ISOTOPES

PRINCIPLES AND APPLICATIONS

THIRD EDITION

Gunter Faure

Teresa M. Mensing

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Principles and Applications

Third Edition

GUNTER FAURE AND TERESA M. MENSING

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Preface

This book contains a comprehensive presentation of all aspects of isotope geoscience and is intended to be used in universities and colleges as a textbook in lecture courses for senior undergraduate and first-year graduate students in the earth sciences. In addition, this book will serve as a source of information for professionals in the earth sciences and related disciplines. The encyclopedic function of this book is enhanced by a detailed table of contents and by author and subject indexes. The book also contains a large number of original diagrams with extended captions that facilitate browsing and convey information without requiring close reading of the text. In addition, each chapter contains cross-references to other parts of the book where related information can be found.

The third edition of this book has been completely rewritten, reorganized, and expanded in order to bring it up to date and to make it useful to students and professionals in the earth sciences and related fields. As presently configured, the third edition can be used in support of several lecture courses, including isotope geochronometry, environmental isotope geochemistry, environmental radioactivity, stable isotope geochemistry, and graduate-level seminars in all of these subjects. In addition, this book contains information that is relevant to igneous petrology, ore deposits, stratigraphy, oceanography, hydrology, atmospheric science, soil science, archeology/anthropology, medical geochemistry, and meteoritics.

The presentation of the subject matter in each chapter starts with the relevant basic principles and proceeds from there to the derivation of the equations and to statements of the assumptions on which the equations are based. All of the substantive chapters contain applications of isotope systematics to the solution of interesting problems in geology and related disciplines. Each chapter ends with a summary of important insights and with lists of references.

The references at the ends of most chapters have been subdivided in order to help students to pursue a topic of their choosing beyond the material presented in the text. In addition, the references to subjects that are not fully developed in the text or that support data tables are presented in compressed form in appropriate places in the text and are not repeated in the end-of-chapter reference lists. Most of the papers used in this book were published between about 1990 and 2002. However, some references date back to the 1960s and 1970s, when many seminal papers were published that are the foundation of current research.

Additional indexes, a solutions manual, and a set of numerical problems that illustrate the principles presented in each chapter are available at www.wiley.com/college/faure. The solution of numerical problems by students is an important learning experience that will give them the necessary confidence to test the calculations and conclusions of research reports in the scientific literature. Future earth and environmental scientists must be able to make such calculations in order to understand in quantitative terms whatever phenomenon they are investigating. The emphasis in this book is on figuring out how something works and to use that insight to solve problems by means of calculations. However, this book does not teach mathematical modeling or how to program computers to interpret large data sets.

In addition, this book does not contain detailed information on analytical procedures and on the instrumentation that is required to make accurate and precise measurements of isotope abundances and decay rates. Students who are planning a research career in isotope geoscience should serve an apprenticeship with a master scientist in order to learn the skills that are necessary in their chosen field and to acquire the work habits that are required to achieve success.

Although most universities and colleges do not have operational isotope-research laboratories, isotope geoscience should be a standard item of the curriculum in all Earth Science Departments because isotopic data have become a major source of information in all branches of the earth sciences and related fields. In fact, the wide range of applications of isotopic data provides an overview of many subjects of earth science that are traditionally taught as separate entities.

The material in this book is presented in five parts. The first part (Chapters 1–4) is introductory and presents important background information. Students who are well prepared should be able to bypass these chapters without difficulty. Nevertheless, we have included them to assure that all students can build on a common base in the more substantive chapters that follow. The second part (Chapters 5–15) presents the dating methods based on the accumulation of radiogenic isotopes of Sr, Ar, Ca, Nd, Pb, Hf, Os, Ce, and Ba. The third part (Chapters 16–19) is devoted to isotope geochemistry, including mixing theory and applications of radiogenic isotopes to the origin of igneous rocks, to the transport of these isotopes from the continents to the oceans, and to the isotope compositions of Sr, Nd, Pb, Os, and Hf in the oceans. The fourth sequence of chapters (20–25) deals with the natural radioactivity resulting either from the presence of short-lived daughters of long-lived radioactive parents or from the presence of radionuclides produced by interactions with cosmic rays, by induced fission of ^{235}U in nuclear reactors and nuclear weapons, and by capture of neutrons released by uranium fission. The last section of the book (Chapters 26–30) contains summaries of the isotopic compositions of H, B, Li, C, N, O, Si, Cl, and S and other elements Cu, Fe, Se, and Br whose atoms are fractionated in nature. These elements are among the most abundant in the crust of the Earth and provide useful information on a wide range of geological materials, primarily in terms of isotopic equilibration temperatures and as monitors of certain biological, chemical, and physical processes in nature.

The scope of this book reflects the applicability of isotopic data in a wide range of terrestrial and extraterrestrial settings. It also reflects the ingenuity of the scientists who work in this field. Isotope geoscience is still at the forefront of the earth sciences and therefore continues to attract the brightest young scientists in the world today.

We are grateful to our colleagues who have shared their insights with us by sending us reprints of their papers and by speaking to us about their work. Others

sent us comments about the second edition of this book and made suggestions for its improvement. We thank all of them by listing their names in alphabetical order and apologize in advance to anyone whose name we failed to mention: G. Åberg, F. Albaréde, L. T. Aldrich, C. J. Allègre, H. L. Allsopp, E. Anders, J. Andersson, R. L. Armstrong, H. Baadsgaard, H.-M. Bao, E. Bard, E. Barrera, M. Barton, K. Bell, K. Benkala, S. M. Bergström, R. A. Berner, M. Bielsky-Zyskind, J. M. Bigham, B. A. B. Blackwell, P. D. Boger, M. D. Bottino, J. R. Bowman, O. van Breemen, D. J. Brookins, D. Buchanan, H. S. Cao, D. H. Carr, L. M. Centeno, S. Chaudhuri, W. A. Cassidy, J.-F. Chen, S. E. Church, N. Clauer, R. N. Clayton, W. Compston, U. G. Cordani, H. Craig, J. H. Crocket, G. Crozaz, G. K. Czamanske, R. D. Dallmeyer, E. J. Dasch, J. L. DeLaeter, C. F. Davidson, G. M. Denton, P. Deines, D. J. DePaolo, S. Deutsch, T. Ding, R. S. Dietz, B. R. Doe, R. Doig, A. Dreimanis, R. Eastin, H. Elderfield, D. H. Elliot, W. C. Elliott, C. Emiliani, S. Epstein, W. G. Ernst, H. W. Fairbairn, H. Faul, R. Felder, R. J. Fleck, R. V. Fodor, K. A. Foland, E. Fortner III, B. M. French, F. A. Frey, G. M. Friedman, S. J. Fritz, C. D. Frost, R. Fuge, P. D. Fullagar, H. Furness, W. S. Fyfe, E. M. Galimov, M. Gascoyne, P. W. Gast, T. W. Gevers, B. J. Giletti, S. S. Goldich, A. M. Goodwin, I. M. Gorokhov, N. K. Grant, P. Grootes, R. Grün, B. L. Gulson, J. D. Gunner, U. Haack, A. N. Halliday, M. Halpern, G. N. Hanson, R. S. Harmon, S. R. Hart, R. Harvey, C. J. Hawkesworth, K. S. Heier, A. Heimann, J. M. Hergt, L. F. Herzog, H. H. Hess, M. Hochella, J. Hoefs, A. W. Hofmann, A. Holmes, J. Hower, P. M. Hurley, E. Iberall-Robbins, M. Ikramuddin, E. Jäger, B. M. Jahn, L. M. Jones, R. I. Kalamarides, F. Kalsbeek, A. Karam, E. Keppens, S. E. Kesler, R. W. Kistler, L. Koch, C. Koeberl, L. N. Kogarko, G. T. Kovatch, T. E. Krogh, G. Kurat, M. D. Kurz, P. R. Kyle, D. Lal, M. A. Lanphere, G. Lee, W. P. Leeman, W. E. LeMasurier, P. C. Lightfoot, J. F. Lindsay, H. J. Lippolt, D. Long, L. E. Long, K. R. Ludwig, G. W. Lugmair, W. B. Lyons, J. D. Macdougall, R. Mauche, J. McArthur, M. T. McCulloch, R. H. McNutt, A. Menzies, J. H. Mercer, M. Mohlzahn, R. Montigny, S. Moorbath, S. M. Morse, L. A. Munk, S. B. Mukasa, V. R. Murthy, E.-R. Neumann, L. O. Nicolaysen, K. Nishiizumi, K. Notsu, J. D. Obradovich, R. K. O'Nions, V. M. Oversby, L. B. Owen, J. M. Palais, R. J. Pankhurst, J. J. Papike, W. J. Pegram, Z. E. Peterman, N. Piatak, R. T. Pidgeon, W. H. Pinson, Jr., F. A. Podosek, J. L. Powell, D. E. Pride, H. N. A. Priem, P. Pushkar, D. C. Rex, H. Sakai, V. J. M. Salters, S. M. Savin, M. Schidlowski, J.-G. Schilling, W. R. Van Schmus, C. C. Schnetzler, J. W. Schopf, J. Schutt, H. P. Schwarcz, N. R. Shaffer, D. M. Shaw, S. B. Shirey, E. T. C. Spooner, A. Starinsky, R. H. Steiger, G. Steinitz, P. Stille, A. M. Stueber, E. Stump, K. V. Subbarao, J. F. Sutter, M. Tatsumoto, H. P. Taylor, Jr., S. R. Taylor, J. Teller, M. Thiemens, R. N. Thompson, G. R. Tilton, K. K. Turekian, R. J. Uffen, H. C. Urey, J. Veizer, J. W. Valley, P. Vidal, T. A. Vogel, F. A. Wade, M. Wadhwa, H. Wänke, R. M. Walker, R. K. Wanless, G. J. Wasserburg, P. N. Webb, K. H. Wedepohl, K. S. Wehn, I. Wendt, G. W. Wetherill, J. T. Wilson, P. J. Wyllie, H. S. Yoder, D. York, R. E. Zartman, and A. Zindler. We are especially grateful to Betty Heath for her tireless efforts and skill in wordprocessing the text. We also thank Karen Tyler and Pei Jian Zhou who worked with us on this book. Last but not least, we thank James Harper of John Wiley and Sons for making the necessary decisions that enabled us to publish this book.

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