cepted (for example, giant fibers of earthworm and squid), the weight of evidence from silver impregnation and, especially in recent years, from electron microscopy is against any such continuity. Physiologically, however, we have a new appreciation of the complexity-within-unity of the neuron. Like a person, it is truly a functional unit, but it is composed of parts of very different function not only with respect to metabolism and maintenance but also in the realms of processing diverse input and determining output—that is, of integration. The impulse is not the only form of nerve cell activity; excitation of one part of the neuron does not necessarily involve the whole neuron; many dendrites may not propagate impulses at all; and the synapse is not the only locus of selection, evaluation, fatigue, and persistent change. Several forms of graded activity—for example, pacemaker, synaptic, and local potentials—each confined to a circumscribed region or repeating regions of the neuron, can separately or sequentially integrate arriving events, with the history and milieu, to determine output in the restricted region where spikes are initiated. The size, number, and distribution over the neuron of these functionally differentiated regions and the labile coupling functions between the successive processes that eventually determine what information is transferred to the next neuron provide an enormous range of possible complexity within this single cellular unit.

In the face of this gradual but sweeping change in functional concepts, any statement but the most diffuse about expectations for the future must be very dangerous. Nevertheless I will venture to suggest that in the near future we will gain significant new insight at this unitary level of neurophysiology with respect to the functions and differentiations among dendrites, the chemical and perhaps ultramicroscopic specification of different kinds of surface membrane, additional labile processes, sites of possible persistent change, and the normal functional significance of intercellular reactions mediated by graded activity without the intervention of all-or-none impulses.

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CURRENT PROBLEMS IN RESEARCH

Rock Magnetism

The magnetization of ancient rocks bears on the questions of polar wandering and continental drift.

S. K. Runcorn

Polar wandering, as a geological hypothesis, seems to have been first mentioned in correspondence between Halley and Hooke. It is interesting that it was then invoked as an explanation of the occurrence of marine fossils in sedimentary rocks well above sea level! In the early days of geology, Buffon and the "catastrophic school" were advocates of the shifting pole hypothesis as an essential element in the evolution of the earth's crust. Apparently Francis Bacon first suggested that continental drift had occurred when he noticed the similarity of the Atlantic coast lines of South Africa and South America.

Wegener gave the first thorough discussion of these hypotheses, opening a lively geological and geophysical discussion which reached its height in the 1920's. Of late, these important hypotheses have been discounted, partly because the geological data were complicated and by no means conclusively in favor of them and partly for the less legitimate reason that a tenable explanation of the supposed phenomena had not been put forward. Darwin's famous paper on polar wandering was thought to have disposed of the possibility. The suggested explanations of continental drift were shown by Jeffreys and others to be incompatible with the inferences successfully drawn by geophysists on the strength of the earth's interior. Yet Wegener's book, though dated, makes a strong case for continental drift. Later writers, such as Du Toit, amassed a great deal of information from structural geology and paleontology which, by its nature, could hardly appear decisive to the scientists in other fields and which perhaps unintentionally obscures some of the simpler and very persuasive reasons for serious consideration of continental drift. Moreover, these arguments are essentially qualitative, and their various presuppositions are open to criticism. They were therefore, perhaps unfortunately, not widely considered.

Recently, renewed interest in the problem of polar wandering and continental drift has resulted from paleomagnetic measurements. The directions of the permanent magnetization of certain sedimentary and igneous rocks of many ages from various parts of the world have now been determined. Most of the rocks studied have been well-bedded red sandstones

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and basaltic lavas. These rocks often possess a high degree of magnetic stability and have consistent directions of magnetization over considerable distances within one continent in any one geological period. Other rocks are known to be permanently magnetized, but have not yet been so extensively studied. Basaltic lavas are found to have a strong permanent magnetization (with intensity of 10^{-2} to 10^{-3} electromagnetic units); red sandstones, a less strong magnetization (with intensity of from 10^{-5} to 10^{-7} electromagnetic units). Except in Cenozoic times (the last 60 million years) these magnetizations are in different directions from the magnetization induced by the present geomagnetic field.

The possibility that the magnetization of rocks could be used in the investigation of polar wandering and continental drift has long been recognized. This follows from the supposition that the nondipole and equatorial dipole components of the geomagnetic field are oscillatory phenomena, and indeed changes in these components have been observed in recent centuries. This "geomagnetic secular variation" occurs because the field originates in the earth's fluid core (only a negligible amount arises from the ferromagnetism of the crust.) Averaged over periods of the order of the free-decay time of electric currents in the core (a few thousand years), the field is reasonably expected, on theoretical grounds, to be that of a dipole at the geocenter oriented along the axis of rotation. If, therefore, mean directions of magnetization of a rock series, based on samples sufficiently spread stratigraphically to eliminate the secular variation, are found to be different from the present mean field, there is a strong indication that those rocks were magnetized when they were in a different orientation with respect to, and at a different angular distance from, the axis of the earth's rotation at that particular geological time.

It is interesting to note that William Gilbert, who was unaware of the existence of secular variation when he published his great work *De Magnete* in 1600, concluded (*1*) that "unless there should be a great dissolution of a continent and a subsidence of the land such as there was of the region Atlantis of which Plato and the ancients tell, the variation (i.e. the declination) will continue perpetually immutable (in any one place)." As will be seen later, it appears that Gilbert's words were somewhat prophetic.

Physical Process of Magnetization of Lavas

The magnetic mineral in a basaltic lava is usually a member of the magnetite-ulvospinel solid-solution series. The Curie point of these is a maximum (575°C) for pure magnetite and decreases with increasing titanium content. The process of magnetization of a lava has been very carefully studied by reheating samples of lava in the laboratory in zero magnetic field until the Curie point is reached and then cooling them in fields of about ½ gauss, meanwhile observing the magnetic moment of the sample at different temperatures (see, for example, *2*). In principle, the process by which magnetization is acquired on cooling is now well understood, from the standpoint of both experiment and theory. Normally, the coercive force and the intensity of magnetization decrease with temperature, the decrease being particularly rapid just below the Curie point. Consequently, in the presence of the geomagnetic field, the lava becomes strongly magnetized as it cools below the Curie point when its coercive force is low. On cooling to ordinary temperature, the coercive force rises to about 50 gauss, and subsequent changes in the direction of the geomagnetic field have no further influence on the magnetization.

In some cases, however, the magnetization of the iron-oxide minerals is anomalous. Nagata (*3*) has found and carefully studied a pumice which becomes magnetized in a direction opposite to the field in which it cools, thus verifying a remarkable prediction made by Néel (*4*). This process occurs because the magnetic minerals are tiny intergrowths of two ferri-ilmenites. The component of higher Curie point becomes magnetized first as the pumice cools, but when the Curie point of the other component is reached, the geomagnetic field within the mineral has been overwhelmed by a field in the opposite direction due to the magnetization of the former component. Under certain conditions the "reversed magnetization" of the second component may outweigh the

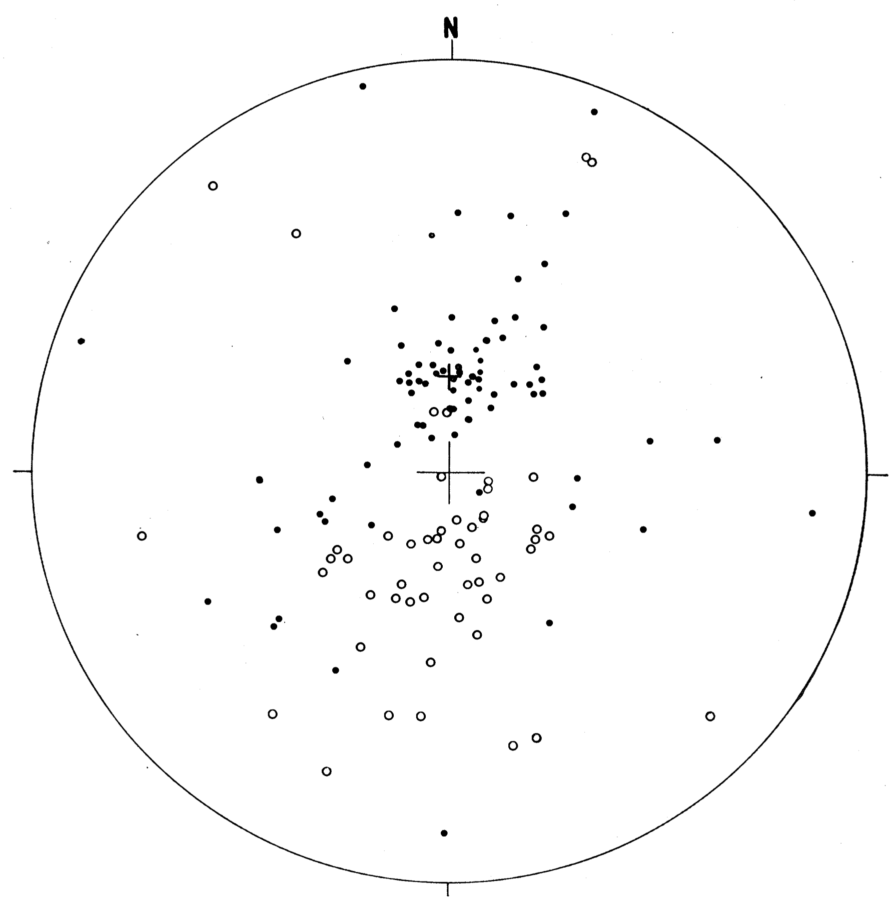


Fig. 1. Directions of magnetization of Columbia River lavas: (solid circle) plotted on lower hemisphere; (open circle) plotted on upper hemisphere. (Cross) Field direction corresponding to geocentric dipole along present geographical axis. [From measurements in C. D. Campbell and S. K. Runcorn, *J. Geophys. Research* 61, 449 (1956)]

first. Such intergrowths are a common feature of the iron-oxide minerals in rocks, and so, although no other example of the phenomenon discovered by Nagata has yet been found in lavas, it has been held that similar processes are responsible for natural magnetizations with polarities opposite to that of the present geomatic field. Such reversals have been found in the Tertiary lavas of the Columbia River plateau (Fig. 1), Iceland, Japan, and the Central Massif of France. They are also common in sediments and occur at all times in the geological column, though apparently with varying frequencies. The alternative explanation of these widespread reversals of magnetization throughout the geological column is, of course, that the geomagnetic field has, every few millions of years, reversed its polarity.

The fact that Tertiary lavas, when examined today, have not been found to possess the self-reversal property which Nagata discovered cannot be held to exclude completely the possibility that they did not possess this property at the time of their cooling and magnetization, for slow changes take place in the iron oxide minerals with time. However, the natural occurrence of reversed magnetization is so widespread that it would be exceedingly strange if reversals are to be attributed mainly to these anomalous processes rather than to real and frequent reversals of the polarity of the field. However, nature can, on occasion, cover its tracks very well, and it may be said that the decisive experiment on this problem is yet to be performed. One test, however, has now been made in a large number of cases, and provides strong evidence in favor of real reversals of the geomagnetic field.

Many workers who have measured the magnetization of dykes and lava flows have also measured the magnetization of the country rock at small distances from the point of contact with the lava or dyke. The sampled country rock was heated, during the intrusion of the dyke or the extrusion of the lava, above its Curie point and so lost its original magnetization and acquired a thermoremanent magnetization at the same time as the lava or dyke. In every case so far reported the magnetization acquired by the country rock is in the same sense as that of the lava or dyke. Cases of dykes in contact with older lava flows were reported by Hospers in the lava flows in Iceland. Cases of lavas in contact with underlying sediments which were baked red were reported by Roche in the Central Massif of France and by Opdyke and Runcorn (5) in the lava fields near Flagstaff, Arizona. If it is supposed that reversals of the geomagnetic field do not occur and that the reversed magnetizations which are observed in approximately 50 percent of Cenozoic lavas are due to the self-reversal property of the iron oxide minerals they contain, then one should, in about 50 percent of the cases studied, find the country rock and the igneous rock which bakes it having magnetizations in opposite senses. Although these contact-zone observations require further careful documentation, I feel that they exclude the possibility of any widespread "self-reversal" in nature.

There is another piece of evidence which bears on this question of reversal. No lava of Recent times (that is, since the last ice age) has been observed to acquire a reversed magnetization. This fact again seems to me to exclude the possibility of the widespread occurrence of a self-reversal of the Nagata type, although it does not exclude the widespread occurrence of a reversal which occurs through slow chemical change or through exsolution processes which might take a length of time of the order of a geological period to occur.

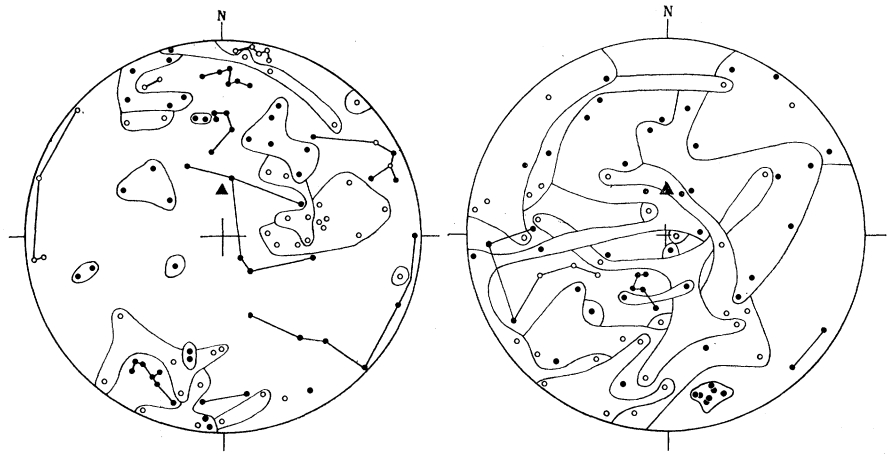


Fig. 2. Directions of magnetization in 47 conglomerate pebbles. (Left) Very fine sandstone pebbles with small internal dispersion; (right) fine, medium, and coarse sandstone pebbles with large internal dispersion. Lines enclose pebbles of definite New Red Sandstone age which have the same direction of magnetization and link together pebbles of presumed New Red Sandstone age which have the same direction of magnetization. Plane of projection is the horizontal. [From D. W. Collinson, K. M. Creer, E. Irving, S. K. Runcorn, *Phil. Trans. Roy. Soc. London* **250**, 83 (1957)]

Physical Process of Magnetization of Sediments

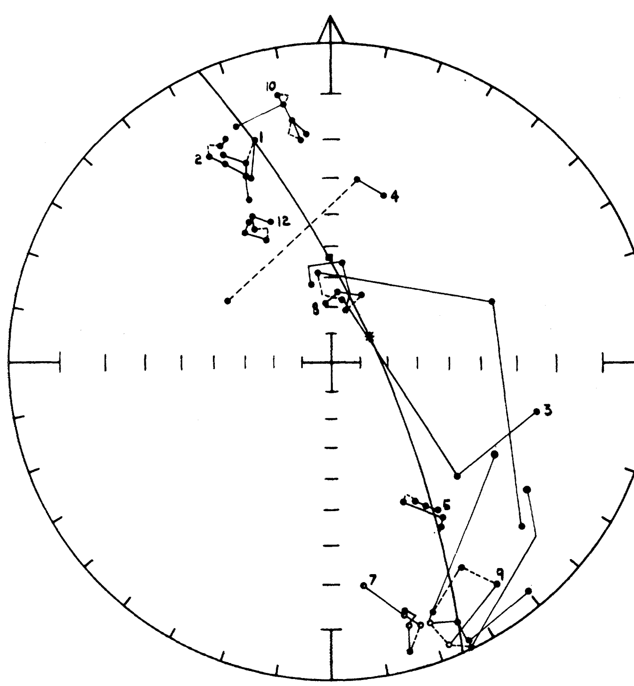
The first careful examination of the magnetization of sediments was made on the varved clays of New England and Sweden, which have been deposited in glacial lakes in the last several thousand years. There seems little doubt that the remanent magnetization of these clays arises from the magnetic orientation of the iron oxide grains, which retain some of the magnetization originally acquired in the igneous rocks from which the clays were derived by erosion. The varved clays may easily be dispersed and redeposited in the laboratory under magnetic fields of various strengths and orientations, and it has been proved by Johnson, Murphy, and Torreson (6) and by Griffiths and King (7) that the clays become magnetized roughly in the direction of the field but with an "inclination error." This error arises from the tendency of the elongated or discoidal grains to lie parallel to the bottom. Since the particles will usually be magnetized along a long axis, the permanent magnetization of the clay has a lower angle of magnetic inclination than the field in which the particles are deposited. Griffiths and King have also shown that currents in the water may affect the direction in which the elongated particles settle and hence may affect the direction of acquired magnetization.

However, the study of varved clays has only limited application in paleomagnetic studies, for these clays are of very infrequent occurrence in the geological column, and it is unwise to infer from these studies the process by which other sediments, particularly red sandstones, acquired their magnetization. Laboratory experiments have only limited application to this subject, as it is impossible to infer or to reproduce exactly the physical and chemical conditions in which rock is laid down. It is possible that the remanent magnetization of varves may give a more correct value for the direction of the field at the time of magnetization than the laboratory experiments suggest, for it has been shown experimentally that, even after deposition, the water in the pores between the grains of the sediment enables the denser and smaller iron oxide grains to rotate in the direction of the field, and this process would appear not to be subject to the two causes of misalignment described above. As the varves are the only deposits showing annual layers, they would appear to be ideal for the careful study of the short-term changes of the earth's magnetic field, known as the secular variation.

By far the most widely studied of other sediments are the red sandstones and shales; it is an observed fact that red sandstones and shales are frequently much more strongly magnetized than other sediments and can very often be shown to possess "magnetic stability." By this is meant that they acquired a permanent magnetization early in their geological history and have retained it unaltered (at least within a few degrees) since. This important fact has been determined by the use of a "field" test of stability, first suggested by Graham (*8*). By finding pebbles in a conglomerate bed which were derived from the rock formation under study and determining the directions of magnetization which they have at present, information about the stability of the rock since the conglomerate bed was formed can be obtained. For example, in Fig. 2 pebbles of Torridonian (late Precambrian) sandstone in a Triassic conglomerate are seen to have directions of magnetization in random directions in space, as they must have had when the conglomerate was formed. This is evidence that the Torridonian sandstone has had magnetic stability over the last 150 million years. Similarly, folded or tilted beds which have directions of magnetization which agree with those of flat-lying beds of the same geological formation elsewhere only after allowance has been made for the geological dip, must have been magnetically stable since the tectonic movements took place. Had the original magnetization acquired when the beds were formed been unstable and a new magnetization been imposed by some agency after the rocks had attained their new positions, then the present directions of the magnetizations of the various samples would be more nearly parallel.

Even when the red sandstones are not completely magnetically stable, the instability often takes a simple form: The rocks acquire a component, of intensity varying from specimen to specimen, directed along the mean geomagnetic field in recent times, which is known to be that of a dipole orientated along the present axis of rotation of the earth. Thus, the resultant directions of magnetization of samples from such a formation form a streak, rather than a well-grouped set, in a plane containing the present "dipole" direction and the direction of the field at the time of the formation of the rocks. Some information about the latter direction can therefore be obtained even from unstable rocks. An example is shown in Fig. 3. The cause of such a magnetization has not yet been established, although it is known that iron oxide minerals of a certain grain size cannot retain magnetization for long periods, and presumably an appreciable component of iron oxide of the critical grain size is present in some samples of the sediments. Such grains would slowly pick up a magnetization from the ambient magnetic field and so produce the above-mentioned effect.

The comparative magnetic stability of the red sandstones can reasonably be ascribed to the high coercive force (many thousands of gauss) of the hematite grains which they contain. The small grains forming the red coating of the quartz grains, of which the sandstones are mainly composed, and the black detrital iron oxide grains, which are usually present to the extent of about 1 percent of the whole rock, are usually found to be hematite. Miller and Folk



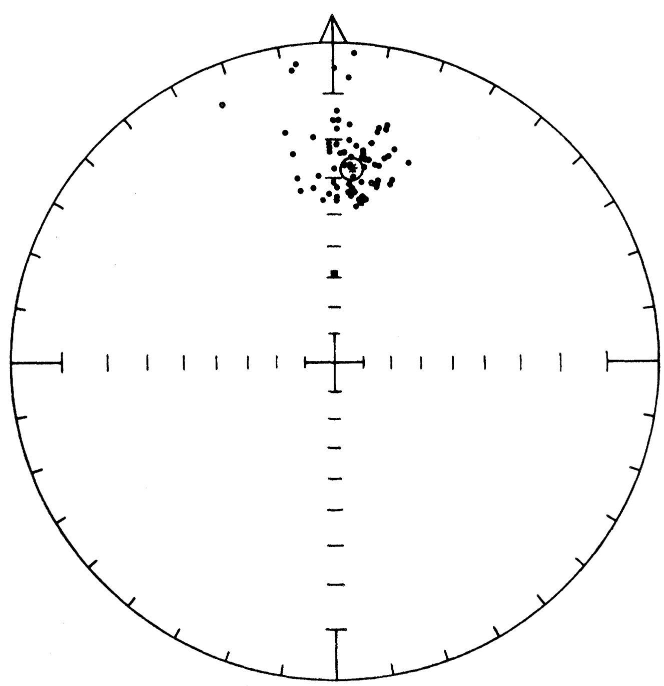


Fig. 3 (left). Streaking in Chinle formation (Upper Triassic) from Moab, Utah. Solid square indicates present dipole field. Solid line and solid circles are on the lower hemispheres of the projection; dashed line and open circles are on the upper hemispheres of the projection. Fig. 4 (right). Magnetic directions in Triassic beds, Frenchtown, New Jersey. Solid square indicates present dipole field. Solid circles lie on the lower hemispheres of the projection; open circles lie on the upper hemispheres of the projection.

(9) point out that red beds, in contrast to grey-green and white sediments, usually contain abundant detrital iron oxides, but they incorrectly describe these black detrital grains as magnetite and ilmenite. It is not known which component carries the remanent magnetization, and it is likely that in some rocks it is the coating and, in some, the detrital minerals. It has, however, been shown by laboratory experiments that the crystallization of hematite from iron hydroxide soaking into a pure quartz sand in the earth's magnetic field leaves the sample permanently magnetized in the direction of the geomagnetic field. This phenomenon, called "chemical magnetization," deserves further study, but it seems reasonable to assume that, in the course of a chemical change producing a ferromagnetic mineral (even at ordinary temperature) the iron ions will become free to turn into the direction of a weak field and that, on the completion of the chemical change, the material will remain permanently magnetized unless it is exposed to a field of very much greater intensity. Another possibility is that the hematite grain grows beyond a critical size below which it has a very low coercive force but above which it is very stable. Such a process is suggested by Néel's theory of the magnetization of single-domain grains (10). The directions of magnetization of sediments which acquired their magnetization in this way would not, of course, be expected to possess inclination error.

It has been mentioned that the commonest recognizable form of magnetization acquired by rocks since deposition is magnetization directed along the earth's present field, and one possible mechanism by which this is obtained has been described. Such magnetization is not uncommon in rocks now exposed in the southwestern United States, and it is also possible that it is a recent chemical magnetization. In a hot climate in which there are at times heavy rains, it is possible that in the surface layers some of the hematite becomes hydrolyzed. Later on, the hydroxide formed decomposes to hematite again, which then picks up a magnetization parallel to the present field. This process would be expected to be particularly important in porous sediments.

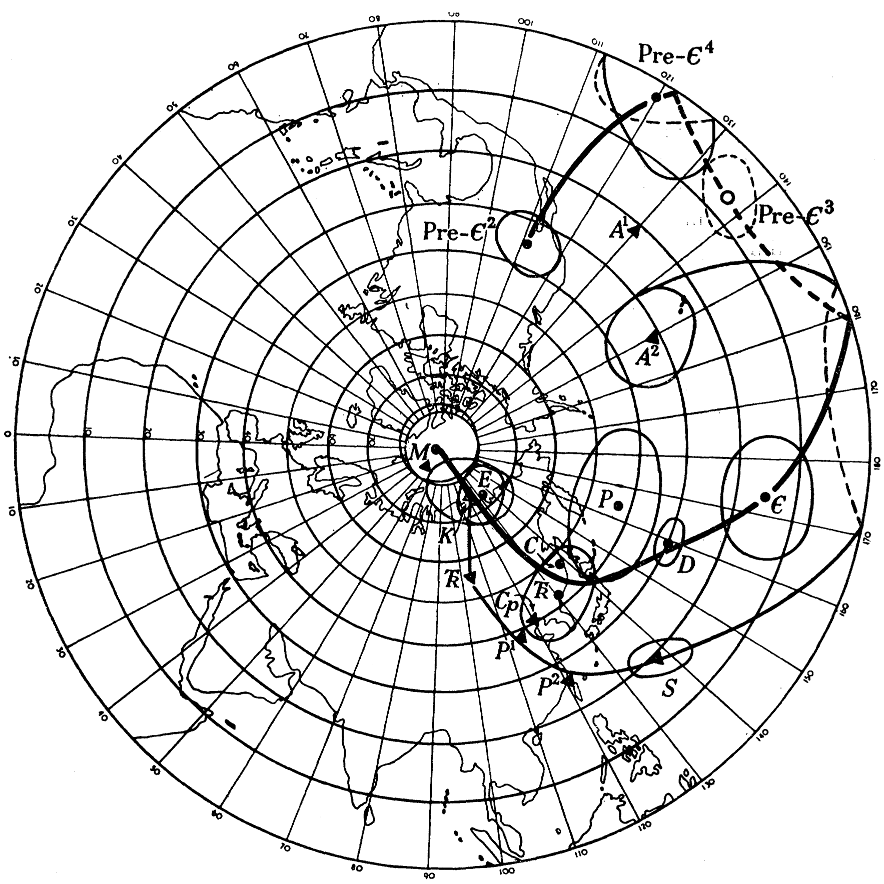


Fig. 5. Polar wandering paths for North America and Europe. (— ● —) Path inferred from British rocks, plotted in northern hemisphere; (- - ○ - -) path inferred from British rocks, plotted in southern hemisphere; (— ▲ —) path inferred from American rocks, plotted in northern hemisphere; (- - - - - - -) path inferred from American rocks, plotted in southern hemisphere. (M) Miocene; (E) Eocene; (K) Cretaceous; (T_R) Triassic; (P) Permian; (C_P) Cambrian, Pennsylvanian; (D) Devonian; (S) Silurian; (O) Ordovician; (ε) Cambrian. (A) Algonkian (late Precambrian of the United States): (A^1) Hakatai shales (Doell's measurements); (A^2) Hakatai (south rim of Grand Canyon). (Pre-ε) Late Precambrian of Great Britain: (Pre-ε^2) lower Torridonian; (Pre-ε^3) Langmyndian; (Pre-ε^4) Upper Torridonian.

Other Sources of Secondary Magnetization

In the early days of study of rock magnetism, any anomalous magnetizations found in rocks were usually ascribed to very special causes (see 11), as it had not then been understood that rock formations usually possess a reasonably uniform magnetization over considerable areas. Lightning, in particular, was cited as a source of magnetizations in rocks, and effects of this kind were demonstrated by placing lava samples around the bottom of lightning conductors. There seems little doubt that lavas in exposed positions may get strong, but very localized, magnetizations in this way, though sufficient studies do not seem to have been made of such anomalies.

Recently the effect of mechanical stress on the direction of remanent magnetization has been discussed. Graham (12) has shown by laboratory experiments that the direction of magnetization of lavas and metamorphic rocks changes appreciably under uniaxial stresses of an order which might be produced by burial beneath some thousands of feet of rock. Although he is not able to show that such effects have irreversible characteristics, it is probably true that, over long periods of time, irreversible changes in the magnetization of rocks might occur in this way. In some rock formations the agreement in the fault patterns over large distances suggests that stress systems are more than a local effect. Thus, it appears desirable to entertain the possibility that magnetostriction effects could alter the original magnetization of rocks in such a confusing way as to prevent the remanent magnetization of rocks under study from throwing light on major geophysical problems. This indeed seems to be what Graham suggests.

However, although laboratory experiments suggest ways in which the magnetization of rocks could be produced at or after deposition and could later be altered, deductions from them have little direct relevance to the interpretation of the remanent magnetization of rocks. This is a surprising point of view only to those who imagine that the physics of the processes by which rocks are formed and the history of the rocks are known in quantitative detail.

There will be those who hold that if this is true we might as well abandon the subject; however, this does not seem to be the way the scientist works—he tries to make sense of those observations of the physical world which can be made. Therefore, while laboratory experiments on the magnetic properties of rocks are interesting for their own sake and need to be pursued extensively, carefully analyzed field measurements are more likely to reveal how any particular rock formation became magnetized.

Results of Paleomagnetic Surveys

A typical example of a well-grouped set of paleomagnetic directions is given in Fig. 4. Some of the scatter may represent the effect of the wobbling of the geomagnetic field about its mean position over the period of time represented by the rock series. The mean direction of such a set of measurements is assumed to correspond to the field which would be produced at that place by a geocentric dipole oriented along the earth's axis of rotation at that time. A simple formula of spherical trigonometry makes it possible to calculate the position of the poles for that geological time on the present globe, that is, assuming for the moment that the present distribution of the continents has remained unchanged.

In the last few years there has been a very rapid increase in the accumulation of paleomagnetic data. The initial aim has been to trace in outline the changes in the earth's magnetic field throughout geological time, as determined by rocks from different continents. For this purpose the sampling has been restricted in certain ways:

1) Study has so far been restricted to rather strongly magnetized rocks. Because initial surveys showed that, in general, among igneous rocks, lavas, and, among sediments, red sandstones, are most strongly magnetized, the study has largely been restricted to these. It is not known that weakly magnetized rocks are intrinsically less useful for purposes of this study, but strongly magnetized rocks can be more easily measured, and consequently changes in their magnetization in the course of the laboratory processes can be more easily observed.

2) The main sampling has been carried out in those areas where very little tectonic movement has occurred, on the grounds that stress and rise of temperature might irreversibly affect the original direction of magnetization.

3) Surveys throughout the geological column have been made, rather than very extensive collections of rocks from one particular period, although certain rock series, such as the Torridonian sandstone, have been studied in great detail.

In the interpretation of paleomagnetic data it has been assumed, on the basis of theory, that the geomagnetic field, when averaged over some thousands of years, is a dipole directed along the axis of rotation. This theory has experimental support in that it accords with paleomagnetic observations for late Tertiary and Quaternary times in different areas of the world. Collections of samples from rock formations selected in the way described above have been measured on an astatic magnetometer, and their directions of magnetization have been checked in some cases with a spinner magnetometer.

We have taken steps to eliminate, or allow for, the effect of magnetization acquired in recent times along the present direction of the earth's magnetic field. Where possible, the field tests of stability of magnetization of folded beds and conglomerates have been used. A degree of stability is invariably found in such rocks. In the vast majority of cases a geological formation gives a well-grouped set of directions of magnetization, from which the mean can be calculated. The mean has been designated as being the direc-

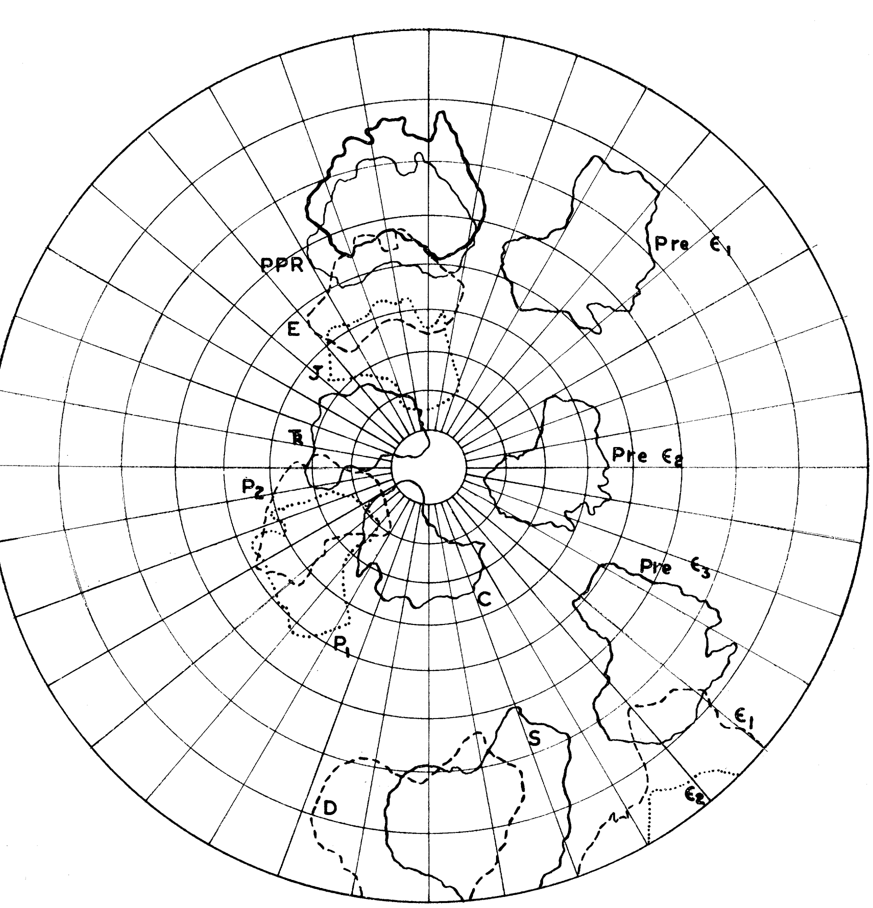


Fig. 6. Stereographic projection showing position of Australia relative to the pole. (PPR) Pliocene, Pleistocene, and Recent (newer volcanics of Victoria); (E) Lower Tertiary, probably Eocene (older volcanics of Victoria); (J) Mesozoic, probably Jurassic (Dolerite sills of Tasmania); (T_R) Triassic, probably lower Triassic (Brisbane tuff); (P_2) Permian, Upper Marine Series (volcanics of Illawarra coast); (P_1) Permian, Lower Marine Series (volcanics of Hunter Valley); (C) Upper Carboniferous (Kuttung red varvoid sediments and Kuttung lavas); (D) Devonian, probably Lower Devonian (Ainslie volcanics); (S) Upper Silurian (Mugga porphyry); (ϵ_2) Middle Cambrian (Elder Mountain sandstone); (ϵ_1) Lower Cambrian (Antrim plateau basalts); (Pre-ϵ_3) Top of Upper Proterozoic (Buldiva quartzite); (Pre-ϵ_2) Upper Proterozoic (Mallagine lavas); (Pre-ϵ_1) lower part of Upper Proterozoic (Edith River volcanics).

tion of the magnetic field of a given geological period (or part of a period) minus the effect of the geomagnetic secular variation. The pole position calculated from this direction and from the present geographical latitude and longitude of the site is not only the mean magnetic pole for that period of time but is assumed to be the pole of rotation of the earth relative to the continent in question.

From Precambrian times to the present, pole positions have been determined relative to Great Britain, North America, and Australia (Figs. 5 and 6). The following features of these pole positions, or "polar wandering curves," as they are called, have been found:

1) Pole positions of successive geological periods lie on a reasonably smooth curve, and they lie successively nearer the present pole as their age diminishes.

2) The curves drawn through these pole positions for the two continents of Europe and North America are of roughly similar shape, whereas that for Australia is different.

3) There is systematic displacement between the curves for Europe and North America which has been interpreted by Runcorn (*13*) as showing that, after Triassic times, a relative motion of North America and Europe took place. It is not by any means easy to be specific about the value of this displacement, but estimates range from a value of about 24° (see Figs. 7 and 8) to 45° (see *14*).

4) Results obtained in Australia (*15*), South America (*16*), and South Africa (*17*) lead one to suppose that a very considerable amount of continental drift occurred in the Southern Hemisphere in Mesozoic times.

Statistical Methods in Measuring Rock Magnetism

It is, perhaps, at first sight surprising that measurements of the paleomagnetic directions of, say, a dozen samples from a rock formation hundreds of feet thick and covering hundreds of square miles may provide an adequate estimate of the direction of the earth's field during the epoch in which these rocks were laid down. To the geologist a rock formation is a series of rocks, whose lithological character enables them to be traced and, in consequence, mapped, over a considerable area of country. The rocks comprising the formation will be laid down in similar environments or in a series of alternating environments. A formation usually spans a fraction of a geological period—perhaps some million years. In the case of basaltic lava flows, a single flow may be traced over many tens of miles, over which its thickness remains remarkably constant. Therefore it must have flowed out, solidified, and cooled below the Curie point within a few months. Consequently, in a single flow one might expect the lava to record the direction of the earth's field at a point of time. The flow lying upon it will likewise provide a record of the value for the field at another point of time, perhaps many hundreds or thousands of years later. In practice it seems that the directions of magnetization of samples from a single lava flow are scattered because of the magnetic disturbances produced by neighboring flows, but this problem has not yet been studied carefully.

In a sedimentary formation the time relations between different samples present a difficult problem. Commonly, a sediment possesses innumerable bedding planes, recognizable today as planes of weakness which are revealed by erosion. Such planes represent surfaces on which the rate or type of deposition changed, or down to which erosion removed previously deposited sediment. Such bedding planes may therefore represent long intervals of time. Between successive bedding planes the sedimentary material may be deposited rapidly; these may become magnetized in a time much less than that in which the magnetic field can alter by a few degrees—that is, in a time much less than the time scale of the secular variation (*18*). Further, in lacustrine, deltaic, and marine sediments deposited offshore in a transgressing sea, sedimentation is not continuous over the entire area now represented by these rocks. Consequently the sediments are in the form of wedges, which disappear when traced laterally. Similarly, the bottom and top of a sedimentary formation at one place will not represent the same time-span as analogous horizons of the same rock formation in a different place; a time line running through the formation will therefore, in general, make an angle with the bedding planes.

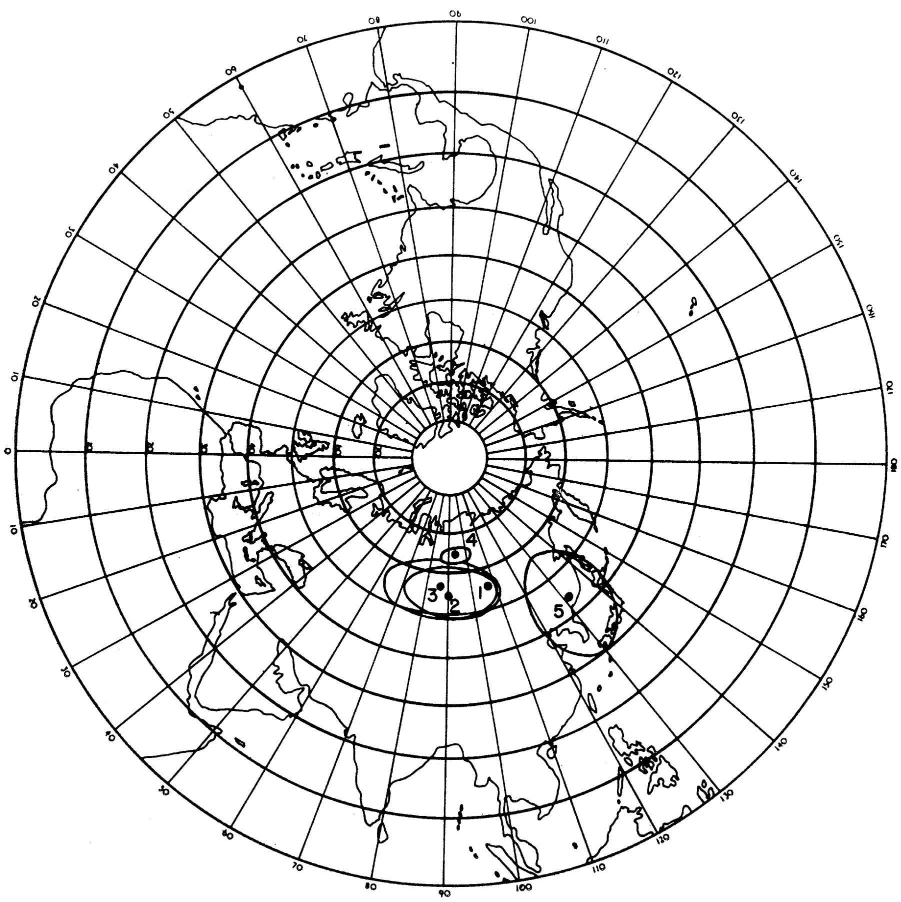


Fig. 7. Upper Triassic pole positions for the United States and Great Britain. (1) Springdale sandstone, Utah; (2) lavas near Holyoke, Massachusetts; (3) lavas and sediments of Connecticut; (4) Newmark series, New Jersey; (5) Keuper marls, England. [P. M. du Bois, E. Irving, N. D. Opdyke, S. K. Runcorn, M. Banks, *Nature* **180**, 1186 (1957)]

The above theory therefore suggests that if samples are selected from different horizons spanning a considerable thickness of the formation, the mean direction should effectively average out the secular variation and any deviations due to polar wandering during the time represented by the formation.

It is found that the directions of such samples are scattered randomly about a mean direction, and Fisher (*19*) has suggested that the relative frequency of directions at an angle θ with this mean is given by $e^{K\cos\theta}$, where K is a measure of the precision. If each of the N directions is represented by a unit vector, then the magnitude of the vector sum R will be much less than N if there is great scatter and will be nearly equal to N in the case of a close grouping of directions. Fisher shows that an estimate of K is provided by $(N-1)/(N-R)$ and that the best estimate of the mean direction is the vector mean. I have given the approximate formula that 63 percent of the directions make an angle with the mean direction of less than $81/\sqrt{K}$ degrees (*18*). I have also shown that the angular radius of the cone of confidence which, described about the calculated mean direction, includes the true mean direction with a probability of 95 percent equals approximately $140/\sqrt{KN}$ in degrees. It can therefore be readily seen that if K is 100, 63 percent of the directions lie within a cone of semiangle of 8° described about the vector mean direction, and the angle of the cone of confidence can be reduced to within 5° by taking about ten samples.

Just as there are local magnetic anomalies on the earth's surface today which alter the direction of the geomagnetic field (for example, at Kursk, U.S.S.R.), so there will undoubtedly be found anomalous paleomagnetic directions.

It may be asked whether it is possible to show that over very considerable areas the direction of the magnetic field deduced from the paleomagnetic measurements is consistent. There are not yet as many measurements relating to this point as one would like. But almost every rock formation which has been studied extends over hundreds of miles, and there is certainly consistency in the paleomagnetic directions to this extent. It is much more interesting, however, to consider whether the paleomagnetic measurements of rock formations of the same age across an entire continent give poles which are in the same place. In this connection it must be noted that the polar-wandering curve indicates a mean movement of the pole of about one-third of a degree per million years, and consequently it is quite possible that, during a geological period, the polar motion (apart from the secular variation which is assumed to be smoothed out in all cases) could lead to discrepancies of up to 20 or 30 degrees in the paleomagnetic directions of rocks of the same geological period. Unfortunately the rocks which have been used so far in studies of paleomagnetism are, of course, those in which fossils are most scarce, and consequently the determination of the geological age to any accuracy very much shorter than a geological period seems rather difficult. However, the Upper Triassic of the United States furnishes an example of the good agreement between pole positions from widely different areas, as is shown in Fig. 7.

Paleowind Directions

For independent evidence of polar wandering, recourse must be had to the evidence of paleoclimatology. The methods geologists have used in such investigations are not quantitative and are open to various objections. It is of interest to consider whether there are more physical methods of determining the latitude and orientation with respect to the axis of rotation of land masses at different geological times.

The explanation of the deflection to the east of the winds blowing toward the equator in the trade-wind zones was given long ago by Hadley and concerns the deflecting action of the Coriolis force on air drawn to the equator. Consequently, it is probable that through geological time there has always been a trade-wind belt, although its extent in latitude may have altered. Recently, Opdyke and Runcorn (*20*) have examined the question of whether the winds in ancient geological time were appropriately orientated relative to the equator of that time. That the direction of the wind which transported sand in the accumulation of certain aeolian deposits may be determined by measurements of the direction of the line of greatest dip in cross-laminated rocks is a theory that has been developed by Reiche (*21*) and Shotton (*22*). These

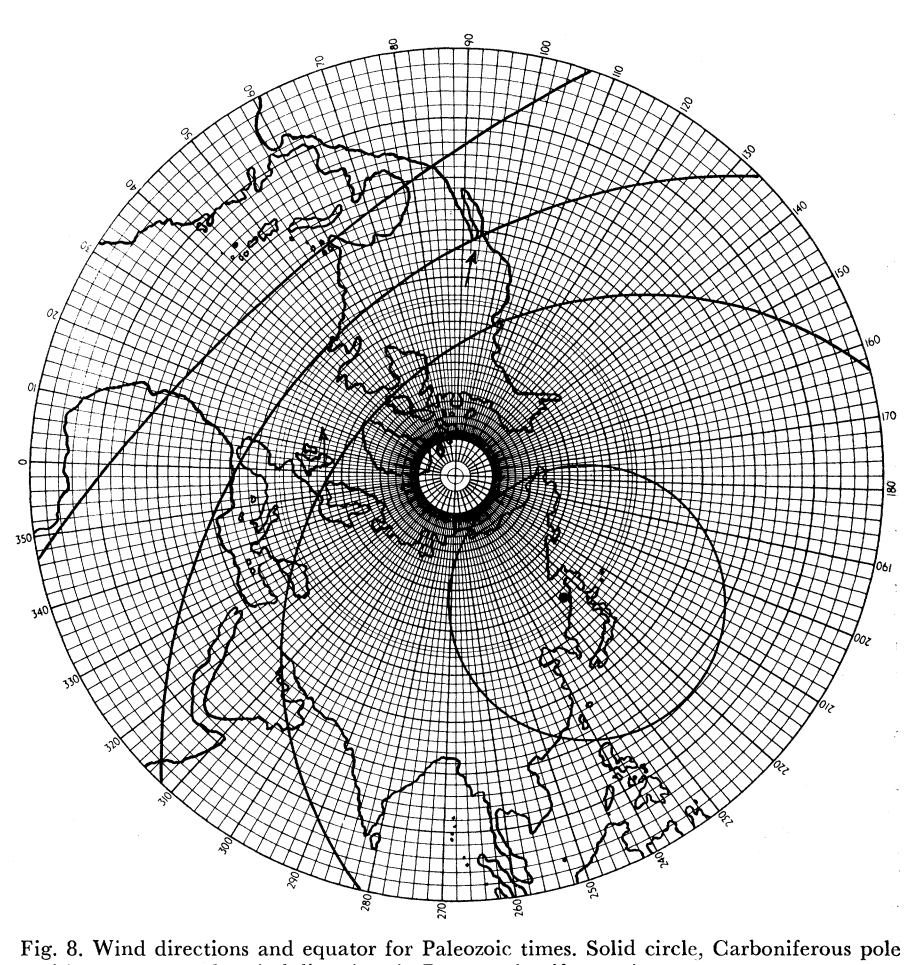


Fig. 8. Wind directions and equator for Paleozoic times. Solid circle, Carboniferous pole position; arrows, paleowind directions in Permocarboniferous times.

authors showed that the Coconino sandstone of Arizona and the New Red Sandstone of Great Britain represent the accumulation of many crescentic or barchan dunes, traces of the lee slopes of which are revealed in exposures of these rocks as cross laminations of large size. Modern barchan dunes have been carefully studied by Bagnold in the Libyan Desert and by many other workers. Steady wind blows sand up the gently sloping windward side of the dune, the sand falling on the lee slope at its angle of repose, about $32\frac{1}{2}°$. The laminations of the lee slope are consequently protected from erosion, and apparently may be preserved (perhaps truncated) if the dune sea consolidates into rock.

The crescentic shape of the dune causes the directions of the line of greatest dip of the cross lamination to be spread over about a right angle, so that the wind direction at one locality is the mean of these directions obtained from a number of cross-laminated units, each of which represents a different part of the dune.

Cross laminations can arise from deposition in rivers and in beach deposits but are usually of smaller scale. There is, however, no single criterion which permits classification of a cross-bedded sandstone as aeolian or not aeolian (*23*). Opdyke and Runcorn (*20*) show that certain parts of the Tensleep, Casper, and Weber sandstones, of Wyoming and Utah, of Pennsylvanian age are likely to be aeolian. They show that the wind which deposited these sandstones came from the northeast quadrant, as is true also in the case of the Coconino sandstone of similar late Paleozoic age, studied by Reiche (*21*). The consistency of these wind directions over a large area is shown in Fig. 9.

It is, of course, true that the wind today is affected by topography, the planetary wind system being considerably distorted in certain areas. The consistency of the wind directions described above, however, indicates that this wind is probably a planetary wind and not one affected decisively by local geography. It must be remembered that the present time is one of unusually high relief, and it may be that the planetary wind system was less distorted in remote geological time. Again, it must be remembered that a rock series represents a long period of time during which local effects may be expected to average out, to some extent. There is an analogy here with rock magnetism, in which the mean direction of magnetization of a geological period apparently averages out the nondipole parts of the geomagnetic field which are of importance at any one instant of time.

It will probably not be possible to map the directions of the ancient winds in the detail in which the ancient magnetic field can be mapped, unless some method apart from the study of aeolian sandstones, which appear to occur infrequently in the geological column, can be found. But it is interesting to see from Fig. 8 how the late Paleozoic wind directions of North America and Great Britain fit in as the northeast trade winds relative to the late Paleozoic equator, derived from paleomagnetic studies.

Geological Evidence of Paleoclimates

The traditional method of inferring the climates of a geological period depends on the type of sediment and on the fossil record. It cannot be said that most of the evidence is of a type which can be interpreted unambiguously. For an exploratory comparison of the paleomagnetic and paleoclimatic evidence, we use two of the least disputable inferences from the geological record.

1) Evidence of glaciation over considerable areas in Permocarboniferous times has been found in Australia, South Af-

Fig. 9. Paleowind directions.

rica, South America, and India. Unless there has been radical change in the climate of the globe as a whole, we can infer that such glaciations were restricted to the then polar regions. Simpson (*24*) suggests that extensive sea-level glaciation could not have occurred at latitudes of less than about 50°. The paleomagnetic observations show that Australia was in high latitudes in Permocarboniferous times and also in late Precambrian times when there is also evidence of glaciation in Australia. Paleomagnetic surveys of South Africa, South America, and India for Permocarboniferous times are of key importance.

2) Occurrence of extensive red beds suggests either a hot, humid or a hot, arid climate. It is difficult to see how such conditions could occur except near the equator if the axis of rotation of the earth is nearly perpendicular to the ecliptic. Similarly, dune sandstones and evaporites indicate a position close to the equator. Abundant beds of the type described are typical of northern Europe and Great Britain from the Devonian to the Triassic, of western United States between Pennsylvanian and Jurassic times, and of eastern United States between the Silurian and Triassic. The paleomagnetic determinations put Great Britain and the United States in low latitudes during Paleozoic and early Mesozoic times. Dividing the values of the paleomagnetic angles of inclination less than about 30° by 2 gives the corresponding latitudes quite accurately (*25*).

Hypothesis of Polar Wandering

The evidence of paleomagnetism, with which that of paleoclimates does not conflict, suggests that the poles of rotation of the earth and the land masses have gradually changed their relative positions. We must therefore briefly consider the mechanism by which polar wandering and continental drift could have been brought about. The latter involves more degrees of freedom than the former, but, fundamentally, both require that the earth be able to flow if subjected to steady stresses over millions of years, and both require that there be internal movements of some kind. Recently the mechanics of polar wandering has been discussed in outline. Clearly, what is required is that if the axis of figure of the earth is displaced from the axis of rotation by an infinitesimal amount, the stresses due to the centrifugal forces will cause the earth to flow so that the equatorial bulge will return to a plane perpendicular to the new axis of rotation. The time constant of this process appears to be between a few hundred thousand years and a few million years. The physical cause which displaces the two axes in the first place is a matter for conjecture. Random disturbances in the crust or processes in the mantle are possibilities. Mountain building and convection currents in the mantle have been shown to be adequate causes. It should perhaps be emphasized that no change in the direction of the axis of rotation in space, that is, no change in the angular momentum of the earth, is involved in these processes.

Hypothesis of Continental Displacements

Probably most geologists and geophysicists feel reluctant to admit the possibility of relative displacements of the continental masses in the recent history of the earth. It is often stated that a sound reason for such skepticism is the absence of any adequate theory of the mechanism by which such continental displacement could have taken place. This is an argument which should not be given much weight. Not until the last few years has there been an adequate theory for the existence of the geomagnetic field, but scientists did not previously disbelieve in the existence of the field for this reason.

That the coast line of much of South Africa and South America fits together is of course a fact which the exponents of continental drift have thought very significant. Jeffreys' (*26*) statement that the fit is a poor one has recently been shown to be untrue by Carey (*27*). It is significant also that the mid-Atlantic ridge follows a line parallel to these two coast lines.

It is perhaps significant that the continental displacements of thousands of miles since the late Mesozoic represent an annual rate of movement of the same order as that occurring along the San Andreas fault (*28*). By geodetic observations this has been determined to be 1 centimeter per year at the present time. Geological correlation suggests that there has been a displacement of possibly 350 miles in 100 million years, or 0.6 centimeter per year. The existence of this relative motion in the earth's crust today implies that movements deeper in the crust are taking place for which we have no adequate theory. We have no means of knowing whether such movements are capable of causing relative movements of larger areas of continental material.

Perhaps thermal convection in the mantle is occurring, and this may be the explanation of continental drift. It is well known that the present distribution of continents and oceans has certain regularities. The oceans and continents are diametrically opposite, and only 3 percent of the area of the continents has land antipodal. Prey and Vening Meinesz have expressed this fact mathematically by showing that if the height or depth of the rock surface is expressed as a series of spherical harmonics, the first, third, fourth, and fifth harmonics are predominant. Vening Meinesz draws the inference that the present distribution of the continents is fixed by the presence in the mantle of convection currents with a certain number of cells. One would infer that the continental rafts would be drawn toward those parts of the world where the convection currents are falling. At first sight it appears strange that the dispersion of the continents occurred so late in the history of the earth. If the above argument is accepted, then the dispersion of the continents at the end of Mesozoic time must reflect a change in the convection patterns in the mantle at that time.

It is not easy to suggest a reason for a change in the convection pattern so late in geological time, but it may be the result of a gradually growing core, which, as its radius increased, would favor convection with a higher number of cells. It has been suggested that the present concentration of the land masses in one hemisphere is the result of a primevil convection current consisting of a single cell which swept the continental material to one area. Such a single cell convection pattern would, however, be set up only if the heavy iron core was then very small. The idea of a core growing through geological time, rather than one formed initially, has been postulated by H. C. Urey in recent years, and may now receive support from continental drift.

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News of Science

Scientists at Space Agency Seminar Compare Views on Composition and Origin of Van Allen Radiation Layer

On 26 and 27 March the Theoretical Division of the National Aeronautics and Space Administration held a conference on problems associated with the Van Allen radiation layer. The conference, one of a series of seminars on current theoretical problems in space exploration, was organized by NASA.

The discovery of an intense layer of radiation in the outer atmosphere first reported by Van Allen and his collaborators at the State University of Iowa, constitutes the most significant research achievement of the IGY satellite program. The discovery was reported by Van Allen on 1 May 1958, at a meeting of the National Academy of Sciences, and confirmed by Sputnik data released by the U.S.S.R. at the Moscow IGY conference in August 1958. The layer probably provides the explanation of the aurora borealis and other geophysical phenomena, and it will also influence the design of vehicles for manned space flight.

As yet, very little is known regarding the properties of the layer, and its origin and geophysical effects have been the subject of extensive speculation. At the beginning of the year it was clear that the time had arrived for an informal meeting on these problems. In accordance with its policy of stimulating and coordinating research in frontier areas of the space sciences, the National Aeronautics and Space Administration invited a group of physicists to Washington for a symposium on the theoretical problems associated with the existence of the Van Allen layer.

The conference included three formal papers, by T. Gold (Harvard), E. N. Parker (Chicago), and N. Christofilos (Lawrence Radiation Laboratory), which served as nuclei for the discussion. These were supplemented by contributions from S. F. Singer (Maryland), P. Kellogg (Minnesota), E. Ray (Iowa), C. McIlwain (Iowa), and many other participants. A series of vigorous debates generated high ambient temperatures, which testified to the success of the meeting.

Trapped in Orbits

A large amount of provisional material on the radiation layer has been published in the press and in the scientific literature. Some of the material is well enough established to stand the test of time, and this can be summarized very briefly. First, the layer is known to consist of charged particles because the intensity variations follow the configuration of the earth's magnetic field. The magnetic field acts on charged particles, but it does not act on neutral particles or on radiation. We know from a great deal of theoretical work, which goes back to papers published by the Norwegian physicist Stoermer 50 years ago, that these charged particles may be trapped in orbits in which they spiral about the lines of magnetic force in the manner of a helix, traveling back and forth between the north and south magnetic poles.

If the particle is produced on a line of magnetic force at an altitude which is well out of the atmosphere, where the air density is low, then it can live for a long time, going back and forth from one reflection point in the Northern Hemisphere to the conjugate point in the Southern Hemisphere. The estimates of the lifetime depend on altitude, and they range from seconds at a few hundred kilometers to years out at a thousand kilometers. Lifetime estimates have been made by Christofilos, Singer, and Kellogg; these were among the few theoretical results on which there was agreement at the conference.

Under the circumstance of extended lifetimes the particles can be fed into the layer at a very slow rate, but, because they stay there so long the population of particles will nonetheless build up to very substantial values. That is the key to the formation of the Van Allen layer.

Hard and Soft Components

The Pioneer III space rocket extended the radiation measurements out to a distance of 110,000 kilometers from the earth and showed that the layer actually contains two separate zones, with centers at 13,000 and 25,000 kilometers, respectively. The population of the inner zone may be divided into a soft component, with energies of the order of 100,000 volts, and a hard component, with energies of 6 million volts or more. The hard component is so named because it has sufficient energy to penetrate a 1-centimeter slab of aluminum in front of the shielded counters. It has always been assumed that the soft component consists of electrons, because electrons of the same energy and intensity had already been observed in rocket flights into the upper atmosphere. The penetrating particles of the hard component remained unidentified, but at the conference McIlwain and Ray reported for the Iowa group the result that these particles were definitely protons, with energies in the neighborhood of 100 million volts. The identification of the penetrating particles as protons rested on analysis of unexpected variations in the Explorer IV data, which indicated their specific ionization to be roughly 4 times minimum.