

Earth and Space Science



TECHNICAL REPORTS: DATA

10.1029/2019EA000762

Key Points:

- Ocean Networks Canada provides continuous ocean observatory data from northern Cascadia gas hydrate sites since 2009
- Examples from the research output show the advantages and relevance of such data for the advancement of science
- Continuing these marine observations for decades plus open data access yields strong future potential for the science community

Correspondence to:

M. Scherwath,
mscherwa@uvic.ca

Citation:

Scherwath, M., Thomsen, L., Riedel, M., Römer, M., Chatzievangelou, D., Schwendner, J., Duda, A., & Heesemann, M. (2019). Ocean observatories as a tool to advance gas hydrate research. *Earth and Space Science*, 6. <https://doi.org/10.1029/2019EA000762>

Received 25 JUN 2019

Accepted 1 OCT 2019

Accepted article online 24 OCT 2019

Ocean Observatories as a Tool to Advance Gas Hydrate Research

M. Scherwath¹ , L. Thomsen², M. Riedel³ , M. Römer⁴ , D. Chatzievangelou² , J. Schwendner^{5,6}, A. Duda^{5,6}, and M. Heesemann¹

¹Ocean Networks Canada, University of Victoria, British Columbia, Canada, ²Department of Physics and Earth Science, Jacobs University Bremen, Bremen, Germany, ³GEOMAR Helmholtz Centre for Ocean Research Kiel, Kiel, Germany, ⁴MARUM Center for Marine Environmental Sciences, University of Bremen, Bremen, Germany, ⁵German Research Center for Artificial Intelligence, DFKI Bremen, Bremen, Germany, ⁶Now at Kraken Robotik GmbH, Bremen, Germany

Abstract Since 2009, unprecedented comprehensive long-term gas hydrate observations have become available from Ocean Networks Canada's NEPTUNE cabled ocean observatory at the northern Cascadia margin. Several experiments demonstrate the scientific importance of permanent power and Internet connectivity to the ocean floor as they have advanced the field of gas hydrate related research. One example is the cabled crawler Wally at Barkley Canyon, enabling live in situ exploration of the hydrate mounds and its associated benthic communities through the crawler's mobility and permanent accessibility throughout the year. Another example is a bubble-imaging sonar at Clayoquot Slope, revealing the strong relationship between ebullition of natural gas and tidal pressure, without apparent correlation to earthquakes, storms, or temperature fluctuations, in year-long continuous recordings. Finally, regular observatory maintenance cruises allow additional science sampling including echo-sounder surveys to extend the observatory footprint. Long-term trends in the data are not yet apparent but can also become evident from continuous measurements, as ocean observatories such as NEPTUNE are built for a 25-year lifetime, and expansion of the observatory networks makes these findings comparable and testable.

Plain Language Summary Natural gas near the ocean floor creates a rapidly changing environment where it is important to collect data continuously in order to determine the magnitude, speed, and potential mechanism of change. This long-standing challenge of year-round access to the deep ocean has been tackled by Ocean Networks Canada through cabling the northern Cascadia seafloor, providing power and Internet communication—ideal for power-hungry instruments, large data volumes, and real-time access. The presence of gas influences the shape of the seafloor, animal activity, and potential escape of methane, a potent greenhouse gas. A seafloor crawler Wally was operated around deep canyon mounds of gas hydrate (a solid gas-water composite) since 2009 and helped discover environmental changes influencing sea life. Further along the continental slope, an acoustic sonar monitored rising methane bubbles where the bubbling appears to be controlled neither by earthquakes, winter storms, nor subtle temperature changes but actually strongly by tidal pressure. Regular maintenance of the observatory by ship allows more data to be collected near the cabled seafloor sites, extending the observations to a larger area. Ocean observatories are built to last decades and therefore more data for more research can be collected, potentially detecting relatively slow processes as well.

1. Introduction

Gas hydrate systems are dynamic environments with potential long-term variations that require continuous long-term observations to fully understand the complete spectrum of these systems (e.g., Berndt et al., 2014; Heeschen et al., 2003; Suess et al., 2001). Seasonal repeat measurements through research expeditions have been the traditional means for detecting any changes to the gas hydrate systems; however, revisiting sites has always been competing with exploring new areas, and even if environmental changes were detected, the speed at which these changes occurred as well as the dynamic range of these changes remained unknown (Krüger et al., 2005). Permanent seafloor observatories can fill these important gaps in the time series offshore, and the most advantageous way to continuously monitor the seafloor is live with high power and high data bandwidth, facilitating the broadest range of experiments and allowing to manipulate the experiments

©2019. The Authors.

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

to optimize the recording parameters in reaction to any events (Barnes et al., 2011; Favali et al., 2015). Canada is operating cabled observatories since 2006, is providing direct access to, and serves continuous data from two highly active gas hydrate systems on the northern Cascadia margin since 2009, thus enabling the science community to begin to understand these dynamic changes in ways not seen before (Barnes et al., 2011; Heesemann et al., 2014).

2. Cascadia Margin and its Gas Hydrate Research Seafloor Infrastructure

The Cascadia margin has been known for the occurrence of gas hydrate from seismic bottom simulating reflectors that indicate where free gas accumulates below the gas hydrate stability zone, a spectacular finding in the form of a recovered large block of gas hydrate from a fishing trawler, and was subject to intensive scientific drilling campaigns (Riedel et al., 2009; Spence et al., 2001). Furthermore, large quantities of free gas escape the seafloor as seen on ships' echo-sounding data, indicating the abundance of natural gas necessary for the formation of gas hydrates (Riedel et al., 2018).

Ocean Networks Canada (ONC) operates the cabled NEPTUNE observatory (Figure 1) with two nodes at gas hydrates sites, Barkley Canyon, where hydrate mounds, exposed hydrate, and thermogenic methane occur, and Clayoquot Slope, about 50 km further northwest, with abundant gas venting in an area of predicted large fluid flow from the accretionary prism of the Cascadia subduction zone (Heesemann et al., 2014).

Table 1 summarizes the instrumentation of both NEPTUNE hydrate sites. Some of these are experiments funded by the original network construction proposal, and some have been added later for externally funded projects. The seafloor instrument platforms or junction boxes are flexible in their use, and ONC is open for other externally funded projects to expand or replace the existing monitoring configuration.

ONC is the scientific facility behind these experiments and undertakes the installation and maintenance of the network as well as the data management and archiving. ONC was established in 2007 as a major initiative of the University of Victoria, assuming the operation and maintenance of world-leading ocean observatories for the advancement of science and the benefit of Canada. ONC's data policy is to have all the data openly accessible for free to the science community through the ONC data portal Oceans 2.0 with various options to search for, plot, annotate and download data, watch videos from observatory cameras and remotely operated vehicles (ROVs), or integrate an automatic data access tool in the form of an Application Programming Interface including web services (<http://www.oceannetworks.ca/data-tools>). As of summer 2019, the underlying data archive contained 900 Tb of data with roughly 50 Tb of uncompressed data added every quarter, from overall 700+ instruments with 8,000+ sensors connected. The data portal at <https://data.oceannetworks.ca> has about 30,000 registered users, and in fiscal year 2018–2019, an estimated 17,500 anonymous and registered users viewed or accessed data from the archive.

Since 2015, the U.S. Ocean Observatories Initiative's Cabled Array offshore Oregon also carries out complementary gas hydrate related observations at Southern Hydrate Ridge, enabling comparison studies between three gas hydrate regimes at the Cascadia Margin (Delaney & Kelley, 2015).

3. Scientific Advances on Gas Hydrates From the Cabled Observatory

3.1. Seafloor Crawler Wally at Barkley Canyon

A deep-sea crawler has been developed as a universal mobile sensor system, affectionally named Wally, and is the world's first Internet-Operated Vehicle (Thomsen et al., 2015). It has been remotely operated at the Barkley Canyon hydrates site since 2009 predominantly by the Principal Investigators in Germany. It uses caterpillar tracks for motion and is driven by sight along a set of markers lining the way around hydrate mounds. Additional developments through the German program ROBEX (ROBotic Exploration of eXtreme environments, 2012–2017) brought improvements for autonomous operation and additional manipulators (Thomsen et al., 2015). Its greatest advantage is the mobility via tele-operations and thus to regularly visit different sites to observe floral and faunal changes or manipulative experiments (Aguzzi et al., 2015; Purser et al., 2013).

3.1.1. Ocean Circulation Promoting Methane Release

The crawler Wally was used to investigate the importance of oscillatory deep ocean currents on methane release in Barkley Canyon (Thomsen et al., 2012). The results show that periods of enhanced bottom

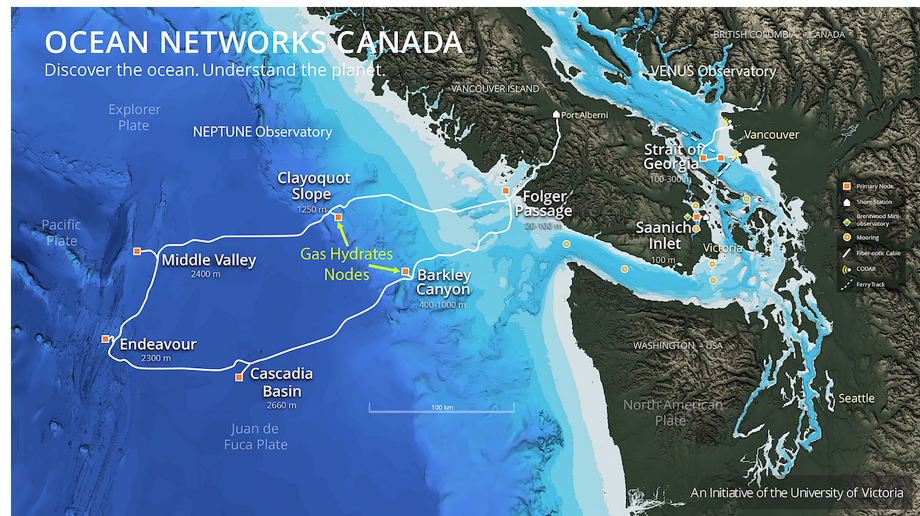


Figure 1. Ocean Networks Canada's cabled west coast observatories with the two gas hydrate nodes: At Clayoquot slope and Barkley canyon.

currents associated with diurnal shelf waves, internal semidiurnal tides, and also wind-generated near-inertial motions could modulate methane seepage. Enhanced bottom currents were sufficient enough to erode gas hydrates within the hydrate stability field when these were not covered by either seafloor biota or sediments. The calculated seepage varied between 40 and 400 mol CH₄/m⁻²/s⁻¹ that was 1–3 orders of magnitude higher than dissolution rates of buried hydrates through permeable sediments and well within the experimentally derived range for exposed gas hydrates under different hydrodynamic boundary conditions (Thomsen et al., 2012). The study concludes that submarine canyons that display high hydrodynamic activity can become key areas of enhanced seepage as a result of emerging weather patterns due to climate change.

3.1.2. High-Frequency Patterns of Species Abundance

Due to the 890-m depth of the Barkley Canyon hydrates site, the periodical element of the benthic community activity is not expected to be directly linked to the day-night sunlight cycle. Different oceanographic parameters can trigger populational behavior and shape it into diel (~24-h-based) patterns (Aguzzi et al., 2010; Doya et al., 2014; Wagner et al., 2007). In order to detect such activity patterns and identify which

Table 1
Summary of ONC Gas Hydrate Sites' Instrumentation

Location (depth)	Installation	Description
Barkley Canyon (890 m)	Seafloor crawler Wally	World's first Internet-Operated Vehicle (IOV) with multiple sensor packages including camera, Conductivity Temperature Depth (CTD) sensor, current meter, methane sensor, fluorometer, turbidity meter; more details in main text below
	Two 675 kHz imaging rotary sonars	Sonars are scanning at 100-m radius across <i>Wallyland's</i> hydrate mounds and potential gas flares and are able to track Wally.
Clayoquot Slope (1,250 m)	Environmental sensors	Temperature, salinity, pressure, oxygen, and currents
	ACORK	Advanced Circulation Obviation Retrofit Kit (ACORK) at hole U1364A since 2010, down to 300-m depth below seafloor, with temperature, pressure, bottom-hole seismometer, and tiltmeter
	SCIMPI	Simple Cable Instrument for Measuring Properties In situ (SCIMPI) at hole U1416A, down to 240-m depth below seafloor, with temperature, pressure, and resistivity sensors; running autonomously with regular data downloads
	260-kHz rotating multibeam sonar	Sonar is scanning for gas bubbles at 100-m radius; described in more detail below.
	Broadband seismometer	With a differential pressure gauge, potential for seafloor compliance
	Tiltmeter	At seafloor
	CSEM	Partially working controlled-source electromagnetics (CSEM) experiment that was discontinued in 2013
	Environmental sensors	Temperature, salinity, pressure, oxygen, and currents

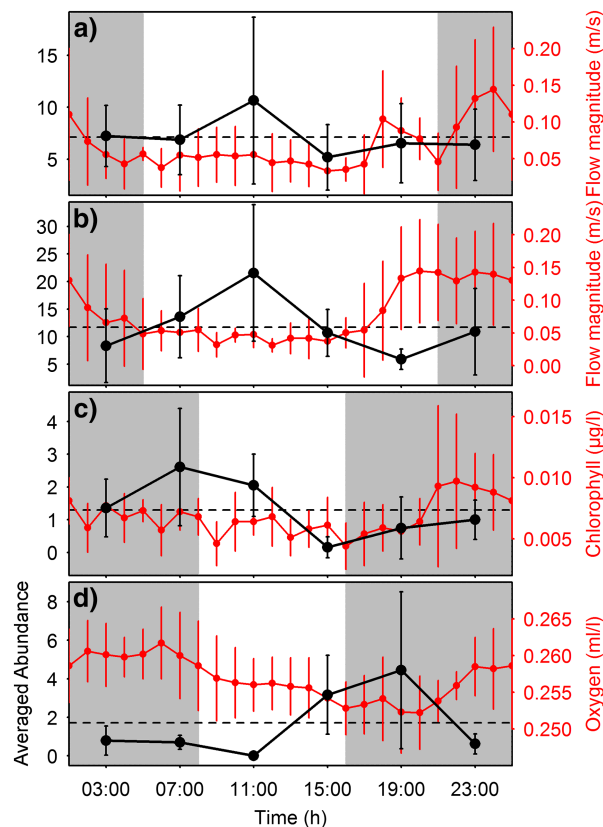


Figure 2. Waveforms of animal abundances (black, 4-h sampling frequency) as the average (\pm SD) of the 5-day sampling period, superimposed on environmental parameter waveforms (red, hourly). *Anoplopoma fimbria* in (a) June and (b) July, (c) *Eptatretus stoutii* in December, and finally, (d) juvenile crabs in December 2013. The dashed horizontal lines correspond to the midline estimating statistic of rhythm (MESOR) (Aguzzi et al., 2006). Shaded parts represent the approximate night duration at the time of the study. X axis values correspond to local time (PST; modified after Chatzievangelou et al., 2016).

parameters condition them, linear, back and forth video transects (~ 20 m) were performed in June, July, and December 2013, at a 4-h frequency for five consecutive days during each month (Figure 2, Chatzievangelou et al., 2016).

Periodic fluctuations in visual counts of the most abundant megafaunal species (i.e., sablefish *Anoplopoma fimbria*; Pacific hagfish *Eptatretus stoutii*, and a group of juvenile crabs) confirmed the existence of diel rhythmic activity controlled by oceanographic parameters. Sablefish (i.e., swimmers) were present during low current velocities, possibly applying an energy saving strategy in the hypoxic waters of the hydrates site. Hagfish responded to fluctuations in chlorophyll concentration, indicating a use of phytodetritus as an alternative food source. Finally, crabs emerged during dissolved oxygen minimums, possibly suppressing a general cryptic behavior in order to fight transient hypoxia (Figure 2, Chatzievangelou et al., 2016).

Wally's characteristics offer a series of advantages over more traditional sampling methods when it comes to in situ chronobiological studies in the deep sea. Long-term, 24/7, multiparametric oceanographic data acquisition and visual monitoring capabilities increase scientific accuracy and cost efficiency. In comparison to fixed camera imaging, greater spatial coverage can be achieved by the crawler, balancing the counts of slow-moving species. Operational autonomy in a new generation of crawlers will provide data sets over longer periods of time than short ROV surveys. Finally, its nonextractive nature gives this platform an edge over trawling.

3.1.3. High-Resolution Structural Seafloor Imaging

The primary instrument for the observation of Wally's area of coverage has traditionally been video cameras. They allow the qualitative assessment of structure and shape of the seafloor. Three parallel laser lines could be used for sizing. In 2016, a new instrument was deployed on Wally, which combines a smart camera system, line laser, and lighting on a pan-tilt unit (PTU), to generate 3D scans of the environment. The laser line and

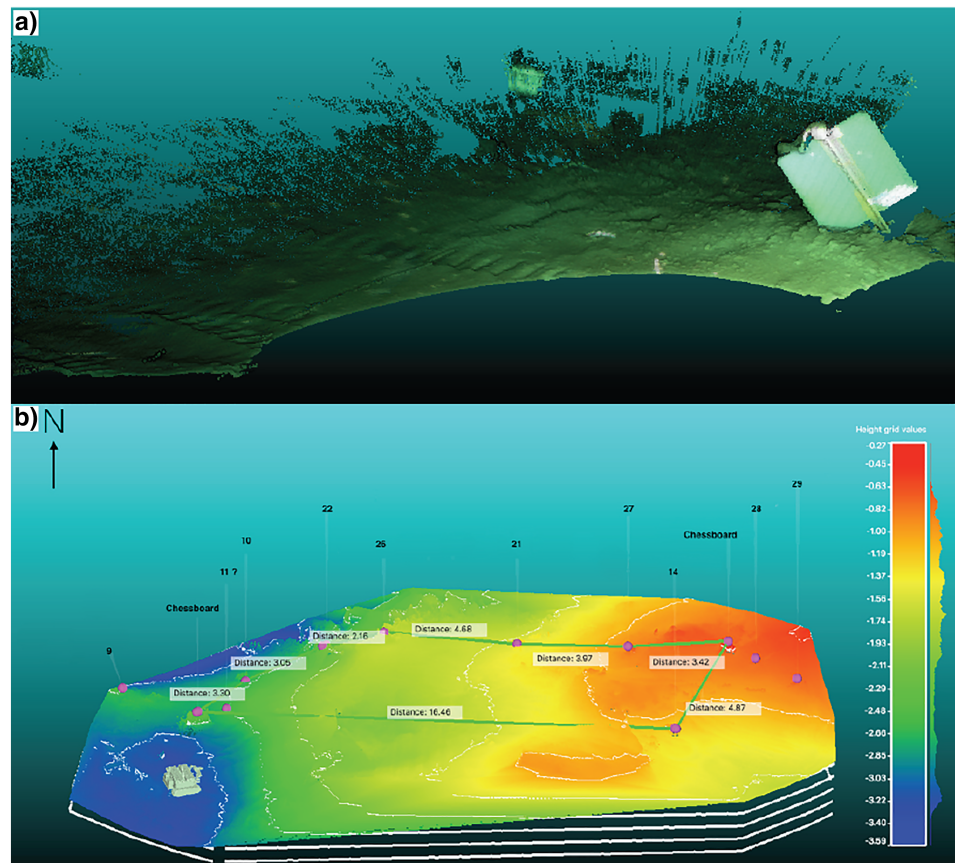


Figure 3. Precise seafloor mapping using line lasers, high-resolution camera, and PTU. (a) Single scan taken by the 3D camera system; the resulting point cloud data can be used for precise measurements of scale. (b) Map of the eastern region of Wally's operational area; bottom left shows a to-scale model of the Wally system; the map has been generated from 24 individual scans with the 3D laser camera; the resulting data can be used for navigation and tracking of changes in morphology of the terrain. PTU = pan-tilt unit.

the camera have a known relative position to each other. This can be used to accurately calculate the distance for each pixel of the projected laser in the camera image (Duda et al., 2015). By moving the PTU, the laser is swept over the scene and generates dense point clouds with high accuracy (Figure 3(a)).

A seafloor crawler is particularly suited for the recording of such point clouds: Unlike flying ROV systems, Wally has the ability to hold a static position for the duration of the scan. Each point cloud that is generated can cover a radius of around 5–7 m of terrain at a 180° radius in front of the crawler. Multiple scans can be combined through a process called registration. In this way, larger maps of the surrounding can be generated with a very high resolution and color mapping (Figure 3(b)).

The registration process can—in structured terrain—be used to perform relative localization to a known map. This is especially useful in application scenarios like cabled observatories, where the system remains in one dedicated area. The continuous generation of scans over time provides the ability to track changes in the shape of the surrounding, which is particularly interesting in areas of active gas hydrates.

3.2. Vent Imaging at Clayoquot Slope

Clayoquot Slope (Figure 1) is a region of abundant fluid fluxes with many observed gas vents around this ONC node. Early gas hydrate studies have focused around the seismic anomaly Bullseye Vent that has been subject to several ocean drilling campaigns (Riedel et al., 2009). The area's many highly active gas emissions make it an optimal site for continuous sonar monitoring of bubbles escaping the seafloor, and since 2010 a 260-kHz, 100-m range multibeam sonar has been scanning the bottom water and seafloor, although good quality records are only available since 2012 first from a site near Bubble Gulch and since 2014 from a site called Gastown Alley (Römer et al., 2016).

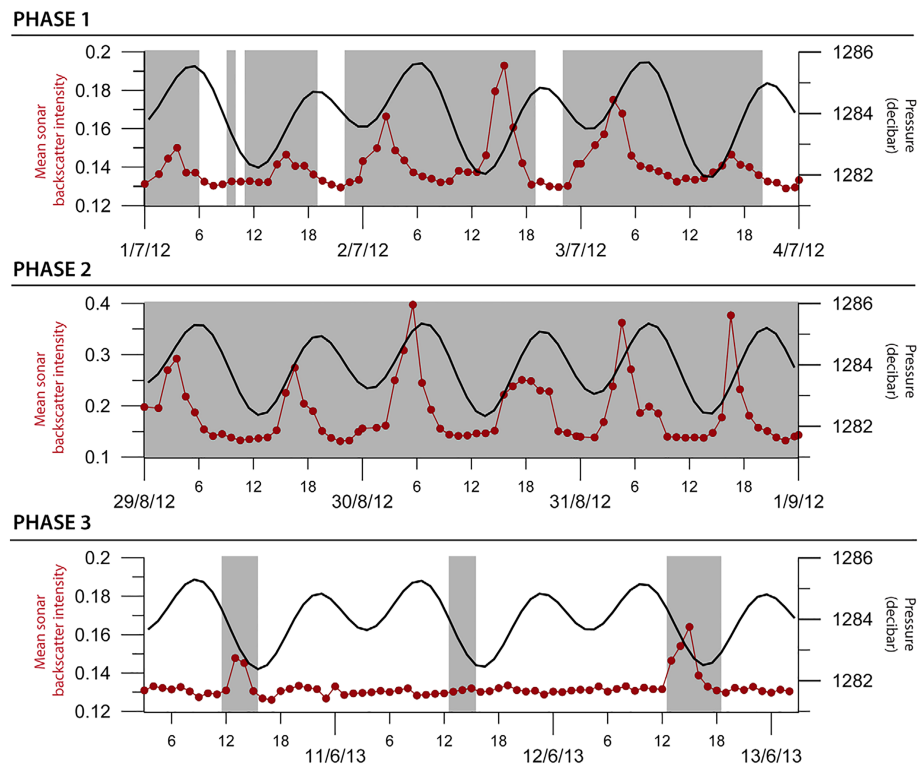


Figure 4. Examples of three days for each activity phase (1) intermittent, (2) mostly continuous, and (3) of short activity, with gray bars indicating the presence of gas bubbles, showing the relationship between mean sonar backscatter intensity (red) with the tidal pressure curve (black line), with a typical negative correlation with the tidal cycle (modified after Römer et al., 2016).

In addition to continuous monitoring of a single emission site, a significantly larger footprint of gas vent observations can be made during annual observatory maintenance cruises as well as other regular research expeditions. Combining the results from permanent 24/7 observations of the single site with data of opportunity along the margin then allows us to extrapolate the knowledge from this individual site to make margin-wide estimates of gas fluxes (Riedel et al., 2018).

3.2.1. Tidally Controlled Gas Bubble Emissions

Hourly sonar observations of gas emissions near Bubbly Gulch from 2012 to 2013 reveal the temporal variability and determine the controlling factors behind cold seep activity (Römer et al., 2016). This was correlated with conductivity, temperature, pressure, currents, and ground shaking. A clear correlation of gas emission with bottom pressure changes controlled by tides was found, whereas other oceanographic conditions or earthquake activity were not found to explain the observed gas activity (Römer et al., 2016).

In addition to the tidal control, there also appeared to be an overarching periodicity of the seafloor gas activity in the form of three different, months-long phases of bubble emissions: (1) alternating activity and inactivity of up to several days each, (2) a period of several weeks of permanent activity with short breaks, and (3) short activity phases of few hours lasting several months; examples are shown in Figure 4 (Römer et al., 2016).

During times of interrupted gas emission activity in a tidal cycle, exsolution of gas during falling tides is observed, where tidally induced pressure changes influence the sub-bottom fluid system by shifting the methane solubility. These pressure changes affect the equilibrium of forces allowing free gas in sediments to emanate into the water column at decreased hydrostatic load. During periods of very high or permanent activity, a constant supply of methane must be present in the shallow subsurface where temporarily an increase in gas emission during low but increasing pressure is observed, without completely depleting the reservoir (Römer et al., 2016). In 2014, the sonar was relocated to an area of constant activity, exhibiting the same pattern, but an exhaustive analysis of the data has yet to occur.

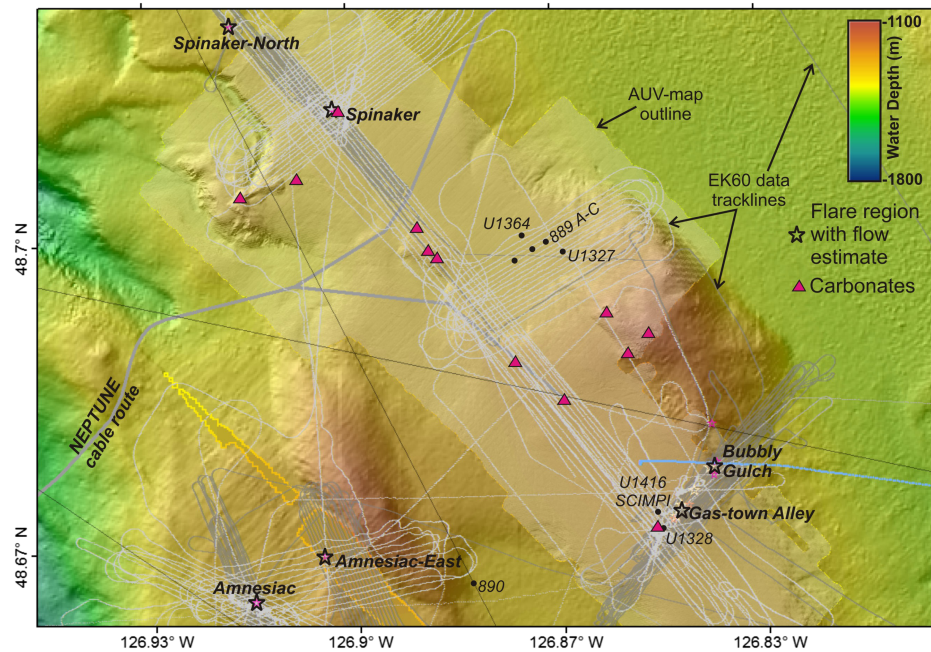


Figure 5. Map of known vent locations near Clayoquot slope, where gas flow estimates can be obtained from ship-based split-beam multifrequency echo-sounder data, together with NEPTUNE sites, research expedition's footprint, and carbonates indicating potential old vent sites.

3.2.2. Repeat Observations of Natural Gas Vent Fields

Regional observations of gas vents during ship expeditions exhibit a large distribution of bubble emission sites near the Clayoquot Slope node, as shown in Figure 5. These vent sites have been mapped since the early 2000s with research cruises by the Geological Survey of Canada's Pacific Geoscience Centre, the Monterey Bay Aquarium Research Institute, the U.S. National Oceanic and Atmospheric Administration, and ONC. A margin-wide analysis of all available echo-sounding data has been carried out, including the estimation of flux rates (Riedel et al., 2018). Mapping with a ship-based split-beam 18- to 720-kHz multifrequency echo sounder over one vent region (e.g., Gastown Alley) throughout a tidal cycle shows flux variations similar to those described above from the continuous multibeam sonar data. However, ship-based echo sounding is limited by the amount of ship time necessary to identifying phases in gas flux variations, and furthermore, the ship data could also be compromised by ship motion and weather state. Therefore, it is essential to include the long-term observatory results (see above) to quantifying absolute flux rate estimates as much as it is necessary to extend the ocean observatory footprint with research expeditions to extrapolate single-point results.

3.3. Monitoring Processes Below the Seafloor

Besides observing seafloor and water column, cabled observatories can also provide a link to below the seafloor. ONC has placed its Clayoquot Slope node at the target area for ocean drilling to study gas hydrate systems that naturally was subject to structural imaging through seismic and electromagnetic methods and led to the installation of seabed monitoring experiments.

3.3.1. Instrumented Boreholes

Three drilling campaigns instrumented boreholes at Clayoquot Slope: in 1992, hole 889C from ODP Leg 146 (Westbrook et al., 1994) for autonomous temperature and pressure logging, sealed by a Circulation Obviation Retrofit Kit, but ultimately leaking through unstable sediment intrusion from below; in 2010, hole 1364A from International Ocean Discovery Program Expedition 328 (Davis et al., 2012), an Advanced Circulation Obviation Retrofit Kit initially instrumented with pressure and temperature, since 2017 cabled and equipped with additional temperature sensors as well as a bottom-hole seismometer and a tiltmeter primarily for subduction monitoring (McGuire et al., 2018) but usable for hydrate system research; in 2013, hole 1416A from International Ocean Discovery Program Expedition 341S with an autonomous Simple Cabled

Instrument for Measuring Parameters In situ measuring pressure, temperature, and resistivity, in an open but self-collapsing hole surrounded by active venting, producing interesting but not trivially interpretable data, and regularly visited by ONC (Insua et al., 2014).

3.3.2. Seafloor Compliance and Electromagnetics

Gas hydrates in the seabed influence the seabed stiffness and also its electrical resistivity. Seafloor compliance is a measure of the seabed stiffness and describes the deformation of the seafloor through infragravity waves, and correlation of the broadband seismometer data with seafloor pressure data inferred an increase in hydrate content by up to 13% over 203 days (Roach & Edwards, 2015). The same location did not experience any changes in seafloor resistivity from a controlled-source electromagnetic (CSEM) experiment at least in the shallow part that was monitored on the ONC network by a CSEM system where only the nearest of five receivers returned any meaningful results (Gehrmann et al., 2012).

4. Conclusions

Examples of cabled ocean observatory gas hydrate studies were enabled by ONC at the NEPTUNE hydrate nodes at Barkley Canyon and Clayoquot Slope, exhibiting not only the advantages of having permanent high power and direct access through the Internet to the seafloor but also, moreover, some key results that could not have otherwise been obtained. Wally the seafloor crawler at the Barkley Canyon hydrate mounds is operated in real time from Europe and has acquired a time series necessary to identify the relationship between methane concentrations and ocean circulations as well as species abundance and multiparametric oceanographic data. Permanent gas bubble emission observations at Clayoquot Slope correlate well with ocean tides and exhibit various phases of venting activity, and we demonstrate the potential to extrapolate these results to temporal observations from ship-based surveys around the same area, expanding the observatory footprint. A large amount of unstudied data is still available at ONC through the Oceans 2.0 data portal to the research community to extend this research, and ONC is open for other externally funded projects to expand or replace the existing monitoring configuration.

Acknowledgments

We thank the Editor Paolo Diviacco and two anonymous reviewers for their help and constructive feedback. Ocean Networks Canada is an initiative of the University of Victoria and has primarily been funded by the Canadian Foundation for Innovation, Transport Canada, Fisheries and Oceans Canada, and the Canadian Province of British Columbia. The seafloor crawler Wally has been funded by Jacobs University and the German Helmholtz Alliance *Robotic Exploration of Extreme Environments—ROBEX*. Analysis of the bubble-imaging sonar was funded through the DFG-Research Center/Cluster of Excellence *The Ocean in the Earth System*. All seafloor data are available at <https://data.oceannetworks.ca>, which is a verified DataCite repository (<https://repositoryfinder.datacite.org/>). Ship-based echosounding data were acquired by the Geological Survey of Canada's Pacific Geoscience Centre (PGC), the Monterey Bay Aquarium Research Institute (MBARI), the U.S. National Oceanic and Atmospheric Administration (NOAA), and the Ocean Networks Canada, and details and links to the data sources and the corresponding vent locations are available in Riedel et al. (2018) at <https://doi.org/10.1038/s41467-018-05736-x>.

References

- Aguzzi, J., Bullock, N. M., & Tosini, G. (2006). Spontaneous internal desynchronization of locomotor activity and body temperature rhythms from plasma melatonin rhythm in rats exposed to constant dim light. *Journal of Circadian Rhythms*, 4, 6. <https://doi.org/10.1186/1740-3391-4-6>
- Aguzzi, J., Costa, C., Furushima, Y., Chiesa, J. J., Company, J. B., Menesatti, P., et al. (2010). Behavioral rhythms of hydrocarbon seep fauna in relation to internal tides. *Marine Ecology Progress Series*, 418, 47–56. <https://doi.org/10.3354/meps08835>
- Aguzzi, J., Doya, C., Tecchio, S., de Leo, F. C., Azzurro, E., Costa, C., et al. (2015). Coastal observatories for monitoring of fish behaviour and their responses to environmental changes. *Reviews in Fish Biology and Fisheries*, 25(3), 463–483. <https://doi.org/10.1007/s11160-015-9387-9>
- Barnes, C. R., Best, M. M. R., Johnson, F. R., Pautet, L., & Pirenne, B. (2011). Understanding earth/ocean processes using real-time data from NEPTUNE Canada's widely distributed sensor networks, north-East Pacific. *Geoscience Canada*, 38(1), 21–30.
- Berndt, C., Feseker, T., Treude, T., Krastel, S., Liebetrau, V., Niemann, H., et al. (2014). Temporal constraints on hydrate-controlled methane seepage off Svalbard. *Science*, 343(6168), 284–287. <https://doi.org/10.1126/science.1246298>
- Chatzievangelou, D., Doya, C., Thomsen, L., Purser, A., & Aguzzi, J. (2016). High-frequency patterns in the abundance of benthic species near a cold-seep—An internet operated vehicle application. *PLoS ONE*, 11(10), e0163808. <https://doi.org/10.1371/journal.pone.0163808>
- Davis, E. E., Heesemann, M., & the IODP Expedition 328 Scientists and Engineers (2012). IODP expedition 328: Early results of Cascadia subduction zone ACORK observatory. *Science Reports*, 13, 12–18. <https://doi.org/10.2204/iodp.sd.13.02.2011>
- Delaney, J. R., & Kelley, D. S. (2015). Next-generation science in the ocean basins: Expanding the oceanographer's toolbox utilizing submarine electro-optical sensor networks. In P. Favali, L. Beranzoli, & A. de Santis (Eds.), *Seafloor Observatories: A New Vision of the Earth from the Abyss* (pp. 465–502). Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-642-11374-1_18
- Doya, C., Aguzzi, J., Pardo, M., Matabos, M., Company, J. B., Costa, C., et al. (2014). Diel behavioral rhythms in sablefish (*Anoplopoma fimbria*) and other benthic species as recorded by the deep-sea cabled observatories in Barkley canyon (NEPTUNE-Canada). *Journal of Marine Systems*, 130, 69–78. <https://doi.org/10.1016/j.jmarsys.2013.04.003>
- Duda, A., Schwendner, J., & Gaudig, C. (2015). SRSL: Monocular self-referenced line structured light, in: 2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), 717–722, IEEE. <https://doi.org/10.1109/IROS.2015.7353451>
- Favali, P., Beranzoli, L., & De Santis, A. (2015). *Seafloor Observatories: A New Vision of the Earth from the Abyss*. Springer, Berlin, Heidelberg: Springer-Praxis Books. <https://doi.org/10.1007/978-3-642-11374-1>
- Gehrmann, R., Schwalenberg, K., Riedel, M., Dosso, S. E., Mir, R. A., & Edwards, R. N. (2012). Controlled source electromagnetic study on the response of cold vent sites and gas hydrate occurrences on the northern Cascadia margin, American Geophysical Union fall meeting, San Francisco, USA, 3-7 Dec. 2012.
- Heeschen, K. U., Tréhu, A. M., Collier, R. W., Suess, E., & Rehder, G. (2003). Distribution and height of methane bubble plumes on the Cascadia Margin characterized by acoustic imaging. *Geophysical Research Letters*, 30(12), 1643. <https://doi.org/10.1029/2003GL016974>
- Heesemann, M., Insua, T. L., Scherwath, M., Juniper, S. K., & Moran, K. (2014). Ocean networks Canada from geohazards research laboratories to smart ocean systems. *Oceanography*, 27(2), 151–153. <https://doi.org/10.5670/oceanog.2014.50>

- Insua, T. L., Moran, K., Kulin, I., Farrington, S., Riedel, M., Scherwath, M., et al. (2014). One year of data of SCIMPI borehole measurements, American Geophysical Union fall meeting, San Francisco, USA, 15-19 Dec. 2014.
- Krüger, M., Treude, T., Wolters, H., Nauhaus, K., & Boetius, A. (2005). Microbial methane turnover in different marine habitats. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 227(1-3), 6-17. <https://doi.org/10.1016/j.palaeo.2005.04.031>
- McGuire, J. J., Collins, J. A., Davis, E. E., Becker, K., & Heesemann, M. (2018). A lack of dynamic triggering of slow slip and tremor indicates that the shallow Cascadia megathrust offshore Vancouver Island is likely locked. *Geophysical Research Letters*, 45, 11,095-11,103. <https://doi.org/10.1029/2018GL079519>
- Purser, A., Thomsen, L., Barnes, C., Best, M., Chapman, R., Hofbauer, M., et al. (2013). Temporal and spatial benthic data collection via internet operated Deep Sea crawler. *Methods in Oceanography*, 5, 1-18. <https://doi.org/10.1016/j.mio.2013.07.001>
- Riedel, M., Scherwath, M., Römer, M., Veloso, M., Heesemann, M., & Spence, G. D. (2018). Distributed natural gas venting offshore along the Cascadia margin. *Nature Communications*, 9(1), 3264. <https://doi.org/10.1038/s41467-018-05736-x>
- Riedel, M., Willoughby, E. C., Edwards, N., Hyndman, R. D., Spence, G. D., Chapman, N. R., et al. (2009). Gas hydrate offshore Vancouver Island, northern Cascadia margin. In T. Collett, A. Johnson, C. Knapp, & R. Boswell (Eds.), *Natural Gas Hydrates - Energy Resource Potential and Associated Geologic Hazards*, AAPG Memoir (Vol. 89, pp. 433-450). Tulsa, OK: American Association of Petroleum Geologists (AAPG). <https://doi.org/10.1306/13201156M893353>
- Roach, L. A. N., & Edwards, R. N. (2015). A temporal trend in compliance measurements near a gas hydrate accumulation, northern Cascadia. *Geophysics*, 80(5), EN119-EN126. <https://doi.org/10.1190/geo2014-0531.1>
- Römer, M., Riedel, M., Scherwath, M., Heesemann, M., & Spence, G. D. (2016). Tidally controlled gas bubble emissions: A comprehensive study using long-term monitoring data from the NEPTUNE cabled observatory offshore Vancouver Island. *Geochemistry, Geophysics, Geosystems*, 17, 3797-3814. <https://doi.org/10.1002/2016GC006528>
- Spence, G. D., Chapman, N. R., Hyndman, R. D., & Cleary, C. (2001). Fishing trawler nets massive 'catch' of methane hydrates. *Eos*, 82, 621-627. <https://doi.org/10.1029/01EO00358>
- Suess, E., Torres, M. E., Bohrmann, G., Collier, R. W., Rickert, D., Goldfinger, C., et al. (2001). Sea floor methane hydrates at Hydrate Ridge, Cascadia Margin. In C. K. Paull & W. P. Dillon (Eds.), *Natural gas hydrates: Occurrence, distribution, and detection*, Geophysical Monograph 124 (pp. 87-98). Washington, DC: American Geophysical Union. <https://doi.org/10.1029/GM124p0087>
- Thomsen, L., Barnes, C., Best, M., Chapman, R., Pirenne, B., Thomson, R., & Vogt, J. (2012). Ocean circulation promotes methane release from gas hydrate outcrops at the NEPTUNE Canada Barkley canyon node. *Geophysical Research Letters*, 39, L16605. <https://doi.org/10.1029/2012GL052462>
- Thomsen, L., Purser, A., Schwendner, J., Duda, A., Flögel, S., Kwasnitschka, T., et al. (2015). Temporal and spatial benthic data collection via mobile robots: Present and future applications, OCEANS 2015 - Genova, Genoa, IEEE. <https://doi.org/10.1109/OCEANS-Genova.2015.7271596>
- Wagner, H. J., Kemp, K., Mattheus, U., & Priede, I. G. (2007). Rhythms at the bottom of the deep sea: Cyclic current flow changes and melatonin patterns in two species of demersal fish. *Deep-Sea Research Part I*, 54, 1944-1956. <https://doi.org/10.1016/j.dsr.2007.08.005>
- Westbrook, G. K., Carson, B., Musgrave, R. J., et al. (1994). Proceedings of the ocean drilling program, initial reports, 146 (part 1), College Station, TX (Ocean Drilling Program). <https://doi.org/10.2973/odp.proc.ir.146-1.1994>