



Michael E. Evans Friedrich Heller

Environmental Magnetism

Principles and Applications
of Enviromagnetics



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Michael E. Evans
*University of Alberta
Edmonton, T6G 2J1 Canada*

Friedrich Heller
*Swiss Federal Institute of Technology Zürich
8093 Zürich, Switzerland*



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Environmental Magnetism

This is Volume 86 in the
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A complete list of books in this series appears at the end of this volume.

Foreword

Perhaps it is best to confess right away my personal perspective on Forewords: in other words, what a Foreword is and isn't. It definitely is not a "book review"; instead it should be a welcoming invitation for the reader to the contents of the book and its special character, avoiding as much as possible the opprobrium of being dubbed an "advertising copy," a gushing and uncritical paean of praise. It is also more fun to write a Foreword, especially in this case because I have had the good fortune of knowing the two authors for over three decades. I met Ted Evans when he came to his first meeting of the American Geophysical Union in the heady early days of global plate tectonics. I remember having animated discussions about the reality of the natural submicrometer-sized magnetite grains in basalts, whose presence he had to infer from single domain-like magnetic properties. They were too small to be studied by an optical microscope; however, in a couple of years he and M.L. Wayman took transmission electron micrographs to prove the existence of natural single domain magnetite, a much sought after but also much missed natural magnetic carrier. In Friedrich Heller's case, what caught my attention was his work on the basalts used to construct Hadrian's Wall near the boundary between Scotland and England. Through a laboratory study of acquisition of viscous magnetization in a known field, Heller and Markert could "date" the placement of the basalts in the wall from their natural (viscous) magnetization. It thrilled me that in both cases purely magnetic measurements could lead to applications in mineralogy and archaeology. It is only natural then that, some thirty years later, these two authors and long-standing friends of each other have joined forces to write the first authoritative "how to" book on Environmental Magnetism.

As Evans and Heller recall in their preface, this interdisciplinary field of scholarly inquiry was born only in 1986, with the publications of the eponymous monographs by R. Thompson and F. Oldfield. And yet, while this latter book was a collection of novel applications of magnetism to lake and fluvial sediments, the present volume is more of a consolidated description, from basics to applied, of a mature discipline. In some ways, another recent monograph, *Quaternary Climates, Environments and Magnetism*, edited by B. Maher and R. Thompson, is the true descendant of Thompson and Oldfield's *Environmental Magnetism*. The present volume could be used as a textbook for beginning graduate students with a background in college physics, as well as for specialists in biology, archaeology, or atmospheric pollution, or for others who are curious about the strengths and weaknesses of environmental magnetism as a tool of choice. I cannot help mentioning, tongue in cheek, that while perusing this

volume, the readers will also gather a great vocabulary, with the likes of cardiomagnetism, pneumomagnetism, malacology, magnetoclimatology and phreatomagmatism. (I think I know which of my two friends is responsible for including these terminologies, a “hazard” of interdisciplinary research.) One other related volume comes to mind, D. Dunlop and Ö. Özdemir’s *Rock Magnetism: Fundamentals and Frontiers*. Readers with a background in physics, whose taste may be whetted by this volume, would do well to consult Dunlop and Özdemir for explanations with greater depth and subtlety than the present volume, whose emphasis lies in clarifying the interdisciplinary connection.

And, speaking of such connections, it is necessary once more to emphasize the broad sweep of the topics covered in this book. From pedologists to geomorphologists, isotope geochemists to microbiologists, all will have an opportunity to truly appreciate what environmental magnetic techniques can or cannot do, and *why*. In the future, when one more marine geologist asks me whether sediment magnetic susceptibility is directly or inversely proportional to paleotemperature, I will enjoy saying, “Neither; why don’t you look up Evans and Heller?” Somehow the importance of first constructing an intelligent model of the natural process before interpreting environmental magnetic parameters has not been communicated well enough to the geoscience community. Evans and Heller have done a wonderful job of providing examples to do just that, and do it well.

Colleagues, raise your glasses with your fluid of choice to this timely, comprehensive, and comprehensible work!

Subir K. Banerjee
Institute for Rock Magnetism
University of Minnesota—Twin Cities
U.S.A.

Preface

Environmental magnetism is a relatively new science. It essentially grew out of numerous interdisciplinary studies involving sediments in British lakes, but soon expanded to include sediments in other natural archives that also retain records of past global changes. Prominent among these are marine sediments, windblown deposits on land, and the thin layer of soil covering much of the continents. The materials residing in these various settings are of two main types: one transported in from elsewhere, the other created *in situ*. Material flux takes place in the hydrosphere, the atmosphere, and the cryosphere, the most important agents being rivers, ocean currents, ground water, wind, rain, snow, glaciers, ice sheets, and icebergs. We will be looking at examples of all of these.

For the most part, the transported material itself exists in granular or particulate form, typically in the size range 10^{-4} – 10^{-5} m. Depending on the ambient conditions, these mineral grains may suffer some chemical change (such as oxidation) during transport and deposition, but by and large they are passive and inert. However, once they are in place, many chemical changes may occur. Indeed, some grains may entirely disappear while others may be created. This is particularly so in soils (the pedosphere), which harbor a complex interplay of chemical, physical, and biological activity. Whatever the particular history of a given geological repository, experience shows that magnetic measurements can be of great value in our attempts to understand the environmental conditions that prevailed in the past. This is because magnetic minerals—particularly iron oxides—occur more or less universally, iron being one of the most common elements in the Earth's crust. They may be present in minor amounts (usually less than 1%), but they are easily, rapidly, and nondestructively detected.

Early developments along these lines were brought together in the seminal 1986 textbook, *Environmental Magnetism*, by Roy Thompson and Frank Oldfield that marked the real birth of the subject. From this promising beginning, the subject has matured into a full-fledged scientific discipline practiced throughout the world. By the mid-1990s, the level of activity was such that an updated review was provided by Verosub and Roberts (1995). Furthermore, specialized laboratories were coming on stream, entire conferences were being devoted to the latest advances, and the relevant literature was growing exponentially. At the start of a new millennium, the time seemed ripe for a new, state-of-the-art summary and analysis.

Anyone setting out to cover such a broad subject must endeavor to strike a balance between the underlying principles (which embrace physics, chemistry, biology, mineralogy, geography, geology, and geophysics) and the major applications

(which range from archeology to zoology). Our goal has been to provide sufficient groundwork to allow advanced undergraduates, graduate students, and interested professionals (all of diverse backgrounds) to grasp the essential aspects of magnetism, mineralogy, and the many processes by which the observed magnetic signals are encoded in the various natural archives. The latter half of the book then introduces a wide selection of real examples chosen to reflect the diversity of topics that lend themselves to enviromagnetic analysis. In addition to various aspects of past global change (e.g., ice ages, Milankovitch theory, paleoprecipitation), these cover the assessment of material flux by various agents (e.g., wind, ground water, ocean currents) in different environments, magnetism in the biosphere (e.g., magnetotactic bacteria, cardiomagnetism, homing pigeons), pollution monitoring (e.g., soil contamination, sewage outfall, pneumomagnetism), and archeology (e.g., magnetic mapping, speleomagnetism, hominid evolution). Finally, we close by stepping back, as it were, and taking an overview of the Earth's magnetic environment in order to place the whole subject into its planetary perspective.

The exponential increase in publications that was occurring when we set out to write this book has continued unabated, and we have been compelled to be selective. Even so, the bibliography contains in excess of 600 entries, three quarters of which were published in the years since Thompson and Oldfield's book appeared.

We are grateful to Frank Cynar, who first invited us to embark on this project and who has been a constant source of encouragement and guidance throughout. Likewise, we are indebted to the entire production team: Angela Dooley, Jennifer Helé, Kelly Mabie, and Nancy Zachor—without their skill and dedication, our efforts would never have come to fruition.

We thank the many friends and colleagues who have helped us by providing data, photographs, figures, and other information: Geoff Bartington, Cathy Batt, Teresa Bingham-Müller, Ulrich Bleil, Jan Bloemendal, Mark Dekkers, Ramon Egli, Brooks Ellwood, Jörg Fassbinder, Fabio Florindo, Maja Haag, Paul Hesse, Kalevi Kalliomäki, Karen Kohfeld, Kurt Konhauser, Masuru Kono, Carlo Laj, Jean-Louis Le Mouél, Neil Linford, Derek Lovley, Tadeusz Magiera, Jim Marvin, Adrian Muxworthy, Clare Peters, Nikolai Petersen, Chris Pike, Andrew Roberts, Joe Rosenbaum, Robert Scholger, Simo Spassov, Joe Stoner, Gerhard Stroink, Matsuori Torii, Piotr Tucholka, Hojatollah Vali, and Marianne Vincken.

We are grateful to Beat Geyer, Gerry Hoye, and Dean Rokosh for much help with the art work, always willingly, efficiently, and cheerfully carried out.

We thank our families for their constant understanding and moral support, particularly during the more difficult times. It is a special pleasure to record the joy and inspiration that the presence of little Andreas has provided.

The whole undertaking would never have been successfully concluded without the patience, encouragement, and unfailing support of Anita and Barbara, to whom we express our heartfelt gratitude.

Michael E. Evans and Friedrich Heller
Edmonton and Zürich, February 2003

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INTRODUCTION

1.1 PROSPECTUS

Our environment — be it local or global — is in need of care and attention. This brute fact has now forcefully registered itself in the minds of all people bent on survival — that is, most of us. A clear demonstration is provided by unprecedented attempts to reach international agreements — the Montreal Protocol, the Rio Summit, the Kyoto Accord. It is also the driving force behind an enormous range of scientific inquiry aimed at providing a better understanding of the complex interplay of factors which constitute what is now referred to as earth systems science, involving atmosphere, hydrosphere, biospheres, and lithosphere. Indeed, it is quite legitimate — perhaps even necessary — to extend the field of inquiry even further. The lithosphere is no more than a mosaic of slabs at the mercy of viscous upwelling and downwelling currents deeper in the Earth, in a region called the asthenosphere. At even greater depths is the liquid core, wherein complex motions generate the geomagnetic field, which, in turn, is responsible — through its interaction with the solar wind — for the magnetosphere. And so on . . .

This book is concerned with one tiny aspect of this vast interconnected web of scientific effort, namely the occurrence and uses of magnetic materials in the natural and cultural environment. At first sight, it is perhaps surprising that magnetism has become a useful topic in environmental studies. There are several reasons, the two most fundamental being that, first, *all* substances exhibit some form of magnetic behavior and, second, iron is one of the commonest elements in the Earth's crust. The former follows from the basic nature of matter, the latter from a cosmic accident. There are more practical considerations, however. With modern equipment, it is experimentally easy to detect useful magnetic signals from environmental materials, such as soils and various sediments, even if the magnetic component makes up less than a thousandth of the whole sample. Magnetism thus provides a tracer of environmental conditions. To make use of this tracer, however, knowledge of the magnetic substances involved and of their relevant magnetic properties is required. Furthermore, some understanding of the techniques used is necessary if the possibilities —

and limitations — of the subject are to be properly appreciated. All this groundwork occupies Chapters 2, 3, and 4.

The rest of the book is devoted to a discussion of the many applications of magnetic measurements in various environmental settings on land, in lakes, in the ocean, and even in various biological organisms (including humans). Once sequestered in a suitable host, magnetic particles constitute a natural archive of conditions existing in former times. If we can learn how to interpret such records, we have the possibility of investigating not only the present but also the past. Chapter 5 is concerned with the two central aspects of this goal, namely how the information was captured in the environmental record and how we can succeed in decoding what is there. An important aspect relates to the time dimension (Chapter 6). The next five chapters then discuss specific topics in which environmental magnetism is involved: paleoclimate (Chapter 7), mass transport (Chapter 8), biomagnetism (Chapter 9), pollution (Chapter 10), and archeology (Chapter 11). Finally, Chapter 12 gives a brief planetary perspective of our magnetic environment.

In order to explain the basic concepts, we often consider simplified situations, but a number of case histories are also brought into the discussion to guard against straying too far from harsh reality. These are chosen on pedagogic grounds, for the force with which they illustrate the point in question and not for their overall significance in the research spectrum. Hence they are not necessarily the first, nor the fullest, nor even the best-known examples. To redress the balance, we provide an extensive bibliography. There is now a vast corpus of published data from sites representing all environmental settings in all parts of the globe, with the result that even the bibliography is inevitably selective.

1.2 AN EXAMPLE

Before taking the plunge — wrestling with experimental details, digesting basic magnetic data, appreciating the significance of the case histories, and generally coming to terms with the subject as a whole — let us pause to consider an instructive example. We choose one with which we are personally familiar and which vividly illustrates the interconnectedness of the many topics impinging on environmental magnetism (Heller and Evans, 1995).

In parts of China, there exists a thick blanket of windblown dust that has accumulated over the last few million years and now stands at thicknesses commonly exceeding a hundred meters (Fig. 1.1). For millennia, this *huangtu* (yellow earth) has been the substrate on which civilizations have prospered, providing both the means of agricultural production and the raw material for domestic and artistic ceramics (including the celebrated terracotta army of the emperor Qin Shi Huang). In recent years, this material has attracted a great deal of scientific interest for another reason: stratigraphic fluctuations in the magnetic minerals it contains provide evidence of the waxing and waning of ice ages. Broadly speaking, sediments formed during cold, dry (glacial) times are about half as magnetic as their warm, moist (interglacial) counterparts. The magnetic minerals are essentially behaving like a combined geological

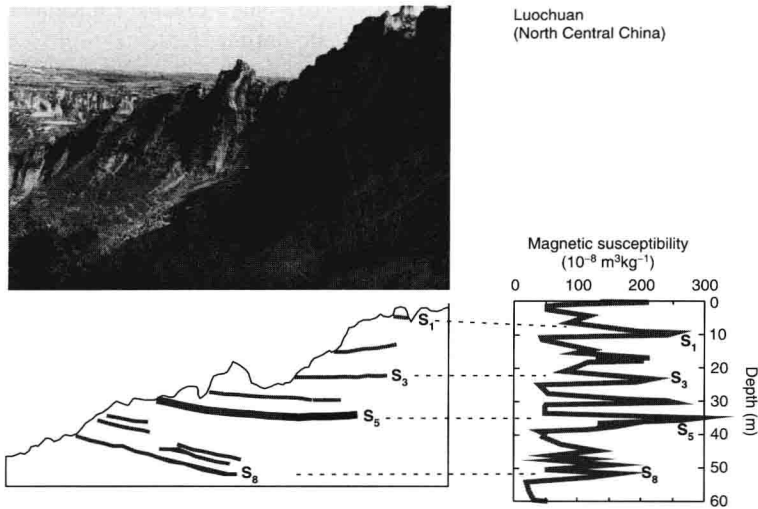


Figure 1.1 The famous sedimentary section at Luoquan, China. The alternating yellow and brown strata provide a visible manifestation of past climatic changes. During cold, dry glacial periods, windblown dust accumulates. When conditions become warmer and wetter, interglacial soils are formed, turning the yellow pristine dust a rich brown color. This process is dramatically reflected in the magnetic susceptibility variations shown in the depth profile at the lower right. Some of the prominent soils are indicated (strictly speaking, they should be referred to as buried fossil soils or paleosols). See color plate.

thermometer and rain gauge. If we were to succeed in calibrating it, actual quantitative estimates of ancient temperatures and precipitation would be forthcoming. In the meantime, we speak of the magnetism as a *paleoclimatic proxy*.

The ice ages themselves are driven by very small changes in the Earth's motion in space caused by gravitational attraction between the planets of the solar system. Detailed astronomical calculations show that the Earth's orbital parameters vary with certain specific periodicities (measured in tens to hundreds of thousands of years), and spectral analysis has shown that these periodicities can be identified in the magnetic profiles. Furthermore, the deposition of dust in China is strongly influenced by the Asian monsoonal atmospheric circulation system, which is one of two major systems controlling climate change in the northern hemisphere (the other being the North Atlantic air-ocean system). Magnetic data help demonstrate that the monsoon system itself has intensified over the last million years due to uplift of the Tibetan Plateau, which itself is driven by forces in the asthenosphere. Another crucial magnetic contribution concerns the thorny problem of how all these events can be properly arranged in geological time. Until about 20 years ago, the actual time span covered by these Chinese sediments was poorly known. Then it was discovered that, as well as carrying a paleoclimatic signal, these thick sequences of dust carry a record of the times when the Earth's magnetic field as a whole flipped polarity, magnetic north becoming magnetic south and vice versa. Because the times when these inversions took place are accurately known, they provide a suitable clock. Thus, we see

how the magnetism of the *huangtu* brings together such diverse topics as celestial mechanics, climatic variability, atmospheric circulation, plate tectonics, and the dynamics of the Earth's core. Not bad for a pile of dust!

1.3 SCOPE OF THE SUBJECT

Because all matter consists of atoms with circulating charged particles, everything in and around us is, strictly speaking, magnetic. However, for the moment, we need only note that environmentally important minerals, for our purposes, fall in the broad subset of materials exhibiting properties like those of iron—*ferromagnetism*. Pure elemental iron is found in meteorites and on the moon's surface, but it is extremely rare in terrestrial samples: there is too much oxygen around. Consequently, we need to consider certain compounds of iron, such as the iron oxide magnetite (Fe_3O_4).

How do such minerals get into environmental circulation in the first place? There are many sources. (1) They can be formed naturally as a small part of many igneous rocks, such as basalt. After erosional breakdown, these grains are released and eventually find their way into river catchments, from which they may be delivered to the sea or into lakes. In both cases, sediments are formed. (2) If geological circumstances change, these sediments may in time be eroded and subsequently redeposited. (3) Alternatively, mineral grains may find themselves in arid environments from which they may be entrained into the atmosphere and then deposited downwind—perhaps repeatedly. (4) Volcanic eruptions may produce ash clouds that deliver mineral particles directly to the atmosphere. (5) An entirely different source is biological, particularly from the so-called magnetotactic bacteria. These fascinating organisms create pure magnetite particles some tens of nanometers in diameter, which they use for navigational purposes. After death, the organic parts decay but the magnetic particles remain. (6) Complex chemical and biological processes involved in soil development are another important source of magnetic minerals in the environment. (7) Human activity also adds magnetic material to the environment as a result of the burning of fossil fuels and industrial activities such as steel production. This list is illustrative rather than exhaustive. It serves to indicate the wide variety of pathways that characterize environmental magnetism, and it makes clear the convenience of dealing with the available data in terms of particular environmental settings. Here is a quick preview of some of the topics covered in detail later:

- **Lakes** have long been appreciated as repositories of magnetic paleoenvironmental information (Thompson *et al.*, 1975). They are, however, often limited to relatively short times in the past—the last 10,000 years or so. On the other hand, this can provide high time resolution so that even historical events such as deforestation can be identified in the magnetic record. Some lake studies have managed to penetrate deeper into the past, as in the case of Lac du Bouchet in France (Thouveny *et al.*, 1994) and Lake Baikal in Siberia (Peck *et al.*, 1994). Magnetic data from these two investigations provide important proxies for climatic change over the past 140,000 years and 5 million years, respectively.