Geomagnetism: Theories of Since 1900

American Geophysical Union, The Geophysics History Project
http://www.agu.org/history/mf/articles/Geomag20.html

Concerning production of the main magnetic field of the Earth, its secular and diurnal variation, and induced fields.

A definitive history of geomagnetism is yet to be written, but brief accounts have appeared in various publications. The story up to 1940 has been summarized (Chapman and Bartels, pp. 898-936). Perhaps the most complete account is by David R. Barraclough (pp. 584-592). Brief accounts have also been given by Stuart Malin (in Jacobs, ed., Geomagnetism, 1: 1-50), and others (Multhauf and Good, pp. 1-46; Good, pp. 524-526; and Parkinson, pp. 347-355).

The explanation of the Earth's magnetic field has been one of the major problems in earth science for many years. The explanation given by William Gilbert (1544-1603) in 1600, of permanent magnetization within the Earth, had to be abandoned when it was realized that the temperature within most of the Earth is higher than the Curie point of magnetic materials. The hope that the Curie point increases with pressure was investigated experimentally in 1931 by Leason Heberling Adams and J. Wilbur Green and theoretically by J. C. Slater (presented at the 1932 meeting of the New England Section of the American Physical Society) and found to be groundless. The position in 1939 can be summarized by the statement (Chapman and Bartels, p. 701) "It cannot be said that at present any satisfactory explanation of the Earth's main field is available".

It is useful to summarize the observed phenomena for which any satisfactory theory of the main field must allow. To a first approximation the field is that of a centered dipole almost parallel to the axis of rotation. Changes amounting to a large fraction of the field have occurred in the geologically short time span of a few centuries. These changes are known as secular variation. A prominent feature is the tendency for the field to drift westward at a rate of several degrees per century. These facts have been known for a long time. Since 1943 more evidence has come from the magnetization of rocks. Over tens of thousands of years the magnitude of the field has varied by a factor of three or four. In spite of this rapid variation, the field has behaved much as it does today for the last three billion years. During that time there have been many sudden (i.e. taking less than ten thousand years) reversals of the field in which the direction everywhere changed by 180ø. The close relationship between the magnetic and rotation axes appears to have persisted throughout.

In 1948 Horace Welcome Babcock measured the magnitude of the magnetic fields of the Sun and some stars. The result suggested a relation between angular momentum and magnetic moment, as pointed out by Patrick M. S. Blackett in 1947. A plethora of papers appeared offering various relations between the angular momentum and magnetic moment, some claiming the authority of unified field theory. Attempts to settle the question by determining the vertical gradient of the field, however, gave contradictory results. Finally, on the basis of laboratory experiments, Blackett himself abandoned the idea in 1952.

When Blackett's idea was abandoned, attention was confined to various ways in which electric currents could continue in the interior of the Earth. The possibility that the magnetic field was caused by the rotation with the Earth of a system of electrostatic charges was discussed by several authors. The idea goes back to William Sutherland who suggested in 1903 that an anisotropic distribution of polar molecules within the Earth would furnish sufficient charge density. Various authors have suggested ways of accounting for the necessary distribution of charge.

Most twentieth-century ideas of the mechanism of generation of the Earth's magnetic field originated with a brief publication by Joseph Larmor in 1919. One of his suggestions was that the magnetic field of the Sun might be generated by convective motion driving a dynamo which might generate electric currents sufficient to support the observed field. Of his several suggestions, this was the one he favored.

The Earth's field is approximately, but not exactly axisymmetric. Thomas George Cowling, a mathematician who collaborated with Chapman, investigated the feasibility of Larmor's idea. In 1934 he showed on physical grounds that an axisymmetric field could not be produced by a hydromagnetic dynamo. This was the first of a number of "anti-dynamo" theorems. Summaries can be found in the literature (Jacobs, The Earth's Core, pp 129-130), (Jacobs, Geomagnetism, Vol II p 206). The restriction to axisymmetric fields in Cowling's theorem was not appreciated and, for many years, it inhibited the development of the idea of a dynamo. Cowling himself stated (Cowling, p. 9) "Too much emphasis was put on my theorem" Walter M. Elsasser, a product of the famous G”ttingen school of physicists, came to California in 1936 as a result of the Third Reich's purges, and abandoned nuclear physics for geophysics. The modern era in main field theory may be said to begin with a series of papers by Elsasser, starting in 1939. These papers showed that a self-excited magneto-hydro-dynamic dynamo is possible in a simply connected medium, such as the Earth's core, provided the symmetries expressed in the anti-dynamo theorems are avoided. But Elsasser gave no numerically calculated results. These first came in 1954.

Edward (Teddy) Crisp Bullard (1907-1980) was a product of the Cavendish Laboratory when Lord Rutherford was in charge. He became one of the most important innovators in the revolution in geology known as Plate Tectonics. Perhaps his most important work was in marine geophysics. His interest in geomagnetism grew out of his work on de-gaussing ships during World War Two. He was one of the few prominent geophysicists of his generation able to use the novel electronic computers. He and H. Gellman in 1954 calculated the action of an alpha-omega type dynamo. The omega effect is the conversion of a poloidal field to a toroidal one by the differential rotation of the conducting medium. The alpha effect, first discovered by Eugene N. Parker and developed by S. I. Braginski is the contrary conversion of a toroidal field into a poloidal one by the vertical convection of the medium together with twisting due to Coriolis force. A self-sustaining dynamo will occur if the resulting poloidal field sufficiently augments the original poloidal field, as occurs in the homopolar generator. References are in Jacobs (Geomagnetism, 2: 246).

To illustrate the idea of a homopolar generator, Bullard in 1955 considered a modification of the disk dynamo invented by Michael Faraday: a rotating disk electrically connected to a concentric coaxial coil. A very interesting extension of this was produced by Tsuneji Rikitake in 1958. He considered two coupled disk dynamos in which the coil of one was attached to the disk of the other. The interesting feature of this arrangement is that it can show the kind of reversals observed in the geomagnetic field.

A concept central to the work of Bullard and Gellman, and many others, is the idea of "frozen flux lines". A system of currents once set up in the core (assuming reasonable conductivity) will persist for tens of thousands of years. This implies a slow migration of flux lines through the conductor. If the conductor moves appreciably in a sufficiently short time, the magnetic field must move with it, as if the field were "frozen" into the moving conductor. This concept, which is also of great importance in magnetospheric physics, originated with Hannes Alfven. In 1950 he suggested what has come to be known as the "twisted kink" theory. It differs only in details from the alpha-omega dynamo and is of historical interest as an early application of the idea of frozen flux, a concept that is often called Alfven's theorem. Despite the widespread use of this theorem in the physics of the core, Gerry Bloxham and David Gubbins presented evidence, in 1985, that diffusion of flux through the core might be an important feature in the generation of secular variation.

Difficulties with the alpha-omega dynamo as presented by Bullard and Gellman were pointed out by R. D. Gibson and Paul Harry Roberts (pp. 108-120), and others. The difficulty is that each spherical harmonic considered generates higher order harmonics because of the asymmetry necessary to avoid the anti-dynamo restrictions. These higher order terms form a divergent series. George Backus in 1958 overcame this divergence by the rather unnatural step of requiring that the flow stop periodically while the higher order terms decay. At about the same time Arvid Herzenberg devised a dynamo consisting of two rotating spheres with their axes of rotation at right angles. A working model of this dynamo was constructed in 1963 by Frank J. Lowes and I. Wilkinson. Although rather unlikely in nature, these models did show that a self-excited dynamo is a possibility and that the objections to the Bullard-Gellman dynamo are not fundamental.

E. Harry Vestine, a Canadian physicist working at the Department of Terrestrial Magnetism in Washington, proposed in 1954, that poloidal currents could possibly be generated by temperature differences at the core-mantle boundary. In the presence of a poloidal magnetic field they would produce toroidal Hall currents in the lower mantle which might in turn augment the original poloidal field, thus resulting in a self-sustaining dynamo. The mechanism depends on the Hall coefficient and conductivity of the lower mantle, neither of which are well determined. An interesting feature of this mechanism is that no toroidal magnetic field is required, so that the energy required is less than for dynamos of the alpha-omega type.

In 1895 John Hopkinson estimated the decay time of currents in the Earth to be thousands of millions of years, and on this basis, hypothesized that the magnetic field was a remanent of a field generated early in the Earth's life. A more realistic estimate of the conductivity of the core led Elsasser to realize in 1947 that the decay time was small compared with the age of the Earth, and that a permanent source of energy was required. The source of this energy is still controversial. Elsasser originally (1939) considered that thermo-electric power derived from temperature differences in different parts of the core-mantle boundary would supply the required energy. David R. Inglis and Edward Teller also supported the idea of thermo-electric power. Bullard in 1940 favored thermal energy, produced by cooling of the core or by radioactivity. The inefficiency of this process became clear with the application of thermodynamics by Bachus, Gubbins, and David Loper between 1975 and 1979.

In 1971, Gary H. Higgins and George C. Kennedy estimated the melting point of iron at the pressures of the outer core. Their conclusion was that the thermal gradient through the core would be less than the adiabatic gradient. This means that the liquid core would be stably stratified and purely thermal convection could not occur. However, as pointed out by Don L. Anderson the estimate of the temperature gradient depends on the melting point discontinuity at the inner core boundary, which in turn depends on the influence of impurities in the liquid iron. In 1971 these were thought to be mainly sulfur.

An interesting mechanism was envisaged by Willem V. R. Malkus in 1963. The torque imposed on the Earth by the Sun and Moon, because of its ellipticity, causes a precession of the axis of rotation about the normal to the ecliptic with a period of twenty six thousand years. The torque imposed on the core, with its smaller ellipticity, is less, so it tends to precess at a slower rate. Nevertheless it is forced to precess with the rest of the Earth. Therefore the mantle imposes a torque on the core, which tends to cause fluid flow in the core. There is some controversy as to whether this flow is adequate to power the dynamo as M. G. Rochester and his coworkers pointed out in 1975.

The most popular theory in the late twentieth century concerning the source of power has involved freezing of the material of the liquid outer core onto the solid inner core. The outer core is thought to be composed of liquid iron, but its density is too low for pure iron at the prevailing pressure. There is a light component, which has been variously considered to be silicon, sulphur or oxygen. As the core loses heat, pure iron freezes onto the inner core leaving liquid rich in the light component. This material is less dense than the surrounding material and therefore convects upward, forming a flow with a vertical component. This mechanism was first suggested by Braginskiy in 1964 and was developed by Gubbins and Loper about 1977. If this mechanism were valid, there should be a compositional difference between the outer and inner core. T. G. Masters found evidence to support this difference, based on Earth oscillations (Gubbins and Masters, pp. 24-25).

Henry T. Hall and Rama Murthy in 1971 realized that the residual liquid left at the inner core boundary would be buoyant. They seem to have been unaware of Braginskiy's suggestion, and considered that "although the fluid motions of the outer core are dominated by thermal convection due to the presence of 40K, low density, sulfur rich material rejected from the inner core may play an important role in the convective motion of the outer core" (Cox and Cain, p. 592).

All theories of the origin of the Earth's main field in the twentieth century depend upon the physical properties of the core, as derived from seismic data and Earth oscillations. Although these have proven more reliable than any other data, several details have not been clarified, and these can have an influence on the validity of some theories of the source of the main field (Gubbins and Masters, pp. 1-50).

Interest in the structure of the core-mantle boundary was initiated by the discovery of Raymond Hide and Malin in 1971 that there is a correlation between the global gravitational and magnetic fields. This suggested some topography on the boundary, but negative seismic evidence precluded the existence of topography greater than two kilometers. Seismic waves reflected from the core-mantle boundary indicated a lateral variation in reflectivity. In the 1980s the idea of "crypto-continents" was expressed by some authors. These would be patches of mantle, at its base, of continental size, that are hotter and better electrical conductors than the rest of the mantle. They have been considered to be the cause of areas of low secular variation. Gubbins considered in 1979 that the present decrease in the axial dipole field (5% per century) is due to the increase in intensity and southward movement of a patch of reversed flux at the core-mantle boundary, at present south of Africa. He considered reversals to occur when the intensity of the reverse flux regions increases enough to exceed the effect of the normal flux regions.

Another fruitful field of research has been that of turbulent dynamos. The general theory was outlined in 1950 by George Keith Batchelor. The idea of "mean field electrodynamics" in which a steady and possibly axisymmetric flow and field are perturbed by small scale fluctuations was initiated by M. Steenbeck and F. Kraus in 1969. The closely similar theory of magnetohydrodynamic waves in the Earth's core was treated at length by Braginskiy and summarized in his 1967 paper.

The early workers in the subject, such as Elsasser and Bullard tried to deal with all aspects of the problem of the origin of the main field. After 1980 the tendency was to deal separately with three aspects: (i) the source of energy, (ii) the kinematic dynamo, in which a flow of conducting fluid is assumed, and the resulting field calculated, and (iii) the dynamical problem, in which a flow pattern is determined from the imposed forces, including the Lorentz force which depends on the magnitude of the magnetic field. The dynamical problem is the most difficult and has made least headway to date. So many variables are involved, several of which are poorly determined, that most treatments omit some variables, often without justification. Perhaps the most important advances in this field were made by Friedrich H. Busse and reported in a series of papers from 1975 to 1978. He found that the liquid would flow in a series of rolls with axes parallel to the axis of rotation (thus accounting for the proximity of the geomagnetic and rotation axes) and showed that these can produce a magnetic field.

The magnetohydrodynamic mechanism for the main geomagnetic field, as outlined above, accounted for most of its observed features, such as its almost axisymmetric form and approximation to a dipole. It allowed for, but did not predict, secular variation and reversals. Several other mechanisms were suggested but none accounted as well for the observed properties of the field.

Bibliography for the origin of the main field can be found in several reviews such as Gubbins and Masters (pp. 48-50), Jacobs' Geomagnetism (2: 177, 246, and 303), and in the appropriate volumes of Physics Abstracts. An important conference on the core-mantle interface took place in March 1972, and was reported by Alan Cox and Joseph Cain (pp. 591-623). The report has a useful bibliography as well as abstracts of the papers presented.

Diurnal variation is another topic in geomagnetism about which theories have developed since 1900. Like many advances in geomagnetism the discovery of diurnal variation resulted from an improvement in instrumentation. In 1772 George Graham constructed a compass that could be read more precisely than any before. While observing with this he noticed that the north-seeking end of the compass needle declined more to the east during the mornings and more to the west during the afternoons. This phenomenon, which involves the whole field, has been called "diurnal variation". In 1759 J. Canton found a seasonal effect in diurnal variations suggesting strongly a solar control. In 1850 K. Kriel, in Prague, found a small but distinct variation with a period of half a lunar day (i.e. 12 h 25 m). Attempts to explain the phenomenon appeared occasionally during the nineteenth century, such as Faraday's suggestion involving the paramagnetism of oxygen. In the 1882 edition of Encyclopedia Britannica Balfour Stewart put forward his dynamo theory of diurnal variation. Work since then has been devoted to justifying and filling in details of this theory.

Soon after Stewart's suggestion Arthur Schuster showed, using Gauss's harmonic analysis technique, that the major part of the diurnal variation originated outside the Earth. This was implicit in Stewart's theory, in spite of the fact that the atmosphere was then considered to be an insulator; indeed little was known about the electrical properties of gases. Several similar analyses, in terms of spherical harmonics have been done since (Chapman and Bartels, pp. 684-698; Parkinson, pp. 263-264).

For several decades the science of geomagnetism was dominated by the figure of Sydney Chapman (1888-1970). After studying engineering at Manchester (where Schuster was Professor of Physics) he read mathematics at Cambridge. He held positions at Manchester, Cambridge, Greenwich Observatory, and Imperial College before becoming Professor of Natural Philosophy at Oxford in 1946. Here his important work on the theory of plasmas, the ionosphere and magnetic storms was started. Before having to retire from Oxford, he resigned and spent the last seventeen years of his life shuttling seasonally between Fairbanks, Alaska, and Boulder, Colorado -- the winters in Alaska: "You can't see the aurora in the summer". He was one of the leading organizers of the International Geophysical Year (1957-1958). He was a prolific writer. Cowling, in the Royal Society obituary, listed 406 papers and seven books of which Chapman was author or coauthor. One of his early (1913) contributions was to devise a notation for the various types of diurnal variations, which is still in use. Thus the variation with a period of one solar day and derived from quiet days is designated Sq, for the lunar variation, L, for solar variations derived from disturbed days, SD, and so on.

The effect of solar heating, as suggested by Stewart, is hard to quantify, but the lunar effect must be entirely due to gravitational tides and therefore subject to calculation. The semi-diurnal lunar tides were well known and, in a series of papers starting in 1913, Chapman analyzed in detail the lunar variations that should result from the known lunar tides. Two significant results appeared. The phase of the upper atmosphere winds was opposite to that required, and an integrated conductivity of 2.5 x 104 siemens was required in the upper atmosphere. This unlikely conductivity led Ross Gunn, in 1928, to look back to a variation of the paramagnetic theory of Faraday. He considered the paramagnetic effect of gyrating ions in the ionosphere as a mechanism for the diurnal variation. Gunn appeared to overestimate the number of ions. Geoffrey Ingram Taylor's work on atmospheric oscillations showed that, with a realistic model, a nodal surface develops in the middle atmosphere, so that the flow of air is in opposite directions above and below this surface, thus explaining the phase contrast found by Chapman. In 1927 G. H. Pedersen pointed out that electrons could travel across the magnetic field only by virtue of collisions. Meanwhile radio exploration of the ionosphere, initiated by George Breit and Merle Tuve in the U.S.A. and Edward Victor Appleton in Britain, revealed an electron density that gave an integrated conductivity of only five siemens.

In 1937 Chaim Leib Pekeris investigated the dynamics of tidal flow and concluded that the quantity that remains constant with height is the kinetic energy density, not the velocity, as had been assumed by earlier workers. The resulting higher velocity in the ionosphere required a conductivity of only 25 to 50 siemens. The theory was finally cleared up by William George Baker and David Forbes Martyn in 1953 when they recalculated the ionospheric conductivity taking into account the effect of electrostatic charges which confine the current flow to the ionosphere, and make it act like a thin conducting shell.

David Forbes Martyn (1906-1970) was one of the most prominent physicists in Australia in the mid-twentieth century. After obtaining a BSc in his home town of Glasgow, and a PhD from London University, he migrated to Australia in 1929. He was soon involved in researching the behavior of charged particles in electromagnetic fields, and the propagation of radio waves in the ionosphere. He held a number of positions in government instrumentalities in the early days of radio sounding of the ionosphere. Finally he was head of the Upper Atmosphere Laboratory at Camden, near Sydney.

The same calculations of Baker and Martyn explained a phenomenon noticed after recording at the Huancayo Observatory, Peru, started in 1922. The observatory is situated very close to the magnetic equator, where the inclination is zero. At all low latitude stations the diurnal variation rises during the morning to a northward maximum at noon. At Huancayo the noon maximum was found to be two or three times as great as at other low latitude sites. By 1947 the same phenomenon had been found at other sites sufficiently close to the magnetic equator. This indicated a narrow stream of electrical current running eastward close to the magnetic equator. In 1951 Chapman named this the "equatorial electrojet". The explanation offered by Baker and Martyn involved the electric field caused by electrostatic charges on the upper and lower surfaces of the thin conductor formed by the lower ionosphere, which has the effect of increasing the conductivity in an east-west direction.

The height at which the electrojet and other dynamo currents flow cannot be determined from surface measurements of the diurnal variation field. Stewart considered that the upper troposphere might be their location. When the height distribution of electron density was determined by radio probing of the ionosphere, the region of maximum conductivity appeared to be the E region at a height of between 100 and 150 km (60 and 90 miles). This site for the dynamo current was confirmed by rocket-borne magnetometers. However in 1975 Malin expressed some doubts about this, based on the relation between L and the height of the E-layer.

Since the paper of Baker and Martyn, a number of papers on diurnal variation have appeared, several being improved analyses using the greater number of observatories available during and after the International Geophysical Year. On the theoretical side, Hiroshi Maeda in 1953 discussed coordinates that fit the behavior of the diurnal variations better than either geographic or geomagnetic coordinates. He also commented on the difficulty of defining Sq at high latitudes in a paper in 1973 entitled "What is Sq?". In 1969 V. M. Mishin and his colleagues in Irkutsk pointed out the effect of field-aligned currents that effectively link the northern and southern hemispheres. A considerable amount of work has been done on specifying details of the equatorial electrojet; this was summarized by R. G. Rastogi (Jacobs, Geomagnetism, Vol. III, pp. 461-526).

Since the advent of space probes there has been some interest in the interaction between the magnetosphere and ionosphere. However the atmospheric dynamo as originally suggested by Stewart and quantitatively developed by Baker and Martyn appears to be the main source of the diurnal variation, with the possible exception of some high latitude phenomena, discussed elsewhere in this volume. Reference to the early work on diurnal variation will be found in Chapman and Bartels, (pp. 964-968), and later work in Parkinson, (pp. 398-424). The most recent summary is by Wallace Campbell (Jacobs, Geomagnetism, 3: 455-460).

One of the by-products of Schuster's 1889 analysis of the diurnal variation was the realization that varying external fields could induce appreciable fields of internal origin. Because the vertical components of the external and internal fields are of opposite phase, the resultant vertical field is much less than expected from a purely external field.

Chapman and Bartels summarized the situation in 1939. They presented detailed calculations of the induced currents flowing in the "uniform core model", i.e. a model consisting of a uniform concentric sphere whose radius and conductivity were chosen to fit the data derived from solar and lunar diurnal variations (pp. 711-749). They also quoted the work of Chapman and Price on the main phase of magnetic storms, which did not agree with the model derived from diurnal variation. Mention was also made of a landmark paper by B. N. Lahiri and Price in 1939 in which they treated the conductivity as a continuously increasing function of depth, with a conducting shell near the surface, which they tentatively identified as the effect of the oceans. Earth currents were discussed (pp. 417-448) and some attempt was made to explain them in terms of induction by the varying magnetic field, but there was no suggestion that by combining geomagnetic and telluric results some information about earth resistivities could be obtained.

After 1950 the subject developed along two lines. One was the determination of the distribution of global conductivity, treating the Earth as having spherical symmetry. The second was the determination of conductivity structure locally, including the detection of lateral gradients in conductivity.

The work of Chapman, Price and their collaborators had put the theory of overall global conductivity on a firm basis by 1939. The principal advance since then was to probe to greater depths by using variations with periods longer than one day, and the development of inversion theories. The most prominent work in the former field was that by Roger J. Banks published in 1969 and 1972.

The second, and more extensively studied, branch of the subject has dealt generally with local conditions, although it has been used to probe to considerable depths. The idea of combining earth (or "telluric") currents with geomagnetic variations originated with Andrei Nikolaivich Tikhonov in 1950, and was more fully developed in 1953 by Louis Cagniard, who coined the name "magneto-tellurics". The potential difference between two probes in the ground is compared with simultaneous magnetic variations of the same frequency. High frequency ratios are controlled by conditions at shallow depth while low frequencies probe to greater depths. Thus a great range of frequencies is required, which taxes the instrumentation. Much of the early work was done by Thomas Madden and his students at the Massachusetts Institute of Technology during the decade starting in 1967.

After Cagniard's paper in 1953, James Wait criticized some of the assumptions implicit in the magneto-telluric technique. There followed an interesting exchange of letters published in Geophysics, volume nineteen. The principal contention was the uniformity of the primary field. Wait quoted observations at high latitudes and claimed that a more exact formula, containing higher orders of the reciprocal propagation constant should have been used. The primary field can be expressed as the sum of a number of waves, but whether these are physical waves or merely mathematical concepts, was left in doubt. Cagniard eventually agreed with Wait, but it was not at all clear that he was convinced of the reality of waves travelling at imaginary angles. Workers in the 1970s and 1980s tended to follow Cagniard's approach. One of the most prominent names in the development of magneto-tellurics is that of Albert Price. Essentially a mathematician, he was professor of Applied Mathematics at Exeter University for many years. Apart from his early work with Chapman and Lahiri, he investigated the assumptions inherent in Cagniard's work in 1962. He initiated the theory of induction in thin layers, in papers published in 1949 and 1950, later applied to the oceans. In collaboration with Walter Jones he initiated the method of calculating the response of "two-dimensional" models in 1970, in which the conductivity depends not on depth alone but also on one horizontal dimension. This was later extended by Jones in 1974 and by John Weaver in 1976, and has been used as a standard part of the process of forward modelling.

After 1970 a considerable effort was devoted to devising inversion methods for magneto-telluric data. An inversion method is an algorithm for which the input is a sequence of observed data (usually the ratio of electric to magnetic fields) and the output is a distribution of electrical conductivity. The earlier interpretation methods ("forward modelling") consisted of modelling a distribution of conductivity, calculating a corresponding parameter, and comparing this with the observed value of the same parameter. Almost all inversion methods are fundamentally based on the work of Gel'fand and Levitan, published in 1955. An inversion method applicable to geophysics generally was enunciated by Backus and Gilbert in 1967, and was adapted to magneto-telluric data by Robert Parker in 1970. Peter Weidelt, in 1972, devised a slightly different method and suggested a number of criteria to ensure that the data are consistent with a model in which the conductivity depends on depth only. Later algorithms, such as that of Gaston Fischer and B. V. LeQuang published in 1981, try to define a family of models all of which are consistent with the data.

The difficulty of calculating the response to three dimensional bodies is severe, especially if they are of irregular shape. Therefore scale modelling, such as that performed by Harry Dosso and his coworkers in Canada since the early 1960's has been of great help. The calculation of induced currents in a number of particular shaped conductors has been summarized by Rikitake (pp. 126-220).

Julius Bartels, as early as 1939, observed that even closely spaced observatories often recorded rather different time variations, especially in the vertical component. This was recognized as being the result of lateral inhomogeneities in underground conductivity. During the 1950s study of these conductivity anomalies was pursued by two schools; the German school of Horst Wiese, Ulrich Schmucker, and others, and the Japanese school with Rikitake as principal investigator. In 1959 Parkinson drew attention to the effect of the oceans on magnetic variations at coastal sites.

According to theory, a uniform horizontal inducing field over a conductivity distribution depending on depth only (as was assumed by Cagniard) produces no vertical component. Thus the ratio of vertical to horizontal fields is a measure of the lateral gradient of conductivity. This technique was developed by James Everett and R. D. Hyndman in 1967 and later used by many investigators such as Ian Gough and his coworkers in North America in 1982, Edward Lilley in Australia in 1972, and Rokityansky, Van'yan and others in eastern Europe during the 1970s and 1980s..

Much work has gone into solving the problem of electro-magnetic induction in the oceans. The first attempt was made by Bullard and Robert Parker in 1970. Since then a series of papers by Rod Hewson-Brown, Peter C. Kendall and their collaborators, (1973-1983), Bruce Hobbs and Graham Dawes (1979), and others have appeared. The oceans are of such irregular shape that generally some simplifications must be made.

The conductivity distribution of the ocean floors is a parameter of considerable geological interest. The challenge of operating magneto-telluric equipment on the ocean floor was taken up by Charles Cox and Jean Filloux at Scripps Institute of Oceanography from 1971. Details are given by Filloux (Jacobs, Geomagnetism, 1: 143-248)

The results of induction field surveys give much more significant information if the conductivity results can be interpreted in terms of rock type and physical properties. The early work on the conductivity of minerals, such as that of R. D. Harvey in 1928, concentrated on economic minerals such as oxides and sulfides. Apart from deposits of such minerals the commonest control on the conductivity of near surface rocks are porosity and the salinity of the interstitial water. This was first studied by K. Sundberg in 1932 and John J. Jakosky and R. D. Hopper in 1937, and, expressed by the empirical law that bears his name, by G. E. Archie in 1942. The linear conductivity anomalies often located by measurements of the time varying magnetic field, have usually been ascribed to zones of higher than average porosity. A feature that may be important is the presence of graphite, which can change the conductivity greatly even in minute amounts.

The principal hope in deep geomagnetic probing is that a knowledge of conductivity will give information on temperature. Work on the temperature dependence of the conductivity of mantle material was done by Takesi Nagata in 1937, and was continued by H. P. Coster in 1948, by Harry Hughes in Cambridge and by K. Noritomi in Japan in the mid 1950's. The relation is complicated because temperature is only one of the variables controlling conductivity. Oxygen fugacity, impurities, crystal form and chemical composition can all have important effects.

Comprehensive bibliographies are given by E. I. Parkhomenko (pp. 243-262 and 297-308).

Science, like other activities, can often be seen more clearly from a distance. In the mid 1990s we can see some of the major breakthroughs of the 1960s but only in the future will we be able to see clearly the relative importance of later work. The situation is complicated by the greater number of scientists working during the latter half of the twentieth century. When a Faraday or a Maxwell stood alone in the field, producing monumental publications at rare intervals, the target for historians was clearer than in the latter half of the twentieth century, when great numbers of scientists are busy writing papers about their narrow specialty. When Sir Arthur Schuster discovered the induced field he remarked "This we might have expected".(p. 469). Editors a century later would be loth to waste space on such remarks. Autobiographical articles, such as that of T. G. Cowling (pp. 1-18) are all too rare.

The few authoritative accounts of the history of geomagnetism usually specialize on the early periods. Several articles by Crichton Mitchell and H. D. Harradon are examples. Barraclough (p. 584) states "For the present century no attempt has been made to be at all comprehensive and the choice of topics is, no doubt, influenced by my own interests".

Perhaps it is not too much to hope that the articles in this volume may guide others to a more detailed investigation of the history of geomagnetism during the twentieth century.

W. Dudley Parkinson

Bibliography


```
Barraclough, David R. "Geomagnetism: Historical
Introduction."  In The Encyclopedia of
Solid Earth Geophysics, edited by David E. James, 584-
```

592. New York: van Nostrand Reinholt, 1989.

Chapman, Sydney, and Julius Bartels. Geomagnetism. Oxford: Oxford University Press, 1940.

Cowling, T. G. "Astronomer by Accident." Annual Review of Astronomy and Astrophysics 23 (1985): 1-18.

Cox, Allan, and Joseph C. Cain. "International Conference on the Core-Mantle Interface." EOS 53 (1972): 591-597

Crichton Mitchell, A. "Chapters in the History of Terrestrial Magnetism" Terrestrial Magnetism and Atmospheric Electricity 37 (1932): 105-146; 42 (1937):241-280; 44 (1939):77-80.

Gibson, R.D., and P. H. Roberts. "Some Comments on the Theory of Homogeneous Dynamos." In Magnetism and the Cosmos, edited by W. R. Hindmarsh, F. J. Lowes, P. H. Roberts, and S. K. Runcorn, 108-120. Edinburgh: Oliver and Boyd, 1965.

Good, Gregory A. "Geomagnetism and Scientific Institutions in the 19th Century." EOS 66 (1985): 521, 524-526.

Gubbins, D., and T. G. Masters ."Driving Mechanism for the Earth's Dynamo". Advances in Geophysics 21 (1979): 1-50.

H. D. Harradon. "Some Early Contributions to the History of Geomagnetism." Terrestrial Magnetism and Atmospheric Electricity 37 (1932): 105-146; 42 (1937): 185-198.

Jacobs, J. A., editor. Geomagnetism. London: Academic Press, Volumes I and II, 1987, Volume III, 1989.

Jacobs, J. A. The Earth's Core. London: Academic Press, 1975.

Multhauf, Robert P., and Gregory Good. A Brief History of Geomagnetism. Washington D. C.: Smithsonian Institution Press, 1987.

Parkhomenko, E. I. Electrical Properties of Rocks. New York: Plenum, 1967.

Parkinson, W. D. Introduction to Geomagnetism. Edinburgh: Scottish Academic Press, 1983.

Rikitake, Tsuneji. Electromagnetism and the Earth's Interior. Amsterdam: Elsevier, 1966

Schuster, Arthur. "The Diurnal Variation of Terrestrial Magnetism." Philosophical Transactions of the Royal Society of London A180 (1889): 467-512.