

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.



Irina Artemieva is an Associate Professor at the University of Copenhagen, Denmark. She was awarded an M.S. in Physics from Lomonosov Moscow State University, a Ph.D. in Geophysics from the Institute of Physics of the Earth, Moscow and a Doctor of Science (dr. habil.) degree from the University of Copenhagen. Professor Artemieva has worked as a researcher at the Russian/USSR Academy of Sciences, Moscow, at the Universities of Uppsala (Sweden) and Strasbourg (France), and at the United States Geological Survey in California. She was Science Co-ordinator of the European Science Foundation/

International Lithosphere Programme EUROPROBE program 1999–2001. She is also a member of the Academia Europaea and a Fellow of the Royal Astronomical Society, London.

Cambridge University Press

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

Irina M. Artemieva

Frontmatter

[More information](#)

Cambridge University Press

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

Irina M. Artemieva

Frontmatter

[More information](#)

The lithosphere

An Interdisciplinary Approach

IRINA M. ARTEMIEVA

University of Copenhagen, Denmark

Also affiliated with the Institute of Physics of the Earth, Russian Academy of Sciences, Moscow, Russia



CAMBRIDGE
UNIVERSITY PRESS

Cambridge University Press
978-0-521-84396-6 - The Lithosphere: An Interdisciplinary Approach
Irina M. Artemieva
Frontmatter
[More information](#)

CAMBRIDGE
UNIVERSITY PRESS

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

© Irina Artemieva 2011

This publication is in copyright. Subject to statutory exception and to the provisions of relevant collective licensing agreements, no reproduction of any part may take place without the written permission of Cambridge University Press.

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

Cambridge University Press has no responsibility for the persistence or accuracy of URLs for external or third-party internet websites referred to in this publication, and does not guarantee that any content on such websites is, or will remain, accurate or appropriate.

Cambridge University Press

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

Irina M. Artemieva

Frontmatter

[More information](#)

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.

Cambridge University Press

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

Irina M. Artemieva

Frontmatter

[More information](#)

Contents

<i>Foreword by Professor S. Cloetingh</i>	<i>page</i> xiii
<i>Preface</i>	xv
<i>Acknowledgements</i>	xviii
1 What is the lithosphere?	1
1.1 Historical note	1
1.2 Lithosphere definitions	3
1.2.1 Defining the lithospheric base	3
1.2.2 Elastic lithosphere	5
1.2.3 Thermal lithosphere	7
1.2.4 Seismic lithosphere	8
1.2.5 Electrical lithosphere	10
1.2.6 Petrologic lithosphere	10
1.3 Concepts related to the lithosphere	11
1.3.1 Boundary layers	11
1.3.2 Perisphere and tectosphere	12
1.4 An unnecessarily confusing concept?	13
2 Age of the lithosphere	15
2.1 Introduction to isotope geochronology	15
2.1.1 Geochemical classification of elements	15
2.1.2 Radioactive decay and the isochron equation	19
2.1.3 K/Ar	21
2.1.4 Rb/Sr	23
2.1.5 U/Pb	24
2.1.6 Sm/Nd	26
2.1.7 Re/Os	30
2.1.8 Lu/Hf	32
2.1.9 Mantle evolution from Hf and Nd isotopes	34
2.1.10 Model ages	35
2.2 Age of the crust and the lithospheric mantle	37
2.2.1 Continental crust	37
2.2.2 Oceanic crust	42
3 Seismic structure of the lithosphere	47
3.1 Laboratory studies of seismic properties of rocks	47

3.1.1	Introduction	47
3.1.2	Effects of pressure and temperature	49
3.1.3	Effect of grain size variations	53
3.1.4	Effect of mineralogy	57
3.1.5	Anisotropy	58
3.1.6	Melt and fluid inclusions	64
3.1.7	Melt-depletion and mantle composition	67
3.1.8	Density–velocity relationship	72
3.2	Summary of seismic methods	74
3.2.1	Types of seismic waves	74
3.2.2	Theoretical limits on seismic wave resolution	75
3.2.3	Methods of seismic data interpretation	77
3.3	Major seismic discontinuities in the lithosphere	83
3.3.1	The crust	83
3.3.2	Seismic discontinuities in the upper mantle	96
3.4	Receiver function (converted waves) studies	101
3.4.1	The method	101
3.4.2	Examples of PRF and SRF studies of the crust and the upper mantle	107
3.5	Controlled source methods: reflection/refraction studies of the upper mantle	115
3.5.1	Seismic reflection studies	115
3.5.2	Seismic refraction and wide-angle reflection	125
3.6	Teleseismic seismology	134
3.6.1	Elastic tomography	134
3.6.2	Elastic tomography models of the upper mantle	148
3.6.3	Origin of seismic velocity anomalies in the upper mantle	174
3.6.4	Seismic anisotropy in the upper mantle	187
3.6.5	Lithosphere thickness from elastic tomography	201
3.6.6	Anelastic tomography	207
3.7	Seismic lithosphere: summary	214
4	Thermal regime of the lithosphere from heat flow data	220
4.1	Field observations and laboratory data	220
4.1.1	Heat flow measurements	220
4.1.2	Thermal conductivity	224
4.1.3	Thermal expansion, thermal diffusivity, and specific heat	229
4.1.4	Heat production	230
4.2	Heat flow data	249
4.2.1	Global compilations of surface heat flow	249
4.2.2	Global trends in surface heat flow	251
4.3	Thermal regime of oceanic lithosphere	251
4.3.1	Age dependence of seafloor topography and heat flow	251
4.3.2	Normal oceans	255
4.3.3	“Anomalous” oceans	266

4.4 Thermal regime of continental lithosphere	270
4.4.1 Heat flow on the continents	270
4.4.2 Continental geotherms	274
4.4.3 Thickness of thermal lithosphere	297
4.5 Heat flow balance of the Earth	310
4.6 Thermal lithosphere: summary	313
5 Thermal state of the lithosphere from non-thermal data	317
5.1 Xenolith data	317
5.1.1 Xenoliths: advantages and disadvantages	317
5.1.2 Xenoliths and the boundary layers	323
5.2 TBL and xenolith geotherms	328
5.2.1 Geothermobarometers	328
5.2.2 Kink in xenolith geotherms	333
5.2.3 Garnet geotherms: CBL or TBL?	336
5.2.4 Xenolith geotherms and TBL thickness	342
5.2.5 Lithosphere thickness in Archean cratons	343
5.3 Geotherms constrained by seismic data	349
5.3.1 Correlations between seismic velocity, attenuation, and temperature	349
5.3.2 Seismic constraints on temperatures: methodology and uncertainties	352
5.3.3 Seismic constraints on temperatures: major results	360
5.4 Magnetic methods to determine lithospheric geotherms	365
5.4.1 Major principles	365
5.4.2 Calculation of lithospheric geotherms from magnetic data	366
5.4.3 Curie temperature of mantle minerals	367
5.4.4 Depth to the Curie point	369
5.5 Summary of non-thermal studies of lithosphere thermal state	371
6 CBL and lithospheric density from petrologic and geophysical data	374
6.1 Tectosphere and CBL	374
6.1.1 The tectosphere hypothesis	374
6.1.2 Mantle melting and composition of the lithospheric mantle	376
6.1.3 Oceanic and cratonic trends	382
6.1.4 CBL and compositional heterogeneity of continental mantle	385
6.1.5 The effect of CBL on TBL	398
6.2 Xenolith constraints on mantle density	399
6.2.1 Method and uncertainties	399
6.2.2 Density of oceanic mantle	401
6.2.3 Density of continental mantle	402
6.2.4 Isopycnicity	405
6.3 Are xenoliths representative of the cratonic upper mantle?	410
6.3.1 Sampling bias	410
6.3.2 Why should xenoliths be representative?	411
6.3.3 Is the cratonic mantle dry or wet?	413

6.3.4 Mantle density from geophysical data	415
6.3.5 Spatial correlations of seismic velocity anomalies and kimberlites	419
6.4 Summary	420
7 Electrical structure of the lithosphere	425
7.1 Electromagnetic and magnetotelluric techniques	425
7.1.1 Electric conduction in rocks	425
7.1.2 EM and MT methods	426
7.1.3 Interpretations of magnetotelluric data	427
7.1.4 Resolution of MT methods	429
7.2 Experimental data on electrical conductivity	430
7.2.1 Effect of lithology	430
7.2.2 Temperature dependence of conductivity in mantle rocks	432
7.2.3 High-temperature anisotropy of olivine conductivity	434
7.2.4 Pressure dependence of olivine conductivity	436
7.2.5 Oxygen fugacity and redox buffers	436
7.2.6 Fe and Al variations in olivine	438
7.2.7 Effect of highly conducting phases	441
7.2.8 Partial melts	442
7.2.9 Role of water	446
7.2.10 Other processes	452
7.2.11 Frequency dependence of electrical conductivity	452
7.3 Synthetic conductivity–depth profiles for the upper mantle	453
7.4 Regional electrical conductivity profiles in the oceanic upper mantle	456
7.4.1 Major marine experiments	456
7.4.2 Major conductivity types in the oceanic mantle	457
7.4.3 Age dependence of conductivity in oceanic mantle or the coast effect?	458
7.4.4 Pacific Ocean: fluids or anisotropy?	460
7.4.5 Mid-ocean ridges: mantle melting	464
7.4.6 Hotspots: melt dehydrated mantle?	466
7.4.7 Subduction zones and continental margins	468
7.5 Electrical structure of the continental upper mantle	472
7.5.1 Continent-scale conductivity patterns	472
7.5.2 Typical conductivity curves for different continental provinces	474
7.5.3 Stable continents	477
7.5.4 Paleosubductions, suture zones, and craton margins	482
7.5.5 Extensional regions	486
7.5.6 Orogens	489
7.5.7 Electrical anisotropy of continental mantle	494
7.6 Electrical asthenosphere	495
7.6.1 High-conductivity mantle layer and electrical asthenosphere	495
7.6.2 Thickness of electrical lithosphere	496
7.6.3 Correlations between electrical, thermal, and seismic LABs and the lithospheric age	499

7.7	Electrical lithosphere: summary	502
8	Flexure and rheology	505
8.1	Rheology of rocks	505
8.1.1	Introduction to rock deformation	505
8.1.2	Major mechanisms of non-linear deformation	515
8.1.3	Selected experimental results on rock deformation	525
8.1.4	Lithosphere strength	541
8.2	Flexural isostasy: the approach	552
8.2.1	Lithosphere isostasy	552
8.2.2	Elastic thickness of the lithosphere	556
8.2.3	Flexural isostasy: assumptions	558
8.2.4	Methods for estimation of effective elastic thickness T_e	561
8.2.5	Limitations, problems, and uncertainties	565
8.3	Lithosphere flexure and rheology	579
8.3.1	Flexure models of oceanic lithosphere	579
8.3.2	Flexure models of continental lithosphere	588
8.3.3	Seismogenic layer and T_e	603
8.3.4	Lithosphere flexure: summary	605
9	Evolution of the lithosphere	607
9.1	Formation of the early lithosphere	607
9.1.1	Early lithosphere: geological and geochemical evidence	607
9.1.2	Models of early lithosphere formation	622
9.2	Lithospheric processes in time	628
9.2.1	Plate tectonic processes and mantle dynamics	628
9.2.2	Crustal growth and recycling	645
9.2.3	Global secular trends and episodicity of lithospheric processes	650
9.3	The lithosphere is not forever	656
9.3.1	Thermal erosion by mantle convection and plumes	657
9.3.2	Rayleigh–Taylor instability and lithosphere delamination	661
9.3.3	Basal drag and mantle convection	663
9.3.4	Lithosphere recycling in subduction zones	667
10	Summary of lithospheric properties	670
	<i>References</i>	678
	<i>Subject index</i>	767
	<i>Geographical index</i>	772

Cambridge University Press

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

Irina M. Artemieva

Frontmatter

[More information](#)

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 multidisciplinary nature 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. Sobolev, 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

Acknowledgements

The publishers listed below are gratefully acknowledged for giving their permission to use original and redrawn figures based on illustrations in journals and books for which they hold the copyright. The original authors of the figures are cited in the figure captions, and I thank them for being able to use their figures. Every effort has been made to obtain permission to use copyrighted materials, and sincere apologies are rendered for any errors or omissions. The publishers would welcome these being brought to their attention.

Copyright owner	Journal	Figure number
American Geophysical Union	Journal of Geophysical Research	3.10, 3.11, 3.18, 3.20, 3.21, 3.22, 3.24, 3.45, 3.47, 3.49, 3.53, 3.54, 3.55, 3.56, 3.57, 3.58, 3.72, 3.77, 3.79, 3.80, 3.81, 3.84, 3.90, 3.93, 3.95, 3.97, 3.124, 3.127, 3.130, 4.11, 4.12, 4.28, 4.30, 4.41, 4.42, 4.43, 4.45, 5.19, 5.21, 6.4, 6.25, 7.5, 7.17, 7.34, 7.20, 8.32, 8.44, 8.45, 8.46, 8.55, 8.56
	Geophysical Research Letters	3.98, 3.111, 3.129, 5.20, 8.38, 8.53
	Geodynamics Series	3.14, 6.10
	Geophysical Monographs	7.20, 8.11, 8.17, 8.20, 8.23
	Geochemistry, Geophysics, and Geosystems	5.9, 6.26, 8.40
	Reviews of Geophysics	3.112, 3.114, 4.16, 4.22, 4.25, 4.33, 6.5, 8.53, 9.9
	Reviews of Geophysics and Space Physics	2.23
	AGU Reference Shelf	7.32
Geological Society of America	Geology	3.90
	GSA Today	9.2
	Tectonics	9.4
Elsevier	Earth-Science Reviews	2.2, 2.6
	Earth and Planetary Science Letters	3.5, 3.8, 3.43, 3.51, 3.105, 3.115, 3.125, 4.9, 5.10, 5.23, 6.8, 7.19, 8.21, 8.40, 8.41, 8.50, 8.61, 8.62
	Journal of Geodynamics	8.43
	Lithos	2.5, 2.7, 2.8, 2.13, 2.18, 2.20, 2.21, 3.78, 4.32, 6.15, 7.2

Copyright owner	Journal	Figure number
	Ore Geology Review	9.1
	Tectonophysics	3.59, 3.80, 3.102, 3.104, 3.119, 4.48, 4.49, 5.3, 5.14, 6.16, 6.17, 6.24, 8.12, 8.13, 8.15, 8.19, 8.26, 8.28, 8.33
	Physics of the Earth and Planetary Interior	3.7, 3.10, 3.13, 3.31, 3.62, 3.91, 6.14, 8.57
	Precambrian Research	6.8, 6.16, 6.23
	Quaternary Science Review	3.93
	Treatise on Geochemistry	2.6, 2.10
	Geochim. Cosmochimica Acta	2.11, 2.12
	Chemical Geology	2.11
Nature Publishing Group	Nature	2.9, 2.15, 2.18, 2.24, 2.25, 3.44, 3.63, 3.113, 3.116, 3.122, 9.20
The Center for American Progress (www.americanprogress.org)	Science progress	3.76
Oxford University Press	Journal of Petrology	6.6
National Research Council Canada	Canadian Journal of Earth Sciences	3.65, 3.67, 4.12
Wiley-Blackwell	Geophysical Journal International	3.83, 3.114, 4.40, 5.16, 7.5, 7.10, 8.39, 8.54, 8.56
American Association for the Advancement of Science	Science	2.4, 3.42, 3.106, 7.48, 9.23
Cambridge University Press		2.3, 3.17, 3.60, 3.61, 6.21, 7.19, 8.3, 8.16, 8.18, 8.20, 8.22, 8.31, 8.47, 8.48
Academic Press		3.66
Springer		8.6, 8.30
Princeton University Press		7.16
Geological Survey of Finland		9.3