OCEANS BACKGROUND REPORT

THE BOWIE SEAMOUNT AREA

Pilot Marine Protected Area
In Canada's Pacific Ocean

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SUMMARY

Seamounts are underwater mountains that form through volcanic activity. Many seamounts support rich biological communities, and may be thought of as "oceanic oases". Bowie Seamount is one such underwater mountain that is located in Canadian waters, 180km west of the Queen Charlotte Islands. Unlike most seamounts, which are usually quite deep (typically 1000's of metres below the sea surface), Bowie Seamount rises from a depth of 3100 m to within 25 m of the surface. Scientific exploration of the Bowie ecosystem has been limited. However, the seamount is known to support significant populations of rockfish and sablefish as well as a rich bottom community. Research has shown that the high productivity of shallow seamounts like Bowie results in part from peculiar interactions with ocean currents. These flow features play a role in transporting animals to seamounts, and are essential to the long-term maintenance of these communities as well. Nevertheless, since seamounts are both small and geographically isolated these oceanic oases are, in fact, quite vulnerable to overfishing.

1. What is a Seamount?

Seamounts are undersea mountains that rise steeply from the sea floor but which do not penetrate the sea surface. Typically, seamounts are formed by volcanic activity over hotspots in the earth's crust. Spreading of the sea floor away from these hot-spots via plate tectonic movements means that seamounts are often arranged in long chains or clusters that radiate out from such spreading zones. Geologically, seamounts are also interesting in that they are often much younger than the surrounding sea floor.

Despite the fact that most people are unfamiliar with seamounts, they actually represent one of the most common types of deep sea topographic features. Estimates vary, but recent work suggest that there may be as many as 50,000 seamounts greater than 1000 m in height in the Pacific Ocean alone. Fewer data are available for the Atlantic Ocean, but seamounts greater than 1000 m in height certainly number in the 1000's.

When a seamount becomes tall enough to break the sea-surface it becomes an oceanic island. The Hawaiian Islands, the Azores and Bermuda were all subsurface seamounts at some point in the past. In fact, most of the isolated oceanic islands peppered throughout the tropical southeast Pacific Ocean originated as seamounts. Interestingly, since sea-level has changed over geological time scales, some seamounts that are currently below the sea surface would have been islands during the last Ice Age when sea-level would have been 100's of metres shallower.

2. Bowie Seamount

Physical Description

Located about 180 km west of the Queen Charlotte Islands in the northeast Pacific Ocean, Bowie Seamount is by far the shallowest seamount in Canadian waters. From a bottom depth of nearly 3100 metres, Bowie Seamount rises to within only 25 metres of the surface. By comparison, if it were on land, Bowie Seamount would stand about 600 metres higher than the summit of Whistler Mountain, and only 800 metres below that of Mount Robson, the highest peak in the Canadian Rockies.

At its oblong base, Bowie Seamount is nearly 55 km long and 24 km wide. Its summit is actually composed of two relatively flat terraces. The deeper of the two extends between 200-250 metres below the sea surface. The shallower terrace ranges between 60-100 metres below the sea surface, but it is also dotted with smaller steep pinnacles that penetrate to within 25m of the surface. Given the fierce storms that occur in the northeast Pacific in winter (with wave heights in excess of 20 metres not uncommon!), it is little wonder that hydrographic charts list Bowie Seamount as a potential hazard to navigation.

Geological History

Bowie Seamount was formed by undersea volcanic activity along fractures in the sea floor. While most seamounts in the Pacific Ocean are millions of years old Bowie is comparatively quite young. Geological studies show that the base of the seamount formed less than a million years ago. Interestingly, the summit of Bowie Seamount is even younger and shows signs of having been volcanically active as recently as 18,000 years ago. Given that sea-levels during the last Ice Age would have been at least 100m shallower than they are today, geologists hypothesize that Bowie Seamount would have once stood above sea-level as either a single oceanic island or as a small cluster of shoals. This hypothesis is supported by the finding of wave-cut terraces and rounded beach rocks near the seamount summit. If we were able to go back in time 18,000 years and visit the spot where Bowie Seamount sits today, we would see instead an offshore island that was still volcanically active.

Biology at Bowie Seamount

From a biological perspective, Bowie Seamount has been relatively unexplored. The only real scientific investigation of the Bowie community took place in 1969 when SCUBA divers equipped with underwater cameras explored the seamount summit. Their photos show both a rich fish community and a diverse collection of bottom dwelling organisms. Numerous seaweed species were also observed, likely due to the seamount's proximity to the surface where there is ample light. This algal cover may play an important role in providing refuge to young fish.

Most of the fish observed by the divers were adult and juvenile rockfish of the genus *Sebastes*. Most abundant were widow rockfish (*Sebastes entomelas*), yellow-eye rockfish (*S. ruberrimus*), and red-striped rockfish (*S. proriger*). Interestingly, when fisheries scientists examined the gut contents of these fish they found evidence of a high level of cannibalism, with the adult rockfish apparently feeding heavily on the juveniles. A commercial rockfish fishery has been conducted on Bowie Seamount since the early 1980's. Initial exploratory fishing by the Department of Fisheries and Oceans (DFO) using longlines and gillnets extended the list of fish species known to inhabit Bowie Seamount. In addition to the species previously reported, the scientists also caught large numbers of rougheye rockfish (*Sebastes aleutianus*), plus lesser numbers of 10 other rockfish species. Non-rockfish species included sablefish (*Anoplopoma fimbria*), lingcod (*Ophiodon elongatus*), halibut (*Hippoglossus stenolepis*), kelp greenling (*Hexagrammos decagrammus*), red irish lord (*Hemilepidotus hemilepidotus*), blue sharks (*Prionace glauca*), plus two species of skate (*Raja* spp.).

The number of vessels involved in the Bowie fishery has never been very great, owing to the long distance offshore. Currently DFO only grants a few "scientific permit" licenses each year, and with these licenses comes the added responsibility of collecting biological and oceanographic data for use by DFO scientists. Although the species of choice used to be yelloweye rockfish, recent declines in catch rates have led fishers to switch their efforts to rougheye rockfish (*S. aleutianus*). Additionally, a small number of sablefish are caught at Bowie each year.

During their early research on the Bowie fish stocks, scientists had noted that the size range of some of the rockfish species was larger than that seen in commercially exploited populations on the BC coast. They also found that very large rockfish were quite common. This and the fact that both adult and juveniles have been observed over Bowie suggests that these rockfish populations are self-sustaining. That is, they probably do not rely on regular emigration of rockfish from the neighbouring continental shelf. Previous research has shown that the rockfish populations on Cobb Seamount (a similarly shallow seamount 500 km southwest of Vancouver Island) are self-sustaining and may even be genetically isolated from coastal populations. Whether the Bowie rockfish are similarly isolated remains to be seen. However, it is worth noting that since larval rockfish are not usually found very far offshore it is highly unlikely that regular emigration from shelf populations occurs. In any case, the long distance to the coast coupled with the limited area of the seamount summit make the Bowie rockfish populations particularly vulnerable to overfishing.

3. The Biology of Seamounts

Seamount Fish Stocks

In general, the biological productivity of seamounts is much higher than that of the surrounding waters. This is especially true of shallow seamounts, like Bowie Seamount and Cobb Seamount in the northeast Pacific. Not surprisingly, most of the biological and commercial interest in shallow seamounts stems from the fact that they often support rich fish stocks. Although some 75 species of fish and shellfish have been caught over seamounts, only a very few are specifically targeted. They include:

- **Pelagic Armourhead** (*Pseudopentaceros wheeleri*), which are fished over seamounts of the Northern Hawaiian Ridge and the Southern Emperor Seamount Chain in the western north Pacific Ocean.

- **Orange roughy** (*Hoplostethus atlanticus*), which occurs mainly around seamounts and banks over the North Chatham Rise, Ritchie Bank and Challenger

Plateau around Australia and New Zealand.

- **Alfonsin** (*Beryx splendens*), which are fished in Emperor Seamount Chain in the western North Pacific and the Kyushu-Palau ridge in the Philippine Sea.

In the northeast Pacific Ocean, vessels from both Canada and the United States conduct commercial fisheries over about a dozen seamounts. The species targeted are usually either the various rockfish species (*Sebastes* spp.) or the black-cod or sablefish (*Anoplopoma fimbria*).

Other Marine Life

In addition to fish stocks, other types of marine life abound on and around seamounts. For instance, a number of scientific studies have shown that phytoplankton and zooplankton, the microscopic plants and animals at the base of marine food webs, are more abundant around shallow seamounts than in the surrounding oceanic waters. At the other end of the food chain sharks, tunas, squids and even certain dolphin species sometimes congregate around seamounts.

Seabirds have also been shown to be more abundant in the vicinity of shallow seamounts. Recent work at Cobb Seamount (500 km southwest of Vancouver Island) showed that black-footed albatross were 14 times more abundant over the seamount than in the surrounding waters. Numbers of several other species, notably fork-tailed petrels and Leach's storm petrels were also significantly higher near Cobb Seamount. In fact, it might even be said that seabirds were indirectly responsible for the *discovery* of Cobb Seamount. In the late 1950's, American fisheries scientists working about 500 km southwest of Vancouver Island noticed unusually high concentrations of albatross and other seabirds in the area. Upon closer investigation, the scientists discovered the existence of a previously unknown seamount that rose from 3000 m to within only 25 m of the surface. They named Cobb Seamount after their research vessel, the *R.V. John Cobb*.

Bottom Communities

The bottom communities of seamounts are also usually teeming with a rich array of animals and plants. Photographic surveys conducted on shallow seamounts in the Pacific ocean using SCUBA, remotely operated submarines, and baited underwater cameras have all recorded high densities of crabs, lobsters, scallops, snails and other molluscs, starfish, sea-urchins, sea-lilies and sea anemones, plus various types of hard and soft corals. In parts of the world some of these bottom-dwelling species are also harvested. For instance, rock lobsters (*Jasus tristani*) are fished on Vema Seamount in the southeast Atlantic Ocean off the coast of Africa, as are smaller numbers of king crab (*Lithodes couesi*) and snow crab (*Chionocetes tanneri*) on seamounts in the northeast Pacific. In the western north Pacific there is also a valuable trade in precious corals collected from shallow seamounts of the Hawaiian Islands and the Emperor Seamount Chain. Although a number of coral species are targeted, pink and red corals of the genus *Corrallium* are said to be particularly prized. This high productivity found at shallow seamounts stands in stark contrast to the very low productivity that characterizes open ocean waters. It is easy to see why shallow seamounts have often been described as "oceanic oases".

4. Why Are Seamounts So Productive?

Physical Oceanography

Given that seamounts do support rich biological communities in otherwise rather unproductive regions of the ocean, one might well ask how such communities are established in the first place. One might also wonder whether such communities are stable in the long term and, if so, how are they maintained so far from the coast? Indeed, these questions have intrigued oceanographers for decades, since rich seamount fish stocks were first reported in the late 1950's. However, only recently have we begun to understand how such ecosystems function.

The short answer is that the productivity of seamount ecosystems is related to the way ocean currents behave when they encounter a very steep object such as a seamount. This is not a simple interaction, however, and a variety of physical oceanographic processes are involved. When oceanic currents encounter a very steep object like a seamount, most of the water is diverted around the object. Some of the water also flows up the slope and over the object. In doing so, a couple of things happen. The first is that cold, deep, water flows upwards, or "upwells", along the seamount flank. The second is that as the currents interact with the topography, strong turbulent mixing takes place in the waters above the seamount.

In many parts of the open ocean, nutrients are in rather short supply near the surface. In fact, this "nutrient limitation" is what usually limits phytoplankton growth. In contrast, cold, deep, upwelled waters usually contain lots of unused nutrients. Once these nutrients are injected into the surface waters via upwelling and turbulent mixing, they become available to the phytoplankton. The upwelling also serves to transport phytoplankton even closer to the surface, where there is more light available for photosynthesis. The combined result of these interactions can be a localized burst of phytoplankton production, termed a "bloom". In recent years, scientists have indeed observed "blooms" of high phytoplankton abundance over shallow seamounts.

In addition to causing upwelling and turbulent mixing, currents flowing past seamounts also generate other novel effects. Given that seamounts are often arranged in chains or clusters, they have the potential to divert ocean currents and to cause meanders and eddies to form. For instance, scientists have that observed during its northward progress along the east coast of the United States, the Gulf Stream occasionally meanders and sometimes spins off eddies in the vicinity of the New England Seamount Chain. Likewise, the Kuroshio Current, the western Pacific counterpart to the Gulf Stream, produces meanders and eddies as it passes over the numerous seamounts of the Emperor Seamount Chain near Japan.

The most interesting of the seamount flow phenomena, however, are the closed recirculating eddies that have occasionally been observed over seamount summits. Oceanographers refer to these closed eddies as "Taylor columns", after the scientist who first described them. Such closed eddies form only under a very limited range of oceanographic conditions that depend on the size and height of the seamount in question and the speed of the approaching current. If conditions are right, however, the closed eddy that forms may be trapped over the seamount indefinitely. Although scientists are still uncertain whether such eddies may be *permanent* features, in at least one case a Taylor column over Cobb Seamount (500 km southwest of Vancouver Island) was observed to persist to for at least a month.

Interactions Between Biology and Physics

These seamount "flow phenomena" are also very important from a biological perspective. As noted above, the combination of upwelling and mixing of nutrients can increase the amount of phytoplankton in the waters around shallow seamounts. Many scientists believe that this step is critical to the formation of the rich communities that exist on seamounts. The reason is that phytoplankton form the base of most marine food chains. Increasing the amount of phytoplankton therefore provides an increased food supply for the zooplankton, the tiny shrimp-like animals that are the main "grazers" of the ocean. Moving even further up the food chain, zooplankton represent the primary food supply for many species of fish. By putting all of these steps together, an increase in phytoplankton results in an increase in zooplankton and, therefore, an increase in local supply of food for fish, seabirds, and the other animals described above.

In addition to fostering local production of food, shallow seamounts also serve simply to provide a suitable habitat for shallow water organisms. Some animals, like the rockfish found on Bowie, Cobb and other shallow seamounts take advantage of the zooplankton that are carried across the seamount summit by ocean currents. In fact, scientists have observed these fish ascending 100's of metres into the water over the seamount to feed. For this reason, scientists believe that in addition to locally produced food, the productivity of most seamount communities is also dependent on a regular supply of "upstream" productivity that drifts past the seamount.

How are Seamount Communities Established and Maintained?

Of course, this still doesn't answer the question of how fish and bottom-dwelling organisms come to be on isolated seamounts in the first place. The simple answer is that the species found in any given seamount community probably arrived there by chance. The thing to keep in mind is that with most seamounts being hundreds of thousands, if not millions of years old, plants and animals have had a very long time to get there!

In some cases, the species that scientists find on seamounts occur nowhere else. This suggests that some animal populations have been isolated on seamounts long enough to have evolved into new species. This is a rather rare occurrence, however. After years of using submarines and cameras to collect samples, scientists have determined that seamount communities are a fairly random collection of cosmopolitan species (found throughout the world's oceans), plus a subset of species that probably originated on the nearest continental shelf. The fact that not all species from the continental shelf are found on offshore seamounts implies that some species are much better than others at colonizing these isolated areas.

The early life stages, or larval forms, of many marine animals spend time drifting as plankton in the ocean currents. If enough of these larvae drift and settle on a given seamount, there is a good chance that they will mature and reproduce there. The problem comes in the next generation when these new colonizers reproduce and release *their* larvae. The same ocean currents that helped these animals colonize the seamount in the first place may now carry their young *away* into the open ocean. Of course, just as currents carried the original colonizers to the seamount, there is always the chance that new colonizers will arrive each year. However, ocean currents are not always predictable, and so there is no guarantee of a regular supply of new colonizers.

How then do isolated seamount populations persist through time? Research at several shallow seamounts has suggested that, in part, the answer has to do with the previously described closed eddies that sometimes form over seamounts. It is thought that these eddies play two roles. First, given that the closed eddies can be 10's of kilometres in diameter, they can collect plankton and larval forms and concentrate them over seamounts. This increases the probability of new colonizers successfully reaching the seamount on a regular basis. Second, for animals that have already colonized the seamount and which are now attempting to reproduce, the eddy may serve to trap their larval forms in the general vicinity of the seamount. This increases the chance that at least some of the young will settle back on the seamount.

Not all animals have larval stages that drift helplessly in the plankton. Some species of bottom-dwelling organisms give birth to young that settle immediately to the bottom. At first glance, this would appear to be a good strategy for seamount organisms, as it would minimize the number of young lost from the seamount. Indeed, explorations on Cobb Seamount, 500 km southwest of Vancouver Island, have found a surprising number of such species. In this case the puzzling part is not how populations of such species persist on isolated seamounts, but how they get there in the first place given that their larval forms are not suited to colonizing new areas. Scientists believe that the adults of such species probably arrive on offshore seamounts via “rafting”, or drifting, while attached to kelp, wood or other objects. Although this might seem an unlikely means of colonizing new areas, once these “direct developers” do reach a seamount they have a good chance of establishing a stable population.

Interestingly, the fish group that seems to do the best on shallow seamounts are the rockfish. As mentioned above, at least a dozen rockfish species occur on Bowie Seamount alone. Unlike most fish that release planktonic eggs that drift in the plankton before hatching weeks or months later, rockfish are notable in that they are live-bearing. That is, they release live young that can already swim. It has been hypothesized that this feature of the rockfish life cycle accounts in large part for their success in colonizing offshore seamounts. For the reasons described in the previous section, once rockfish initially colonize a seamount, there is a good chance that in subsequent years their young will be trapped in the closed eddy and settle back on the seamount to form the next generation.

5. The Threat of Overfishing

Without doubt, the single biggest threat to isolated seamount communities is overfishing. As described in the previous section, the seamount communities we observe today likely formed over millions of years. Of particular concern is that with seamount communities often being quite isolated, they are unlikely to be quickly recolonized if overfished.

Fishing on seamounts began in the late 1960's, when Russian vessels began taking large numbers of pelagic armourhead (*Pseudopentaceros wheeleri*) and alfonsin (*Beryx splendens*) over seamounts in the central north Pacific. By 1969, the annual catch of armourhead from seamount exceeded 130,000 tonnes. By the mid-1970's other nations, notably Japan, also began targeting these two species, but catch rates had already fallen to below 30,000 tonnes. By about 1976, the fishery had collapsed altogether. Commercial exploration was extended to seamounts in other parts of the world oceans. In each case where commercially valuable stocks were discovered, the chain of events was the same. Although catch rates would be initially quite high, none of the seamount stocks could sustain significant fishing pressure for very long and were fished down very quickly, often in just a single season.

The most recent new fishery for a seamount associated species began around 1980, when significant numbers of orange roughy (*Hoplostethus atlanticus*) were discovered on seamounts and banks around New Zealand and southeast Australia. Annual catches were around 30,000 - 40,000 tonnes throughout the 1980's, but have since declined dramatically. In fact, in response to the declines in orange roughy stocks, the Australian government has recently announced a plan to establish a series of marine protected areas around the seamounts where they spawn.

The rapid collapse of pelagic armourhead and orange roughy stocks underscores just how little we really know about seamount fish stocks in general. In the case of pelagic armourhead, it turns out that their complex life cycle ensures extremely high year-to-year variation in recruitment, the number of young fish that survive to join the adult population. In such populations, heavy fishing pressure has the potential to rapidly destroy a stock’s ability to maintain itself. Likewise, the fishery for orange roughy was initiated before anything was known about the life cycle or reproductive behaviour of the species. Unfortunately, it turns out that in the absence of fishing, orange roughy experience very low levels of natural mortality. In addition, orange roughy are extremely long-lived (maximum ages of up to 150 years!) but extremely slow growing, and do not mature until about 32 years of age. This combination of traits means that orange roughy are extremely prone to overfishing, since their extremely low reproductive capacity renders them incapable of rapid recovery. From the previous discussions it is clear that seamount ecosystems, and particularly seamount fish stocks, are very fragile. Given the rarity of these sorts of environments and the delicate balance between biology and physics required to ensure their continued survival, we should be very cautious when considering any future fishing activity on seamounts.

6. Future Research on Bowie Seamount

Although it is fair to say that scientists have learned a lot about seamount ecosystems over the past 30 years, it is also true that our experience is based largely on observations of only a few seamounts. In particular, only a handful of very shallow seamounts have ever been studied in any great scientific detail. By creating a pilot Marine Protected Area (MPA) at Bowie Seamount we will have an opportunity to learn more about these unique environments. In this section we provide a list of some specific questions that can, indeed must, be addressed before we can truly claim to understand how the Bowie ecosystem functions.

Biodiversity

Critical to understanding how any ecosystem functions is a full knowledge of what species comprise the ecosystem. Currently, our knowledge of what species exist on Bowie is based on the data collected by divers in the 1960's, plus the very limited fisheries data collected by commercial vessels. What is needed is a full biological survey of the seamount community to establish the current level of biodiversity. Measures of biodiversity also allow scientists to estimate ecosystem health and to track the effects of conservation strategies such as MPAs. Of course, the logistics of conducting scientific research so far offshore are by no means trivial. Add to this the great depth range that Bowie Seamount covers (3100m) and the most effective means of conducting such an inventory is to employ a remotely operated submersible equipped with underwater cameras.

Genetic Isolation

Much of the interest in conserving seamount ecosystems stems from the fact that such communities are often partially, if not completely, genetically isolated from neighbouring continental shelf communities. Although Bowie Seamount is located about 180km from the BC coast, in oceanic terms this is really not all that far. In other words, although it is unlikely that there is a *regular* or *predictable* recruitment of organisms from the BC coast, *episodic* recruitment from the coast to the seamount probably does occur from time to time. Therefore, it seems unlikely that populations on Bowie will experience strong genetic isolation.

Nevertheless, this hypothesis needs to be formally tested. Preliminary DNA samples have already been collected from some rockfish species on Bowie. These types of analyses should be extended to include other species, such as some of the bottom-dwelling invertebrate species with limited dispersal capacity. Establishing to what degree the community is genetically isolated will be important when deciding what level of protection the Bowie ecosystem requires and whether fishing should still be allowed there in the future.

Interactions With Ocean Currents

As discussed previously, a variety of flow features such as upwelling, turbulent mixing and the formation of Taylor columns are all believed to play an important role in determining the productivity of seamount ecosystems. Whether any of these features even occur at Bowie is currently unknown. Therefore, to better understand how the Bowie ecosystem functions, and to what degree it relies on these sorts of flow features, current measurements should be collected from the seamount. If it turns out that the Bowie community is somewhat isolated from coastal communities understanding the local flow regime will help us determine whether these sorts of flow features are retaining larvae over the seamount. On the other hand, if it turns out that the Bowie community is not isolated, understanding the local flow regime will enable us to determine the most likely “seed populations” for the species found on the seamount.

<u>Regional Importance of Bowie Seamount</u>

Until now we have been considering Bowie Seamount in isolation. It is also possible, however, that Bowie is also important on a regional scale. From a physical perspective, the *effective* size of the seamount is likely much larger than its *actual* size. For example, research at Cobb Seamount shows that “seamount effects” can be detected in the composition and abundance of plankton up to 30 km away from the seamount summit. Given their similar size, Bowie Seamount probably also has a similar effect on the surrounding waters.

It is also possible that in addition to those species that live permanently on Bowie Seamount, there may be others that use the seamount as an occasional feeding area during annual migrations. Potential candidates include the various whale and seabird species which perform major north-south migrations along the BC coast each summer and fall. In fact, it has even been suggested that the migratory routes of some seabirds are based on the availability of other such “refuelling stations” around the north Pacific Ocean.

Finally, it is interesting to consider whether the Bowie ecosystem exports production downstream. Shallow seamounts often generate large eddies which, rather than becoming trapped like Taylor columns, get swept off the seamount and are carried downstream by background currents. Especially in low productivity oceanic waters, the amount of phytoplankton and zooplankton contained in such eddies may be much higher than background levels. As such, these seamount-generated eddies may represent an important regional source of production. Of course, verifying any of these hypotheses will require further field work at Bowie Seamount in the future.

Figures

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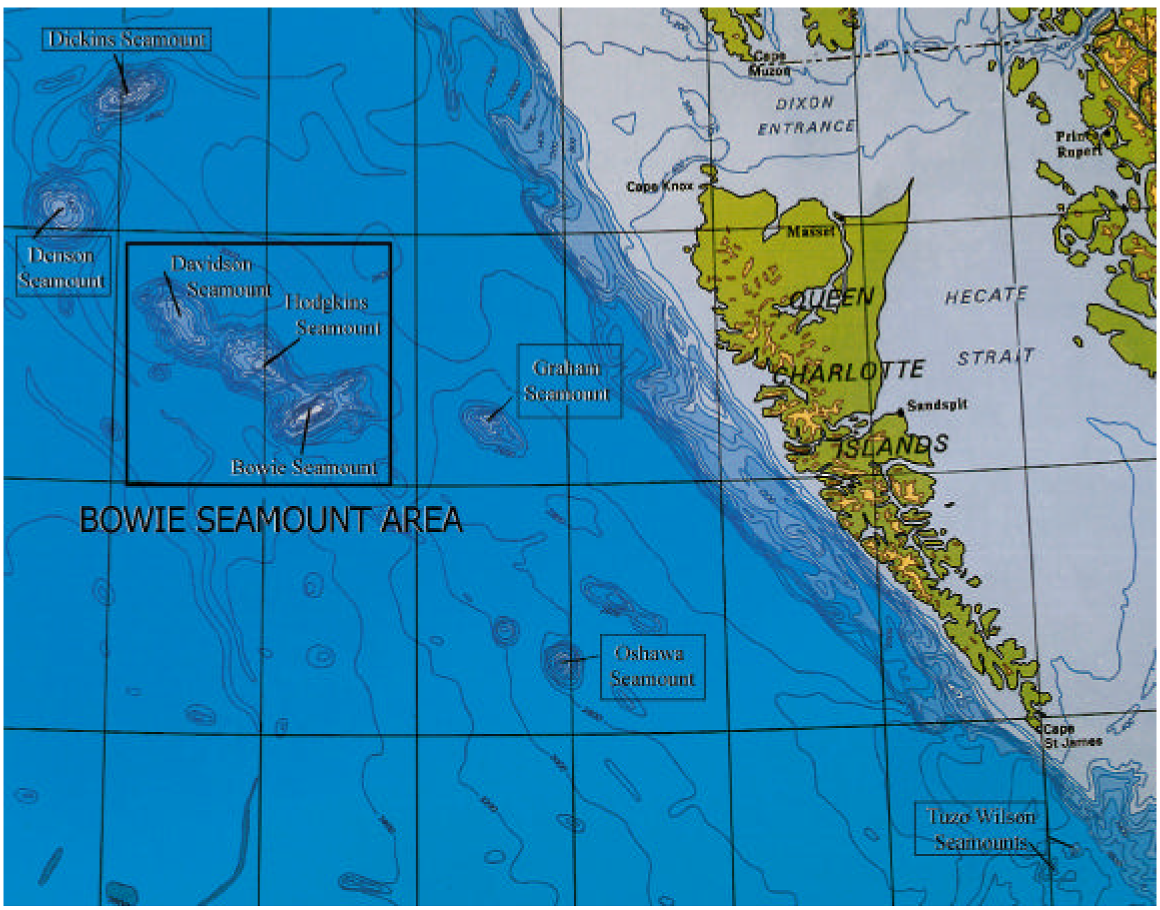

Figure 1. Bathymetric map of Bowie Seamount Area.
(Department of Energy, Mines and Resources.)

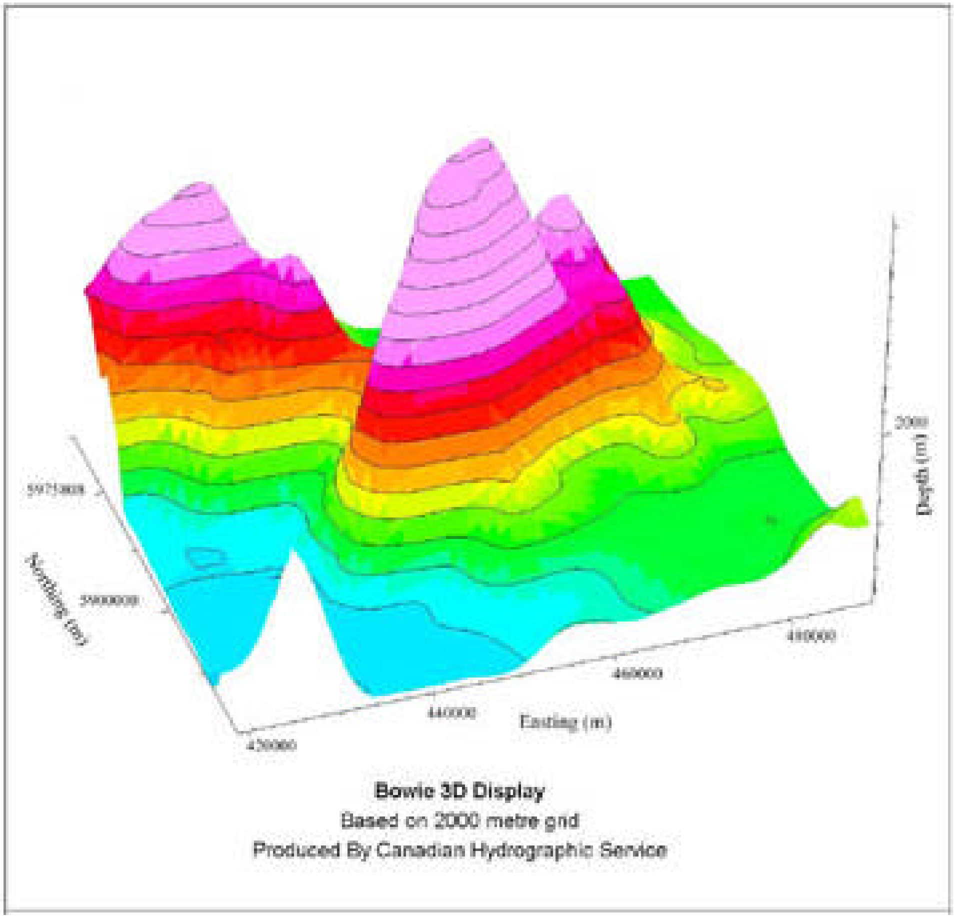

Figure 2. A generalized three-dimensional bathymetric veiw of Bowie Seamount.
(Produced by the Canadian Hydrographic Service, Sidney, B.C.)

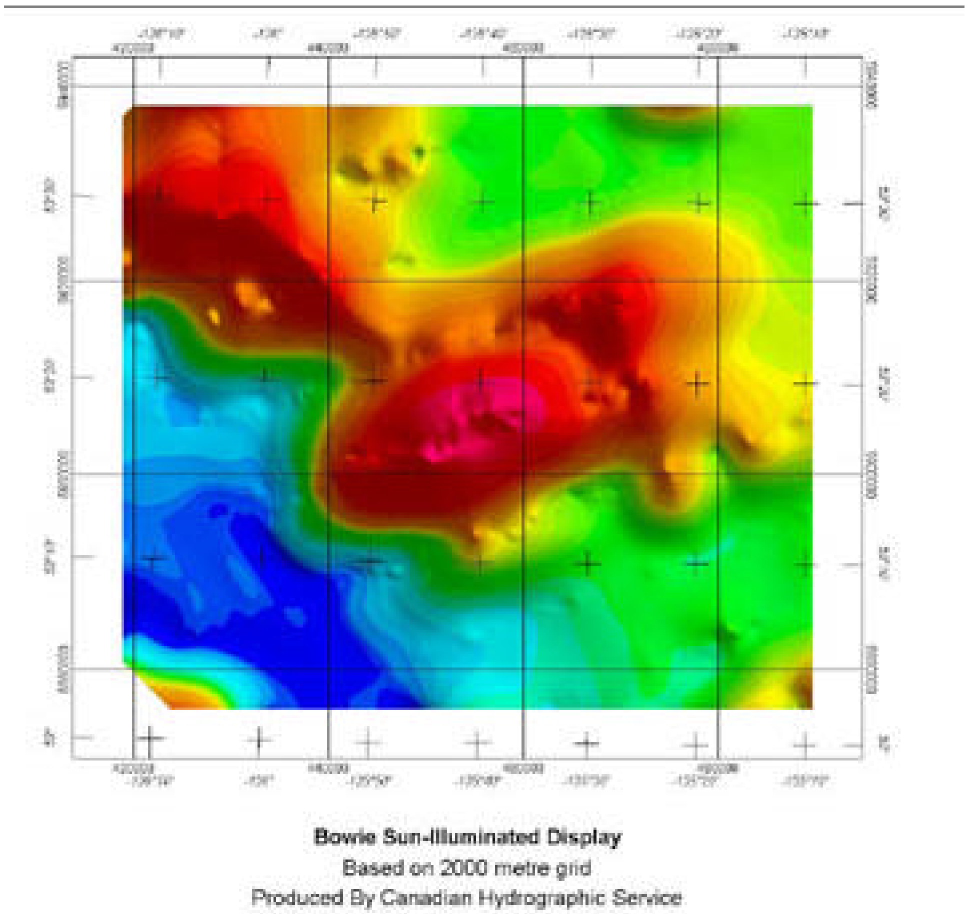

Figure 3. A generalized two-dimensional bathymetric veiw of Bowie Seamount.
(Produced by the Canadian Hydrographic Service, Sidney, B.C.)

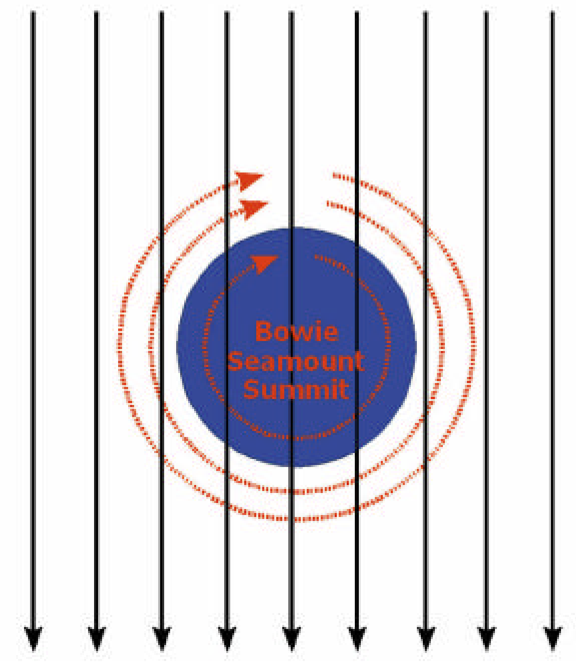

Figure 4. A schematic representation of ocean circulation (plan view) at Bowie Seamount.

(Produced by the Department of Earth and Ocean Science, University of British Columbia)

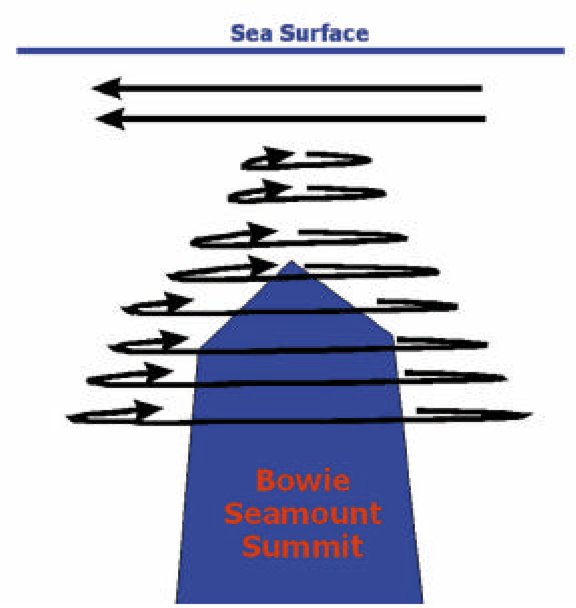

Figure 5. A schematic representation of ocean circulation (side view) at Bowie Seamount.

(Produced by the Department of Earth and Ocean Science, University of British Columbia)