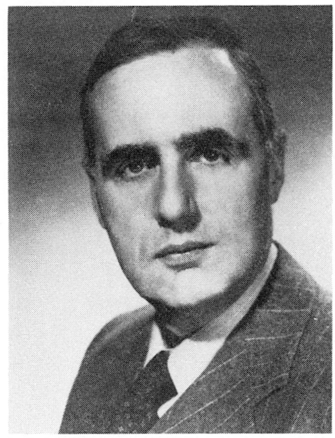
Memorial to Edward Crisp Bullard
1907–1980

J. TUZO WILSON
Department of Physics, University of Toronto
Toronto, Canada



Sir Edward Bullard, a professor of geophysics at Scripps Institution of Oceanography and former professor of geodesy and geophysics at Cambridge, was one of the most brilliant and successful geophysicists of this century. His quick mind, his warm and generous personality, and his keen sense of humor made him a natural leader and teacher; he attracted many friends and admirers, all of whom knew him as Teddy. With their help, he broadened the long tradition of theoretical study of physics of the earth at the University of Cambridge into an outstanding program of both experimental and theoretical geophysical research.

He made notable contributions to the study of gravity, geomagnetism, and heat flow; his work also enhanced our knowledge and improved computational methods in most branches of physics of the solid earth, including studies of the ocean floors, seismology, and age determinations.

He was born on September 21, 1907, at Norwich, England, where his family had for three generations owned and operated a brewery. His grandfather, Sir Harry Bullard, had been mayor of Norwich and twice elected to Parliament. On the first occasion, as Teddy Bullard was fond of relating, Sir Harry had been refused his seat on account of election irregularities, but after waiting the statutory ten years, he ran again and was re-elected.

His father succeeeded to the family business but, although kindly, he was argumentative and dyslexic; dyslexia also slightly affected Teddy in his youth. Thus, Teddy's early life was unhappy except for summer visits to a large country house that his maternal grandfather, Sir Frank Crisp, had built near Henley. It was later purchased by one of the Beatles. Not happy in flat surroundings, Sir Frank had a model of the Matterhorn about 30 meters (100 feet) high built in his garden. It was ornamented with lead figures and waterfalls, which he like to look at through some of the telescopes in his collection of 3,000 antique optical instruments.

At the age of twelve, Teddy was sent to boarding school. His masters took an interest in him, and he quickly became an excellent student, leaving Repton School in 1926 to enter Clare College at Cambridge. He graduated three years later with first class honors in physics, chemistry, mathematics, and mineralogy. A studentship enabled him to spend the next two years doing research in electron scattering with Harrie Massey, under the direction of Patrick Blackett and Sir Ernest Rutherford. Teddy regarded that as splendid training, especially in the design and construction of instruments, which was then in a primitive state. The results of his research were inexplicable when examined according to the classical theory of collision, but they were in excellent agreement with the new wave mechanics view of diffraction around a spherical atom. Unfortunately, this led to no job, although he had married by this time (1931) and needed one. Until then, he had not thought of geophysics.

Fortunately, several paths converged to create interest in the subject at the University of Cambridge. The oldest was the tradition of physical study at Cambridge. This tradition dated back to Sir Isaac Newton and was being continued by a few scholars at the university who made theoretical studies of the physics of the earth. The latest was Sir Harold Jeffreys, whom Teddy held in the highest regard. He once remarked to me that the only time he felt in the presence of genius was whenever he met Sir Harold. Later, Maurice Ewing told me that he had similar views and regarded Jeffreys' book *The Earth* as his bible in geophysical theory. At that time, the British government was in need of many geodesists and senior surveyors to organize the mapping of a vast empire; upon retiring as Director General of the Geological Survey of India, Sir Gerald Lenox-Conyngham had come to Cambridge in 1922 as Honorary Reader in Geodesy to organize this training. Another factor was the presence of Professor Newall, an astronomer who lived in Madingley Rise, the house that later became Teddy's headquarters.

As a consequence, in 1931 the Department of Geodesy and Geophysics came into being, with the appointment of Sir Harold Jeffreys as Reader, Teddy as Demonstrator, and Leslie Flavill as Technician. The only instrument in the department was a fine set of gravity pendulums that had just been donated. Teddy and his wife Margaret then decided to go to East Africa to measure gravity over the rift valleys, which then were nearly inaccessible. After many adventures, he did an elegant job, although the conclusions he reached were in error because he had underestimated the depth of light sediments in the valleys. As he was fond of telling graduate students, the resulting long, precise paper, published in a very reputable journal, established his reputation.

At that time I spent two years in Cambridge, beginning in 1932, but until Bullard returned, there was no teaching or research in geophysics there, apart from eight lectures delivered each year by Harold Jeffreys, concerning his own theoretical studies.

Four years later, Bullard was awarded the Smithson Fellowship of the Royal Society, which enabled Ben Browne to join the department. Bullard and Flavill then designed a seismometer that enabled them to use seismic reflections to survey the depths of sedimentary beds over southern England. The next year, R. M. Field of Princeton University persuaded Bullard to extend this method to studies of the continental shelf. At the same time, Field helped Maurice Ewing make similar measurements on the other side of the Atlantic. Both found great basins of sedimentary rocks.

Many measurements of the temperature gradient in deep bore holes were available, but to estimate heat flow from the earth, measurement of the conductivity was also needed. With H. E. Benfield, Teddy devised the necessary technique, built instruments, and made the first heat-flow measurements in South Africa and England. Later, with the help of R. Revelle and A. E. Maxwell at Scripps Institution, he was able to extend their use to ocean floors. In only eight years, Bullard had achieved remarkable success in experimental measurements of gravity, seismology, and heat flow.

In 1939 he was attached as civilian consultant to H.M.S. *Vernon*, an Admiralty laboratory devoted to problems of mine warfare, particularly of the magnetic mines that the Germans were laying in coastal waters with great success. Teddy arranged for ships to be fitted with coils of wire through which currents were passed to reduce the vertical component of the magnetic field of the ship. This method, called degaussing, proved effective, and Teddy went on to deal with different types of mines and to advise the Navy and Air Force on other problems of operational analysis and research. These successes added to the sense of self-confidence he had already gained at the Cavendish Laboratory under Rutherford.

On return to Cambridge, he found the place in disarray, with the elderly Lenox-Conyngham still in charge, and no money. Discouraged, Bullard soon accepted an offer to become head of the Department of Physics at the University of Toronto. There, due to the early efforts of L. Gilchrist, a group had been active in investigating methods of geophysical prospecting for ore and petroleum since about 1927. Also on the staff was N. B. Keevil, who with the help of A. O. Nier and H. D. Thode, had nearly completed a mass spectrometer for radiometric age determinations. Bullard helped to get the instrument operating. He also found that the University had recently installed FERUT, an early computer built by Ferranti; Bullard was able to make good use of it in computations concerning the dynamo theory of Earth. During the summer, he visited Scripps for the first time and made heat flow measurements at sea. He thus established a lasting connection with that institution.

In spite of these successes, both Margaret and he greatly missed Cambridge and England. There was then no opening at the university, so in the following year he accepted the position of Director of the National Physical Laboratory at Teddington in London. There he was again successful and received a knighthood. After six years, he resigned to take a lower position at Cambridge than the one he had left, but in 1964 he was promoted to professor of geodesy and geophysics.

Meanwhile, Maurice Hill had built up a relatively large group of marine geophysicists, who were using seismic reflection methods at sea, including a towed magnetometer and Bullard's methods for measuring heat flow. Jack Miller had also developed mass spectometry, while J. Hospers, S. R. Runcorn, and E. Irving had made important strides in the study of paleomagnetism, which was soon to lead to Vine and Mathews' success in studying the magnetic lineations on the Indian Ocean floor.

Bullard himself used the university's computers to work on the dynamo problem of Earth's magnetism. Having little funds to pay staff, he persuaded colleges, especially Churchill College, to accommodate visiting professors. Many came, from several countries, to exchange ideas with and to extend the enthusiasm of those at Madingley Rise. Teddy also arranged funds with which to construct an additional building. His retirement in 1974, along with other changes, made it possible in 1980 for the university to amalgamate the three departments of Geology, Mineralogy and Petrology, and Geodesy and Geophysics into a single Department of Earth Sciences, with the same facilities.

Bullard retired to Scripps, where he was made a professor. He became an American citizen and married Ursula Curnow. In spite of failing health, he gave lectures, supervised graduate students, and continued to publish research papers until the time of his death.

SELECTED BIBLIOGRAPHY OF E. C. BULLARD

1933 The effect of a magnetic field on relative gravity determinations with invar pendulums: Proceedings of the Cambridge Philosophical Society, v. 29, p. 288–296.

1936 Gravity measurements in East Africa: Royal Society of London Philosophical Transactions, ser. A, v. 235, p. 445–531.

—— (with Jolly, H.L.P.) Gravity measurements in Great Britain: Royal Astronomical Society Monthly Notices, Geophysical Supplement 3, p. 443–477.

1938 The theory of the Benioff seismograph: Royal Astronomical Society Monthly Notices, Geophysical Supplement 4, p. 336–340.

—— Thermal conductivities of rocks (report of a committee): British Association for the Advancement of Science, Report, p. 271–277.

—— Underground structure near Cambridge, *in* The Cambridge region: Appendix to British Association for the Advancement of Science, Report, p. 4–5.

—— The disturbances of temperature gradient in the earth's crust by inequalities of height: Royal Astronomical Society Monthly Notices, Geophysical Supplement 4, p. 360–362.

—— (with Gaskell, T. F.) Seismic methods in submarine geology: Nature, v. 142, p. 916.

1939 (with Mace, C.) Gravity measurements in Cyprus: Royal Astronomical Society Monthly Notices, Geophysical Supplement 4, p. 473–480.

—— Heat flow in South Africa: Royal Society of London Proceedings, ser. A, v. 173, p. 474–502.

Note: I wish to thank D. P. McKenzie, who very kindly provided me with a copy of a memorial notice he had written and a complete bibliography.

1940 (with Gaskell, T. F., Harland, W. B., and Kerr-Grant, C.) Seismic investigations on the Palaeozoic floor of east England: Royal Society of London Philosophical Transactions, ser. A, v. 239, p. 29–94.
____ Geophysical study of submarine geology: Nature, v. 145, p. 764–766.
____ Submarine canyons: Nature, v. 146, p. 432.
____ The geophysical study of submarine geology: Royal Institution of Great Britain, Proceedings, v. 31, p. 139–147.
1941 The continental shelf: Nature, v. 148, p. 672–673.
____ (with Gaskell, T. F.) Submarine seismic investigations: Royal Society of London Proceedings, ser. A, v. 177, p. 476–499.
1942 Radioactive heat generation in rocks: Royal Astronomical Society Monthly Notices, Geophysical Supplement 5, p. 41–47.
1944 Geological time: Manchester Literary and Philosophical Society, Memoirs and Proceedings, v. 86, p. 55–82.
1947 The time necessary for a bore-hole to attain temperature equilibrium: Royal Astronomical Society Monthly Notices, Geophysical Supplement 5, p. 127–130.
1948 (with Cooper, R.I.B.) Determination of the masses necessary to produce a given gravitational field: Royal Society of London Proceedings, ser. A, v. 194, p. 332–347.
1948 The secular change in the Earth's magnetic field: Royal Astronomical Society Monthly Notices, Geophysical Supplement 5, p. 248–257.
1949 The magnetic field within the Earth: Royal Society of London Proceedings, ser. A, v. 197, p. 433–453.
____ Terrestrial magnetism: Physics Today, v. 2, p. 6–13.
____ Electromagnetic introduction in a rotating sphere: Royal Society of London Proceedings, ser. A, v. 199, p. 413–443.
1950 The origin of the Earth's magnetic field (the Halley lecture): Observatory, v. 70, p. 139–143.
____ (with Freedman, C., Gellman, H., and Nixon, J.) The westward drift of the Earth's magnetic field: Royal Society of London Philosophical Transactions, ser. A, v. 243, p. 67–92.
____ The transfer of heat from the core of the Earth: Royal Astronomical Society Monthly Notices, Geophysical Supplement 6, p. 36–41.
1951 (with Niblett, E. R.) Terrestrial heat flow in England: Royal Astronomical Society Monthly Notices, Geophysical Supplement 6, p. 222–238.
1952 Heat flow through the floor of the eastern North Pacific Ocean: Nature, v. 170, p. 200.
1953 Is the Earth's dipole moment increasing?: Journal of Geophysical Research, v. 58, p. 277–278.
1954 Introduction to a discussion on "The floor of the Atlantic Ocean": Royal Society of London Proceedings, ser. A, v. 222, p. 287–289.
____ A comparison of oceans and continents: Royal Society of London Proceedings, ser. A, v. 222, p. 403–407.
____ The flow of heat through the floor of the Atlantic Ocean: Royal Society of London Proceedings, ser. A, v. 222, p. 408–429.
____ (with Gellman, H.) Homogeneous dynamos and terrestrial magnetism: Royal Society of London Philosophical Transactions, ser. A, v. 247, p. 213–278.
____ The interior of the Earth, *in* Kuiper, G. P., ed., The Solar System; Volume 2, The Earth as a planet: Chicago, University of Chicago Press, p. 57–137.
____ The stability of a homopolar dynamo: Cambridge Philosophical Society Proceedings, v. 51, p. 744–760.

1956 (with Maxwell, A. E., and Revelle, R.) Heat flow through the deep sea floor: Advances in Geophysics, v. 3, p. 153–181.
____ Edmond Halley; The first geophysicist: Nature, v. 178, p. 891–892.
1958 The secular variation of the Earth's magnetic field (Chree lecture): Physical Society Yearbook for 1958, p. 47–60.
1960 The automatic reduction of geophysical data: Geophysical Journal, v. 3, p. 237–243.
1961 (with Day, A.) The flow of heat through the floor of the Atlantic Ocean: Geophysical Journal, v. 4, p. 282–292.
____ Forces and processes at work in ocean basins, *in* Oceanography: American Association for the Advancement of Science Publication 67, p. 39–50.
____ (with Griggs, D. T.) The nature of the Mohorovicić discontinuity: Geophysical Journal, v. 6, p. 118–123.
1962 The deeper structure of the ocean floor: Royal Society of London Proceedings, ser. A, v. 265, p. 386–395.
____ (with Hill, M. N., and Mason, C. S.) Chart of the total force of the Earth's magnetic field for the northeastern Atlantic Ocean: Geomagnetica, p. 186–191
1963 (with Munk, W. H.) Patching the long-wave spectrum across the tides: Journal of Geophysical Research, v. 68, p. 3627–3634.
____ (with Mason, R. G.) The magnetic field over the oceans, *in* Hill, M. N., ed., The sea, Volume 3: New York, Wiley Interscience, p. 175–217.
____ The flow of heat through the floor of the ocean, *in* Hill M. N., ed., The sea, Volume 3: New York, Wiley Interscience, p. 218–232.
1964 Continental drift: Geological Society of London Quarterly Journal, v. 120, p. 1–34.
1965 (with Everett, J. E., and Smith, A. G.) The fit of the continents around the Atlantic: Royal Society of London Philosophical Transactions, ser. A., v. 258, p. 41–51.
____ (with Allan, D. W.) The secular variation of the Earth's magnetic field: Cambridge Philosophical Society Proceedings, v. 62, p. 783–809.
____ The detection of underground explosions: Scientific American, v. 215, July, p. 19–29.
1966 Concluding remarks to a discussion on recent advances in the technique of seismic recording and analysis: Royal Society of London Proceedings, ser. A, v. 290, p. 472–476.
1967 The removal of trend from magnetic surveys: Earth and Planetary Science Letters, v. 2, p. 293–300.
____ Electromagnetic induction in the Earth: Royal Astronomical Society Quarterly Journal, v. 8, p. 143–160.
____ (with Booker, J., and Gasty, R. L.) Paleomagnetism and age of rocks from Easter Island and Juan Fernandez: Geophysical Journal, v. 12, p. 469–471.
1968 Reversals of the Earth's magnetic field (the Bakerian Lecture for 1967): Royal Society of London Philosophical Transactions, ser. A, v. 263, p. 481–524 (reprinted in Selected Lectures of the Royal Society, v. 3, 1970).
____ Closing review, *in* Phinney, R. A., ed., The history of the Earth's crust: Princeton, New Jersey, Princeton University Press, p. 231–235.
1969 The origin of the oceans: Scientific American, v. 221, September, p. 66–75.
1971 (with Gubbins, D.) Geomagnetic dynamos in a stable core: Nature, v. 232, p. 548–549.
____ (with McKenzie, D. P.) Remarks on uncertainties in poles of rotation in continental fitting: Earth and Planetary Science Letters, v. 11, p. 263–264.
1972 Geomagnetic dynamos, *in* Robertson, E. C., ed., The nature of the solid Earth: New York, McGraw-Hill, p. 232–244.
1974 Minerals from the deep sea: Endeavour, v. 33, p. 80–85.

1975 The emergence of plate tectonics; A personal view: Earth and Planetary Sciences Annual Reviews , v. 3, p. 1–30.

____ Plate tectonics and oil accumulation, *in* Yorath, C. J., and others, eds., Canada's continental margins and offshore petroleum exploration: Canadian Society of Petroleum Geologists Memoir 4, p. 1–7.

____ William Maurice Ewing: Biographical Memoirs, Fellows of the Royal Society, v. 21, p. 269–311.

1977 (with Gubbins, D.) Generation of magnetic fields by fluid motions of global scale: Geophysical, Astrophysical and Fluid Dynamics, v. 8, p. 43–56.

1980 William Maurice Ewing, 1906–1974; A biographical memoir: U.S. National Academy of Sciences Biographical Memoirs, v. 51.

1981 (with Malin, S.R.C.) The direction of the Earth's magnetic field at London, 1570–1975: Royal Society of London Philosophical Transactions, v. 299, p. 357–423.

Printed in U.S.A. 12/87