Seamounts in California Waters

Marine Conservation Institute
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Table of Contents

1. Summary

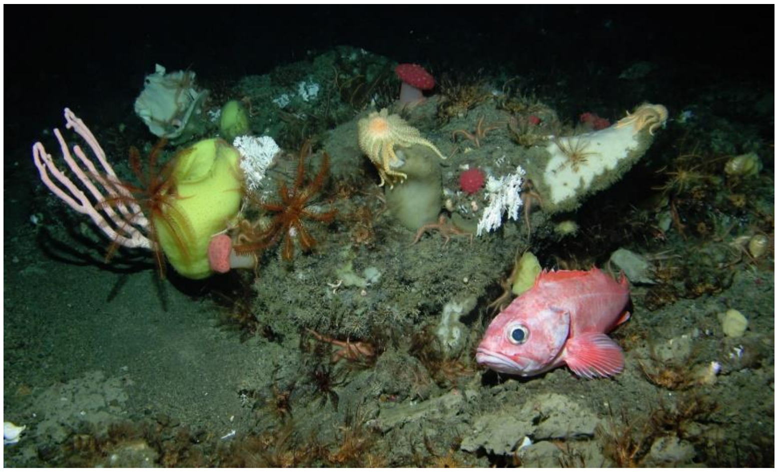


Figure 1.1: A diverse assemblage of benthic organisms on a sponge garden at Mendocino Ridge. Image courtesy of NOAA.

Seamounts are massive underwater volcanoes that support incredible levels of biodiversity. These extremely productive features act as oases in the often sparsely populated deep sea, supporting high abundances of benthic (Figure 1) and pelagic organisms including corals, sponges, anemones, crabs, fish, sharks, seabirds, turtles, whales, dolphins. Californian seamounts stand poised at a critical conservation junction. With the advent of new technology and increasing commercial interest in the deep sea, a barrage of threats including fishing, oil and natural gas extraction, seafloor mining, and climate change endanger these fragile ecosystems. Despite the high potential to lose these seamount ecosystems in the coming decades they are shockingly bereft of protection, making effective and long-term conservation planning critical for saving these habitats before they are irrevocably damaged. In this report, we provide a general overview of the 63 seamounts in California waters with a focus on their environmental conditions, biology, sensitivity to anthropogenic threats, and conservation status.

2. Introduction to Seamounts

2.1 Seamount Characterization

Seamounts are massive underwater volcanoes that occur in every ocean basic across the planet. They are traditionally characterized as a discrete underwater terrain feature that extends higher than 1,000 m off the seafloor and is approximately conical (length:width ratio <2) in form (IHO 2008). While some recent studies have attempted to classify much smaller features (as small as 50-100 m in height) as seamounts, this approach creates significant issues. These smaller features do not exert the same control on the current regime and other oceanographic factors that large seamounts do, and should not be expected to play an equivalent role in the broader ocean ecosystem. In addition, they are much more difficult to discern from most methods of predicting the global distribution of seamounts, which often relies on the use of satellite altimetry data. Therefore, smaller submarine volcanoes less than 1,000 m tall are typically characterized as knolls, and features less than 500 m tall are typically referred to as hills. The most recent global seamount census identified 10,234 seamounts (including 283 guyots) covering 2.2% of the seafloor (7,859,200 km^2) (Harris et al. 2014; see Section 3.1 of this report for an overview of global estimates and methodology). As of 2010, fewer than 300 seamounts have been sampled, limiting our ability to understand and conserve these important habitats (Rowden et al. 2010).

2.2. Seamount Formation

Seamounts are volcanic in origin. They occur more frequently than terrestrial volcanoes, and are generally much taller. Most are created on oceanic crust either on spreading ridges, subduction zones, or on the interior of plates over mantle hotspots. Seamounts typically follow a geologic pattern of initial growth, subsequent volcanic activity, subsidence (sinking), and eventually extinction (cessation of volcanic activity). As lava erupts on the deep seafloor, a seamount typically begins to grow with axial symmetry (i.e., the typical cone-shape commonly observed in terrestrial volcanoes), but large seamounts often lose this shape and become more ridge-like as the uneven distribution of stress leads to rifting and fissure eruptions outside the primary cone. The vast majority of seamounts are comprised primarily of basaltic rock, although a small minority are formed from serpentine mud (generally termed 'mud volcanoes'; Fryer 1992) and the uplift of oceanic crust (Schmidt and Schminke 2000).

The growth of a seamount can stem from a variety of types of volcanic activity. At oceanic spreading centers where tectonic plates are diverging apart from each other, magma escapes and cools in the cold seawater, creating submarine volcanic rock formations that grow larger with each subsequent eruption. Mid-ocean spreading centers typically produce a number of relatively small seamounts, with their abundance roughly correlating with the spreading rate (White et al. 1998). Other seamounts form near subduction zones, where tectonic plates are converging and one plate slides under the other. The subducted plate begins to melts as it moves towards Earth's hot interior, creating hot magma that bubbles its way up to the seafloor, erupting and giving birth to a feature known as an island arc seamount (Cloos 1993). Large seamounts often form in the interior of plates. These intraplate seamounts typically form at hotspots, areas where super-hot magma plumes burst through the oceanic crust. As the oceanic crust moves across the hotspot a series of volcanoes forms, giving rise to some of the long seamount chains observed today such as the Hawaiian-Emperor Chain (Tarduno et al. 2003). Rarer types of intraplate seamount that did not form over a hotspot also exist. Instead, these seamounts are believed to have formed when magma forced its way through ancient spreading centers in part due to decompression melting, a process in which the Earth's mantle melts as it moves upwards through the crust due to rapid decreases in pressure (Davis et al. 2002).

Large seamounts may eventually grow tall enough to breach the surface of the ocean and become islands. These islands often continue to grow due to subsequent volcano eruptions into the atmosphere, but like all seamounts they will eventually sink. Seamounts are so massive that they cause the ocean crust beneath them to flex and compress, leading to the subsidence of the entire feature (Detrick et al. 1978). The crust below seamounts can also cool if volcanic activity ceases or significantly slows, resulting in thermal contraction that causes further subsidence. For seamounts that were once islands, the winds and waves they were exposed to can erode their summits into flat tops. These seamounts are known as guyots, named after the Swiss geographer Arnold Guyot. They are relatively rare in our oceans – scientists estimate that there are almost 10,000 seamounts, but only 283 guyots (Harris et al. 2014).

2.3 Physical Oceanographic Effects

Seamounts exert strong influences on both local and global current regimes, and generally have enhanced hydrodynamic activity compared to the surrounding seafloor. Due to their size and shape in the water column, they have a strong influence on the hydrodynamic regime in ways that are often favorable for a plethora of marine life. Seamounts accelerate ocean currents, generate surface and internal waves, form strong eddies, increase upwelling, and amplify tides and mixing (Lueck and Mudge 1997). As massive structures extruding high into the water column, they generate sufficient friction to convert solar and lunar tidal forces into internal tides – waves below the surface of the ocean that typically occur along the boundary between layers with different densities. These internal tides increase vertical and lateral ocean mixing by introducing turbulence, and play a major role in both local and global circulation patterns (Garrett 2003). Seamounts also create (Royer 1978) – and sometimes destroy (Herbette et al. 2003) – eddies, circular ocean currents. The extent to which a seamount exerts a force on circulation patterns is dependent primarily on its height in the water column, depth of its summit, morphology, local oceanographic conditions (current flow, temperature, salinity, etc.), and to a lesser degree, its hydrothermal activity (Lavelle and Mohn 2010). One of the most ubiquitous circulation patterns observed on seamounts is the Taylor cap (also known as a Taylor column or cone), a stationary circulation pattern that can concentrate and retain food and larvae over the seamount. Depending on the conditions, seamounts can also generate significant downwelling over their summits due to the creation of closed vertical circulation cells, and/or promote enhanced upwelling along their flanks (Eriksen 1991). The height above the summit that is subjected to these "seamount effects" can vary from the order of hundreds to thousands of meters up through the water column (Roden 1987), and in some seamounts has been found to increase primary productivity by as much as 60% (but typically only 5–10%; Pitcher et al. 2007) by transporting and retaining nutrient rich water.

Seamounts also significantly alter local currents, often enhancing current flow across steep slopes, pinnacles, and canyons, while blocking stronger currents from reaching depressions and flat areas. These local current alterations can have significant influences on the distribution of benthic organisms across a single seamount. Many studies have found that suspension feeders, including cold-water corals and sponges, have strong preferences for steep, elevated terrain features that experience accelerated current flow (e.g. Georgian et al. 2014; Rowden et al. 2017).

2.4 Benthic Seamount Ecosystems

The deep sea comprises the largest environment on the planet, but its expansive ecosystems remain largely unexplored. Deep-sea habitats below 200 m account for 90% of the world's oceans by both volume and area (Armstrong et al. 2012) and cover approximately 65% of the earth's surface (Danovaro et al. 2010). Despite decades of intensive research, less than 0.0001% of the deep sea has been directly surveyed (Gjerde 2006). The deep sea provides a number of direct and indirect ecosystem services including the provisioning of oil and gas, minerals, and living resources (e.g., fishery species and biochemical compounds), waste disposal, climate regulation, and cultural services including education, scientific research, public interest, and tourism (reviewed in Armstrong et al. 2012).

Seamounts support a wide array of marine life, creating hotspots of biodiversity in otherwise sparse areas of open-ocean and deep-sea environments. In part, this stems from the large effects that seamounts exert on the physical environment in their vicinity (see Section 2.3). This suite of current alterations enhances food and nutrient supply to benthic suspension feeders, removes waste products, reduces sedimentation, transports larva, and enhances primary productivity near the surface (and therefore export productivity to the seafloor) (Rogers 1994; White et al. 2007). A wide variety of benthic ecosystems are associated with seamounts, often founded on the three-dimensional habitat structures created by cold-water corals and sponges.

Cold-water corals and sponges are critical foundation species in the deep sea and frequently occur on seamount habitats. These organisms provide vital ecological services including the creation of complex habitat structures (Cordes et al. 2008), the alteration of local hydrodynamic conditions (Dorschel et al. 2007; Mienis et al. 2009), carbon sequestration (van Weering et al. 2003), and nutrient and carbon cycling (van Oevelen et al. 2009). As a result, deep-sea coral and sponge communities house a large diversity of associated organisms (Costello et al. 2005; Roberts et al. 2006) and act as important habitats and nurseries for commercially important fish (eg. Baillon et al. 2012). Many cold-water corals are extraordinarily long lived, with many species living hundreds to thousands of years (Roark et al. 2009; Roberts et al. 2009). Deep-sea sponges are the oldest known animals in the world, with one specimen estimated to have lived for 11,000 years (Jochum et al. 2012). This extreme longevity, coupled with slow growth rates (Roberts et al. 2009), limited dispersal ability (Brooke and Stone 2007), low reproductive outputs (Orejas et al. 2002), and high mortality rates of new recruits (Doughty et al. 2014) makes it difficult or even impossible for these communities to fully recover from significant disturbances (Prouty et al. 2011; Van Dover et al. 2014).

In addition to the factors that drive enhanced biodiversity on seamounts, their isolated nature can drive speciation and gives rise to endemic species (Rogers 1994; de Forges et al. 2000) that are not found on similar ridges or escarpments, or even on neighboring seamounts (but see Lundsten et al. 2009). On average approximately 20% of seamount species are considered to be endemic to seamounts (Stocks and Hart 2007). While the enhanced current flows past seamounts may increase the transport of larva in some cases, Taylor columns can trap larva in circular eddies, effectively geographically isolating the seamount from even closely neighboring areas (Mullineau and Mills 1997). Due to the lack of extensive field surveying throughout the deep sea, it is likely that many seamounts house currently undiscovered, endemic species – meaning that extensive habitat destruction on even one seamount could potentially result in the loss of a species or subspecies.

2.5 Pelagic Seamount Ecosystems

In addition to the diverse benthic communities often found on seamounts, a wide variety of pelagic organisms also rely on seamount habitat, including tuna, billfish, sharks, sea turtles, seabirds, and marine mammals (Sedberry and Loefer 2001; Waring et al. 2001; Santos et al. 2007; Morato et al. 2008; Morato et al. 2010). Seamounts have dramatic effects on the ocean currents around them (see Section 2.3); these altered current systems frequently enhance and concentrate the supply of nutrients, food, and larvae above seamounts (Morato et al. 2010). As a result, the waters overlying seamounts are often oases with higher than normal productivity (Worm et al. 2003) and a significantly higher species diversity within 40 km of their summits (Morato et al. 2010). The enhanced productivity and retention of food sources above seamounts appears to favor species at higher tropic levels, resulting in large aggregations of pelagic predators (Genin 2004). In addition, seamounts are important aggregating locations for migratory species including sharks, billfish, teleost fish, and whales (Tsukamoto 2006; Pitcher et al. 2007;

Morato et al. 2008). In some cases, the strong magnetic signature of seamounts allows these migratory species to more effectively navigate the open ocean and provides a method for species with large open ocean ranges to meet for mating (e.g., Klimley 1993). The enhanced productivity and navigation utility of seamounts results in a large number of pelagic species – including many commercially important species – using them as nurseries, feeding grounds, migratory pathways, and mating grounds.

2.6 Socioeconomic Importance of Seamounts

Seamount habitats provide a large number of ecological services that have direct socioeconomic benefits. Quantifying the economic value of marine environments is difficult, especially in deep-sea environments where the benefits to humans may be more indirect and less tangible than in other marine systems. Folkersen et al. (2018) assessed a range of deep-sea valuation attempts and concluded that it is "impossible to estimate the (total) value of the deep-sea in monetary terms…". Nonetheless, economic valuation of habitats can be a useful tool to help decision makers compare competing management strategies by contextualizing the value of an ecosystem in a comparable framework. Few attempts have been made to estimate the value of seamount ecosystems, however Ressurreição and Giacomello (2013) recently estimated the economic value of the Condor Seamount in the Azores. They focused their valuation on human activities with direct economic outputs and assessed the total revenue for each: tuna fisheries (€15,259), whale watching (€5,280), demersal fisheries (€431,723), scientific research (€343,757), shark diving (€194,111), big-game fishing (€61,040), and scuba diving (€3,240). They stress that their valuation was limited and likely underestimated the intangible and indirect benefits associated with the full ecological services provided by the seamount. However, they were able to conclude that non-extractive uses of the seamount were far more economically valuable than previously realized. Although this study has not been repeated for other seamounts, it is sensible to consider the economic value of all uses when investigating tradeoffs and management rationales.

When making an economic determination between conservation and resource extraction, it is important to also apply the precautionary principle: until we are fully aware of the uncertainties associated with action that may cause harm, it is judicious to wait to act until there is an appropriate degree of certainty. In the case of seamounts, we often have only explored a small fraction of the total habitat and cannot fully assess the value of the ecosystems and the functions and services they provide. It is also important to note that once damaged, these ecosystems may not recover in our lifetime, and that ecological restoration efforts are likely to be cost-prohibitive or technologically infeasible in deep-sea habitats (Van Dover et al. 2014).

2.7 Anthropogenic Threats to Seamounts

The advent of improved technology to explore and study deep-sea ecosystems has also exposed the substantial damages already being incurred by human activity. Some of the largest documented damages to seamount habitats have occurred as the result of bottom trawl fisheries (Puig et al. 2012; Pusceddu et al. 2014), which cause extensive physical damage to benthic environments. Deepwater coral and sponge reefs are often targeted for trawling due to their high abundances of commercially fished species (Hall-Spencer et al. 2002), in some regions severely damaging 30-50% of surveyed reefs (Fosså et al. 2002). With the collapse of many coastal and shelf fisheries, the industry has progressively targeted deeper species (Koslow et al. 2000), resulting in considerable losses in the richness, diversity, and abundance of deep-sea communities (Cryer et al. 2002). In addition to direct physical damage, bottom trawling resuspends sediments that can smother benthic filter feeders including cold-water corals and sponges even outside of the trawled area (Palanques et al. 2001). While the majority of documented damages have resulted from bottom trawling practices, long-line fishing gear has also been observed to disturb deep-sea habitats (Orejas et al. 2009). In the North Pacific Ocean, bottom trawling has largely been restricted to more coastal, shallow waters (generally <2,000 m), while long-line fishing has occurred throughout the region (Figure 2.1).

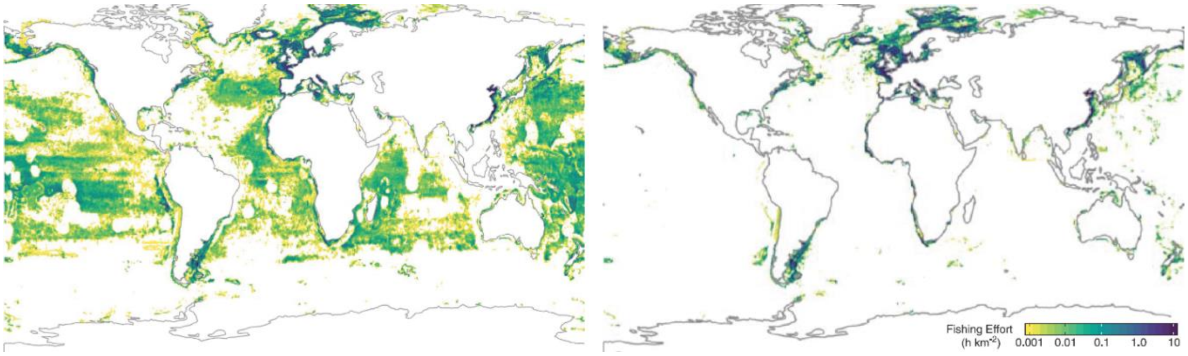


Figure 2.1. Global fishing effort (hours per km^2) for all gear types (left) and bottom trawling (right). Figures are from Kroodsma et al. (2018).

In future oceans, it is predicted that the effects of anthropogenic climate change will pose a significant threat to deep-sea ecosystems around the world (e.g., Guinotte et al. 2006), as more acidic, warmer, deoxygenated, and food-limited conditions become increasingly prevalent (Mora et al. 2013). Cold-water corals in the Pacific Ocean already grow in waters with low aragonite and calcite saturation states (Thresher et al. 2011; McCulloch et al. 2012; Jantzen et al. 2013). Ocean acidification is projected to significantly reduce aragonite and calcite saturation states (Feely et al. 2012), making it difficult or impossible for corals to continue to calcify and create reef structures (Turley et al. 2007). As deeper waters warm (Mora et al. 2013), marine organisms may exhibit reduced calcification rates (Georgian et al. 2016), altered metabolic activity (Dodds et al. 2007), and changes in gene expression (Carreiro-Silva et al. 2014). Climate change is also expected to result in the decreased export of particulate organic carbon to the seafloor and reduced dissolved oxygen levels (Mora et al. 2013), which may hamper the ability of organisms to metabolically compensate for other stressors (Georgian et al. 2016).

Resource extraction from the seafloor also poses a significant threat to deep-sea ecosystems. Oil and natural gas exploration and extraction activities have a number of detrimental effects in the deep sea, ranging from large-scale disturbances from spills and resulting cleanup efforts (Fisher et al. 2014), and smaller-scale but chronic disturbances from small oil leaks, drill tailings, and weighting agents (Larsson and Purser 2011). The exploration and extraction of deep-sea minerals threatens to physically damage large swaths of the seafloor in a similar fashion as bottom trawling (reviewed in Boschen et al. 2013). While still in its infancy, deep-sea mining may soon affect areas such as the cobalt-rich seamounts in the Hawaiian Seamount Chain (Schlacher et al. 2013).

Marine organisms are a key focus of bioprospecting: the search for and commercial development of valuable natural compounds. Because the ratio of possibly valuable natural compounds to compounds screened is greater in marine-sourced materials, marine bioprospecting has a higher probability of commercial success. Most major pharmaceutical firms have marine research programs (Arico and Salpin 2005), and bioprospectors have shown a special interest in species with unique traits that allow them to endure extreme environmental conditions, such as those living on seamounts and other deep-seabed ecosystems (Thornburg et al. 2010). Scientific research in these extreme environments will likely increase as technology advances and becomes more available, potentially resulting in the oversampling of some communities.

3. Characterizing California's Seamounts

3.1 Seamount Survey Methodology

Despite their massive size, the sheer area of unexplored seafloor and historic paucity of accurate bathymetric data has made simply estimating the global number of seamounts a significant challenge. Confounding these efforts has been the shifting definition of 'seamount' across different studies; historically defined as volcanic features rising more than 1 km above the seafloor, some studies have attempted to delineate features as small as 50-100 m as seamounts. A number of studies have estimated the global distribution of seamounts using the best-available satellite bathymetry (Table 3.1; Menard 1959; Jordan et al. 1983; Craig and Sandwell 1988; Wessel 2001; Kitchingham and Lai 2004; Hillier and Watts 2007; Wessel et al. 2010; Kim and Wessel 2011; Yesson et al. 2011; Harris et al. 2014).

The most straightforward method to identify seamounts is by using bathymetry data at an appropriate resolution and accuracy to resolve the size and morphology of even small seamounts. However, only a small portion of the ocean has been mapped in any detail (10% of the seafloor at a resolution of 1-minute; Becker et al. 2009). Early studies used a manual approach based on existing bathymetric profiles of the seafloor, extrapolating from the seamounts found in the area examined to a global estimate (e.g., Menard 1959). Other studies have used similar, albeit more sophisticated, approaches by extrapolating from the seamounts uncovered in single-beam echosounder surveys (Jordan et al. 1983) or from multi-beam bathymetry collected along narrow swaths along ship tracks (Hillier and Watts 2007). Modern mapping efforts generally use various forms of satellite altimetry, usually relying on the remote sensing of gravity anomalies. This approach benefits from the full global coverage of the dataset, but has limits in the size of seamounts that can be detected due to the course resolution of the data. Accordingly, global estimates of seamounts have varied considerably, with estimates ranging from approximately 8,000 to over 125,000 seamounts taller than 1 km worldwide (see Figure 3.1).

Table 3.1: Brief overview of the history of global seamount estimates. Number of seamounts are reported only for features greater than 1 km in height for studies that assessed multiple size groups.

Study	Method	No. of Seamounts
Menard (1959)	Extrapolation from manual counts derived from existing bathymetric profiles	10,000
Jordan et al. (1983)	Extrapolation from single-beam bathymetry	30,000-50,000
Craig and Sandwell (1988)	Satellite altimetry	8,556
Kitchingman and Lai (2004)	Global digital elevation map	14,287
Hillier and Watts (2007)	Bathymetry along ship tracks	40,076
Wessel (2001)	Satellite altimetry	11,880
Wessel et al. (2010)	Satellite altimetry	125,000
Kim and Wessel (2011)	Satellite altimetry	8,458

Yesson et al. (2011)*	Global digital elevation map derived from a satellite-gravity model	33,452
Harris et al. (2014)*	Global digital elevation map derived from a satellite-gravity model	10,234

*Databases used in this study.

In this report, we relied on the more recent global seamount estimates in Yesson et al. (2011) and Harris et al. (2014). Both studies relied on the most up-to-date global seafloor digital elevation map, SRTM30+ (with a resolution of 0.0083° or approximately one kilometer at the equator) (Smith and Sandwell 1997; Becker et al. 2009), which is largely based on satellite altimetry but also incorporates multi- and single-beam echosounder data where available. Harris et al. (2014) applied a more stringent algorithm to delineate seamounts based on their size (>1 km in height) and morphology (they required an approximately conical shape). The authors identified 9,951 seamounts and 283 guyots. In contrast, Yesson et al. (2011) identified 33,452 features as seamounts. Approximately 89% of the Yesson et al. (2011) seamounts were also identified by Harris et al. (2014). However, only 45% of the Yesson et al. (2011) seamounts were determined to be seamounts in Harris et al. (2014), suggesting that the 2011 study overestimated the correct number. A large portion of the seamounts identified by Yesson et al. (2011) were characterized as ridge features in Harris et al. (2014), suggesting that the 2011 study correctly identified complex and large topographical features, but failed to differentiate seamounts and other seafloor features based on their morphology. We attempted to include as many probable seamount features from both datasets as possible, while excluding obvious errors. In addition, we adjusted the number of seamounts based on a manual inspection of the underlying bathymetry data. For example, we manually removed several seamounts originating from the Yesson et al. (2011) database that were ridge-like in structure, but included several not found in Harris et al. (2014), which sometimes grouped neighboring summits as a single seamount. As more accurate and precise data are collated, and as algorithms for identifying seamounts continue to improve, we expect that the predicted number of seamounts in California waters will change.

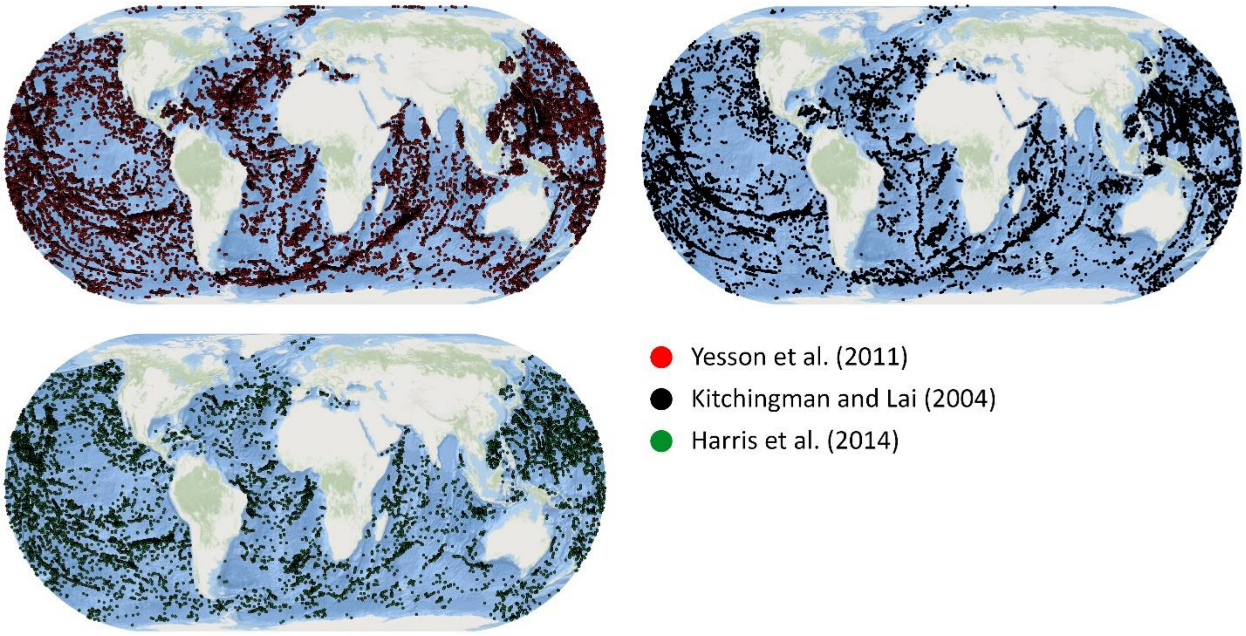


Figure 3.1: Global distribution of seamounts according to Yesson et al. (2011), Kitchingman and Lai (2004), and Harris et al. (2014). See Table 3.1 for the total numbers of seamounts estimated in each study.

3.2 Distribution

The United States is home to more seamounts than any other country. Its exclusive economic zone (EEZ) contains approximately 7.3% of the world's seamounts (743 in total), covering an area of more than 667,500 km^2. Globally, the majority of seamounts exist outside national jurisdiction however, with more than 58% of seamount habitats occurring outside of national EEZs.

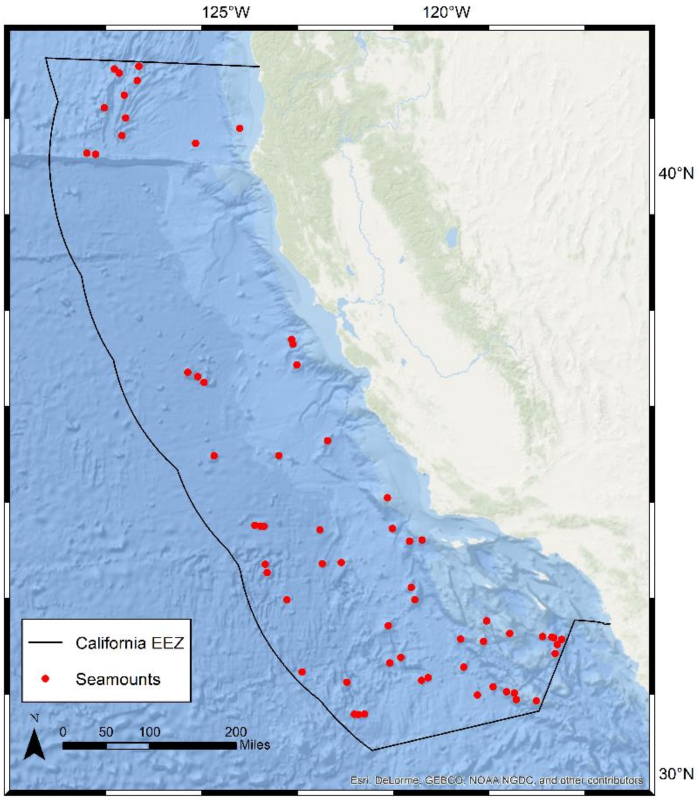


Figure 3.2: Distribution of seamounts within the California Exclusive Economic Zone (EEZ).

Within California waters, there are an estimated 63 seamounts (Figure 3.2; see Section 3.1 for calculation methodology). The average summit depth of California seamounts is 1,994 m, with a minimum depth of 30 m and a maximum depth of 4,218 m (Table 3.2). Compared to other ocean basins, the North Pacific holds the most seamounts (3,934 seamounts, 40% of the global total), with California waters holding 1.6% of the North Pacific seamounts and 0.62% of the global total. Approximately half (31) of the California seamounts have summits shallower than 2,000 m, the deepest extent of most bottom trawling activity (Morgan and Chuenpagdee 2003). On average, the seamounts are located 178 km offshore, with the closest seamount located 21.9 miles offshore and the farthest seamount located 347.7 km offshore (Table 3.2). The average distance to the nearest neighboring seamount is 32.1 km, with a minimum distance of 4.1 km and a maximum distance of 120.5 km.

Table 3.2 Spatial characteristics of California seamounts.

Metric	Average	Minimum	Maximum
Distance Offshore (km)*	178.0	21.9	347.7
Summit depth (m)	1,994	30	4,218
Distance to nearest seamount (km)	32.1	4.1	120.5

*Includes Channel Islands as shoreline.

The majority of seamounts (55 out of a total of 63) are located in the abyss (Figure 3.3), defined as the area of seafloor located above the hadal zone (deeper than 6,000 m) and below the continental slope (defined as “the deepening seafloor out from the shelf edge to the upper limit of the continental rise, or the point where there is a general decrease in steepness”; IHO 2008) (Harris et al. 2014). There are seven seamounts located on the continental slope, and one seamount located on the continental shelf (defined as: “a zone adjacent to a continent (or around an island) and extending from the low water line to a depth at which there is usually a marked increase of slope towards oceanic depths”; IHO 2008). A total of 22 seamounts occur on oceanic ridges, 13 are located on the continental rise (including some on fan deposits and terraces on the continental rise), and nearly all occur on large escarpments (seafloor gradients exceeding 5° slope over an area of at least 100 km^2) (Figure 3.4).

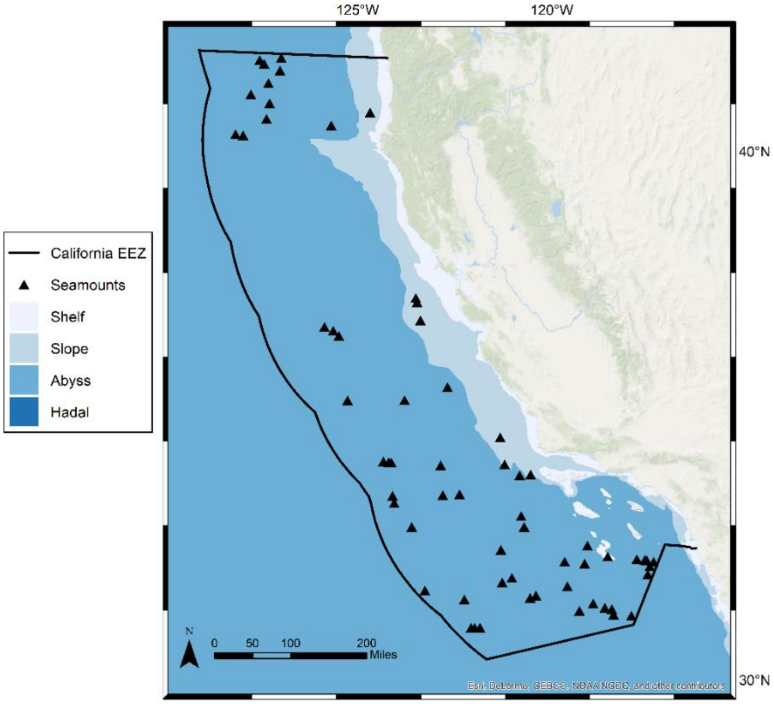


Figure 3.3: Benthic classification of the California EEZ. Data from Harris et al. (2014).

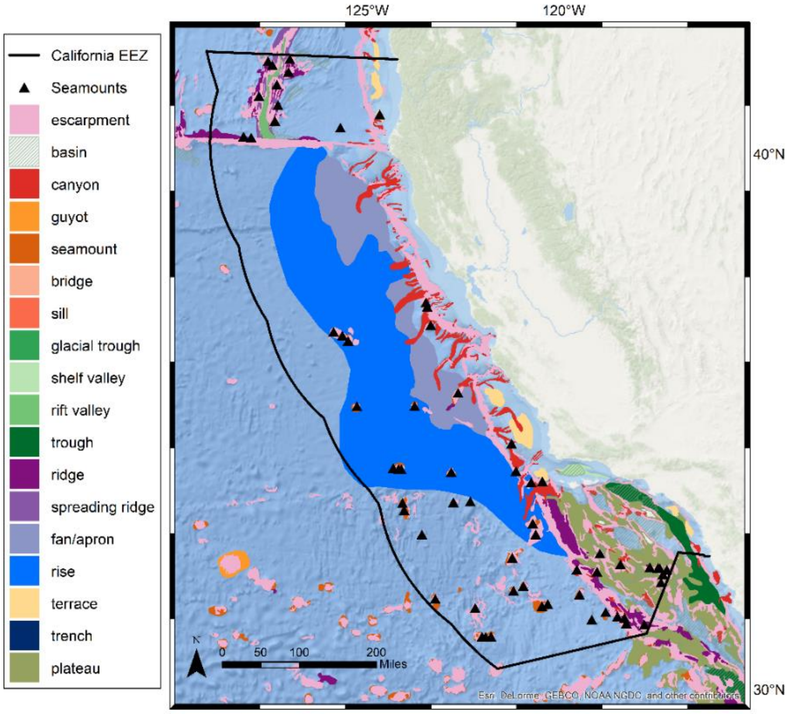


Figure 3.4: Seafloor morphology of the California coast. Data from Harris et al. (2014).

3.3 Geology of California Seamounts

Seamounts are ubiquitous throughout California waters due to the large amount of tectonic activity in the region. In fact, there is even evidence that the remnants of an ancient seamount exist on land in the Mendocino National Forest in Northern California (MacPherson 1983). These seamounts provide important benthic habitats that are geologically distinct from neighboring deep-sea environments. While large portions of the deep sea are flat and sediment covered, seamounts often provide the exposed hard substrate and complex and steep terrain features that are necessary for many species of cold-water corals, sponges, and associated species to survive. Together, these features make seamounts not only interesting geologic features, but hotspots of biodiversity as well (see Sections 2.4 and 5.1).

As with most seamounts, seamounts in California waters are largely comprised of various forms of basalt – a common volcanic rock type that forms when iron-rich lava cools in the cold seawater of the deep ocean. Other observed rock types include granite and sandstone (erratics transported from neighboring environments), hawaiite, mugearite, andesite, glass sands, hyaloclastic, and trachyandesite (Davis et al. 2002). Sampled rocks were frequently found to be encrusted with manganese oxide, a potential target for deep-sea mining operations. The distribution, morphology, and orientation of the California seamounts reflects the convoluted tectonic history of the region. As they occur near the continental margin, their morphology differs noticeably from open ocean and ridge seamounts, which often occur as isolated, fairly symmetrical cones (Clague et al. 2000). Instead, they typically have a complex morphology that generally includes an elongated axis, northeast to southwest orientation, and a series of multiple cones and ridges with sediment filled troughs (Davis et al. 2002). In addition, they typically formed from a large series of relatively small eruptions spanning several million years, rather than fewer, larger eruptions over a short period of time (Davis et al. 2010).

Most of the well-studied seamounts (Table 3.3) in California are examples of intraplate volcanoes that formed away from the edges of tectonic plates, including Gumdrop Seamount, Pioneer Seamount, Rodriguez Seamount, Guide Seamount, and Davidson Seamount (Davis et al. 2002). These intraplate volcanoes generally did not form over hotspots however, as is commonly observed in other parts of the Pacific Ocean (e.g. the Hawaii-Emperor Chain). As a result, linear chains of seamounts are not commonly observed in California waters, with the notable exception of the Taney Seamounts, although these are near-ridge seamounts (on the Pacific-Farallon spreading center) and did not form over a hotspot (Clague et al. 2000). Accordingly, the distribution of observed seamounts is seemingly more random than in other ocean regions, albeit with a trend towards an increase in the number of seamounts in the southern portion of the California EEZ (a trend that continues south into Mexican waters) (Figure 3.2).

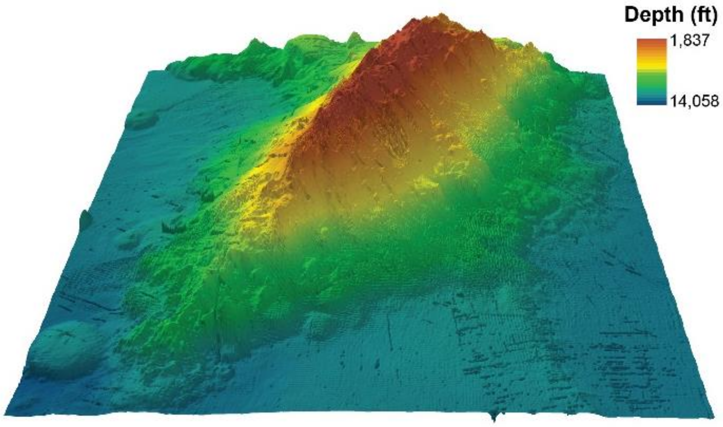


Figure 3.5: Three-dimensional view of the San Juan Seamount. Warmer colors indicate shallower depths.

Many seamounts in California waters were once ancient islands, including San Juan Seamount (Paduan et al. 2009) (Figure 3.5). San Juan started to form approximately 20 million years ago and was volcanically active for an estimated 9.7 million years. It most recently erupted approximately 2.8 million years ago, existed as a series of eight small islands for approximately one million years, and receded beneath the surface approximately 10–14 million years ago. Some of the exposed surfaces of the seamount were eroded by wind and waves, as evidenced today by weathered rocks and the remnants of sandy beaches. However, the main culprit for the sinking of San Juan back beneath the waves is not erosion, but rather subsidence due to the massive force it exerts on the oceanic crust beneath it. In the case of San Juan Seamount, the ocean crust also compressed significantly due to thermal contraction once volcanic activity ceased.

Rodriguez Seamount was once an island standing as tall as 230 feet above sea level, with an area of 2.6 square miles (Paduan et al. 2009). Like the neighboring San Juan Seamount, it has since sunk back beneath the waves largely due to the subsidence of the ocean crust beneath it. Due to the erosional forces it was exposed to as an island, its modern summit largely consists of a large flat dome, qualifying Rodriguez as a guyot – a flat-topped seamount. Rodriguez Seamount is another example of an intraplate volcano (Davis et al. 2002). However, it is a relatively rare type of intraplate seamount that did not form over a hotspot. Instead, it formed when magma forced its way through ancient spreading centers in part due to decompression melting, a process in which the Earth's mantle melts as it moves upwards through the crust due to rapid decreases in pressure. Rodriguez was volcanically active for around 2 million years as it formed, with evidence suggesting that its more recent eruptions occurred in shallow water. Like other guyots, the erosional forces of wind and waves scoured the summit into a flat top prior to its subsidence back beneath the waves, producing the flat, sandy dome observed today.

The Taney seamount chain are examples of near-ridge seamounts, forming near fast-spreading ridges (4.9 cm yr^{-1}) on diverging tectonic plates (Clague et al. 2000). The chain formed from a series of eruptions from shallow, large-volume magma chambers that eventually collapsed, forming a large caldera. Calderas are large sinkholes that form when volcanoes collapse in on themselves, generally because the now-empty magma chamber can no longer support the massive weight of the volcanic rock above. The oldest and largest volcano in the Taney chain has undergone three large caldera collapses in its history, leaving the seamount with a unique half-moon shaped summit. The other seamounts have smaller calderas, some of which were partially filled in with subsequent lava flows. One of the summits has evidence of a somma, a unique summit formation that is created when an old caldera is filled in with a shield created by younger lava flows. Due to their morphology, scientists initially believed that the seamounts were relatively young. However, subsequent argon dating revealed that they are approximately 26 million years old (Coumans et al. 2011).

Davidson Seamount, one of the best surveyed seamounts in California waters, was formed an estimated 20 million years ago, with its last volcanic eruption occurring well over 9 million years ago. Today, the volcano is considered to be extinct, but is still growing at a barely perceptible rate due to the minute accumulation (1–7 mm per year) of ferromanganese oxide crusts. It formed on top of an ancient spreading center, as evidenced by symmetric magnetic anomalies on either side (Lonsdale 1991).

Table 3.3: Physical characteristics of the seamounts with the most extensive geologic surveys in California waters.

Seamount	Age (millions of years)	Height (m)	Dimensions (km)	Summit Depth (m)	Type
Davidson Seamount	20	2,400	42x13.5	1,260	Intraplate – ancient spreading center
Gumdrop Seamount	22-24	Poorly defined base	Poorly defined base	1,210	Intraplate – ancient spreading center
Pioneer Seamount	11	1,930	12.8x12.8	820	Intraplate – ancient spreading center
Taney Seamounts	26	1,980	60x12	1,930	Near-ridge spreading center
Guide Seamount	17	1,440	16.5x5	1,680	Intraplate – ancient spreading center
Rodriguez Guyot	10–12	1,675	13x13	650	Intraplate – ancient spreading center
San Juan Seamount	19	2,960	70x30	560	Intraplate – ancient spreading center

4. Oceanographic Conditions of California Seamounts

4.1 Broad-Scale Circulation in California Waters

The California coast is a major upwelling region, which brings cold and nutrient-rich water to shallow ecosystems and is the primary driver of the high levels of biological productivity in the region (Kudela et al. 2008). The dominant current in the region is the California Current, a persistent surface current that is responsible for transporting cold and nutrient-rich water from the subarctic (Hickey 1998). It encompasses the majority of seamount habitat in California waters, extending from the shelf break to 1,000 km offshore. In the vicinity of Point Conception, the current splits into an offshore dominant current and an inshore current that contributes to the Southern California Eddy and dictates the current flow in and around the Channel Islands (Hickey 1979). Beneath the California Current, the California Undercurrent transports warm, nutrient-poor waters from the equator (Pierce et al. 2000). Combined, these current systems produce a clear oxygen minimum zone with very low oxygen concentrations (often <0.5 ml l^{-1}) along the upper continental shelf (Deuser 1975). Depending on conditions and year, this oxygen minimum zone may extend deeper than 1,000 m. California waters are also heavily influenced by the El Niño Southern Oscillation. El Niño years typically bring periods of lower primary surface productivity, weaker upwelling, and increased storm activity. In contrast, La Niña years are marked by high surface productivity.

4.2 Environmental Data

A suite of environmental variables was examined to characterize the summit conditions at each California seamount, and compared to conditions in non-seamount habitats (Table 4.1). Since cold-water corals, sponges, and many other benthic seamount fauna are suspension feeders and therefore reliant on the vertical transfer of surface productivity (Duineveld et al. 2007), the particulate organic carbon (POC) flux (mg C m^{-2} d^{-1}) to the seafloor was also included as a proxy for food availability, along with horizontal and vertical current fluxes. The saturation state of the calcite polymorph of calcium carbonate, temperature (°C), salinity (psu), and dissolved oxygen (ml L^{-1}) were included due to their known biological relevance to cold-water octocorals and other organisms (e.g., Mortensen and Buhl-Mortense 2004; Orejas et al. 2009; Georgian et al. 2014; Naumann et al. 2014; Georgian et al. 2016).

Table 4.1: Description and source of environmental data used to characterize seamount summit conditions. All variables were calculated at the seafloor unless otherwise indicated.

Variable name	Units	Native Resolution	Reference
Depth	meters	0.0083°	Becker et al. 2009 Sandwell et al. 2014
Carbonate Chemistry			
Total alkalinity	µmol l^{-1}	3.6x0.8-1.8°	Steinacher et al. (2009)
Dissolved inorganic carbon	µmol l^{-1}	3.6x0.8-1.8°	Steinacher et al. (2009)
Omega aragonite (Ω_{ARAG})		3.6x0.8-1.8°	Steinacher et al. (2009)
Omega calcite (Ω_{CALC})		3.6x0.8-1.8°	Steinacher et al. (2009)
Particulate Organic Carbon	g C m^{-2} yr^{-1}	0.05°	Lutz et al. 2007
Water Chemistry			
Dissolved oxygen	ml l^{-1}	1°	Garcia et al. 2014a
Salinity	pss	0.25°	Zweng et al. 2013
Temperature	°C	0.25°	Locarnini et al. 2013
Nutrients			
Phosphate	µmol l^{-1}	1°	Garcia et al. 2014b
Silicate	µmol l^{-1}	1°	Garcia et al. 2014b
Nitrate	µmol l^{-1}	1°	Garcia et al. 2014b
Current Regime			
Horizontal current velocity	m s^{-1}	0.5°	Carton et al. (2005)
Surface Conditions			
Chlorophyll *a*	mg m^{-3}	4 km	Aqua Modis (NOAA)
Photosynthetically Available Radiation	W m^{-2}	4 km	Aqua Modis (NOAA)
Sea Surface Temperature	°C	4 km	Aqua Modis (NOAA)

Bathymetric data for the study area were obtained from the SRTM30+ layer (Becker et al. 2009; Sandwell et al. 2014) downloaded from: topex.ucsd.edu/WWW_html/srtm30_plus.html. Ocean data in the SRTM30+ layer were originally derived from Sandwell et al. (2014), the LDEO Ridge Multibeam Synthesis Project, the JAMSTEC Data Site for Research Cruises, the NGDC Coastal Relief Model, and the International Bathymetric Chart of the Oceans. The native resolution of the SRTM30+ layer is 0.0083°, or approximately one kilometer.

Dissolved oxygen, salinity, temperature, and nutrient data were obtained from the World Ocean Atlas (v2 2013). Carbonate data (Ω_{ARAG}, Ω_{CAL}, dissolved inorganic carbon, and total alkalinity) were obtained from modeled data in Steinacher et al. (2009). Particulate organic carbon (POC) flux at the seafloor was obtained from Lutz et al. (2007). Chlorophyll *a* and photosynthetically available radiation (PAR) data were obtained from NOAA’s Aqua MODIS program at a resolution of 4 km, and were resampled to match the extent and resolution of the bathymetry data with no interpolation.

Benthic variables (WOA data, carbonate data, and current data) were transformed to match the extent and resolution of the bathymetry layer using a variable up-scaling approach that approximates conditions at the seafloor (Davies and Guinotte 2011). Briefly, each gridded layer was first interpolated to a slightly higher resolution (typically 0.5-1°) than its native resolution using inverse distance weighting, resampled to match the extent and resolution of the bathymetry data, and draped over the bathymetry data within its depth range. This technique has been demonstrated to work effectively for many global and regional scale variables (Davies and Guinotte 2011; Yesson et al. 2012). WOA data were available as 102 depth-binned layers from depths of 0-5500 m, with a vertical resolution of 5 m (from 0-100 m), 25 m (100-500 m), 50 m (500-2000 m), and 100 m (2000-5500 m). Carbonate data (Steinacher et al. 2009) were available in 33 depth-binned layers: 6, 19, 38, 62, 93, 133, 183, 245, 322, 415, 527, 661, 818, 1001, 1211, 1449, 1717, 2014, 2340, 2693, 3072, 3473, 3894, 4329, 4775 m. SODA current data were available in 50 depth bins of: 5, 15, 25, 35, 46, 56, 66, 77, 88, 99, 110, 122, 135, 149, 164, 181, 201, 225, 253, 288, 330, 382, 447, 525, 619, 729, 855, 997, 1152, 1320, 1498, 1683, 1875, 2071, 2271, 2474, 2679, 2885, 3092, 3300, 3509, 3718, 3927, 4136, 4346, 4556, 4765, 4975, 5185, and 5395 m. For deeper depths, we assumed that conditions at the seafloor were relatively stable and consistent with values at the maximum depth with available data.

4.3 Analysis of Environmental Data

To assess whether the 63 California seamounts have unique oceanographic parameters, we compared the environmental conditions at the summit of each seamount to a set of 1,000 randomly selected points on the seafloor (Figure 4.1). Random points were restricted to both the geographic extent and depth range of the seamount distribution in California waters. Student's t-tests assuming unequal variances were used to explore patterns that emerged from the comparison.

Environmental conditions on seamounts were generally significantly distinguishable from non-seamount habitats (random points) (Table 4.2). Seamount summits (1,994±1,152 m; see Figure 4.2) were significantly shallower than random points (3,620±854) (Student's t-test, $p<0.001$), likely explaining many of these differences, as depth is highly correlated with many of the environmental variables examined. However, environmental differences cannot be solely attributed to distance offshore. Seamount summits were an average of 178± km from shore, which was not significantly different from the random points (average distance of 174±72 km) (Student's t-test, $p=0.75$).

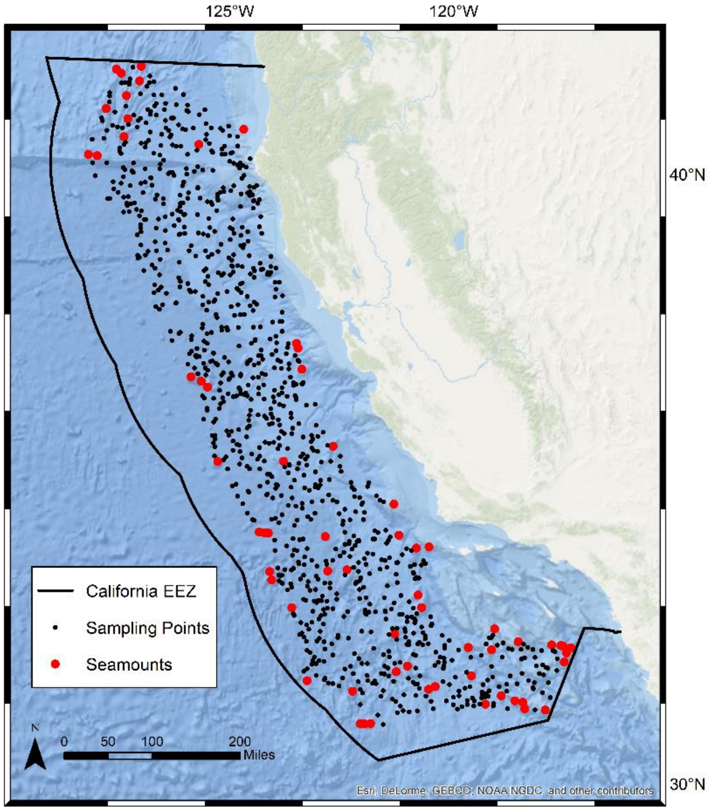


Figure 4.1. Sampling approach used to delineate seamount and non-seamount habitat.

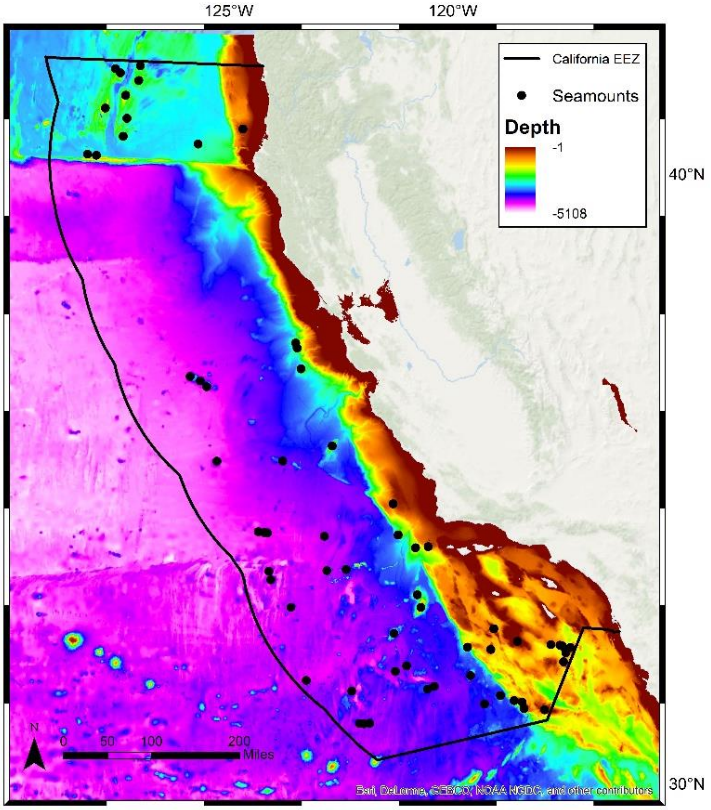


Figure 4.2: Bathymetry of coastal California (meters).

Table 4.2. Oceanographic parameters at seamounts within the California EEZ and at 1,000 random points with the depth range and geographic extent of the seamount distribution. * indicates a significantly different value (Student's t-test, α=0.05).

	Seamount Summits			**Non-Seamount Seafloor**		
Parameter	**Average**	**Min.**	**Max.**	**Average**	**Min.**	**Max.**
Depth (m)	1,994*	30	4,218	3,620	4,657	28
Omega aragonite	1.07*	0.67	2.55	0.74	0.62	2.36
Omega calcite	1.67*	1.02	3.94	1.14	0.94	3.68
Dissolved inorganic carbon (μmol l^{-1})	2.29*	2.06	2.34	2.34	2.01	2.35
Total alkalinity (μmol l^{-1})	2.42*	2.29	2.46	2.46	2.21	2.46
Particulate organic carbon (mg C m^{-2} yr^{-1})	8.5*	2.3	40.1	5.8	2.3	91.2
Nitrate (μmol l^{-1})	39.2	1.9	44.3	38.5	5.1	45.0
Phosphate (μmol l^{-1})	2.9*	0.5	3.3	2.7	1.0	3.3
Silicate (μmol l^{-1})	141.7*	3.7	177.2	170.3	11.7	181.0
Temperature (°C)	3.3*	1.5	15.4	1.71	1.48	11.23
Salinity (pss)	34.5*	33.5	34.7	34.7	33.1	34.7
Dissolved Oxygen (ml l^{-1})	1.86*	0.33	5.66	2.82	0.34	5.71
Horizontal current (10^{-3} m s^{-1})	4.99*	0.16	28.80	1.04	0.01	24.33
Chlorophyll *a* (mg m^{-3})	0.54	0.21	1.78	0.57	0.21	4.75
Sea surface temperature (°C)	16.2*	12.6	18.4	15.36	11.66	18.06
Photosynthetically available radiation (W m^{-2})	33.6*	28.9	37.1	32.7	28.9	36.6

4.4 Implications of Oceanographic Conditions for Benthic Communities

The oceanographic conditions at the summits of California seamounts have considerable implications for the benthic organisms that commonly inhabit these features, particularly with regards to conditions that are expected to change rapidly due to climate change in the coming decades: temperature, dissolved oxygen, productivity, and the saturation state of calcium carbonate.

Temperature is the predominant factor controlling the distribution of deep-sea corals, giving rise to the moniker "cold-water corals" (Roberts et al. 2009). California seamount summits had temperatures ranging from 1.5–15.4°C with an average of 3.3°C (Table 4.2; Figure 4.5). The observed range is slightly broader than the general temperature range given for cold-water corals and associated species (4–12°C; Roberts et al. 2006), although numerous examples of cold-water coral growth outside these vales exist in Chile, the Mediterranean Sea, and elsewhere (e.g. Jantzen et al. 2013; Maier et al. 2012). However, seamounts at or near the higher end of this temperature range may experience losses in suitable habitat for cold-water corals and other benthic organisms in future oceans. Many deep-sea organisms are adapted to a relatively narrow temperate niche and cannot tolerate the rapid increases predicted to occur due to ongoing climate change. Studies examining the physiological response of cold-water corals to the increased temperatures expected with our current rate of global warming have generally found strong negative effects (e.g. Dodds et al. 2007; Lunden et al. 2014; Naumann et al. 2014). While the predicted temperature increases in the deep-sea appear relatively small (0.03–3.63°C by the year 2100 between depths of 200–3,000 m; Sweetman et al. 2017), it may be sufficient to reduce the amount of seamount habitat that is suitable for cold-water coral growth, especially if coupled with large scale disruptions to current systems expected to occur as the oceans warm (Winton et al. 2013).

Seamount summits in California waters frequently coincide with the depth of the oxygen minimum zone, and have relatively low dissolved oxygen concentrations with an average of 1.86 ml l^{-1} and a range of 0.33–5.66 ml l^{-1} (Table 4.2; Figure 4.4). Values below 1.4 ml l^{-1} are generally considered to by hypoxic. While many other cold-water coral and sponge habitats similarly occur in oxygen minimum zones (e.g. Davies et al. 2010), further reductions in oxygen concentrations may move seamount fauna outside of their viable niche space (see Dodds et al. 2007; Lunden et al. 2014). Dissolved oxygen concentrations are generally region- and season-dependent in California waters, with many areas experiencing temporary hypoxic conditions in the late summer as water temperatures warm. Anthropogenic impacts are rapidly expanding oxygen minimum zones because warmer waters cannot hold as much oxygen, increased stratification in the upper ocean reduces oxygen transport to deep-sea habitats, and nutrient loading (often the result of fertilizer runoff) causes local depletions that can lead to hypoxic dead zones (Keeling et al. 2010). The deep-sea is expected to see reductions in dissolved oxygen of approximately 2-4% by the year 2100 (Cocco et al. 2013; Sweetman et al. 2017). Accordingly, seamounts with higher present-day dissolved oxygen levels may not see dramatic shifts in benthic communities, while seamounts in oxygen minimum zones that already have near-hypoxic conditions may become unsuitable for a wide array of organisms.

Particulate organic carbon (POC) flux to benthic habitats is a critical factor determining the success of seamount ecosystems because these habitats are most frequently founded by an array of suspension feeders including cold-water corals and sponges. Cold-water corals are entirely reliant on the rain of plankton and detritus from the surface for food, and typically cluster in areas with high surface productivity and subsequent export to deep waters (Tittensor et al. 2009). POC flux typically has strong correlations with depth (due to the decay of surface productivity as it falls through the water column) and distance from shore (due to the boost to surface productivity from terrestrial runoff). This makes it difficult to fully ascertain its full role in structuring seamount communities (e.g., Georgian et al. 2014), especially in complex current systems (such as the California Current and California Undercurrent) where the lateral advection and upwelling of nutrient rich waters may play a large role (e.g., Rowe et al. 2008). In California waters, seamount summits have a relatively small POC flux (average POC at the seafloor of 8.5 mg C m^{-2} day^{-1}) compared to other cold-water coral habitats (Table 4.2; Figure 4.3). For example, cold-water coral reefs in the Gulf of Mexico receive a POC flux of 46 mg C m^{-2} day^{-1} (Georgian et al. 2014), and Norwegian reefs receive 459 mg C m^{-2} day^{-1} (Wagner et al. 2011). This observation is likely due to the offshore nature of most seamounts in California waters, as inshore waters off the coast of California are generally highly productive due to the upwelling of nutrient rich waters and terrestrial runoff. In future oceans, POC flux to deep waters is expected to decrease by as much as 6–13% (Mora et al. 2013) due to reductions in surface phytoplankton productivity (Jones et al. 2014); however, areas with strong upwelling may see increases in POC flux instead (Smith et al. 2013). Therefore, the future of food influx to California seamounts remains uncertain in future oceans. However, organisms at seamounts with low POC fluxes may have difficulty maintaining their current growth and population dynamics if even moderate reductions occur in future oceans. As food availability can also help modulate the response of cold-water corals to other stressors (Georgian et al. 2016), this may also reduce the resilience of California seamount habitats to climate change and fishing pressure.

The saturation state (Ω) of calcium carbonate determines the energetic costs associated with the formation of calcium carbonate skeletons and shells. At high saturation states when $\Omega > 1$, the precipitation of calcium carbonate is thermodynamically favored, making calcification less energetically costly (Turley et al. 2007). At low saturation states when $\Omega < 1$, the dissolution of existing calcium carbonate material is favored, and calcifying organisms have to exert increasing amounts of energy to maintain calcification rates. With ongoing ocean acidification, reductions in pH will cause saturation states to drop, potentially causing declines in a wide array of marine calcifiers including coccolithophores (Riebesell et al. 2000), calcareous algae (Kuffner et al. 2008), mollusks (Gazeau et al. 2013), Foraminifera (Spero et al. 1997), and corals (Chan and Connolly 2013). Perturbations to the carbonate system are expected to be particularly hazardous to deep-sea organisms because they already persist in relatively low pH, low saturation state conditions (e.g. Lunden et al. 2013). Seamounts in California waters currently exist at low saturation states approaching undersaturation, with an average Ω_{ARAG} of 1.07, with many seamount summits experiencing chronically undersaturated waters ($\Omega<1$) (Table 4.2; Figure 4.6). This factor alone has been proposed as a mechanism to explain why the Pacific margin lacks large mound and reef structures that scleractinian cold-water corals frequently form in other ocean basins (Wickes 2014; Gómez et al. 2018); cold-water coral colonies in California waters are typically smaller and patchier than in other regions. While cold-water corals are known to be able to grow and calcify in undersaturated conditions (e.g. Thresher et al. 2011; Jantzen et al. 2013), there are increased energy costs that may detrimentally affect the ability of these species to grow, reproduce, and respond to other stressors (McCulloch et al. 2012). With a current average Ω hovering just above undersaturation, even small decreases associated with future ocean acidification may considerably affect the taxa that form the foundation for many California seamount ecosystems. Saturation states in the Pacific Ocean are already being reduced by more than 3% per decade, with rapid changes expected in future oceans (Feely et al. 2008; Feely et al. 2012), putting many of the cold-water coral taxa found on California seamounts at considerable risk.

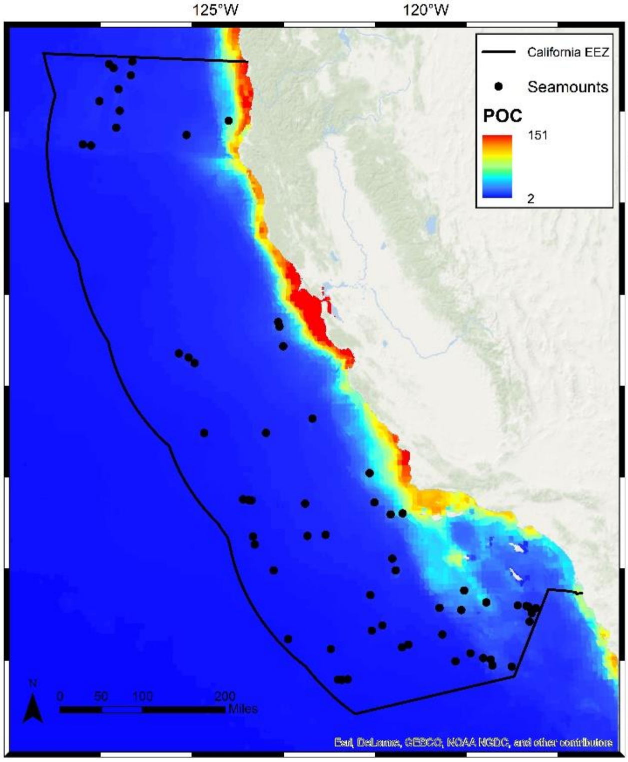


Figure 4.3: Particulate organic carbon (POC) (g C m^{-2} day^{-1}) on the seafloor off the coast of California.

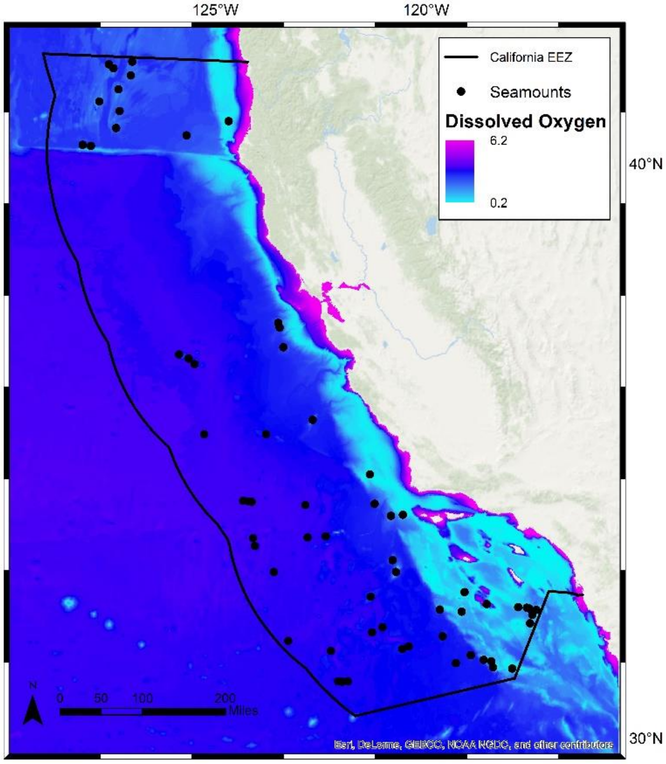


Figure 4.4: Dissolved oxygen (m l^{-1}) on the seafloor off the coast of California.

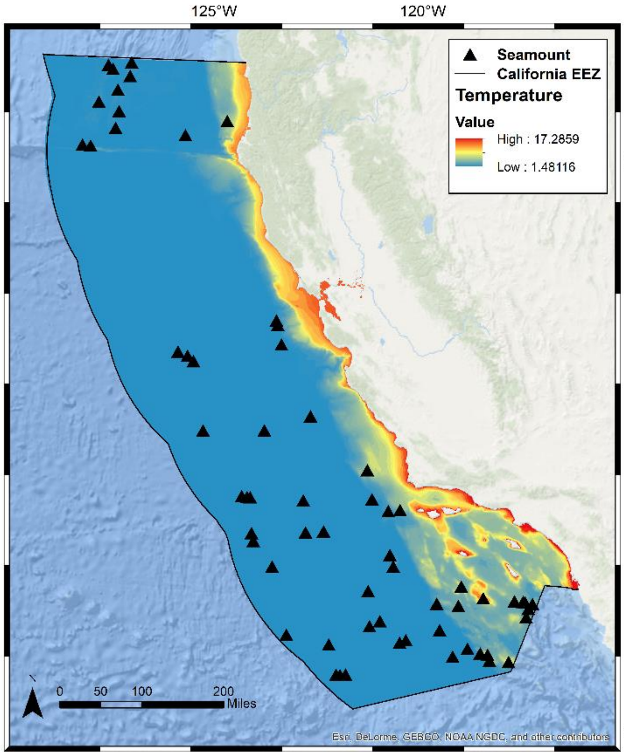


Figure 4.5: Temperature (°C) at the seafloor off the coast of California.

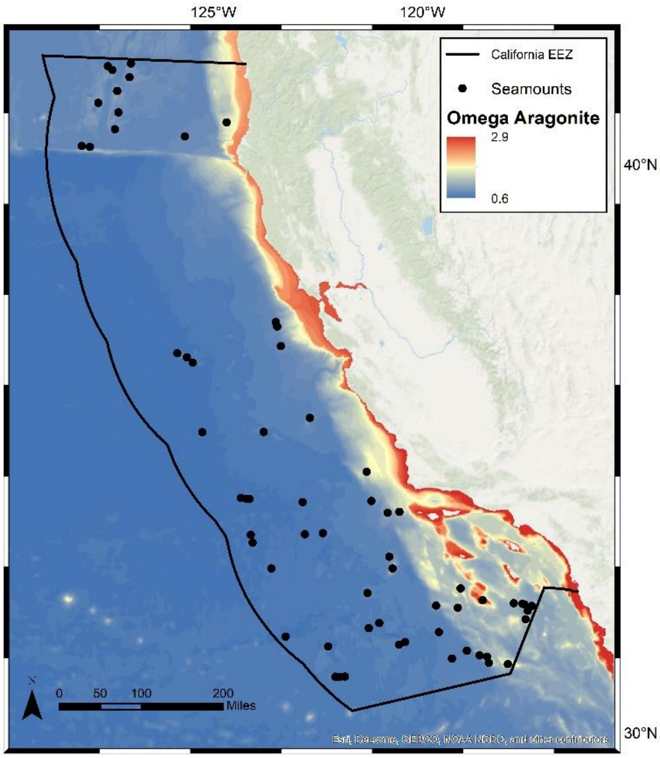


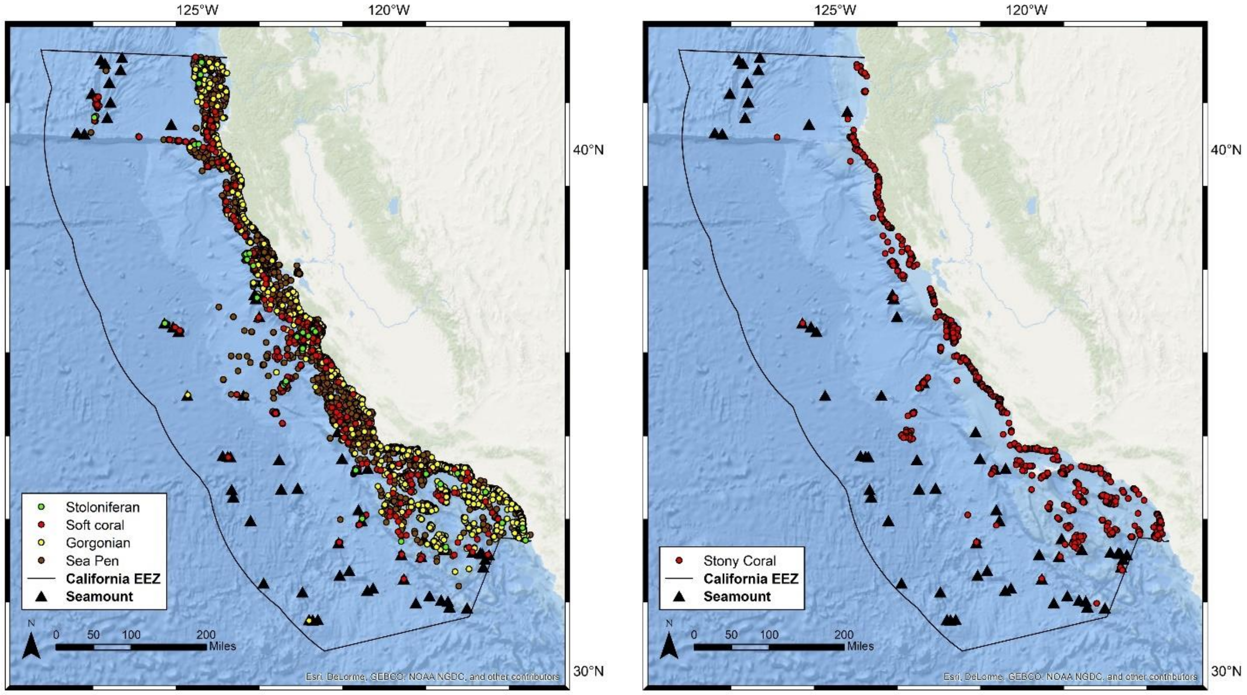
Figure 4.6: Omega aragonite (saturation state of aragonite) on the seafloor off the coast of California.

5. Biodiversity of California Seamounts

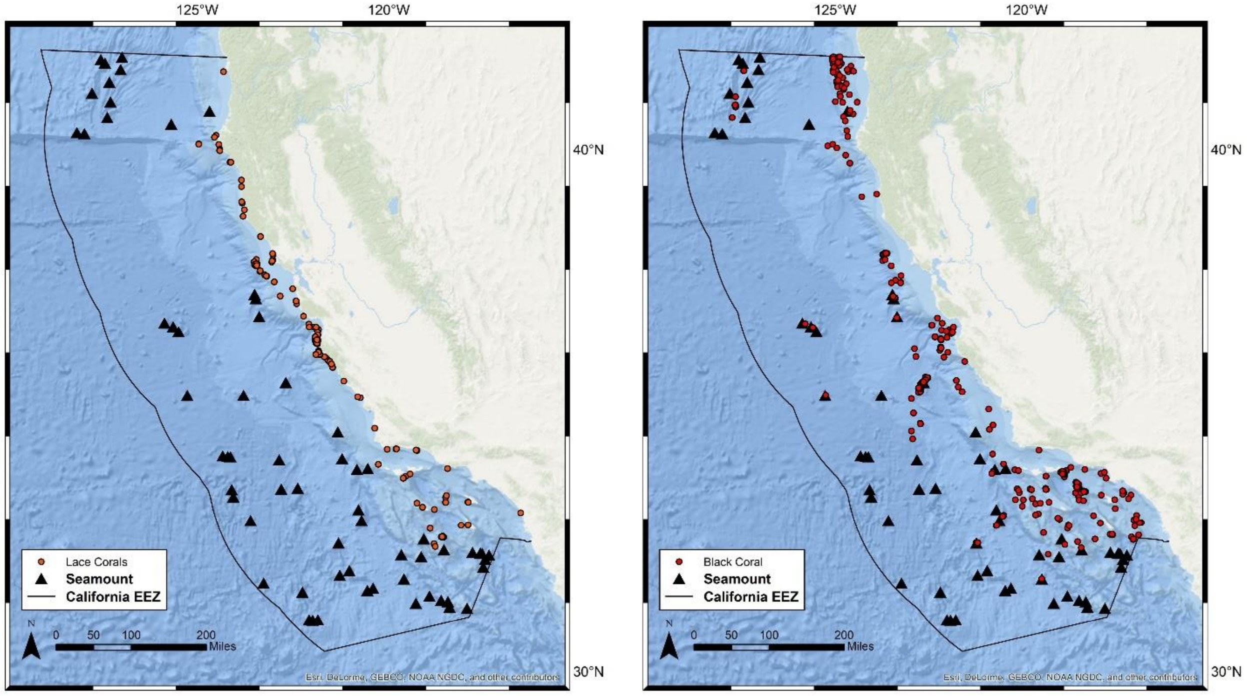
5.1 Benthic Ecosystems

Figure 5.1: Yellow Picasso sponge and white sponges on Davidson Seamount. Image courtesy of NOAA and MBARI.

Benthic seamount ecosystems in California waters are often founded on the habitat created by cold-water corals and sponges (Figure 5.1), which are prevalent throughout the California deep sea. Out of the entire NOAA Deep Sea Coral and Sponge Database, more than half (51.5%) of all occurrence records are located within California waters (366,187 records). Out of these, 106,552 are located within 40 km of a seamount (29%), and 84,925 (23%) are located within 10 km of a seamount. Table 5.1 shows the cold-water coral and sponge taxa that occur within 40 km of seamounts, and Figure 5.2 and 5.3 shows the distribution of coral and sponge records by taxa. The number of occurrence records in close proximity to seamounts is especially noteworthy given the clear sampling bias present in the dataset; most sampling and therefore most records occur relatively close to shore and away from the deeper, more remote seamounts. Therefore, the number of cold-water corals and sponges on and near seamounts in California waters, especially on seamounts farther offshore, is likely to be significantly underestimated.


Alcyonacea

Scleractinia (Stony Corals)


Stylasteridae (Lace Corals)

Antipatharia (Black Corals)

Figure 5.2: Distribution of cold-water coral occurrence records in the California EEZ, separated by broad taxonomic groupings (Alcyonacea, Scleractinia, Antipatharia, and Stylasteridae). Data are from the NOAA Deep Sea Coral and Sponge Database.

Porifera (Sponges)

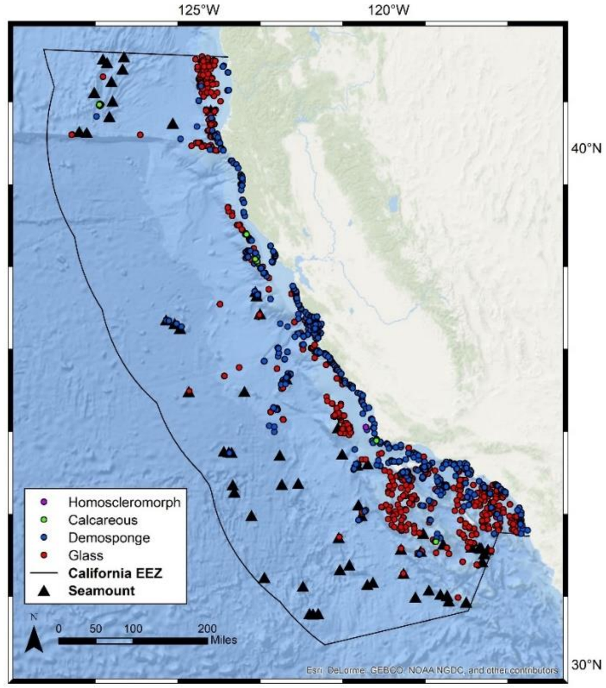
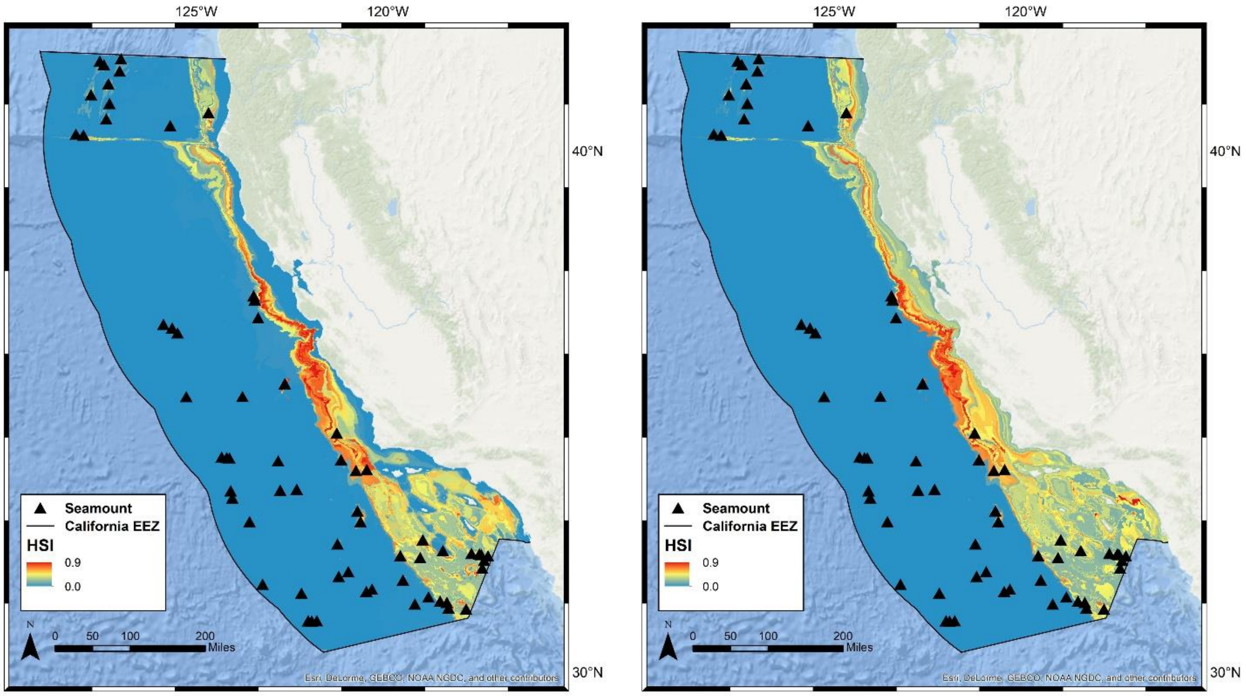


Figure 5.3. Distribution of sponge occurrence records in the California EEZ. Data are from the NOAA Deep Sea Coral and Sponge Database.

Habitat suitability models are a commonly used method to overcome sampling limitations of deep-sea surveying and fill in knowledge gaps concerning the distribution of marine species across large swaths of the seafloor. Guinotte and Davies (2014) produced suitability models for a number of cold-water coral taxa along the United States West Coast (Figure 5.4). The models predicted that extensive regions of suitable habitat for stony corals (Scleractinia) occur in relatively shallow waters, at intermediate depths for soft and gorgonian corals (Alcyonacea), and in deeper waters for black corals (Antipatharia). Interestingly, they showed that National Marine Sanctuaries contained more highly suitable habitat than surrounding areas, but also predicted that significant amounts of suitable habitat occur outside of any protected area or fishery closure (see Section 7 for current protection). However, the authors note that improved environmental data would increase the validity of the model, and also add that significant sampling bias in the occurrence records may have introduced significant errors in regions with little or no sampling effort. Therefore, it is likely that cold-water coral communities exist on offshore seamounts that are located outside of the model predictions for highly suitable habitat.

Alcyonacea - Scleraxonia

Alcyonacea - Holaxonia



Scleractinia (Stony Corals)

Antipatharia (Black Corals)

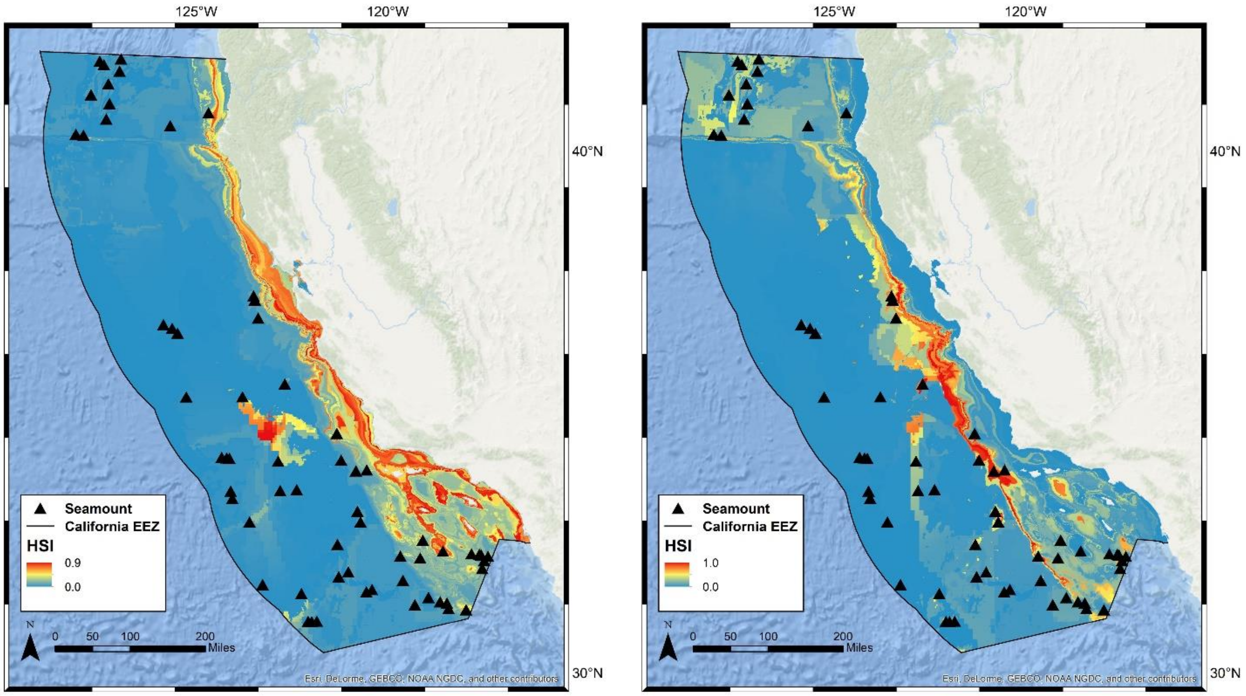


Figure 5.4: Habitat suitability models for cold-water coral taxa in the California EEZ. Warmer colors indicate areas that are predicted to be more suitable for each taxon. Data are from Guinotte and Davies (2014).

More extensive field surveys are needed in order to fully characterize the benthic habitats across California seamounts, especially on more remote, currently unexplored seamounts.

However, the surveys that have been conducted paint a clear picture of biodiverse hotspots with large abundances of corals, sponges, and associated fish and invertebrates. For example, a 2009 MBARI expedition surveyed 66% of the Pioneer Seamount depth range and discovered 110 invertebrate species (Lundsten et al. 2009). Pioneer Seamount and the neighboring Gumdrop Seamount have a particularly dense cover of benthic organisms, dominated by cold-water corals (23 species), crinoids, and sponges. The high abundances of benthic organisms at Pioneer Seamount have been attributed due to its shallow summit depth and associated increased nutrient availability. A number of newly discovered species can also be found at these seamounts, including numerous soft corals (*Chrysogorgia sp.*, *Isidella tentaculum*, and *Gersemia juliepackardae*), urchins (*Araeosoma leptaleum*), sea stars (*Hippasteria tiburoni*), and the gumdrop jelly (*Tiburonia granrojo*).

Davidson Seamount is one of the best surveyed and well-known seamounts in California waters. Expeditions to the seamount have uncovered extensive cold-water coral and sponge ecosystems. It is home to more than 230 species, including 25 species of deep-water corals – some of which are bamboo corals over 200 years old (McClain et al. 2009; De Vogelaere et al. 2005). At least 15 previously unknown species have already been discovered on Davidson Seamount (eight sponges, three corals, one ctenophore, one nudibranch, one polychaete, and one tunicate), with expectations for more as additional areas of the seamount and surrounding regions are surveyed (Burton and Lundsten 2008). Interestingly, communities on Davidson Seamount vary considerably with depth; one study found that as little as 20% of species occurred on both the summit and base of the seamount (McClain et al. 2010). These data suggest that even within a single seamount, community composition should not be viewed as uniform, but rather a mosaic of communities uniquely adapted to location-specific conditions (e.g. subtle changes in temperature, sediment, current flow, dissolved oxygen, pH, etc.). Finally, studies of Davidson and neighboring seamounts have demonstrated that most species are not endemic to individual seamounts (e.g., McClain et al. 2009), suggesting that seamounts in California waters should be construed as a broad network of seamounts connected via larval dispersal rather than isolated features.

Rodriguez Seamount contains similarly diverse (133 currently identified taxa) and abundant communities structured largely by 26 species of cold-waters corals including massive bubblegum (*Paragorgia*) and bamboo (*Isidella*) colonies. The habitat created by these corals supports a large number of associated sponges, crionoids, brittle stars, anemones, sea urchins, sea cucumbers, worms, crabs, and as many as 20 fish taxa. In 2004, a new octocoral species *Gersemia juliepackardae* was discovered on the seamount, and in 2008 the bamboo coral *Isidella tentaculum* was described based on observations from both Rodriguez and Pioneer Seamounts (Etnoyer 2008). However, the summit of Rodriguez is notably less diverse than neighboring seamounts (Lundsten et al. 2009). In part, this is likely due to the fact that the summit lies within the oxygen minimum zone, where extremely low oxygen concentrations may prevent many species from thriving. Its unique morphology as a guyot may also be a driving factor. The flat, sandy dome of Rodriguez Seamount lacks the rocky habitats that many corals, sponges, and other benthic species require. Instead, the summit is dominated by species well-adapted to sedimented environments including sea cucumbers (Holothuroidea) and sea pens (Pennatulacea), one of the few deep-sea corals that are able to grow in sand and mud sediments.

California seamounts and their cold-water coral communities are also critical habitats for a number of commercially important benthic species. Recent work in California suggests that seamounts may be the dominant source of larva for coastal fish populations (Lundsten et al. 2009; McClain et al. 2009; McClain et al. 2010; McClain et al. 2014). At Tanner and Cortes Banks, over 137 fish species have been observed, including 50 rockfish and at least 56 commercially or recreationally fished species (Love et al. 2009). The abundance and diversity of fish at these sites has been directly linked to the structure provided by cold-water coral and sponges (Love and Yoklavich 2006; Tissot et al. 2006; Yoklavich and Wakefield 2015). Economically important crustaceans and mollusks, such as the endangered white abalone, are also found in high abundances on some California seamounts (e.g., Hobday et al. 2001; Stierhoff et al. 2012; Stierhoff et al. 2014).

Table 5.1 Species and genera of cold-water coral and sponge taxa that occur within 10 km of a seamount in the California EEZ. Data are from the NOAA Deep Sea Coral and Sponge Portal.

Scientific	Taxa	Common Classification
Alternatipathes alternata	Antipatharia	Black Coral
Antipathes dendrochristos	Antipatharia	Black Coral
Bathypathes alternata	Antipatharia	Black Coral
Chrysopathes sp.	Antipatharia	Black Coral
Lillipathes sp.	Antipatharia	Black Coral
Trissopathes pseudotristicha	Antipatharia	Black Coral
Umbellapathes sp.	Antipatharia	Black Coral
Asbestopluma (Asbestopluma) monticola	Demospongiae	Demosponge
Thenea muricata	Demospongiae	Demosponge
Amphidiscophora	Hexactinellida	Glass Sponge
Aphrocallistes vastus	Hexactinellida	Glass Sponge
Atlantisella sp.	Hexactinellida	Glass Sponge
Caulophacus (Caulophacus) cyanae	Hexactinellida	Glass Sponge
Chonelasma sp.	Hexactinellida	Glass Sponge
Farrea occa	Hexactinellida	Glass Sponge
Farrea truncata	Hexactinellida	Glass Sponge
Heterochone calyx	Hexactinellida	Glass Sponge
Hexactinella sp.	Hexactinellida	Glass Sponge
Hyalonema sp.	Hexactinellida	Glass Sponge
Regadrella sp.	Hexactinellida	Glass Sponge
Saccocalyx pedunculatus	Hexactinellida	Glass Sponge
Sclerothamnopsis compressa	Hexactinellida	Glass Sponge
Staurocalyptus sp.	Hexactinellida	Glass Sponge
Tretodictyidae	Hexactinellida	Glass Sponge
Acanella sp.	Alcyonacea	Gorgonian Coral
Acanthogorgia sp.	Alcyonacea	Gorgonian Coral
Calyptrophora bayeri	Alcyonacea	Gorgonian Coral
Calyptrophora cf. antilla	Alcyonacea	Gorgonian Coral
Chromoplexaura sp.	Alcyonacea	Gorgonian Coral
Chrysogorgia monticola	Alcyonacea	Gorgonian Coral
Chrysogorgia pinnata	Alcyonacea	Gorgonian Coral
Eugorgia rubens	Alcyonacea	Gorgonian Coral
Iridogorgia sp.	Alcyonacea	Gorgonian Coral
Isidella tentaculum	Alcyonacea	Gorgonian Coral
Keratoisis philippinensis	Alcyonacea	Gorgonian Coral
Keratoisis profunda	Alcyonacea	Gorgonian Coral
Lepidisis sp.	Alcyonacea	Gorgonian Coral

Leptogorgia chilensis	Alcyonacea	Gorgonian Coral
Narella sp.	Alcyonacea	Gorgonian Coral
Paragorgia pacifica	Alcyonacea	Gorgonian Coral
Paragorgia regalis	Alcyonacea	Gorgonian Coral
Parastenella ramosa	Alcyonacea	Gorgonian Coral
Plumarella sp.	Alcyonacea	Gorgonian Coral
Psammogorgia sp.	Alcyonacea	Gorgonian Coral
Swiftia kofoidi	Alcyonacea	Gorgonian Coral
Swiftia sp.	Alcyonacea	Gorgonian Coral
Swiftia torreyi	Alcyonacea	Gorgonian Coral
Anthoptilum grandiflorum	Alcyonacea	Sea Pen
Anthoptilum murrayi	Alcyonacea	Sea Pen
Funiculina sp.	Alcyonacea	Sea Pen
Halipteris californica	Alcyonacea	Sea Pen
Kophobelemnon sp.	Alcyonacea	Sea Pen
Pennatula grandis	Alcyonacea	Sea Pen
Pennatula phosphorea	Alcyonacea	Sea Pen
Protoptilidae	Alcyonacea	Sea Pen
Ptilosarcus sp.	Alcyonacea	Sea Pen
Umbellula lindahli	Alcyonacea	Sea Pen
Anthomastus sp.	Alcyonacea	Soft Coral
Bathyalcyon robustum	Alcyonacea	Soft Coral
Gersemia juliepackardae	Alcyonacea	Soft Coral
Heteropolypus ritteri	Alcyonacea	Soft Coral
Clavularia grandiflora	Alcyonacea	Stoloniferan Coral
Telesto nuttingi	Alcyonacea	Stoloniferan Coral
Dendrophyllia sp.	Scleractinia	Stony Coral (Branching)
Lophelia pertusa	Scleractinia	Stony Coral (Branching)
Caryophyllia sp.	Scleractinia	Stony Coral (Cup Coral)
Coenocyathus bowersi	Scleractinia	Stony Coral (Cup Coral)
Desmophyllum dianthus	Scleractinia	Stony Coral (Cup Coral)
Javania sp.	Scleractinia	Stony Coral (Cup Coral)

5.2 Pelagic Ecosystems

A wide variety of pelagic species use seamounts as nurseries, mating grounds, feeding grounds, and migratory pathways. Seamounts generate complex current systems that act to transport and concentrate nutrients in the upper water column, resulting in high primary productivity and food availability (Worm et al. 2003). This enhanced productivity above seamounts supports high diversities of pelagic fish, sea turtles, seabirds, and marine mammals (Morato et al. 2010).

In California waters, a number of important pelagic species rely on seamounts. In the waters above Cortes and Tanner Banks, several pelagic predators are known to aggregate, including northern bluefin tuna, bigeye thresher sharks, and swordfish (Yoklavich and Wakefield 2015), as well as loggerhead, olive ridley, green, and leatherback sea turtles (Ferraroli et al. 2004; Yoklavich and Wakefield 2015). California seamounts are also critically important for more than 35 species of marine mammals including Dall’s porpoise, pilot whales, bottlenose dolphins, orcas, sperm whales, gray whales, humpback whales, blue whales, fin whales, northern elephant seals (Kaschner 2007; Oleson 2007; Maxwell et al. 2012; Jefferson et al. 2014; Yoklavich and Wakefield 2015). These seamounts are also important feeding grounds for a number of seabirds, which are drawn to these highly productive waters that are abundant with prey including small fish, plankton, and squid (Yen et al. 2006; Morato et al. 2008). Approximately 75 seabird species reproduce, overwinter, or migrate through California aters, supported in part by seamounts and the influences they exert on surrounding regions (Briggs et al. 1987; Baird 1993; Newton and DeVogelaere 2010; Santora and Sydeman 2015).

It is not clear whether every seamount has a significant impact on pelagic aggregations. Morato et al. (2010) found that only seamounts with summits shallower than 400 m had an effect, much shallower than the average depth of seamounts in California waters (1,994 m). However, the extent to which seamounts exert a strong influence can extend vertically into the water column for thousands of meters (Roden 1987), suggesting that even deep seamounts can influence pelagic species given the right conditions. While many pelagic aggregations are observed over shallower seamounts closer to shore, there is evidence that suggests that remote, offshore seamounts are particularly important feeding grounds because they concentrate prey items in an otherwise food-poor environment (Morato et al. 2010).

6. Threats to California Seamounts

6.1 Fisheries

Fisheries currently represent the most widespread, direct anthropogenic threat to deep-sea ecosystems (reviewed in Clark et al. 2015), and are considered to have the largest impact on California seamounts (Halpern et al. 2009). Bottom-trawling for groundfish is particularly damaging to fragile cold-water coral and sponge ecosystems. Once disturbed, these communities may not recover for decades or longer (Gage et al. 2005), even if effective protection is later implemented (Huvenne et al. 2016). Cold-water coral reefs are often targeted for trawling due to their high abundances of commercially fished species (Hall-Spencer et al. 2002), in some regions severely damaging 30-50% of reef structures (Fosså et al. 2002).

Despite conservation efforts to further restrict fishing activities in California waters, West Coast fishery landings increased by 27.4% from 2016 to 2017, with an associated 12.3% increase in revenue (Harvey et al. 2019). Landings in 2017 were approximately one standard deviation higher than the long-term mean. This increase was primarily driven by large increases in the hake, Dungeness crab, and market squid fisheries, while finfish, market squid, shrimp, and salmon decreased considerably (Figure 6.4). Groundfish landings (excluding hake) were previously in a near-historic low from 2013-2017, but increased slightly in 2017. The relative abundance of rockfish increased during the 2013–2017 period and remained largely stable during 2018 (Figure 6.3). Figure 6.2 shows the spatial footprint of fishing activity according to Global Fishing Watch vessel data from 2012–2016, with most fishing activity occurring in relatively shallow waters close to the coast. Most trawling in the United States EEZ occurs in waters shallower than 1,000 m. One study found that from 2010–2012, as much as 29.5% of the region from Northern California to Washington was trawled in this depth range, producing landings of 305 tons year^{-1}(Amoroso et al. 2018).

Shallow nearshore areas, such as Cortes and Tanner Banks, are more likely to be heavily fished. Recreational and commercial fisheries target this highly productive area for a wide range of species including tuna, swordfish, rockfish, seabass, sea urchins, squid, mackerel, and spiny lobsters. While commercial fishing catches have been decreasing on the banks over the past several decades, the average annual catch is valued at approximately $400,000 – approximately 0.5% of the total California catch. Recreational fishers catch an estimated 5,000-10,000 fish per year, with an estimated industry value of $6.5 million (Pondella et al. 2018).

California's set gillnet and drift gillnet fisheries are the second and the fourth worst bycatch fisheries in the nation, with staggering bycatch rates of 65% and 63%, respectively (Keledjian et al. 2014). The drift gillnet fishery for swordfish and thresher sharks is a major conservation concern in these waters, as the nets, extending a mile in length, are cast overnight to drift and catch large, pelagic fish. The expansive nets inevitably entangle other species, including sea turtles and whales that drown or are seriously injured from entanglement. The drift gillnet fishery was responsible for the entanglement or death of almost 550 marine mammals over a five-year period, and entanglements on the United States West Coast have been steeply rising since 2015 (Figure 6.1). This fishery's estimated worth was $1.1 million in 2011 (NOAA 2013). The set gillnet industry uses nets anchored to the seafloor, targets California halibut, angel shark and white seabass, and is also a serious conservation concern. Because of their devastating ecological impacts, gillnets were banned in nearshore waters off southern California in 1994, but they are still permitted in federal waters (Keledjian et al. 2014). In just a three-year period, the set gillnet fishery discarded more than 30,000 sharks and rays. The estimated worth of this fishery was $450,000 in 2011 (Keledjian et al. 2014).

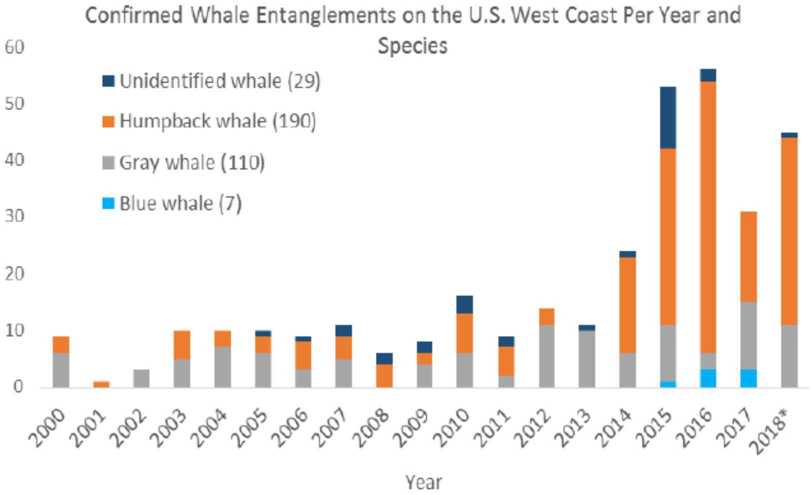


Figure 6.1: Whale entanglements (reported) along the West Coast from 2000–2018. Figure is from Harvey et al. (2019).

West Coast abalones have also been overfished: commercial and recreational overfishing caused abalone decline and the closure of many California abalone fisheries (California 2005). In 2001, the white abalone, *Haliotis sorenseni*, became the first marine invertebrate to be listed under the Endangered Species Act. Since the species listing, population surveys of white abalone have found their highest densities at Cortes and Tanner Banks (Stierhoff et al. 2012) where the abalone fishery was closed in 1997, and will be closed for recreational fishers until at least 2021.

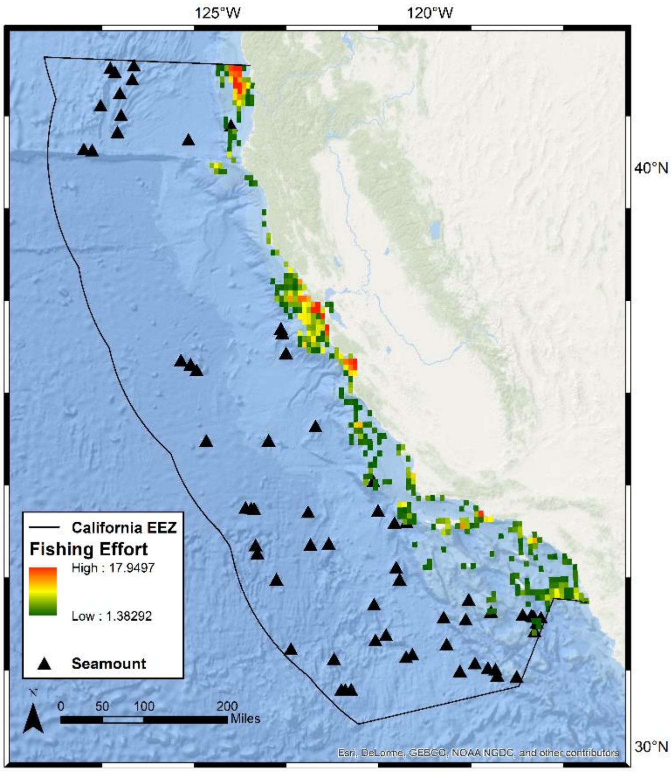


Figure 6.2: Cumulative fishing effort in the California EEZ from 2012–2016. Data are from Global Fishing Watch.

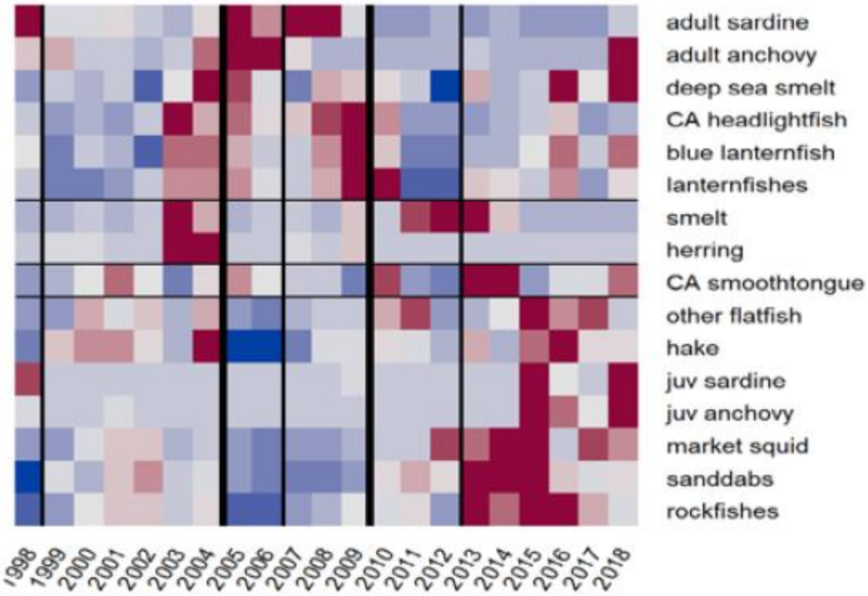


Figure 6.3: Cluster analysis showing the relative abundance of key West Coast fish species from 1998–2018. Colors indicate relative abundance (red=abundant; blue=rare). Figure is from Harvey et al. (2019).

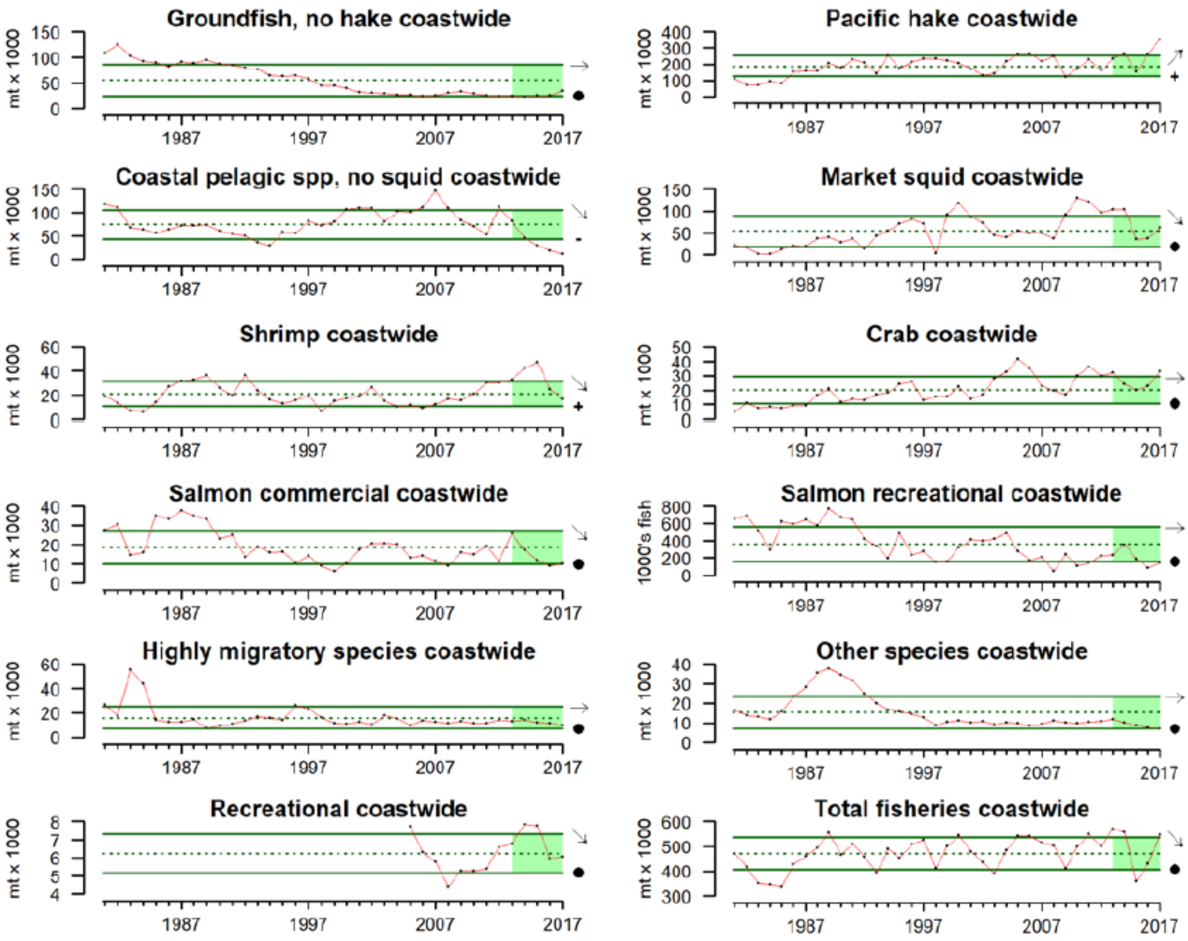


Figure 6.4: Annual landings of West Coast commercial and recreational fisheries from 1981–2017. Dashed line is the mean across all data. Solid horizontal lines are the standard deviation. Figure is from Harvey et al. (2019).

6.2 Marine Litter

Despite their remoteness, California seamounts are not immune to the detrimental effects of human waste products that are intentionally or accidentally deposited into the ocean. Marine litter is rapidly becoming a global issue, with an estimated 6.4 million tons of litter entering the oceans each year (Jeftic et al. 2009), including intentionally or accidentally abandoned or disposed of fishing gear, plastics, and other solid waste products. Woodall et al. (2015) examined marine litter across multiple ocean basins and found that litter was prevalent throughout the entire study region regardless of remoteness and distance from shore. The authors also found that marine litter, primarily comprised of derelict fishing gear, was especially widespread on seamount habitats, ostensibly due to the targeting of these locations by fisheries. On some seamounts, fishing gear accounts for over 70% of the marine litter present (Pham et al. 2014). This litter has considerable implications for ecosystem health via the physical disruption of benthic environments (e.g. entanglement with corals; Pham et al. 2013) and ghost fishing, in which marine species continue to be caught or killed by abandoned nets, traps, lines, and other litter. A comprehensive assessment review of litter off the coast of Monterey, California revealed that litter was most abundant in deep waters (between depths of 2,000–4,000 m, however fishing litter was more common in shallower waters), was comprised of 33% plastic and 23% metal, and tended to cluster together due to the topography of the seafloor (Schlining et al. 2013).

6.3 Climate Change

Seamounts off the coast of California will be subject to ongoing and future climate change and ocean acidification (Figure 6.5). As humans emit increasing amounts of carbon dioxide into the atmosphere, a cascading chain of evens will significantly affect marine ecosystems around the world. The excess accumulation of carbon dioxide and other greenhouse gases in the atmosphere is causing global temperatures to rise; ultimately, 80% of this surplus heat is stored in the oceans (Levitus et al. 2005). Bathyal habitats between 200–3,000 m in depth in the Pacific Ocean are expected to see increases in temperature of up to 3.6°C by the year 2100 (Sweetman et al. 2017), pushing many seamount inhabitants out of their viable niche space (see Section 4.4). Increased vertical stratification and long equilibrium times of deep-ocean convection suggests that temperatures in the deep sea will continue to rise for centuries even if atmospheric warming is stopped or even reversed (Hansen et al. 2005; Purkey and Johnson 2010). Ocean warming will also lead to considerable decreases in dissolved oxygen concentrations, due to the lower solubility of oxygen in warm water and reductions in oxygen transport to deep waters (Keeling et al. 2010). While the predicted change in Pacific Ocean bathyal habitats is relatively small (reductions of up to 0.05 ml l^{-1}; Sweetman et al. 2017), this may push already low-oxygen seamount habitats occurring in oxygen minimum zones into hypoxia.

In addition to global warming, increased carbon dioxide emissions will directly affect marine ecosystems via ocean acidification. The oceans absorb 25-30% of the carbon dioxide that humans produce, resulting in significant alterations to the entire carbonate system (Sabine and Feely 2007). pH levels will decrease (giving rise to the term ‘ocean acidification’), fewer carbonate ions will be available (the ions typically used by marine calcifiers), and the saturation state of calcium carbonate will be lowered. Lower saturation states make it more energetically costly for marine calcifiers, including cold-water corals, to produce calcium-carbonate structures. pH in the bathyal zone of the Pacific Ocean is predicted to be reduced by as much as 0.31 units by the year 2100, a magnitude of change that has been found to considerably reduce calcification in reef-building cold-water corals (Lunden et al. 2014; Georgian et al. 2016).

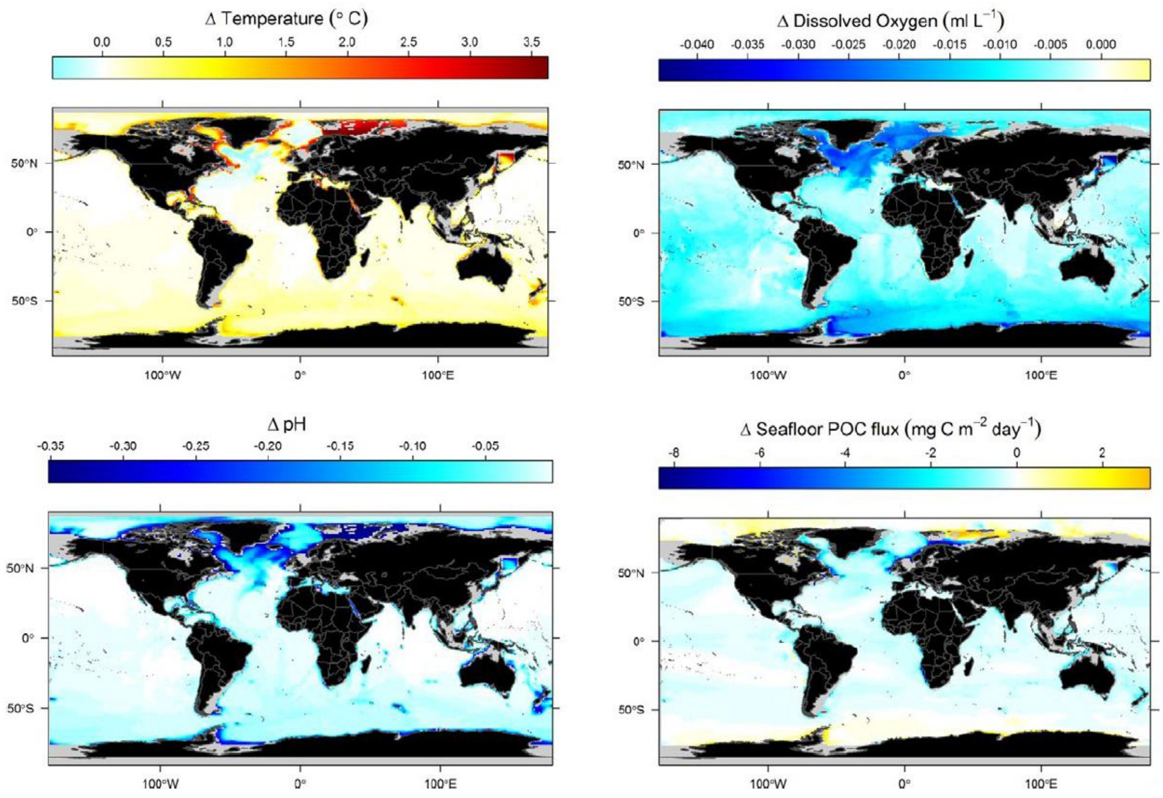


Figure 6.5: Climate change projections of changes to seafloor temperature (°C), dissolved oxygen (ml L^{-1}), pH, and particulate organic (POC) flux (mg C m^{-2} day^{-1}) predicted to occur by the year 2100. Figures are from Sweetman et al. 2017.

Despite the risk that climate change poses to California seamount habitats, there is some evidence to suggest that some seamounts could actually act as important climate refugia in future oceans. Seamounts that are already close to unsuitable conditions with respect to temperature, carbonate saturation state, and dissolved oxygen (see Section 4.4) may not fare well with even minor changes caused by ongoing climate change and ocean acidification. However, it is possible that other seamounts may act as climate-resilient refugia. Seamounts may have been refugia during historic, intense environmental change (Hubbs 1959; Samadi et al. 2007), and, therefore, the deep, cool waters surrounding seamount slopes could potentially provide refugia for benthic marine life from future ocean changes (Clark et al. 2012). Ocean acidification impacts on coral habitat, while generally intense, are also likely to be less extreme for seamounts than for other deep-sea habitats, as they may act as ‘shallow-water’ refugia for stony corals from the detrimental effects of ocean acidification at greater depths (Tittensor et al. 2010).

While anthropogenic climate change will still affect the deep-sea off the coast of California, the region is not projected to experience the drastic changes that are expected to occur in many other deep-sea habitats, and especially in coastal environments. Seamounts in particular have been hypothesized to serve as important climate refugia in the future, as their upper flanks and summits will experience more moderate changes than other deep-sea habitats (Tittensor et al. 2010). While seamounts in the North Atlantic are projected to become significantly less suitable for stony corals by the year 2100, many Pacific seamounts are expected to largely maintain current levels of suitability (Tittensor et al. 2010). In regions where the particulate organic carbon (POC) flux to the seafloor will remain largely unchanged, there may be sufficient food supply to allow organisms to metabolically compensate for other climate stressors. Seamounts ecosystems that rely on the upwelling of nutrient-rich waters may be more climate-resilient, as upwelling is predicted to increase with global warming (Bakun 1990). Previous studies on deep-sea corals have found that when feeding rates can be maintained or elevated, corals were still able to calcify new skeletal material even under very low pH conditions (Georgian et al. 2016).

Additionally, as the California coast is already subject to relatively low pH, low dissolved oxygen concentrations, and low POC flux compared to other oceans, organisms may be pre-adapted to dealing with further reductions in these values caused by man-made climate change (see Aitken et al. 2008). A growing number of field and experimental studies supports this hypothesis. The occurrence of cold-water corals across a large range of pH values, coupled with their ability to tightly regulate the pH of their internal calcifying fluid (McCulloch et al. 2012), suggests that they may have developed adaptive mechanisms that will render them relatively resilient to the effects of ocean acidification. Subsequent laboratory experiments have confirmed that cold-water corals are less sensitive to changes in pH and temperature than their shallow-water counterparts (e.g., Form and Riebesell 2012; Wall et al. 2015; Georgian et al. 2016). Therefore, the ability of seamount ecosystems to survive future ocean changes is still uncertain, and may result in a patchy mosaic of resilient and susceptible seamounts.

6.4 Deep-Sea Mining

The deep sea is believed to hold large quantities of untouched energy resources, precious metals, and minerals (reviewed in Boschen et al. 2013). Manganese nodules and other polymetallic nodules are likely targets for mining operations, which could result in seamount habitats being targeted for future mining expeditions. As hydrothermal vents hold high-grade Seafloor Massive Sulfides (SMS) deposits, they are also a prime target for deep-sea mining. Increasing worldwide demand for copper and gold is already prompting mining companies to explore the seafloor for these high-grade sulfides. The only hydrothermal vent systems that are currently known to occur within the United States EEZ are off the north coast of California, at the plate boundaries along the triple junction at Gorda Ridges (Clague 2016). Given the large amount of tectonic activity in the region, however, it is likely that undiscovered vent systems exist on or near seamounts in California waters. At hydrothermal vents, the fractures in the seafloor allow ambient seawater to percolate down through the seabed where molten rock warms it. As the water seeps deeper in and temperatures increase to 350-400°C, changes in seawater chemistry cause metals, silica and sulfide to leach from the surrounding rock. When these chemical-rich fluids are warmed, they become buoyant, rise, and mix with the cold, deep-ocean waters, causing the metals and sulfides to precipitate out of solution.

Technological advancements have enabled greater access to deep-sea resources, making deep-sea mining increasingly possible (Boschen et al. 2013). Though early mineral leases for Gorda Ridges were abandoned due to a lack of technology and low commodity prices (Dover 2011), recent renewed interest in mining means that this site, as well as other deep-sea habitats in California, could one day be targeted for exploitation. Deep-sea mining is extremely physically destructive to the seabed, and will generate turbid, potentially toxic sediment plumes that are likely to affect benthic communities over a wider area (Sharma et al. 2001). The ecological recovery of disturbed sites would then be dependent on recolonization from nearby populations, but little is known about the connectivity of these populations and full recovery could take decades or even hundreds of years (Levin et al. 2016).

6.5 Ship Traffic

California hosts 11 major ports spanning its long coast between the North Coast and San Diego County. Los Angeles and Long Beach Ports contain the U.S.' largest port complex and are essential elements in global enterprise. Together, these ports facilitate one-fourth of all container cargo traffic in the United States and vessel traffic poses a number of threats to the marine environment, including oil or chemical spills, discharges, ship-based pollution, exchange of ballast water, and noise pollution (MBNMS 2012).

The U.S. Navy uses state and federal waters along the western seaboard for a wide variety of activities. The Southern California Range Complex (SCRC) is a very large area that extends more than 600 nm southwest into the Pacific Ocean, encompassing 120,000 nm^2 of sea space, 113,000 nm^2 of special use airspace, and over 56 mi^2 of land area spread across several islands (Boerger et al. 2013). Likewise, the Northwest Training and Testing study area (NWTT) encompasses land, air, and sea areas that extend westward approximately 250 nm into the Pacific Ocean from the Strait of Juan de Fuca and southerly parallel to the coast into northern California, encompassing the Gorda and Mendocino Ridges (United States Department of the Navy 2014). In recognition of the undeniable ecological significance of the SCRC and NWTT, the Navy prepared environmental impact statements for its activities in 2013 and 2014. They found many diverse environmental impacts, from explosive byproducts and acoustic interference to vessel strikes, confirming that there are many threats to marine life associated with the Navy's activity in both the SCRC and NWTT (Boerger et al. 2013; United States Department of the Navy 2014).

6.6 Oil and Natural Gas Exploration and Extraction

California has four oil platforms off its coast, and the California State Lands Commissions administers 29 offshore oil and gas agreements in its state waters. The Federal Government, through the Bureau of Ocean Energy Management, has granted 43 active leases in Southern California's Pacific Outer Continental Shelf Region. The California State Lands Commission halted new leasing of state offshore tracts after the 1969 Santa Barbara oil spill that spewed an estimated 4.2 million gallons of crude oil (Foster et al. 1970; Foster 1972). This spill created a 35-mile-long oil slick along California's coast and killed thousands of birds, fish and marine mammals. The California legislature passed the California Coastal Sanctuary Act in 1994 to prohibit new offshore leasing. Even so, in 2015, 142,800 gallons of crude oil spewed onto a biologically diverse coastline after a corroded, old pipeline ruptured near Refugio State Beach in Santa Barbara County (Addassi et al. 2017; Defran et al. 2017). The oil reached four MPAs that safeguard ecologically sensitive regions, and state workers eventually collected 202 dead birds and 99 dead mammals. The spill's full impact will never be known since many marine animals can travel long distances before dying. As the Trump administration pushes for new offshore oil and gas exploitation in California there is a possibility that new exploration and extraction will occur, at the ultimate expense of seamount habitats and surrounding waters.

7. Protection of California Seamounts

7.1 Jurisdiction

Conservation of the seamounts within California waters is not tied to the same nebulous jurisdictional issues that seamounts on the high seas are subject to (e.g. Ardon et al. 2008). Per federal and state law, the state of California controls the waters within three nautical miles of its coastline. The federal government manages the remaining 197 nautical miles between California state waters and the boundary of the United States exclusive economic zone (EEZ). California has a number of marine protected areas (MPAs) within its jurisdiction along the coast (see below). In addition, there are four federally managed National Marine Sanctuaries: Channel Islands, Cordell Bank, Greater Farallones, and Monterey Bay.

The majority of seamounts in California waters are in areas managed by the Pacific Fishery Management Council (PFMC). The PFMC ultimately derives its authority from the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), the primary law governing fisheries management in US federal waters. The MSFCMA's ultimate goal is to promote the 'optimal exploitation' of coastal fisheries, accomplished via the creation of eight regional councils with the task of managing fish stocks and associated ecosystems. The PFMC is the regional council responsible for governing the United States EEZ off the coast of Washington, Oregon, and California – a total area of 317,690 square miles. The council manages approximately 119 species of fish including salmon, groundfish, sardines, anchovies, mackerel, tunas, sharks, and swordfish. While the council's stated focus is fisheries management, they are also mandated by the MSFCMA to identify and protect essential fish habitat (EFH) and habitat areas of particular concern (HAPC).

7.2 Marine Protected Areas

Across the entire United States EEZ, approximately 46% of seamount habitat is located within an existing marine protected area (MPA); the vast majority of this protection is located in the or Papahānaumokuākea and Pacific Remote Islands Marine National Monuments (Marine Conservation Institute 2019). Protection for seamount habitats in California waters is much weaker, leaving these vulnerable ecosystems exposed to a myriad of threats (described in Sections 2.7 and 6). There are a number of marine reserves, sanctuaries, protected areas, special closures, and other management areas along coastal California (Figure 7.2). Of these, only a limited number are no-take reserves that prohibit all extractive activities (Figure 7.2). California state has a large number of relatively small protected areas enacted by the Marine Life Protection Act of 1999, however these areas are all located in nearshore habitats and do not overlap with any seamount habitats (Figure 7.2).

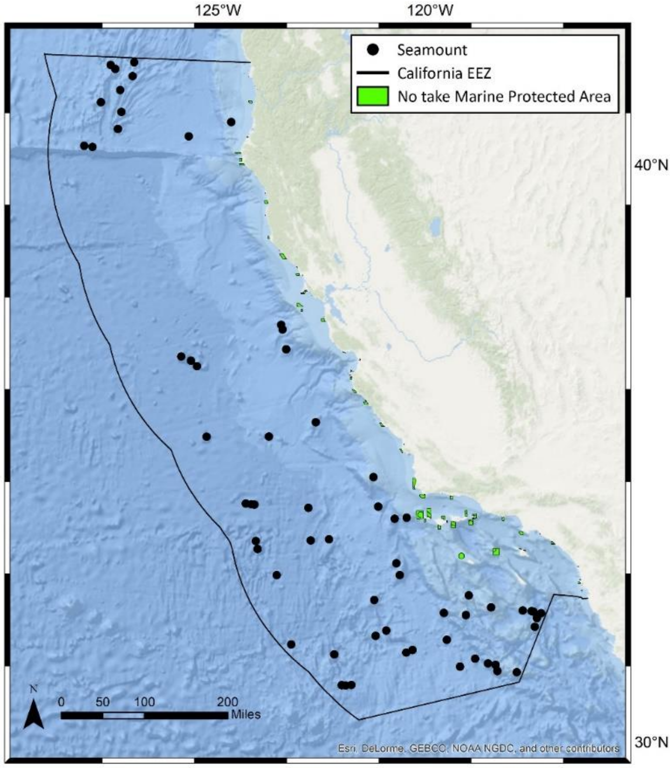


Figure 7.1: No take marine reserves within California waters. Data are from the Atlas of Marine Protection.

Only one seamount is located within a National Marine Sanctuary (Figure 7.2). Davidson Seamount was added to the Monterey Bay National Marine Sanctuary during a 2008 expansion, making it the first seamount to gain official protection in U.S. waters (the expansion also added

775 square miles to the sanctuary). The MBNMS was originally designated in 1992, and confers federal protections to a large swath of coastal waters extending more than 275 miles south of San Francisco. The pristine nature of Davidson Seamount, along with its incredibly high biodiversity and abundance of benthic organisms, led to its inclusion in the MBNMS. However, in 2017, a Presidential Executive Order authorized the U.S. Department of Commerce to reevaluate the status of marine sanctuaries and monuments in light of renewed interest in these areas as targets for offshore oil and natural gas drilling. Commercial interest in deep-sea habitats highlights the importance of the protections that Davidson Seamount currently enjoys, but also contextualizes the alarming lack of protection for other seamounts in United States waters.

Despite the lack of traditional marine protected areas for seamount habitats off the coast of California, there are a number of regulations that provide limited protection for seamounts as managed by the Pacific Fisheries Management Council (described below). These regulations are currently in a transition period following a recently updated Pacific Coast Groundfish Fishery Management Plan.

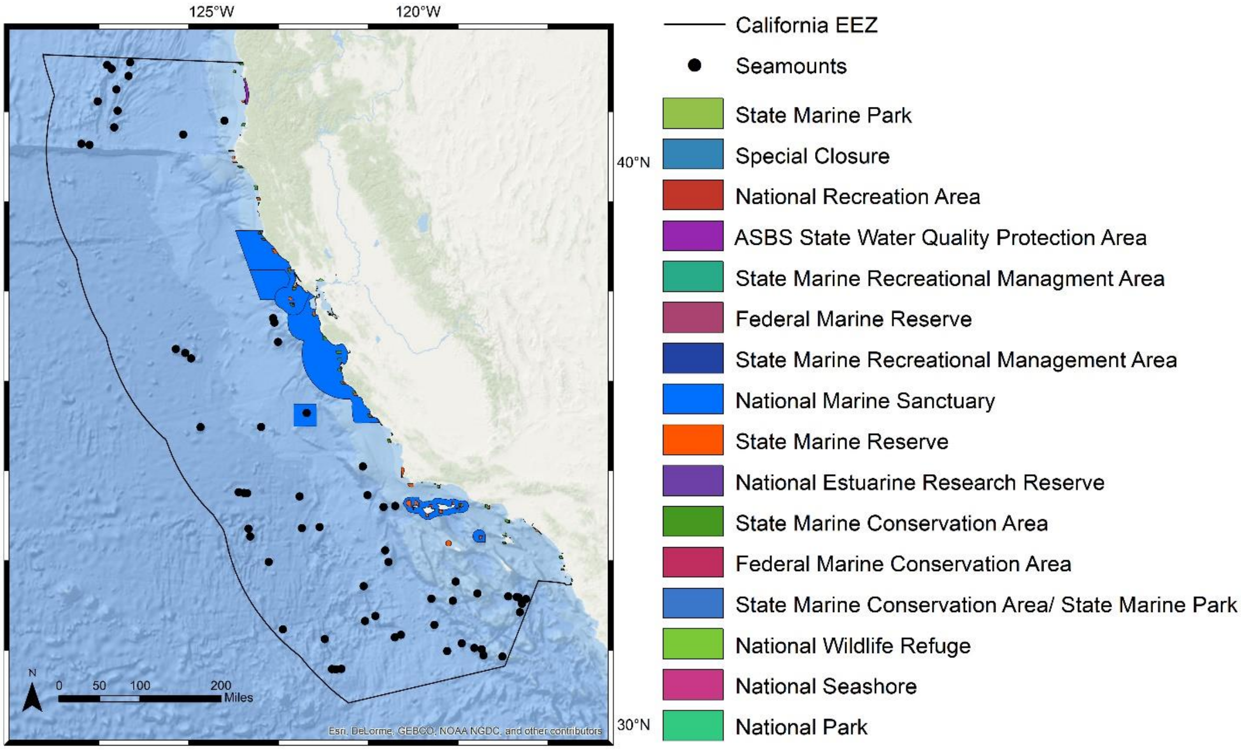


Figure 7.2: Marine protected areas (MPAs) of various types within California waters. Data are from the Atlas of Marine Protection.

7.3 Rockfish Conservation Areas (RCAs)

Rockfish Conservation Areas (RCAs) are large-scale fishery closures extending along the entire United States West Coast along approximately specified depth contours (Figure 7.3). RCAs have been in place since late 2002, but may change annually or even seasonally. The current boundaries were specified in 2015 and include closures for commercial fishing for non-groundfish with trawl gear, commercial fishing for groundfish with trawl gear, and commercial fishing for groundfish with non-trawl gear. Figure 7.3 shows the 2015 closures for commercial fishing for groundfish with trawling gear. None of the RCA closures overlap with seamount habitat in California waters. These closures are subject to reopening with the new groundfish fisheries management plan (see below).

7.4 Essential Fish Habitat (EFH)

Essential Fish Habitat (EFH) is a designation established in 1996 by an addition to the MSFCMA. With this provision, Regional Fisheries Management Councils are mandated to identify habitats used by all life stages of the fisheries they manage, including areas important for spawning, breeding, feeding, or growing to maturity. EFH have been mapped for more than 1,000 managed fishery species, based on a large suite of data including presence/absence, abundance, and growth, reproductive, survival, and production rates. It is important to note that not all EFH's are closed to fisheries; partial and temporary closures are common. Figure 7.4 shows the current EFH in California waters, and Figure 7.5 shows the EFH's with either complete or partial closures, which specify the various types of fishing gear permitted or excluded. Habitat Areas of Particular Concern (HAPC; Figure 7.6) are a subset of EFH areas that are considered high priorities for conservation. HAPC's must

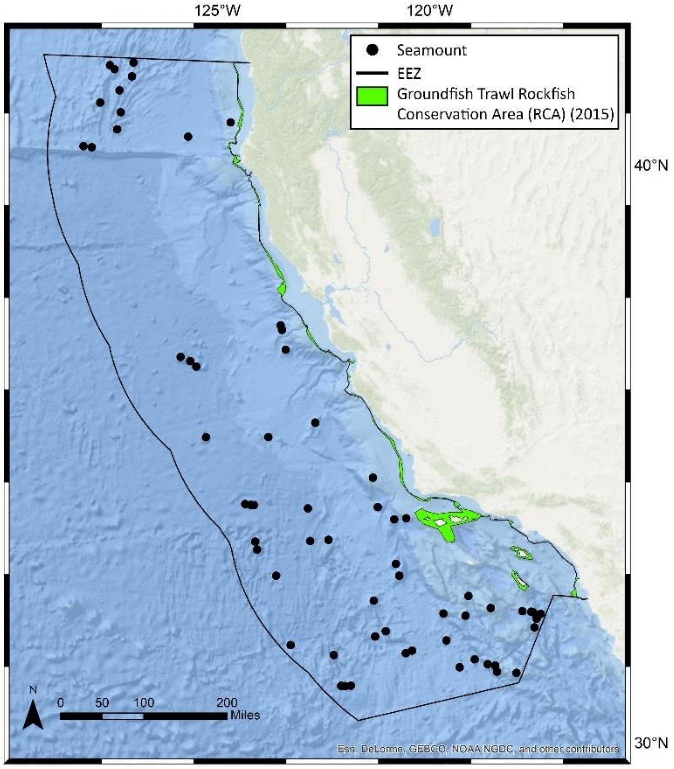


Figure 7.3: Rockfish Conservation Area (RCA) along the California coast showing the 2015 closures for commercial fishing for groundfish with trawling gear

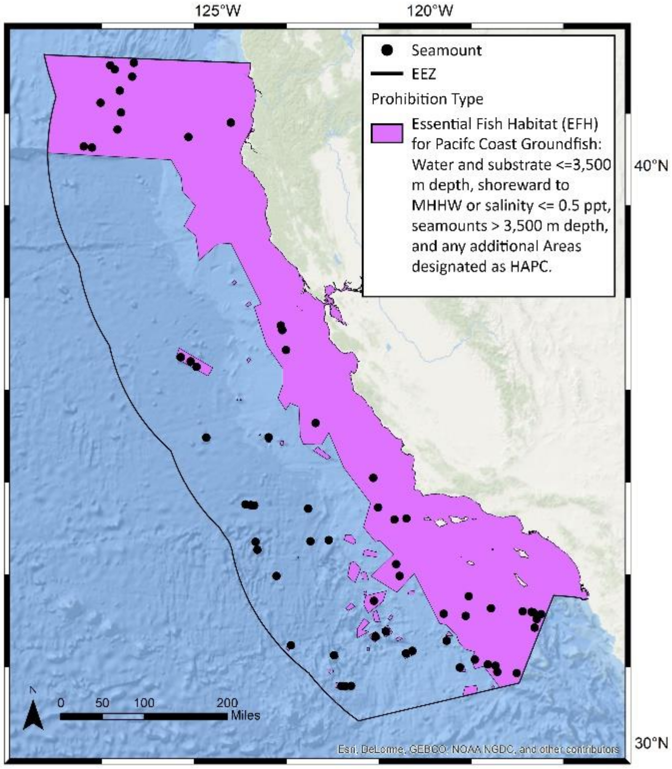


Figure 7.4: Essential Fish Habitat (EFH) designated in 2006 within the California EEZ.

provide major ecological functions, have a particular sensitivity to decline, be stressed from development, or be a rare habitat. While HAPC designation does not automatically close the area to fishing, they are used to help prioritize regional conservation efforts. Common examples of HAPC s on the United States West Coast include estuaries, kelp beds, seagrass beds, rocky reefs, and seamounts. In addition to groundfish HAPC’s, salmon HAPC’s are used to identify key inshore areas for salmon spawning and nursery habitats. Numerous seamounts in California waters occur within EFH habitat (Figure 7.4), as well as EFH closures (Figure 7.5) and HAPC s (Figure 7.6). EFH and HAPC designations and closures are subject to imminent change with the newly proposed groundfish fisheries management plan (see below).

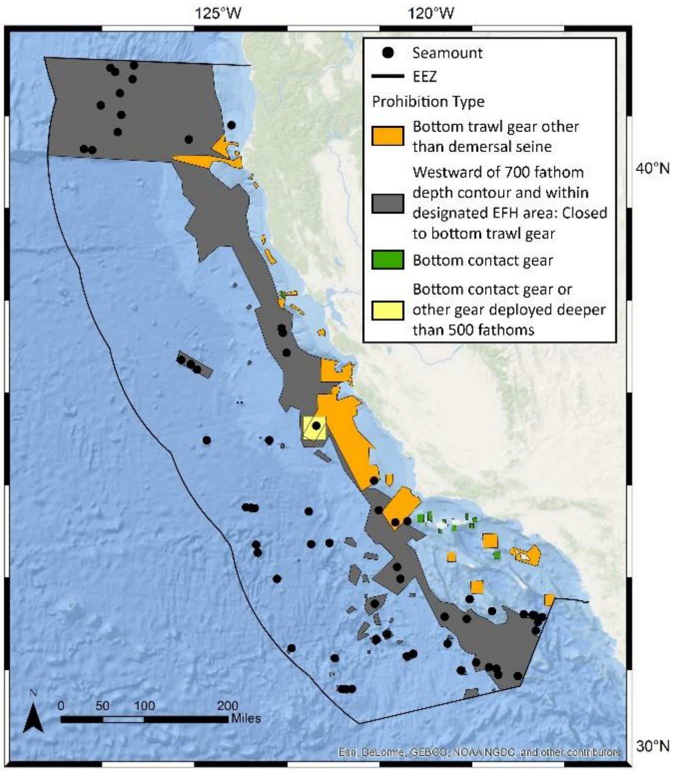


Figure 7.5: Essential Fish Habitat (2006) closures to protect groundfish habitat in California waters, specified by the fishing gear permitted or excluded.

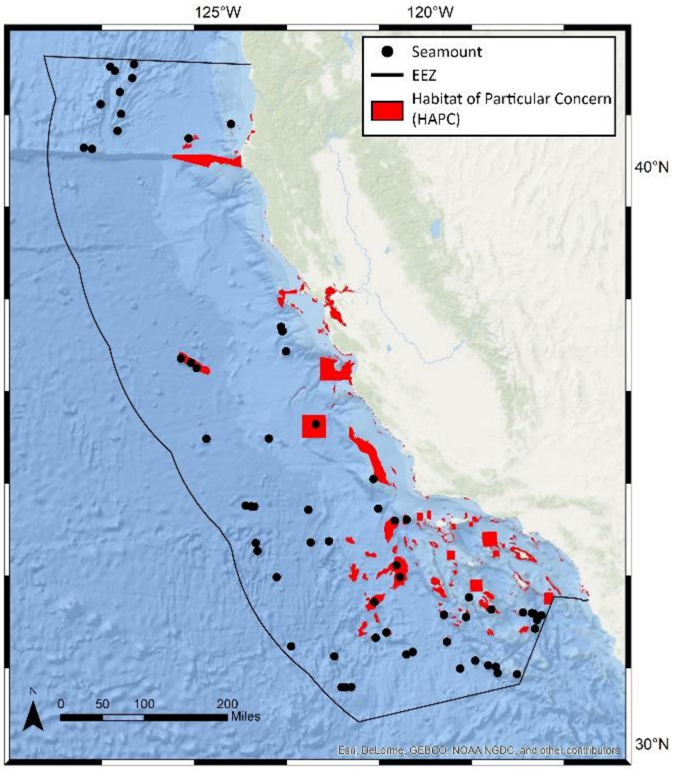


Figure 7.6: Habitat Areas of Particular Concern (HAPC) in California waters.

7.5 Upcoming Conservation Changes (Amendment 28)

In April 2018, a new Pacific Coast Groundfish Fishery Management Plan (FMP), known as Amendment 28 (NFMS 2019), was approved by the Pacific Fishery Management Council (PFMC). The plan is expected to be implemented in January 2020 at the earliest, and must first be approved by the NOAA National Marine Fisheries Service (NMFS). The new FMP establishes new and revised bottom trawl closures while also reopening previously closed areas, with the ultimate goal of protecting groundfish habitat and stocks while simultaneously maintaining optimal fisheries access. The proposed FMP will: 1) reopen the groundfish trawl RCA (Figure 7.3), 2) Reopen 3,000 square miles of currently closed EFH (Figure 7.7), 3) Close an additional 13,000 square miles of EFH including the majority of the Southern California

Bight (Figure 7.7), and 4) Close approximately 123,000 square miles of deep-sea habitat (>3,500 m) to all bottom contact fishing gear (Figure 7.7). The opening of the groundfish trawl RCA reestablishes a historically heavily fished region that was closed in 2002 to help recover depleted fishery stocks. The closure of waters deeper than 3,500 m was intended to protect the increasingly common discoveries of cold-water corals; however, these corals are also found in much shallower waters in habitats that are not strongly protected. A number of conservation organizations submitted comments to the PFMC in response to the originally released FMP proposal, supporting a number of improved protection measures including the addition of the deep-water fishing closure below 3,500 m, retaining the original RCA closures, including methane seep habitats as EFH, closing untrawled areas in the Southern California Bight, and closing the “Football” region in the Greater Farallones National Marine Sanctuary.

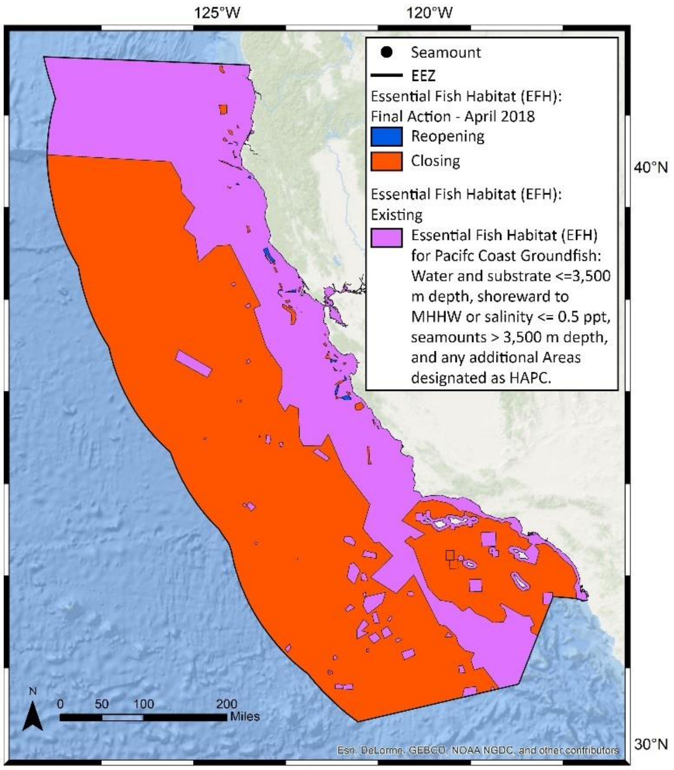


Figure 7.7: Modifications to EFH and fishery closures proposed under Amendment 28 to the Pacific Coast Groundfish Fishery Management Plan.

8. Conclusions

8.1 Conservation Status of the California Seamounts

The remoteness of seamounts, resulting from both their depth and distance to populated land masses, has greatly contributed to their current state of preservation. While evidence of anthropogenic disturbance is frequently observed and will likely increase in the near future, these seamounts likely constitute one of the more untouched ecoregions on the planet (Clark and Tittensor 2010; Clark et al. 2010). While many seamount habitats show signs of serious habitat disturbance, it is still possible to find pristine seamounts untouched by trawls or other direct anthropogenic disturbance. Therefore, the California seamounts represent a unique conservation opportunity to instill strong protections before these fragile ecosystems are irrevocably damaged.

8.2 The Future of Seamount Conservation

Given the likelihood that benthic communities in the deep sea will be adversely affected by a number of anthropogenic stressors, it is necessary to devise effective, science-based management strategies for ensuring their continued survival. Restoration of deep-sea environments is generally prohibitively expensive or impossible with current technology, making preemptive management activities critical for preserving these vulnerable habitats (Van Dover et al. 2014). While global stressors stemming from the effects of climate change will be extremely difficult to mitigate over large areas, efforts to reduce perturbations from acute stressors such as bottom trawling may prove to be both practical and fruitful.

Recently, considerable effort has been put into establishing some deep-sea habitats as marine sanctuaries and protected areas (e.g., Fosså et al. 2002; Hall-Spencer et al. 2009), although the paucity of data concerning deep-sea environments often impedes conservation efforts. Due to the known detrimental impacts to benthic communities stemming from bottom trawling (Watling and Norse 1998; Gage et al. 2005; Clark and Koslow 2007; Norse et al. 2012), recent United Nations resolutions 61/105 require the identification and protection of vulnerable marine ecosystems (VMEs) from adverse impacts from bottom fishing (UNGA 2007). Spatial closures are an important tool for effectively managing bottom trawling fisheries and preventing significant adverse impacts to VMEs in the deep sea. However, designating the location and extent of closures is challenging because the distribution of VMEs is generally poorly known, and there is often political and social opposition to restricting fishing opportunities.

Seamount habitats in California waters deserve strong, long-lasting protections. There are currently two primary avenues to pursue conservation goals: 1) the creation and expansion of permanent marine protected areas (ideally no take reserves), and 2) improved fishery regulations by the Pacific Fishery Management Council. While human-related activities are often inherently at odds with the conservation of marine habitats, there remains promising opportunities to advocate for optimal, science-based conservation measures that will effectively protect all of the seamounts in California waters.

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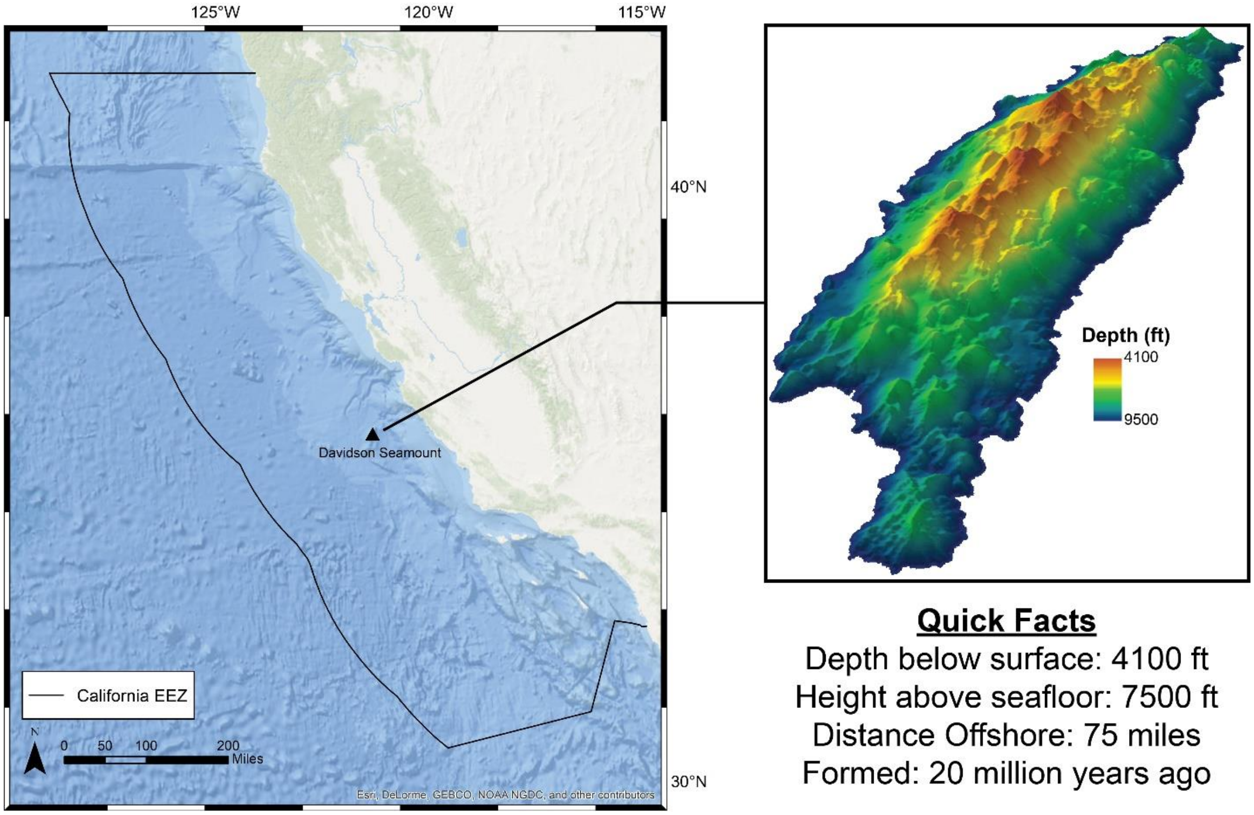
Appendix 1: California Seamount Case Studies

The following case studies explore some of the better-explored and studied seamounts off the coast of California. They were originally prepared as a series of public outreach blogs posted to the California Seamount Coalition website, Marine Conservation Institute's blog 'On the Tide', and the Mission Blue website.

Marine Conservation Institute is a co-founder of the California Seamount Coalition along with Surfrider Foundation and Wildcoast. Scientists believes that there are more than 60 seamounts in the offshore waters of California. The California Seamount Coalition is bringing awareness to these underwater treasures and working to secure their long-term protection.

For more information visit the website – www.CaliforniaSeamounts.org

Davidson Seamount: A Deep-Sea Oasis



Quick Facts

Depth below surface: 4100 ft
Height above seafloor: 7500 ft
Distance Offshore: 75 miles
Formed: 20 million years ago

Position of the Davidson Seamount within California waters (left) and three-dimensional map of the Davidson Seamount (right).

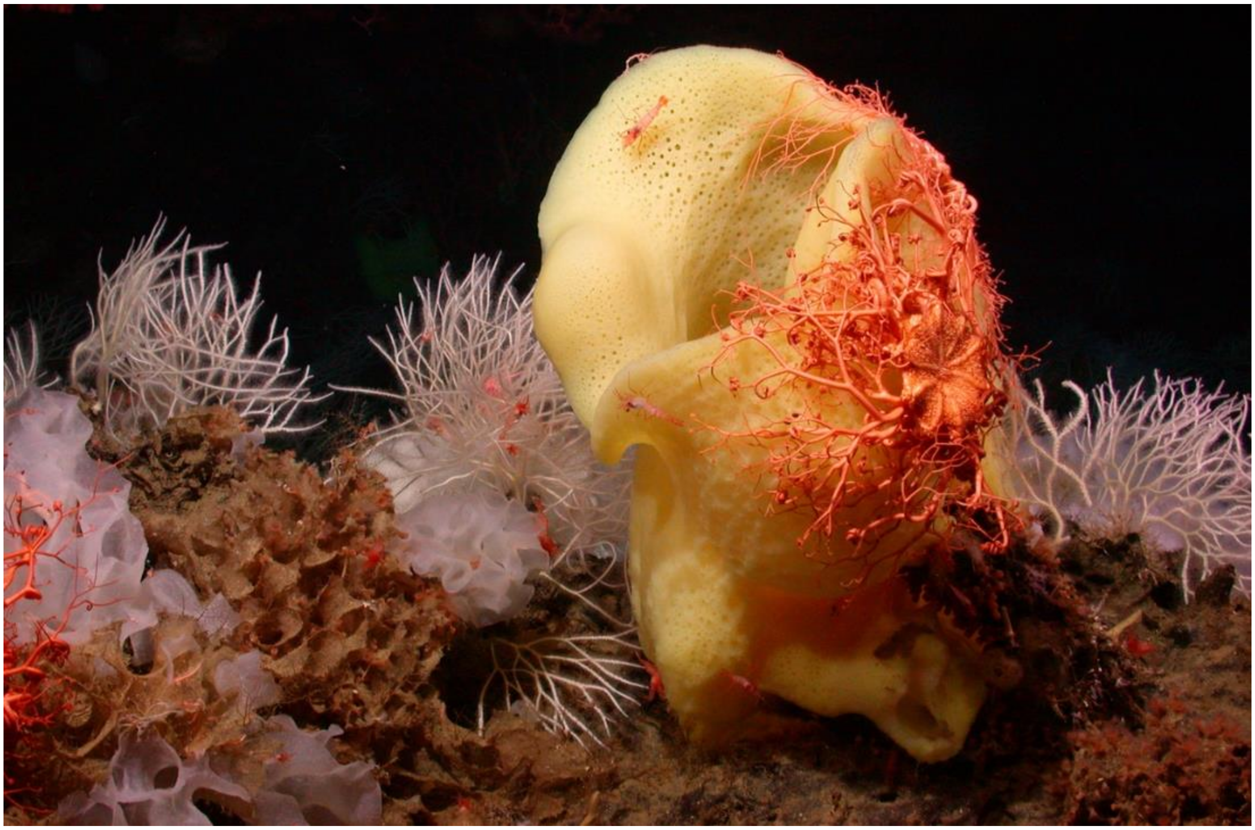
Davidson Seamount is an underwater volcano located just 75 miles off the coast of California. Its summit rises an impressive 7500 feet above the surrounding seafloor, yet still remains hidden beneath 4100 feet of water. One of the largest seamounts in U.S. waters, it is uniquely oblong in shape – extending over a massive area 26 miles long and 8 miles wide. The seamount formed an estimated 20 million years ago, with its last volcanic eruption occurring well over 9 million years ago. Today, the volcano is considered to be extinct, but is still growing at a barely perceptible rate due to the minute accumulation (1-7 mm per year) of ferromanganese oxide crusts.

Davidson Seamount was the first seamount officially recognized in U.S. waters. In 1938, it was designated by the United States Board on Geographic Names, named after George Davidson, a geographer and astronomer responsible for much of the early charting of the west coast. Accordingly, it has attracted more exploration and scientific study than other seamounts in U.S. waters, with a large number of survey expeditions over the past several decades. Scientists have used a variety of sophisticated instruments to plumb the depths of this massive seafloor mountain. One of the earliest surveys occurred in 2002, when a joint MBARI and NOAA mission used a remotely operated vehicle (ROV) to visually survey the flanks and summit of the seamount. ROVs are specially built robots that are controlled by a pilot onboard a research vessel, and can be outfitted with cameras, manipulator arms, sampling devices, and a wide variety of sensors. Since 2000, over 30 ROV dives have been conducted on Davidson Seamount, with additional observations coming from other technologies including automated underwater vehicles (AUVs) – robots that can be programmed to conduct surveys without a pilot controlling them, towed camera systems, and multibeam echosounders that map the shape of the seafloor using sonar. Despite these repeated expeditions to Davidson Seamount, less than 1% of its area has been surveyed.

A sea anemone, bearing a striking resemblance to a Venus flytrap, on the Davidson Seamount off California. Image courtesy of NOAA and MBARI.

Seamounts are highly productive ‘oases’ in the deep sea, providing ecologically crucial habitats that support biodiversity hotspots throughout the world’s oceans. In part, this stems from the large effects that seamounts exert on local currents, resulting in reduced sedimentation rates, the increased upwelling of nutrient-rich water, and the greater influx and retention of food. As a result, seamounts are often hotspots of endemic species that do not occur in other marine environments; on average approximately 20% of seamount species are considered to be endemic to seamounts. A wide variety of organisms are associated with seamounts, including pelagic species such as tuna, sharks, billfish, seabirds, sea turtles, and marine mammals, as well as benthic organisms such as deep-water corals and other invertebrates.

Davidson Seamount is no exception. It is home to more than 230 species, including 25 species of deep-water corals – some of which are bamboo corals over 200 years old. Deep-water corals and sponges are particularly important as they create three-dimensional habitat structures that provide food and shelter for a large number of associated species, including many commercially important fish. These deep-water coral reefs can be considered the ‘old-growth forests’ of the ocean – they are long-lived, slow growing, and extremely slow to recover following disturbance. Amazingly, 15 previously unknown species have already been discovered on Davidson Seamount; more may be discovered in subsequent expeditions.



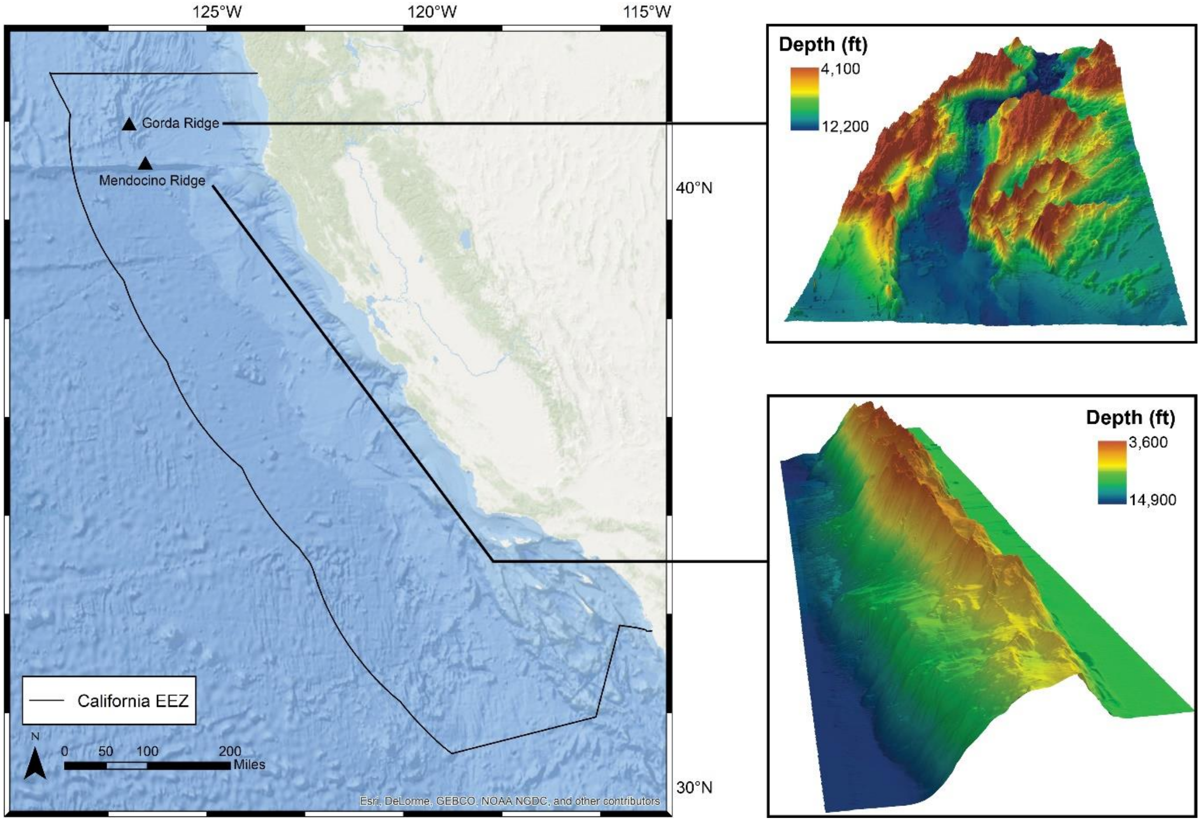
An orange basket star covers a Picasso sponge at Davidson Seamount, California. Image courtesy of NOAA and MBARI.

Seamount ecosystems are increasingly at risk from a number of anthropogenic disturbances including pollution, oil and natural gas extraction, deep-sea mining, fishing, and climate change. In many areas, including Californian waters, these habitats have been significantly damaged by bottom-trawling fisheries that drag enormous nets along the seafloor, indiscriminately catching corals, sponges, and fish. While global-scale disturbances – such as ocean warming or acidification – are difficult to mitigate, removing or reducing local disturbances –such as fishing and oil drilling – can greatly improve these ecosystem’s health and natural resilience to other stressors. The habitat structures created by deep-water corals and sponges in these ecosystems are extremely fragile and highly sensitive to disturbance – once damaged, these areas may not recover within our lifetimes. Therefore, it is imperative that we enact strong protection for these habitats before they are irrevocably damaged.

While most deep-sea habitats are not well protected (out of sight, out of mind), Davidson Seamount was added to the Monterey Bay National Marine Sanctuary (MBNMS) in 2008, making it the first seamount to gain official protection in U.S. waters (the expansion also added an impressive 775 square miles to the sanctuary). The MBNMS was originally designated in 1992, and confers federal protections to a large swath of coastal waters extending more than 275 miles south of San Francisco. The pristine nature of Davidson Seamount, along with its incredibly high biodiversity and abundance of benthic organisms, led to its inclusion in the MBNMS. However, in 2017, a Presidential Executive Order authorized the U.S. Department of Commerce to reevaluate the status of marine sanctuaries and monuments in light of renewed interest in these areas as targets for offshore oil and natural gas drilling. Commercial interest in deep-sea habitats highlights the importance of the protections that Davidson Seamount currently enjoys, but also contextualizes the alarming lack of protection for other seamounts in U.S. waters.

Yellow Picasso sponge and white sponges on Davidson Seamount. Image courtesy of NOAA and MBARI.

Gorda and Mendocino Ridges – California's Test Cases for Deep-Sea Mining



Position of Gorda and Mendocino Ridges within Californian waters (left), and three-dimensional maps of each (right).

The Gorda and Mendocino Ridges are a complex series of oceanic ridges just off the coast of northern California, and are home to unique deep-sea ecosystems including hydrothermal vents and cold seeps. Unfortunately, these areas may be at risk from future deep-sea mining efforts. It is critical that we enact protection for these diverse habitats before they are irrevocably damaged by commercial activities.

Hydrothermal Vents

Only discovered in 1977, hydrothermal vents are incredible deep-sea ecosystems that form due to the venting of extremely hot and mineral rich fluids into the water column. Hydrothermal vents occur when fractures in the seafloor allow seawater and magma to meet, resulting in the venting of extremely hot (750°F and higher) fluids into the water column. These fluids are hot enough to cause minerals such as silica, sulfide, and heavy metals to leach from the surrounding rocks. When vent fluids hit the cold seawater above, these minerals precipitate into a cloud of either black (iron sulfide) or white (calcium and silicon) particles that look like a large plume of smoke, and eventually solidify into large chimney-like structures.

Tubeworms cover a deep-sea hydrothermal vent near the Galápagos Islands. Image courtesy of NOAA.

Entire communities of deep-sea species rely on these vent fluids as their sole source of energy – one of the only ecosystems on the planet that does not ultimately rely on sunlight. These ecosystems rely on chemosynthetic bacteria that can convert hydrogen sulfide into organic compounds that form the basis for entire hydrothermal vent food chains. Some of these bacteria are housed by other organisms – the most notable being giant tubeworms that have no digestive system, but instead feed solely on the organic matter their symbiotic bacteria produce, and can grow to be five feet tall.

Cold Seeps

Like hydrothermal vents, cold seeps are areas of the seafloor where hydrocarbon-rich (typically methane and hydrogen sulfide) fluids leak (or 'seep') into the water column. Like their name suggests, cold seeps are much colder than the fluids at hydrothermal vents. However, these fluids also form the basis for entire ecosystems – starting with the bacteria that convert these chemicals into organic matter. When these bacteria are free-living (not housed in another organism), the process of metabolizing seep fluids also generates calcium carbonate, eventually creating rocky substrate that is colonized by deep-sea organisms such as cold-water corals and sponges. These bacteria have also evolved to live inside organisms such as *Bathymodiolus* mussels, which in turn get all of their food from their bacteria residents.


A field of chemosynthetic mussels at a cold seep. Image courtesy of NOAA.

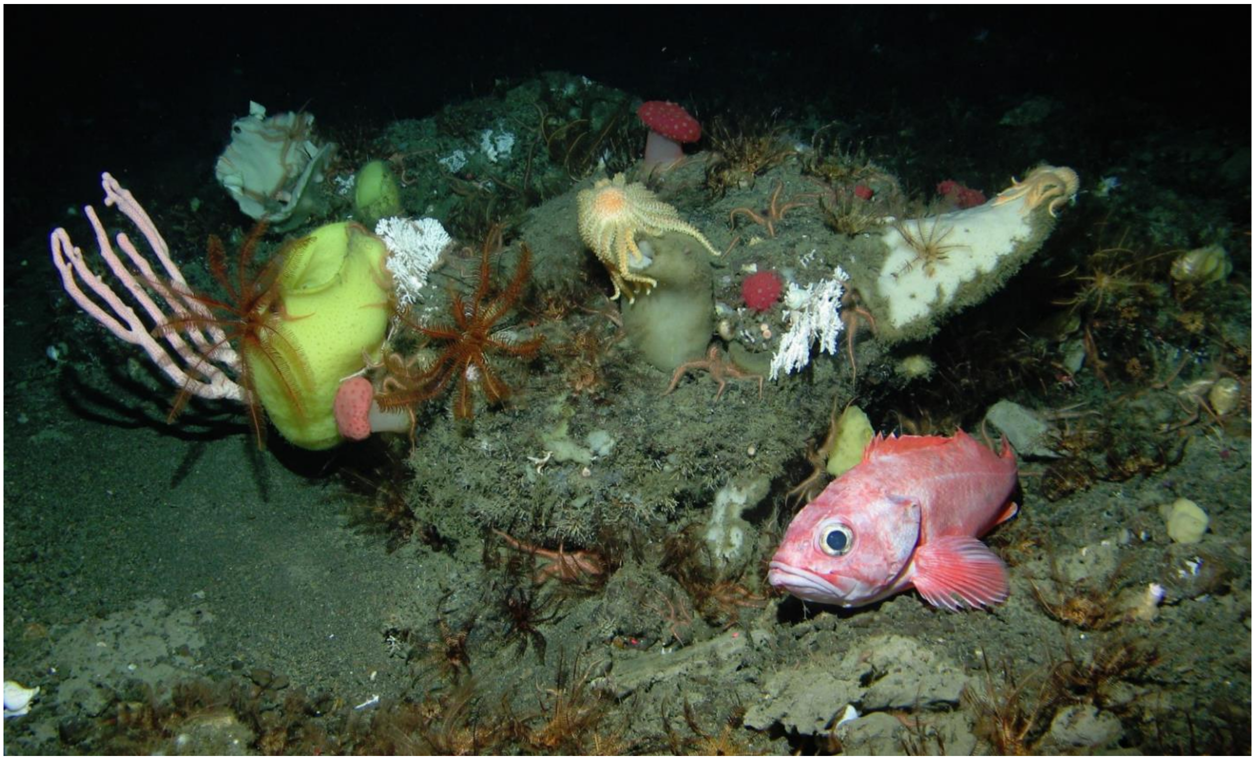
Gorda Ridge

Gorda Ridge is located approximately 120 miles off the coast of northern California at the intersection of the Gorda Plate, the Juan de Fuca Plate, and the Pacific Plate. As the Pacific and Gorda plates move apart due to plate tectonics, the resulting spreading center created the ridge approximately 30 million years ago, and continues to cause volcanic and seismic activity in the region. A large eruption was observed as recently as 1996, covering an area of seafloor over 650 feet and two miles long with lava. As a result of this tectonic activity, Gorda Ridge houses the only known hydrothermal vent ecosystem within the U.S. exclusive economic zone, home to unique vent species such as vestimentiferan tubeworms (*Ridgeia piscesa*), and a newly discovered species of limpet (*Lepetodrilidae gordensis*).

Mendocino Ridge

Mendocino Ridge is located off the coast of northern California along the Mendocino Fracture Zone, which extends for over 3,000 miles east across the Pacific Ocean. The eastern part of Mendocino Ridge, known as the Gorda Escarpment, exists at the boundary of the Pacific and Gorda Plates, resulting in high levels of seismic and volcanic activity. As a result, the area houses cold seep communities. While chemosynthetic bacteria and the tubeworms, clams, and mussels they inhabit form the basis for these communities, the resulting surge in productivity in the otherwise sparsely populated deep sea has resulted in some of the highest deep-sea fish and octopus biomass ever documented. High densities of brooding octopuses (*Graneledone boreopacifica*) led scientists to label this area a reproductive ‘hot-spot’, suggesting that these ecosystems are important habitats even for species that are not exclusively located on cold seeps.

Therefore, the loss of the seep habitats on Mendocino Ridge may have large ramifications for the health and diversity of other deep-sea habitats in the region.



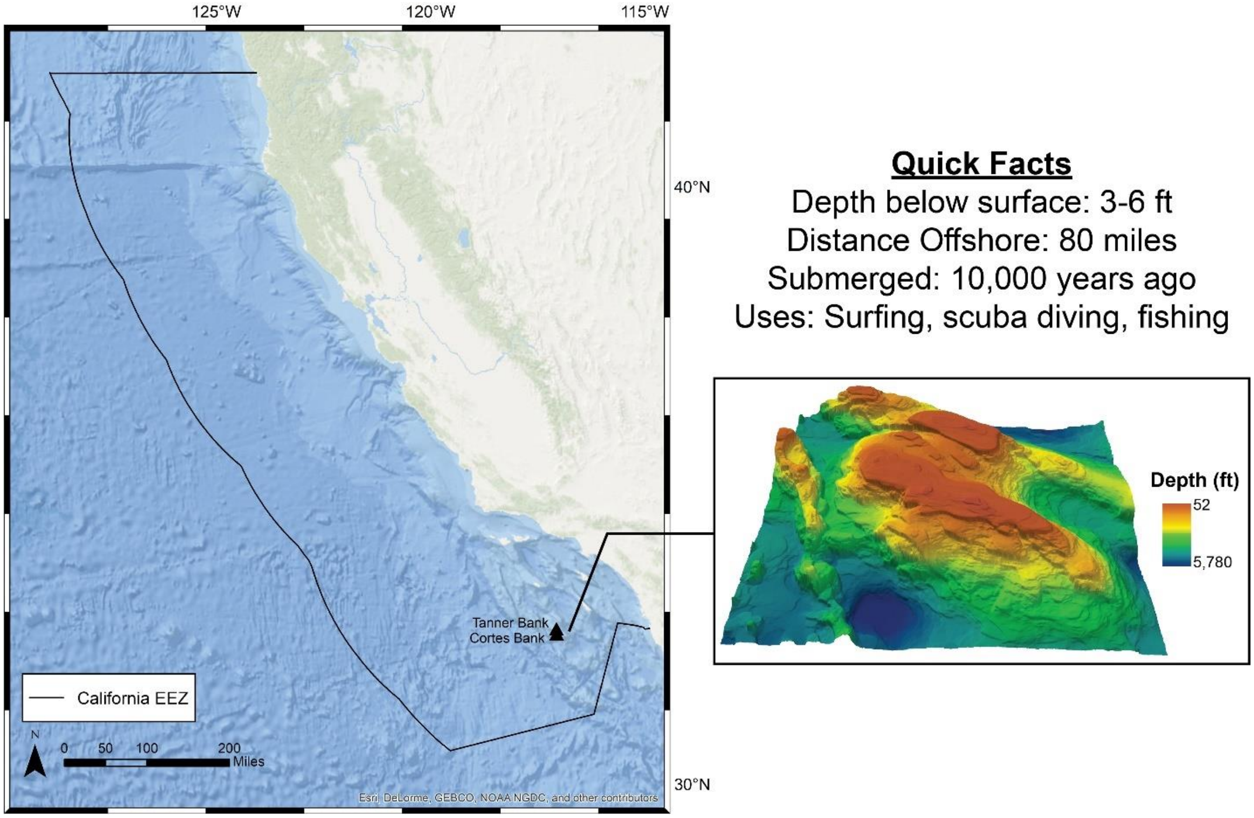
A diverse assemblage of benthic organisms on a sponge garden at Mendocino Ridge. Image courtesy of NOAA NWFSC.

Deep-Sea Mining

After decades of damage stemming from bottom-trawl fisheries and the extraction of oil and natural gas, the deep sea faces a new threat: the deep-sea mining of seafloor minerals. The deep sea holds large quantities of untouched precious metals and other minerals. The minerals deposited by vent fluids make hydrothermal vents prime targets for the deep-sea mining of silver, gold, copper, manganese, cobalt, and zinc. Recent technological advancements, coupled with the rising demand and prices of these minerals, have made deep-sea mining increasingly commercially viable. Several companies have obtained mining leases for large areas of the seafloor, and preliminary mining operations have already been conducted off the coast of Japan.

Unfortunately, deep-sea mining causes wholesale destruction to benthic ecosystems. Large areas of the seafloor are ripped apart by the massive machines used to mine ore. Neighboring habitats not in the direct mining area are still affected by the turbid and potentially toxic plume of sediments released during the mining process. While early mineral leases for Gorda Ridge were abandoned due to a lack of technology and low commodity prices, renewed interest in deep-sea mining means that these sites may be targeted in the future. It is critical to enact strong protections to safeguard the unique and diverse ecosystems found on the Gorda and Mendocino Ridges before they are destroyed by deep-sea mining or other anthropogenic disturbances.

Cortes and Tanner Banks: Recreation and Biodiversity Hotspots



Quick Facts
Depth below surface: 3-6 ft
Distance Offshore: 80 miles
Submerged: 10,000 years ago
Uses: Surfing, scuba diving, fishing

Position of Cortes and Tanner Banks within California waters (left) and three-dimensional map of the banks (right).

Cortes and Tanner Banks

Cortes and Tanner Banks are twin seamounts located approximately 80 miles off the coast of California, and just five miles from each other. As recently as 10,000 years ago, the banks would have been classified as islands instead of seamounts, as rocky outcrops on their summits breached the ocean surface due to a lower sea level during the last ice age. Today, these sunken islands lie just below the surface. Bishop Rock, the high point on Cortes Bank, is typically only submerged by approximately 3-6 feet of water depending on tides and ocean swell. During storms, it is even possible to see the rocky tip of this seamount in the troughs of large waves!

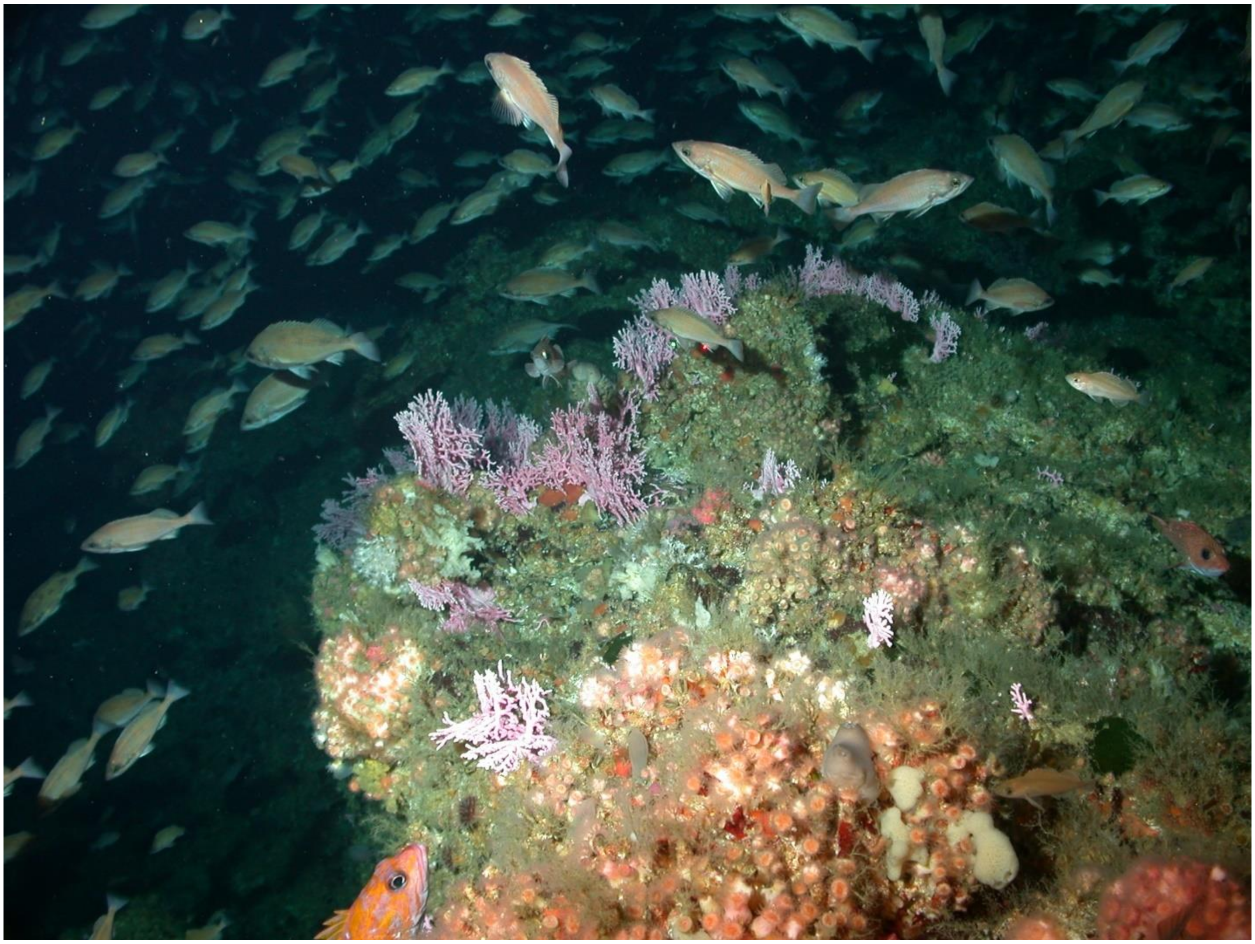
A large part of these seamount's notoriety lies in their nearness to the surface. Bishop Rock creates a serious shipping hazard – in 1986 the *USS Enterprise* aircraft carrier smashed into the bank, costing the Navy $17 million dollars in repairs. Another shipwreck – the *SS Jalisco* – was intentionally brought to Cortes Bank to scuttle it and create an artificial island designed to harvest abalone. Before the ship was maneuvered into the correct place however, it smashed into Bishop Rock and sank into deeper waters. Soon after, the federal government claimed the banks as U.S. territory, crushing any dreams of future artificial islands.

Bright pink hydrocorals (S*tylaster californicus*) and squarespot rockfish (*Sebastes hopkinsi*) cover the seascape at Tanner Bank. Photo courtesy of NOAA Southwest Fisheries Science Center.

Recreational Activity at the Banks

The shallowness of Cortes and Tanner Banks also supports a myriad of reactional activities. The banks are popular destinations for scuba divers, who flock to the area in search of clear water, shipwrecks, massive kelp forests, abundant coral and fish life, and lobster fishing. Using only their hands, divers report catching massive California spiny lobsters (or 'bugs' as they are known in the fishing community) at the banks weighing up to 10 pounds each.

The unique geography of the banks has also cemented their status as a legendary surfing spot. The offshore and deep-water location of these seamounts brings massive, fast-moving ocean swells that sweep over their shallow summits, resulting in some of the world's largest breaking waves. While the world record for surfing the largest wave moves around often (currently, an 80 foot wave in Portugal), it has been broken at Cortes Bank several times in the past decade – most recently with Mike Parson's 77-footer in 2008.



Brown stony corals (*Coenocyathus bowersi*, foreground) and pink hydrocorals (*Stylaster californicus*, background) provide habitat for a large school of rockfish at Cortes Bank. Photo courtesy of NOAA Southwest Fisheries Science Center.

Biodiversity at the Banks

In addition to creating massive waves for surfers, the size and shape of Cortes and Tanner Banks causes the upwelling of cold and nutrient-rich water to the surface, supporting a highly productive ecosystem brimming with marine life. Like many seamounts, the banks are home to a large number of habitat-forming benthic organisms including cold-water corals and sponges. The structures produced by these species support a large number of associated benthic species including anemones, sea stars, and rockfish. An astonishing 137 fish species, including 50 rockfish species, have been observed at the banks. Due to the shallowness of their summits, these seamounts are unique in their ability to host over 34 species of marine algae – important habitat formers and nutrient recyclers. The banks also provide critical habitat for the endangered white abalone.

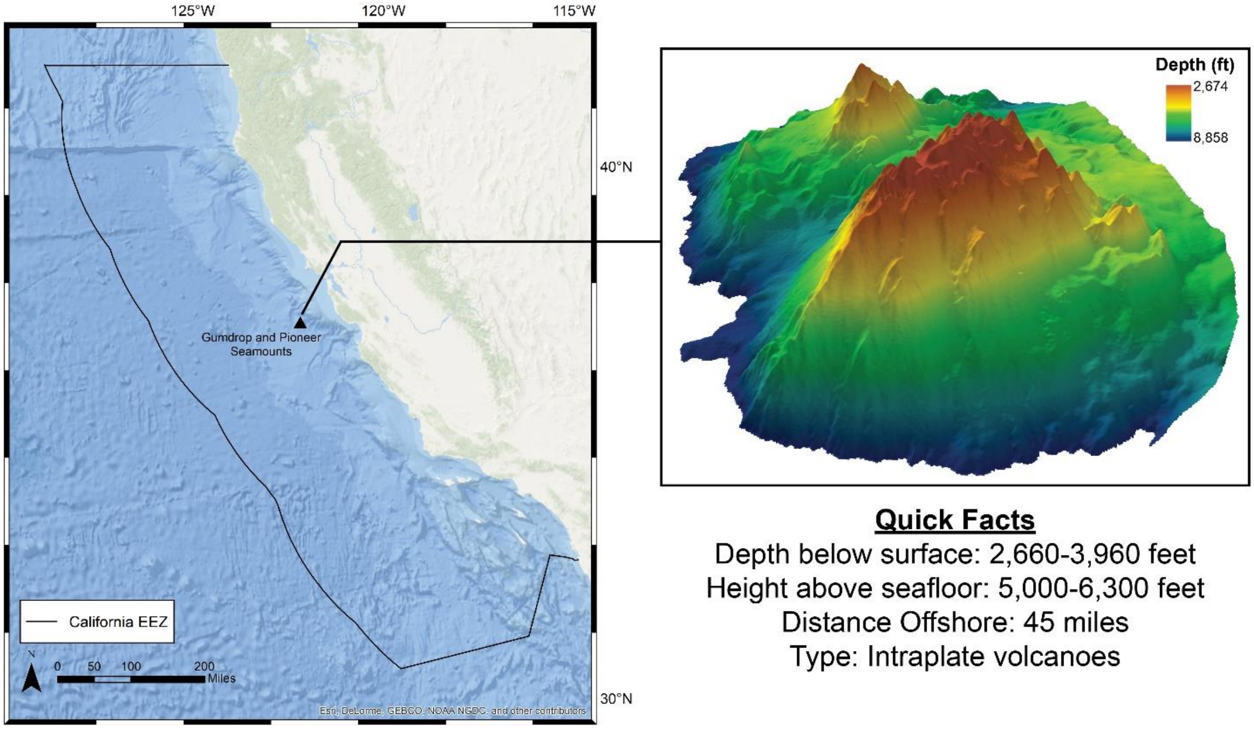
A gray whale (*Eschrichtius robustus*) and her calf, one of the many marine mammal species that use the productive waters above Cortes and Tanner Banks to feed or reproduce. Photo courtesy of NOAA Fisheries.

The nutrient-rich waters around the banks also support a thriving array of pelagic life. Many predatory fish migrate above the seamounts, including albacore, skipjack bluefin tuna, swordfish, thresher sharks, and leopard sharks. The area is also home to four species of endangered sea turtles (loggerhead, olive ridley, green, and leatherback), and is an essential feeding, reproductive, and migratory habitat for over 35 species of marine mammals. The banks are seasonally visited by endangered blue and fin whales, and are key migratory pathways for gray and humpback whales. In addition, dolphins, sea lions, orcas, sperm whales, and elephant seals can be seen foraging in the area.

Fishing Impacts

Unfortunately, Cortes and Tanner Banks are heavily fished. Recreational and commercial fisheries target this highly productive area for a wide range of species including tuna, swordfish, rockfish, seabass, sea urchins, squid, mackerel, and spiny lobsters. Recreational fishers catch an estimated 5,000-10,000 fish per year, with an estimated industry value of $6.5 million. While commercial fishing catches have been decreasing over the past several decades, the average annual catch is valued at approximately $400,000 – approximately 0.5% of the total California catch. The abalone fishery, which historically heavily targeted the banks, was closed to commercial activity in 1997, and will be closed for recreational fishers until at least 2021 due to alarming population declines. It is critical to secure protection for the vibrant and productive ecosystems at Cortes and Tanner Banks before they are irrevocably harmed by fishing or other human impacts.

Gumdrop and Pioneer Seamounts – Offshore Seabird Havens



Esri, DeLorme, GEBCO, NOAA NGDC, and other contributors

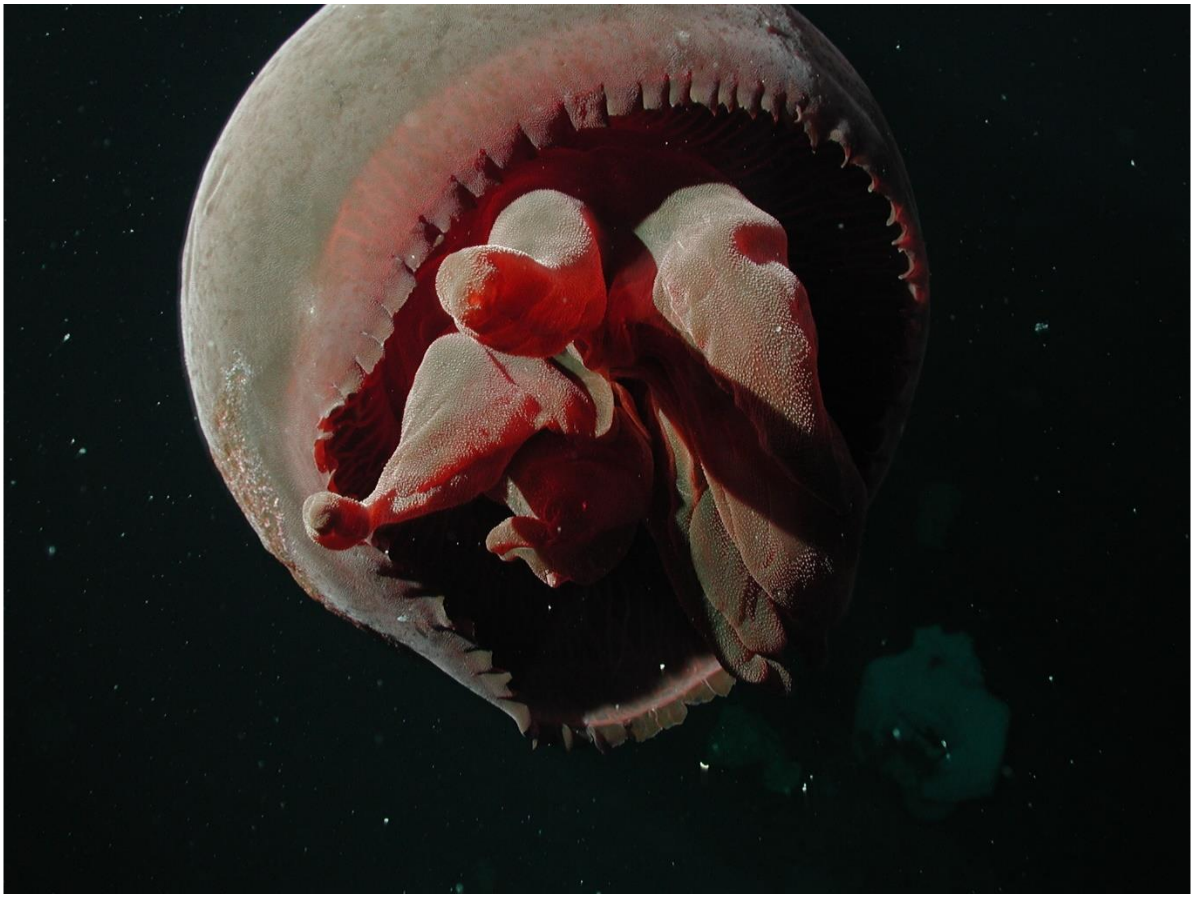
Quick Facts

Depth below surface: 2,660-3,960 feet
Height above seafloor: 5,000-6,300 feet
Distance Offshore: 45 miles
Type: Intraplate volcanoes

Left: position of Gumdrop and Pioneer Seamounts within California waters. Right: three-dimensional map of Pioneer Seamount (foreground) and Gumdrop Seamount (background).

Gumdrop and Pioneer Seamounts

Gumdrop and Pioneer are neighboring seamounts located approximately 45 miles off the coast of California, close to San Francisco. The summit of Pioneer Seamount sits approximately half a mile (2,690 feet) below the surface, while Gumdrop Seamount is even deeper – 3,960 feet down. The seamounts are largely made up of various forms of basalt – a common volcanic rock type that forms when iron-rich lava cools quickly. Unlike many seamounts, which often form at the tumultuous intersection of two or more tectonic plates, they are both examples of intraplate volcanoes. Along with neighboring seamounts including Davidson, Guide, and Rodriguez, these types of volcanoes form within a single tectonic plate due to plumes of extremely hot mantle forcing its way through weaknesses in the Earth's crust – in this case, likely due to the occurrence of an ancient spreading center. These seamounts also have a unique morphology, as they are comprised of a series of cones and ridges separated by sediment-filled troughs, as opposed to the more typical conical seamounts.



Only scientifically described in 2003, the gumdrop jelly (*Tiburonia granrojo*) was named after a rare observation on Gumdrop Seamount in 1998. Photo courtesy of NOAA/MBARI.

Home to Newly Discovered Species

While Gumdrop and Pioneer have unique origins compared to many other seamounts, they support similarly high levels of biodiversity. Pioneer Seamount has a particularly dense cover of benthic organisms, dominated by cold-water corals (23 species and counting!), crinoids, and sponges. Scientists attribute the high abundances of benthic organisms at Pioneer Seamount due to its shallower summit depth and associated increased nutrient availability. A number of newly discovered species can also be found at these seamounts, including numerous soft corals (*Chrysogorgia* sp., *Isidella tentaculum*, and *Gersemia juliepackardae*), urchins (*Araeosoma leptaleum*), sea stars (*Hippasteria tiburoni*), and the gumdrop jelly (*Tiburonia granrojo*). The gumdrop jelly (also called ‘big red’) was named after a rare observation in 1998 on Gumdrop Seamount, one of only 22 sightings in the world. This incredible sea jelly can grow to be 30 inches across, and has thick oral arms instead of the whip-thin tentacles found in most other species.

Seamounts as Seabird Havens

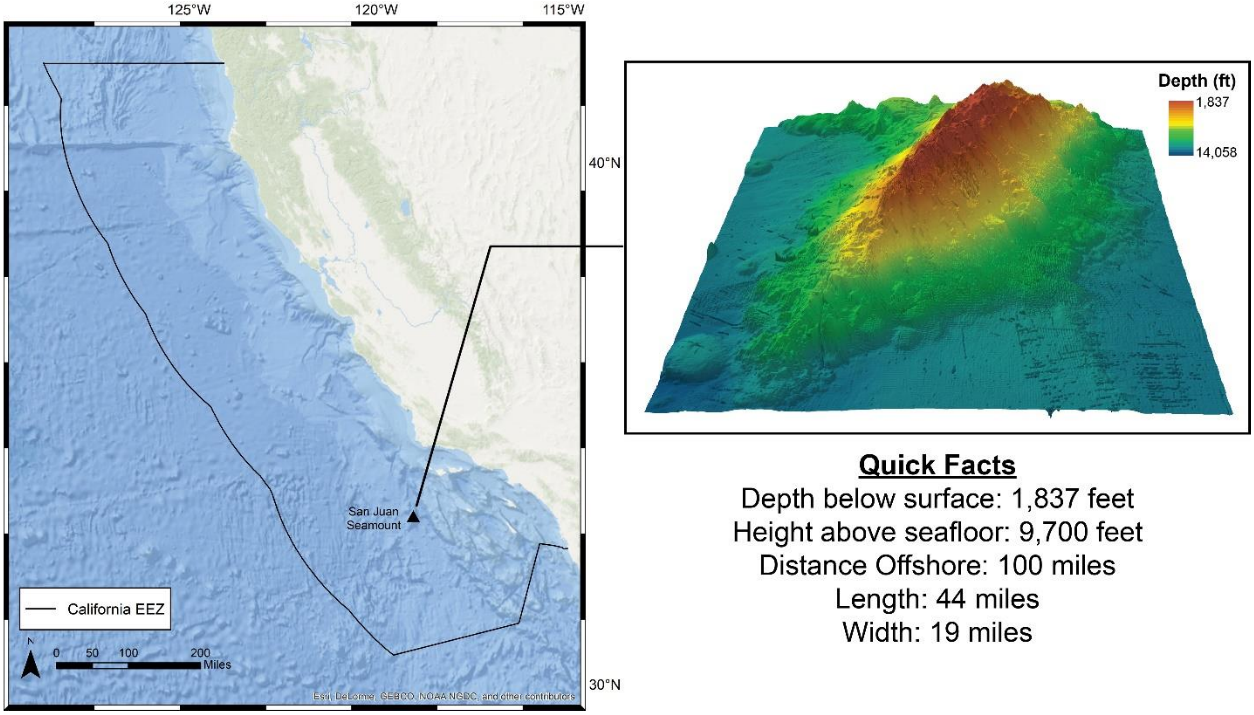
Surprisingly, these massive volcanoes located thousands of feet below the surface of the ocean also support a pelagic ecosystem teeming with life, including a variety of seabirds. Seabirds have long been known to associate with seamounts, using the productive waters above as important foraging grounds. Charles Darwin, more famous for his theory of evolution, was among the first to describe this remarkable association. Seamounts are so massive that they generate their own current patterns, often causing the upwelling of cold, nutrient rich water from the deep ocean. This supports a large diversity and abundance of life, including the upper water column prey that seabirds feed on. In one study of seamounts in the north Pacific Ocean, seabirds were found to be 2-40 times more abundant in the waters above seamounts as compared to other stretches of open ocean.

A breeding rhinoceros auklet (*Cerorhinca monocerata*), one of the many seabird species that relies on the productive waters above Gumdrop and Pioneer Seamounts to forage. Photo courtesy of Mick Thompson (CC BY-NC 2.0).

Shearwaters, albatrosses, petrels, terns, and auklets travel thousands of miles to feed in the productive waters above Gumdrop and Pioneer. As a result, these seamounts have become travel destinations for pelagic bird watching tours, with avid birders hoping to spot species that are less commonly seen near the coast. Some species, like Cook's petrel (*Pterodroma cookii*) and the rhinoceros auklet (*Cerorhinca monocerata*), have been shown to preferentially feed in more productive, cooler waters, explaining their annual migration to Gumdrop and Pioneer. Cook's petrel, listed as a 'vulnerable' species, breeds on small islands off the coast of New Zealand, but makes the long trek to these seamounts every year to feed.

Unfortunately, seabirds are in a steep decline. Global seabird populations have declined by almost 70% since 1950, with an estimated two hundred and thirty million seabirds lost. Wide-ranging pelagic species, which includes those that frequent seamount habitats, have experienced the biggest losses. While great efforts are being made worldwide to protect breeding and nesting habitats for threatened, vulnerable, or endangered seabirds, it is important to also protect the vital foraging grounds that occur above seamounts. Seamount ecosystems are threatened by a large array of human disturbances, including pollution, climate change, deep-sea mining, oil drilling, and fisheries. Protecting these fragile seamount ecosystems will help conserve seabirds, as well as the incredible – often yet to be discovered – benthic life that inhabits them.

San Juan Seamount: An Ancient Archipelago



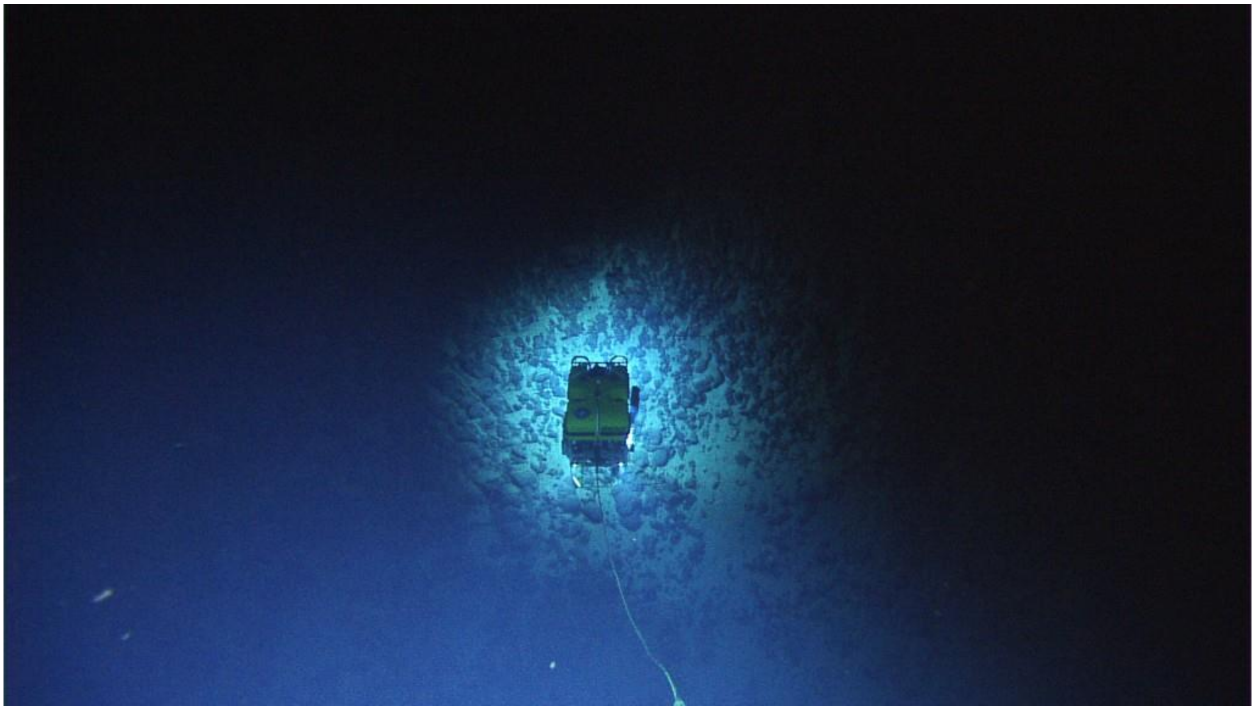
Quick Facts

Depth below surface: 1,837 feet
Height above seafloor: 9,700 feet
Distance Offshore: 100 miles
Length: 44 miles
Width: 19 miles

Position of the San Juan Seamount within California waters (left) and three-dimensional map of the San Juan Seamount (right).

San Juan Seamount

Seamounts are massive underwater mountains – usually extinct volcanoes – that tower thousands of feet above the seafloor. Some seamounts however, including the San Juan Seamount off the coast of southern California, were once ancient islands. San Juan started to form approximately 20 million years ago when seafloor eruptions spewed massive quantities of basalt and other volcanic rocks into the water column. San Juan was volcanically active for an estimated 9.7 million years, and it most recently erupted approximately 2.8 million years ago. For around a million years before it slipped back beneath the waves (10-14 million years ago), it existed as a series of eight small islands, maxing out at 460 feet above sea level with a total area of approximately one square mile (a little larger than Monaco and Vatican City – the world's smallest countries). Today, the summit of San Juan seamount sits 1,837 feet below the surface of the ocean. Some of the exposed surfaces of the seamount were eroded by wind and waves, as evidenced today by weathered rocks and the remnants of sandy beaches. However, the main culprit for the sinking of San Juan back beneath the waves is not erosion, but rather subsidence. Seamounts are so massive that they can cause the ocean crust beneath them to flex and compress, making the seamount sink lower and lower. In the case of San Juan Seamount, the ocean crust also compressed significantly due to thermal contraction – meaning that the crust shrank as it cooled down once volcanic activity ceased.



The remotely operated vehicle (ROV) *Hercules* explores the San Juan Seamount. Photo courtesy of Ocean Exploration Trust.

Deep-Sea Exploration

San Juan Seamount was first explored in 1941 when a single dredge recovered rocks from a depth of 5,000 feet (two other dredges were attempted, of these one was damaged and the other lost). In 2003 and 2004, the Monterey Bay Aquarium Research Institute conducted the first visual surveys of the seamount using a considerably more advanced approach, subsequently followed by a 2016 expedition by Ocean Exploration Trust. Just by looking at the incredible imagery that these expeditions returned with, you mighty correctly guess that our ability to study the deep sea has improved considerably since 1941.

The deep sea is challenging to explore. Surveying seamounts requires technology that can handle a highly pressurized, dark, and cold environment. Early approaches, including dredging, box coring, and towed camera arrays, are limited in their capabilities but are still widely used because they are inexpensive and easy to operate. One of the biggest innovations in deep-sea research was the introduction of submersibles that allow for directed exploration of the seafloor. Human occupied vehicles (HOVs) are submersibles that carry small teams of scientists into the deep sea, allowing them to maneuver across the seafloor to take photographs and videos, collect biological and geological samples, and measure environmental conditions using a large variety of sensors. Remotely operated vehicles (ROVs) are robotic submersibles that are piloted from a ship. They remain attached to the ship with a long tether that supplies power to the ROV and transmits images, video, and other data back to the ship. Some expedition vessels (for example, the *Okeanos Explorer* and the Nautilus) have recently begun to live telecast the video from ROV surveys over the internet, allowing anyone to follow along in real time from the shore. Automated underwater vehicles (AUVs) are the most recent addition to the submersible fleet.

Like HOVs and ROVs, these vehicles can visually survey the seafloor and carry a multitude of sensors. However, AUVs carry out their surveys without being piloted by a human, operating according to a pre-programmed mission. AUVs can generally carry out longer missions and cover much greater areas of the seafloor than ROVs and HOVs, but have reduced sampling abilities and cannot navigate highly complex environments.

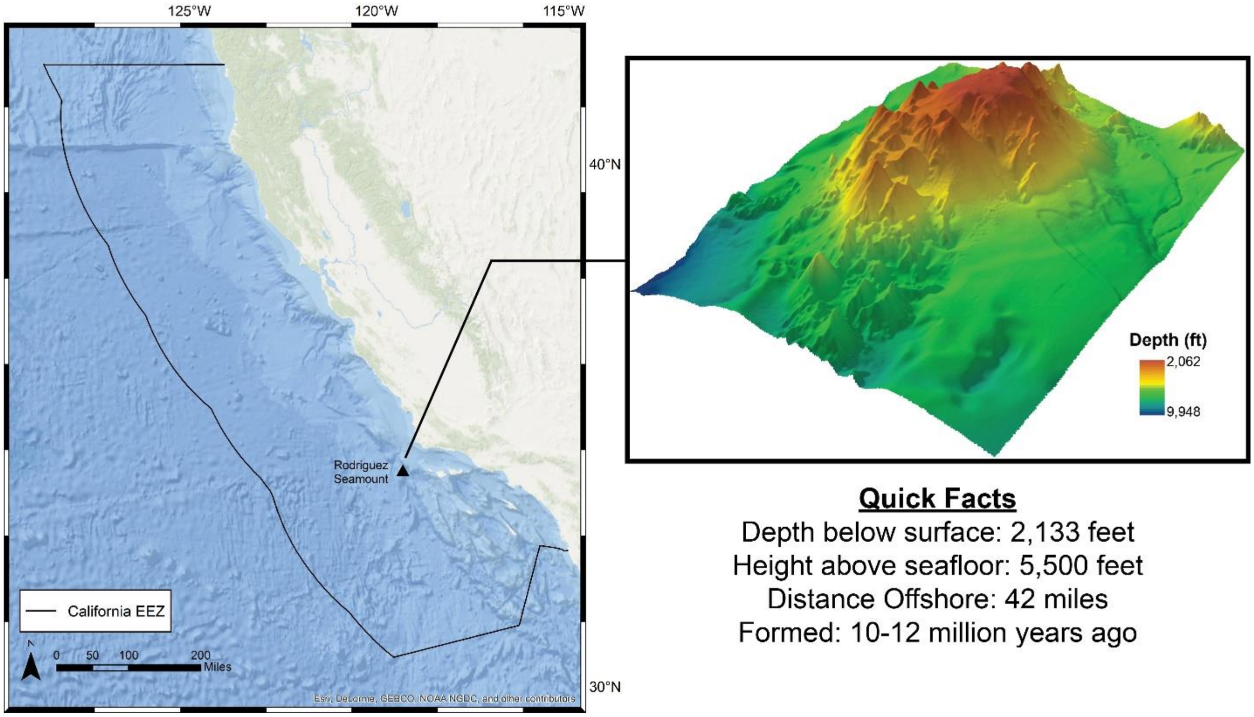
Marine Conservation Institute staff member Samuel Georgian pilots a remotely operated vehicle (ROV) during an expedition on the Exploration Vessel Nautilus, in collaboration with Ocean Exploration Trust.

San Juan Marine Life

The expeditions to San Juan Seamount have uncovered an incredible array of life, including benthic communities dominated by cold-water corals, sponges, xenophyophores, and echinoderms, and fish assemblages that include grenadiers, Pacific flatnose, and halosaurs. Xenophyophores are giant amoeba-like protists comprised of only a single cell – despite their surprisingly large size of up to eight inches across! They create ‘tests’, or skeletal structures, made of sediment and shell fragments that serve as important habitat structures for worms, copepods, crustaceans, brittle stars, and snails. The seamount is also home to rare species, including the deep-sea file clam (*Acesta sphoni*) that only lives on a few seamounts and canyons off the coast of California. The bamboo corals that grow on San Juan Seamount are long-living (150-300 years) species that are important archives for reconstructing past ocean conditions, with significant implications for better understanding how climate change will shape our future oceans. In addition to its diverse benthic life, San Juan Seamount provides an excellent pelagic habitat for a number of species including large predatory fish, seabirds, and marine mammals.

A xenophyophore, one of the unique deep-sea organisms found on San Juan Seamount. Photo courtesy of NOAA.

Rodriguez Seamount – A Geologic Rarity



Quick Facts

Depth below surface: 2,133 feet
Height above seafloor: 5,500 feet
Distance Offshore: 42 miles
Formed: 10-12 million years ago

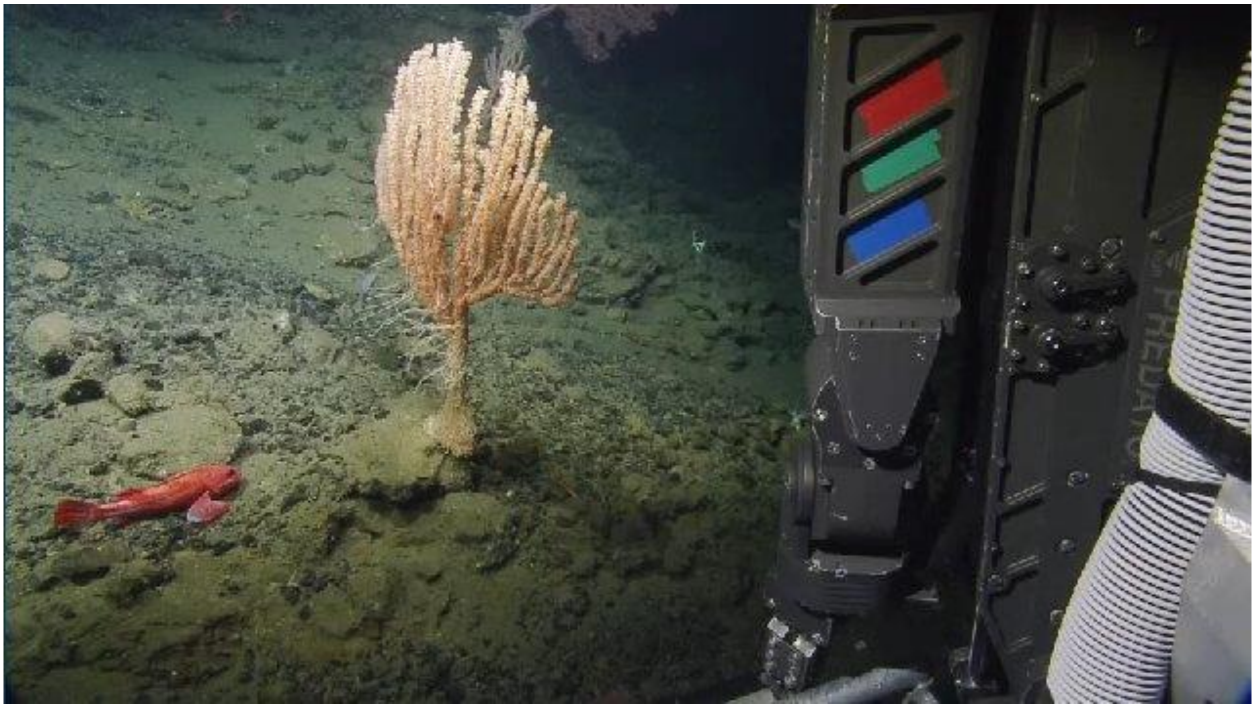
Position of Rodriguez Seamount within California waters (left) and three-dimensional map of the Rodriguez Seamount (right).

Rodriguez Seamount is a 10–12 million-year-old seamount located approximately 42 miles off the coast of southern California. It towers over a mile above the seafloor, with its tallest summit cone standing over a little over 2,000 feet below the surface. Once upon a time, Rodriguez was an island standing as tall as 230 feet above sea level, with an area of 2.6 square miles. Like the neighboring San Juan Seamount, it has since sunk back beneath the waves largely due to the subsidence of the ocean crust beneath it. Due to the erosional forces it was exposed to as an island, its modern summit largely consists of a large flat dome, qualifying Rodriguez as a guyot – a flat-topped seamount. Guyots, named after the Swiss geographer Arnold Guyot, are relatively rare in our oceans – scientists estimate that there are almost 10,000 seamounts, but only 283 guyots.

Pillow lava, a unique type of basalt rock that forms during underwater volcanic eruptions. Photo courtesy NOAA.

How do guyots – or any seamounts – form? The process generally takes millions of years and involves a complex series of geologic events. Seamounts typically follow a geologic pattern of initial growth, subsequent volcanic activity, subsidence (sinking), and eventually extinction (cessation of volcanic activity). The growth of a seamount can stem from a variety of types of volcanic activity. At oceanic spreading centers where tectonic plates are diverging apart from each other, magma escapes and cools in the cold seawater, creating submarine volcanic rock formations that grow larger with each subsequent eruption. Other seamounts commonly form near subduction zones, where tectonic plates are converging and one plate slides under the other. The subducted plate begins to melts as it moves towards Earth's hot interior (our planet's core clocks in at a whopping 10,800°F – as hot as the surface of the sun), creating hot magma that bubbles its way up to the seafloor, erupting and giving birth to a seamount.

While seamounts are commonly found on the intersection of tectonic plates, some form within single plates. These intraplate seamounts typically form at hotspots, areas were super-hot magma plumes burst through the oceanic crust. The Hawaii Islands and accompanying seamounts formed this way, with new islands forming in a line as the Pacific plate slowly (only 3-4 inches per year) drifts over a hotspot. Rodriguez Seamount is another example of an intraplate volcano. However, it is a very rare type of intraplate seamount that did not form over a hotspot. Instead, it is believed to have formed when magma forced its way through ancient spreading centers in part due to decompression melting, a process in which the Earth's mantle melts as it moves upwards through the crust due to rapid decreases in pressure. Rodriguez was volcanically active for around 2 million years as it formed, with evidence suggesting that its more recent eruptions occurred in shallow water. Like other guyots, the erosional forces of wind and waves scoured the summit into a flat top prior to its subsidence back beneath the waves, producing the flat, sandy dome observed today.



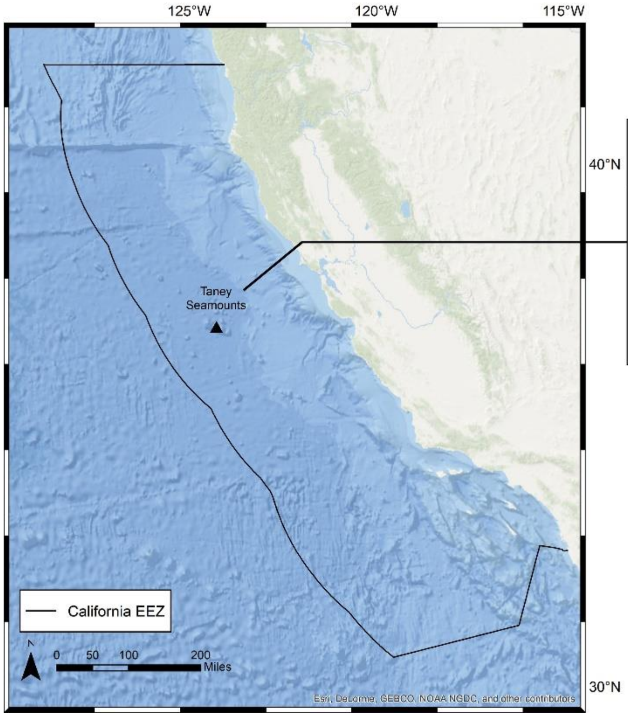
New species alert! The deep-sea coral *Isidella tentaculum*, discovered on Rodriguez Seamount in 2008. Photo courtesy of Ocean Exploration Trust.

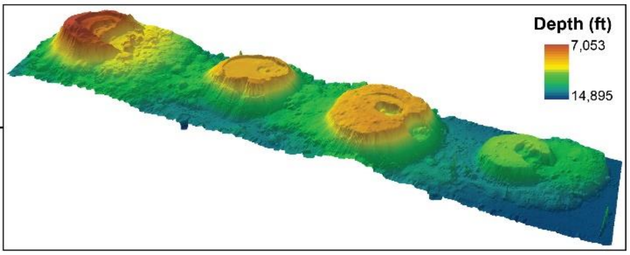
Like other seamounts, Rodriguez is home to an astonishing variety of marine life. Expeditions to the seamount have uncovered a plethora of organisms including sponges, crinoids, brittle stars, anemones, sea urchins, sea cucumbers, worms, crabs, 20 fish taxa, and 26 species of corals including massive bubblegum (*Paragorgia*) and bamboo (*Isidella*) colonies. However, the summit of Rodriguez is notably less diverse than neighboring seamounts. In part, this is likely due to the fact that the summit lies within the oxygen minimum zone, where extremely low oxygen concentrations may prevent many species from thriving. Its unique morphology as a guyot may also be to blame. The flat, sandy dome of Rodriguez Seamount lacks the rocky habitats that many corals, sponges, and other benthic species require. However, it is the perfect environment for sea cucumbers, the dominant animal group on the summit. Sea pens, one of the few deep-sea corals that are able to grow in sand and mud sediments, are also abundant on the summit.

Despite the low diversity of the summit of Rodriguez, the seamount on the whole still houses an incredible array of organisms, with 133 taxa identified in one expedition alone. In 2004, a new octocoral species *Gersemia juliepackardae* was discovered on the seamount, and in 2008 the bamboo coral *Isidella tentaculum* was described based on observations from both Rodriguez and

Pioneer Seamounts. These observations continued the long tradition of species being discovered on seamounts – in one study, 29–34% of identified seamount species were new to science! It is imperative that we enact protection for vulnerable seamount habitats now, or we run the risk of destroying species before they are even discovered.

Taney Seamounts: Collapsed Calderas and New Species





Quick Facts

Chain of five seamounts
Depth below surface: 1.2 miles
Distance Offshore: 140 miles
Age: 26 million years
Type: Near-ridge seamounts

The Taney Seamounts are a chain of five seamounts spanning a distance of 33 miles across the seafloor off the coast of California. The seamounts are an example of near-ridge seamounts, which generally form near fast-spreading ridges on diverging tectonic plates. Fast is a relative term – the ridge near the Taney Seamounts has a spreading rate of 4.9 cm per year! The Taney chain formed from a series of eruptions from shallow, large-volume magma chambers that eventually collapsed, forming the calderas seen today. Calderas are large sinkholes that form when volcanoes collapse in on themselves, generally because the now-empty magma chamber can no longer support the massive weight of the volcanic rock above. The oldest and largest volcano (nine miles across and 6,500 feet tall) in the Taney chain has undergone three large caldera collapses in its history, leaving the seamount with a unique half-moon shaped summit. The other seamounts have smaller calderas, some of which were partially filled in with subsequent lava flows. One of the summits has evidence of a somma, a unique summit formation that is created when an old caldera is filled in with a shield created by younger lava flows. Due to their morphology, scientists initially believed that the seamounts were relatively young. However, subsequent argon dating revealed that they are approximately 26 million years old.

Chaunacops coloratus, a rare species of anglerfish discovered in 1891and filmed in the wild for the first time at the Taney Seamounts. Photo courtesy of NOAA.

Like other seamounts off the coast of California, the Taney Seamounts are highly productive 'oases' in the deep sea, providing ecologically crucial habitats that support a large diversity of organisms. In part, this stems from the large effects that the seamounts exert on local currents, providing critical resources for benthic organisms including sediment and waste removal, nutrient and food influx, and larval dispersal. A 2010 expedition to the Taney Seamounts documented a large diversity and density of seafloor life including cold-water corals, sponges, brittle stars, sea stars, mollusks, sea cucumbers, anemones, sea urchins, and worms. The ecological patterns uncovered in the expedition may also help shed light on why seamounts are such havens for benthic diversity. In many deep-sea habitats, the abundance of organisms decreases with depth – often believed to relate to the reduced rain of food and nutrients from more productive surface waters. However, the Taney Seamounts survey discovered that abundance did not change with depth. Instead, different depth zones on the seamounts were characterized by different, but equally dense, assemblages of seafloor animals. For example, sponges began to replace corals at deeper depths, being theoretically better equipped to handle the harsher physical conditions, but still filling a similar ecological niche.

A deep-sea acorn worm. A new species of acorn worm (*Saxipendium implicatum*) was described in 2012, and is believed to only live on the Taney Seamounts, Davidson Seamount, and Guide Seamount. Photo courtesy of NOAA.

The Taney Seamounts are also home to a number of newly discovered and rare species. The chain is home to a rare species of anglerfish (*Chaunacops coloratus*), which was described in 1891 and filmed in the wild for the first time at Taney Seamounts. Observations from an expedition to Taney Seamount also contributed to the discovery of a new and rare species of sea jelly (*Tiburonia granrojo*), which can grow to be 30 inches across! In 2012, a new species of acorn worm (*Saxipendium implicatum*) was described, with evidence suggesting that it is endemic to Guide, Davidson, and Taney Seamounts. If human activity had decimated life on just these three seamounts prior to 2012, this species could have become extinct before we even knew it existed!