Shark Trails of the Eastern Pacific

Tracking their subjects by satellite, biologists learn when sharks migrate, where they go, and how they use magnetic clues on the ocean floor for navigation.

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I remember vividly, although it was more than 30 years ago, my first boat trip in the Bay of La Paz, about 150 kilometers north of Cabo San Lucas. Not a fish was visible in clear blue waters as I motored across the bay toward the long brick-red cliffs of Espiritu Santo Island. Suddenly the surface became turbulent with splashing water here and there: A myriad of fish were feeding on comb jellyfish, shrimp-like euphausids, and other floating zooplankton. I heard a roaring sound, turned my head, and saw a flying fish skipping across the surface of the water to escape a pursuing dolphinfish. We had arrived at El Bajo, an underwater mountain rising from the depths of the ocean floor to just 20 meters from the surface.

I hastily put on my long, eel-like swimming fins, mask, and snorkel and jumped into the water along with my doctoral mentor, Donald Nelson. There before us was a stunning mass of underwater life. Near the surface, a column of thousands of colorful mackerel extended as far as we could see. Below them was a huge, doughnut-shaped swirl of mangrove snappers, each the size of a small dog. At last we came on a massive school of hammerhead sharks (Sphyrna lewini): more than a hundred of them, resembling a formation of World War II bombers in the sky. I took three deep breaths and dove downward through the school, with sharks moving slightly to either side. From a depth of 30 meters underwater, I could see their beautiful black silhouettes above me. I turned around and swam upward, and moments after the surface came into view, with male and female creole fish making pulsing upward dashes to release their gametes in a large white cloud in the water column. Such an abundance of life was concentrated around this underwater mountain, yet it seemed to be surrounded by empty, lifeless ocean.

For the diver who suddenly comes upon these throngs of underwater life, it is curious that so many creatures aggregate at a seamount, more than 1,000 meters above the ocean floor, and not in the vast expanse of deep water around it. The explanation is a matter of flow dynamics. Water moves more rapidly as it is forced to flow between the surface and the shallow peak of the seamount, just as the wind is stronger at a mountain pass—where an air mass has less space through which to move—than on a broad plain. The speed of the water flow, in turn, enhances the diversity of fishes present, because krill that compose the scattering layer are forced toward the surface and over the top of the seamount, where planktivorous fish concentrate up-current of this area to feed on them.

When I first encountered this burst of biodiversity in the midst of a vast expanse of uninhabited ocean, the stark contrast appealed to me as a scientific mystery—one I have been engrossed in investigating ever since. Now, however, even the busiest hotspots in this part of the Pacific Ocean are seeing declines in their populations as human predation, by deliberate fishing and as accidental “bycatch,” take their toll. As early as 2005, in my American Scientist article “The Home of Blue Water Fish,” I made note of the shrinking biodiversity to be found at many ocean hotspots. In particular, the number and variety of sharks has been dropping for decades, as the practice of gillnetting has become more common. Scalloped hammerhead sharks have been one of the hardest-hit species, as attested by their inclusion in July 2014 on the U.S. Endangered Species List.

Although S. lewini is the first shark species to earn this dubious distinction, others may not be far behind: Its close cousins the great hammerhead (S. mokarran) and the smooth hammerhead (S. zygaena), as well as several more distant shark relatives, are named by the Convention on International Trade in Endangered Species (CITES) as animals whose trade is subject to strict international control.

For migratory creatures such as sharks, however, whose daily or yearly travels can take them across many international borders, simply placing upper limits on their legal trade may not be enough to maintain even the current population levels. My colleagues and I recommend a more positive step: designating specific areas in the eastern Pacific as off-limits to shark fishing altogether.

The idea of protecting these “eating machines,” as they have been called, may seem at first to go against common sense. If sharks have been valued at all, it is because the meat from their fins is served in a soup that is...
considered a delicacy in some countries, so a successful shark hunt can bring in plenty of cash. This business model succeeds only in the short term, however, because shark fisheries have invariably collapsed as they transitioned from artisanal to widescale fisheries. The current rate of exploitation exceeds the capacity of recovery for many shark populations, driving them to a clear decline.

Deep Sea Motivation
Getting around underwater is a specialized skill. Marine species live in an opaque environment, and because their vision is limited to less than 30 meters, even in the clearest of waters, their migration cannot be guided by the sight of topographic features on the sea floor. In any case, very little light penetrates the deep waters. How then does a hammerhead shark, for instance, regularly find its way back to a particular seamount after traveling distances of up to 20 kilometers in search of food? What are the signals on which it relies for navigation?

We set out to answer this question, with support from the National Science Foundation, by studying the orientation mechanism in hammerhead sharks of the eastern Pacific Ocean. The key, we found, resides in the Earth’s magnetic field. Seamounts and most oceanic islands are created by volcanic eruptions over many thousands of years. During an eruption, molten basalt from the Earth’s mantle penetrates the sea floor and flows out of the cone and away from the volcano as lava. The basalt contains tiny particles of single-domain, dipolar magnetite that align with the current polarity of the Earth’s magnetic field. If the next eruption takes place many thousands of years later—and if Earth’s field polarity has reversed itself in the meantime, as it has done repeatedly throughout geological time—the magnetic particles in the basalt of the new lava flow will then align with the new polarity of the Earth’s field. The seafloor around the seamount consists of a series of radiating bands whose magnetic particles either align with the Earth’s current polarity and thus add to that area’s magnetic intensity, or else have the opposite polarity and thus subtract from the area’s magnetic intensity. In effect, the alternating stripes of strong and weak magnetization produce a relief map whose features vary in their magnetic intensity rather than their depth.

At an underwater hotspot, a school of hammerhead sharks mingles with other fishes.

Phillip Colla/Oceanlight.com.
Our survey of the magnetic field surrounding El Bajo revealed that the outbound and return paths of the sharks we were studying coincided with these magnetic ridges and valleys. I hypothesized, therefore, that the magnetic variations in the ocean floor presented the sharks with the equivalent of a route map, and in a 1993 paper in *Marine Biology* I coined the term *topotaxis* for an animal’s orientation to these magnetic-topographic features. It is the sharks’ attraction to seamounts and offshore islands in the eastern Pacific Ocean, and their absence from the wide expanse of the pelagic ocean, that makes it feasible to protect them in their natural habitat by creating shark parks: safe havens or marine reserves that include a significant part of the surrounding open waters, where fishing for sharks could be prohibited.

**Tracking Sharks with Electronic Tags**

Designating certain areas in the eastern Pacific as shark preserves could be an effective conservation measure only if these areas were drawn on the basis of a thorough, scientific understanding of the animals’ habitat and behavior. The area set aside as a shark preserve cannot simply be limited to the seamount, however, because most sharks do not stay at the seamount at all times of the day. Earlier research on hammerheads has established that deep-water squids comprise more than two-thirds of their diet, a finding that suggests they leave the seamount for a good part of the time to feed in the surrounding pelagic environment.

To investigate where the sharks spend their time when not at the seamount, we made free-dives and used a pole spear to attach electronic tags to sharks that emit ultrasonic signals. Each shark received a tag with a unique signal, enabling us to follow individuals with underwater receivers anchored at the edge of steep slopes, which descend into the deep waters surrounding the islands. Other tags that pulse more frequently were attached to sharks to determine how far they move away from the island during their nighttime or daytime foraging excursions. We tracked these sharks by placing in the water a staff with a directional hydrophone, rotating it to detect the strongest signal, and then moving the boat in this direction to situate it above the shark. The animal’s position was then approximated from the GPS coordinates of the boat.

Satellite tags were also used to find out where the sharks go when they...
aren’t frequenting the islands surrounded by tag-detecting monitors. We placed two types of satellite tags on sharks, including, for the first time, the largest fish, the whale shark (*Rhinocodon typus*). A pop-up archival tag was affixed to the dorsal surface of the shark as a means to estimate the animal’s position from measurements of light recorded each minute while the shark swam underwater. After a preset interval, this transmitter floated to the surface so that its radio stage could transmit the daily estimates of the shark’s position to the Advanced Research and Global Observation Satellite (ARGOS), a mission of the Space Test Program within the Department of Defense. The satellite circled the Earth within range of the shark, six times a day, near the equator.

The second type of satellite tag was designed to transmit a signal of a very stable radio frequency once its antenna broke the surface of the water. Such a signal allowed the shark’s position to be calculated on the basis of the Doppler shift, or the change in frequency of the signal emitted from the animal, recorded by the ARGOS satellite as it passed over the shark. All this information on the movements of sharks can be used to create realistic boundaries of shark parks, where it may be possible to enforce a prohibition on fishing for them with long lines and gill nets.

To begin gathering information on the sharks’ travel patterns, we tracked one scalloped hammerhead shark far away from shore for a 24-hour period. This individual left the seamount at dusk, swam 20 kilometers away from the seamount, reversed its direction 180 degrees, and to our amazement returned to the seamount by dawn. It followed a course between the edge of a steep, rising magnetic slope to the east and a magnetic plateau to the west of the seamount. These features, termed magnetic lineations by geophysicists, may explain how the shark was able to return after its 20-kilometer excursion into the surrounding waters. As far back as 1985, British biologist Margaret Klinowska speculated that similar magnetic guidelines play a role in the stranding of whales along the west coast of Great Britain, where these bands intersect the shoreline because of shifting plate movements.

All the sharks we tracked by boat demonstrated a similar pattern, remaining in a school at the seamount during the day but moving offshore at night to distances of up to 20 kilometers. When moving away from the seamount and returning to it they traveled fast, swimming in a “yo-yo” pattern up and down in the water column, and exhibited extraordinary directionality to their movement. When farthest from the seamount, however, they dashed back and forth in different directions over a small area in equal amounts of time around the entire island. Further evidence that the sharks prefer a particular hotspot along the coast of Wolf Island came from James’s arduous tracking of both hammerhead and Galápagos sharks (*Carcharhinus galapagensis*) over one- to two-day periods. One hammerhead shark tracked over a period of 48 hours stayed predominantly off the coast of Shark Point, a large volcanic promontory halfway down the east-

Sharks are often captured in nets, their fins are removed for sharkfin soup, and they are released into the water to die. At other times, when they become trapped in nets set to catch other fish, they are usually released intact; nevertheless, the stress of capture can cause physiological damage and even death. (Photograph courtesy of www.seawatch.org.)
Commuter Sharks

At more remote areas such as the Revillagigedo Islands off the coast of Mexico, Malpelo Island off the coast of Columbia, and coastal islands like Coiba Island just 10 kilometers from mainland Panama, we carried out extensive tagging studies at each island. We then sorted the many species of sharks into three groups: round-the-clock residents of the waters around the island, daytime or nighttime migrants, and nomadic species. The whitetip reef shark (*Triaenodon obesus*), named for its conspicuous white-tipped dorsal fin, is a member of the first group. Mauricio Hoyos-Padilla, director of the non-profit *Pelagios Kakunjá* in Mexico, placed coded tags on whitetip reef sharks at Roca Partida, a rock resembling the Empire State Building that juts upward from the continental shelf off the coast of Baja California. We tagged a member of the first group. Mauricio Hoyos-Padilla, director of the non-profit *Pelagios Kakunjá* in Mexico, placed coded tags on whitetip reef sharks at Roca Partida, a rock resembling the Empire State Building that juts upward from the continental shelf off the coast of Baja California.

The Galápagos sharks showed a different pattern of movement, remaining offshore both day and night without making offshores migrations at night. Adult Galápagos sharks are fairly solitary and are often encountered swimming alone close to shore near the rockfall on Wolf Island. In contrast, the juveniles tend to form small schools, which often circled us when at the surface while we search for adult hammerhead sharks to tag. On occasion, both Galápagos sharks and hammerheads migrate long distances into the pelagic environment. One out of six hammerhead sharks carrying a surface satellite transmitter traveled 600 kilometers to the west out into the eastern Pacific from Wolf Island over a period of roughly two months. One out of ten Galápagos sharks did the same, moving a similar distance in the same direction. Taking our observations on the whole, however, it appears that both species of sharks spend the majority of the time in an insular habitat, although at times even the Galápagos sharks make nighttime migrations away from the island.

Another inhabitant of these waters, the small-tooth sandtiger shark (*Odontaspis ferox*), can easily be recognized by its narrow pointed teeth, which are ideal for piercing the soft skin of its preferred food, mesopelagic (deep sea–dwelling) squid. The small-tooth sandtiger shark forms small groups at depths greater than 30 meters at the El Monstruo Reef (a name based on the common name of the species in Spanish) at the southern end of Malpelo Island. I have collaborated with Sandra Bessudo and German Soler, of the Malpelo Foundation, in tagging the sharks at this island. We placed a coded tag on an individual that spent the month of March going back and forth between the Monstruo Reef and the Naufragio Reefs along the coast during the daytime. After that period it was absent from dusk to dawn, foraging in the deep waters around the island.

The silky and sandtiger sharks make daytime foraging excursions in the surrounding waters. These daytime excursions away from land are apparent in the detection record of a silky shark (*Carcharhinus falciformis*) tagged at Wolf Island, one of the two northernmost islands of the Galápagos Archipelago. From mid-May to mid-July, the silky shark made daytime excursions away from the island, as evident in the absence of data points on a plot of tag detections between 6 a.m. and 6 p.m. We placed acoustic and satellite transmitters on silky sharks at the Galápagos, Cocos, and the Revillagigedos, and found they also make long-distance migrations.
When traveling directly between their refuge and a feeding zone, sharks cruise at a speed of roughly 1 meter per second, or 3.6 kilometers per hour. Multiply this by 12 hours, and you have a little over 40 kilometers. This number must be divided by two, as the sharks make an outbound trip and a return. Hence, the maximum amount of displacement from the starting point would be 21.6 kilometers. In reality, the distance traveled is generally less, because on reaching their foraging grounds the sharks no longer move forward but begin dashing in one direction and then in another after prey. The hammerhead we tracked at Espíritu Santo swam as far as 19.4 kilometers from the seamount before it turned around and returned to the seamount. This seems consistent with the above calculations of the maximum distance to be traveled, confirming our estimate of the size a shark park would need to be.

Nomadic Whale Sharks
The whale shark, which visits the islands of the eastern Pacific only for short periods, presents a different kind of conservation challenge. The records we collected from one whale shark are typical of the species: At Darwin Island, one of the smallest in the Galápagos Archipelago, this individual spent only 8 hours near a particular site at one day and 12 hours from noon to midnight on the following day (Darwin Island has been nicknamed the “bus stop” for its procession of these bus-sized creatures), then went undetected for the rest of the year.

To find out where these wanderers go when they leave the neighborhood of these islands, it was necessary to place surface-transmitting satellite tags on them—no small task in itself. Although whale sharks move their tails back and forth slowly, they travel very rapidly through the water column. This makes tagging them while free diving difficult, and with scuba gear almost impossible. Alex Hearn, of the University of California-Davis and the Turtle Island Restoration Network, solved the first problem by using a propeller-driven booster attached to his scuba tank. The push of a button propelled him forward much more rapidly than if he were to swim.

From the tagging and tracking of roughly 40 whale sharks during 2011 and 2012, we found they travel extremely long distances. Some sharks moved westward far out into the oligotrophic eastern Pacific; others moved eastward along the coast of Peru. The latter were most likely heading toward the coast of Peru in order to feed in the plankton-rich waters of the Humboldt Current—but then, unexpectedly, they migrated from there out into the plankton-deficient waters of the Eastern Pacific. These whale sharks were almost all adult females whose abdomens were noticeably distended. Could they be making the westward migration to give birth? We hope to investigate this intriguing question in the future.

Hector Guzman, a scientist at the Smithsonian Tropical Research Institute in Panama, tagged over 50 whale
sharks from 2009 to 2012 around Coiba Island and the Pearl Island Archipelago, near mainland Panama. (Whale sharks aggregate there for several months to feed, which they do by extracting zooplankton and very small fishes from the water flowing through their mouth and past their strainer-like gill rakers.) Individuals tagged in Coiba Island moved west toward the Cocos and Malpelo islands, swimming within 300 kilometers of the northern Galápagos Island and returning northward close to the shores of Colombia via Gorgona Island, thus illustrating the outlines of a connected ocean habitat between all sites along the politically defined Eastern Pacific Corridor. Another group of sharks migrated northward along the Central American coast, reaching the Gulf of Tehuantepec, in Mexico.

Why Do Sharks Need Protection?
Protecting sharks in the eastern Pacific would bring benefits not only for science but also for local economies, because shark ecotourism is a rapidly growing business. No longer do visitors flee in panic when they hear someone exclaim, “Sharks in the water!” Instead they quickly don their scuba gear and enter the water to view these beautiful creatures. With divers paying about $4,500 per person for a trip to dive sites at the Galápagos Islands, the sharkwatching business now represents a major part of the local economy. Hence there are both immediate and long-term benefits to protecting the sharks rather than fishing for them. By contrast, fisheries for sharks have rarely been sustainable over time, owing to the unique life history of the cartilaginous fishes. The scalloped hammerhead grows slowly, with males and females reaching maturity at 10 and 14 years, respectively. The female has only 15 to 31 pups every other year—a very small brood as compared, for instance, with the female Atlantic cod, which becomes mature in four years and then spawns every year, producing somewhere between 2.5 and 9 million eggs. Although the sharks produce only a few young in their lifetime, these are near-replicates of the adults and hence ready to live independently. In the past this was a successful reproductive strategy: Few predators could feed on neonates that were so well equipped to defend themselves. However, young sharks are easily captured by humans using long lines and drift nets.

A high proportion of the sharks caught in nets are neonates or pregnant females en route to nursery areas or mangrove and estuaries in the mainland. We have always wondered why none of the sharks we tagged among the Galápagos Islands reached the coastal areas of the Gulf of Chiriqui off the Panama coast, where Guzman operates 14 acoustic stations. Over the course of five years he received no signals, and he believes it is because the coastal areas of Panama and even the entrance to the main estuaries are blocked with hundreds of fishing nets, making the chances of survival negligible for those pregnant females visiting the coast to give birth. Unfortunately, we have reason to expect similar scenarios in many mainland nursery areas along the western coasts of Costa Rica, Colombia, and Ecuador.

Knowledge of these ecological and geological constraints should help us optimize the size of marine reserves for several species of sharks in the Eastern Pacific, where the seamounts and islands are of volcanic origin. Darwin and Wolf Islands were first created long ago, as the plate moved westward, and are now disappearing as the constant wave action erodes their coasts. The volcanic origin of Wolf Island is evident from the circular rim of a volcanic crater that rises above the surface of the sea at the northern end of the island. Warm waters from the subtropical gyre and Panamanian
Current flow past Darwin and Wolf Islands most of the year, making these
coasts an ideal habitat for sharks.

Although sharks are currently protected by law in the Galápagos Marine
Reserve, which extends 40 miles from the coasts of each of the islands, long-
lining and gill netting for other species are permitted within the reserve, and
sharks are taken as bycatch. To prevent these inadvertent losses, a shark park
could be established around the two islands that would prohibit the tak-
ing of sharks, even as bycatch when fishing for other species. The studies
that we have carried out indicate that a boundary of 25 kilometers from shore
would encompass their movements and make a good outer boundary to a
no-fishing zone. Our tag-detecting monitors have recorded hammerhead
sharks moving back and forth between Darwin and Wolf Islands, which are
separated by 30 kilometers. Hence, we would propose the establishment
of an oblong-shaped park that extends 25 kilometers around both islands but
is conjoined between the two islands to provide protection for the sharks
migrating between the islands.

Designating similar no-fishing zones within 25 kilometers of the shoreline
would help at other sites. Such zones could be established at Malpelo Island off Colombia; Cocos Island off Costa Rica; San Benedicto, Socorro, Roca Partida, and Clarion is-
lands of the Revillagigedos group off the tip of Baja; and Las Animas Island in the Gulf of California off the west-
ern coast of Mexico. This would en-
sure that the shark populations remain healthy at locations where they were
once much more abundant. Coastal
nursery areas, which are particularly vulnerable to human fishing activity,
must come under protection as well.

Successful implementation of shark parks at offshore islands and inshore
nursery areas will require enhanced regional and international cooperation.
The need for these shark parks must be brought to the attention of multi-
national organizations such as the Comisión Permanente del Pacífico Sur,
United Nations Commission on the Law of the Sea, South Pacific Regional
Fisheries Management Organization, Inter-American Tropical Tuna Commis-
sion, and with the cooperation of other agencies such as the Inter-American
Commission for the Protection and Conservation of Sea Turtles. Hence the
protection could be extended to more vulnerable species such as some pelagic
fishes, sea turtles, and marine birds.

The creation of shark parks would thus provide a sustained opportunity for
divers worldwide to view these beautiful creatures in their natural habitat,
and, most important, to preserve marine habitats and ensure the essential
ecosystem services of this unique re-
gion of the eastern Pacific Ocean.

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Bibliography
Bessudo S., G. Soler, A. P. Klimley, J. T. Ket-
chum, R. Arauz, and A. Hearn. 2011. Ver-
tical and horizontal movements of hammerhead sharks (Sphyrna lewini) at Malpelo Island in the Eastern Tropical Pacific. Envi-
rionmental Biology of Fishes 91:165–176.
ment record of long-term plume-spreading
center interaction. Journal of Petrology 46:
109–133.
Hearn, A. J., Ketchum, and A. P Klimley. 2010. Hotspots within hotspots? Hammerhead shark movements at Wolf Island in Galá-
point of towed satellite tags provide first evidence of return migrations of whale sharks (Rhincodon typus) at the Galápagos Islands, Ecuador. Animal Biotlemetry 1:1–11.
Ketchum, J. T., A. Hearn, A. P Klimley, C. Pe-
ñaherrera, E. Espinoza, S. Bessudo, G. Soler, and R. Arauz. 2014. Seasonal changes in movements and habitat preferences of the scalloped hammerhead shark (Sphyrna lewi-
Ketchum, J. T., et al. 2014. Inter-island move-
ments of scalloped hammerhead sharks (Sphyrna lewini) and seasonal connectivity in a marine protected area of the eastern tropical
Klimley, A. P. 1993. Highly directional swim-
ning by scalloped hammerhead sharks, Sphyrna lewini, and subsurface irradiance, temperature, bathmetry, and geomagnetic field. Marine Biology 117:2–32.
Klimley, A. P., P. B. Butler, D. R. Nelson, and A.
Klimley, A. P., F. Voegeli, S. C. Beavers, and B.

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