The Compass in the Ice

Everyone knows that a freely-moving magnetic needle will align itself to north, making it rather useful for finding one's way in unknown areas or when visibility is poor. The principle of the magnetic compass has been known for more than a thousand years, and has been of inestimable value to navigators. Even migratory birds and other animals seem to have an inbuilt compass which permits them to home in on their destinations with uncanny precision. However, a compass several thousand years ago would not have pointed to the north pole; throughout the earth's history, the geomagnetic field has reversed its polarity again and again.

Even though the earth's magnetic field, or geomagnetic field (Fig. 1) has been investigated in detail for more than 300 years, Einstein referred to it as one of the greatest unsolved mysteries of science. Since then many outstanding questions regarding the origin and alignment of the geomagnetic field (Fig. 2) have been answered (see box). However, the reason why the polarity of the magnetic field has reversed itself on a number of occasions throughout earth's history is still a riddle (Fig. 3). Before an answer to this riddle can be found, the polarity and strength of the magnetic field must be reconstructed as far back in time as possible. EAWAG has been able to show that the measurement of radioisotopes in ice cores represents a new method of calculating the geomagnetic field.

Paleo Records Reveal the Earth's Magnetic Field

Traditionally, paleomagnetists use sediments and volcanic rock to reconstruct the geomagnetic field. In sediments, it is the magnetic particles which have been deposited layer by layer throughout the past that are of interest. As long as these particles remained mobile within the sediment, they would align themselves with the magnetic field like a compass needle. The stronger the magnetic field, the more they display this characteristic. This allows the direction and intensity of the earth's past magnetic field to be determined from sediment cores. Similarly, volcanic rock reveals the past through the outpouring of high temperature rock mass from deep within the earth's interior during a volcanic eruption. So long as the lava is fluid, it is not magnetizable. Only during cooling do ferro-magnetic particles align themselves with the geomagnetic field.

These methods of geomagnetic field reconstruction are most applicable when the magnetic field was strong, the sediment homogeneous and rich in magnetic particles, and the recorded magnetic field not disturbed subsequently by other processes.

Origin, Orientation and Strength of the Geomagnetic Field

The earth is surrounded by a magnetic field (Fig. 1). The origin of this magnetic field lies in the convection fluxes of fluid iron in the earth's center: as in the case of water, hot iron rises to the outside and cold iron sinks to the center.

The direction of the axis of the magnetic field does not correspond to the earth's axis; i.e. the magnetic poles do not coincide with the geographic poles (Fig. 1). In addition, the magnetic poles are continually migrating. In the last 2000 years, the magnetic north pole has shifted thousands of kilometers over the Arctic (Fig. 2). About 300 years ago it reached Greenland. Today it lies in Canada, and it is unclear where it will go in the future.

Not only has the orientation of the magnetic field varied over time, its strength has done likewise. Of particular interest is when the field strength approaches zero. In this case, when the field intensity increases again, a reversal of polarity can occur, meaning that the magnetic north pole is suddenly in the southern hemisphere, where it usually remains for several hundred thousand years before flipping back again to the northern hemisphere. The timing of a reversal does not appear to follow any particular pattern, and is, therefore, impossible to foresee. The last reversal of polarity, the so-called Brunhes-Matuyama polarity reversal, occurred some 780,000 years ago (Fig. 3).

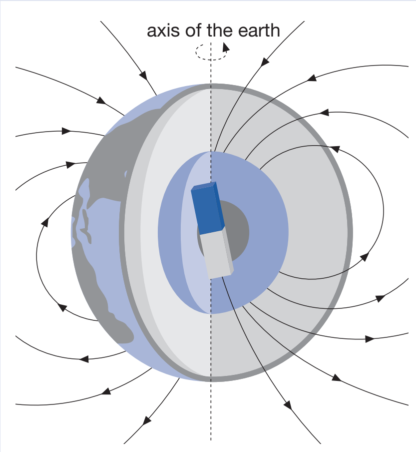

Fig. 1: The geomagnetic field can be depicted in simplified form as a dipole field produced by an imaginary bar magnet located at the earth's center. This bar magnet is slightly askew with respect to the earth's axis of rotation.

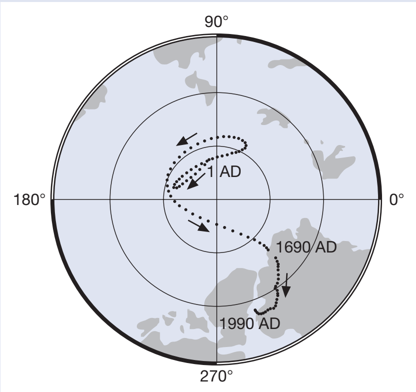

Fig. 2: Migration of the magnetic north pole through the Arctic during the last 2000 years [1]. The migration continues.

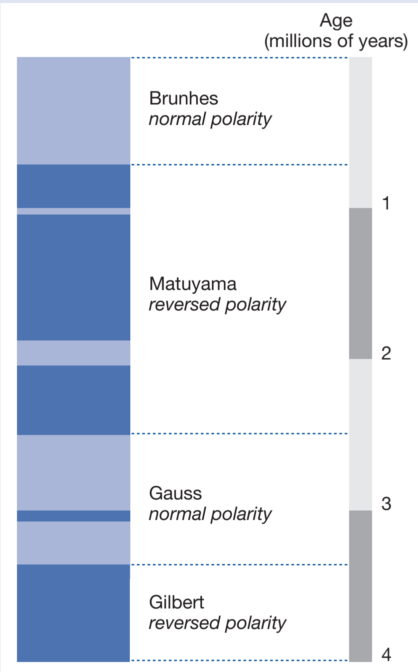

Fig. 3: Reversals of the polarity of the geomagnetic field over the past 4 million years. In the light-blue time periods the polarity was the same as today; in the dark-blue periods the polarity was reversed. Some epochs are named after researchers dedicated to solving the riddles of the geomagnetic field.

The Radioisotope Method

The new radioisotope method is based on the analysis of polar ice cores. Although this ice consists almost entirely of only the purest of water, and contains effectively no magnetic particles, it can nevertheless reveal invaluable information concerning the history of the geomagnetic field. This information can be read from the trace amounts of radioisotopes, such as beryllium-10 (^{10}Be) and chlorine-36 (^{36}Cl), found in the ice. A strong geomagnetic field shields the earth from cosmic radiation, reducing the production of radionuclides. When the magnetic shield is "switched off", however, the global nuclide production rate more than doubles. If we assume that the slow change in ^{10}Be and ^{36}Cl found in the ice is caused by the magnetic field, and that the faster solar variations are averaged out, then we have at our disposal a new, completely different method of reconstructing the historical strength of the geomagnetic field. It differs from the traditional methods in that its sensitivity actually increases with decreasing field strength. Another advantage of this new method is that it is hardly affected at all by local variations in the magnetic field.

Is the Radioisotope Method Reliable?

In order to assess whether the radioisotope method does in fact produce reliable results, we have made a direct comparison of the two methods. Figure 4 shows the magnetic field strengths as reconstructed from ^{10}Be and ^{36}Cl concentrations in the GRIP ice core from Greenland [2], and from traditional measurements of Mediterranean Sea sediment cores [3]. Apart from a few digressions, the results of the two methods agree well. The radionuclide measurements, for example, confirm that the earth's magnetic field weakened about 40,000 years ago to around 10% of its current strength. However, just before a reversal of polarity could occur, it returned to its old state.

The radioisotope method has therefore passed its baptism of fire. In the future, it can be used to analyze the entire time range covered by ice cores and sediment cores, thereby making it possible to reconstruct the geomagnetic field back to about one million years ago.

And what about the future? When can we expect a new reversal of polarity? For about 2000 years the magnetic field strength has decreased continuously, so if the rate remains constant we will experience another magnetic polarity reversal within about another 2000 years. We humans will not notice this, but for migratory birds, which rely on the geomagnetic field for orientation, it is unclear what effect this will have on their ability to find their destinations.

Jürg Beer, portrait on page 5.

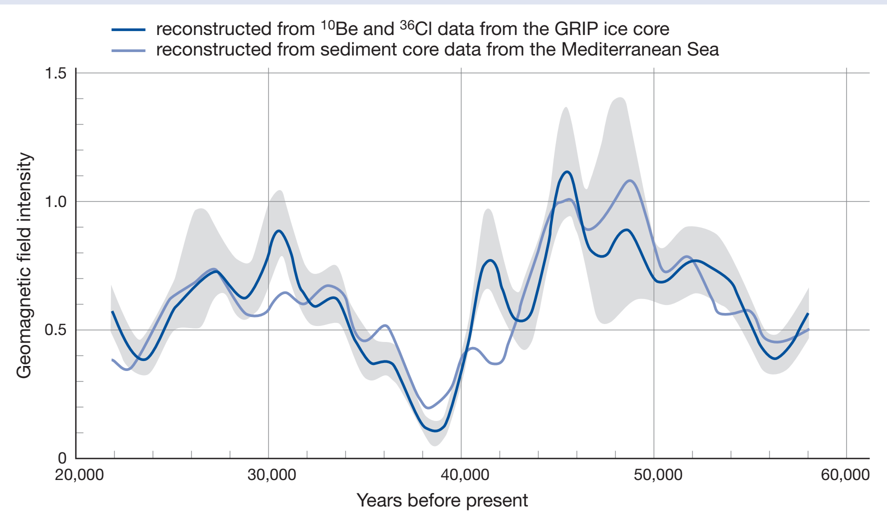

Fig. 4: Reconstruction of the geomagnetic field strength over the time period 20,000–60,000 years before present. Comparison of the radioisotope method (dark-blue curve: combined ^{10}Be and ^{36}Cl data from the GRIP ice core [2]) with traditional methods (light-blue curve: orientation of magnetic particles in a sediment core from the Mediterranean Sea [3]). The gray band represents the range of uncertainty of the radioisotope method. The range of uncertainty of the traditional method is not shown.

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[2] Wagner G., Masarik J., Beer J., Baumgartner S., Imboden D., Kubik P.W., Synal H.-A., Suter M. (2000): Reconstruction of the geomagnetic field between 20 and 60 kyr BP from cosmogenic radionuclides in the GRIP ice core. Nuclear Instruments and Methods in Physics Research B *172,* 597–604.
[3] Tric E., Valet J.P., Tucholka P., Paterne M., LaBeyrie L., Guichard F., Tauxe L., Fontugne M. (1992): Paleointensity of the geomagnetic field during the last 80,000 years. Journal of Geophysical Research *97,* 9337–9351.