Preface

The purpose of this book is to explain the theoretical studies that deal with geologic structures as constraints so as to understand the deformation of the lithosphere of terrestrial planets and satellites. Topics range from tectonic processes at mesoscale to global scales. The term “tectonophysics,” within the meaning of those studies, is usually regarded as a branch of geophysics. However, this book is all about the middle ground between geology and geophysics. The audience includes researchers, advanced undergraduate, and graduate students in geology, geophysics, and planetary science.

Tectonic activity in orogenic belts, island arcs, and rift zones lasted for millions of years, so that geological observations are necessary for understanding tectonics. The word “tectonics” means the natural processes that create geologic structures on meso to regional scales or on a global scale. Folds and faults are not the only objects of tectonics. This realm of science covers not only folds and faults, but also structures that were created through natural deformation processes in the shallow parts of terrestrial planets and of icy and rocky satellites. They include the formation of mountain belts, sedimentary basins, and impact craters. Although microscopic deformations and interplay between tectonics and climate are important issues today, they are omitted from this book. Geophysical observations including seismological and geodetic observations, which have provided important data for tectonophysics, are not included.

Geologic structures, stratigraphic sequences, and the surface topography of terrestrial planets and satellites are record of geologic processes from the past. They are the clue to understanding the internal evolution of the bodies. They can constrain deep processes, and their orbital evolution. Mechanical properties depend on rock types, so that the difference in type is visualized as geologic structures in some cases. If so, we are able to estimate the composition of the heavenly bodies from their geologic structures.

Theories of faulting, folding, and vertical movements are explained in this book so that the reader can not only understand the phenomena themselves but also their origins. We shall find that the answers to many questions on those structures, including the following, depend on circumstances:

- Can we know paleo stress fields from faults?
- Does the subsidence that resulted in the formation of a sedimentary basin simultaneously indicate crustal thinning?
- Does clockwise paleomagnetic rotation in a shear zone indicate a dextral sense of shear?

It is important to know what kind of conditions justify them.

To construct theoretical models for geologic structures, continuum mechanics is a basic and indispensible tool, as rock masses occupy continuous spaces at depth. We call such a continuous medium a continuum, in that physical variables, such as force, temperature, etc., are continuous. This assumption makes mathematical treatment very easy. However, continuum mechanics is not always familiar to geologists and undergraduate students, so that the basic equations of continuum mechanics are explained with the use of models. In addition, basic formulas of vectors and tensors for the mechanics is provided in an appendix. This book covers a wide range of topics on geologic structures with scales from outcrops to planetary bodies, so that I believe that a brief explanation is necessary for the geological background or implications of each of the topics. Accordingly, explanations on continuum mechanics and geological ones are provided alternatively.

Continuum or solid mechanics has been developed in mechanical engineering to deal with artificial structures which are made of materials with known mechanical and chemical properties. Nevertheless, Y. C. Fang wrote, in the epilogue of his textbook “Foundations of solid mechanics,” that the reader must have a feeling that the panorama of solid mechanics is somewhat unreal. The examples selected and discussed in the book are idealized problems... The real material behaves in a complicated way [61]. Tectonic phenomena are still more complex.

What is the benefit of the theoretical treatment of geologic structures and of the use of geological constraints? Geological data are usually less precise than geophysical data. Can the theories predict future tectonic movements and help prevent natural disasters? They may be difficult, even if they are possible, because the crust and mantle are so heterogeneous that their mechanical properties vary by many orders of magnitude. In addition, the temporal and spatial scales of tectonics are so large that rocks at great depths are inaccessible and estimation of the parameters that control the properties is usually difficult. Coupled with several other factors makes it still more difficult. In many instances we do not know even how to ask questions about outcrops.

Instead, the theories provide insights into tectonic phenomena. Using proper interpretations of idealized results, we can discuss how and which factors control tectonic phenomena under what conditions. Theoretical and quantitative models not only provide insights, but also enable us to verify our understanding of the phenomena. The following statement by Fung [61] is appropriate for tectonic researchers as well as for engineers: Central questions constantly asked by an engineer are: how can a problem be idealized... And how can an idealization be evaluated as to its adequacy with respect to the real situation?

Ultimately, the striking feature of this book is the detailed description of analytical models for geologic structures, stratigraphy, and topography that were the results of tectonics over geological timescales in the terrestrial planets and satellites. The results of numerical simulation, which is now an important tool for tectonophysics, are only briefly referred to, mainly in the last chapter.

Geologists have studied the structures as aspects of natural history. When I was a student in geology, I learned from many geophysical articles that a wealth of geological observations were
used as constraints for tectonophysics. However, there were a few textbooks acting as a go-between for geologic structures and geophysics. This book is the outcome of my endeavors and aspirations for bridging the gap from the geological side. This is relevant to the difference between this book and the recognized textbook by Turcotte and Schubert [245]. There are two points that discriminate the textbooks: (1) this book takes the scope of the problem areas generally restricted in geology, and (2) the candid usage of tensorial equations the basics of which are briefly explained in Appendix C. Tensor calculus in general is not simple. However, only orthogonal coordinates and second-order tensors are used in this book, making the tensors intelligible to readers who have studied linear algebra and elementary calculus. Every time an important concept is introduced, topics on its application to tectonics are presented. The representations give easy access to a comprehensive understanding of continuum mechanics that, in turn, provides the coherent architecture of this book with a variety of topics. A few textbooks [186, 190, 233, 184] are similar in ethos, but they deal with geologic structures ranging from micro- to regional scales. This book covers meso- to global scales, and takes topics from other planets and satellites as well as from the Earth.

This book consists of three parts. The first and second parts introduce the equations of continuum mechanics and their applications. Apart from the basics of continuum mechanics, special topics are discussed in the last part.

In Part I, strain and stress are formulated. Chapter 1 in this part formulates deformations. Contrasting to this chapter in which finite deformations are discussed as tectonics for a geological time scale results in finite deformations, Chapter 2 is limited to infinitesimal deformations, and describes the time rate of deformation. The limitation allows us to linearize problems and to link to stress in Part II. Chapters 1 and 2 describe the kinematic aspects of tectonics. Chapter 3 introduces stress and balance equations to formulate statics in tectonics. Chapter 4 explains the principal stresses and stress fields.

Part II links stress and strain together for the discussion about the dynamical aspects of tectonics. The part consists of five chapters. Chapter 5 briefly explains how materials behave under loading and introduces the representation theorem, that is, a tight mathematical constraint for the stress-strain relationship of isotropic materials. Chapter 6 explains brittle faulting and the brittle strength of the crust. Chapter 7 puts forward the equations of linear elasticity and their applications to the state of stress in the shallow parts of the crust. Based on those equations, Chapter 8 explains the elasticity of the lithosphere and geological implications. Newtonian fluid is introduced in Chapter 9. Topics in this chapter includes the viscous relaxation of topographic undulations on the Earth, Mars, and icy satellites, and the formation of long wavelength undulations as the surface manifestations of mantle convection. Linear stability theory for Newtonian fluids is applied to the formation of spatially periodic geologic structures including folds and boudins. Plasticity is introduced in Chapter 10 to formulate the yielding of flexed sedimentary slabs and the collapse of large-scale impact craters. The equations of the power-law rheology of rocks and water ice are also presented in this chapter.

Part III is devoted to special topics. Chapter 11 discusses how to estimate paleo stresses from mesoscale faults. Chapter 12 explains the mechanical strength of the lithosphere.

This book has four appendices. The list of symbols is provided in Appendix A. A formulation of
stress inversion that was developed in the last few years is briefly introduced in Appendix B, which supplements Chapter 11. Appendix C provides the basic equations of vectors and tensors, which are referred to in the preceding parts. There are exercises at the end of each chapter. Answers for most of the questions are presented in Appendix D.

**Remarks**

**Symbols**  We will use a few kinds of variables, namely, scalars, vectors and tensors. Scalar variables are denoted by italic symbols such as $A$. Bold italic and san-serif fonts indicate, respectively, vectors and tensors, for example $\mathbf{A}$ and $\mathbf{A}$.

**Coordinates**  We adopt the right-handed Cartesian coordinates as standard. If we consider models where gravitational force is significant, we use the coordinates $O-xyz$ with the $z$ axis pointing vertically downwards. Vector components are denoted in this case as $\mathbf{a} = (a_x, a_y, a_z)^T$, where the superscript $T$ indicates matrix transpose. If it is not the case, we use the Cartesian coordinates $O-123$, and we write vector components as $\mathbf{a} = (a_1, a_2, a_3)^T$.

**Sign convention for stress and strain**  Attention must be paid to the signs of stress and strain, because Earth science and continuum mechanics have different sign conventions. Tensional stress and elongation are positive stress and strain, respectively, in continuum mechanics. Structural geologists define compression and elongation as positive stress and strain. This sign convention is natural for Earth scientists as the state of stress at depth is commonly compressional. However, tensile stresses results in elongation. Accordingly the fashion of continuum mechanics is theoretically more natural than that of Earth science. Both sign conventions have reasons. Consequently, we use both fashions and distinguish them by assigning different symbols as follows. The symbols $\mathbf{S} = (S_{ij})$ and $\mathbf{\sigma} = (\sigma_{ij})$ represent tension and compression as positive stresses. They are different only in sign, so that $\mathbf{S} = -\mathbf{\sigma}$. Corresponding to them, $\mathbf{E}$ and $\mathbf{e}$ represent extension and contraction as positive infinitesimal strains, respectively.

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