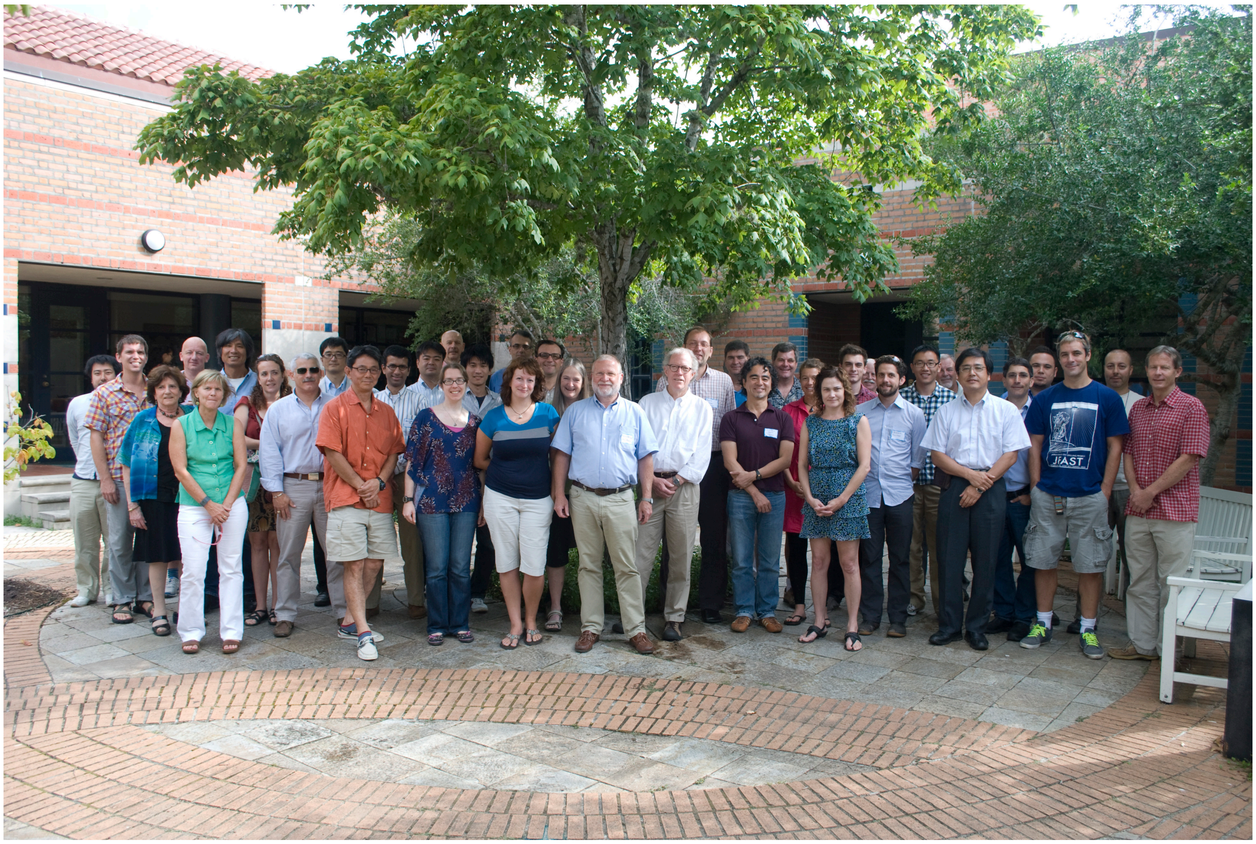
Observatories in Scientific Ocean Drilling

September 10-11, 2012
Houston, Texas



Conveners
Brandon Dugan, Heinrich Villinger, Nori Kyo

Steering Committee
Keir Becker, Earl Davis, Katrina Edwards, Achim Kopf, Geoff Wheat

Executive Summary

To assess the state of the art for observatories in scientific ocean drilling and to discuss the role that observatories have in the International Ocean Discovery Program (IODP) for post-2013 scientific drilling, forty-five scientists, engineers, and national funding representatives participated in a two-day workshop at Rice University in Houston, TX, USA. The Consortium for Ocean Leadership and the Integrated Ocean Drilling Program, Management International Inc. (IODP-MI) provided funding for the workshop. The workshop participants discussed the scientific achievements and technological developments of 20+ years of observatory science and then addressed the science and technical needs to address community-driven science goals stated in the IODP science plan [*Bickle et al*., 2011].

The workshop started with historic overviews and summaries of observatories in the Ocean Drilling Program (ODP) and Integrated Ocean Drilling Program (IODP) as well as discussions of the technical capabilities of the different IODP platforms (JOIDES Resolution, Chikyu, mission-specific platforms). Two key points were emphasized in this discussion: (1) the success of observatory science has benefited from adaptive technical developments centered around science problems; and (2) with appropriate lead time, each observatory platform developed to date has been versatile in application.

The primary tasks of the workshop were carried out in breakout groups which focused on: (1) geophysical frontiers for observatories; (2) microbiological/geochemical frontiers for observatories; and (3) technological challenges for observatories. There is a legacy of geophysical sampling and observations that have focused on convergent margins and hydrology of oceanic crust. Frontier geophysical questions requiring observatories include: what is the physical state of fluids, sediments, rock; how do they vary with location, depth, and time; and how do system conditions and properties respond to natural and induced perturbations? There is a need for more active experiments as well as passive monitoring of stresses, strains, and fluid pressures. Another conclusion was that all types of margins could be studied with observatories to address the Earth in Motion theme of the IODP Science Plan. The microbiology/geochemistry breakout group identified some of the achievements with observatories such as analysis of molecular community composition, in situ experiments on the interaction of biological communities and minerals, assessing alteration records by extracting in situ fluids, and time-series analysis of chemical data to address fluid flow through the crust. The group identified that many of the technology developments through microbiological/geochemical science have been driven by science needs. Examples include fiberglass casing designs and minimization of sample contamination. Microbiological and geochemical studies still have some basic questions that can be resolved through dedicated observatory science. These questions include: what are the extents of life in the Earth subsurface; what is the biogeography of microbes; and how can these microbes help us better understand the evolution of life? While collecting data for these questions, other process-based question can be addressed including microbe activity and rates of global biogeochemical cycling. The technology group agreed that scientific questions should drive technological development, and identified overarching areas where technology could help maximize science needs outlined in the science plan. First-order technological needs include low power microcontrollers and sensors capable of operating for one or more years between remotely operated vehicle (ROV) visits for data downloads and maintenance. It is desirable to be able to exchange storage media and sensors in situ. Another tier of need will be advanced geochemical

and biogeochemical sensors for long-term deployments, as many of these sensors show considerable drift. A third need, one required for any multi-level observatory, is reliable packers for formation isolation. Previous packer results have been mixed. Reliable downhole packers may also help minimize contamination for geochemical and microbiological studies. One of the long-term technology needs required for many biological, chemical, and physical experiments is adaptation for high temperature (>175°C) sensors and cables.

Paramount to the success of observatory science and associated technological development is a stable and successful funding model. Previous observatory programs were partially supported by commingled funds and third-party sources (external federal grants or private funding). With the new IODP structure, the disappearance of commingled funds, and a tougher overall financial climate, it was repeatedly emphasized that all observatory science must develop a life-cycle planning model. This includes planning for development and construction of equipment before an expedition, and establishing a detailed funding plan for regular maintenance and data recovery. This should begin early in the process (e.g., pre-proposal stage) so when the science is evaluated, the longevity of the observatory project can be appreciated at scientific and technical levels, and evaluated in the context of overall funding needs and infrastructure availability. Within the context of observatory life-cycle, the workshop participants discussed the need for a systematic means to manage, store, distribute, and archive data. The data are collected primarily with federal funds, and thus there are fair-use and availability requirements that must be met. Future funds should be allocated to developing permanent data management and storage with systematic metadata to allow the most efficient use of the data by a wide range of users.

The workshop wrapped up with discussions on expanding the visibility of observatory science. At the scientific level this involves expanding the science community to new colleagues who may be unaware of the use and value of borehole observatories. This could be facilitated through collaboration with other focused initiatives (e.g., GeoPRISMS, C-DEBI). Such opportunities could help maximize science output with leveraged funding. Another avenue for visibility is outreach and education. Time-series data have the opportunity to capture real-time transients, and connection to cabled networks can provide real-time access to these events. The community should develop teaching modules around observatory data for educational outreach, but also should take advantage of time-series observations of global-scale events (e.g., earthquakes and tsunami) and share them with public audiences.

Introduction and Background

The use of observatories in scientific ocean drilling provides numerous opportunities to extend the science value of boreholes by installing sensors and collecting fluid samples that provide time-series data that can be used to understand dynamic processes at various time scales. Such data can be coupled with core, log, and seismic data to interpret local and regional geosystem behavior over time and in response to perturbations. As resolution and sampling have increased, we continue to learn about Earth systems, but we also observe new cycles and behaviors [*Becker and Davis*, 2005]. Technological advancements and scientific needs have pushed the original CORK (Circulation Obviation Retrofit Kit) design from pressure and temperature measurements and fluid sampling at one interval to multi-level observatories with expanded capabilities for downhole instrumentation. These advancements in observatory science make us well positioned to push forward our scientific boundaries in multiple Earth-science fields as proposed in the International Ocean Discovery Program (IODP) science plan [*Bickle et al*., 2011]. Explicit within the IODP Science Plan for 2013-2023 is the need to use long-term observatories as a scientific platform to address the key research themes: Climate and Ocean Change; Biosphere Frontiers; Earth Connections; and Earth in Motion. This enlistment of observatories as a key platform for temporal and spatial characterization of ocean systems is a significant advancement owing to the success of previous observatories and an acknowledgement that long-term observatories are crucial to solving newly discovered and newly posed problems in geophysics, geochemistry, biology, and hydrology.

Observatories provide high-resolution sampling that can document the Earth response to earthquakes, tsunami, climate change, and chemical or biological processes. Connection of observatories to cabled networks will provide real-time data and instant access to data and will enhance hazard analysis and response. Real-time access will facilitate interactive teaching opportunities during quiescent times or exciting teachable moments. Integration with cabled networks (e.g., NEPTUNE Canada, DONET Japan, OOI USA) will also extend scientific collaboration and engineering development for observatories. In order to build, install, and maintain observatories that will address the pressing scientific themes and questions posed in the Science Plan, we need an educated and motivated observatory community.

Observatory science has evolved over 20+ years, starting in the Ocean Drilling Program (ODP) with the concept to isolate the subsurface from seafloor processes in order to understand fluid and heat transport in oceanic crust overlain by sediment. This led to the initial design of the CORK (Circulation Obviation Retrofit Kit) [*Davis et al*., 1992]. A review of CORK designs and operations can be found in *Becker and Davis*, 2005. The original design evolved with scientific requirements to sample pressure and temperature in multiple zones (e.g., Advanced CORK), collect porewater for chemical studies (Osmosamplers), and to characterize subsurface life (FLOCS [FLow through Osmo Colonization Systems; *Orcutt et al*., 2010, 2011] and BioOsmoSampling Systems). In addition, geophysical experiments drove the development of seismic observatories including seismometers, tiltmeters, and strainmeters [e.g., *Sacks et al*., 2000]. In the ODP, over 25 borehole observatories based on the original CORK, its modifications, and seismic/strain instrumentation were installed [Figure 1][*Becker and Davis*, 2005]. This long-lived history of CORKs and similar observatories has led to a large volume of publications (see Appendix III). Future observatory science will continue to expand our scientific knowledge as we push forward our frontiers. This workshop was convened to address the future observatory needs in terms of science goals, technology needs, observatory planning, and funding.

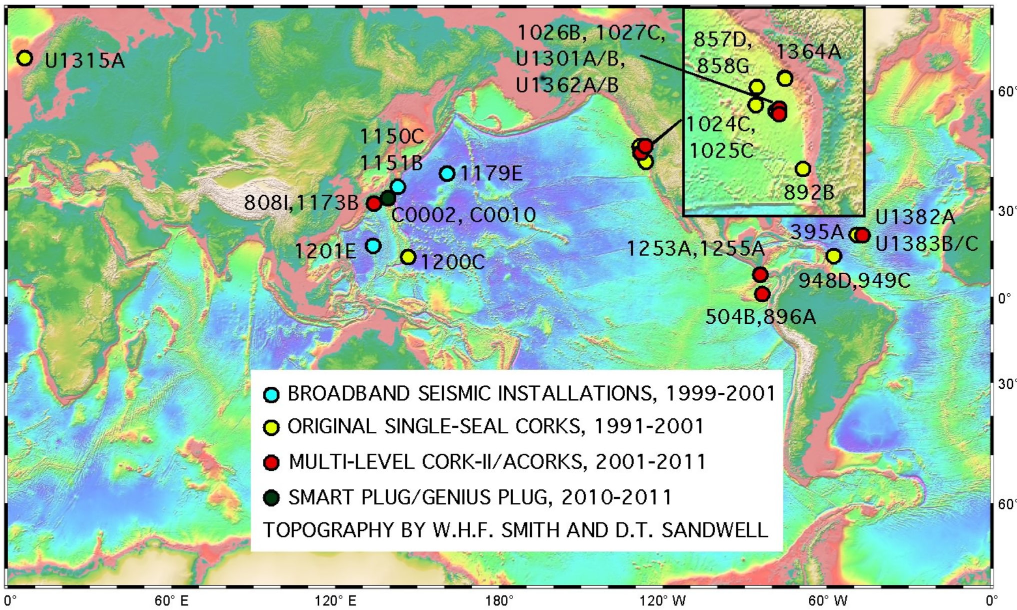


Figure 1. Location of ODP/IODP CORK installations through IODP Exp. 332. Figure compiled by K. Becker.

Workshop Overview

The workshop started with whole-group plenary sessions, then had breakout group discussions to focus on science needs (geophysical, microbiological/geochemical) and technical needs, and then more plenary discussions to integrate breakout group discussions, to focus on planning and funding observatories, to assess life-cycles for observatories and their data, and to evaluate opportunities for expanded collaboration and coordination with other programs, and outreach. See Appendix I for a full workshop agenda and Appendix II for a list of participants. All presentations are archived online (http://earthscience.rice.edu/department/research/dugan/Observatories/).

To review the history and capabilities of observatory science, we started with a broad overview of observatories in ODP/IODP (K. Becker) and a review of existing observatory technology (E. Davis). Becker provided the basic evolution of the CORK from the initial design to multi-level systems, summarized the breadth of applications of CORKs, and summarized where they have been deployed [Figure 1]. Davis reviewed CORK experimental applications including determining the steady-state formation temperatures and pressures in ridge crest, ridge flank, and subduction zone settings, estimating formation and fluid physical properties on formation-appropriate scales, and documenting pressure transients associated with seismic and aseismic deformation. This demonstrated how data and theory can be coupled to constrain hydrologic, seismic, and geodynamic processes. Davis also summarized the observatory conditions that yield high quality data.

We then had presentations to address the current engineering capabilities of the JOIDES Resolution (K. Grigar) and the Chikyu (N. Kyo, Y. Namba, S. Tockzo). These talks emphasized the need for engineering and science integration throughout the planning and the deployment processes, and highlighted the similar capabilities of both platforms for multiple types of standard and modified IODP observatories [Figures 2, 3, and 4]. This was followed by non-standard observatory concepts such as smart plugs, genius plugs, and MeBo CORKs (A. Kopf) that provide simple, small-scale alternatives to full-scale observatories, and in the case of MeBo CORKs can be deployed without a drillship, adding versatility to deployment and recovery [Figure 5].

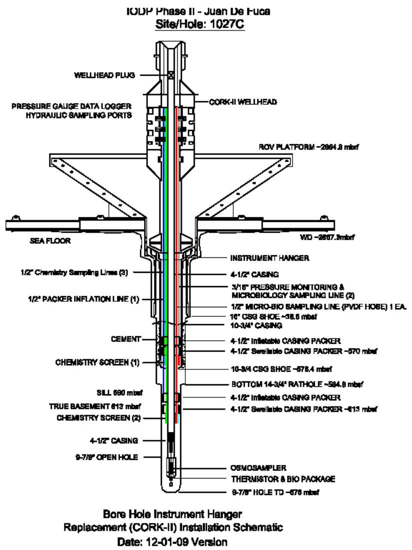


Figure 2. Drawing of observatory instrument hanger for Site 1027C deployed by JOIDES Resolution.

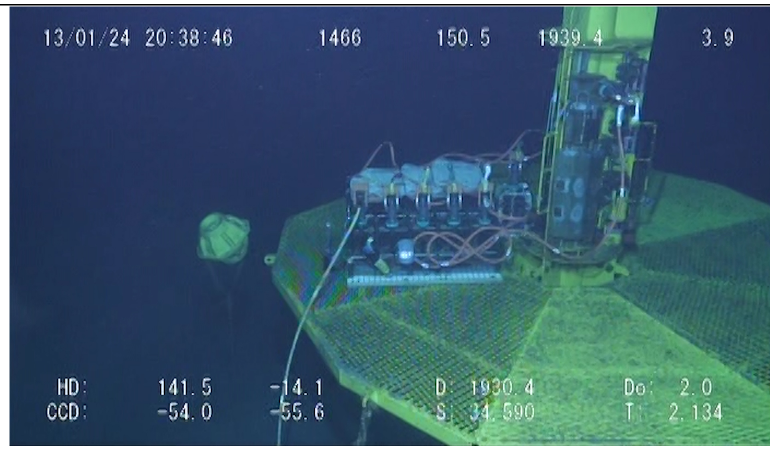


Figure 3. Photo of IODP C0002 Long-Term Borehole Monitoring System (LTBMS). Image from N. Kyo.

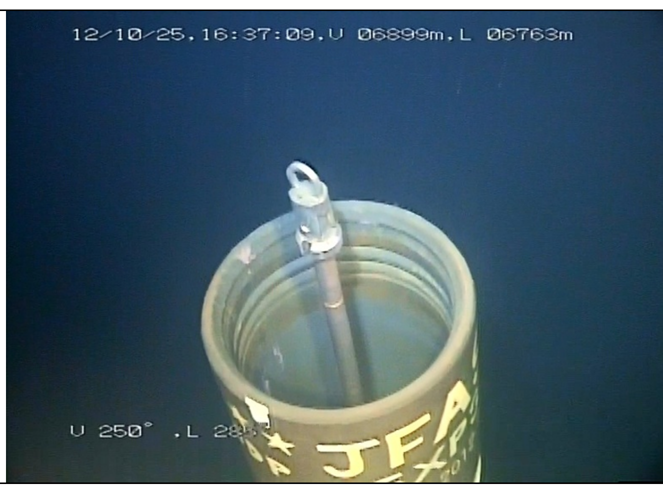


Figure 4. Photo of the J-FAST Observatory wellhead. Information on Expedition 348 instrumentation can be found in Chester et al. [2012]. Figure from N. Kyo.

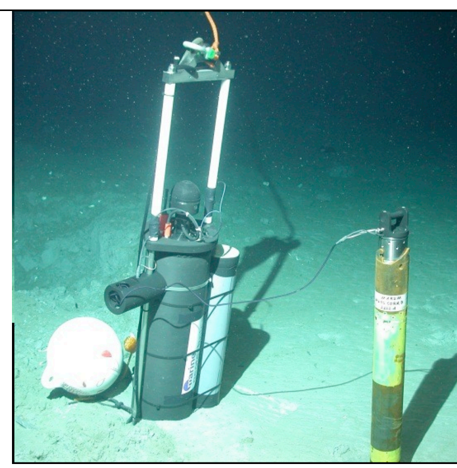


Figure 5. *Example of MeBo CORK deployed in shallow subsurface.*

Another simplified system that will be tested in May 2013 is the Simple Cabled Instrument for Measuring Parameters In Situ (SCIMPI) (S. Farrington) [Figure 6]. SCIMPI is a modular system that is deployed in an uncased borehole. Integrity of the installation will depend on borehole collapse to seal the sensors, but this will eliminate the need for casing, will simplify installation, and will reduce installation time (for details see http://publications.iodp.org/scientific_prospectus/341S/). Next were presentations on the values and evolution of fluid sampling, and how we can take advantage of legacy boreholes to return and install observatories such as CORK-Lite (K. Edwards, G. Wheat) [Figure 7]. By identifying existing, cased holes researchers can design observatory systems in well-characterized regions, but without full infrastructure deployment as casing is already in place. This may facilitate more observatories to be installed when vessels are in regions of opportunity but without taking the time for a full expedition.

Figure 6. *SCIMPI being prepared for field testing. Silver modules are sensors.*

Figure 7. *CORK-Lite system for Legacy Boreholes. Details can be found in Wheat et al. [2012].*

The technology assessment summary ended with a presentation on the state-of-the-art application of long-term observatories used in industry (L. Jackson, S. Lovell). This talk provided industry's perspective on reservoir monitoring to optimize production while reducing risk. Industry is using advanced sensor technology primarily for pressure and temperature monitoring, both of which can be used to evaluate flow conditions and history. This presentation showed the natural overlaps between industry and academia in terms of long-term, in situ monitoring, thus solidifying the need to engage in more cooperative discussion between the communities. Embedded in the presentations and discussions, it was clear that observatory examples are numerous, beyond what can be captured in one workshop. To provide an extension beyond what was presented at the workshop, we provide a representative compilation of observatory-related publications (Appendix III).

The remainder of the workshop focused on breakout group discussions on Science and Technology Goals and Needs, Observatories in the new IODP, Data Management, Access, and

Archiving, Expanding the Community and Science Impact, and Society, Education, and Outreach. Each of these had extensive discussions and are summarized below.

Science and Technology Goals and Needs

To address how observatories fit into the science goals of the post-2013 IODP, we separated into three breakout group groups:

Group 1: Geophysical Frontiers in IODP Borehole Observatories
Group 2: Microbiological/Geochemical Frontiers in IODP Borehole Observatories
Group 3: Technological Challenges for IODP Borehole Observatories

The groups were charged with assessing the current state of the art, how observatories have contributed to ODP and IODP science, and what the needs are to address future science goals. Embedded in the latter discussion was how the science fits with the questions posed in the Science Plan. After individual breakout group discussions, we reconvened to exchange ideas and identify where natural overlaps exist.

Group 1: Geophysical Frontiers in IODP Borehole Observatories

Group 1 had the goals of establishing what geophysical frontiers can be readily addressed with long-term observatories and how these problems relate to the IODP science plan. To guide the discussion, the group addressed three questions:

1) What key geophysical advancements have been made through observatory science?
2) What key science questions remain that require observatories to be resolved?
3) What are near-term and long-term needs (scientific or technological) for significant advancement in borehole observatory science?

The installation of observatories and data from long term monitoring have facilitated the determination of in situ properties that have helped define numerous physical, chemical, and microbiological processes (e.g., response to tides, long-period formation pressure changes and seismic events, induced and natural flow) and characterized steady-state and transient properties (e.g., pressure, temperature, compressibility, shear modulus, permeability, effective porosity, fluid/gas properties, some solid properties). Observatories have advanced our understanding of fluid, solute, and energy transport by providing quantitative data that partially overlaps with measurements that can be made with the drillstring, but also provide information on areas that are otherwise inaccessible (hard rock, deep/unstable holes) as well as long-term, time-series data.

Geophysical frontiers and science questions that require observatories fell into two basic categories. The first was common or overarching science problems or processes; the second included questions specific to geologic settings.

Common questions, addressed in part or in whole by most subseafloor observatory systems relate especially to studying problems within the Earth In Motion theme of the IODP science plan. Observatories provide the ability to measure temporal variability in fluid and sediment properties, which greatly expands understanding beyond the single-sampling aspects of cores, petrophysical logs, and geophysical surveys. Questions that can only be addressed with observatories include: (1) what is the physical state of fluids, sediments, rock, and how do they vary with location, depth, and time; and (2) how do system conditions and properties respond to natural and induced perturbations. These can be addressed by some appropriate combination of passive monitoring and active in situ experiments.

In addition to basic questions, the group discussed how observatory science is necessary to address questions at seafloor spreading centers and ridge flanks, convergent margins and fault zones, and passive margins where unstable conditions and gas hydrates may be present. Observatories at spreading centers and ridge flanks could provide data on how stress is transmitted in oceanic lithosphere, variability in crustal hydrology including fluid and energy transport magnitudes and directions, how crustal properties vary at decadal time scales and over geologic time (zero-age to old oceanic crust), and how fluids interact between oceanic crust and sediment. Along convergent margins and within associated fault zones, time-dependent data are largely required to decipher the state of fluid pressure and composition, temperature, and stress state during different portions of the earthquake cycle and in regions that deform differently (aseismic creep vs seismic slip). By monitoring in situ conditions specific details can be addressed like how rock systems respond to tectonic strains, how deformation occurs during microseismicity, and what are the various modes associated with slow slip, episodic tremor and slip, and large earthquakes. Monitoring of subduction inputs and comparison with the subduction zones will also help decipher primary controls on the position of decollements, the origin of fault zones, the fate of fluids in subduction zones, and the hydration of the upper mantle.

Previous observatory science in passive margin settings has been limited, yet many important questions can be investigated. One area of IODP and societal interest along passive margins is the role of overpressures in submarine landslide processes. Observatories can provide data on the origin and maintenance of these pressures, and potentially the conditions immediately after a failure. Another area of active research should be the evolution and demise of gas hydrate provinces in regions like the Arctic. Such systems are dynamic and will respond to sea-level rise and changes in ocean temperature. To understand the response of hydrate to changing environmental variables requires fluid pressure and gas concentration monitoring. At an applied level, passive margins may yield extensive reservoirs for CO_2 injection and storage, but that will require initial observatory monitoring to test reservoir and seal conditions and long-term monitoring to understand fluid-rock interactions and long-term storage of CO_2. One last region for monitoring is the connection of onshore-offshore hydrologic systems that have transients driven over short timescales (e.g., storms) and over long timescales (e.g., sea-level fall and rise).

The third objective of the breakout group was to establish what the near-term and long-term goals are for scientific and technological advancement in geophysical problems. The group did not attempt to define the time-scales but did identify numerous areas where advancement can be and should be made, for example in minimizing power consumption for data collection, storage, and transmission, and possibly in expanding power availability by harnessing power from tides or currents. Another area for advancement is simplifying data transmission such as rapid transmission techniques that do not require direct electrical transmission, underwater mateable USB memory sticks, and quickly removable and recoverable devices. From a new tool technology standpoint, the group identified gravity meters, strain monitoring of casing, adaptation of tools for alternative drilling (e.g., shallow subseafloor drilling with MeBos), sensors for electrochemical measurements, and adaption of sensors for high temperatures.

Group 2: Microbiological/Geochemical Frontiers in IODP Borehole Observatories

Group 2 had the goals of establishing what microbiological and geochemical frontiers can be readily addressed with long-term observatories and how these problems relate to the IODP science plan. To guide the discussion, the group addressed three questions:

1) What key microbiological and geochemical advancements have been made through observatory science?
2) What key science questions require observatories to be resolved?
3) What are near-term and long-term needs (scientific or technological) for significant advancement in borehole observatory science?

While early observatories were designed for geophysical measurements, modifications to observatory designs and development of different sensors have resulted in multiple key advancements in microbiology and geochemistry. In the microbiological realm sampling of recovered fluid samples have allowed analysis of molecular community composition and in situ experiments have facilitated analysis of the geomicrobiology (interaction of biological communities and minerals). Building off observatory science, there have been short-term observation tools developed to determine in situ biomass in boreholes (DEBI-t) [*Edwards et al.*, 2012]. In the geochemical realm, scientists have been able to assess alteration records by extracting in situ fluids and have been able to do time-series analysis of chemical data (osmosamplers) to address fluid flow through the crust. While working on expanding these frontiers, there have been associated technological advancements. Two areas that have been crucial for development are fiberglass casing design and minimization of sample contamination.

The group expanded discussions to address where advancements should be made and what key questions can be addressed through observatory science in the next phase of IODP. Microbiological and geochemical studies still have some basic questions that can be resolved through dedicated observatory science. These questions include what are the extents of life in Earth's subsurface, what is the biogeography of microbes, and how can these microbes help us better understand the evolution of life. While collecting data for these questions, other more process-based question can be addressed. Processes that should be addressed with time-series data include what controls the activity of life, what are the budgets and rates of global biogeochemical cycles, what elements contribute to these cycles, and what role does biology play in alteration of oceanic crust. These processes are also linked directly to some of the geophysical frontiers related to the hydrogeology of the oceanic crust and the limits of hydrothermal circulation in the oceanic crust.

Many of the tools and technologies required to address these science questions are in development, however other tools still need advancements before implementation. For downhole measurements the DEBI-SELECT tool provides downhole biological logging and is being modified to allow for fluid sampling, oxygen sensing, and mass spectrometry. More advancements and needed modifications are flow cytometry for cell counts, Raman spectroscopy, in situ preservation, and in-situ molecular analyses. Such downhole logging tools could also be ported to long-term observatories. Other observatory measurements that are needed are real-time flow measurements, in situ QPCR (quantitative real time polymerase chain reaction), gamma detectors, time-lapse camera, and an in situ ATP sensor.

As the tools and technologies advance, we also need to work on contamination issues that hinder microbiological and geochemical work. At the simplest level, tools must be continually assessed and adapted to minimize contamination. We also need to develop a library of common contaminants and their impacts to basic science.

Group 3: Technological Challenges for IODP Borehole Observatories

Group 3 focused on the technological advancements that have been made in parallel with observatory science, and addressed the existing technological challenges for observatory science. The group addressed four questions:

1) What have been major technology advances in ODP/IODP observatories?
2) What are the key technologies that are established?
3) What are the major technological challenges that exist?
4) What are the near-term and the long-term needs?

Over the last 20 years a number of highly successful borehole observatory developments have opened up entirely new fields of observational science. High-resolution pressure sensors provide insight into short- and long-period variations of strain related to geodynamic processes at plate margins. Osmosamplers are a very good example of a technical development which is adapted to sampling fluids in a borehole over long period of time; they are simple, robust, easily adaptable to different sampling strategies, operate without external power supply, and are inexpensive. Downhole temperature monitoring, either with conventional thermistor strings or fiber optic technology (DTS), is possible over long time spans (although the use of DTS is limited due to its high power consumption). GeoMicrobe systems installable on a CORK landing platform have been developed to sample and analyze fluids from a CORKed borehole over a period of one year.

However, experiences from past sensor deployments in CORKs show that there are a number of overarching needs for addressing a variety of problems in different fields. It is obvious that simple and robust sensor designs with sufficient resolution required by the scientific goals are essential for a successful seafloor borehole observatory program.

Highest on the list are low power microcontrollers and sensors capable of operating for several years between ROV visits for data downloads and maintenance. Examples are seismometers and DTS (distributed temperature sensing). New developments in consumer electronics such as smart phone technology may help achieve some of these low-power goals. Along the same lines it would be highly desirable to be able to exchange storage media (‘Underwater USB stick’) and sensors in situ to reduce the time required for site visits.

Geochemical and biogeochemical sensors for long-term deployments in CORKed boreholes do not yet exist but will be in high demand for future CORK installations. The main problem is that chemical and biochemical sensor technology is still in a developing phase and many of these sensors show considerable drift over long time periods. Sensors for low or high pH environments are not available for long-term in situ measurements.

The success of downhole measurements in a CORKed borehole with different measurement levels relies completely on the reliability of the packers which seal different horizons from each other. Whereas the top seal of the CORKs (inside the CORK head) worked very well in separating the borehole from the ocean, experiences with different types of down-hole packers have been very mixed. The development of a reliable downhole packer, which does not contaminate geochemical and microbiological studies, is a high priority. Development of packers for high temperature environments is also highly desired.

Observations in boreholes at high temperatures (>175°C) have been on the "wish list" for a long time and will be a long-term goal for the future. There are a number of hardware limitations which will ultimately impose a natural temperature limit, and there are financial limitations as these developments are very expensive and relevant to a small number of users.

Observatories in the new IODP

As we transition into a new phase of IODP, we also move into a new funding system. Observatory science has greatly expanded our scientific horizons, but funding is becoming more challenging. Difficulties result from the complexity of mixing IODP operational costs, observatory instrumentation costs (covered by third parties such as NSF or the private sector), and continued funding for data recovery and instrumentation updates. In addition to long-term funding needs there are short-term alignments related to releasing funds to build instrumentation in time for an expedition. Thus there is a need to align funding and ship schedules with enough time for facilities to develop and prepare the appropriate deployment plan and capacity. Lastly, 20+ years of observatory science proves that some observatories last for 10+ years, and that many signals of interest require decades of observations. This requires a long-term funding plan to continue to extract new information from these installations. With changes in funding structure and limitations of funding sources, the group isolated some key areas where efforts should be dedicated to ensure the continued use and success of observatories in the post-2013 IODP. As a community we should strive to:

1) Optimize experimental design: Careful selection of observatory plans to fit the most important goals; early planning should focus on choosing the right tool(s) for the science and keeping an eye on costs, complexity, and flexibility for future opportunities. This requires early discussions between the scientists, the engineers, and the operator.
2) Leverage planned programs that may provide valuable opportunities for borehole observatory installations: Take advantage of other programs and funding opportunities to minimize and share overall operational costs.
3) Emplacement of holes that can be used for future observatories: When drilling can leave holes in a state that could provide future observatory instrumentation at modest cost and with minimal additional time (e.g., leave seal subs in place in casing hangers, add simple umbilicals and valves when setting is appropriate); this could save costs for future, legacy borehole operations.

With changes in operations and ship scheduling in the future IODP, the group also discussed various changes to the way in which observatory science may need to be proposed and evaluated. Currently we know that the funding structure will change, but the details are yet to be determined other than costs will be absorbed differently. Investigators need knowledge of the changes, and should work with the Facilities Boards to develop implementation strategies in proper context of funding scenarios; most likely each Facilities Board will address observatory projects on a case-by-case basis. Funding and implementation strategies will also need to address the life-cycle plan for the observatory early in the proposal process. Below are key points that the group highlighted for planning future observatories.

> *Proposing Observatory Science* – In order to achieve success with observatories, investigators must adhere to the science objectives outlined in the IODP Science Plan for 2013-2023. Developing fundamental and testable science programs that address the science plan is necessary to meet the rigor of peer-review and evaluation within the new IODP. For observatories to be included in a proposal it needs to be demonstrated that the observatory is absolutely necessary to accomplish the science goals. Within that context, one can pursue alternative avenues to develop/augment observatory technology to collect the best data for science-driven problems. Strong science will lead to high ranking by the peer-review process, which can then lead to a higher likelihood of an expedition being scheduled. Technology-driven proposals are, by nature, much more difficult to support.
>
> *Life-Cycle Planning* – All PIs who propose IODP projects that require an observatory, should be well informed about the relative costs of an observatory and should develop a life-cycle plan for the observatory. Previous observatory science has shown that observatories can collect data for decades, yet previous IODP proposals did not include a detailed plan for the entire life-cycle funding. To achieve the observatory science, a full plan should be established and summarized in any observatory proposal. We made a concerted effort to document the entire life cycle of a proposal requiring observatory science with milestones and funding options (Table 1).
>
> Two striking facts are apparent from Table 1 regarding the life cycle of an observatory. First there is heavy reliance on national funding agencies for observatory science from initial proposal through working with the data. All proposals with observatories need to consider this early in the planning stage to come up with effective and efficient funding strategies that include leveraging other programs or alternative funding sources where applicable. PIs should also be realistic in the length of an observatory plan from the initial workshop through archiving of the data. A second striking feature is that currently we have no well-developed mechanism or funding source for data management, archiving, and access. As this is an important aspect to the community we had a separate discussion on it (see below).

Table 1: Example of Observatory Life-Cycle Planning and Funding

Milestone/Task	Potential Funding
Proposal workshop to discuss science plan and observatory needs	National funding sources
Site survey to locate sites, meet drilling requirements, and plan for observatory	National funding sources, industry funding, use existing data
Drilling pre-proposal outlining science plan and observatory plan	No funding needed
Full drilling proposal with detailed science and observatory plan	No funding needed
Observatory design	National funding source, private foundations
Observatory construction including science and technical infrastructure	National funding sources, private foundations, maybe operators
Installation	National funding sources, operator
Sample and data retrieval including length of operations and number of retrieval operations	National funding sources, private foundations
Data reduction and analysis	National funding sources
Data management, archiving, and access	Unknown but necessary

Matching Shiptrack with Science Needs and Technology Planning – Related to the difficult funding scenarios and the long-term viability of observatories, it is apparent that the science community needs to develop longer-term planning for implementation of observatories. The current planning cycle within IODP is supported heavily by federal funding agencies but it is not a long enough cycle for full planning and development of the most effective science plans that include observatories. To facilitate better planning the scientists need to be well appraised of where ships will be over long time frames. With longer lead times on ship scheduling and ship tracks as proposed for post-2013 IODP, this should help line up longer lead times for observatories that use the JOIDES Resolution or Chikyu. Mission specific platform (MSP) projects tend to have longer lead times based on the needs to locate and procure services for each project, and more detailed discussions should be had with European Science Operator regarding planning and implementation of observatories with an MSP.

Legacy Projects – In light of the complex funding and planning processes associated with observatories, there is an alternate model for some types of observatory science. That model is using legacy boreholes for observatory science. The benefit of legacy boreholes is that the borehole exists and has some of the essential infrastructure (e.g., casing) for installing a long-term observatory. By taking advantage of the existing borehole, drilling and initial installation costs can be minimized. To take best advantage of existing holes, scientists need to do an inventory of existing holes and evaluate what the minimal infrastructure and time would be to complete the installation of the observatory. PIs should also identify when potential legacy holes may be along the upcoming shiptrack to minimize transit costs and take advantage of windows of opportunity for quick installations during regular transit times. There were also discussions about working to create future drilling holes that could be minimally prepared during regular drilling to leave them in a condition for future observatories. While this could not be done with every hole, investigators should always keep in mind when holes could become viable locations for future observatories. If that is the case, they may consider staging a hole for later use.

APLs for simple installations or retrofits or archiving – Another approach to proposing observatory science is the use of Ancillary Project Letters (APLs). APLs have been used in the past to do data downloads, equipment recovery, and observatory installations at well-characterized locations taking advantage of the shiptrack. In future IODP operations, APLs again may serve as an avenue for doing quick installations, partial installations (e.g., casing for a future legacy hole), or for equipment and data recovery. Each APL will have to be addressed on a case-by-case basis through discussions with the operator.

Data Management, Access, and Archiving

With the wealth of data and technological development accumulated through 20+ years of observatory science, it is imperative that a systematic mechanism for managing and archiving observatory information be developed. This has been done in an ad hoc fashion in ODP/IODP but a formalized mechanism is needed to expand the use of observatory data. To accomplish this we need both improved archiving of engineering and technological developments as well as a detailed data management and an open-access system. Previous attempts have had incremental success, but this needs serious attention for observatories post-2013 to maximize science output in the light of fiscal shortfalls.

Traditionally in development of any observatory program, there are a series of engineering discussions involving the PIs, the operators, the funding agencies, and the IODP-MI. Meeting minutes and observatory plans are made in these meetings, and should be archived for future PIs to evaluate. A simple way to implement this would be to include all meeting minutes and observatory planning needs in the appendix to the Expedition report. This would provide online access to the outside world for planning purposes. We anticipate these notes and plans will capture general planning and operational discussions and overall details of the observatory plan.

Of equal importance to archiving the engineering and development details is providing adequate and consistent data management, access, and archiving for data and/or samples that are collected through observatory science. All ODP/IODP shipboard data is managed and publically available by the USIO (http://www.oceandrilling.org/Data_Samples/default.html), CDEX (http://sio7.jamstec.go.jp/), and ESO (http://iodp.wdc-mare.org/front_content.php?idcat=390). Data and samples from observatories, however, do not have any standard formats, protocols for distribution, or easily searchable database even as the data are largely provided through IODP operations and national funding sources. Public funding agencies require that data and samples be archived properly and made publically available. Therefore to meet the funding agency guidelines and to increase the value and usage of observatory data, it is imperative that the observatory community develop a means to manage and distribute data. A grassroots effort has been started (http://www.corkobservatories.org) that provides an initial start for such a management and distribution network. This effort could be augmented or formalized by an (inter)national data storage location such as one of the IODP databases or the National Geophysical Data Center (http://www.ngdc.noaa.gov/) to provide large storage systems with regular backup and maintenance. While exploring different options for such a system, the group decided that this effort will need a lead person/organization to formalize the database structure and to accumulate the existing data in consistent formats with appropriate metadata. The database would also need to accommodate different origins of the data whether it is retrieved via IODP or non-IODP operations. This would set the standard for future observatory data to be uploaded and managed. As with the observatories themselves, the development of a management and access database will require some development and maintenance funding. This need should not be overlooked by the scientists or the funding agencies. We have 20+ years of progressive development and we have a science plan that requires more observatory use and development. The history needs to be appropriately archived and we need to establish protocols for archiving and distributing of these valuable data and samples.

Expanding the Community and Science Impact

One means to expand the use of observatory science beyond the ocean drilling community and to increase the value of the overall data streams and samples is to engage other programs. By developing collaborative projects with other disciplines, there could be scientific benefits to both communities and cost-sharing opportunities. Two arenas discussed for linkages were marine geodesy and oceanography. Observatories provide a seafloor template that could also serve as a benchmark for marine geodesy that is linked back to surface buoys, which are precisely located by GPS. This provides a simple, relatively inexpensive way to increase marine geodetic coverage using instrumentation that will be installed with the observatory. This could quickly increase marine geodetic data sets and help us learn more about seafloor movements. Another community to engage is the oceanography community. This could be simply done by sharing data sets with physical and chemical oceanographers as observatories are known to record signals (e.g., pressure and temperature transients) that are linked to weather and oceanographic phenomena. Also seafloor observatories adjacent to borehole observatories would provide a shallow-to-deep linkage of oceanographic forcing on seafloor fluxes. These local, seafloor fluxes could also engage marine biological and geochemical scientists that are interested in productivity and activity at the seafloor.

As the community expands and the science impact grows, we will be required to develop more technology at the boundaries of disciplines. To help accomplish this, we need to explore all avenues for communication with industry. ODP/IODP and the energy industry have shared information on drilling and coring techniques and on certain aspects of observatory design. The group endorses this type of technical exchange especially as we embark on deep, high-temperature targets. The group also suggests exploring communication with other industry affiliates, such as the environmental industry, where specialized sensors (e.g., geochemical sensors) may be used or are under development. Service companies are another way to explore tool development and deployment. A presentation by Schlumberger exemplified this as they are looking at different types of temperature sensors that are highly versatile and have deployment flexibility, which is a big improvement over traditional fixed-sensor type strings. The community should reach out to industry in the early planning stages to evaluate where advice or technology can be shared and so effective cost planning can be done.

Society, Education, and Outreach

Observatories provide the ability to engage scientists as well as the general public. At the simplest level, there is a need to educate on the types of data that can be collected and how it will be connected. Examples of this exist for CORKs (https://www.youtube.com/watch?v=stqhtI-N7eg). With these basic demonstrations developed, we need to expand the options to reach the general public. Existing data sets could be used to develop teaching or educational modules for use in schools and highlight the value of temporal data. Such teaching modules could be publicized and distributed through coordinated outreach programs such as the Deep Earth Academy (http://www.oceanleadership.org/education/deep-earth-academy/educators/classroom-activities/). These activities would allow education of young students not only about deep Earth drilling but also about the value of time-series data to understand dynamic processes in geology, geophysics, geochemistry, and microbiology. Last, as observatories become cabled and connected to real-time networks (e.g., NEPTUNE, DONET) we must make a strong effort to provide links to the data especially when important events are observed, such as a seismic event recorded in pressure transients. We should not be limited to traditional outreach activities. As observatory science pushes new frontiers for technology and engineering, we can reach out to other broader media sources. An excellent example of this was the WIRED magazine piece on using observatories to understand deep sea life (http://www.wired.com/magazine/2011/11/st_cork/).

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Appendix I: Workshop Agenda

Observatories in Scientific Ocean Drilling
Workshop Agenda

Sunday, 09 September 2012

17:00		Informal Ice Breaker at Little Woodrow's

Monday, 10 September 2012

8:30		Introduction, Workshop Objectives and Logistics B. Dugan, N. Kyo and H. Villinger
8:45		Introduction to Observatories in ODP/IODP K. Becker
9:15		Existing CORK Observatory Technologies and Experimental Applications E. Davis
9:45		Coffee Break
10:00		Engineering and Platform Capabilities JOIDES Resolution K. Grigar
10:15		Engineering and Platform Capabilities Chikyu N. Kyo, Y. Namba, and S. Toczko
10:30		Alternative Concepts for Borehole Observatories and Legacy Boreholes A. Kopf, S. Farrington, G. Wheat, K. Edwards, K. Becker
11:30		Production Well Monitoring in Industry Lee Jackson and John Lovell
12:00		Lunch Break
13:30		Introduction to Post-2013 IODP Science Plan and Research Themes B. Dugan and A. Fisher
13:45		Introduction of the Breakout Groups BG-1: Geophysical Frontiers in IODP Borehole Observatories A. Fisher, E. Solomon BG-2: Technological Challenges for IODP Borehole Observatories E. Araki, K. Becker BG-3: Microbiological/Geochemical Frontiers in IODP Borehole Observatories K. Edwards, G. Wheat
15:45		Coffee Break
16:15		Future IODP Structure Y. Kawamura
16:30		Outlook for Day 2
18:00		Texas BBQ Dinner @ Rice University

Tuesday, 11 September 2012

9:00		Breakout Groups continue
10:30		Coffee Break
11:00		Breakout Groups Summaries and Discussion BG-1: A. Fisher, E. Solomon BG-2: E. Araki, K. Becker BG-3: K. Edwards, G. Wheat
12:00		Lunch Break
13:30		Funding Borehole Observatories J. Allan, T. Janacek, K. Edwards, E. Araki, A. Kopf
14:00		Management, Distribution and Archiving of Data and Samples M. Heesemann, H. Villinger
14:30		Approaches to Promote Future Borehole Observatories B. Dugan, A. Kopf, N. Kyo
15:00		Wrap-up Discussion
16:00		End of meeting

Appendix II: List of Participants

U.S. Participants
1) James Allan – NSF
2) Paulo Antunes – Univ. Mass-Amherst
3) Keir Becker – Univ. Miami-RSMAS
4) James Cowen – Univ. Hawaii
5) Brandon Dugan – Rice Univ.
6) Katrina Edwards – Univ. Southern California
7) Cindy Evans – NASA JSC
8) Steve Farrington – Transcendev
9) Andrew Fisher – Univ. California, Santa Cruz
10) Patrick Fulton – Univ. Texas
11) Kevin Grigar – Texas A&M
12) David Huey – Stress Engineering
13) Samuel Hulme - MBARI
14) Katie Inderbitzen – Univ. Alaska, Fairbanks
15) Lee Jackson – Schlumberger
16) Tom Janecek – NSF
17) Jackie Kane – St. Ursula Academy
18) Miriam Kastner – Univ. California, San Diego
19) John Lovell – Schlumberger
20) Beth Orcutt – Bigelow Lab
21) Tom Pettigrew – Pettigrew Engineering
22) Evan Solomon – Univ. Washington
23) Gowtham Subbarao – Scripps Institute of Oceanography
24) Kush Tandon – Shell
25) Laura Wallace – Univ. Texas
26) Zhankun Wang – Texas A&M
27) Geoff Wheat – Univ. Alaska, Fairbanks

International Participants
28) Louise Anderson – Univ. Leicester, UK
29) Eiichiro Araki – JAMSTEC/DONET, Japan
30) Earl Davis – Geological Survey of Canada
31) Nobu Eguchi – JAMSTEC/CDEX, Japan
32) Sebastian Hammerschmidt – MARUM, Germany
33) Martin Heesemann – University of Victoria, Canada
34) Ryota Hino – Tohoku University
35) Issa Kagaya – IODP-MI, Japan
36) Yoshi Kawamura – IODP-MI, Japan
37) Toshinori Kimura – JAMSTEC/DONET, Japan
38) Masa Kinoshita – JAMSTEC, Japan
39) Kazuya Kitada – JAMSTEC, Japan
40) Achim Kopf – MARUM, Germany
41) Nori Kyo – JAMSTEC/CDEX, Japan

42) Yasuhiro Namba – JAMSTEC/CDEX, Japan
43) Tianhaozhe Sun – University of Victoria, Canada
44) Sean Toczko – JAMSTEC/CDEX, Japan
45) Heinrich Villinger – University of Bremen, Germany

Appendix III: Compilation of ODP/IODP Observatory and CORK References

(note: compilation is representative but does not include all scientific drilling observatory references)

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