insulating; and so on. A living polymerization method for NCAs should lead to block copolypeptides with new and useful properties.

Deming has demonstrated successful synthesis of such materials, and has created a new family of polypeptides that link combinations of acidic, basic and hydrophobic domains, all with excellent control of molecular architecture. The prospects for application in biomedical engineering, drug delivery and selective separations appear to be excellent. When it comes to polymerization, "For the living there is hope, but for the dead there is none"[8]. □

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Magnetoreception

Homing in on vertebrates

Joseph L. Kirschvink

Imagine being set adrift in a canoe in the middle of an ocean. Which way would you paddle? Most humans would be as lost as lost can be, but creatures such as pigeons, turtles and whales have no difficulty navigating in such circumstances. How they do so remains one of the biggest mysteries in the behavioural sciences, at the centre of which is the question of how organisms might sense the Earth's magnetic field and use it for navigation and homing (a topic with a chequered history — see box, overleaf). The mystery, however, is gradually being solved, and the latest instalment in the story comes in Walker and colleagues' study of rainbow trout (page 371 of this issue[1]).

All known sensory systems have specialized receptor cells designed to respond to the external stimulus, and these are always coupled to neurons to bring this information to the brain. In modern times the main objection to claims that magnetoreception is genuine was biophysical[2] — that there was no evidence of appropriate receptors.

Figure 1 **Magnetite-bearing teeth of the mollusc *Cryptochiton stelleri*. Each tooth is about 1 mm in size, and capped with a layer of black magnetite (Fe_3O_4). (Photo, H. A. Lowenstam.)**

The first clue towards meeting this objection came in an obscure place, the teeth of small molluscs. The late Heinz A. Lowenstam discovered that the major lateral teeth of the chitons are capped by massive amounts of a hardening agent, the permanently magnetic mineral magnetite (Fe_3O_4) (Fig. 1). Later, with the development of ultrasensitive superconducting moment magnetometers, came the recognition that tiny (parts per billion) levels of biogenic magnetite are naturally present in animals as diverse as insects, birds, fish and even humans[3,4]. The final crack in the biophysical arguments against magnetoreception came with the discovery of the magnetotactic bacteria and protists (Fig. 2), which possess linear chains of either single-domain magnetite or greigite (Fe_3S_4). They provide unequivocal examples of biological activity being influenced by the geomagnetic field.

Magnetite seems made for magnetoreception. A typical magnetotactic bacterium is only a few micrometres in size, but contains enough magnetite to make its rotational energy in the geomagnetic field exceed the thermal background energy by factors of 20 or more. The cells are very good, passive compasses, and will align with the Earth's magnetic field even when dead. The equivalent of only a single magnetotactic bacterium, connected to a single sensory neuron in a higher animal, could give that animal — ant, honeybee, trout or even whale — an extraordinarily good magnetic compass sense.

If this were all of the magnetite used for magnetoreception, finding and characterizing the receptor would be a needle-in-the-haystack operation. Fortunately, things are more complex. There are at least two types of response to the geomagnetic field — a simple compass, and another which is the result of sensing small fluctuations in the intensity of the background field. This latter sense has been implicated as a component of the navigational 'map' used by whales, turtles and birds[5]. Extensions of the biophysical analyses indicate that an array of a few thousand to a million magnetite-containing cells could yield responses to total intensity fluctuations of better than 0.1 per cent, as is observed behaviourally[5], and that this entire receptor system could fit within a 1-mm cube and yet have a magnetite content of no more than 1 part per million (ref. 3). There is still no requirement for the receptors to be concentrated into such a small volume, but these calculations make the odds of finding them much better than previously thought.

Simple experiments using short but strong magnetic pulses (which exceed the coercive force of the magnetite) have shown that both the magnetic compass and intensity sensory systems involve the use of permanently magnetic materials such as magnetite[6,7]. Linear chains of single-domain biological magnetite crystals suitable for magnetoreception are easy to extract from animals and image[8] (Fig. 3); and electrophysiological studies in birds have consistently identified fibres in the ophthalmic branch of the trigeminal nerve as the carriers of magnetic-field information[7].

So to Walker *et al.*[1], who have made two truly important advances. First, they have developed a simple laboratory conditioning regime for training rainbow trout to respond to magnetic cues. In principle, this could be extended to other vertebrates to tackle such

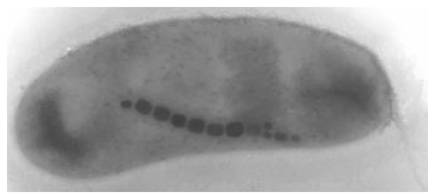

Figure 2 **A freshwater magnetotactic bacterium. The chain of dark objects is composed of crystals of magnetite, which have the proper size and shape to behave as perfect, single magnetic domains. The largest crystals are about 70 nm in length. (Photo courtesy of A. Kobayashi.)**

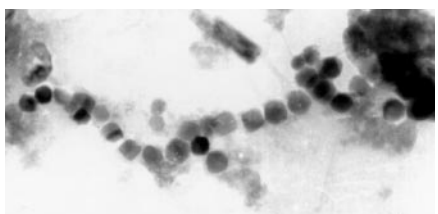

Figure 3 **A linear chain of biogenic magnetite crystals, extracted from tissues in the frontal region of the sockeye salmon[8], *Oncorhynchus nerka*, a close relative of the rainbow trout, *O. mykiss*. These are also single magnetic domains, with crystal alignments similar to those in magnetotactic bacteria. (Photo courtesy of S. Mann.)**

From Mesmer to animal magnetism

Over the years, many examples of sensory systems that humans apparently do not possess have popped up in interesting places among the vertebrates. Some are extensions of known senses – echolocation in bats and whales, infrasound and ultrasound detection in birds, and the sex-pheromone receptors (the vomeronasal system) in the nose of most higher vertebrates. Others, such as the electroreceptive organs of sharks and rays, and the infrared detectors of snakes, depend on highly specialized receptor cells. These discoveries generated little scientific controversy.

Not so biomagnetism, which in the late eighteenth century received an early bad rap from the activities of Franz Anton Mesmer and his followers. The mesmerites claimed that they could cure disease by exposing patients to magnetized objects, a claim debunked by a commission (which included Benjamin Franklin) appointed by King Louis XVI. The subject then fell into a long period of disrepute until the 1940s, when experiments suggesting that pigeons might use geomagnetic cues during homing generated great interest. These, however, were difficult to reproduce; likewise, conditioning experiments designed to elicit magnetoreception in the laboratory also failed.

The main stumbling block was in seeing how a geomagnetic stimulus could be converted into a signal that an individual cell could detect. Back-of-the-envelope calculations ruled out most of the obvious methods (paramagnetism, electrical induction, the Hall effect, nuclear magnetic resonance). The simplest strategy – that of having a small permanent magnet – was dismissed on the grounds that there were no physiological ferromagnetic materials[2]. As discussed in the main text, the discovery of magnetite eventually knocked that argument on the head.

Meantime, behavioural experiments kept on coming up with apparent geomagnetic effects on animal behaviour. But it took nearly two decades to realize that the geomagnetic compass used by adult birds was programmed to be ignored if other orientation cues (such as a Sun or star compass, polarized skylight, infrasound and ultrasound) were present. These orientation cues constitute a complex but consistent web of interacting responses, which are used not only by birds but in all major vertebrate groups and many invertebrates (reviewed in ref. 5). **J.L.K.**

questions as threshold sensitivities and frequency response, as has been done with similar conditioning experiments with honeybees[6].

Second, and even more excitingly, they have traced the sensory nerves back to possible magnetoreceptor cells. After confirming that the ophthalmic branch of the trigeminal nerve in fish contains magnetically receptive fibres, as it does in birds[7], they used a lipid-tracing dye to map the fibres back to the brain and to the location of putative receptor cells. Attempts to trace the avian magnetoreceptive nerves have failed because of the problem of identifying magnetite crystals in optical sections. Walker and colleagues' application of confocal laser microscopy provided the techniques for both tracing individual neurons back through a complex three-dimensional path and, by calibrating the confocal reflections with magnetotactic bacteria, for identifying possible magnetite crystals in the target cells.

Note, however, that the iron oxide mineral has not yet been identified conclusively. The cells containing the confocal reflections have distinctive shapes and always lie within a discrete sublayer of the olfactory lamellae (at the tips, near the distal terminals of fine branches of the trigeminal nerve), and the particles have similar size and shape to those extracted from salmon[8] (Fig. 3). But follow-up studies with conventional transmission electron microscopy and electron diffraction are required to confirm that the iron oxide is indeed magnetite.

A huge range of organisms can sense magnetic fields[5]. Do humans remain an exception? We certainly have a trigeminal nerve, with an ophthalmic branch, and we can also make biogenic magnetite. At least one other vertebrate sensory system thought to have been lost in the final stages of human evolution — the sex-pheromone-sensing vomeronasal organ — has recently been found to be both present and functional[9] (human vomeronasalins now form a booming perfume industry). Other effects, such as the ability of a 1-millitesla static field to elicit epileptiform activity in patients preparing for brain surgery[10], have also emerged. Finally, some humans, particularly Polynesian navigators, seem able to judge direction in the absence of all obvious cues (Sun, Moon, stars, waves and so on)[11]. So there is hope for our lost canoeist — the final word on the existence of human magnetoreception has certainly not yet been written. □

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Extraterrestrial impacts

The big splash

Jan Smit

Seventy per cent of the Earth is covered with sea water, and most of that is ocean, so most of the large asteroids and comets striking the planet should hit deep water. But very little remains of these impacts — virtually all evidence of large impacts, in the form of craters and associated debris, is found on land. On page 357 of this issue[1], Gersonde *et al.* describe the evidence for and consequences of the impact of an asteroid, 1–4 km in diameter, in a 5,000-m-deep ocean basin, 1,500 km southwest of Chile. The asteroid hit the Earth in the late Pliocene, some 2.15 million years ago.

The new results come from three piston cores, taken in the course of the 1995 FS *Polarstern* expedition to the Bellingshausen Sea in the Southern Ocean. This expedition was dedicated to finding more remains of this, the only known oceanic impact, because piston cores, taken 30 years ago in the same area by the USNV *Eltanin*, yielded the iridium anomaly typically associated with extraterrestrial impacts, and melted and unmelted meteoritic debris. This debris identified the impactor as an asteroid, a basaltic achondrite which was named the Eltanin meteorite. But many questions remained.

The *Polarstern* cores were taken in different depths of water — one on a seamount (depth 2,707 m), one at intermediate depth