A mini-workshop to encourage the scientific community to develop proposals for optimizing the OOI-node on Hydrate Ridge

March 4-5, 2016

Hotel Galvez, Galveston, TX

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Executive summary and recommendations

This report summarizes discussions from a mini-workshop held after the Gordon Research Conference (GRC) on Natural Gas Hydrates March 4-5, 2016. The workshop was focused on opportunities presented by the Ocean Observatories Initiative (OOI) Cabled Array at Southern Hydrate Ridge.

Below we report findings subsequent from the 2007 GHOBS Workshop; background information on the current status of the OOI site (D. Kelley, U.W; D. Manalang, U.W); a report on lessons learned from the Ocean Networks Canada (Neptune) cabled observatory (M. Scherwarth and L. Thomsen); and new sensor technologies (e.g. L. Thomsen, A. Michel). We have received explicit permission from these investigators to provide here key points from their GRC and follow-up presentations at the mini-workshop.

We then outline a set of outstanding research questions and approaches that can be utilized to advance our understanding of processes operating at Hydrate Ridge with applications that can be broadly transferred to gas-hydrate bearing provinces and subduction zones worldwide. These ideas were framed by all participants over the course of one afternoon, and are presented in the context of two main themes: 1) *Gas Hydrate System Dynamics*; and 2) *Biological communities, activities and dynamics associated with variations in biogeochemical fluxes and physical properties.*

It is our hope that the information summarized in this document generates excitement for the use of this powerful facility, and that ideas outlined here may serve as a launching ground for the development of new and successful proposals from the community at large. We recognize that the cabled observatories are breaking ground not only with the science and technological advances they can facilitate, but also in development of new models for collaborative use of the facility. The participants stressed the need for continued communication and outreach to both the community at large and the general public, and provided the following recommendations:

- We encourage members of the scientific community interested in the use of observatories to register at the OOI portal (http://oceanobservatories.org/) to receive regular status updates for various aspects of the OOI, including current schedules for making all OOI data available and enhancements for full functionalities that remain for completion of the OOI Cyberinfrastructure.
- In addition to these communications and OOI-hosted webinars, we recommend periodic (annual) workshops for all scientists involved, and those interested in submitting proposals, to achieve the collaboration and transparency needed for optimal use of the facility.
- Formation of small working groups on various topics including science, data, and technology.
- We recognized the need to strengthen cross agency and international collaboration to maximize the use of this facility.
- We identified the need to strengthen collaborations with Ocean Networks Canada (ONC), especially the two gas hydrate sites, because this will allow us to benefit from their experience and established contacts, to improve logistics and operations for both observatories, and to broaden the study footprint with cross comparisons. We envision the possibility of mutual development of approaches that can maximize both financial and intellectual investments.

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1. Introduction

It has been eight years since the last workshop focused on cabled observations of a gas hydrate system. The Gas-Hydrate Observatories (GHOBs) Workshop was held in Portland, OR in 2007 to outline ideas for the use of a cabled observatory facility to investigate gas hydrates. Based on analyses of the scientific goals and proposed strategies defined in the 2007 GHOBs Workshop, and the wealth of expertise, knowledge, and technological advances that have taken place since then, the gas hydrate scientific community is now well poised to move this research to the next phase of continuous monitoring through the use of a cabled observatory.

The cabled sites at Southern Hydrate Ridge (SHR) have been streaming data to shore since 2014, and data are becoming available through the Ocean Observatories Data Portal (http://oceanobservatories.org/data-portal/). Hence, the community is at a critical junction to develop specific plans and strategies for optimizing the scientific returns provided by this new facility and to begin developing plans for expansion capabilities. Here we report on ideas that were put forth by participants of the Hydrate Ridge mini-workshop and the 2016 Gordon Research Conference on Natural Gas Hydrates, in Galveston, TX. The mini-workshop discussions (March 6, 2016) built from two specific GRC sessions: "Challenges and Opportunities for Sensor Technology Applications" (3 presentations) and "New OOI Node on Hydrate Ridge" (2 presentations). These ideas, herein, are not meant to be a comprehensive view of the community's interests, but to serve as a launching point to stimulate a larger group of interested scientists to join in the efforts to utilize this powerful new facility.

2. Summary of 2007 GHOBs report and motivation for 2016 mini-workshop

The GHOBs report (http://www.oceanleadership.org/programs-and-partnerships/usssp/workshops/past-workshops/usssp-past-workshops-2007/gas-hydrate-observatories-workshop/), indicated that cable-connected observatories located at gas hydrate-bearing sites will provide data essential for:

1) Identifying factors that influence subsurface fluid flow and how this flow relates to stabilization and destabilization of gas hydrates;

2) Studying the effects of microbial activity on gas hydrate processes;

3) Gaining a better understanding of the role of gas hydrates in the global carbon cycle and their potential as an energy resource; and

4) Exploring the effects of gas hydrate formation/destabilization on slope stability.

This report defined an "Observatory Gold Standard," as a comprehensive program that includes continuous monitoring of the water column and seafloor in an area of known surface manifestations of fluid venting and gas hydrate deposits, linked to borehole monitoring of the methane reservoir, the gas hydrate stability zone, and transfer zones.

This report also indicated the need for a 2-phase approach, whereby an observational phase is needed to determine the natural baseline for the system and its response to various natural forcing functions (e.g., co-seismic strain events, tidal loading, current-induced temperature variations, etc.), and an experimental phase, when human-made perturbations are applied to the system.

The 2016 Hydrate Ridge mini-workshop focused on research that could be conducted in the near-term, focusing on seafloor and water column observations. Topics that were discussed included:

1) Microbial activities and dynamics, particularly how they respond to variations in flux;

2) Mechanisms for gas transfer from the subsurface to seafloor;

3) Magnitude and variability in the flux of carbon to the water column from seeps.

In addition, it was recognized that the OOI cabled research facility will accelerate the development of new technologies, instrumentation, platforms, and materials capable of withstanding long-term exposure to high pressures in a corrosive environment, which in turn can be applied to a variety of other observatory settings.

3. New observations at Southern Hydrate Ridge.

There is significant new information on the dynamic nature of gas hydrate systems based on five years of studies from a series of OOI-University of Washington expeditions leading to the complete installation of the cabled infrastructure at Southern Hydrate Ridge (Figure 1) and at two Ocean networks Canada (ONC) seep sites. At a high level, results from this work shows that substrate, water column temperature, methane concentration, venting, and species abundance vary over short distances and that drivers of heterogeneity vary over timescales of seconds to years.

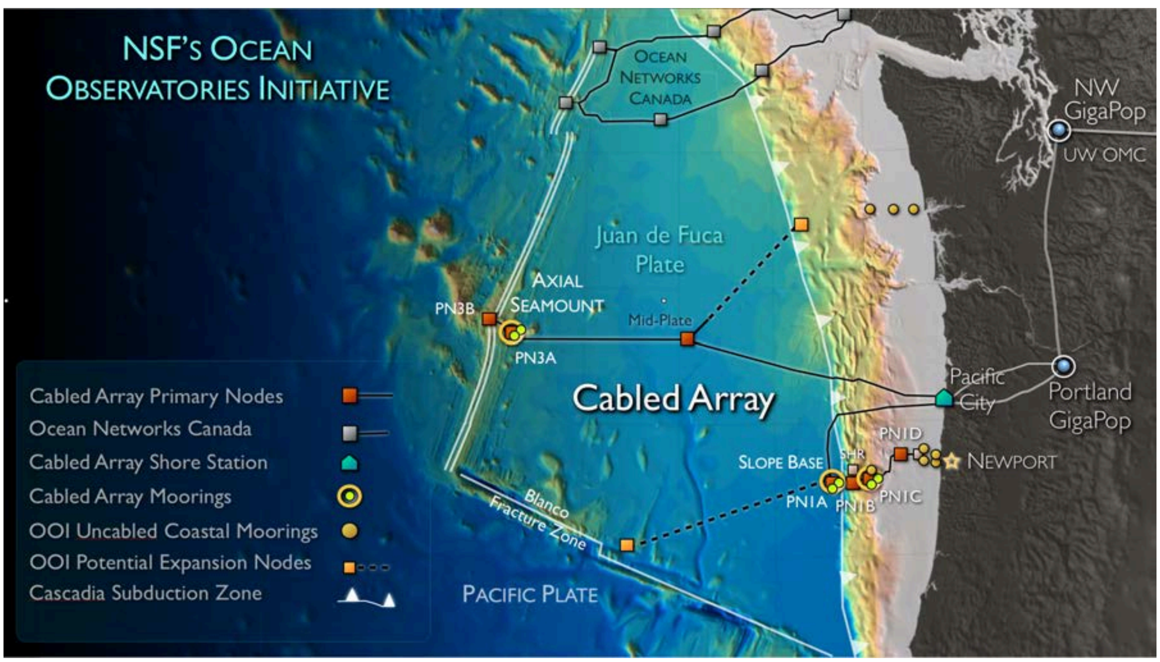

Figure 1. Location of the two cabled arrays in the NE Pacific. This is now the most highly instrumented area in the world's ocean.

As part of the site survey work, the entire seep site at Southern Hydrate Ridge was mapped at < 5 m resolution and detailed photomosaics are now available (Figure 2). This is the first place where an entire >300 m by >300 m seep was imaged at the scale of an individual fish. Every seep has been mapped in detail with the areal extent of bacterial mats quantified. Periodic surveys of the seeps have revealed spectacular changes since 2010, when the site was first visited. Two sites (Einstein's Grotto and Smokey Caverns) that were initially characterized by a gentle, hummocky terrain in 2010, were unrecognizable by 2015. Grotto now is bounded by a circular, very rugged collapse area, bacterial mats that were present in 2010 are gone or have colonized new locations on the seafloor, and a very large orifice that emits explosions of methane bubbles and sediment is at the base of the original small mound. At Smokey Caverns, an extremely rugged, semi-linear collapsed area developed, hosting large blocks of lithified sediment and 2 m tall walls. Fire hose-like jets of bubbles are emitted from very large openings at the base of the walls, and translucent, sediment-free blocks of hydrate are exposed on the seafloor and within the bounding walls. Here too, the density of bacterial mats and animals has changed dramatically. By 2015, significant collapse of the steep-sided walls had occurred.

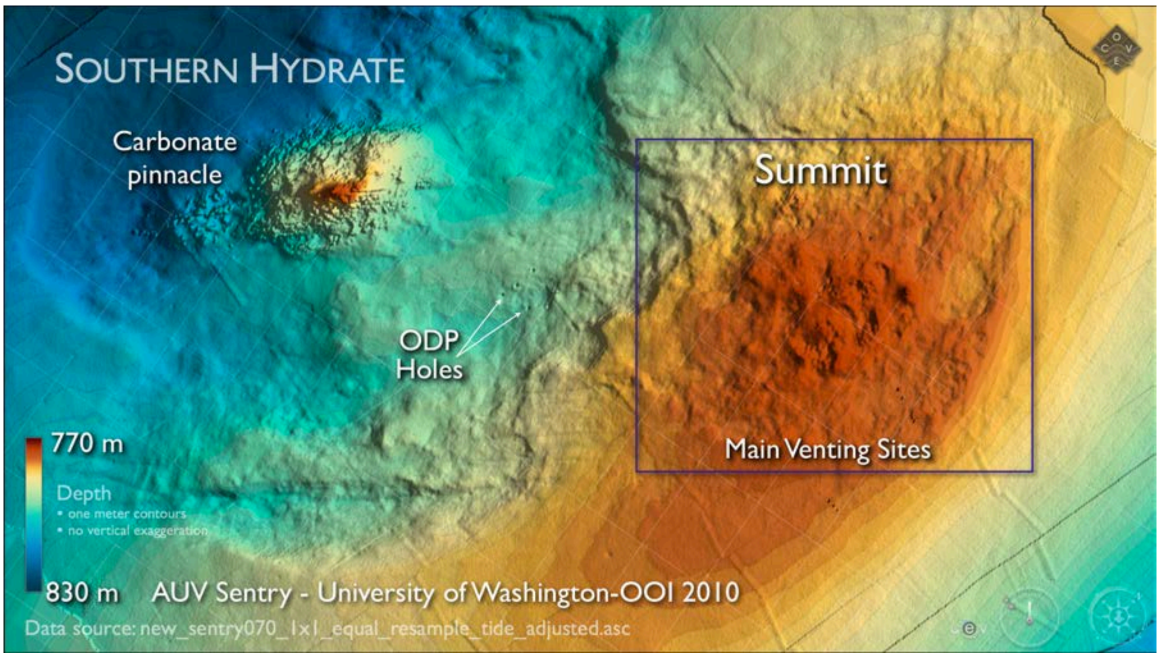

Figure 2. High-resolution bathymetric map of Southern Hydrate Ridge from a 2010 *Sentry* survey. The summit site is now extensively instrumented with cabled infrastructure. Two new sites of venting were discovered in 2014, one between the Summit site and the carbonate pinnacle, and one at the pinnacle, which rises 36 m above the seafloor.

Water column imaging using the EM302 hull-mounted sonar system on the *R/V Thompson*, and repeated sampling and imaging using the *ROV ROPOS* and CTD hydrocasts identified two new sites of bubble plumes away from the main seep site (Philip et al., 2016). More importantly, the plume study shows that although plume sources remained stable within the main seep area, the intensity of the methane discharge varied significantly over hours to days to years. The bubble plumes rose several hundred meters above the seafloor and above the gas hydrate stability field. Initial views of both digital still imagery and ADCP data streaming from the cable support the observations of plume variability (which can now be viewed continuously), as well as changes in seafloor morphology and microbial mat density/location.

These observations illustrate the extreme dynamic nature of these systems, and the need to fully quantify these changes in time and space, if we hope to arrive at a global estimate of mass and energy transfer across the seafloor at seeps.

4. Status of the cabled observatory on Southern Hydrate Ridge (D. Kelley and D Manalang)

Installation of the cabled infrastructure at Southern Hydrate Ridge (Figures 2 and 3) was completed in 2014 (http://interactiveoceans.washington.edu/story/VISIONS_14). A 10 km extension cable from Primary Node PN1B, to the south, connects to a low voltage node LV01A, which provides power and bandwidth to a low power (LV01B) and medium power junction (MJ01B) box at the summit of the ridge. The site currently hosts:

- 3 short-period seismometers on 386 m- to 604 m-long extension cables
- 1 broadband seismometer with an accelerometer (buried in a caisson) coupled to a low frequency hydrophone
- 1 current meter and temperature sensor
- 1 75 kHz ADCP
- 1 mass spectrometer
- 1 digital still camera with pan and tilt capabilities
- 1 uncabled osmotic fluid sampler
- 2 benthic flow meters

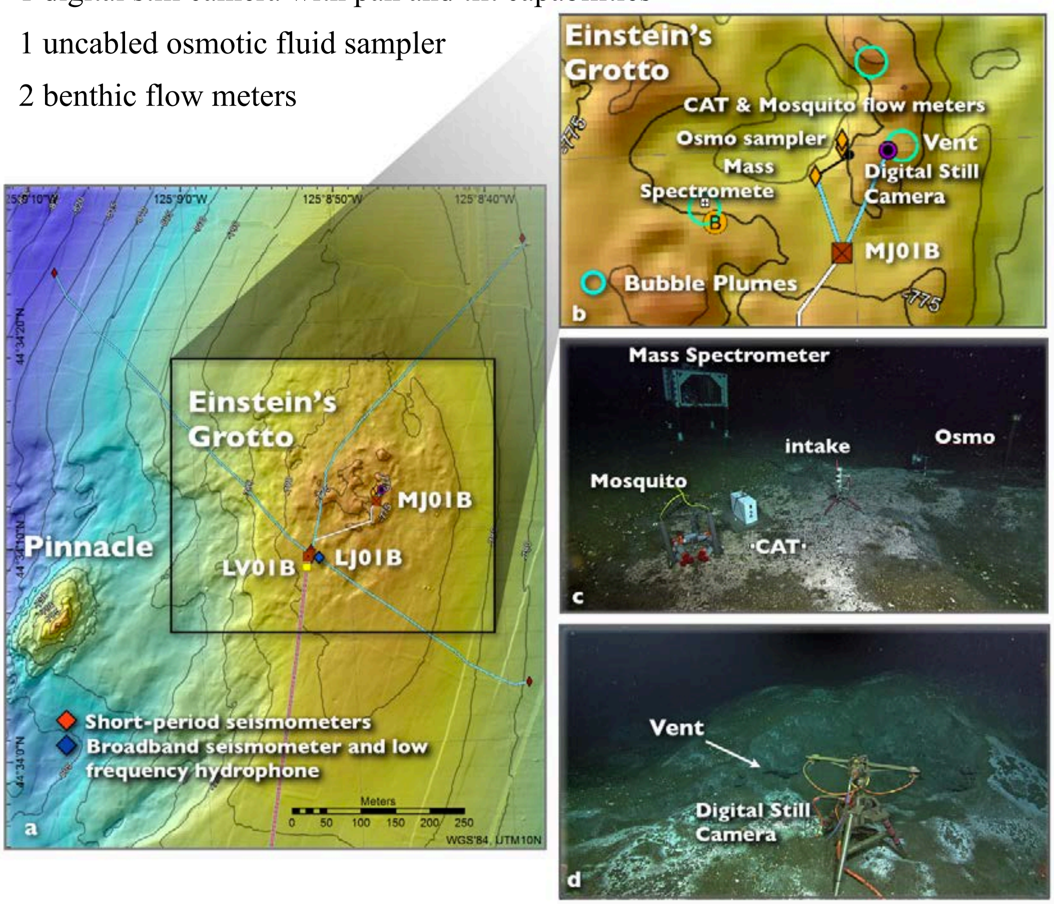

Figure 3. a) High level overview of the location of cabled array infrastructure at Southern Hydrate Ridge showing the Low Power (LJ01B), Low Voltage (LV01B) and Medium Power (MJ01B) junction boxes that have significant expansion capabilities. b) Instruments and location of bubble plumes near Einstein's Grotto. c) The mass spectrometer, fluid sampler, and flow meters west of the venting orifice at Grotto. d) The large hummock and venting orifice imaged by the camera.

Highly detailed site surveys (bathymetric, water column, and photomosaic-mapping) were completed prior to installation of the array. Based on this work, the vigorously venting 'Einstein's Grotto' seep was chosen as the initial focused instrumentation site (Figure 3a-d; MJ01B). Based on community input, the local seismic array of short-period seismometers extends 386- 604 m away from the focused site, with a buried broadband seismometer and a hydrophone located adjacent to active seepage (Figure 3a; i.e. LJ01B). The UW Cabled Array team performs intense instrument testing (e.g. electrical, mechanical, burn in, integration) on each instrument, each junction box, and the fully instrumented secondary junction boxes in the lab and this rigorous protocol is followed by ship-testing just prior to deployment. In 2015, instruments at the Einstein's Grotto site were turned during the annual Operations and Maintenance cruise (http://interactiveoceans.washington.edu/story/VISIONS_15). Significant expansion capabilities are provided by the secondary junction boxes through daisy chaining.

Information on the cabled infrastructure is available on the OOI website (http://oceanobservatories.org/) and on the UW Interactiveoceans website (http://interactiveoceans.washington.edu/). All streaming and uncabled OOI data ingested into OOINet continues to be available for plotting (http://oceanobservatories.org/data-portal/). All raw data are currently available (https://rawdata.oceanobservatories.org/files/). Ingestion is an early step in the full data flow process and these data have not yet gone through the quality control process. Data products are viewable through the portal, with many products streaming/viewable in real-time.

Historical cruise data are available for download from the OOI website. Delivery of the Cabled Array seismometer and bottom pressure data from bottom pressure-tilt instruments are through IRIS http://www.iris.edu/hq/. Co-located temperature, and bottom pressure tilt plots are provided by Dr. Bill Chadwick's website, available at http://www.pmel.noaa.gov/eoi/rsn/

5. Lessons learned from Ocean Networks Canada (ONC)

Ocean Networks Canada started streaming ocean floor data in 2006 from VENUS (Salish Sea, inshore) and in 2009 from NEPTUNE (Pacific, offshore), which are ONC's major observatories (Figure 4). There are two gas hydrates sites on the NEPTUNE array: Barkley Canyon (hydrate mounds and outcrops) and Clayoquot Slope (active vents). Information is available at oceannetworks.ca.

Some of the lessons learned during the 10-year operation of these observatories are summarized below. Where applicable, many of the lessons/observations described below, were incorporated into the initial planning phases of the Cabled Array and adopted into the design and operations.

1) It is important to co-locate sensors; however, it is also important to develop protocols to avoid interferences among instruments (e.g. hydrophones detect sonars, seismometers and BPRs detect moving platforms). Similarly, manipulating experiments (e.g. seafloor enrichments), while important, do contaminate or alter sites for some time and require mutual agreements between scientists. Selection of clean vs. contaminated sites is valuable, but this requires a good knowledge of contamination distance. ONC offers annotated time series warning about known noise contamination.

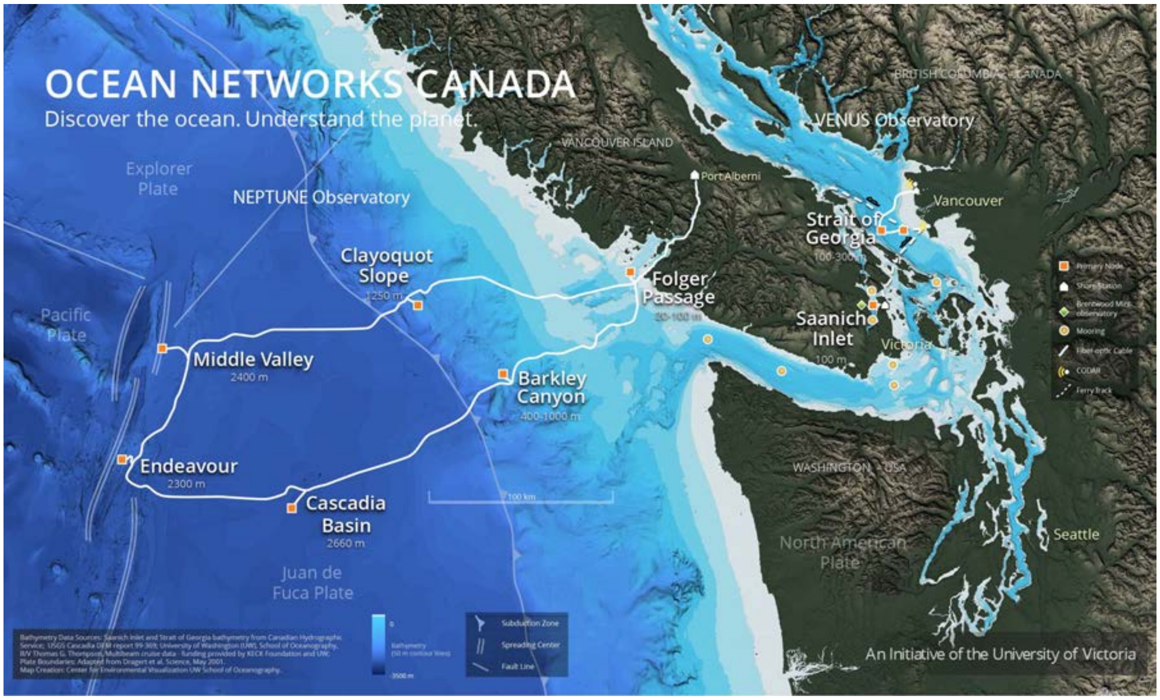

Figure 4. Location of cabled infrastructure that is part of the Ocean Networks Canada network.

2) It is important to collaborate and connect research, but there is a need to consider observatory aspects. For example, ONC developed master drivers that slave instruments to not interfere (but potentially create data gaps), and this requires additional software development resources in a proposal.

3) It is also important to consider seafloor calibration requirements, adding follow-up ship time into proposal. Custom made instrument reliability is not predictable, and there are some examples of instruments that worked well, while others have not been so successful.

4) ONC science experiments don't have expiration dates. A way in for new proposals would be to end old experiments. Limited experiment life time lowers O&M costs.

Some researchers have no intent to publish while more data are coming, consequently end dates build pressure on the research community to demonstrate successes, publish, or apply for extra time if required.

5) Sampling and analyses coordination and sample data availability is valuable. ONC realizes the importance to collaborate and establish common basic procedures for sample analysis from observatory efforts (cruise or instrument samples), a well as the need for a common sample data base (through international programs like iSamples, etc., into NOAA's NGDC or other databases). ONC is considering the use of Digital Object Identifiers (DOIs) for samples and data sets.

6. Examples of new sensor technologies

6.1 Insights from observations using the "Wally" Crawler in northern Cascadia (L. Thomsen).

Cabled research infrastructure enables sensors, instrument packages, and platforms to receive power and transmit data from the deep-sea in real-time. By attaching mobile research platforms to these cabled networks, the investigation of spatial and temporal variability in environmental conditions and/or faunal behavior across the deep seafloor is now possible. For example, the "Wally" Crawler is a mobile instrument platform (130 × 106 × 89 cm, LWH) with caterpillar tracks that allow a footprint on the seafloor of 0.35 m^2 with a weight of ~10 g/cm^2. This platform was used to track environmental and faunal changes over time, increasingly illuminating the nature of the relationships between fauna abundance, fauna behavior and bacterial mat abundance with spatial and temporal environmental variability. Ecosystem specific temporal changes in parameters such as methane concentration within seawater or local physical processes such as substrate collapse following gas hydrate dissolution, and more general seasonal environmental changes have been observed with the crawlers. These include chlorophyll flux change following variation in surface production throughout the year, differences in storm regularity and suspended sediment load between seasons, local accumulations of benthic fauna during mating seasons, specific feeding behavior of jellyfish under low flow-conditions, variability of clam movement, and dial/seasonal changes in megafaunal community dynamics. Strong changes in benthic community structure occur at distances of 3 to 5 m away from a seep site and characteristic soft bottom communities typically found at continental margins are found 10 to 50 m away from the seeps. The dynamic nature of this environment results in community structure changes within a few days. Commonly evident on the gas hydrate mound images are highly mobile fauna such as fish, crabs and various mollusks, with large, sulfate reducing bacterial mats also visible, which constantly change in coverage over a scale of days, with larger changes in coverage taking place over scales of months. These data provide additional evidence for the dynamic nature of these systems, and the unique opportunities offered by cabled observatories to characterize, constrain these processes with the aim to generate a robust understanding of this unique ecosystem and its contribution to global carbon budgets.

6.2 Near-infrared laser spectrometry (A. Michel)

Through the development of new *in situ* chemical sensors will come a greater understanding of deep-ocean biogeochemistry. Recent advances in chemical sensors have already started to revolutionize oceanography and expand the breadth and depth of deep sea/seafloor exploration. Laser-based spectroscopic sensors have been developed for highly sensitive measurements of atmospheric gases. The use of gas equilibration techniques, such as gas permeable membranes, is opening up the possibility to use these same techniques in the deep ocean. A novel in situ laser-based spectrometer [*Wankel et al. 2013*] has been designed for the analysis of carbon isotopes of methane ($\delta^{13}CH_4$) of deep ocean fluids, Michel and Wankel have achieved a sensor capable of dual isotope measurements [*Michel et al. 2015*]. The sensor can now analyze *in situ* both the carbon isotopes of methane and dissolved inorganic carbon (DIC, CO_2). An in line acidification module was added to enable dissolved inorganic carbon (DIC) measurements to be made, and subsequently achieve the $\delta^{13}CO_2$ measurements. A bubble trapping methodology was designed and implemented for the collection and analysis of both CH_4 and CO_2 from deep-sea bubbles.

Current research focuses on the development of new deep-sea sensors for both CH_4 and CO_2 analysis that use advanced laser-based spectroscopy methodologies.

7. Opportunities provided by the OOI cabled facility on Southern Hydrate Ridge

The reports from the breakout sessions, detailed below, provide a guide to build upon as the community develops ideas and projects aimed at answering key scientific questions. Some approaches to address these issues are listed below (Sections 8 and 9), but we envision new ideas coming forth from the wider science community.

The OOI 25-year design of the cabled infrastructure and the long-term presence at Southern Hydrate Ridge provides a unique opportunity to monitor the impact of decadal-scale changes on seep ecosystems, such as:

- The El Niño-Southern Oscillation and the Pacific Decadal Oscillation.
- Increasing bottom-water temperatures.
- Variations in the spatial and temporal extent of hypoxia in the oceans.
- Seismic activity related to the Cascadia subduction zone.
- Dynamics in subsurface plumbing and gas fluxes from subsurface reservoirs

In addition, the basic infrastructure and baseline measurements and contextual sensors provided by the cable provide a unique opportunity to develop technologies and methods that have broader applicability to:

- Studies of methane-rich seafloor systems worldwide.
- The consequences/impact of anthropogenic release of methane.
- Monitoring hydrocarbon infrastructure.
- Flow assurance research.
- Development of mitigation technologies for biofouling and hydrate growth on instrumentation.
- Linkages of methane release and water column ecosystems

8. Theme 1: Gas hydrate system dynamics

Investigating the role of seafloor methane and methane hydrates in the global marine carbon cycle at a range of spatial and temporal scales remains a fundamental research question. The establishment of the cabled observatory at the well-characterized SHR site provides the opportunity to address fundamental, first-order questions about gas hydrate systems, particularly at those characterized by high gas fluxes. The workshop participants identified *understanding the fluxes and sinks of methane throughout the gas hydrate system* as the most fundamental issue that can be addressed. A full systems approach to gas hydrate research involves investigation of (1) the deep subseabed source region for methanogenesis, gas accumulation and fluid migration; (2), the shallow sedimentary section within the gas hydrate occurrence zone; (3) the dynamics of gas venting into the overlying ocean; and (4) and the fate of methane in the ocean and release into the atmosphere. The key processes and questions that can be addressed through monitoring are discussed below from a bottom-up perspective extending from the gas transport horizon below the regional gas hydrate stability zone across the seafloor and into the water column.

8.1 Key questions under this theme

I. What is the flux of gas into the gas hydrate stability zone and what mechanisms allow it to reach the seafloor?

Seafloor infrastructure and future observations in CORKed boreholes will provide critical constraints on the subsurface plumbing system for fluid and gas and how they vary through time. Based on existing seismic, LWD, and core data, methane is inferred to be supplied to SHR through a 2-4 m thick permeable zone of coarse-grained turbidites called Horizon A, located 15-20 m below the base of the hydrate stability zone at the SHR summit. The gas pressure in Horizon A is inferred to be at or near lithostatic pressure, and hydraulic fracturing has been invoked to explain the presence of hydrate-filled fractures and the rapid gas flux observed at this site. Key questions pertaining to gas transport through the GHSZ are:

- What are the rates of gas transport through Horizon A and how do these rates vary through time?
- What is the plumbing system extending from the regional gas hydrate stability zone to the seafloor?

In addition, there are two competing hypotheses for the mechanism driving the bypass of gas through the hydrate stability zone: 1) Gas is transported rapidly through fracture systems and gas hydrate formation along the flow path is inhibited by water availability or hydrate nucleation kinetics; and 2) The pressure-temperature boundary defining the hydrate stability zone is perturbed by high pore water salinity caused by salt exclusion from the hydrate crystal structure along the flow path. ***Observations made across the SHR seep site will provide constraints on the mechanism(s) allowing for the transfer of free gas through the hydrate stability field.***

It is likely that this plumbing system is variable through time, as is the temporal and spatial flux of methane and fluids through the hydrate stability zone, to the sulfate-methane transition zone, and across the seafloor. Continuous observations at SHR can provide critical observations required to understand the processes driving this spatial distribution and temporal behavior. Key outstanding questions include:

- What is the flux of methane into gas hydrates along the transport pathway?
- What is the relative significance between the flux of dissolved methane and the flux of methane gas?

II. What are the fluxes of water and gas across the seafloor and how do they vary through time?

Recent coring, seafloor fluid flow meter, and sonar observations clearly show that the fluxes of water and gas across the seafloor vary considerably in both space and time. Key questions that can be addressed through continuous seafloor observations include:

- What are the vertical and lateral fluxes of water and gas and how do they vary through time?
- What is the impact of these fluxes on the seafloor and subseafloor biological

communities?

- What are the rates of authigenic mineral precipitation, which are controlled by these fluxes?

- Is the carbonate pinnacle currently active/growing and is authigenic carbonate currently precipitating in this feature?

III. How are the dynamics of gas transport and hydrate formation manifested on the broader seafloor morphology?

Dynamic gas and water fluxes contribute to gas hydrate formation and overpressures within the sediment column that are likely spatially heterogeneous and temporally variable.

-What are the macrobiological manifestations of these processes?

- How does the biology respond to seep wide variability of fluxes and gas hydrate dynamics over time?

IV. What are the mechanisms that control bubble plume dynamics and the distribution of methane in the water column?

Once the gas bypasses the gas hydrate and microbial filters and is emitted at the seafloor, bubble plumes are the important pathway for gas transfer through the water column. Hydrate Ridge can serve as a benchmark for constraining the mechanisms that control bubble plume dynamics and the distribution of methane in the water column. This observatory provides an excellent opportunity to refine and tune bubble propagation models that predict the fate of methane in the ocean. Key questions include:

- What is the spatial and temporal variability in the flux of bubbles at the seafloor, this is essential for constraining the magnitude of the methane flux over characteristic timescales?
- What is the temporal variability in bubble plume rise heights and the spatial and temporal variability in the detrainment of methane into the water column?
- What are the rates of aerobic methane oxidation in the water column?
- What are the processes controlling the transfer and distribution of methane through the water column?

V. Is gas hydrate rafting a significant process transporting methane from the seafloor to the upper water column?

This is a hypothesized mechanism for the transfer of methane from the seafloor to the atmosphere at deep seeps system. This process may not be that important today, but could have been more important in the past if the gas supply to the regional hydrate stability zone varies through time, particularly through the earthquake cycle or through glacial-interglacial cycles.

- Can we observe gas hydrate rafting?
- Is it widespread across the seep site?
- What is the relative significance between passive methane fluxes and hydrate rafting?

VI. How does the upper limit of methane hydrate stability along the upper continental slope respond to changing bottom water temperature?

The upper limit of methane hydrate stability is the most sensitive portion of the global hydrate reservoir to changes in temperature and pressure. Considering that there is contemporaneous warming of bottom water at the upslope limit of gas hydrate stability along the Cascadia margin, observations here will provide a wealth of information of how the mechanics, hydrology, geochemistry, and microbiology responds to retreat of the gas hydrate reservoir. This also provides a modern analog to periods of bottom water warming in the past like the Paleocene-Eocene Thermal maximum and Holocene climate variability. Though this boundary does not occur at Southern Hydrate Ridge, it is within reach of an extension cable from the primary node.

- How does the system respond to gas hydrate dissociation driven by modern bottom water warming at the upper limit of gas hydrate stability?

8.2 Approaches

The approach for addressing the science questions developed during the workshop was an effort to acquire a broad range of observations using multiple techniques and tools focusing on the methane system. Observations focus on three main areas:

1) Pathways and flow rates from deep sources;

2) Migration and interaction at the seafloor; and

3) Interaction, dispersion and migration through the water column and potentially into the atmosphere.

Subsurface

The primary approach for observations of subsurface migration will rely on geophysical techniques for identifying pathways, mechanisms, and gas accumulations needed to characterize the dynamics of gas migration. The first goal is a combination of both active and passive seismic experiments. Passive monitoring would enable us to characterize the seismic activity within the subsurface by identifying possible source locations that define active faults within the upper plate that are not well imaged with seismic reflection profiles. Microseismic earthquakes will provide critical clues to active stress changes within the upper plate. Passive monitoring can also be used to characterize tremor that could also be very effective to identify and potentially track gas migration within major gas migration pathways such as Horizon A or other subsurface faults that can be seen in seismic data.

Characterizing the subsurface will also require an active source seismic component using short-period OBSs and the installed OOI seismometers to complement existing survey data and observations made with passive monitoring described above. This effort would focus on two goals, 1) to further constrain quantities of gas and hydrate in more detail than is possible with existing data, and 2) to conduct repeat surveys to track subsurface changes in gas and hydrate concentrations below and within the gas hydrate stability zone. The four installed seismometers could be used to conduct targeted, small-scale repeat surveys on a frequent, basis using seafloor seismic sources ideally, or surface sources from ships when an opportunity allows. The primary goal would be to accurately identify specific gas and fluid migration events and their relationship to other activity, such as fault slip, tidal fluctuations, storm events, etc. Critical to this effort is detailed characterization of the subsurface broadly around Hydrate Ridge to establish an accurate baseline for subsequent targeted repeat surveys.

In addition to seismic observations, we expect that electromagnetic techniques have large potential for further constraints on gas and gas hydrate concentrations within the subsurface. EM coupled to continuous shallow subseafloor observations of salinity (conductivity probes), fluid flow meters, and OsmoSamplers would potentially be the best opportunity to characterize unusually briny fluids produced from salt exclusion from hydrate formation. Uncertainties in interpreting resistivity anomalies as gas and gas hydrates can be addressed with collocated EM and seismic observations, and potentially implement new emerging techniques for joint EM and seismic inversion.

Seafloor

The approach for addressing methane dynamics and changes in animal and bacterial mat distribution at the seafloor is focused on repeat mapping, continuous observations, and sampling and monitoring. We viewed the main game-changer in making seafloor observations is the potential to deploy a hovering AUV system with a docking station. An AUV would allow repeat high-resolution mapping to identify and characterize seafloor morphology changes related to vent activity such as the development of seafloor mounds and depressions, hydrate and authigenic carbonate formation, as well as hydrate rafting. In addition to mapping, a hovering AUV would be able to make a suite of additional measurements and map them aerially around the seafloor of SHR. Such observations should include an underwater mass spectrometer, cavity ring-down spectrometer to measure methane isotopes, forward-looking sonar to monitor bubble plume activities, Eh sensor, pH sensor, and CTD measurements to constrain oceanographic conditions and seawater properties.

In addition to the observations made from an AUV, we envision a suite of seafloor observations to make a wide variety of measurements of physical and chemical conditions on or near the seafloor. Of the physical measurements, absolute pressure gauges and seafloor fluid flow meters will be critical for detecting geodetic movements related to the tectonic setting that may be linked to earthquakes, microseisms and tremor, and involved in triggering of hydrogeologic activity. Absolute pressure gauges could also be used along with tiltmeters to monitor localized uplift and subsidence within specific vents as venting activity fluctuates, and could be used for broader characterization of bulk changes in volume beneath the summit of SHR as gas and fluid migrate through SHR and hydrates form and dissolve. Other physical measurements to monitor seafloor and near-seafloor conditions are shallow penetrometers to measure pore pressure, distributed temperature sensors on the seafloor that can monitor temporal and spatial variations in temperature, fluid flow meters and continuous pore water chemical samplers that can monitor water fluxes, biogeochemical fluxes, and rates of geochemical reactions, and stationary cameras to monitor changes in seafloor morphology due to vent activity and possible ice rafting events.

The physical measurements at the seafloor would be complemented with instrumentation to monitor chemical species and conditions, as well to quantify bubble fluxes and variability. The primary focus would be on continuous sonar observations of bubble fluxes and both subseafloor and bottom water measurements of O_2, H_2S, pH, CH_4, and CO_2, and pH with benthic landers and on near-seafloor moorings coupled with ADCP to monitor methane oxidation and to quantify seep-wide methane fluxes through eddy covariance methods.

Water Column

One of the most critical observations needed for understanding the dynamics of methane flux is continuous observation of gas migration from out of the seafloor and through the water column. Methane flares (or plumes) have been shown to be common globally, ready markers of venting activity, and highly variable in their activity (vigorous bubble plumes have been documented at SHR since 2010, during OOI cruises). Most of the methane is typically transferred to the water column during bubble propagation, but some possibly rises to the sea surface and may be released into the atmosphere. The approach we would take in addressing the dynamic of flux through the water column would be to implement side-looking sonar and additional upward-looking sonar techniques to image and monitor the rising bubbles within the water column from seafloor stations or stations within the water column (possibly mounted on profilers or other instruments within the water column). In addition to acoustic measurements for monitoring bubbles, CTD (mounted on profilers) with sensors for measuring CH_4, pH, CO_2, and O_2 will be needed to measure oceanographic conditions and assess methane reactions within the water column. Furthermore, current meters and ADCP measurements will be needed to detect current motions critical to track and fully characterize the fate of methane from the seafloor into the water column and potentially to the atmosphere.

9. Theme 2: Microbial activities and dynamics associated with variations in biogeochemical fluxes and gradients. Magnitude and variability in the flux of carbon to the water column from seeps

The workshop participants fully recognized the significance of the biological/chemical interactions at play on SHR, their response to geologic and physical forcings and their impact of these combined processes on the overall carbon fluxes. It is clear now that the ecological system at SHR and other seep sites is highly dynamic and complex. At the same time, the ongoing discoveries of methane seepage along continental margins worldwide highlights the importance of fully constraining the biogeochemical impact of these systems to the global carbon budgets.

9.1 Key questions under this theme

I. What are the controls on the biological community structure and function at cold seeps in general and specifically at HR.

Portions of the biological communities at HR have been described previously, but many aspects of community structure and function are only partly understood. We need a comprehensive understanding of the community structure from the micro to macro scale (viruses, prokaryotes, protists, fungi, and metazoans) and its variability on spatial and temporal scales. Temporal scales can extend from diurnal (tidal), seasonal, to interannual/decadal variability. Spatial scales can vary from micrometers (individual cells and sediment particles) to meters (metazoan communities) to kilometers (seep fields).

- Can this be extrapolated over time at Hydrate Ridge?

- The community structure is temporally and spatially variable – what are the systematics controlling this change?
- How stable is the community with respect to geophysical and chemical changes, and how can we adequately measure these?
- How do communities evolve as the seep matures?
- How does the presence of authigenic minerals impact community structure and activity?

II. What is the fate of methane released from the seafloor, and the role of microbes as methane sinks?

Most of the observations suggest that the methane gas phase dissolves into the water column, and only gas released from shallow seeps makes it directly to the atmosphere. Whereas there are still questions on the physical processes that control the methane transport, here we focus on the biological coupling in particular.

- How much of the methane is consumed by organisms?
- What controls the organism response to presence of methane?
- What are the transport patterns of organisms in the water column?
- Is there transport of organisms via bubble transport?
- Is there any flow of seep carbon into the pelagic ecosystem?
- Is there a way to characterize the microbial community in the water column?
- What is the role of the variability in the water column at the point of dissolution on microbial response?

III. What are the biological controls of carbon cycling?

We have made significant advances in our understanding of the major pathways driving carbon cycling at seep sites, namely anaerobic oxidation of methane (AOM), methanogenesis, aerobic oxidation of methane (MOx), organoclastic sulfate reduction of organic carbon. However, significant questions still remain.

- What are the rates and relative importance of methanogenesis, AOM, aerobic MOx, and organoclastic sulfate reduction, and how may these change over time?
- What are the roles of other microbial carbon metabolisms?
- How do micro- and macro-faunal benthic communities alter carbon cycling?
- What are the controls, rates, mechanisms, and spatial relationships of microbially driven processes in the shallow subsurface?
- How does a seep impact biological communities and carbon cycling in distal ecosystems? Over what spatial scales do these impacts extend?
- What are the biogeochemical controls on the formation of authigenic minerals ($CaCO_3$).

9.2 Approaches

Several approaches, many of which require integration and coordination, are needed to unravel the complexity of interactions at play in a system as dynamic as that of SHR. A list of some proposed strategies:

1. Develop systematic comparison between seep and non-seep sites, to constrain processes that are endemic to seepage locations. This effort necessitates a full geochemical and biological characterization and understanding of the natural variability of the non-seep sites.
2. Site management. When designing an experiment it is crucial to consider the stability of the environment, as well as scale and monitoring of disturbances. Since any probing of the seafloor/subsurface would inevitable result on a disturbance of its ecosystem, it is critical to determine *a priori* what can be learned about the system by monitoring its response to the disturbances. A long-term record of the response would be valuable to constrain the stability of the environment and allow for predictions of its response to other natural or anthropogenic perturbations.
3. Integrated use of fluid flux meters (i.e. Mosquitos and CAT meters), cameras, and OsmoSamplers, electrodes and sensors to monitor natural variability at the seafloor in a wide range of scales that capture the full dynamics of the system. An advantage of the cabled observatory is that it allows for analyses of flux/sensor information with additional correlative data on the physics of the system.
4. Active perturbation experiments. These experiments will allow for rigorous and quantitative testing of current hypothesis of system response to chemical perturbations. Examples of such experiments include controlled methane injections to non-seep environments, and tracer and push-pull experiments in sediments.
5. Application of advanced vehicle technologies (ROV&AUV) as event response (seismic, hydrodynamic) monitoring and sampling. AUV's can maintain a continual presence at the site through a cabled docking station, and with hovering and repeat 3D surveying capabilities can document methane flux into the water column, quantification of bubble plume extent in space and time, and distribution of animal and bacterial mats over time.
6. Repeat photomosaic surveys, augmented with chirp sonar, that expand point camera data to the regional scale.
7. Correlative analyses of seismicity with structure and fluxes at seeps sites to validate the temporal connectivity to seafloor expression.
8. Ship-based measurements. Consider developing working groups to optimize utilization of ship time for collecting samples. There are important science questions that to date cannot be answered by the observatory alone, though future advances in technology may permit such measurements in situ. Discrete sampling may also be important for ground truth and calibration purposes.

9.3 Examples of technologies of that could be applied or need to be developed

Recognizing that some key measurements cannot be yet done *in situ* with available technologies, we encourage the development of sensors and taking advantage of the cabled facility as a platform for testing novel technologies. While geomicrobiology investigations are still largely based on the collection of samples, the next phase of probing the biosphere will involve the development of *in situ* biosensors and bio-assays (e.g. MBARI's Enviromental Sample Processor for identification of organisms and their gene products) that allow us to further understand the interrelationships between fluid transport of metabolites and community structure. A few examples of such technologies include:

- Chemical sensors (H_2S, CH_4, O_2, pH, turbidity, chlorophyll, physics), including microprofilers for lateral and vertical transects, distributions and fluxes.
- DNA and RNA sequencing to identify total and active portions of microbial communities, genomic potential, and gene expression.
- Image analysis for estimating fluxes of bubbles from active seeps.
- "Smart" sampling systems that can be triggered by specific environmental conditions/events.
- Application of fiber optical technology to monitor physical (e.g. temperature) and chemical (e.g. methane concentration, pH, specific molecules) variability in 3D and 4D.

10. Acknowledgements

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Mini-workshop Agenda

<u>FRIDAY MARCH 4TH, 2016</u>

08:15- 09:30 Joint Session

08:15-08:30 Welcome, summary of workshop objectives and logistics (Torres and Solomon)

08:30-08:45 Key points from previous workshops: 2007, 2015 (Torres)

8:45-09:00 GRC Summary: a short recap of ideas, concepts, challenges discussed during the GRC- (Solomon)

09:00-09:20 Brief review of SHR, infrastructure and sensors in place, how to access core data (Kelley)

09:20-09:40 Update on Neptune Canada, what is deployed, challenges to gas hydrate system observations, lessons learned (Scherwath, Thomsen)

09:40-10:00 How to expand observations at SHR, how to design and implement new sensors (Manalang)

10:00-10:20 Showcase of technologies (~5-10 minutes each, Ussler, Solomon)

10:20-10:30 Discussion

10:30-10:45 Coffee Break

1045-1200 Breakout session 1
Questions:

1. What is known, what are the exciting new results?
2. What is unknown, what are the key outstanding/exciting questions?
3. How can these questions be addressed with the SHR observatory?
4. What additional sensors are required to address these questions?
5. What new technologies need to be developed?
6. What are the challenges?

<u>Breakout Group 1:</u> Gas hydrate system dynamics (Bangs and Dugan)

Subtopics – mechanisms for gas and fluid transfer from subsurface to seafloor, how to expand observatory to understand subduction zone processes

<u>Breakout Group 2:</u> Microbial activities and dynamics associated with variations in biogeochemical fluxes and gradients (Treude and Thurber)

Subtopic – magnitude and variability in the flux of carbon to the water column from seeps

12:00-13:00 Lunch

13:00-14:00 Joint Session
Leaders of breakout session 1 present ideas, strategies, and perceived challenges, followed by discussion.

14:00-15:30 Breakout Session 2-

Define integrated experiments and sensors/technologies/approaches needed. Both groups will be discussing this topic, to generate ideas for experiments to use the facility. People switch around so that the same people are not in the same group they were in for the morning breakout session and to have more of an interdisciplinary view.

Questions:

1. Based on the science questions/challenges discussed above, select a few (3-4) topics you think can be addressed with monitoring strategies?
2. For each, state how an interdisciplinary (geophysical, hydrogeological, chemical, biological) approach can benefit from simultaneous acquisition of correlative data?
3. What measurements are needed, which instruments are cabled-based, which are complemented by expedition-based measurements?
4. Requirements for shiptime/ROV/ access to cable facility?

Breakout Group 1: Integrated experiments (M. Riedel and J. Johnson)

Breakout Group 2: Integrated experiments (Collier and Sahling)

15:30-16:00 Coffee Break

16:00-17:30 Joint Session

Discussion of ideas from breakout groups with summary of strategies, plans, approaches

SATURDAY MARCH 5TH, 2016

Steering Committee – writing report outlining integrated priorities, strategies, perceived challenges, and proposal guidance

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