Gravity and Magnetic Exploration

Principles, Practices, and Applications

This combined study and reference text provides a comprehensive account of the principles, practices, and application of gravity and magnetic methods for exploring the subsurface using surface, subsurface, marine, airborne, and satellite measurements. Key current topics and techniques are described, including high-resolution magnetic investigations, time-variation gravity analysis from surface and satellite gravity measurements, absolute and gradient gravimetry, and the role of GPS in mapping gravity and magnetic fields. The book also describes the physical properties of rocks and other Earth materials that are critical to the effective design, implementation, and interpretation of surveys, and presents an overview of digital data analysis methods used to process and interpret anomalies for subsurface information.

Each chapter starts with a general overview and concludes with a list of key concepts that help readers review what they have learned. An appendix provides a grounding on basic data analysis using simple and accessible mathematical notation. Study questions and problem sets on an accompanying website, together with computer-based exercises available online, give readers hands-on experience of processing, modeling, and interpreting gravity and magnetic anomaly data. A comprehensive suite of full-color case histories on the book's website illustrates the practical utility of modern gravity and magnetic surveys in energy, mineral, environmental, archaeological, and engineering exploration and lithospheric studies, as well as their potential limitations.

This book is an ideal text for advanced undergraduate and graduate courses but also serves as a reference for research academics, professional geophysicists, and managers of exploration programs that use gravity and magnetic methods. It is a valuable resource for all those interested in petroleum, engineering, mineral, environmental, geological, and archaeological exploration of the lithosphere.

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"Written by three leading researchers, this is a comprehensive textbook that takes its readers from the fundamentals of potential fields through modern data acquisition, processing, modeling and inversion to practical interpretation. The theory and mathematical derivations are suitable for both beginners and experienced geophysicists. Well-organized and nicely illustrated, it is both informative and clearly written."

– Professor Dr Alan Green
Institute of Geophysics, ETH-Swiss Federal Institute of Technology

"This extensive work is much more than just a textbook: it includes detailed discussions, such as the philosophy of modeling and the nature of errors, which are critical to properly interpreting gravity and magnetic data, but are often glossed over. A very useful addition to practitioners' reference shelves and an excellent textbook for advanced students."

– Roger C. Searle, Professor Emeritus
Department of Earth Sciences, Durham University

"The geophysical applications of gravity and magnetic techniques have advanced a great deal in the twenty-first century. Thus, this rigorous book covering the physical basis, analysis, interpretation, and applications of these techniques is a timely and important contribution. It is designed to serve both the student and practitioner and is enhanced by an innovative website."

– Professor G. Randy Keller
Geology and Geophysics, University of Oklahoma;
Director of Oklahoma Geological Survey

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Preface

Objectives of this book

Investigations of terrestrial gravity and magnetic fields are among the oldest methods for determining the nature and processes of the Earth. Despite the development of an increasing number of additional complementary investigative methods, some of which have better subsurface resolution, the gravity and magnetic methods continue to have an important, often decisive role, in a wide variety of terrestrial investigations. In contrast to the several available texts on specific topics in gravity and magnetics, this book provides an overall, modern resource on the principles, practices, and applications of both the gravity and magnetic methods to exploring the Earth. Although these aspects of the gravity and magnetic methods are well grounded in widely described and accepted principles, they are continually undergoing practical improvements and expanded understanding. The continued improvements result from enhanced technology for acquiring, processing, and interpreting data made possible largely by increasing computational power and new techniques. Special emphasis in gravity and magnetic exploration is being placed on high sensitivity mapping of anomalies at the extremities of their spectra, both shorter and longer wavelengths, increasing the vertical and horizontal resolution of individual anomaly sources, and investigating the temporal variations in the gravity and magnetic fields of the Earth which permit new insights into Earth processes. It is hoped that this book which sets a benchmark in our current knowledge of gravity and magnetic exploration will encourage further developments in these methods and applications.

Both the theory and practice of gravity and magnetic methods applied to subsurface investigations are described in this book. The book considers the methods from the planning and organization of surveys through the analysis and interpretation of observations by digital computations incorporating both physical and geological principles. Case histories in supplemental chapters, which are available on an accompanying website, illustrate the advantages and limitations of the methods in a variety of applications including near-surface engineering and archaeological studies, mineral and energy resource investigations, and planetary crustal and subcrustal studies. A final chapter of this book summarizes these applications.

This presentation of gravity and magnetic methods differs substantially from existing books. For example, it takes into account the rapidly accelerating availability of subsurface, terrestrial, marine, airborne, and satellite measurements that the current information age is mapping in prodigious volumes. Further, it develops strategies on the combined use of these anomaly fields for solving subsurface problems. It also describes the newest standards and methods for reducing gravity and magnetic data to a usable form, as well as modern instrumentation for observing both absolute and relative total field and vectorial components.

The book emphasizes practical procedures and applications, and the physical properties and geological principles that constrain subsurface analyses of gravity and magnetic fields. It describes all major modern topics of gravity and magnetic methods that are likely to be of general interest. More general descriptive material and procedures are highlighted, and reference is made to alternate procedures or approaches. However, necessarily numerous computational and interpretational procedures described in the geophysical literature which may have a more limited application are not included because of space limitations. Wherever possible, examples of these methods are briefly described and pertinent literature is cited to guide the interested reader to additional information. Derivations of equations are restricted to those of general interest and details of many procedures are not included in the descriptions. Therefore the reader of this text will need to make abundant use of the many references cited for more detailed and comprehensive treatment of specialized topics.

The book can serve university courses in exploration and general Earth geophysics, gravity exploration, and magnetic exploration at the advanced undergraduate and beginning graduate levels. It uses mathematics up to and including basic differential equations, but develops the methods in simple digital array operations with minimal use of arcane and complex notations from integral and differential calculus. Thus, this book is much more computationally oriented than most previous works because the reader can readily implement and explore analytical results with electronic computing. Consistent abbreviations and terminology are used throughout the book.

The book is not only a textbook, but also serves as a reference for practioners, that is for professional geophysicists, geologists, engineers, and other scientists who have limited experience in the application of the gravity and magnetic methods to subsurface problems. Especially useful in this regard are the supplemental case histories, which have extensive reference lists. The explanation of the gravity and magnetic methods along with the case histories will also facilitate the efforts of project managers to develop optimal strategies for implementing geophysical methods in solving subsurface problems. Thus, the book serves a wide audience ranging from advanced undergraduate and beginning graduate students in the Earth and planetary sciences and engineering to professional geoscientists and engineers in academia, government, and industry.

Related books

This comprehensive book is unique in the breadth of the content and approach. However, a number of books pertaining to the gravity and magnetic exploration methods and their interpretation are available that the reader may find to be useful supplements to this book. A selected list of these books includes *Introduction to Potential Theory* (Sigl, 1985), *Interpretation of Filtered Gravity Maps* (Steiner and Zilahi-Sebess, 1988), *Geophysical Data Analysis* (Menke, 1989), *Geophysical Inverse Theory* (Parker, 1994), *Potential Theory in Gravity and Magnetic Applications* (Blakely, 1995), *Geologic Applications of Gravity and Magnetics: Case Histories* (Gibson and Millegan, 1998), *Geophysical Inverse Theory and Regularization Problems* (Zhdanov, 2004), *Principles of the Gravitational Method* (Kaufman and Hansen, 2008), *Principles of the Magnetic Methods in Geophysics* (Kaufman *et al.*, 2008), *Gravity and Magnetic Interpretation in Exploration Geophysics* (Murthy, 2010), *Gravity and Magnetic Methods for Geological Studies* (Mishra, 2011), *Field Geophysics* (Milson and Eriksen, 2011), Fundamentals of Gravity Exploration (LaFehr and Nabighian, 2012), and Acquisition and Analysis of Terrestrial Gravity Data (Long and Kaufmann, 2013).

Organization of this book

This book consists of 14 chapters organized into two principal parts, dealing with gravity and magnetic exploration, plus an introductory chapter and a final chapter dealing with applications. The initial chapter describes the basis and foundations of the gravity and magnetic methods, the general components of the geophysical process, and the nature of geophysical data. The final chapter considers the application of gravity and magnetic methods to near-surface studies including engineering, environmental, and archaeological investigations, energy and mineral resource exploration, and geologic studies of the lithosphere.

Each of the two principal parts consists of six chapters involving an introduction to the method, germane potential theory, the physical property involved in the method, and three final chapters which describe the acquisition, processing, and interpretation of the data. Finally, an appendix deals with data systems processing principles which are important to the processing and interpretation of gravity and magnetic methods. Included in the appendix are a discussion of gravity and magnetic data bases and standards, mathematical methods widely employed in gravity and magnetic methods, anomaly analysis, and data graphics. It serves as important background to both the gravity and magnetic chapters.

The gravity and magnetic parts each contain six chapters that may be used independently in separate courses or study programs. Overlap between the parts is minimal, but some methods and principles are more fully developed in one part than in the other part. For example, some depth determination methods used in both gravity and magnetic studies are more comprehensively described in the magnetics chapters because they are more widely used and successful in this application. The text explains the need for the reader to study fuller explanations elsewhere to achieve a comprehensive understanding of the methods.

As a study aid to the reader, each chapter is introduced with an overview and concludes with a summary section listing the key concepts of the chapter. The overview is not an abstract, but rather provides the reader with a broad, generalized summary of the chapter that is a useful guide in reading and studying the chapter. The summary key concepts draw the reader's attention to the more important concepts that are presented. They are not a listing of what should be known upon reading the chapter, but rather guide

the reader in reviewing what has been emphasized in the chapter.

Important elements of the book are the illustrations and tables, which aid in understanding principles and provide useful data tabulations and examples of gravity and magnetic methods and their analysis. They are derived both from the literature and from original composition for the book. Numerous references guide the reader to the source of specialized information and additional details on a topic. Readers seeking additional definitions of the geoscience terms in geophysics and geology used in this book should consult the *Encyclopedic Dictionary of Exploration Geophysics* (SHERIFF, 2002) and the *Glossary of Geology* (NEUENDORF *et al.*, 2005), respectively.

A website, www.cambridge.org/gravmag, accompanying the book provides useful supplemental material for the user of the book. Several black and white illustrations in the book are reproduced in color on the website to enhance their utility to the reader. Additionally, a few complex figures are shown in expanded size for improved legibility. Four additional chapters are provided on the website that describe the applications of both the gravity and magnetic methods to near-surface investigations, energy resources, mineral resources, and lithospheric investigations. The application chapters review the use of the methods and cite examples. The examples demonstrate the scale and magnitude of the anomalies, their breadth of application, and the limitations of the methods. The selection of examples is necessarily limited, but we have attempted to reach a balance in the selection process of including traditional applications plus unique examples to illustrate the range of applications. Placing these chapters on the website has permitted greater coverage, extensive use of color in the illustrations, and provision for updating examples with improvements in technology and broadening the range of problems addressed by the gravity and magnetic methods.

Study questions and exercises

In addition to the supplemental material, the website contains study questions for the first 13 chapters of the book. These questions foster further understanding of the topics of these chapters and serve as a study guide for the reader and a resource for instructors. Exercises, problem sets, and practical examples of application of the gravity and magnetic methods are also presented on the website. Exercises have been developed with the cooperation of Geosoft, Inc. utilizing special versions of their Oasis montaj software. The reader of this book can readily access the Geosoft Inc. software through the link provided on the website to process and interpret the data supplied for the exercises. The exercises are keyed to specific sections of chapters of the book where the user can gain knowledge of the basis, background, and application of the methodologies employed in the programs. Efforts will be made to keep the software available and the exercises up to date with current practice in the gravity and magnetic exploration profession. Updates of the content are identified on the website.

Some of the exercises on the website involve the forward calculation of anomalies, both gravity and magnetic, and discussion of the results of the modeling. These calculations can be performed using the special Oasis montaj versions for this book. Alternatively, the software for modeling, inversion, and filtering of profile gravity and magnetic anomaly data prepared by Professor Gordon R. J. Cooper, University of Witwatersrand can be used. The latter software can be obtained on the website http://www.wits.ac.za/academic/science/geosciences/research/geophysics/gordoncooper/6511/software.html. Descriptions of these programs and their use are presented with the software.

Units

The units used in geophysical methods are diverse, depending largely on the application of the methods. In this book the normal practice is to use SI units. SI is the abbreviation for Le System International d'Unites, which is a system of units that is broadly accepted internationally by governmental agencies and professional societies. This system has similarities to the metric system of units, but is not identical to it. The base and supplementary units of the SI system together with their combinations, called derived units, that are common to geophysical studies in this book are listed in Table 1.2 of Chapter 1. In this book the exception to the use of SI units is in the description of certain case histories. The original units used in reporting the results of the study, which may not be SI units, are used for consistency with the original information.

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We also want to acknowledge the continuing assistance from our Cambridge University Press editor, Laura Clark, and also her patience in dealing with three authors with a wide variety of commitments that complicated the completion of the book.