Bullard, SIR Edward Crisp (1907-1980), marine geophysicist, was born on 21 September 1907 at 1 Heigham Grove, Earlham Road, Heigham, Norwich, the only son and eldest of four children, of whom the last were twins, of Edward John Bullard (1875-1950), a Norwich brewer, and his wife, Eleanor Howes (1877-1962), daughter of Sir Frank Crisp first baronet (*d*. 1917), solicitor and vice-president of the Linnean Society, and his wife Catherine (née Howes). Bullard's first schooling was at Norwich High School for Girls, which took both girs and boys in the lower class, and in 1916 he went on to Norwich Grammar School, where he was extremely unhappy; things improved when he was sent to Aldeburgh Lodge (now Orwell Park School), Suffolk, in 1919, and his lifelong interest in physics was kindled while at Repton School, Derbyshire (1921-6). He entered Clare College, Cambridge, in 1926 and obtained first-class honours in both parts of the natural science tripos, taking physics, chemistry, mathematics and mineralogy in Part I (1928) and specialising in physics in Part II (1929).

On graduation, Bullardf began research for his PhD at the Cavendish Laboratory under Patrick Blackett and Lord Rutherford. He initially worked with Harrie Massey (1908-1983) on a study of electron scattering in gases and, later, with Philip Moon building an analogue device to solve Schrödinger's equation (which describes the wave-like behaviour of electons in the atom). At the height of the economic depression in 1931, he took Rutherford's advice to 'take any job you can get' (Munk, v) and accordingly accepted an invitation from Sir Gerald Lenox-Conyngham to join his fledgling department of geodesy and geophysics as a demonstrator. On the strength of this post, Bullard married Margaret Ellen (*b*. 1907), daughter of Frederick Bevan Thomas, a civil engineer with the Indian railways and his wife Annie Whitmarsh (née Phelps), on 25 July 1931. Described as 'an immensely talented [but] restless romanticist' (Revelle, 4), Margaret assisted Bullard with much of his early experimental work, 'keeping many of the notebooks and making the thermal conductivity measurements' (McKenzie, 76). In the 1950s she published three novels based on their lives in Cambridge, Toronto and La Jolla.

On joining Lenox-Conyngham, Bullard developed techniques to greatly improve the accuracy of the department's large invariable pendulum, used to measure the strength of the Earth's gravity field. As a result, he became a consultant to the Anglo-Iranian Oil Co. and gained his Ph.D. (in physics and atomic physics) in 1932, and his application of this geophysical method to investigate the geological structure of the East African Rift Valley in 1933-4 established his reputation. He was awarded a

Smithsonian research fellowship of the Royal Society (1936-43) and Cambridge's Sedgwick prize in March 1937. By 1936, he had recognised the potential for academic research of the secret seismic survey techniques used by oil companies. Aided by Leslie Flavill, an instrument designer and mechanic of genius, C. Kerr-Grant, Thomas Gaskell and the geologist Brian Harland, Bullard built equipment and by refraction survey during 1937-8, combined with evidence from boreholes, successfully elucidated the sub-surface structure of much of eastern England.

In contrast, the geology of the ocean floor was at this time still largely unknown. In the autumn of 1936 Bullard met the American geologist Richard Field (1885-1961), who described measurements of the thicknesses of sediments on the continental shelf off the Virginia coastline made by Maurice Ewing (1906-1974) the previous year. Field recommended similar work on the opposite side of the Atlantic, and invited Bullard to accompany Ewing on a cruise to observe the seismic techniques used. Consequently in July 1938 and June 1939, Bullard, Gaskell and Flavill improved on Ewing's refraction survey technique with sea-floor geophones by using hydrophones floating close to the sea surface (thereby paving the way for modern marine seismic surveys), and measured sediment thicknesses on a transect south-west of Land's End, Cornwall. This showed that, as Ewing had found, the basement sloped down towards the continental edge and confirmed the existence of a major Atlantic sedimentary basin.

Although many measurements of the increase of the earth's temperature with depth had been made in the nineteenth century using mines and boreholes, lack of knowledge of the thermal conductivity of the rocks through which they passed made it impossible to know whether observed variations in thermal-gradient were caused by changes in heat-flow or conductivity. At the instigation of Harold Jeffreys (1891-1989), reader in geophysics in Lenox-Conyngham's department, in 1935 the British Association for the Advancement of Science established a committee to remedy this situation. Bullard developed improved techniques for measurement of thermal conductivity, setting definitive standards which 'have remained largely unchanged' (McKenzie, 75) since. Unexpectedly low temperature gradients had recently been reported from very deep boreholes in South Africa. In 1938-9, Bullard's measurements showed that the anomalous results were accounted for by high thermal conductivities of the local rocks through which the boreholes passed. This enabled him to obtain the first reliable estimate of heat-flux through the continents.

In November 1939 Bullard joined HMS *Vernon*, the Royal Naval Mine and Torpedo School, Portsmouth. Ships naturally acquire a magnetic field during their construction and this made them an easy prey to German magnetic mines. Bullard was placed in charge of finding ways to protect ships from magnetic and acoustic mines. Demonstrating when necessary an utter disregard for the formalities of normal civil service rules his group, which included Flavill and Gaskell, successfully developed methods for sweeping mines and neutralising ship magnetic fields. Within eighteen months shipping losses from mines had been reduced to such an extent that, in 1941, Bullard could move to London, to join Blackett's Naval Operational Research Group in the Admiralty. He first worked on strategies for conducting marine warfare; on analysis of data which Reginald Jones's (1911-1997) Scientific Intelligence Unit at the Air Ministry was obtaining regarding the German rocket and flying-bomb programme; and then on strategies for attacking the firing sites in northern France. In 1944 Bullard was appointed assistant director of operational research. In later years, he 'thought of these wartime accomplishments when he was so young as the most important things he had ever done' (Revelle, 2). He remained an advisor to the Admiralty until his retirement from Cambridge in 1974.

Bullard returned to Cambridge as reader in experimental geophysics in 1945, then head of department in 1947. He tried to continue with seismic and heat-flow research and, as a result of his wartime duties, began work on problems of the earth's magnetic field, but he became increasingly frustrated by lack of equipment, financial support and ship time. In the spring of 1948 (the year he gained his ScD from Cambridge) he became chairman of the physics department at the University of Toronto. There he continued work on heat-flow, and began theoretical studies to show how movement of fluid material in the core of the Earth could act as a self-sustaining dynamo, and hence as the source of the geomagnetic field. He encouraged departmental research in geochemistry and methods for the dating of rocks using natural radioactive decay. Despite this, both he and his family were unhappy in Canada, and he accepted directorship of the National Physical Laboratory, Teddington. In June-July 1949 at the Scripps Institution of Oceanography, La Jolla, California, he designed and, with graduate student Arthur Maxwell (*b*. 1925) built, a prototype of the first deep-sea probe capable of accurately measuring the thermal gradient in the sediments of the ocean floor.

Although he could be forgetful, Bullard was a skilled and sometimes buccaneering manager and an excellent academic supervisor: 'Running things needs confidence ... I learned a lot from Rutherford. A thing you must do is spend time with people who are in trouble, either emotional, financial or scientific .... you have to remain calm, sympathetic and reasonable' (McKenzie, 80-81). So, despite his 'disconcerting and invigorating habit of dropping into a laboratory or office, hearing what the occupant was doing, and almost always telling him how to do it better' (Cook, 16), he was seen as an effective and well-liked director of the national Physical Laboratory and was created knight batchelor in 1953 in recognition of this service and his wartime work.

While at the laboratory he persued development of the heat-probe—'I had superb facilities and no question as to who was going to use them. ... If I said do something, they did it' (Shor, 74). The first successful measurements were made in the deep ocean basin, south-west of Ireland, in July 1952. Bullard was now able to complete calculations underpinning his dynamo model, one of the first non-military applications of computational fluid-mechanics, using the ACE computer at the National Physical Laboratory.

In 1955 Bullard returned to Cambridge (at a third of his Teddington salary) as Bye fellow of Gonville and Caius College; he became assistant director of research in the department of geology and geophysics (1956), reader in geophysics (1960), and the first professor of geophysics (1964-74). He was a fellow of Churchill College from 1960 and a visiting professor at the La Jolla laboratories of the Institute of Geophysics and Planetary Physics, University of California (1963-74). He was by now a firm champion of the idea that the ocean floor was essentially different in nature from that of the continents, while his own principal fields of research continued to be geomagnetics and heat-flow, and his department became a major centre for paleomagnetic and marine research. By 1954 analysis of heat-flow data obtained in collaboration with Roger Revelle (1909-1991) and Maxwell of the Scripps Institution, from the Pacific and Atlantic, had shown results hotter than anticipated, and by 1956 Bullard had located a zone of high heat-flow associated with the mid-oceanic ridge. This supported his 1954 hypothesis that excess heat-flow could be explained by upwards transportation of heat from the inner earth by convection. In 1959, although Alfred Wegener's (1880-1930) theory of continental drift was still regarded as complete heresy by the majority of geologists, Bullard, although recognising that there could be counter-arguments, suggested that recent paleomagnetic evidence of polarwandering paths (obtained by his former student Keith Runcorn (1922-1995) and others), also indicated that drift could be a reality, and that the mid-Atlantic ridge might mark the place at which the ocean was widening. Evidence from paleomagnetism and magnetic and gravity surveys of the sea floor continued to accumulate and Bullard and his colleague Maurice Hill (1916-1966) were among the first to introduce computer processing methods to marine geophysical data-reduction. However, interpretation of what such results implied remained controversial. In 1963, in a lecture to the Geological Society, London, Bullard ‘at last came out in favour of continental drift without reservations’ (Bullard, 16), concluding that the consensus of evidence supporting drift was now convincing and that thermal convection currents, driving seafloor spreading, provided a plausible mechanism. Inspired by Jeffrey’s disbelief in previous attempts to demonstrate the closeness-of-fit of the margins of the continental shelves across the Atlantic, Bullard now recalled Euler’s (1776) theorem, that any motion of a sphere over itself can be regarded as a single rotation about a given axis. Working with Alec Smith and J.E. Everett, he used the theorem to compute a very convincing match, which they presented at a symposium on drift organised by Blackett, Runcorn and Bullard in 1964. With growing understanding of the nature of spreading at mid-oceanic ridges and Tuzo Wilson’s (1908-1993) recognition of the presence of major transform-faults, Bullard’s computational method underpinned the eventual acceptance, in 1966-7, of the concept of plate-tectonics. Thereafter, his research was mainly concerned with the origin of the earth’s magnetic field.

In quite different roles, Bullard participated in the 1958 conference of experts held in Geneva to establish the technical criteria necessary to monitor a nuclear test-ban treaty; as joint chairman of the Anglo-American Ballistic Missile Committee; and in the Pugwash conferences in the 1960s. As a result he maintained an interest in the detection of underground nuclear explosions. He also served on a number of committees in the Ministry of Defence; as a director of the family firm, Bullard & Sons. (1950-55), and of IBM UK (1964-75); and as a consultant to the US President’s Office of Science and Technology Policy, the California Energy Commission and the Jet Propulsion Laboratory of the California Institute of Technology on high-level radioactive waste disposal (1975-8). He was elected to the Royal Society in 1941 and received many honours, including its Hughes and Royal medals (1953, 1975); the Chree medal (Physical Society, 1956); Day medal (Geological Society of America, 1959); gold medal of the Royal Astronomical Society (1965); Agassiz medal (US National

Academy of Science, 1965); Wollaston medal (Geological Society, London, 1967); the Bowie and Ewing medals (American Geophyical Union, 1975, 1978); the Vetlesen prize (often regarded as the geological equivalent of the Nobel prize, 1968); and honorary ScD degrees from the Memorial University of Newfoundland (1970) and the University of East Anglia (1976). His favourite was reputed to be the stuffed albatross awarded to him in 1976 by the American Miscellaneous Society for 'the most incomprehensible paper of the decade in geophysics' (Revelle, 6)—a reference to his work on the dynamo theory.

There were four daughters from Bullard's first marriage (Belinda, Emily, Henrietta and Polly), the middle two of whom were twins. The marriage was dissolved in January 1974 and on 11 June he married Mrs. Ursula Margery Curnow (1924-1989), daughter of Ernest James Cooke, medical practitioner, of Christchurch, New Zealand. Although his health was beginning to fail, Bullard and his new wife emigrated to California in September 1974, where he resumed his (previously visiting) position as a professor at the Scripps Institution. With the 'calm and steady' painter and sculptor, Ursula, Lady Bullard, he was able to 'find peace and ... genuine happiness' (Revelle, 4).

After a courageous fight against prostate cancer Bullard died in his sleep on 3 April 1980, at his home, 2491 Horizon Way, La Jolla, California, a few hours after the completion of the manuscript (with S.R.C. Malin) of his 196th scientific article, a historical review of the direction of the earth's magnetic field at London since the sixteenth century. His ashes were scattered at sea off the La Jolla coast. Memorial services were held at the Scripps Institution, on 16 April; and in Cambridge on 24 May 1980.

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