The Earth's Magnetism

The fact that the grains of ancient rocks are lined up like tiny compass needles has led to the astonishing conclusion that the earth's magnetic poles have wandered and reversed

by S. K. Runcorn

The magnetic field of the earth was the subject of one of the earliest treatises ever written on experimental science: *De Magnete*, published in 1600 by the English physician William Gilbert, who is sometimes called the father of electricity. By then it was known that a magnetized needle not only tended to point north but, if free to move vertically, would also dip in the Northern Hemisphere and point above the horizon in the Southern Hemisphere. Seeking to explain this behavior, Gilbert had made a sphere of loadstone and tracked its magnetic lines of force with dip needles. The needle's pointings and dips over this model followed approximately the scheme of its behavior in traveling over the surface of the earth. From which Gilbert concluded that the earth acted like a large magnet.

How was it magnetized? From century to century this became an ever more baffling riddle. Gilbert naturally inferred that the interior of the earth was made of a magnetic material. But scientists eventually realized that the core of the earth was much too hot to be permanently magnetized. And this problem was dwarfed by others far more subtle. In the first place, the axis of the magnetic field apparently was not the same as the axis on which the earth rotated: it was tipped so that the magnetic north pole was hundreds of miles away from the geographic North Pole. In the second place, systematic surveys over the earth showed that the compass deviated from true north in a most irregular fashion. Further, the pattern of the magnetic field was found to be changing over the centuries. There could be only one conclusion: the interior of the earth, where its magnetism was generated, was not rigid as had been thought. It must be in dynamic flux. As a famous geomagnetician of the early 19th century, Christopher Hansteen, truly said: "The earth speaks of its internal movements through the silent voice of the magnetic needle."

Let us see what the needle has to say. The strength of the earth's magnetic field, as measured by the force needed to deflect a compass needle from its preferred direction, is very small. At its strongest, near the poles, the field is several hundred times weaker than that between the poles of a toy horseshoe magnet. In general the needle tends to line up along north-south arcs around the earth, dipping down toward the ground near the north magnetic pole and pointing upward near the south pole [*see upper chart on opposite page*]. But there are very few places on earth where the needle actually points precisely to the true north. Its direction varies from region to region, so that the field seems to be full of irregular eddies. Over the long run the field is also changing in strength and direction. This secular change has been recorded at magnetic observatories for more than 400 years.

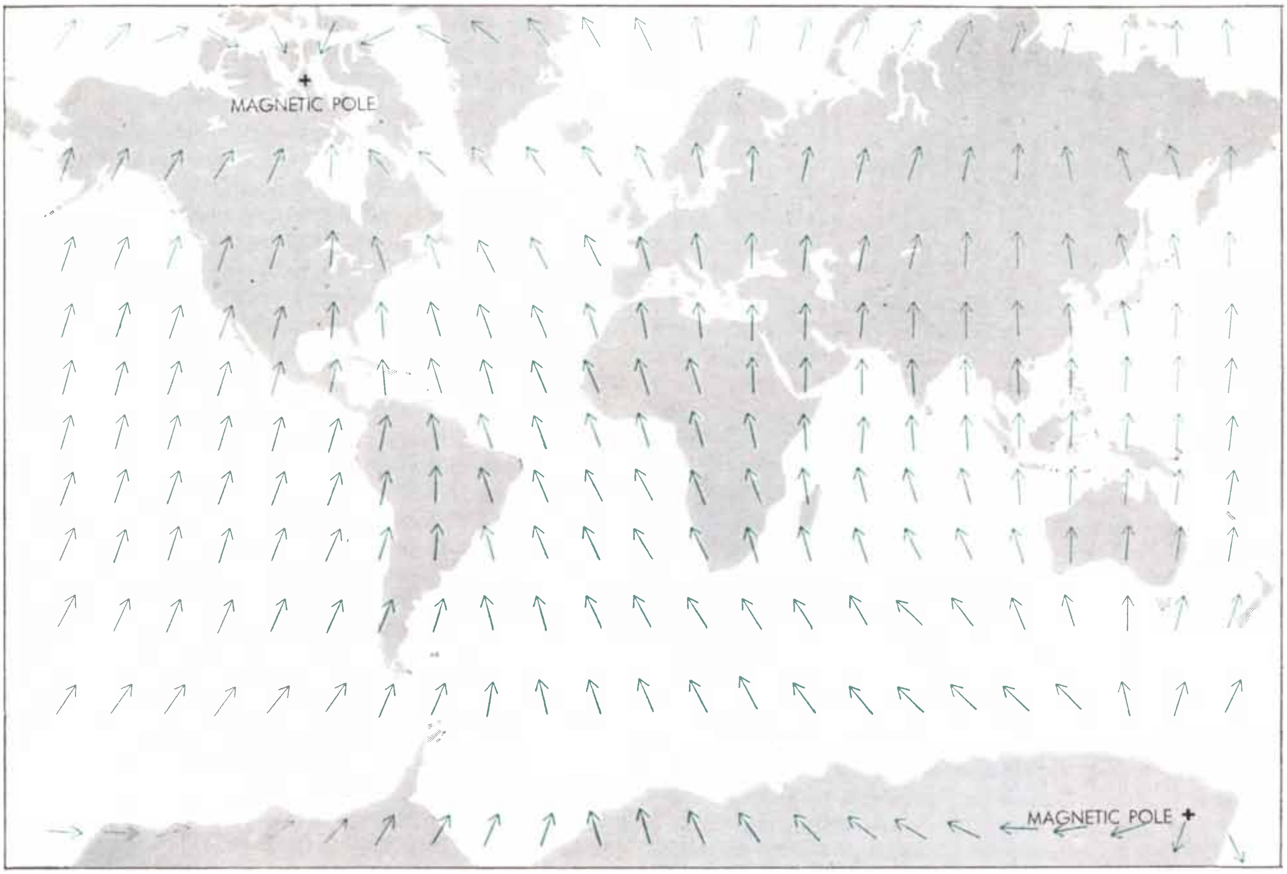
We now have many reasons to believe that the earth's field is made up of two components. First, there are constant lines of magnetic force which are always lined up with the earth's axis of rotation. Second, this main field is modified by other lines of force, produced by some different mechanism within the earth, which vary irregularly over the earth and change with time. We call the irregularities the "residual" field: it is measured by subtracting the main axial field from the actual field as traced by the compass. If we plot these differences over the earth—the amount of deviation from the main field in direction and strength at various places—we obtain a picture which represents the residual field [*lower chart on opposite page*].

Thus the compass readings suggest that the earth is magnetized in two different ways. It has a primary magnetism which is related directly to the earth's rotation. It also has shifting secondary magnetisms which are superposed on the primary force.

Observations made over the years tell us something about the nature of the changes in this secondary or "residual" magnetism. The residual field is slowly moving westward around the earth. And the pattern itself (the direction and intensity of the residual magnetism at various points) changes rapidly—within decades, years or even months. The residual field may be likened to a formation of moving clouds: it is continually changing in form and also drifting as a whole. The drift has been steadily westward throughout the centuries of observation. At the rate it has been moving, the residual field would travel full circle around the earth in about 1,600 years. For an effect connected with the "solid" earth, this is an astonishingly rapid evolution.

When we look farther into the earth's magnetic history, a still more remarkable story unfolds. In the past few years it

MAGNETIC FIELD of the earth is represented in the two charts on the opposite page. The top chart shows the total field, which has a regular component, as might be produced by a bar magnet in the earth's core, and an irregular component. The bottom chart shows the irregular component alone. This is obtained by subtracting a uniform north-south field from the total observed field. In the top chart the arrows indicate the direction in which a compass needle would point. In the bottom chart they indicate how it would point if there were no axial field.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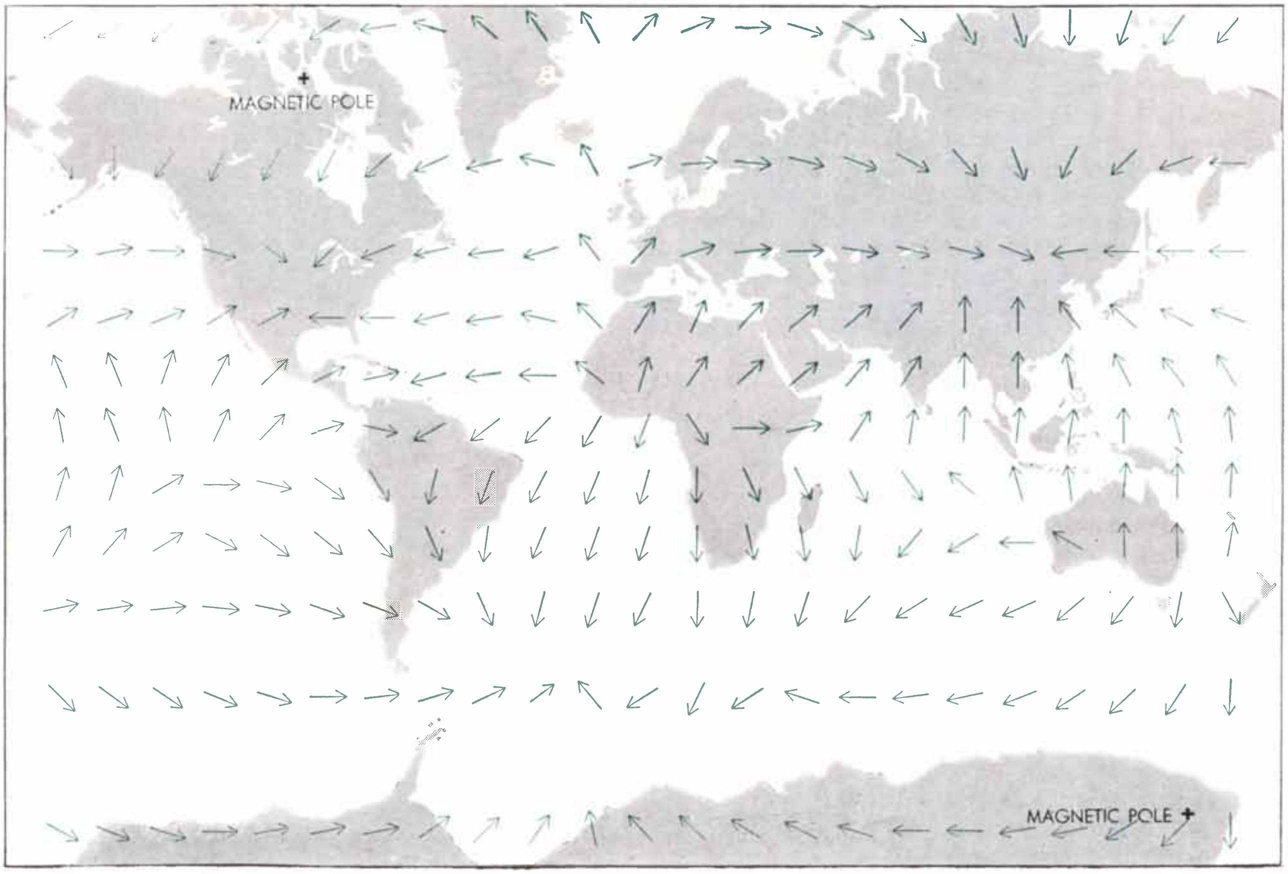
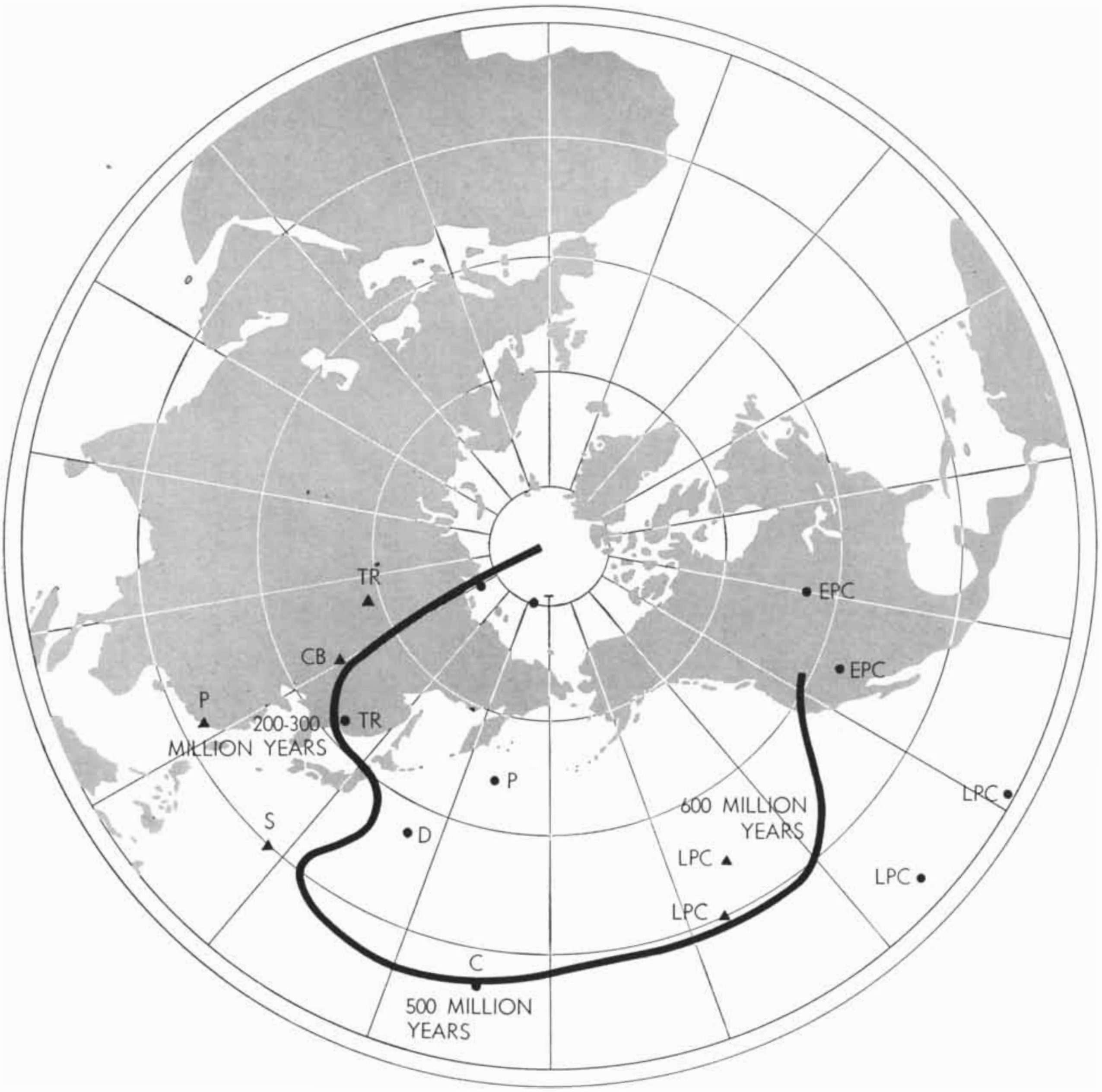
MAGNETIC POLE


MAGNETIC POLE
MAGNETIC POLE

has become possible to read the magnetic record for millions of years by means of certain natural compass needles which nature has frozen into the rocks. The needles are grains of magnetic iron oxide minerals, such as hematite (Fe_2O_3) and magnetite (Fe_3O_4). At high temperatures atoms of these minerals readily line up along a weak magnetic field. Thus when hot, molten lava first pours out on the surface from a volcano, its iron mineral grains become magnetized in the direction of the local geomagnetic field. After the grains cool, their magnetization can no longer be influenced appreciably by any change in the earth's field. Consequently the grains are magnetic fossils, recording the direction of the earth's field at the time the rock was formed. In certain parts of the world lava flows, piled upon one another in hundreds of layers, provide a veritable calendar of magnetic history. Iceland and the northwestern U. S. are rich in such deposits, some of them exposed in the walls of canyons.

Sedimentary rocks also may contain magnetic records. After magnetized particles were eroded from old volcanic rock, they would tend to line up along the earth's field when they settled in sediments. When the beds hardened into rock, the magnetic particles would be fixed in the direction of the field at the time.

Reading these magnets in rocks at various places around the world, we find evidence of astounding changes in the earth's main axial field. During the Tertiary period (between 60 million and one



APPARENT WANDERINGS of the North Pole are roughly traced by the heavy line on this map. The points on which the line is based are represented by dots and triangles. The dots refer to positions of the pole derived from the magnetization of rocks in the British Isles; the triangles, to positions derived from the magnetization of rocks in North America. The ages along the line indicate that the pole was near that position at that time. The letters refer to the positions of the pole in geologic periods: EPC, Early Pre-Cambrian; LPC, Late Pre-Cambrian; C, Cambrian; S, Silurian; D, Devonian; CB, Carboniferous; P, Permian; TR, Triassic; T, Tertiary.

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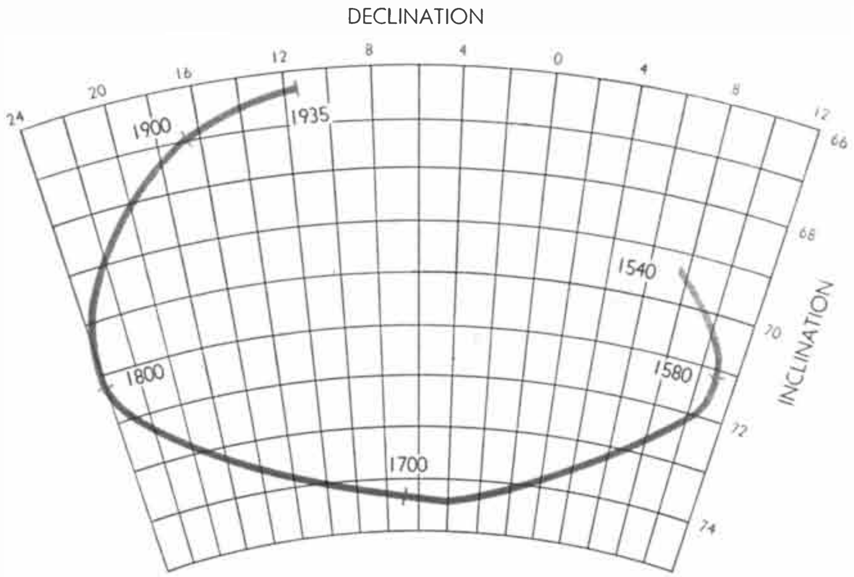


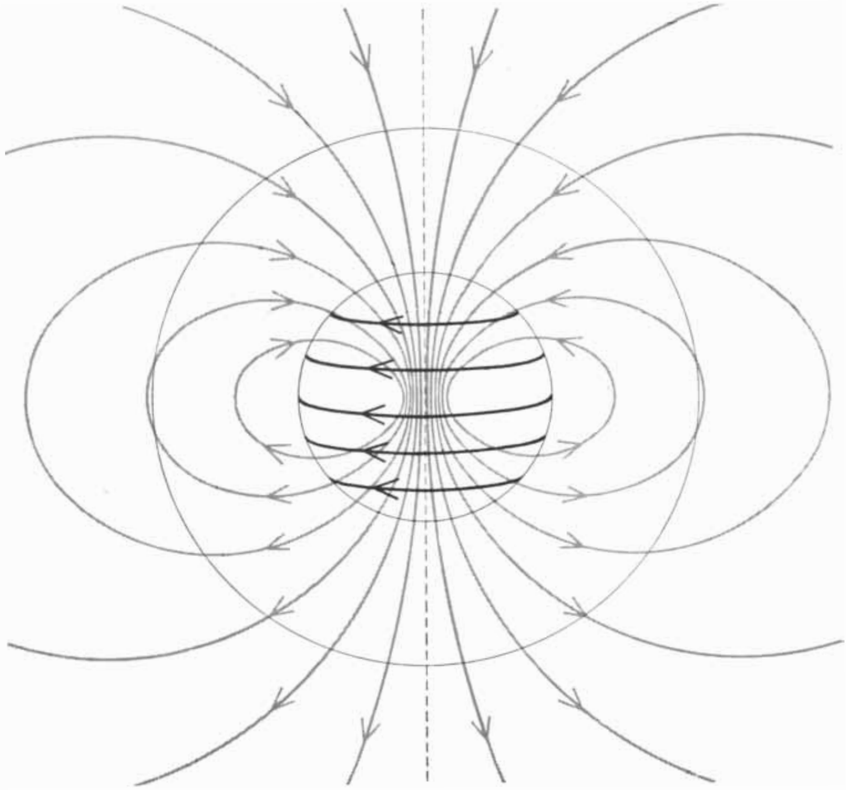
WESTWARD DRIFT of the irregular part of the earth's main magnetic field is clearly reflected by observations made in London. The north pole of a magnet, freely suspended to swing both horizontally and vertically, would have traced out the gray curve. Each date marks the point on the curve that gives the directions of the compass needle in that year.

million years ago) the north and south geomagnetic poles reversed places several times! It appears from the evidence of lava layers that after hundreds of thousands of years of stability the field would suddenly break up and reform with opposite polarity.

It should be said that not all students of geomagnetism accept this interpretation of the geologic records. Some prefer to believe that the iron oxide grains somehow reversed their magnetic directions independently of the earth's field. But the more rocks and locations we examine, the more the evidence accumulates that the earth did reverse its field many times.

So our attempts to explain how the earth's magnetism is generated must account for two types of fluctuation: the

LAYERS OF ROCK in Grand Canyon comprise a record of the local magnetic field at the time they were deposited as sediments. Their magnetic particles lined up with the field.

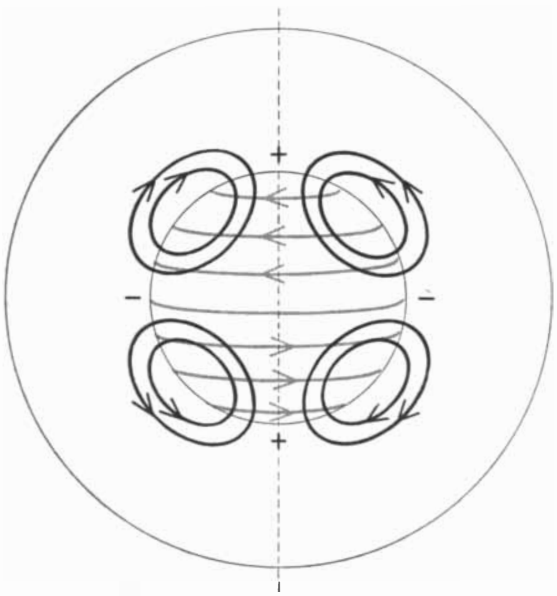


AXIAL DIPOLE FIELD of the earth is indicated by the gray lines. The electric current flow which could produce it is shown by the black lines following the surface of the core.

shifts of the main field and the secular variations of the residual field.

More than a century ago the great German mathematical physicist Karl Friedrich Gauss proved beyond question that the magnetic field must originate inside the earth. Today there can no longer be much doubt that it is generated by electric currents due to motions of material in the interior. The first suggestion as to how movements in a liquid core might explain the changing field came in 1939 from the physicist Walter M. Elsasser.

As a start, let us imagine that the earth's main magnetic field is produced by the system of electric currents in the conducting nickel-iron core pictured in the upper illustration on this page.



ELECTRIC MODE FIELD of magnetism is present within the earth's core, as shown by the gray lines. The lines of current necessary to support this field are indicated in black.

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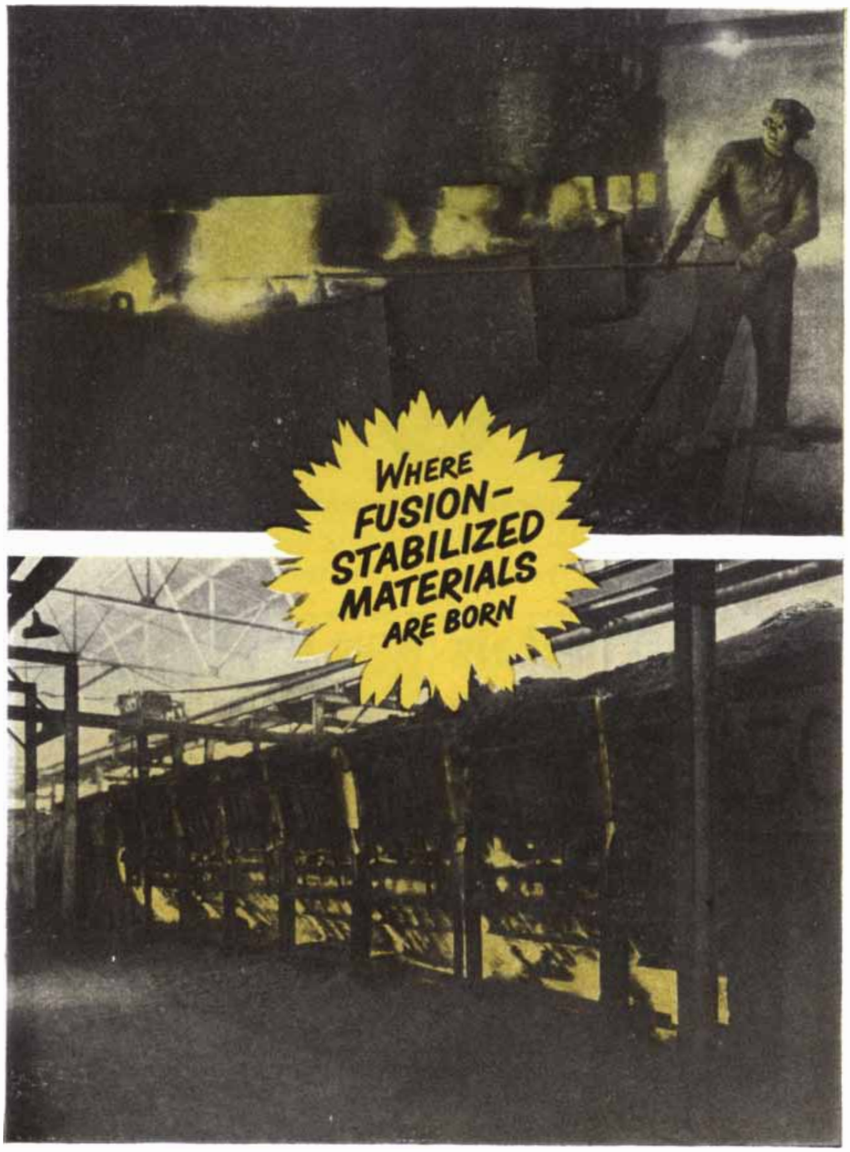

Above: Norton arc-type furnaces. *Below:* Norton resistance-type furnace.

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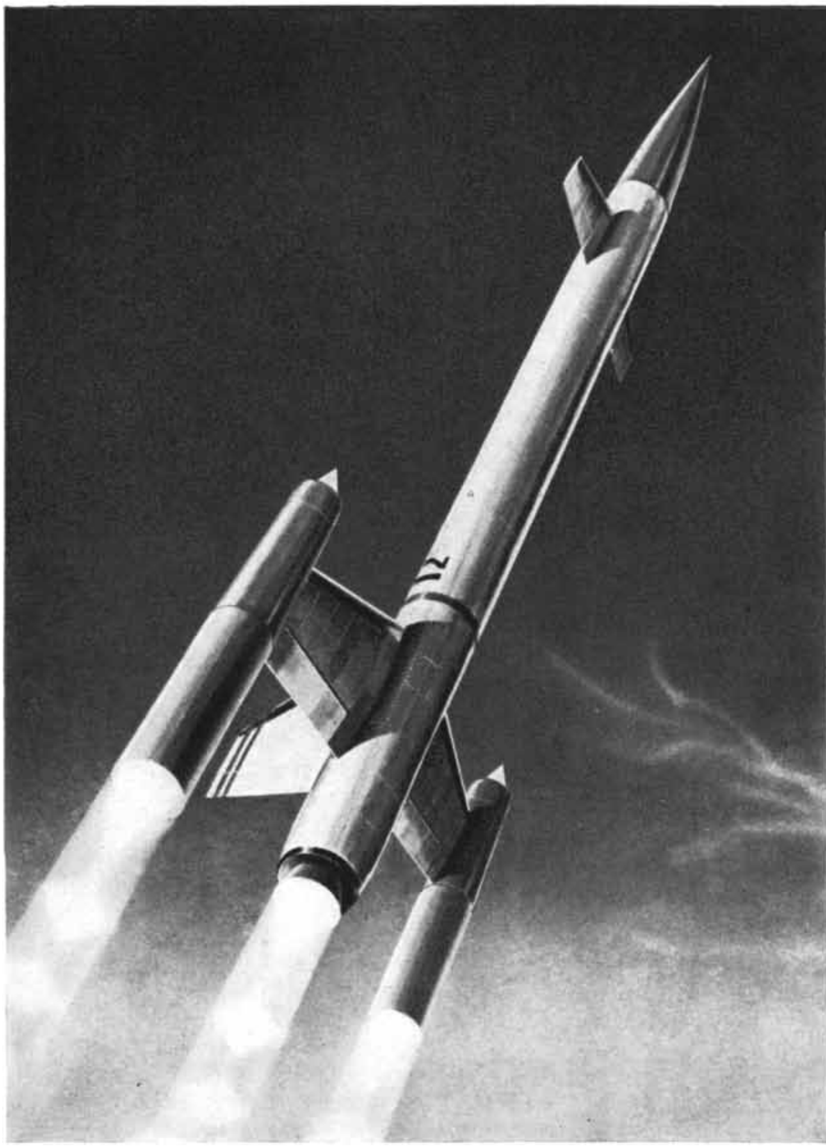
Convection motions within the fluid core might set up local eddies or whirlpools. Secondary electric currents generated in these areas would then generate a number of irregular magnetic fields, constituting the residual geomagnetic field. Changes in the unstable fields would be rather slow, because the extremely dense fluid of the core is much more sluggish than familiar liquids. Such a model would account for the geographical variations and the slowly changing pattern of the earth's residual field.

As for the westward drift, if our picture of the generating mechanism is correct we must suppose that the core of the earth is turning within the mantle around it. That is to say, the core is rotating from west to east more slowly than the mantle. There is good astronomical evidence for such a surmise. The speed of the earth's spin is not constant: very accurate measurements indicate that the time of its daily rotation varies continually by a minute amount. But the law of angular momentum says that if the rotational speed of the earth's surface changes, there must be an offsetting change of speed somewhere within. Thus if the mantle speeds up, the core must slow down, and *vice versa*.

The simplest way to account for these changes in speed is to suppose that the core and the mantle exert a force on each other which is produced by electric currents. (The effect would be analogous to that between the rotating armature and the field coils of an electric motor.) Any change in the currents of the core would alter the strength of the force between it and the mantle and affect their relative speeds of rotation. A large, abrupt change would cause a sudden and appreciable acceleration or deceleration of the rotation of the earth's surface. As a matter of fact, in 1897 its rotation suddenly speeded up by nearly three thousandths of a second per day, and in 1914 it decreased by about the same amount.

Now the simple model we have considered would leave unexplained some important aspects of the earth's magnetic field. To begin with, why should the currents flow around the axis of the core in one direction rather than the other, so that the magnetic field is oriented north-south? Secondly, there is the difficulty of the reversal of the magnetic poles. If this model were correct, we would have to suppose that from time to time in geologic history the currents died out and then started in the opposite direction.

The model had to be modified, and the basic ideas for a more satisfactory one were first suggested by Elsasser. He saw that another pattern, roughly the con-



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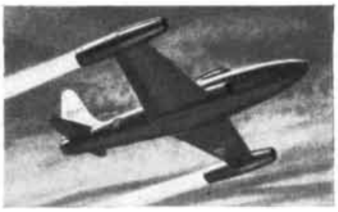

RAMJETS

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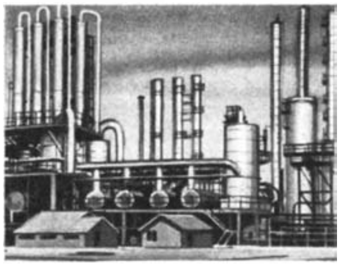

PROPELLANTS

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new team impetus for supersonic propulsion

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verse of the foregoing, was theoretically possible. In the first model, currents flow east-west around the core and set up a north-south field. The other possibility is that currents may flow north-south and set up a magnetic field which girdles the core in the east-west direction [*lower diagram on page 158*]. This magnetic field is called an "electric mode field." Confined to the surface of the core, the field cannot be observed on the earth's surface. The field we observe is a secondary effect: when liquid in the core moves across the electric mode field, it generates currents which produce the earth's north-south magnetic field.

Such a model solves the major difficulties of the simple scheme first suggested. The reversal of the poles can be explained by assuming certain plausible changes in the pattern of convective movement of liquid in the core. Moreover, the substantial changes in the speed of the earth's rotation become easier to explain: the earth's surface magnetism is not strong enough to account for the necessary force between the core and the mantle, but the electric mode field around the core, unobservable outside the earth, could be sufficiently strong.

We are still left with the problem of explaining how the primary currents responsible for the electric mode field arise in the first place. There are various possible speculations: the currents might originate from chemical action or temperature differences which produced a voltage difference between the poles and the equator of the core (one volt would be enough), or from some sort of self-exciting "dynamo" mechanism involving the core and the mantle.

Whatever the mechanism, there seems no doubt that the earth's field is tied up in some way with the rotation of the planet. And this leads to a remarkable finding about the earth's rotation itself. Aside from the complete reversals, or flip-flops, of the magnetic field, the magnetic poles have wandered gradually throughout the period of magnetic history readable in the rocks. We can only suppose from this that the earth's axis of rotation has changed also. In other words, the planet has rolled about, changing the location of its geographic poles [*see map on page 154*]. Either mountain building or convection currents in the mantle might account for this rolling. If the hypothesis of the wandering poles is verified, naturally it will be of great importance to geologists. It may explain, for example, the known fact that in the remote geological past there were glaciers near the present equator.