Deformation of Earth Materials

Much of the recent progress in the solid Earth sciences is based on the interpretation of a range of geophysical and geological observations in terms of the properties and deformation of Earth materials. One of the greatest challenges facing geoscientists in achieving this lies in finding a link between physical processes operating in minerals at the smallest length scales to geodynamic phenomena and geophysical observations across thousands of kilometers.

This graduate textbook presents a comprehensive and unified treatment of the materials science of deformation as applied to solid Earth geophysics and geology. Materials science and geophysics are integrated to help explain important recent developments, including the discovery of detailed structure in the Earth's interior by high-resolution seismic imaging, and the discovery of the unexpectedly large effects of high pressure on material properties, such as the high solubility of water in some minerals. Starting from fundamentals such as continuum mechanics and thermodynamics, the materials science of deformation of Earth materials is presented in a systematic way that covers elastic, anelastic, and viscous deformation. Although emphasis is placed on the fundamental underlying theory, advanced discussions on current debates are also included to bring readers to the cutting edge of science in this interdisciplinary area.

Deformation of Earth Materials is a textbook for graduate courses on the rheology and dynamics of the solid Earth, and will also provide a much-needed reference for geoscientists in many fields, including geology, geophysics, geochemistry, materials science, mineralogy, and ceramics. It includes review questions with solutions, which allow readers to monitor their understanding of the material presented.

Shun-ichiro Karato is a Professor in the Department of Geology and Geophysics at Yale University. His research interests include experimental and theoretical studies of the physics and chemistry of minerals, and their applications to geophysical and geological problems. Professor Karato is a Fellow of the American Geophysical Union and a recipient of the Alexander von Humboldt Prize (1995), the Japan Academy Award (1999), and the Vening Meinesz medal from the Vening Meinesz School of Geodynamics in The Netherlands (2006). He is the author of more than 160 journal articles and has written/edited seven other books.

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An Introduction to the Rheology of Solid Earth

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Preface

Understanding the microscopic physics of deformation is critical in many branches of solid Earth science. Long-term geological processes such as plate tectonics and mantle convection involve plastic deformation of Earth materials, and hence understanding the plastic properties of Earth materials is key to the study of these geological processes. Interpretation of seismological observations such as tomographic images or seismic anisotropy requires knowledge of elastic, anelastic properties of Earth materials and the processes of plastic deformation that cause anisotropic structures. Therefore there is an obvious need for understanding a range of deformation-related properties of Earth materials in solid Earth science. However, learning about deformation-related properties is challenging because deformation in various geological processes involves a variety of microscopic processes. Owing to the presence of multiple deformation mechanisms, the results obtained under some conditions may not necessarily be applicable to a geological problem that involves deformation under different conditions. Therefore in order to conduct experimental or theoretical research on deformation, one needs to have a broad knowledge of various mechanisms to define conditions under which a study is to be conducted. Similarly, when one attempts to use results of experimental or theoretical studies to understand a geological problem, one needs to evaluate the validity of applying particular results to a given geological problem. However, there was no single book available in which a broad range of the physics of deformation of materials was treated in a systematic manner that would be useful for a student (or a scientist) in solid Earth science. The motivation of writing this book was to fulfill this need.

In this book, I have attempted to provide a unified, interdisciplinary treatment of the science of deformation of Earth with an emphasis on the materials science (microscopic) approach. Fundamentals of the materials science of deformation of minerals and rocks over various time-scales are described in addition to the applications of these results to important geological and geophysical problems. Properties of materials discussed include elastic, anelastic (viscoelastic), and plastic properties. The emphasis is on an *interdisciplinary approach*, and, consequently, I have included discussions on some advanced, controversial issues where they are highly relevant to Earth science problems. They include the role of hydrogen, effects of pressure, deformation of two-phase materials, localization of deformation and the link between viscoelastic deformation and plastic flow. This book is intended to serve as a textbook for a course at a graduate level in an Earth science program, but it may also be useful for students in materials science as well as researchers in both areas. No previous knowledge of geology/geophysics or of materials science is assumed. The basics of continuum mechanics and thermodynamics are presented as far as they are relevant to the main topics of this book.

Significant progress has occurred in the study of deformation of Earth materials during the last ~30 years, mainly through experimental studies. Experimental studies on synthetic samples under well-defined chemical conditions and the theoretical interpretation of these results have played an important role in understanding the microscopic mechanisms of deformation. Important progress has also been made to expand the pressure range over which plastic deformation can be investigated, and the first low-strain anelasticity measurements have been conducted. In addition, some large-strain deformation experiments have been performed that have provided important new insights into the microstructural evolution during deformation. However, experimental data are always obtained under limited conditions and their applications to the Earth involve large extrapolation. It is critical to understand the *scaling laws* based on the physics and chemistry of deformation of materials in order to properly apply experimental data to Earth. A number of examples of such scaling laws are discussed in this book.

This book consists of three parts: Part I (Chapters 1–3) provides a general background including basic continuum mechanics, thermodynamics and phenomenological theory of deformation. Most of this part, particularly Chapters 1 and 2 contain material that can be found in many other textbooks. Therefore those who are familiar with basic continuum mechanics and thermodynamics can skip this part. Part II (Chapters 4–16) presents a detailed account of materials science of time-dependent deformation, including elastic, anelastic and plastic deformation with an emphasis on anelastic and plastic deformation. They include, not only the basics of properties of materials characterizing deformation (i.e., elasticity and viscosity (creep strength)), but also the physical principles controlling the microstructural developments (grain size and lattice-preferred orientation). Part III (Chapters 17–21) provides some applications of the materials science of deformation to important geological and geophysical problems, including the rheological structure of solid Earth and the interpretation of the pattern of material circulation in the mantle and core from geophysical observations. Specific topics covered include the lithosphere–asthenosphere structure, rheological stratification of Earth's deep mantle and a geodynamic interpretation of anomalies in seismic wave propagation. Some of the representative experimental data are summarized in tables. However, the emphasis of this book is on presenting basic theoretical concepts and consequently references to the data are not exhaustive. Many problems (with solutions) are provided to make sure a reader understands the content of this book. Some of them are advanced and these are shown by an asterisk.

The content of this book is largely based on lectures that I have given at the University of Minnesota and Yale University as well as at other institutions. I thank students and my colleagues at these institutions who have given me opportunities to improve my understanding of the subjects discussed in this book through inspiring questions. Some parts of this book have been read/reviewed by A. S. Argon, D. Bercovici, H. W. Green, S. Hier-Majumder, G. Hirth, I. Jackson, D. L. Kohlstedt, J. Korenaga, R. C. Liebermann, J.-P. Montagner, M. Nakada, C. J. Spiers, J. A. Tullis and J. A. Van Orman. However, they do not always agree with the ideas presented in this book and any mistakes are obviously my own. W. Landuyt, Z. Jiang and P. Skemer helped to prepare the figures. I should also thank the editors at Cambridge University Press for their patience. Last but not least, I thank my family, particularly my wife, Yoko, for her understanding, forbearance and support during the long gestation of this monograph. Thank you all.