CHAPTER 1

Overview

1.1 What Are Structural Geology and Tectonics?

The Earth is a dynamic planet. The evidence is all around us. Earthquakes and volcanic eruptions regularly jar many parts of the world. Many rocks exposed at the Earth's surface reveal a continuous history of such activity, and some have been uplifted from much deeper levels in the crust where they were broken, bent, and contorted. These processes proceed in slow motion on the scale of a human lifetime, however, or even the scale of human history. The "continual" eruption of a volcano can mean that it erupts once in one or more human lifetimes. The "continual" shifting and grinding along a fault in the crust means that a major earthquake might occur once every 50 to 150 years. At the almost imperceptible rate of a few millimeters per year, high mountain ranges can be uplifted in the geologically short span of only a million years. A million years, however, is already more than two orders of magnitude longer than the whole of recorded history. These processes have been going on for hundreds of millions of years, leaving in the Earth's crust a record of constant dynamic activity.

Structural geology and tectonics are concerned with the reconstruction of the inexorable motions that have shaped the evolution of the Earth's outer layers. These terms are derived from similar roots. *Structure* comes from the Latin word *struere,* which means "to build," and *tectonics* from the Greek word *tektos,* which means "builder." The motion may be simply a rigid body motion that transports a body of rock from one place to another with no change in its size or shape and, therefore, no permanent imprint. Or the motion may be a deformation that breaks a rock or changes its shape or size and thus leaves a permanent record. The structures discussed in this book result from permanent deformation of the rocks; they provide a record of the nature of that deformation.

For example, the Earth's crust breaks along faults, and the two pieces slide past one another. Sections of continental crust break apart as oceans open, and they collide with each other as oceans close. These events result in bending and breaking of rocks in the shallow crust and in puttylike flowing of rocks at greater depth. Mountain ranges are uplifted and subsequently eroded, exposing the deeper levels of the crust. The breaking, bending, and flowing of rocks all produce permanent structures such as fractures, faults, and folds that we can use as clues to reconstruct the deformation that produced them. Even on a much smaller scale, the preferred alignment of platy and elongate mineral grains in the rocks and the submicroscopic imperfections in crystalline structure all help us trace the course of the deformation.

The fields of structural geology and tectonics both deal with motions and deformation in the Earth's crust and upper mantle. They differ in that structural geology is predominantly the study of deformation in rocks at a scale ranging from the submicroscopic to the regional, whereas tectonics is predominantly the study of the history of motions and deformation at a regional to global scale. The two realms of study are interdependent, and at the regional scale, structural geology and tectonics overlap considerably. Our interpretation of the history of large-scale motions must be consistent with the observations of deformation that has occurred in the rocks. Conversely, the origins of deformation can be understood in the context of the history of the large-scale motions that we deduce from plate tectonics.

Structural geology and tectonics have undergone a period of rapid development since the 1960s. Structural geology has changed from an almost purely descriptive discipline to an increasingly quantitative one. Application of theoretical principles of continuum mechanics,[1] the ability to deform rocks directly in the laboratory, and the ability to study deformed minerals at the submicroscopic level have yielded new insights into the processes of deformation and the formation of structures. The insight gained from such studies has been used in many field-based investigations vastly to improve our understanding of naturally deformed rocks.

Tectonics has undergone a revolution based largely on the formulation of the theory of plate tectonics. This theory now provides the framework for study of almost all large-scale motions and deformation affecting the Earth's crust and upper mantle. Field-based studies have taken on new meaning because plate tectonic theory has given us a new basis for the tectonic interpretation of structures and the history of regional deformation.

Geophysical data have become increasingly important to both structure and tectonics, as indicated by the number of diagrams throughout this book that present geophysical data. Seismic and gravity studies provide information on the geometry of large-scale structures at depth, which adds the critical third spatial dimension to our observations. Studies of rock magnetism and paleomagnetism, as well as seismology, provide data on past and present motions of the plates, which are essential for reconstructing global tectonic patterns.

Structure and tectonics also depend on other branches of geology, which, however, we do not emphasize in this book. Petrology and geochemistry provide data on temperature, pressure, and ages of deformation and metamorphism, which are necessary for the accurate interpretation of deformation and its tectonic significance. Sedimentology and paleontology are also important in reconstructing the patterns and ages of tectonic events.

1.2 Structure, Tectonics, and the Use of Models

All field studies in structural geology and many in tectonics rely on observations of deformed rocks at the Earth's surface. These studies generally begin with observations of features at outcrop scale—that is, a scale of a few millimeters to several meters. They may then proceed "downscale" to observations made at the microscopic or even electron-microscopic level of microns[2] or "upscale" to more regional observations at a scale of hundreds to thousands of kilometers. At the largest scale, observations are generally based on a compilation of observations from smaller scales. *None of these observations alone provides a complete view of all structural and tectonic processes.* Our understanding increases as we integrate our observations of the Earth at all scales. In addition to direct observation of the Earth, we also use the results of laboratory experiments and mathematical calculations in making our interpretations.

Our first task in trying to unravel the deformation and its history is to observe and record, carefully and systematically, the structures in the rock, including such features as lithologic contacts, fractures, faults, folds, and preferred orientations of mineral grains. In general, this process consists of determining the geometry of the structures. Where are the structures located in the rocks? What are their characteristics? How are they oriented in space and with respect to one another? How many times in the past have the rocks been deformed? Which structures belong to which episodes of deformation? Answering these and similar questions constitutes the initial phase of any structural investigation.

In some circumstances, determining the geometry of rock structures is an end in itself (it is important, for example, in the location of economic deposits). For understanding the processes that occur in the Earth, however, we need an explanation for the geometry. Ultimately we want to know the kinematics of for-

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[1] Continuum mechanics is the study of the mechanics of continua, which are deformable materials whose properties vary smoothly or remain constant in any direction throughout a given volume. Rocks and many other substances, such as metals, are generally composed of grains that are very small compared with the volume being described. Thus their behavior approximates that of a continuum, and for purposes of analysis, we can ignore inherent discontinuities such as grain boundaries. This approximation enables us to describe the deformation of the rock in simple mathematical terms.

[2] One micron is one micrometer, or one-millionth (10^{-6}) meter, or one-thousandth (10^{-3}) millimeter.

mation of the structures—that is, the motions that have occurred in producing them. Beyond that, we want to understand the mechanics of formation—that is, the forces that were applied, how they were applied, and how the rocks reacted to those forces to form the observed structures.

In large part, we improve our understanding by making conceptual models of how structures form and then testing predictions derived from the models against observation. Geometric models are three-dimensional interpretations of the distribution and orientation of structures within the Earth. They are based on mapping, geophysical data, and any other information we have. We present such models as geologic maps and as vertical cross sections along a particular line through an area.

Kinematic models prescribe a specific history of motion that could have carried the system from the undeformed to the deformed state or from one configuration to another. They are not concerned with why or how the motion occurred or with what the physical properties of the system were. The model of plate tectonics is a good example of a kinematic model. We can assess the validity of such models by comparing the geometries of the motion and deformation observed in the Earth with those deduced from the model.

Mechanical models are based on our understanding of basic laws of continuum mechanics, such as the conservation of mass, momentum, angular momentum, and energy, and on our understanding of how rocks behave in response to applied forces. This latter information comes largely from laboratory experiments in which rocks are deformed under conditions that reproduce as nearly as possible the conditions within the Earth. Using mechanical models, we can calculate the theoretical deformation of a body of rock that is subjected to a given set of physical conditions such as forces, temperatures, and pressures. A model of the driving forces of plate tectonics based on the mechanics of convection in the mantle is an example of a mechanical model. Such models represent a deeper level of analysis than kinematic models, for the motions of the model are not assumed but must be a consequence of the physical and mechanical properties of the system. Thus the models are constrained not only by the geometry of the deformation, but also by the physical conditions and mechanical properties of the rocks when they deformed.

We use geometric, kinematic, and mechanical models to help us understand deformation on both the small scale and the global scale. It is important to realize, however, that even though we may be able to invent some model whose properties resemble observations of part of the Earth, such a model is not necessarily a good one. Predictions based on a model tell us only about the properties and characteristics of the *model*, not the actual conditions in the Earth. The relevance of a model for understanding the Earth, therefore, must always be tested.

Observations guide the formulation of models. The models in turn provide predictions that can be compared with reality, thereby stimulating new observations of the real world. Comparisons of what the model predicts with what we observe of the Earth constitute tests of the model's relevance. New observations that confirm the predictions support the model. To that extent, we accept it as a reasonable representation of the processes occurring in the Earth. If at any time observations contradict the predictions, we must refine the old model or reject it and devise a new one. Our understanding of structural and tectonic processes improves gradually by a continual repetition of the processes of making observations, formulating models based on those observations, deriving predictions from the models, testing the models with new observations, and fine-tuning the models accordingly. This process, in fact, is common to all science.

1.3 The Interiors of the Earth and the Other Terrestrial Bodies

Although most structural and tectonic processes discussed in this book are observed either at the surface or within the outermost layer of the Earth (the crust), the large scale at which these motions are consistent indicates that they reflect deeper, interior processes. Moreover, Earth is not alone in the solar system. In this age of space exploration, the models we make of the dynamic processes in the Earth are relevant to our understanding of other planets.

According to current models, the Earth is divided into three approximately concentric shells; these are, from the center outward, the core, the mantle, and the crust (Figure 1.1). The core is composed of very dense material believed to be predominantly an iron–nickel alloy. It includes a solid inner core and a liquid outer core. Surrounding the core is the mantle, a thick shell much lower in density than the core and composed largely of solid magnesium–iron silicates. The crust is a thin layer of relatively low-density minerals that surrounds the mantle. It is composed of igneous rocks of granitic to basaltic composition, sediments and sedimentary rocks, and their metamorphic equivalents, predominantly sodium, potassium, and calcium alumino-silicates.

The temperature of the Earth increases with depth with a gradient of approximately 30°C per kilometer in the crust and upper mantle and with considerably smaller gradients deeper within the Earth. Several

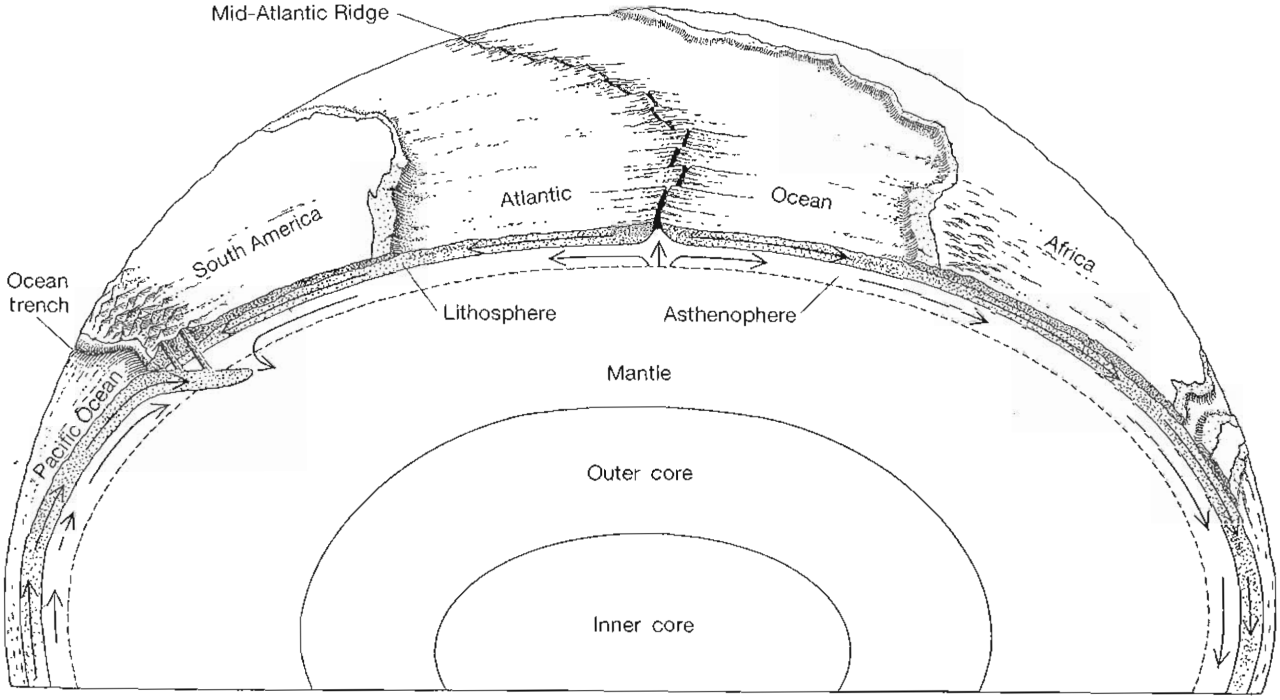

Figure 1.1 Diagrammatic cross section of the Earth showing the inner and outer core, the mantle, the lithosphere, and the crust. The spreading centers and subduction zones of plate tectonics are also indicated.

sources of heat account for this increase of temperature with depth: residual heat trapped during the original accretion of the Earth approximately 4500 million years ago, heat produced continually by the spontaneous decay of radioactive elements within the Earth, possibly latent heat of crystallization from slow solidification of the liquid outer core, and heat produced by the dissipation of tidal energy resulting from the gravitational interaction among the Earth, Moon, and Sun.

The increase of temperature with increasing depth results in a flow of heat energy toward the surface that may involve the convective cycling of material both within the liquid core and within the solid mantle. Heat convected out of the core is transferred to the lower mantle and is then carried toward the surface in a separate mantle convection system. The top of the mantle is a relatively cold, strong boundary layer called the lithosphere, which includes the crust and upper mantle to a depth of about 100 km. Heat escapes through the lithosphere to the surface largely by conduction and by transport in upward-migrating igneous melts.

Our studies of structural geology and tectonics focus on the motion and deformation of the lithosphere, as revealed mostly in its outer 20 to 30 km. It puts into perspective the task of understanding the dynamics of the Earth to realize that what we have available to study is the thin rind of relatively cold material that probably rides passively on top of mantle convection currents.

The Earth is one of a class of similar objects in the solar system called the terrestrial bodies. They are the innermost four planets (Mercury, Venus, Earth, and Mars), Earth's Moon, and several moons of Jupiter and Saturn, including Io, Titan, and Europa. All the terrestrial bodies apparently consist of a central core of very dense material that is probably an iron–nickel alloy, a mantle of dense silicates, and a thin crust of relatively low-density silicates. The inner four planets differ in size and relative volume of core. The core is proportionately greatest for Mercury and is progressively smaller for Venus, Earth, and Mars. The core of the Moon is relatively smaller still.

Although our study of the other terrestrial bodies is in its infancy, the current state of our knowledge invites fascinating comparisons with the Earth and speculation about the origin of various similarities and differences. As our understanding of the other terrestrial bodies increases, it will provide tests for models we have devised to explain dynamic processes occurring within the Earth. These models will have to account for the presence or absence of such processes on the basis of the size, structure, and internal physical conditions of the other terrestrial bodies.

1.4 Characteristics of the Earth's Crust and Plate Tectonics

The crust of the Earth is broadly divided into continental crust of approximately granitic composition and oceanic crust of roughly basaltic composition. Land—that part of the Earth's surface above sea level—is principally continental, the exceptions being islands in the oceans. At the present time, 29.22 percent of the Earth's surface is land and 70.78 percent is oceans and seas. Continental crust makes up 34.7 percent of the total area of the Earth, and it underlies most of the land area as well as the continental shelves and continental regions covered by shallow seas, such as Hudson's Bay and the North Sea. The remaining 65.3 percent of the Earth is oceanic crust (Figure 1.2).

The distribution of the Earth's surface elevation is strongly bimodal. Most of the continental surface lies within a few hundred meters of sea level, and most of the ocean floor lies approximately 5 km below the sea surface. This distribution is evident from the two types of hypsometric diagrams shown in Figure 1.3. The term *hypsometric* is derived from the Greek words *hypsos*, which means "elevation," and *metron*, which means "measure." The cumulative plot (Figure 1.3*A*) shows the total percentage of surface above a given elevation; the specific plot (histogram) shows the percentage of the surface within a given elevation interval. The continental freeboard, the difference in elevation between continent and ocean floor (Figure 1.3*B*), results from a number of factors, including the thickness and density differences between the continental and oceanic crusts, tectonic activity, erosion, sea level, and the ultimate strength of continental rocks, which determines their ability to maintain an unsupported slope above oceanic crust.

The characteristics of the Earth's crust are largely the direct or indirect result of motions of the lithosphere. The theory of plate tectonics describes these motions and accounts for most observable tectonic activity in the Earth, as well as the tectonic history recorded in the ocean basins. The theory holds that the Earth's lithosphere is divided at present into seven major and several minor plates that are in motion with respect to one another (Figure 1.2) and that the motion of each plate is, to a first approximation, a rigid-body motion. Deformation of the plates is concentrated primarily in belts tens to hundreds of kilometers wide along the plate boundaries. In a few regions, however, deformation extends deep into plate interiors.

The different types of boundaries between these plates include divergent boundaries, where plates move away from one another; convergent or consuming

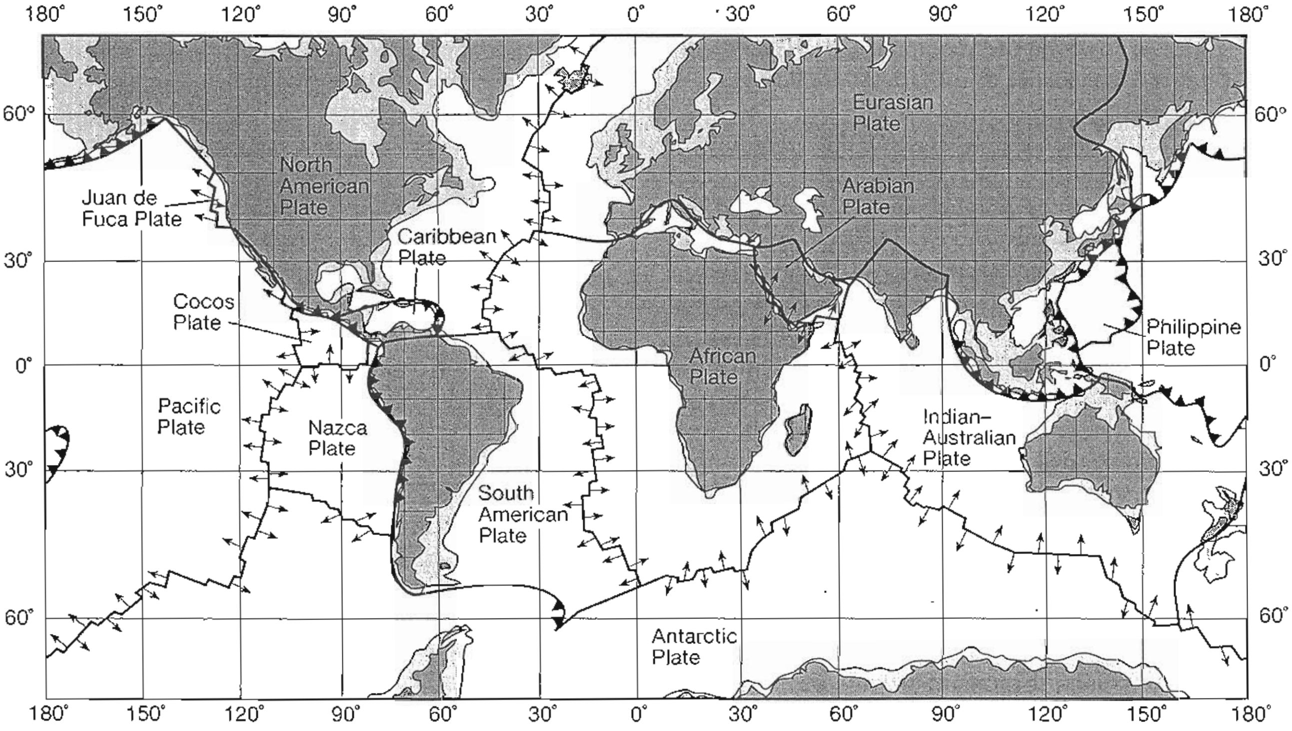

Figure 1.2 Distribution of land, continental shelves, ocean basins and tectonic plates on the surface of the Earth.

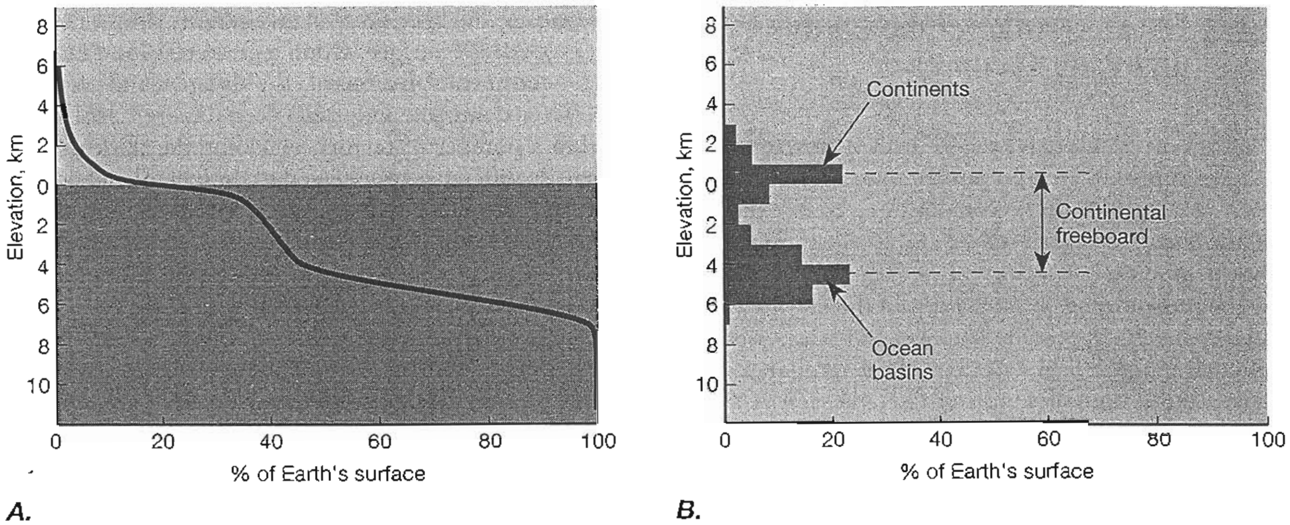

Figure 1.3 Distribution of topographic elevations on the Earth. *A.* Cumulative curve showing the percent of the Earth's surface that is above a particular elevation. *B.* Histogram showing the percent of the Earth's surface that falls within each 1-km interval of elevation. The continental freeboard is the difference between the dominant elevations of the continents and of the ocean basins.

boundaries (also called subduction zones), where plates move toward each other and one descends beneath another; and conservative or transform fault boundaries, where plates move horizontally past one another, without creation or destruction of lithosphere.

The most direct evidence for plate tectonic processes and sea floor spreading comes from the oceanic crust, where divergent motion at mid-oceanic ridges adds new material to lithospheric plates. As indicated in Figure 1.4, however, the maximum age of the oceanic crust limits this evidence to the last 180 million years—that is, to the *last 4 percent* of Earth history. Any evidence of plate tectonic processes for the preceding 96 percent of Earth history must come from the continental crust, which contains a much longer record of the Earth's activity. We must therefore learn to understand the large-scale tectonic significance of deformation in the continental crust so that we can see further back into the history of the Earth's dynamic activity.

In the geologic record, highly deformed continental rocks tend to be concentrated in long linear belts comparable to the belts of deformation associated with present plate boundaries. This observation suggests that belts of deformation in the continental crust record the existence and location of former plate boundaries. If this hypothesis is correct, and if we can learn what structural characteristics of deformation correspond to the different types of plate boundaries, we can use these structures in ancient continental rocks to infer the pattern and processes of tectonic activity. In this sense, the plate tectonic model has united the disciplines of structural geology and tectonics and made them interdependent.

The types of structures that develop in rocks during deformation (characteristically along plate boundaries) depend on the orientation and intensity of the forces applied to the rocks; on the physical conditions, such as the temperature and pressure, under which the rocks are deformed; and on the mechanical properties of the rocks, which are strongly affected by the physical conditions. At relatively low temperatures and pressures and at a high intensity of applied forces, a rock generally undergoes brittle deformation by loss of cohesion along discrete surfaces to form fractures and faults. At relatively high temperatures and pressures (but below the melting point) and at a relatively low intensity of applied forces, a rock commonly reacts by ductile deformation[3]—the flow, or coherent change in shape, of the rock in the solid crystalline state. This behavior may produce folding of stratigraphic layers, the stretching and thinning of layers, and the parallel alignment of mineral grains in the rock to form pervasive planar and linear preferred orientations.

In the belts of deformation along the plate boundaries, the different relative motions of adjacent plates, that is, whether the boundary is divergent, convergent, or conservative, largely determine the style of defor-

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[3] We use the term *ductile* to imply coherent nonrecoverable deformation that occurs in the solid state without loss of cohesion (brittle fracturing) at the scale of crystal grains or larger. The term has broader significance in other contexts, but there is no other word that adequately describes this behavior. In particular, the term *plastic* has other specific connotations that do not accurately reflect the behavior we wish to describe. See the introduction to Part III for a more detailed discussion of these terms.

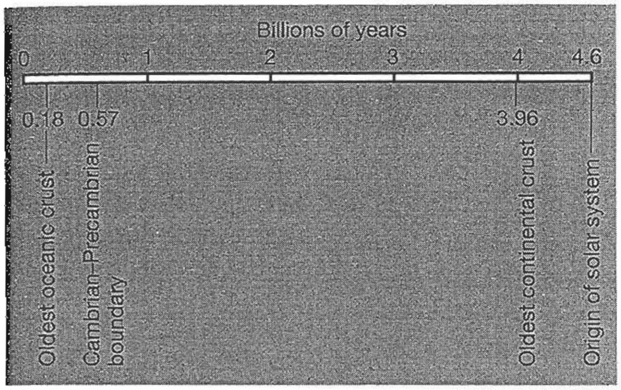

Figure 1.4 Time line showing different events in Earth's history and the ages of the oldest oceanic and continental crusts.

mation. Differences between oceanic and continental crust also affect the nature of deformation along plate boundaries.

At divergent boundaries, oceanic crust is produced by the partial melting of upwelling mantle material to form basaltic magma. Igneous intrusion and extrusion of these basalts produce the new oceanic crust. The relative motion of the plates creates structures in the crust that accommodate stretching, such as systems of normal faults near the surface and ductile thinning at deeper levels. When a divergent plate boundary develops within a continent, the associated stretching and thinning lower the mean elevation of the boundary zone, resulting in flooding of the surface by the sea. Such stretched and thinned continent commonly underlies the wide continental shelves (Figure 1.2).

Subduction zones at convergent boundaries are the places where oceanic crust is recycled back into the mantle. The plate plunges back into the interior of the Earth. Sediments on the down-going plate are partly scraped off, and partial melting of the down-going plate produces characteristic volcanic arcs on the over-riding plate. Structures at the plate boundary are predominantly systems of thrust faults. Along the volcanic arc, however, normal faults are common. If a continent is involved with either the over-riding or the down-going plate at a subduction zone, it commonly experiences shortening and thickening of its crust by means of characteristic systems of thrust faults.

At conservative or transform fault boundaries, the structures that form are typically systems of strike-slip faults or, at deeper levels, vertical zones of ductile deformation that have a subhorizontal direction of displacement.

A variety of secondary structures also develop in any of these tectonic environments, so the presence of any particular structure per se is not necessarily diagnostic of the type of boundary at which it developed. The genesis can be inferred only after a careful study of the regional pattern of the structures and their associations.

Structural and tectonic processes profoundly influence other Earth processes as well. For example, the continents have varied in number, size, and geographic position as a result of plate tectonic processes. As plate tectonics changed the shape and distribution of continents and ocean basins, the patterns of oceanic and atmospheric circulation changed accordingly. The resulting changes in environmental conditions affected the patterns of sedimentary environments, as revealed by studies of stratigraphy and sedimentology, and the patterns of natural selection and evolution, as revealed by paleontologic studies.

Because plate boundaries are sites of major thermal anomalies in the crust and upper mantle, these areas control the occurrence and distribution of igneous and metamorphic rocks, which are studied in "hard rock" petrology. Similarly, the formation, concentration, and preservation of mineral deposits are profoundly affected by structures and their tectonic environments, as well as by the thermal anomalies at plate boundaries. As the Earth's resources are increasingly depleted, increasingly sophisticated and subtle exploration strategies are required in order to find and develop new deposits. Structural geology and tectonics are assuming a crucial role in the search for metal and hydrocarbon deposits.

1.5 Summary and Preview

In a sense, the study of Earth deformation processes is a detective exercise. As in all other branches of geology, our evidence is usually incomplete, and we must use all available paths of investigation to limit the uncertainties. Thus we study modern processes to help us understand the results of past deformations. We use indirect geophysical observation to detect structures that lie beneath the surface where we cannot see them. We make observations on all scales, from the submicroscopic to the regional, and try to integrate them into a unified model. We perform laboratory experiments to study the behavior of rocks under conditions that at least partially reproduce those found in the Earth. And we use mechanical modeling, in which we apply the principles of continuum mechanics to calculate the expected behavior of rocks under different conditions.

At the level of this book, we cannot hope to cover all these aspects in detail. Our aim, rather, is to provide a thorough basis for field observation of geologic structures and to introduce the various paths of investigation that can add valuable data to our observations and lead to deeper understanding of structural and tectonic processes. We hope also to instill an appreciation for the interdependence and essential unity of the disciplines of structural geology and tectonics.

We have arranged the topics to be covered into four major parts following this introductory Part I: Part II covers the structures typically associated with brittle deformation. Part III discusses structures formed during ductile deformation. Part IV deals with rheology, or the characteristics and mechanisms of ductile flow in rocks. And Part V discusses tectonics and the relationships among plate tectonics, crustal deformation, and the structures formed in different tectonic settings.

Our approach is first to describe the characteristics and geometry of the different types of structures that we can observe in the field. For each class of structures, we then discuss possible kinematic models that can account for the observations. After discussing the types of structures in each section, we present a more detailed analysis of their formation by introducing relevant concepts from continuum mechanics and pertinent results from laboratory experiments. We introduce the concept of stress in Part II to describe the intensity of forces so that we can explain the origin of fractures and faults in rocks. We introduce the concept of strain in Part III to describe deformation so that we can better understand the structures formed during ductile deformation.

The manner in which deformation of rock depends on the intensity of forces applied to it is determined by the relationships between the stress and the strain. These relationships are the subject of Part IV, where we also discuss the mechanisms that give rise to the flow of rocks and the characteristic microstructures that result from the operation of those mechanisms.

By applying these ideas to the observable deformation in the Earth, we can understand the conditions necessary for the formation of different structures, and this in turn helps us to determine the deformational processes and tectonic environments in which structures form. Our presentation generally follows the process of research and interpretation, which must of necessity start with the geometric analysis of the structures that exist in the rocks, and which then ideally proceeds to kinematic and mechanical interpretation of those structures.

Finally, in Part V, we look briefly at the major tectonic features of the Earth's crust with particular emphasis on orogenic belts (mountain belts). For two centuries, orogenic belts have fascinated those who study the Earth. They preserve much of the information that exists about the interaction of plates with each other through geologic history.

In a companion volume we examine in more detail the tectonic processes that are ultimately the origin of the deformation recorded by structures. We explore modern tectonic processes and describe the structures and associations of structures that develop in response to these processes.

Using the models that we construct from observations of recent tectonic processes, we look at systems of structures in ancient orogenic belts that are exposed largely in major mountain ranges of the world. By studying the structures, and by applying our understanding of how they form, we try to reconstruct the geometry, the kinematics, and the mechanics of their formation and finally to integrate this information into a tectonic interpretation consistent with the tectonic models. In this manner, we can push our reconstructions of the tectonic history of the Earth further and further back into the past, where the geologic record becomes increasingly fragmentary and obscure.

Finally, we briefly compare what we currently understand to be the tectonics of the nearby terrestrial bodies (the Moon, Mercury, Venus, and Mars) with the tectonics of the Earth.

The current theory of plate tectonics does not answer all the questions we have about the structural and tectonic evolution of the Earth. And, of course, tectonic processes have not necessarily remained the same throughout the Earth's entire history. One of the challenges of modern structural geology and tectonics is to study ancient deformation to see whether, in fact, models based on modern tectonics are appropriate, or whether the observed structural patterns and associations require different models for the various stages in the Earth's evolution. Plate tectonic theory is a major advance in our understanding, but it is itself evolving. The problems that remain today are generating provocative research questions. Answering them will lead to further advances.

We hope these books will stimulate the curiosity and ambition of a new generation of geologists to explore in greater detail the various paths of investigation we introduce and, ultimately, to create new approaches to enhance our understanding.

Additional Readings

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