PART A

FUNDAMENTALS

CHAPTER ONE

Overview

1.1 INTRODUCTION

Did you ever take a cross-country drive? Hour after hour of tedious driving, as the highway climbed hills and dropped into valleys? The monotonous gray rocks exposed in road cuts largely went unnoticed, right? You passed pretty scenery, but it was static and seemed to tell no story simply because you did not have a basis in your mind with which to interpret your natural surroundings. It was much the same for scholars of generations past, before the establishment of modern science. The Earth was a closed book, hiding its secrets in a language that no one could translate. Certainly, ancient observers marveled at the enormity of mountains and oceans, but with the knowledge they had at hand they could do little more than dream of supernatural processes to explain the origin of these features. Gods and monsters contorted the Earth and spit flaming rock; and giant turtles and catfish shook the ground. Then, in fifteenth-century Europe, an intellectual renaissance spawned an age of discovery, during which the Earth was systematically charted, and the pioneers of science cast aside dogmatic views of our universe that had closed peoples' minds for the previous millennia and began to systematically observe their surroundings and carry out experiments to create new knowledge. The scientific method was born.

In geology, the stirrings of discovery are evident in the ink sketches of the great artist and inventor Leonardo da Vinci (1452–1519), who carefully drew the true shapes of rock bodies in sketches to understand the natural shape of the Earth (Figure 1.1). In the seventeenth century came the first description of rock deformation. Nicholas Steno (1631–1686) examined outcrops where the bedding of rock was not horizontal, and speculated that strata that do not presently lie in horizontal layers must have in some way been *dislocated* (the term he used for deformed). Perhaps Steno's establishment of the **principle of original horizontality** can be viewed as the birth of structural geology. By the beginning of the eighteenth century, the structural complexity of rocks in mountain ranges like the Alps was widely recognized (Figure 1.2), and it became clear that such features demanded explanation.

The pace of discovery quickened during the latter half of the eighteenth century and through the nineteenth century. In his "Theory of the Earth with Proofs and Illustrations," James Hutton (1726–1797) proposed the concept of **uniformitarianism** and provided an explanation for the nature of **unconformities.** Since the publication of this book in 1785 there has been a group of scientists who recognize themselves as geologists. These new geologists defined the geometry of structures in mountain ranges, learned how to make geologic maps, discovered the processes involved in the formation of rocks, and speculated on the origins of specific structures and on mountain ranges in general.

Ideas about the origin of mountains have evolved gradually. At first, mountain ranges were thought to be a consequence of a *vertical push* from below, perhaps

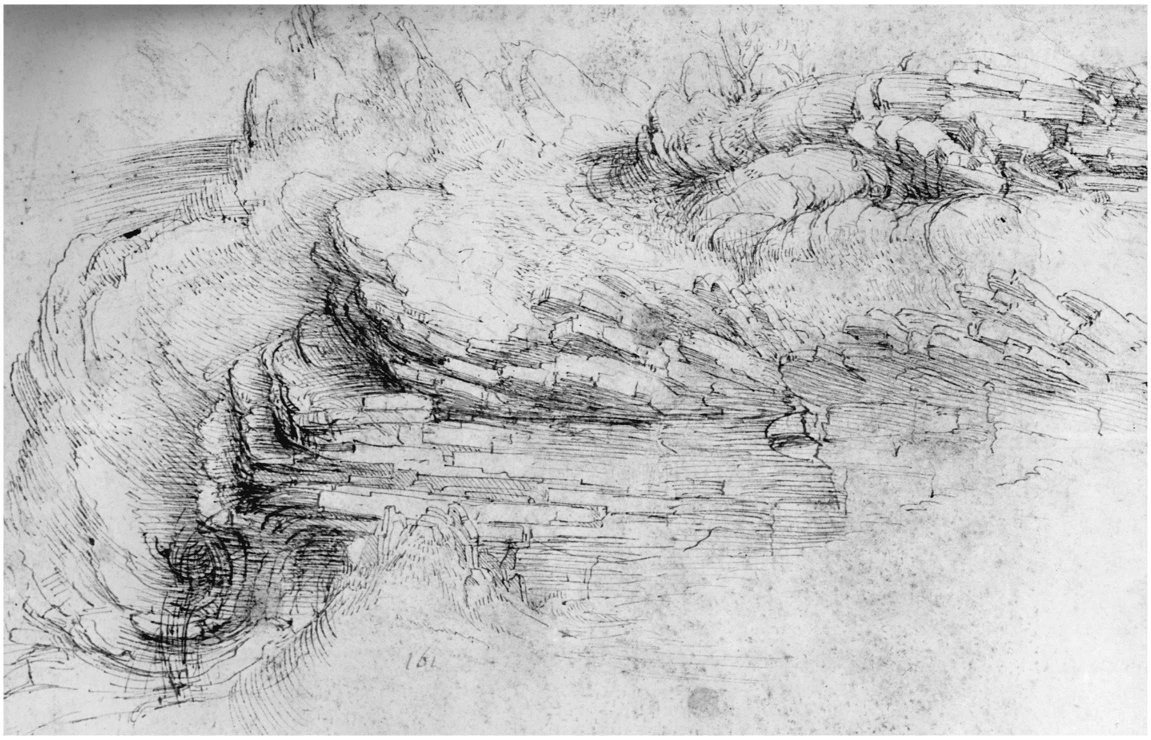


FIGURE 1.1 Sketch by Leonardo da Vinci showing details of folded strata in the mountains of Italy (ca. 1500 AD). In recent years it was discovered that in addition to his careful observations of the natural world, da Vinci also completed insightful friction experiments.

FIGURE 1.2 Aerial view of the European Alps (France).

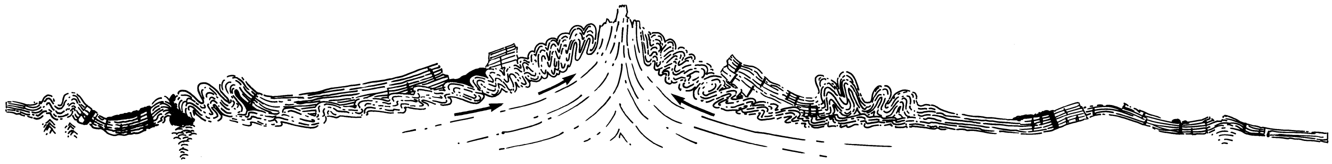


FIGURE 1.3 Model of mountain building and associated deformation as represented by G. P. Scrope (1825). The uplift is caused by intrusion of an igneous core, and the folds are generated by down-slope movement.

associated with intrusion of molten rock along preexisting zones of weakness, and folds and faults in strata were attributed to gravity sliding down the flanks of these uplifts (Figure 1.3). Subsequently, the significance of *horizontal forces* was emphasized, and geologists speculated that mountain ranges and their component structures reflected the contraction of the Earth that resulted from progressive cooling. In this model, the shrinking of the Earth led to wrinkling of the surface. One of the more notable discoveries (about 1850) was the recognition by James Hall (1811–1898) that Paleozoic strata in the Appalachian Mountains of North America were much thicker than correlative strata in the interior of the continent. This discovery led to the development of the **geosyncline theory,** a model in which deep sedimentary basins, called geosynclines, evolved into mountain ranges. Contraction theory and geosynclinal theory, or various combinations of the two, were widely accepted until the 1960s, when the views of Alfred Wegener (1880–1930), Arthur Holmes (1898–1965), and Harry Hess (1906–1969) led to the formulation of a very different model. Building on the work of Alfred Wegener's **continental drift theory** and Arthur Holmes's mantle convection model, Harry Hess proposed the revolutionary idea of a mobile seafloor **(seafloor spreading hypothesis)** that lead to the formulation of **plate tectonic theory.** In this theory, the Earth consists of several, rigid plates that change in space and time. The interaction between these plates offers a unifying explanation for the occurrence of mountain ranges, ocean basins, earthquakes, volcanoes, and other previously disparate geologic phenomena.

As the foundations of geology grew, diverse features of rocks and mountains gained names, and the once amorphous, nondescript masses of rock exposed on our planet became history books that preserve the Earth's biography. Perhaps your concept of the planet has evolved rapidly as well, because of the courses in geology and other sciences that you have taken thus far. Now, as you drive across the countryside, you scare the daylights out of your passengers as you twist to see and discuss roadside outcrops. The rocks are no longer gray masses to you, but they contain recognizable patterns and shapes and fabrics. The purpose of this book is to increase your ability to interpret these features, and particularly to use them as clues to understanding the processes that have shaped and continue to change the outer layers of the Earth.

1.2 CLASSIFICATION OF GEOLOGIC STRUCTURES

When you finished your introductory geology course, you probably had a general concept of what a geologic structure is. The term probably brings to mind images of folds and faults. Perhaps you had the opportunity to take a field trip where you saw some of these structures in the wild. These features are formed in response to pushes and pulls associated with the forces that arise from the movement of tectonic plates or as a consequence of differential buoyancy between parts of the lithosphere. But what about bedding in a sedimentary rock and flow banding in a rhyolite flow; are these structures? And what about slump folds in a debris flow; are they structures? Well . . . yes, but the link between their formation and plate motion is less obvious. So, maybe we need to have a more general concept of a geologic structure.

The most fundamental definition of a **geologic structure** is a geometric feature in rock whose shape, form, and distribution can be described. From this definition it is obvious that there are several ways in which geologic structures can be subdivided into groups. In other words, by necessity there are several different, yet equally valid classification schemes that can be used in organizing the description of geologic structures. Different schemes are relevant for different purposes, so we will briefly look at various classification schemes for geologic structures that will return in subsequent chapters. At first, these various classification schemes may seem very confusing. Thus, we recommend that you start by recognizing the basic geometric classes as the foundation of your understanding. As you learn about these classes, refer back to the lists below, and see how a particular geometric class fits into one or more of the classification schemes.

I. Classification based on *geometry,* that is, on the shape and form of a particular structure
  - *Planar (or subplanar) surface*
  - *Curviplanar surface*
  - *Linear feature*

  This subdivision represents perhaps the most basic classification scheme. In this scheme we include the following classes of structures: joint, vein, fault, fold, shear zone, foliation, and lineation.

II. Classification based on geologic *significance*
  - *Primary:* formed as a consequence of the formation process of the rock itself
  - *Local gravity-driven:* formed due to slip down an inclined surface; slumping at any scale driven by local excess gravitational potential
  - *Local density-inversion driven:* formed due to local lateral variations in rock density, causing a local buoyancy force
  - *Fluid-pressure driven:* formed by injection of unconsolidated material due to sudden release of pressure
  - *Tectonic:* formed due to lithospheric plate interactions, due to regional interaction between the asthenosphere and the lithosphere, due to crustal-scale or lithosphere-scale gravitational potential energy and the tendency of crust to achieve isostatic compensation

  The first four items in this scheme can be grouped as *primary and nontectonic structures,* meaning that they are not directly related to the forces associated with moving plates. We purposely say "can" because in many circumstances these categories of structures do form in association with tectonic activity. For example, gravity sliding may be triggered by tectonically generated seismicity, and salt domes may be localized by movement of tectonic normal faults. These first four categories will be discussed in Chapter 3. The fifth category of structures is very large and forms the primary focus of this book.

III. Classification based on *timing* of formation
  - *Syn-formational:* formed at the same time as the material that will ultimately form the rock
  - *Penecontemporaneous:* formed before full lithification, but after initial deposition
  - *Post-formational:* formed after the rock has fully formed, as a consequence of phenomena not related to the immediate environment of rock formation

IV. Classification based on the *process* of formation, that is, the deformation mechanism
  - *Fracturing:* related to development or coalescence of cracks in rock
  - *Frictional sliding:* related to the slip of one body of rock past another, or of grains past one another, both of which are resisted by friction
  - *Plasticity:* resulting from deformation by the internal flow of crystals without loss of cohesion, or by non-frictional sliding of crystals past one another
  - *Diffusion:* resulting from material transport either solid-state or assisted by a fluid (dissolution)

V. Classification based on the mesoscopic *cohesiveness* during deformation
  - *Brittle:* formed by loss of cohesion across a mesoscopic discrete surface
  - *Ductile:* formed without loss of cohesion across a mesoscopic discrete surface
  - *Brittle/ductile:* involving both brittle and ductile aspects

  Note that the scale of observation (in this case, mesoscopic) is critical in the distinction between brittle and ductile deformation, because ductile deformation can involve microscopic-scale fracturing and frictional sliding.

VI. Classification based on the *strain* significance, in which a reference frame, usually the Earth's surface, is defined
  - *Contractional:* resulting in shortening of a region
  - *Extensional:* resulting in extension of a region
  - *Strike-slip:* resulting from movement without either shortening or extension

  Note that shortening in one direction can be, but does not have to be, accompanied by extension in a different direction, and vice versa. Also, regional deformation usually results in the vertical displacement of the Earth's surface, a component of deformation that is commonly overlooked.

VII. Classification based on the *distribution of deformation* in a volume of rock
  - *Continuous:* occurs through the rock body at all scales
  - *Penetrative:* occurs throughout the rock body, at the scale of observation; up close, there may be spaces between the structures

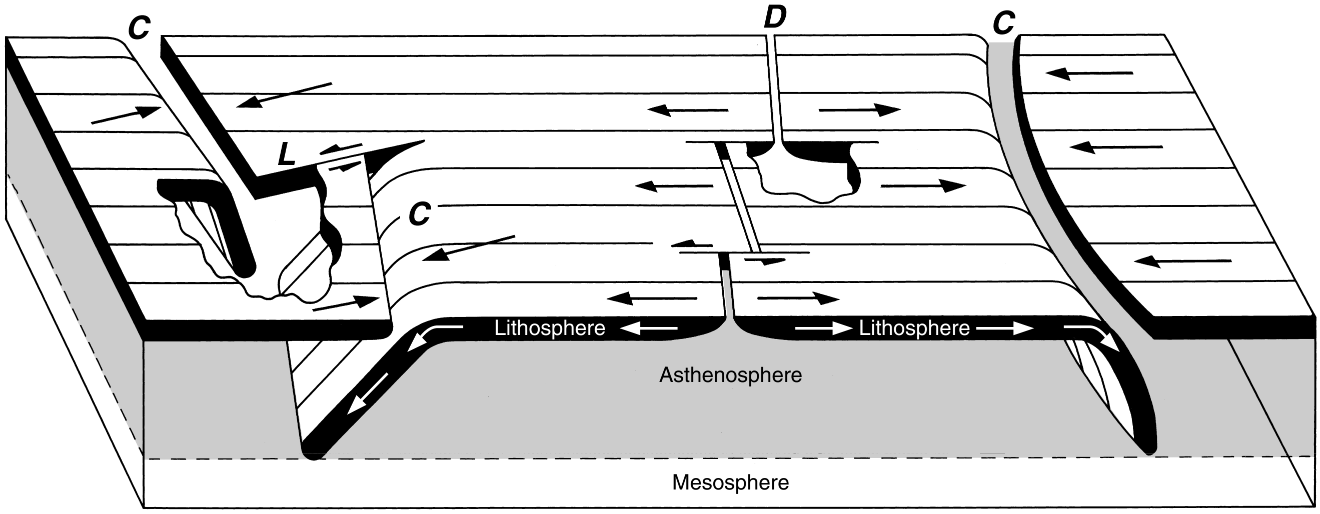


FIGURE 1.4 The principal features of plate tectonics. Three types of plate boundaries arise from the relative movement (arrows) of lithospheric plates: *C*—convergent boundary, *D*—divergent boundary, and *L*—lateral slip (or transform) boundary.

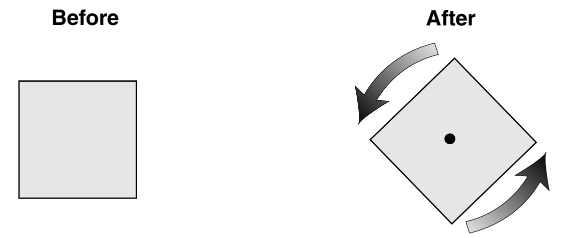
- *Localized:* continuous or penetrative structure occurs only within a definable region
- *Discrete:* structure occurs as an isolated feature

We can conveniently consider the basic geometric classes of structures to be a manifestation of the mesoscopic cohesiveness of deformation. Joints, veins, and certain types of faults are manifestations of primarily brittle deformation, whereas cleavage, foliation, and folding are largely manifestations of ductile deformation processes. Thus, in this book we subdivide our discussions of specific structures into two parts: "Brittle Structures" (Part B) and "Ductile Structures" (Part C). As a first approximation, brittle deformation is more common in the upper part of the crust, where temperatures and pressures are relatively low, and ductile deformation is more common in the deeper part of the crust, because it is favored under conditions of greater pressure and temperature. Also, ductile deformation is commonly a manifestation of plastic deformation and diffusion, whereas brittle deformation is a consequence of fracturing and frictional sliding. However, it is important to emphasize right from the start that different processes can act in the same places in the Earth. The processes that occur at any given time may reflect geologic variables such as **strain rate,** which is the rate of displacement in the rock body (Chapter 5). For example, a sudden increase in strain rate may cause rock that is deforming in a ductile manner (by folding) to suddenly behave in a brittle manner (by fracturing). You can see this remarkable effect by, respectively, slow and quick pulling of a piece of SillyPutty®.

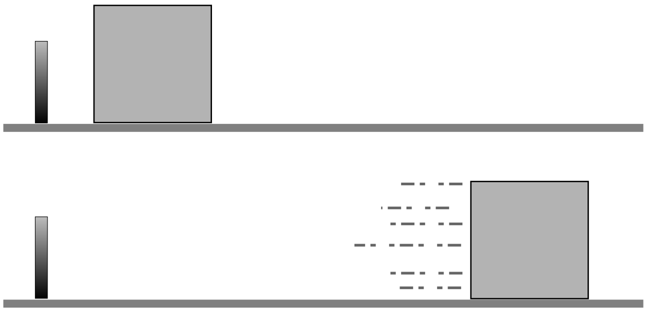
Ultimately, most crustal structures are a consequence of plate tectonic activity, which is the slow (on the order of centimeters per year) but steady motion of segments of the outer, stiff layer of the Earth, called the **lithosphere,** over the weaker **asthenosphere.** The forces that this motion generates, especially those from interactions at plate boundaries, produce the structures we study in the field and in the laboratory. The three types of plate motions are **convergence, divergence,** and **lateral slip** (Figure 1.4). Without the activity that arises from these plate motions, such as deformation, volcanism, and earthquakes, the Earth would be as dead as the Moon. In other words, plate tectonics provides the global framework to examine the significance of structures that occur on local and regional scales.

1.3 STRESS, STRAIN, AND DEFORMATION

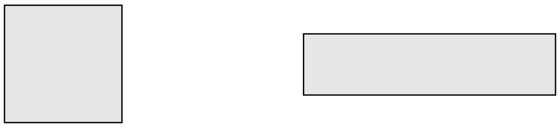
We have already used the words stress, strain, and deformation without definition, because these are common English words and most people have an intuitive grasp of what they mean. Stress presumably has something to do with pushing and pulling, and strain and deformation have something to do with bending, breaking, stretching, or squashing. But in standard English, stress and strain are often used interchangeably; for example, advertisements for aspirin talk about "the stress and strain of everyday life." In structural geology, however, these terms have more exact



(a) Rotation



(b) Translation



(c) Strain

FIGURE 1.5 The three components of deformation: (a) rotation, (b) translation, and (c) strain.

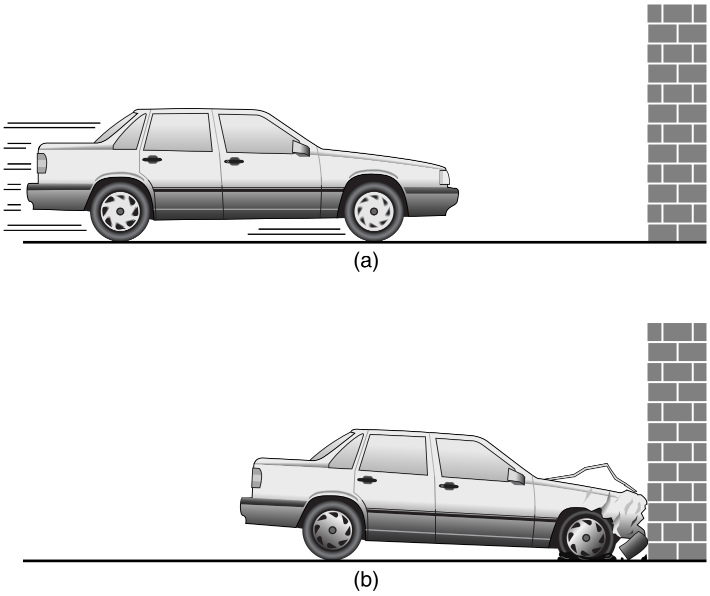


FIGURE 1.6 Strain in the real world. (a) A car approaches a brick wall in a crash test; (b) the same car after impact. Note the extreme distortion of the front (i.e., inhomogeneous strain distribution).

meanings, so right from the start we want to clarify their usage (and avoid headaches).

The **stress** (σ) acting on a plane is the force per unit area of the plane ($\sigma = F$/area). We will see in Chapter 3 that when referring to the stress at a point in a body, a more complicated definition is needed. **Deformation** refers to changes in shape, position, or orientation of a body resulting from the application of a differential stress (i.e., a state in which the magnitude of stress is not the same in all directions). More specifically, deformation consists of three components (Figure 1.5): (1) a **rotation,** which is the pivoting of a body around a fixed axis, (2) a **translation,** which is a change in the position of a body, and (3) a **strain,** which is a distortion or change in shape of a body (Chapter 3). To visualize a strain, consider the test crash of a car that is rapidly approaching a brick wall (Figure 1.6a). In Figure 1.6b, the car and the wall have attempted to occupy the same space at the same time, with variable success. Since the structural integrity of the car is less than that of the wall, the push between car and wall squashed the car, thereby resulting in a strain. In *homogeneous strain,* the strain exhibited at one point in the body is the same as the strain at all other points in the body. Cars are designed so that strain is *heterogeneous,* meaning that the strain is not equal throughout the body, and the passengers are protected from some of the impact.

What about translation and rotation? These components of deformation are a bit harder to recognize, but they do occur. For example, a rigid body of rock that has moved along a fault plane clearly has been translated relative to the opposing side of the fault (Figure 1.7a), and a fault block in which strata are inclined relative to horizontal strata on the opposing wall of the fault has clearly been rotated (Figure 1.7b). Such rotations occur at all scales, as emphasized by work in paleomagnetism, which demonstrates that continental blocks have been rotated around a vertical axis as a consequence of shear along major strike-slip faults and plate boundaries.

In order to describe deformation, it is necessary to define a *reference frame.* The reference frame used in structural geology is loosely called the undeformed state. We can't know whether a rock body has been moved or distorted unless we know where it originally was and what its original shape was. Ideally, if we know both the original and final positions of an array of points in a body of rock, we can describe a deformation with mathematical precision by defining a *coordinate transformation.* For example, in Figure 1.8a, four points (labeled *m, n, o,* and *p*) define a

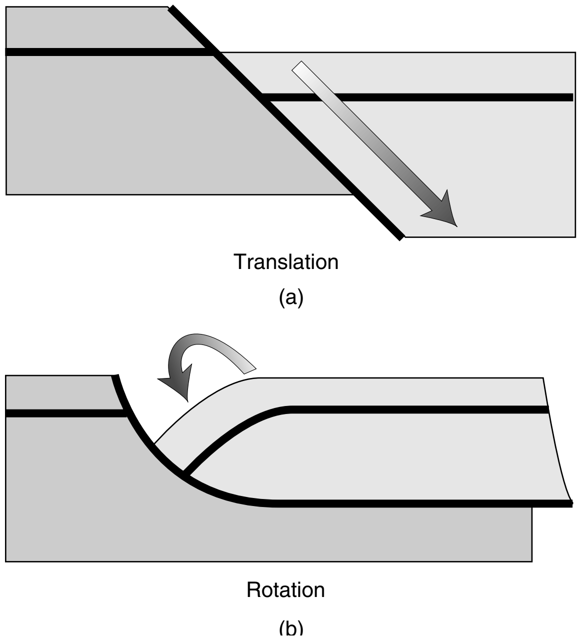


FIGURE 1.7 The translational and rotational components of deformation shown schematically along a fault. (a) A translated fault block; (b) a rotated fault block in the hanging wall.

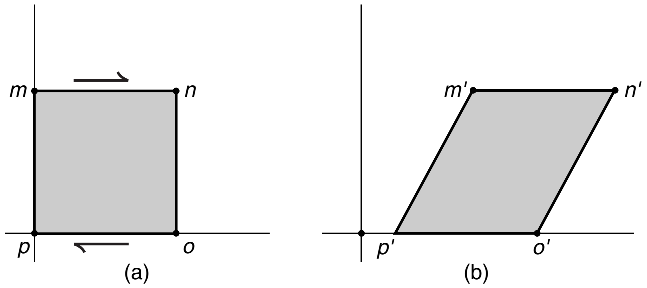


FIGURE 1.8 Deformation represented as a coordinate transformation. Points *m, n, o,* and *p* move to new positions *m′*, *n′*, *o′*, and *p′*.

square in a Cartesian coordinate system. If the square is sheared by stresses acting on the top and bottom surfaces, as indicated by the arrows, and moved from its original location, it changes into a parallelogram that is displaced from the origin (Figure 1.8b). The deformation can be described by saying that points *m, n, o,* and *p* moved to points *m′*, *n′*, *o′*, and *p′*, respectively. In other words, coordinates of all four corners of the square have been transformed. If you are mathematically adept, you will probably realize that this transformation can be described by a mathematical function, but we won't get into that now . . . wait until Chapter 3.

In many real circumstances, we don't have an external reference frame, so we can only partially describe a deformation. For example, at an isolated outcrop we may be able to describe strain—say, because of the presence of deformed fossils—but we have no absolute record of translations or rotations. Then we may talk about *relative displacement* and *relative rotation.* A flat-lying bed of Paleozoic limestone in the Midcontinent region of the United States was at one time below sea level and, because of plate motion, it was formed at a different latitude than today, but we can't immediately characterize these movements.[1] If, however, we see a fault offset a limestone bed by 2 meters, we say that one side of the fault has moved 2 m relative to the other side.

1.4 STRUCTURAL ANALYSIS AND SCALES OF OBSERVATION

At this point, we know what a structure is and we know what a geologist means by deformation. We also know that there is a group of people who call themselves **structural geologists.** But what do structural geologists do? One way to gain insight into the subject of structural geology is to think about the type of work that structural geologists carry out. Not surprisingly, structural geologists do structural analysis, which involves many activities (outlined in Table 1.1). Throughout the book you see that we use tables like this to summarize concepts and terms. Many terms not specifically mentioned in the text can be found in these tables, which serve as convenient reference points throughout the text.

Looking at Table 1.1 you will note that in many of the definitions we have to refer to the **scale of observation.** For the results of a structural analysis to be interpretable, the scale of our analysis must be taken into account. For example, a bed of sandstone in a single outcrop in a mountain may appear to be undeformed. But the outcrop may display only a small part of a huge fold that cannot be seen unless you map at the scale of the whole mountain. Structural geologists commonly refer to these relative scales of observation by a series of subjective prefixes. **Micro** refers to features

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[1] Paleomagnetic and paleontologic methods are primarily used for this in the Paleozoic. In the Mesozoic and Tertiary, ocean-floor magnetic anomalies are available as well, but in the Precambrian only the paleomagnetic approach remains.

TABLE 1.1 **CATEGORIES OF STRUCTURAL ANALYSIS**

Descriptive analysis	The characterization of the shape and appearance of geologic structures. It includes development of a precise vocabulary (jargon) that permits one geologist to create an image of a structure that any other geologist can understand, and development of methods for uniquely describing the orientation of a structure in three-dimensional space.
Kinematic analysis	The determination of the movement paths that rocks or parts of rocks have taken during transformation from the undeformed to the deformed state. This subject includes, for example, use of features in rocks to define the direction of movement on a fault.
Strain analysis	The development of mathematical tools for quantifying the strain in a rock. This activity includes the search for features in rock that can be measured to define strain.
Dynamic analysis	The development of an understanding of stress and its relation to deformation. This activity includes the use of tools for measuring the present-day state of stress in the Earth, and the application of techniques for interpreting the state of stress responsible for microstructures in rocks.
Mechanism analysis	The study of processes on the atomic scale to grain scale that allow structures to develop. This activity includes study of both fracture and flow of rock.
Tectonic analysis	The study of the relationship between structures and global tectonic processes. This activity includes the study and interpretation of regional-scale or megascopic structural features, and the study of relationships among structural geology, stratigraphy, and petrology.

that are visible optically at the scale of thin sections, or that may only be evident with the electron microscope; the latter is sometimes referred to as submicroscopic. **Meso** refers to features that are visible in a rock outcrop, but cannot necessarily be traced from outcrop to outcrop. **Macro** refers to features that can be traced over a region encompassing several outcrops to whole mountain ranges. In some circumstances, geologists use the prefix **mega** to refer to continental-scale deformational, such as the movements of tectonic plates over time. Of course there are no sharp boundaries between these scales, and their usage will vary with context, but a complete structural analysis tries to integrate results from several scales of observation.

Each scale of observation has its own set of tools. For example, optical and electron microscopes are used for observations on the microscale, and satellite imaging may be used for observations on the macroscale. The mesoscopic recognition and description of rocks and their structures are of fundamental importance to field analysis, which requires a set of eyes,[2] a hammer, a compass, and a hand lens. Field work is, in fact, pretty much a low-tech, low-budget affair unless you are working in the High Himalayas, Antarctica (Figure 1.9), or some similarly remote setting that requires extensive logistics (like expeditions, planes, and helicopters). For structural field work we record observations on lithologies and rock structures in notebooks or on portable devices and we measure the orientation of geometric elements with a compass. The compass to a structural geologist is like the stethoscope to a doctor: it is the professional's tool (and should be clearly visible at all times).

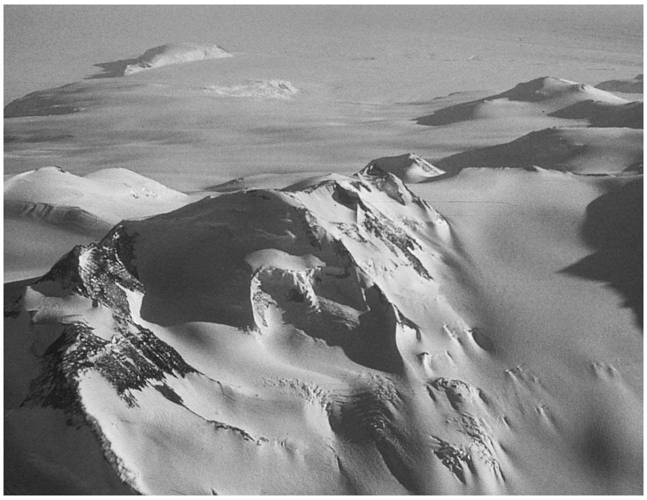

FIGURE 1.9 Field area in Antarctica.

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[2] Aided by corrective lenses in the case of the authors.

TABLE 1.2	TERMINOLOGY RELATED TO GEOMETRY AND REPRESENTATION OF GEOLOGIC STRUCTURES
Apparent dip	Dip of a plane in an imaginary vertical plane that is not perpendicular to the strike. The apparent dip is less than or equal to the *true dip*.
Attitude	Orientation of a geometric element in space
Cross section	Plane perpendicular to the Earth's surface
(True) dip	The slope of a surface; formally, the angle of a plane with the horizontal measured in an imaginary vertical plane that is perpendicular to the strike (Figure 1.10a)
Dip direction	Azimuth of the horizontal line that is perpendicular to the strike (Figure 1.10a)
Foliation	General term for a surface that occurs repeatedly in a body of rock (e.g., bedding, cleavage)
Lineation	General term for a penetrative linear element, such as the intersection between bedding and cleavage or alignment of elongate grains
Pitch	Angle between a linear element that lies in a given plane and the strike of that plane (also *rake*) (Figure 1.10b)
Plunge	Angle of linear element with earth's surface in imaginary vertical plane
Plunge direction	Azimuth of the plunge direction
Position	The geographic location of a geometric element (e.g., an outcrop)
Profile plane	Plane perpendicular to a given geometric element; for example, the plane perpendicular to the hinge line of a fold
Rake	Angle between a linear element that lies in a given plane and the strike of that plane (also *pitch*)
Strike	Azimuth of the horizontal line in a dipping plane or the intersection between a given plane and the horizontal surface (also *trend*) (Figure 1.10a)
Trace	The line of intersection between two nonparallel surfaces
Trend	Azimuth of any feature in map view; sometimes used as synonym for *strike*

Basic geometric principles, the ways of describing geometric features, and concepts related to constructions such as structure contours and spherical projections are explained in structural geology laboratory manuals. So, in this text we will limit ourselves to the short descriptions of terms and associated concepts in Table 1.2, some of which are illustrated in Figure 1.10.

1.5 SOME GUIDELINES FOR STRUCTURAL INTERPRETATION

In closing this introductory chapter, we make a few general comments on structural analysis. Good scientific work requires that one separates *observations* from *interpretations,* which equally holds for geologic mapping. Yet, a geologic map, a cross section, or a block diagram without interpretation misses the unique insights of the investigator. If you spend the time collecting and digesting data, you are best suited to make the interpretations (or, educated guesses). The following suggestions may help with map interpretation, but note that they hardly do justice to the intricate process of interpretation; our aim with these guidelines is mostly to point you in the right direction.

The assumptions on which interpretations are based do not hold universally; in fact, after some field experience you may disagree with one or more of the points listed. In our experience, however, the guidelines in Table 1.3 enable a reasonable, first-order interpretation of the geometry of an area.

Each individual guideline in Table 1.3 is valid under a given set of circumstances, but remember that, except for the laws, they remain mere assumptions; no

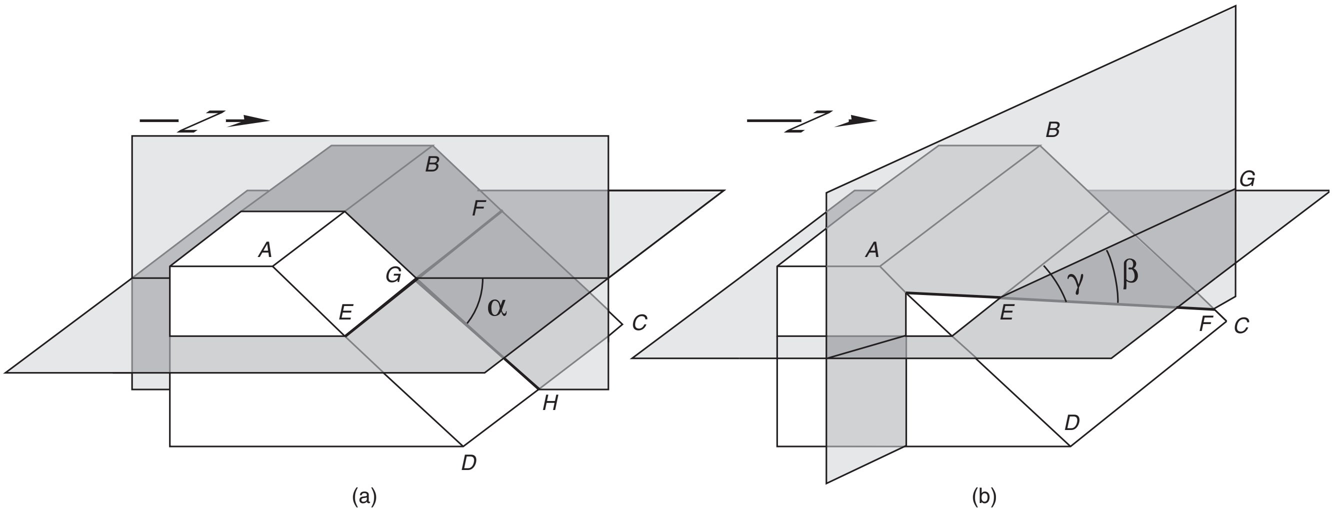

FIGURE 1.10 (a) Attitude of a plane: dip, dip direction, and strike. The strike of dipping plane *ABCD* is the intersection with an imaginary horizontal plane (line *EF*). The dip of plane *ABCD* is given by the angle α, while line *GH* represents the dip direction. Note that there are two possible directions of dip for a given strike. Thus, when using dip and strike, the general direction of dip must also be included (e.g., 090°/45° N). Alternatively, the attitude of plane *ABCD,* using dip direction and dip, is uniquely described by 000°/45°. (b) Attitude of a line: plunge, plunge direction, and pitch. Line *EF* lies in dipping plane *ABCD.* The plunge of line *EF* is the angle β, which is measured from the horizontal (line *EG*) in an imaginary vertical plane that contains both line *EF* and line *EG;* line *EG* is called the plunge direction. The attitude of line *EF,* using plunge and direction of plunge, is given by 30°/315°. The pitch (angle γ) is the angle that line *EF* makes with the horizontal (strike) of a plane (here: plane *ABCD*) containing the line. Note that when the pitch of a line is recorded, the attitude of the reference plane must be given, as well as the side from which the pitch angle is measured (here: 000°/45°, 40° W).

TABLE 1.3 SOME GUIDELINES FOR THE INTERPRETATION OF DEFORMED AREAS

- Strata are deposited horizontally. This is the Law of Original Horizontality, which makes bedding an internal reference frame.
- Strata follow one another in chronological, but not necessarily continuous, order.[3] This is known as the Law of Superposition.
- Separated but aligned outcrops of the same lithologic sequence imply stratigraphic continuity.
- Strata occur in laterally continuous and parallel layers in a region.
- Sharp discontinuities in lithologic patterns are faults, unconformities, or intrusive contacts.
- Deformed areas can be subdivided into a number of regions that contain consistent structural attitudes (structural domains). For example, an area with folded strata can be subdivided into regions with relatively constant dip direction (or even dip), such as the limbs and hinge areas of large-scale folds.
- The simplest but internally consistent interpretation is most correct.[4] This is also known as the least-astonishment principle.

more, no less. Whenever possible your assumptions should be tested by adding more observations, and when the assumptions continue to hold, only then may your interpretation be valid. This approach follows a proven scientific method, called the **testable working hypothesis,** which eventually leads to a **model.** If the model is very successful it may become a **law,** but this is rare in geology. Regardless, there is always room for alternative interpretations and models.

Increasingly, subsurface data from drilling and geophysical methods are available to structural geologists, and they should be used to test and constrain your interpretation. Drilling is restricted to the upper 10 km of the crust, but provides samples of deeply buried

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[3] See the description of *facing* in Chapters 2 and 10. If younging directions are unknown, *transposition* may present complications (Chapter 12).

[4] But no simpler than that (paraphrasing Albert Einstein).

layers that can be compared with exposed rock units. This is a powerful test for the cross sections and block diagrams you construct. Using two-dimensional and three-dimensional deep seismic reflection imaging we get an indirect view of the deeper parts of the Earth (see Chapter 15). Seismic reflection profiles are obtained by recording the travel times of sound waves that bounce off layers in the Earth. The technique requires careful data processing such as **stacking** and **migration,** which improve the signal-to-noise ratio and localize reflectors. Correlation of these reflectors with features that are exposed at the surface or obtained from drilling gives important information on the nature of the deep structure.

1.6 CLOSING REMARKS

In this opening chapter, we quickly traveled through the history of structural geology; the types of geologic structures; the meaning of stress, strain, and deformation; and the nature of structural analysis. Of course we only scraped the surface of these topics. Our goal was to give you a first idea of what the field of structural geology and tectonics entails. Except for the historical considerations, all these topics will return in detail throughout the text. The chapters of the book are grouped into "Fundamentals" (Part A), describing the theory and background that are needed for the interpretation of natural structures, "Brittle Structures" and "Ductile Structures" (Parts B and C), reflecting a distinction that is based on the distribution of strain in deformed bodies, and "Tectonics" and "Regional Geology" (Parts D and E), discussing some of the fundamentals of plate tectonics and plate boundaries, and perspectives on the geology of selected regions around the world. Ultimately, we will have examined structures on all scales, ranging from single atoms to the outcrop, to the mountain belt, and to the whole Earth. The relationships of these structures provide us with a relatively recent but remarkably complete picture of the tectonic evolution and inner workings of our dear planet.

ADDITIONAL READING

Many books explore field and geometric analysis, and computer and geophysical applications in structural geology. The following selection is based on our own usage, which is by no means complete.

Groshong, R. H., 1999. *3-D structural geology: A practical guide to surface and subsurface map interpretation.* Springer Verlag.

Lisle, R. J., 1996. *Geological structures and maps: A practical guide* (2nd edition). Oxford: Butterworth-Heinemann.

Marshak, S., and Mitra, G., 1988. *Basic methods of structural geology.* Englewood Cliffs: Prentice Hall.

McClay, K., 1987. *The mapping of geological structures. Geological society of London handbook.* Berkshire: Open University Press.

Rowland, S. M., and Duebendorfer, E. M., 1994. *Structural analysis and synthesis* (2nd edition). Boston: Blackwell.