Reversals of the Earth's Magnetic Field

Some volcanic rocks are magnetized in a direction opposite to that of the present magnetic field of the earth. The reason is that the earth's field has reversed nine times in the past 3.6 million years

by Allan Cox, G. Brent Dalrymple and Richard R. Doell

When molten volcanic rocks cool and solidify, the magnetic minerals in them are magnetized in the direction of the earth's magnetic field. They retain that magnetism, thus serving as permanent magnetic memories (much like the magnetic memory elements of a computer) of the direction of the earth's field in the place and at the time they solidified. In 1906 the French physicist Bernard Brunhes found some volcanic rocks that were magnetized not in the direction of the earth's present field but in exactly the opposite direction. Brunhes concluded that the field must have reversed. Although his observations and conclusion were accepted by some later workers, the concept of reversals in the earth's magnetic field attracted little attention. In the past few years, however, it has been definitely established that the earth's magnetic field has two stable states: it can point either toward the North Pole as it does today or toward the South Pole, and it has repeatedly alternated between the two orientations.

There was no basis in theory for anticipating this characteristic of the earth's magnetic field. Moreover, theory on the whole subject of the earth's magnetism is so rudimentary that the mechanism of reversal is still far from being understood. Nevertheless, the magnetic memory of volcanic rocks, together with the presence in the same rocks of atomic clocks that begin to run just when their magnetism is acquired, has made it possible to draw up a time scale that shows no fewer than nine reversals of the earth's field in the past 3.6 million years. This time scale is a valuable tool for dating events in the earth's history and may help earth scientists to deal with such large questions as how much the continents have drifted.

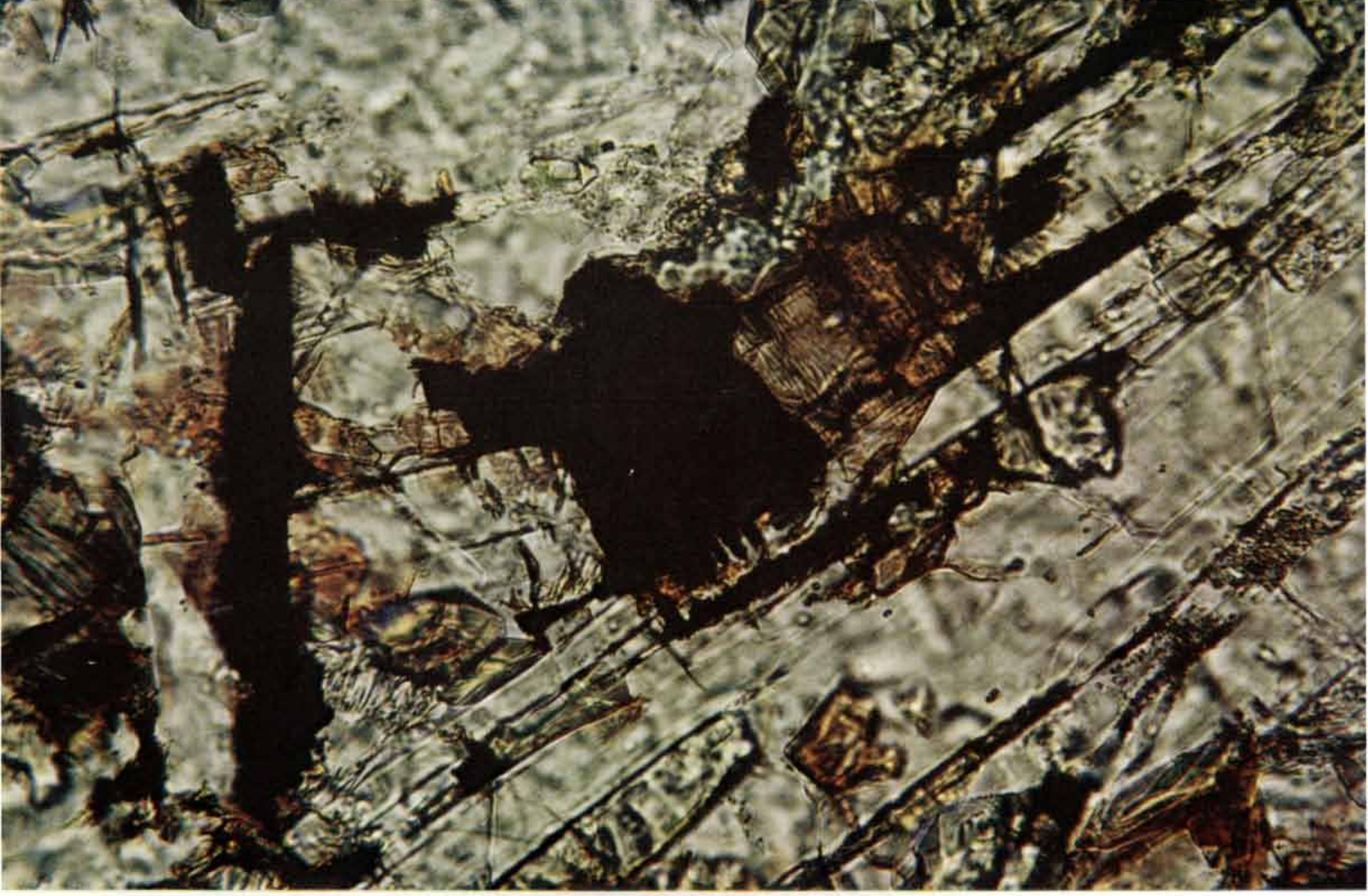
The earth's magnetic field is the field of an axial magnetic dipole, which is to say that it is equivalent to the external field of a huge bar magnet in the core of the earth aligned approximately along the planet's axis of rotation (or to the external field of a uniformly magnetized sphere or of a loop of electric current in the plane of the Equator). The lines of force in such a field are directed not toward the geographic poles but toward the magnetic poles, and the angle at any point between true north and the direction of the field is called the declination. The lines of force are also directed, except at the Equator, toward or away from the center of the earth, and the angle above or below the horizontal is called the inclination. It is along these lines of force that the memory elements in volcanic rocks have been oriented.

The memory elements themselves are magnetic "domains": tiny bodies in which magnetism is uniform. These bodies consist of various iron and titanium oxides that can be recognized quite easily under the microscope because, unlike most rock-forming minerals, they are opaque to transmitted light and are excellent reflectors of incident light [*see illustrations on opposite page*].

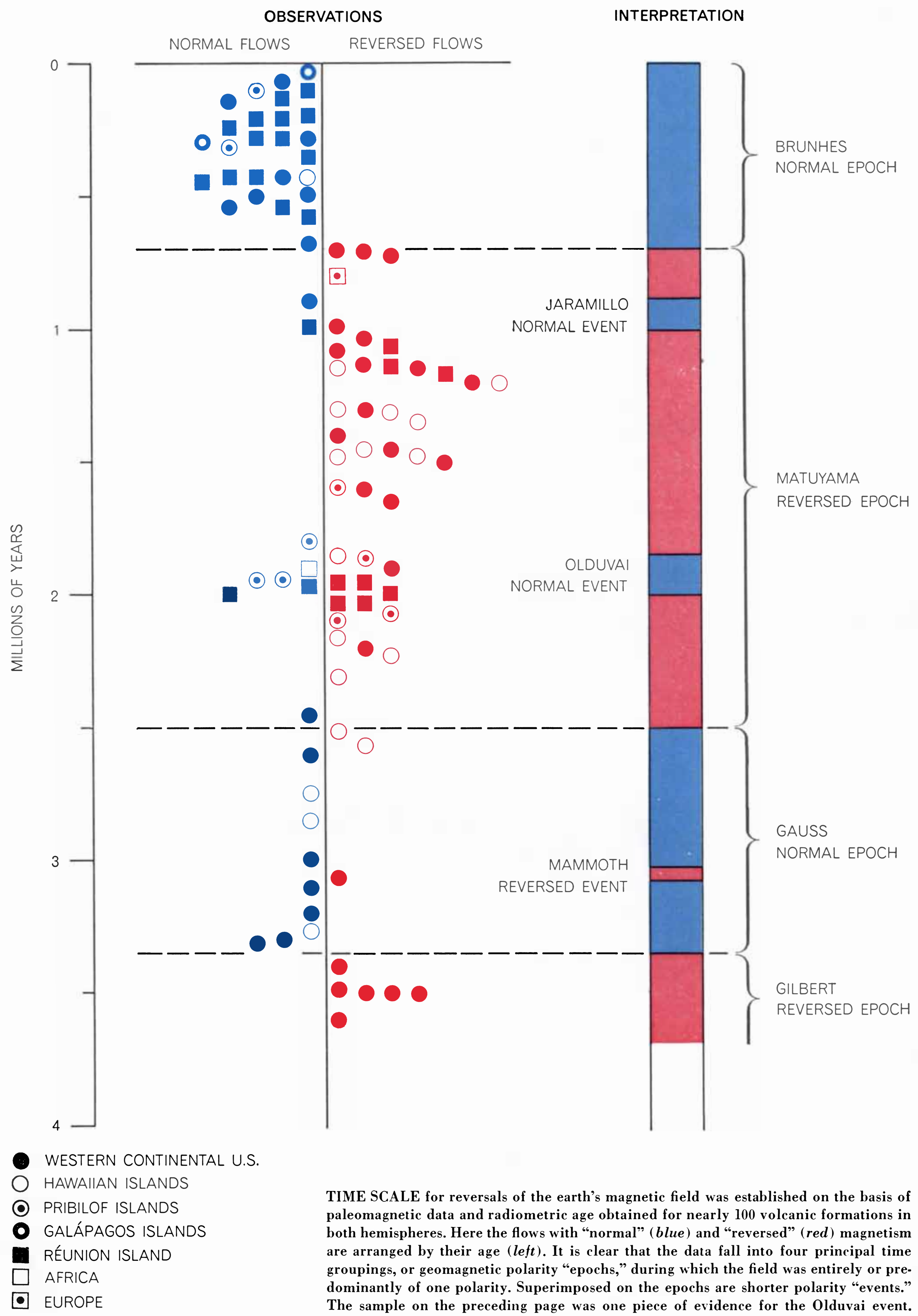
At high temperatures the iron and titanium oxides are nonmagnetic. They become magnetic only after they cool to a critical point called the Curie temperature, which for the common minerals in volcanic rocks may be as high as 680 degrees centigrade or as low as about 200 degrees, depending on chemical composition. These temperatures are well below those at which rocks crystallize (about 1,000 degrees C.), so that it is clear that rocks are not magnetized by the physical rotation and orientation in the earth's field of previously magnetized grains in the molten lava, as was once thought. As the minerals begin to cool through the Curie temperature, even the earth's weak field of less than one gauss is adequate to partly magnetize them. That is because this initial magnetization is "soft," like that of iron or ordinary steel, both of which are easily magnetized by weak magnetic fields. As the rocks continue to cool, the minerals undergo a second abrupt change: the initially soft magnetism acquired in the earth's field is frozen in and becomes "hard," like the magnetism of a man-made permanent magnet.

The pertinent question for the geophysicist is how well these magnetic memory elements function as recorders of the earth's field. Do they record its direction accurately? The most direct way to assess the accuracy of volcanic rocks as recorders is to measure the magnetism of such rocks that flowed out and cooled recently in places where the magnetic field that existed at the time of flow is known. We have made such measurements on three lava flows that formed on the island of Hawaii in the years 1907, 1935 and 1955.

To obtain samples of undisturbed rock from the solid parts of a lava, a hollow cylindrical diamond drill is generally used. From five to eight cylindrical "cores" are taken from each lava flow to obtain a representative magnetic direction for the entire flow rather than for one isolated sample; each core's orientation with respect to the horizontal and to true north is accurately recorded before it is removed. Back in the laboratory the sample's magnetic vector is determined with a magnetometer [*see middle illustration on page 47*]. The results of the measurements on the three formations indicate that lava flows record the direction of the earth's magnetic field with an



BASALT from the Pribilof Islands, seen in two photomicrographs made by Norman Prime of the U.S. Geological Survey, is one of the samples studied by the authors. The magnetic minerals, complex intergrowths of iron and titanium oxides, are opaque and therefore appear dark in transmitted light (*top*) and very bright in reflected light (*bottom*). The large clear minerals that are pale green in the top photograph and black in the bottom one are feldspars and contain the radioactive potassium isotope used for dating. The age of this rock is 1.95 million years; its magnetism approximately parallels that of the present field. Magnifications are about 600 diameters.



TIME SCALE for reversals of the earth's magnetic field was established on the basis of paleomagnetic data and radiometric age obtained for nearly 100 volcanic formations in both hemispheres. Here the flows with "normal" (*blue*) and "reversed" (*red*) magnetism are arranged by their age (*left*). It is clear that the data fall into four principal time groupings, or geomagnetic polarity "epochs," during which the field was entirely or predominantly of one polarity. Superimposed on the epochs are shorter polarity "events." The sample on the preceding page was one piece of evidence for the Olduvai event.

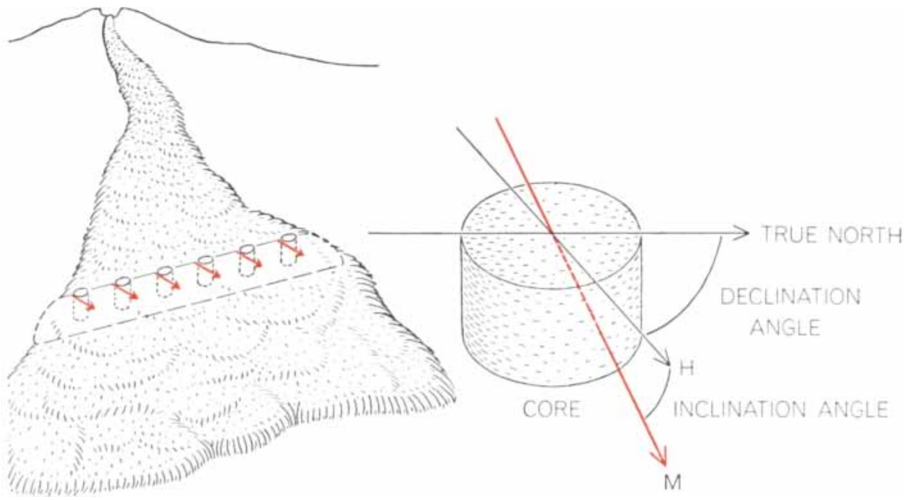
accuracy of several degrees, which is ample for most geophysical applications.

If rock magnetism is to provide a record of the ancient earth's field, the magnetic record must also be stable. Is the magnetism of rocks soft like that of iron and ordinary steel or is it hard like that of permanent magnets? This question of stability is so critical that laboratory tests to deal with it have become an integral part of paleomagnetic research. The usual technique is to place a sample from a rock formation in a kind of magnetic "washing machine," subject it to a rapidly alternating magnetic field and determine the amount of magnetism that survives. The natural magnetism of most volcanic rocks turns out to be comparable in stability to the magnetism of the hardest permanent magnets [*see illustration on next page*]. Once the magnetic hardness of the rocks from a given flow is established, the magnetic cleaning process can be used to strip away from each sample whatever soft magnetism has been acquired (from such sources as lightning strokes) since the rock solidified, leaving only the hard magnetism that reflects the direction of the original ambient field.

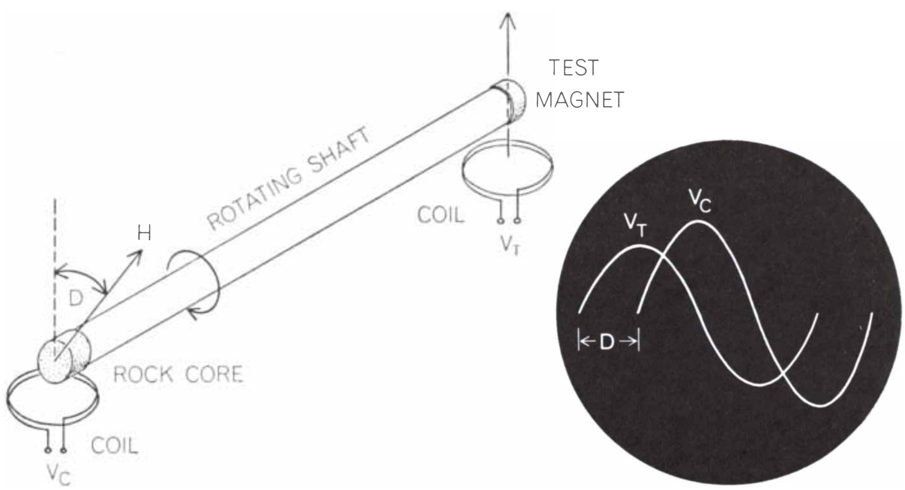
It is clear, then, that paleomagnetism is accurate and stable enough to provide information about past states of the earth's magnetic field. In assessing such information one must of course take into consideration the movement of rock masses that takes place over a period of geologic time; the deviation of a sample's magnetism from the direction of the present field could reflect mountain-building, warping along faults or continental drift. Our studies of magnetic reversal have been restricted, however, to relatively young rocks and to volcanic formations we can be fairly sure are still oriented as they were when they solidified.

We began our paleomagnetic research on the island of Hawaii, where we had tested the technique and where the superb lava flows exposed on the flanks of volcanoes provide magnetic records going back about half a million years. We collected samples from 107 of these flows and found that their declination angles clustered at around 10 degrees east of true north and their inclination angles at around 30 degrees below the horizontal [*see illustration on page 49*]. This was just about what we expected on the basis of the dipole nature of the earth's field.

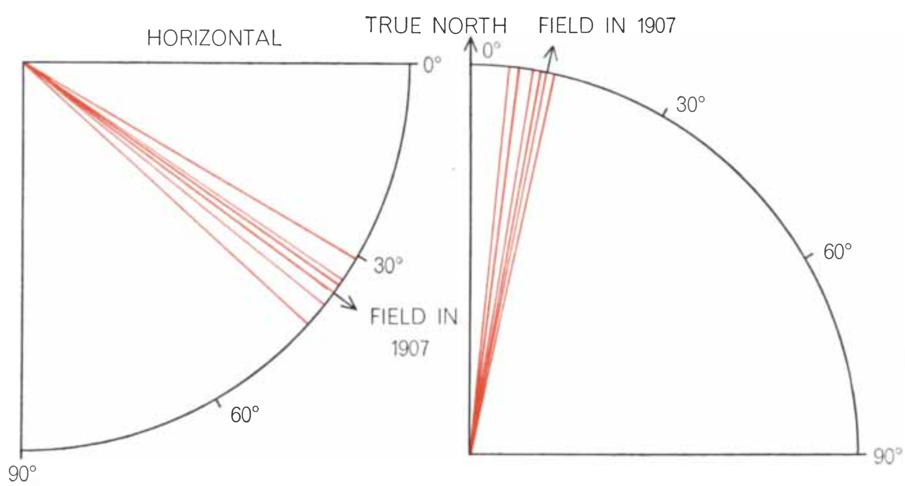
Studies of other young volcanic rocks along the eastern edge of the Pacific



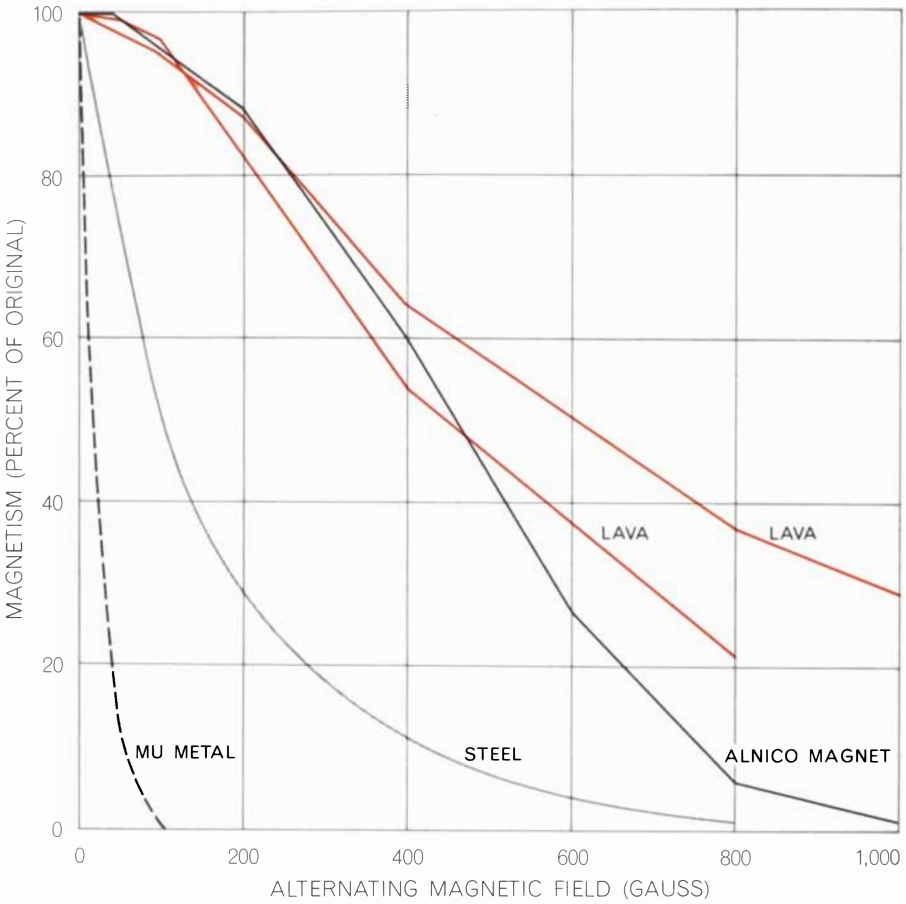
SAMPLES for paleomagnetic studies are cores drilled from volcanic formations. The direction of magnetization (*M*) is expressed as the declination angle between true north and the horizontal projection (*H*) of *M* and the inclination angle of *M* above or below horizontal.



CORE is mounted on a magnetometer. As the shaft rotates, electrical signals (V_C *and* V_T) are induced in the coils by the core and a test magnet and can be displayed on an oscilloscope. The intensity and direction of the core's magnetism are determined by comparing the magnitudes of the signals and their phase shift, which is equal to the declination (*D*).



ANGLES (*color*) of inclination (*left*) and declination (*right*) of six cores from a 1907 Hawaiian lava flow cluster about the known angles of the 1907 field. Although angles obtained from individual cores vary, the average values are accurate measures of the historic field.



"HARDNESS" of the magnetism of basalt samples is expressed as the amount of magnetism remaining after "washing" in alternating magnetic fields of various strengths. The stability of the rocks' magnetism is far greater than that of the alloy "mu metal" or of steel; it is comparable to that of the alloy Alnico, of which permanent magnets are often made.

ocean basin have yielded similar results. At the high latitude of the Pribilof Islands in the Bering Sea the magnetic vectors of the lava flows are inclined steeply downward, as one would expect for a dipole field in high latitudes, whereas in the Galápagos Islands on the Equator the magnetic vectors are almost horizontal. Measurements in many parts of the world indicate that during the time spanned by these young lava flows (roughly half a million years) the earth's field was essentially dipolar and was aligned as it is today.

Quite different results are obtained when paleomagnetic techniques are applied to somewhat older lava flows. Only about half of these flows are magnetized in the same direction as the younger ones; the remainder are magnetized in the opposite direction. For example, some volcanic rocks at middle latitudes in the Northern Hemisphere are magnetized toward the south and upward, rather than toward the north and downward [*see upper illustration on page 50*]. In recent years this "antiparallel" magnetism has been found in thousands of samples of volcanic rock from all over the world by scores of investigators working independently. Sampling has been particularly intensive in the range of ages between 3.5 million years ago and the present, and the paleomagnetic results obtained are always remarkably similar. The magnetic vectors fall into two groups: "normal" vectors nearly parallel to the present field of the earth and "reversed" ones that are nearly opposite. Most of the data are clustered within 30 degrees of these two directions, with very few vectors oriented in intermediate directions [*see lower illustration on page 50*].

The immediate implication is that the earth's magnetic field has indeed reversed its direction in the past. Brunhes so interpreted his results in France in 1906, although he cautiously restricted field-reversal to the area from which he collected his samples. In 1929 Motonori Matuyama also found evidence that the field had reversed, but he too restricted his conclusions to the area in Japan from which his samples had come. The accumulating evidence that reversed magnetic directions are invariably opposite to the present field direction at the sampling site led in time to the hypothesis that the sample reversals are not local but global; in other words, that the entire field reverses.

An important alternative explanation must be considered before the field-reversal hypothesis can be accepted. The alternative is that rocks magnetized in reverse may possess some special mineralogical property that causes them to become so magnetized in a normal field. The existence of such "self-reversal" in rocks was suggested in 1950 by John Graham, then at the Carnegie Institution of Washington's Department of Terrestrial Magnetism, as an explanation for the occurrence of both normal and reversed magnetism in rock samples that had formed simultaneously. Graham's suggestion stimulated the French physicist Louis Néel to examine the problem from the viewpoint of solid-state physics, and Néel soon discovered several ways in which self-reversal might occur. Experimental confirmation came almost immediately. At the Philips Research Laboratories in the Netherlands, E. W. Görter synthesized an iron-chromium-manganese compound that underwent self-reversal, and S. Uyeda and T. Nagata of the University of Tokyo found a self-reversing volcanic rock.

It is thus apparent that at least some volcanic rocks are not infallible magnetic recorders. Like laboratory recorders that are hooked up backward, they sometimes record a signal that is not only wrong but is exactly wrong by 180 degrees. If all reversed magnetism could be explained in this way, the experimental evidence for reversals in the earth's magnetic field would vanish. An obvious experiment is to heat and then cool rock samples in a known field and measure their acquired magnetization. This operation has been performed on many hundreds of rock samples with reversed magnetism, and fewer than 1 percent have turned out to be self-reversing.

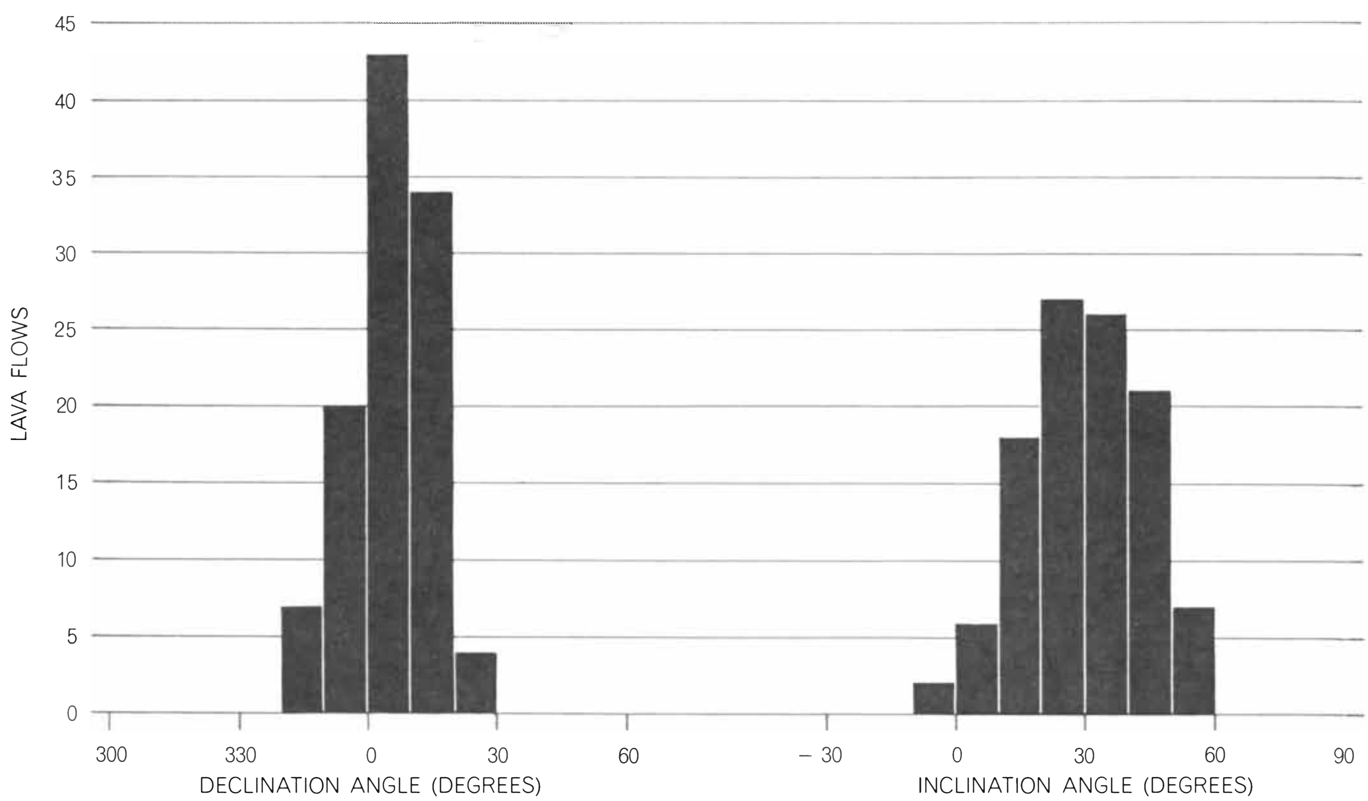
Therefore the laboratory evidence favors the field-reversal hypothesis. Like many rock-forming processes, however, the acquisition of natural magnetism cannot be reproduced with complete fidelity in the laboratory. The missing ingredient is time, and for certain of the theoretical self-reversing processes this ingredient is crucial. For example, John Verhoogen of the University of California at Berkeley has shown theoretically that whereas certain iron oxides containing impurities of aluminum, magnesium or titanium would be magnetized normally when cooled rapidly in a normal magnetic field, the magnetism could be reversed as the atoms in the cooled oxide reordered themselves toward an equilibrium distribution. The calculated time required for this self-reversal is on the order of 100,000 to a million years, so that it could hardly be reproduced in the laboratory. The theoretical studies by Néel and Verhoogen showed that the fact that self-reversal is rare in the laboratory does not make it safe to conclude that it is equally rare in nature. How, then, could one determine the geophysical significance of reversed magnetism? Two main lines of experimental attack have been pursued during the past decade, each closely related to one of the two proposed reversal-producing processes.

One approach was to search for a correlation between the magnetism of rocks and their mineralogy. Even though self-reversals may not always be reproducible in the laboratory, if all reversed magnetism is due to a process occurring on the mineralogical level, rocks with reversed magnetism should be somehow different from those with normal magnetism; chemical processes being the same the world over, the unique mineralogical properties associated with reversed magnetism should appear in rocks from all over the world.

This approach has been pursued most actively by P. M. S. Blackett at the Imperial College of Science and Technology in London and Rodney Wilson at the University of Liverpool. In some sequences of rocks Wilson has found a correlation between reversed magnetism and mineralogical properties, but in other rocks he finds no such correlation. Like Wilson, we have occasionally noted a correlation between mineralogy and magnetism within a sequence from one locality, but such a local correlation may well stem from the tendency of volcanic flows to occur in pulses. Between two successive pulses separated by a long time interval the mineralogical character of the lavas commonly changes; if the polarity of the earth's field also happens to change in this interval, there will be an apparent correlation between mineralogy and polarity. In short, mineralogical investigations have not yielded evidence that all or even most reversed magnetism is produced by self-reversal.

The second experimental approach followed from an implication of the field-reversal theory: If the earth's magnetic field alternates between intervals when it is normal and intervals when it is reversed, the geologic ages of normal and reversed rocks should fall into corresponding intervals. Data bearing on the age and magnetism of rocks should provide a yes-or-no answer to the validity of the field-reversal theory and, if the theory is valid, should yield a time scale for reversals. Matuyama had noted in 1929 that the geologic age of all the rocks with reversed magnetism in Japan was early Pleistocene (about a million years ago), whereas younger rocks invariably had normal magnetism. The strongest possible evidence in support of the field-reversal theory would be to extend Matuyama's study to show that rocks from all parts of the world, regardless of mineralogy, occur in similar normal and reversed sequences that are time-dependent.

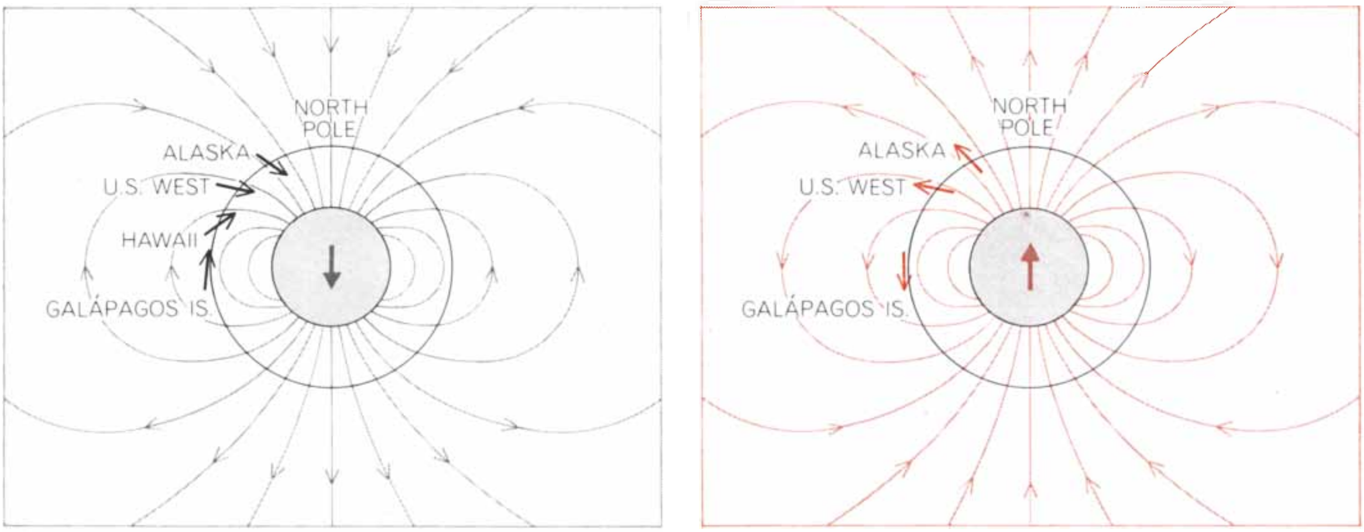
The difficulty lay in finding a sufficiently precise method for establishing the age relations of normal and reversed rocks. Many techniques that yield fairly precise age relations when applied to older rocks are based on plant and animal fossils; these techniques begin to break down when applied to the past million years or so because of the slow rate at which evolution proceeds and the time required for plant and animal migrations. A solution that suggested itself was some kind of radioactive clock, and



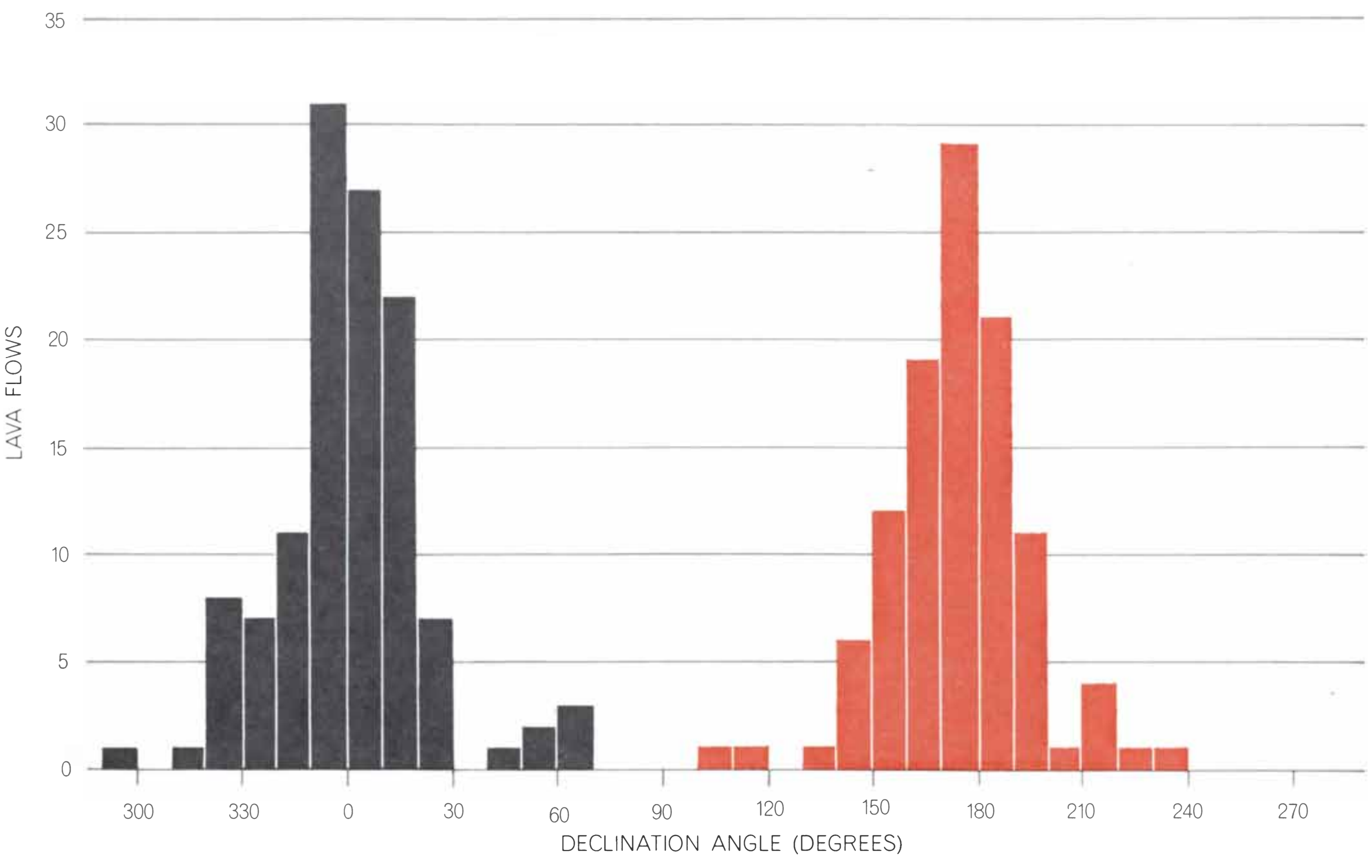
PALEOMAGNETIC RESULTS are shown for 107 volcanic formations on the island of Hawaii. Each angle represented in these histograms is an average derived from five or more cores in one lava flow. The data are grouped in a mean northerly direction and at a mean inclination of about 30 degrees below the horizontal. That is, they roughly parallel the present direction of the earth's field.

our search quickly narrowed to the potassium-argon clock first suggested in 1940 by Robley D. Evans of the Massachusetts Institute of Technology and now widely applied in geological investigations. Potassium 40, a radioactive isotope that constitutes .012 percent of all potassium, can be found as a chemical constituent in most rock-forming minerals. It decays at a known and constant rate to argon 40, a gas that forms no known compounds.

The argon is trapped within the crystal structure of the minerals, and if the minerals are not heated or changed in some way, it accumulates there. Its amount is a function of the amount of potassium present and the length of time since the decay and entrapment processes began. Therefore by measuring the amount of potassium 40 and argon 40 in a rock one can calculate its age. Argon will not accumulate as long as the rock is in a molten state, so for volcanic rocks



INCLINATION ANGLES from flows in Alaska, the U.S. West (California, Idaho and New Mexico), the island of Hawaii and the Galápagos Islands are shown by the heavy colored arrows. The flows range up to three million years in age. The angles fall into two distinct groups: a "normal" group aligned with the earth's present field, that of a bar magnet pointed toward the South Pole (*left*), and a "reversed" group appropriate to an oppositely oriented field (*right*). All the flows on Hawaii had normal magnetism.



DECLINATION ANGLES from 229 flows up to three million years old in Alaska, the western U.S., Hawaii and the Galápagos Islands display a similar twofold grouping: northerly (normal) and southerly (reversed). Intermediate directions are seldom observed.

the potassium-argon clock is started only when the rock solidifies.

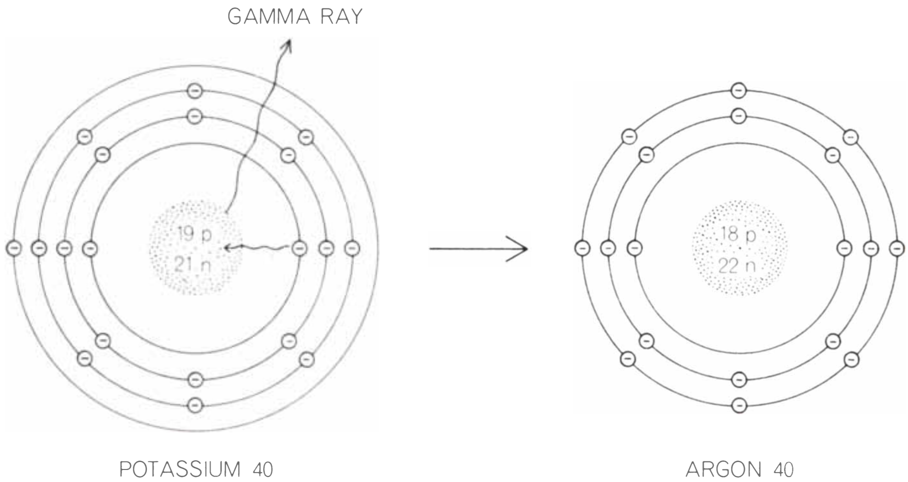
The amount of potassium 40 in a sample is usually determined by measuring all the potassium in the sample by standard chemical methods and then calculating the potassium 40 from its known relative abundance. The argon determination is more difficult because the amounts are extremely small. In a typical 10-gram sample of basalt a million years old the amount of argon 40 from potassium 40 is 10^{-9} (.000000001) gram, and the accuracy of the dating depends on the accuracy with which this argon can be measured. A sample of the rock or mineral is placed in a gas-extraction apparatus and melted to release the accumulated argon 40. Reactive gases such as oxygen, nitrogen and water are removed. During the extraction a known amount of isotopically enriched argon, called the tracer, is mixed with the gas from the sample, so that the final argon gas consists of three components: the argon 40 whose amount is to be determined; the tracer, which is mostly argon 38 but which also contains some argon 36 and argon 40, and contaminating argon from the atmosphere, for which a correction must be made. This argon mixture is analyzed with a mass spectrometer that gives the relative amounts of the three isotopes of argon. Knowing the amount of the enriched tracer and its isotopic composition, and the relative composition of atmospheric argon and of the total gas mixture, one can calculate the amount of argon derived from potassium 40. This information is used with the results of the potassium analysis to determine the age of the rock.

For the reversal problem the potassium-argon method has several distinct advantages over other dating methods. It can be applied to a wide variety of volcanic rocks. It is also the only dating method that can be applied in the range from a few thousand to several million years ago. And, as we have noted, the potassium-argon clock starts to run at exactly the same time the magnetic record is frozen into a volcanic rock.

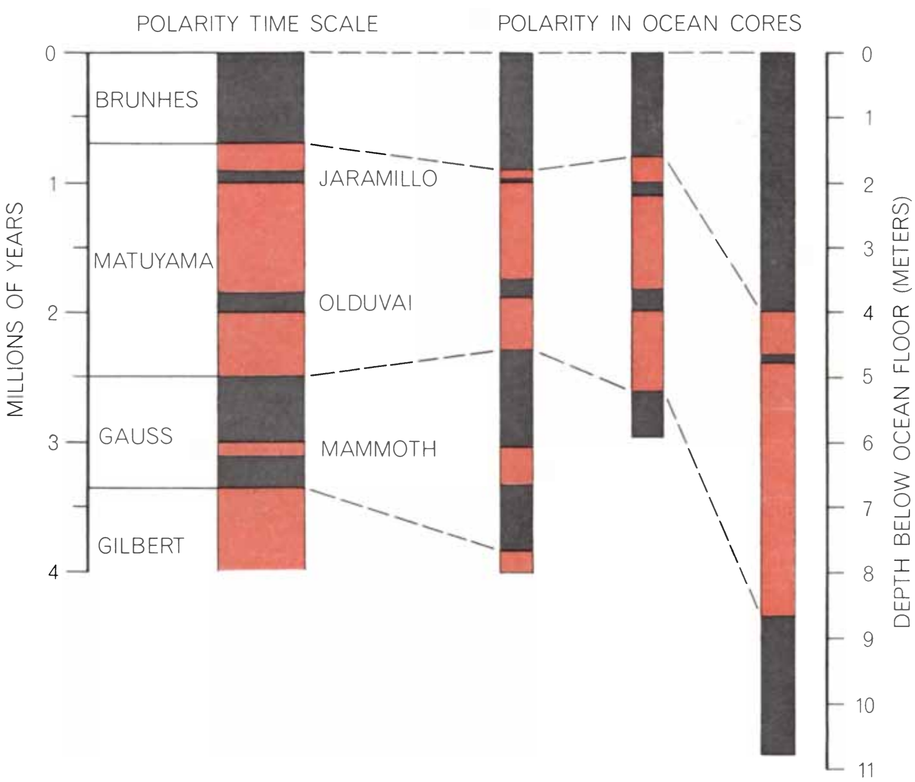
The potassium-argon dating method has now been successfully applied to rocks from nearly 100 magnetized volcanic formations with ages ranging from the present back to 3.6 million years [*see illustration on page 46*]. This work has been done primarily by ourselves at the U.S. Geological Survey laboratory in Menlo Park, Calif., and by Ian McDougall, D. H. Tarling and F. H. Chamalaun at the Australian National University. Relevant data have also been contributed by M. Rutten of the University of Utrecht and by C. S. Grommé, R. L. Hay, J. F. Evernden and G. H. Curtis of the University of California at Berkeley. The rocks that were investigated came from different parts of the world and are of different types, so that the available data come from heterogeneous sources.

As the illustration on page 46 shows, the ages of these magnetically normal and magnetically reversed rocks are well grouped in distinct sequences, leaving little room for doubting the reality of geomagnetic field reversals. To explain them by self-reversal would require an unreasonable kind of coincidence involving synchronous worldwide changes in the nature of the processes by which minerals are formed and magnetized.

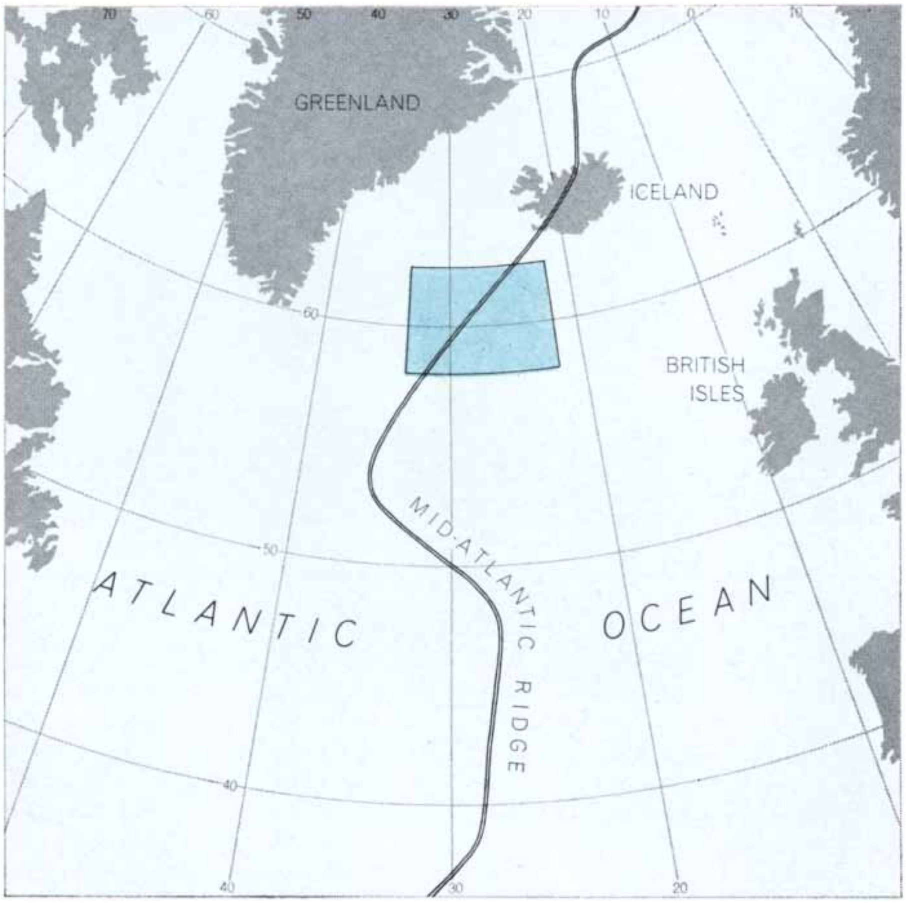
Four major normal and reversed se-



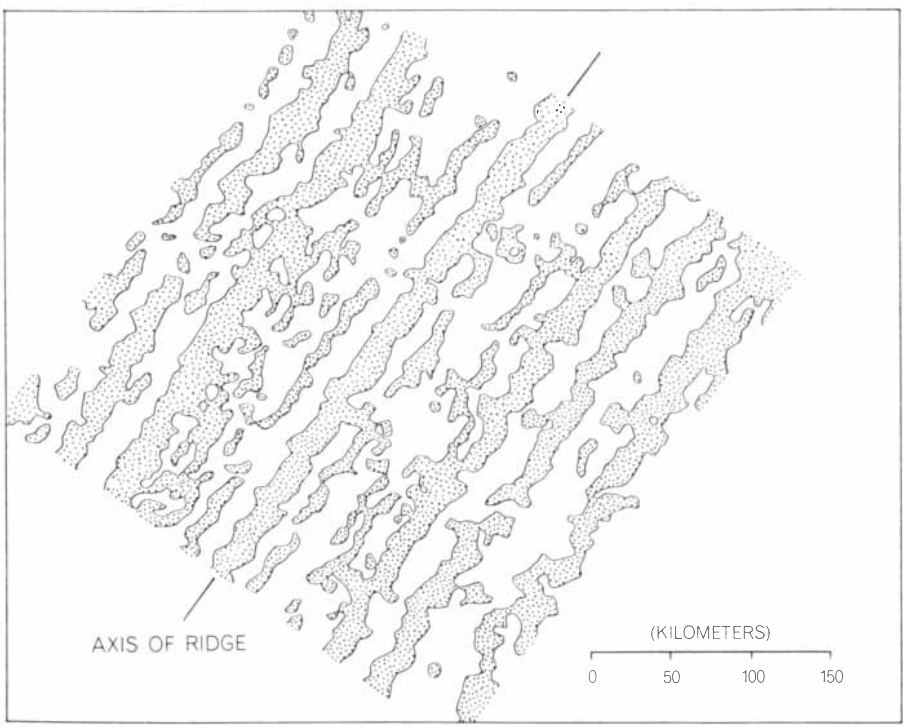
POTASSIUM-ARGON CLOCK by which reversals of the earth's field are dated is based on the decay of potassium 40 to yield argon 40. In the decay an extranuclear electron captured by the potassium nucleus converts a proton to a neutron and a gamma ray is emitted.



DEEP-SEA SEDIMENTS confirm the field-reversal time scale. Magnetic particles become oriented in the direction of the earth's field as they settle through the water; a core that samples many layers of sediments may record a series of normal (*gray*) and reversed (*color*) epochs and events. Here cores from antarctic waters are correlated with the time scale.



MAGNETIC ANOMALIES have been discovered in ocean floors, particularly along mid-ocean rises. One pattern was mapped in an area (*dark color*) on the mid-Atlantic ridge.



ANOMALY PATTERN in the area delineated on the map at the top of the page is strikingly symmetrical. The parallel bands in which the earth's field is stronger (*stippled*) or weaker (*white*) than the regional average are oriented along the ridge's axis. The magnetic bands are presumably produced by bands of rock with normal and reversed magnetism.

quences are defined by the paleomagnetic and radioactive-clock data for the past 3.6 million years. We call these major groupings geomagnetic polarity epochs and have named them for people who made significant contributions to our knowledge of the earth's magnetic field. Superimposed on the polarity epochs are brief fluctuations in magnetic polarity with a duration that is an order of magnitude shorter. We call these occasions polarity events and have named them for the localities where they were first recognized.

The polarity events are important for theories of the earth's magnetism because they emphasize the irregular nature of reversals of the earth's field. The first polarity event to be discovered was the "Olduvai" normal event, which is recorded in a flow in Olduvai Gorge in Tanzania that was investigated in 1963 by Grommé and Hay. At first the Olduvai flow was thought to lie within the "Gauss" normal polarity epoch and hence was not recognized as an anomaly. When better dating of the epochs placed the date of the Olduvai flow within the "Matuyama" reversed epoch, it appeared to be an unexplained anomaly in an otherwise coherent picture.

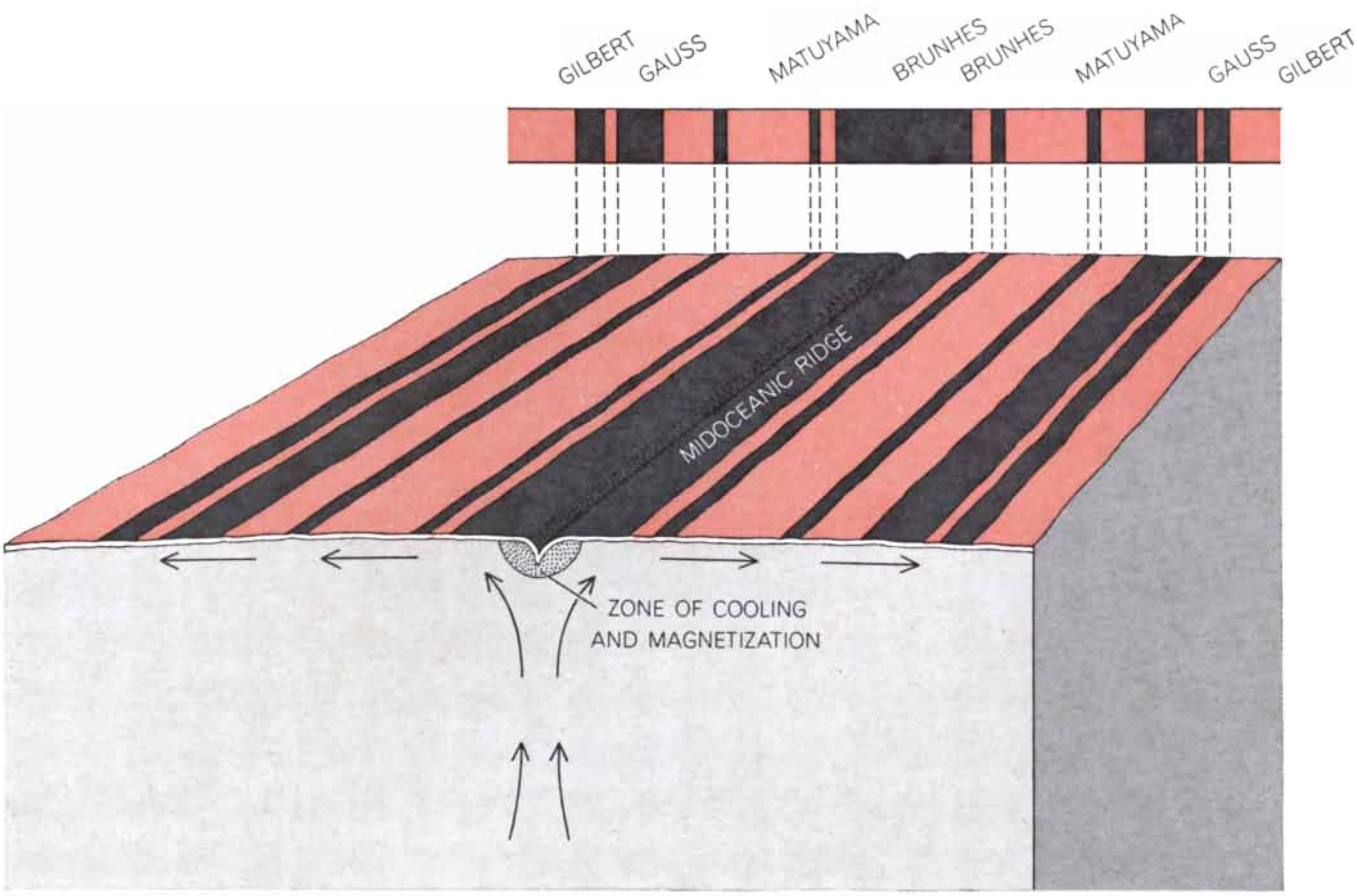
The explanation that the Olduvai result represents a brief, worldwide fluctuation in polarity was first advanced by us after we discovered in the Pribilof Islands three lava flows that are normally magnetized, like the Olduvai flow, and that have similar ages of about 1.9 million years. These flows were sandwiched between reversed flows that gave slightly older and slightly younger ages, providing the evidence that confirmed the existence of polarity events. Since then we have recognized and named two additional events: a reversed one that was recorded 3,050,000 years ago at Mammoth, Calif., and a normal one recorded about 900,000 years ago in some rocks near Jaramillo Creek in New Mexico. The Jaramillo event was recently confirmed by Chamalaun and McDougall in their study of lava flows on Réunion Island in the Indian Ocean, where they also found two additional flows that represent the Olduvai event.

Only rarely does a sequence of lava flows succeed in capturing a record of a polarity transition. This indicates that the time required for a complete change of the earth's magnetic field from one polarity to another is amazingly short; our best estimate of the transition time is 5,000 years. This is based on the ratio between the number of lava flows that happen to have recorded the earth's field during a transition and the number of flows with clearly defined normal or reversed directions. An indirect estimate of this kind is necessary because the potassium-argon dating method is unable to resolve age differences as small as 5,000 years. On the scale of geologic time, polarity transitions appear to be almost instantaneous, and they therefore provide sharp time markers indeed.

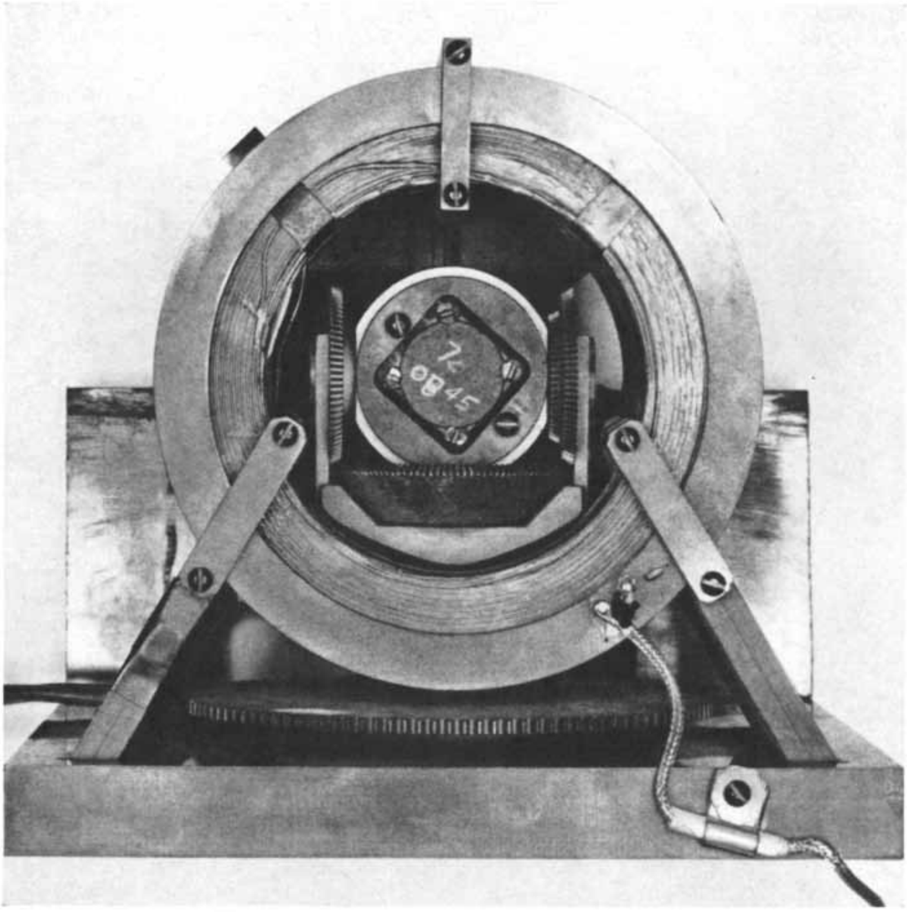
The idea that the earth's magnetic field reverses at first seems so preposterous that one immediately suspects a violation of some basic law of physics, and most investigators working on reversals have sometimes wondered if the reversals are really compatible with the physical theory of magnetism. The question is meaningful only within the context of a broader question: Why does the earth have a magnetic field? Geophysicists are simply not sure. After centuries of research the earth's magnetic field remains one of the best-described and least-understood of all planetary phenomena. The only physical mechanism that has been proposed as the basis of a tenable theory is the mechanism of a magnetohydrodynamic dynamo. According to this theory, which has been developed primarily by Walter M. Elsasser, now at Princeton University, and Sir Edward Bullard of the University of Cambridge, the molten iron-and-nickel core of the earth is analogous to the electrical conductors of a dynamo. Convection currents in the core supply the necessary motion, and the resulting electric currents create a magnetic field. The entire regenerative process presumably began with either a stray magnetic field in the earth's formative period or with small electric currents produced by some kind of battery-like action [see "The Earth as a Dynamo," by Walter M. Elsasser; SCIENTIFIC AMERICAN, May, 1958].

The mathematical difficulties of this theory are immense. It is impossible to predict what the intensity of the earth's field should be or whether it fluctuates or remains stationary. Certainly the theory is in too rudimentary a state for one to predict whether reversals should or should not occur or should occur only under certain conditions. On the other hand, complete mathematical solutions have been obtained for simple theoretical models of dynamos, and these models do show spontaneous reversals of magnetic field; some of the models show sequences of reversals that are strikingly similar to the geomagnetic polarity time scale. These results at least demonstrate that magnetic reversals are possible in self-regenerating dynamos. The fact remains that observations are leading theory in this area of investigation, and any complete theory of geomagnetism will eventually have to accommodate the observed reversals of the field.

Meanwhile geologists are applying the reversal time scale to establish age relations among rocks they would be hard put to date any other way. An especially important application is in determining the ages of deep-sea sediments, which are very difficult to date beyond the short range of 200,000 years. It has long been recognized that fine-grained sediments may become magnetized in the earth's field as they drift slowly downward in quiet water. Recently C. G. A. Harrison and B. M. Funnell of the Scripps Institution of Oceanography and N. D. Opdyke and D. E.



SPREADING of the ocean floor could explain the magnetic-anomaly patterns. According to one theory (*see text*) convection currents bring molten material up under the mid-ocean ridge, where it cools, becomes magnetized and then spreads laterally away from the ridge. Symmetrical bands of normal and reversed rocks would be produced by the combined effect of field reversal and spreading.



"MAGNETIC WASHING MACHINE" devised by the authors subjects a sample placed in the chamber (*center*) to an alternating magnetic field while rotating it about three perpendicular axes. The sample's hard magnetism is unaffected, but the soft component, forced to change direction repeatedly, is destroyed as the alternating current is reduced to zero.

Hayes and their colleagues at the Lamont Geological Observatory of Columbia University have observed magnetic reversals in the sediments of deep-sea cores [*see bottom illustration on page 51*]. In one core in particular (from the Bellingshausen Sea near Antarctica) Opdyke and Hayes found a polarity record going back to the "Gilbert" epoch, or 3.6 million years, in which the pattern of reversals is remarkably similar to the pattern of our polarity time scale. Even the brief polarity events are clearly discernible. These findings confirm the reversal time scale determined from volcanic rocks and suggest that polarity studies can provide a method for determining rates of sedimentation and for establishing worldwide correlations among various deep-sea sediments, two problems that have long perplexed oceanographers. Magnetic studies are also helping to establish stratigraphic links between marine and continental rocks. Magnetic-reversal stratigraphy has shown, for example, that sediments of glacial origin on Iceland and at the bottom of the Bellingshausen Sea were both deposited at about the end of the "Gauss" normal polarity epoch, or about 2.5 million years ago—a fact of considerable importance for Pleistocene geology.

Reversals may explain certain puzzling magnetic anomalies characteristic of many oceanic areas, particularly those adjacent to the mid-ocean rises, or ridges [see "The Magnetism of the Ocean Floor," by Arthur D. Raff; SCIENTIFIC AMERICAN, October, 1961]. These anomalies are parallel bands, extending for hundreds and even thousands of miles, in which the intensity of the earth's magnetic field is higher or lower than the average for the region. It is easy to see how the presence of normal and reversed magnetized rock formations in the crust of the earth, which would add to and subtract from the earth's main dipole field, could account for such findings. Many of the magnetic-anomaly patterns, however, display a striking symmetry around the crests of certain mid-ocean ridges [*see illustrations on page 52*] that is difficult to explain on the basis of familiar volcanic processes.

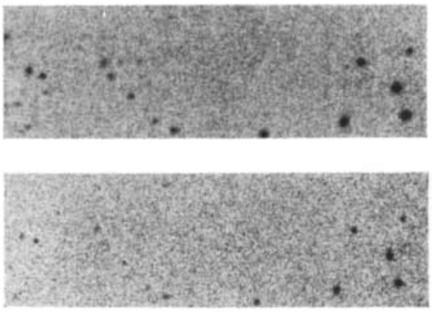
Recently F. J. Vine, now at Princeton University, and J. H. Matthews of the University of Cambridge have pointed out that ideas advanced by Harry H. Hess of Princeton and by the Canadian geophysicist J. Tuzo Wilson to account for certain characteristics of ocean basins and their margins and also for the drifting of continents may shed light on the symmetrical anomalies. Hess and Wilson had suggested that convection currents in the earth's mantle, the layer below the crust, may bring material up to form a mid-ocean ridge and then move the material outward, away from the ridge [see "Continental Drift," by J. Tuzo Wilson; SCIENTIFIC AMERICAN, April, 1963]. If successive bands solidified and were magnetized during successive polarity epochs, Vine and Matthews reported, the symmetry of the patterns could be explained on this basis. So could the particular spacing of the bands along the mid-Atlantic ridge, for example, provided that the sea floor is spreading at the rate of about one centimeter per year [*see illustration on preceding page*]. This rate is consistent with earlier estimates by Wilson. Although the hypothesis of sea-floor spreading seems to be inconsistent with some other lines of evidence and has been resisted by many oceanographers and geologists, the magnetic evidence seems to reinforce it.

Reversals of the earth's magnetic field may even have implications for the history of life on our planet. R. J. Uffen of the University of Western Ontario pointed out in 1963 that if the magnetic field of the earth disappears or is greatly attenuated during a reversal in polarity, the earth would lose some of its magnetic shielding against cosmic rays; with the resulting increase in radiation dosages, mutation rates should increase. Paleomagnetic evidence for the behavior of the earth's field during polarity transitions is fragmentary, but there are indications that the field may be only about a fifth as intense as in normal times. Uffen argues on paleontological grounds that rates of evolution were exceptionally high at times when the earth's magnetic field was undergoing many changes in polarity, although the support for this conclusion in the paleomagnetic record is rather weak. Cores examined by Opdyke and Hayes do provide some support for Uffen's theory in that major changes in the assemblages of microfossils appear near two of the magnetic-polarity changes. Much additional information is needed, however, before it will be possible to judge the extent to which field reversals may have affected life on the earth.

The hope of doing each other some good prompts these advertisements

You want a fast emulsion?

We have recently made a photographic emulsion based on a new line of reasoning (*J. of the Optical Society of America*, 55:907) and sent it out on some plates to the Palomar Observatory. Here is a comparison at 10× of what the new plate saw (*top*) with what was seen



before in a certain tiny piece of sky near Messier 101.

The new emulsion extends the limit of optically observable celestial objects by another magnitude or two. You might think that to record such a faint trickle of photons—perhaps the oldest physical entities sensible to man—might require a new high in emulsion speed. Not so. The trick was turned by going to a slower emulsion, but of a very special nature. It doesn't lose the tiny difference made by the age-old photons among all the other photons around, even with the hour-long exposure required for a statistically significant sampling of the photons.*

Though a plateful of spaghetti impresses far more inhabitants of this planet than does a plateful of new galaxies, we ourselves are sufficiently impressed to make the plate a regular product, hereafter designated KODAK *"Spectroscopic" Plate, Type IIIa-J. Information about it and other plates and films designed for long-time exposures can be obtained from Dept. 918, Eastman Kodak Company, Rochester, N.Y. 14650.*

Here are three men from Dept. 918 photographed by the light of a single match. They are exploring the extent of customer interest in the film on which they were photographed. Unlike the emulsion for plumbing the universe, this one is just plain more sensitive to light than any we have ever before offered.

Plain? That depends. It depends on processing. An experimental product still designated "S.O. 166," this film can be processed to a negative in the routine way—by hand or in a KODAK VERSAMAT Film Processor—and appear to be no faster than our older superfast films. With those films, if you try to compensate for too skimpy exposure by tripling the development time, all you do is convert more silver halide into black silver without much reference to the light values in the subject you were trying to photograph. With S.O. 166, extended development can multiply the effective light sensitivity as much as fourfold before the fog closes in. There is some sacrifice in sharpness and granularity, but the resolving power is enhanced by the higher contrast that is obtained. For streamer chambers (research hardware for the other end of the scale from galaxies), re-entry studies, fast rises on P-11 phosphor screens, surveillance of dimly lit antisocial activities, and applications that require fleeting signals to be recorded on a go or no-go basis, S.O. 166 is probably great and should outsell galactic plates by a factor of many thousands.

The three on a match would be interested to learn of your requirements. Don't expect any S.O. 166 yet for the family camera.

*Controlled baking of the plate yields greater sensitivity by improving its reciprocity characteristic and its quantum efficiency. This means that you get to use a lot of photons that would otherwise be lost and therefore get your sampling done in a shorter time. Contrary to our naive conjecture, you do not lose the advantage of improved S/N which was acquired by going to a fine-grain emulsion and long exposure. Moral: you can have your cake and eat it too—if it's baked twice, once at the factory and once in your own oven!

A corporation's thoughts about "science"

A corporation is an artificial person. It can therefore aspire to immortality. Furthermore the device affords a convenient façade for lively mortals.

If we hadn't had good people we wouldn't be where we are today, but we don't have enough of them to face the problems of the years ahead.

We are getting smarter. We now understand that just people aren't enough. We require *individuals*—no two too much alike.

Ideally, we hope by these words to attract into our midst an individual who will proceed to scientific accomplishments that freshman textbooks of the 1990s can scarcely ignore. An alternative ideal outcome would be to attract another and very different individual who will eventually turn from direct personal contribution to science and will wind up as chairman of the corporation's board of directors in the 1990s.

The effort will still have been worthwhile if it merely advises a few scientists that our size, organic integration, and diversification mean for the individual freedom of choice where his scientific interests and experiences can lead him as the years go on. We serve human needs both through the photographic process and through technologies now grown far away from photography. Thus we find economic support for a very broad range of fundamental studies on which the technologies may possibly feed. Hence the freedom in area of work.

We have come to appreciate also the need for freedom in choosing an approach to scientific problems. Strongly motivated scientists we can set free to put up to 100% of their working time into research. They can have assistance and auxiliary laboratory services by colleagues themselves well recognized as experts in their techniques—a situation that fortunately prevails in the Kodak Research Laboratories. They can communicate freely with peers and yet need not carry the "teamwork" figure of speech to where one forgets his own name in return for a dry stall and an assured bag of oats.

Anyone of any race who is approaching the threshold of a working career in chemistry, physics, or possibly in biology and who feels himself or herself sufficiently swayed by this eloquence to try to match interests developed in graduate school against what we currently imagine to be our own research interests should establish communication through Dr. Dudley B. Glass, Eastman Kodak Company, Rochester, N.Y. 14650.

Vitamin E in Pittsburgh and Rochester

We have reported a curious finding in *The American Journal of Clinical Nutrition* (17:351). Blood level of α-tocopherol (the substance principally responsible for the physiological vitamin E effect) averaged 358 ± 21 μg per cent in a group of 37 Pittsburghers whose serum lipids we were permitted to analyze. None of them had given their physicians any clinical evidence of vitamin E deficiency, but many were in an economic status that had brought them with other medical problems to a public hospital. This compared with 507 ± 32 μg per cent for a group of 37 persons in Rochester, N.Y., randomly picked from a healthy, working population, some of whom had been taking multivitamin tablets but no special vitamin E supplementation.

Besides vitamin E in bulk for the pharmaceutical and animal agriculture industries, Distillation Products Industries (Division of Eastman Kodak Company), Rochester, N.Y. 14603, also markets EASTMAN CHROMAGRAM *Sheet, the convenient new medium for thin-layer chromatography—convenient for anyone in a position to see for himself how significant might be the differences in tocopherol level in the population's plasma. Paper cited gives suggestions on the procedure.*

Kodak