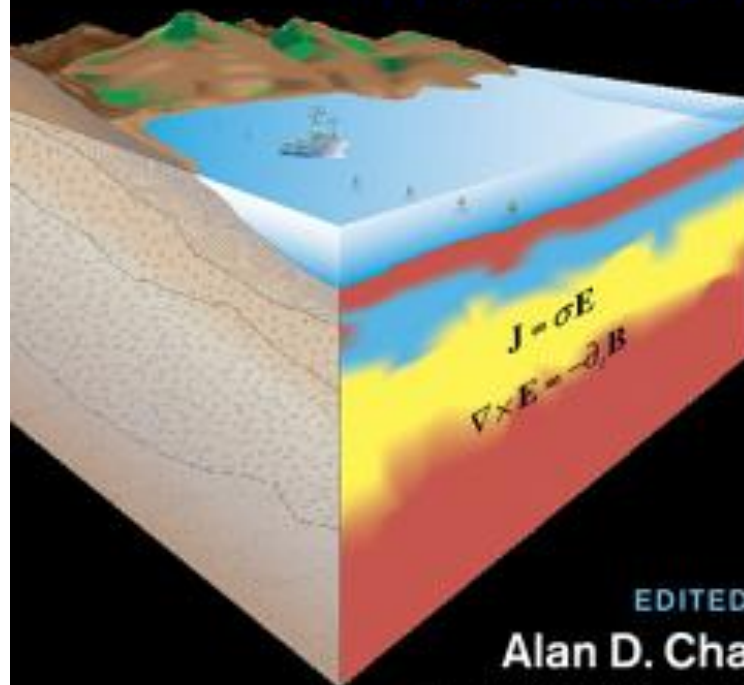


The Magnetotelluric Method

Theory and Practice



EDITED BY
Alan D. Chave
and Alan G. Jones

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THE MAGNETOTELLURIC METHOD

Theory and practice

The magnetotelluric method is a technique for imaging the electrical conductivity and structure of the Earth, from the near-surface down to the 410 km transition zone and beyond. It is increasingly used in geological applications and the petroleum industry. This book forms the first comprehensive overview of magnetotellurics, from the salient physics and its mathematical representation, to practical implementation in the field, data processing, modeling, and geological interpretation.

Electromagnetic induction in 1D, 2D, and 3D media is explored, building from first principles, and with thorough coverage of the practical techniques of time-series processing, distortion, numerical modeling and inversion. The fundamental principles are illustrated with a series of case histories describing geological applications. Technical issues, instrumentation and field practices are described for both land and marine surveys.

This book provides a rigorous introduction to the magnetotelluric method for academic researchers and advanced students, and will be of interest to industrial practitioners and geoscientists wanting to incorporate rock conductivity into their interpretations.

ALAN D. CHAVE is a Senior Scientist at Woods Hole Oceanographic Institution. He has also been a Chartered Statistician (UK) since 2003, and has taught a graduate-level course in statistics in the MIT/WHOI Joint Program for 20 years. For over 30 years, he has conducted research utilizing the magnetotelluric method, primarily in the oceans, and has pioneered research into producing modern magnetotelluric processing methods. Dr Chave has also designed instrumentation for optical and chemical measurements in the ocean, and has played a leadership role in developing long-term ocean observatories worldwide. He has been an editor of *Journal of Geophysical Research* and editor-in-chief of *Reviews of Geophysics*.

ALAN G. JONES is Senior Professor and Head of Geophysics at the Dublin Institute for Advanced Studies, and has been using magnetotellurics since the early 1970s. He has undertaken magnetotellurics in Europe, southern Africa, Canada and China, for problems ranging from the near-surface (groundwater contamination) to mining, geothermal studies and tectonics of the deep mantle (to 1200 km). He has been instrumental in many developments of magnetotellurics, from processing and analysis to modeling/inversion and interpretation. He was awarded the Tuzo Wilson Medal of the Canadian Geophysical Union in 2006, appointed to *Academia Europaea* in 2009, and made a member of the Royal Irish Academy in 2010.

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During the course of writing this book, we received the sad news of the death of Peter Weidelt while on a visit to Turkey, where he was planning to complete Chapter 4. Peter's influence on magnetotellurics was profound, as he was especially responsible for giving the method a rigorous mathematical and physical grounding that constitutes the basis for many of the developments of the past few decades. Peter was a humble and generous man whose scientific contributions and humanity are sorely missed. This book is dedicated with warmth to his memory and with respect to his legacy.



Picture taken by Bai Denghai at the Schmucker Symposium on 27 July 2009, just four days before Peter's untimely death.

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Preface

Just as electromagnetics was the last aspect of classical physics to be fully understood and theoretically described in the mid-nineteenth century, so was electromagnetics the last of the classical methods of physics to be utilized in geophysics, particularly exploration geophysics, to understand the Earth. Of the two basic types of electromagnetic methods, namely controlled-source and natural-source, this book describes the theory and application of natural-source electromagnetics, named “magneto-tellurics” ironically by a renowned seismologist, Louis Cagniard, in 1953, from “magneto” inferring magnetic fields and “telluric” inferring electric fields in the ground (*tellus*, Latin for “earth”). Magnetotellurics (the hyphen was dropped during the mid-1970s) has, since its early inception and embryonic years in the 1950s and 1960s, grown in stature to the extent that it is now a formidable geophysical tool for obtaining high-resolution information about the lateral and vertical variations in electrical conductivity that can be related to resources and geological processes.

This book was originally conceived as being written entirely by two people, but given the extensive breadth of the subject, they modestly decided that others needed to be invited to contribute chapters in their areas of specialty. Thus, the book comprises 10 chapters, each penned by one or more leading experts, and is organized in logical order (at least to the editors). The hope, of course, is that the whole is greater than the sum of its parts, such that the individual styles do not detract from the continuous theme.

The motivation behind the book is that there is no comprehensive and rigorous volume on modern magnetotellurics that is current, circumscribing today’s thinking, approaches and methods. The extensive review papers from the biennial “EM Induction Workshops” are excellent, but are not cohesive. The recent volume *Practical Magnetotellurics* by Fiona Simpson and Karsten Bahr, also published by Cambridge University Press, serves as a useful introductory text describing practical aspects, but is not as comprehensive.

The book is aimed to educate and inform at many levels. It is intended for the whole spectrum of readers, from the established practitioner in magnetotellurics, to graduate and advanced undergraduates in geophysics, to other geophysicists and other geoscientists. It can be read continuously, or can be read in parts, as the need arises.

Chapter 1, by Alan Chave and Alan Jones, provides an introduction to the book and particularly describes the historical perspective up to around 1960. A special place is

reserved for the role of the Japanese, whose investigations in the 1910s to 1940s have not been appreciated at the same level as the two papers, by Andrey Tikhonov and Louis Cagniard, that are often cited as establishing the field. Certainly, the Cagniard–Tikhonov magnetotelluric method should be renamed the Cagniard–Rikitake–Tikhonov method (the order of the names is immaterial, as the work was undertaken independently by all of them).

Chapter 2, by Chave and the late Peter Weidelt, describes the theoretical basis for magnetotellurics, starting with the Maxwell equations and working through one-, two- and three-dimensional (1D, 2D and 3D) solutions. The 1D magnetotelluric response is presented as a limiting case of a vertical magnetic dipole source, bringing out the role of a quasi-uniform source. Much of this is standard, but, for the first time in a book, a thorough treatment is presented of the electromagnetic fields produced by water motion.

Chapter 3 that follows – given the breadth of the topic, the Earth’s electromagnetic environment – is split into two parts. The first part, by Rob Evans, deals with laboratory studies of the electrical conductivity of rocks and minerals. This is a field that saw significant investment through the 1970s and 1980s, but suffered from quiescence through the 1990s. Encouragingly, there are more groups now undertaking measurements on rocks and understanding the physics of electrical conduction through them. In the second part, Ari Viljanen then follows by covering the nature and influence of external source currents flowing above Earth. For the most part, magnetotelluricists can reasonably assume a plane-wave model, but in equatorial and auroral latitudes this is not the case, and consideration has to be given to the effects of non-uniform sources.

Chapter 4, by Weidelt and Chave, gives a thorough treatment of the magnetotelluric response and magnetic transfer functions. The mathematical properties of the response function and its rotational invariants are explored in 1D, 2D and 3D. Chave also wrote Chapter 5, which follows on from Chapter 4 and describes the estimation of the response function using modern robust methods.

Chapter 6, by Jones, describes the next step in the logical chain of processing and analysis, which is evaluation of the derived response functions for distortion effects and its inherent dimensionality and directionality. Older magnitude-based methods are shown to be unsuitable, and newer phase-based methods are advocated.

Chester (Chet) Weiss penned Chapter 7, and presents the forward problem in magnetotellurics – determining the fields that would be observed given a particular conductivity distribution. Particular focus is given to the similarities and distinctions between finite differences and finite elements. Chapter 8 is concerned with the magnetotelluric inverse problem, and William (Bill) Rodi and Randall (Randy) Mackie describe various minimization algorithms in 1D and 3D.

The last two chapters that complete the book are concerned with practical aspects and the purposes of magnetotellurics, namely instrumentation and field procedures (Chapter 9) and case histories and geological applications (Chapter 10), authored by Ian Ferguson, with Jones and Chave also participating in the last chapter. It is hoped that those outside magnetotellurics will be enthralled by Chapter 10, and will appreciate what magnetotellurics can bring to addressing geological problems.

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Preface

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This book would not exist without the dedication, warmth and wisdom of those who were leaders of the field when the editors and chapter authors were young, aspiring students. To recognize some of these people always runs the danger of, by omission, inadvertently not recognizing others, but from a very personal perspective Alan Chave wishes to thank Chip Cox, Jean Filloux and Nigel Edwards, and Alan Jones wishes to recognize Rosemary Hutton, Ian Gough, Ulrich Schmucker and Peter Weidelt, who aided them in their training and development during their formative graduate and postgraduate years. The reviewers of the chapters of this book are all gratefully thanked for their generous advice. They were: Nestor Cuevas, Gary Egbert, Mark Everett, Colin Farquharson, Uli Matzander, Nils Olsen, Anne Pommier, Pilar Queralt, Art Richmond, Jeff Roberts, Weerachai Siripunvaraporn, David Thomson, Martyn Unsworth and John Weaver.

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