# Noble Gas Geochemistry

*Noble Gas Geochemistry* discusses the fundamental concepts of using noble gases to solve problems in the earth and planetary sciences.

The discipline of noble gas geochemistry has become a major branch in the earth and planetary sciences. It offers a powerful and unique tool in resolving problems such as the origin of the solar system, evolution of the planets, Earth formation, mantle evolution and dynamics, atmospheric degassing and evolution, ocean circulation, dynamics of aquifer systems, and numerous applications to other geological problems. This book gives a comprehensive description of the physical chemistry and cosmochemistry of noble gases before leading on to applications for problem solving in the earth and planetary sciences. Abundant tables and figures for noble gas elemental and isotopic data in the solar system (terrestrial, meteoritic, solar, etc.) are included.

There have been many developments in the use of noble gases since publication of the first edition of this book in 1983. This second edition has been fully revised and updated. The book will be invaluable to graduate students and researchers in the earth and planetary sciences who use noble gas geochemistry techniques.

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## Second Edition

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# Preface to the Second Edition

When the first edition of *Noble Gas Geochemistry* was published in 1983, this discipline was still comparatively underdeveloped, and few people seemed to expect that this apparently arcane subject would become one of the major tools of geochemistry. But noble gases have become mainstream, spoken of in the same breath as Pb, Sr, and Nd. Due to unique properties such as extreme scarcity in nature and (almost) perfect lack of chemical interaction, noble gases are now being used as a geochemical tracer to address a variety of problems in the earth and planetary sciences in ways that other tracers cannot. In this light, we thought that the time was ripe to revise the first edition in accordance with recent developments.

Current noble gas geochemistry deals with very broad subjects ranging from the origin and evolution of the earth and the solar system to local geological problems. A single-volume monograph cannot deal comprehensively with all these issues. In this revised edition, we, therefore, decided to concentrate on the more fundamental aspects of noble gas geochemistry, necessarily forcing us to give short shrift to many specific geological applications. Considerable space is devoted to a general discussion of the physics and chemistry of noble gases. In the last decade, much laboratory work has led to progress in understanding adsorption, absorption, and diffusion of noble gases in melts and in solids. These subjects are directly relevant to earth science; hence, in Chapter 2 we present extensive discussions with as much recent data as possible. Chapter 6 is essentially new and constitutes the longest chapter, in accordance with rapid development in this field. Mantle evolution is one of the most successful examples of noble gas geochemistry in recent application, and topics such as mantle dichotomy, in noble gases as in other systems, and the evolution of solid earth-atmosphere system are central issues attracting heated debate.

Since the discovery of nontrivial amounts of extraterrestrial noble gases in meteorites by Gerling and his colleagues in the early 1950s, noble gas measurements have been integral to meteorite studies and have contributed greatly to our understanding not only of the origin of meteorites but also of the planetary system as a whole. Because the scope of this book has to be limited, however, we have had to be content with a relatively concise review of this subject, concentrating on aspects with special relevance to noble gas *geo*chemistry (Chapter 3). Recent developments in meteorite studies clearly suggest that a deeper understanding of terrestrial noble gases can only be gained in the framework of noble gas *cosmo*chemistry. Hence, in Chapter 7 we discuss terrestrial noble gases in the general context of cosmochemistry. Interaction of cosmic rays with terrestrial materials is another specific example that shows the importance of nonterrestrial noble gases in noble gas geochemistry. This new field is discussed in Chapter 5.

The second edition is essentially a new book except for Chapter 4 (Water), which is somewhat modified, and Chapter 2, which maintains the original flavor but with some significant new material.

Thanks to the advent of commercial high-precision mass spectrometers for the analysis of extremely small quantities of noble gas in the mid-1980s, a large amount of high-quality noble gas data are now available in numerous publications. This accessibility has made a direct comparison of experimental data from different laboratories much easier and has also greatly aided meaningful interpretation of the data. In this spirit, we have tried to accommodate as much basic data for terrestrial noble gases as possible in table and figure formats, mostly taken from recent publications. In dealing with these data, however, we have focused on our own views while trying to attend to and illuminate diverse interpretations. Readers seeking more extended advocacy of alternative views will readily find them in the liberal literature citations herein.

Finally, we owe much to too many colleagues to do justice to them in a reasonable space. But we acknowledge the special help of Bob Walker, Kazuo Saito, Tom Bernatowicz, Takuya Matsumoto, Rainer Wieler, and Jun-Ichi Matsuda. We also give special thanks to the McDonnell Center for the Space Sciences at Washington University for its assistance in helping the authors get together.

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During the copyediting stage of this book we learned of the death of John H. Reynolds, and it seems fitting to add some remarks here. Although everybody has forebears, many view John Reynolds as the "father" of the study of the natural occurrence of noble gases; for decades he was the scientific leader of this discipline. John built the machine – the one that graces the cover of this book – that was truly useful for analyzing the tiny amounts of noble gases that commonly characterize natural materials, using principles that even today lead people to speak of Reynolds-type mass spectrometers. It was not enough to build and further develop the instrument,

however. For many years John applied this capability to scientific investigations, asking many questions, answering some, but most importantly opening doors, first in cosmochemistry and then in terrestrial geochemistry, and in large measure establishing the agenda of this discipline. He was rigorous, he was intuitive, he was careful, he was bold, and, amazingly often on important issues, he was right. Perhaps even more important, many of the people now called noble gas geochemists or cosmochemists got their skills and scientific passion in Berkeley, as John's students, postdocs, or visitors, or from those who were there. We learned much from him, we owe him much, and of John Reynolds it can truly be said that noble gas geochemistry just wouldn't be the same without him.

# Preface to the First Edition

In addition to being the collective name for the elements in the rightmost column of the periodic table of the elements, the term "noble gases," also "rare gases" or occasionally "inert gases," is a convenient label for the branch of the scientific enterprise concerned with studying the occurrence and distribution of these elements in nature, particularly in the earth and the terrestrial planets. This research area is usually considered part of geochemistry, although other labels would serve as well.

The most familiar and most widely practiced area of geological research involving noble gases is, of course, geochronology, especially K–Ar dating. There are many good books about geochronology and it is not our intention to try to add another. Noble gas geochemistry, the subject of this book, will mean here what it usually suggests in the geological and planetary science community: the study of the natural occurrence of noble gases and what may be learned thereby, other than determination of the ages of rocks.

In the last two decades the discipline of noble gas geochemistry has prospered, at least by the measure of getting its own sessions at scientific conferences and attracting practitioners in sufficient numbers that, regrettably, they no longer all know each other or are even familiar with each other's work. In spite of its fruits, however, noble gas geochemistry often seems to non-practitioners to have much the air of the secret society and its dark art. Among the deplorable consequences of this circumstance are too many cases where good science and important scientific results obtained from noble gases are widely ignored and, on the other hand, too many cases of uncritical acceptance of noble gas results and interpretations which are ambiguous, misleading, out of context, fatuous, or outright nonsense.

Among the reasons which could be advanced to explain why noble gas geochemistry has not been very well integrated into the larger scientific community of which

it is part is, basically, unfamiliarity. Many of the traditional academic disciplines are involved in the study, and there are no courses in noble gas geochemistry in graduate school. There is also no book which covers the field, and we hope that this one will fill that need. The general style is that of the review paper: The intent is for professional level and currency and, within the limitations of scope, comprehensiveness, with sufficient background and introduction to encourage access by the student of the geosciences. A major aim of this book is that it not only be useful to our colleagues in the field but that it help those in other specializations form a critical appreciation of "noble gases."

Our intent is to take the "geo-" in geochemistry literally, i.e. our focus is on terrestrial noble gases. Still, even more than in most specializations, it is impossible to develop an appreciation of terrestrial noble gases without a corresponding appreciation of the features which have emerged from the study of noble gases in extraterrestrial materials, notably meteorites. Accordingly we have included a chapter on noble gas "cosmochemistry." This is background material, however, and not an attempt to treat this subject as thoroughly as we hope to have treated the terrestrial subjects; such an attempt would require a considerable widening of the scope of this book.

The writing of this book was planned and initiated while one author, on sabbatical leave, was a guest in the other's home institution. This was made possible by support from the Japan Society for the Promotion of Sciences, and we are very glad to express our appreciation to the JSPS. We would also like to thank the McDonnell Center for the Space Sciences at Washington University for a variety of kinds of support which greatly facilitated the preparation of this book.

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