alter the resting metabolic rate of volunteers. They conducted several studies, all with essentially the same results. When exercise is truly strenuous or prolonged, it does appear to alter the resting metabolic rate for 24 to 48 hours afterwards.

For example, in one study Bouchard and Tremblay recruited ten moderately obese young women. The women had about 32% body fat, whereas nonobese women have about 20% fat. The women trained for 11 weeks, spending six sessions and a total of 5 hours each week on aerobic exercise, including aerobic dancing, swimming, and running. Their resting metabolic rate, expressed per kilogram of fat-free mass, increased by 8%.

Bouchard and Tremblay also looked at the effects of de-training. They asked highly trained long-distance runners to refrain from exercising and determined that their resting metabolic rates declined by 6.6% after 3 days of rest.

But there were large individual differences in responses to exercise which Bouchard and Tremblay attribute to inheritance. They studied six pairs of monozygotic twins, for example, who exercised vigorously for 2 hours each day. On average, the twins' metabolic rates increased but, said Tremblay, "there was much individual variation" within the group. Yet each pair of twins had identical responses. "Whenever one twin had an increase in resting metabolic rate, so did the other," Bouchard said.

Although the results of Bouchard and Tremblay seem to disagree with those of Pi-Sunyer, both groups of investigators think the contradiction is more apparent than real. Whether exercise has an effect on metabolism, said Bouchard, "depends on the quantity and intensity of the exercise." In order to make a difference, exercise has to "either be very intensive or go on for a very long time."

Pi-Sunyer points out, however, that the average person who exercises will not experience sustained increases in the metabolism. "The mild activity that is considered realistic for the average fat lady or fat man you ask to exercise is not likely to have an effect," he said.

Pi-Sunyer does not intend to discourage people from exercising to lose weight. "You are getting a caloric effect just from the exercise," he said. His results on the effects of moderate exercise, he explained, "are not to say exercise is not good or helpful." But he added that the widespread promotion of exercise as a way to effect a sustained increase in the metabolic rate "fools people into thinking they are getting more out of exercise than they really are." ■

GINA KOLATA

Tracking the Wandering Poles of Ancient Earth

New analyses support the contention that Earth's poles have wandered across the globe, at times as fast as continental drift

SINCE the turn of the century, the North Pole has crept about 10 meters toward eastern Canada. By the standards of continental drift that is a near gallop, but the drift of North America had nothing to do with it. Instead, the North Pole appears to be wandering.

Such true polar wandering, if sustained long enough, could considerably confuse efforts to backtrack from the present positions of drifting continents to their positions in the distant geologic past. At the present rate of polar wander, for example, Philadelphia with its reasonably temperate climate would find itself 10° closer to the North Pole, at the latitude of southern Labrador, in just 10 million years.

But has polar wandering been rapid enough and has it persisted long enough to affect maps of past continental positions? Recent estimates of the magnitude of past polar wander have been dropping toward insignificance as better data have become available. But new analyses that extend the most thorough published study, which found only 5° of wander during the past 90 million years, show that a relatively sudden polar shift of 10° to 15° occurred between 70 million and 100 million years ago. That shift would have been at least half as fast as the present observed rate and comparable with continental drift rates. What could have caused such polar wander is unknown, but it must have involved the redistribution of mass on or within the planet.

When Roy Livermore of the British Geological Survey in Keyworth and his colleagues started their search for polar wander, they knew that it would be a tricky business. If the very ground is moving—as part of tectonic plate motion—as well as the pole, where is the benchmark against which polar wander can be measured? Today it is the stars and quasars. Conveniently enough, given the lack of dinosaurian astronomical observations, Earth's spin axis is fixed with respect to the stars, with the exception of some periodic, predictable wobble. It is actually Earth that slowly tumbles like a rolling ball beneath the pole—where the spin axis meets the surface—to create "polar wander." Geoscientists merely assume for their own convenience the perspective in which Earth is fixed and the pole wanders.

Given the stability of the spin axis, Livermore and his colleagues followed the line of reasoning that has become popular in the field. They retraced to a given time the erratic wanderings of the plates on the basis of the record of sea-floor spreading preserved in ocean crust. They then located the magnetic pole at that time from the magnetic signature frozen in rocks and sediments formed then. Presumably, the magnetic pole and the spin axis coincide, at least when averaged over some tens of thousands of years. That provides one reference frame, one of fixed orientation.

Livermore and his colleagues took exceptional care in locating paleomagnetic poles in that they included data from both the major continents and the huge Pacific plate, an area omitted from other studies. The Livermore group was also the first to allow for irregularities in the magnetic field that might produce spurious pole motion.

Having located the spin axis at a certain time in the past, they then compared this fixed point with a second reference frame, the set of hot spots that form volcanic centers such as Hawaii and Iceland. There is some uncertainty here. Presumably hot spots mark the top of plumes of magma that rise nearly 3000 kilometers through the mantle from near the core. There is no general agreement yet about how securely these plumes are fixed within the mantle. Livermore and others who have taken similar approaches assume that hot spots do not move significantly with respect to the mantle. If the pole "wanders" over time with respect to hot spots, then it is the mantle, if not the entire Earth, that has reoriented with respect to the pole.

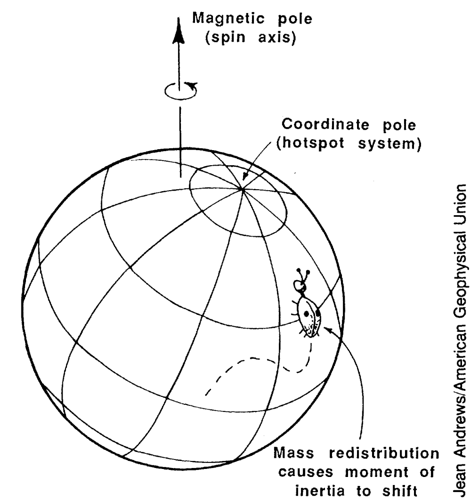
Not everyone is that sanguine about the fixity of hot spots. Clement Chase of the University of Arizona has attempted to measure any motion of individual hot spots with respect to the hot spot frame of reference. Hot spots do move, he says, up to 2.5 centimeters per year versus typical plate speeds of 5 centimeters per year. "The reason they appear to be fixed," he says, "is that the motion is semi-coherent." North Pacific hot spots as a group are moving to the north, those in the South Pacific to the south, and those in the Indian Ocean to the northwest.

If such motion were steady, hot spots would not be much of a reference frame, but Chase sees evidence of unsteady, perhaps random motion over tens of millions of years. The best outcome that Chase sees for polar wander searches would be that all the hot spot motion is random, which would produce no net error in the polar wander record but would create considerable noise.

Hot spot stability aside, Livermore and his colleagues found that the pole had shifted not much more than 5° during the past 90 million years. That is about 0.5 centimeter per year, the smallest polar wander relative to hot spots yet published. Between 100 million and 200 million years ago the shift was greater, up to 17° to 19°, but these researchers believed that the polar wander of the older record, like that of more recent times, would shrink as better data became available.

As he labored on a review of polar wandering while on sabbatical in Livermore's laboratory, Richard Gordon of Northwestern University realized that at least one check on the quality of the present data would be rather straightforward. Just as soon as he had written the test into his review paper's "Directions of Future Research" section, he and Livermore performed it. They compared paleomagnetic pole positions with another reference frame, one called the mean-lithosphere frame. The tectonic plates that make up the lithosphere have obviously been jostled this way and that, like ice floes on a choppy sea. If this random motion were removed, any mean motion of the lithosphere, like a field of ice floes being blown downwind, would be revealed. Gordon reasoned that if the pole wandered the same way with respect to both the hot spot frame and the mean-lithosphere frame, then the motion must be in the paleomagnetic data and would not be due to errors in the reconstruction of plate motions.

Gordon and Livermore took the same data that Livermore had used to determine paleopole–hot spot motion and determined paleopole–mean-lithosphere motion. They found little or no shifting of the outer shell of Earth as a whole during the past 65 million years, confirming the results of the earlier study. Gordon and Donna Jurdy, also of Northwestern, reported similar results in a paper that appeared last November in the *Journal of Geophysical Research*. But Gordon and Livermore did find a shift of about 14° that occurred sometime between 70 million and 100 million years ago, a time period not covered by the study of Gordon and Jurdy. If the shift required the full 30 million years, the pole would have wandered at about 5 centimeters per year. From a 1983 analysis of Pacific paleomagnetic data alone, Gordon had reported a similar shift between 90 million and 80 million years ago. "We think there is now strong evidence," says Gordon, "for a shift of the lithosphere and the mantle in Late Cretaceous time [65 million to 100 million years ago]."



The little bug that couldn't. *In a simplified version of an illustration from a 1969 paper by Peter Goldreich and Alar Toomre, a bug representing a concentration of mass on an idealized Earth begins its journey to the spin axis (a pole fixed in space) from the equator. If he moves too slowly, he will never reach the pole but always remain at the equator. The pole will "wander" away from the bug as Earth tumbles to keep the bug's mass at the equator, which is the most stable arrangement.*

Other, less comprehensive studies that have appeared recently tend to support Livermore and Gordon's results. Jean Andrews of Lamont-Doherty Geological Observatory found rapid polar wander during the Late Cretaceous in a study published in 1985, as have Vincent Courtillot and Jean Besse of the Earth Physics Institute in Paris. "With respect to the past 100 million years, all the recent studies are in about 80% agreement," says Gordon. The differences are due largely to the selection of different sets of paleomagnetic data by different workers, he notes. Deciding which are the most reliable paleomagnetic data has always been a controversial subject, prompting the playful label of "paleomagician" for practitioners in the field. More well-dated, widely accepted paleopole determinations are clearly needed.

Just what might be driving the apparently intermittent polar wander remains a mystery. It must be some sort of mass redistribution. Earth is most stable when its most massive parts are farthest from its spin axis, that is, on the equator. If a mass redistribution were to occur elsewhere on a uniform Earth, the planet would reorient itself to put the mass concentration on the equator. Major ice sheets that wax and wane over millions of years are massive enough and they may be causing the present polar wander, but the Late Cretaceous is thought to have been too warm for ice sheets.

Jurdy has shown that the sinking of cold, dense ocean plates into the mantle could also contribute to polar wandering. About 60 million years ago the pattern of such subduction and its associated plate motions were different than today. But both then and now the combined effect of subducting plates and the hot spot system—another major anomaly in mass distribution—tended to place the most stable spin axis within 1° of the actual spin axis despite the intervening polar wander of about 10°.

Now there is suggestive evidence that a change in polar wander accompanied a major reorganization of plate motions about 40 million years ago, when the collision of India with Asia snuffed out 10,000 kilometers of subducting plate. The resulting changes in plate motion apparently caused the Pacific plate to make a 45° left turn, as is evident in the bend of the Hawaiian hot spot trace. Courtillot and Besse find an abrupt, hairpin turn in their path of polar wander between 30 million and 40 million years ago that they attribute to the plate motion reorganization. William Sager of Texas A&M University and Ulrich Bleil of the University of Bremen have found a cessation of polar wander at about 40 million years ago, a coincidence that they find "interesting."

Courtillot and Besse, expanding on earlier suggestions of a link between episodes of polar wander and the tendency of the magnetic field to reverse and flip its poles, are proposing that the deep mantle is also involved. On the basis of correlations between their record of polar wander and the frequency and duration of magnetic reversals, they hypothesize that the transfer of heat from the uppermost core to the lowermost mantle leads to periodic episodes of activity in the core and mantle. Cooler, falling blobs in the core produce frequent reversals and then episodes of hotter, rising blobs in the mantle produce increased mantle convection, hot spots, polar wander, and, most speculatively, mass extinctions like that at the end of the Cretaceous when the dinosaurs died out. ■ RICHARD A. KERR

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