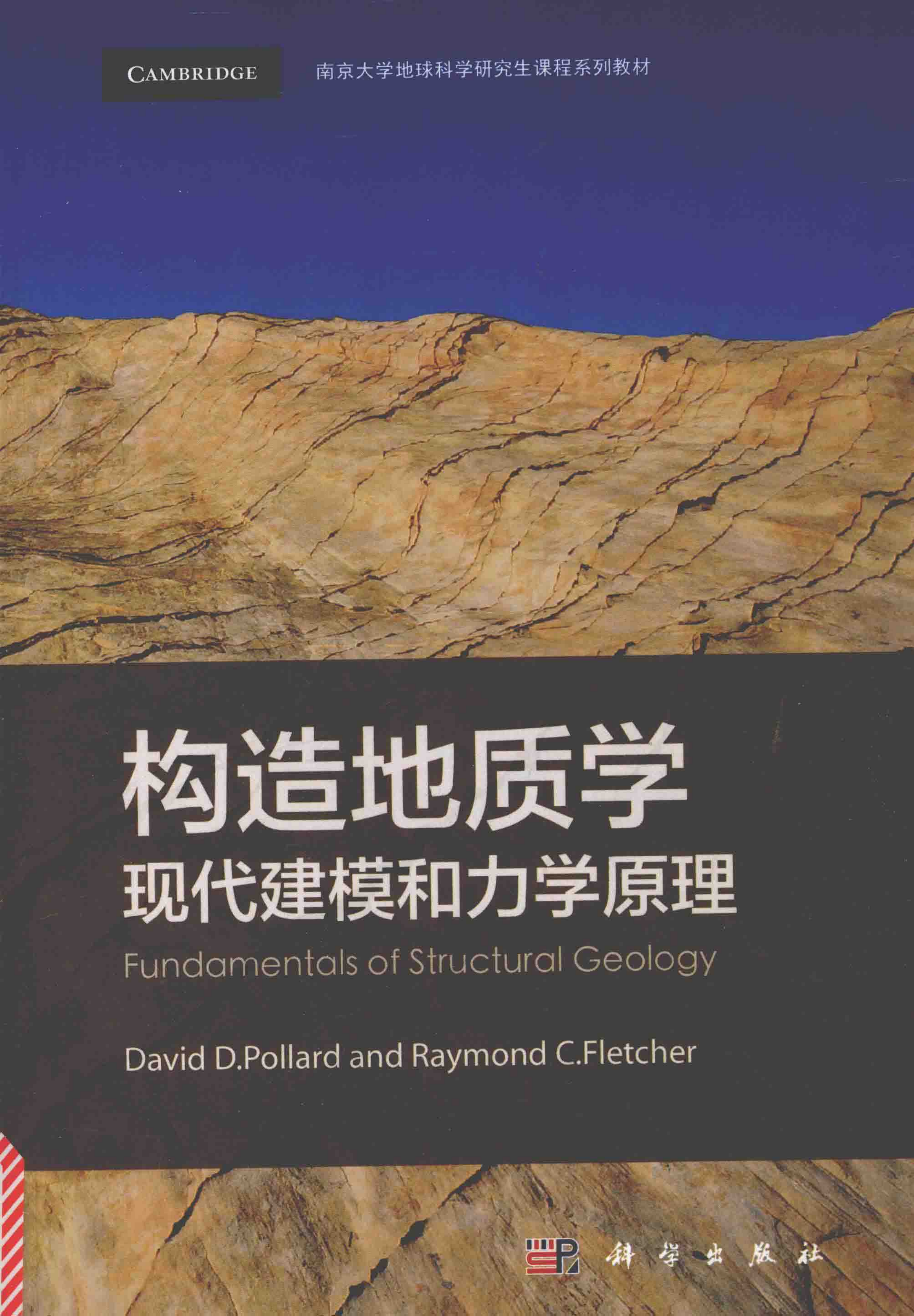

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南京大学地球科学研究生课程系列教材

构造地质学

现代建模和力学原理

Fundamentals of Structural Geology

David D.Pollard and Raymond C.Fletcher

科学出版社

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内容简介

本书提供了一个现代的定量化方法来研究地质构造。在传统内容基础上，突出了定量描述方法论，几何学和运动学方法。本书介绍了微分几何学地质建模；综合了常规的地图空间信息和赤平投影方向数据建模，为地质构造的重现提供了一个有效手段。

本书适用于高校地质学相关学科教师、高年级本科生和研究生，地矿部门研究机构相关研究人员，特别是构造地质学、地球物理学、岩石力学和岩土工程等领域研究人员。

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Fundamentals of Structural Geology

Fundamentals of Structural Geology provides a new framework for the investigation of geological structures by integrating field mapping and mechanical analysis. It emphasizes the observational data, modern mapping technology, principles of continuum mechanics, and the mathematical and computational skills, necessary to map, describe, model, and explain deformation in the Earth's lithosphere quantitatively.

Assuming a basic knowledge of physical geology, introductory calculus, and physics, this advanced textbook builds on more traditional courses that emphasize descriptive terminology, geometric techniques, and kinematics. In a significant departure from conventional textbooks on the subject, differential geometry is introduced and applied to quantify descriptions of geological structures. Differential geometry integrates the spatial information conventionally found on maps with orientation data from stereograms to provide reproducible descriptions of geological structures. By starting from the fundamental conservation laws of mass and momentum, the constitutive laws of material behavior, and the kinematic relationships for strain and rate of deformation, the authors demonstrate the relevance of solid and fluid mechanics to structural geology. The constitutive relations used in the book are sufficiently elementary to enable students to gain physical insight from analytical solutions, but are adequately realistic to provide compelling correlations to observational data.

This book offers a modern quantitative approach to structural geology for advanced undergraduate and graduate students and researchers in structural geology and tectonics. It will also interest those working in related disciplines, including geophysics, rock mechanics, field mapping, hydrogeology, petroleum and geotechnical engineering, and natural hazard mitigation. The book is supported by a website (www.cambridge.org/ 0521839270) hosting images from the book, additional colour images, student exercises and MATLAB® scripts. Solutions to the exercises are available to instructors.

DAVID POLLARD is the Morris Professor of Earth Sciences in the Department of Geological and Environmental Sciences at Stanford University where he co-directs the program in Structural Geology and Geomechanics. He and his students are using quantitative field data and principles of structural geology, combined with laboratory and computer modeling, to address questions about processes of faulting, fracturing, and rock deformation. The research aims to understand how faults and fractures evolve in the Earth's crust; how they affect the flow of magma, groundwater, and hydrocarbons; and what role fractures play in earthquake generation and volcanic eruption

RAYMOND FLETCHER is a Research Professor in the Department of Geosciences at the Pennsylvania State University. He and his collaborators study the continuous deformation of rock as in the emplacement of mantled gneiss domes, rock folding, and basin and range necking. He also works on processes linking chemical aspects of mineral growth or dissolution in rocks and deformation. Currently he is studying folding near the base of ice sheets, and the evolution of structures and rheological behavior of composite rock masses.

Preface

Fundamentals of Structural Geology is a textbook that emphasizes modern techniques of field data acquisition and analysis, the principles of continuum mechanics, and the mathematical and computational skills necessary to describe, model, and explain quantitatively the deformation of rock in Earth's lithosphere.

With precise location data now available from the Global Positioning System (GPS) and powerful computer systems now transportable in a backpack, the quantity of reproducible field data has increased dramatically. These new data sets demand better methods for describing the geometry of structures, and we address this demand by introducing the basic concepts of differential geometry, which provide unambiguous descriptions of curved lineations and surfaces in three dimensions. Data sets from a variety of field areas are provided via the textbook website to promote the practice of opening field "notebooks" to the entire community of researchers, and as input for student exercises (see below).

Textbooks in structural geology provide elements of continuum mechanics (e.g. separate chapters on stress and strain), but rarely are these concepts tied together with constitutive laws or formulated into equations of motion or equilibrium to solve boundary or initial value problems. These textbooks largely beg the questions: what methodology should one adopt to solve the problems of structural geology; and what are the fundamental constructs that must be acknowledged and honored? These constructs are the conservation laws of mass, momentum, and energy, combined with the constitutive laws for material behavior and the kinematic relationships for strain and rate of deformation. We use these constructs to build a rational methodology for the investigation of tectonic processes and their structural products.

This textbook is designed for senior undergraduate students and graduate students who have taken an introductory physical geology course, mathematics courses that include differential and integral calculus in several variables, and a physics course covering mechanics and heat. We consider these courses to be the essential mathematical and scientific pre-requisites for a course using this textbook. Elementary concepts of vector analysis, matrix theory, linear algebra, ordinary and partial differential equations, and computer programming with MATLAB® are used throughout, but are introduced in such a way that a formal course in these subjects, while helpful, should not be considered a pre-requisite. The authors view this textbook as appropriate for a first course in structural geology, but recognize that many students will come to a course using this book after a traditional course that emphasizes the descriptive terminology, geometric techniques, and kinematic concepts of the discipline.

Although designed as a text for students, this book also should be useful as a reference for researchers in structural geology, and as an aid for updating instructors and professionals who have been exposed only to traditional courses and textbooks on the subject. Furthermore, this book should be attractive to scientists in related disciplines (geophysics, rock mechanics, tectonics, geotechnical engineering, and petroleum engineering) who are looking for a modern summary of the fundamentals of structural geology. We encourage students and professionals from these disciplines to learn about the modern methods and tools of structural geology so that they can effectively interact with geologists on multi-disciplinary projects.

One of the opportunities and challenges of publishing a textbook in the twenty-first century is the fact that the printed volume is no longer the only vehicle for communication between authors and readers. Accordingly, we have prepared a homepage for *Fundamentals of Structural Geology* that is available on the World Wide Web (www.cambridge.org/0521839270) and provides the following supplementary materials for readers, instructors, and students:

- Full color images for all outcrop photographs used in the text

- Full color images for key graphical results used in the text
- Supplementary outcrop photographs, maps, and cross sections
- A repository for supplementary images contributed by readers
- Exercises for students that reinforce the concepts introduced in the text
- Data sets from field mapping campaigns for use in the exercises
- Solutions to the exercises for instructors with password protection
- Sample MATLAB® m-files for the exercises
- Sample MATLAB® m-files for recreation of graphical figures found in the text
- A repository for exercises and MATLAB® m-files contributed by readers
- Errata

With a laptop connected to the Web and an LCD projector instructors can use the color outcrop images in the classroom to illustrate geological concepts, and run the m-files with their own choice of parameters for a dynamic demonstration of the mechanical concepts. We envision readers of the textbook having this website open on their desktop to enhance their learning experience. Today desktop PCs provide the necessary CPU power, 3D graphics cards provide the visualization environment and speed, and professional programmers have written applications such as MATLAB® that provide most of the computational tools needed by structural geologists.

For the authors of this textbook, it is not sufficient to focus on understanding the structural history of the Earth as an arcane academic exercise. We believe that structural geologists can make important contributions in natural resource recovery (including water, oil, gas, and minerals), in the assessment of natural hazards (including earthquakes, landslides, and volcanic eruptions), and in the management of the environment (for example the long-term storage of radioactive materials and the contamination of fractured aquifers by hazardous chemicals). It is the authors' hope that students and instructors alike will be as captivated as we have been by the remarkable opportunities and challenges of structural geology. Great satisfaction in the practice of this science is achieved when one successfully brings together the beauty of the natural world and the physical world of continuum mechanics to achieve a better understanding of rock deformation and the development of structures. By doing so one contributes to the knowledge of Earth's remarkable history and to the solution of important practical problems facing society today.

Acknowledgments

David Pollard would like to acknowledge four teachers who shaped his understanding of structural geology as an undergraduate and graduate student. Donald B. McIntyre of Pomona College provided the spark that ignited his curiosity about the subject and put it in an historical context. Arvid M. Johnson of Stanford University introduced him to the tools of mechanics and to a rational way to approach physical processes in the field and laboratory. John G. Ramsay of Imperial College taught him how to measure deformation in outcrop and investigate the geometry and kinematics of rock subject to ductile deformation. Neville J. Price of Imperial College introduced him to rock mechanics and the analysis of rock subject to brittle deformation. These teachers provided a diversity of viewpoints of structural geology that was fascinating as well as challenging, and the origins of many of the themes played out in this textbook can be traced directly to their classrooms. Arvid Johnson's role in the formative stages of work on the textbook was particularly important.

David Pollard was privileged to study with students who were colleagues at Pomona College, Stanford University, and Imperial College, and later to work with students in a teaching and advisory capacity at the University of Rochester, the US Geological Survey (Menlo Park), and Stanford University. Many of these students have participated in research that helped to shape the concepts and methods described in this book. They include: Atilla Aydin, Ze'ev Reches, Gary R. Holzhausen, John W. Cosgrove, Otto H. Muller, David R. Dockstader, Paul T. Delaney, Paul Segall, Jon H. Fink, J. Russell Dyer, Russell K. Davies, Laurie L. Erickson, Marie D. Jackson, Peter C. Wallmann, Stephen J. Martel, Allan M. Rubin, Larry G. Mastin, Jon E. Olson, Sarah D. Saltzer, Scott S. Zeller, Andrew L. Thomas, Carl E. Renshaw, Roland Bürgmann, Pauline M. Mollema, Marco Antonellini, Haiqing Wu, Peter P. Christiansen, Stephen K. Matthäi, Joshua J. Roering, J. Ramón Arrowsmith, George Hilley, Emanuel J. M. Willemse, Michele L. Cooke, Elissa Koenig, Juliet G. Crider, W. Lansing Taylor, Simon A. Kattenhorn, Taixu Bai, Laurent Maerten, Scott S. Young, Frantz Maerten, Stephan Bergbauer, Peter Eichhubl, Phillip G. Resor, Kurt R. Sternlof, Patricia E. Fiore, Ian W. Mynatt, W. Ashley Griffith, Nicolas Bellahsen, Gaurav Chopra, and J. Ole Kaven.

David Pollard would like to thank John Suppe of Princeton University and Patience A. Cowie of Edinburgh University for hosting sabbaticals that provided important time for development of the materials presented here. He gratefully acknowledges the help of the staff of the Department of Geological and Environmental Sciences and the Branner Earth Sciences Library at Stanford University. Also, he extends special thanks to the Seeley G. Mudd Science Library at Pomona College and to the National Cello Institute for providing an idyllic venue for preparation of the manuscript.

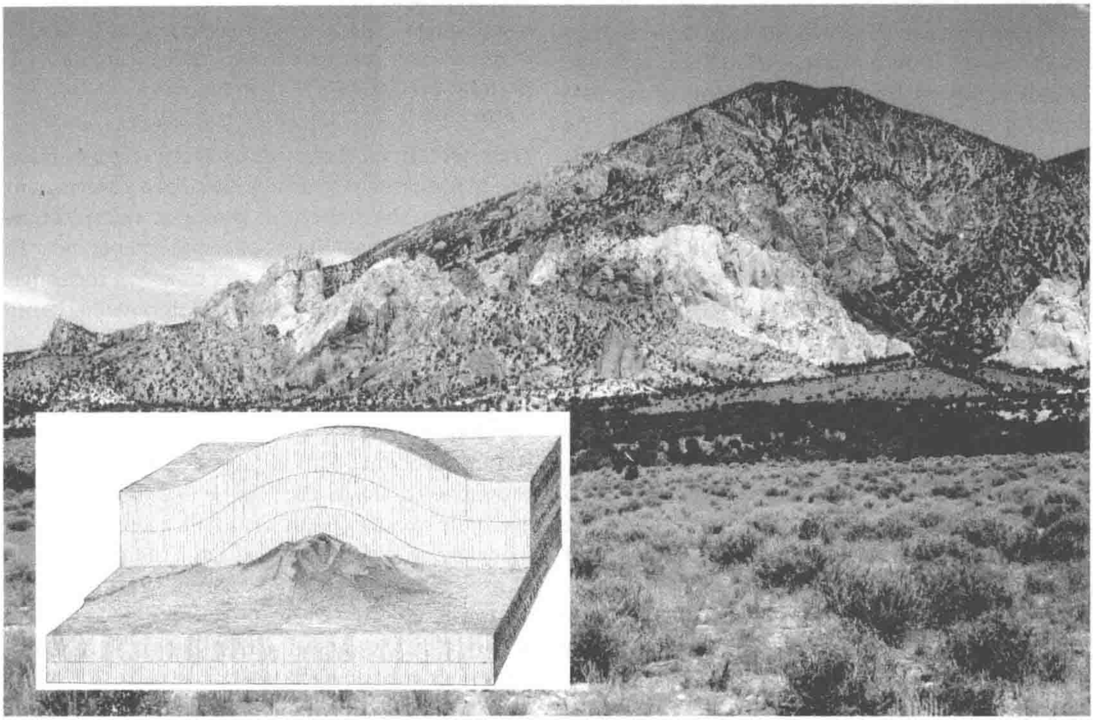
Raymond Fletcher would like to acknowledge several people who contributed to his education as a structural geologist. William F. Brace (MIT) awarded him a C in the undergraduate structural geology course, giving useful incentive for further study of a subject that Bill's treatment showed to consist of an intriguing combination of field observation and mechanical analysis. Bill Brace also gave excellent advice on what not to do as a Ph.D. research project prior to the arrival at Brown University of his Ph.D. advisor William M. Chapple. Bill Chapple provided guidance in formulating a tractable complete mechanical model for the emplacement of a gneiss dome and M. A. Jaswon pointed him toward a method of analysis. Interaction with Bill Chapple over many years continued to enrich his experience. The foundation for his understanding of continuum mechanics was provided by the lucid presentation of this subject in a two-semester course at Brown University by E. T. Onat. Arvid M. Johnson introduced him to the disciplined mapping of small-scale structures in the field interspersed with more freewheeling discussions of mechanical modeling. Memorable discussions over coffee and pastry with Bernard Hallet continue to provide him with imaginative ideas, such as treating the Basin-and-Range Province as a

Contents

Chapter 12 | Model development and methodology

Chapter 1

Motivations and opportunities



Mt. Hillers, southern Henry Mountains, UT. The mountain is cored by igneous rock and surrounded by upturned beds of sandstone and shale. G. K. Gilbert coined the term "laccolite" for these structures in the late 1870s and proposed models for this process of mountain building based on mechanical principles. Inset: Frontispiece from G. K. Gilbert's *Report on the Geology of the Henry Mountains* (Gilbert, 1877). To the rear of this illustration the sedimentary strata form the structural dome of Mt. Ellsworth, and to the front the eroded remnant of the dome represents the current topography of this mountain. Photograph by D. D. Pollard.

The sciences do not try to explain, they hardly even try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that it is expected to work (quote from John von Neumann; Gleick, 1987, p. 273).

In this chapter we motivate the study of structural geology by introducing selected topics that illustrate the extraordinary breadth of interesting problems and important practical applications of this discipline. For example, we use the Imperial Valley earthquake of 1979 along the San Andreas Fault zone to describe techniques for geological hazard analysis. In a second example the lineaments visible in radar images of Venus provide the data for investigating tectonic processes on a planet other than our own. This is followed by an investigation of normal faulting in a hydrocarbon reservoir under the North Sea, off the coast of Norway, to introduce an application to petroleum exploration and production. Then we describe the pattern of small faults, veins, and solution surfaces from an exposure in southern France, an example that demonstrates the practice of structural geology at the human scale. The concept of "anticracks" that emerged from this academic investigation is now being used to help explain the origin of huge earthquakes a hundred kilometers below Earth's surface. Finally, we describe a mechanism for mountain building that was discovered in the Henry Mountains of southern Utah in the late nineteenth century by one of the pioneers of structural geology, G. K. Gilbert.

The frontispiece for this chapter is a photograph of Mt. Hillers in the southern Henry Mountains. Like all the photographs that appear as grayscale images in this book, a color image of this photograph is available at the textbook website along with images of related exposures and scenes. These are presented as monitor resolution images for quick viewing with a web browser or for LCD projection in the classroom for teaching purposes.

1.1 Earthquake hazards in southern California

Academic researchers have learned that society may not be content to continue funding the arcane studies of ancient rocks that have been the mainstay of the National Science Foundation's Tectonics Program in the past. Darrel Cowan, then President of the Geological Society of America's Structural Geology and Tectonic Division, concluded:

> We are at the end of the era when an unquestioning public belief in the benefits of basic scientific research almost automatically led to increased budgets at the NSF (National Science Foundation) Program level. Already, NSF management and the Congress want to hear arguments about how research, and especially new programs, will address important social issues: environmental changes and hazards, exploitation, waste, and recycling of natural resources, and the like (Cowan, 1992).

Thus, whether a career in the Earth sciences takes one to industry or to academia or to a government laboratory, the structural geologist should know how to address problems of social importance. To this end, we integrate aspects of active tectonics, engineering geology, and petroleum geology into this book to show how structural geology can contribute to solving problems in these areas.

Most inhabitants of southern California are familiar with earthquakes and the geological hazard associated with living in an active tectonic province, although the recurrence time of major events is great enough to instill a sense of complacency in many citizens. On the other hand, Earth scientists and government officials are acutely aware that destructive earthquakes could occur at any moment. Teams of scientists and engineers supported by federal and local governments are monitoring the continuing activity of the faults in this area and have tools in place to capture data from the next significant event (Yeats *et al.*, 1997).

What are the data that these scientists and engineers are hoping to capture? Perhaps the most fundamental aspect of faulting is the fact that the rock and soil on either side of the fault slip past one another. There is relative motion of these two masses more or less parallel to the fault surface. For example, Fig. 1.1 is a photograph taken across the trace of the Imperial Fault in the Imperial Valley of southern California shortly after a magnitude 6.5 earthquake struck on October 15, 1979. The vertical surface just behind the observer's feet is one surface of the fault exposed at the time of the earthquake. Relative to the ground on which the observer is standing, slip on the fault offset the two small drainage channels upward and to the right. By identifying soil particles (say in the bottom of the drainage channel) that were adjacent before the slip, one can make precise measurements of the offset. Using a tape measure, the geologist records the horizontal, *strike slip* component of relative motion as about 5 cm, and the upward, *dip slip* component as about 20 cm.

To characterize the behavior of a fault, one would like to know the magnitudes and directions of this relative motion in terms of the displacements, velocities, and accelerations of originally adjacent particles over the entire fault. The relative motion of particles is directly measurable only at (or very near) the surface of the Earth for active faults, and yet the fault might extend to depths of 10 km or more. Furthermore, one would like to know the distributions of these quantities over the entire time the two surfaces of the fault were in relative motion. In other words one would like to know the spatial and temporal distributions of displacement, velocity, and acceleration for particles of rock or soil in the vicinity of the fault. Given such information we could begin to understand the mechanisms that control fault slip and, perhaps, be in a position to be predictive about such events.

1.1.1 Contributions from geology, geodesy, and geophysics

Figure 1.2 is a schematic illustration of some of the tools used to monitor the slip across faults in active tectonic regions (Thatcher and Bonilla, 1989). The illustration in Fig. 1.2a represents a vertical cross section along the fault with contours of slip magnitude. The tools used to estimate the *slip distribution* fall within three different disciplines in the Earth sciences: namely geology, geodesy, and geophysics. The geologist measures the offset of geological structures and formations across a fault at the surface as well as the offset of whatever cultural markers might be present (Fig. 1.2b). By walking along the surface trace of the fault, the structural geologist can gather data on many different types of geological and cultural features and plot a graph of fault slip at the surface versus distance along the fault. Usually the geologist records only the total slip between a time before the earthquake and a time after the earthquake, and cannot measure the velocities or accelerations that occurred during the slip event.

Fig 1.1 Ground rupture along the northern trace of the Imperial Fault in southern California after the October 15, 1979, magnitude 6.5 earthquake. View is to the southwest. The strike and dip components of slip are identified based on the offsets of the small stream channels. The relative motion is right-lateral strike slip (~5 cm) and dip slip (~20 cm) down to the northeast. See website for color image. Photograph by D. D. Pollard.

Although the data gathered by geologists provide the most direct measurement of slip at the Earth's surface, they only record the slip at certain points along the fault and these data may not be similar to the distribution of slip at depth. For example, the offset of a fence line at the surface may be strongly influenced by a thick layer of relatively soft soil or unconsolidated sediments overlying the more rigid rock below. Models are required to interpolate the surface slip between these data points and to extrapolate these surface measurements to the sub-surface. Using elasticity theory, one could specify remote stresses and stresses along the fault as boundary conditions and solve for the slip distribution over the fault surface. One could search for boundary conditions that produced a slip distribution best matching the slip measured at the surface. Of course the model parameters themselves may be poorly constrained, and there may be many possible slip distributions at depth that are consistent with data from the surface. None-the-less, such modeling exercises are the only way for the geologist to extrapolate data from the surface to the sub-surface.

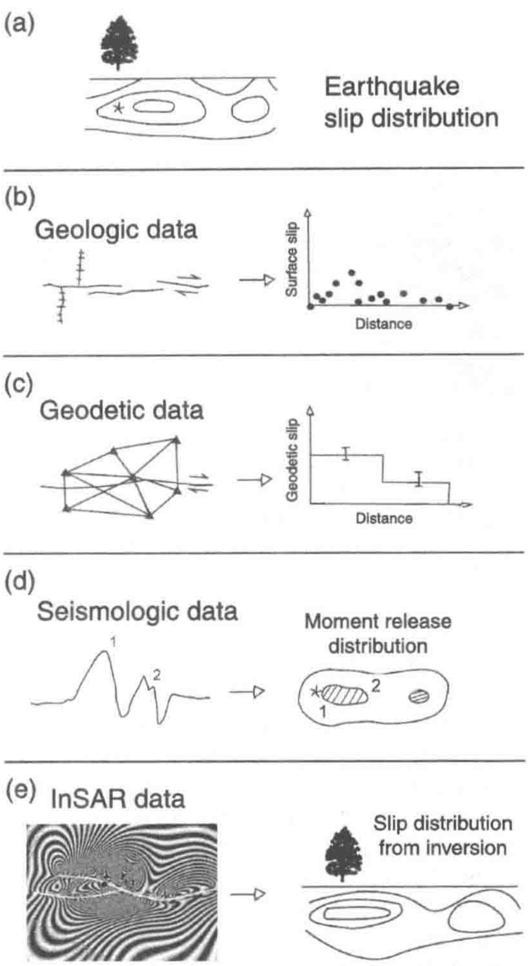


Fig 1.2 Schematic diagram of four different methods for estimating the slip on a fault (Thatcher and Bonilla, 1989). The actual slip is contoured on the fault surface in (a). Illustrations (b)–(d) show how geologists, geodesists, and seismologists gather data (left column), and graphical representations of these data are shown to the right. (e) Interferometric synthetic aperture radar (InSAR) data provide the field of displacement at the surface near a fault which can be inverted to estimate the slip distribution.

The geodesist measures the changes in lengths, angles, and/or elevations between surveyed benchmarks usually located at scattered points some distance from the fault (Fig. 1.2c). Such measurements are often more precise than geological measurements because high-precision instruments are used to gather the data and the bench marks are fixed to carefully designed and stable monuments. In some cases the instruments are permanently mounted at the survey locations and record data that can be used to calculate velocities and accelerations. In these respects the geodetic data can provide a better constraint on the deformation associated with faulting.

On the other hand the benchmarks usually are not located at the fault itself, so they do not directly record fault slip, even at the surface. Rather, a model (usually based on elasticity theory) is employed that requires as input the location and geometry of the fault and the mechanical behavior of the rock mass underlying the geodetic network. These models usually treat the fault as a set of segments, each with a constant slip, so the output is slip at the surface for different segments of the fault (Fig. 1.2c). The geodetically inferred slip is consistent with the changes in line lengths or angles between the benchmarks of the array, but clearly depends upon the chosen segment geometry and the other model parameters. More elaborate models are capable of calculating slip distributions at depth from the geodetic data. Because the geodetic data come from widely scattered locations away from the fault, the geometry and mechanical behavior of the sub-surface materials over a large volume of rock must be provided as model input.

The third category of data is taken from seismograms recorded both in the vicinity of the fault and at distant stations at the time of the earthquake (Fig. 1.2d). Although the locations of the seismographs may be even more remote from the fault than the geodetic benchmarks, these instruments continuously record the shaking of the ground due to the passage of *seismic waves* generated at the fault. Therefore, they can provide a wealth of data for inferring the behavior of the fault. In this example pulses on the seismogram are correlated to areas on the fault at depth that slipped at slightly different times or at different distances from the recording instrument. What is actually calculated is the *seismic moment* on the fault over these areas, but this can, in principle, be related to the average slip. By combining data from many seismographs a picture of the moment release distribution on the fault can be constructed. In practice the instruments may not be ideally located, and there may not be as many as one would desire.

Models of the sub-surface fault geometry are needed as well as the mechanical properties (seismic wave velocities) of the rock from the fault to the location of the seismographs.

The use of interferometric synthetic aperture radar (InSAR) for the detection of ground displacements associated with earthquakes was highlighted in articles appearing in the early 1990s (Massonnet *et al.*, 1993; Prescott, 1993; Zebker *et al.*, 1994). The radar signal is transmitted from a satellite to the ground surface where it is reflected back to the satellite and recorded as a set of pixels making up an image of the surface. Knowledge of the travel time and speed of the signal provide the information necessary to calculate the range, or distance, from the satellite to each reflective site on the surface. If the same region is imaged at two different times, for example before and after the earthquake, the difference between the two images can be used to calculate the component of the surface displacement directed toward the satellite. The resulting image (Fig. 1.2e), called an *interferogram*, is similar to a contour map of the displacement component on which the white and black bands (called fringes) are the contours. The fault segments are shown as fine white lines superimposed on this image. By invoking a model (usually based on elasticity theory) for the location and geometry of the fault segments and the mechanical behavior of the rock mass, one may use this displacement distribution on Earth's surface to calculate the corresponding slip distribution on the fault. The abundance of data provides considerable constraint on the unknown slip distribution below Earth's surface and very exciting avenues for new research on faulting.

It should be obvious from this discussion that the different disciplines contribute information that is based on different observations in different locations and over different length and time scales. Yet scientists from all three disciplines are studying the same physical phenomenon, faulting, and they are using the same tools to build their models, namely elasticity theory. In this textbook we focus on the geological data and the models that are used to relate measurements of slip to fault behavior. On the other hand each discipline is providing important pieces of the puzzle, so structural geologists should be aware of the concepts and contributions from geophysics and geodesy to the study of faulting. In addition important insights are attained from studying the effects of faulting on the geomorphology of the landscape (Arrowsmith *et al.*, 1996; Arrowsmith *et al.*, 1998). The most comprehensive view of faults and the faulting process will come from an integration of all these data and that integration will be most effective in the context of building well-constrained models.

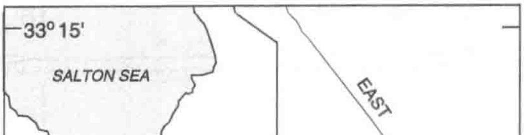


Fig 1.3 Map of the region affected by the October 15, 1979, earthquake in southern California (Wosser *et al.*, 1982). The epicenter is shown as a star in the lower right-hand corner.

1.1.2 Conceptual and mechanical models for the 1979 earthquake rupture

On October 15, 1979, the magnitude 6.5 earthquake rupture began just south of the US–Mexico border and spread approximately 35 km to the north into southern California (Fig. 1.3), breaking ground along the trace of the Imperial Fault (Johnson *et al.*, 1982; Wosser *et al.*, 1982). Many agricultural features such as fence lines and canals provided markers to measure the slip

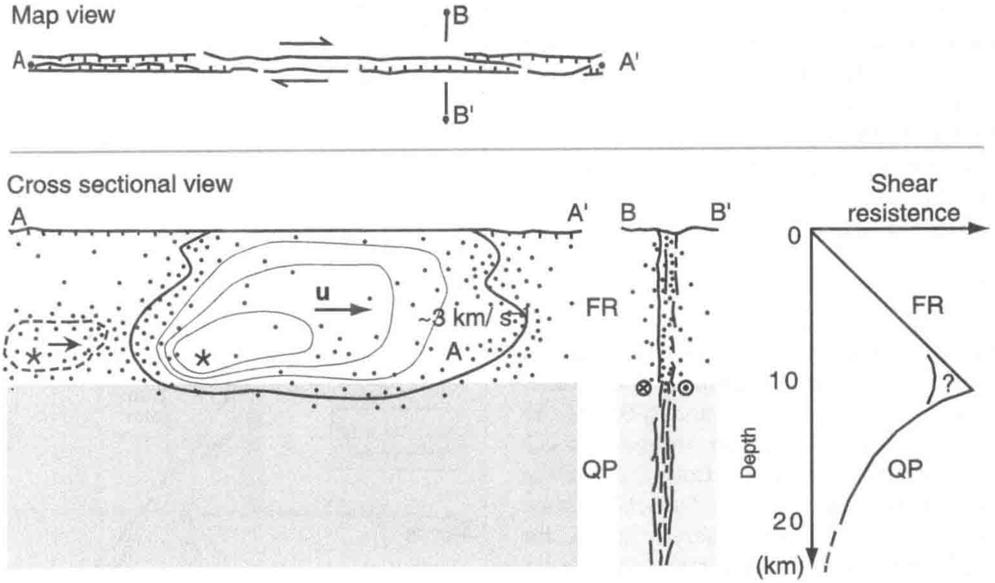


Fig 1.4 Three views of a crustal-scale strike slip fault. Map view illustrates the fault as a zone of deformation. Cross section A–A′ in the fault plane includes a contour map of the slip (**u**) which goes to zero at the fault tipline and is greatest near the hypocenter (star). Cross section B–B′ perpendicular to the fault plane suggests that slip mechanisms are frictional resistance (FR) in the upper part of the crust and localized quasi-plastic flow (QP) in the lower part. The graph at the right indicates a linearly increasing resistance to shearing with depth to the brittle–ductile transition, and then a non-linear decreasing resistance to shearing with depth. Reprinted from Sibson (1989) with permission from Elsevier.

across the fault trace. The farmers, homeowners, businesses, and municipalities in the Imperial Valley, mostly around the town of El Centro, sustained over twenty million dollars in damage. Fortunately, there was no loss of life and few catastrophic failures of man-made structures in this event. On the other hand, earthquakes of similar magnitude often are accompanied by many deaths in regions with less stringent building codes, or no building codes at all. These events testify to the destructive power of earthquakes and to the need to understand such hazards. Because earthquakes are generated by sudden slip on faults, we need to understand the mechanisms and behaviors of faults in order to develop informed hazard mitigation policy. Just what are the causes and consequences of dynamic rupture on faults? Some answers to this question have come from research by scientists and engineers over the past few decades, but much remains to be understood.

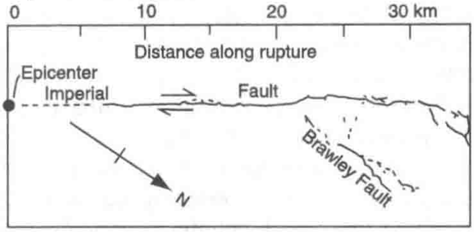
In the previous section we described how geologists, geodesists, and geophysicists use models to extrapolate information on displacements or accelerations from the locations where data are measured on the Earth's surface to the fault in the sub-surface. These models help us to understand the behavior of faults where they cannot be observed directly and they provide insights concerning earthquake faulting as a structural process. The faulting process is conceptualized at the crustal scale in Fig. 1.4 for a vertical fault with strike slip motion (Sibson, 1989). Each view of this conceptual fault model reveals different aspects of faulting at the crustal scale. The map view shows a zone of fractures and deformation, rather than two surfaces in contact. This suggests that faults can be more complex than a single fracture and that shearing of material in a fault zone may characterize the deformation rather than slip between two surfaces. The vertical cross section viewed parallel to the fault indicates that frictional resistance (labeled "FR" in Fig. 1.4) to slip on a fault operates to depths of perhaps 10 km and plastic flow (labeled "QP") is associated with distributed shearing in a zone at deeper levels. Thus, the mechanisms of faulting may change with depth as temperature and pressure increase, such that brittle fracture and friction dominate at shallow depths and ductile flow dominates at greater depths. In this conceptual model the resistance to shearing increases with depth to this transition and then decreases with depth. In a vertical section viewed perpendicular to the fault (A–A′), dynamic shearing begins at depth, near the *brittle–ductile transition* and spreads out over the fault surface at a velocity of about 3 km s^{-1}, eventually reaching the Earth's surface.

The Imperial Valley earthquake is noteworthy because it occurred within a dense array of geodetic and geophysical instruments and there were abundant cultural features for the geologists to measure at the surface (Savage *et al.*, 1979). The mechanical model reviewed here was constructed using data from the seismographs and strong motion instruments that monitored this event (Archuleta, 1984). The results are not unique and the choice of model parameters could be debated, but that is not the issue here. This model provides an excellent example of the insight one can gain about phenomena that are otherwise totally inaccessible to direct observation.

Figure 1.5a is a map of the rupture traces for both the Imperial and Brawley Faults as compiled by geologists from observations at the Earth's surface. The photograph shown in Fig. 1.1 was taken near the northern end of the Imperial Fault. The map also shows rupture traces along the Brawley Fault that trend oblique to the Imperial Fault. Apparently the Brawley Fault slipped at about the same time as the Imperial Fault, but the relative motion on the Brawley Fault was primarily dip slip. Note that the southern half of the Imperial Fault rupture trace is drawn as continuous, whereas it is drawn as composed of discrete segments in the northern half. Also shown on Fig. 1.5a is the rupture *epicenter*, the point at the surface of the Earth immediately above the point where rupture initiated, as inferred by geophysicists from seismic records. This location is dependent upon a model for the seismic wave velocities of the crustal rocks. Note that the epicenter was approximately 5 km south of the southernmost surface break.

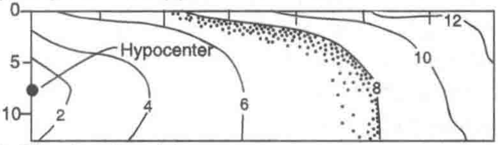
Each of the observations made in the previous paragraph brings up interesting questions about faulting. Why did the rupture not break to the surface immediately over the epicenter? Why would a second fault rupture at the same time as the Imperial Fault, and why is the trace of the second fault obliquely oriented? What does the discontinuous nature of the rupture trace tell us about faulting? Some of these questions can be addressed with models for the rupture process.

(a) Map view of rupture

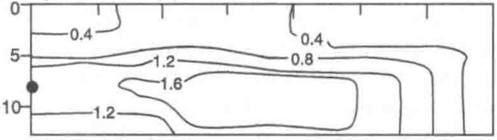


Vertical cross sections of rupture

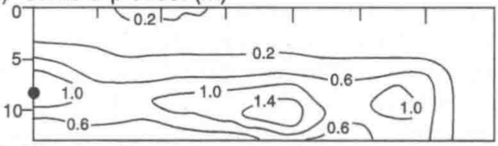
(b) Rupture time (s)



(c) Slip duration (s)



(d) Strike slip offset (m)



(e) Dip slip offset (m)

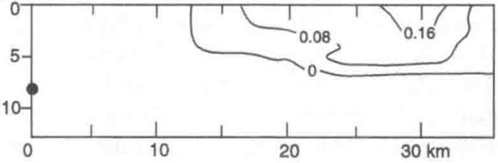


Fig 1.5 Map and cross sections of the Imperial Fault and the Brawley Fault for the October 15, 1979, earthquake in southern California (Archuleta, 1984): (a) map of the rupture trace; (b)–(e) vertical cross sections parallel to the fault trace with contours of the model rupture time, slip duration, strike slip offset, and dip slip offset.