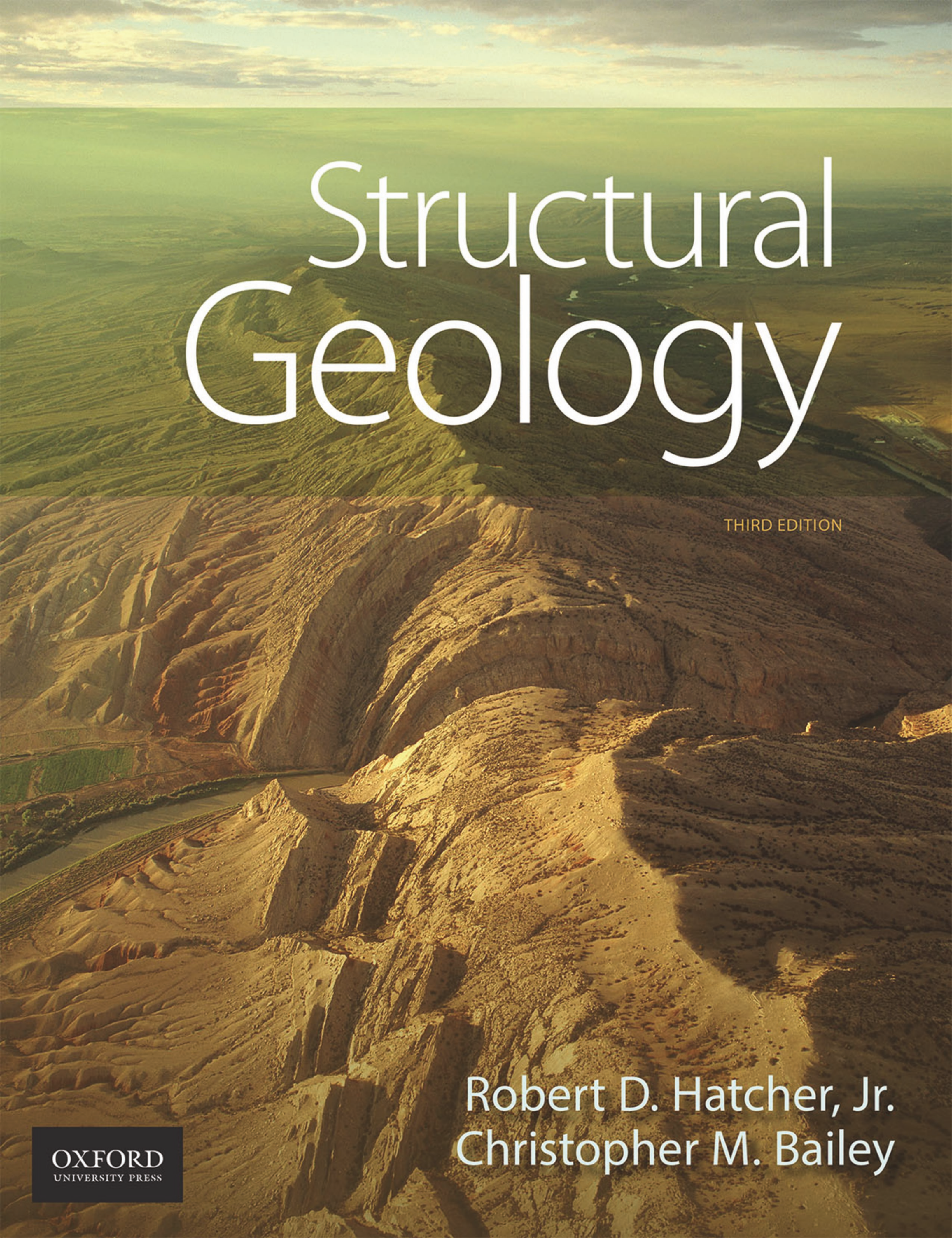


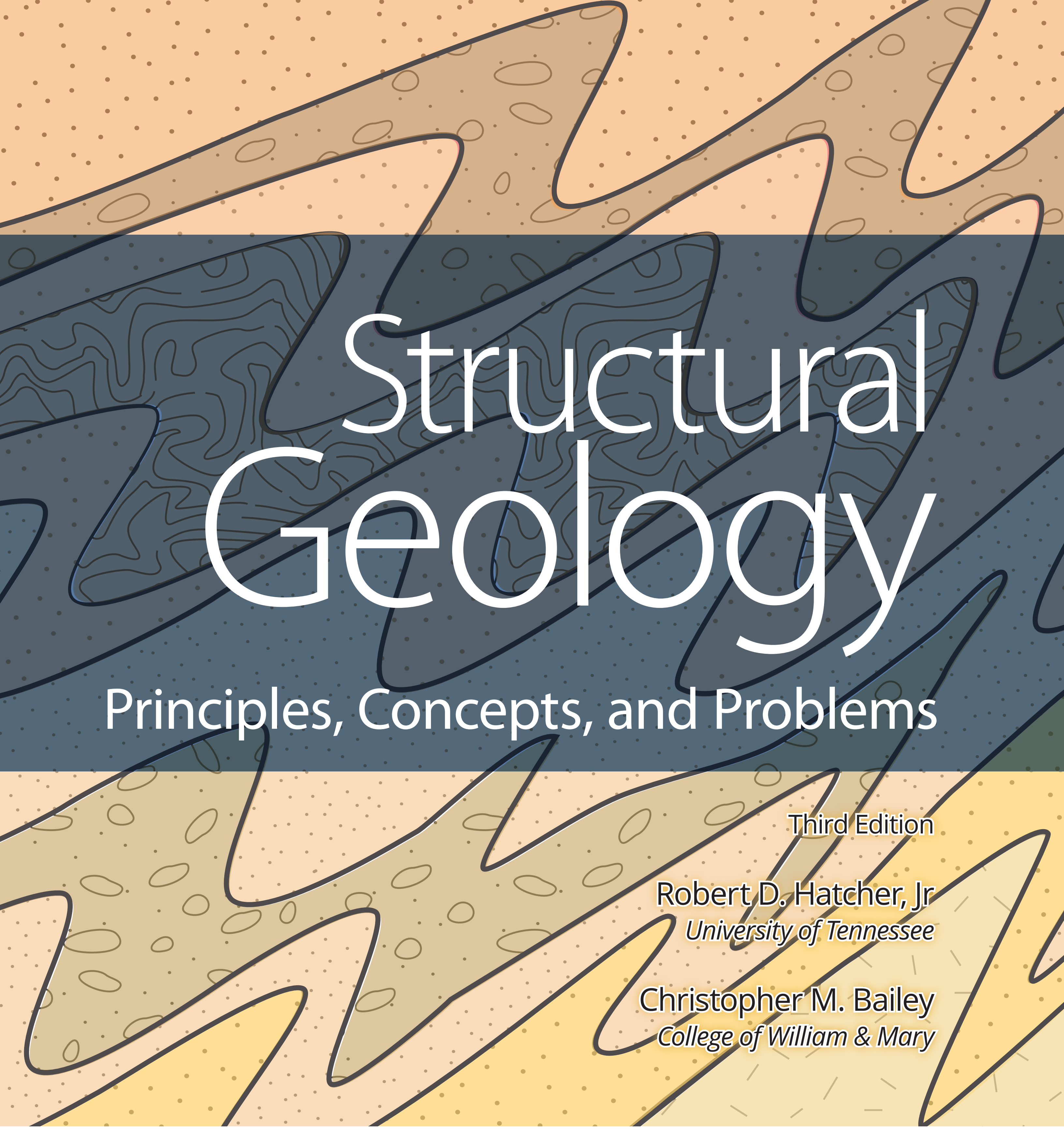
Structural Geology

THIRD EDITION

Robert D. Hatcher, Jr.
Christopher M. Bailey

OXFORD UNIVERSITY PRESS

Structural Geology



Structural Geology

Principles, Concepts, and Problems

Third Edition

Robert D. Hatcher, Jr
University of Tennessee

Christopher M. Bailey
College of William & Mary

New York Oxford
OXFORD UNIVERSITY PRESS

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COVER: Bighorn River water gap through Sheep Mountain anticline, north of Greybull, Wyoming. Photo by Michael Collier.

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We dedicate this book to our parents, teachers, and other mentors.

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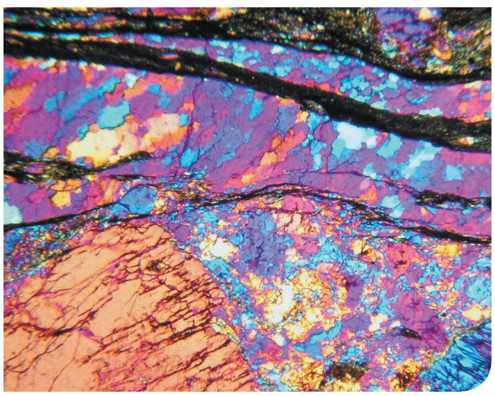

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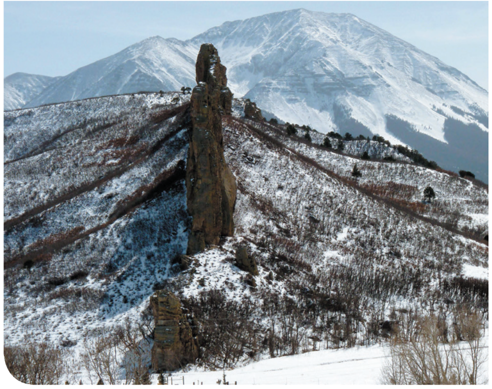

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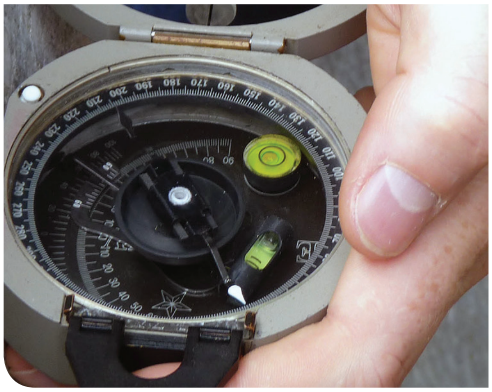

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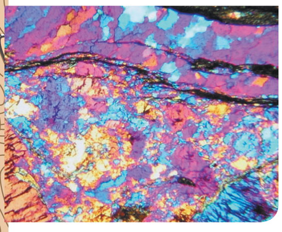


Preface to the Third Edition

The third edition of *Structural Geology: Principles, Concepts, and Problems* is a complete revision from the first two editions. Each chapter has been rewritten with many new figures and color added to numerous illustrations throughout the book. We have added a new chapter on geochronology, and the 3rd edition integrates many new and exciting developments in structural geology and tectonics from the past two decades. Chuck Bailey joined as co-author; this will be evident in chapters where his expertise has had a major impact on improvement of the technical quality, but also on the overall quality of the book. Our numerous meetings, e-mail, and phone conversations proved especially valuable in that they enabled us to work through issues that arose and helped with incorporation of review comments. We feel, however, that the basic thread woven through the first two editions has carried into the third: to present a balanced coverage of all topics in modern structural geology at a level appropriate for students in junior-senior-level structural geology courses offered today in most geology programs in North America.

To the Users of This Book

The arrangement of chapters in the book follows the same outline as previous editions, with no major organizational changes. One thing that may be noticeable is that much of the discussion of the historical basis of concepts and ideas has been moved to essays. This permits students who are interested in the historical development of structural geology to explore further, but it does not interrupt the overall flow of chapters.

One of the pedagogical tenets we have followed in this and previous editions is including more information in each chapter than can be covered in one or two class periods. This makes the book both a text and a reference document, which we consider a positive attribute of our book. Another is the use of different letter styles throughout the book for terms we consider to be most important for students to remember (in bold italic), important but not imperative to be learned (in italic), or for information only (regular type). The Glossary at the end of the book contains all of the first two categories and many of the last.

The 21 chapters are arranged in five parts. The introductory section is intended for review and to present information not usually included in structural geology texts. One of our goals was to provide an initial section of four chapters that reviews basic concepts, and presents two topics rarely covered in the courses most students have taken before taking structural geology: geochronology and geophysics. These two chapters are not intended to be exhaustive summaries of these subjects, but to present a basic understanding of geochronology and geophysics that bears on the subject of structural geology. They are intended to form an integral part of understanding the basis of processes related to rock deformation, timing of deformation, and geometry of structures. A section introducing down-hole geophysics was included in the geophysics chapter, because so many students receive bachelors and masters degrees and then become employed in the engineering/environmental, seismic hazard assessment, and petroleum industries where down-hole geophysical data are commonly utilized. The four introductory chapters can be presented as an integral part of the course, or assigned as collateral reading. We feel that they belong at the front of the book so they can be covered—or not—at the beginning of the course to review existing concepts like plate tectonics and non-tectonic structures, then introduce the basis of radiometric age determinations and the principal topics from geophysics that are useful in structural geology—and afterward move on to the basic subject matter of structural geology.

The section on mechanics introduces stress, strain, material behavior, and microstructures. In discussing the order of presentation in this section, we feel that the presentation of strain should follow the discussion of stress, recognizing that some structural geologists advocate presenting strain early with stress toward the end of the course. Our feeling is that these subjects belong together early in the course, and should be covered sequentially with stress first. The chapters on stress, strain, and material behavior present some of the topics found in the basic strength of materials courses in engineering curricula—with a geologic bias—and with less mathematics. The microstructures chapter provides an introduction to deformation processes that occur on a micro-scale. It lays a foundation for presentation of microstructures later in the book.

The section dealing with fractures and faults begins by introducing the most pervasive geologic structures on the Earth's surface: joints. This is followed by a chapter describing the basic properties of faults and shear zones, and introduces shear-sense indicators that permit us to determine the movement sense on a fault at the outcrop- or micro-scale. It also emphasizes that not all faults are simple brittle structures confined to the upper crust, but may be broad, ductile shear zones that form along faults in the deep crust. The chapter on fault mechanics presents the mechanical basis for faulting. The following three chapters discuss the three primary fault types and their nature in greater detail.

The section on folds and folding contains three chapters: a chapter dealing with the fundamental properties of folds, another dealing with fold mechanics, and a third deals with complex folds. This section also serves to bring out the fact that folds are not all ductile structures as frequently presented—they form in the brittle realm as well.

The last section in the text dealing with rock fabrics and structural analysis contains four chapters. The chapter on cleavage and foliations introduces the most common planar structure in metamorphic rocks, and discusses the mechanics of how these structures form. The chapter on lineations (*not* lineaments) discusses the different kinds of linear structures in rocks. The chapter on structures in plutons discusses the wide variety of plutons and their associated structures. The structural analysis chapter outlines various ways to analyze geologic structures that can be brought to bear for structures that formed at different scales in different geologic environments. It involves integration of different techniques and many of the structures discussed in earlier chapters.

Our wish beginning with the first edition remains the same: as teachers, we want students to enjoy their structural geology course. Earth's structures and the tectonic processes that form them are both important and intriguing. We view the world around us with a sense of wonder, and hope this book provides a scientific framework to help understand it. The learning process need not be difficult or painful, but it should be challenging and can be approached as a game: the rules of the game should be spelled out by your instructor at the beginning of the course. The degree to which your instructor becomes involved in the course from the beginning largely determines the quality of the course and how much students derive from it. The text chosen helps to determine the level at which the course is taught and the kinds of material to be covered. The balanced coverage in this text is intended to enhance the involvement of both students and instructors in structural geology. Finally, we hope this book will kindle the interests of students who use it and some will choose to become structural geologists—a measure of success for any structural geology course.

Acknowledgments

The late Nancy L. Meadows, in the Tectonics and Structural Geology Research Group at the University of Tennessee, played a critical role in quality control of pre-publisher editing and proofing chapters, checking references, compiling the glossary and references, and, in the first two editions, constructing and checking the indexes. We are eternally grateful for her long-term contributions to the quality of this book. Andrew L. Wunderlich, also in our research group, made a major contribution to this third edition by providing outstanding graphics and ArcGIS support, constructing preliminary layouts of each chapter and appendices in InDesign prior to review, compiling the spreadsheet with old and new glossary terms, and conducting the final check of references against the text. Rebecca J. Christ did some editing and particularly compiled a massive spreadsheet containing the information on permissions for figures.

The Science Alliance Center of Excellence at the University of Tennessee has provided both salary and stipend support for RDH (and many graduate and undergraduate students) for the past three-plus decades. This has permitted travel to many places, particularly mountain chains and continental shields, which would have otherwise been inaccessible, to better understand the structure and evolution of continental crust. Many of the photos published in this textbook could not have been made without this support.

We have benefitted from the many outstanding undergraduate and graduate research students that we've worked with during the past several decades. These students enabled us to become better structural geologists, and challenged us to provide cogent explanations of sometime complex mechanics and processes. They also have encouraged us to learn along with them, so that we benefitted from their questions and persistence to understand our subject.

Both of us have led and participated in numerous field trips where professionals and students are presented with possible solutions to complex structures and tectonic histories. Many times, the additional sets of eyes have pointed out critical—previously unseen—features that facilitated the understanding of the structural and tectonic histories of poorly known areas.

Gilles Allard (University of Georgia, Emeritus) kindly provided contact with Réal Daigneault (Québec Geological Survey and Université du Québec à Chicoutimi), who gave us two illustrations for Chapter 6. Rick Law (Virginia Tech) patiently listened to and answered numerous questions about quartz deformation by RDH and contributed an illustration that was incorporated into Chapter 8. We are grateful to former University of Tennessee undergrad and M.S. student Ching Tu (Schlumberger Corp.), and Walter Wunderlich (TVA design engineer, retired), who offered useful improvements to some of the mathematics in Chapter 5.

Our third edition has benefited enormously from constructive reviews of chapters commissioned by Oxford University Press. A few of the reviewers disagreed with our pedagogical philosophy, but their comments were constructive and quite useful in improving our book. These reviewers are: two anonymous reviewers, Joseph Allen (Concord University), Andy Bobyarchick (University of North Carolina–Charlotte), Maria Brunhart-Lupo (Colorado School of Mines), Gabriele Casale (Appalachian State University), Robert Cicerone (Bridgewater State University), Randy Cox (University of Memphis), Anna Crowell (University of North Dakota), Ernest Duebendorfer (Northern Arizona University), Eric Ferré (Southern Illinois University), Mary Hubbard (Montana State University), Kristin Huysken (Indiana University Northwest), Jamie Levine (Appalachian State University), Ryan Mathur (Juniata College), Melanie Michalak (Humboldt State University), Devon Orme (Montana State University), Terry Panhorst (University of Mississippi), Mitchell Scharman (Marshall University), Christian Schrader (Bowdoin College), John Singleton (Colorado State University), Jaime Toro (West Virginia University), Frederick Vollmer (SUNY–New Paltz), David West (Middlebury College), Paul Wetmore (University of South Florida), Laura Wetzel (Eckerd College), Michael Williams (University of Massachusetts), and Martin Wong (Colgate University).

Earlier constructive reviews of third-edition chapters commissioned by Pearson/Prentice Hall were also beneficial in the evolution of this edition of our book, and are much appreciated. These reviewers are: Jeffrey Amato (New Mexico State University), Cynthia Coron (Southern Connecticut State University), David Foster (University of Florida), Ron Harris (Brigham Young University), Eric Horsman (East Carolina University), Eric Jerde (Morehead State University), Paul Karabinos (Williams College), and John Weber (Grand Valley State University).

We also express our deep appreciation to our most recent Pearson/Prentice Hall editor Andrew Dunaway and our Oxford editors, Dan Kaveny and Dan Sayre, for their encouragement and enthusiastic support of our efforts to complete the third edition of this textbook.

Bob Hatcher
Chuck Bailey

PART 1

Introduction

OUTLINE

Introduction

A stone, when it is examined, will be found a mountain in miniature.

JOHN RUSKIN, 1858, *Modern Painters*

For centuries the shapes of continents and ocean basins, the linearity of mountain ranges, the distribution of volcanoes, and the cause of earthquakes have fascinated humans (Figure 1–1). Today we know that most of these features are produced by deep-seated processes operating since the Earth formed; these processes have shaped both past and present configurations of tectonic plates (Figure 1–2). The effects of earthquake and volcanic activity are constant reminders that the Earth is a dynamic planet and that tectonic plates are driven by awesome forces. Most of Earth's human population is influenced by tectonic activity; unfortunately, earthquakes and volcanic eruptions threaten many people (Figure 1–1).

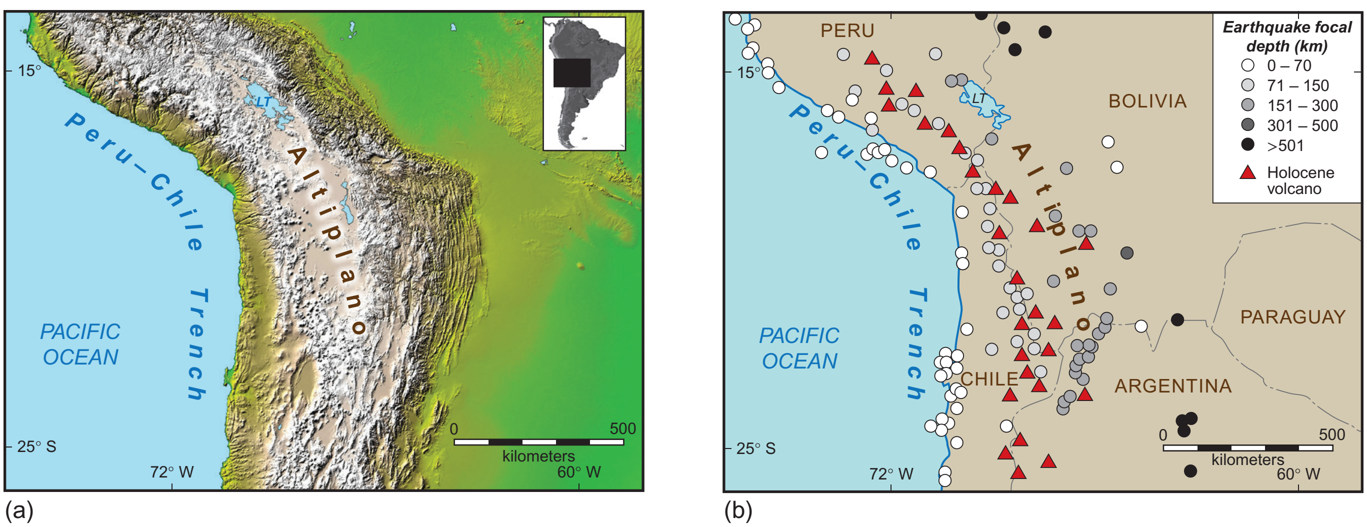


FIGURE 1–1 (a) Shaded relief map of part of western South America. The Andes Mountains stand out in strong relief. As the Nazca Plate is subducted along the Peru-Chile Trench, South America undergoes crustal thickening, uplift, and volcanism. The Altiplano is a high plateau with an average elevation over 3,300 m. LT—Lake Titicaca. (Map created from Shuttle Radar Topography Mission [SRTM] image PIA03388.) (b) Locations and focal depths of earthquakes ($M_w \geq 6$) since 1973 and distribution of Holocene volcanoes. Notice that earthquake focal depths generally increase with distance inland from the Peru-Chile Trench. (Data from U.S. Geological Survey National Earthquake Information Center and the Smithsonian Institution's Global Volcanism Program.)

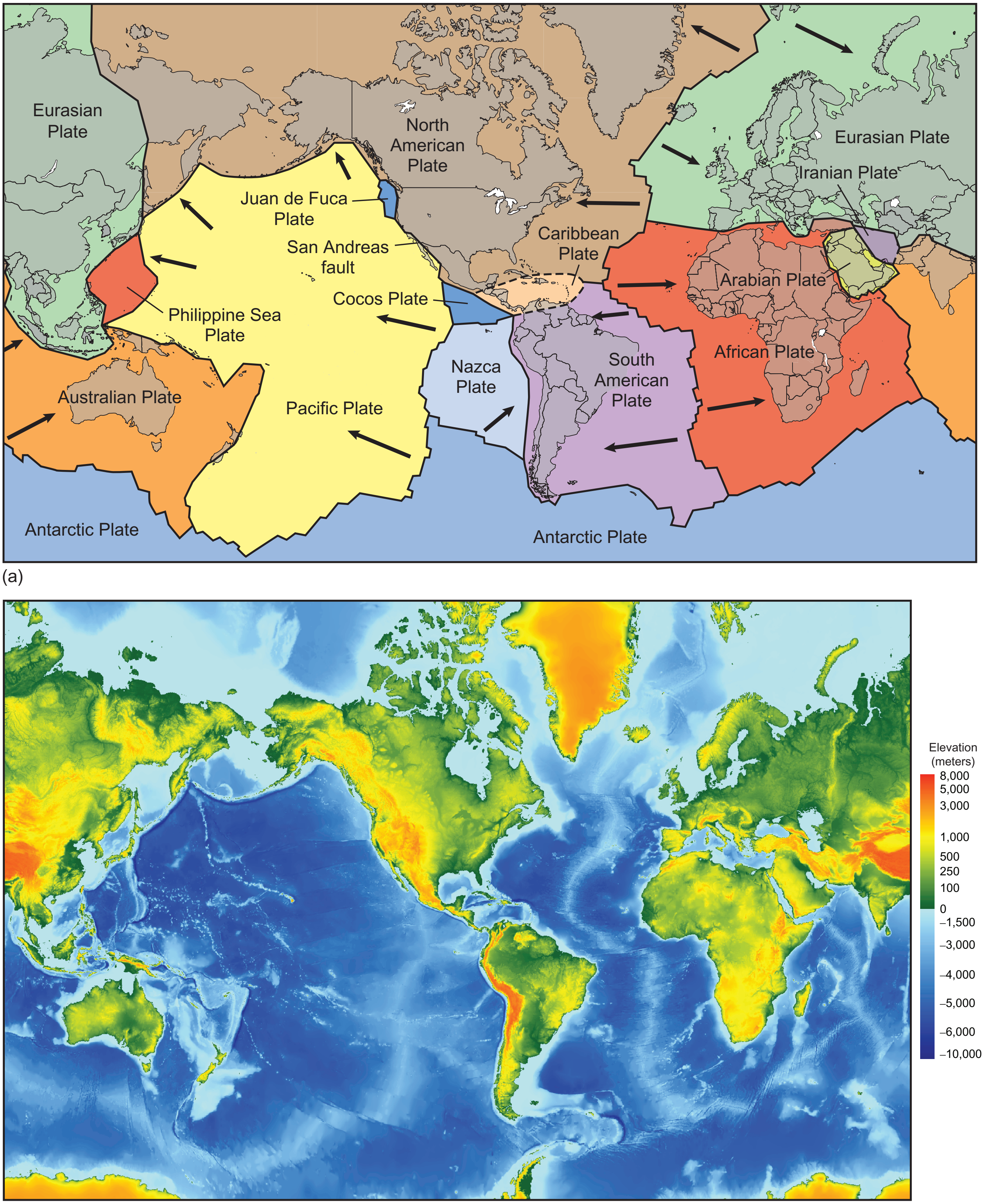


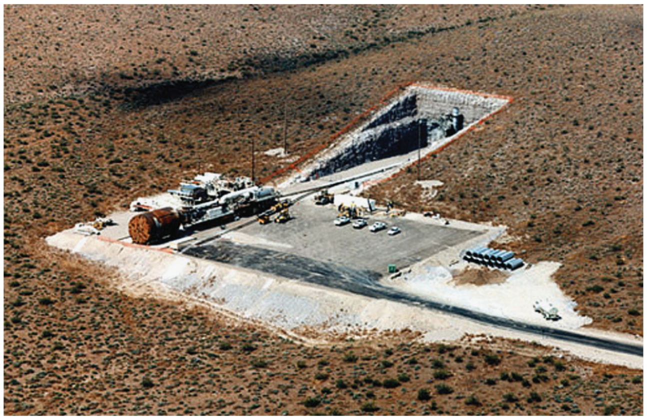
FIGURE 1–2 (a) Names and distribution of Earth's tectonic plates. Arrows indicate plate motion direction, and length of arrows indicate rate of motion. (U.S. Geological Survey.) (b) Shaded relief map of continents and ocean basins illustrating their relationship to plates and plate boundaries. Relief map generated from U.S. Geological Survey Global 30 Arc-Second Elevation (GTOPO30) and Intergovernmental Oceanographic Commission/International Hydrographic Organization General Bathymetric Chart of the Oceans (GEBCO) digital elevation models.

Aside from the imminent danger and practical need to comprehend and mitigate the dangers associated with these hazards, most geologists feel a basic scientific urge to understand these processes. Structural geologists are concerned with deformation of rocks and why parts of the Earth's crust are bent into smoothly curved shapes—producing folds—but others, sometimes in the same regions, are broken by faults. We also want to understand both the processes that produce structures and the history of how the structures formed. The opening quote by Ruskin is applicable to the structural geologist as we consider the nature and origin of structures from regional scale down to grain scale.

Structural geology is the study of rock deformation. It considers the geometry, dynamics, kinematics, and mechanics of earth structures and has great relevance to society and the world economy. It is readily applied to engineering problems that involve the foundations of bridges, dams, buildings, and power plants where large excavations are necessary, as well as highways where excavations extend for long distances. Studies of geologic structures beneath buildings, dams, and highway cuts are of great importance because of the potential for renewed motion along faults and other fractures, as well as concern for the stability of slopes and geologic materials. Siting large engineered structures in active fault zones, like the U.S. West Coast, is not desirable, but sometimes it is impossible to build them in tectonically quiet areas. Therefore, geologists and engineers must work together from the design stage through construction to evaluate which structures are still active and might affect engineering works, as well as to minimize cost.

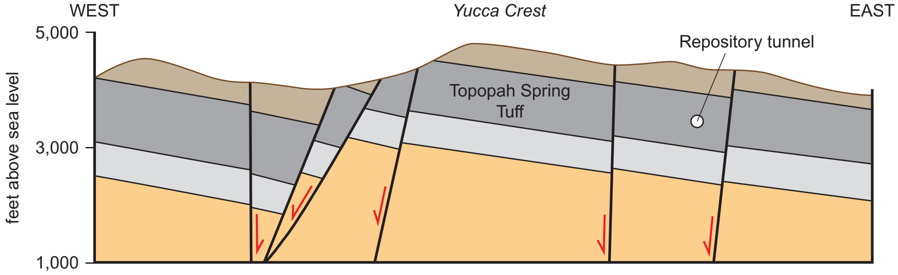
Environmental problems and land-use planning—such as earthquake hazards, waste isolation and disposal, and controls on the distribution of ground water—provide additional applicability for structural geology. Documenting the antiquity or recent movement of faults is an important aspect that requires understanding of structural geology. Location of sites for disposal of municipal, industrial, and radioactive waste requires application of structural and tectonic principles. Understanding the controls of large structures, such as folded layers of permeable and impermeable rocks that contain ground water, and small structures, such as fractures, on the distribution of ground water provides additional applications for this discipline. The proposed (now shelved) Yucca Mountain Repository in southern Nevada (Figure 1–3) is a controversial underground storage facility intended to safely house the United States' spent nuclear fuel and radioactive waste for at least 25,000 years. Over the past two decades the structural geology, mechanical characteristics, seismic history, and ground water flow paths were extensively studied in order to characterize the

(a)



(b)

FIGURE 1–3 (a) Oblique aerial view to the south of Yucca Mountain crest showing coring activities. (b) Oblique aerial view of the south portal into Yucca Mountain; note 25 ft diameter tunnel boring machine. (a and b retrieved from University of North Texas Web Archive, http://www.ymp.gov.) (c) Geologic cross section through Yucca Mountain illustrating gently tilted volcanic rocks cut by a series of steeply dipping normal faults. (Modified from Day et al., 1998.)



(c)

site; key questions include recurrence interval and magnitude of seismic and volcanic activity, and permeability associated with fractures in the volcanic bedrock.

Structural geology has long had a close working relationship with petroleum and mining geology. The ability to project fault surfaces, geologic contacts, and other structures to depth is used to great advantage by geologists who explore for valuable minerals and petroleum. Tectonic principles have been applied to understanding larger trends and regional processes that control the concentration of mineral deposits and hydrocarbons.

Structural geology considers the geometry, dynamics, kinematics, and mechanics of earth structures. *Geometry* refers to the shape and orientation of structures on any scale. A first-order, and non-trivial, task for structural geologists is to accurately describe the geometry of Earth structures. Geometric understanding occurs over a wide range of scales, from field mapping of regional-scale structures to measuring the orientation of crystal axes in individual mineral grains under the microscope.

Dynamics deals with the study of motion of bodies in response to forces that produced the motion. In contrast, *kinematics* deals with the motion of materials independent of the forces that caused the motion. Rock masses can be uplifted from great depths in the crust, rotated between fault blocks, and translated hundreds to thousands of kilometers from their place of origin. Rock structures provide important kinematic clues, and this evidence is observable over a wide range of scales.

Mechanics focuses on the effects of forces or stresses on materials. Understanding the geometry and mechanical properties of a rock mass provides information related to how it will behave when put under stress. It is important to remember that we typically study structures after they form, frequently millions to billions of years later; thus we must infer the nature and magnitude of forces that affected the rocks as well as the *physical conditions* (pressure, temperature, fluid content) present when the structures formed. Some structural geologists conduct experiments deforming rocks under controlled conditions in the laboratory; this mechanical understanding is valuable for interpreting natural structures.

(a)

(b)

FIGURE 1–4 Structures are three-dimensional. Consider the famed Sydney Opera House (a) and its distinctive shell roof, and then think about the shapes of folds such as the Sheep Mountain anticline in Wyoming (b). This oblique aerial view (U.S. Department of Agriculture) nicely illustrates the three-dimensionality of the anticline. It is cored with Precambrian crystalline rocks and flanked by Paleozoic and Mesozoic sedimentary rocks of differing resistance to erosion that hold up flanking ridges and underlie valleys. Note the small folds in the lower left-hand part of the photo that mimic the shape of the main fold.

Structural geology is similar to architecture in that both disciplines require an ability to visualize objects in three dimensions. Visualizing objects in three dimensions can be difficult. Perhaps begin by thinking about familiar objects such as the room where you live, the decorations on the wall, and the locations of furniture; and then move on to less familiar geologic structures (Figure 1–4). Keep in mind that most of us also had difficulty with 3-D visualization when we began studying structural geology, but learning to visualize objects in three dimensions comes through practice. The shapes of geologic structures change through time, along with the physical conditions that formed them. In particular, the contrast in shape and type between structures formed near the Earth's surface and those formed at great depth under the weight of overlying rocks and at high temperatures indicates profound differences in physical conditions. As the elevation of a mountain range is reduced by erosion, physical conditions affecting the crust change both near the surface and at depth. An appreciation of structural geometry thus permits us to make better interpretations of kinematics and mechanics, and ultimately of the origins of earth structures.

Tectonic structures are produced in response to stresses generated, for the most part, by plate motion within the Earth, and include faults and folds, along with other structures. They make up the tectonic framework of the Earth.

(a) (b)

FIGURE 1–5 Continuous (ductile) and discontinuous brittle structures in rocks. (a) Folded gneissic layering produced by ductile flow in metasedimentary rocks along Long Island Sound near Lyme, Connecticut. (b) Brittle deformation produced several sets of fractures in Precambrian metasedimentary rocks near Central City, Colorado. Scale is indicated by 3 to 5 m tall trees in foreground. (RDH photos.)

The kinds of structures that form in different parts of the crust are determined by: (1) prevailing temperature and pressure; (2) rock composition; (3) the nature of layering; (4) contrast in properties with direction between and within individual layers (***anisotropy***) or the lack of contrast (***isotropy***); and (5) amount and character of fluids within the rock mass. How rapidly the mass is deformed and the orientations of stresses applied to it also influence the kinds of structures produced. These factors determine whether deformation will be continuous (***ductile deformation***) or discontinuous (***brittle deformation***), producing a great variety of structures both in the Earth and on other planets (Figure 1–5).

Structures may also form as products of nontectonic processes, such as extraterrestrial impacts, landslides, and other features formed by gravity. It is useful to distinguish between tectonic and nontectonic structures (Chapter 2), because some nontectonic structures closely resemble—even mimic—structures formed by tectonic processes.

Much knowledge about geologic structures is derived from observing and attempting to understand structures in the field; thus, one of our goals is to improve our abilities to recognize, describe, measure, and interpret both subtle and obvious geologic structures in rocks. Also, a better understanding of physical and chemical principles and the ability to use mathematics and computers are needed to bridge the gaps between field, laboratory, and theoretical studies. The link between field and laboratory studies is both essential and supportive, for structural geology is divisible into subdisciplines of scale, structures, and processes, most of which overlap in geologic time. For example, laboratory studies determining fluid pressure that facilitates movement on faults are supported by field observations of evidence that fluid was present when a fault was active.

The study of ***field relationships*** is an exceptionally important aspect of structural geology because it provides limitations for formulating kinematic and mechanical models. In structural geology, we try to understand how small structures form and how they are related to larger structures and, ultimately, to crustal deformation and plate tectonics. A geologist undertaking a field-based structural study may: (1) make accurate geologic maps and cross sections of the structural geometry; (2) measure orientations of small structures to provide information about the shapes and relative positions of larger structures in the field; (3) study the overprinting sequence of structures to determine the variation in deformation conditions through time; (4) use these structures to understand the kinematic history; and (5) apply rock-mechanics principles and data to relate structures to forces that were present in the Earth during deformation. These different components will not be completed at the same time or in the sequence listed here.

Today there are many tools available to structural geologists that improve our work in the field. The *Global Positioning System (GPS)* permits the precise geolocation of structural data and samples. Software on "smart" phones and tablet computers facilitates recording, viewing, and manipulating data in the field, and some feature compasses and clinometers that make accurate strike and dip measurements (Appendix 2).

Rock mechanics is the application of physics to the study of rock materials. It deals with rock properties and the relationships between forces and resulting structures, as well as with the study of structures produced in the laboratory in an attempt to duplicate natural structures (Figure 1–6). In the laboratory, we can simulate the higher temperatures and pressures that exist at great depths. Alternatively, very weak materials such as salt, gelatin, clay, putty, and paraffin, which behave like rocks being deformed at higher temperatures, may be used to produce experimental structures at room temperature. A disadvantage of laboratory experiments is that they cannot be run

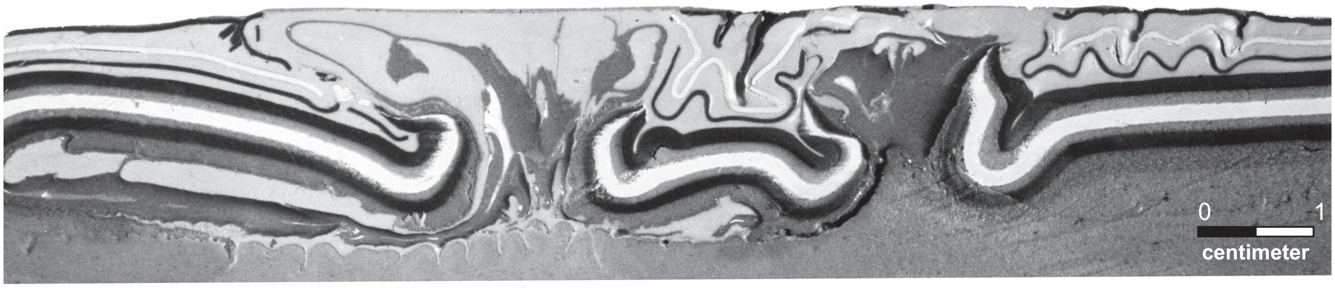


FIGURE 1–6 Experimental structures made in a centrifuge from viscous materials of different densities and fluid properties. Compare the shapes of these structures at this scale with those in Figures 15–18, 15–28, 16–2, 16–9, 16–21, 16E–1, and 17–14a. (From *Tectonophysics*, v. 19, H. Ramberg and H. Sjöström, p. 105–132, Fig. 15, © 1973, with kind permission from Elsevier Science, Ltd., Kidlington, United Kingdom.)

over geologic time—thousands to millions of years. They must be run on rocks and minerals at temperatures and pressures far above those normally occurring in nature so that deformation rates will occur rapidly enough that the person conducting the experiment will live to see the results! Artificial or natural materials deformed at reasonable rates that simulate the behavior of rocks must be scaled up to approximate natural processes.

Tectonics and ***regional structural geology*** involve larger features. Studies of mountain ranges, parts of continents, trenches and island arcs, oceanic ridges, entire continents and ocean basins, and their relationships to stresses and tectonic plates are included in these subdisciplines. ***Plate tectonics*** deals specifically with plate generation, motion, and interactions. Separating tectonics from regional structural geology is difficult. Regional structural geology is more commonly concerned with continental structures or well-imaged parts of the ocean floor and uses data from detailed studies of small structures to reconstruct the deformational history and tectonics of a region. Moreover, geophysical data (Chapter 4) and information derived from other disciplines of geology must be integrated with structural data for use in regional structural geology and tectonics. Use of geophysical data in structural geology is more common now because technology has made available more data of higher quality, especially seismic reflection, magnetic, and gravity data.

It is easy to see that the many subdivisions of structural geology are related to other disciplines in geology as well as to the other sciences. Direct applications are made from physics to study the origin of geologic structures. Isotopic data are frequently useful in working out the absolute timing of deformation, and geochemical data may help to determine mobility of fluids and elements during deformation. The chemical composition of highly deformed rocks may indicate the original material (*protolith*) and the environment before deformation.

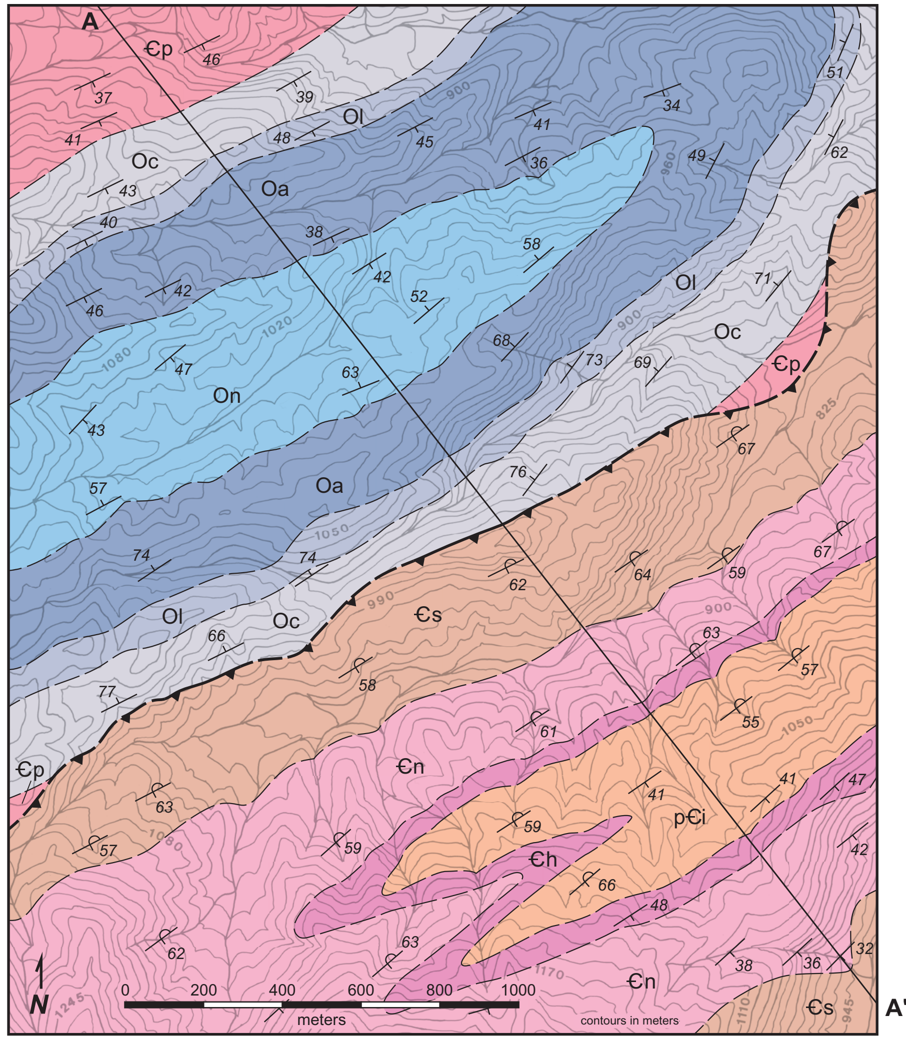
As mentioned earlier, the concept of ***scale*** is of great importance in structural geology. Structures—such as geologic contacts, foliations, faults, and folds—are commonly observed in the field in both hand specimen and at outcrop (or ***mesoscopic***) scale. ***Microscopic*** structures require magnification to be observed, and include many foliations and linear structures. Mountainside to map-scale structures are called ***macroscopic*** structures. Scales and geometric perspectives of geologic cross sections must be maintained between the map from which the section is constructed and the section itself (Figure 1–7).

Plate Tectonics

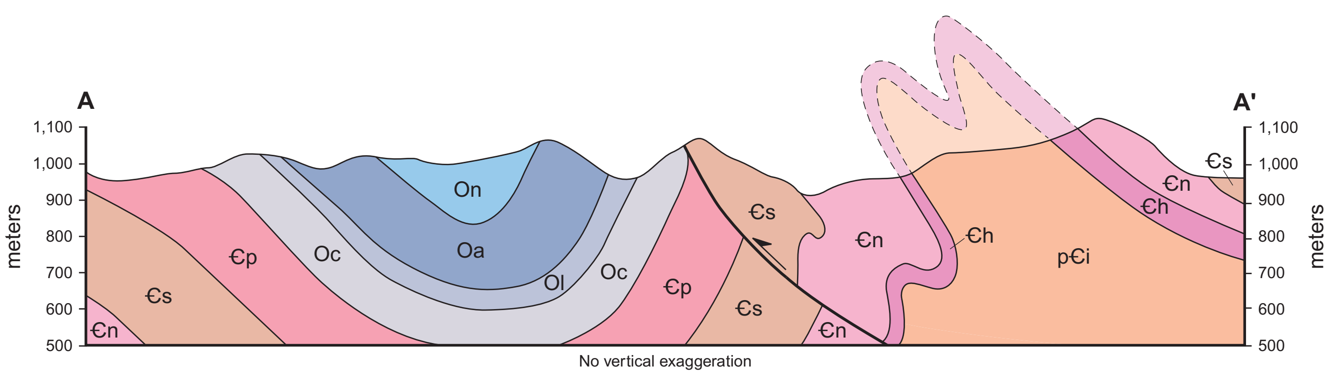
Plate tectonics is the framework within which all tectonic structures form. This paradigm is as fundamental to the Earth sciences as atomic theory is to physics and chemistry and as evolution is to biology. Early formulation of the theory is attributed to Harry Hess, who during the 1930s conceived the *tectogene concept* of the subsiding crumpling crust driven by mantle convection. Isacks et al. (1968) first published a unified theory of plate tectonics. According to the principle of plate tectonics, new oceanic crust formed at the ***oceanic ridges*** ultimately is consumed by ***subduction*** in ***oceanic trenches*** (Figure 1–8). While this process can recycle all ocean crust in ~200 m.y., continental crust has a pivotal role in recording geologic events in the 4.5 Ga history of Earth.

The present surface of the Earth is divisible into seven major plates and several smaller plates (Figure 1–2). The thickness of plates corresponds to that of the ***lithosphere***, which is on average about 100 km thick and includes all of the crust and part of the upper mantle (Figure 1–8). The lithosphere is conveyed above a weaker, more plastic layer in the mantle known as the ***asthenosphere*** (Figure 1–9). Geophysical evidence demonstrates that the asthenosphere is a solid, but it is sufficiently weak so it flows over geologic time. Gravitational processes and convection in the mantle drive plate generation and consumption. There are three basic configurations of plate boundaries: (1) *divergent* (ocean ridges); (2) *convergent* (subduction zones); and (3) *transform*.

FIGURE 1–7 Hypothetical geologic map (a) and cross section (b) illustrating macroscopic structures and relationships. Note that constructing an accurate cross section requires close attention to scale, strike, and dip of bedding (Appendix 1), and position of geologic contacts on the topographic surface. The symbols **On**, **Oa**, **Ol**, and so on identify each rock unit by its age (**O**—Ordovician, **Ꞓ**—Cambrian, **pꞒ**—Precambrian), and the name of each rock unit, e.g., **On**—Newala Formation. See inside front cover for explanation of dip-strike symbols.



(a)



(b)

The kinematics of plate motion may be described using an Eulerian theorem that represents the motion of plates on a sphere, in which displacement on the surface increases away from a rotational axis (Euler pole). Angular displacement of a plate involves rotation about the Euler pole, an imaginary line passing through the center of the Earth, and rotation of a plate about this axis is expressed by its angular velocity (ω) on the sphere (Figure 1–10a). Although the velocity increases away from the pole of the spreading axis, the angular velocity remains constant.

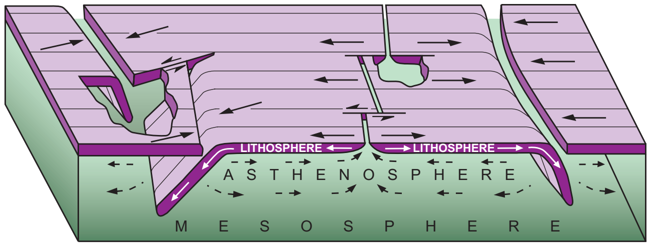


FIGURE 1–8 Generation of lithospheric plates at spreading centers (oceanic ridges) and destruction in subduction zones—a simple statement of plate tectonics theory. Differences in rate of motion or displacement between plates are taken up by transforms connecting segments of ridges, trenches, and other boundaries. Arrows indicate motion direction. Ocean crust is colored purple. (From Isacks et al., Seismology and the new global tectonics: Journal of Geophysical Research, v. 78, p. 5855–5899, © 1968 by the American Geophysical Union.)

Each plate has an angular velocity on the sphere (determined by the absolute motion and its position relative to the pole) with respect to other plates. Differences in movement rate between plates are balanced by ***transform faults*** (Figure 1–10b). Plate boundaries where three plates meet are called ***triple junctions*** (Figure 1–10c) and they connect ridge, trench, transform segments, or various combinations of the three boundaries.

Dewey and Bird (1970) outlined a model for the development of mountain chains as a result of either subduction (Cordilleran mountain chains—Andes, North American Cordillera) or continent-continent or continent-arc collision (collisional mountain chains—Alps, Appalachians, Himalayas). Generation of mountain chains is complex, and most collisional orogenic belts also had an earlier history of subduction. Wilson (1966) suggested that a proto-Atlantic Ocean had closed at the end of the Paleozoic, producing the Appalachian–Variscan mountain chain of North America and Europe, making up the supercontinent of Pangea, and then had reopened to form the present Atlantic. This cyclical closing and opening of ocean basins has become known as the ***Wilson cycle (supercontinent cycle)***.

Another plate tectonic corollary is that of ***accretionary tectonics***, whereby *suspect* and *exotic terranes* are moved by plate motion to collision with each other or with continents. A ***suspect terrane*** is a rock mass whose original position is questionable with respect to adjacent terranes or the continent to which it is presently attached. An ***exotic terrane*** bears no resemblance to the mass to which it is attached and may have originated on the opposite side of a major ocean. Hamilton's (1979) compilation of the geology of the Indonesian region demonstrates that a complex of volcanic arcs, continental fragments, oceanic crust, and large continental blocks (such as Australia) are all in the initial stages of being accreted to Asia as Australia moves northward. The boundaries of suspect and exotic terranes with surrounding terranes are always faults. Overlap sequences, deformational and metamorphic overprints, and

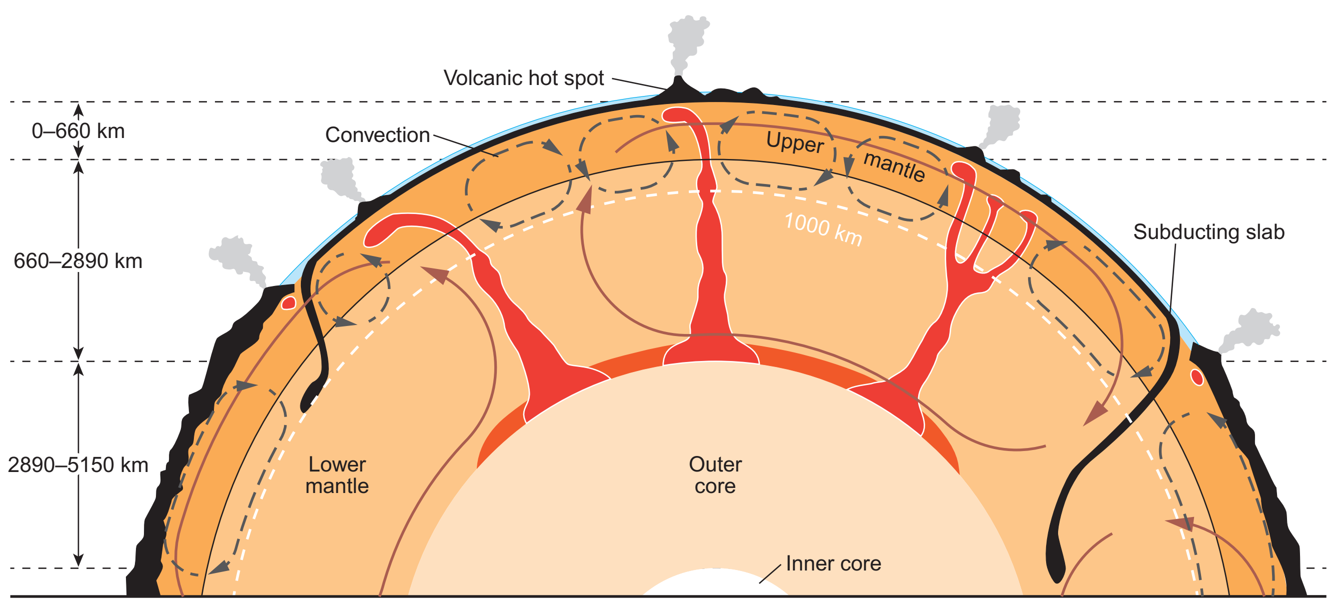


FIGURE 1–9 Plumes (red columns) that ascend through the mantle may originate in low-velocity zones near the outer core boundary in pools of material that could be partially melted or enriched in iron. They are strong and unbent by lower mantle convection—a sign that they are an important mechanism for releasing heat from the core (and driving convection in the upper mantle). Subducting slabs (black) plow downward into the mantle returning material to various depths. In addition, breakoff of descending slabs may produce rebound of the lithosphere and uplift of mountain chains above subduction zones. (From E. Hand, 2015, *Science*, Volume 349, Issue 6252.)