A Tale of Dead Whales

by Joseph Kirschvink

THE ABILITY of migratory animals to find their way accurately over long distances in unfamiliar territory has puzzled man for centuries. In the past two decades behavioral experiments have shown that some birds and bees, as well as some bacteria and fish, can detect magnetic fields. It seems likely that they are using this sensitivity to the earth's geomagnetic field to help orient themselves and for navigation, but there have been few opportunities to test these assumptions in nature. Our recent studies of dolphins and whales, however, have given us a chance to discover why animals might want to detect the weak features of the geomagnetic field and how they could use them to find their way.

The modern study of biological sensitivity to magnetic fields goes back to the discovery in the 1960s of magnetite biomineralization by Heinz Lowenstam, professor of paleoecology, emeritus. Lowenstam was studying fossil reefs, which are often exposed as mushroom-shaped islands at or near the intertidal zone in the equatorial Pacific. He discovered that the undercut indentations in the rock were not caused, as had been previously thought, by wave action, but by the grazing of a primitive group of molluscs called chitons. These animals scrape algae off the surface of the rock with their long rows of teeth. In order to do this scraping the teeth need to be very hard, and Lowenstam found that they are made of magnetite, an iron oxide mineral that is strongly magnetic. These teeth stick like iron filings to a magnet (*E&S* June 1964). This was the first discovery of an example of biomagnetism.

But it was not known then how organisms make these magnets. In fact, when the phenomenon was first discovered, the petrologists objected because they thought that magnetite forms only at high pressures and high temperatures. They found it difficult to believe it could be produced in the mouth of a stupid little sea animal. Lowenstam and his students have shown over the years, however, that the magnetite grains are indeed true biochemical precipitates, not grains that are picked up in the sand and incorporated into the beast. They have been able to trace iron from the blood through the cells surrounding an anatomical structure called the radular sack, and then into the magnetite crystals that wind up in the tooth. So it's very clear that the chitons are making this stuff, and they make it for a purpose. The magnetite is very hard (it has a hardness of about 6 on the Mohs scale), hard enough to carve away the endolithic algae growing inside the surface of the rocks.

That remained the only known case of magnetite being made by organisms until 1975 when Richard Blakemore, then a graduate student at the Woods Hole Oceanographic Institute, discovered quite by accident that bacteria from the mud of a local pond moved when he waved a magnet near them. It turned out later that a whole variety of these organisms is found all over the earth. Blakemore and his collaborators have since done extensive transmission electron microscopy on these bacteria and discovered that each bacterium has a magnetosome — a linear arrangement of magnetite crystals. It's simply a bar magnet that swims.

These magnetic crystals look very peculiar when blown up to high resolution. They are usually hexagonal prisms — small, irregular cubes — whereas in nature it's typical for a magnetite crystal to occur as an octahedron. We can now recognize these biomagnetic crystals in the fossil record, and by studying these "magnetofossils" we hope to determine the time of origin of the magnetic bacteria. They also seem to be very important in understanding the fossil magnetism of sedimentary rocks.

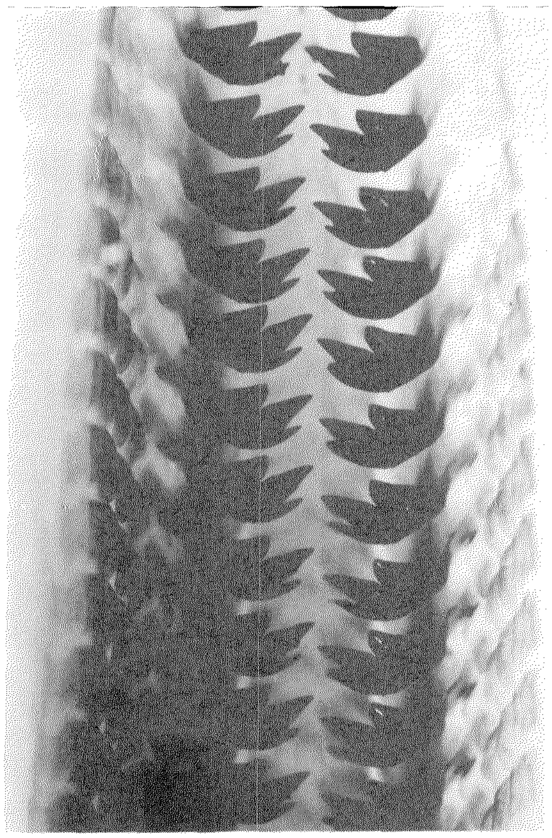
At about the same time, behavioral biologists discovered that bacteria were not the only organisms that were able to detect a magnetic field. Martin Lindauer and Hermann Martin in Würzburg, Germany, did a series of bizarre experiments with honeybees in the late 1960s and early 1970s. Bees normally build their honeycombs in vertical sheets, and somehow a swarm of bees working in the dark can decide the direction in which these sheets should hang. The German scientists demonstrated dramatically that a magnetic compass was involved by putting a swarm of bees in a circular barrel with a large magnet on top of it and letting them build their combs. In the presence of the magnet the bees could not agree on a single direction and produced a cone-shaped blob of wax rather than parallel sheets of honeycomb.

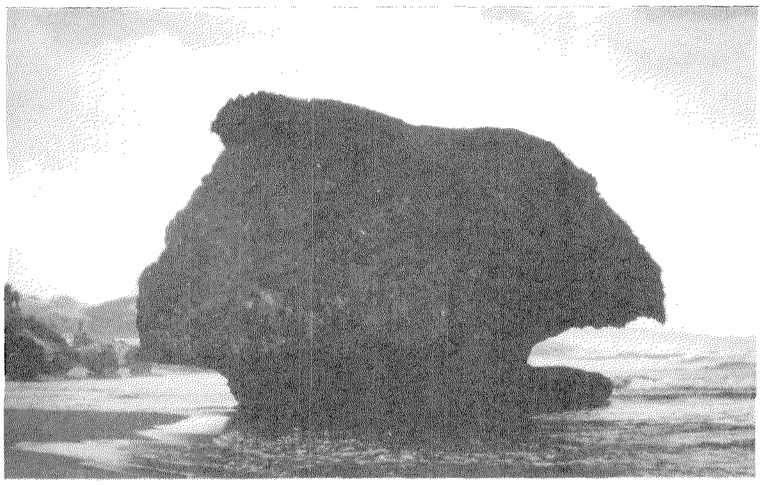
Magnetic sensitivity has been documented in homing pigeons as well as bees. Many of these experiments were conducted at Cornell by the late Bill Keeton and at the State University of New York at Stony Brook by Charles Walcott (now at Cornell). During the 1970s these two groups discovered a variety of magnetic effects on homing pigeons by attaching paired coils to the birds' heads or little bar magnets (or, as a control, brass bars) to their backs. With these coil-and-magnet setups they could change the direction of the magnetic field running through the birds' heads.

When they released the birds and tracked them home, they noticed that on sunny days there was virtually no difference between the birds with magnets and those with brass bars. Birds have a very nice sun compass. By looking at the position of the sun in the sky and comparing it with their internal clocks, they can get a very accurate estimate of where north is. On cloudy days, however, some very interesting things happen. The birds with the brass bars still fly more or less directly home, but the ones with magnets on their backs go off in random directions. They don't know where home is.

Changing the direction of the magnetic field through the head with paired coils also yielded interesting results. If the magnetic field goes down through the head, it approximates the normal direction of the field in the northern hemisphere. So you're actually adding to the present field, and in this situation the birds go preferentially toward home. But if you flip the field so that it runs up through the top of the head, you can make the birds fly away from home.

These experiments on honeybees and homing pigeons suggest that they have a magnetic compass sense. Somehow if the animal





The chiton's long rows of teeth (left) carve fossil reefs into mushroom shapes (right) as this marine mollusc scrapes the rocks in search of algae. The teeth are made of magnetite, an extremely hard, iron oxide mineral that is strongly magnetic.

is deprived of other information, it can figure out which way north is. Another of Walcott's experiments, however, involved releasing pigeons at magnetic anomalies. Normally when a pigeon is released it will fly in small loops before determining the straightest path to its home loft. When Walcott and his crew released pigeons at an iron mine magnetic anomaly (a peak in the local magnetic field, from 2 to 6 percent over the background field) the birds became very confused. A few of them eventually wound up going off in what might be the home direction, but a significant fraction just wandered off and flew randomly around the area, apparently unsure of which way to go. They seemed to avoid local magnetic highs in favor of the lows. This experiment has been repeated several times now, in Italy and Switzerland as well as in the United States, and it seems to be holding up. The birds appear at first to be trying to escape the magnetic anomaly and then trying to figure out where they are. Something about the perturbations in the field is disturbing them in some way, even on sunny days. These birds do actually get home eventually, but they take two to three times longer than does a bird released a few miles away.

How do the birds and bees do it? As an undergraduate at Caltech I worked with Lowenstam on the magnetic properties of chiton teeth and was quite familiar with biomineralization. Later, when I was a graduate student at Princeton, a group of biologists there successfully replicated some of the German bee experiments, and I got the idea that magnetite might also be responsible for their magnetic sensitivity. But how could we test this idea? Geologists routinely look at rocks for magnetic materials, and our favorite mineral in rock magnetism is magnetite. We applied standard geological techniques to this problem and soon had located small amounts of magnetite in bee abdomens and pigeon heads.

We have subsequently developed laboratory techniques for extracting and looking at these magnetic particles. We have some very sensitive instruments, for example, a superconducting magnetometer that uses something called a SQUID (superconducting quantum interference device), which can detect picogram quantities of magnetite. It's so sensitive that it can register the magnetic moments of dust particles in the air. But we needed just the right animal. The problem is that you can't use a metal knife to dissect the animal because the knife would leave a trail of highly magnetic metal particles. It is difficult, however, to conduct an accurate dissection on small honeybees or bird heads using only broken bits of glass and plastic. We needed to find a better animal to study, and the tuna turned out to be one of the best animals that we could find. These fish spend their entire lives in the deep sea, far away from all sources of terrestrial contamination. They also have large heads that are much easier to dissect that those of a bird or bee.

I started collaborating with Michael Walker and others at the National Marine Fishery Service (NMFS) in Hawaii to see, first of all, whether or not tuna have a magnetic sense, and second, whether we could locate any concentrations of magnetite in the fish. The yellowfin tuna was under particularly intensive study at the NMFS; its known migratory range extends over most of the Pacific. Walker did a lot of behavioral work, training fish to swim through hoops and using a conditioning paradigm — feeding the fish if it swims through a hoop at the right time and punishing it with no food if it does not. We could measure the ability of the fish to detect the magnetic field, then, by feeding it only after it swims through the hoop when a magnetic field is turned off rather than on. After a while the fish began to learn to go through the hoop to get the food when the field was right, which showed that the tuna have a good magnetic sense.

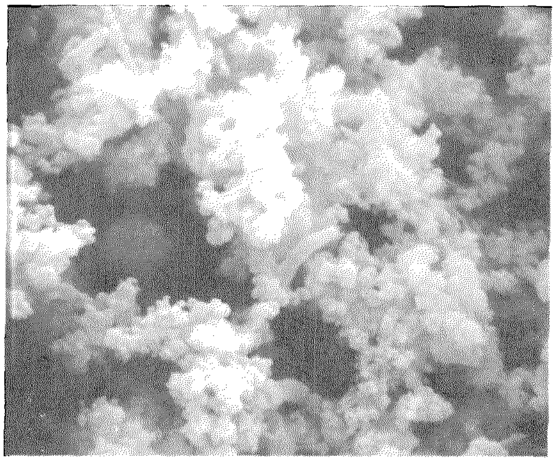
When we started looking into the head of the tuna, we found a reliable pocket of magnetic material within a sinus in the dermethmoid bone at the tip of the fish's snout. The magnetic particles, which turned out to be magnetite, are located in a structure a few millimeters long by a few millimeters wide, nestled within the top of this cavity inside the bone. The small, regularly shaped magnetic crystals are similar to those found in a few species of bacteria.

From other studies we've done we know that a nerve runs to this cavity from the lateral-line sensory system of the fish. This particular set of nerves usually goes to structures known as hair cells, which are very sensitive receptors for motion. The nervous system can detect a change of even a few angstroms in these hairs' position. Since we know that this particular type of nerve usually goes to such receptors, we're currently hunting for them in the tuna dermethmoids. The only problem is that the magnetite is present in concentrations of about five parts per billion of volume. The search entails going section by section throughout the whole structure where we found the magnetite. We hope that within a year or two we'll find something like hair cell receptors associated somehow with these magnetic chains.

All of the behavioral studies that I've mentioned so far have been contrived and are really not natural. For example, there's nothing in the experiments that shows us what a bird is actually doing when it's trying to fly somewhere. What we want to know is why these animals are using the magnetic field in the first place, and what possible information about navigational problems these weak field sensors can provide. And how can they be thrown off by just a weak anomaly? There seems to be something about the weak fluctuations in the magnetic field that interferes with the pigeons' ability to figure out their position.

So, in order to study the movements of naturally migrating animals, we have turned to whales. Whales are nice to work with because they're big. You can see them, even from airplanes, and when they land on the beach you can usually find them. There are national agencies, such as the Smithsonian Institution and the Coast Guard, that routinely report on the location of stranded whales. And there are systematic searches of marine animals and whales that are done over marine shelves within the 200-mile economic zone. So we have a data base to work with. Dead whales simply washed ashore are of no interest if you want to know whether whales have a magnetic sense or what they're using the magnetic field for. But the mass strandings, where whole schools of live whales come ashore for some unknown reason and beach themselves, are most interesting for our studies because they might tell us something about what the animals are doing at sea. In addition, Margaret Klinowska, a cetacean biologist at Cambridge University in England, has recently claimed that whales tend to avoid magnetic anomalies when they are about to beach themselves. An investigation of this with American data clearly seemed worthwhile.

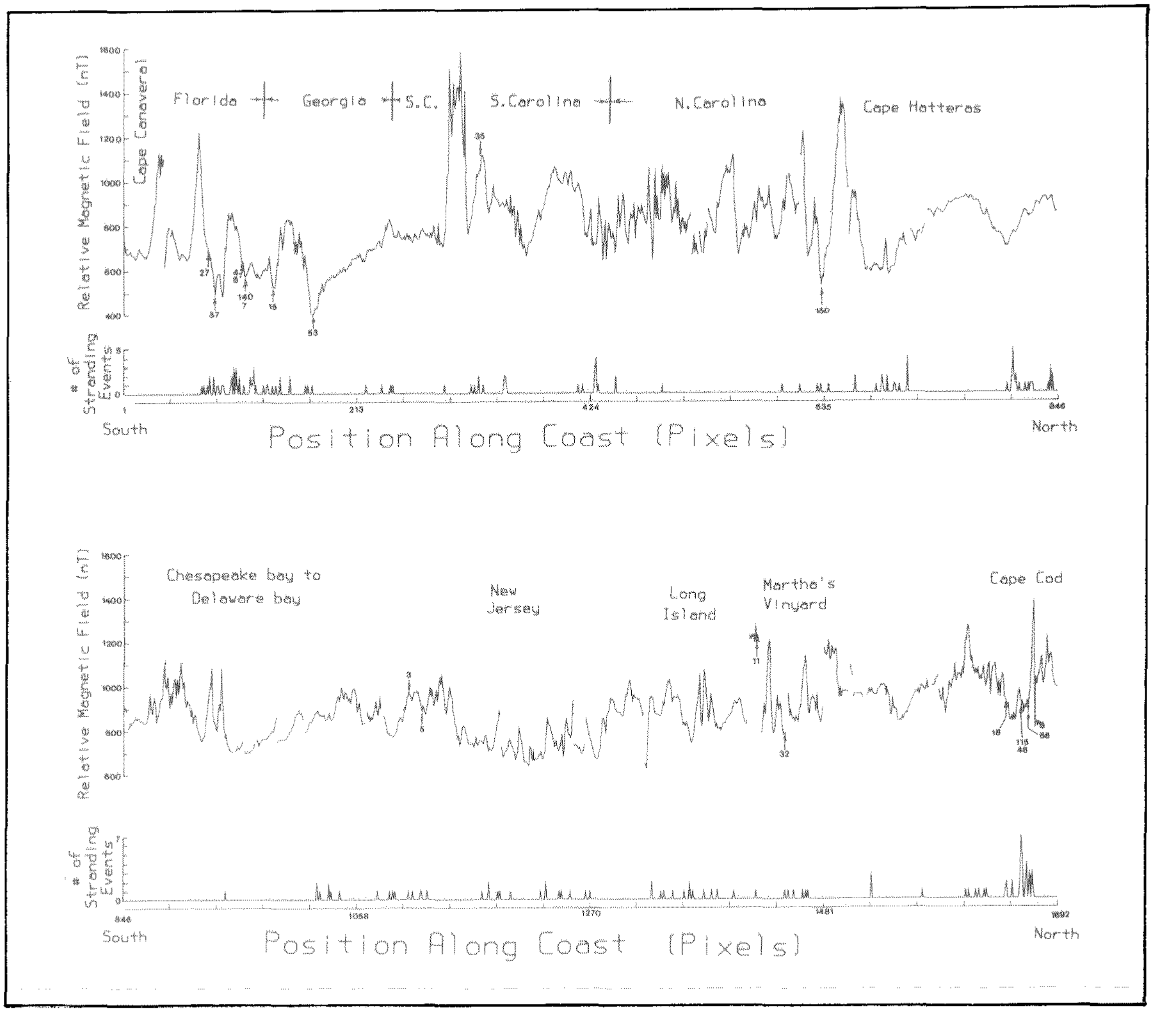
About a year ago I started a cooperative project with James Westphal, professor of planetary science, and Andrew Dizon of the NMFS to see whether we could use these data to determine whether whales had a magnetic sense and, if so, how they are using it. We



This scanning electron micrograph shows the magnetic material contained within a bone of the tuna's snout. This structure may send information on the Earth's magnetic field to the tuna's brain.

combined three data sets. During the 1970s the U. S. Geological Survey had done an extensive series of aeromagnetic surveys from Florida to Cape Cod. They just flew an airplane back and forth every few miles, towing a magnetometer to get a picture of the offshore magnetic field. The data from this survey are shown plotted in false color on the cover of this magazine. Magnetic field values go from low (dark blue) to high (yellow). On top of that we've plotted a high-resolution digital representation of the shoreline made by the U.S. National Center for Atmospheric Research. The red dots and crosses show the location of all whale stranding events, taken from the Smithsonian Institution's computerized directory. The large crosses represent more than 30 whales in stranding events, the small crosses between 3 and 30, and the red dots one or two whales. Visually there seems to be a strong association between points on the coastline where whales come ashore and the topography of the magnetic field. For example, the site where a large dark blue magnetic minimum — part of the East Coast magnetic anomaly — hits the Georgia shore is precisely where 53 pilot whales beached themselves. But since the range from deepest blue to brightest yellow represents only about a 4 percent change in the background field, the whales would have to be using an extremely high-resolution sense to be able to pick up the variations.

In all the years of cetacean work, nothing has been found until recently to explain why mass strandings occurred where they did. There's no bathymetric relief that characterizes these particular sites along the coastline; it's all the same depth. There are no obvious current or temperature differences. So a simple remaining hypothesis is that whales may



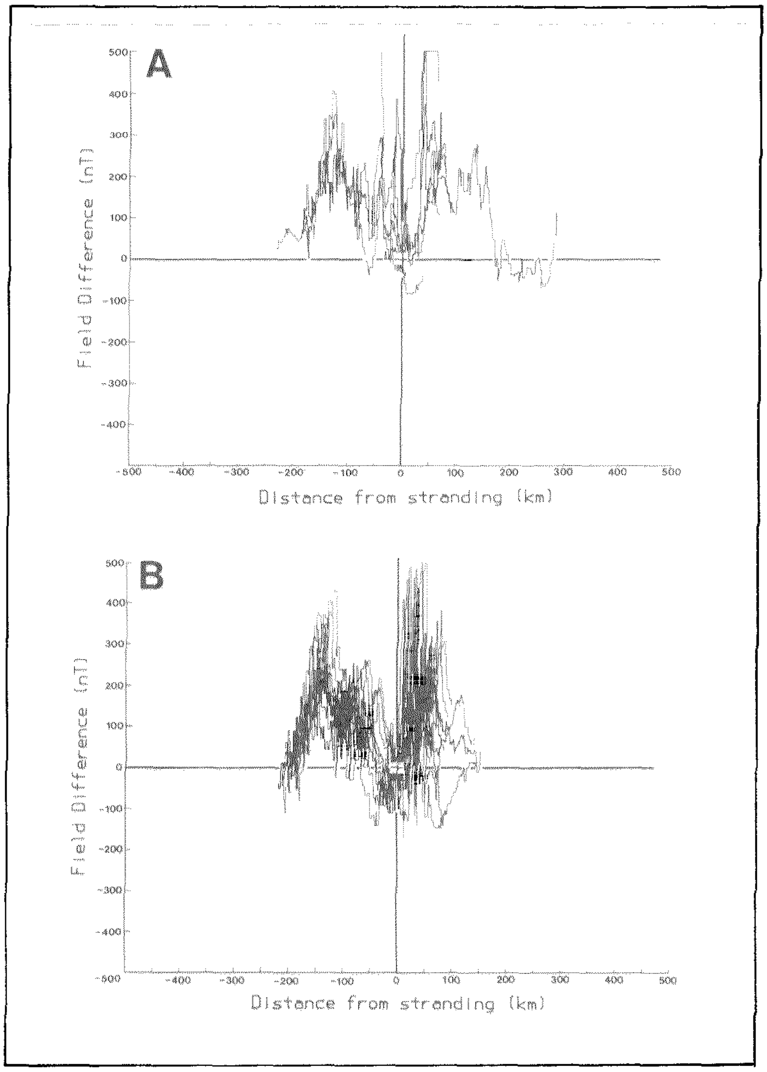
This diagram contains a plot of the relative magnetic field in sequential segments along the coast from Cape Canaveral, Florida, to Cape Cod, Massachusetts, along with a histogram showing the number of cetacean stranding events in each coastal pixel. Many strandings coincide with low points in magnetic field strength.

be following weak changes in the magnetic field and that this is reflected in their stranding locations.

We went about testing this hypothesis using a simple statistical analysis — by determining whether the associations of whale strandings with magnetic lows could be explained as random events. First we unraveled the Atlantic coastline and plotted the variations in the aeromagnetic data along it. This is shown in the diagram that plots this as well as the number of whale strandings at particular points along the coast. Just looking at it, some correlations seem obvious. It certainly looks nonrandom, but there are a number of statistical approaches that can test it.

The best statistical approach turned out to be to examine the local coastal neighborhood around each stranding event. Where a line of magnetic minima ("valley") intersects the shore, the total field should increase on either side of it. So if we assume that there is *no* relationship between magnetic fields and strandings, it implies that, on the average, the magnetic field along the coast should be neither higher nor lower than the field at the stranding sites, and the differences between field values at those sites and neighboring sites should be zero. Systematic departures from zero, on the other hand, would indicate correlation with magnetic highs and lows. This technique lends itself to a direct test of significance through Monte Carlo simulations — creating (in a computer) millions of random whales, throwing them on the beaches, and seeing how many randomly fall into the magnetic valleys.

We ran this analysis on 212 stranding events from the Smithsonian records — separated by species and combined. Although there is variation among species (and species representing about 10 percent of the total appear to beach themselves at magnetic highs), the tendency for most cetaceans to strand near magnetic low spots is clearly seen in the combined results. Profiles of these results can be shown in what I call "spider" diagrams because of the long thin "legs" radiating out from a central point,



In these "spider diagrams", for (A) Balaenoptera physalus *(the fin whale) and (B)* Lagenorhynchus acutus *(the Atlantic white-sided dolphin), the central point represents the locations of strandings and the legs radiating from that point represent the magnetic fields of adjacent coastline. The upward radiation of the legs indicates that these species preferentially beach themselves at local magnetic minima.*

which represents the intersection (0,0) of the axes of relative coastal distance and magnetic field. Random strandings would yield legs radiating in all directions, while stranding points at magnetic highs would send the legs into the bottom quadrants, and those at magnetic lows would have legs pointed upward into the top quadrants. These spider plots illustrate the data for two species, *Balaenoptera physalus* and *Lagenorhynchus acutus*, which gave the strongest results in our analysis. It is obvious that the average tendency is for the legs to point upward.

So it is clear that cetaceans possess a highly developed sensitivity to the geomagnetic field, which probably enables them to use it for guidance. We are currently looking at data from the Cetacean and Turtle Assessment Program, an aerial counting operation over the continental shelf financed by the Bureau of Land Management and managed through the University of Rhode Island. We have plotted the positions of various species by season to get an idea of migrating and feeding patterns and compared this to the magnetic field data. Visually, at least, there seems to be no strong relationship to the magnetic field where they are feeding, but when they are migrating up and down the coast there seems to be a much better one. Usually the migrating whales can be found in the magnetic valleys, as if they were following them.

Why might aquatic animals be interested in following the magnetic field? Imagine that you're left in a rowboat in the middle of the Atlantic Ocean without a compass, sextant, or any other instrument. How can you keep track of where you're going? You can determine latitude if you can see celestial cues, but measuring your east-west position is much more difficult. The early English navigators trying to circumnavigate the world had the same problem: If you can't measure longitude, you can't make maps. But a turtle dropped in the middle of the Atlantic knows how to head for home.

A clue to how aquatic animals may use the magnetic field has come to light in the past 30 years as marine geologists have studied the magnetic fields over the ocean floor. The ocean floor is formed at the mid-ocean ridges, where basaltic magma wells up and solidifies, spreading the sea floor apart. As the earth's magnetic field has reversed many times over the millions of years the ocean floor has been in the making, a record of those reversals has been left recorded by the volcanic rocks on the ocean bottom. These magnetic stripes trend north-south in a very regular manner away from the spreading ridges and have allowed geologists to date regions of the sea floor.

They also might be providing longitudinal reference points for magnetically sensitive animals. We haven't tested this hypothesis yet, but we think that when we can do a global study of migratory animals in the world's oceans, we will find the animals following the magnetic valleys, using them to keep track of relative longitude. Magnetic highs would be much more difficult to follow, since they are more prone to "noise" from positive susceptibility anomalies centered over seamounts and ocean fracture zones. If this proves true, it would have major implications for commercial fisheries that exploit magnetically sensitive fish, such as tuna and salmon, and should lead to better techniques for resource estimation and management. □