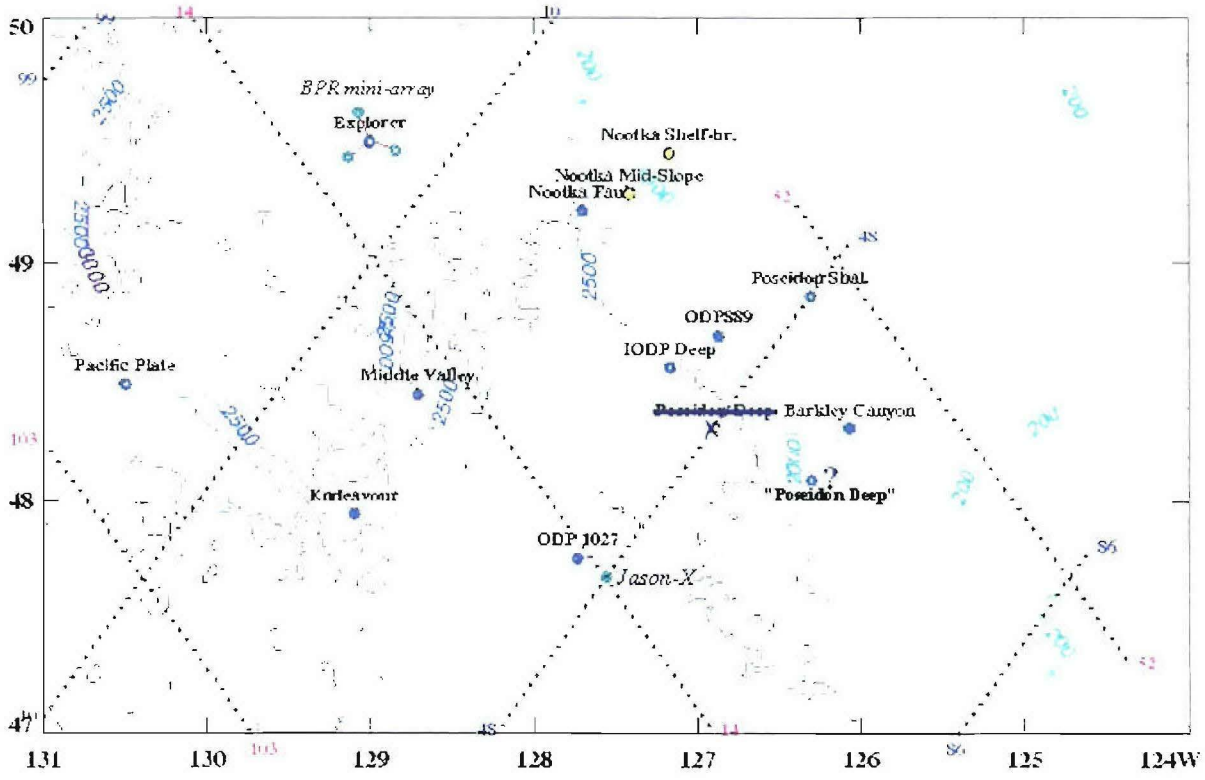

Figure D-1: Some proposed Neptune Canada Sites. The Juan de Fuca hydrogeology program is at "ODP 1027". (Figure courtesy of Josef Cherniawsky, Institute of Geosciences, Canada.)

Appendix E: Inventory of Borehole Observatory Technology

CORKs

Since COSOD-II [*JOIDES*, 1987](almost 20years ago) there have been various efforts at making long-term measurements in boreholes on the seafloor after the drill ship has left the site. For historical reasons, these seem to separate into two classes: CORKs (for fluid sampling, pressure and temperature monitoring) and seismic observatories. In both cases the technology has continuously evolved and it is difficult to define "standard" configurations. CORKs, CORK-II's and Advanced CORKs are described in the ODP and IODP literature [*Becker and Davis*, submitted; *Davis et al.*, 1992; *Fisher et al.*, submitted; *Graber et al.*, 2002; *Jannasch et al.*, 2003; *Shipboard_Scientific_Party*, 2002] (http://www-odp.tamu.edu/publications/tnotes/tn31/INDEX.HTM). Although most CORKs have been installed by the drill ship, two CORKs have been installed by wireline re-entry [*Becker and Davis*, submitted; *Becker et al.*, 2004].

Many groups have been involved in borehole seismic observatories (independently of CORKs). A review of third party borehole seismic experiments during the Ocean Drilling Program has been given by Swift et al [*Swift et al.*, 2003] and is available at: http://msg.whoi.edu/msg.html The borehole seismic observatories are summarized here:

Drill Ship Supported Seismics

Clamped in formation and cabled to the surface - sensor run down inside drill pipe into open hole and then pipe stripped off from around the cable - [*Duennebier et al.*, 1987]

Stinger with cable to the surface - sensor installed from the end of drill pipe with cable brought out in a side wall entry sub - cemented - Ngendie - [*Adair et al.*, 1987]

Stinger without cable to surface - sensor installed from the end of drill pipe with cables terminating in acquisition electronics at the seafloor - cemented - [*Suyehiro et al.*, 1992]Schlumberger temperature probe

Submersible Assisted Re-entry Seismics

Logging winch lowered to the seafloor with flotation - LeGrand (IFREMER) and Montagner [*Legrand et al.*, 1989; *Montagner et al.*, 1994; *Spiess et al.*, 1992].

Wireline-ROV Assisted Re-entry Seismics

Installed on a cable from research vessel with seafloor acquisition system in the instrument string - LFASE, OSNPE [*Legrand et al.*, 1989; *Montagner et al.*, 1994; *Spiess et al.*, 1992; *Stephen et al.*, 2003; *Sutherland et al.*, 2004].

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