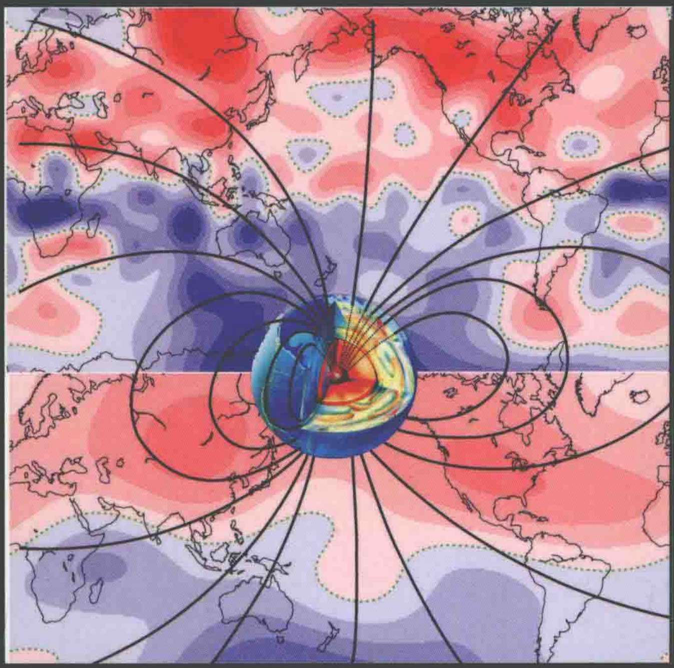
ELSEVIER

Treatise on Geophysics

Volume 5

Geomagnetism



Volume Editors Masaru Kono

Editor-in-Chief Gerald Schubert

TREATISE ON GEOPHYSICS

Editor-in-Chief

Professor Gerald Schubert

Department of Earth and Space Sciences and Institute of Geophysics and Planetary Physics, University of California Los Angeles, Los Angeles, CA, USA

Volume 5
GEOMAGNETISM

Volume Editor

Dr. Masaru Kono

Tokyo Institute of Technology, Tokyo, Japan

ELSEVIER

AMSTERDAM BOSTON HEIDELBERG LONDON NEW YORK OXFORD
PARIS SAN DIEGO SAN FRANCISCO SINGAPORE SYDNEY TOKYO

Elsevier B.V.
Radarweg 29, 1043 NX Amsterdam, The Netherlands

First edition 2007

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Catalog Number: 2007934548

ISBN: 978-0-444-51928-3

Printed and bound in Spain

07 08 09 10 11 10 9 8 7 6 5 4 3 2 1

TREATISE ON GEOPHYSICS

Preface

Geophysics is the physics of the Earth, the science that studies the Earth by measuring the physical consequences of its presence and activity. It is a science of extraordinary breadth, requiring 10 volumes of this treatise for its description. Only a treatise can present a science with the breadth of geophysics if, in addition to completeness of the subject matter, it is intended to discuss the material in great depth. Thus, while there are many books on geophysics dealing with its many subdivisions, a single book cannot give more than an introductory flavor of each topic. At the other extreme, a single book can cover one aspect of geophysics in great detail, as is done in each of the volumes of this treatise, but the treatise has the unique advantage of having been designed as an integrated series, an important feature of an interdisciplinary science such as geophysics. From the outset, the treatise was planned to cover each area of geophysics from the basics to the cutting edge so that the beginning student could learn the subject and the advanced researcher could have an up-to-date and thorough exposition of the state of the field. The planning of the contents of each volume was carried out with the active participation of the editors of all the volumes to insure that each subject area of the treatise benefited from the multitude of connections to other areas.

Geophysics includes the study of the Earth's fluid envelope and its near-space environment. However, in this treatise, the subject has been narrowed to the solid Earth. The *Treatise on Geophysics* discusses the atmosphere, ocean, and plasmasphere of the Earth only in connection with how these parts of the Earth affect the solid planet. While the realm of geophysics has here been narrowed to the solid Earth, it is broadened to include other planets of our solar system and the planets of other stars. Accordingly, the treatise includes a volume on the planets, although that volume deals mostly with the terrestrial planets of our own solar system. The gas and ice giant planets of the outer solar system and similar extra-solar planets are discussed in only one chapter of the treatise. Even the *Treatise on Geophysics* must be circumscribed to some extent. One could envision a future treatise on Planetary and Space Physics or a treatise on Atmospheric and Oceanic Physics.

Geophysics is fundamentally an interdisciplinary endeavor, built on the foundations of physics, mathematics, geology, astronomy, and other disciplines. Its roots therefore go far back in history, but the science has blossomed only in the last century with the explosive increase in our ability to measure the properties of the Earth and the processes going on inside the Earth and on and above its surface. The technological advances of the last century in laboratory and field instrumentation, computing, and satellite-based remote sensing are largely responsible for the explosive growth of geophysics. In addition to the enhanced ability to make crucial measurements and collect and analyze enormous amounts of data, progress in geophysics was facilitated by the acceptance of the paradigm of plate tectonics and mantle convection in the 1960s. This new view of how the Earth works enabled an understanding of earthquakes, volcanoes, mountain building, indeed all of geology, at a fundamental level. The exploration of the planets and moons of our solar system, beginning with the Apollo missions to the Moon, has invigorated geophysics and further extended its purview beyond the Earth. Today geophysics is a vital and thriving enterprise involving many thousands of scientists throughout the world. The interdisciplinarity and global nature of geophysics identifies it as one of the great unifying endeavors of humanity.

The keys to the success of an enterprise such as the *Treatise on Geophysics* are the editors of the individual volumes and the authors who have contributed chapters. The editors are leaders in their fields of expertise, as distinguished a group of geophysicists as could be assembled on the planet. They know well the topics that had to be covered to achieve the breadth and depth required by the treatise, and they know who were the best of their colleagues to write on each subject. The list of chapter authors is an impressive one, consisting of geophysicists who have made major contributions to their fields of study. The quality and coverage achieved by this group of editors and authors has insured that the treatise will be the definitive major reference work and textbook in geophysics.

Each volume of the treatise begins with an 'Overview' chapter by the volume editor. The Overviews provide the editors' perspectives of their fields, views of the past, present, and future. They also summarize the contents of their volumes and discuss important topics not addressed elsewhere in the chapters. The Overview chapters are excellent introductions to their volumes and should not be missed in the rush to read a particular chapter. The title and editors of the 10 volumes of the treatise are:

Volume 1: Seismology and Structure of the Earth
Barbara Romanowicz
University of California, Berkeley, CA, USA
Adam Dziewonski
Harvard University, Cambridge, MA, USA

Volume 2: Mineral Physics
G. David Price
University College London, UK

Volume 3: Geodesy
Thomas Herring
Massachusetts Institute of Technology, Cambridge, MA, USA

Volume 4: Earthquake Seismology
Hiroo Kanamori
California Institute of Technology, Pasadena, CA, USA

Volume 5: Geomagnetism
Masaru Kono
Okayama University, Misasa, Japan

Volume 6: Crustal and Lithosphere Dynamics
Anthony B. Watts
University of Oxford, Oxford, UK

Volume 7: Mantle Dynamics
David Bercovici
Yale University, New Haven, CT, USA

Volume 8: Core Dynamics
Peter Olson
Johns Hopkins University, Baltimore, MD, USA

Volume 9: Evolution of the Earth
David Stevenson
California Institute of Technology, Pasadena, CA, USA

Volume 10: Planets and Moons
Tilman Spohn
Deutsches Zentrum für Luft-und Raumfahrt, GER

In addition, an eleventh volume of the treatise provides a comprehensive index.

The *Treatise on Geophysics* has the advantage of a role model to emulate, the highly successful *Treatise on Geochemistry*. Indeed, the name *Treatise on Geophysics* was decided on by the editors in analogy with the geochemistry compendium. The *Concise Oxford English Dictionary* defines treatise as "a written work dealing formally and systematically with a subject." Treatise aptly describes both the geochemistry and geophysics collections.

The *Treatise on Geophysics* was initially promoted by Casper van Dijk (Publisher at Elsevier) who persuaded the Editor-in-Chief to take on the project. Initial meetings between the two defined the scope of the treatise and led to invitations to the editors of the individual volumes to participate. Once the editors were on board, the details of the volume contents were decided and the invitations to individual chapter authors were issued. There followed a period of hard work by the editors and authors to bring the treatise to completion. Thanks are due to a number of members of the Elsevier team, Brian Ronan (Developmental Editor), Tirza Van Daalen (Books Publisher), Zoe Kruze (Senior Development Editor), Gareth Steed (Production Project Manager), and Kate Newell (Editorial Assistant).

G. Schubert
Editor-in-Chief

Contributors to Volume 5

W. Baumjohann
Space Research Institute, Austrian Academy of Sciences, Graz, Austria

J. E. T. Channell
University of Florida, Gainesville, FL, USA

C. Constable
University of California at San Diego, La Jolla, CA, USA

S. Constable
University of California, San Diego, La Jolla, CA, USA

D. J. Dunlop
University of Toronto, Toronto, ON, Canada

D. A. D. Evans
Yale University, New Haven, CT, USA

C. C. Finlay
ETH Zürich, Zurich, Switzerland

J. S. Gee
University of California, San Diego, La Jolla, CA, USA

G. Hulot
Institut de Physique du Globe de Paris/CNRS and Université Paris 7, Paris, France

A. Jackson
ETH Zürich, Zurich, Switzerland

C. L. Johnson
University of British Columbia, Vancouver, BC, Canada

D. V. Kent
Rutgers University, Piscataway, NJ, USA

J. L. Kirschvink
California Institute of Technology, Pasadena, CA, USA

M. Kono
Okayama University, Misasa, Japan

C. Laj
Laboratoire des Sciences du Climat et de l'Environment, Unité Mixte CEA-CNRS-UVSQ, Gif-sur-Yvette, France

P. McFadden
Geoscience Australia, Canberra, ACT, Australia

R. Nakamura
Space Research Institute, Austrian Academy of Sciences, Graz, Austria

N. Olsen
Danish National Space Center/DTU and Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

Ö. Özdemir
University of Toronto, Toronto, ON, Canada

M. E. Purucker
Goddard Space Flight Center/NASA, Greenbelt, MD, USA

J. L. Rasson
Institut Royal Meteorologique, Dourbes, Belgium

T. D. Raub
Yale University, New Haven, CT, USA

C. V. Reeves
Earthworks BV, Delft, The Netherlands

T. J. Sabaka
Raytheon at NASA Goddard Space Flight Center, Greenbelt, MD, USA

L. Tauxe
University of California San Diego, La Jolla, CA, USA

G. M. Turner
Victoria University of Wellington, Wellington, New Zealand

K. A. Whaler
University of Edinburgh, Edinburgh, UK

T. Yamazaki
Geological Survey of Japan, Tsukuba, Ibaraki, Japan

EDITORIAL ADVISORY BOARD

Contents

5.01 Geomagnetism in Perspective

M. Kono, Okayama University, Misasa, Japan

5.01.1 Early History

The Earth has its own magnetic field (the geomagnetic field), which is confined by the action of the solar wind into a volume called the magnetosphere (*see* Chapter 5.03). This field is not steady, but varies with time due partly to the interaction with the solar wind, but more importantly by its own physical processes. Direct observation of such changes has been carried out only in the last few centuries, but with indirect measurements we can understand the field behavior millions of years back in time. In this extended time frame, there is evidence that the polarity of the magnetic field reversed frequently, and that the magnetic dipole axis in very ancient times was significantly displaced from the present rotational axis (the North and South geographic Poles).

It is of considerable interest how such knowledge was acquired over several centuries. We will take a brief tour of the historical events that provided important steps in formulating our understanding of the geomagnetic field. In doing so, we have to rely solely on the written records, which is the reason why only the European and Chinese histories are referred. There are many works on this topic; among them, the important ones are Mitchell (1932–46), Harradon (1943–45), Needham (1962), and Yamamoto (2003). The English translations of Chinese literature below were taken from Needham (1962). Chinese sentences given together with English were taken from the Japanese translation of this book (Hashimoto *et al.*, 1977).

When we talk about the earliest recognition of the magnetism of the Earth, we should be careful to discriminate two separate issues; that is, the attractive force exerted by a magnet on iron, and the north- (or south-) seeking property of the magnet. The former can be taken as the forerunner to the science of magnetism, while the latter is the basis for appreciation of the magnetic field associated with the Earth. Our main interest is in the geomagnetic field, but it is necessary to look into magnets first.

5.01.1.1 Attractive Force of the Magnets

The earliest observation of the natural magnets (lodestone or loadstone) is attributed to the Greek philosopher Thales of Miletos (624–546 BC). Thales did not leave any writings of his own, but Aristoteles (384–332 BC) wrote about him in *De Anima* ('On the soul') about two centuries later. According to this, Thales taught that the lodestone has a soul, because it could set another body (iron) in motion. Diogenes Laertius also wrote that Thales admitted that souls exist even in nonliving matters based on the observation that the magnets and ambers can attract things. This suggests that Thales knew not only about the attractive force of magnets, but also that due to the static electricity of ambers, that can be seen when they are rubbed by clothes (Mitchell, 1937).

References to the attractive force of magnets appear quite often in Greek manuscripts (e.g., Platon, Aristoteles, Democritus, Lucretius), and there is no doubt that this force was well known to the ancient Greeks. This may be because the attractive force appeared to them as a very remarkable phenomenon since it can act on materials which are not in contact. In these, the magnets were referred to mostly as the rock of Magnesia (λιθος μαγνησιη). Magnesia is the name of a place either in Macedonia, Crete, or Asia Minor. The names of magnetism as well as magnetite (Fe_3O_4) were derived from this Greek word.

Ancient Chinese people made similar observations, but the records are somewhat later than the corresponding Greek ones. In *Lü Shih Chhun Chhiu* 呂氏春秋 (Master Lü's Spring and Autumn Annals), written in the late third century BC, it is said that "the lodestone calls the iron to itself, or attracts it" 慈石召鐵、或引之也. After that, reference to magnets appear abundantly in the Chinese literature (e.g., *Huai Nan Tzu* 淮南子 (The Book of Huai Nan) in the first century BC, and *Lun Hêng* 論衡 (Discourses Weighed in the Balance) in 83 AD).

The attractive force that magnets exert on iron was a wonder in ancient times, and it was often attributed to magical power. Its full understanding had to wait until the nineteenth century when the magnetic force was explained by physical theorems such as Ampère's and Gauss's laws in the framework of electromagnetic theory.

5.01.1.2 Early Chinese Compasses

The fact that magnets have the property to align in the north–south direction was discovered by the ancient Chinese. From about the second century AD, there are many Chinese texts referring to "south-pointing carriage" which, in many instances, were described as guiding the soldiers in thick fogs to the right direction to beat the enemies. Many people thought that this was a device that used the property of magnets. However, it is now considered to be some mechanical device made up of gears and axles rather than an instrument similar to a magnetic compass (Needham, 1962). A more interesting sentence appears in the above-mentioned *Lun Hêng* (AD 83), which means that "when the south-controlling ladle is thrown upon the ground, it comes to rest pointing at the south" 司南之杓。投之於地。其柢指南. Wang Chen-To (1948) suggested that the first two letters (south-controlling) were changed in the process of hand copying from the original 'south-pointing', the fourth letter (ladle) means a spoon worked out from a lodestone into that shape, and the eighth letter (ground) actually indicates a diviner's board. Now, a diviner's board was used in ancient China for the purpose of telling fortunes, and it is inscribed with the constellation of Great Bear in the center, and the names of 24 directions on the circle around it. With these interpretations, the sentence can be taken to describe an instrument for seeking south using a magnet! Note that the Great Bear is the symbol of the pole and the spoon also has a shape reminiscent of its form.

Wang (1948) went further to show the credibility of his interpretation, by making a model of this instrument, with a bronze earth-plate and a spoon cut from the lodestone (see **Figure 1**). A photo of the actual instrument is shown in Needham (1962) and reproduced in Merrill *et al.* (1996). When Needham visited China, he was shown by Wang Chen-To himself the experiment in which the lodestone spoon gradually rotated to the southward direction and settled there. Although this effort is very impressive, it is rather doubtful if Chinese at this early age really used an instrument which can be identified as the ancestor of the magnetic compass. The interpretation, as suggested by Wang, is not completely convincing. Moreover, there is a conspicuous absence of the references to compass-like instruments for about a thousand years afterwords.

A well-known early record about the magnetic compass is *Mêng Chhi Pi Than* 夢溪筆談 (Dream Pool Essays) written by Shen Kua 沈括 at about 1088 AD. In this book, it is said that "Magicians rub the point of a needle with the lodestone; then it is able to point to the south. But it always inclines slightly to the east, and does not point directly at the south" 方家以磁石磨針鋒。則能指南。然常微偏東。不全南也。 The text explains how to make a magnetic needle, its south-seeking property, and moreover the fact that there is slight difference between the true south and its pointing direction (i.e., the first mention of the declination). Shen Kua further says that "It is best to suspend it by a single cocoon fibre of new silk attached to the centre of the needle by a piece of wax the size of a mustard-seed – then, hanging in a windless place, it will always point to the north" 以芥子許蝋綴於針腰。無風處懸之。則針常指南. This is the earliest written record about the magnetic compass using a magnetic (magnetized) needle.

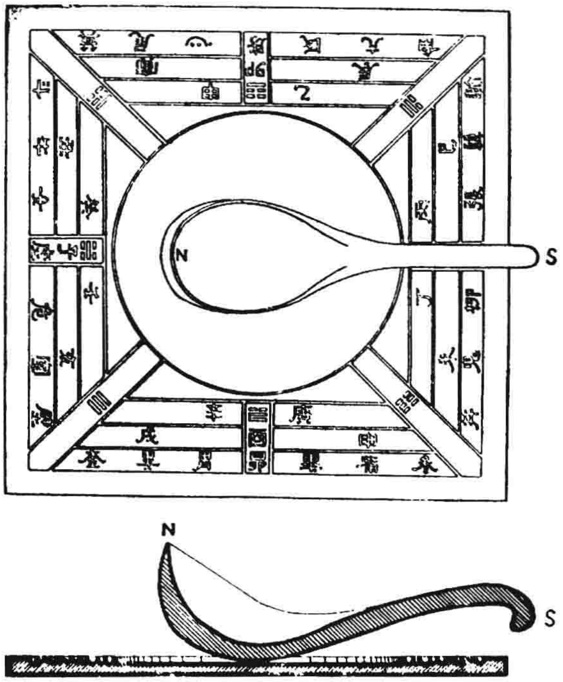


Figure 1 An ancient Chinese compass with the lodestone cut in the shape of a spoon, restored by Wang (1948).

Regarding the oldest compass, existence of an even earlier record was pointed out also by Wang (1948). The text was found in *Wu Ching Tsung Yao* 武經總要 (Collection of the Important Military Techniques) which is a compendium of military technology edited by Tsêng Kung-Liang 曾公亮 and completed in 1044. In this, it is said that "When troops encountered gloomy weather or dark nights, and the directions of space could not be distinguished, they let an old horse go on before to lead them, or else they made use of the south-pointing carriage, or the south-pointing fish to identify the directions." 若遇天景曀霾夜色暝黑。又不能辨方向。則當縱老馬前行令識道路。- 或出指南及指南魚。以辨所向。 After that, how to make this fish is described. "Now the carriage method has not been handed down, but in the fish method a thin leaf of iron is cut into the shape of a fish two inches long and half an inch broad, having a pointed head and tail. This is then heated in a charcoal fire, and when it has become thoroughly red-hot, it is taken out by the head with iron tongs and placed so that its tail points due north. In this position, it is quenched with water in a basin, so that its tail is submerged several tenth of an inch. It is then kept in a tightly closed box. To use it, a small bowl filled with water is set up in a windless place, and the fish is laid as flat as possible upon the water-surface so that it floats, whereupon its head will point south".

Apparently, this magnetic pointer (fish) is given a thermoremanent magnetization (TRM) by quenching from high temperature and keeping it in the north–south direction. The record is very convincing as the description is detailed as well as correct. This communication can be taken as the first description

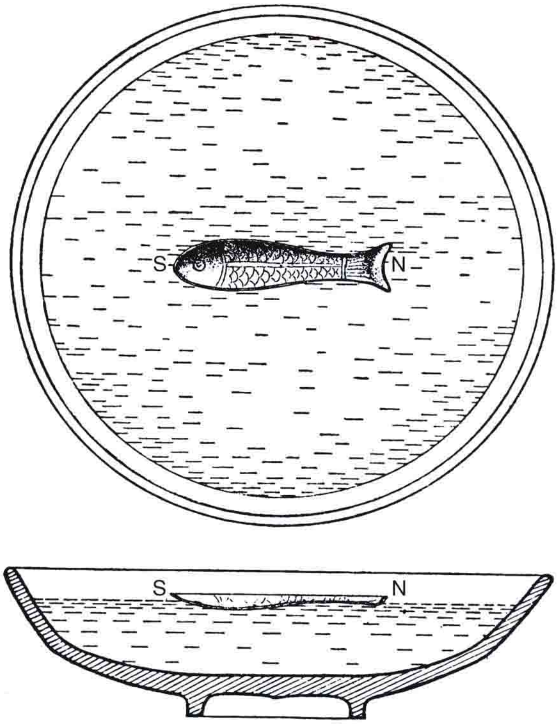


Figure 2 Illustration of a Chinese fish compass by Wang (1948).

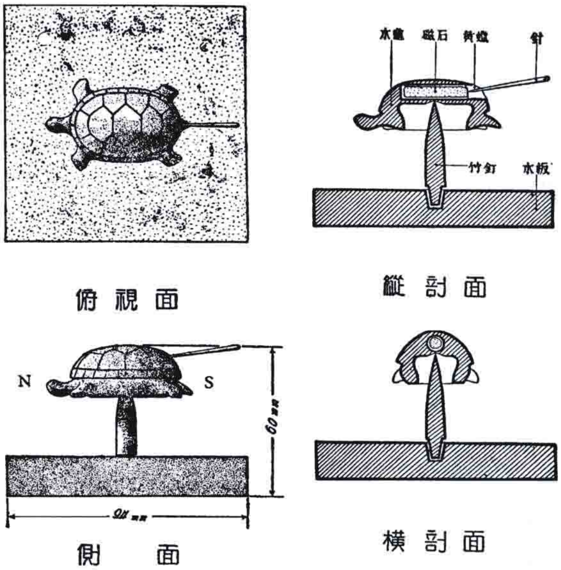


Figure 3 Illustration of a Chinese turtle compass by Wang (1948). Clockwise from top left, plan view, length-wise section, transverse section, and side view.

of the magnetic compass (wet type). **Figure 2** shows Wang's reconstruction of this compass.

The dry pivoted compass was described in *Shih Lin Kuang Chi* 事林廣記 (Guide through the Forest of Affairs), an encyclopedia compiled around 1150 by Chhen Yuan-Ching 陳元青見. In this compass, an wooden turtle has a tail made of a magnetic needle. A thin bamboo stick stands from the baseboard and holds the turtle at the hole made in its belly. The turtle rotates and points to the north because of the magnetic needle (**Figure 3**).

5.01.1.3 Magnetic Compass in European Documents

It is not clear when the knowledge of the magnetic compass reached Europe, and when it was first used in navigation. Gilbert wrote that it was brought to Europe by the Venetian Marco Polo, but there is evidence that the compass was used well before his return to Europe in 1295. It is often thought that the knowledge of the compass came from China through the intermediary of the Islam civilization. There is no written evidence, however, and the appearance of the compass is earlier in European documents than in Islamic ones (Mitchell, 1932; Needham, 1962).

The earliest record of the north–south-seeking property of the compass in Europe appears to be that of Alexander Neckham (1157–1217) of St. Albans, England. In two treatises, *De Utensibibus* and *De Naturis Rerum* written about 1190, he described the use of the magnetic needle in navigation to indicate north, and that the needle is put on a pivot which may be the form of a primitive compass (Mitchell, 1932). Guyot de Provins of France (1184–1210) wrote a poem called *La Bible* around 1205, in which he described a floating compass. Jacques de Vitory of Kingdom of Jerusalem (1165–1240) left a similar document (*c.* 1218). These people were all monks or priests, and they only referred to the compass as having the noble property (to point always to the same direction). It is therefore natural to think that the properties of the compass were known to mariners well before it became popular so that the priests could use it for allegory in these writings (Mitchell, 1932).

5.01.1.4 *Epistola* of Petrus Peregrinus

Petrus Peregrinus (Roman name for Pierre Pélerin) wrote *Epistola* (*Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt militem: De magnete*, Letter of

Pierre Pélerin of Maricourt to Sygerus of Foucaucourt, soldier, concerning the magnet) in 1269, while he took part in the siege of the southern Italian town of Lucera, by the army of Charles the Count of Anjou. Maricourt and Foucaucourt are names of towns in Picardy, France. It has the form of a letter (*Epistola*) to a soldier called Sygerus of Foucaucourt. Although it was not published in printed form until 1558, many hand copies were circulated widely in western Europe in medieval times. In this booklet (**Figure 4**), Peregrinus explained various properties of the magnet (lodestone) based on experimental observations. In fact, this can be regarded as the first scientific treatise describing observations and experiments carried out for the purpose of clarifying natural phenomenon. The conclusions were derived logically based on observations and experiments.

The *Epistola* is composed of two parts. The first part is made up of 10 chapters, in which properties of magnets are discussed. The second part covers the technical use of the magnets, such as the construction of a magnetic compass. The second part also contains a discussion of a perpetual motion machine using magnets. This is certainly invalid from the present-day knowledge of physics, but it cannot be blamed as an error, because it was written long before the concepts of thermodynamics or energy conservation were formed.

All of the material written in *Epistola* may not have been discovered by Peregrinus himself (Harradon, 1943), but this does not decrease the importance of *Epistola* as the first scientific paper in the human history. The most important properties of magnets described by Peregrinus were as follows.

1. *Finding the two magnetic poles*: To show that a magnet has two poles, grind and polish the magnet into a spherical shape. Next, put a small needle-shaped iron on this sphere, and write a line along its direction dividing the sphere into two equal parts (this defines a magnetic meridian). Move the needle to a different position and write the second division line. Peregrinus noted that, even if the above process is repeated at many places, all the lines meet at the same point on the sphere. The intersection of great circles defines two poles, the north and south magnetic poles.
2. *Determination of the polarity of the poles*: To determine which is the north and which is the south pole, place a magnet on a wooden plate which floats on the water surface in a large-enough container. After some time, the magnet settles into a north–south direction, and thus the north and south magnetic poles can be determined. This method is quite similar to the method of using a natural magnet as a compass (to put on water a wooden fish containing a natural magnet) in Chinese documents (see **Figure 2**). Peregrinus concludes that the magnet rotates so that the two poles are in the same direction as the celestial poles.
3. *Forces between two magnetic poles*: Using two magnets with poles marked as above, one magnet floating on the water and another held by a hand, it can be shown that the two poles attract each other if the S pole of the second is brought near the N of the first, or vice versa. On the other hand, they repel each other if the two poles are of the same polarity (N to N, or S to S).
4. *A magnetic pole cannot be isolated*: To show this, Peregrinus describes an experiment of cutting the magnet into two halves. Then, new poles appear at the cut end. The polarity of these new poles are opposite to the one at the other end of the cut pieces,


PETRI PEREGRINI
MARICVRTENSIS
De Magnete, ſeu Rota perpe-
tui motus, libellus.
Diui FERDINANDI Rho
manorum Imperatoris auſpi-
cio, per Achillem P. Gaſſerum
L. nunc primum pro-
mulgatus.

AVGSBVRGI IN
SVEVIS.
Anno Salutis
1558.

Figure 4 The title page of *Epistola*.