The lithosphere

An Interdisciplinary Approach

Modern Earth science suffers from fragmentation into a large number of sub-disciplines with limited dialog between them, and artificial distinctions between the results based on different approaches. This problem has been particularly acute in lithospheric research, where different geophysical techniques have given rise to a multitude of definitions of the lithosphere – seismic, thermal, electrical, mechanical, and petrological.

This book presents a coherent synthesis of the state-of-the art in lithosphere studies based on a full set of geophysical methods (seismic reflection, refraction, and receiver function methods; elastic and anelastic seismic tomography; electromagnetic, magnetotelluric, thermal and gravity methods; and rheological modeling), complemented by petrologic data on mantle xenoliths and laboratory data on rock properties. It also provides a critical discussion of the uncertainties, assumptions, and resolution issues that are inherent in the different methods and models. Most importantly, it discusses the relationships between methods and presents directions for their integration to achieve a better understanding of the processes that affect the lithosphere and thereby shape the Earth on which we live.

Multi-disciplinary in scope, global in geographical extent, and covering a wide variety of tectonic settings over 3.5 billion years of Earth history, this book presents a comprehensive overview of lithospheric structure and evolution. It is a core reference for researchers and advanced students in geophysics, geodynamics, tectonics, petrology, and geochemistry, and for petroleum and mining industry professionals.

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Cambridge University Press
978-0-521-84396-6 - The Lithosphere: An Interdisciplinary Approach
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CAMBRIDGE
UNIVERSITY PRESS

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University Printing House, Cambridge CB2 8BS, United Kingdom

Published in the United States of America by Cambridge University Press, New York

Cambridge University Press is part of the University of Cambridge.

It furthers the University's mission by disseminating knowledge in the pursuit of education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9780521843966

First published 2011 (Twice)
Second Edition 2012
Reprinted 2013

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data
Artemieva, I. M. (Irina Mikhailovna), 1961–
Lithosphere : an interdisciplinary approach / Irina M. Artemieva.
p. cm.
ISBN 978-0-521-84396-6 (hardback)
1. Lithosphere. 2. Earth – Crust. 3. Geodynamics. I. Title.
QE511.A78 2011
551–dc22
2011002467

ISBN 978-0-521-84396-6 Hardback

To my teachers who became friends,
to the friends who became my teachers,
to all my family who have always been
my best friends and my best teachers.

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Foreword

The lithosphere is one of the most fundamental elements in solid Earth science in general, and in plate tectonics, in particular. As a result, solid Earth scientists from different backgrounds have studied the Earth's lithosphere intensively. In doing so, most studies have focused on particular areas and/or on the use of particular methodologies. Plate-tectonics, with its early breakthroughs in understanding first order patterns in sea-floor spreading controlling ocean floor bathymetry, age distribution, and horizontal motions, by its nature, has set the stage for a quantitative framework for the oceanic lithosphere.

The inferences from thermal modeling, seismological studies, and studies of the mechanical behaviour of the lithosphere, including results from marine geophysical studies of flexure of the lithosphere seaward of trenches and under seamounts, integrated with experimental studies of rock mechanics, had already led to an early realization of the need to reconcile different definitions of the lithosphere. This is even more the case for studies of the continental lithosphere, affected by a much longer geological evolution and characterized by significant heterogeneity in both its crustal and mantle components.

By now, the lithosphere is probably the best studied part of the plate-tectonics system. Seismic tomography has led to the realization that lithosphere slabs can interact with the mantle at depths much greater than had earlier been anticipated. At the same time growing awareness exists of the crucial role of the interaction of lithosphere and surface processes, including erosion and sedimentation, affected by climate.

Whereas large-scale lithosphere research programs, such as the International Lithosphere Programme, in their early studies mainly constrained crustal structure and lithosphere thickness and composition, these programs now make a major effort to integrate the study of the lithosphere in the context of connecting the deep Earth and the surface processes. The TOPO-EUROPE, EUROARRAY, EPOS, and the US EarthScope large-scale integrated research initiatives are exemplary for this. In the context of these recent developments, the interdisciplinary overview of lithosphere research developed by Irina Artemieva in this book is very timely. Of particular value here is her successful integration of an exceptionally broad suite of geophysical approaches with insights from petrology and geochemistry.

In doing so, the author, to the benefit of the readership also provides an in-depth coverage of the secular evolution of the lithosphere through all geological periods, much of which is based on her global research, including knowledge of the lithosphere in Eurasia. The book includes a comprehensive discussion of topics, including laboratory studies of physical properties of crustal and upper mantle rocks, methods in lithosphere research, and lithosphere structure in most oceanic and continental tectonic settings as constrained by a multiplicity of geophysical techniques.

As pointed out by the author, lithosphere research is at a very dynamic stage, with many fundamental questions to be further resolved. At the same time, it is to be expected that, with its very up-to-date coverage of recent progress on both oceanic and continental lithosphere and evolution, this book will serve as a reference for years to come.

Sierd Cloetingh
President, International Lithosphere Programme
Professor, VU University, Amsterdam

Preface

Recent progress in geophysical and geochemical studies has brought us far in the understanding of the structure, origin, and evolution of the lithosphere. The goal of this book is to summarize geophysical (and, to some extent, geochemical) data collected in the laboratory and in the field on the properties of the lithosphere. It reflects the state of the present understanding of the lithosphere structure and the processes that formed and shaped it. As any other book, it reflects the author's interpretations that may not necessarily be shared by other researchers. It also reflects the author's particular interests and, for this reason, the book has *a strong focus on the lithospheric mantle*, while the crustal structure is discussed in significantly less detail. The motivation for this discrimination is that, owing to historical reasons, the crustal structure is much better known and is much better understood than the structure of the lithospheric mantle. While it is universally understood that the crust is highly heterogeneous, many geophysical models still treat the lithospheric mantle as an almost homogeneous layer.

The suggestion to write a "Lithosphere" book came largely from Walter Mooney almost a decade ago. By that time I have already been much troubled by the question of how results from lithosphere studies using different geophysical techniques could be compared with each other, and how they could be compared with xenolith data. For example, if the seismic lithosphere is reported to be 220 km thick, does this estimate agree or disagree with a thermal estimate of 160 km, an MT estimate of 200 km, and a xenolith-based estimate of 180 km? Clearly, there are many assumptions behind each of the approaches, and there are theoretical and practical limitations and uncertainties associated with different techniques. It is not easy to find all of them; however, any cross-disciplinary comparison of the results would be meaningless without knowing model resolution and theoretical assumptions. Someone said that the writer is an unsatisfied reader. So my motivation in writing this book came from a wish to find the answers to questions like the one above. This is reflected in the structure of the book.

My general idea was to provide readers who specialize in a particular geophysical technique in lithospheric studies, with a simple reference book for comparison of their results with laboratory data and various geophysical–petrologic interpretations. For this reason, each chapter starts with a basic introduction for those unfamiliar with the subject. Advanced readers may skip these parts and move to an overview of laboratory data, modeling results, and interpretations. A summary of the resolution limitations and the uncertainties of different geophysical or petrological methods will facilitate understanding of how results can be compared across the various techniques used in lithosphere studies. It is not the aim of this book to teach *how to apply* these methods, but to provide information on *how to use the results* of these methods.

For this reason, the book intentionally omits mathematics and includes only very few equations; it will also facilitate reading by a large number of students. The corresponding theory can be found in other books, from general physics courses to specialized books in geodynamics, seismology, and potential fields. References to key publications are provided in the introduction to each chapter. The reference list includes the complete list of publications used in the preparation of the book. Its length reflects my wish to credit the authors of the original studies and those scientists who have pioneered different types of research on the upper 400 km of the Earth. It also gives the reader an opportunity to find the original publications and to form a personal judgment on various aspects of lithosphere research. The results of lithosphere studies are often controversial, and some of the topics are still the subject of heated debates. I have tried, as far as possible, to avoid making judgments when contradictions exist but rather to present the arguments of both sides.

The book reviews recent results in seismic, electromagnetic, gravity, thermal, rheological, and petrological studies of oceanic and continental lithosphere, followed by a chapter that focuses on the processes of lithosphere formation and evolution, and a chapter that summarizes the state of present understanding of lithosphere structure and methods used in its study. Owing to the very complex and controversial situation that exists with lithosphere definitions (part of which is due to semantics, the other part originating from the true multidisciplinarity of lithosphere research), Chapter 1 focuses on definitions of the lithosphere and related concepts such as thermal, mechanical, chemical, and rheological boundary layers, tectosphere, and perisphere.

Chapter 2 discusses applications of isotope geochronology to lithosphere studies. The structure of Chapters 3–8 is very similar. Each chapter begins with a review of laboratory data on the physical properties of the lithosphere that are the key parameters for the method discussed. This is followed by a brief summary of the method, with a major focus on basic assumptions, theoretical and practical limitations, and uncertainties. Then, field observations of lithosphere properties and their interpretation in terms of lithospheric structure and crustal and mantle processes are reviewed. Each chapter ends with a brief summary of the lithospheric structure of major tectonic provinces as constrained by the methods discussed. There is inevitably some redundancy between different chapters, since some lithospheric properties are studied using different techniques. Work on this book took several years; due to a continuous flow of new, and often contradictory results, some inconsistency may remain between the parts written at different times.

Many researchers have contributed to the writing through numerous formal and informal discussions, although most of them may have been unaware, particularly since work on the book took such a long time. I would like to acknowledge, in particular, my discussions with D. L. Anderson, N. Arndt, L. Ashwal, S. Bogdanova, G. Bokelmann, K. Burke, E. Burov, M. Cara, S. Cloetingh, K. Condie, E. Debayle, D. Eaton, Y. Elesin, K. Fuchs, A. Forte, D. Francis, A. O. Gliko, S. Grand, W. Griffin, H. Grütter, S. Haggerty, W. Hamilton, G. Houseman, C. Jaupart, A. Jones, T. Jordan, M. K. Kaban, S.-I. Karato, R. Keller, M. Kopylova, J. Korenaga, O. L. Kuskov, S. Lebedev, C.-T. Lee, A. Levander, D. Mainprice, J.-C. Mareschal, D. McKenzie, R. Meissner, W. D. Mooney, R. O'Connell, Y. Podladchikov, K. Priestly, G. Ranalli, T. Redfield, J. Ritsema, D. Scholl, N. Shapiro, A. Shulgin, F. Simons, S. V. Sobovev, W. Spakman, S. Stein, M. Talwani, H. Thybo,

T. Torsvik, R. van der Voo, L. P. Vinnik, R. Wortel, D. Yuen, V. N. Zharkov, M. Zoback. The book, however, reflects only the author's view on the subject which may differ from the opinions of other researchers, and all mistakes in the book are mine. My special thanks go to those of my colleagues who endured the pain of reading and commenting on the manuscript: W. Stratford, Y. Cherepanova, A. Frassetto, and above all H. Thybo. The friendly, professional atmosphere at USGS, Menlo Park, as well as its fantastic library were particularly important at the initial stages of work on the book. Financial support from Carlsbergfondet, Denmark, during the following years made it possible to complete the task. However, without the real long-term supporting patience of the editor, Susan Francis, the book would not have been possible. Sara Hoffritz has helped immensely with obtaining copyright permissions and I am happy to thank her. All of the figures have been prepared or redrawn by the author.

The book summarizes our present understanding of the lithosphere, its origin, structure, evolution, and impact on global mantle dynamics and plate tectonics. It shows that much remains to be understood, in particular on the path of merging geophysical and geochemical field and laboratory observations and their joint interpretations. I hope the book will be useful to those who are working in the exciting and still controversial field of multidisciplinary studies of the lithosphere.

Irina M. Artemieva
Copenhagen
July 2010

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Cambridge University Press
978-0-521-84396-6 - The Lithosphere: An Interdisciplinary Approach
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