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THE STUDY OF EARTH'S MAGNETISM (1269–1950): A FOUNDATION BY PEREGRINUS AND SUBSEQUENT DEVELOPMENT OF GEOMAGNETISM AND PALEOMAGNETISM

Vincent Courtillot[1] and Jean-Louis Le Mouël[1]

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[1] This paper summarizes the histories of geomagnetism and paleomagnetism (1269–1950). The role of Peregrinus is emphasized. In the sixteenth century a debate on local versus global departures of the field from that of an axial dipole pitted Gilbert against Le Nautonier. Regular measurements were undertaken in the seventeenth century. At the turn of the nineteenth century, de Lamanon, de Rossel, and von Humboldt discovered the decrease of intensity as one approaches the equator. Around 1850, three figures of rock magnetism were Fournet (remanent and induced magnetizations), Delesse (remagnetization in a direction opposite to the original), and Melloni (direction of lava magnetization acquired at time of cooling). Around 1900, Brunhes discovered magnetic reversals. In the 1920s, Chevallier produced the first magnetostratigraphy and hypothesized that poles had undergone enormous displacements. Matuyama showed that the Earth's field had reversed before the Pleistocene. Our review ends in the 1940s, when exponential development of geomagnetism and paleomagnetism starts.

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1. INTRODUCTION

[2] Geomagnetism and paleomagnetism have been remarkably successful disciplines of the geosciences in the twentieth century. Central to them is the quest for a detailed understanding of the origin of the Earth's magnetic field, considered one of the five most important unsolved problems in physics by Albert Einstein over a hundred years ago (e.g., M. G. Kivelson, www.igpp.ucla.edu/mpg/lectures/mkivelson/faculty97/lecture.html). Central to their development in previous centuries was the quest for orientation tools, mostly at sea.

[3] Geomagnetism and paleomagnetism (taken in a broad sense) have produced many successes in the past decades (and hold much promise for the coming decades). This covers an incredibly rich spectrum of space (from local to global, covering over 7 orders of magnitude) and time (from under a second to close to the age of the Earth, over 17 orders of magnitude) variations of the geomagnetic field but also progress in dynamo theory and planetary magnetism, confirmation of the importance of the magnetic memory of natural and artificial materials, better understanding of the physics and mineralogy of fossil magnetism, with theoretical and economic consequences in physics and well beyond, applications of rock magnetic memory to plate kinematics, paleogeography, and continental drift, discovery of geomagnetic field reversals, introduction of new accurate means to measure geological phenomena against a high-resolution timescale, new ideas about links with the climate and environment, and more.

[4] Many books and treatises on these two fields are available, and most introduce the subject with a succinct historical perspective [e.g., *Chapman and Bartels*, 1940; *Irving*, 1964; *Malin*, 1987; *Merrill et al.*, 1996]. In the course of using those to prepare a short set of lectures on the history of the geosciences, we felt that we had to return to a significant number of original books and papers, mostly from the nineteenth and early twentieth century but actually once going back to the thirteenth century. In reading those we found a significant amount of material we felt had not been either sufficiently or accurately enough described in available texts. We therefore felt that there could be some use in writing up our findings, even if many are already accessible to a reasonably determined reader. This is, of course, not the work of professional historians, and therefore cannot be considered as a professional history paper. It is more like careful storytelling but with as often as possible

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a return to and verification of original or close to original sources.

[5] The paper therefore attempts to summarize some of the major steps in the joint histories of geomagnetism and paleomagnetism. It mainly spans the period from the founding work of Peregrinus in 1269 to an arbitrary end around 1950 (many of the actors of the following half century being still alive and much information being readily accessible). Section 2 is more concerned with developments in geomagnetism (though important bases of rock magnetism were concurrently founded) until the nineteenth century, and section 3 is concerned with what would become the bases of paleomagnetism from the mid nineteenth century onward. Many well-known discoverers and steps of discovery are covered in the paper, together with emphasis on less well known figures who played a major yet too often disregarded role. We give only a very brief account of the situation in the 1940s when our review ends, opening the way for the half century that saw the exponential development of geomagnetism and paleomagnetism. The aim of this review is to emphasize what this "modern" phase owes to the preceding ones and to provide students of the discipline with some historical background that may not always be easy to access.

[6] Prior to our contribution the most recent comprehensive review, with an extensive list of references, has been written by *Stern* [2002], with somewhat more emphasis on external geomagnetism and less on paleomagnetism than our attempt, of course reflecting the dominant focus of our respective research activities. The very exhaustive history of *Jonkers* [2000] [see also *Jonkers*, 2003], and the review of the latter book by *Love* [2004], is another major historical enterprise that the reader should be referred to (particularly for the period 1600–1800) before embarking with us.

2. MOSTLY (BUT NOT ONLY) GEOMAGNETISM

2.1. Early History (Sixth Century B.C. to Thirteenth Century A.D.)

[7] The first important dates in the discovery of natural magnetism are listed in most textbooks, though original sources may not always be reliable or may not have been verified. We refer the reader for instance to *Needham* [1962], *Jonkers* [2000], *Aczel* [2001], and *Stern* [2002] for further details and references. Below are some of the most significant dates.

[8] The description of the power of the lodestone (i.e., naturally magnetized minerals, mainly the iron oxide magnetite, also spelled "loadstone") against gravity is explained by Thales of Miletus in the sixth century B.C. in terms of an animist philosophy (this is related by *Pliny the Elder* [1938] in his *Natural History*). In his *De Natura Rerum*, *Lucretius* [1924] in the first century B.C. describes various properties of the magnet, involving in a poetic way attraction by the lodestone at a distance and concepts close to permanent magnetization and magnetic stability. The "floating" compass (a magnetized needle placed in a hollow straw floating on water [*Smith*, 1992], sometimes called a "wet" compass) is developed for divining purposes by the Chinese between the first and sixth century A.D. and is known to Europeans by the mid-twelfth century. The "pivoted" compass (a pivoted needle or "dry" compass) is introduced in Europe in the thirteenth century [*Jonkers*, 2000]; the discovery of declination (i.e., the distinction between geographic and magnetic north) probably occurs in China between the eighth and ninth centuries; the first datable mention of the compass occurs in the 1088 chronicle of Shen Gua (or Shon Kua, 1030–1093) [*Needham*, 1962].

[9] The Chinese compass may have penetrated with caravans into Europe [*Needham*, 1962]. However, *Smith* [1992] believes that the two compasses of China and Europe were invented and evolved independently. The first, almost coeval, writings about use of the magnetic compass to indicate direction are by Alexander Neckham (1157–1217, around 1200), Guyot de Provins (1184–1210, around 1205), and Jacques de Vitry (~1165–1240, around 1204) [*Radelet de Grave*, 1982; *Smith*, 1992]. Most refer to a "floating" compass. Neckham for instance describes accurately the phenomena of attraction and repulsion and proposes a theory of magnetic force. The style of all three contributions implies that the phenomenon had already been known for some time and allows one to estimate that the "floating" compass was familiar in Europe by about 1150 A.D. [*Smith*, 1992]. Guillaume d'Auvergne (~1180–1249) establishes some experiments demonstrating magnetic induction. Vincent de Beauvais (~1190–1264) writes a major encyclopedia (the *Speculum Naturale*, popular until the eighteenth century) between 1220 and 1244, with chapters on the magnet and on the "adamant" in which he recognizes magnetic poles (or corners) which he terms "anguli."

2.2. Petrus Peregrinus's "Epistola de Magnete" (1269)

[10] One of the first key figures in geomagnetism remains Pierre de Maricourt, better known as Petrus Peregrinus ("the pilgrim"). *Smith* [1992] lists several important figures who discussed magnetism prior to Peregrinus's work, such as John of St. Amand (1261–1298), Albertus Magnus (~1200–1280), St. Thomas Aquinas (~1225–1274), and Roger Bacon (~1213 to ~1292). *Smith* [1992, p. 74] attempts to show that there is little in Peregrinus that was not already widely known and that all he did was to "collect, summarize, experiment upon, and extend the considerable knowledge of magnetism available in 1269." *Jonkers* [2000] similarly attributes Peregrinus's fame to the desire to establish clear historical demarcations, when "the concept had been formulated in writing" before. We believe these to be rather severe downplay of the importance of the work. The *Epistola de Magnete* is, among other things, the first written text where a pivoted compass is carefully devised and where the concept of magnetic poles is discussed extensively.

[11] The *Epistola de Magnete*, which has an interesting though still partly mysterious history, indeed remains one of the first landmarks of scientific magnetism. A reproduction of the original text in Latin, together with a translation and a

short introductory overview, has been published by *Radelet de Grave and Speiser* [1975]. *Smith* [1970, p. A11] considers the letter as "the most important advance in knowledge of magnetic properties to emerge from Europe since the discovery of lodestone by the Greeks," written centuries before the far better known contribution of *Gilbert* [1600]. Erwin Panofsky puts Peregrinus at the head of his list of the most important scientists from the Middle Ages. Bacon himself was aware of his work, and so was Gilbert, who quoted entire sentences from the letter. Its remarkable clarity and very modern table of contents (with a general introduction, a description of experimental phenomena, a theory to explain these phenomena, a new experiment proposed to confirm the theory, and a section on applications) show that Peregrinus had a clear and well-structured mind and was a keen observer and an ingenious experimentalist. Of course his work is only qualitative and not quantitative. Because of its importance we describe it in some detail. The following paragraphs summarize the work of *Radelet de Grave and Speiser* [1975] (which lists manuscripts, editions, and translations, the most recent one prior to theirs being a 1943 work in English by Harradon).

[12] Peregrinus (active 1261–1269) was a knight from Picardie who wrote his small masterpiece letter on the magnet on 8 August 1269, while participating in the siege of the Italian town of Luceria (or Lucera) by Charles of Anjou. In his letter to a close friend, Syger de Foucaucourt, he first insists on the need to know the nature of things, to be well versed in the celestial movements, but also to be good at using one's hands to build instruments and experiments that make the "marvelous effects" [*Radelet de Grave and Speiser*, 1975, p. 203] visible to the eye. He first describes the lodestone by its color, homogeneity, weight, and (magnetic) strength: It should look like "polished iron altered by corrupted air" (the idea of oxidation) [*Radelet de Grave and Speiser*, 1975, p. 204]. He then carves a sphere from the lodestone and uses a thin needle to trace meridians on various places at the surface of the sphere: "all lines on the stone will meet at two points, as all of the world's meridian circles meet at the two opposite poles of the world" [*Radelet de Grave and Speiser*, 1975, p. 206]. William Gilbert will borrow this concept in order to find the poles of a magnet. Peregrinus distinguishes and names the north and south poles of the magnet and suggests that they can also be found by a probabilistic method of dropping a needle and seeing "where it attaches the more often and the more strongly" [*Radelet de Grave and Speiser*, 1975, p. 207], showing an understanding that magnetic strength is larger at the poles. He also proposes to look for the place where a suspended needle will be perpendicular to the surface of the sphere (i.e., ±90° inclination, recall that geomagnetic inclination will be discovered only some 300 years later). He ensures that "if you do this precisely and the chosen stone is homogeneous, then the two points will be exactly opposed, as are the poles of a sphere" [*Radelet de Grave and Speiser*, 1975, p. 207]. Peregrinus then arranges the sphere on a floating wooden plate and states that the plate will rotate until "the north pole of the stone stops in the direction of the north pole of the sky" [*Radelet de Grave and Speiser*, 1975, p. 208]. His "magnes rotundus" he believes represents the heavens, with the poles corresponding to the celestial ones (similar ideas were formulated by Roger Bacon around 1266–1268 [*Jonkers*, 2000]). He next studies how different stones attract or repel each other and states the following rule (he does cite God, but as ruling nature through a law): "the north part of a stone attracts the south part of another" [*Radelet de Grave and Speiser*, 1975, p. 209]. He rightly argues for attraction of contrary poles but erroneously concludes that repulsion of similar poles does not occur (this conceptual error due to the fact that magnetic poles can actually not be isolated and that in his experiment the latter situation is unstable). In passing, he argues against the "stupid ideas" [*Radelet de Grave and Speiser*, 1975, p. 210] of other researchers, confirming without giving accurate reference that others had published theories on the magnet previously (see section 2.1).

[13] Peregrinus describes how iron, when touched by lodestone, becomes magnetized; he shows that the direction the needle points to is actually the celestial poles and not the nearby "nautical star" (Polaris). However "astonishing," this is demonstrated by "experiment" [*Radelet de Grave and Speiser*, 1975, pp. 211–212]. He does seem to understand the difference between the properties of orientation (felt by a dipole) and attraction (felt by a pole). Also, he states that only "mediocre researchers" [*Radelet de Grave and Speiser*, 1975, p. 218] could believe that it was the Earth's poles that attracted the lodestone, because that would be where (most of) that lodestone originally came from. He concludes [*Radelet de Grave and Speiser*, 1975, pp. 218–219]:

> we are forced to suppose that a force penetrates the poles of the stone, not only coming from the northern part but also the southern, rather than coming from mineral sites, the obvious proof being that man, wherever he is, sees with his eyes that the stone orients itself following the meridian's direction.

[14] Peregrinus explains how a piece of magnetized iron can easily be remagnetized in the opposite polarity and then explains in detail the famous experiment of the broken magnet, in which each fraction still has two opposing poles, which can never be isolated one from the other; he describes in great detail the behavior of the broken pieces as they attract or repel each other and how the original magnet can be reconstructed in two different ways; in doing this it is clear that Peregrinus has abstracted drawings and figures in mind. His wording shows some understanding of the numerical equivalence of action and reaction. He finally [*Radelet de Grave and Speiser*, 1975, p. 217] proposes four principles which are sufficient to deduce and explain all observed properties and effects: (1) "intentio ad assimilare" (intent to make similar, lodestone-magnetizing iron in its image) and (2) "intentio ad unire" (intent to unite, e.g., the broken parts of a larger magnet) and then two conservation principles (3) "idemptitas" (conservation of the nature of

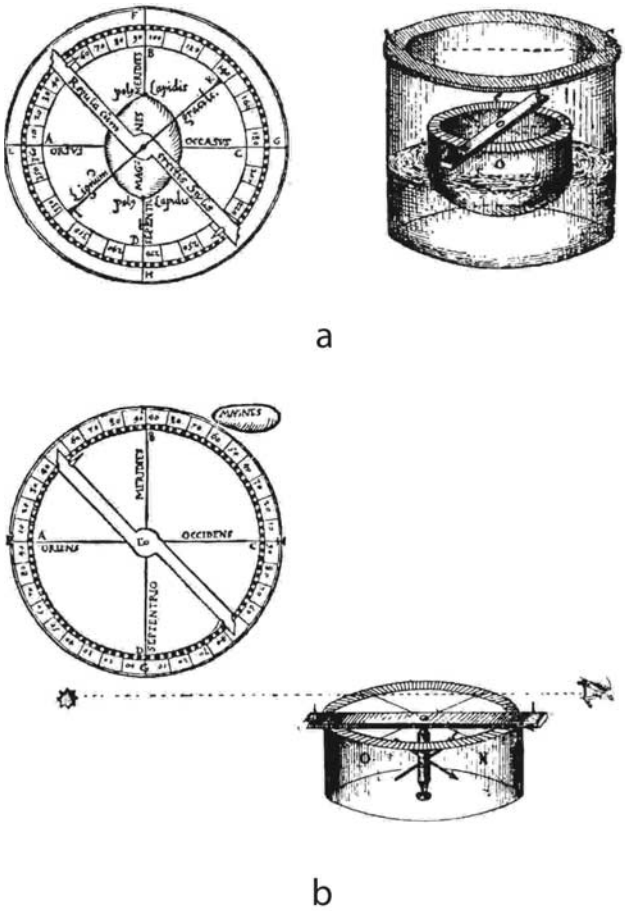

Figure 1. Models of the two compasses discussed by Petrus Peregrinus (1269): (a) the "wet" or floating compass and (b) the "dry" pivoted compass. From *Smith* [1970]. Copyright Elsevier 1970.

poles) and, finally, (4) "similitudo" (what you find after reuniting broken segments is identical to the original).

[15] In the second part of his letter, Peregrinus proposes plans to build two floating compasses ("instruments which depend on the understanding of the natural functioning of the magnet" [*Radelet de Grave and Speiser*, 1975, p. 221]), with advice as how to use them to orient oneself when there is wind, at night, under a transparent lid, using either a lodestone or a magnetized iron needle (Figure 1). In the latter case, declination is not corrected for, whereas it happens to be in the former (at least at the time and site of building of the instrument) as shown by Figure 1. However, Peregrinus was not aware of the concept of declination or of the fact that the Earth itself behaved as a magnet. In his last chapter, Peregrinus proposed to build an instrument that could produce perpetual motion, in which he appears to have had understanding of the notion of momentum ("impetus"), though he did not have the tools to understand that such motion was physically impossible. It is clear that Peregrinus must have borrowed from other scholars who had studied the loadstone, and his text demonstrates that there was prior knowledge of a number of properties of the magnet, but there is no known remaining document prior to his that states the problem in writing. The *Epistola de Magnete* may be one of the first documented pieces of empirical work in geomagnetism (and beyond that in physics), empirical work that has remained at the heart of the discipline. Some 30 versions of manuscript copies of the *Epistola* were made in the following centuries. The first printed edition, which was prepared by a physician of Lindau, Achilles Gasser, appeared in Augsburg in 1558 (see www.iee.org/TheIEE/Research/Archives/Histories&-Biographies/Peregrinus.cfm). However, the work seems to have attracted less attention than it deserved until William Gilbert mentioned it in his *De Magnete*.

2.3. From the Thirteenth to the Sixteenth Century

[16] The compass was soon in rather common use in western Europe, and declination (then called "variatio") was discovered. Johannes Müller, known as Regiomontanus, encouraged manufacture of portable sundials provided with a magnetic needle in Nuremberg after 1471. From the time of Regiomontanus's master Georg von Peuerbach (who died in 1461) to the early seventeenth century, Nuremberg was to be the largest production center of Kompasse [*Jonkers*, 2000]. That declination (D) had been discovered (though its actual discoverer is unknown) is attested to by double marks (one for true north, the other a few degrees away) on compasses built at least as early as 1451. The discovery probably dates from the earlier years of the fifteenth century, though most writers on magnetism and dials failed to mention declination explicitly until about the end of the sixteenth century [e.g., *Chapman and Bartels*, 1940]. Marks on compasses from the same time used by mariners also show a dual marking that depends on the ship's port of origin. A letter written by Georg Hartmann (1489–1564) of Nuremberg in 1544 shows that he had observed a declination of 6°E at Rome in 1510, when he knew that the value in Nuremberg was 10°E. *Körber* [1965] mentions two instrument makers working in France in the first half of the sixteenth century: Coignon, who recorded a value of 10°E in Dieppe in 1534, and Kunstler Bellarmatus, who recorded a value of 6°30′E in Paris in 1541. Joao de Castro sailed from Portugal to the East Indies in 1538 carrying a carefully improved instrument, with the mission to thoroughly test it: The instrument was a "brujula de variacion" developed by Felipe Guillen a decade earlier in Seville. Joao de Castro undertook many observations and can in a way be considered as one of the discoverers of crustal magnetism: He discovered spatial variations of *D* in the Bay of Bombay, which he attributed to the disturbing effects of underwater rock masses (this is near where the large basaltic and rather strongly magnetized Deccan traps outcrop). In the 1890s, G. Hellman, quoted by *Chapman and Bartels* [1940], considered Castro to be the most important representative of scientific maritime investigations of the time, and the method he tested was universally introduced on ships and was used until the end of the sixteenth century (for more on seafaring and the Earth's magnetic field see the comprehensive volumes of *Jonkers* [2000]).

[17] Inclination (*I*) (then called "dip" or "declinatio," which is of course a bit confusing and should not be mistaken for declination) was discovered (through the slant

of a balanced needle after it had been magnetized) in 1544 by G. Hartman, who found a very small value (9° rather than the expected 70°). Dip was then rediscovered and measured more accurately by Robert Norman (second half of the sixteenth century) in London in 1576 [*Norman*, 1581]. Having mounted a needle on a cork in such a way that the device was neutrally buoyant, Norman observed that there was no net force applied to it when the needle came to rest dipping because of the geomagnetic field [*Vershuur*, 1993]. He therefore came close to understanding that only a torque was applied to it by the field. The first recorded measurement in Paris had to wait until 1660 [*Alexandrescu et al.*, 1996]. The paucity of dip measurements in the seventeenth century, which played such a role in William Gilbert's work, may be due to the difficulty of obtaining them and their lack of immediate use to navigators. In 1589, Giambattista della Porta (1535–1615) described the lines of force (an anachronic term, but the concept of mapping also inclination was clearly there) of the magnet once again and used iron filings, a technique still used in classrooms, to make them apparent.

[18] The sixteenth century saw a flourish of ideas in which internal versus heavenly sources best represented magnetism on Earth. The poles were placed by most in the heavens. A rising, competing school of thought tried to bring the "seat of magnetic power" back to Earth, residing, for instance, in clusters of magnetic material, in general isolated islands, or mountains built of pure lodestone. These were preferentially located in the Indian Ocean or in the polar regions. Both the heavenly and subterranean (or crustal) hypotheses can actually be traced far back in history. Some sixteenth century authors also tried to reconcile both views by connecting polar mountains in some way to the pole star. Recognition of a tilted dipole is also at the basis of the idea of using changes in magnetic declination at the global scale to attempt to infer longitude. *Poirier* [2002] gives a brief account of the early ideas from Joao de Lisboa (dating from 1508 and printed in 1514 [*Jonkers*, 2000]) and della Porta (more on this in section 2.5).

[19] *Jonkers* [2000] notes that the crustal model is more easily adaptable than the celestial one to new observations and that this may have been the reason why it became preponderant in the later part of the sixteenth century. Indeed, throughout the late fifteenth and the entire sixteenth century, sailors used the compass and reported increasing numbers of observations of irregularities, leading some to believe that the magnetic effect ("field," now consisting of declination and inclination) was actually of terrestrial origin. Two variants of this terrestrial view soon came into conflict: William Gilbert (1544–1603) was to defend one; Guillaume le Nautonier (1557–1620) would defend the other, which would cost him fame in the following centuries. In the former view, local irregularities were attributed to local sources (based on observations of the effects of irregularities in Gilbert's terella) altering the global field, implying a form of truly crustal magnetization (in a modern geophysical sense); the latter denied such local influences and proposed that D anomalies were actually of a global scale (global field only, without local anomalies) and could be used in the quest for longitudes (soon leading some to sources in a "core").

2.4. William Gilbert's "*De Magnete*" (1600)

[20] William Gilbert's book is often regarded as one of the first "modern" treatises in physics. It actually follows Peregrinus' letter closer than has often been realized but provides much more material, with clear experiments and descriptions. *Stern* [2002] has given the most recent summary of Gilbert's works, from which the following is largely excerpted. A medical doctor to the Queen and the president of the Royal College of Physicians, Gilbert undertook his attempt to find and summarize all known at his time on magnetism (that is in 1581, the year Norman confirmed the existence of dip). Gilbert confirmed the main properties of permanent magnetism: the broken magnet experiment, induction of magnetization into iron by a lodestone, and loss and acquisition of magnetization by iron upon successive heating and cooling. He also studied electrostatic attraction and its differences from magnetic attraction. His main claim to fame is the idea that the compass needle pointed north because the Earth itself attracted it as a giant magnet would. He observed both the north seeking property of small magnetized needles suspended above his terella (the equivalent of Peregrinus's magnes rotundus) and the change in dip angle as a function of position with respect to the terella's poles.

[21] Gilbert apparently gave a single diagram of this simple yet essential property, which we know for instance to be one of the fundamental bases of the application of paleomagnetism to paleogeographic reconstructions. Actually, as early as the late 1590s, Henry Briggs, a professor of geometry at Gresham College in London, published a table of inclination as a function of latitude portraying rather closely the equation $\tan(I) = 2\tan(\lambda)$, which is now immediately derived from the potential of an axial dipole (I being inclination and λ latitude). Mark Ridley, a student of Gilbert, produced an alternate scheme [*Ridley*, 1613] and suggested that latitude dependence of inclination implied that the dipole should be located in the deeper regions toward the Earth's nucleus rather than in the crust [*Jonkers*, 2000], an early suggestion of the existence of a core as the seat of geomagnetism (see Figure 2 which is discussed further in section 2.5).

[22] *Jonkers* [2000] notes that in his sixth book on revolution, Gilbert proposes that the cosmical exchange of magnetic forces is responsible for the ordering of the heavens in a heliocentric system. Some of these ideas appeared to challenge the view that the Earth was the immovable center of the universe [*Stern*, 2002] and led to accusations of heresy (Galileo Galilei had a copy of the book). *Vershuur* [1993, p. 31] notes:

> For at least half a century following the publication of *De Magnete*, Gilbert's insights were at the heart of what came to be called the magnetical philosophy, which allowed a wide range of phenomena to be erroneously accounted for in terms of magnetism. For example, proselitizers of both the geocentric and the heliocentric views of the heavens were to draw upon it for inspiration.

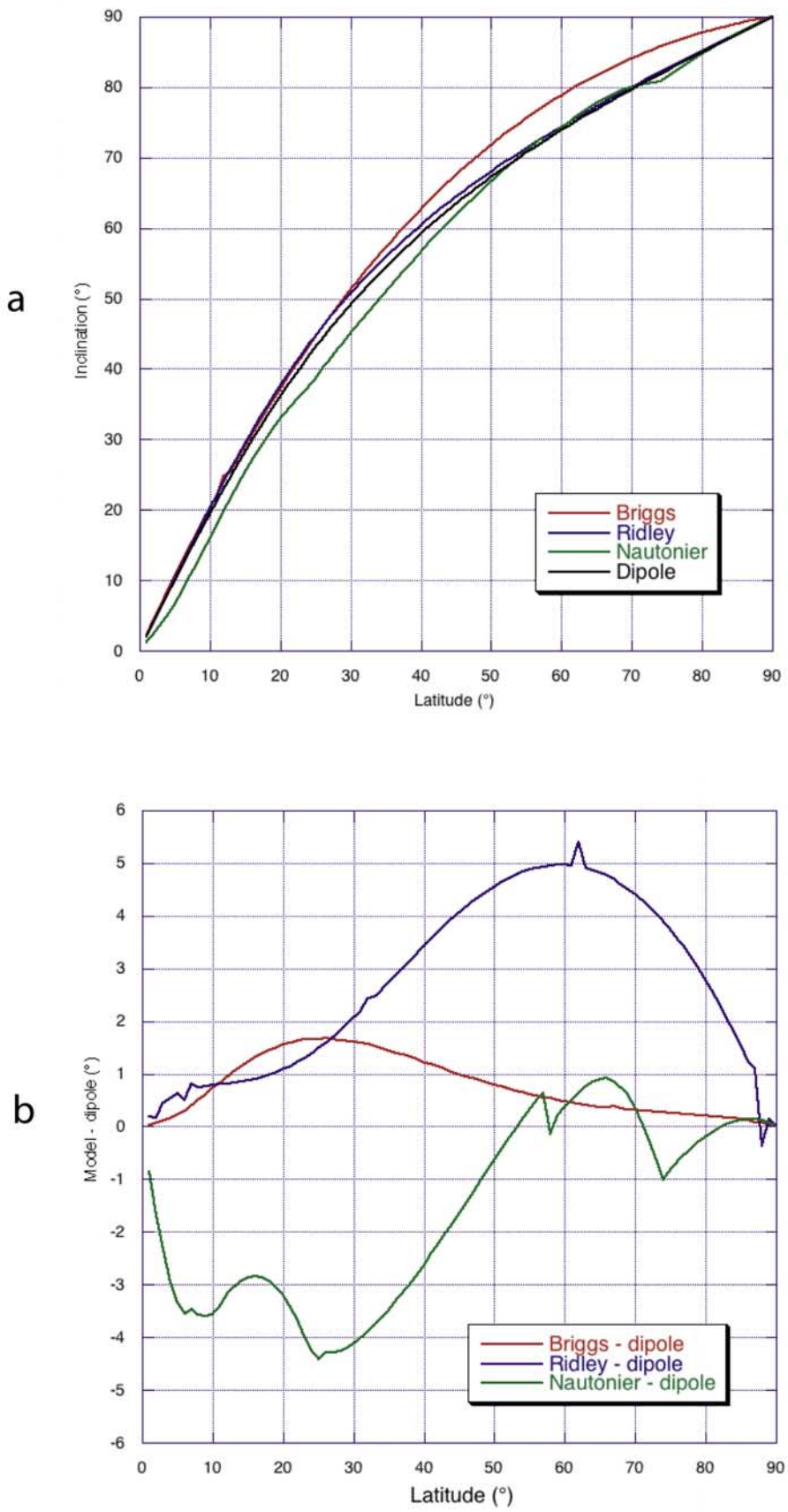
a
Inclination (°)
Latitude (°)
Briggs
Ridley
Nautonier
Dipole
b
Model - dipole (°)
Latitude (°)
Briggs - dipole
Ridley - dipole
Nautonier - dipole

Figure 2

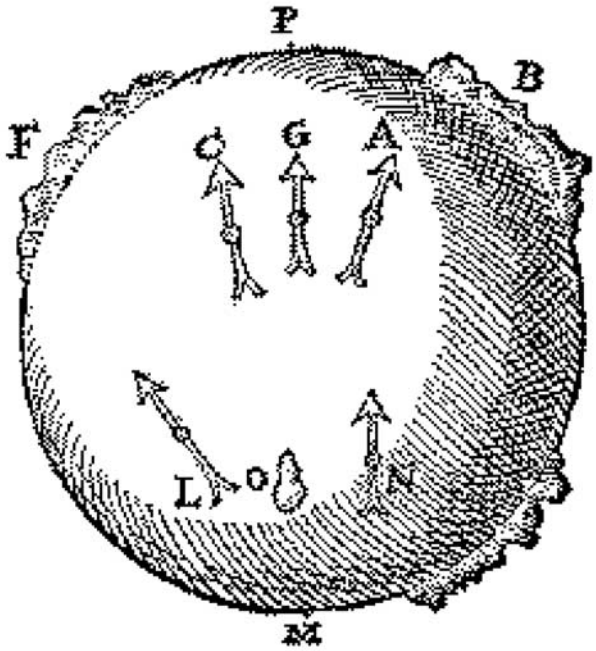

Figure 3. *Gilbert*'s [1600] terella with local "mountains" (crustal anomalies) and anomalies in magnetic declination due to these.

Gilbert himself, for instance, believed that the daily rotation of the Earth was due to its magnetism. His speculations on this question were at least as obscure as those of Peregrinus on the fact that the rotation of his terella was commanded by the Heavens. William Barlowe, who was contemporaneous with Gilbert, showed rather easily that the generation of rotation by the "magnetic properties of the Earth was a pure chimere" [*Barlowe*, 1618]. Gilbert ridiculed attempts to generate perpetual motion (as had been the case for Peregrinus, to whom we have seen how much Gilbert actually owed): "Oh that the gods would at length bring to a miserable end such fictitious, crazy, deformed labors, with which the minds of the studious are blinded!" Gilbert had to deal with declination and the fact that magnetic and geographic north often do not coincide. Since he attributed magnetic attraction to the mass of the Earth, he defended the idea that local bumps in the globe (he had "mountains" and "ocean basins" carved on his terellas), i.e., crustal anomalies in modern terms, could be responsible for departures of observations from a purely dipolar field aligned with the rotation axis (Figure 3). As a consequence of immobility of geographical outlines, Gilbert predicted that the magnetic field (declination) would never change in time.

2.5. Guillaume le Nautonier's *"Mecometrie de l'eymant"* (1601)

[23] Only a couple of years after the publication of Gilbert's book, le Nautonier published his own accounts. le Nautonier's role has recently been recognized by *Mandea and Mayaud* [2004]. le Nautonier was born in 1557 in Aquitaine and, being surrounded by books and instruments, developed an early interest in "that little piece of iron which seems to live and have judgment" [*Mandea and Mayaud*, 2004, p. 165]. A doctor in theology from Lausanne, he traveled through Europe and became an excellent mathematician and geographer. In his *Mecometrie de l'eymant* (literally "Measurement of longitude with a magnet") he shows his profound knowledge of Latin, Greek, and Hebrew and his talent as historian, geographer, astronomer, mathematician, navigator, observer, and instrument inventor. He quotes accurately an impressive number of previous authors (235), the most recent names (to him) being those of Gerard Mercator, Robert Norman, and Giambattista della Porta. The last section of his book consists of 196 pages of tables giving the value of declination and inclination as a function of latitude and longitude in the two hemispheres, showing that his main incentive came from an attempt to help mariners. le Nautonier's work covers the last decade of the sixteenth century, and sentences where he quotes Gilbert were most likely added at the last minute (the King's privilege for printing is dated 15 October 1601, and the published reference is dated 1603). le Nautonier's central theme of research was "the property of the magnetic needle for showing the direction one must travel in the middle of the ocean or on land" [*Mandea*, 2000, p. 75]. le Nautonier emphasizes the importance of the observations showing that declination varied (more or less smoothly) with location on the globe. Following Mercator, who had estimated that the magnetic north pole actually lay near 75°N, 73°E, he concludes that the power of orientation displayed by the magnet comes from the Earth, and his experiments on a spherical piece of lodestone lead him to suggest that the Earth itself is magnetized like such a lodestone. In his additions he refers to Gilbert and explains that his discovery was made independently, well before Gilbert's book had been provided to him. *Mandea and Mayaud* [2004, p. 167] quote the following:

> One should not omit William Gilbert, English philosopher and doctor, who in almost six books maintained that the Earth was a large magnet, and his works having been brought to me as I was writing this, since I was confirmed in the reasons which I knew and had defended, I did not want to omit the others he brings on the subject, whether I had already argued in their favor or not, neither deprive him from the recognition which belongs to him for having worked to clarify his point. . ..

Figure 2. (a) "Predicted inclination" as a function of geographical latitude as given by Edward Wright in 1599 following Henry Briggs, by Guillaume le Nautonier in 1603, and by Mark Ridley in 1613 (data table and references given by *Jonkers* [2000, pp. 729, 734]) and for a geocentric axial dipole. (b) Differences between each one of the three previous sets of values and the inclination for a geocentric axial dipole.

Figure 4. First appearance of the geomagnetic equator (marked EQUATOR MAGNETIS) in the work of *le Nautonier* [1603] (slightly deformed because of picture acquisition [see *Mandea and Mayaud*, 2004]).

Mandea and Mayaud [2004] note that le Nautonier was convinced by friends to translate his original Latin text into French for better understanding by mariners, which considerably reduced the diffusion of his work (Gilbert's was in Latin).

[24] le Nautonier introduces the dipole through a remarkable geometrical technique, noting from observations available to him that declination was close to zero on the Canary Islands meridian, mainly negative to the west of it and positive to the east. He has measures in Novaya Zemlya with very large D variations (which Gilbert was aware of but refused a priori to consider) and boldly proposes that all measures can be explained by an offset grid of magnetic meridians and parallels (Figure 4), in which the zero magnetic meridian is at the Canary Islands geographic meridian and the dipole (magnetic axis) is tilted by 22.5° (*Mandea and Mayaud* [2004] explain how this figure was arrived at from a set of four widely separated observations and delicate geometrical constructions on a sphere). He shows that the south magnetic pole is on the 0° meridian, whereas the north magnetic pole is on the 180° meridian, and constructs the magnetic equator as a sinusoid, and even more remarkably the loci of maxima of D (the 90° magnetic meridians, whose shapes in any projection are quickly recalculated with a computer but which must have required astute graphical constructions from le Nautonier); from this le Nautonier derives his tabled values. Although le Nautonier's pole was off by a large amount (mainly because of lack of observations in northern Canada, the Pacific, and the Arctic), his model (which can rightfully be called so) accounted reasonably well for a large number of observations and was conceptually superior (seen from a modern perspective) to Gilbert's, in which the magnetic and rotational axes had to coincide (because seeing only an irregular pattern of declination, he saw no reason to conclude otherwise). Using this model, le Nautonier could therefore derive magnetic variation D and inclination I at any place on the globe, using spherical constructions: The theory he put forward was mathematically complete, and his geometrical analysis correct. Any navigator could, in principle (though not in practice), find longitude by looking in his tables, based on a measurement of latitude (e.g., through an observation of Polaris) and one of magnetic declination (e.g., by taking bearings on a rising astronomical body).

[25] Anthony Linton referred to le Nautonier's work in England in 1609, but thereafter it was contested, for instance, in 1610 by Edward Wright. It was also violently criticized in 1611 in France by Didier Dounot. *Jonkers* [2000, p. 318] closes a brief account of le Nautonier's work by quoting *Dounot*'s [1611] criticism, concluding that "unfounded assumptions, errors in calculation and data manipulation" demonstrate "impudence, ignorance and chicanerie" on the part of the author. However, *Poirier* [2002], quoting from the original text of le Nautonier's contribution and Dounot's harsh criticism, shows that the latter was simply wrong in his reasoning.

[26] *Ridley* [1613] pointed out that le Nautonier and Linton had each "set forth different magneticall poles" and so instead of discovering a method to find the longitudes of places they had instead obtained a method to find the "longitude of unprofitable labors" [*Mandea*, 2000, p. 77]. In 1639, Henry Bond revived le Nautonier's idea of a tilted dipolar field and supported it with evidence from London. However, le Nautonier's views were again rejected, based on a refusal to accept systematic deviations of *D* on a global scale, by Georges Fournier in 1643 and Jacques Grandami in 1645, and they fell into neglect. Edmond Halley noted in 1701 [see *Jonkers*, 2000] that a measurement of declination in the South Atlantic could provide a crude estimate of longitude (because isogons run roughly north-south) but not in the North Atlantic. It may in some instances be sufficient to model the Earth's present magnetic field using a dipole tilted 10.5° to the rotation axis, with its Northern Hemisphere pole at 71.5°W longitude.

[27] It is interesting that whereas Gilbert dealt extensively with many aspects of general magnetism, le Nautonier focused entirely on geomagnetism. He should be remembered for his introduction of an equivalent of Carl Friedrich Gauss' inclined dipole, which rightly rejects Gilbert's insistence that the magnetic and rotation axes should coincide (of course this is the "instantaneous case" and not the long-term paleomagnetic mean, for which this coincidence indeed occurs; it is an astute starting point but with magnetic poles misplaced), and for publishing the first map with a clearly marked magnetic equator, distinct from the geographical one. We now know, of course, that le Nautonier's concept of an inclined dipole was right to first order but that space and time variations of declination due to higher-order core and crustal sources, added to instrumental problems onboard a ship, rendered his method of determining longitude from declination practically inapplicable.

[28] *Jonkers* [2000, volume 2, pp. 729–736] has tabled the values of inclination as a function of latitude provided by Edward Wright (following Henry Briggs from 1599), *le Nautonier* [1603], Ridley (in two different versions, one from 1613 and the other from 1635, the latter being a simple reproduction of Wright's), and Athanasius Kircher (in 1641) (see *Jonkers* [2000, p. 317] for references). These are shown (but for Kirscher's data) as a graph in Figure 2a. The first curve ever published, that of Briggs, is quite smooth and fits what we now know to be the dipole formula quite well at low latitudes (up to 30°). The second by le Nautonier fits at high latitudes (above 50°) and is more irregular. The third by Ridley is both remarkably smooth and fits the dipole formula everywhere to better than 2°. Differences are better seen in Figure 2b and reveal to some extent the methods used by respective authors. The curves of Briggs and Ridley seem to imply a regular mathematical or geometrical construction, whereas the discontinuities in le Nautonier's curve reveal a piecewise attempt to fit observations more locally. Of course (in least squares terms) the fit of the axial "Gilbertian" field to the actual Earth's field is worse than that of a tilted dipole, but le Nautonier's tilt (poles) was not very close to the actual tilt (poles). Strangely, Kircher's later table leads to more irregular and worse fits than the three previous attempts.

2.6. State of Things in the Middle to Late Seventeenth Century (Gellibrand, Descartes, Boyle, and Halley)

[29] The next key discovery was that of magnetic secular variation. Early developments have been reconstructed by *Jonkers* [2000]. A careful set of observations in Limehouse (London) had allowed William Borough to establish a value of 11 1/4°E for declination in 1580. Early in 1622, Edmund Gunter, professor of astronomy at Gresham College, found smaller values at another location and returned to Borough's original site to find a declination of 5°56′E. Because the early values of Borough might have suffered from major uncertainties that he could not evaluate, Gunter refrained from concluding on the observed change. John Marr, an instrument maker who had collaborated with Gunter on his earlier measurements, made his own new observations confirming significant change, which led Henri Gellibrand (1597–1636), a successor of Gunter, to repeat observations where Gunter had actually performed his first 1622 observations: *Gellibrand* [1635] found an average of 4°05′E. In his "*Discourse mathematical on the variation of the magnetic needle*," he concluded in 1635: "Hence therefore we may conclude that for the space of 54 yeares (. . .) there hath been a sensible diminution of 7 degrees and better." This was the first clear account of the fact that the magnetic effect of the Earth could change in the course of decades, with important consequences for navigation and orientation and raising intriguing new scientific questions. It falsified one of Gilbert's predictions. One of Gellibrand's statements (quoted by *Chapman and Bartels* [1940, p. 911]) could be taken as the first request to establish a magnetic observatory:

> If any affected with magneticall Philosophy shall yet desire to see an experiment made for their owne particular satisfaction, where I may prevaile, I would advise them to pitch a faire stone parallel to the Horizon there to rest immoveable, and having a Needle of a convenient length strongly touch't by a vigorous Magnet to draw a Magneticall Meridian thereby, and yearely to examine by the application of the same (well preserved from the ayre and rust, its greatest enemies) whether time will produce the like alteration.

The discovery of secular variation first led some to worry that magnetic observations were now rendered useless, but it soon produced the opposite reaction that new energy should be put into magnetic data collection in order to identify the nature and source of the changes and better understand the underlying phenomena.

[30] The seventeenth century was marked by fast growing numbers of measurements of magnetic directional elements. The Royal Society in London and the Académie des Sciences in Paris supported the building of astronomical observatories, focused on the problem of determining longitude at sea, and in some cases fostered magnetic research. In 1667, members of the Académie des Sciences measured declination on the site of the proposed Paris Observatory, which was completed in 1670: Regular measurements were

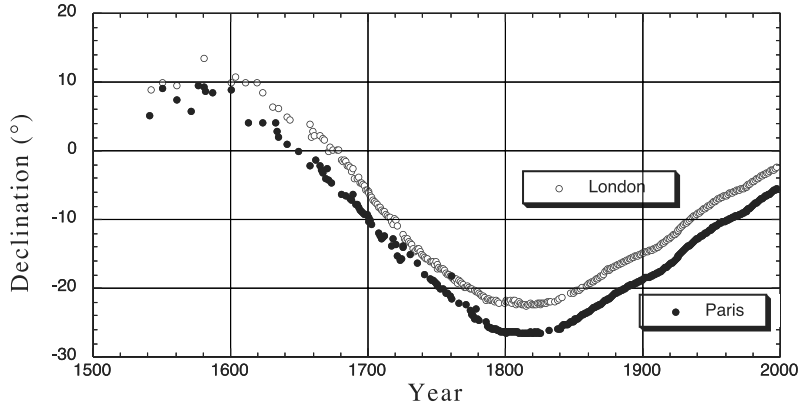

Figure 5. Reconstructed series of direct measurements of declination in Paris and London from the mid sixteenth century to the present [see *Alexandrescu et al.*, 1996, 1997].

initiated by Abbé Jean Picard (1620–1682) in the southwestern corner of the observatory gardens. Historical series of *D* and *I* measurements dating back to the sixteenth and seventeenth centuries have been gathered by *Malin and Bullard* [1981] for London and *Alexandrescu et al.* [1996] for Paris, and a comparison of both (Figure 5) was published by *Alexandrescu et al.* [1997], illustrating the value of historical measurements to modern science (and hopefully encouraging further research of dormant, as yet unknown geomagnetic data). Historical accounts of measuring technique and instruments can be found in these articles and in references therein.

[31] René Descartes (1586–1650), a key natural philosopher of the mid seventeenth century, attempted to explain natural phenomena based on a mechanistic theory of ever present rotating vortices ("tourbillons"). Magnetism was thought to be due to microscopic screw-like vortices flowing in opposite directions through tubes that permeated matter, thus forming closed loops. By contrast, Pierre Gassendi (1592–1655) favored an atomistic view, but as far as magnetism is concerned, the accounts were not that different. It may be interesting to spend some time to show how these ideas were compiled and taught to the interested public in the second half of the seventeenth century by one of Descartes' disciples.

[32] Jacques Rohault (1620–1675) decided to diffuse Descartes' mechanical views and philosophy through very successful weekly conferences in Paris, which he eventually published as a book (*Traité de Physique* in 1671) (we have used the 1682 printing [*Rohault*, 1682]). His method relies on illustration through experiments (he was a keen experimentalist and essentially redid and sometimes improved experiments which he taught). We are concerned here with his chapter on magnets, in which the experiments he describes are not new but are remarkably well conceived and executed. He gives a "proof of the tourbillons" by dropping iron filings on a piece of cardboard in which a magnet has been inserted and gives a lovely illustration of field lines (Figure 6). He illustrates many examples of more complex magnets and field lines, gives the way to determine poles using them, and explains the broken magnet experiment: He actually saws a piece of magnetite and shows that the parts "require" to be placed with opposite poles alongside each other and shows how field lines are strongly modified, thus demonstrating what we would today call the minimization of the external, demagnetizing field. He gives a good quantitative estimate of the secular variation of declination in Paris between 1570 and 1670, based on his own determinations. He carefully discusses how lodestone can magnetize iron without touching it, he heats then cools in a vertical position a piece of steel and notes that it acquires a permanent magnetization in the Earth's field (a thermal remanent magnetization or TRM in modern terms), and he notes that all magnetization is lost when the magnet is held long enough over a fire.

[33] Because we will not use the term lodestone any longer in this paper, as it has become obsolete, it may be worth mentioning, as is done by *Stern* [2002], that the magnetiza-

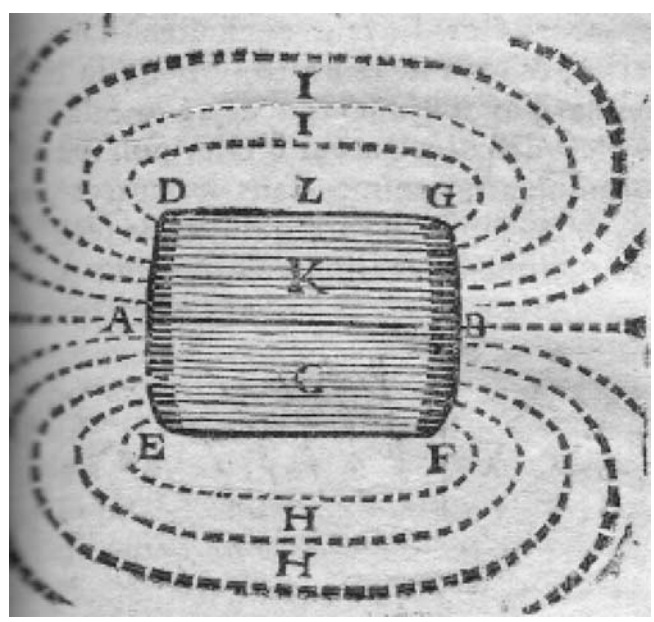

Figure 6. Early illustration of field lines from a piece of lodestone (magnetite) drawn by *Rohault* [1682, volume II, p. 141].

tion of naturally occurring magnetite ore still raises puzzling questions. *Wasilewski and Kletetschka* [1999] suggest that electric currents produced by lightning are needed to account for the intense magnetization of lodestone.

[34] Robert Boyle (1627–1691), one of the founders of the Royal Society of London (1662), was a proponent of atomistic views and showed, in close association with Robert Hooke (1635–1703), that magnetic action still persisted in a vacuum. He performed heating and shock experiments on magnetic material and concluded that variations in magnetic properties mainly arose from alteration of the iron's texture under mechanical action. In 1691, Boyle noted that a brick could also acquire a stable remanent magnetization (modern terms) upon cooling from high temperatures, but an experimental verification would have to wait almost 2 centuries for Giuseppe Folgheraiter. However, we see that in the last decades of the seventeenth century, what we now call the thermal remanent magnetization of metals and some iron oxides in man-made artifacts had been observed and in a way recognized, along with what would later be called the Curie temperature of demagnetization, above which permanent magnetization is lost. Boyle's work led to the creation by the Society of a Magnetics Committee (active 1650s to 1680s), which ended up rejecting Gilbert's philosophy and making magnetism lose its status as a separate discipline of enquiry: *Jonkers* [2000] believes that the resulting confusion may be the reason why Isaac Newton failed to apply to magnetism the rigor he applied to gravity and therefore left it to Charles-Augustin Coulomb to establish quantitatively the law of magnetic attraction in 1785.

[35] Several "magnetic schemes" and theories flourished in the second half of the seventeenth century. How the successive notions of a precessing dipole and moving multipoles were introduced has been told in detail by *Jonkers* [2000]. In 1639, Henry Bond correctly predicted that declination would become zero in 1657. Pursuing the goal of determining longitudes at sea, as had been done by many since (and before) le Nautonier, Bond proposed that this secular variation was due to precession of the dipole with a period of 600 years at a colatitude of 8°30′. In 1680, Peter Perkins, a professor of mathematics at Christchurch in Guilford, concluded from a collection of observations that there were four rather than two meridians with zero declination on the globe, i.e., a four-pole system. Perkins died that same year, and Edmond Halley (1656–1742) was the next to make similar (though much more elaborate and articulate) proposals in 1683 and 1692. In 1683, on the basis of no more than 50 values available at the time, he proposed a system of four poles with unequal strengths, with colatitudes between 7° and 20°, all undergoing westward motion. Astronomer John Flamsteed, a friend of Perkins, suspected that Halley had plagiarized Perkins's scheme. In any case, Halley proposed a second theory in 1692: The interior of the Earth consisted of two concentric magnetic shells, an outer solid shell fixed with respect to the crust, i.e., the surface of the Earth, and a deeper solid nucleus or core separated from the crust by a fluid and rotating at a different velocity, the period being on the order of 700 years. Each sphere carried a dipole, hence there were four magnetic poles, but neither pair was antipodal. Halley anticipated that more data might imply more layers and dipoles. Intensive data collection and synthesis and the making of magnetic charts based on these data mark the beginning of the next century.

2.7. Eighteenth Century (Halley, Wilcke, Graham, Cassini, Buffon, Euler, Coulomb, and de Saussure)

[36] In the eighteenth century, significant progress was made in the fields of electricity and magnetism. Hence, from this period onward, we will only recall those major discoveries or works relevant to some areas of geomagnetism and what would become the foundations of paleomagnetism. Edmund Halley's action as the leader of the first global magnetic survey (1698–1700) on the *Paramore* resulted in famous charts (1701 for the Atlantic and 1702 for the world) of lines of equal values of D (isogons, then known as "Halleyan lines"), which remain classics (Figure 7); these isogons follow in part and vindicate some of le Nautonier's ideas but are far more detailed, being based on larger numbers of measurements. Guillaume Delisle compiled very large amounts of data and criticized the Halley charts in 1710, finding many errors and inconsistencies [*Jonkers*, 2000], but many more charts were published in the following decades which confirmed the importance and value of the concept.

[37] Around 1720, William Whiston (1667–1752) prepared the first inclination chart for southeastern England and the coast of Normandy in the hope that because secular variation of dip was slower they would provide a better way to determine longitude (still the same pursuit). The first world chart of lines of equal values of I (isoclines, which were then called parallels of inclination) was published by Johann Carl Wilcke (1732–1796) in 1768 in Stockholm [*Wilcke*, 1768].

[38] Shorter-term variations, which we now know to be due to external sources, were discovered in the first quarter of the century. In 1722, George Graham (1675–1751) discovered the daily or diurnal variation of declination. In 1716, Halley had had the idea to connect the Earth's magnetic field with the occurrence of an aurora over London, and in 1741, Graham in London and Andreas Celsius in Uppsala observed simultaneous perturbations, indeed due to the polar aurora [see, e.g., *Stern*, 2002]. *Arago* [1854, p. 481] reports that, based on 5 years of daily measurements of declination, from 1783 to 1789, Jean-Dominique Cassini (1747–1845) deduced a seasonal pattern (part of the annual variation).

[39] In 1743, Daniel Bernoulli (1700–1782) won a prize from the Paris Academy of Sciences for the best way to build an instrument to measure inclination; the modern uses of "declination" and "inclination" were apparently introduced by him at that time. Leonhard Euler (1707–1783) measured inclination at Berlin using that design 2 years later. In 1757, Euler showed that a nonantipodal dipole (i.e., a noncentered dipole) could explain part of the declination features observed for a double dipole. This led him to reject

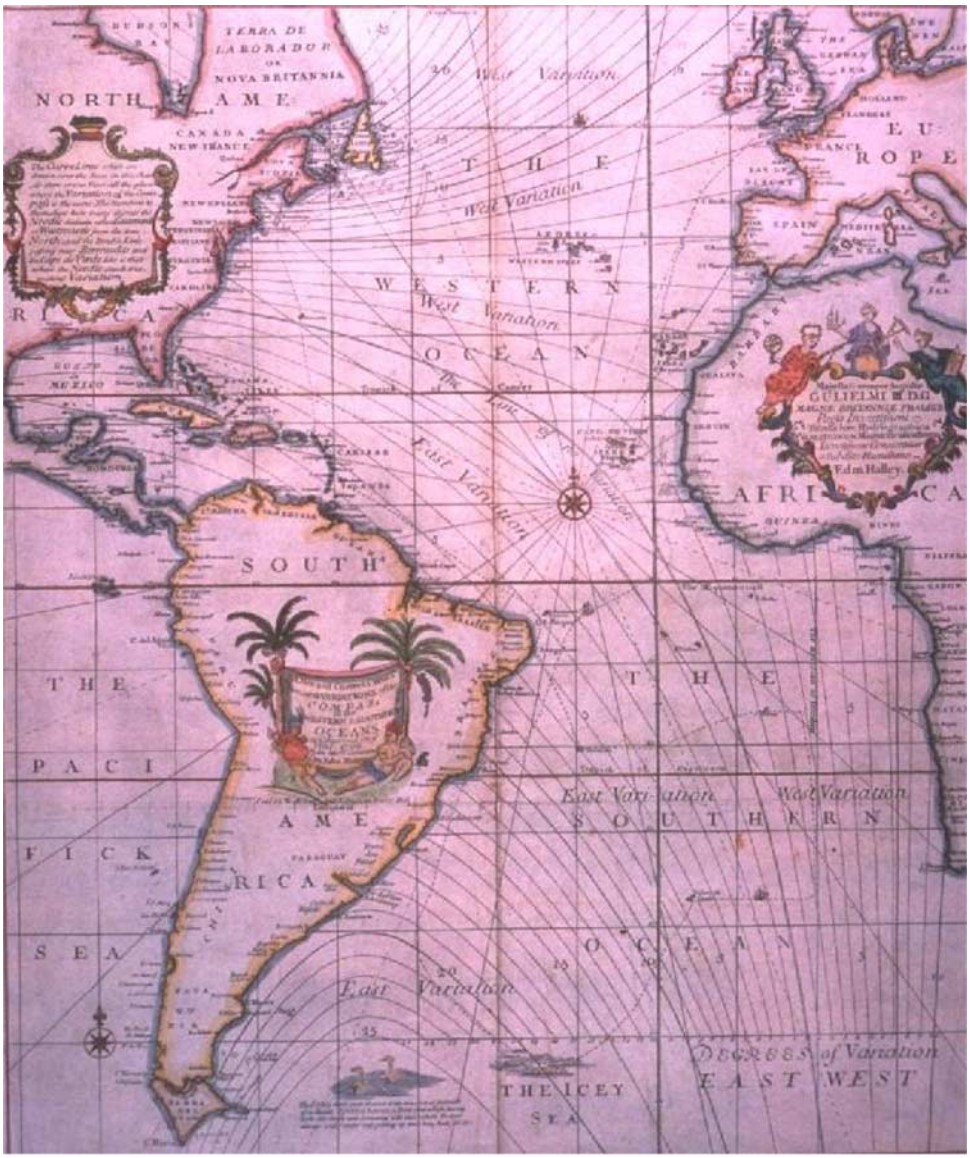

Figure 7. Halley's (1701) original map of magnetic declination over the Atlantic Ocean [see also *Halley*, 1715].

the need for a magnetic source in the deeper core and to revert to the model of a field purely due to crustal magnetization. Already in 1744, Georges Louis Leclerc, comte de Buffon (1707–1788), had advocated a crustal quadrupole, with the location of poles changing because of earthquakes, eruptions, and mining of iron ore (for details see *Jonkers* [2000]; note that Buffon's quadrupole involved four surface poles and did not carry with it the present-day mathematical notion of a multipole located at the center of the sphere).

[40] In 1773 the Academy of Sciences offered a prize to whoever would design a magnetic needle that would show the true magnetic meridian and the tiny diurnal variation. The prize was won in 1777 by Charles-Augustin Coulomb (1736–1806) with his remarkable torsion balance (see principle and references given by, e.g., *Stern* [2002]). This was a basis for most magnetic instruments for the next 2 centuries. Coulomb showed that the magnetic repulsion between like poles varies as the inverse square of distance. He also showed that electrostatic force varies in the same way. Nineteen years later, Henry Cavendish used a similar torsion balance to measure the much weaker gravitational attraction between small spheres and to determine the constant of universal gravitation.

[41] Around 1780, Horace-Bénédict Necker de Saussure (1740–1799) noted the anomalies which perturb compass readings in some mountains and attributed them to iron deposits. He tried to measure the attractive force using a sort of primitive magnetometer (a "pendule à balle de fer" or pendulum with an iron ball) and noted that "heat is the most general cause of variations of the magnetic force, in that it increases upon cooling and decreases upon a temperature rise" (quoted by *Fournet* [1848, p. 4]). He observed the effect of distance on magnetic force but did not publish his observations. The first studies of field intensity had been made by Jacques Mallet in 1769 [*Jackson*, 2001] and then Jean-Charles de Borda in the Canary Islands in 1776, but neither detected significant changes of intensity with

geographical position. Robert Paul de Lamanon (see section 2.8) would be one of the first to succeed in 1785.

[42] Magnetism of natural materials had been a topic of interest for a long time. Our search for early references is certainly far for complete. However, we note a significant letter by *Beccaria* [1777, p. 382], who notes analogies between the magnetism imparted to bricks by lightning and that of iron-bearing stones. He writes to a Count of Brusasque, who described to him his own observations: "You see, one of your lightning-struck bricks has taken the strength to attract by one of its sides the southern pole of the magnetized needle and the north one by the opposite side" and "As in iron, and in iron-bearing bodies, the hardness of magnetism imparted by lightning seems to be in relation to its resistance in receiving it," where hysteresis is almost already envisioned. Beccaria concludes with a statement which could be seen as rather visionary by present-day geomagnetists and paleomagnetists: "... it might also happen that bricks and stones (...) may one day provide material to build the magnetic theory."

2.8. Turn of the Nineteenth Century: Spatial Variations and Remote Expeditions (de Rossel, de Lamanon, von Humboldt)

[43] At the age of 26, Alexander von Humboldt (1769–1848) (see *Botting*'s [1994, p. 31] biography and also *Malin and Barraclough* [1991] and *Jackson* [2001]; see also *von Humboldt*'s [1855] masterpiece *Kosmos*) conducted intense activities in Bayreuth: "He (...) became interested in terrestrial magnetism after discovering a serpentine rock with a polarity opposite to that of the earth." In 1797, von Humboldt led a magnetic expedition to the Palatinate, where he attributed the many anomalies of the compass to the rocks near the summit. He mapped many "punti distinti" or isolated magnetic points (or poles) near the summit and noted that all magnetic north (south) poles congregated on the southeastern (northwestern) slopes around the summit. He proposed that lightning acting on local rocks was responsible for the pattern. In 1798, in Paris, preparing for a natural history expedition that was to take him to South America, he discussed his research and got advice on equipment and methods from famous scientists from the Academy and Bureau des Longitudes, including Jean-Baptiste Delambre, Pierre Simon Laplace, Joseph Jérôme de Lalande and Borda. In this expedition (1799–1803) with botanist Aimé Bonpland he undertook a wide-ranging program of magnetic measurements, including inclination, and, a novelty at the time, relative intensity measurements using a pendulum apparatus. In 1802 the two scientists located the magnetic equator

> recrossing the Andes near Caramaca"; "Humboldt's measurement of the magnetic intensity of the earth at this spot served as a reference point for all geomagnetic measurements for the next half century. (...) He had (...) 124 magnetic readings taken over 115° of longitude and from latitude 52° North to 12° South which clearly showed that magnetic intensity increased with latitude and later led Gauss to formulate his theory of magnetic fields

[*Botting*, 1994, p. 193]. In 1804, von Humboldt published a first sketch of lines of equal magnetic strength or "isodynamic zones." He averaged his original measurements in five latitudinal zones and found a regular decrease of the total magnetic force from poles to equator: "J'ai regardé la loi du décroissement des forces magnétiques, du pôle à l'équateur, comme le résultat le plus important de mon voyage américain" ("I looked at the law of decrease of magnetic forces, from pole to equator, as the most important result from my American voyage"). He was a name coiner and invented the terms "isodynamics" (lines of equal magnetic intensity), "isoclines" (lines of equal magnetic dip), and "magnetic storm" [*Botting*, 1994, p. 223].

[44] von Humboldt actually had two predecessors who made in situ measurements and recognized the variation of magnetic intensity against a broad range of latitudes: de Lamanon [*Milet-Mureau*, 1797; *Théodoridès*, 1985], who was to be recognized by von Humboldt himself and Elisabeth Paul Edouard de Rossel who was recognized by *Sabine* [1838] [see *Lilley and Day*, 1993, pp. 97 and 102]. Young Robert Paul de Lamanon (1752–1787) was in charge of magnetic observations on board the purposely named ship "*La Boussole*" on the La Pérouse circumnavigation of the globe. Although his three inclination circles were not very accurate, de Lamanon noted:

> J'ai observé pendant 24 heures de suite l'inclinaison de la boussole, pour trouver le moment auquel nous passerions l'équateur magnétique; et j'ai trouvé le vrai zéro d'inclinaison le 8 octobre (1785) à huit heures du matin par 10°46′ environ de latitude sud

("I observed for 24 hours in a row the inclination of the compass, in order to find the moment when we would cross the magnetic equator; and I found the true zero of inclination on October 8 (1785) at 8 in the morning by approximately 10°46′ South latitude"). de Lamanon never returned to France: He was killed at the age of 35 with 11 others in the Samoa Archipelago. von Humboldt (1845–1858) wrote in *Kosmos* (as cited by *Théodoridès* [1985, p. 232]) about de Lamanon's observations, which had failed to be printed in the expedition's book:

> It is stated expressly "that the attractive force of the magnet is less in the tropics than when one moves toward the poles, and that magnetic intensity, deduced from the number of oscillations of the dip needle, changes and increases with latitude."

von Humboldt concludes that if the Academy had authorized early publication of these findings in 1787, "the theory of terrestrial magnetism would not have waited for eighteen years a progress which would come through the discovery of a new class of phenomena" (as cited by *Théodoridès* [1985]).

[45] An expedition of two ships under Bruny d'Entrecasteaux was sent in 1791 to search for the La Pérouse expedition [*Lilley and Day*, 1993]. Elisabeth Paul Edouard de Rossel (1765–1829) reported six magnetic intensity

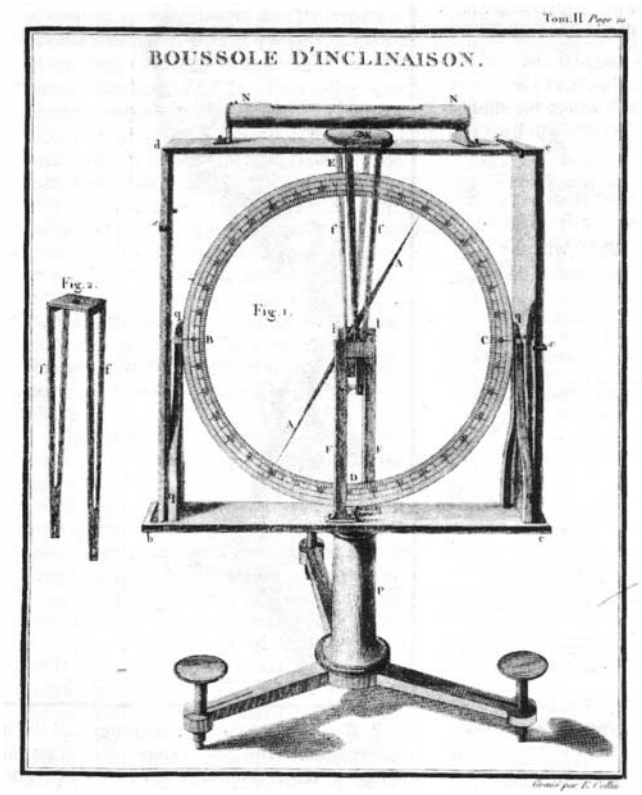

Figure 8. Inclinometer of E. P. E. de Rossel (used 1791–1794) [from *Lilley and Day*, 1993].

measurements performed by timing 100 oscillations of a vertical dip needle (Figure 8) [*de Rossel*, 1808]. These measurements, performed between 1791 and 1794 with consistent instruments and methods, near 48°N, 28°N, 3°S, 7°S, and 43°S, the latter in Van Diemen's Land in Tasmania, allowed de Rossel to conclude

> By comparing the experimental results obtained during the expedition with each other it is evident that the oscillations of the needle were more rapid at Paris and Van Diemen's Land than at Surabaya in the Isle of Java and at Amboyna; and that therefore the magnetic force is greater near the poles than at the equator

(cited by *Lilley and Day* [1993, pp. 97 and 102], see also *Sabine* [1838]). *Lilley and Day* [1993] have replotted de Rossel's data (dip as a function of oscillation period), fitting them very nicely with the formula for a tilted geocentric dipole and deriving the calibration constant for the instrument.

[46] In 1837, Admiral L. I. Duperrey noted that for similar inclination values, intensity was larger on the western than on the eastern coasts of South America. *Duperrey* [1837] attributed this to the fact that magnetic meridians, which tend to be close to great circles in Europe, are more like small circles in South America; he demonstrated it by mathematical methods, showing that "isoinclination" lines (or isoclines) can never be "isointensity" lines (or isodynamics) in their entirety (except on a perfectly dipolar Earth).

2.9. First Half of the Nineteenth Century: From Laboratory Instruments to Magnetic Observatories (von Humboldt, Arago, Hansteen, Gauss, and Sabine)

[47] The first nonmagnetic huts devoted to magnetic observations were built in the late eighteenth century. John Macdonald's 1794 description of his observatory in Sumatra is given by *Chapman and Bartels* [1940]. Macdonald found that the range of daily variation of declination was smaller in the tropics. This was confirmed by Duperrey using a Gambey compass. Declination was measured three times a day at Greenwich from 1818 to 1820, but this was then discontinued until 1841. François Arago (1786–1853) performed a beautiful series of observations at the Paris observatory also using Gambey's instrument from 1820 to 1835, having three successive nonmagnetic huts built from 1823 onward. He had been since 1809 a very close friend of von Humboldt; and this was to become a 44 yearlong "fraternité." Arago was somewhat forgotten afterward, though he had produced the tens of thousands of excellent measurements and observations (150,000 magnetic measurements performed by himself!) from which others inferred more theoretical physical laws (we do not dwell here on his many other contributions to the studies of gases, light, steam engines, meteorology, climate, internal heat and "plutonism," geodesy, and, of course, astronomy, which was his central field of expertise [see, e.g., *Sarda*, 2002]).

[48] Back in Berlin, von Humboldt himself established a "mini" magnetic observatory. For instance, he

> spent every night from May 1806 until June 1807 recording the magnetic declination, (. . .), between midnight and morning. In all, he made 6000 readings and once spent seven sleepless days and nights by his instruments taking a reading every half hour (. . .). In this way, they discovered that the magnetic needle, which had deviated to the east during the day, had deviated still more by midnight but returned to the west by dawn. In December, they had the good fortune to observe the violent fluctuations of the needle during a display of northern lights (aurora borealis) and later found the same effects sometimes occurred when there were no northern lights visible. Humboldt ascribed this effect to what he called a "magnetic storm"- a technical term which has passed into international usage

[*Botting*, 1994, p. 203]. In 1807, von Humboldt performed relative measures of horizontal intensity in Italy with Louis-Joseph Gay-Lussac and was able to draw the first real isodynamical lines. Isodynamic charts for horizontal density (H) and total intensity or force (F) were published some 20 years later (1825–1826) by Christopher Hansteen (1784–1873) from Norway, the units being those introduced by von Humboldt [*Chapman and Bartels*, 1940]. More complete charts were subsequently published by Duperrey in France (1833) and Edward Sabine in the United Kingdom (1837).

[49] von Humboldt should probably be considered as the major driving force behind the establishment of a modern concept of magnetic observatories and the idea to establish a worldwide network of these. His first program involved

eight periods of simultaneous measurements each year, each lasting 44 hours when the needle would be observed at least once per hour [*Chapman and Bartels*, 1940]. In 1828, von Humboldt organized the first major meeting of the German Association of Naturalists and physicians (Versammlung deutscher Naturforscher und Ärzte) in Berlin. von Humboldt was among those who recognized the mathematical genius of Gauss and attracted him to problems in magnetism:

> What the 1828 congress did do for Humboldt as a result of his contact with Gauss was re-stimulate his old interest in magnetic observations. In the autumn he had a special magnetic hut, which contained no metal but copper and was completely draught-proof, erected in the garden of his friend Abraham Mendelssohn-Bartholdy (. . .). Humboldt and a team of assistants peered through a microscope at a black line on an ivory scale illuminated with candlelight. Every hour, night and day, they recorded the fluctuations in the magnetic declination. H. was particularly interested in obtaining simultaneous observations at different places in order to determine whether the variations were terrestrial in origin or depended on the position of the sun. To this end, simultaneous readings were made in Paris and 216 feet down at the bottom of a mine in Freiberg, and later were extended, at Humboldt's instigation, right the way round the world

[*Botting*, 1994, p. 263].

[50] In 1829, von Humboldt undertook a second great voyage through the Urals and Siberia. This expedition gave von Humboldt an occasion to plan [*Botting*, 1994, p. 277]

> for a chain of geomagnetic observation stations stretching right the way round the world. In St. Petersburg in 1829 he had already recommended to the Russian authorities the practical and scientific advantages to be gained from setting up a series of magnetic and meteorological stations all the way across European and Asiatic Russia (. . .) and within six years a number of such stations were in operation all the way from St. Petersburg to Peking and Alaska. (. . .). The USA already had a network of similar stations, and Gauss had arranged another network of observatories, called the Göttingen Association, across Europe from Ireland to Germany. Humboldt realised that to complete the round-the-world circle he needed to persuade the British Government to establish stations in their territories overseas and in April 1836 he wrote a letter to the Duke of Sussex (. . .) in which he proposed that permanent stations should be set up in Canada, St Helena, Cape of Good Hope, Jamaica, Ceylon and Australia.

[51] We note in passing that René Just Haüy introduced the astatic needle in 1817, further developed by Barlow [*Chapman and Bartels*, 1940]. This greatly magnified the sensitivity of the instrument, and the principle would be used at least until the beginnings of paleomagnetism in the 1950s following P. M. S. Blackett and E. Thellier. With Wilhelm Weber (1804–1891) as his assistant, Gauss devised a suspension for observatory magnets [*Stern*, 2002]. He was able to demonstrate changes as minute as a few seconds of arc. In 1832 they decided to use an auxiliary magnet which led to a new way to measure not only the Earth's magnetic field directional components but also intensity in an absolute way for the first time (i.e., with reference to both a weight and a length). This would allow calibrating measurements in all observatories. Gauss considered this to be "of special importance for future centuries, in which we may expect that there will be changes in the absolute intensity, as important as we have long known in the magnetic declination and inclination."

[52] In 1838, von Humboldt wrote to the Royal Geographical Society (as cited by *Botting* [1994]):

> I beg to invite the influential members of your Society to be good enough to propagate Gauss' manner of observing in all new stations where intelligent people can be found. Points near the magnetic equator and those which are in high latitudes in the southern hemisphere. . . would be most desirable if they would observe at the same epochs indicated by M. Gauss.

In 1834, Gauss and Weber began at Göttingen to take part in von Humboldt's scheme. The observing interval was reduced to 5 min. Associated observatories formed the Göttingen Magnetic Union (Magnetische Verein). As early as 1836, Gauss advocated measuring the full vector and not only *D*. The baseline and scale values were introduced in 1837. Until 1841, regular observations outside northern Europe remained quite scarce.

[53] Following von Humboldt's suggestion of 1836, magnetic observatories were established in many British colonies. In May 1831, John Ross (1777–1856), was the first observer able to locate the "north" magnetic pole, near 70°05′N, 96°46′W. The second "visit" took place only 70 years later, in April 1904, when Roald Amundsen (1872–1928) found it near 70°31′N, 96°34′W. Both Ross and Amundsen had been primarily interested in finding the Northwest Passage. Another 50 years elapsed until the third visit by Paul Serson and Jack Clark who located the magnetic pole at 73.9°N, 100.9°W. Five campaigns have taken place since 1947, and the accelerated motion of the pole has been tracked and told by *Newitt et al.* [2002]. A 1839 Ross expedition to the Antarctic located the "south" magnetic pole (we follow common usage, calling "north" and "south" the magnetic poles closer to the north and south geographical poles, respectively, though the reverse terminology should be used, since the north end of the magnetic needle is attracted to the south pole of the Earth's field).

[54] Observatories were established in Canada, the South Atlantic, Tasmania, and India. Edward Sabine oversaw four of the new observatories. He made sure the full magnetic vector was measured and carefully separated "permanent" and "not permanent," zero-mean, or "irreversibly varying" (e.g., drifting secular variation) components. From these observations, Sabine concluded that magnetic disturbances vary in intensity in parallel with sunspot variations [*Chapman and Bartels*, 1940]. He established the duties of personnel in a magnetic observatory in terms that are far from obsolete today. As another example, *Coupvent des Bois* [1850] reported intensity measurements performed between 1838 and 1840 at 42 stations around the world, many in the Pacific and Indian oceans, on board the *Astrolabe* and *Zélée*. John Lamont (1805–1879) was another key figure of the Göttingen Magnetic Union. He introduced a remarkable nonmagnetic field instrument (the

"Reisetheodolit") in 1842 and undertook an impressive program of regional magnetic surveys of the full magnetic vector for Bavaria and southern Germany, central Europe, France and Spain, and Belgium, Holland, Denmark, and Prussia between 1854 and 1859 [*Soffel*, 2006].

[55] A major synthesis of magnetic measurements retrieved from archives covering the last 4 centuries has been initiated by David Gubbins and his group (A. Jackson, J. Bloxham, and A. R. T. Jonkers), and most historical models of the field going back to the 1600s are based on this enormous work [*Bloxham and Gubbins*, 1989; *Bloxham and Jackson*, 1992; see also *Barraclough*, 2000]. Photographic recording, introduced at Greenwich in 1847, was a major advance in making recordings more complete and easier to store and analyze.

2.10. First Half of the Nineteenth Century: Theories and Models (Arago, Hansteen, Oerstedt, Ampère, Poisson, Gauss, and Faraday)

[56] In 1820, Arago showed that an electric current could be used to magnetize iron, immediately following Hans Christian Oerstedt's discoveries of which he saw a demonstration organized by Auguste de la Rive in Geneva. Two years later he discovered "rotational magnetism," showing that a rotating conducting plate deviated a magnetized needle placed above it (for this he was awarded the 1825 Copley medal of the Royal Society).

[57] Hansteen should be remembered by solid Earth geophysicists for his statement:

> The mathematicians of Europe since the times of Kepler and Newton have all turned their eyes to the heavens, to follow the planets in their finest motions and mutual perturbations: it is now to be wished that for a time they would turn their gaze downward toward the earth's center, where also there are marvels to be seen; the earth speaks of its internal movements through the silent voice of the magnetic needle.

[58] At this point it may be useful to recall the names of two great physicists whose contributions to understanding of magnetism at that time were very prominent. In the spring of 1820, Hans Christian Oerstedt (1777–1851) lectured on electricity and magnetism at his home in Copenhagen. Possibly accidentally [*Stern*, 2002], Oerstedt observed that a magnetic needle moved whenever current flowed in a nearby wire. Shortly after the report reached Paris, André-Marie Ampère (1777–1836) understood the reason for the observations, which he confirmed and extended, opening the way to a new view of (electro) magnetism. Ampère showed that an electric current flowing in a wire loop acted like a short magnet and that current flowing in parallel wires led to attraction (repulsion) of the wires if the current directions were the same (opposite). Magnetism of iron could be due to microscopic loop currents at the atomic scale. The work attracted Gauss' attention, and von Humboldt encouraged him further in that direction from 1828 on.

[59] Carl Friedrich Gauss (1777–1855) is a true giant in the history of mathematics and physics and a great name in the history of geomagnetism. Because biographical sketches are easily accessible (e.g., references given by *Chapman and Bartels* [1940] or G. D. Garland as quoted by *Stern* [2002]), we only mention his main discoveries and contributions to geomagnetism rather cursorily, based on these previous references. In 1803 at the age of 26, Gauss wrote (cited by *Chapman and Bartels* [1940, p. 927]): "I believe that there may be much still to discover concerning the magnetic force of the earth, and (...) this offers a greater field for the application of mathematics than has yet been supposed." Gauss' "geophysical" views of the interior structure of the Earth were interesting though they have not withstood further progress in the field. He considered that the varying geomagnetic field was not "due to a few magnets near the earth's center" but rather "the result of all the polarised particles of iron contained within the earth, owing more to those near the surface." He attributed secular variation to gradual thickening of the crust and thought that the poles were located in the coldest regions because that would be where the crust would be thickest.

[60] Gauss, of course, is famous for inventing the expansion of field potentials in spherical harmonic series and applying the new mathematical technique to the few full vector measurements available to him at the time (in the process also inventing the technique of least squares). Using spherical harmonics, Gauss was able to conclude that the dominant magnetic sources of the field could only be of internal origin (amounting up to 99% of the total), with the dipole (to which his name would later be associated by geophysicists) being the dominant term. When gravitational masses or electrical charges (poles) are considered, the source is the simplest possible and slowest to decay away from the pole, diminishing with distance r as $1/r^2$. With two increasingly close poles of opposite sign and equal magnitude a dipole is formed, and the field decreases as $1/r^3$. Because there are no magnetic monopoles, this is the leading term in the Earth's (or for that matter any) magnetic field. Gauss may not have been the first to establish the "inverse cube of distance law" for the magnetic field. In 1825, Denis Poisson (1781–1840) published a paper ("Solution d'un problème de magnétisme terrestre" or "Solution of a problem in terrestrial magnetism") in which he determined the expression for the dipole moment (r^{-3}) and higher-order terms (powers of r^{-5} and beyond), clearly establishing the general inverse cube law. Gauss published his main magnetic results in two memoirs, one in 1832 "Intensitas vis magneticae terrestris ad mensuram absolutam revocata" ("Intensity of the terrestrial magnetic force recalled to an absolute measurement") and the other in 1838 "Allgemeine Theorie des Erdmagnetismus" ("General theory of Earth's magnetism"). The absolute measurement of the horizontal component of the magnetic field is generally attributed to Gauss in the 1832 memoir. However, again Poisson published on the topic [*Poisson*, 1825]. *Arago* [1854, p. 631], in a long notice devoted to Poisson, tells how he imagined a method which does not require the invariability of the magnetization (moment) of the comparison needle and adds "M. Gauss improved this method, whose first idea will forever belong

to Poisson." *Mascart* [1900] wrote "The first practical method for determining the absolute value of the horizontal component is due to Poisson." However, it is fair to say that Poisson's method, which involves two separate needles oscillating in the Earth's field and then in each other's field superimposed on the Earth's field (providing actually more equations than unknowns), was never employed. The early history of absolute measurements and the distribution of magnetization within the magnets used to perform them involves the names of Coulomb, Jean-Baptiste Biot, Poisson, Gauss, Arago and Mascart and has recently been discussed by *Leprêtre and Le Mouël* [2005].

[61] The formula which links the inclination of the magnetic vector to the magnetic latitude in the case of a purely centered dipole field is simple (see section 4) yet of paramount importance to paleomagnetism. It may be interesting to mention that in the Arago archives at the Academy of Sciences in Paris, there is a report dated 31 January 1831 in which François Arago reports on a memoir by Morlet "... a formula which MM. Bowdich, Mollweide and Krafft had already published and after which the tangent of the inclination of the magnetic needle is equal to the double of the tangent of magnetic latitude" (our translation, J.-P. Poirier personal communication, 2003). This could not be established without the formula for the field of a dipole, given by Poisson some 5 years earlier and by Gauss the following year.

[62] Some of the first "modern" steps to understand the physical sources of planetary magnetism can be linked with Michael Faraday's (1791–1867) work. Particularly noteworthy in our context, Faraday defined properly the concept of "lines of force" or field lines that allowed visualizing the field in a more comprehensive and rapid way (recall that these are well drawn in several of *Rohault*'s [1682] figures from the mid-1600s!). However, Faraday noted that field strength and not only direction could also be visualized by bunching of field lines and introduced the essential concept of a "magnetic field." This was to be extended by James Clerk Maxwell as the "electromagnetic field." Faraday also discovered electromagnetic induction, the result of relative motion between a magnetic source and an electrical conductor. Summing up the principles proposed by Oerstedt, Ampère, Arago, and himself, he devised the famous "disk dynamo," which still bears his name. This would open the way to twentieth century research that has established the dynamo as the most probable source of the Earth's main magnetic field lying in the conducting, convecting iron core. The second half of the nineteenth century would see some of the foundations on which paleomagnetism and rock magnetism were to be established and developed in the twentieth century.

3. MOSTLY (BUT NOT ONLY) PALEOMAGNETISM

3.1. Birth of Rock Magnetism Around 1850 (Fournet, Delesse, Melloni, and Sidot)

[63] After about 1850 the histories of physical magnetism, electromagnetism, and geomagnetism remain strongly interconnected. The most significant discoveries have to do with short-term variations and external field sources: They have been told in several textbooks and reviews [e.g., *Chapman and Bartels*, 1940; *Malin*, 1987; *Stern*, 2002]. From here on, we focus more on the histories of rock (or mineral) magnetism and paleomagnetism and their relation to internal field sources. Instruments were being developed which allowed the measurement of weaker magnetic fields, hence weaker magnetizations. Enormous progress resulted from the work of two men, Joseph Fournet and Achille Joseph Delesse, the latter being quoted in most histories of paleomagnetism, yet having largely drawn from the former, who seems to have been forgotten.

[64] Fournet (1801–1869), the first holder of the chair in Geology in Lyons, published a long essay in 1848 (much quoted by Delesse, but then not any more afterward), entitled "Aperçus sur le magnétisme des minerais et des roches, et sur les causes de quelques anomalies du magnétisme terrestre" (or "Glimpses on the magnetism of ores and rocks, and on the causes of some anomalies in terrestrial magnetism"). In that essay he wrote a review of all experimental methods proposed up to his time and gave a long descriptive list of magnetic ores and then rocks. He repeatedly mentioned the works of de Saussure, Haüy, and Delesse himself. We find it worth quoting (in our translation) several excerpts from his essay. *Fournet* [1848, p. 6] writes:

> We have observed that pieces of magnet which have been extracted recently from mines and have been maintained in their original position, sometimes had their poles located in the reversed position with respect to that they should have presented in the hypothesis where they would have acquired their property because of the action of a magnet located at the center of the earth.

He carefully makes a distinction between "simply attractable ore" (induced magnetization) and "ore endowed with polarity" (remanent magnetization) and performs numerous contradictory experiments in order to understand how one goes from one type of magnetization to the other: He studies the influence of air or light as a function of time, rubbing or influencing materials from a distance with a magnet, analyzes the repeated action of electrical sparks, etc. He then reviews magnetic minerals (most often citing their original site of collection): "fer oxidulé" (i.e., magnetite Fe_3O_4, which we translate as "oxidulated iron"), iron titanates, "fers oligistes" (i.e., hematite Fe_2O_3, which we translate as "oligist iron"), alumino-silicates, garnets, peridot, pyroxenes, etc. He then goes on to describe igneous and metamorphic rocks: Granites, which are "rarely magnetic," syenites and serpentines, which are "strongly magnetic," trachytes, obsidians, "which possess poles," basalts, lava, and various tuffs, etc. He finds that "serpentine (...) with its schistose structure (...) is magnetipolar in its smallest fragments, its magnetic axes being usually parallel to the direction of rock sheets," and that "basalts from all countries are magnetic, most often strongly so; they are even magnetipolar. These properties are generally attributed to the presence of oxidulated or

titanated iron.'' (Note that ''magnetipolar,'' ''multipolar,'' and ''polar magnetic polarity'' are apparently used at the time to refer to what we would today call permanent or remanent magnetization.) In 1788, Faujas de St-Fonds (the man who recognized that basalt was a volcanic rock and the first holder of a chair in Geology in France) had written a small but very complete memoir on traps (for which, incidentally, he found the correct chemical composition but which he thought, however, were distinctly different from volcanic basalts and considered as sedimentary rocks deposited at the bottom of an ocean). *Faujas de St-Fonds* [1788] even observed that trap specimens acted on the magnetic needle. Fournet confirmed this and noted that this was true only of unaltered traps. He thought that this action only ''manifested itself by attraction'' (likely meaning an induced effect), whereas compact basalts are ''frequently multipolar'' (meaning with a remanent magnetization). He therefore concurred that the two types of rocks must be distinct, when they are ''so often mistaken for one another'' (!). Half of Fournet's paper is concerned with ''geologicomagnetic phenomena.'' After citing the etymology of the word magnet proposed by Lucretius in *De Natura Rerum* (that there were abundant supplies of magnetic iron near two distinct cities of Asia Minor both called Magnesia), Fournet described one of the very first three-component magnetic anomaly profiles acquired by Karl Kreil, director of the Prague observatory, in 1846 in the eastern Alps, where not only iron minerals but the influence of altitude (to which an entire chapter was devoted) were invoked. *Fournet* [1848, p. 30] made shrewd comments on attempts to determine the magnetic pole in the Antarctic (in 1836 and 1841), noting that ''one should not lose sight of the influence of local causes, influence which can be understood and which belongs entirely to the realm of geology.'' He recalled von Humboldt's recommendation that either at sea or on ice one should always examine the possibility of an influence due to sea or ice bottom mineralogical composition. Let us quote some final, savory words from *Fournet* [1848, p. 51] on how to properly locate a magnetic observatory, avoiding crystalline rocks in favor of limestone terranes:

> Physicists take the greatest precautions to eliminate iron in these observatories which they call houses, pavilions, magnetic tents. It seems (...) that experimentalists (...) should primarily have studied the influence which diverse rocks can exert on their instruments, since experiments are generally performed not very high above ground (...) I have long thought to an association in which a geologist would be included (...) One would arrive at something even more precise than the ideas of M. Necker de Saussure on the coincidence of the direction of mountain ranges or their strata and iso-intensity curves.

Fournet [1848, p. 53] concludes in a language that we will let the reader savor:

> Je laisse maintenant aux physiciens à décider si mes conclusions ne sont pas intempestives. En publiant cette notice, je n'ai eu d'autre dessein que celui de leur épargner de fausses et pénibles tentatives, et si mon but n'a pas été atteint, ils me pardonneront du moins d'avoir lancé des éclaireurs, véritables enfants perdus, dans un domaine que la géologie n'en aura pas moins à revendiquer un jour comme l'un des plus beaux fleurons de sa noble couronne.

(The approximate translation is ''I will now let physicists decide if my conclusions are not too bold. In publishing this essay, I had no other aim but to spare them false and painful attempts, and if my goal has not been reached, they will at least forgive me to have launched scouts, really lost children, in a domain that geology will certainly claim one day as one of the most beautiful jewels of its noble crown.'')

[65] Starting from Fournet's review, Delesse (1817–1881) analyzed in a very modern experimental way magnetism of minerals and rocks. We summarize here his main, 1849 paper. *Delesse* [1849] first described his instrument, where the ''magnetic fluid'' is concentrated in the variable air gap of a horseshoe-shaped magnet. He was able to define the notion of coercivity (''force coercitive'') which depends on chemical composition. He found that this was zero for soft iron but became significant through the addition of O, S, P, Si, and C to iron. He also found that shock could sometimes increase magnetic ''power.'' *Delesse* [1849, p. 198] found that any magnetic substance could become ''multipolar'' but that this was a weak effect in hematite:

> Those minerals which are already multipolar owe this to the fact that their magnetisation is acquired either by action from the earth, or from nearby magnets already formed in the rock, or because of mechanical and atmospheric causes.

Whatever the shape of the sample, magnetization is often uniform, and there are always two (and only two) poles. A sample can always be remagnetized in the opposite direction (both polarities are always possible); poles are not on remarkable crystallographic axes, but intensity of magnetization depends on the direction of the applied field. Delesse clearly states that all recent lava flows are uniformly magnetized in a direction parallel to the local magnetic field, which can be considered one of the founding statements of paleomagnetism. Despite the tremendous work of Fournet and Delesse many natural scientists will continue for decades to consider that rocks containing various combinations of iron behave as temporary and not as permanent magnets [*Chevallier*, 1925a, 1925b].

[66] A most important contemporary figure is Macedonio Melloni (1798–1854). Having built a very sensitive astatic magnetometer, Melloni established the permanent magnetization of 108 different species of volcanic rocks. He showed that the total amount of material which could be attracted by a magnet gave no clue as to the intensity of the Earth's magnetic field, because it is the magnetic state (e.g., remanent versus induced), not the amount of substance, which matters. He carefully explored the origin of thermal remanent magnetization and formulated hypotheses that he then tested experimentally. He deduced that in recent lava

flows the upper surface should be a southern (magnetic) one and that maximum "action" (magnetization) should be found in the direction of the applied (Earth's) field. He verified this on lavas from Vesuvius and found that the intensity of magnetization of ancient lavas was similar to newer ones and had "tenaciously" preserved their primitive magnetic state. He fired fragments of lava until they were red and let them cool: Even after slow cooling, when steel does not acquire magnetization, lavas do acquire a permanent magnetization in the direction of the Earth's field. In 1853, *Melloni* [1853a] wrote to Arago about "the general law of permanent magnetisation of lavas." He proposed that anomalous declinations observed on Etna were due to the lavas from the volcano itself. *Melloni* [1853a, 1853b] noted the loss of magnetization upon heating and acquisition upon cooling:

> This magnetisation is stable and does not depend on position given afterwards to the cooled lava fragment; but one can easily invert its poles (. . .) by reddening again the piece, and letting it cool in a proper disposition with respect to the magnetic axis of the globe.

He added

> These deviations [the anomalous declinations observed on Etna] absolutely do not, in my opinion, come from the absolute amount of material that reacts to the magnetic needle (. . .) but actually from the amount of direct force, i.e. the degree of magnetisation that the rocks possess naturally.

This could be considered as one of the birth certificates for paleomagnetism: Shortly after 1850 it is clear that natural remanent magnetization in a lava is parallel to the direction of the Earth's magnetic field at the time and location of cooling of the lava. However, as noted later by *Brunhes* [1906], Melloni made no quantitative measurements to further prove his hypothesis.

[67] In 1868, T. Sidot communicated to E. Becquerel his research on the polarity of synthetic magnetite and pyrite. He finds that these do gain "polar magnetic polarity" (i.e., a stable remanence) upon cooling, that when the magnetizing field is reversed, magnetization is reversed, and that the direction of magnetization coincides with that of the applied field not of the crystallographic axes of the material. *Sidot* [1868, p. 176] concludes:

> The facts I have indicated should attract the attention of geologists and mineralogists on how to envisage polar magnetisation of natural minerals, since the direction of the magnetic axis of the globe at the time when they were formed probably gave them the magnetisation that we observe in them.

3.2. Around 1900 (Curie, Folgheraiter, Brunhes, and David)

[68] In a beautiful series of three papers published in 1894, Giuseppe Folgheraiter (1856–1913) showed that Melloni's results for the Vesuvius lavas could be extended to other magnetic rocks (in that case from Latium) [*Folgheraiter*, 1894a, 1894b, 1894c]. He successively studied the magnetization of rocks in situ of samples brought back to the laboratory and the magnetization they artificially acquire upon a series of experiments. Folgheraiter first distinguished permanent from induced magnetization (induced by the Earth's field or the "reciprocal" induction from a needle). Using two needles with different moments he showed that "reciprocal" induction is negligible. He found that the upper surface of outcrops (lava flows) always displays a south pole (and the lower one a north pole): The Earth itself is the original "inductor." After carefully orienting and removing samples from the outcrop (his samples are 10 cm long small cylinders up to 1 kg in weight), he used a magnetometer to separate induced and permanent magnetizations (rotating the sample by 180° in front of the magnetometer). He found that, in general, induced magnetization is much less than the permanent one in basalts; he found the reverse in "piperino" (an agglomerate of volcanic dust or tuff). He also noted that rocks formed at low temperatures acquire a permanent magnetization after some time, maybe the first note of acquisition of viscous remanent magnetization. Folgheraiter then heated samples to 800°C for 1 hour and cooled them for 2 hours: The acquired magnetization was found to be unchanged 3 months after the experiment and was parallel to the Earth's magnetic field at the time of cooling. The "piperini" which were originally not or little magnetized acquired a magnetization after heating, which Folgheraiter understood to be due to a chemical transformation (see below). Folgheraiter extracted a magnetic substance he identified as magnetite and weighed it. He noted that in certain tuffs and baked clays, there was a strong magnetization and no extract (i.e., no magnetite): So there must be another magnetic mineral than magnetite (hematite). Folgheraiter therefore concluded that heat could not only produce a remagnetization of preexisting material in the direction of the Earth's field but also create new magnetic species from nonmagnetic ones, i.e., the transformation of hematite into magnetite.

[69] From 1895 to 1900, *Folgheraiter* [1896, 1897, 1899b] focused on the remanent magnetization of bricks: "Baked earth preserves acquired magnetisation with a level of tenaciousness, which we cannot assert for any other substance, including steel" [*Folgheraiter*, 1899a, p. 9]. He found that bricks from a Roman wall dating back 2000 years had preserved their magnetization (random in the wall given the bricks had been arranged together). *Folgheraiter* [1899a] proposed a first evaluation of variations in inclination from 800 B.C. to 100 A.D., a period of 9 centuries (Figure 9). The values found for Greek and Etruscan vases from the eighth century B.C. were slightly negative! This surprising result was severely contested (Carlheim-Gyllenskjöld [*Brunhes*, 1906, p. 706]) and has been considered as erroneous until very recently [*Gallet et al.*, 2003]. There is no doubt that Folgheraiter established archeomagnetism as a field of study and an experimental method.

[70] The son of a physics professor (at various colleges then at the University of Dijon where he ended his career as

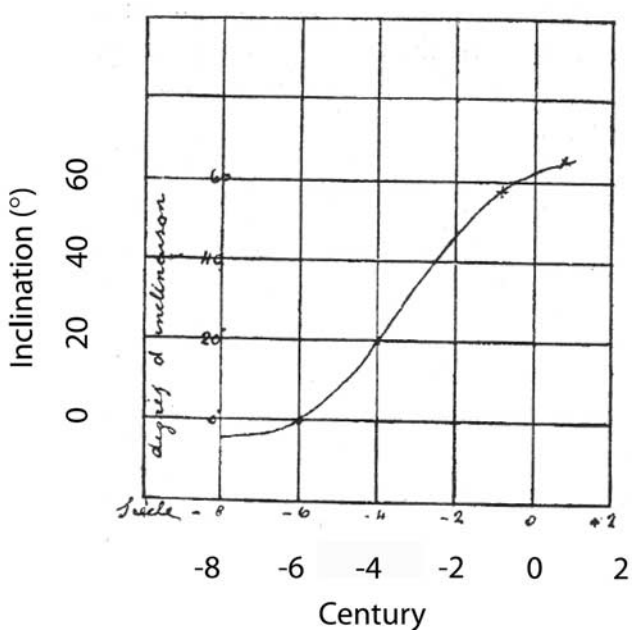

Figure 9. *Folgheraiter*'s [1899a] original figure displaying the variations of inclination between 800 B.C. and 100 A.D.

dean of sciences), Bernard Brunhes (1867–1910) was a very brilliant student, finishing first at the 1889 national physics teacher examination ("agrégation"). His biography has recently been summarized by *Didier and Roche* [1999] [see also *Laj et al.*, 2002]. Brunhes next did a thesis in optics in Paris and then became a physics professor successively in Lille and Dijon (where he succeeded his father), studying electricity, acoustics, thermodynamics, and X rays. He finally came to Clermont-Ferrand in 1900, when he was appointed director of the Puy-de-Dôme observatory (which had been built in 1876). He was an office neighbor to geologist Philippe Glangeaud, who introduced him to the local scene and was to have an important influence on orienting his later research on rock magnetism. Brunhes soon took on a bright young physics assistant, Pierre David, whom he selected to help him with meteorological observations at the mountain observatory, which he greatly improved. David would become his (short) lifelong colleague and with him would publish on atmospheric phenomena, telluric currents, and earthquakes, besides the work which is of interest to us here. Brunhes would come with his family for summer vacation to the top of Puy-de-Dôme and developed a keen interest in archeological observations of the temple of Mercury. Glangeaud attracted Brunhes' attention to the existence of "natural bricks" (porcelanites), which had resulted from baking of clay-rich soil by an overlying lava flow. Brunhes became interested and collected oriented samples, from which he cut 8 cm cubes whose magnetization he measured. He found that magnetization was homogeneous and yet different from the present-day field orientation at the site [*Brunhes and David*, 1901; see also *Brunhes* [1903], and *David* [1904]. Recalling Melloni's (by then 50 years old) work and more recent results of Folgheraiter, *Brunhes* [1906, p. 709] quickly understood that the stability of rock magnetism would allow him to retrieve the past field directions:

> Brick presents exceptional interest because the many experiments by Folgheraiter on potteries and his observations on fragments of antique vases show that the remnant magnetisation of baked clay presents an absolute stability. If, in these strata of natural clay, one finds a well defined direction of magnetisation which differs from the present terrestrial field direction, one has ground to believe that the magnetisation direction is indeed that of the earth's field at the time when the volcanic flow transformed the clay into brick.

Because baked clays were rare, Brunhes turned to lavas. He found that these were more strongly magnetized, had a similar direction, but yielded less homogeneous results. In a quarry in Royat he discovered in an outcrop where a clay layer was sandwiched between two flows that the direction of the underlying flow was different from that of the clay and flow above. David turned to a study of the trachyte-made flagstones at the temple of Mercury on top of Puy-de-Dôme. He found that magnetization from several samples taken from the same slab was identical but that declinations varied from stone to stone. However, absolute values of inclinations were identical in four stones. He concluded that "terrestrial action could not have modified magnetisations since at least the 2000 years the stones had been in place" [*Brunhes*, 1906, p. 723]. David (cited by *Brunhes* [1906, p. 724]) was even able to locate the former quarries from which the slabs had been extracted, though he found magnetic intensity there "a bit weak" (!):

> The exact knowledge of the quarry (. . .) would be of great archeological interest, since it would allow one to bring new evidence regarding this other problem, still without a solution: which path did the Gallo-Romans use to reach the summit of Puy-de-Dôme? It would be curious if one was put on the right path by studies of terrestrial magnetism.

Thus, as early as 1904, potential archeological applications of rock magnetism were clearly envisioned.

[71] The key discovery resulted from a chance finding [*Didier and Roche*, 1999]. An engineer informed Brunhes of an outcrop of baked clay under a basalt flow near Pontfarein (Cantal, France). Brunhes found that both rocks, both well in place and not having been disturbed since emplacement, had the same negative inclination (−75°): This was by the way the first baked contact test in history, and it was a success [*Laj et al.*, 2002]. Moreover, samples collected 100 m away had the same magnetization, excluding the possibility that magnetization could have been due to lightning. *Brunhes* [1906, p. 716] was led to an astonishing conclusion:

> What comes out of these numbers is first that the North pole in these samples is rotated to the South; but mainly this North pole is upwards rather than downward. Inclination is negative. Therefore, if the magnetisation direction of metamorphosed clay gives us the direction of the earth's field at the epoch of the flow, we know that at a moment of the Miocene epoch, in the neighborhood of Saint-Flour, the North pole was directed upwards; it is the earth's South pole which was closest to central France. This conclusion seems to me to be unavoidable. Indeed it is impossible to admit that this long horizontal layer of metamorphic clay could have been turned upside down, because otherwise the lava that cooked it would now be found below and not above. This lava (. . .) has the same direction of magnetisation as the clay it covers.

Nineteen hundred five is the date of discovery of magnetic reversals. This would start a long controversy. As late as 1967, in his Bakerian lecture, Sir Edward Bullard could still say regarding magnetic reversals that "None of the proposed explanations is able to explain all the facts, and the correlation of oxidation and magnetic polarity may be seen as one of the major problems of earth science." *Brunhes* [1906, p. 719] continued "It is clear that one can base on the study of the direction of magnetisation of in situ rocks a method to test the concordances or discordances between various geological strata," announcing tectonic applications of paleomagnetism. However, in foreseeing magnetostratigraphic applications he warned that "It would be premature to go further, and to speak, in the present state of the question, of attempts at geological chronology." *Brunhes* [1906, p. 720] also announced applications of paleomagnetism to volcanology, when he compared the mechanism of emplacement of the Puy-de-Dôme volcano and that recently described by Alfred Lacroix (cited by *Brunhes* [1906, p. 720]) on the occasion of the Mount Pelée eruption of 1902: "The distinction between the central needle and pieces which are simple fragments of it seems to be made possible by a study of the direction of magnetisation at various points." Brunhes even calculated the mean magnetization of the volcano (assuming a simple geometrical shape and uniform magnetization) based on the vertical component of the magnetic anomaly and found 0.0024 cgs units, which he then compared to the measured mean magnetization of his samples, 0.0027 cgs!

[72] Brunhes' sampling and measurement technique seems remarkably modern to us: He would carefully orient cubic samples (though he does not seem to have used a solar orientation) and in his laboratory determine the three components of the moment along the sides of the cube with a Mascart declinometer (in the first Gauss position), four separate measurements being averaged for each face of the cube. Intensity measurements were made by comparison to a bar magnet with known moment. Some of the samples measured in 1901 were remeasured in 1906 after having been stored in random positions, and no change was noted, ensuring full stability over 5 years. Though he did not always use the terms we use today, *Brunhes* [1906] clearly recognized the differences between TRM, lightning-induced isothermal remanent magnetization (IRM), and viscous remanent magnetization (VRM). *Laj et al.* [2002] recently revisited some of Brunhes' main results. Their account starts with Brunhes' last major paper (1906) on the subject before his untimely death at the age of 43. Laj et al. could perform full and careful demagnetization of their samples in a way unknown at the time of Brunhes and found mean directions virtually identical to those of Bruhnes for the baked clays of Pontfarein (Figure 10). In the case of the lava directions, Brunhes was apparently lucky to obtain from a single sample a direction close to what *Laj et al.* [2002] found with 15 demagnetized samples. However, as they pointed out, Brunhes was well aware of the possibility of viscous secondary magnetizations masking in part the primary direction. Laj et al. further determined the age of the flow (using the *Cassignol and Gillot* [1982] K-Ar technique) as being 6.16 ± 0.08 Ma and the paleointensity of the field (using the Thellier-Thellier technique, see section 3.3) as 33.8 ± 3.0 mT, both of course unattainable results to Brunhes but adding precision to his remarkable discoveries. In his short lifetime and for decades after his death, Brunhes' findings met only with skepticism among French physicists. The first to follow suit consistently would be Alexandre Roche almost a half century later.

[73] A number of other scientists contributed to magnetism around the turn of the century. We should of course not forget Pierre Curie (1859–1906), who in 1895 discovered that magnetic susceptibility varied inversely with absolute temperature and whose name has been given to the temperature at which permanent magnetism (ferromagnetism) disappears. *Nagata* [1953] quoted Charles Maurain (1871–1967) from the *Maurain* [1901] paper on magnetization of igneous rocks. G. E. Allen noted in 1909 that TRM in lavas was much more intense than IRM. In 1910, Paul Langevin (1872–1946) published his theory of paramagnetism, and the next year Pierre-Ernst Weiss (1865–1940) published his theory of ferromagnetism. *Nakamura and Kikuchi* [1912] stated that when cooled in the Earth's field, natural rocks acquire a strong TRM parallel to the field, but this does not seem to go much beyond what had been established by Melloni a half century earlier [see *Glen*, 1982, pp. 100–101].

3.3. From 1920 to 1940 (Mercanton, Chevallier, Matuyama, Koenigsberger, and Thellier)

[74] From at least 1906 to 1922, Paul-Louis Mercanton (1876–1963) measured the magnetization of basalts from Greenland and the Spitzbergen (now known to be part of the 60–55 Myr old North Atlantic magmatic province) using a very sensitive astatic magnetometer. Some of his conclusions were judged to be robust by *Chevallier* [1925a, 1925b]: that lavas would become magnetized in the direction of the Earth's field upon cooling and that this magnetization was very stable; that intensity of magnetization was stronger if cooling was faster (this issue has not been generally confirmed); and that induced magnetization in these rocks was negligible. Chevallier was not so sure about some other conclusions, namely, the presence of negative inclinations in the Northern Hemisphere at certain epochs and a large (60°) variation in inclination over the 8 centuries B.C. (Folgheraiter's old result). In 1926, Mercanton pub-

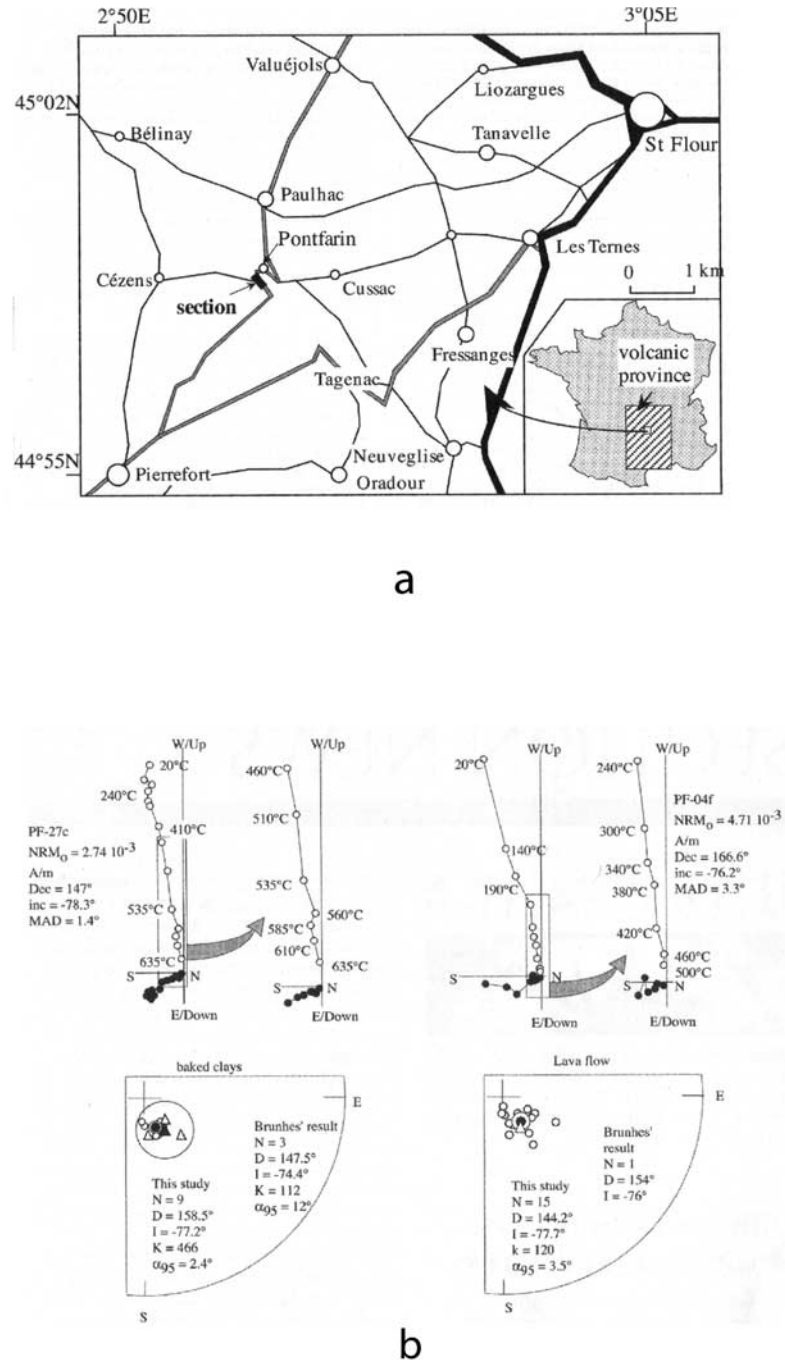

Figure 10. Paleomagnetic directions measured by *Brunhes and David* [1901]. (a) the location of Pontfarein (or Pontfarin) in south central France near Saint Flour [*Laj et al.*, 2002]. (b) Paleomagnetic results from (bottom left) baked clays and (bottom right) lava flow at Pontfarein, with some representative vector demagnetization diagrams, the new results (circles) by *Laj et al.* [2002], and Brunhes' and David's original results (triangles).

lished a four-page note in French in *Terrestrial Magnetism and Atmospheric Electricity* (the ancestor of *Journal of Geophysical Research*, when you could still publish in French in it) under the title (translated) "Inversion of terrestrial magnetic inclination in the geological ages," in which he insisted on the stability of reversed magnetizations "From the onset most of these arctic specimens and the best showed, a surprising fact even after the findings of Brunhes in Pontfarein, a reversal of the sense of terrestrial magnetic inclination in the tertiary ages" [*Mercanton*, 1926, p. 188]. In addition, *Mercanton* [1926, p. 189] asked the following essential question: "Would the reversal revealed thus by northern lavas have a counterpart in lavas from the southern hemisphere? It was proper to search for this (. . .) I obtained

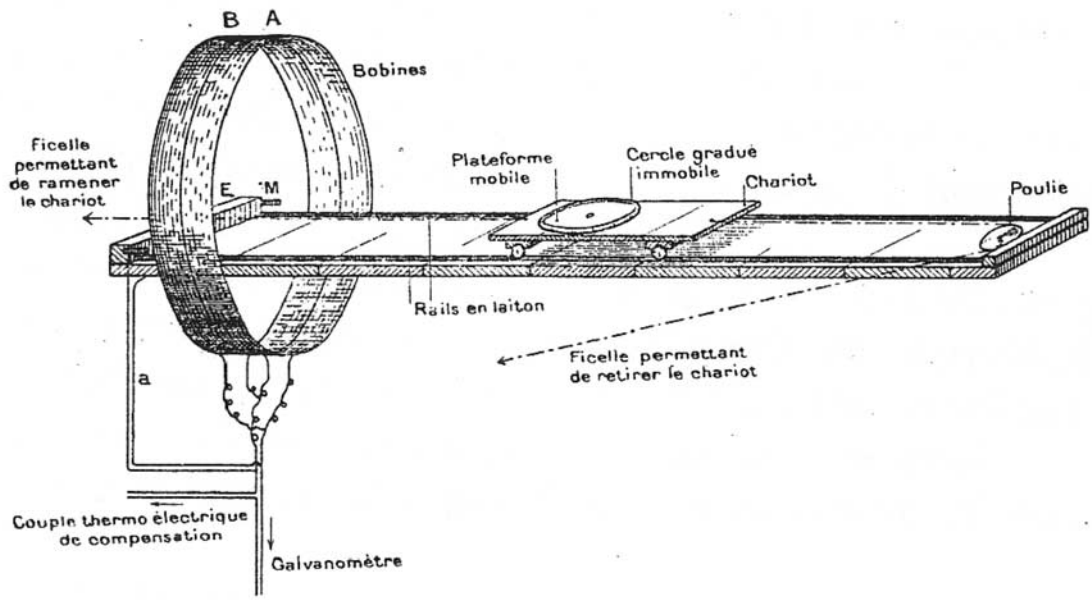

Figure 11. Mobile tray and coils used in conjunction with a ballistic galvanometer by *Chevallier* [1925b] to measure rock sample magnetization. Reprinted from *Chevallier* [1925b, Figure 4] with kind permission from Springer Science and Business Media.

Australian samples." Also, *Mercanton* [1926, p. 189] proposes a tentative first positive answer:

> So, the reversal in the sense of terrestrial magnetic inclination found in the northern hemisphere would be found also in the other hemisphere. If further research vindicates this observation one can guess its important consequences for the history of our globe: magnetic poles would have undergone enormous displacements.

Mercanton [1926, p. 189] then asked the International Union of Geodesy and Geophysics to extend its observational (paleomagnetic) base and asked that a laboratory be established to centralize sample archiving and study their magnetic properties "using a simple and quick method which should now be elaborated." In addition, in a bold final sentence in this important short note, *Mercanton* [1926, p. 190] writes:

> I finally observe that if a link exists between the rotation axis of our globe and its magnetic axis, the considerable displacements of the magnetic axis which our researches would discover would unexpectedly corroborate the large displacements of the axis of rotation argued for by A. Wegener.

This is to our knowledge the very first clear statement that paleomagnetism could be a way to demonstrate and measure polar wander and/or continental drift. This view would, for instance, be later defended by Beno Gutemberg in 1940. Mercanton was also the first to report a reversed magnetization in latites (a variety of trachyandesite lava) from near Kiama in New South Wales. *Graham* [1955] and *Irving and Parry* [1963] would later term Kiaman the long reversed polarity interval without magnetic reversals during which the rocks first measured by Mercanton were formed. In the 1930s, *Mercanton* [1932] sampled lavas in Iceland and the islands of Mull and the Faroes, sailing on Jean-Baptiste Charcot's *Pourquoi-Pas*? He almost always found what we would now call "normal" inclinations in Iceland, except in some lower flows, and reversed ones in the Faroes and Mull. He described a first magnetostratigraphic section with a succession of three reversals (R, N, R, R, N) in these "tertiary" lavas. In these later papers, *Mercanton* [1931, 1932] did not cite his own 1926 paper and did not speak of continental drift anymore. We have not found papers more recent than 1932 by him.

[75] Raymond Chevallier (dates not found) was active from 1921 until 1955, in the first part of his career contemporary with Mercanton (they both quote each other's work in part). He was an assistant in mathematical physics with the Collège de France (Paris) at the time of his doctoral work (1925). Using Brunhes' techniques, *Chevallier* [1925a, 1925b] chose to study the magnetization of lavas from the twelfth to seventeenth century on Etna in Sicily: "I have preferred to multiply results in a narrow interval so that I could solidly establish a part of a curve, rather than provide uncertain results in a large interval. The chronology of Etna lavas also imposed this frame of work." Chevallier was careful to ensure that the horizontal (reference) plane has been well preserved since solidification of the lava and made sure that his sites allowed easy enough use of a theodolite. He observed the Sun and provided the complete method to orient the sample with these Sun readings. He measured accurately local declination of the present field and selected areas in which there were no large magnetic anomalies. He carefully described his technique using a ballistic galvanometer (Figure 11) and discussed the hypotheses which needed to be verified for a reliable measurement: that time had not altered magnetization, that

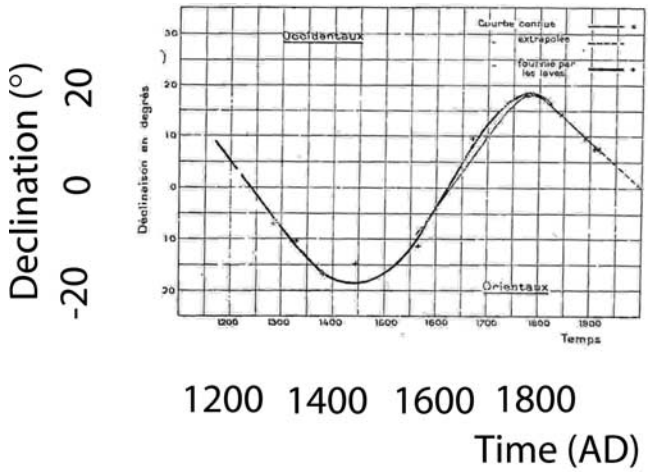

Figure 12. Secular variation of declination in Sicily as determined by *Chevallier* [1925b] based on some 100 blocks from 10 distinct lava flows (1200–1900 A.D.) seeming to suggest a "periodicity" of 750 years (though the author was careful not to conclude so based on this limited data set). Reprinted from *Chevallier* [1925b, Figure 5] with kind permission from Springer Science and Business Media.

it had neither been modified by shock, and that magnetic perturbations due to local anomalies had been eliminated through sufficient sampling density and subsequent averaging. ("It is possible to pass from the field in a volcanic terrane to the regular field outside of the massif.") After having studied 10 flows from Etna and having performed a considerable amount of orienting and sampling work (samples at a site which by today's standards and with today's tools can be collected in at most a few hours would then have required days of hard labor), Chevallier concluded in his thesis and in a couple of papers [*Chevallier*, 1925a, 1925b] excerpted from it that declination had varied in a periodic way from 1200 to 1900 A.D., with an amplitude of about 40° (Figure 12). On the other hand he found inclination variations irregular, which he attributed to magnetic anomalies due to underlying lavas. Chevallier's magnetic measurements were of excellent quality, with an accuracy better than 2°, as has been verified extensively by *Tanguy* [1980]: before his 1925 thesis, in a 1924 memoir, Chevallier summarized the historical documents on which he based assigned ages of individual flows (see details given by *Tanguy* [1980]). The main source, *Sartorius von Walterhausen* [1880], turned out to be often unreliable or erroneous and to this day underlines the main limitation of proper archeomagnetic work. Hence the notion of periodic variations of declination was subsequently abandoned and interest in inclination was largely lost (because of the erroneous interpretation of its irregular variations). This has been reviewed by *Tanguy* [1980], who has redone and largely extended Chevallier's study of Etna. Chevallier, who was a contemporary of still living scientists, is known to have continued work, but he mostly focused on magnetic mineralogy of various iron and titanium oxides, on which he published until 1955, and he was lost from paleomagnetists' sight (in the 1960s, David Dunlop wrote to his university for reprints and was informed that he had died (D. Dunlop, personal communication, 2006)).

[76] At about the same time as Chevallier's and Mercanton's early work, Frantz Levinson-Lessing (1926) studied the stability of NRM of igneous rocks in Kursk (cited by *Glen* [1982]). A more significant contributor from the same epoch is Motonori Matuyama (1884–1956) from Japan. In a paper quoted in most histories of paleomagnetism, *Matuyama* [1929] reported on a magnetic study of more than 100 Tertiary basalts coming from 38 sites in Japan and Manchuria (northern China). He found that many of these lavas were reversely magnetized and that their polarity was correlated to stratigraphic position. In a famous image (Figure 13) he showed that magnetizations were arranged in two groups, a Pleistocene one being normal and a pre-Pleistocene one antipodal. He clearly identified what we know today is the most recent field reversal, appropriately separating the Brunhes and Matuyama chrons, and stated that the polarity of the Earth's magnetic field depended on time in an organized way. Matuyama and Mercanton (and Chevallier) do not appear to have been aware of each other's work and do not cite each other, and Mercanton's 1926 and later contributions have been somewhat overlooked since.

[77] In 1933, Johann G. Koenigsberger showed the importance of magnetite and maghemite as carriers of NRM and proposed the first theory for thermal remanence, which was generally accepted in the following years. For Alexei Khramov (*Khramov* [1958] cited by *Glen* [1982, p. 103]), "He is the first to pose the problem in a scientific way, to examine in a critical way previous work, and to realise numerous experiments to determine the magnetic properties of many igneous and metamorphic rocks."

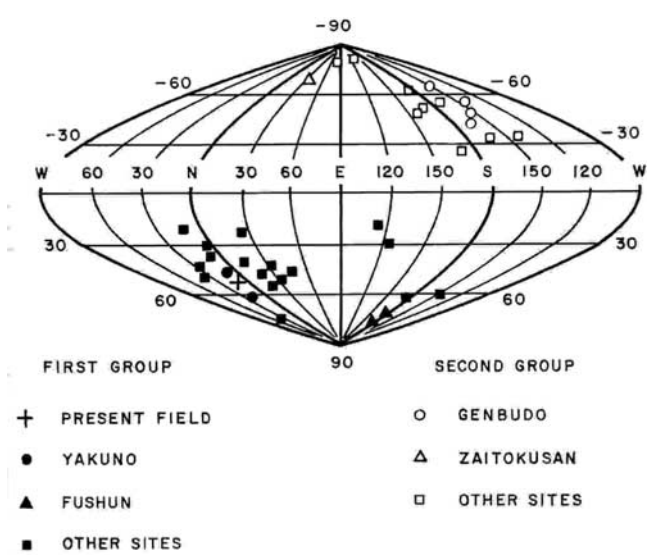

Figure 13. Poles based on magnetic directions in Quaternary basalts as determined by M. Matuyama in 1929, revealing the two opposite polarities of the past field (original paper reproduced by *Cox* [1973]).

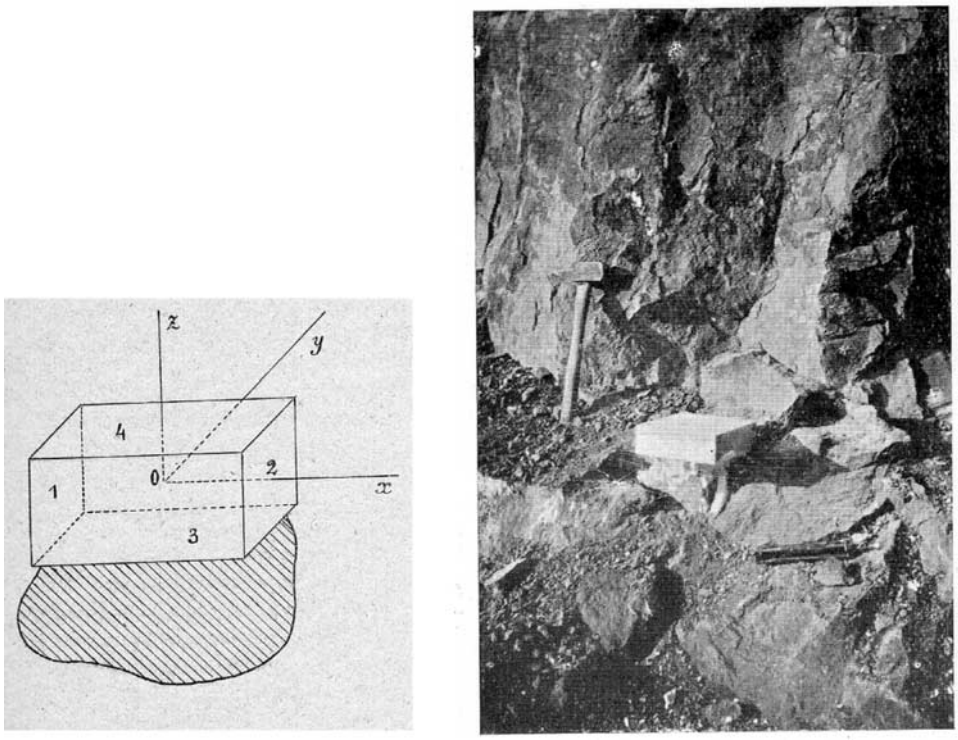

Figure 14. Method of orienting and collecting rock samples using a "plaster of Paris cap" ("chapeau de plâtre") pioneered by E. Thellier [from *Thellier*, 1938, Figures 44 and 45].

Koenigsberger's work marks the onset of an acceleration of research on the remanent magnetization of common natural magnetic minerals in order to provide techniques to ascertain the confidence that can be assigned to paleomagnetic measurements. He may possibly be considered as the trigger to following work on magnetic mineralogy by Thellier, Nagata, Graham, Kawai, Roquet, etc. [see, e.g., *Nagata*, 1953]. Also, it may be of interest to paleomagnetists to note that in 1934, Hans Gelletich undertook a magnetic survey of dikes in Pilansberg (South Africa), which he found to be reversely magnetized over a distance of 150 km, with both older and younger neighboring rocks being normal.

[78] One of the main researchers on rock magnetism and archeomagnetism (though certainly not paleomagnetism in its modern sense as we will soon see) in the 1930s was doubtlessly Emile Thellier (1904–1987) (see *Le Goff et al.* [2006] and *Dunlop and Papusoi* [2007] for recent biographies). He was often assisted by his wife Odette Thellier (1907–1997). As early as 1932, E. Thellier used an astatic magnetometer to measure the induced and remanent magnetization of both unbaked and baked clays. The next year, O. Thellier built an improved apparatus to measure sedimentary rocks. In 1936, E. Thellier proposed his (subsequently famous) sampling technique for large rocks or archeomagnetic samples using a cover (or "hat") of Paris plaster (Figure 14), which considerably improved the accuracy of sample orientation, automatically provided with three attached planar faces forming an oriented Cartesian coordinate system. It also reduced sampling time to 1 hour (and measurement time in the laboratory was about 15 min). Turning shortly to basalts, E. Thellier established the existence of VRM, with angular variations sometimes exceeding a few degrees in only 3 days. *Thellier* [1937a, p. 3] wrote

> Basalts do not therefore possess a stable permanent magnetisation, and preliminary attempts on other basalts with very different origins allow us to suppose that this is a general characteristic of these lavas, certainly due to their mineralogical composition (magnetite). Contrary to what has been thought, these rocks probably cannot be used, contrary to baked clays, for researches on the time variations of the earth's magnetic field.

In his thesis, *Thellier* [1936, 1938, p. 301] concluded that basalts are "almost without interest." Although he would, in 1940, describe a Mexican lava [*Thellier*, 1940] "with a remarkable stability," he remained more than dubious of applications of paleomagnetism to prehistorical rocks until his retirement in 1971 (both authors of the present paper heard Thellier's lectures in the 1960s and early 1970s, in which he affirmed his lack of confidence in any magnetic data acquired on samples less than a liter in volume and doubted that paleomagnetism could bring forward any meaningful proof of continental drift). He would then turn back to baked clays and make a number of remarkable and lasting contributions to rock magnetism and paleomagnetic laboratory practice (cleaning methods and paleointensity determinations [e.g., *Thellier*, 1941a, 1941b, 1941c]). *Thellier* [1937b] proposed a new technique of thermal demagnetization in field free space (which was to become a

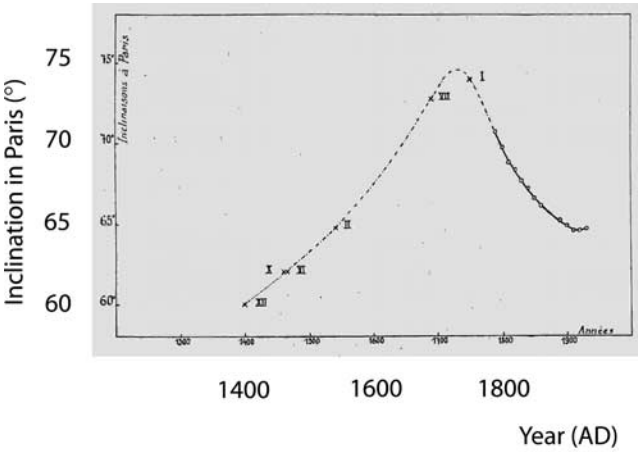

Figure 15. *Thellier*'s [1938, Figure 42, p. 74] first determination of variations of inclination in Paris from 1400 to 1900 A.D. Note that there are only six "archeomagnetic" determinations. However, three other determinations in other locations in France are in good agreement once reduced to the site of Paris.

standard tool of paleomagnetic analysis), and revealed the differences in behavior of IRM versus TRM upon such treatment. *Thellier and Thellier* [1942] described a new method to determine past field intensities recorded by man-made artifacts. In the same year they published their findings on the additivity of partial TRM, which was to form the observational basis of Néel's theory of ferromagnetism and the practical basis of thermomagnetic analysis of rocks. Although this is just beyond the "cutoff" time which we have selected for this paper, we note that the other important demagnetizing technique, i.e., using alternating magnetic fields, was also elaborated in Thellier's laboratory, in 1954.

[79] Applying their methods to archeological samples from France and Germany from various periods, *Thellier* [1938] published the first of a series of continuously updated secular variation curves for inclination between 1400 and 1900 A.D. (Figure 15). It is interesting to compare it to the early attempts of Folgheraiter in 1895 or Chevallier in 1925, 4 decades and 1 decade, respectively, before Thellier's: This is clearly the first version of a curve that looks more or less as it does today, though it has been considerably extended into the past, owing in part to later work of the Thelliers and their students and colleagues (in 1951, for instance, they determined the paleodirection on a fragment of hearth in Carthage, dated 146 B.C.).

3.4. After 1940

[80] The scene fills with new characters after 1940, when our account should possibly have stopped. However, we find it difficult to impose an abrupt truncation and leave matters hanging in the air in January 1940. Hence we include this final, much less developed section of the paper.

[81] With the 1940s the number of outstanding geomagnetists and paleomagnetists who should be quoted increases exponentially, and much of this work is rather extensively described in several excellent textbooks [e.g., *Nagata*, 1953; *Irving*, 1964; *Cox*, 1973; *Merrill et al.*, 1996; *Allègre*, 1983; *Glen*, 1982; *Oreskes*, 1999]. In the decade of the 1940s, at least a dozen names must be mentioned: the Thelliers, Nagata, Ising, McNish, Johnson, Torreson, Elsasser, Blackett, Bullard, Graham, and Néel. *Thellier and Thellier* [1942] published paleointensity measurements on bricks dated from 1465. They found that the decrease in field intensity noted by world magnetic observatories since the first historical absolute measurements by Gauss applied at a similar rate over the last 5 centuries: "The probability of a continuous and large decrease in terrestrial magnetisation, at least over the last centuries, is reinforced." Interest in the possibility that the Earth's field might altogether reverse in the coming millennia continues to this day. Takesi Nagata in Japan continued work on acquisition of TRM by ferromagnetic grains in bricks and igneous rocks under the influence of the weak geomagnetic field. He extended Koenigsberger's theory of TRM. From 1943 on, he explained the effects of thermal demagnetization observed by the Thelliers and then the effects of static (first introduced by *Johnson et al.* [1948]) and alternating (to be introduced by *Thellier and Rimbert* [1954]) demagnetization. This understanding will subsequently prove essential to proper cleaning of later magnetic overprints to uncover the primary magnetization of rocks and artifacts. In 1943 in a pioneering study, Gustaf Ising found secular changes of 10° in declination and 20° in inclination when studying lake varves in Sweden dated from a period of about 350 years. Between 1938 and 1948, Alvin McNish, Ellis Johnson, and Oscar Torreson studied submarine sediments off the coasts of Labrador, dating back to 20,000 years. *McNish and Johnson* [1938] cautiously concluded "Until many more data have been obtained, judgment must be withheld as to whether or not these measurements represent the direction of the earth's magnetic field at the time the sediments were formed; it is the writers' opinion that they do." However, in 1948, with the addition of better data from New England covering the period from 15,000 to 9000 B.C., which looked a lot like modern secular variation, they felt much more positive, and their study would have seminal influence in triggering Blackett's interest in past geomagnetism. These studies can be considered the founding papers of lake sediment studies of paleosecular variation. In 1946 another student of Thellier, Juliette Roquet [*Roquet and Thellier*, 1946], extended investigations to synthetic minerals of both fine and coarse grain sizes and natural materials containing different size fractions. She would later in her 1954 thesis perform the first systematic rock magnetic study of grain size dependence of thermal remanence [e.g., *Le Goff et al.*, 2006].

[82] In 1919 Joseph Larmor (1857–1942) had proposed that the magnetic field of the Sun and of the Earth could be maintained by a self-excited dynamo. *Larmor* [1919] noted that

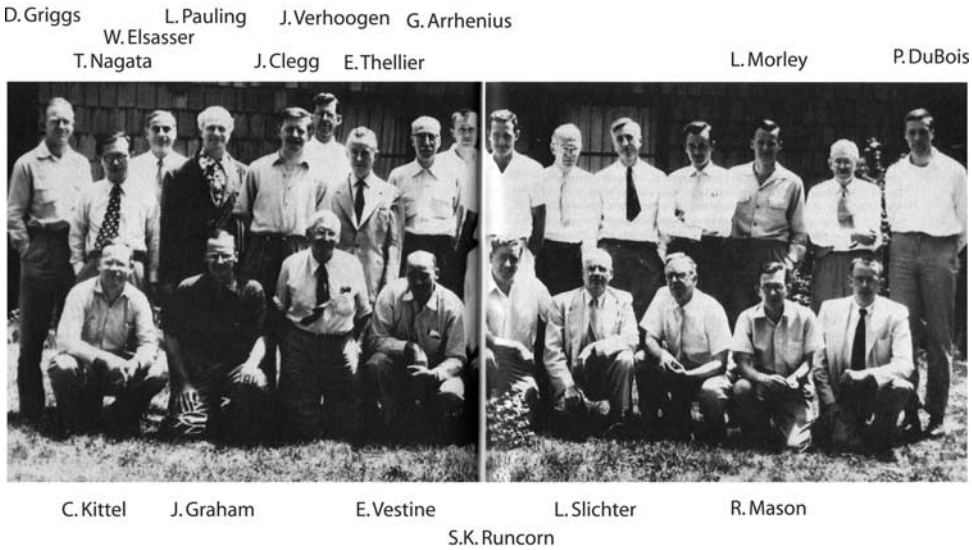

Figure 16. The National Science Foundation conference on the "anomalous magnetization of rocks" at University of California, Los Angeles, in August 1954. E. Thellier and T. Nagata are among the pre-1950 scientists cited in this review. W. Elsasser, E. Vestine, J. Graham, S. K. Runcorn, J. Verhoogen, R. Mason, and L. Morley are among those who will make history in the 1950s. Photograph from *Glen* [1982].

> the phenomena observed at the Sun surface suggest an internal circulation, partly in meridian planes. In presence of a magnetic field, such a motion induces an electric field acting on the moving material; if a conducting circuit happens to circle the solar axis, an electric current will flow along it, which will in turn be able to enhance the inducing magnetic field. In this way it is possible that the cyclic internal motion acts like an auto-excited dynamo and maintains a permanent magnetic field from insignificant beginnings. The same possibility could apply to the Earth.

The mechanism proposed by Larmor, being axisymmetric, was shown to be insufficient by Thomas Cowling (1906–1990) [*Cowling*, 1934]. The celebrated "antidynamo Cowling theorem" led most scientists to doubt the possibility that a self-excited dynamo could be the cause of the geomagnetic field for over a decade. However, from 1939 onward, Walter Elsasser (1904–1991) [*Elsasser*, 1939] and Edward Bullard (1907–1980) [*Bullard*, 1949a, 1949b] gave new impetus to dynamo theory. This is a lively subject, which has undergone major advances in the following 50 years, for instance, with the first demonstration of a successful (more or less "Earthlike") numerical dynamo by *Glatzmeier and Roberts* [1995]. In 1947, future Nobel laureate P. M. S. Blackett (1897–1974) proposed that the angular momentum and magnetic moment of a rotating body would always be parallel, a fact, which, if true, would lead to the impossibility of geomagnetic reversals (back to Brunhes' work). Two important existence theorems for a geodynamo were given a few years later by *Backus* [1958] and *Herzenberg* [1958].

[83] Nineteen forty nine is a rich year for magnetism, for dynamo theory with the work of Bullard, for theoretical rock magnetism with the first paper by Louis Néel (1904–2000) on ferromagnetism (together with ferrimagnetism and antiferromagnetism), which would later earn him a Nobel prize, and for paleomagnetism with an important paper by John W. Graham from Carnegie Institution of Washington, who introduced field stability tests (the fold and conglomerate tests, still universally used). With Torreson, Graham developed a new magnetometer, the spinner magnetometer, with a sensitivity that would allow measuring the magnetization of sediments and that would become the workhorse of paleomagnetic laboratories around the world until the late 1970s, when cryogenic magnetometers appeared. Placing too much confidence on fossils determined by others (as Chevalier had done on Etna with dating of historical lavas), Graham found both magnetic polarities in the same layer and first concluded in favor of magnetization by strong foci of secular variation, then later thought it was due to magnetic self-reversal. These negative (and we now know erroneous) inferences would exert significant influence in the early 1950s.

[84] In the 1950s, dozens of new names must be mentioned. Figure 16 shows participants to a 1954 National Science Foundation meeting on "anomalous magnetization of rocks" where some of these can be seen: authors of some major contributions from the prewar period (including Nagata and Thellier) and the (relative) newcomers, with Elsasser, Vestine, and Graham and the young Runcorn, Verhoogen, Mason, and Morley. In 1952, Blackett published the extremely important and influential results of his "negative experiment," discounting his 1947 views recalled above. Some distinguished scientists have been a bit forgotten or the importance of their contributions overlooked. Such is the case for instance of Alexandre Roche who made major contributions to paleomagnetism of lavas and identification of field reversals at a time when his teachers (Thellier mostly) disbelieved the results of this work, or

Jan Hospers [*Frankel*, 1987]. Many of these will be the leaders of the discoveries of the 1960s and 1970s and the teachers of the present generation of scientists: Ted Irving, Seiya Uyeda, Keith Runcorn, Ken Creer, Neil Opdyke, Ian Gough, Alexei Khramov, Allan Cox, Mike McElhinny, or Frank Stacey. This may be the place to briefly recall that in the 1950s, paleomagnetism had basically established the reality of continental drift, which would, however, not be generally accepted before results from the oceans, not the continents, started flowing in the mid-1960s. In the early 1950s, S. Warren Carey (1911–2002) sent a 30 m long core of Jurassic dolerite from Tasmania to Blackett predicting that one should find a vertical inclination: This was verified in Blackett's original paleomagnetic laboratory. Runcorn, who had transferred to Australian National University (ANU), and J. Jaeger invited young Irving to Canberra for a energetic sampling program, which was to establish the ANU paleomagnetic laboratory. Ian Gough and Anton Hales had been studying the magnetization of dolerites in the Karroo province of southern Africa since 1950. Carey had samples taken from the banks of the Hudson and in Parana (South America). This led to the 1956 symposium in Hobart, where verification of the past existence of Gondwana was at hand (this is also where Carey accepted continental rifting but not subduction and launched his campaign to promote the idea of Earth expansion, but this is another story [see, e.g., *Allègre*, 1983; *Oreskes*, 1999]).

4. CONCLUDING REMARKS

[85] We have purposely attempted to summarize the joint histories of geomagnetism and paleomagnetism. Their links are strong and should be fairly obvious. Yet, in the twentieth century, these disciplines have too often been considered as separate branches. However, the time when geomagnetism was taught in physics departments and paleomagnetism in geology departments should now be a thing of the past. There are profound connections between the two domains. Ours is a further attempt to underline the growing importance of having scientists of the two affiliations work ever more closely together. In this review we have placed particular emphasis on the life and works of those scientists whom we believe were the most important in some respect in the development of the two disciplines or on some that may have been unduly (from our point of view, of course) overlooked previously. The joint histories of geomagnetism and paleomagnetism are also linked in an interesting way with exploration activity, involving mineralogists and geologists on land and sailors at sea, the key role being played by the compass. Our account stops near the mid twentieth century for two reasons: First, the growth in the number of active scientists being exponential (it is well known that well over 90% of the scientists who ever lived are alive today), there was no way we could achieve a proper treatment in the frame of this paper. For instance, in the development of rock magnetism and paleomagnetism, only 20 scientists must be quoted between 1700 and 1940, when a dozen have made very important contributions in the 1940s, more than three dozen in the 1950s, and ever more since. Second, it is more difficult (though certainly exciting) to attempt to write history when it is still in the making and proponents are your living colleagues. In any case, there are excellent papers and books recounting these more recent events [e.g., *Irving*, 1964; *Glen*, 1982; *Allègre*, 1983; *Merrill et al.*, 1996; *Oreskes*, 1999]. We should also stress the fact that our review focuses on European (and for the more recent period American) work, in part because this is where much of the work was done but also because Asian and Russian work was not easily accessible to us. We made attempts to include more Asian literature but realized that the task was too great, with unexpected problems (see acknowledgments). Such an extension of our review would be a good project for the new generation of geomagnetists and paleomagnetists.

[86] *Stern* [2002] concludes that geomagnetism has rejuvenated itself repeatedly over the centuries by solving major problems and shifting its focus to new targets and new methods. Geomagnetism was much in the limelight in the period between the two world wars with increasing understanding of the external magnetic field in relation with intercontinental radio communications and the magnetic field of the Sun. Paleomagnetism was much in the limelight after World War II as continental drift was demonstrated and plate tectonics was constructed as a global theory to explain it. Although it may seem that scientific excitement has shifted toward genetics and information technology, geophysics in general and geomagnetism and paleomagnetism in particular still hold a treasure trove of unsolved problems. Fully understanding the dynamics of field generation in the core, with its rich spectrum going from jerks to secular variation to reversals, comparing the magnetic fields of planets and understanding fully why they are so different, linking internal magnetism to geodynamics and plate tectonics and possibly to the evolution of life, understanding the signal of magnetic particles in meteorites, assessing the reality of a snowball Earth or fast episodes of true polar wander, devising new more accurate clocks to measure fine-scale geological time, constraining models of climate change over timescales ranging from decades to hundreds of millions of years, and timing the emergence of global warming and its connections to solar processes are only a few of the challenging problems for the coming generation of young scientists. As in every science they will be interested to realize when making their new discoveries that they too are standing on the shoulders of their predecessors.

[87] **ACKNOWLEDGMENTS.** This paper started as a couple of lectures to our IPGP graduate students and colleagues in a seminar series on the history of geosciences initiated by Claude Allègre. We found that a significant part of the material we had uncovered was not fully or accurately represented in historical introductions to geomagnetism and paleomagnetism found in major earlier textbooks. Claude Allègre, Jean-Paul Poirier, Frédéric Perrier, Mioara Mandea, Maurice Recq, Yves Gallet, Carlo Laj, Jean-Claude Tanguy, Maxime Le Goff, Masaru Kono, and Michèle Courtillot are thanked for their help at various stages of preparation of the paper. Masaru Kono (personal communication, 2003)

assembled a collection of early Japanese papers in the early 1980s, including papers by Nakamura, Kikuchi, and Matuyama, but this was unfortunately lost in subsequent moving. Associate Editor Michael Manga and reviewers David Dunlop and John Tarduno (and an anonymous third reviewer) are heartily thanked for their patience and their detailed and constructive advice. We note here a number of additional references mentioned by J. Tarduno that the reader might find useful: *Brekke and Egeland* [1986], *Good* [1985, 1988], *Green* [1972], *Le Grand* [1990], and *Silverman* [1998]. This is IPGP Contribution NS 2160.

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