8.4 History of the magnetic method in exploration

There is little doubt that the Chinese were the first to observe and employ the directional properties of magnetic objects in navigation. They may have invented and used the compass as early as 2600 before the Common Era, but more likely it was as late as 1100 in the Common Era before the compass was used as a navigational instrument. The compass was first noted in Europe around 1200, but the reference by an English monk suggests that the compass had previously been known for an extended period of time. In 1269, P. de Maricourt (P. Peregrinus) investigated the properties of a spherical lodestone. He studied the dipolar nature of magnetic objects and named the poles after the geographic directions that they pointed to (i.e. north and south). He also identified the forces of attraction between unlike poles and the repulsion between like poles.

Although the matter was possibly observed earlier by the Chinese and also by Christopher Columbus in his voyages of discovery of the Caribbean Islands in 1492, N. Hartmann in 1510 is credited as the first European to record the declination of the geomagnetic field. In 1544, he was also the first to observe the inclination of the field. Towards the end of the sixteenth century, R. Norman constructed the first inclinometer with the dipping magnetic needle located on a horizontal pivot. With it he was able to show that the inclination of the field corresponds to that on a spherical lodestone, indicating that the cause of the directional component of the compass was within the Earth. This led in 1600 to the publication of William Gilbert’s famous book De Magnete, which postulated that the Earth is a giant magnet.

C. Coulomb markedly improved the sensitivity of the compass in the 1770s. With this instrument he was able to study daily variations in the field that had been discovered earlier in the century by G. Gellibrand and G. Graham. From his observations, he discovered the inverse square law of magnetics that bears his name and is equivalent to Newton’s law of gravitation. In 1820, H.C. Ørsted observed the effect on a magnet of a nearby current carrying wire, thus for the first time relating electricity and magnetism. In that same year, A. Ampere explained these observations in terms of forces between electrical fields, showing that the origin of magnetism lies in electrical fields. The actual origin of the geomagnetic field has long been the subject of speculation. Early theories focused on the presence of permanently magnetized material distributed in various ways within the Earth. However, in 1919, J. Larmor proposed an origin by an internal self maintaining dynamo such as has been suggested for the origin of strong magnetic fields observed on the Sun. In the late 1940s, W. Elasser and E. Bullard contributed to the theory that the origin lies in motions of electrically conducting material in the fluid outer core of the Earth. These studies on the origin and reversal of the geomagnetic field continue today.

In the early nineteenth century, Baron von Humboldt made magnetic intensity measurements in widely separated locales, observing that the intensity of the field varies over the surface of the Earth. He also conducted the first magnetic survey associated with local geology. However, local variations in the direction of the magnetic field had been mapped as early as 1640 in Sweden in the search for buried magnetic iron ore deposits. Declination measurements on a local basis were made with a Sun compass, where the shadow cast by the Sun is used to determine geographic north which is then compared with the direction of magnetic north indicated by the compass heading. These measurements were brought to New York and New Jersey to locate hidden iron ore deposits early in the eighteenth century, and similar measurements in Michigan in 1844 were used to discover the iron-rich rock formations of the Lake Superior region.

In the early part of the nineteenth century, C. F. Gauss developed instrumentation and procedures for measuring the absolute intensity of the geomagnetic field, in contrast to the relative observations made of declination and inclination. Gauss also published papers between 1832 and 1840 giving the framework for
our current theories of terrestrial magnetism. His associate W. E. Weber introduced the Earth inductor, which measures the intensity of the field by measuring the induced current in an oriented wire coil that rotates in the geomagnetic field. In 1842, H. Lloyd made a significant contribution by constructing a counterbalanced magnetic needle. Observations with this instrument can be used to determine both dip and intensity of the magnetic field. A variant of this instrument, the dip needle, a hand-held counterbalanced needle that oscillates in a vertical plane, was used extensively in mineral exploration from the early 1900s to after World War II. A more sensitive variation of this instrument is the Hotchkiss superdip, in which the counter balance is moved off the axis of the magnetic needle; this was developed in 1915 and used throughout the Lake Superior iron ore district and other mining areas. However, the most widely used Lloyd-type instrument was developed by A. Schmidt in 1915. This instrument was capable of the precision required to map geological formations containing minor magnetic minerals, not just high-magnetic polarization units. It was the standard for geological mapping of both the vertical and horizontal intensity of the geomagnetic field for 40 years. In 1930, A. S. Eve and D. A. Keys reported on the use of this instrument in mapping an iron copper sulfide ore body and dikes in the Sudbury mining district of Canada. A successful magnetic gradiometer was constructed and used in geological mapping by I. Roman and T. C. Sermon in the early 1930s, using two Earth inductors at a fixed distance from each other.

Airborne measurements of adequate sensitivity for geological studies were initiated shortly after World War II, with a flux-gate magnetometer incorporating the basic sensor developed by J. D. C. Hare and further developed and patented in 1940 by V. Vacquier. This was made into a practical instrument during the war for use in detecting submerged submarines. The flux-gate magnetometer, which measures the relative total intensity of the geomagnetic field, has been largely replaced by the resonance magnetometer which measures the absolute scalar magnetic intensity without an orientation requirement. The first full-scale airborne magnetic survey for geological purposes was conducted in 1945 in the Naval Petroleum Reserve No. 4 in northwestern Alaska by the US Geological Survey. The proton-precession magnetometer, developed by R. Varian, became available for geomagnetic exploration in the 1950s and was rapidly converted to use in marine and airborne measurements as well as satellite magnetic studies and gradiometer studies. Although other types of magnetometers have been developed through the years following World War II, variations of the resonance magnetometer are the principal instrument used in magnetic observations today. It is these magnetometers that have permitted the global mapping of the geomagnetic field at a range of scales.

Observations of the near-Earth magnetic field have been made from Earth-orbiting satellites since Sputnik 3 was launched in 1958. Improved measurements covering larger portions of the globe were made using subsequent satellites, notably Cosmos 49, the polar orbiting geophysical observatories (POGO) of the late 1960s, and Magsat which orbited the Earth for 7 months starting in November 1979. The latter mission was dedicated to magnetic observations, providing useful information on the nature of the lithosphere as well as global temporal and spatial variations in the geomagnetic field. More recently, the satellite missions Ørsted (1999) and CHAMP (2000) have given new insight into the geomagnetic field and its use in lithospheric studies. Magnetometers deployed on the lunar Apollo (1960s), Clementine (1992), and Lunar Prospector (1997) missions mapped the weak magnetic field of the Moon, whereas the Viking mission (1979) obtained magnetic field observations of Venus. The Mars Global Surveyor (1996) mission has also mapped the martian magnetic field. These magnetic observations from space have provided new insight into the origin and tectonic evolution of the rocky planetary bodies, as well as a better understanding of the Earth’s magnetic field and its interpretation.

No history of geomagnetism would be complete without mention of paleomagnetism, which is the study of the permanent magnetization of rocks, and its impact on exploring the Earth. Intense permanent
magnetization was recognized in rocks other than lodestones in the late eighteenth century, but it was largely believed to be the result of lightning strikes. It was the observation by Delasse in the mid-nineteenth century that permanent magnetization in some rocks parallels the Earth's magnetic field that opened up opportunities to use paleomagnetism to study the Earth and its processes. P. David and B. Brunhes reported in the early twentieth century that some rocks are reversely magnetized to the current geomagnetic field. In 1926, P. Mercanton observed that rocks from widely scattered locations across the Earth are reversely as well as normally magnetized, suggesting that the reversal of the permanent magnetization is a result of ancient reversals of the magnetic field. He suggested that paleomagnetism could be used to evaluate hypotheses of polar wandering and continental drift because of the approximate correlation of the axes of rotation and the geomagnetic field. In the ensuing few decades, secular variation and intensity of the Earth's magnetic field were studied in rocks, baked hearths, and pottery. In 1952, P.M.S. Blackett reported on an astro-magnetism experiment in which improved techniques were developed for measuring the moment and direction of the magnetic field of materials. Studies of the paleomagnetism of rocks throughout the world by J. Graham, P. M. S. Blackett, K. Runcorn, E. Irvine and others led to the support of the continental drift hypothesis.

By accurately dating rocks whose magnetization had been determined, A. Cox and R. R. Dalrymple in 1960 established the first magnetic field reversal chronology over the past 3.6×10⁶ years. Subsequently, this chronology has been greatly expanded and its resolution improved. The history of reversals of the geomagnetic field led F. J. Vine and D. H. Matthews in 1963 to explain the origin of the symmetric magnetic anomalies on either side of the oceanic ridges. They proposed that the oceanic crust splits along the ridge, allowing intrusion of basalt, which, upon cooling, takes on a remanent magnetization parallel to the geomagnetic field. The alternating sign of the magnetic anomalies reflects the reversing magnetization of the oceanic crust and its movement away from the oceanic ridge with time as new material is intruded into the central ridge. Thus, the production of oceanic crust results in a magnetic tape-recording that forms the basis of the theory of seafloor spreading and plate tectonics. Observations of the magnetic field at sea, and an understanding of the reversal and timing of the reversal of the geomagnetic field as identified in rocks, led to the hypothesis of plate tectonics that dominates modern Earth sciences.


5.1.3 The physical origins of magnetism

By the end of the eighteenth century many characteristics of terrestrial magnetism were known. The qualitative properties of magnets (e.g., the concentration of their powers at their poles) had been established, but the accumulated observations were unable to provide a more fundamental understanding of the phenomena because they were not quantitative. A major advance was achieved by Charles Augustin de Coulomb (1736–1806), the son of a noted French family, who in 1784 invented a torsion balance that enabled him to make quantitative measurements of electrostatic and magnetic properties. In 1785 he published the results of his intensive studies. He established the inverse-square law of attraction and repulsion between small electrically charged balls. Using thin, magnetized steel needles about 24 inches (61
Alessandro Volta (1745–1827) invented the voltaic cell with which electrical currents could be produced. The relationship between electrical currents and magnetism was detected in 1820 by Hans Christian Oersted (1777–1851), a Danish physicist. During experiments with a battery of voltaic cells he observed that a magnetic needle is deflected at right angles to a conductor carrying a current, thus establishing that an electrical current produces a magnetic force.

Oersted’s result was met with great enthusiasm and was followed at once by other notable discoveries in the same year. The law for the direction and strength of the magnetic force near a current-carrying wire was soon formulated by the French physicists Jean-Baptiste Biot (1774–1862) and Felix Savart (1791–1841). Their compatriot André Marie Ampère (1775–1836) quickly undertook a systematic set of experiments. He showed that a force existed between two parallel straight current carrying wires, and that it was of a type different from the known electrical forces. Ampère experimented with the magnetic forces produced by current loops and proposed that internal electrical currents were responsible for the existence of magnetism in iron objects (i.e., ferromagnetism). This idea of permanent magnetism due to constantly flowing currents was audacious for its time.

At this stage, the ability of electrical currents to generate magnetic fields was known, but it fell to the English scientist Michael Faraday (1791–1867) to demonstrate in 1831 what he called “magneto-electric” induction. Faraday came from a humble background and had little mathematical training. Yet he was a gifted experimenter, and his results demonstrated that the change of magnetic flux in a coil (whether produced by introducing a magnet or by the change in current in another coil) induced an electric current in the coil. The rule that governs the direction of the induced current was formulated three years later by a Russian physicist, Heinrich Lenz (1804–1865). Unhampered by mathematical equations, Faraday made fundamental contributions to understanding magnetic processes. Instead of regarding magnetic and electrical phenomena as the effects of centers of force acting at a distance, he saw in his mind’s eye fictional lines of force traversing space. This image emphasized the role of the medium and led eventually to the concept of magnetic field, which Faraday first used in 1845.

Although much had been established by the early 1830s, it was still necessary to interpret the strengths of magnetic forces by relating magnetic units to mechanical units. This was achieved in 1832 by the German scientist and mathematician, Carl Friedrich Gauss (1777–1855), who assumed that static magnetism was carried by magnetic “charges,” analogous to the carriers of static electricity. Experiment had shown that, in contrast to electric charge, magnetic poles always occur as oppositely signed pairs, and so the basic unit of magnetic properties corresponds to the dipole. Together with Wilhelm Weber (1804–1891), Gauss developed a method of absolute determination of the intensity of the Earth’s magnetic field. They founded a geomagnetic observatory at Göttingen where the Earth’s magnetic field was observed at regular intervals. By 1837 global charts of the total intensity, inclination and declination were in existence, although the data had been measured at different times and their areal coverage was incomplete. To analyze the data-set Gauss applied the mathematical techniques of spherical harmonic analysis and the separation of variables, which he had invented. In 1839 he established that the main part of the Earth’s magnetic field was a dipole field that originated inside the Earth.

The fundamental physical laws governing magnetic effects were now firmly established. In 1872 James Clerk Maxwell (1831–1879), a Scottish physicist, derived a set of equations that quantified all known relationships between electrical and magnetic phenomena: Coulomb’s laws of force between electric charges and magnetic poles; Oersted’s and Ampère’s laws governing the magnetic effects of electric
currents; Faraday’s and Lenz’s laws of electromagnetic induction; and Ohm’s law relating current to electromotive force. Maxwell’s mathematical studies predicted the propagation of electric waves in space, and concluded that light is also an electromagnetic phenomenon transmitted through a medium called the *luminiferous ether*. The need for this light-transmitting medium was eliminated by the theory of relativity. By putting the theory of the electromagnetic field on a mathematical basis, Maxwell enabled a greater understanding of electromagnetic phenomena before the discovery of the electron.

A further notable discovery was made in 1879 by Heinrich Lorentz (1853–1928), a Dutch physicist. In experiments with vacuum tubes he observed the deflection of a beam of moving electrical charge by a magnetic field. The deflecting force acted in a direction perpendicular to the magnetic field and to the velocity of the charged particles, and was proportional to both the field and the velocity. This result now serves to define the unit of magnetic induction.

Since the time of man’s first awareness of magnetic behavior, students of terrestrial magnetism have made important contributions to the understanding of magnetism as a physical phenomenon. In turn, advances in the physics of magnetism have helped geophysicists to understand the morphology and origin of the Earth’s magnetic field, and to apply this knowledge to geological processes, such as global tectonics. The physical basis of magnetism is fundamental to the geophysical topics of geomagnetism, rock magnetism and paleomagnetism.