MARINE BIOLOGY

Sea Turtles Master Migration With Magnetic Memories

Finding the right direction in life is never easy for youngsters, but loggerhead sea turtle hatchlings have it tougher than most. Emerging late at night from nests on Florida and Caribbean beaches, the hatchlings must enter the water and find a path through ocean currents where a wrong turn spells death. The right turns, in contrast, lead to safe feeding grounds in the mid-Atlantic and eventually back to their birthplaces, where the now-grown turtles nest. How the turtles manage this complex navigational feat has been a real puzzle.

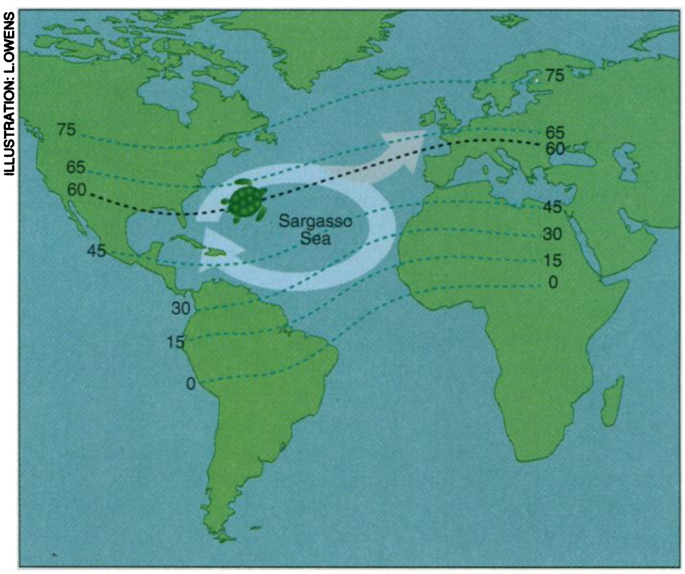
Now marine biologist Kenneth Lohmann of the University of North Carolina at Chapel Hill has found what appears to be a compelling solution: Turtles seem to carry a remarkably sophisticated magnetic compass in their heads. The compass lets them use Earth's magnetic field—lines of magnetic force that flow around the planet from the magnetic South Pole to the North Pole—to tell one direction from another. More importantly, the compass enables them to sense how far north or south they've come. Lohmann argues that turtles use this sense along with two other directional cues—light bouncing off the ocean and wave motion—to get out into the world and home again.

The results "may solve the long-standing mystery of long-distance navigation in sea turtles," says Lohmann, who will describe this work in a forthcoming issue of the *Journal of Experimental Biology*. "This is a major breakthrough,"says Brian Bowen, a marine biologist at the University of Florida. "Ken has come up with a plausible mechanism and the data to support it." Eventually, because many sea turtle species are endangered, biologists hope to use this information to help pick protected nesting beaches that the animals can easily find.

The loggerhead travel itinerary looks like this: After hatching, the turtles find their way to the Gulf Stream and ride it north and then east, towards the coast of Portugal. There the turtles must avoid a northward fork in the current that could send them to a chilly death in waters near England. Instead, they head south along another fork to feed on the abundant supply of invertebrates in the Sargasso Sea, in the middle of the North Atlantic. They circle around the Sargasso for 5 to 7 years, until they return to their birthplaces to nest.

Researchers have wrangled for 3 decades over the sensory cues sea turtles might use to make this trip. Sun position or a keen sense of smell were two popular nominees. More recently, in 1985, researchers detected particles of the magnetic mineral magnetite in turtles' brains, fueling speculation that the animals might have some ability to use Earth's magnetic field to orient themselves. These particles have been found in other species, from bacteria to people, although their role as navigational aids has never been pinned down (*Science*, 15 May 1992, p. 967).

ILLUSTRATION: LOWENS



Incredible journey. Turtle hatchlings use a 60-degree magnetic inclination line *(black)* to guide them from Florida beaches, across ocean currents *(light blue)*, to feeding grounds in the Sargasso Sea.

Lohmann wanted evidence to support the magnetic speculation, and he decided to begin at the beginning, with hatchlings. Previous work had suggested that new hatchlings on the beach move towards starlight or moonlight reflected off the ocean at night, but Lohmann wanted to learn if a magnetic sense guided them thereafter. So he placed the hatchlings in a harness tethered to a swivel arm in the center of a large circular tank (actually an upended fiberglass satellite dish). The apparatus allowed the hatchlings to swim in any direction for hours, while the swivel arm, connected to a computer, created a continuous record of their movements. Lohmann then surrounded the tank with a magnetic coil system that could create a field around the swimming turtles.

He started the turtles off with a dim light in the east, as they would see on an east-facing beach, and then doused it, leaving them in darkness. The hatchlings kept swimming east, but then Lohmann rocked their world, turning on the coils and reversing the field so that it flowed from north to south. Sure enough, the turtles reversed, too: They stopped swimming east and began swimming towards the new "magnetic east," which, since the field was reversed, was really west.

But the picture isn't a simple one. Lohmann found that the initial alignment of the turtles' internal compass depends on the direction of the light they first see. When the light came from magnetic west, instead of east, the hatchlings always swam towards magnetic west, even in the dark. Since starlight and moonlight reflect more brightly off water than land, Lohmann speculates this initial light ensures turtle compasses point them towards the open ocean.

However, the turtles don't even rely on their newly set magnetic compasses when they first enter the water, Lohmann found. Instead, the turtles orient by swimming directly into the waves. When turtles were released at sea in an experiment, they always swam into the waves, no matter what direction the waves came from. Since waves near shore come in toward a beach, swimming into them is a good strategy for heading offshore.

Yet in the open ocean waves come from all directions, so they can't be of much navigational help. Lohmann guessed that the magnetic compass took over at this point, so he decided to test exactly how effective it was. Using his tank apparatus, he simulated the magnetic changes that accompany the turtles' migratory journey. As Earth's magnetic field loops out of the magnetic South Pole and dives back into the planet at the North Pole, it changes its orientation relative to the planet's surface. At the poles, the angle of the field relative to Earth's surface is steep—90 degrees—but it gradually decreases towards the equator, where the field is basically horizontal; the angle is 0 degrees. The ability to sense these angles can be a navigational aid, telling an animal how far north or south it is.

Lohmann began to vary the inclination of the magnetic fields surrounding the hatchlings. At a 57-degree angle, which corresponds to the angle at the Florida beaches, he found that the turtles swam east. Then, at 60 degrees, something drastic happened. The turtles insisted on heading south. Lohmann was shocked by the turtles' "large shift in direction for only 3 degrees inclination angle." But then he realized that 60 degrees corresponded to the fork in the Gulf Stream off Portugal—an ideal site for natural selection of a magnetic inclination sense. "It is pretty easy to see how those mutants who tended to head south when they encountered a 60-degree inclination angle were much more likely to survive than those who


K. LOHMANN

Loggerhead on a leash. The apparatus helped researchers track turtles' behavior in magnetic fields.

didn't and ended up cold-shocked on the coast of Great Britain," says Lohmann.

According to Lohmann, the loggerhead migration picture now looks like this: Hatchlings emerge from their beachfront nests at night and head toward the bright light coming off the ocean, setting their magnetic compasses. Once in the water, they swim directly into the waves. Swimming into the waves keeps the youngsters heading away from the coast. When they hit the Gulf Stream, they ride the current, relying on their magnetic inclination compasses to tell them when to turn and head south for the Sargasso Sea. Then, in late adolescence, they find the magnetic inclination angle of the Florida beaches and ride it home.

Many marine biologists, such as Michael Salmon of Florida Atlantic University in Boca Raton, say Lohmann's scenario makes a persuasive case. But David Owens of Texas A&M University says the North Carolina scientist may have left out a major factor: smell. "I think [Lohmann's research] is great. These contraptions he has developed are elegantly simple, but I still happen to think that olfaction is important," says Owens. He suggests the two senses may work in tandem and that sniffing out location clues may allow the turtles to fill in details on their large-scale magnetic maps.

Further experiments may reveal whether smell indeed fits into this navigational scheme. When that work is done, says Lohmann, scientists may be able to trick turtles into nesting on specific beaches designated as protected sites, helping the endangered animals to survive. And that, he continues, would produce yet another sense—one of satisfaction.

–Lisa Seachrist

VOLCANOLOGY

Throttling Back the Great Lava Floods?

Floods in any form wreak havoc, but the kind of floods that struck 16 million years ago near the Columbia River were the stuff of nightmares. Great cracks opened in the Earth and erupted repeatedly, each time gushing a thousand cubic kilometers of lava or more, along with noxious gases that could have spread destruction over a broader area. The closest comparison in historical times, the 1783 Laki eruption in Iceland, unleashed a piddling 12 cubic kilometers over 5 months—but the exhalations of even that eruption were enough to devastate the island and throw a chilling pall over Europe.

Given the magnitude of the ancient lava floods, some scientists have suggested that these eruptions and even larger ones like those that produced the Deccan Traps of India 65 million years ago might have triggered, or at least contributed to, major extinctions, including the disappearance of the dinosaurs. But if volcanologist Stephen Self of the University of Hawaii is right, these eruptions now look a shade less catastrophic.

Specialists in flood basalts, the remnants of these flows, had assumed that each eruption, which formed a layer of lava tens of meters thick and hundreds of kilometers long, took place in a matter of days. But Self and his colleagues see signs that flood basalts "erupted more slowly," he says. Rather than days, "it has to be longer than a few weeks"—more likely a year, even several years. A slower pace would have prolonged the environmental insult from noxious gases, but also given natural cleanup processes such as rainfall a better chance to limit the damage.

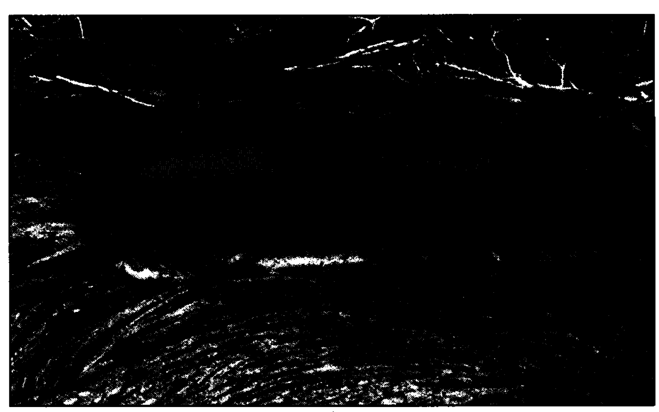
Volcanologists had settled on a sudden torrent of lava because they could see no way for that lava to remain hot and liquid for long enough to flow slowly across hundreds of kilometers. Some slow-moving lavas from present-day volcanoes do manage to stay hot over relatively great distances; in the lavas known as pahoehoe, for example, the outer skin of a flow solidifies, forming an insulating tube that pipes hot, fluid lava great distances. But geologists could find few signs of lava tubes in the Columbia River basalts, leaving them to assume that the eruptions gushed lava so fast it tumbled hundreds of kilometers before freezing.

But Self and his students think they have found clues that mark the Columbia River flood basalts as slow-moving pahoehoe after all. Among them are "spiracles"—partially filled vertical tubes. Other researchers had explained spiracles as the result of steam blasting up through the lava as it flowed over swampy ground. But recent observations on Kilauea suggest that similar structures might form in pahoehoe.

The process that might be responsible was recently documented by Ken Hon of the U.S. Geological Survey (USGS) in Denver and his colleagues. An advancing sheet of lava a few tens of centimeters thick stalls as its crust thickens, but magma continues to push under the crust, lifting it and inflating the flow to a thickness of from 1 to 5 meters. George Walker of the University of Hawaii went on to suggest that when two abutting lobes of pahoehoe lava inflate, fingers of lava are injected into the growing suture between the lobes, forming spiracle-like columns.

Self and his colleagues think the same suturing process operated in the Columbia River flows—along with the tube formation that allows pahoehoe to flow long distances. The tubes, they say, are hard to see because on the gentle slope of the plateau the broad, thin tubes probably never drained, so that little was left to mark their presence.

Spacecraft imagery may lend support to this idea, as planetary scientists Jeffrey Taylor and Barbara Bruno of the University of Hawaii, along with Self, reported last month at the Lunar and Planetary Science Conference in Houston. This group had already shown that the margins of pahoehoe flows are more convoluted than those of faster moving flows. That test can't be applied to terrestrial flood basalts, because erosion and vegetation have erased their edges. So Taylor, Bruno, and Self looked at 15 flows of equivalent size on Venus, Mars, and the moon. All but two of the huge lava flows, they reported, bear the telltale wiggly mar-


K. HON

Flow inflation. When this Hawaiian lava forms a crust, underlying fluid lava can inflate a flow to many times its original thickness.