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Hydrothermal Vent Ecosystems

Écosystèmes des cheminées hydrothermales

Joseph H. Banoub

Science Branch
Department of Fisheries and Oceans
P. O. Box 5667
St. John's NL A1C 5X1

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ABSTRACT

State-of-the-art scientific technological development has made it possible for humans to reach the Earth's last frontier, that is the deepest areas of the sea and hence, discover hydrothermal vents. Hydrothermal vents possess unique, unscathed hidden ecosystems with oasis-like luxuriant and immense biological diversity. However, the biological communities and their inhabitants in these hydrothermal vents are starting to feel the pressure of human impact. In addition to deep-sea fishing, novel entrepreneurial discovery expeditions have been increasingly undertaken, and their different aims have shifted from geological and geophysical mining exploring studies to ecological, biological, and physiological studies. Recently, another newly invented biotechnological activity, described as the "bioprospecting" of the hot vents, has been started in search of new targeted products having potential as pharmaceuticals, molecular probes, enzymes, cosmetics, nutritional supplements, and agrichemicals. Unfortunately, it has been determined that these deep-sea technological activities, in addition to the fisheries in these areas, introduce a new and potentially serious threat for these deep-sea communities.

This publication's main intent is the statement position that deep-sea fishes qualify as endangered; hence the sustainable use of the deep sea and the organisms that inhabit it should be promoted and encouraged.

RÉSUMÉ

Les développements scientifiques à la fine pointe de la technologie ont permis à l'humain de percer les derniers secrets de la Terre, soit ceux des régions les plus profondes de l'océan, et ainsi de découvrir les cheminées hydrothermales. Les cheminées hydrothermales possèdent des écosystèmes cachés uniques et intacts avec une biodiversité luxuriante et immense qui ressemble à une oasis. Cependant, les communautés biologiques et organismes qui habitent ces cheminées hydrothermales commencent à ressentir les pressions de l'activité humaine. Outre la pêche en eau profonde, il y a eu de plus en plus de nouvelles expéditions de découvertes par des entreprises, et les différents objectifs sont passés des études d'exploration minière géologiques ou géophysiques aux études écologiques, biologiques et physiologiques. On a récemment commencé à y pratiquer une autre activité de biotechnologie nouvellement mise au point, qu'on appelle la « bioprospection » des sources hydrothermales, laquelle consiste à rechercher de nouveaux produits ciblés ayant un potentiel comme produits pharmaceutiques, sondes moléculaires, enzymes, suppléments nutritifs et produits agrochimiques. Malheureusement, il a été établi que ces activités technologiques dans les profondeurs océaniques, en plus de la pêche dans ces zones, posent des menaces nouvelles et possiblement graves pour ces communautés sous-marines.

Le principal objectif de cette publication est de poser l'énoncé de principe selon lequel les poissons des mers profondes sont admissibles au statut d'espèces menacées; ce faisant, l'utilisation durable des eaux profondes de la mer et des organismes qui y vivent devrait être favorisée et encouragée.

1.0 INTRODUCTION

In 1977, the exciting discovery of hydrothermal vents was made by scientists diving in the *Alvin* to the Galapagos spreading center in the eastern Pacific off Ecuador, where at a depth of about 2.5 km, they saw the spectacular sight of clouds of what looked like black smoke gushing out from tall chimneys on the deep ocean floor (black smoker) (Corliss *et al*. 1979).

Vents form where the planet's crustal plate has magma welling up from below forming mountain ranges known as the mid-ocean ridges. These mid-ocean ridges are a 46,000-mile-long chain of mountains that wraps around the Earth like the seams on a baseball (lt 1995). The hydrothermal vents are formed when magma from the deep parts of the Earth emerges at the spreading centers forming cracks that then permits seawater to seep a mile or two down into the hot rock (Figures 1 and 2). Consequently, seawater penetrates the crust and is heated by the magma, to produce hot water loaded with high concentrations of various metals and dissolved sulphide, which emanate into the ocean, forming a hot vent (Figure 3) (Corliss *et al.* 1979). Formation of the large, polymetallic chimneys takes place when dissolved minerals and metal ions carried upward by the hydrothermal fluids precipitate on contact with cold seawater. The flanks of the chimneys and the surrounding seawater support an abundant fauna that forms an unusual mosaic community whose composition is constantly changing in response to shifting temperature and chemical conditions (Speer and Rona 1989).

A few vents have also been found at seamounts, underwater volcanoes that are not located at the intersection of crustal plates. The largest vent field, called TAG (short for Trans-Atlantic Geotraverse), is about the size and shape of a football stadium (Zeng *et al.* 2001). Other fields have more fanciful names like Clam Acres, Mussel Bed, Rose Garden, Garden of Eden, Broken Spur, and Lucky Strike. The “Snow Blower” field is named for the white, flaky bacteria discharged from its vents (Zeng *et al.* 2001). Genesis is a vent that sputtered out but came back to life a few years later (Rudnick 1995).

Deep-sea habitats are shaped by geological processes. A new seafloor, following formation by magmatic accretion, exists for a few million years as a bare-rock volcanic terrain. This is followed by tens of millions of years as a sedimented abyssal plain before finally being subducted (a geologic process in which one edge of one crustal plate is forced below the edge of another in the trenches) (Bogdanov *et al.* 2008; Herzig and Hannington 2006).

Hydrothermal vents host an array of life which has adapted to living in often highly toxic waters and complete darkness. In addition to surviving at high pressures, organisms found in these environments must also be able to thrive at extreme temperatures (Gage 1996).

Hydrothermal vents can be situated both at shallow and abyssal depths. Maugeri *et al.* (2002) reported that the degree of fauna variation changed at the depth of approximately 200 m. Deep sea (>200 m) hydrothermal communities were found to differ from shallow-water ones (<200 m) in a much higher ratio of vent obligate taxa (Maugeri *et al.* 2002). Though deep-sea hydrothermal vents are typically low in biodiversity at the macro-organism level, they host one of the highest levels of microbial diversity on the planet (Gage and Tyler 1996; Sibuet and Olu 1998). The bacteria colonizing this area use sulphur from the waters of deep-sea vents as a source of energy and can be found both in the water column and as surface colonies on the rocks near hot vents (Maugeri *et al.* 2002). Active hydrothermal vents are believed to exist on Jupiter's moon Europa, and ancient hydrothermal vents have been speculated to exist on Mars.

Cold seeps occur mostly along continental margins, and are a result of methane or methane-hydrate ice, hydrogen sulphide, or other hydrocarbon-rich fluid leakages from the sediments. The cold seeps provide energy for bacteria of which clams, mussels, and tubeworms feed upon (Craig *et al.* 1987). The cold seeps bacteria process sulphides and methane through chemosynthesis into chemical energy (Butler *et al.* 2001; Dia *et al.* 1993; Ritger *et al.* 1987; Wallmann *et al.* 1997). Where methane seeps out of the bottom of seas and oceans below 600 m depth, methane hydrate is solid since methane freezes at low temperatures and high pressure. Cold adapted organisms found in cold seeps prosper at temperatures close to the freezing point of water and in the deep sea have to be adapted to both extreme temperatures and extremely high pressures (Butler *et al.* 2001; Dia *et al.* 1993; Ritger *et al.* 1987; Wallmann *et al.* 1997).

1.1 CANADIAN SETTING

Spreading ridge crests do not enter Canadian waters in either the Arctic or Atlantic oceans. At the latitude of Canada, the Mid-Atlantic Ridge bisects Iceland and runs east of Greenland (Delaney *et al.* 1984; Tunnicliffe and Thomson 1999).

In the northeast Pacific the Juan de Fuca/Explorer ridge system sponsors hydrothermal vent habitats. Here, there are only three known sites in Canadian waters. The hydrothermal venting regions of the Endeavour Hot Vents Area lie in the offshore waters of the northeast Pacific. Located at 256 km southwest of Vancouver Island (Clayoquot Sound), and centered at 47^{o}57'N and 129^{o}06'W, this seafloor spreading centre falls within Canadian jurisdiction (Fig. 3) (Delaney *et al.* 1984; Tunnicliffe and Thomson 1999). The Endeavour Hot Vents Area is part of the Juan de Fuca Ridge which is comprised of seven segments. The ridge is a seafloor spreading zone where new rock is formed and spreads to each side of the ridge crest. This process pushes the huge Pacific Plate westward toward Japan and the small Juan de Fuca Plate eastward toward British Columbia and the northwestern United States (Delaney *et al.* 1984; Tunnicliffe and Thomson 1999).

Associated with seafloor spreading and upwelling magma is the process called hydrothermal circulation. Here, water under the crust is heated and eventually ejected as 'hot vents'. There are several major sites of hydrothermalism along the Juan de Fuca Ridge – of which Endeavour Hot Vents Area is the largest and most diverse (Delaney *et al.* 1984).

1.2 GLOBAL SETTING

Mid-ocean ridges and, therefore, hydrothermal sites are found in all the oceans of our planet. However, not all parts of the ridges are actively heated or have hot water circulation. Since global exploration is far from complete we know of only about 25 distinct vent sites in the world (Edwards *et al.* 2005). The northern end of the East Pacific Rise is presently subducted under North America and is extended by the San Andreas Fault. This ancient system re-emerges off the Oregon coast as Juan de Fuca Ridge (Delaney *et al.* 1984). The northern extension, Explorer Ridge, is truncated by the Queen Charlotte Fault system. Compared to other systems in the world, this termination is most unusual because of the interference of a continental mass that is Canada (Edwards *et al.* 2005).

2.0 THE HYDROTHERMAL HABITAT

The totally unexpected discovery of a lush community of exotic and unusual sea life, such as giant tube worms, huge clams, mussels and so on thriving around the hot springs, has changed our understanding of the planet Earth and life on it (Krüger *et al.* 2005). Discovery of vent ecosystems has altered our assumption that all ecosystems are dependent on sunlight and photosynthesis. The fact that life can exist without sunlight therefore means the possibility of finding life on other planets. Hydrothermal vents are underwater oases, providing habitat for many creatures that are not found anywhere else in the ocean (Butterfield 2000; Krüger, *et al.* 2005) due to the extreme environmental conditions of no sunlight, tremendous pressure (300 atm), and very high temperatures (the highest measured vent temperature is $400^{o}C$ and very acidic vent waters (pH as low as 2.8) (Tunnicliffe *et al.* 1998). As such, the waters around deep ocean hydrothermal vents support unique ecosystems. Generally, the organisms common to vent areas include various forms of microbes, such as the *archaea* bacteria, macro-fauna containing mussels, crabs, shrimps, worms, anemones, fish, octopii, snails, limpets and so on. New hydrogen sulphide (H_2S)-oxidising bacteria which live symbiotically with larger fauna, forming the base of the ecosystem's food chain (Fujiwara 2002; Mombelli *et al.* 2002), have also been found around hydrothermal vents.

As mentioned, the energy source that sustains deep ocean hydrothermal vent ecosystems is not sunlight, but rather energy from chemical reactions (chemosynthesis) (Nelson and Fisher 1995; Nelson and Fisher 1995; Zierenberg *et al.* 2000). Hydrogen sulphide gas, an element that is lethal to most terrestrial organisms, is produced when seawater reacts with the sulfate contained in rocks below the ocean floor and is therefore present in the hydrothermal fluids coming out from vents. However, vent bacteria use this hydrogen sulfide as their energy source instead of sunlight. In turn, these bacteria sustain larger organisms in the vent community and are the basis of survival of the entire ecosystem as they break down H_2S and use this energy along with oxygen to convert CO_2 to sugars (Nelson and Fisher 1995; Nelson and Fisher 1995; Zierenberg *et al.* 2000).

2.1 MICROBIAL COMMUNITIES IN EXTREME ENVIRONMENTS

During the past two decades an increasing number of new genera and species of thermophilic bacteria have been isolated from deep-sea hydrothermal vent communities (Nelson and Fisher 1995). It has been established that extremophilic bacteria survive and thrive at harsh conditions such as very acidic/basic pH, low/high temperatures, high salt concentrations, elevated hydrostatic pressure, and even in the presence of radiation. The thermophilic and hyperthermophilic bacteria grow respectively at either high or very high temperatures. Of the other types of extremophilic bacteria in vent communities, psychrophiles grow best at low temperatures; acidophiles and alkaliphiles are optimally adapted to live in environments with particularly acidic or basic pH values, respectively; barophiles grow best under pressure; and halophiles require NaCl for growth (Horikoshi 1998).

Most extremotolerant microorganisms are members of the domain Archaea (Eichler 2001). The unique Archae bacteria possess adaptation mechanisms to extreme pressure, temperature, toxicity, and pH values that makes them particularly attractive to industry and the pharmaceutical sector. Addtionally, it is the chemosynthetic archaea bacteria that form the base of the food chain, supporting diverse organisms, including giant tube worms, clams, limpets and shrimp (Eichler 2001).

Studying the life cycle of vent organisms is difficult as researchers have visited only a fraction of the ocean's hot spots. In these, they have been able to observe vent life only by shining bright lights on creatures accustomed to inky darkness, and many specimens die quickly when removed from their unique environment. Underwater cameras are helping scientists make less intrusive observations, but diving expeditions are still the most useful way to gather information on such organisms (Eichler 2001; Horikoshi 1998; Nelson and Fisher 1995;).

2.2 BIOCHEMICAL CHARACTERISTIC OF THE EXTREME BACTERIAL ORGANISMS

To be able to survive in such extreme environments, all biomolecules within the cells of extreme bacterial organisms, including proteins, nucleic acids, and lipids, must be adapted to properly function under these conditions. Therefore, deep-sea vent microbial communities are highly diverse metabolically, physiologically, and taxonomically (Horikoshi 1998; Nelson and Fisher 1995; Zierenberg *et al.* 2000). The extremophiles bacteria produce an amazing array of enzymes capable of catalyzing specific biochemical reactions under extreme conditions, which is of particular interest to industry (Zierenberg *et al.* 2000). These enzymes are often able to perform industrial processes under conditions where conventional proteins would be denatured. They may have various applications like detergent production, sugar chemistry, lipid and oil chemistry, and food processing (Horikoshi 1998; Nelson and Fisher 1995; Zierenberg *et al.* 2000).

The barophiles bacteria are microorganisms adapted to living under extreme pressure. Research on the physiology and molecular biology of deep-sea barophilic bacteria has identified pressure-regulated operons and shown that microbial growth is influenced by the relationship between temperature and pressure in the deep-sea environment (Eichler 2001; Hoyoux *et al.* 2004; Nakasone *et al.* 1998). Enzymes produced by these high pressure adapted bacteria are often more functional under high pressure conditions than at atmospheric pressure (Hoyoux *et al.* 2004). Thus, one of the possible biotechnological applications of such deep-sea microorganisms may be in high pressure bioreactor systems (Georlette *et al.* 2004; Hoyoux *et al.* 2004).

Thermophilic bacteria grow optimally at temperatures between 45^o and 80^oC, while hyperthermophiles have growth optima over 80^oC. Enzymes or other components mediating vital physiological processes of these bacteria are therefore adapted to these temperatures. Proteins from hyperthermophilic bacteria are generally able to remain stable at temperatures close to or higher than the boiling point because they are more compact in their structure (Georlette *et al.* 2004). For example, *Thermococcus peptonophilus* bacterum, isolated from a deep-sea hydrothermal vent, produces an SDS-resistant protease which is stable in boiling water; a thermostable DNA polymerase has also been isolated from the deep-sea hydrothermal vent microorganism *Thermococcus litorali* (Daniel and Cowan 2000; Lopez-Garcia, Forterre 2000) .

2.3 HYDROTHERMAL VENT FAUNA (GROUNDFISH SPECIES)

The waters around the deep ocean hydrothermal vents can reach 400ºC, creating highly unique environmental characteristics. The macro-fauna that are common to vents include: mussels, crabs, shrimps, worms, anemones, fish, octopi, snails, limpets and so on. As previously stated, H_2S-oxidising bacteria, which live symbiotically with larger fauna, form the base of the ecosystem's food chain (Yayanos 1995).

Most vent fauna are new to science – many of them are not found anywhere else and they cannot survive outside vent conditions. The vestimentiferan giant tube worms are one of the most miraculous animals that live in vent ecosystem. Giant tube worms are up to 3 m long and 10 cm in diameter and can grow more than 33 inches per year, making them the fastest growing marine invertebrate. These worms do not have a mouth, gut or digestive system, but rather have red, blood-filled plumes at the top of the worm's body where hemoglobin binds with hydrogen sulfide and transports it to the bacteria housed inside the worm. In return, the bacteria oxidize the hydrogen sulfide and convert carbon dioxide into carbon compounds that nourish the worm. Giant tube worms do have a head, collar, trunk, and anchor, but no mouth or eyes (Corliss and Ballard 1977).

The Pompeii worm (*Alvenella pompejana*) is an organism that has only been found in hydrothermal vents, and living closer to vents than any other species, it ranks as the most heat-tolerant among higher order life forms. These worms reside in tubes, where, when in the tube, the worm’s tail end basks in water as hot as 400ºC while its head rests in water that is much cooler at about 200ºC. The appearance of grey fleece or ‘hairs’ on the worm’s back are actually bacteria, which act as protective thermal blanket for the worm and also detoxify lethal toxic chemicals. Besides the giant tube worms, which have only been found in the Pacific to date, other vent associated worms include pencil-size Jericho worms with accordion-like tubes; orange worms covered with tiny bristles; small benthic worms that wriggle through the mud; and finger-length, dark red palm worms that stand upright, topped with wig like fronds (Tunnicliffe 1991). A special class of small worms, called Alvinellids (named after the sub), live on the walls of mineral deposits that form around vents (Van Dover and Lutz 2004). Tube worms reproduce by spawning, where they release sperm and eggs which combine in the water to create new worms (Van Dover and Lutz 2004).

Mussels, shrimp, clams, and crabs are also abundant at many vents, but are different than species that commonly consumed (Van Dover and Lutz 2004). The cocktail-size shrimp that dominate vents in the mid-Atlantic, for example, have no eyes. However, at least one species has an extremely sensitive receptor on its head that may be used to detect heat or even dim light coming from vents (Fisher *et al.* 2000). Biologists have observed a variety of smaller crustaceans around vents, including miniature lobsters called galatheids, and amphipods resembling sand fleas (Macpherson *et al.* 2005; Nozomu *et al.* 2000). They have also observed snail-like limpets the size of BBs, sea anemones, snakelike fish with bulging eyes, and even octopi, which exist occupy the upper trophic levels of a vent system. In the meantime, bacteria remain the first organisms to colonize newly formed vents, arriving in a snow like flurry and then settling to form white mats or tendrils attached to the ocean floor (Fisher *et al.* 2000; Tunnicliffe 1991; Van Dover and Lutz 2004).

Recently the discovery of a new species of blind deep-sea crab whose legs are covered with long, pale yellow hairs has been reported. This crab was first observed in March 2005 by marine biologists using the research submarine Alvin to explore hydrothermal vents along the Pacific-Antarctic ridge, south of Easter Island. This animal was nicknamed the "Yeti crab," after the fabled Yeti, the abominable snowman of the Himalayas, because of its hairy legs (Macpherson *et al.* 2005).

3.0 A NEW HYPOTHESIS: IS SUSTAINABLE BIOPROSPECTING ACTIVITY ACCEPTABLE?

The increasing research and fisheries activity in the deep sea highlights important issues surrounding sustainability. Deep-sea expeditions are increasingly frequent, and their focus has been shifting in the last few years from geological and geophysical studies to ecological, biological, and physiological studies, and more recently to bioprospecting (Marianne 2007).

When focusing on the bioprospecting of marine organisms it is natural to look for organisms that have adapted to and survived life in particularly harsh environments, such as the low or no light, high pressure, low energy, and either near-freezing or superheated temperatures experienced in the deep sea (Fujiwara 2002; Marianne 2007).

Most deep-sea investigations are still considered to be purely scientific, but the potential of the marine environment for the discovery of new drug sources and cures for diseases has lead to increasing commercial exploration (Egorova and Antranikian 2005; Tehei and Zaccai 2005). Likewise, vent organisms have wide industrial applications. They may be useful to combat industrial pollution (such as hydrogen sulphide) and clean up sites contaminated with Cu, Cd, and Hg amongst. These organisms may also help aid in the development and manufacture of new heat resistant industrial chemicals and new drugs to combat germs now resistant to plant and soil based drugs (Margesin and Schinner 1997).

Drugs derived from marine organisms cover a variety of applications such as antibiotics, anti-cancer, antioxidant, anti-fungal, anti-HIV, anti-tuberculosis, and antimalaria. The various applications and the desire for finding new drugs seem to be endless, resulting in a considerable pressure on the marine environment. The deep-sea hydrothermal vents seem thus to have an enormous potential in pharmaceutical applications. Therefore, to take advantage of this unique opportunity it is important to do so with caution (Demirjian *et al.* 2001; Gomes and Steiner 2004; Mattila *et al.* 1991; Margesin and Schinner 1997; Schiraldi and De Rosa 2002; Tunnicliffe 1990).

Proteins and enzymes of ultrathermophilic *archaea* in hot vent waters have unusually high thermal stabilities and hence, such enzymes are expected to have longer shelf life, produce less waste, and have lower risk of contamination. They will also permit reactions to run hotter, faster and more pure, and they will be biodegradable (Chien *et al.* 1977). It is anticipated that extremozymes can help to dry the oil wells productive capacity by thinning oil which is too thick for extraction. It can also be used to convert corn starch to sugar. Finally, the extremozymes can help anaerobic bioremediation and host other industrial processes by speeding up biological and chemical reactions (Demirjian *et al.* 2001; Mattila *et al.* 1991). Another class of protein enzymes, the eurythermal enzymes, can function effectively in a wide range of temperatures. They find applications in pharmaceutical, textile, paper and detergent industries. The eurythermal enzymes act as catalysts to break down fats, wood etc, as well as DNA and operate in organic solvent (Gomes and Steiner 2004; Schiraldi and De Rosa 2002).

The molecular biology techniques currently available make sustainable bioprospecting possible in many ways. Genomic libraries can be created to preserve all the genetic material found in marine organisms for the future. Important genes may be isolated and biomedical compounds may be produced through recombinant technology. Proteins can then subsequently be replicated from genetically modified organisms without requiring harvesting of the original organisms. Therefore, it appears that bioprospecting of microorganisms can indeed be performed on a sustainable basis if the sampling is done with caution (Altschul *et al.* 1997; Mancuso *et al.* 2005).

4.0 SHOULD WE CONSIDER THE DEEP SEA AN ENORMOUS RESOURCE OR A VERY FRAGILE ECOSYSTEM?

Increasing bioprospecting activity, with commercialization as a goal, raises issues of who owns the resources being explored, and whether they are within or outside of exclusive economic zones. However, regardless of who “owns” the microbes, animals, or plants that produce bioactive compounds, life in the deep sea should be provided enhanced protection (Marianne 2007). In an ideal world, we are morally and legally responsible to work “together” to protect the endangered species at sea or on land. However, it is important that laws protecting biodiversity do not stop research and development blindly, but rather protect the environment within sensible frames.(Marianne 2007; Tarasov *et al.* 2005).

Extensive sampling around hydrothermal vents may disturb these and other unique ecosystems. Therefore, collections from these areas should be limited. Conservation of biodiversity is crucial, not only for the environment itself, but also for the biotechnology industry. In certain marine ecosystems, such as coral reefs or the deep-sea floor, experts estimate that the biological diversity is higher than that of a tropical rain forest (Marianne 2007).

Hydrothermal vents, in some instances, have led to the formation of exploitable mineral resources via the deposition of seafloor massive sulphide deposits. The Mount Isa orebody located in Queensland, Australia, is an excellent example of this (Perkins 1984). Recently, mineral exploration companies, driven by the elevated price activity in the base metals sector during the mid-2000s, have turned their attention to the extraction of mineral resources from hydrothermal fields on the seafloor (Net Resources International 2010).

Notably, significant cost reductions to the type of activity described above are, in theory, possible. For example, consider that in the case of the Mount Isa ore body: large amounts of capital were essential for building the complex exchanges such as the sinking of the shafts, the associated underground infrastructure, then laboriously drilling and blasting the ore, and crushing and processing to extract the base metals (Net Resources International 2010). However, the Marshall hydrothermal recovery system is a patented proposal to exploit hydrothermal vents for their energy and minerals in a less complex manner (Marshall Hydrothermal 2010). In this, a hydrothermal field, consisting of chimneys and compacted chimney remains, can be reached from the surface via a dynamically positioned ship or platform, using conventional pipe, mined using modified soft rock mining technology (continuous miners), brought to the surface via the pipe, concentrated and dewatered, and then shipped directly to a smelter. While the concept may sound far-fetched, it uses already proven technology derived from the offshore oil and gas industries, and the soft-rock mining industries (Marshall Hydrothermal 2010).

Two companies are currently in the late stages of commencing to mine massive sulphides from the seafloor. Nautilus Minerals is in the advanced stages of commencing extraction from its Solwarra 1 deposit in the Bismarck Archipelago, located in the territorial waters of Papua New Guinea (PNG), where they have been exploring the deposit site since 2005 (Nautilus Minerals 2006). Neptune Minerals is another leading explorer and developer of precious- and base-metal seafloor massive sulphide (SMS) deposits, with granted exploration licences totalling more than 261,146 km^2 in the territorial waters of New Zealand, Papua New Guinea.(Marshall Hydrothermal 2010). Neptune Minerals is at an earlier stage with the summit caldera of two southern Kermadec frontal arc volcanoes (Brothers and Rumble II West) of the approximately 1200 km long Kermadec-Havre arc-back-arc system. Both of these companies are proposing using modified existing technology. Nautilus Minerals, in partnership with Placer Dome (now part of Barrick Gold), succeeded in 2006 in returning over 10 tonnes of mined SMS to the surface using modified drum cutters mounted on an Remote Operated Vehicle (ROV) - a world first (Marshall Hydrothermal 2010; Net Resources International 2010; Nautilus Minerals 2006; Perkins 1984;).

4.1 IMPACT BIOPROSPECTING SAMPLING ON THE FRAGILE ECOSYSTEMS OF HYDROTHERMAL VENTS

Hydrothermal vents are starting to feel the pressures of intense research activity, bioprospecting, and mineral exploration. Current scientific sampling methodologies allow reaching unique ecosystems that were previously not accessible. However, this increasing human presence also results in an increasing pressure on these previously hidden ecosystems (Marianne 2007).

As mentioned before, the communities living around the hydrothermal vents contain a unique set of species which are often entirely new to science (Macpherson *et al.* 2005; Marketmire 2010). Small, unique ecosystems develop around each vent – composed of exotic species of animals and microbes that can live under extreme conditions of temperature, pressure, and toxic substances (Haefner 2003; Marianne 2007).

Recently, reports indicating the significant differences between deep and shallow-water hydrothermal vent communities have been published (Marketmire 2010). These reports highlight the higher ratio of vent obligate taxa and a dominance of symbiotrophic forms that occur in deep-sea hydrothermal vent communities (Marianne 2007; Marketmire 2010).

With respect to the potential impacts of seafloor mining on hydrothermal vent ecosystems, environmental impacts could include the creation of dust plumes from mining machinery affecting filter feeding organisms, collapsing or reopening of vents, methane clathrate release, or even sub-oceanic land slides (Marianne 2007; Marketmire 2010).

4.2 IMPACT OF DEEP-SEA FISHERIES ON THE FRAGILE ECOSYSTEMS OF HYDROTHERMAL VENTS

The sustainable use of ocean resources is of utmost importance to both fisheries and research (Haefner 2003; Marianne 2007). Increasing pressures on deep-sea fisheries have been observed with the depletion of fisheries close to shore. According to World Wildlife Fund (WWF), the fast and largely unregulated expansion of deep-sea fisheries is placing unsustainable pressure on the deep-sea ocean's wealth of marine life, where deep-sea fishes often qualify as endangered (Cailliet *et al.* 2001; Devine *et al.* 2006; Marianne 2007).

Deep-sea ecosystems are extremely vulnerable to intensive fishing pressure since many deep-sea species have particularly long lives and reproduction cycles – slow growth and late maturity in these species is due to the colder, darker, and less nutrient-rich environment compared to shallower waters (Devine *et al.* 2006; Marianne 2007). These particular life history characteristics mean that deep-sea stocks may be severely depleted when their sustainability is not ensured (Cailliet *et al.* 2001; Devine *et al.* 2006).

Analysis of orange roughy (*Hoplostethus atlanticus*) commercial deep trawl fisheries worldwide indicated a severe depletion of those stocks examined (Lack *et al.* 2003; Macpherson *et al.* 2005). The orange roughy, also called red roughy, is a relatively large deep-sea fish belonging to the slimehead family (*Trachichthyidae*) and one of the slowest growing of all deep-sea fish.

The species is found in cold (3-9°C), deep (bathypelagic, ~180-1809 m) waters of the Western Atlantic (off northern Nova Scotia), Eastern Atlantic (from Iceland to Morocco; and from Walvis Bay, Namibia to off Durban, South Africa), Indo-Pacific (off New Zealand and Australia), and in the Eastern Pacific off Chile. Orange Roughy can live to be 125 years of age, yet not become sexually mature until around 25 years of age. Therefore, extensive fisheries of this and species with similar traits may eradicate their existence completely (Anderson and Clark 2003; Lack *et al.* 2003; Marianne 2007).

Coral reefs, also a form of deep-water habitat, provide a home for a diversity of animals, such as sea fans, sponges, worms, starfish, brittle stars, sea urchins, crustaceans, and fish. Deep-sea coral reefs are also attractive targets for fishers as some fish species can be found in high concentrations there (Marianne 2007; Watling and Norse 1998). However, due to the gear-types that are being used in deep-sea fisheries, not only deep-sea fish species are being eradicated through this activity; deep-sea trawling may wipe out whole communities through irreparable damage to coral reefs (Watling and Norse 1998). For example, bottom trawlers fishing for orange roughy in the Tasman Sea in 1997 pulled up an average of 10 tons of coral per tow, and it was estimated that 10,000 tons of coral were destroyed in the capture of 4,000 tons of fish (Lonsdale 1977; Marianne 2007; Roberts *et al.* 2003). Notably, there seems to be even more species of corals in cold and deep ocean waters than in tropical shallow waters (Lonsdale 1977; Marianne 2007; Roberts *et al.* 2003).

Recovery of corals after disturbance is often slow because recruitment is patchy and growth to maturity takes years, decades, or more for some structure forming species. Since deep-living species tend to grow more slowly than shallow-water species, the long-term impact of trawling is magnified as trawl depths increase (Lack *et al.* 2003; Lonsdale 1977; Marianne 2007).

5.0 HYDROTHERMAL SITES AND INTERNATIONAL GOVERNANCE

Most of the productive hydrothermal sites in the world are not found in waters that are under the jurisdiction of any nation. Those vents that are located in national territorial waters seem to be within the jurisdiction of nations that do not have marine protected area policies (such as Mexico, Ecuador, Fiji, Papua New Guinea). Papua New Guinea, for example, is examining the potential for mineral exploitation of the known vent sites in its waters (Leary 2007).

The international science community that works on the global ridge crest system is informally organized through an overseer organization called *InterRidge*, of which Canada is an Associate Member (Delaney *et al.* 1984; Edwards *et al.* 2005; Howlett Rayner 2005). This program focuses on multidisciplinary studies of the ridge crest throughout the world and designs specific studies to optimize international collaboration (Marianne 2007).

In 2005, the InterRidge Biological Studies *Ad Hoc* Committee recommended the establishment of *Biological Reserves* at intensively studied vents (Interridge 2009). It was felt that these reserves were required partly to disseminate information about on-going observations that require no interference. The community also wanted to demonstrate its commitment to the protection of a ecosystem vulnerable in its localized nature and its dependency upon venting. A specific call has also been made to establish areas that are protected from the same type of mining proposed in Papua New Guinea. To date, many protected areas initiatives have been established for the protection of the deep-sea environments, where some countries have already restricted access to certain fragile ecosystems, such as hydrothermal vents and coral reefs (Interridge 2009).

Studies of a few vents within two fields have demonstrated signs of human activity. Generally, the natural variability within the vent systems, including the toppling and re-growth of sulphide structures occurring on a yearly basis, is so high that it is difficult to assess human effects. However, it is known that the death of assemblages due to fluid rerouting is a very common effect. Fundamentally, the pressures from research activity are very low. Therefore, placing restrictions on research activities in these types of areas may not be the way to deal with the fear of eradicating deep-sea species or communities (Marianne 2007).

Ultimately, rules and regulations to govern activities in deep-sea environments, including scientific research, fisheries, and mining and other industries, are required in order to avoid eradicating the organisms that live there (Interridge 2009).

6.0 COMPARISON BETWEEN COLD SEEPS AND HYDROTHERMAL VENTS

Cold seeps were first discovered in the late 1980's in the Monterey Canyon at a depth of 3200 meters. Cold seeps are sites where fluids seep from the sea floor, similar to undersea springs, and are often called methane- or sulphide-seeps because the seeping fluids are rich in these compounds. Although the seeping fluids are the same temperature as the surrounding seawater, they are termed "cold seeps" to distinguish them from hydrothermal vents, where extremely hot water is vented from the seafloor. These cold seep areas support life in total darkness and sometimes appear as an oasis of life in an otherwise desert-like region (ICRI 2007; Tunnicliffe and Thomson 1999).

Compared to hydrothermal vents, cold seep flow rates are usually slow and temperatures are only slightly different from the surrounding seawater. In deep waters, seep processes are related to geological phenomena such as subduction, petroleum or natural gas escape, artesian flow, and catastrophic erosion or submarine slope failures (Jacobs University 2006). Subduction zone seeps occur on geologically active (i.e. tectonic plate movement) continental margins. In this setting, the compression of oceanic sediments against the overriding continental plate creates deep overpressure zones where water within the sediment is forced out along faults (Jacobs University 2006; Tunnicliffe and Thomson 1999).

On passive continental margins, "salt tectonics" can also create conduits for seeping fluids. For example, in the deep waters of the Gulf of Mexico, ancient salt deposits lie below sediments where hydrocarbons and methane have accumulated. Salt being lighter than compacting sediment, it tends to push upward as a salt dome, creating -deep cracks in the sediments through which gasses and petroleum escape at the seafloor (Jacobs University 2006; Tunnicliffe and Thomson 1999).

Seep fluids are often rich in methane that is produced by the microbial or thermal degradation of organic matter in deep subsurface sediments. Migrating seep fluids can also be enriched in hydrogen sulphide in near-surface sediments by microbial sulphate reduction coupled to methane oxidation (Tunnicliffe *et al.* 2003; Tunnicliffe and Thomson 1999).

Cold-seep areas that have so far been studied are at depths ranging from 400 to 6000 m in the Atlantic and the Eastern and Western Pacific and in the Mediterranean Sea; they occur in different geological systems, some on active and some on passive margins (Martin *et al.* 1996).

Seep environments exhibit a fauna taxonomically similar to that of hydrothermal vents, including the the presence of *vestimentiferan* tubeworms, and *vesicomyid* and *mytilid* bivalves, where there is evidence of their use of carbon from methane through symbiotic bacteria (Martin *et al.* 1996; Tunnicliffe and Thomson 1999). Generally, the dominant cold-seep species are large bivalves (families *Vesicomyidae* and *Mytilidae*) but there are also symbiont-containing species of other bivalve families, *pogonophoran* worms, and sponges. However, unlike hydrothermal vents, specialized carnivores have not been reported in high abundance (Martin *et al.* 1996; Tunnicliffe and Thomson 1999).

Many deep-water seep environments are also the site of significant reservoirs of petroleum and natural gas. In the Gulf of Mexico, offshore exploitation of oil and gas in proximity to seep communities has been ongoing for decades. Still, the effects of human activites on seep ecosystem function and biodiversity are not well documented (Gage 1996; Tunnicliffe and Thomson 1999).

It is expected that exploratory drilling and the installation and operation of production platforms will produce both localized and widely spaced disturbances in seep areas. However, the depletion of subsurface oil and gas reservoirs may also eventually affect the energy supply to seep communities – but this remains to be investigated. It can be expected that more widespread impacts may eventually come from the exploitation of subsurface gas hydrate deposits in seep environments. Reserves of methane ice occupy significant volumes within the seabed of continental margins worldwide, and recent global estimates of gas hydrate reserves greatly surpass total known world petroleum reserves. Although exploitation of these subsea gas hydrates is probably many decades away, it is possible their extraction could involve large-scale disturbance of the seabed and consequent effects on seep communities (Gage and Tyler 1996; Marianne 2007).

7.0 THE ENDEAVOUR HYDROTHERMAL VENT MPA

Early in 2003, Canada became the first country to formally take measures to protect and conserve deep ocean hydrothermal vents. The Endeavour Hydrothermal Vents Marine Protected Area (MPA) is found in the northeast Pacific Ocean at 2200 m depth, 200 km southwest of Vancouver Island, Canada. Since their discovery in 1982, the Endeavour Hydrothermal Vents have been a focus of significant research by Canadian and international scientists (Fig. 4 and 5) (Butler *et al.* 2001; Tunnicliffe and Thomson 1999).

The 4x6 nautical mile (82 km^2) Endeavour MPA encompasses 5 vent fields that include features such as large hot black smoker chimneys and surrounding lower temperature vents. The vent fields span a wide range of hydrothermal venting conditions characterized by different water temperatures, salt content, mineral chimney morphology and animal abundance. However, temperatures associated with the black smokers are typically in excess of 300°C (Baker *et al.* 1985; Butterfield *et al.* 1990). It has also been documented that the Endeavour Hydrothermal Vents are home to at least 12 species found nowhere else (Fig. 6-8) (Butterfield and Massoth 1994; Converse *et al.* 1984).

The Endeavour MPA has been created to set the area aside for scientific research. Research activities in the MPA are monitored by a Management Committee to mitigate use conflicts and environmental disturbance. Included in the present MPA Management Plan are provisions such as zones for sampling and 'observation only' areas to ensure the pristine nature of the area and permit long-term observations of natural change and response to natural disturbances

(Campbell *et al.* 1988; Delaney *et al.* 1981; Delaney *et al.* 1984; Embley *et al.* 1993; Embley and Chadwick 1994). Since The Endeavour Hydrothermal Vents MPA has been designated to ensure the protection of these hydrothermal vents and the unique ecosystems associated with them, regulations or this MPA prohibits the removal, disturbance, damage or destruction of the venting structures or the marine organisms associated with them; however, they do allow for scientific research that will contribute to the understanding of the hydrothermal vents ecosystem (Butterfield *et al.* 1990; Butterfield and Massoth 1994; Campbell *et al.* 1998; Converse *et al.* 1984; Delaney *et al.* 1981; Delaney *et al.* 1984; Embley *et al.* 1993; Embley and Chadwick 1994; Marianne 2007; Delaney *et al.* 1984; Tunnicliffe and Thomson 1999;).

The manned US submersible *Alvin* and the unmanned vehicle *Jason* have undertaken a number of scientific missions in the area of the Endeavour Hydrothermal Vents. Fisheries and Oceans Canada has also conducted extensive acoustic and moored instrument programs in the area since 1985 and joint Canada-US studies have made use of the Canadian ROPOS (Remotely Operated Platform for Ocean Sciences)(Butler *et al.* 2001; Tunnicliffe and Thomson 1999) for scientific study.

8.0 CONCLUSION

It is understood that the fragile ecosystems such as deep-sea hydrothermal vents and coral reefs have an enormous potential in contributing to future medical advances, and to provide knowledge of how the marine organisms survive in their environment (Baker *et al.*). Based on this, a powerful argument can be put forward for the protection of these deep-sea environments as a means to facilitate continued learning and to prevent species eradication before they are even identified (Marianne 2007).

Other arguments for the conservation of vent species can be developed from the same sources that have led to the present global interest in the preservation of biodiversity. In addition, cutting edge biological science has become an key stakeholder in this resource, where millions of research dollars annually are directed to laboratory and field studies of vent organisms (Marianne 2007).

Vent biology, in its brief history, has made major contributions to the development of basic models of life processes. Most recent editions of university textbooks in biology and ecology now use examples from hydrothermal vents to illustrate lessons on symbiosis, detoxification, adaptation to extreme conditions and ecosystem function. The visually spectacular and extreme nature of vent communities also makes them popular subjects for the science media and science education sectors (Marianne 2007).

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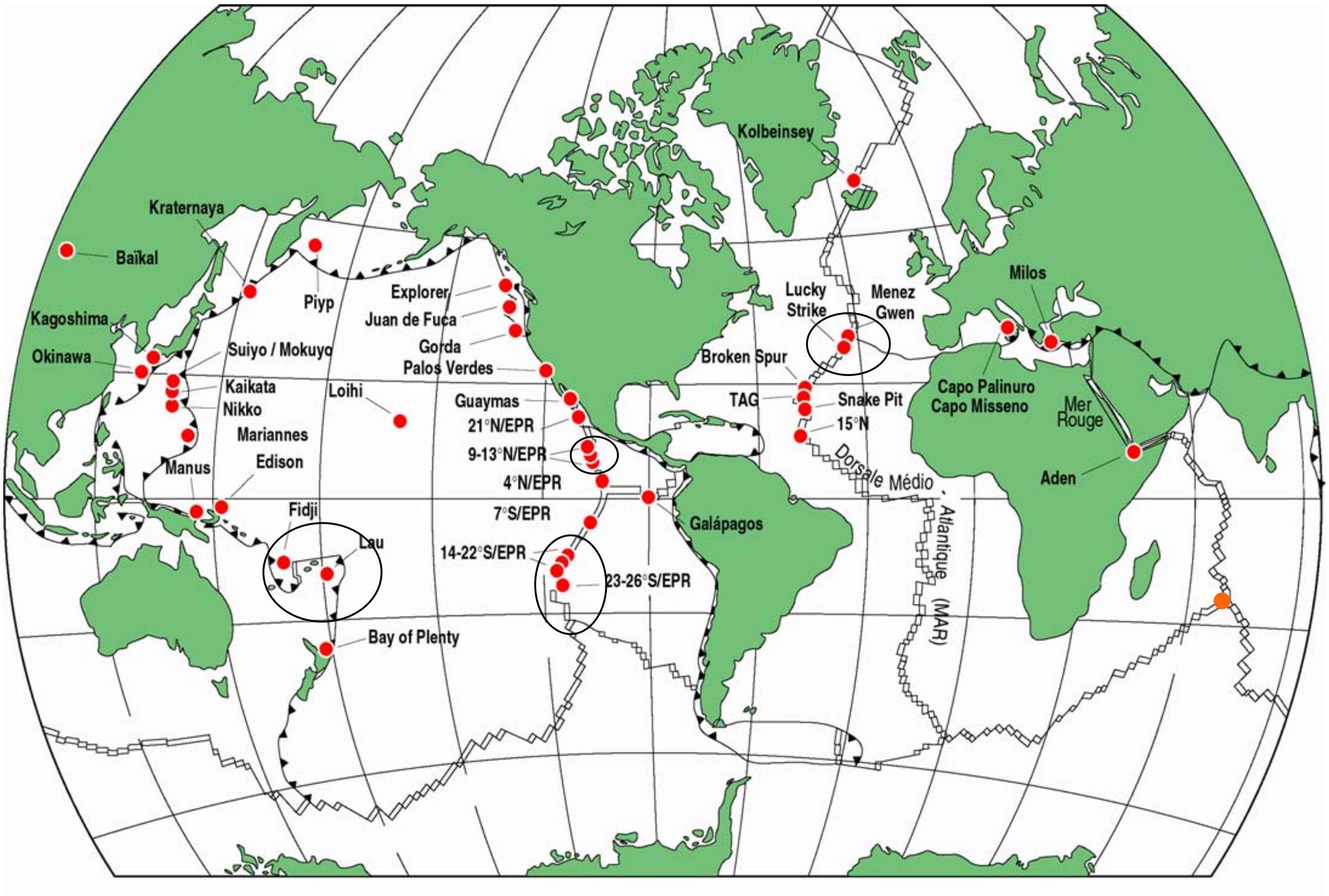
APPENDIX I



Position géographique des zones hydrothermales connues présentant une faune associée.

Figure 1. Geographical positions oh hydrothermal zones

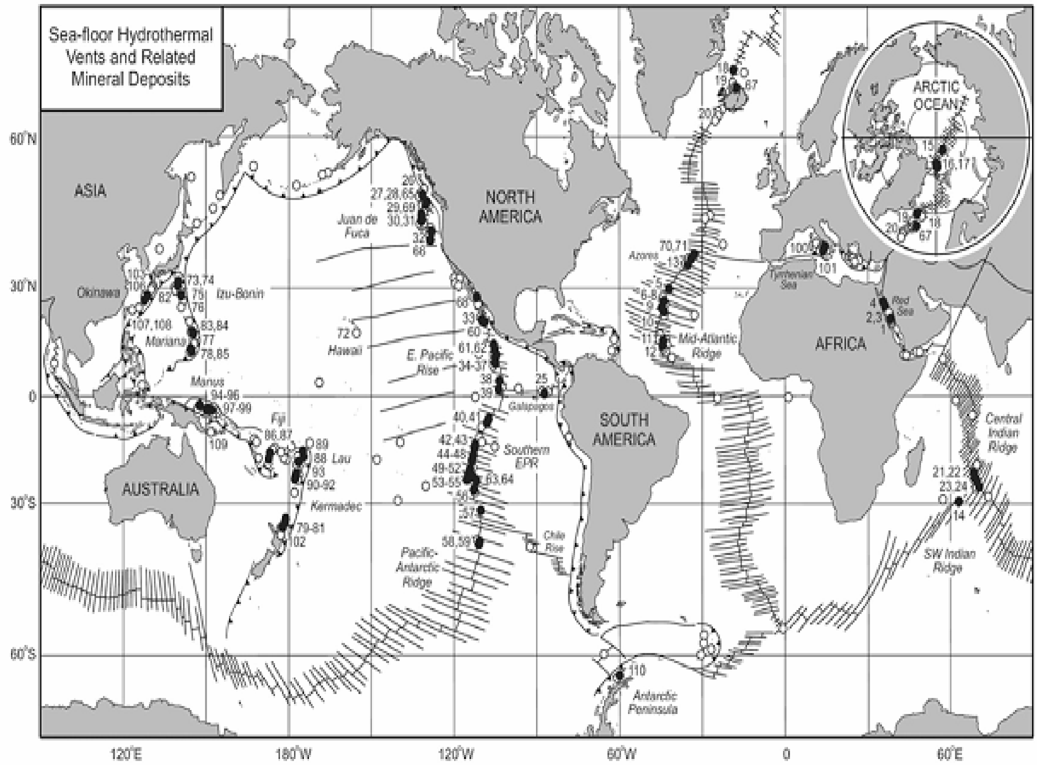


Figure 2. Distribution of sea-floor hydrothermal vents and related mineral deposits. Numbers refer to high temperature hydrothermal vents and related polymetallic sulfide deposits (closed circles). Other hydrothermal deposits and low-temperature vent sites, including Fe-Mn crusts and metalliferous sediments, are indicated by open circles. Major spreading ridges and subduction zones are indicated.(From Oceans background report. The Endeavour hot vents Area: A Pilot Marine Protected Area in Canada's Pacific Ocean. V. Turncliffe1 and R. Thomson; 1999).

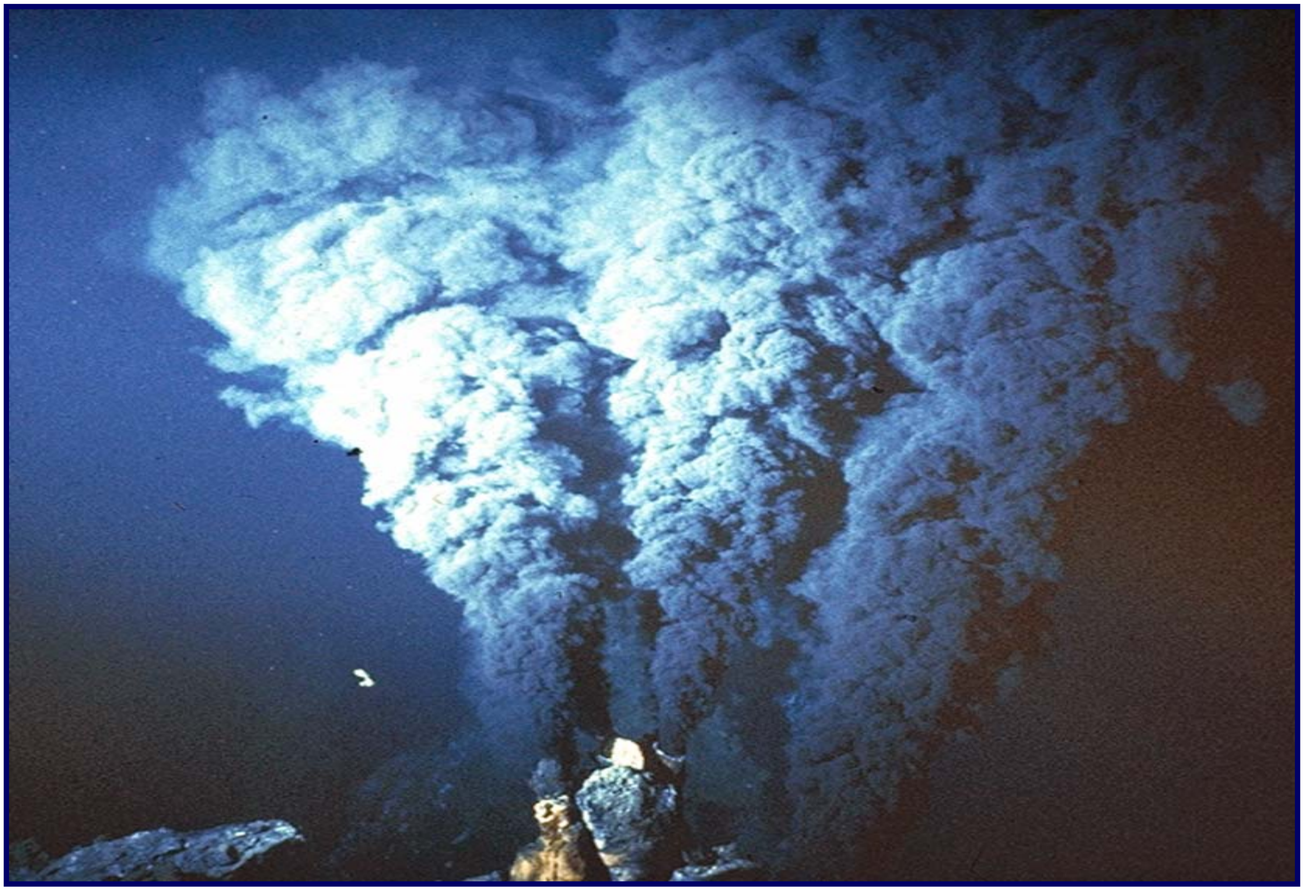


Figure 3. A hydrothermal vent geyser on the seafloor. It continuously spews super-hot, mineral-rich water that helps support a diverse community of organisms. Although most of the deep sea is sparsely populated, vent sites teem with a fascinating array of life.

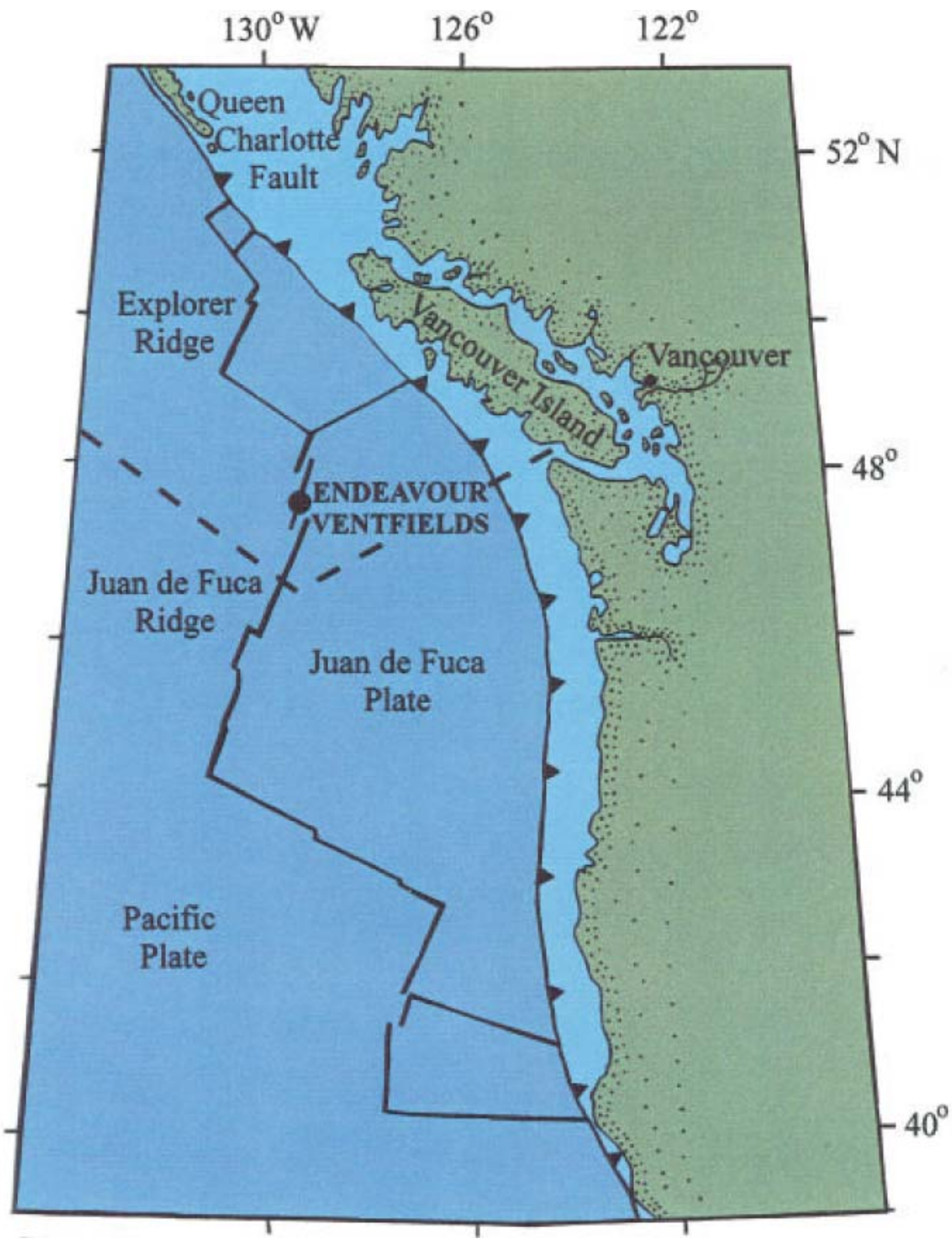


Figure 4. Location map of the Endeavour ventfields on Juan de Fuca Ridge in the northeast Pacific dotted line represents Canadian jurisdictional boundary. Oceans background report. The Endeavour hot vents Area: A Pilot Marine Protected Area in Canada's Pacific Ocean. V. Turncliffe1 and R. Thomson; 1999).

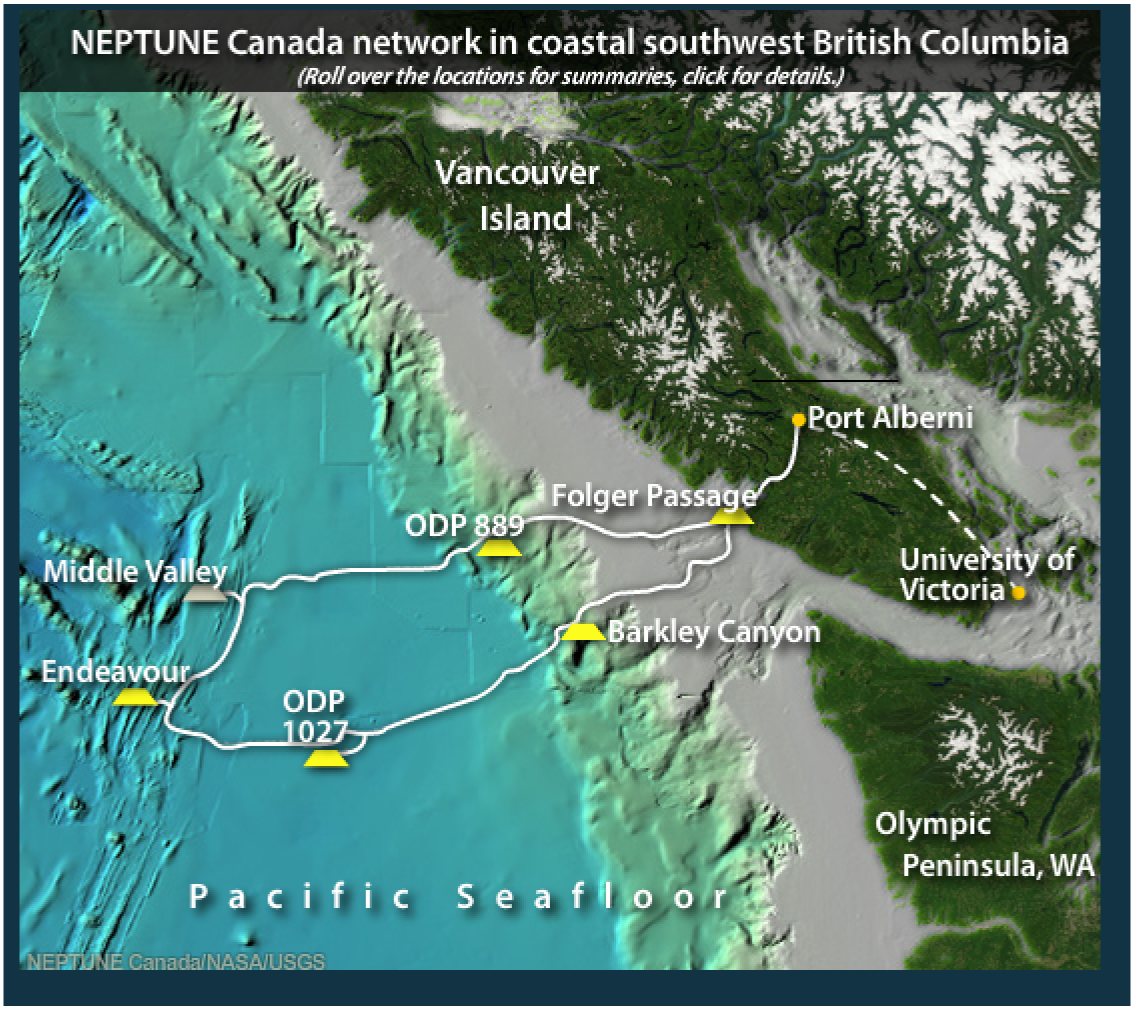


Figure 5. More detailed location map of the Endeavour ventfields on Juan de Fuca Ridge in the northeast Pacific dotted line represents Canadian jurisdictional boundary. (From Neptune Canada).

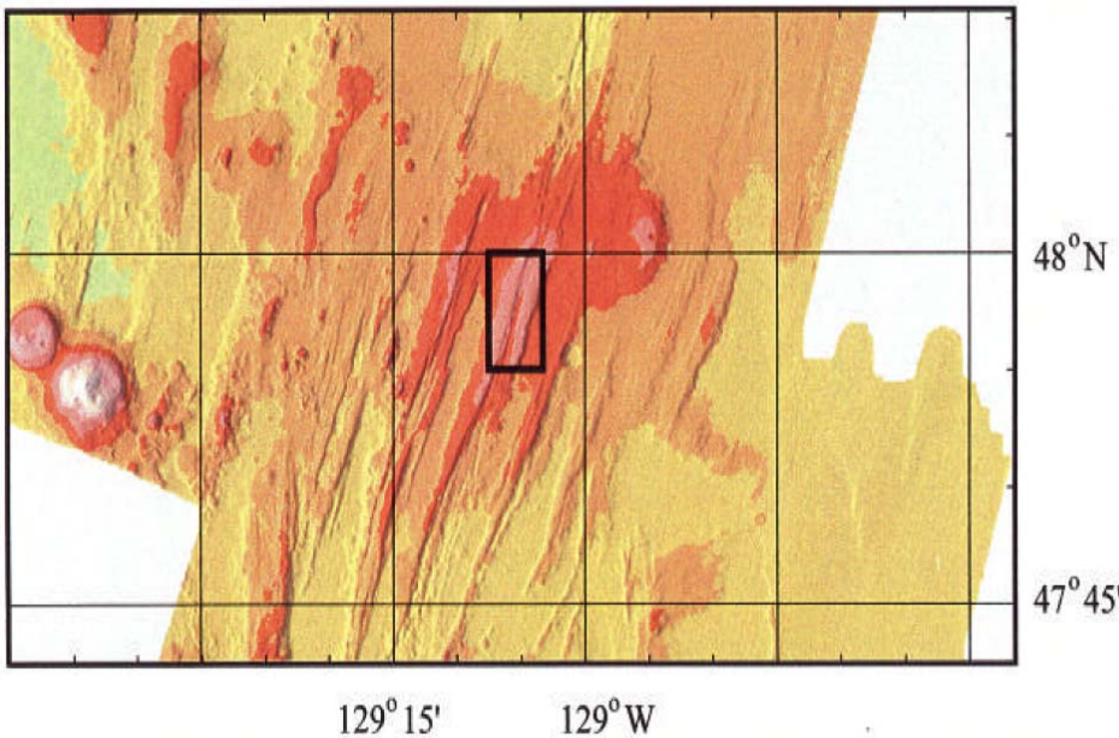


Figure 6. Represents a multibeam seafloor topographic representation of the Endeavour Hot Vent area spreading centre. The spreading axis lies in the central valley. Boxed area is the proposed boundaries of the Endeavour ventfields site as presented in the following diagram. Oceans background report. The Endeavour hot vents Area: A Pilot Marine Protected Area in Canada's Pacific Ocean. V. Turncliffe1 and R. Thomson; 1999).

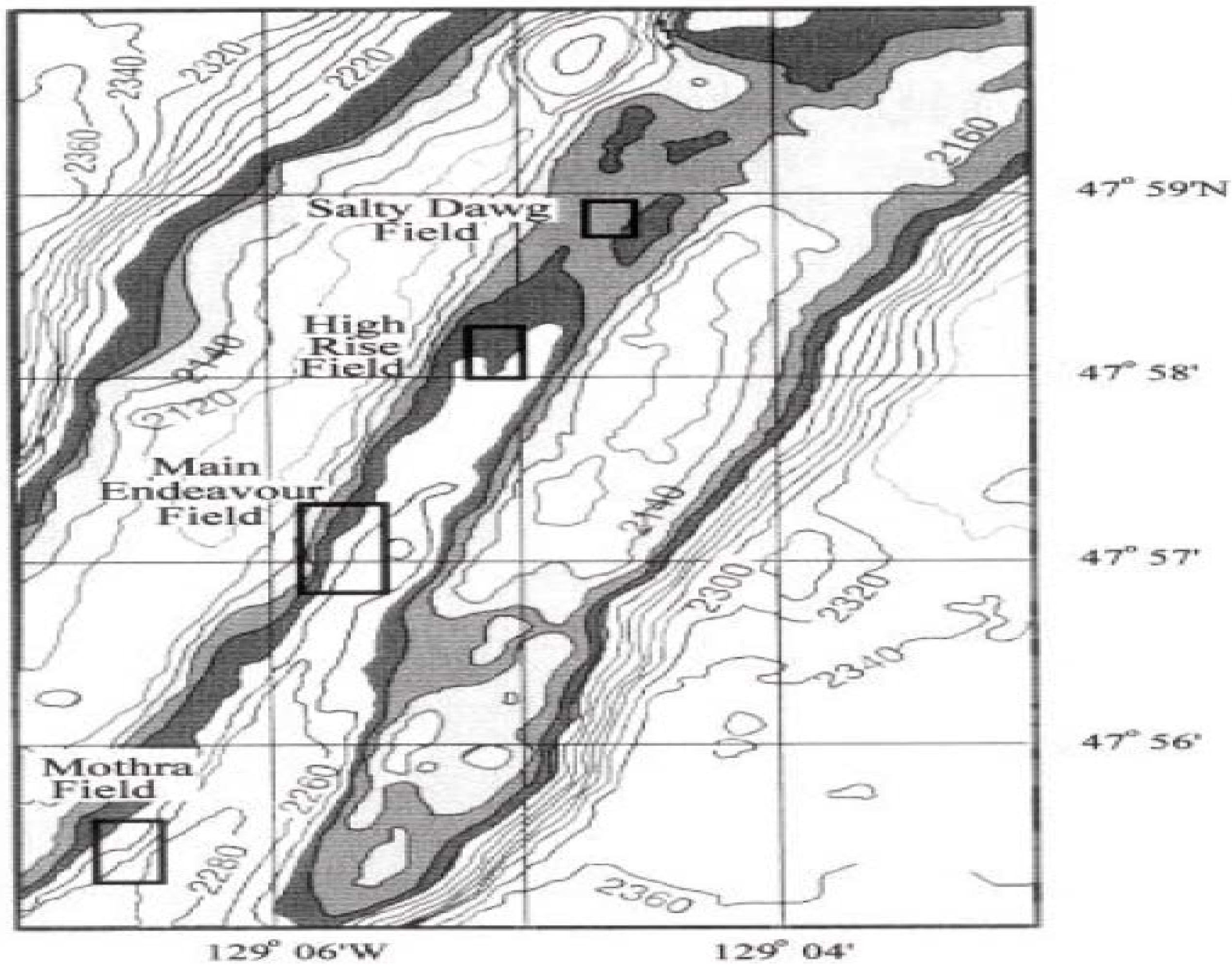


Figure 7. Geological map of the High Rise Vent field illustrates the dispersion of sulphide structures and tubeworm fields. Distances around the box are in meters. Godzilla is illustrated in the following diagram. (From Oceans background report. The Endeavour hot vents Area: A Pilot Marine Protected Area in Canada's Pacific Ocean. V. Turncliffe1 and R. Thomson; 1999).