Title
EEZ Seeps: Exploration, Exploitation, and Conservation

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Exploration, Exploitation, and Conservation

by
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Abstract

Growing exploitation of the deep sea warrants an economic and political analysis of cold seep resources in the United States Pacific Exclusive Economic Zone. Methane seeps are currently being explored for utilization by the energy industry, fisheries, and bioprospecting programs. This paper examines these direct human uses of chemosynthetic communities, addresses their costs, and explores both current US policies and potential policies for management and conservation. To date, policies concerning the EEZ have been sector-specific and authority split between various agencies. The US needs a comprehensive framework with a focus on collaboration between agencies and should include the protection of benthic features like hydrothermal vents and cold seeps. In the interim, various strategies can be implemented to manage chemosynthetic communities in the EEZ.

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Introduction to Seeps

In 1977, the discovery of hydrothermal vents in the Galapagos Rift exposed scientists to the first of many fascinating communities that function independently of the sun (Lonsdale 1977). A few years later, the Florida Escarpment revealed another type of light-independent community called a methane seep (Paull *et al*. 1984). At methane seeps (a type of cold seep), fluids rich in methane and hydrogen sulfide escape from fissures in the seafloor (Figure 1). Unlike most ecosystems, which obtain energy from photosynthetic primary producers, hydrothermal vents and cold seeps depend on chemosynthesis by bacteria and archaea to harvest chemical energy and support its animal community (Tunnicliffe *et al*. 2003; Van Dover *et al*. 2000; Kiel & Tyler 2010). Sulfide, which is toxic to aerobic tissues, is present in high levels at these geological features on the seafloor. Despite these extreme conditions, life at these biological "hot spots" flourishes, creating dense aggregations of animals.

***Figure 1**. Bathymodiolus mussels and gas bubbles from the Baltimore Canyon seep (image: Marine Conservation Institute 2012).*

Although hydrothermal vents and cold seeps are highly productive environments in the deep sea, they demonstrate lower species richness with a few well-adapted species dominating the environment (Kiel and Tyler 2010; Bernardino *et al*. 2012). Vent and seep specialists, like siboglinid tube worms, vesicomyid clams, and bathymodiolus mussels, house microbial symbionts in their tissue that perform chemosynthesis,

***Figure 2**. From left to right: orange bacterial mat at the Del Mar methane seep (Scripps Institution of Oceanography); siboglinid tube worms from Costa Rica (Woods Hole Oceanographic Institution); bathymodiolus mussels at the Florida Escarpment (Texas A&M).*

thereby creating food for their invertebrate host (Van Dover *et al*. 1989; Tunnicliffe *et al*. 2003). Invertebrates that harbor symbiotic bacteria make up the majority of animal biomass at chemosynthetic ecosystems.

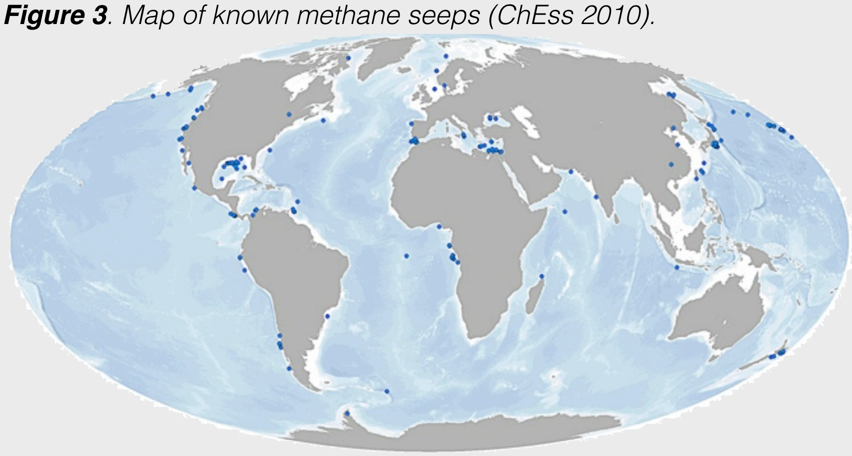
Due to their unique geological and biological attributes, seep ecosystems are ample ground for scientific research and economic opportunity. Because they indicate the presence of energy deposits, seeps may be sites of future energy extraction. A food source in the deep sea, chemosynthetic communities may contribute to the health of fish stocks. Harsh environments at seeps spur unique adaptations of organisms that may provide natural products for humans through bioprospecting.

As scientists develop new technologies, the deep sea is an expanding frontier of exploration and exploitation of oil and gas, mining, fishing, and bioprospecting. However, like all marine natural resources, deep-seep ecosystems are vulnerable to overexploitation and ecological damage. The deep sea presents an opportunity to properly establish policies to manage natural resources before human activities are already in place. To develop sound policy and management, it is necessary to look at the potential uses of a resource and evaluate the resource in market and non-market terms (Armstrong et al. 2010). To date, no analysis has focused on the opportunities of a seep environment and their associated costs.

Scientists are finding more and more human scars on deep-sea environments. It is important to mitigate the negative effects of human activities in order to ensure healthy ecosystems. Management and policy governing chemosynthetic communities has been investigated in the international realm - mainly due to interest in preserving hydrothermal vent systems, which generally form outside of national boundaries (Ardron et al. 2011; Van Dover et al. 2012). However, there has been little consideration of the management of cold seeps which tend to form on continental margins, including within the US EEZ (Figure 3).

Rarely has management preceded industry (e.g. the US implemented fisheries management only after the decline of fish stocks; a framework for seabed management followed offshore drilling by oil and gas corporations). The Pacific EEZ presents an opportunity to refine the legal framework for use of the EEZ and transcend the sector-specific nature of US ocean policy through agency collaboration. This overarching goal should be

Figure 3. *Map of known methane seeps (ChEss 2010).*



coupled with small steps that employ current laws to protect potential chemosynthetic communities. By investigating means of managing a network of cold seeps along the continental margin off the West Coast, this paper applies current US policies to benthic features in the US EEZ. To best preserve the health of these chemosynthetic communities, short-term management strategies should be implemented within the context of a greater long-term conservation framework.

Energy and Mineral Extraction

Fossil Fuels

Many deep-water seep environments are 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 occurring for decades and are considered an indicator of active deep petroleum systems (Holland 2012; Juniper 2003; Talukder 2012). Though deepwater production of oil in the Gulf of Mexico began in 1979, deepwater drilling did not become an industry-wide trend until Shell Oil discovered oil 3,000 feet beneath the surface of the Gulf in 1989 (Richards 2011). Today, there are approximately 5,900 active leases, encompassing nearly 32 million acres in the Gulf of Mexico (BOEM 2011). Seep environments scatter the seafloor in the Gulf and exhibit a variety of biological communities dominated by tube worms, clams and mussels (Boland 2010).

Ideally, resource utilization requires a balance of environmental and economic interests. Production of oil and gas is incredibly lucrative, but can cause one of the single largest environmental hazards. Oil spills greatly harm local biology, alter environmental conditions in the region, and require millions to billions of dollars to clean up. New technology that drills into deep-water sediments opens up the ocean to blowouts - even more catastrophic disasters, parts of

Figure 5. *BP/Deepwater Horizon Oil and Gas Disaster (image: US Coast Guard 2010).*

which we do not completely understand (e.g. the behavior of oil and gas under cold, high-pressure conditions). This risk is exemplified by the 2010 BP/Deepwater Horizon Oil and Gas Disaster, which released 205.8 million gallons (4.9 million barrels of oil) into the Gulf of Mexico. It affected an area the size of Oklahoma including 600 miles of beaches and wetlands (Norse and Amos 2010). Eighty miles offshore and 5,000 feet deep, the drill's location dramatically reduced BP's ability to respond quickly and effectively.

Exploratory drilling, installation, and operation of oil platforms produce localized disturbances most likely affecting nearby cold seeps. An area of future research, depletion of subsurface oil and gas reservoirs can alter the chemical energy supply to surrounding seeps, thereby possibly extinguishing the food source to the seep communities (source). The effects of the BP/Deepwater Horizon Oil and Gas Disaster on seep ecosystem function and biodiversity have not been studied. The blowout did damage deep-sea coral communities in the area (White *et al*. 2012) and from the thick level of oil which coated the seafloor, it seems likely that all benthic biology was affected in some way (Norse and Amos 2010).

Globally, offshore oil drilling accounts for about one-third of all oil production, a level that is expected to rise to one-half by 2015 (Richards 2012). While there are only 43 producing offshore leases in the Pacific, the inevitability of their installation should be met with thought-out management with attention to unique benthic features such as chemosynthetic systems.

Mining

In 1965, grossly overestimated values of *extractable* metals on the seafloor were published, painting a picture of an inexhaustible supply of highly-valued manganese nodules - deep-sea ores containing minerals like manganese, cobalt, nickel and copper - in the Pacific Ocean. This inspired over 100 research cruises and incited a "gold rush" mentality. From 1965 to 1984, more than $650 million (in 1982 US dollars) were spent on developing technologies and exploring for deep-sea manganese nodules around the globe. Unfortunately for these potential marine miners, high production costs and sufficient terrestrial supply of metals rendered deep-sea mineral mining a losing venture in the 20th century (Glasby 2002).

The deep seafloor contains valuable minerals including manganese, copper, cobalt, nickel, gold, and zinc. Deep-sea minerals have not yet been exploited due to prohibitive costs of past and current technologies. However, advances in technology could make deep-sea mining an economically attractive possibility. In early 2013, Lockheed Martin obtained an exploration license to access a large area in the Pacific Ocean for manganese nodules. The proposed plan entails underwater vehicles to rove across the seafloor scooping up nodules like a vacuum cleaner and sending them up pipes to ships on the surface. Lockheed Martin estimates a $60-billion revenue over thirty years, though acknowledges the environmental harm it will inflict (Werth 2013).

Hydrothermal vents hold "seafloor massive sulfides," deposits rich in copper, gold, zinc, and other metals created as a result of geochemical activity. For example, the Solwara 1 site near Papua New Guinea has a copper grade of approximately 7% whereas the land-based copper grade averages 0.6%. Companies like Nautilus Minerals have already developed the technology to mine seafloor massive sulfides though international legal issues have prevented their usage (Nautilus 2013).

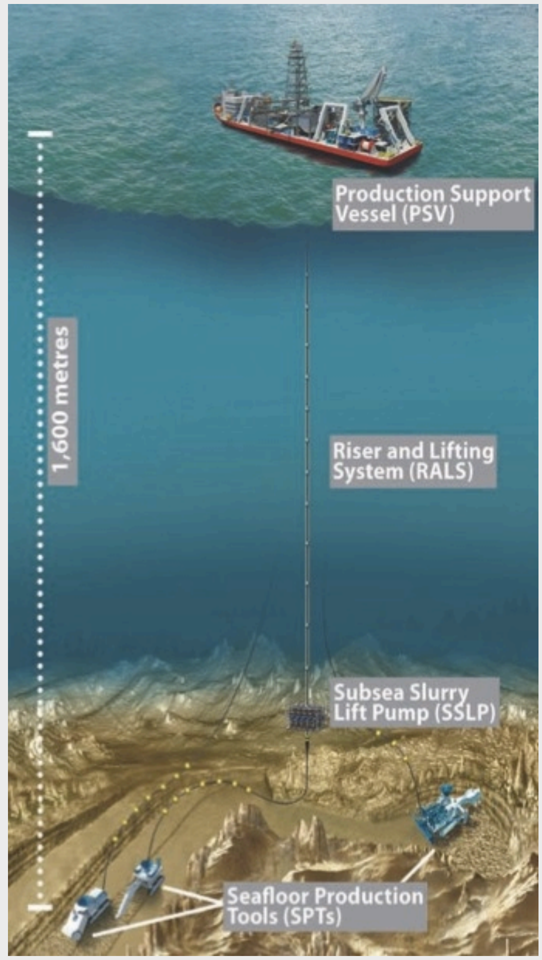


Figure 6. *Schematic of technology to extract minerals at Seafloor Massive Sulphide sites (Nautilus Minerals 2013).*

As of now, geological seeps are not discussed as potential hard mineral mining sites. The necessary in-depth geological studies and chemical analyses have not been conducted at methane seeps; and thus, their potential as a source of minerals is unknown. However, marine mining's failed history reinforces the fact that mining marine minerals is only economical when the costs of bringing them to market under prevailing conditions are favorable. The market price of minerals is one of the determinants of exploration effort (Marvasti 2012). Currently, terrestrial reserves remain high enough to accommodate the demand for most minerals, leaving the market price too low for the high up-front costs of marine extraction in most circumstances.

In addition to the market costs, environmental costs and resource externalities also need to be considered when assessing deep-sea mining. Like most mined resources, marine mineral deposits are not renewable on a human time-scale; deposits require tens of thousands of years to concentrate metals to levels economical for extraction (Halfar and Fujita 2002; Rona 2003). Mining completely depletes the resource, creating a large negative resource and environmental externality.

Methane Hydrates

Though difficult to extract with current technologies, gas hydrates could be a large energy source at deep methane seeps. Gas hydrates are ice-like materials formed from a framework of water molecules containing large, intra-lattice voids occupied by gas (Boswell 2007). Off the continental shelf and under the Arctic permafrost, low temperatures and high pressure cause methane and water to crystallize into these ice-like deposits that hold high amounts of energy. Globally they are estimated to contain more energy than all known deposits of fossil fuels (Demirbas 2010).

In 1995, the United States Geological Survey provided the first comprehensive quantification of this potential energy source for the US, reporting 320,000 trillion cubic feet of methane in domestic hydrate deposits (Collett 1995). Seep systems at the right temperature, depth, and geological conditions, such as Oregon's Hydrate Ridge, have large amounts of gas hydrates (Hovland 2000).While knowledge of gas hydrates has grown over the past twenty years, commercialization of gas hydrates remains economically unviable. The production at viable rates is technically feasible under the right conditions: high-density deposits close to the sediment surface (Bosewell 2007). Methane seeps are attractive to developers as certain seep systems contain high gas hydrate concentrations in a small area, making them an efficient source to target (Tinivella and Giustiniani 2012).

In March 2013, Japan Oil, Gas and Metals National Corporation (JOGMEC) produced tens of thousands of cubic meters of gas at a deep-sea site 80 kilometers off the coast of Japan. Boring through 270 meters of sediment to reach the 60-meter-thick methane hydrate reservoir, tapping into the rich marine deposit 1-kilometer deep presented a myriad of challenges. Methane cools its surroundings as it dissociates from the ice, potentially creating new hydrates that could slow production and clog up the well. To avoid such problems, JOGMEC carefully lowered the pressure in the reservoir, while keeping the methane in gas form. Ultimately, it was able to extract ten times more than previous extraction attempts by using this depressurization method (Cyranoski 2013).

***Figure 7**. Japan successfully producing gas from methane hydrate (image: JOGMEC 2013).*

Methane seeps containing hydrates will be commercially exploited only when the price of petroleum oil and conventional gas rises substantially (and in the absence of significant other technology such as solar and wind). The benefit of production, determined by energy market price and rate of methane production, must outweigh the total extraction cost (exploration, drilling, production, etc.) to be a lucrative endeavor. As few of these parameters are currently known with respect to gas hydrates, economic evaluation of gas hydrate resources remains highly speculative (Boswell and Collett 2011).

The developing technologies involve the injection of heat to destabilize the hydrates or extraction through seafloor strip-mining, both which are very environmental destructive (Boswell and Collett

2011). Deep-sea hydrate extraction could dramatically alter seep habitats. Some scientists believe that there is a possibility of destabilizing methane hydrate and this has intense safety and environmental implications (see Judd *et al*. 2002). A regulatory framework needs to be established as industry moves forward in developing the commercial potential of methane-hydrate deposits on the seafloor. The serious hazards to the marine environment should be a primary consideration.

Fishing

A Rockfish Refuge

Serving as a refuge, seep habitats may attract fish assemblages including some commercial species. Thousands of black egg capsules pepper the Concepción methane seep off the Chilean coast and mud volcanoes in the Mediterranean Sea. Sharks and rays lay these large egg capsules at seeps, and newly hatched juveniles use the habitat as a nursery (Treude *et al*. 2011). Aside from these observations, there is a dearth of published information on fish assemblages associated with vent and seep communities; thus, the degree to which seep habitat is significant to fish is unknown. However, extensive fishing activity has been documented over seeps and vents, suggesting the systems hold aggregations of commercial fishes (Baco *et al*. 2010).

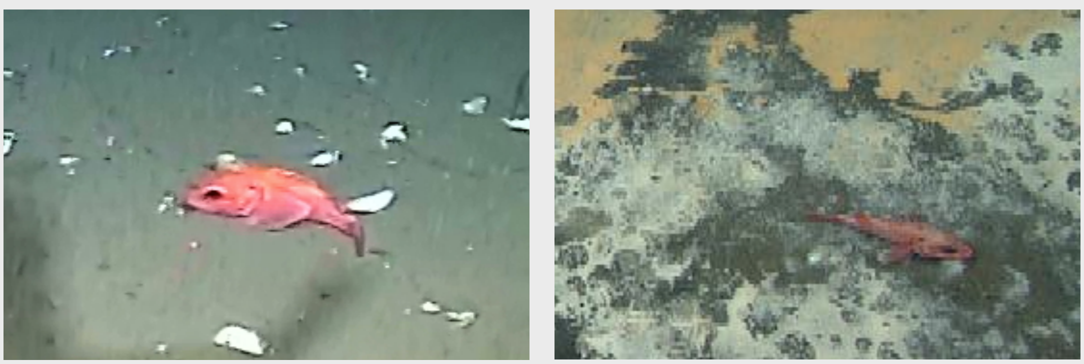


Figure 8. *ROV images of thornyhead rockfish at Del Mar methane seep (Scripps Institution of Oceanography 2012).*

Recently, ROV footage revealed high densities of rockfish over bacterial mats at the Del Mar methane seep (Grupe et al., in prep). The longspine thornyhead rockfish *Sebastolobus altivelis* is specialized to life in the oxygen minimum zone (Jacobson and Vetter 1996; Friedman *et al*. 2012). Adapted to the low-food conditions of this zone, the longspine thornyhead requires a very small amount of food (it only needs to consume approximately 5% of its body weight every 4 months). The Del Mar methane seep - 1,030 meters deep - is a high biomass oasis on the outskirts of the oxygen minimum zone. Energetically, the seep is capable of holding a large aggregation of these rockfish. Research needs to be conducted at seep sites to assess the densities of rockfish and to investigate the seep characteristics that are being utilized by the rockfish (e.g. protection, food source, spawning area).

Figure 9. *Trawling boats in Massachusetts (image: Saving Seafood).*

The Impacts of Bottom Trawling

In the 1960s and 1970s, the decline of shallow-water fisheries led the industry to expand into the deep sea, which appeared to be an inexhaustible resource. However, many deep-sea fisheries collapsed due to dense aggregations of fish around specific habitat sites, the life-history of deep-sea fishes, and advances in bottom-trawling fishing equipment (Roberts 2002). Compared to other deep-sea fishing methods, bottom-trawling results in a higher catch with less effort for fishers. Along with the depletion of fish, bottom-trawling destroys vital benthic habitats with heavy machinery, like trawl doors weighing several metric tons. The negative externalities on habitat were not included in fisheries management plans until recently (Norse *et al*. 2012).

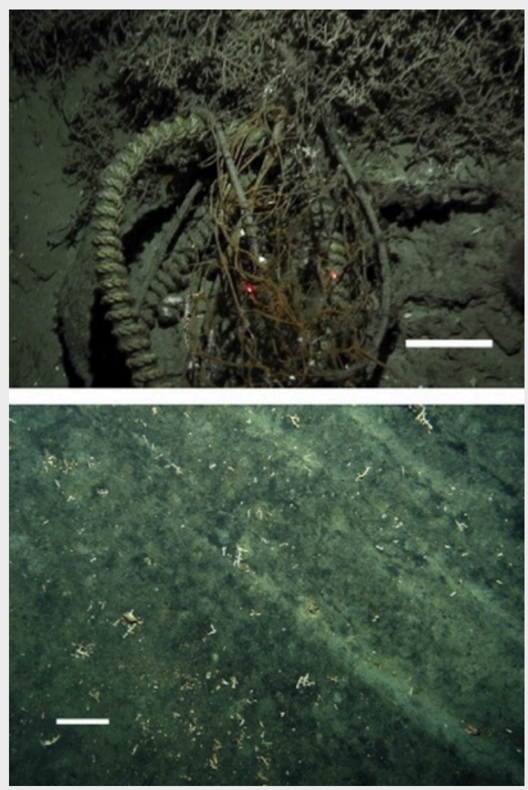


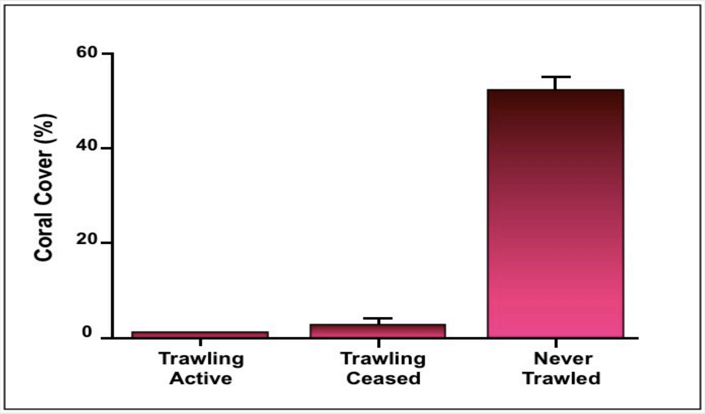
Figure 10. *Trawling equipment and trawling scars on the New Zealand seafloor. Note: scale bar is 20cm (Baco et al. 2010).*

Off the coast of Chile and New Zealand, scientists discovered new seeps that had been extensively damaged from trawling as evidenced by scrape marks and tangled fishing equipment littered at seep sites, before the systems were even discovered (Baco *et al*. 2010; Sellanes *et al*. 2008). Because of dense aggregations of organisms over productive benthic areas, geological and biological features - like deep-sea coral reefs and methane

Lessons from Bottom-Trawling on Cold-Water Coral Reefs

Less than 1% of the world's seafood comes from deep-sea fisheries; yet, it produces one-third of the world's by-catch (Norse *et al*. 2012; Armstrong *et al*. 2009). Extensive scientific work has been conducted on the resiliency (or lack thereof) of deep-sea coral reefs to trawling. Mobile fishing gear that targets benthic fishes removes attached and emergent fauna, like corals and sponges, reducing seafloor complexity. In a response to hard branching corals catching and tearing fishing nets, fishermen developed cost-reducing techniques like dragging heavy chains to remove branching corals and other obstructions from the bottom prior to the trawl (Rogers 2002; Norse *et al*. 2012).

Figure 11*. Observed coral cover on Tasmania seamounts categorized by trawling impact. Note: "Trawling active" refers to areas trawled within six months of observation. "Trawling ceased" refers to seamounts trawled 5-10 years before observation (Althaus et al. 2009).*



Since cold-water corals are slow growing, reefs do not recover after experiencing bottom-trawling in observed time-series data (Althaus *et al*. 2009). Reefs trawled are scattered with broken coral branches and sedimentation from trawling greatly inhibits the future settlement of coral larvae. When sedimentation subsides and coral can settle, they are too slow-growing to sustain the fishery. About half of the *Lophelia* reefs in Norway have been destroyed by fishing and still show limited signs of recovery (Armstrong *et al*. 2009).

seeps - become targets of bottom trawling (Quattini *et al*. 2012; Koslow 1997; Baco *et al*. 2010). Fish often aggregate on continental slopes near carbonate rocks associated with methane seepage, or near corals that settle on these carbonates.

To date, there has not been a time-series study to assess the ability of methane seeps to recover from bottom trawling. Without protection against trawling, methane seeps face a similar fate to numerous cold-water coral areas (see Figure 9). At seeps, fishermen would be inclined to use the same destructive techniques on the carbonate rock structures that protrude from the seafloor. It is unclear if and how bottom-trawling equipment would destabilize the geology of the seep, but it is clear that it would inevitably alter bacterial mats and invertebrates as well as reduce seafloor complexity.

Bioprospecting

Bioprospecting is the search for genetic and biochemical resources that humans can use for medicines and other technologies. Resources can come in the form of biochemical catalysts and other biologically produced substances, biological processes from which to model new technologies, and genetic material. Marine organisms have been evolving for much longer than their terrestrial counterparts, and as a result have developed a greater breadth of adaptations. For example, venom of the cone snail (*Conus*) targets and blocks specific neuron channels in its prey and was instrumental in the creation of a pharmaceutical pain killer called Prialt. Scientists adapted the natural toxin to pinpoint and suppress specific pain without altering the functions of the rest of the nervous system (Zewers 2007). More than 15,000 natural products have been discovered from marine microbes, algae, and invertebrates and show great potential as anti-cancer, anti-HIV/AIDS drugs, and other pharmaceuticals (Maxwell 2005; Haefner 2003; Foley *et al*. 2010).

Most marine products have come from shallow and often tropical marine environments due to the ease of research and extraction, but scientific focus has shifted to the deep-sea and its potential medical and technological uses. Deep-sea organisms have developed special adaptations to survive in dark, cold, and highly pressurized environments. Scientists have proven that their adaptations can resist fatal human diseases as genetic material extracted from marine organisms is used to create anti-cancer, anti-inflammatory, and anti-viral drugs (Zewers 2007).

Natural Products from the Deep Sea

The main sources of biological metabolites come from microbes and deep-sea invertebrates like corals (Cnidaria) and sponges (Porifera). The unique adaptations of *Streptomyces*, a type of bacteria found in deep-sea sediments, are currently utilized to create about 75% of antibiotics on the market. The microbes have been identified to possess enzymatic functions with the potential to treat human diseases ranging from diabetes, to cancer, to obesity (Bettie *et al*. 2011). *Pseudomonas*, a bacteria found in Northern Pacific deep-ocean sediment, produces protease, a type of enzyme that can not only be used for the development of environmentally friendly seawater antifouling applications, but it has the potential to be used for the protection of biomedical devices: for instance, the enzyme can be used to create protective coating to prevent bacterial colonization of catheters (Dobretsov *et al* 2007; Danese 2002). Microbial marine genetic resources also play a role in many applications of hazardous waste treatment and pollution control. Natural products from marine bioprospecting has successfully removed dangerous

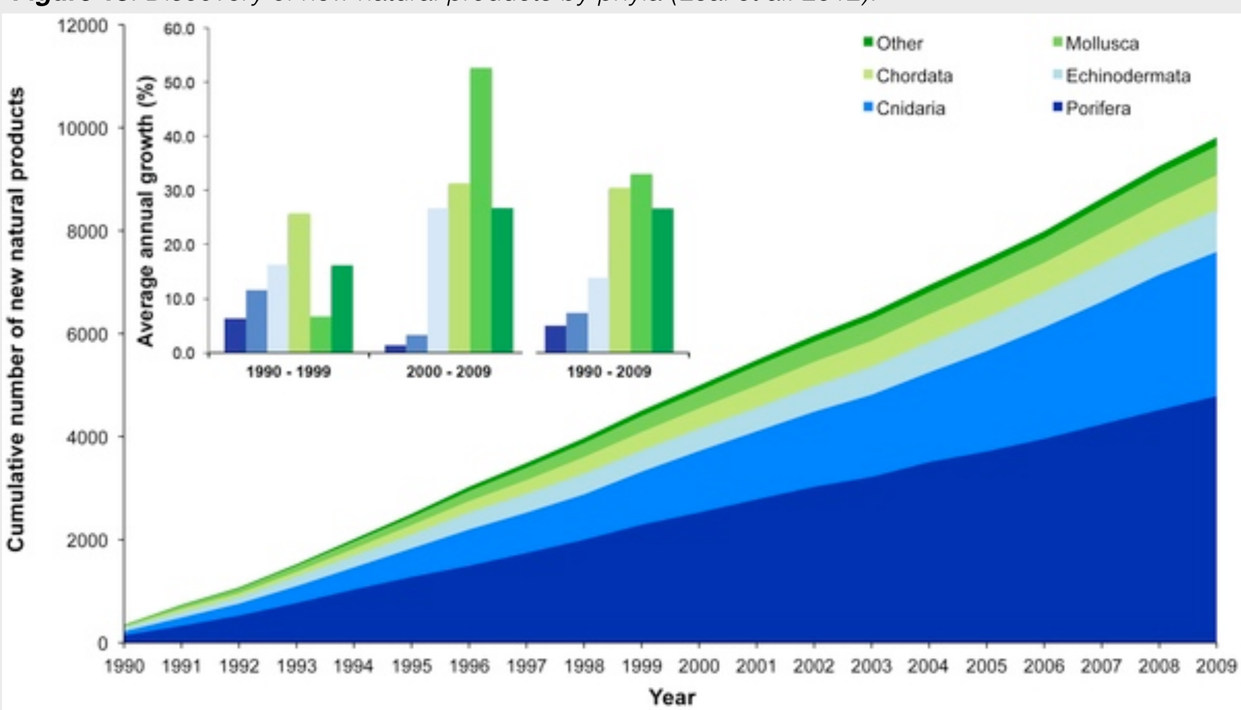
Figure 12. *Deep-Sea Bioprospecting Pharmaceuticals*

Product	Use	Source
Multiple antibiotics	Treatment of bacterial infections	Deep-sea sediment bacteria *Streptomyces*
Salinosporamide A	Cancer-fighting drug	Deep-sea hydrothermal vent microbe, *Salinospora*
Orthopedic Implants	Bone grafting	Deep-sea coral (Family: Isididae) found >1,000m in Pacific Ocean
Thermos polymerase	UV protection, prevention of skin damage	Extremophile *Thermos thermophilus* from hydrothermal vents (Sederma)
Dictyostatin-1	Cancer-fighting drug; works on multi-drug resistant tumors	Deep-sea sponge (Family Corallistadae) found >500m in Caribbean

chemical substances such as phenol, calcium, and chloride from the wastewater of industrial factories (Zewers 2007).

At the deepest point on the planet, the Challenger Deep, scientists discovered the deep-sea crustacean, *Hirondellea gigas*. This abnormally large amphipod digests wood and other fallen material using cellulases. This biological chemical may be useful in the development of bio-ethanol fermentation (Kobayashi *et al*. 2012).

Figure 13. *Discovery of new natural products by phyla (Leal et al. 2012).*



Leal (2012) suggests that sessile, soft-bodied marine invertebrates must rely on chemical defenses, which arose through their evolutionary history to deter predators, to keep competitors away, or to paralyze prey. Consequently, these organisms are more likely to be a source of natural products than highly mobile organisms (See Figure 13). Several compounds generated by deep-sea corals contribute to the arsenal of cancer-fighting treatments and other medical innovations for procedures such as bone-grafting (Foley *et al*. 2010; Maxwell 2005).

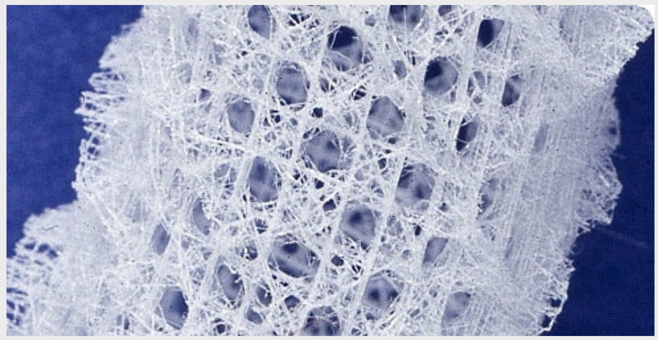


Figure 14. *The bleached skeleton of a glass sponge (image: Natural History Museum, London).*

The uses of marine-derived compounds from invertebrates extend outside of the pharmaceutical arena. *Euplectella,* a deep-water glass sponge, forms silica-based “glass” spicules that are strikingly similar in structure to fiber-optic cables (Figure 13). The glass sponge supersedes fiber-optic technology in strength and ease of fiber formation (e.g. the sponge forms these structures without the addition of heat). *Euplectella* is currently being used to improve the quality of fiber-optic cables and efficiency in their production (Graham 2003).

Bioprospecting Chemosynthetic Communities

The discoveries of deep-sea environments like hydrothermal vents (Lonsdale 1967) and cold seeps (Paull *et al*. 1984) reinvigorated a new regime of ocean bioprospecting (Figure 15). Chemosynthetic ecosystems provide valuable information about adaptations of life to extreme conditions. Although bioprospecting of the deep sea is in its infancy, deep-sea hydrothermal vents and cold seeps are predicted to yield the majority of future marine genetic resources. Thornburg *et al*. (2010) argues that bioprospecting vent and seep communities is one of the most cost-effective strategy in the deep ocean because of the dense aggregation of bacteria, archaea, and invertebrates. Sampling these communities would yield more potentially applicable biological products.

Figure 15. *Natural Products from Chemosynthetic Communities (UN University, Institute of Advanced Science; UNESCO).*

Product	Use	Source
FuelzymeTM	Ethanol production from corn	Hydrothermal vent enzyme
VenuceaneTM	DNA cloning, sequencing and amplification	*Thermus thermopiles*, vent microbe
Pyrolase	Hydraulic Fractionation	Hydrothermal vent enzyme

Chemosynthetic communities expose scientists to adaptations that exceed their imagination. Since deep-sea hydrothermal vent fluids are enriched with toxic metals, vent organisms show incredible tolerance to harsh conditions. A hydrothermal vent bacteria, *Alcanivorax*, was found to be tolerant to mercuric mercury [Hg(II)] (an incredibly toxic metal in its most toxic form). Research suggests that these bacteria have an ecological role in mercury detoxification and can be used in industrial and pharmaceutical development (Crespo-Medina *et al*. 2009; Vetriani *et al*. 2009).

Developed from a hydrothermal vent biological enzyme, the product Pyrolase operates at high temperatures to break down viscous materials for the recovery of natural gas through hydraulic fracturing (Arico and Saplin 2005). Natural gas from "fracking" generates revenues of $13 billion per year globally (Society of Petroleum Engineers 2012).

The majority of current bioprospecting activities are small-scale independent research institutions or university programs, which are exploratory in nature and not directly related to commercial enterprise. However, pharmaceutical firms like Merck, Eli Lilly, Pfizer have marine biotechnology departments. The limited accessibility to the deep sea makes extraction and cultivation of marine genetic resources a long and expensive process. Since bioprospecting in the deep sea is a relatively new industry centered around unexplored ecosystems and organisms, it is unclear how much investment will then be required to develop these raw materials into marketable products (Hunt and Vincent 2006). The timeline to develop and market a new drug generally spans between fifteen and twenty years and can cost up to $800 million (Zewers 2007). Marine chemical ecology is still several decades behind its terrestrial counterpart, and exploring the deep sea is substantially more costly and time-consuming. However, marine pharmaceutical bioprospecting shows much greater potential for anti-cancer agents than terrestrially derived pharmaceuticals (Zewers 2007).

Chemically complex ecosystems, seeps are prospects for the discovery of medically useful compounds including cold-active biocatalysts, bioremediation, surfactants and bioantifreeze (Bull 2000). Seep organisms along the Pacific continental margin have adapted not only to the harsh conditions of the deep sea, but also to high concentrations of toxic sulfide. Their adaptations to chemical extremes offer unique pharmaceutical and technological opportunities.

Management of Seeps

Management and policy governing chemosynthetic communities has been investigated in international policy, mainly due to interest in preserving hydrothermal vent systems that generally occur outside of national boundaries (Ardron *et al*. 2011; Van Dover *et al*. 2011). However, there has been little consideration of the management of cold seeps, which tend to form on continental margins within national jurisdiction. While management of international waters serves to bring nations together, most exploration and exploitation of the seafloor occurs closer to the coast.

The Exclusive Economic Zone (EEZ) is the spatial area 12 to 200 nautical miles from shore within which the coastal nation has preeminent economic, legislative and management rights (see Figure 16). The designation was adopted in 1982 under the UN Law of the Sea Convention (UNCLOS). UNCLOS gives the coastal nation

> "sovereign rights for the purpose of exploring and exploiting, conserving and managing the natural resources, whether living or non-living, of the waters superjacent to the seabed and of the seabed and its subsoil, and with regard to other activities for the economic exploitation and exploration of the zone," (UNCLOS Article 56).

This sovereignty also applies to the sea-bed and subsoil under the territorial sea through the continental shelf provision which declares that nations can explore and exploit "the mineral and other non-living resources of the sea-bed and subsoil together with living organisms belonging to sedentary species" (UNCLOS Article 77). The US has not formally

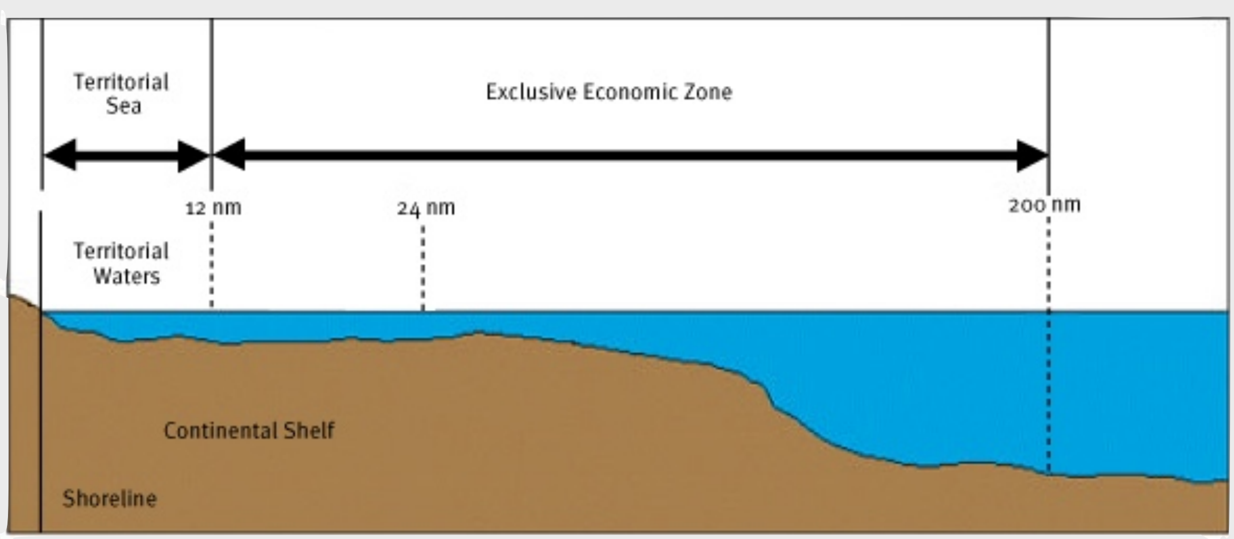


Figure 16. *Jurisdiction boundaries as defined by UNCLOS and adopted as customary law by the US.*

ratified the treaty but accepts most of it as customary law. Little analysis has been conducted on the management of chemosynthetic systems in the US EEZ. The United States has many different legal mechanisms for managing human activity - some more feasible than others and all with different degrees of protection. The complication in governing a seep system is that it falls within the jurisdictions of many overlapping US laws and agencies. Both conservation and

US Agencies & Acronyms

DOI	*Department of the Interior*
BOEM	**Bureau of Ocean Energy Management**
MMS	Mineral Management Service (now BOEM)
DOC	*Department of Commerce*
NOAA	**National Ocean and Atmospheric Agency**
NMFS	National Marine Fisheries Service
PFMC	Pacific Fisheries Management Council

US Laws, Regulations & Acronyms

NEPA	**National Environmental Protection Act**
EIS	Environmental Impact Statement
OCSLA	**The Outer Continental Shelf Lands Act**
CZMA	Coastal Zone Management Act
NTL	Notice to Lessees & Operators & Pipeline Right-of-way Holders
DHMA	Deep Seabed Hard Mineral Resources Act
MHRDA	Methane Hydrate Research & Development Act
MSA	**Magnuson–Stevens Fishery Conservation & Management Act**
EFH	Essential Fish Habitat
HAPC	Habitat of Particular Concern
MPA	**Marine Protected Area**
NMSA	National Marine Sanctuaries Act
-----	Antiquities Act
-----	**Oceans Act**
NOP	National Ocean Policy

exploitation efforts have been delayed by the intricately entangled sector-specific nature of these laws.

National Environmental Protection Act

The National Environmental Protection Act (NEPA), signed in 1970, is a procedural law critical to environmental protection in the United States. NEPA states that all Federal agencies consider consequences of “major Federal actions significantly affecting the quality of the human environment” by providing an Environmental Impact Statement (EIS). This detailed assessment shall include:

> "(i) the environmental impact of the proposed action, (ii) any adverse environmental effects which cannot be avoided ..., (iii) alternatives to the proposed action, (iv) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and (v) any irreversible and irretrievable commitments of resources" (42 USC § 4332(C)).

The United States exercises sovereign rights in the EEZ; thus, NEPA applies to the EEZ (*Natural Resources Defense Council v. United States Navy)*. All federal agencies must comply with NEPA's procedural requirements. NEPA also requires a Federal agency to "consult with and obtain the comments of any Federal agency which has jurisdiction by law or special expertise" (4332(C)). After consultation, the acting Federal agency is not required to alter its proposed actions.

The Outer Continental Shelf Lands Act

In the 1950s, oil production became the second-largest revenue generator for the United States (after income taxes). Development began to move offshore leading to the passage of the Outer Continental Shelf Lands Act in 1953 (OCSLA), a substantive law that establishes management of submerged lands in federal waters (3-200 miles offshore). Under OCSLA, the Bureau of Ocean Energy Management (BOEM), formerly of the Mineral Management Service (MMS), grants seafloor-use leases to the highest qualified bidder for energy extraction activities.

It is BOEM's responsibility to balance the potential for environmental damage with the potential for energy supply by leasing offshore areas for energy development and enacting regulations to promote resource conservation and operational safety. OCSLA requires BOEM to develop leasing plans every five years and issue competitive bidding block lease sales to private parties (43 USC § 1337). BOEM must

> "conduct a study of any area or region included in any oil and gas lease sale or other lease in order to establish information needed for assessment and management of environmental impacts on the human, marine, and coastal environments of the outer Continental Shelf and the coastal areas which may be affected by oil and gas or other mineral development in such area or region" (43 USC §1345).

In addition, all development plans must comply with NEPA. Per OCSLA, BOEM submits a leasing schedule with a corresponding EIS at least every 5 years. The 2012-2017 OCS Oil and Gas Leasing Program describes 15 new scheduled leases in US waters with a detailed EIS in a 2,057-page long document (BOEM 2012).

The leasing of the continental shelf oil and gas resources has been subject to suspensions of activities or moratoria. By including a leasing prohibition in annual Appropriations legislation, Congress restricted oil and gas development in approximately 85% of the US continental shelf from 1982 to 2008. In 1990, President George H. Bush enacted an Executive Withdrawal, which banned leasing or pre-leasing activities in these areas. President Clinton extended the Executive Withdrawal through 2012; however, President George W. Bush lifted the Withdrawal in 2008. In the face of growing public support for domestic oil and gas production, Congress failed to reinstate its moratorium in the same year. Currently, there are two moratoria over oil development: Alaska's Bristol Bay, declared by President Obama, and the Eastern Gulf, restricted under the Gulf of Mexico Energy Security Act (BOEM 2013).

OCSLA also grants states some jurisdiction over offshore oil and gas development in their coastal waters. The OCSLA states that the

> "timing and location of exploration, development, and production of oil and gas among the oil- and gas-bearing physiographic regions of the outer Continental Shelf shall be based on a consideration of… laws, goals, and policies of affected States" (Section 18.2.F).

Coastal Zone Management Act

This provision was further reinforced with the Coastal Zone Management Act of 1972 (CZMA), which aims to preserve, protect, and restore or enhance the resources of US coastal zones (16 USC § 1452). Once a state has a federally approved coastal zone management program, states have authority to review federal actions that "will affect any natural resources, land uses, or water uses" in the coastal zone of a state (16 USC § 1456(c)(1)(A)). This consistency provision of the Act gives states the power to object to any federal action that contradicts their Coastal Zone Management Program (16 USC. 1456(c)).

Through CZMA, states have some influence over activities beyond their immediate offshore boundaries. Deepwater Horizon highlighted the transboundary nature of environmental disasters; an activity occurring in 80 miles offshore in the EEZ intensely impacted the coasts' of Gulf states (Norse and Amos 2010).

In California, debate ensued over 36 existing offshore leases along the central coast in federal and state waters. Firms had obtained leases before 1982, but were unable to develop because of subsequently imposed moratoria. In 2005 the California Coastal Commission sued the DOI for extending these oil leases, which did not comply with California's Coastal Zone Management Program. In *California et al. v. Norton*, the judge ruled in favor of the California Coastal Commission, which argued that the DOI failed to show consistency with the state's Coastal Zone Management Program. The court's determination (affirmed by the US Court of Appeal for the 9th Circuit) effectively halted any possible oil exploration that would have occurred in the lease areas until further environmental studies were completed. Thirty of the 36 debated leases have been relinquished by the lessees, and the remaining six are undeveloped.

Prompted by this debate, California, Washington and Oregon officially expressed their opposition to oil and gas development off their coasts, citing various issues: destruction of scenic beauty, threat to tourism and fishing, and potential impact of an oil spill (BOEM 2012). To accommodate the goals of coastal states and local agencies, BOEM excluded the Pacific Coast from the 2012-2017 Leasing Program (BOEM 2012). Oil development continues at lease sites established before the congressional moratoria. Determined benign to coastal zones, 43 developed (producing) leases exist in the Pacific Region. No restrictions are in place for existing lease sites, although no platforms have been erected since 1989 (BOEM 2012). However, BOEM and the California Coastal Commission recently approved the development of new platforms at the existing Point Arguello leases site (BOEM 2013).

Minerals Mining under OCSLA

While no firm has yet to lease federal waters for hard mineral extraction, it falls under the same provision as oil and gas according to OCSLA, which states “the term ‘minerals’ includes oil, gas, sulfur, geopressured-geothermal and associated resources, and all other minerals” (43 USC 1301 (q)). In 1994, Congress amended OCSLA to elaborate on the extraction of sand, gravel, and shells, allowing BOEM to negotiate - on a non-competitive basis - the rights to OCS sand, gravel, or shell resources for shore protection, wetlands restoration projects, or for use in construction projects. The negotiated-agreement approach is distinctly different from the competitive bidding requirements applied to energy extraction. BOEM has not explicitly discussed using the same process for other types of mineral development in the future, but using the same competitive bidding process currently used for oil and gas for hard marine minerals has been criticized as insufficient to promote development (Farrow 1990). The Amendment also clarified the obligations concerning environmental studies extend to minerals other than oil and gas (43 USC 1337(k)(2)).

Notice To Lessees

When chemosynthetic communities were discovered in the Gulf of Mexico (Paull *et al*. 1984), the MMS played an active role in exploring and mapping these systems as well as protecting them (Boland 2010). To prevent direct harm to a seep, MMS issued a Notice to Lessees and Operators and Pipeline Right-of way Holders (NTL) in 1988 that required mandatory identification and avoidance of chemosynthetic communities. The MMS employed a risk-adverse avoidance policy; lessees need to submit *in situ* imagery (e.g. hard-bottom reflectivity) that shows the absence of seeps prior to exploratory drilling. NTL announces additional regulations and clarifications to lessees and are implemented more swiftly and effectively than an amendment to OCSLA (Boland 2010).

BOEM exercises adaptive management by modifying NTL regulations when science uncovers new information. In light of the discovery of a cold-water coral reef system at 305 meters, BOEM decreased the minimum depth for site-specific biological reviews required for all drilling or pipeline plans from 400 m up to 300 m in the 2010 NTL (Boland 2010). BOEM also increased avoidance buffers multiple times. Currently, firms must not explore within 2,000 feet (610 meters) of chemosynthetic communities (NTL 2010).

Methane Hydrate Research Development Act

In 2000, the US accelerated the nation's hydrate research effort by enacting the Methane Hydrate Research and Development Act (MHRDA). MHRDA encourages research necessary to develop methane hydrate resources as a source of energy (Pub.L. 106-193 (2000)). It promotes unprecedented collaboration between six federal agencies (Department of Energy, Department of Commerce, Department of Defense, Department of the Interior, and the National Science Foundation) to identify and quantify methane hydrate resources, develop extraction technologies, and research environmental risks and mitigation strategies. Congress extended the MHRDA and authorized $155 million in R&D spending to be distributed by the Methane Hydrate Advisory Committee from 2005 to 2010. Since then, pending has decreased; Congress appropriated $10 million for 2012. Currently, the Committee is pursuing a hydrate testing program on Alaska North Slope (Methane Hydrate Advisory Committee 2012).

Magnuson–Stevens Fishery Conservation & Management Act

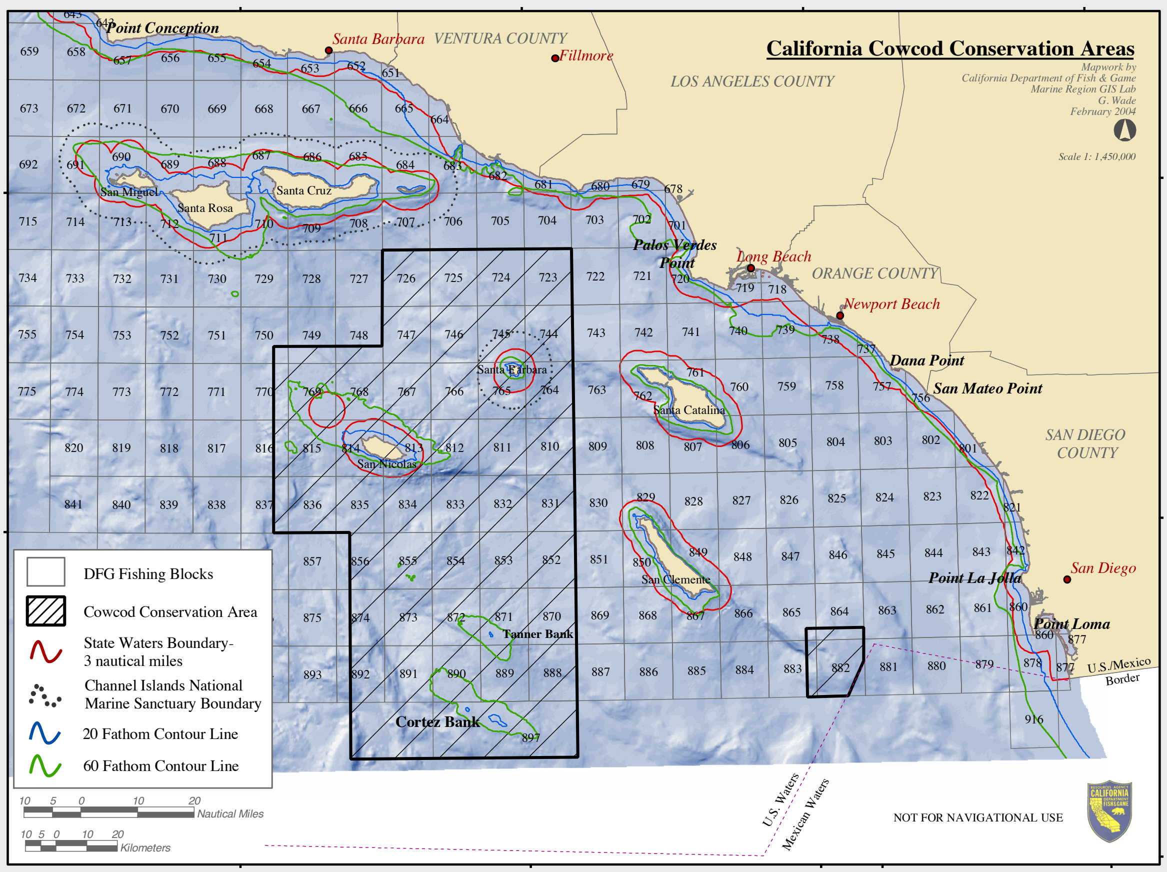
Fisheries management is seemingly unconnected to seep environments, but with advances in bottom-trawling and aggregation of fish over benthic features, fisheries law may play an essential role in protection of seep habitats along the Pacific margin. The Magnuson-Stevens Fishery Conservation and Management Act (MSA) establishes that “conservation and management measures shall prevent overfishing while achieving, on a continuing basis, the optimal yield from each fishery for the United States fishing industry” (16 USC 1851 § 301(a)(1)). To achieve this, the Act divides US waters into eight regions each with its own Regional Fishery Management Council (Regional Council) to manage marine fishes. The Regional Councils assess fish stocks and create fisheries management plans based on biological, ecological, economical, and social factors.

Prompted by the underwhelming consideration of biodiversity on the part of the Regional Councils, Congress amended the MSA with the passage of the Sustainable Fisheries Act in 1996 (Pub. L. 104-297 (1996)). The amendment emphasized the conservation and rebuilding of overfished stocks. Along those lines, Congress instructed Regional Councils to identify Essential Fish Habitat (EFH) - “waters and substrate necessary to fish for spawning, breeding, feeding or growth to maturity" (16 USC § 1801(10)). Once identified, the Council must create guidelines to protect this area from fishing in their Fisheries Management Plan.

The Pacific Fisheries Management Council (PFMC), in cooperation with the National Marine Fisheries Service (NMFS) and California Department of Fish and Game, is responsible for the management of fishery resources in federal waters (3-200 nautical miles) off the US Pacific Coast in California, Oregon and Washington. Federal and state authority is complicated as fishes do not follow jurisdictional boundaries, but California Code Regulation 14 § 189 conforms all state commercial groundfish regulations to federal regulations. This was first enacted in 1996 and continues to be effective today. In June 2005, the PFMC closed approximately 200,000 square nautical miles to commercial bottom trawling to protect the seafloor as part of a comprehensive plan to protect the habitat of over 80 groundfish species (Figure 18). Groundfish tend to be slow-growing and benthic-dwelling fishes. For this reason, multiple seafloor areas were designated as Essential Fish Habitat. In collaboration with other federal and state agencies, the Council created the Rockfish Conservation Areas and Cowcod Conservation Areas, habitats areas that are important to the overfished species in the Pacific (PFMC 2005).

The Council also established Habitat Areas of Particular Concern (HAPC), a subset of EFH that are particularly ecologically important, sensitive to disturbance, and rare (50 CFR 600.815(a)(8)). EFH and HAPC can prevent or limit only *fisheries* activities in the designated area; it does not prohibit oil, gas, and mineral development. When another federal agency desires to conduct an

Figure 18. *Map of California Bight jurisdictional boundaries and conservations areas (California Department of Fish & Game).*



activity in an EFH/HAPC designated area, only the consultation of the Regional Council/NOAA is required, not an alteration of proposed action if deemed harmful.

The HAPC designation is a means to prevent harmful fishing like bottom-trawling in valuable seep areas. The consultation process of HAPC could be used as a mechanism to discourage other federal agencies from development of infrastructure or extraction at chemosynthetic sites. A more thorough assessment is needed to determine the role seep environments play in the life-cycles of commercial fishes and, until then, the US should enact a precautionary approach and protect this potentially significant benthic feature.

Marine Protected Areas

Chemosynthetic communities could also be protect by implementing a Marine Protected Area (MPA), which is "any area of the marine environment that has been reserved by Federal, State, territorial, tribal, or local laws or regulations to provide lasting protection for part of all the natural and cultural resources within" (E.O. 13158). The United States designates MPAs as a tool to conserve the living resources of the oceans under their management and to avoid conflicts between various user groups (McGrath 2003).

The National Marine Sanctuaries Act

In 1972, Congress passed the Marine Protection, Research, and Sanctuaries Act. Later renamed the National Marine Sanctuaries Act (NMSA). It has been constrained by its early architecture, which lacks a singular purpose for conservation. Proponents of the act intended it to mimic the

***Figure 19**. Map of US National Marine Sanctuaries (NOAA)*

Wilderness Act, which established terrestrial national parks and reserves; however, opposition from certain industries led to ambiguity in the law's construction, and the NMSA fell short of the envisioned system (Morris 2013).

The Act allows NOAA, under the Department of Commerce, to designate marine sanctuaries, but lacks a strategy and criteria for implementation (Morris 2013). In addition, the law incorporates provisions for multi-uses, such as fishing and oil extraction, that deviate from - and in many cases contradict - the conservation intent (Chandler and Gillian 2007). The Act burdens NOAA to prove that the benefits of protection outweigh the economic gain from human use. Usually, the negative economic impacts of designation are perceived to trump the need for protection. Since its existence, the Act has only resulted in 13 sanctuaries, most of which are still used in various ways

Figure 20. *Marine Sanctuaries that protect Deep-Sea Areas (source: NOAA.gov).*

Sanctuary	Year of Designation	Sanctuary Characteristics
Channel Islands	1980	A confluence of warm and cold water currents with a variety of marine life. Expansion by NOAA in 2007 to include deeper waters.
Gulf of the Farallones	1981	An extensive marine habitat, including deep-sea corals and bird colonies.
Cordell Bank	1989	The continental slope where upwelling of nutrient-rich deep water supports a flourishing ecosystem. The sanctuary goes to a depth of 470m and contains deep-sea corals.
Monterey Bay	1992	Habitats including shores, kelp forests, an underwater canyon and the Davidson Seamount, which was added in 2007 as an example of offshore seamount with special geological and ecological value.

by humans (Morris 2013).

The Act is further crippled by amendments that make designation a long, laborious legal process, during which politically powerful lobby groups can add constraints to protection (Morris 2013). With the aim of achieving maximum consensus between conservation and exploitation interests, proposed designations must gain congressional attention and approval, undergo a lengthy, politically complicated period of interagency consultation, and demonstrate clear partisan public processes. For example, NOAA is required to consult with the Regional Fishery Management Council that may be affected by the proposed designation (16 §1433(b)(2)). Regional Councils, influenced by various fishing groups, are inclined to reject “no-take” designations. Because of this provision, many sanctuaries do not protect against fishing (e.g. only 1% of the Florida Keys Sanctuary is off limits to fishing and 10% of Channel Islands Marine Sanctuary are “no-take” zones).

In 2000, Clinton reauthorized the Act, but placed a budget-dependent moratorium on the addition of any new marine sanctuaries. No new sanctuaries have been created since 2000 and no sanctuaries protect chemosynthetic communities.

The Antiquities Act

President George W. Bush circumvented the NMSA difficult designation process in 2006 by using legislation from 100 years earlier: the Antiquities Act of 1906. A brief, concise, and uncomplicated procedural law, the Antiquities Act allowed the President through Presidential Proclamation (8031) to establish the Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. The Act states that

> "the President of the United States is authorized, in his discretion, to declare by public proclamation historic landmarks, historic and prehistoric structures [later changed to "historic and scientific interests"], and other objects of historic or scientific interest that are situated upon the lands owned or controlled by the Government of the United States to be national monuments…" (16 USC § 431).

The Antiquities Act was enacted before the rise of administrative agencies, when public notice and comment became the standard for democratic participation in executive government actions. No laborious consultations or legal formalities are needed for the declaration of a national monument. The President's proclamations gave the Secretary of the Interior (in consultation with the Secretary of Commerce) primary management authority, which was thereafter delegated to the US Fish and Wildlife Service. The Secretary of Commerce, in consultation with the Secretary of the Interior, has authority over fishing in pelagic waters of the monuments; this authority has been delegated to the National Oceanic and Atmospheric Administration (NOAA). Though complicated by the intermingling of agencies, the Act does not have a multi-use provision; fishing, mining and other human activities are not allowed in the Monument per the Antiquities Act (Ardron *et al*. 2011).

In 2009, President Bush exercised this authority again to establish the Mariana's Trench as a National Monument (16 USC § 431-433). This is the only MPA that holds a known chemosynthetic system. This 250,000 square kilometers monument includes a series of active undersea volcanoes and hydrothermal vents in the Pacific Ocean. Among these natural wonders, the Champagne Vent produces almost pure liquid carbon dioxide and the Sulfur Cauldron is a pool of molten sulfur (Figure 21).

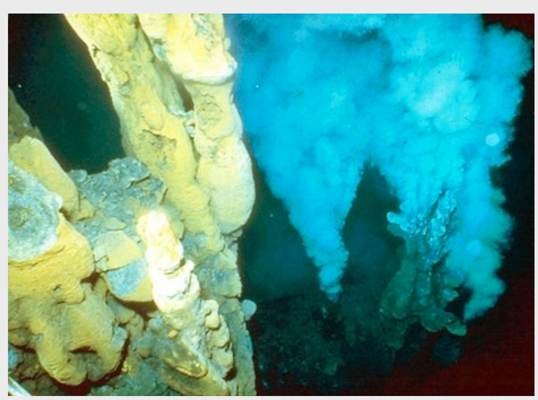


Figure 21. *Champagne Vent in the Mariana's Trench (image: Penn State Science).*

Oceans Act and National Ocean Policy

Moving into the 21st century, Congress passed the Oceans Act of 2000, in an effort to improve ocean stewardship. The Oceans Act created the US Commission on Ocean Policy, which reached the conclusion that there are too many nuanced laws that fragment ocean authority among numerous agencies and undermine goals of ocean conservation (Commission on Ocean Policy 2004). The Commission recommended a new centralized authority for ocean activities and increased emphasis on regional governance. President Obama established an Interagency Ocean Policy Task Force to develop implementation recommendations. The Task Force recommended a Coastal and Marine Spatial Planning initiative and creating the National Ocean Council to direct interagency collaboration (Interagency Ocean Policy Task Force 2010).

Some opponents argue that NOP adds a new layer of federal bureaucracy and that the far-reaching policies and regulations that will only lead to further job loss and economic damage (Hastings 2013). The House of Representatives passed a bill to halt funding for the policy, though the amendment has not passed the Senate. With such strong dissent, implementing the recommendations of the Task Force will be challenging.

While an admirable endeavor, the final recommendations of the Task Force do not specifically address the deep sea. The deep sea is often overlooked and it is important that it be explicitly discussed in NOP. Marine spatial planning is a vital part of ocean management. As industry ventures farther offshore, the inclusion of the deep sea in ocean mapping and the NOP's Coastal and Marine Spatial Planning Initiative is paramount to protect unique benthic features like chemosynthetic communities.

Conclusions

Very little is known about the commercial and ecological of methane seeps, but that should not be a reason to forgo their protection. It is crucial that more research and studies are conducted to learn more about this unique environment. Even if unofficial and not fully formed, some planning is necessary among scientists. Ultimately, the deep sea in the US EEZ will need policies to protect it from the inevitable advancement in human technology to extract natural resources. Destructive human uses threaten chemosynthetic communities and need to be preemptively managed and, in some cases, completely prevented.

> *"Opposing ocean planning is like opposing air traffic control: You can do it, but it will cause a mess or lead to dire consequences."*
>
> *- Representative Edward J. Markey*

The industries that have the potential for exploitation do not work independently of each other. The action of one affects the other, complicating this issue of management even more. Incorporating biological factors of the seep and the costs and benefits of its utilization, we can set ideal management framework. We have the opportunity to correctly manage this habitat, whether through utilization or protection. Most likely, it will be a combination of both.

Working within the sector-specific management of the EEZ, there are means to protect the network of seeps along the West Coast. OCSLA's state-rights consideration and the CZMA allow coastal states like California to protect chemosynthetic communities. More scientific research needs to be conducted to determine the connectivity between these seep systems. In areas where energy development is already taking place, scientists can influence BOEM to enhance avoidance policies of benthic features through NTL. One of the most promising but understudied protection potential is an EFH designation under the MSA.

Once interest in seep resources grow and technology brings production costs down, a comprehensive management framework ensures the consideration of ecosystem connectivity, multiple-use factors, and environmental costs. Unlike most management systems that were implemented after exploitation had already occurred, the US has the potential to establish clear goals, effective regulations, and action plans to successfully manage chemosynthetic features in the US Pacific EEZ.

While legally capable of being protected through current US policies, the seep ecosystems in the Pacific EEZ arguably do not compare to other, more threatened marine areas. When addressing conservation within the political arena, where only a few conservation projects ever make it to fruition, the idea of what should be protected narrows based on rarity, urgency, and feasibility. Charismatic megafauna and extraordinary environments that US constituents can see and experience generate more interest. Without the discovery of a more scientifically vital organism or astounding geological feature, cold seeps on the continental margin will most likely not be a focus of protection.

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