

THE MAGNETIC FIELD OF THE EARTH

Paleomagnetism, the Core, and the Deep Mantle

Ronald T. Merrill Michael W. McElhinny Phillip L. McFadden



INTERNATIONAL GEOPHYSICS SERIES, VOLUME 63



The Magnetic Field of the Earth

Paleomagnetism, the Core,
and the Deep Mantle

This is Volume 63 in the
INTERNATIONAL GEOPHYSICS SERIES
A series of monographs and textbooks
Edited by RENATA DMOWSKA and JAMES R. HOLTON

A complete list of books in this series appears at the end of this volume.

The Magnetic Field of the Earth

Paleomagnetism, the Core,
and the Deep Mantle

RONALD T. MERRILL

*Department of Geophysics
University of Washington
Seattle, Washington*

MICHAEL W. McELHINNY

*Gondwana Consultants
Hat Head, New South Wales
Australia*

PHILLIP L. McFADDEN


*Australian Geological Survey Organisation
Canberra, Australia*



ACADEMIC PRESS

San Diego London Boston New York Sydney Tokyo Toronto

The cover of this book shows the magnetic field for the Glatzmaier–Roberts dynamo at a time when the field is not undergoing a reversal (unpublished figure supplied to us by Glatzmaier, 1996). A change in color of the field lines indicates a change in the direction of the radial component of the magnetic field. On close inspection, the tangential cylinder is apparent in both the magnetic field (cover) and in the velocity field (Fig. 9.7).

This book is printed on acid-free paper. 

Copyright © 1996, 1983 by ACADEMIC PRESS

All Rights Reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopy, recording, or any information storage and retrieval system, without permission in writing from the publisher.

Portions of this work authored by Phillip McFadden may be reproduced in whole or in part for the Official use of the Government of the Commonwealth of Australia. This book is published with the permission of the Executive Director, Australia Geological Survey Organisation.

Academic Press, Inc.

525 B Street, Suite 1900, San Diego, California 92101-4495, USA
<http://www.apnet.com>

Academic Press Limited

24-28 Oval Road, London NW1 7DX, UK
<http://www.hbuk.co.uk/ap/>

Library of Congress Cataloging-in-Publication Data

Merrill, Ronald T.

The magnetic field of the earth : paleomagnetism, the core, and the deep mantle / by Ronald T. Merrill, Michael W. McElhinny, Phillip L. McFadden.

p. cm. -- (International geophysics series)

Includes bibliographical references and index.

ISBN 0-12-491245-1

1. Geomagnetism. 2. Paleomagnetism. 3. Dynamo theory (cosmic physics) I. McElhinny, M. W. II. McFadden, Phillip L. III. Title.

IV. Series.

QC816.M47 1996

538'.72--dc20

96-28566

CIP

PRINTED IN THE UNITED STATES OF AMERICA

96 97 98 99 00 01 QW 9 8 7 6 5 4 3 2 1

Contents

Preface

xiii

Chapter 1 History of Geomagnetism and Paleomagnetism

1.1 Discovery of the Main Magnetic Elements	1
1.1.1 The Magnetic Compass	1
1.1.2 Declination, Inclination, and Secular Variation	5
1.1.3 The Experiments of William Gilbert	6
1.1.4 Magnetic Charts and the Search for the Poles	7
1.2 Fossil Magnetism and the Magnetic Field in the Past	9
1.2.1 Early Observations	9
1.2.2 Reversals of the Magnetic Field	10
1.2.3 Secular Variation	10
1.2.4 Continental Drift	11
1.3 Investigations of the External Magnetic Field	13
1.3.1 Transient Magnetic Variations	13
1.3.2 Early Theories of Magnetic Storms and Auroras	14
1.3.3 The Magnetosphere	15
1.4 Origin of the Earth's Magnetic Field	17

Chapter 2 The Present Geomagnetic Field: Analysis and Description from Historical Observations

2.1 Magnetic Elements and Charts	19
2.2 Spherical Harmonic Description of the Earth's Magnetic Field	25

v

2.2.1	Scalar Potential for the Magnetic Field	25
2.2.2	Basics of Spherical Harmonics	26
2.2.3	Application of Spherical Harmonics to the Earth's Magnetic Field	28
2.2.4	Determination of the Gauss Coefficients	33
2.2.5	Interpretation of Spherical Harmonic Terms	34
2.3	Uniqueness and Other Mathematical Problems	37
2.3.1	Application of Laplace's Equation to the Earth	37
2.3.2	Approximation with a Truncated Series	38
2.3.3	Uniqueness of Source	41
2.3.4	Nonspherical Harmonic Representation of the Earth's Magnetic Field	42
2.3.5	Magnetic Annihilator	44
2.4	Geomagnetic Secular Variation	46
2.4.1	Overview	46
2.4.2	The Magnetic Jerk and Screening by the Mantle	47
2.4.3	Methods Used to Determine the Secular Variation	52
2.4.4	Drift of the Nondipole Field	53
2.4.5	Variations of the Dipole Field with Time	55
2.5	The External Magnetic Field	57
2.5.1	The Magnetosphere	57
2.5.2	The Ionosphere	60
2.5.3	Transient Magnetic Variations, Storms, and Substorms	61
2.5.4	Magnetic Indices	66
Chapter 3 Foundations of Paleomagnetism		
3.1	Rock Magnetism	69
3.1.1	Types of Magnetization Acquired by Rocks	69
3.1.2	Magnetic Hysteresis	71
3.1.3	The Demagnetizing Field and Magnetic Anisotropy	74
3.1.4	Single-Domain Theory for TRM	76
3.1.5	Classical Magnetic Domains	79
3.1.6	Modern Domain Concepts	81
3.2	Magnetic Mineralogy	83
3.2.1	Properties of Magnetic Minerals	83
3.2.2	The Magnetic Record in Rocks	87
3.3	Paleomagnetic Directions and Poles	89
3.3.1	Demagnetization Procedures, Remagnetization, and Consistency Checks	89

3.3.2 The Geocentric Axial Dipole Field Hypothesis	93
3.3.3 Standard Statistical Methods in Paleomagnetism	98
3.4 Paleointensity Methods	102
3.4.1 The Problem	102
3.4.2 Absolute Paleointensities I: The Modified Thellier Method	103
3.4.3 Absolute Paleointensities II: Shaw's Method	105
3.4.4 Relative Paleointensity Measurements	108
3.4.5 Dipole Moments	109
3.5 Age Determinations	110
3.5.1 Potassium–Argon and Argon Isotope Dating	111
3.5.2 Relative Age Determinations	113
Chapter 4 The Recent Geomagnetic Field: Paleomagnetic Observations	
4.1 Archeomagnetic Results	115
4.1.1 Evidence for Westward Drift	115
4.1.2 Motion of the Dipole Axis	118
4.1.3 Variations in the Dipole Moment	119
4.1.4 Deductions from Carbon-14 Variations	125
4.1.5 Dipole Moments before 10,000 yr B.P.	128
4.2 Analysis of Recent Lake Sediments	130
4.2.1 The Recording Mechanism in Lake Sediments	130
4.2.2 Relative Paleointensities	131
4.2.3 Analysis of Declination and Inclination	133
4.2.4 Westward Drift and Runcorn's Rule	136
4.2.5 Interpretations in Terms of Dipole Sources	139
4.2.6 Interpretations Using Spherical Harmonic Analysis	143
4.2.7 Interpretations in Terms of Dynamo Waves	143
4.2.8 Uncertainties in Interpretations of Secular Variation	147
4.3 Geomagnetic Excursions	148
4.3.1 Definition of Excursions	148
4.3.2 The Laschamp Excursion	149
4.3.3 Excursions Observed in Lake and Deep-Sea Sediments	151
4.3.4 Reversals or Excursions during the Brunhes Chron?	153
4.3.5 Models of Geomagnetic Excursions	154
4.4 The Geomagnetic Power Spectrum	155
4.4.1 Time Series Analysis	155
4.4.2 Spectrum from Historical Records	158

4.4.3 Spectrum from Lake Sediment Data	160
--	-----

Chapter 5 Reversals of the Earth's Magnetic Field

5.1 Evidence for Field Reversal	163
5.1.1 Definition of a Reversal	163
5.1.2 Self-Reversal in Rocks	164
5.1.3 Baked Contacts	166
5.1.4 Development of the Polarity Time Scale for the Past 5 Myr	168
5.1.5 Terminology in Magnetostratigraphy	171
5.2 Marine Magnetic Anomalies	172
5.2.1 Measurement and Calculation	172
5.2.2 Sea-Floor Spreading	175
5.2.3 Aspects of Magnetic Anomaly Interpretation	177
5.2.4 Extension of the Polarity Time Scale to 160 Ma	180
5.3 Analysis of Reversal Sequences	186
5.3.1 Independence of Polarity Intervals	186
5.3.2 Statistical Analysis of Reversal Sequences	188
5.3.3 Superchrons	196
5.3.4 Stability of Polarity States	197
5.3.5 Nonstationarity and Inhibition in the Reversal Record	199
5.3.6 Paleointensity and Reversals	203
5.3.7 Summary	204
5.4 Polarity Transitions	204
5.4.1 Recording Polarity Transitions	204
5.4.2 Intensity Changes	206
5.4.3 Directional Changes and Interpretations	209
5.4.4 Reversals and Secular Variation	214

Chapter 6 The Time-Averaged Paleomagnetic Field

6.1 Geocentric Axial Dipole Hypothesis	217
6.1.1 The Past Few Million Years	217
6.1.2 The Past 600 Million Years	222
6.1.3 Paleoclimatic Evidence	224
6.1.4 Longevity of the field	225
6.2 Second-Order Terms	227
6.2.1 The Problems in Time Averaging	227
6.2.2 Spherical Harmonic Analyses	228

6.2.3 The Past Five Million Years	232
6.2.4 Extension to 200 Ma	236
6.3 Variation in the Earth's Dipole Moment	238
6.3.1 Paleointensities and Dipole Moments	238
6.3.2 Absolute Paleointensities — The Past 10 Million Years	239
6.3.3 Relative Paleointensities — The Past Four Million Years	242
6.3.4 Variation with Geological Time	243
6.4 Paleosecular Variation from Lavas (PSVL)	247
6.4.1 Angular Dispersion of the Geomagnetic Field	247
6.4.2 Models of PSVL	249
6.4.3 Angular Dispersion of the Present Geomagnetic Field	255
6.4.4 The Past Five Million Years	257
6.4.5 A Pacific Dipole Window?	259
6.4.6 Variation with Geological Time	261
Chapter 7 Processes and Properties of the Earth's Deep Interior: Basic Principles	
7.1 Seismic Properties of the Earth's Interior	265
7.2 Chemical and Physical Properties	269
7.2.1 Composition	269
7.2.2 Physical Properties	273
7.2.3 Electrical Properties of the Lower Mantle	275
7.3 Thermodynamic Properties of the Earth's Deep Interior	277
7.4 Thermal History Models	281
7.5 Nondynamo Models for the Earth's Magnetic Field	285
7.5.1 Permanent Magnetization	285
7.5.2 Thermoelectric Effects	286
7.5.3 Other Mechanisms	287
7.6 Fluid Mechanics Fundamentals	288
7.6.1 The Navier–Stokes Equation and Boundary Conditions	288
7.6.2 Dimensionless Numbers	292
7.6.3 Instabilities	294
7.6.4 Turbulence	297
7.7 Energy Sources	300

Chapter 8 Introduction to Dynamo Theory

8.1 The Dynamo Problem	305
8.1.1 Disc Dynamos	305
8.1.2 Magnetohydrodynamics and Plasma Physics	307
8.1.3 The Earth Dynamo Problem	308
8.2 The Magnetic Induction Equation	309
8.2.1 Introduction	309
8.2.2 Physical Insight	312
8.3 The α- and ω-Effects of Dynamo Theory	317
8.3.1 α -Effect	317
8.3.2 The ω -Effect and a Heuristic $\alpha\omega$ -Dynamo	320
8.3.3 Dynamo numbers and α^2 - and $\alpha^2\omega$ -Dynamoes	322
8.4 Waves in Dynamo Theory	323
8.4.1 MHD Waves	323
8.4.2 Planetary Waves	328
8.5 Symmetries in Dynamo Theory	329
8.5.1 The Importance of Symmetries	329
8.5.2 The Dynamo Families	330
8.6 Theories for Geomagnetic Secular Variations and Magnetic Field Reversals	333
8.6.1 Secular Variation	333
8.6.2 Reversals	336

Chapter 9 Dynamo Theory

9.1 Vector Spherical Harmonics	339
9.1.1 The Helmholtz Theorem	339
9.1.2 Helmholtz Scalar Equation	340
9.1.3 Helmholtz Vector Equation	342
9.1.4 Free-Decay Modes	344
9.2 Kinematic Dynamoes	346
9.2.1 Toroidal and Poloidal Fields	346
9.2.2 Bullard–Gellman Models	347
9.2.3 Fast Dynamoes	351
9.3 Cowling's Theorem and Other Constraints	353
9.4 Turbulence in the Core	356
9.4.1 The α - and β -Effects	356

9.4.2 α^2 -Dynamos	359
9.5 Dynamo Waves	362
9.6 Dynamics of the Geodynamo	363
9.6.1 Taylor-State versus Model-Z Dynamos	363
9.6.2 Weak-Field Hydromagnetic Models	366
9.6.3 Strong-Field Models	370
9.6.4 The Role of the Inner Core	372
Chapter 10 The Magnetic Fields of the Sun, Moon, and Planets	
10.1 Origin of the Solar System	377
10.2 The Sun	381
10.2.1 General Properties	381
10.2.2 Solar Magnetic Field	383
10.2.3 Solar Magnetic Field Theory	391
10.3 The Moon	392
10.3.1 General Properties	392
10.3.2 The Lunar Magnetic Field	394
10.3.3 Lunar Rock Magnetism	397
10.3.4 Origin of the Ancient Lunar Magnetic Field	399
10.4 Meteorites	399
10.5 Magnetic Fields of the Planets	401
10.5.1 Planetary Magnetism	401
10.5.2 Solar System Dynamos	405
10.6 Geomagnetic Relevance	407
Chapter 11 Examples of Synthesis	
11.1 Fluid Velocities in the Core	409
11.1.1 Overview	409
11.1.2 The Uniqueness Problem	411
11.1.3 Models and Results	413
11.2 Core-Mantle Coupling: Length of Day	417
11.2.1 Nutation and Wobble	417
11.2.2 Electromagnetic Coupling	419
11.2.3 Topographical Coupling	421

11.3 Paleomagnetism and Dynamo Theory	422
11.3.1 Testing Geodynamo Theory	422
11.3.2 Constraints on Dynamo Theory	424
11.4 Variations at the Core-Mantle Boundary and the Earth's Surface	429
11.4.1 Spatial Variation at the CMB	429
11.4.2 Variations of the CMB Boundary Conditions with Time	432
 Appendix A SI and Gaussian CGS Units and Conversion Factors	 437
 Appendix B Functions Associated with Spherical Harmonics	
B.1 The Scalar Potential	439
B.2 The Legendre Functions P_l	440
B.3 The Associated Legendre Functions $P_{l,m}$	441
B.4 Normalization of the Associated Legendre Functions	441
B.5 Inclination Anomaly Model for Zonal Harmonics	443
 References	 445
 <i>Author Index</i>	 509
 <i>Index</i>	 523