EOS, TRANSACTIONS, AMERICAN GEOPHYSICAL UNION

EOS

VOLUME 75 NUMBER 37

SEPTEMBER 7, 1994

PAGES 425-432

Pacific Toy Spill Fuels Ocean Current Pathways Research

PAGES 425, 427, 430

Curtis C. Ebbesmeyer and W. James Ingraham Jr.

While a container vessel was crossing the North Pacific Ocean along the great circle route from Hong Kong to Tacoma, Wash., severe storm conditions were encountered near the International Date Line on January 10, 1992. At 44.7°N, 178.1°E, twelve 12.2-m containers were washed overboard, one of which held about 29,000 plastic bathtub toy animals (Figure 1). Some of the steel cargo containers may have been torn open by the vessel's stays as they fell overboard or may have been ruptured by collisions with other containers.

Ten months after the spill, plastic toys began showing up on beaches near Sitka, Alaska. According to computer simulations the toys drifted toward the southeast Alaska coast, past both the site where about 61,000 Nike shoes spilled from a boat in 1990 and Ocean Weather Station Papa, where many drift bottles have been released.

This spill, like that of the Nike shoes, provides new data for ocean current pathways research because it was far larger than the usual planned instantaneous release of 500–1000 drift bottles. Given the typical 2% recovery rate of objects from the mid-Pacific Ocean, the drift pattern documented here is based on hundreds of recoveries compared with 10 or so drift bottles.

The 6- to 12-cm toys manufactured in China were packaged in a plastic housing glued to a cardboard backing. To check on the probable time for release of the toys, sample packages, obtained from retail stores, were soaked in a bucket of seawater; after a day in water, the glue deteriorated, releasing the toys. Therefore shortly after the container fell overboard, it is possible that up to 29,000 toys were released into the Pacific Ocean.

The beached toys were traced conclusively to one container through the following evidence: according to company records, the toys were shipped in a single container; the vessel's log showed that this container was spilled at the stated date and position; and all four types of toys spilled were found by beachcombers. Unfortunately, the container itself was not found.

Beachcomber Reports Help Track Drift Pattern

To obtain reports of toys found on beaches, articles and advertisements were placed in a newspaper widely distributed near the toys' first landfall. This landfall, consisting of six toys, was found by a beachcomber at ~57.1°N, 135.7°W on November 16, 1992. A second beachcomber found 20 toys at ~57.8°N, 136.4°W on November 28, 1992. Unfortunately, the reports were not specific enough to provide a breakdown of the type of toys recovered at each location. Without this information we were unable to differentiate the windage of each type of toy. From other beachcombers, we learned that approximately 400 toys, positively identified from photographs, were found between November 1992 and August 1993 along approximately 850 km of shore between the city of Cordova and Coronation Island, bordering the eastern Gulf of Alaska.

To expand our search for beached toys, an article was circulated in the monthly newsletter sent to Canadian lighthouse keepers from the Queen Charlotte Islands southward to Vancouver Island. We also presented our findings at a beachcombers' fair held in Washington state. None of the toys were reported south of Coronation Island,

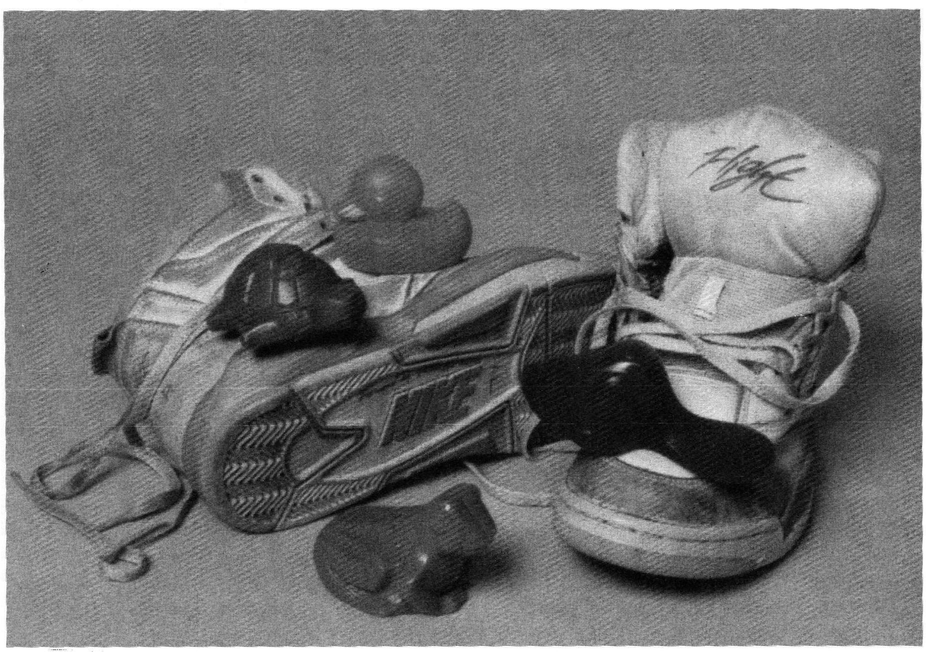

Fig. 1. Photograph of the four types of spilled bathtub toy animals (blue turtle, yellow duck, red beaver, and green frog) compared with a pair of size 12 Nike shoes recovered from the previous spill. Photo credit: Bruce Rowland, Seattle. Original color image appears at the back of this volume.

Curtis C. Ebbesmeyer, Evans-Hamilton, Inc., 731 N. Northlake Way, Seattle, WA 98103; W. James Ingraham Jr., Resource Ecology and Fisheries Management Division, Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way, NE, Seattle, WA 98115-0070

suggesting that once the toys reached the vicinity of Sitka, they drifted north.

Model Is Used to Simulate Drift

To simulate the toys' drift, we used a computer program, the Ocean Surface Current Simulations (OSCURS) numerical model [*Ingraham and Miyahara*, 1988]. This is an empirical ocean-wide model that covers the subarctic and subtropic Pacific Ocean from 20° to 66°N with a 90-km grid. It combines long-term mean surface geostrophic currents with empirically generated surface-mixed-layer currents that are functions of wind speed and direction to form daily current vector fields from which trajectories are interpolated.

Wind speed and direction were derived from the Fleet Numerical Oceanography Center daily sea-level pressure data available between 1946 and 1993. Current speed, C (cm/s), was calculated from $C = 4.8\sqrt{W}$, where W is the wind speed (m/s) and the angle of deflection to the right of the wind was calculated from Weber's function, which increases from approximately 22° to 31° as wind speed increases from 0 to 30 m/s.

The basic equations for the model were established by tuning the Gulf of Alaska portion of the model so that the model trajectories calculated for September 21–December 31, 1978, matched the trajectory of a satellite-tracked drifter for the same dates and starting locations. Further tuning enabled the model to simulate trajectories of drifting objects with windage. By matching simulated trajectory endpoints with recovery dates and locations, the model showed that the drift bottles drifting eastward from 48°N, 165°W in March 1962 and Nike shoes drifting eastward from 48°N, 161°W in May 1990 exhibited similar empirical characteristics over their approximate 9-month interval [*Ebbesmeyer and Ingraham*, 1992].

Simulations Show Toys Took Early Northeastward Turn

To account for the larger windage on the toys, the empirical functions for current speed and angle of deflection were adjusted systematically to determine which model trajectory ended near Sitka, Alaska, at the time of the first reported landfall. Increasing the basic speed coefficient by 50% and subtracting 10° from the basic angle of deflection function caused the end of the trajectory on November 16 to vary 6° in latitude. Holding the angle constant at Weber function minus 5° and varying the basic speed coefficient from a 40 to 50% increase caused the latitude of landfall to vary by approximately 1° of latitude. Of the matrix of combinations of speed coefficients and deflection angles, a unique pair, equivalent to increasing the speed coefficient by 50% and decreasing the angle of deflection function by 5°, provided a close match between the modeled and reported landfall.

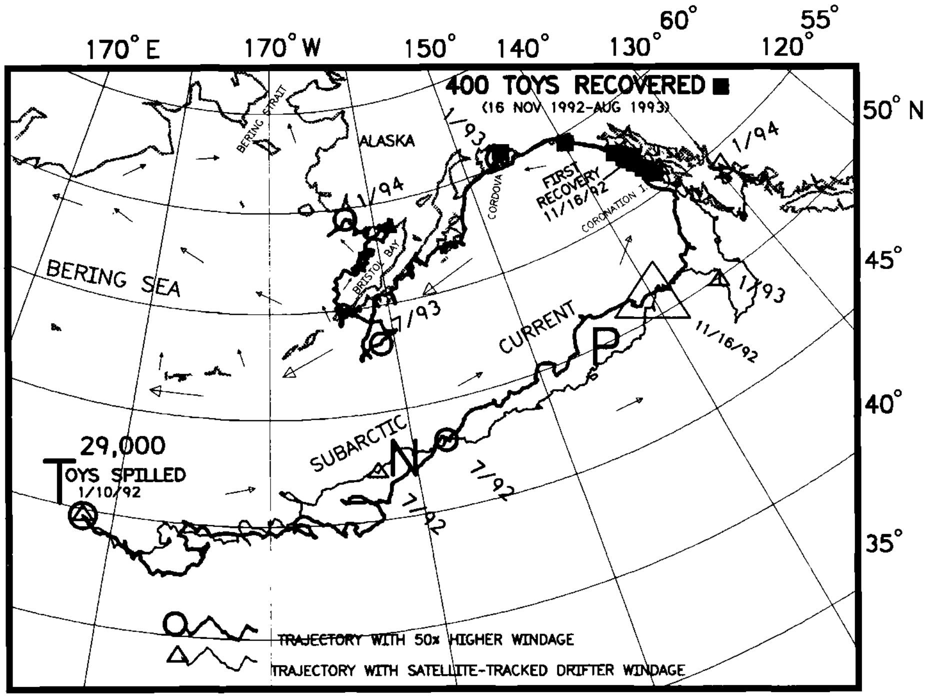

Fig. 2. Site where 29,000 children's bathtub toy animals washed overboard on January 10, 1990 (T), and dates and locations where ~400 toys were discovered by beachcombers. Trajectory of the toys, simulated with OSCURS computer model, passed near the site (N) where 61,280 Nike shoes were spilled and near Ocean Weather Station Papa (P) where 33,869 bottles were released. Thick line with circles on January 1 and July 7, 1992, shows our best estimate for the toys' trajectory; by using a 50% increase in the windage coefficient and a 5° decrease in the angle of deflection function, the track arrived near Sitka, Alaska, at the time of first recoveries, November 16, 1992. Thin line with triangles every 6 months shows the slower trajectory for objects without significant windage. Coded symbols as follows: black square, location of reported toy recoveries; large triangle, location of low-windage objects on November 16, 1992; small symbols, locations on January 1 and July 7 for 1992, 1993, and 1994.

Modeled trajectories for 1992 tuned to high windage drift for toys and tuned to normal drift for satellite-tracked drifters are shown in Figure 2. Although the directions of both trajectories were similar, the trajectory modified for windage made a landfall during the fall, while the unmodified trajectory at that time was still about 900 km offshore and didn't reach the coast until 6 months later. The separation was considerably larger after 2 years of drift.

For perspective, the 1992 toy spill trajectory was compared with trajectories from other years by running OSCURS with the same high-windage coefficients and starting from the same location on January 10 of each year between 1946 and 1993. From the spill location, the eastward flow appears to be orderly and repeatable for about 6 months in a well-defined drift channel that gradually widened until a turning point occurred (Figure 2, near 45°N, 145°W).

The 1992 trajectory, however, branched northeastward unusually early at 45°N, 162°W. Oceanic diffusion, as shown for the Nike shoe drift, is small compared with interannual variability. Beyond the turning point, most of the trajectories turned northward into the Gulf of Alaska, southward along the California coast, or continued straight to the coast. After 10.3 months of drift in 1992, the latitude of the toys' landfall was farther north than 77% of the other simulated trajectories. The large symbols in Figure 3 show where the toys would have been during other years at this time.

For trajectories extending out to 2 years, five major types of trajectories were evident (Figure 3). To represent the northward trajectories, 1959 was selected because of the well-defined loop around the Gulf of Alaska gyre and 1992 because it was the only trajectory penetrating the Bering Sea. For southward trajectories, 1990 passed farthest north of Hawaii, 1961 reached the farthest south, and 1984 looped northeast of Hawaii, illus-trating an area of increased residence time.

Analyzing the Data

Many types of man-made objects drift on the surface of the North Pacific Ocean. The movement of surface drifters is influenced to varying degrees by currents, winds, and waves. As they drift, these objects are constrained to the sea surface and thus cannot follow the motion of water parcels that also move vertically. Though understanding of

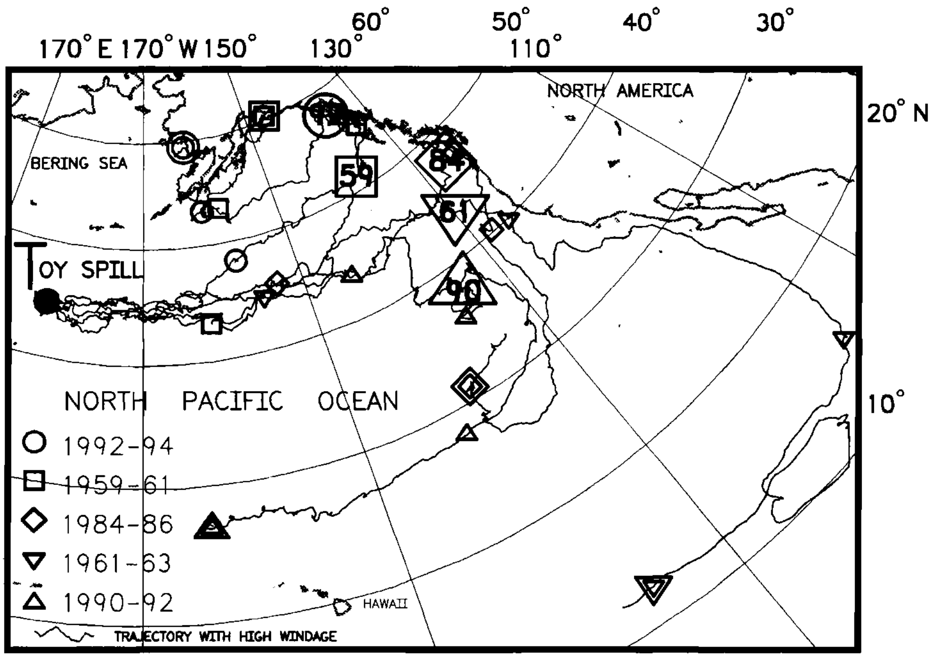

Fig. 3. Five trajectories selected from the set of 48 simulations of the same toy spill each year between 1946 and 1993 on January 10 showing the range of spatial variability on November 16, 1992 (first recovery date; large symbol), and their destinations after 2 years (double symbol; see codes at lower left); 1959 (squares), when the toys would have travelled in a loop around the Gulf of Alaska gyre; 1992 (circles), when the toys after reaching the Sitka area would go westward then northward through Unimak Pass into the Bering Sea; 1961 (inverted triangles), the most southerly trajectory; 1984 (diamonds), when the toys would have looped back to the northeast in an area of increased residence time; and 1990 (triangles), when the toys would have travelled the farthest westward north of Hawaii.

the toy dynamics is incomplete, we believe that they illustrate some aspects of the behavior of objects that float exposed to winds and waves in the 4 cm above the sea surface.

Surface drifters frequently have organisms attached to them, such as corals on glass floats. Depending on the associated windage, the objects and organisms will be transported to various locations in the North Pacific Ocean and adjoining water bodies. Some animals, such as *Velella,* which have adapted wind sailing life strategies, are profoundly affected by winds; early spring conditions in some years leave great numbers stranded in windrows along the beaches of the northwest Pacific Coast.

Our calculations suggest that the fate of long-term drifting objects is not only sensitive to the great interannual variations, but also that the variation increases with the amount of surface area subject to windage. Here we provide a quantitative estimate for the amount of displacement difference between objects that float mostly submerged—Nike shoes—and those that float with considerable area above the water's surface—the plastic toys.

Our best estimate for the toys' trajectory is that it passed close to the Nike shoe spill site, as well as to Ocean Weather Station Papa, where many drift bottles have been released for many years [*Ebbesmeyer and Ingraham,* 1992]. By comparing the recovery rates of the toys and shoes with those of drift bottles, we learned that the containers must have opened, spilling most of their contents.

The total number of toys reported, ~400, is about 1.4% of the 29,000 lost overboard. Historical drift bottle releases made near the toy spill are listed in Table 1. All totaled, 16 bottles were recovered from 663 releases for a recovery rate of 2.4%.

Since we last reported on the Nike shoe spill [*Ebbesmeyer and Ingraham,* 1992], information was obtained that enables the comparison of serial numbers of many recovered shoes with those listed for each container. This revealed that only four of the five containers had opened, releasing up to 61,280 shoes. Furthermore, additional information indicated that at least 1600 shoes were recovered.

Using the updated information, we estimate that at least 2.6% of the shoes spilled were recovered, a value close to that for drift bottle recoveries. Anecdotal evidence suggests that many additional toys were recovered but not reported. Since the recovery rate of toys, shoes, and bottles is approximately equal, it appears that most of the toys and shoes escaped from their containers, except for one container of shoes that sank.

To determine the long-term fate of the toys, the computer simulation was continued beyond the first landfall, showing that the toys traveled counterclockwise around the Gulf of Alaska, and through passes west of the Alaska peninsula. By January 1994, the toys had arrived in the southeast Bering Sea and presumably were trapped in the seasonal sea ice.

The following spring during breakup, given the prevailing currents [*Stabeno and Reed,* 1994], it is reasonable to assume that the toys eventually would be transported northwestward by the Bering Slope Current, then turn north and head for the Bering Strait along the Anadyr coast, or south in the Kamchatka Current toward the Oyashio Current. The toys passing through Bering Strait into the Arctic Ocean would be carried to Point Barrow and from there north of Siberia with the Arctic pack ice, eventually reaching the North Atlantic Ocean. The toys turning south might merge eventually with the Kuroshio Current and be carried past the spill site.

Drifts from the area north of Bering Strait in the Chukchi Sea have been reported from several locations in the North Atlantic: wreckage from *The Jeannette* frozen in the pack ice near Hearld Island in November 1879 was found 5 years later on the southwestern coast of Greenland; three drift casks containing messages released near Point Barrow in 1899 and 1900 were recovered 6–8 years later on the northern coasts of Norway and Iceland and the southwest coast of Greenland; several bottles released in the vicinity of Nome, Alaska, were found approximately 10 years later in Iceland, Ireland, and Norway; and a drift bottle, released June 26, 1979, in the Ber-

Table 1. Drift Bottle Recoveries From Releases Made Near the Toy Spill (44.7°N, 178.1°E).

Date	Latitude	Longitude Released	Number Recovered	Number
May 28, 1960	44.97°N	175.02°W	231	3
March 1, 1962	45.00°N	175.00°W	120	6
March 2, 1962	45.00°N	175.00°W	120	4
February 22, 1966	44.97°N	172.02°E	96	1
February 23, 1966	45.00°N	169.00°E	96	2
Total			663	16

ing Strait was found in western Scotland 7 years later on July 6, 1986.

The drift southward from the Bering Slope Current has been traced by a number of drift bottles and satellite-tracked drifting buoys, some of which were caught in the Kuroshio, and one buoy that subsequently headed southeast from Japan. Furthermore, a survival suit containing the victim's skeletal remains lost in the Bering Sea was found 3 years later in Hawaii. Therefore after a number of years we also expect some of the toys to be dispersed around the North Pacific Ocean, the Arctic Ocean, and the northern North Atlantic Ocean.

Given the substantial release of 29,000 toy animals, we anticipate that by the year 2000 a few toys will have been transported to many oceanic locations in the Northern Hemisphere. We ask your help in reporting any subsequent finds of the toys or other interesting drifting objects.

Acknowledgments

We thank Shannon Flotre, Thad Paulson, Eben Punderson, Alec Provan, Patricia Kurtz, and Dave Husby for their assistance in this research; and beachcombers Laura and Charlee Bower, Steve and Bridget Brady, Robert L. Chevalier, David Pearson, Stan Schoening, Mary Clay Stensvold, Val Svendsen, and John West for detailed reports of many of the toy recoveries. We also thank Dora P. Henry for editing.

References

Ebbesmeyer, C. C., and W. J. Ingraham, Shoe spill in the North Pacific, *Eos, Trans. AGU, 73*, 361, 1992.

Stabeno, P. J., and R. K. Reed, Circulation in the Bering Sea Basin observed by satellite-tracked drifters: 1986–1993, *J. Phys. Oceanogr., 24*, 848, 1994.

Paleomagneticists Discover Rock Trait That May Offer Clues to Seafloor Evolution

PAGE 425

Paleomagneticists at Columbia University have discovered a magnetic trait of seafloor rocks that may provide a new "clock" to map changes to the ocean floors on a timescale of several thousand years—which is a much more refined scale than that offered by prevailing methods. Such a tool may elucidate the evolution of mid-ocean ridges and perhaps even the dynamics of the Earth's field intensity when combined with state-of-the-art uranium calibration techniques.

For decades, scientists have relied on reversals in the magnetic direction of rock found along the Earth's mid-ocean ridges to reconstruct the history of the creation and movement of the Earth's crustal plates, whose boundaries lie along these ridges.

When molten lava rises from the Earth's deep mantle and emerges underwater along the mid-ocean ridges, it solidifies into rock, which becomes magnetized in the direction of the Earth's current magnetic field. A few times every million years, the field has reversed its magnetic north and south poles, creating a symmetrical pattern of alternating "frozen compasses" that are embedded in the rocks as new lava continues to rise.

Indeed, the questions as to how or why rocks retain this memory has long puzzled scientists, and this low-resolution gauge of changes to the seafloor has limited scientists' ability to distinguish the ages of younger seafloor structures and to decipher the mechanism of the formation of mid-ocean ridges in detail.

Now Dennis V. Kent and Jeff Gee paleomagneticists at Lamont-Doherty Earth Observatory, in Palisades, N.Y., have revisited a tried-and-true technology that measures the intensity of the magnetism of oceanic rocks, but with a new perspective.

All along, scientists have known that the rocks' magnetic signal diminished markedly over time as the seawater oxidized the rocks, which are made up of both small grains of about 1 micron and larger grains of about 10 microns. On the basis of measurements of rocks collected from the Mid-Atlantic Ridge, scientists generally concluded that the rocks were oxidized over a period of 500,000 years or about the same timescale of magnetic reversals. Scientists also assumed the magnetic intensity of both sizes of grains was the same and that the grains oxidized uniformly.

Earlier lab tests produced paradoxical results that scientists attributed to some sort of laboratory artifact. The tests yielded specimens with higher unblocking temperatures than Curie temperatures, a finding which scientists were then unable to explain, Kent says. Over the past 25 years for the most part, scientists have accepted the notion that during the thermal demagnetization process in the lab, an artificially higher unblocking temperature was somehow created. Curie temperatures measure the total magnetic potential of all grains in seafloor rocks, while unblocking temperatures measure only the portion of the total magnetic potential, which permanently registers the field reversals.

But Kent and Gee recently reexamined the assumption by testing young basalt samples from the Eastern Pacific Rise with the same widely used thermodemagneticism techniques and reported their findings in last week's *Science*. The scientists determined that as lava solidifies, small grains efficiently align to the existing magnetic field. However, as the rocks cool, the larger grains tend to subdivide into compartmentalized domains, each having opposite magnetic orientations. As a result, the large grains have a negligible net magnetic signal.

But the small grains are too small to compartmentalize. Accordingly, when the lava originally cools, only the small grains retain the natural remanent magnetism.

This means that the small grains, which were assumed to carry the same magnetic character as the larger grains and which were dismissed as unimportant actually provide the most telling information about the rocks' magnetization, Kent says.

In other words, the huge volume of large grains skewed the earlier lab tests and diluted the Curie temperature results. The large grains are still important volumetrically, Kent notes.

The small grains are also more thoroughly oxidized and lose magnetic intensity much faster than the larger grains, a factor that is also important for timescale studies, Kent says. In fact, the pair of paleomagneticists found that the time constant of the decrease in magnetization is at least an order of magnitude faster than scientists previously believed, or on the order of about 20,000 years—not 500,000.

And Kent says it may be even faster than that. "It's conceivable that the alteration is so fast that it may not be relevant for dating," he says. Although this may mean that the magnetic alterations would be lost as an explanation for what is causing the seafloor spreading magnetic anomalies, what "we may be seeing is a surprisingly good signal of the Earth's field intensity," Kent says.

The finding has a great potential for developing a high-resolution map of an evolving seafloor, which begins to form at mid-ocean ridges and spreads outward. If all else fails, the finding may lead to the establishment of a new parameter to understand the dynamo of the Earth.

Reference

D. V. Kent and J. Gee, Grain size-dependent alteration and the magnetization of oceanic basalts, *Science*, 265, 1561, 1994.

Fig. 1. Photograph of the four types of spilled bathtub toy animals (blue turtle, yellow duck, red beaver, and green frog) compared with a pair of size 12 Nike shoes recovered from the previous spill. Photo credit: Bruce Rowland, Seattle.