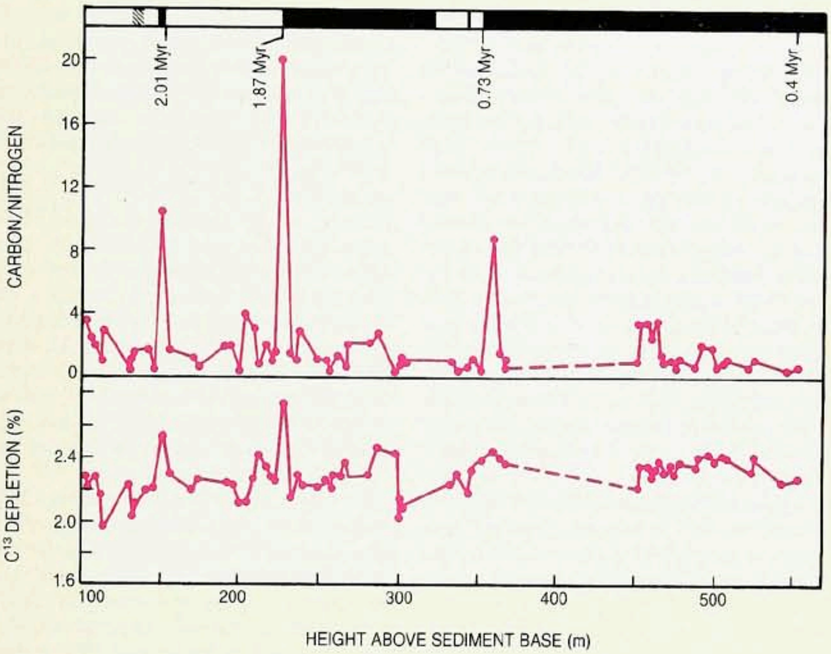
Do asteroid impacts trigger geomagnetic reversals?

It's been about 700 000 years since the last time the Earth's magnetic field reversed its polarity. Considering that the average over the last 30 million years has been about four geomagnetic reversals per million years, we're a bit overdue. But if Berkeley physicists Richard Muller and Donald Morris are right, the onset of the next reversal will be more than just an inconvenience to navigators. In the November issue of *Geophysical Research Letters*,[1] they make an intriguing, if rather speculative, case for the thesis that many, perhaps all, polarity reversals of the dynamo churning in our planet's liquid-iron outer core are caused by the impact of large extraterrestrial objects falling to Earth.

The Muller–Morris scenario, in brief, goes as follows: A sufficiently large asteroid or cometary nucleus hitting the Earth lofts enough dust to set off something like a "nuclear winter." The cold persists long after the dust settles because of the increased reflectivity of the snow-covered continents. In the course of a few centuries, enough equatorial ocean water is transported to the polar ice caps to drop the sea level about 10 meters and thus reduce the moment of inertia of the solid outer reaches of the Earth (crust and mantle) by a part in a million.

"That doesn't sound like much," Morris told us. "But when we realized that this translates into a full radian of slippage between mantle and core in just 500 years, we began to look seriously at the consequences." With the moment of inertia of the crust and mantle "suddenly" decreased, the argument goes, they begin spinning faster than the solid-iron inner core at the center of the Earth. The 2300-km-thick shell of liquid outer core that separates the mantle from the inner core thus acquires a velocity shear, which in the course of about a thousand years destroys the pattern of convective flows that served as the dynamo maintaining the Earth's dipole field.

The new, randomized flow pattern that comes into being twists and tangles up the pre-existing magnetic field lines, rapidly destroying the dipole field. Thus, until a new stable dynamo configuration establishes itself, perhaps 10 000 years later, the geomagnetic field is dominated by short-range higher-multipole components, so that one sees very little field at the Earth's surface. To the extent that the new dynamo has little or no memory of the old, its chance of having the same polarity as its predecessor is roughly 50:50. One would thus expect, on average, one reversal for every two major extraterrestrial impact events. Even when there is no ultimate reversal, the impact will have produced an "excursion," a 10 000-year hiatus with a much reduced surface geomagnetic field. This hiatus, Miller argues, serves to test his hypothesis against some of the competing models of spontaneous geomagnetic reversal.



Organic carbon/nitrogen ratio (upper curve) and carbon-13 isotopic depletion (lower curve), as functions of depth (age) in the exposed Karewa lake sediment in Kashmir, show sharp peaks remarkably coincident with three geomagnetic reversals in the last 2 million years.[3] The peaks are believed to indicate spells of unusual cold. Bars at top indicate magnetostratigraphy of the sediment: black (white) for periods of normal (reversed) geomagnetic polarity. Dates give estimated ages of reversal boundaries and top of sample in millions of years.

In 1905, Albert Einstein ranked the problem of geomagnetism as one of the five most important unsolved problems in physics. The problem is still "unsolved" today, in the sense that there is no detailed consensus as to how the Earth's dynamo works. Theories that attribute reversal to a bistability arising from the simultaneous action of two competing effective dynamos in the liquid-core flow, for example, predict sudden, spontaneous "snap" transitions from one polarity to the other. They would preclude the long, multipole-dominated hiatus anticipated by

Muller and Morris. It has recently become fashionable to think about planetary dynamos as chaotic fluid systems. Though one might expect that the spontaneous reversals characteristic of chaotic systems would always be sudden, dynamo theorist Willem Malkus (MIT) told us that chaotic models can exhibit extended pauses during reversal.

What does the geological record say? Sedimentary layers and once molten rocks record the polarity of the Earth's field at the time they were laid down or solidified, by the orientation of their ferromagnetic components. J.-P. Valet and coworkers at the Centre des Faibles Radioactivités in Gif sur Yvette, near Paris, have recently published a sea floor core analysis[2] displaying a geomagnetic reversal with extraordinary temporal resolution. Cores were analyzed every few centimeters in a region where the sedimentation rate was roughly 10 cm every thousand years. One sees clearly that the reversal is preceded by a sudden drop in the dipole field intensity in less than 2000 years, followed by a delay of about 20 000 years before the reversal finally comes. Both the rapid decay and subsequent hiatus, Muller and Morris write, "are predicted by our model, and inconsistent with [many] previous reversal models."

Tektites, those small glassy objects of varied shape and mysterious provenance, were prized as ornaments by our Cro-Magnon ancestors. Tektites have primarily been found littering four extensive "strewnfields"—both on land and in sea floor sediment. In recent years it has finally become the consensus among geologists that tektites have their origin in the melting and splattering of surface material when large extraterrestrial objects fall to Earth with great impact. Large impact craters have indeed been associated with three of the four known tektite strewnfields.

For the last 20 years, geologist Bill Glass and his colleagues at the University of Delaware have been documenting what appeared to be an extraordinary train of coincidences: Each of the three "tektite events" associated with craters seems to have occurred at just about the time of a geomagnetic reversal. Examining dozens of sea floor cores from the vast Australasian strewnfield, for example, Glass and company found that the microtektite abundance as a function of stratum depth in each core always peaked unambiguously within 20 cm of the magnetic boundary marking the last reversal, 700 000 years ago. (See the figure on page 19.) That is to say, the Australasian tektite event (for which there are several candidate craters on the Asian mainland) must have occurred within a few thousand years (either way) of the latest geomagnetic reversal. The third-most-recent reversal—some 950 000 years ago—is similarly seen to be coincident with the Ivory Coast strewnfield, which is associated with the Bosumptwi crater in Ghana. Before Muller and Morris came along, we had no plausible explanation for Glass's provocative observation that such striking coincidences hold for three of the four known tektite strewnfields.

The 24-km-diameter Ries crater in southern Germany, associated with the Czechoslovak tektite strewnfield, provides the most striking temporal coincidence of all, pointed out ten years ago by Jean Pohl at the Technical University of Munich. The magnetization of the Ries crater's fallback breccias, partially melted by the impact, tells us the polarity of the geomagnetic field at the moment of impact, 14.8 million years ago. The first sediments in the newly formed crater, however, indicate the *opposite* polarity. In other words, there must have been a reversal within the few thousand years between the impact forming the crater and the laying down of the first fine-grained sediment. The odds are 100 to 1 against this being a random coincidence.

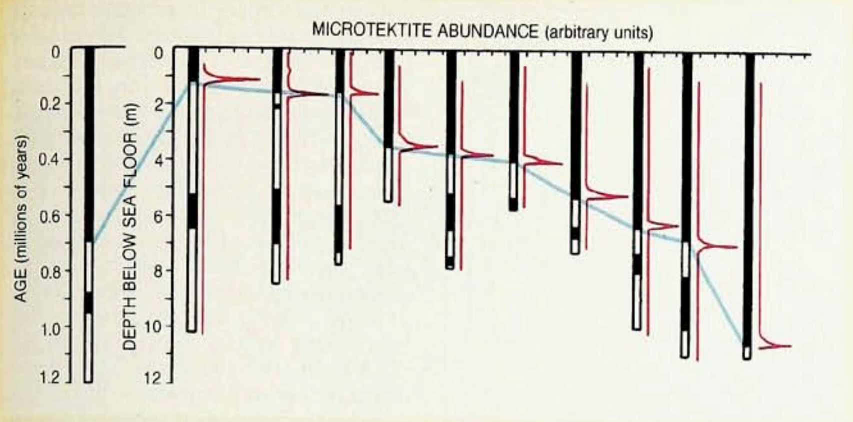
Climate. If the Muller–Morris explanation of these coincidences is correct, one should also find evidence for the abrupt climatic change that, in their scenario, couples the extraterrestrial impact to the subsequent disruption of the Earth's magnetic field. Very striking evidence of this kind was reported a few months ago by R. V. Krishnamurthy and his coworkers at the Ahmedabad Physical Research Laboratory in India.[3] The Karewa plateau in the Vale of Kashmir was once a vast lake. The geomagnetic reversals of the last few million years are precisely documented in the magnetostratigraphy of its deep sediment, now conveniently exposed.

Examining the carbon–nitrogen ratio of the organic component of this same sediment, Krishnamurthy and company found striking, narrow peaks rising an order of magnitude above background at precisely the times (depths) of three geomagnetic reversals, including the most recent. The nitrogen concentration is taken to be a measure of the protein-rich plankton and algae population of the lake water, so that C/N becomes something of a paleothermometer, peaking when unusual cold reduces this population. (See the figure on page 17.) The C/N findings are corroborated in the Karewa sediment by the coincident, if less spectacular, peaking of the isotopic ratio C^{13}/C^{12}, another paleothermometer.

In the calculation of Muller and Morris, a sea-level drop of 10 meters in a few centuries is sufficient to trigger a reversal. Do such abrupt drops happen often enough, and can we correlate them with the times of the reversals? Some 300 geomagnetic reversals have been recorded for the last 170 million years, with a conspicuous dearth in the interval from 110 million to 75 million years before the present. For this same 170-million-year period, about 30 abrupt sea-level drops of 10–200 meters have been documented. (See the figure on page 20.) This is thought to be only a small fraction of the steep drops that actually occurred, and they have not yet been timed with sufficient precision to say how individual drops relate to individual reversals. But when one plots the rough time distribution of known sea-level drops, one finds the same dearth of occurrences in the period around 100 million years ago that characterizes the distribution of reversals.

During that period the seas were significantly warmer than they were in more recent epochs. All this makes sense in the Muller–Morris scheme. When the seas are unusually warm it takes an especially great impact event to make enough ice to produce the requisite speeding up of the crust and mantle. But what about the last million years, when there have been lots of ice ages and very few reversals? The sea-level changes accompanying the recent ice ages are relatively well documented, and most of them do not seem to be abrupt enough for the purposes of Muller and Morris. Ten years ago, Christopher Doake of the British Antarctic Survey did, in fact, suggest that changes in the Earth's spin rate due to the onset or termination of ice ages might trigger reversals. But he did not propose a mechanism for such reversals.

The dynamo. There being no consensus on how the Earth's dynamo works in detail, Muller and Morris claim to base their argument on quite general considerations, not depending on the validity of any specific geomagnetic model. A dynamo is a system of conductors moving in a magnetic field in such a way that the current thus induced provides a positive feedback sufficient to cause an initially weak field to grow exponentially—up to some equilibrium limit. This is easily accomplished if one allows a topology as complex as a homopolar Faraday dynamo. But the problem of planetary dynamo theory is that one must make do with a much simpler topology—in



Microtektite abundance (red curves) as a function of depth (age) in ten sea-floor cores (with different, variable sedimentation rates) from the Australasian strewnfield. Vertical bars show magnetostratigraphy for each core: black (white) for normal (reversed) geomagnetic polarity. Microtektite abundance for each core shows a striking peak very close to the time of the last geomagnetic reversal, 0.7 million years ago, suggesting that the reversal is related to the impact event that produced and scattered the microtektites. Bar at left shows geomagnetic epochs linearly against time, with blue line connecting the 0.7-million-year-old reversal boundary on the different cores. (Data of B. Glass *et al.*)

our case, just a shell of flowing liquid conductor (mostly iron, one assumes) extending outward from the solid-core boundary, 1200 km from the center of the Earth, to the solid-mantle boundary, 2900 km below the Earth's surface. The liquid metal flows in a complex pattern determined by convection, the Coriolis force and the magnetic field itself. The challenge to the theorists is to solve this highly nonlinear flow problem. Computer simulation nowadays seems to offer the greatest promise. Dynamo action requires that the magnetic analog of the Reynolds number exceed some critical value. Because this dimensionless parameter is proportional to the product of the typical flow velocity and linear dimension of the system, a planetary dynamo is well-nigh impossible to simulate in a small-scale physical experiment.

An extraterrestrial intruder 3 km in diameter, Muller and Morris point out, would hit the Earth with a kinetic energy of 10^{29} ergs—enough, they contend, to initiate a climatic sequence that would lower the sea level by 10 meters and thus spin up the crust and mantle by a part per million in a time too short for isostatic adjustment of the moment of inertia of the Earth as a whole. The inner boundary of the mantle at the equator would speed up by about 0.03 cm/sec.

The result, they tell us, will be the creation of a velocity shear in the liquid core. The diurnal circulating angular velocity of the liquid will increase with distance from the inner-core boundary until it matches that of the mantle. For a long time the spin of the small solid inner core will continue to lag. The mechanical viscosity of the hot liquid metal is far too small to sustain such a velocity shear field across a radial distance of several thousand kilometers. Were it not for the effective "magnetic viscosity" that couples the liquid metal to the existing field lines, the bulk of the liquid would largely ignore the speed-up of the mantle above it.

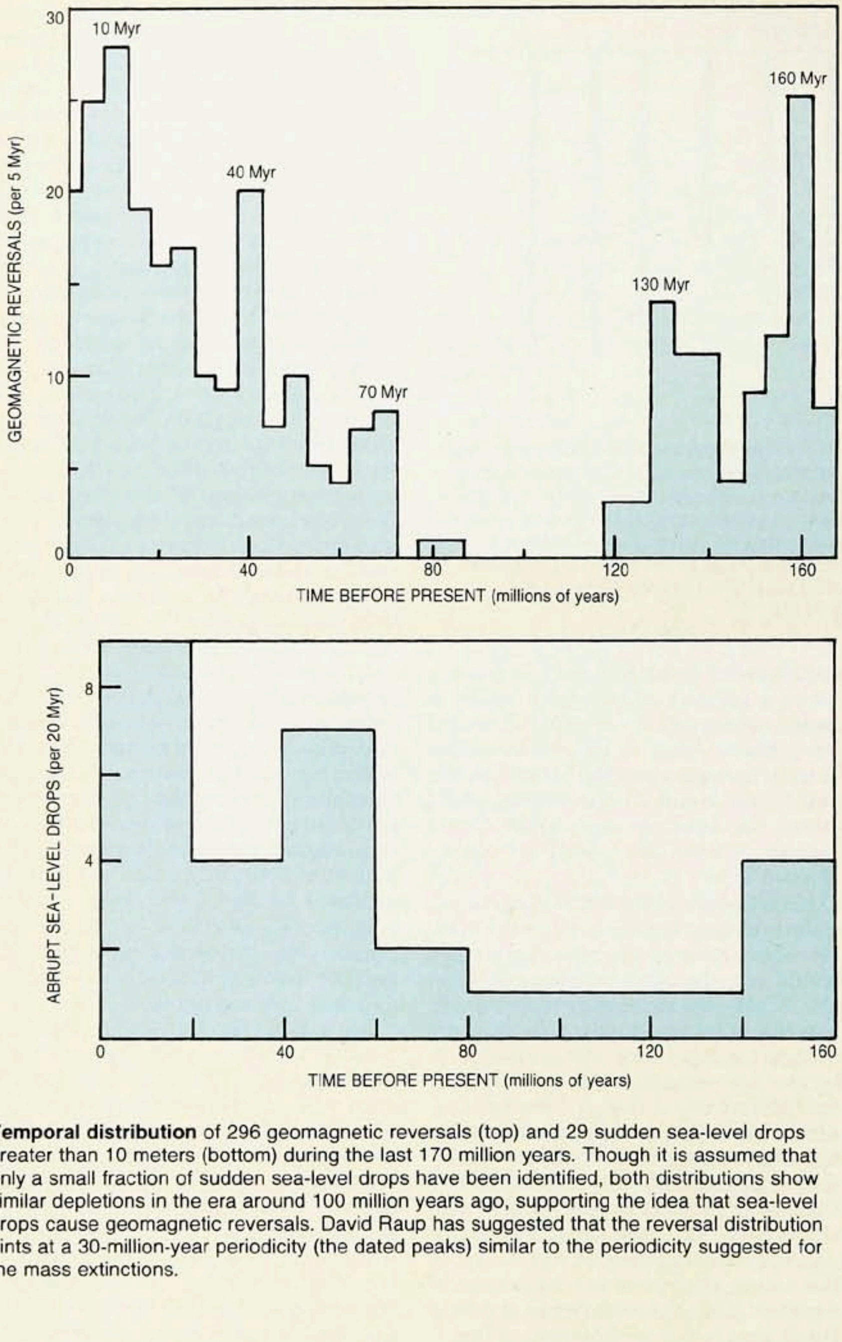
If, on the other hand, the electromagnetic coupling between core and mantle is too strong, the spun-up mantle would transfer angular momentum to the liquid core so quickly that a shear velocity field would disappear in short order. Extrapolating the surface field to the core–mantle boundary, Muller and Morris argue that the electromagnetic coupling is neither too strong nor too weak to maintain the shear velocity field their scenario requires. Dynamo theorist Friedrich Busse (UCLA and University of Bayreuth), however, points to the millisecond variations of the length of day we see on a scale of decades. These observations suggest to Busse that the core–mantle coupling is probably stronger than Muller and Morris would like. "On the other hand," Busse told us, "their scenario is not out of the question. It's the most plausible proposal anyone has come up with—but it's marginal."

In pre-impact equilibrium, the interaction of radial convection transport with the Coriolis and Lorentz forces will have established a set of convective flow cells. For a simplified heuristic picture, one might invoke Busse's recent magnetohydrodynamic computer simulations. Looking down at the equatorial cross section of the Earth, one would see perhaps half a dozen convection vortices arrayed around the liquid-core annulus, carrying lower-density liquid away from the inner core and denser liquid back down. A round trip takes perhaps a thousand years. The buoyancy may be of thermal origin, or it may be due to phase segregation as liquid solidifies at the inner-core boundary. Adjacent vortical cells will have opposite senses of rotation. This is a particularly simple solution, invoked as a basis for discussion. For different parameters one gets less stable, perhaps even chaotic, solutions.

When a sudden speeding up of the mantle imposes a shear flow on this nicely ordered convection flow, the disruption is mortal. The 0.03 cm/sec speed-up of the mantle after a 10-meter sea-level drop, Muller emphasizes, is quite comparable to the pre-existing flow velocities. Orderly buoyant transport depends on columns of liquid with neat, monotonic density variation with distance from the center. The shear field now converts the more or less vertical columns into extended curving arcs, stretching to the east as they encounter the faster shear flow near the mantle. As the shape of the convective cells is severely distorted by the shear flow over a few hundred years, the density distribution no longer supports the previous flow, and the convective engine becomes ineffective. "A blob of high-density liquid will now be confused to find lower-density liquid both above and below it," Morris explains. The convective velocities fall, and the source of kinetic energy for the dynamo is interrupted.

As a new flow pattern establishes itself, it tangles the previous magnetic field lines so badly that the dipole is destroyed in a few hundred years—a hundred times faster than the free decay time of the dynamo.

Extinctions. Muller is no stranger to theories that invoke extraterrestrial *dei ex machina*. Three years ago he was one of the principal proponents of the idea[4] that the great extinctions—for example, the disappearance of the dinosaurs 64 million years ago—occur with a roughly 30-million-year periodicity caused by "Nemesis," a supposed binary sister of our Sun. The present paper does not invoke this controversial hypothesis, but David Raup (University of Chicago) has pointed out[5] that the frequency distribution of the last 300 reversals suggests something like the 30-million-year periodicity he had earlier proposed for the mass extinctions. Nemesis is imagined to do its deadly work by perturbing the Oort cloud of 10^{13} comets orbiting quietly in the outer reaches of our Solar System, thus greatly increasing the rate of serious collisions with the Earth every 30 million years or so.



Temporal distribution of 296 geomagnetic reversals (top) and 29 sudden sea-level drops greater than 10 meters (bottom) during the last 170 million years. Though it is assumed that only a small fraction of sudden sea-level drops have been identified, both distributions show similar depletions in the era around 100 million years ago, supporting the idea that sea-level drops cause geomagnetic reversals. David Raup has suggested that the reversal distribution hints at a 30-million-year periodicity (the dated peaks) similar to the periodicity suggested for the mass extinctions.

Glass and company have also noted apparent correlations between the tektite events and more recent extinctions. A nuclear winter, it seems, is not just unhealthy for planetary dynamos.

The great Cretaceous–Tertiary extinction that deprived us of the dinosaurs does not seem to have been accompanied by a geomagnetic reversal. Muller reminds us, however, that only half of the great impacts produce reversals in his scenario. But it is not yet known whether this geological boundary was coincident with a geomagnetic excursion. He suggests that one ought to take a closer look. Additional tests proposed by the authors include looking in other craters for reversals like that documented in the sediment of the Ries crater. They also look forward to more precise dating of the sudden sea-level drops. Major sea-level falls do tend to be more abrupt than are corresponding rises.

To achieve a sufficient sea-level drop in a particularly warm epoch would require an especially great impact event, with a correspondingly great worldwide deposition of fallout. Therefore it is at such warm-epoch geomagnetic reversals, Muller and Morris suggest, that one has the best chance of finding a stratum laced with telltale shocked quartz or iridium. An excess of iridium in the Cretaceous–Tertiary boundary layer was the clue that started Luis Alvarez and his Berkeley colleagues thinking in 1979 about an extraterrestrial cause for the dinosaur extinction. (See PHYSICS TODAY, May 1982, page 19.) Meteors contain a much higher concentration of iridium than does the Earth's crust.

A mass extinction, in these scenarios, requires only enough summerless years—two might suffice—to starve out an important group of herbivorous animals, and subsequently those who prey on them. A geomagnetic reversal asks more—a much longer period of global cooling, enough to initiate a sufficiently abrupt and deep sea-level drop. Would an impact have such centuries-long climatic consequences? "Although many experts believe these assumptions to be plausible," write Muller and Morris, "there is not yet a consensus that they are true."

The aftermath of a nuclear war might provide relevant data. Conversely, a sudden rise in sea level, due to the melting of the polar ice caps in consequence of the unchecked increase of atmospheric CO_2, might trigger a geomagnetic reversal by slowing down the mantle, the authors point out. "We do not recommend that either of these experiments be carried out to test our prediction."

Malkus, who is organizing a summer school on planetary dynamos this summer at Woods Hole, Massachusetts, finds the geological data intriguing, but he is not persuaded by the proffered explanation. Most dynamo models, he told us, are known to enter chaotic states, in which they are rather insensitive to noise. Such states are characterized by spontaneous reversals. A perturbation from outer space might trigger an occasional reversal, "but the reversal would have happened without such prompting, sooner or later."

Muller responds that in their paper they "don't contend that *all* reversals are due to impacts. We're trying to account for the astonishing coincidences presented by the geological record."

—Bertram Schwarzschild

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