1

Geomagnetism and paleomagnetism: 1946–1952

1.1 Breaking the impasse: the three main paleomagnetic groups

Three groups were primarily responsible for the developments in paleomagnetic work. Two were founded by S. K. (Keith) Runcorn and P. M. S. Blackett; both were physicists who became interested in paleomagnetism through their work in geomagnetism. Runcorn, formerly an assistant lecturer at Manchester University, where he worked for his Ph.D. under Blackett, began in mid-1951 recruiting to his group at Cambridge University. Blackett, Head of the Department of Physics at Manchester University, began forming his group in early 1952, placing John Clegg in charge; Clegg will be introduced in Chapter 2. The third group, at the Department of Terrestrial Magnetism at the Carnegie Institution in Washington, DC, began working in paleomagnetism much earlier, in the late 1930s; its efforts lapsed during World War II, and recommenced afterwards. I deal with the British groups first as it was they who made the startling discoveries, recognizing them as the key to what was to become the first physically based measure of mobilism.

In 1947 Blackett revived interest in fundamental or distributed theories of the origin of the geomagnetic field, arguing that all rotating bodies produce magnetic fields. He constructed an astatic magnetometer specifically to test such theories, a test that proved negative. Runcorn became interested in Blackett's ideas, and carried out, at Edward (Teddy) C. Bullard's (later Sir Edward) suggestion, a different test of the distributed theory for which he earned his Ph.D. This too was negative. Blackett and Runcorn recognized that from studies of the natural remanent magnetization (NRM) of rocks there was much to be learned about the long-term history of the geomagnetic field, and thus better understand its origin. They both realized that Blackett's magnetometer was, with adaptations, well suited for such paleomagnetic studies.

When Runcorn arrived at the Department of Geodesy and Geophysics in Cambridge in 1950, Jan Hospers was already there. Hospers, from the Netherlands, had just begun working on a Ph.D., and planned to undertake a paleomagnetic survey of Icelandic lavas. He had no interest in mobilism, thinking, as almost everyone in the Netherlands then did, that it was a dead issue. His plan was to use variations in the strength (intensity) of magnetization to correlate the lavas.

He quickly found reversals of magnetization, which became his main interest. The directions of magnetization he observed were somewhat dispersed and required statistical analysis. He explained the problem to Runcorn who told R. A. Fisher (recently knighted Sir Ronald), the great evolutionary biologist and statistician. Fisher supplied the statistical method which enabled Hospers to show that the average field in Iceland, regardless of sign, was close to that of a geocentric axial dipole. Runcorn, who was then working on the problem of secular variation, decided to try to use paleomagnetism to study ancient or paleosecular variation, the variation in the strength and direction of the geomagnetic field over hundreds or thousands of years. In June 1951 he hired Edward (Ted) Irving as a temporary assistant to collect oriented samples, and to measure them on Blackett's magnetometer, which he did. Irving also happened to be interested in continental drift, and he figured out how to use paleomagnetism to test it; later that year, with help from Fisher, he initiated the first such test. However, Hospers, Runcorn, and Irving did not immediately redirect their main research programs toward testing mobilism, but continued gathering samples, hoping to learn more about the long-term history of the geomagnetic field, its reversal, and paleosecular variation. Irving and Runcorn soon discovered that fine-grained red sandstones (red beds) recorded well the average direction of the geomagnetic field but not the details of its secular variation that Runcorn had hoped for. This early discovery was crucial because it allowed paleomagnetists to quickly locate reliable recorders of the long-term behavior of the field, records that they needed regardless of whether they were working on problems in geomagnetism or testing mobilism.

Researchers at the Carnegie Institute for Terrestrial Magnetism in Washington, DC, had earlier used paleomagnetism to address problems about secular variation and reversal of the geomagnetic field, and J. W. (John) Graham, a key member of the group, also learned (1949) that paleomagnetism could be used to test mobilism, but he did not act on it for half-a-dozen years, long after British paleomagnetists had begun to do so. Importantly, however, Graham also developed two field tests invaluable to determine the reliability of paleomagnetic data, dependable standbys throughout the mobilism debate.

1.2 Blackett and Runcorn begin their years together at the University of Manchester (1946–1949)

Stanley Keith Runcorn (1922–95) was born in Southport, Lancashire.[1] He had one sibling, a younger sister. He attended King George V Grammar School in Southport, where he excelled early in history and mathematics. Later his headmaster convinced him to study science, and he gained a State Scholarship. He was a prominent member of the school Debating Society where he learned skills he practiced effectively all his life. At school he became a very good swimmer. Later he, with more enthusiasm than skill, became an increasingly elderly rugby and squash player; it was at swimming that he excelled. His enthusiasm for sports is important because it led to his finding two of his best students, Irving and N. D. (Neil) Opdyke.

Runcorn became an undergraduate at Gonville and Caius College, Cambridge University, entering the Faculty of Engineering (then called Mechanical Sciences) in 1941. It was wartime, and in 1943 he took what was then the usual two-year degree, and was recruited into the war effort, into radar work. During this time, he had become more interested in physics than in engineering, and decided not to return to Cambridge. He applied unsuccessfully for a fellowship in the Department of Physics at the University of Manchester. However, Bernard Lovell, already at Manchester where he led the radio astronomy group, encouraged Runcorn to apply for an assistant lectureship in physics because he had heard that Blackett had been impressed with his application. He did so, and found himself (Runcorn, August, 1984 interview with author) "in October of 1946 as an Assistant Lecturer in Physics, having not done physics as an undergraduate subject and not having a Ph.D."

1.3 Blackett's fundamental or distributed theory of the origin of the geomagnetic field and Runcorn's introduction to it

Patrick Maynard Steward Blackett (1897–1974), later Lord Blackett, was a giant among experimental physicists, a charismatic personality and a prominent public figure. His strong support in the 1950s for paleomagnetic work in Britain was likely the principal reason why it prospered there.

Earmarked for a career in the Royal Navy, Blackett at age thirteen entered Osborne Naval College, and two years later the Royal Naval College at Dartmouth where he received thorough training in science and technology as well as in normal naval subjects. He was present at the first Battle of the Falkland Islands (1914), at the huge Battle of Jutland (1916) just off the coast of Denmark, and in several smaller engagements in the Channel and North Sea toward the end of World War I.

He resigned from the Royal Navy in 1919 and entered Cambridge University where he read Part I Mathematics and Part II Physics, wasting no time graduating in 1921. He entered the Cavendish Laboratory under Sir Ernest Rutherford. There Blackett improved on the original design of C. T. R. Wilson's cloud chamber, turning it into a powerful tool for research in nuclear physics and cosmic radiation. Because of this and the discoveries made through it, Blackett received the Nobel Prize in Physics in 1948. He became head of physics departments at Birkbeck College, London, and then at the University of Manchester. In World War II he became "a founder of wartime operational research and one of the heroes in the British triumph in the U-boat campaign" (Nye, 2004: 99). (Accounts of Blackett's scientific career and eventful life are by Lovell (1975), Bullard (1974), Butler *et al*. (1975) and Nye (1999, 2004).)

Blackett returned to the University of Manchester after World War II, where he played a strong role in the national debate on atomic energy and the bomb.

He expanded cosmic ray research, and also became interested in magnetism "while considering the possible influence of the magnetic field of stars in the galaxy on cosmic ray phenomena" (Blackett, 1947: 658). He soon developed a highly speculative "fundamental" or "distributed" theory of geomagnetism whose central idea was that any rotating body produces a magnetic field by virtue of its rotation.

While considering whether the magnetism of stars could influence cosmic rays, Blackett realized that the magnetic moments of the Earth and Sun are nearly proportional to their angular momenta; that

> the magnetic moment P and the angular momentum U of the earth and sun are nearly proportional, and that the constant of proportionality is nearly the square root of the gravitational constant G divided by the velocity of light.
>
> *(Blackett, 1947: 658)*

Blackett was excited, for besides thinking that he had an explanation of the geomagnetic field, he thought this theory of magnetism might "provide the long-sought connection between electromagnetic and gravitational phenomena" (Blackett, 1947: 658). He began reviewing the literature on the origin of the Sun and Earth's magnetic fields, and realized that he was not the first to think that rotating bodies might generate a magnetic field. "I found to my surprise that the essence of these facts had been known for some years, but had, for various reasons, dropped later out of notice" (Blackett, 1947: 658).

The Manchester physicist and mathematician Arthur Schuster had first suggested that the Sun and the Moon might possess a magnetic field by virtue of their rotation. In 1891, Schuster, while discussing the nature of the solar corona, whose luminosity he attributed to electrical discharges, proposed as the source of the discharges a solar magnetic field, which also would explain the shape of the corona.

> If then, as is probable, electric discharges take place near the sun, there must be some cause which keeps up the difference in electrical potential between the sun and outside space. The form of the corona suggests a further hypothesis, which, extravagant as it may appear at present, may yet prove to be true. Is the sun a magnet? We know that a body at such a high temperature cannot be magnetisable, but may not a revolving body act like a magnet, and may not the earth's magnetism be similarly due to the earth's revolution about its axis?
>
> *(Schuster, 1891: 275)*

Schuster carried out experiments, and in 1912 Blackett (1952: 310) learned that Schuster had been unable to detect a magnetic field near a rapidly rotating nonmagnetic body. In 1923, H. A. Wilson (who like Blackett had worked at the Cavendish but eventually moved to Rice Institute in Houston where he much influenced the young Maurice Ewing, who later became a strong anti-mobilist (III, §6.3)) further tested Schuster's idea, but detected no magnetic field (Wilson, 1923), as did W. F. G. Swann and A. Longacre (1928) with the same result. Blackett realized that their magnetometers were not sensitive enough to detect the field predicted by his theory (Blackett (1947: 665–666); he needed a more sensitive instrument.

The magnetic fields of stars were important for Blackett's theory, and he learned from his friend Subrahmanyan Chrandrasekhar, the Indian-born American astrophysicist, that Horace W. Babcock (1947a, b) of Mount Wilson Observatory had recently determined but not yet published the magnetic field of a rapidly rotating star, 78 Virginis, using the Zeeman effect. Babcock was also aware of the relevance of his observation for Schuster's theory. To Blackett's delight, the ratio of magnetic moment to angular momentum of 78 Virginis closely matched that of Earth and Sun.

Blackett presented his idea in November 1946 at the University of Manchester, and in May 1947 to the Royal Society coincident with its publication. Runcorn recalled Blackett's eagerness to publish.

> Blackett was asked to give a talk at the Royal Society in London about his work. He wanted to publish it in the *Proceedings of the Royal Society*. He thought at this time that it was a very hot topic. The Royal Society didn't give any indication that they would publish it quickly so he had it published in *Nature*. He was very cross with Robinson, the President of the Royal Society, for refusing to expedite publication in the *Proceedings*.
>
> *(Runcorn, August 1984 interview with author; last sentence added during August 1993 interview with author)*

Initially Runcorn had wanted to go to Manchester partly to study cosmic rays, and during his first term he helped G. D. Rochester and C. C. Butler with their cloud chamber (Butler *et al*., 1947). Within a month after his arrival, he heard Blackett's presentation, which got him thinking.

> I became very interested. So after this meeting I discussed with him whether there were any experiments to do. The obvious one was, of course, to rotate a mass in the laboratory and see if it had a magnetic field. We did talk about that, and eventually he did an experiment related to that idea.
>
> *(Runcorn, 1984 interview with author)*

Runcorn wanted an independent test of Blackett's theory, and he soon learned of a way not only to test, but also to compare Blackett's theory with its chief rival, the self-exciting dynamo. (Nye (1999) and Nye (2004) give fuller accounts of Blackett's work.[2])

1.4 Elsasser develops a self-exciting dynamo in Earth's core as the source of the geomagnetic field

> It struck me then that if one assumed the metallic core of the Earth to be in convective motion [one could] account in a qualitative way for the remarkable phenomenon of the geomagnetic secular variation, with its unusual time scale … These studies [on secular variation] were interrupted by the War and it was not until right after the War that I was able to put the magnetohydrodynamics of a spherical conductor into mathematical form. This seemed at last to permit a quantitative approach to the secular variation … It left the main problem, the possibility of a dynamo theory, still unsolved. I then realized that I had

overlooked a fundamental mathematical fact, namely, the existence of two sets of aperiodic modes of the sphere, the poloidal and toroidal modes … The discovery that there could be a toroidal field in the Earth's core at once led to the well-known amplifying mechanism of this field by non-uniform rotation and thus to the main step in the dynamo model, suggesting also that the dynamo mechanism consists in a playing back and forth of magnetic fields … It appeared early in my studies that the Coriolis force must be the agent which orders the amplificatory processes of the magnetic field relative to the axis of rotation of the fluid. Apart from much geophysical evidence, a qualitative but strong confirmation of this conclusion has come from the fundamental observations of Babcock on magnetic stars.

(Elsasser, 1959: 93; my bracketed additions)

While Blackett was reinventing the fundamental theory for the origin of the geomagnetic field, Elsasser was busy reviving what became its chief competitor, the self-exciting dynamo, which locates the source of the field within the core. Common to all versions is the idea that the metallic and fluid outer core generates an electric field, which through a coupling process creates Earth's dipole magnetic field. The self-exciting dynamo was first invoked by Sir Joseph Larmor (1919) as an explanation of the magnetic fields of Sun and Earth. He cautioned that his theory would require a highly conducting liquid region deep within Earth for which at the time there was some support from seismology (Oldham, 1906). In 1936 the Danish seismologist Inge Lehmann discovered the solid inner core (Brush, 1996). Larmor's theory caught the attention of T. G. Cowling, an applied mathematician then at University College, Swansea in Wales, who showed (1934: 44) that Larmor's self-exciting dynamo theory failed because no dynamo could be maintained from an axially symmetrical field.

Elsasser (1939) attributed the main field to thermoelectric currents in the metallic core; currents arose from temperature variations brought about by thermal convection maintained by radioactive impurities in the core. Of fundamental importance to the interpretation of paleomagnetic results, he recognized the Coriolis force as responsible for the general correlation between the axis of rotation and that of the main geomagnetic field, and assigned a slight asymmetry to the thermoelectric currents to account for secular variation.

After World War II, Elsasser returned to the problem (Brush, 1996a). In October of 1945 he submitted Part I of a tripartite article (Elsasser, 1946a,b; 1947) in which he described a self-exciting dynamo in Earth's core that accounted for the main field and its secular variation. Bullard (1949: 434) characterized it as a work of "great generality and elegance." At first Elsasser was unable adequately to account for the coupling between electric and magnetic fields. However, he gave a solution in Part III, which appeared in timely fashion six months after the publication of Blackett's fundamental theory. Elsasser introduced his coupling mechanism in this way:

The analysis of Part I and Part II has led to an interpretation of the geomagnetic secular variation in terms of interactions between fluid motions in the earth's core that are the sources of the magnetic field. This analysis suffers from the shortcoming that the current modes which give rise to a magnetic field outside the metallic sphere do not represent a complete set of solutions of the electromagnetic field equations. There exists a second set of solutions, representing modes of the electric type, whose magnetic field is confined to the interior of the conducting sphere. In the preceding parts these models have been disregarded on the assumption that they cannot be excited. It has been found however, that in the theory of inductive coupling by fluid motion there appear definite couplings between the two types of modes and that, therefore, the electric modes are an integral part of the field as described by this theory. It will appear in the course of this paper that from this viewpoint inductive coupling between the magnetic and electric modes is by far the most important feature of the earth's magnetic field.

(Elsasser, 1947: 821)

Elsasser postulated that coupling between electric and magnetic fields within the core provided the needed feedback mechanism to produce the external dipole, main or poloidal field. Because of non-uniform rotation of the conducting fluid core in the presence of a poloidal field, a toroidal field is generated that is entirely internal, the lines of force are parallel to lines of latitude; the field is confined within Earth and cannot be detected outside. Elsasser estimated the strength of the toroidal field to be about ten times that of the external poloidal field.

He speculated about the power source needed to maintain the core motions. He proposed (1947: 831) that the "power is a by-product of the change in Earth's speed of rotation caused by the lunar tide." Noting that although much of the angular momentum released by a decrease in the rate of rotation is either transferred to the Moon as it recedes from Earth or is dissipated by tidal friction in the oceans, neither effect completely exhausts the energy released; enough energy is left over to drive motions within the outer core.

Although Blackett discussed Elsasser's work, he focused on Larmor's older, self-exciting dynamo model and on a new model proposed by the Soviet scientist J. Frenkel. Frenkel (1945) attributed the movement of the metallic core to the action of convection currents, and developed an axially symmetrical self-exciting dynamo model. Blackett (1947: 659) dismissed Frenkel's account, referring to Cowling's theorem, which apparently disallowed axially symmetrical models.

1.5 Runcorn and colleagues carry out the mine experiment and discriminate between fundamental and core theories

On May 15, 1947, Runcorn traveled to London with Blackett, who presented his theory to the Royal Society. Bullard and Sydney Chapman attended. Chapman was professor of natural philosophy at Oxford, and co-author of *Geomagnetism*, then the standard work. Bullard, already interested in geomagnetism, later developed a self-exciting dynamo model based on Elsasser's work. Runcorn recalled:

At this meeting Bullard and Chapman were there, and Bullard threw out an idea during the discussion that, possibly, Blackett's theory might give a different variation of the geomagnetic field with depth from other theories – Blackett's theory involved the whole Earth in generating its magnetic field while other theories placed its source in the core.[3]

(Interview with author, 1984; revised 1993 interview)

Runcorn described the differences Bullard had in mind:

Whereas on core theories both the horizontal and vertical intensities increase with depth according to an inverse cube law, on a distributed theory such as the one recently put forward by Blackett we find, with reasonable assumptions, that while the vertical intensity should increase for small depths as an inverse cube law, the horizontal intensity should decrease.

(Runcorn, 1948: 373)

Bullard had indicated how to test Blackett's theory. While Blackett was designing and constructing his highly sensitive magnetometer and carrying out his laboratory experiment, he could test Blackett's theory and earn his Ph.D. by descending into mines with magnetometers to determine how the intensity of the field changed with depth; did it do so in accordance with Blackett's or Elsasser's theory? Formulating concrete predictions was not easy. Runcorn recalled that at first he and Blackett "couldn't make much of it," but with Blackett's encouragement, he worked out the expected changes and Blackett sent them to Chapman to check.

When we got back [to Manchester], of course, I talked to Blackett about the possibility of an experiment to test the theory by going down in mines with magnetometers, and I undertook to try and work out what one should expect. What one should expect is not very obvious from the very speculative idea that Blackett had talked about. But I did calculations, which Blackett sent to Sydney Chapman. Sydney Chapman wrote back and said that he thought I was wrong, and he would do them himself. He did them himself by a different method involving vector potentials. So Blackett said that I should go to Oxford to see Chapman about this vital question. In the end, Chapman agreed that my method was essentially correct, if unorthodox, though I had made a slight approximation: it concerned how density should be brought into the calculations. By this time I had got really interested in the idea of doing the experiment. I remember Chapman inviting me to lunch. He was a very austere person – indeed, rather frightening to a young person. I always remember Chapman saying, "Well your calculation is not exact." And, I said, "Well, I make an approximation because, there is no chance that we can go down to the center of the Earth with this formula. It is just a question of what the first few kilometers will give." We discussed the difference between our two formulas, and I remember making the terribly brash statement to him, "Well, the trouble is that you are thinking of this problem as a mathematician and I am thinking of it as a physicist." I always remember Chapman's gentle reply: "Well you know I sometimes think of myself as a physicist as well!" Anyway, as he said goodbye he said that we now understand each other. After that we became very friendly, and he was very helpful.

(1984 interview author; revised 1993; my bracketed addition)

With Chapman's help, Runcorn had turned Bullard's idea into a testable prediction. What is more, he had found himself able to hold his own in debate with the top workers in the field. Blackett reported Runcorn's results (Runcorn, 1948) to the Physical Society of London in April 1948.

Deriving predictions, however, was not the only obstacle; securing reliable data was also not easy. Success depended on determining the changes in intensity with depth of the horizontal and vertical components of the geomagnetic field freed of local anomalies due to geology or to human activities. As Runcorn *et al.* put it:

> The essential problem of the experiment is to find conditions in which measured differences of the geomagnetic components between a point on the Earth's surface and a point underground may be attributed to the main field and not to magnetic anomalies arising locally.
>
> *(Runcorn* et al.*, 1950: 784)*

Runcorn chose deep coal mines in Lancashire where the rocks were too weakly magnetized to affect the geomagnetic field. Recruiting undergraduate students to take the many measurements, he launched the mine experiments near the end of 1947. He presented the first results orally to the Royal Astronomical Society on February 27, 1948 (Chapman, 1948a), and with colleagues submitted the final paper in May 1951 (Runcorn *et al.*, 1951). The results from the first mine favored the fundamental, not the core theory; however, the mine "was too near the outskirts of the town of Leigh for a surface survey of adequate size to be made." His team eventually obtained reliable results from five other mines avoiding magnetic disturbances from towns, and concluded: "the experiments must be regarded as decisive evidence against a fundamental origin of the main geomagnetic field" (Runcorn *et al.*, 1951: 148, 150).

Runcorn was not the only one to encounter difficulties with local magnetic anomalies when doing such mine experiments. Anton Hales, who had years before examined Holmes' hypothesis of convection currents (I, §5.6), and D. I. (Ian) Gough, from the Bernard Price Institute of Geophysical Research at the University of Witwatersrand in Johannesburg, performed a similar experiment. At first they, like Runcorn, thought their results favored fundamental rather than core theories (Hales and Gough, 1947). They corresponded with Runcorn, and questioned whether his formula was strictly applicable to their situation, because their surface measurements were done near Johannesburg, 5200 feet (1585 m) above Earth's mean surface level, whereas Runcorn's formula applies strictly to depths below that level. They also suggested that there might be some unknown geological effects. Chapman examined their findings. Besides pointing out a further difficulty with Runcorn's formula and suggesting a more general one, for which he was thanked by Runcorn, Chapman (1948b), thinking like a physicist, correctly noted that more work was needed in mines less disturbed magnetically than the mine chosen by Hales and Gough.[4] Hales and Gough returned to the mine, made additional measurements, and realized, by July 1949, that their results had been affected by the abundance of nearby strongly magnetized intrusive igneous rock; Hales and Gough's results "gave no useful information with regard to the radial variation of the earth's field" (Runcorn *et al.*, 1951: 148).

1.6 Blackett and Runcorn become interested in paleomagnetism; Runcorn accepts a position at the University of Cambridge

Both Blackett and I went to a meeting of the Royal Astronomical Society in which Professor Bruckshaw of Imperial College discussed … reversed magnetization. This was a reversed magnetization of Cleveland dykes of Tertiary age in northern England. He did magnetic surveys across them, and demonstrated that they were reversely magnetized. I think that this was Blackett and my first exposure to paleomagnetism.

(Runcorn, 1984 interview with author)[5]

Much went on at this meeting (February 27, 1948); Runcorn presented his first, erroneous, mine results, and Bullard talked about secular variation, attributing it to changes in electric currents induced by the movement of the conducting core material through the main magnetic field. Although Bullard did not offer his account of the main field until later that year, he located its origin within the core.[6] Bruckshaw followed.

J. McG. Bruckshaw was reader in geophysics at the Royal School of Mines, Imperial College, London. He described the work that he and E. I. Robertson, a research student from New Zealand, had begun during the summer of 1946 on a system of Early Tertiary dykes, extending southeastward from the Isle of Mull in western Scotland to the northeast coast of England. These dolerite dykes had been intruded into much older strata, and had since remained undisturbed. They made magnetic surveys across them, and much to their surprise, the dykes were magnetized in a direction nearly opposite to that of the present geomagnetic field. Noting that such rocks acquire a "residual magnetism" as they cool down "through the Curie temperature of the magnetic material within the dyke" in a direction parallel to the ambient magnetic field, they proposed:

Since there has been no significant earth movement in this region during the 30 million years this dyke system has existed [now known to be ~50 million years], the Earth's field in the area at the time of cooling through the transition temperature would appear to have been approximately in opposition to its present direction.

(Bruckshaw and Robertson, 1949: 316; my bracketed addition)

They continued:

Thus such characteristics (igneous intrusions of inverted polarity) are fairly common in both surface distribution and in age. There can be no doubt of the changed direction of the magnetic field necessary to produce the observed polarization. Whether inverted fields were widespread over the Earth's surface in the past, or whether they were an abnormal, but local, state associated with the conditions necessary for the invasion of the crust by molten magmas cannot yet be decided.

(Bruckshaw and Robertson, 1949: 318)

In his summary of the meeting, Chapman speculated about the possible causes of inverted magnetizations – many were cited in *Geomagnetism*, his book with Bartels