Fisheries and Oceans Canada

Pêches et Océans Canada

Ecosystems and Oceans Science

Sciences des écosystèmes et des océans

Canadian Science Advisory Secretariat

Pacific Region

Science Response 2018/002

ASSESSMENT OF CANADIAN PACIFIC COLD SEEPS AGAINST CRITERIA FOR DETERMINING ECOLOGICALLY AND BIOLOGICALLY SIGNIFICANT AREAS

Context

Cold seeps are benthic marine habitats where reduced chemicals (e.g. hydrogen sulphide and methane) emanate from the seafloor, supplied by subsurface hydrocarbon reservoirs. Microbes metabolize these chemical compounds and form the base of chemosynthetic communities that are not directly dependent on sunlight and photosynthesis. Cold seeps are often characterized by high biological productivity and endemism, and – like hydrothermal vents – are considered biological oases in the normally food-poor deep sea. In this context, seeps (with vents) were addressed in the United Nations World Ocean Assessment I (Le Bris *et al.* 2016).

Canada has committed to identifying Ecologically and Biologically Significant Areas (EBSAs) in its national waters through commitments to the Convention on Biological Diversity (Convention on Biological Diversity 2008). Through the Canada-BC Marine Protected Area (MPA) Network Strategy (Canada 2014), the federal government has also committed to integrating EBSAs into its Marine Protected Area (MPA) networks. Since 2004, eight criteria for assessing candidate EBSAs have been identified: Uniqueness or rarity; Special importance for life history stages of species; Aggregation; Vulnerability, fragility, sensitivity, or slow recovery; Naturalness; Importance for threatened, endangered, or declining species and/or habitats; Biological productivity; and Biological diversity (Ban *et al.* 2016; DFO 2004, 2011). Similarly, at the international level, steps have been taken to protect marine biodiversity at vulnerable marine ecosystems (VMEs, including cold seeps), which have similar criteria as EBSAs but also include Structural Complexity (Ardron *et al.* 2014; United Nations General Assembly 2011).

Although EBSAs have been identified in all four Pacific bioregions (Northern Shelf Ecoregion, Southern Shelf Ecoregion, and Strait of Georgia, (DFO 2013) and Offshore Pacific (Ban *et al.* 2016), these efforts have not included cold seeps, which are considered likely to host unique and productive communities. In the Pacific Region, several cold seeps have been explored via submersibles, and many gas plumes, indicating potential seep locations, have been identified in the water column. However, these sites have not been inventoried systematically or evaluated against the criteria defining EBSAs. As such, they remain unprotected and vulnerable to impacts.

DFO Ecosystems Management Branch, Oceans group, has requested that Science Branch provide an assessment of cold seeps against the EBSA and VME criteria. This science response and the advice arising from it will be used to inform ongoing marine conservation target objectives as well as future conservation efforts in Pacific Region.

This Science Response Report results from the Science Response Process of May 15, 2017 on the Assessment of Cold Seeps against Criteria for Determining Ecologically and Biologically Significant Areas.

Canada

Objectives

1. Compile information on the spatial distribution of known and inferred cold seeps in the Offshore Pacific, Northern Shelf, and Southern Shelf bioregions.

2. Characterize the biophysical, chemical, and ecological attributes of the identified cold seeps in the Offshore Pacific, Northern Shelf, and Southern Shelf bioregions.

3. Evaluate the identified cold seeps according to published national and international criteria for EBSA identification (Ban *et al.* 2016; Convention on Biological Diversity 2008; DFO 2004, 2011), and according to international criteria for VMEs (FAO 2016).

4. Indicate the level of confidence associated with the evaluation of EBSAs, and identify and examine any sources of uncertainty in the data or methods used to inform this evaluation.

This Science Response Report results from the Science Response Process of May 15, 2017 on the Assessment of Canadian Pacific Cold Seeps against Criteria for Determining Ecologically and Biologically Significant Areas.

Background

Ban et al. (2016) recently identified EBSAs for the offshore Pacific region, a process that has also been accomplished for the Northern Shelf, Southern Shelf, and Strait of Georgia Ecoregions (DFO 2013). In the Offshore Pacific Bioregion, EBSAs were found to occur for five different habitat types: hydrothermal vents, seamounts, the continental slope, the Haida eddy region, and the North Pacific Transition zone (Ban *et al.* 2016). During the regional peer review for this CSAS process, however, it was noted that DFO had overlooked considering cold seep habitats for potential EBSAs, despite the fact that they have been labeled EBSAs in other regions and countries (DFO 2015, 2016).

At the international level, deep-sea fisheries that impact the seafloor are managed through the United Nations Food and Agriculture Organization (FAO), which identified criteria for Vulnerable Marine Ecosystems (VMEs) (FAO 2009). Often these occur on seamounts where bottom trawling damages biogenic, structure-forming species like sponges and coral. Accordingly, the VME criteria include "Structural Complexity", which is not an EBSA criterion. Though its purpose is geared toward fisheries management, the VME approach is similar to and can be considered complementary to that of identifying EBSAs (Ardron *et al.* 2014). In 2009 DFO developed the Policy on Managing the Impacts of Fishing on Sensitive Benthic Areas (SBAs) as part of the Sustainable Fisheries Framework (DFO 2009a). The SBA policy, similar to the FAO's VME policy, focuses on areas that are vulnerable to a proposed or ongoing fishing activity. Vulnerability is determined based on the level of harm that the fishing activity may have on the benthic area by degrading ecosystem functions or impairing productivity. SBA does not apply to pristine areas where fishing has not occurred. Though bottom fishing is the human activity most likely to directly impact cold seep habitats, other activities may have indirect or cumulative effects as well (ocean warming, acidification, deoxygenation, plastics pollution, mining, etc.).

Analysis and Response

Introduction to Cold Seeps and Geological Settings

Cold seeps (or "cold vents") are common features along global continental margins, usually occurring between 150-2000 meters deep. These unique habitats are characterized by fluids enriched with reduced compounds that emanate from the seafloor. Typically, these compounds include hydrocarbons (namely methane, but ethane, propane, butane, pentane, and more

complex hydrocarbons may be present) and hydrogen sulphide (Le Bris *et al.* 2016; Suess 2014). Globally, methane is often the dominant hydrocarbon emitted from seeps, so they are commonly referred to as "methane seeps" or "hydrocarbon seeps". However, we will use the term "cold seep" throughout this paper since the molecular makeup of gases in pore fluids is unknown for most seeps off the Pacific margin of Canada. Still, at the few sites where gases have been studied, methane is the dominant hydrocarbon present (Pohlman *et al.* 2009). Chemosynthetic microbes use reduced compounds (e.g. sulphide, methane, and hydrogen) to fix carbon, forming the base of rich food webs and creating biological hotspots in usually food-poor deep-sea settings. Not only do cold seeps contribute to biological productivity, but their high levels of endemism (a characteristic common to most chemosynthetic ecosystems) tend to boost regional diversity (Le Bris *et al.* 2016). While there is no global inventory of cold seeps, hundreds have been documented, and recent estimates suggest there are tens of thousands spread among all the world's continental margins (Merle and Embley 2016; Skarke *et al.* 2014).

There are a variety of geological settings in which cold seeps occur, as they are influenced by tectonic settings, the source of seep fluids, and the interactions between these fluids and the overlying materials through which they flow (Suess 2014). However, general distinctions between seep dynamics at active and passive continental margins can be identified. Along active margins where sediment-laden oceanic plates are subducted beneath continental plates (such as Canada's Pacific coast), lateral compression of sediments leads to dewatering, and increased temperature and pressure causes further dehydration of sediments, with the resulting fluids moving upwards through faults and fractures. Along passive margins (such as Canada's Atlantic coast), sediments accumulate and fluid expulsion occurs due to loading from increased sediment pressure and compaction. Where sediments accumulate quickly (e.g. deltas, productive continental shelves, canyons, depressions and pockmarks), they are frequently rich in organic material and favor sulphate reduction and methanogenesis in the absence of oxygen (Suess 2014).

Along the Cascadia margin, subduction of the Juan de Fuca plate under the North American plate has been ongoing since the Eocene Epoch, leading to an accretionary prism over 4 km thick (Hyndman 1995). Within this prism, layers of thickening sediments experience deformation, horizontal shortening, and fluid expulsion, contributing the likely dominant source of seep fluids along the Canadian Pacific continental margin. The regional seafloor also receives sedimentary subsidies from the highly productive California Current upwelling system and the large amounts of organic-rich material exported through the Strait of Juan de Fuca. Thus, exuded seep fluids may contain hydrocarbons with varying sources and ages.

The source of methane for seeps in subduction zones is frequently frozen methane hydrate, sometimes called clathrate. Hydrate forms under particular temperature-pressure conditions, and is a crystalline ice structure with water molecules surrounding a methane molecule locked in the center. Methane hydrate is stable as long as temperature and pressure remain constant. But increases in temperature or decreases in pressure can allow the "ice" to melt, releasing methane into sediments and leading to its eventual migration into the water column as a gas. Along most continental margins, gas hydrate is stable at depths of 500-600 meters and deeper. The upper boundary of the gas stabilization zone, where warmer temperatures lead to the dissociation and sublimation of hydrates, tends to occur around 500 m along the Cascadia margin (Johnson *et al.* 2015). Recent work has suggested that these thermodynamics may result in higher frequencies of seeps at the top of the stabilization zone, evidenced by a greater number of gas plumes in the water column (Johnson *et al.* 2015). One recent cruise along the Cascadia margin (*Nautilus*-072) discovered hundreds of sites with bubble plumes south of the Juan de Fuca Strait and north of Cape Mendocino, California (Bell *et al.* 2017; Merle and Embley 2016), and recent work on existing older Canadian and open access ship data

discerned over 1000 seep sites across the Cascadia margin (Riedel *et al.* 2016). Plumes (single and multiple) frequently cluster at the heads of canyons. Most plumes occur at shallow depths (<250 m) but the deepest occur over 2000 m. Normalizing the plume abundance relative to the bathymetric depth distribution reveals that the most frequent depth of observation along the Cascadia margin is around 500 m. Johnson et al. (2015) hypothesized that current increases in ocean temperatures may be responsible for increased dissolution of gas hydrates along continental margins, contributing to some of these observed gas plumes at the top of the gas stabilization zone. Based on thermodynamic models, the hydrate stability depth along the Cascadia Margin has shoaled by about 13 m since 1970, and expected increases of 0.9-2.4°C by 2100 could cause the hydrate stability zone to ascend by another 68-75 m, allowing further methane dissociation (Hautala *et al.* 2014). Although the role of this methane release in accelerated climate change is gaining greater scrutiny, evidence does not yet exist indicating hydrate dissociation is a significant contributor to global methane emissions (Ruppel and Kessler 2017).

Biology and Ecology of Cold Seeps

Many of the seafloor features associated with cold seeps – "authigenic" (formed in their present location) carbonates, bacterial mats, and large animals hosting microbial symbionts – directly or indirectly result from biological processes that use methane as an energy source. The anaerobic oxidation of methane (AOM) is accomplished by a microbial symbiosis between a sulphate-reducing bacteria and methane-oxidizing archaea (Boetius and Wenzhöfer 2013). AOM is active in the layers of sediment where sulphate, abundant in seawater and methane are both present. In the sulphate-methane transition zone within seafloor sediments, both types of microbes associate into consortia of cells because their respective metabolisms become energetically favourable when executed together (Orphan *et al.* 2001). In addition to fixing inorganic carbon into sugars, AOM results in methane conversion into bicarbonate, and sulphate into sulphide. These "waste products" have important implications for cold seep ecosystems.

Accumulation of bicarbonate ions leads to the precipitation of carbonate, first into nodules and eventually into larger concretions including boulders and even carbonate pavements on the seafloor. This is an extraordinarily slow process, and a pavement with thickness of several centimeters may take hundreds of years to form (Luff *et al.* 2004). Microbes colonize exposed carbonate rocks, as do animals such as snails, limpets, worms, or amphipods that graze on bacterial filaments or use the outside or inside of rocks as habitat (Levin *et al.* 2015). When cold seeps are active for long periods of time seafloor authigenic carbonates can become prominent mounds that add rugose topography to an otherwise smooth, sedimented seafloor and are detectable with ship sonar. Thus, the metabolic activity of microbes contributes complex three-dimensional features that eventually serve as attachment sites for a diverse suspension-feeding community including sponges, corals, and crinoids, as well as mobile fish and invertebrates (Levin *et al.* 2016). Observations of cold seeps with different assemblages, rates of gas flux, and amounts of carbonate have led to hypothetical models of succession in cold seep ecosystems. Bowden et al. (2013) speculates that the transition from active seep, dominated by chemosynthetic production, to an inactive carbonate mound, dominated by suspension-feeders taking advantage of high current speeds, may take centuries or longer.

The accumulation of hydrogen sulphide as a result of AOM provides chemical fuel for sulphide-oxidizing bacteria (SOB), which form into large colorful mats on the seafloor surface and are consumed by many free-living invertebrates such as gastropods, polychaetes, galatheid crabs, and small peracarid crustaceans (Levin 2005; Sibuet and Olu 1998). Specific groups of (typically) larger fauna have evolved to gain nutrition by hosting endosymbiotic microbes, rather

than through consumption of organic material. These mutualistic microbes are often SOB, but may also include types that metabolize methane, hydrocarbons, or hydrogen; sometimes more than one metabolic group of symbionts are present. Along the Cascadia margin these are typically vestimentiferan tubeworms (~30-200 cm length) and vesicomyid and solemyid clams (~5-30 cm length), but elsewhere may include mytilid mussels (Duperron *et al.* 2007), sponges (Arellano *et al.* 2013), and yeti crabs (Thurber *et al.* 2011).

Cold seeps, like hydrothermal vents, are categorized as chemosynthetic ecosystems due to the community's reliance on chemical energy, rather than photosynthesis (Tunnicliffe *et al.* 2003). They are rich, biological oases in the deep sea. Typically, less than 1% of surface production reaches the seafloor at depths beyond 500 m. The primary productivity from cold seeps creates a rare *in situ* source of food in the deep sea, leading to large animals, dense populations, and production that can be exported to surrounding ecosystems on the continental margin. Additionally, cold seeps contain high levels of habitat heterogeneity. A single seep might have assemblages occupying exposed carbonate, microbial mats on sediments, clam beds, patches of polychaete worm tubes, thickets of larger siboglinid tubeworms, exposed solid gas hydrate, dead shells and tubes in regions that are no longer seeping, and more (Cordes *et al.* 2010; Grupe *et al.* 2015). The existence of so many different seafloor substrates and habitat types creates more niches that can support relatively high levels of diversity, and the unique geochemical setting does not exist in any other place along continental margins. Tubeworms, especially, as a complex biogenic habitat, can support particularly diverse assemblages in cold seep ecosystems (Cordes *et al.* 2009).

Biophysical, Chemical, and Ecological Attributes of Cold Seeps along the Canadian Pacific Continental Margin

Bioregional setting

While cold seeps have been published in the scientific literature for only a handful of locations off the Canadian Pacific coast, they occur in three of the four bioregions in very different settings (Figure 1, Table 1). The best studied seeps are in the Southern Shelf Bioregion, including those in Barkley Canyon (~800 m) and on the Clayoquot Slope (~1300 m; Bullseye Vent region). Both locations have been the subject of geophysical, fluid dynamics, and oceanographic research related to the Integrated Ocean Discovery Program (IODP) and, more recently, Ocean Networks Canada (ONC) (Römer *et al.* 2016). The instrument observatory nodes at these sites collect real-time data (from seismographs, ADCPs, CTDs, etc.), though biological studies have been infrequent thus far. Though little information is published about them, scientists have also discovered cold seeps on the continental slope at the Nootka Fracture Zone, 70 km southwest of Nootka island (~2300 m depth in the Offshore Pacific bioregion; Frye et al. 2006) and on the ridge separating Barkley and Nitinat Canyons (~900-940 m) (Riedel *et al.* 2016). In the Northern Shelf Bioregion, cold seeps have recently been discovered by Natural Resources Canada (NRCan) researchers employing drop camera systems targeting specific geophysical features. These are at the southern tip of Haida Gwaii (~800 m) and in Dixon Entrance (~1000 m) (Barrie et al., unpublished data; Sitka Sound Science Center 2015). Additionally, a cluster of gas plumes observed at depth indicates the likelihood of seeps existing in Ououkinsh Canyon (~950 m) near Brooks Peninsula (Riedel *et al.* 2016).
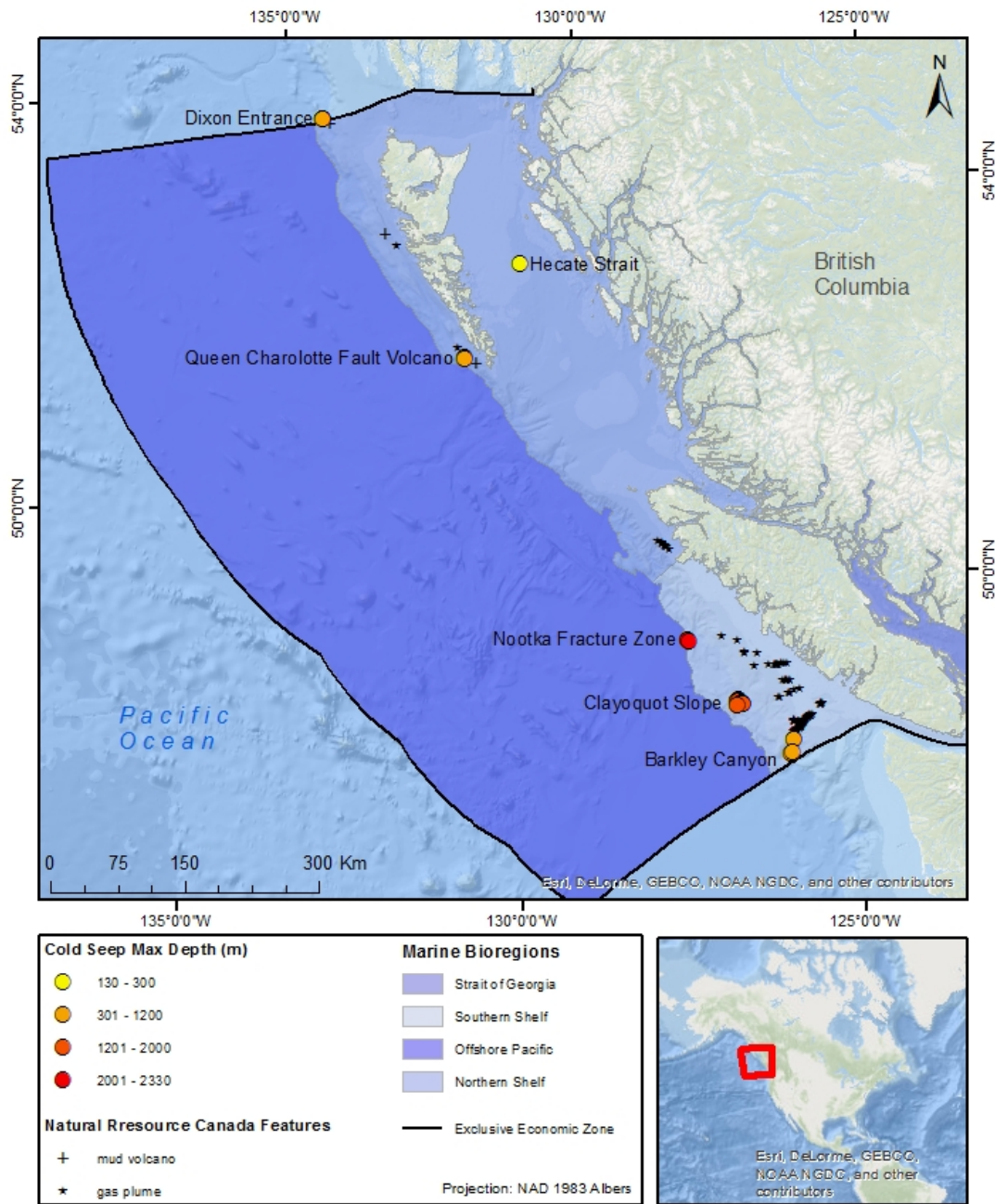
Figure 1. Canadian Pacific cold seep locations by depth. Locations of cold seeps (coloured circles) were compiled from published scientific literature, cruise reports, and theses, and the full list of seeps appears in Table 1 within the appendix. Gas plumes and mud volcanoes were identified using single-beam echo-sounders (Data contributed by J.V. Barrie, Natural Resources Canada). Marine bioregions were classified by DFO (2009b).

Many gas plumes have been detected using single- and multi-beam echo-sounders, suggesting the existence of dozens to hundreds of seeps that have not yet been explored (Riedel et al. 2016, J.V. Barrie personal communication). These plumes emanate from seafloor depths of <250 m, and are especially concentrated at the heads of canyons and near the outflow of the Juan de Fuca Strait. One seep at such shallow depths has been characterized in the Northern Shelf Bioregion in Hecate Strait (~130 m), and this is also the shallowest described seep in Canadian Pacific (Barrie *et al.* 2011). It may be reflective of seeps existing elsewhere on the continental shelf associated with the common gas plumes. The geological history of the Queen Charlotte Basin is conducive to the formation of oil and gas, and many onshore features and offshore pockmarks similar to the Hecate Strait seeps have been detected.

Barkley Canyon Gas Hydrates and Cold Seeps

The IODP found seismic reflection evidence for gas hydrates in the Canadian Pacific in 1985, and first drilled buried gas hydrates in 1992 (IODP Leg 146) (Westbrook *et al.* 1994). Exposed gas hydrates at Barkley Canyon were first discovered by fishermen bottom trawling 80 km west of Vancouver Island. Over 1000 kg of frozen gas hydrate (Spence and Chapman 2001) was trapped in the recovered net. A subsequent remotely-operated vehicle (ROV) survey of Barkley Canyon, revealed massive outcrops of exposed gas hydrate associated with traces of oil at a depth of 855 m (Chapman *et al.* 2004; Lu *et al.* 2007; Pohlman 2006). This discovery was notable since frozen gas hydrate is rarely exposed at the seafloor (Figure 2). Barkley Canyon eventually became a permanently instrumented site of a cabled array called NEPTUNE, operated by ONC with geophysical, oceanographic, and biological data being collected continually. The hydrate outcrops that occur in Barkley Canyon are unique within Canadian waters, as most commonly, gas hydrate is buried under sediments (Lu *et al.* 2007).

The geological processes that created methane hydrate at Barkley Canyon are unique in a global sense (Chapman *et al.* 2004). Most hydrates in continental slope sediments are microbially-created and are of a form called Structure I. Barkley Canyon, however, is the first known location along a continental margin where thermogenic gases (mainly methane) lead to gas hydrates in forms called Structure II and Structure H (Lu *et al.* 2007). These hydrates contain much more complex hydrocarbons (e.g. isopentane, methylcyclopentane) than structure I hydrates, and they are associated with high temperatures during formation (Chapman *et al.* 2004; Lu *et al.* 2007). They are known on the seafloor at only a handful of sites around the world, and are usually associated with oil and gas reserves. The seeps in Barkley Canyon do also contain some biogenic methane that is not related to fossil fuels, but is associated with the rapid accumulation of sediments at the end of the Last Glacial Maximum followed by microbial methanogenesis (Pohlman 2006; Pohlman *et al.* 2009). A majority of the methane and other hydrocarbons present at this site is likely sourced from deep petroleum reservoirs (Pohlman *et al.* 2005).

Gas release and fluid flow from seeps in Barkley Canyon have been studied using instruments linked to the ONC cabled observatory. Internal tides, surface waves on the shelf, and wind-generated currents all affect bottom currents, enhancing rates of hydrate dissociation and methane release to the water column (Thomsen *et al.* 2012). The high hydrodynamic activity at this site is likely linked to its location inside a submarine canyon, so other cold seeps within canyons might experience similarly elevated rates of gas release. Despite the high levels of background methane in the water column, most methane in the sediments is consumed by chemosynthetic microbes, so it is the dissociation of exposed hydrate that contributes most of the measured methane (Pohlman 2006). The finding that large amounts of thermogenic gas hydrate can exist on the seafloor in relatively stable conditions has led some to hypothesize that continued ocean warming could dramatically increase rates of methane release into the oceans from specific locations (Johnson *et al.* 2015).

The areas around exposed hydrate in Barkley Canyon contain chemosynthetic communities characterized by white filamentous microbial mats (likely *Beggiatoa*) and many vesicomyid clams (Figure 2). At the gas hydrate site, infaunal distribution relates to chemosynthetic production and food quality, and the influence of methane extends to at least 20 m beyond the outcrop. Sediment communities are dominated by oligochaetes and also contain dorvilleids and solemyid bivalves (*Acharax* sp.). This assemblage is distinct from nearby regions in Barkley Canyon that lack methane seepage and the related food resources it contributes to sediments (N. Campanya-Llovet, personal communication).

ONC's cabled observatory includes a remotely-controlled benthic crawler ("Wally") with cameras, which allows scientists to make frequent observations of the Barkley Canyon environment and ecosystem. Photomosaics covering about 30 m^2 of the gas hydrate site revealed dramatic changes over five months, including variability in white microbial mats and changing locations and numbers of clams, which move in response to seep fluids (Purser *et al.* 2013). Another set of photomosaics displayed significant variability in microbial mat coverage and clam locations in just two days. These ecosystem changes over days and months highlight the temporal variability in cold seeps (Cordes *et al.* 2010) and importance of repeated observations over time.

In a separate study focusing on patterns of megafaunal movement and abundance, Chatzievangelou et al. (2016) repeated 20-m transects during five-day periods over several months and noted diel patterns of movement for hagfish (*Eptatretus stoutii*), sablefish (*Anoplopoma fimbria*), and juvenile tanner crabs (*Chionoecetes tanneri*). While the proximity of these predators to seeps in Barkley Canyon might seem to suggest consumption of local prey items, their movement mainly correlated with tidally-driven bottom flow and chlorophyll concentration, a sign their foraging is focused on food sinking from shallower depths (Chatzievangelou *et al.* 2016).

Additional seeps are known from the Barkley-Nitinat Ridge, 15 km south of the Barkley Canyon hydrate site. These have not been as well studied as the gas hydrate sites, but researchers from the Monterey Bay Aquarium Research Institute (MBARI) have collected imagery of extensive bacteria mats and massive carbonate boulders associated with the seeps on this ridge (M. Scherwath, personal communication; Barr 2011). At this location (the "Tully Gas Vent Field") several species of black corals, sea pens, and gorgonians have been documented living on carbonates (OBIS 2017).

Clayoquot Slope Cold Seeps

The sub seafloor structure of the Clayoquot Slope region is relatively well known, thanks to the IODP and associated studies. The Clayoquot Slope contains a number of gas seeps spread over an area approximately 2 km by 4 km at depths about 1300 m (see detailed maps in Paull *et al.* 2015a; Riedel *et al.* 2010; Römer *et al.* 2016). The high amount of gas flux in this region is thought to originate from accretionary wedge sediments, millions of years old. Some of these seeps are associated with mounds, but also gas vents from many flat areas. Bullseye Vent, where IODP drilled and first found gas hydrates in 1992 (Westbrook *et al.* 1994), is no longer venting gas. Four of the main actively venting sites are Bubbly Gulch, Gastown Alley, Amnesiac, and Spinnaker. A large carbonate outcrop, Cucumber Ridge, also contains cold seeps and extensive chemosynthetic communities, although fluid flow is less vigorous (possibly due to physical blockage from the carbonates). ROV surveys have also revealed many smaller areas of seepage that occur within this region, such as Gastown Alley, a flat sedimented area that stretches 1.5 km northeast from Bullseye Vent to Bubbly Gulch. These sites are referred to collectively as the Clayoquot Slope seeps, though their distinct geochemical and physical

characteristics translate to distinct biological communities (Figures 3-4; Breen 2002; Furlong 2013).

Where Barkley Canyon contained large amounts of thermogenic methane, gases measured emanating around Bullseye Vent on the Clayoquot Slope had biogenic origins, were not as tightly linked to fossil fuel sources, and were almost pure methane (>99%) (Pohlman *et al.* 2009). Gas hydrate recovered in cores from this site had different isotopic and hydrocarbon signatures, so it represents a mixture of biogenic and thermogenic origins. Gases with those signatures do not appear in the water column, so hydrate at Clayoquot is not dissociating at the rate of exposed hydrates in Barkley Canyon. In fact, the pore fluids within sediments are saturated with methane at Bubbly Gulch (Lapham *et al.* 2013). Gas release at the nearby Gastown Alley is highly variable and correlates with tidal cycles, where reduced pressure during falling tides allows an increase in flux of bubbles (Römer *et al.* 2016). Temporal variability in the geochemical environment may influence changes observed in biological communities, as clams appeared in Bubbly Gulch in 2011 after being absent the previous two years (Lapham *et al.* 2013).

Breen (2002) provides one of the few detailed biological descriptions of any of Canadian Pacific cold seep based on surveys conducted by the ROPOS ROV of the Clayoquot slope in May 2001 (Figure 4). Video imagery of seep surveys was analyzed for numbers of individual seeps sites and relative seep density. The surveys encountered 30 seep sites on the northern carbonate mound (likely the same feature as Cucumber Ridge; the highest site density of one seep per 97 m^2 surveyed), 3 seep sites at "Blank Zone 1" (near what is now called Bullseye Vent and Gastown Alley; one seep per 338 m^2), and 11 seep sites on Skate Scarp (just SE of the carbonate mound on Cucumber Ridge; one seep per 1868 m^2). Four known animal hosts of chemosynthetic symbionts were collected: the bivalves *Phreagena (Calyptogena) kilmeri*, *Archivesica (Vesicomya) gigas*, and *Solemya reidi*, and the vestimentiferan tubeworm *Lamellibrachia barhami*. These are fauna endemic to chemosynthetic habitats and are normally found at cold seeps. However, *L. barhami* is observed at sedimented hydrothermal vents at Middle Valley (Southward *et al.* 1996), *A. gigas* occurs at vents and seeps in Guaymas Basin (Mexico) and Costa Rica (Levin *et al.* 2012), and *S. reidi* has been found in coastal hypoxic sediments near sewage outfalls and logging booms (Felbeck 1983; Reid 1980). Though not cold seeps, these are environments in which the microbial breakdown of organic matter removes oxygen and leads to high sulphide concentrations in sediments.

The Blank Zone in the 2001 survey on the Clayoquot slope ("blank zone" refers to blank areas seen in low-frequency echo-sounder data that indicate locations of likely gas under the seafloor) was the least active area, with only three seeps seen, the largest of which was measured to be 1.2 m^2. However, vesicomyid clams were present at each seep, and tubeworms were seen at one seep site. Carbonate rock was also present, though most of the benthos was sedimented. At one particular seep, Breen (2002) noted a "preponderance of polychaetes" sticking out of the sediment and deposit feeding. This behaviour has been observed in ampharetids (*Amphisamytha* sp. was common in sediment tube cores) or spionids living in high densities at other cold seeps (Thurber *et al.* 2010). Areas around seeps usually had low densities of non-seep fauna, but in one case there was a large (>10m) stretch of *Neptunea priboloffensis* (a large buccinid whelk), many of which had laid towers of eggs on the carbonate. Sea fans and sea whips were common, frequently attached to carbonate, and ophiuroids (*Asteronyx)* were associated with the latter.

More seeps were observed at the northern carbonate mound than the other sites, though it should be noted that seep location was based mainly on the locations of chemosynthetic-hosting animals, so gaps of several meters between clusters of tubeworms may have caused the site to be counted as having two seeps instead of one (Breen 2002). Seeps contained

tubeworms, clams, or both, and associated fauna included galatheid crabs ("squat lobsters), caridean shrimp, the gastropod *N. priboloffensis,* ophiuroids, sabellid polychaetes ("feather duster worms"), and hydroids attached to the *Lamellibrachia* tubes. The largest seep with tubeworms was about 4 m^2, though two seeps with vesicomyids were about 9 m^2. In the periphery around seeps, sea whips, sea fans, crinoids, and hydroids were commonly attached to carbonate. Holothurians were occasionally common where there were soft sediments.

Skate Scarp was the only site where *Solemya reidi* was found (although it lives in deep burrows and is often not visible in surveys (Seike *et al.* 2012)), and the vesicomyids and *L. barhami* were also present (Breen 2002). Skate Scarp also seemed to be the only site where tubeworms were much more dominant than clams at certain seeps. The largest seeps were found at this site, including four larger than 11 m^2, and one about 35 m^2, and many were located along a prominent carbonate ridge. Seeps often contained large carbonate slabs and *N. priboloffensis* was very common, though at low densities. At several seeps, *N. priboloffensis* had attached its egg towers to the tubes of *L. barhami*. Other associated fauna included anemones and hydroids, caridean shrimp, sabellids, limpet gastropods, and fish. The peripheral environments of each region were described as having fauna typical of non-seep deep sea communities with lower abundances than was observed at the seeps themselves.

From close-up images (Figure 4), it is clear that white filamentous bacteria covered the clam shells, which likely served as a food source for the many snails (*Provanna* sp.) and limpets (*Pyropelta* sp. and perhaps others) also occupying those shells (Breen 2002). However, large bacterial mats were not observed on the carbonate mound, though they are present at other Clayoquot slope sites. Bacterial mats usually occur in locations with higher fluid flux than symbiont-hosting bivalves and tubeworms, so this may be an indication that the ROV surveys on Cucumber Ridge observed less active seeps than the more vigorously seeping region near Bullseye Vent (currently inactive), Gastown Alley, and gas flares surrounded by soft sediments. As carbonate crusts form and turn into large mounds, upward gas flux may slow, diffuse, or be redirected, restricting rates of AOM and preventing the high-sulphide conditions conducive to extensive microbial mats (Luff *et al.* 2004).

Breen (2002) described the macrofauna recovered from several grabs targeting clams and tubeworms at Skate Scarp and the Blank Zone. Additionally one quantitative sediment core was collected. In total 63 taxa were identified (most to the family level or higher). Taxa frequently encountered in sediments included polychaetes (especially Polynoidae and Phyllodocidae), gastropods, and nematodes. From digital stills, macrofauna associated with clam beds include *Provanna* and *Pyropelta* gastropods, pycnogonids, isopods, and hesionid polychaetes.

Nootka Fault Cold Seeps

The deepest known cold seeps in Canadian Pacific waters occur along the Nootka Fault from about 2260-2290 meters, containing patches of bacterial mats, clams, and tubeworms surrounded by both sediments and blocks of carbonate (LaBonte 2007). Published reports describe acoustic moorings being deployed near known cold seeps (Frye *et al.* 2005, 2006), but we lack of seafloor descriptions and biological studies regarding these sites. Images of *L. barhami* tubeworms and *P. kilmeri* clams in an MBARI research report show that, at minimum, these seeps contain the same chemosynthetic-endemic species characterizing seeps at Clayoquot Slope and Barkley Canyon (Potter 2004). In describing flow meter experiments, Labonte (2007) reported seep clams present at the time of deployment were gone one year later when the instruments were recovered, showing that, as at Clayoquot, these seep communities vary over short time scales, potentially related to fluid flux from the seep. Many hard and soft corals have been documented on hard substrates at the Nootka Fracture Zone (OBIS 2017), so it is possible they are using authigenic seep carbonate as habitat.

Hecate Strait Cold Seeps

The shallowest known cold seeps in Canadian Pacific waters occur in Hecate Strait (Figure 5). The strait was heavily glaciated repeatedly during the Pleistocene Epoch, is covered in thousands of meters of sediment, and experiences complex strike-slip faulting. In an area called Horseshoes fishing ground, a chain of pockmarks (shallow seafloor depressions) host carbonate chimneys that are associated with irregular gas venting (Barrie *et al.* 2011). To the east there are additional pockmarks from 30 to about 200 m across and 2 to 10 m deep (Halliday *et al.* 2008). The area also contains low relief mounds with carbonate sediments, and many of these features are likely associated with active cold seeps on the seafloor. Oil exploration drilling in 1968 determined that there is oil within at least 17 km of the pockmarked area.

Phantom ROV dives and IKU grabs were used to investigate the largest pockmark, which hosted 27 chimneys from 1 to 2 m in height, usually with shell halos. Barrie et al. (2011) reported that many of the chimneys were covered with torn bottom trawl net, signaling both that this area is heavily impacted by fishing and that the carbonate is very consolidated and robust to impacts. The carbonate served as habitat to more species than surrounding sediments, including the predatory Oregon triton (*Fusitriton oregonensis*). The chimneys' hard substrate also served habitat for anemones, hairy tunicates, calcareous serpulid tubeworms, mussels, and brachiopods, none of which can live on soft sediments. Surrounding sediments contained worms, clams, and sea cucumbers. Most of these are common continental shelf species, except for one species of clam (*Solemya reidi*) found in sediments around the chimneys that is dependent on sulfide-oxidizing bacteria; it was considered part of a "typical" seep fauna (Barrie *et al.* 2011), but it also occurs in coastal habitats where high amounts of organics (such as wood) lead to hydrogen sulphide accumulation in sediments (Felbeck 1983; Reid 1980).

Recently Discovered Cold Seeps

Over the past few years, several seeps have been discovered near Haida Gwaii during NRCan research cruises. These are associated with submarine volcanic cones that are venting gas, though they are not currently expulsing magma or other volcanic material. Two side-by-side mud volcanoes just southwest of Haida Gwaii, adjacent to the Queen Charlotte fault, occur at 800 m depth and are actively venting gas (presumably methane). The gas plumes were detectable in single-beam (18 kHz) imagery up to 500 m above the seafloor (J.V. Barrie, personal communication). While description of this site is not yet published, the drop camera captured imagery of chemosynthetic communities associated with the seep, including loose aggregations of vesicomyid clams and discolored grey sediments (Figure 6 A-C). There are also patches of sediment tubes from infaunal polychaetes, thornyhead (*Sebastolobus* sp.), and the soft coral *Anthomastus* sp. Northwest of Haida Gwaii in Dixon Entrance, another seep was discovered on a venting volcanic cone 1000 m deep, again with a gas plume rising though over half the water column to 350 m (Figure 6; Sitka Sound Science Center 2015). In addition to drop camera imagery of chemosynthetic communities (Figure 6 G-J; yellow and white microbial mats, vesicomyids, a tubeworm (likely *Lameillibrachia barhami*)), an IKU grab recovered chemosymbiont-hosting bivalves, including a mussel and the clam *Calyptogena starobogatovi* (Figure 6 D-F).

Recent geophysical surveys over the continental shelf have utilized EK60 single-beam echo-sounder systems to estimate methane flux into the water column. This work, as well as available EM300 and EM302 multi-beam surveys, has revealed many gas plumes containing methane in 50-250 m of water (Capelle and Tortell 2016; Riedel *et al.* 2016;J.V. Barrie, personal communication, Figure 1), some of which could be associated with chemosynthetic communities on the seafloor. The highest densities of gas plumes seem to be near the Strait of Juan de Fuca

(Riedel *et al.* 2016), at the heads of submarine canyons such as northeast of Barkley Canyon, and at the apex of folds and associated faults within the Tertiary mudstones near the shelf break (J.V. Barrie personal communication). Another cluster of plumes was detected on the upper continental slope off of Brooks Peninsula. Given hundreds of gas plumes have been detected during surveys covering a small percentage of the continental margin, it is likely that thousands or even tens of thousands of these plumes exist in the Canadian Pacific. However, the existence of these abundant shallow plumes does not necessarily insinuate similar numbers of undiscovered deeper cold seeps on the continental slope, given the contrasts in geological and oceanographic settings (M. Scherwath, personal communication).

Global and Regional comparisons for Offshore Pacific, Northern Shelf, and Southern Shelf bioregions Cold Seeps

The seep fauna observed at Canadian Pacific cold seeps are known from other cold seeps in the eastern Pacific, but their frequency of occurrence regionally is not well known. The vestimentiferan *Lamellibrachia barhami* was not known north of Oregon (2036 m, Kulm *et al.* 1986) until it was discovered at the Clayoquot Slope seeps (Breen 2002; Spence and Chapman 2001). The appearance of tubeworms in drop camera imagery from Dixon Entrance in 2015 means those seeps may now represent the known northern limit of *Lamellibrachia* in the eastern Pacific (Barrie, unpublished data), and they have also been discovered recently at shallow seeps along the Oregon margin (Merle and Embley 2016).

The vesicomyids reported by Breen (2002) are likely the same species as recovered from other northeast Pacific cold seeps (Oregon, Kulm *et al.* 1986; Central California, Barry and Kochevar 1998; Southern California, Grupe *et al.* 2015), with at least one (*Phreagena kilmeri*) occurring at each of these sites (Johnson *et al.* 2016). *Solemya reidi* occurs in many habitats where hydrogen sulphide accumulates in sediments, both cold seeps (Clayoquot, Hecate Strait) and associated with sewage outfalls and under coastal log booms (Felbeck 1983; Reid 1980). Related species from the genus *Acharax,* identified from Barkley Canyon (Campanya-Llovet and Snelgrove 2016), are also commonly encountered at cold seeps and in oxygen minimum zone (OMZ) sediments in the northeast Pacific, and as they are deep burrowers, are not easily observed without pushcore sampling (Taylor and Glover 2010). *Calyptogena starobogatovi,* recovered from seeps on mud volcanoes off Haida Gwaii, is also endemic to chemosynthetic ecosystems beyond cold seeps. It was first discovered at hydrothermal vents on Axial Seamount along the Juan de Fuca Ridge (Krylova and Sahling 2006). Thus far, no chemosynthetic bivalves or tubeworms have been discovered that are endemic to Canadian Pacific cold seeps, solely.

In addition to revealing biogeographic connections across large spatial scales, the presence of vesicomyids and solemyids supports the hypothesis that cold seep species associations along the Cascadian margin have been maintained for tens of millions of years. Oligocene and Eocene seep deposits on Vancouver Island and in Washington, USA contain fossils of species from these families, in addition to lucinid and thyasirid bivalves, other common symbiont-hosting fauna (Nesbitt *et al.* 2013).

Since little research has been done regarding the biodiversity and community structure of Canadian Pacific cold seeps, it is difficult to compare the ecology of these seeps with others regionally or globally. In addition to sharing symbiont-hosting megafaunal species with regional seeps, those in the OMZ (e.g. Barkley Canyon, or south of Haida Gwaii) lack tubeworms, patterns noted in Oregon and California (Grupe *et al.* 2015; Levin *et al.* 2010). Some of the smaller macrofauna that have been identified occur at other regional seeps (Johnson *et al.* 2010; Levin *et al.* 2017; Warén and Bouchet 1993, 2001), and it seems reasonable to expect there is population connectivity among Canadian Pacific cold seeps and those from Alaska to

California. For example, provannid and pyropeltid gastropods found at Clayoquot Slope seeps occur throughout the northeast Pacific, from Costa Rica to Alaska, reflective of a high dispersal ability (Sasaki *et al.* 2010; Warén and Bouchet 2001), and *Amphisamytha* sp., identified in samples from Clayoquot Slopes, occurs at many cold seep and hydrothermal vents throughout the Pacific Ocean (Stiller *et al.* 2013). As more sampling is conducted and small macrofaunal and meiofaunal specimens are eventually identified, it is likely that species endemic to Canadian Pacific cold seeps will be discovered.

Assessment of Offshore Pacific, Northern Shelf, and Southern Shelf bioregions cold seeps against EBSA criteria

Table 2: Summary of EBSA criteria rankings and overall EBSA assessment (See Table 1, DFO 2016 for definitions of the criteria used in the assessments).

EBSA Criteria	Cold Seep Rating
Uniqueness or rarity (DFO/CBD)	High
Special importance for life history stages of species (DFO/CBD)	High
Importance for threatened, endangered, or declining species and/or habitats (CBD)	No Data
Vulnerability, fragility, sensitivity, or slow recovery (CBD)	High
Biological productivity (CBD)	Medium
Biological diversity (CBD)	Medium
Naturalness (DFO/CBD)	Medium
Aggregation (DFO)	Medium
EBSA Identification	**Meets Criteria**

Uniqueness or rarity

Cold seeps are unique chemosynthetic ecosystems in which the base of the food web is formed by microbes that fix carbon using methane or sulphide as a chemical energy source. Similar microbes are also found in hydrothermal vent ecosystems and in sediments where oxygen is very low, but are otherwise not prominent in most marine ecosystems. Several seeps along the Canadian Pacific margin are also known to contain species that are endemic to reducing ecosystems [tubeworms (*Lamellibrachia barhami*), clams (*Phreagena kilmeri*, *Archivesica gigas*, *Solemya reidi*, *Acharax* sp.)], if not specifically to cold seeps. These organisms have unique trophic strategies in that they host microbial symbionts that produce their food inside their bodies. In some cases they may appear in other low oxygen environments with high concentrations of reduced chemicals (e.g. *S. reidi* in coastal sulphide-rich sediments), but in Canadian waters they have only been found at cold seeps, with the exception of *L. barhami* occurring in the sedimented Middle Valley hydrothermal vents (Tunnicliffe *et al.* 1998).

While cold seeps are known to occur along Canada's Arctic and Atlantic continental margins (DFO 2015; Paull *et al.* 2015b; Skarke *et al.* 2014), only in the Pacific does a subduction zone exist, which creates distinct geomorphological characteristics and deeper source fluids emitted at seeps (Suess 2014). This contributes to the uniqueness of Canadian Pacific cold seeps in a

national context. The Barkley Canyon seep is also unique in a global context, since it is one of very few sites where exposed thermogenic gas hydrate lies on the seafloor of a continental margin, making the site conducive to particular geophysical and geochemical research. Recent detections of hundreds of shallow gas plumes using shipboard echo-sounders have not been accompanied by similar discoveries deeper than 500 m. The handful of known cold seeps at greater depths (Barkley Canyon, Barkley-Nitinat Ridge, Clayoquot Slope, Dixon Entrance, Nootka Fault) may be comparatively rare in Canadian Pacific waters.

Special importance for life history stages of species

Cold seep habitats are critical to the endemic benthic invertebrates living there, especially those hosting symbiotic bacteria that use chemosynthesis to provide their nutrition (e.g. the tubeworm *Lamellibrachia*, vesicomyid and solemyid bivalves). Certain taxa found at Canadian Pacific cold seeps spend the entirety of their adult lives in seep habitats, and stable isotope data from other regions in the world show they attain most or all their nutrition from seep production (Levin and Michener 2002). Additionally, many free-living benthic invertebrates, some of which are endemic to seeps (the gastropods *Provanna* sp. and *Pyropelta* sp.), rely on chemosynthetic primary production for consumption. Anecdotal evidence shows some non-seep species frequently use seep features (especially carbonate rocks) as sites for reproduction. *Neptunea pribiloffensis* egg stacks have been observed on carbonates at the Clayoquot Slope cold seeps. Scientists have not yet investigated the potential for population connectivity among Canadian Pacific seeps, which would influence the importance of any one seep on the metapopulation. Many sessile invertebrates such as corals and sponges indirectly depend on cold seeps because once seeps become inactive, they occupy carbonates precipitated by chemosynthetic microbes. Note this criterion corresponds to DFO's (2004) criterion of "Fitness consequences".

Importance for threatened, endangered, or declining species and/or habitats

Insufficient information currently exists to evaluate cold seeps on the basis of this criterion.

Vulnerability, fragility, sensitivity, or slow recovery

Cold seeps contain taxa and biogenic structures that are fragile and/or long-lived, and may not easily recover if disturbed. Seep tubeworms grow very slowly once mature (cms per year), are extremely long-lived (Fisher et al. 1997), and in some cases have been aged to over 300 years (Cordes et al. 2009). The carbonates themselves are created very slowly by microbial activity over many years (Boetius and Wenzhöfer 2013; Luff et al. 2004), and their structure provides a complex habitat for other species. Disruption of the carbonate (as might be associated with a bottom trawl) can disturb the taxa associated with them, such as fly-trap anemones, corals, sponges, crinoids, and other sessile fauna that occupy carbonates at the periphery of Canadian Pacific cold seeps or at sites of past seepage (Bowden et al. 2013). No studies have measured the ability of seeps recover from human impacts, but scientists hypothesize complete successional processes last decades at minimum, and likely centuries (Bowden et al. 2013; Levin et al. 2016). Some Canadian Pacific cold seeps have already been impacted by fishing activity, but it is unclear to what degree. The seeps in Barkley Canyon were discovered when a fishing boat trawled a chunk of solid methane hydrate (Spence and Chapman 2001); twice fishing trawlers destroyed Ocean Network Canada's seafloor infrastructure at Barkley Canyon (M. Scherwath, personal communication); and ripped fishing nets were found wrapped around some of the seep chimneys in Hecate Strait (Barrie et al. 2011). Of the tubeworms observed at the Clayoquot Slope seeps, none appeared to be new recruits, suggesting that populations may be long-lived with low recruitment rates (Breen 2002). Note this criterion corresponds to DFO's (2004) criterion of "resilience".

Biological productivity

While data have not been collected relating to the productivity of Canadian Pacific cold seeps, it is well understood that when these features occur in the deep sea (>200 meters), they increase biological productivity and biomass of benthic populations relative to surrounding areas (Levin 2005; Ramirez-Llodra et al. 2010). The chemosynthetic primary production at deeper seeps such as Barkley Canyon and the Clayoquot slope increases biological productivity of these ecosystems compared to nearby continental margin habitats. However, since they occur underneath a highly productive upwelling zone, and submarine canyons act to further concentrate organic particles, these particular cold seeps may simply be enhancing productivity of an area where food is already plentiful. Thus, we ranked this criterion as having medium relevance; cold seep productivity will likely take on higher relevance at sites with reduced allochthonous surface production.

Biological diversity

Cold seeps may increase a region's biodiversity because of the number of uniquely adapted species they contain, even though they may have lower species richness (alpha diversity) than other continental margin habitats (Cordes et al. 2010; Levin et al. 2010). In other words, methane seeps may contain fewer species than other habitats on the continental margin, but because many of them are endemic, they serve to increase the number of species occurring in the entire region. In Oregon, the diversity of macrofauna associated with carbonates created by seeps was higher than in surrounding sediments, showing that seeps help increase diversity through novel habitats (Levin et al. 2017). While diversity metrics have not been calculated for any Canadian Pacific cold seeps, Breen (2002) found over 60 species of invertebrates associated with just four sediment grabs and one push core from clam beds.

Naturalness

Cold seeps along the Canadian Pacific margin likely exhibit variable degrees of naturalness based on their depth, remoteness, and surrounding substrata. Seep communities and structures are commonly found to have been damaged by human activitiesupon their discovery, and our lack of observations of cold seeps prior to fishing activity makes it impossible to know with certainty what "pristine" seep ecosystems look like. Since many seeps are distributed in regions where fishing activities occur, most in the Canadian Pacific have probably been impacted to some degree, especially at shallower depths. It was not until the late 1990s and early 2000s that the BC groundfish bottom trawl fishery expanded to depths of 500 m and deeper (Sinclair 2007). Seeps deeper than 1000 m, (such as those on the Clayoquot slope or the Nootka Fracture Zone), are more likely to exhibit a high degree of naturalness, due to reduced trawling pressure. Seeps on the continental shelf (e.g. Hecate Strait, where fishing gear was found wrapped around carbonate chimneys) or in popular fishing grounds (e.g. Barkley Canyon, where gas hydrate was captured in a fishing trawl) are likely to exhibit a low or medium degree of naturalness. Scientific activity also impacts cold seeps, and Canadian Pacific seeps are near ONC research sites that include significant infrastructure. While cable, instruments, and moorings may not directly impact seeps, they detract from the naturalness of the surrounding ecosystem.

Aggregation

Species (such as rockfish, thornyhead, sponge, and coral) may aggregate around seeps due to the structure of the carbonates or to take advantage of secondary productivity (high macrofaunal abundance at seeps represent a potentially significant food source for benthopelagic predators such as fish, crabs, octopus, etc.). Breen (2002) described higher aggregations of non-seep deep-sea fauna at seeps compared to peripheral environments, and

noted aggregations of snails (*Neptunea pribiloffensis*) associated with seep carbonates, to which they attach their egg towers. Observations have provided support for higher densities of fishery-targeted species and other continental slope megafauna at seeps compared to nearby sedimented habitats (Grupe et al. 2015), but similar work has not been conducted in the Canadian Pacific or the northern California Current region. The lack of quantitative data regarding species densities near Canadian Pacific cold seeps and in surrounding habitats prevents this criterion from being scored "high".

Uncertainty

The ecosystems associated with cold seeps in Canadian Pacific waters have not been studied in detail and only a few have been studied at all. The lack of data regarding biodiversity and community structure of these cold seeps contributes the difficulty in making regional or global comparisons with other seeps. As more research focuses on cold seeps off the Canadian Pacific coast, we will obtain more confidence in our evaluation of each of the EBSA criteria including those where we currently have almost no information, such as the "Importance for threatened, endangered, or declining species and/or habitats".

The cold seeps in Canadian Pacific waters are found in at least three oceanographic settings; the continental slope of Vancouver Island (e.g. Barkley Canyon and Clayoquot Slope), the relatively shallow waters of Hecate Strait in a sedimentary basin, and the newly discovered seeps around Haida Gwaii on underwater volcanoes. In addition, recent acoustic data indicate the existence of hundreds of gas plumes over a small proportion (<5%) of the Canadian Pacific continental shelf (Capelle and Tortell 2016; Riedel et al. 2016; J.V. Barrie, personal communication, Figure 1). Seafloor studies have not been paired with the majority of these shipboard detections of plumes, so it is unknown whether they have associated seafloor communities or chemosynthetic fauna that resemble the cold seep ecosystems described in this review. We applied the EBSA criteria to cold seeps with accompanying seafloor observations or data. We have made the assumption that all seeps in the Canadian Pacific that support chemosynthetic communities can be treated similarly in regards to EBSA criteria, but with more research, ecological differences among seeps may emerge, perhaps related to seafloor depth, region, or rate of upward gas flux. As more data become available on cold seeps and gas plumes, the EBSA rankings for various cold seep communities should be re-evaluated, and rarer types of seep communities (e.g. those in deeper canyons, or those with extensive habitat-forming tubeworm bushes) may be deemed worthy of greater protection.

Assessment of Offshore Pacific, Northern Shelf, and Southern Shelf bioregions cold seeps against VME criteria

Table 3: Summary of the FAO criteria for Vulnerable Marine Ecosystems (VME) (See FAO 2009 and FAO 2016 for definitions of the criteria used in the assessments).

VME Criteria	Cold Seep Rating	Relation to EBSA Criteria
Uniqueness or rarity	High	Uniqueness or rarity
Functional significance of the habitat	High	Special importance for life history stages of species Importance for threatened, endangered, or declining species and/or habitats
Fragility	Medium	Vulnerability, fragility, sensitivity, or slow recovery
Life history traits of component species that make recovery difficult	High	Vulnerability, fragility, sensitivity, or slow recovery
Structural complexity	High	*No comparable EBSA criteria*
VME Identification	**Meets Criteria**	**-**

The rationale for uniqueness or rarity and functional significance of the habitat are the same as for the related EBSA criteria (Uniqueness or rarity; Special importance for life history stages of species; Importance for threatened, endangered, or declining species and/or habitats).

The fragility criterion for VMEs is defined as an ecosystem highly susceptible to degradation by human activities (FAO 2009). Since it highlights the effect of humans rather than inherently sensitive habitats, fragile species, or slow recovery of populations, it may be less relevant to cold seeps than the related EBSA criterion related to vulnerability. Seeps are certainly susceptible to degradation by human activities, both direct (mainly bottom trawling, but also cabled infrastructure) and indirect (changes in ocean oxygen content, potential oil spills, and other deep-sea pollution) (Ramirez-Llodra et al. 2010), but to what degree is unclear. That Canadian Pacific cold seep communities are sometimes typified by large, slow-growing, long-lived tubeworms means they score high under the VME criterion Life history traits of component species that make recovery difficult. Moreover, cold seeps are spread out and population recovery may depend on larval dispersal distances and metapopulation connectivity, which is unknown for most species.

Structural complexity has no comparable example from the EBSA criteria. However, cold seeps are characterized by complex physical structures (carbonate mounds and boulders, pockmarks, mud volcanoes) that arise from or are modified by interactions between abiotic conditions and dense biological communities. Ecological processes (succession of microbes and symbiont-hosting animals, metabolic strategies, trophic linkages, diversity patterns, long-term competition of suspension-feeding communities etc.) are highly dependent on the physical structure present at seeps, and diversity is elevated both while the seep is active and also after it senesces (Levin et al. 2016). Additionally, structure created by seep biota (especially tubeworm tubes, but also clam and mussel shells and microbial mats) increases overall species richness, alters diversity patterns, and provides habitat for other endemic seep species.

The FAO VME criteria do not have explicit comparable categories for the EBSA criteria Biological productivity, Biological diversity, or Naturalness (Ardron *et al.* 2014).

Conclusions

Based on this review of cold seeps in Canadian Pacific waters, we recommend that they be classified as EBSAs. Cold seeps rank as having high relevance for three EBSA criteria and medium relevance for four criteria (including Naturalness, which is used only to prioritize among different features). In particular, Canadian Pacific cold seeps are notable for their unique geomorphological characteristics, creating habitats upon which several endemic species depend; their rarity relative to other continental margin features; the vulnerability of long-lived habitat-forming species (tubeworms) to human disturbance; and high rates of biological productivity, especially compared with other regions in the deep sea.

All currently known cold seeps in the Canadian Pacific have been discovered within the past twenty-five years, and the hundreds of recently detected gas plumes indicate many more discoveries await. As more information is published on the biological communities associated with the gas plumes clustered on the continental shelf, the status of these sites should be evaluated against EBSA criteria and compared with known cold seeps. Generally, the depth and offshore location of cold seeps contribute to the difficulty and expense in researching them or exploring for additional sites. Future research cruises should continue to survey under-explored regions along the continental margin so that we can improve our understanding of the number and spatial extent of cold seeps. Additional focus on the collection of biological samples and inspection by taxonomists will inform whether there are seep species endemic to Canadian Pacific waters. The infrastructure built and maintained by ONC, which gathers real-time oceanographic data at Barkley Canyon and Clayoquot Slope, make these sites natural candidates for targeted, collaborative studies. Our understanding of the biology and ecology of cold seep ecosystems will be enhanced by future investigations focusing on temporal and spatial variability of seep communities, population connectivity of seep and carbonate-hosted suspension-feeding assemblages, quantification of trophic subsidies to surrounding margin habitats, and potential linkages between seeps and fishery species (e.g. sablefish, thornyhead, and crabs).

Contributors

Contributor	Affiliation
Benjamin Grupe	DFO Science, Pacific Region
Joy Hillier	DFO Oceans, Pacific Region
Danielle Scriven	DFO Oceans, Pacific Region
Tammy Norgard	DFO Science, Pacific Region
Erika Anderson	DFO Science, Pacific Region
Vaughn Barrie	Natural Resources Canada
Martin Scherwath	Ocean Networks Canada
Verena Tunnicliffe	University of Victoria

Approved by

Carmel Lowe
Regional Director
Science Branch, Pacific Region
Fisheries and Oceans Canada

November 27, 2017

Sources of information

Ardron, J.A., Clark, M.R., Penney, A.J., Hourigan, T.F., Rowden, A.A., Dunstan, P.K., Watling, L., Shank, T.M., Tracey, D.M., Dunn, M.R., and Parker, S.J. 2014. A systematic approach towards the identification and protection of vulnerable marine ecosystems. Mar. Policy 49: 146–154.

Arellano, S.M., Lee, O.O., Lafi, F.F., Yang, J., Wang, Y., Young, C.M., and Qian, P.Y. 2013. Deep Sequencing of *Myxilla (Ectyomyxilla) methanophila*, an Epibiotic Sponge on Cold-Seep Tubeworms, Reveals Methylotrophic, Thiotrophic, and Putative Hydrocarbon-Degrading Microbial Associations. Microb. Ecol. 65: 450–461.

Ban, S., Curtis, J.M.R., St. Germain, C., Perry, R.I., and Therriault, T.W. 2016. Identification of ecologically and biologically significant areas (EBSAs) in Canada's Offshore Pacific Bioregion. DFO Can. Sci. Advis. Sec. Res. Doc. 2016/034. 152 p.

Barr, N. 2011. Deep-sea chemistry. Day 2: Tiny bubbles, great explorations. MBARI Research Blog. (accessed 09 August 2017).

Barrie, J.V., Cook, S., and Conway, K.W. 2011. Cold seeps and benthic habitat on the Pacific margin of Canada. Cont. Shelf Res. 31: S85–S92.

Barry, J.P., and Kochevar, R.E. 1998. A tale of two clams: Differing chemosynthetic life styles among vesicomyids in Monterey Bay cold seeps. Cah. Biol. Mar. 39: 329–331.

Bell, K.L.C., Flanders, J., Bowman, A., and Raineault, N.A. 2017. New frontiers in ocean exploration: The E/V Nautilus, NOAA Ship Okeanos Explorer, and R/V Falkor 2016 field season. Oceanography 30: 94 p.

Boetius, A., and Wenzhöfer, F. 2013. Seafloor oxygen consumption fuelled by methane from cold seeps. Nat. Geosci. 6: 725–734.

Bowden, D.A., Rowden, A.A., Thurber, A.R., Baco, A.R., Levin, L.A., and Smith, C.R. 2013. Cold Seep Epifaunal Communities on the Hikurangi Margin, New Zealand: Composition, Succession, and Vulnerability to Human Activities. PLoS One 8: e76869.

Breen, A. 2002. Biological characteristics of a Vancouver Island margin cold seep assemblage. Thesis (M.Sc.) University of Victoria, 76 p.

Campanya-Llovet, N., and Snelgrove, P.V.R. 2016. Environmental drivers of spatial and temporal variation in infaunal communities at methane hydrates. Presented at 2016 Ocean Sciences Meeting. AGU/ASLO/TOS, New Orleans, LA, 21-27 Feb 2016. (Accessed 28 November 2017).

Canada – British Columbia marine protected area network strategy, 2014. (Accessed 28 November 2017).

Capelle, D.W., and Tortell, P.D. 2016. Factors controlling methane and nitrous-oxide variability in the southern British Columbia coastal upwelling system. Mar. Chem. 179: 56–67.

Chapman, R., Pohlman, J., Coffin, R., Chanton, J., and Lapham, L. 2004. Thermogenic gas hydrates in the northern Cascadia margin. Eos (Wash. DC). 85: 361–365.

Chatzievangelou, D., Doya, C., Thomsen, L., Purser, A., and Aguzzi, J. 2016. High-frequency patterns in the abundance of benthic species near a cold-seep - An internet operated vehicle application. PLoS One 11: e0163808.

Convention on Biological Diversity 2008. Ninth meeting of the Conference of the Parties to the Convention on Biological Diversity Decision IX/20 Sections 14 and 19. Bonn, Germany, 19–30 May 2008.(Accessed 28 November 2017)

Cordes, E.E., Bergquist, D.C., and Fisher, C.R. 2009. Macro-ecology of Gulf of Mexico cold seeps. Ann. Rev. Mar. Sci. 1: 143–168.

Cordes, E.E., Cunha, M.R., Galéron, J., Mora, C., Olu-Le Roy, K., Sibuet, M., Van Gaever, S., Vanreusel, A., and Levin, L.A. 2010. The influence of geological, geochemical, and biogenic habitat heterogeneity on seep biodiversity. Mar. Ecol. 31: 51–65.

DFO 2004. Identification of Ecologically and Biologically Significant Areas. DFO Can. Sci. Advis. Sec. Ecosystem Status Rep. Ottawa, 15 p.

DFO 2009a. Policy for Managing the Impacts of Fishing on Sensitive Benthic Areas. Fisheries and Oceans Canada, Canada. (Accessed 28 November 2017).

DFO 2009b. Development of a framework and principles for the biogeographic classification of Canadian marine areas. DFO Can. Sci. Advis. Sec. Sci. 17 p.

DFO 2011. Ecologically and biologically significant areas - Lessons learned. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 1-14 p.

DFO 2013. Evaluation of proposed ecologically and biologically significant areas in marine waters of British Columbia. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 1-21 p.

DFO 2015. Ecologically and biologically significant areas in Canada's Eastern Arctic biogeographic region. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 1-18 p.

DFO 2016. Proceedings of the Pacific regional peer review of the Identification of Ecologically and Biologically Significant Areas (EBSAs) in the Offshore Pacific Bioregion; February 11-12, 2015. DFO Can. Sci. Advis. Sec. Proceed. Ser. 32.

Duperron, S., Sibuet, M., MacGregor, B.J., Kuypers, M.M.M., Fisher, C.R., and Dubilier, N. 2007. Diversity, relative abundance and metabolic potential of bacterial endosymbionts in three *Bathymodiolus* mussel species from cold seeps in the Gulf of Mexico. Environ. Microbiol. 9: 1423–1438.

FAO 2009. International guidelines for the management of deep-sea fisheries in the high seas. Rome. 73 p. (Accessed 28 November 2017).

FAO 2016. Vulnerable marine ecosystems: processes and practices in the high seas. FAO Fisheries and Aquaculture, Rome, Italy, 185 p. (Accessed 28 November 2017).

Felbeck, H. 1983. Sulfide oxidation and carbon fixation by the gutless clam *Solemya reidi*: an animal-bacteria symbiosis. J. Comp. Physiol. 152: 3–11.

Fisher, C.R., Urcuyo, I.A., Simpkins, M.A., and Nix, E. 1997. Life in the Slow Lane: Growth and Longevity of Cold-seep Vestimentiferans. Mar. Ecol. 18: 83–94.

Frye, D., Freitag, L., Detrick, R., Collins, J., Delaney, J.R., Kelley, D.S., LaBonte, A., and Brown, K. 2006. An Acoustically Linked Moored- Buoy Ocean Observatory. Eos (Washington. DC). 87: 213–218.

Frye, D., Ware, J., Grund, M., Partan, J., Koski, P., Singh, S., Freitag, L., Collins, J., and Detrick, R. 2005. An Acoustically-Linked Deep-Ocean Observatory. Proc. IEEE Oceans 2005 Europe, Brest, France. p. 969–974. (Accessed 28 November 2017).

Furlong, J. 2013. Characteristic morphology, backscatter, and sub-seafloor structures of cold-vents on the northern Cascadia margin from high-resolution autonomous underwater vehicle data. Thesis (M.Sc.) University of Victoria, 171 p.

Grupe, B.M., Krach, M.L., Pasulka, A.L., Maloney, J.M., Levin, L.A., and Frieder, C.A. 2015. Methane seep ecosystem functions and services from a recently discovered southern California seep. Mar. Ecol. 36: 91–108.

Haacke, R.R,, Westbrook, G.K., and Hyndman R.D. (2008). Formation of the bottom-simulating reflector and its link to vertical fluid flow. In Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, Canada.

Halliday, E.J., Barrie, J. V., Chapman, N.R., and Rohr, K.M.M. 2008. Structurally controlled hydrocarbon seeps on a glaciated continental margin, Hecate Strait, offshore British Columbia. Mar. Geol. 252: 193–206.

Hautala, S.L., Solomon, E.A., Johnson, H.P., Harris, R.N., and Miller, U.K. 2014. Dissociation of Cascadia margin gas hydrates in response To contemporary ocean warming. Geophys. Res. Lett. 41: 8486–8494.

He, T., Spence, G.D., Riedel, M., Hyndman, R.D., Chapman, N.R. (2007). Fluid flow and origin of a carbonate mound offshore Vancouver Island: seismic and heat flow constraints. Mar. Geol. 239:83–98. doi:10.1016/j.margeo.2007.01.002

Hyndman, R.D. 1995. The Lithoprobe corridor across the Vancouver Island continental margin: the structural and tectonic consequences of subduction. Can. J. Earth Sci. 32: 1777–1802.

Johnson, H.P., Miller, U.K., Salmi, M.S., and Solomon, E.A. 2015. Analysis of bubble plume distributions to evaluate methane hydrate decomposition on the continental slope. Geochemistry, Geophys. Geosystems 16: 3825–3839.

Johnson, S.B., Krylova, E.M., Audzijonyte, A., Sahling, H., and Vrijenhoek, R.C. 2016. Phylogeny and origins of chemosynthetic vesicomyid clams. Syst. Biodivers. 2000: 1–15.

Johnson, S.B., Warén, A., Lee, R.W., Kano, Y., Kaim, A., Davis, A., Strong, E.E., and Vrijenhoek, R.C. 2010. *Rubyspira*, new genus and two new species of bone-eating deep-sea snails with ancient habits. Biol. Bull. 219: 166–177.

Krylova, E.M., and Sahling, H. 2006. Recent bivalve molluscs of the genus *Calyptogena* (Vesicomyidae). J. Molluscan Stud. 72: 359–395.

Kulm, L.D., Suess, E., Moore, J.C., Carson, B., Lewis, B.T., Ritger, S.D., Kadko, D.C., Thornburg, T.M., Embley, R.W., Rugh, W.D., Massoth, G.J., Langseth, M.G., Cochrane, G.R., and Scamman, R.L. 1986. Oregon subduction zone: venting, fauna and carbonates. Science 231: 561–566.

LaBonte, A.L. 2007. An Investigation of Deformation and Fluid Flow at Subduction Zones Using Newly Developed Instrumentation and Finite Element Modeling. Thesis (Ph.D.) University of California, San Diego, 211 p.

Lapham, L., Wilson, R., Riedel, M., Paull, C.K., and Holmes, M.E. 2013. Temporal variability of in situ methane concentrations in gas hydrate-bearing sediments near Bullseye Vent, Northern Cascadia Margin. Geochemistry, Geophys. Geosystems 14: 2445–2459.

Le Bris, N., Arnaud-Haond, S., Beaulieu, S., Cordes, E.E., Hilário, A., Rogers, A.D., van de Gaever, S., and Watanabe, H. 2016. Chapter 45. Hydrothermal vents and cold seeps. First global integrated marine assessment. United Nations. p. 1-18. (Accessed 28 November 2017).

Levin, L.A. 2005. Ecology of cold seep sediments: Interactions of fauna with flow, chemistry and microbes. Oceanogr. Mar. Biol. An Annu. Rev. 43: 1–46.

Levin, L.A., Baco, A.R., Bowden, D.A., Colaco, A., Cordes, E.E., Cunha, M.R., Demopoulos, A.W.J., Gobin, J, Grupe, B.M., Le, J., Metaxas, A., Netburn, A.N., Rouse, G.W., Thurber, A.R., Tunnicliffe, V., Van Dover, C.L., Vanreusel, A., and Watling, L. 2016. Hydrothermal Vents and Methane Seeps: Rethinking the Sphere of Influence. Front. Mar. Sci. 3: 72.

Levin, L.A., Mendoza, G.F., Gonzalez, J.P., Thurber, A.R., and Cordes, E.E. 2010. Diversity of bathyal macrofauna on the northeastern Pacific margin: The influence of methane seeps and oxygen minimum zones. Mar. Ecol. 31: 94–110.

Levin, L.A., Mendoza, G.F., and Grupe, B.M. 2017. Methane seepage effects on biodiversity and biological traits of macrofauna inhabiting authigenic carbonates. Deep Sea Res. Part II Top. Stud. Oceanogr. 137: 26–41.

Levin, L.A., Mendoza, G.F., Grupe, B.M., Gonzalez, J.P., Jellison, B., Rouse, G., Thurber, A.R., and Waren, A. 2015. Biodiversity on the rocks: Macrofauna inhabiting authigenic carbonate at Costa Rica methane seeps. PLoS One 10: e0136129.

Levin, L.A., and Michener, R.H. 2002. Isotopic evidence for chemosynthesis-based nutrition of macrobenthos: The lightness of being at Pacific methane seeps. Limnol. Oceanogr. 47: 1336–1345.

Levin, L.A., Orphan, V.J., Rouse, G.W., Rathburn, A.E., Ussler, W., Cook, G.S., Goffredi, S.K., Perez, E.M., Waren, A., Grupe, B.M., Chadwick, G., and Strickrott, B. 2012. A hydrothermal seep on the Costa Rica margin: middle ground in a continuum of reducing ecosystems. Proc. R. Soc. B Biol. Sci. 279: 2580–2588.

Lu, H., Seo, Y., Lee, J., Moudrakovski, I., Ripmeester, J.A., Chapman, N.R., Coffin, R.B., Gardner, G., and Pohlman, J. 2007. Complex gas hydrate from the Cascadia margin. Nature 445: 303–306.

Luff, R., Wallmann, K., and Aloisi, G. 2004. Numerical modeling of carbonate crust formation at cold vent sites: Significance for fluid and methane budgets and chemosynthetic biological communities. Earth Planet. Sci. Lett. 221: 337–353.

Merle, S., and Embley, R.W. 2016. NA072-Seeps and Ecosystems of the Cascadia Margin. June 1-20, 2016 Victoria BC, Canada to San Francisco CA, USA. 276 p.(Accessed 28 November 2017).

Nesbitt, E.A., Martin, R.A., and Campbell, K.A. 2013. New records of Oligocene diffuse hydrocarbon seeps, northern Cascadia margin. Palaeogeogr. Palaeoclimatol. Palaeoecol. 390: 116–129.

OBIS. 2017. Ocean Biogeographic Information System. Intergovernmental Oceanographic Commission of UNESCO. www.iobis.org. (accessed 07 March 2017).

Orphan, V.J., House, C.H., Hinrichs, K.-U., Mckeegan, K.D., and Delong, E.F. 2001. Methane-Consuming Archaea Revealed by Directly Coupled Isotopic and Phylogenetic Analysis. Science 293: 484–487.

Paull, C.K., Caress, D.W., Thomas, H., Lundsten, E., Anderson, K., Gwiazda, R., Riedel, M., McGann, M., and Herguera, J.C. 2015a. Seafloor geomorphic manifestations of gas venting and shallow subbottom gas hydrate occurrences. Geosphere 11: 491–513.

Paull, C.K., Dallimore, S.R., Caress, D.W., Gwiazda, R., Melling, H., Riedel, M., Jin, Y.K., Hong, J.K., Kim, Y.G., Graves, D., Sherman, A., Lundsten, E., Anderson, K., Lundsten, L., Villinger, H., Kopf, A., Johnson, S.B., Hughes Clarke, J., Blasco, S., Conway, K., Neelands, P., Thomas, H., and Côté, M. 2015b. Active mud volcanoes on the continental slope of the Canadian Beaufort Sea. Geochem. Geophy. Geosy. 16: 3160–3181.

Pohlman, J.W. 2006. Sediment biogeochemistry of northern Cascadia Margin shallow gas hydrate systems. Thesis (Ph.D.) The College of William and Mary, Virginia. 239 p.(Accessed 28 November 2017).

Pohlman, J.W., Bauer, J.E., Canuel, E.A., Grabowski, K.S., Knies, D.L., Mitchell, C.S., Whiticar, M.J., and Coffin, R.B. 2009. Methane sources in gas hydrate-bearing cold seeps: Evidence from radiocarbon and stable isotopes. Mar. Chem. 115: 102–109.

Pohlman, J.W., Canuel, E.A., Chapman, N.R., Spence, G.D., Whiticar, M.J., and Coffin, R.B. 2005. The origin of thermogenic gas hydrates on the northern Cascadia Margin as inferred from isotopic ($^{13}C/^{12}C$ and D/H) and molecular composition of hydrate and vent gas. Org. Geochem. 36: 703–716.

Potter, B. 2004. The Keck Project (Observatories without Cables): Seafloor Observatory Installation, Intervention, and Troubleshooting. Moss Landing, California, 28 p. (Accessed 10 April 2017)

Purser, A., Thomsen, L., Barnes, C., Best, M., Chapman, R., Hofbauer, M., Menzel, M., and Wagner, H. 2013. Temporal and spatial benthic data collection via an internet operated Deep Sea Crawler. Methods Oceanogr. 5: 1–18.

Ramirez-Llodra, E., Brandt, A., Danovaro, R., De Mol, B., Escobar, E., German, C.R., Levin, L.A., Martinez Arbizu, P., Menot, L., Buhl-Mortensen, P., Narayanaswamy, B.E., Smith, C.R., Tittensor, D.P., Tyler, P.A., Vanreusel, A., and Vecchione, M. 2010. Deep, diverse and definitely different: Unique attributes of the world's largest ecosystem. 7: 2851–2899.

Reid, R.G.B. 1980. Aspects of the biology of a gutless species of *Solemya* (Bivalvia: Protobranchia). Can. J. Zool. 58: 386–393.

Riedel, M., Scherwath, M., Roemer, M., Paull, C.K., Spence, G.D., and Veloso, M. 2016. Natural Gas Venting on the Northern Cascadia Margin. Abstract OS44A-09 presented at 2016 Fall Meeting, AGU, San Fran. Cal. 12-16 Dec 2016. (Accessed 28 November 2017).

Riedel, M., Tréhu, A.M., and Spence, G.D. 2010. Characterizing the thermal regime of cold vents at the northern Cascadia margin from bottom-simulating reflector distributions, heat-probe measurements and borehole temperature data. Mar. Geophys. Res. 31: 1–16.

Römer, M., Riedel, M., Scherwath, M., Heesemann, M., and Spence, G.D. 2016. Tidally controlled gas bubble emissions: A comprehensive study using long-termmonitoring data fromthe NEPTUNE cabled observatory offshore Vancouver Island. Geochem. Geophys. Geosy. 17: 3797–3814.

Ruppel, C.D., and Kessler, J.D. 2017. The Interaction of Climate Change and Methane Hydrates. Rev. Geophys. 55: 126–168.

Sasaki, T., Warén, A., and Kano, Y. 2010. Gastropods from recent hot vents and cold seeps: systematics, diversity and life strategies. The Vent and Seep Biota. (accessed 23 March 2015).

Seike, K., Jenkins, R.G., Watanabe, H., Nomaki, H., and Sato, K. 2012. Novel use of burrow casting as a research tool in deep-sea ecology. Biol. Lett. 8: 648–651.

Sibuet, M., and Olu, K. 1998. Biogeography, biodiversity and fluid dependence of deep-sea cold-seep communities at active and passive margins. Deep. Res. Part II Top. Stud. Oceanogr. 45: 517–567.

Sinclair, A. 2007. Trends in Groundfish Bottom Trawl Fishing Activity in BC. Can. Sci. Advis. Sec. Res. Doc. 2017/006. 26 p. (Accessed 28 November 2017).

Sitka Sound Science Center 2015. Actively venting underwater volcano discovered in Dixon Entrance. SitNews. Ketchikan, Alaska. (accessed 07 March 2016).

Skarke, A., Ruppel, C., Kodis, M., Brothers, D., and Lobecker, E. 2014. Widespread methane leakage from the sea floor on the northern US Atlantic margin. Nat. Geosci. 7: 657–661.

Southward, E.C., Tunnicliffe, V., Black, M.B., Dixon, D.R., and Dixon, L.R.J. 1996. Ocean-ridge segmentation and vent tubeworms (Vestimentifera) in the NE Pacific. Geol. Soc. London, Spec. Publ. 118: 211–224.

Spence, G.D., and Chapman, N.R. 2001. Fishing Trawler Nets Massive "Catch" of Methane Hydrates. Eos (Washington. DC). 82: 621–622.

Stiller, J., Rousset, V., Pleijel, F., Chevaldonné, P., Vrijenhoek, R.C., and Rouse, G.W. 2013. Phylogeny, biogeography and systematics of hydrothermal vent and methane seep *Amphisamytha* (Ampharetidae, Annelida), with descriptions of three new species. Syst. Biodivers. 11: 35–65.

Suess, E. 2014. Marine cold seeps and their manifestations: geological control, biogeochemical criteria and environmental conditions. Int. J. Earth Sci. 103: 1889–1916.

Taylor, J.D., and Glover, E.A. 2010. Chemosymbiotic bivalves. The Vent and Seep Biota. Springer Netherlands. p. 107-135.

Thomsen, L., Barnes, C., Best, M., Chapman, R., Pirenne, B., Thomson, R., and Vogt, J. 2012. Ocean circulation promotes methane release from gas hydrate outcrops at the NEPTUNE Canada Barkley Canyon node. Geophys. Res. Lett. 39: L16605.

Thurber, A.R., Jones, W.J., and Schnabel, K. 2011. Dancing for food in the deep sea: Bacterial farming by a new species of Yeti crab. PLoS One 6: 1–12.

Thurber, A.R., Kröger, K., Neira, C., Wiklund, H., and Levin, L.A. 2010. Stable isotope signatures and methane use by New Zealand cold seep benthos. Mar. Geol. 272: 260–269.

Tunnicliffe, V., Juniper, S.K., and Sibuet, M. 2003. Reducing Environments of the Deep-Sea Floor. Ecosystems of the World. p. 81–110. (Accessed 28 November 2017).

Tunnicliffe, V., McArthur, A.A.G., and McHugh, D. 1998. A Biogeographical Perspective of the Deep-Sea Hydrothermal Vent Fauna. Adv. Mar. Biol. 34: 353–442.

United Nations General Assembly 2011. Sustainable fisheries, including through the 1995 Agreement for the Implementation of the Provisions of the United Nations Convention on the Law of the Sea of 10 December 1982 relating to the Conservation and Management of Straddling Fish Stocks and HIghly Migratory Fish Stocks, and related instruments: resolution/adopted by the General Assembly. 66/68:1-30. (Accessed 28 November 2018).

Warén, A., and Bouchet, P. 1993. New records, species, genera, and a new family of gastropods from hydrothermal vents and hydrocarbon seeps. Zool. Scr. 22: 1–90.

Warén, A., and Bouchet, P. 2001. Gastropoda and Monoplacophora from hydrothermal vents and seeps: New taxa and records. Veliger 44: 116–231.

Westbrook, G.K., Carson, B., Musgrave, R.J., Ashi, J., Baranov, B., Brown, K.M., and et al. 1994. Proceedings of the Ocean Drilling Program, Initial Reports. College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.ir.146-1.1994. (Accessed 28 November 2017).

Appendix

*Table 1: Canadian Pacific cold seep names, locations, depths, and sources of data. * indicates source of coordinates given in table.*

Region	Seep Name	Latitude	Longitude	Depth (m)	Source
Haida Gwaii	Dixon Entrance Seep	54.277163	-134.195518	997	*Barrie J. V. unpublished data, Sitka Sound Science Center (2015).
Haida Gwaii	Dixon Entrance Seep	54.277523	-134.19518	996	*Barrie J. V. unpublished data, Sitka Sound Science Center (2015).
Haida Gwaii	Dixon Entrance Seep	54.278015	-134.194702	993	*Barrie J. V. unpublished data, Sitka Sound Science Center (2015).
Haida Gwaii	Dixon Entrance Seep	54.278782	-134.193973	988	*Barrie J. V. unpublished data, Sitka Sound Science Center (2015).
Haida Gwaii	Dixon Entrance Seep	54.280852	-134.196493	1019	*Barrie J. V. unpublished data, Sitka Sound Science Center (2015).
Haida Gwaii	Haida Gwaii west central	53.185633	-132.84395	682	*Barrie J. V. unpublished data
Haida Gwaii	Queen Charlotte Fault	52.031283	-131.447383	802	*Barrie J. V. unpublished data

Region	Seep Name	Latitude	Longitude	Depth (m)	Source
Haida Gwaii	Queen Charlotte Fault volcano	52.020467	-131.448083	819	*Barrie J. V. unpublished data
Hecate Strait	Hecate Strait Seep	53.004167	-130.6541667	130	Barrie et al. (2011)
Nootka fracture zone	Nootka seep site	49.313	-127.697	2320	*Frye et al. (2005), Frye et al. (2006)
Nootka fracture zone	Proposed UW site	49.295	-127.68	2260	*Frye et al. (2005), Frye et al. (2006)
Clayoquot Slope	Spinnaker Flare	48.714	-126.902	1323	*Paull et al. (2015a), Furlong (2013)
Clayoquot Slope	Cucumber Ridge	48.707067	-126.909967	1330	Breen (2002), Reidel et al. (2010), *He et al. (2007)
Clayoquot Slope	Cucumber Ridge	48.702222	-126.925	1330	*Furlong (2013), estimate of site location from map
Clayoquot Slope	Cucumber Ridge	48.7	-126.9	1313	*Breen (2002), approximate coordinates only
Clayoquot Slope	Ridge Crest Crater	48.692	-126.8581	1215	Furlong (2013), estimate of site location from map, *Paull et al. (2015a), detailed map

Region	Seep Name	Latitude	Longitude	Depth (m)	Source
Clayoquot Slope	Bubbly Gulch	48.675	-126.84	1268	*Paull et al. (2015a)
Clayoquot Slope	Gastown Alley	48.6681	-126.848	1260	*Römer et al. (2016)
Clayoquot Slope	Gastown Alley	48.67	-126.8422	1260	*Römer et al. (2016)
Clayoquot Slope	Bullseye Vent	48.6669	-126.8525	1268	*Paull et al. (2015a)
Clayoquot Slope	Bullseye Vent	48.669	-126.849	1258	*Paull et al. (2015a)
Clayoquot Slope	Blank Zone 1	48.666667	-126.833333	1270	*Breen (2002)
Clayoquot Slope	Amnesiac Flare	48.661667	-126.9183333	1290	Haacke et al. (2008), *Riedel et al. (2010)
Barkley Canyon	Methane gas hydrates	48.312778	-126.065833	890	*Chapman et al. (2004)
Barkley Canyon	Hydrate mounds	48.311	-126.0655167	859	*Pohlman (2006)
Barkley-Nitinat Ridge	Tully gas vent field	48.177	-126.099	905-908	*NOAA Deep Sea Coral Data Portal cnidarians, OBIS (2017) lists cnidarians at "Tully Vent Field"

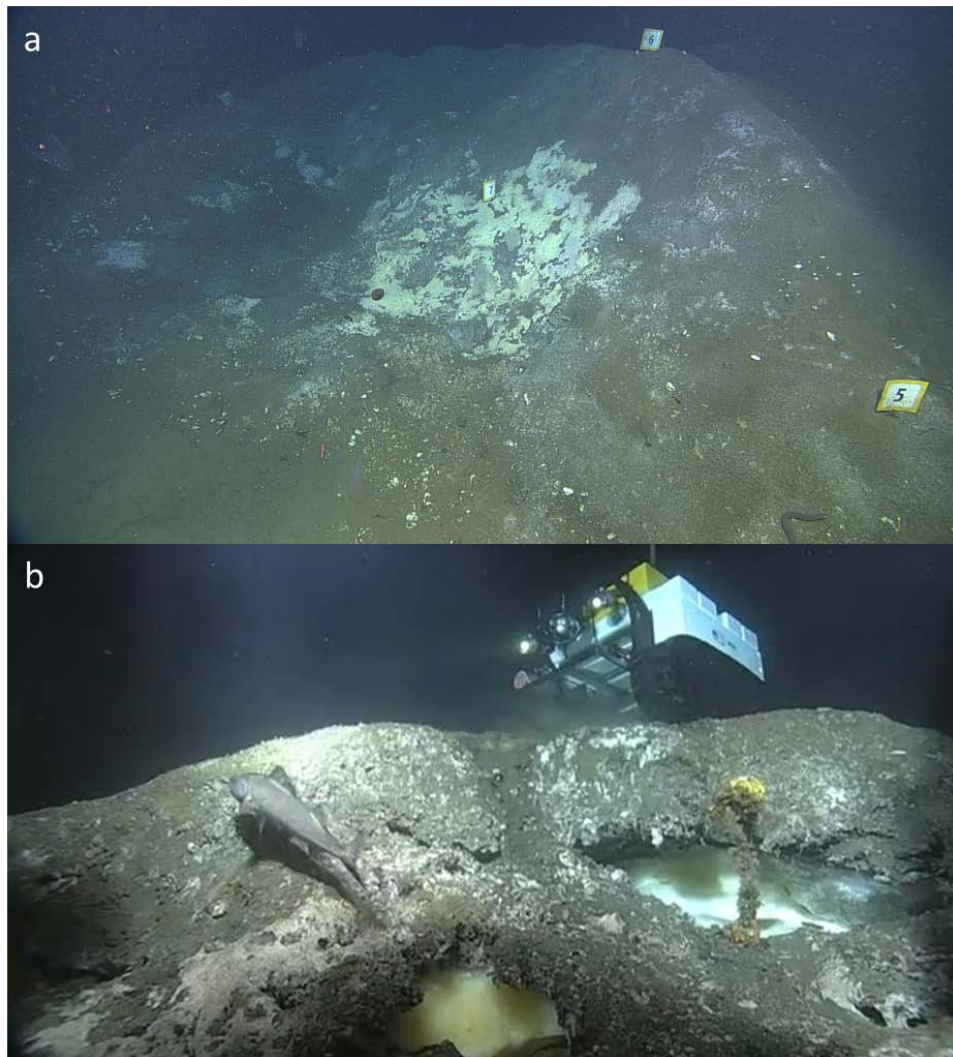| Region	Seep Name	Latitude	Longitude	Depth (m)	Source
Barkley-Nitinat Ridge	Barkley-Nitinat Ridge	48.18795	-126.080733	940	*Scherwath M. personal communication, Barr 2011, Paull et al. (2015a)

Figure 2. Images from Barkley Canyon. A) Typical bacterial mat associated with mounded sediments; B) a sablefish swims by exposed gas hydrate while the ONC rover "Wally" collects environmental data and imagery. Field of view (FOV) is about 3m. Photos by Ocean Networks Canada.
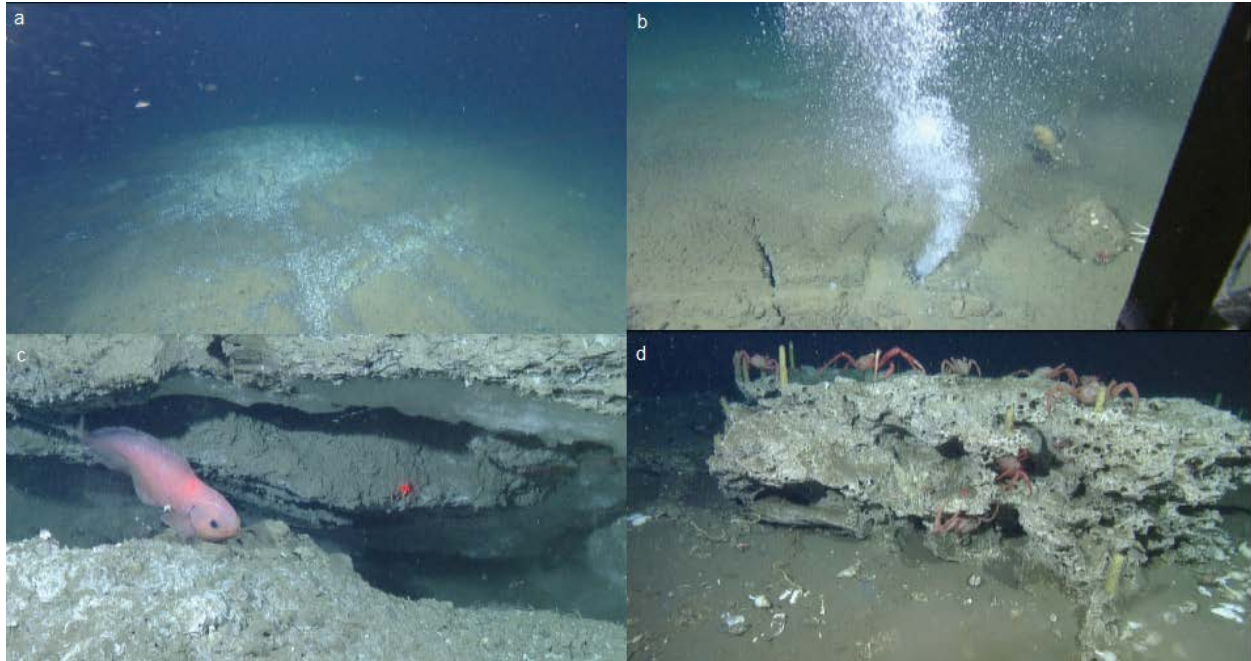
Figure 3. Images from MBARI dives to active cold seeps on Clayoquot Slope. A) flanks of Bubbly Gulch with which bacterial mat (FOV = 3m); B) plume of gas emanating from a hole following use of a push core at Bubbly Gulch (FOV = 2m); C) a snailfish (Liparidae, Careproctus) in a crack where massive gas hydrate is exposed at Spinnaker Vent (FOV = 50cm); D) authigenic carbonate bolder at Spinnaker Vent, providing habitat for many crabs, Neptunea egg cases (yellow columns) with clams in sediments; (FOV = 3m). Images previously published in Paull et al. (2015a) and used here with permission from the Geological Society of America.
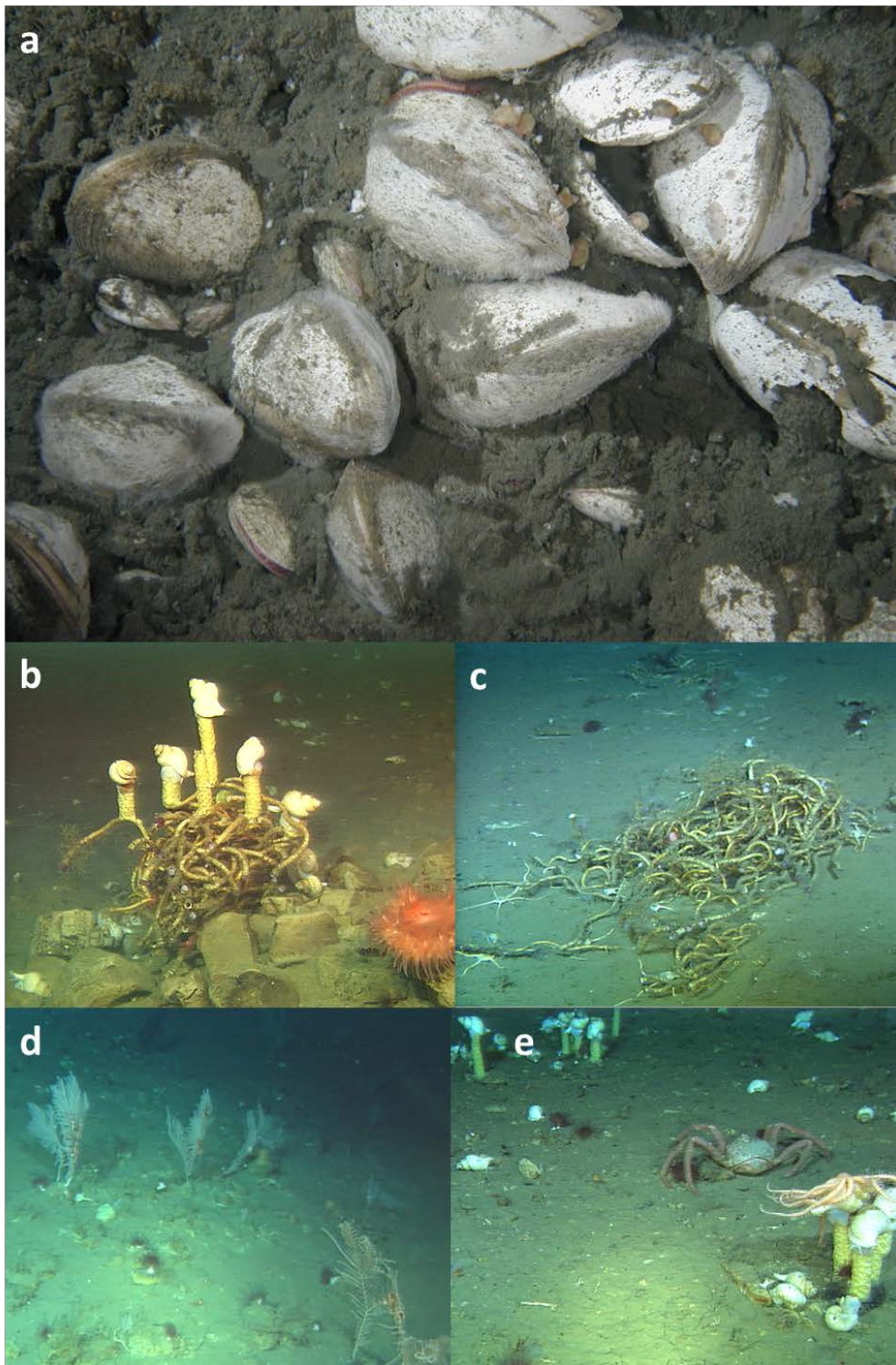
Figure 4. Images from ROPOS dives in 2001 at cold seeps on Cucumber Ridge ("northern carbonate mound" in Breen (2002)). A) live vesicomyid clams with various epifaunal species; B) clump of living tubeworms (Lamellibrachia barhami) with female Neptunea sp. sitting atop egg towers; C) L. barhami clump on seep sediments; D) sea fans, sea urchins, and brittle stars (non-seep fauna) living on carbonates; E) Neptunea sp. egg towers, spider crab, and sea star; FOV is about 1 m, except panel A is ~30cm. Images provided courtesy of V. Tunnicliffe.
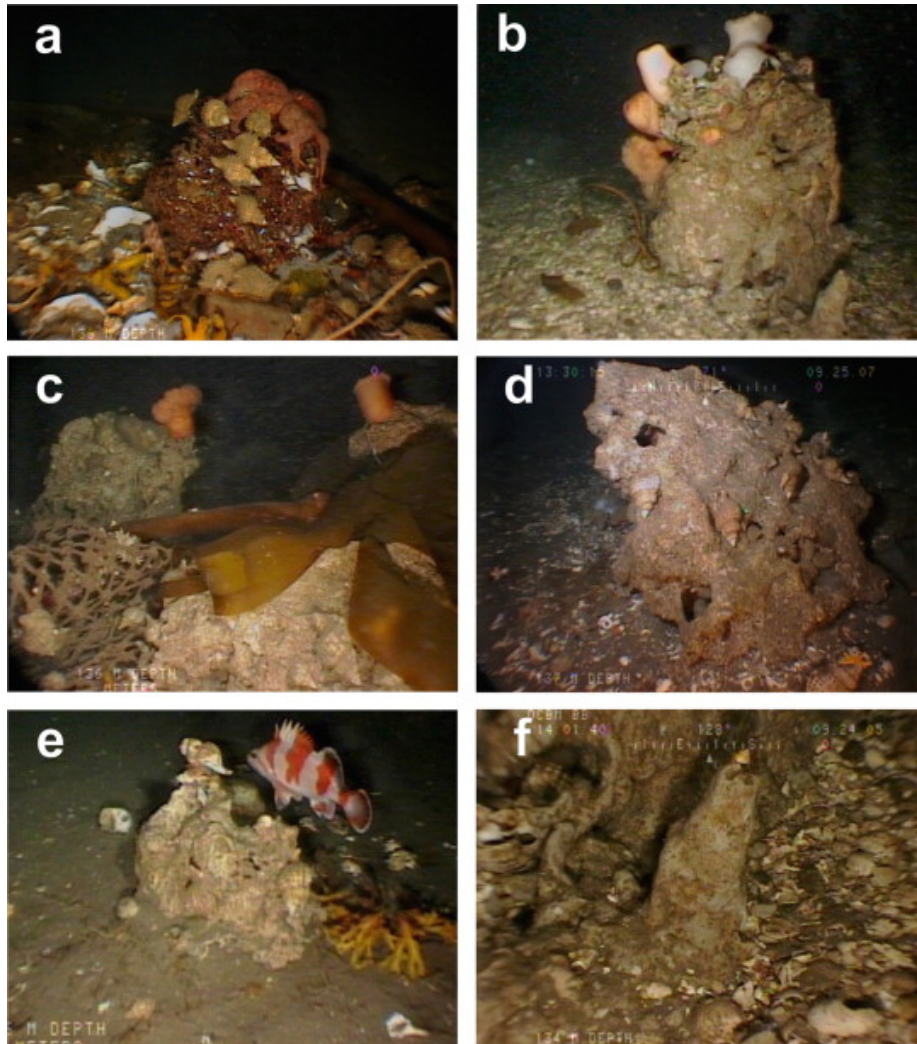
Figure 5. Images of carbonate chimneys formed at Hecate Strait cold seeps (~135m depth). A) sea star Pycnopodia helianthoides *feeding on Oregon tritons (*Fusitriton oregonensis*); B) anemones (*Metridium gigantium*) occupy many chimneys; C) fishing gear wrapped around carbonate chimney; D) carbonate chimney with tritons; E) redbanded rockfish (*Sebastes babcocki*) were associated with carbonate chimneys; F) gas bubbles were observed emanating from a small vent surrounded by shelly debris. Field of view was not provided, but appears to be 50-100 cm for most images. Images previously published in Barrie* et al. *2011 and used here with permission from Elsevier.*
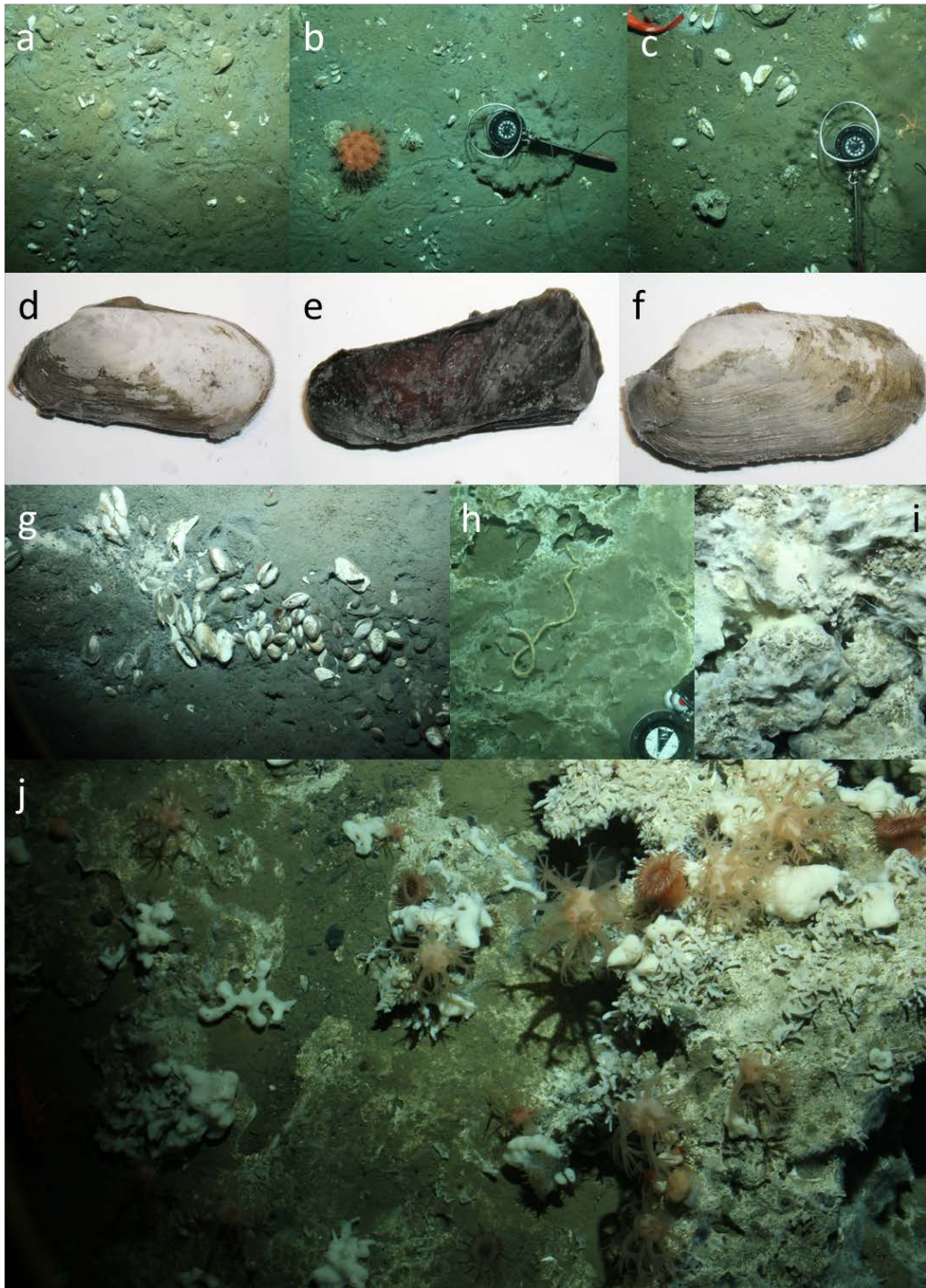
Figure 6. A-C) Drop camera images from cold seeps discovered off Haida Gwaii in 2011 (station 2011002PGC-26); D-F) chemosymbiont-hosting bivalves including Calyptogena starobogatovi *and an unidentified mussel (E) recovered in IKU grabs at Dixon Entrance seeps off Haida Gwaii in 2015 (station 2015004PGC-32); G-J) drop camera images from Dixon Entrance seep (station 2015004PGC-31) including vesicomyid clams (G), a* Lamellibrachia *tubeworm (H), filamentous bacteria covering seep carbonate (I), and suspension-feeding sponges and soft corals on carbonates (J). Images provided courtesy of J.V. Barrie, Natural Resources Canada.*

This Report is Available from the:

Centre for Science Advice
Pacific Region
Fisheries and Oceans Canada
3190 Hammond Bay Road
Nanaimo, BC V9T 6N7

Telephone: (250) 756-7208
E-Mail: csap@dfo-mpo.gc.ca
Internet address: www.dfo-mpo.gc.ca/csas-sccs/

Correct Citation for this Publication:

DFO. 2018. Assessment of Canadian Pacific Cold Seeps against Criteria for Determining
Ecologically and Biologically Significant Areas. DFO Can. Sci. Advis. Sec. Sci. Resp.
2018/002.

Aussi disponible en français :

*MPO. 2018. Évaluation des suintements froids du Pacifique canadien par rapport aux critères
de détermination des zones d'importance écologique et biologique. Secr. can. de
consult. sci. du MPO, Rép. des Sci. 2018/002.*