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PART E

REGIONAL PERSPECTIVES

CHAPTER TWENTY

A Global View

20.1 INTRODUCTION

In Chapters 16 through 19, we introduced you to a variety of tectonic settings and we described geologic structures that are commonly associated with these environments. To put rock deformation in context, we did not limit our descriptions to structural features of these environments, but also included information concerning petrologic and sedimentologic features that accompany deformation. Our discussion focused on response to plate motion at the three basic types of plate margins, and ranged from what happens during the inception of a divergent margin (rifting) to the death of a convergent margin (collision ± strike-slip). The expression of tectonism in these various settings can be dramatic, as it results in regional belts of deformation, metamorphism, and igneous activity (Figure 20.1). These belts are known as *orogens,* and the set of processes that create them is called *orogeny.* Much of what is known about plate tectonic processes comes from the study of recent plate margins, rifts, and collision zones. Plate interactions, however, leave a permanent scar in the lithosphere, even after the associated physiography has long since eroded away. Through field study we are increasingly able to get a good understanding of ancient plate tectonics in our planet's history, as described in the subsequent chapters that contain regional perspectives.

We believe that it is best to focus on natural examples to understand the nature and consequences of plate tectonic processes, including orogeny. Thus, we devote the final chapters of this book to case studies of major deformation belts around the world. Each study is written by one or more experts, in his or her own style, so that you will get a flavor of how different geologists think and how they approach tectonics. When you talk with these seasoned geologists, chances are that you quickly share their excitement about the area in which they work. The excitement may stem from discovering key outcrops for understanding regional deformation or new insights into an aspect of fundamental significance for crustal evolution. The experts have tried to capture some of their excitement in these essays, rather than offering comprehensive review papers.

When you collect additional reading material on the areas described here or on other areas, you will rapidly learn that views vary and, sometimes, that they are contradictory. The observations, of course, stand, but alternative interpretations are often possible, especially in the case of regional tectonics. You will find that the essays which follow emphasize large-scale processes, but also that the scenarios are often based on small-scale observations. This relationship between observations on varying scales mirrors the approach we have taken throughout the book: processes on different scales are not separate and unrelated entities; rather, they form part of an integrated framework for studying the deformation of rocks and regions.

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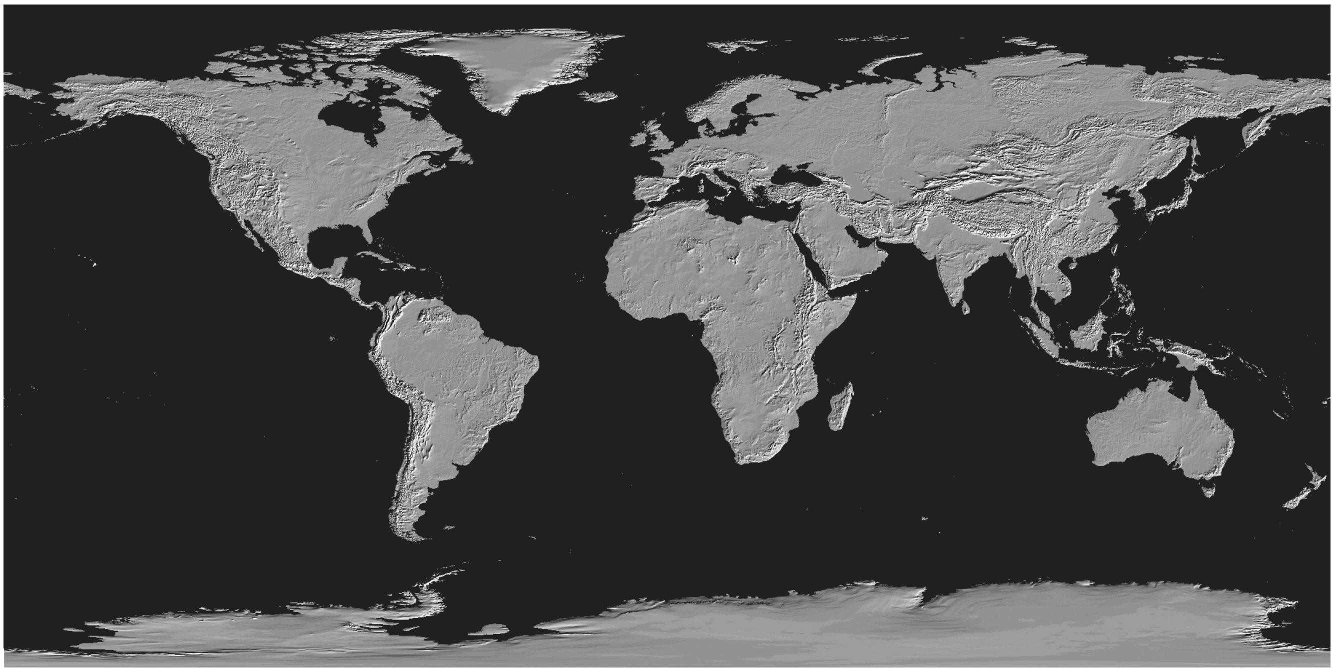

FIGURE 20.1 Shaded-relief map of the world.

20.2 GLOBAL DEFORMATION PATTERNS

The most impressive deformation features that are exposed at the Earth's surface are concentrated along relatively narrow belts at active plate margins (Figure 20.2). Today's active mountain belts, such as the European Alps, the Himalayas, the North American Cordillera, and the Andes of South America, mark convergent plate boundaries. From a human perspective the term "active" mainly means earthquakes and volcanoes, but from a geologic perspective this term implies continuing relative displacements at these margins on the timescale of millions of years. Ancient mountain belts, such as the Caledonides, the Appalachians, the Altaids, and the Tasmanides, were formed at plate boundaries and oceans that have all but disappeared; only remnants are preserved in these orogens as ophiolites, volcanic arcs, oceanic plateaus, and so on. These remnants are often able to provide us with much of the area's geologic history. Even farther back, into the Precambrian, we no longer see the mountainous physiography of orogens preserved, that is, there is little or no related topography. Yet these flat, inactive regions (called **cratons**) include deeply eroded levels of once vast mountain belts that formed from tectonic processes perhaps similar to those active today. Later in this chapter we speculate on some contrasts between modern and ancient orogens, which is a topic of great interest.

Not all deformation, however, takes place at plate margins. Some of the great historical earthquakes occurred within continental interiors; for example, the 1811–1812 New Madrid earthquakes in central North America. Evidence for tectonic activity is also preserved by large intracratonic basins, such as the (mostly) Paleozoic Michigan Basin that contains as much as 5 km of sediment, by arches, and by massive rift zones, such as today's East African Rift and the Proterozoic Midcontinent Rift of North America. Thus, we conclude this set of chapters on regional perspectives by discussing the fascinating deformational features of plate interiors, focusing on the Midcontinent area of the United States.

The continental regions of Earth preserve a long history, going back as far as 4 Ga. This is in marked contrast to today's ocean basins, where the oldest rocks are on the order of 200 Ma. It is perhaps ironic that, although many of the fundamentals of plate tectonics were formulated from the study of today's ocean basins, we uncover Earth's ancient history by focusing our attention on the continents. When reading the essays you will find that we have gotten a remarkably detailed understanding of this ancient history, especially for the Phanerozoic, and increasingly for Proterozoic times also. The Archean, however, remains

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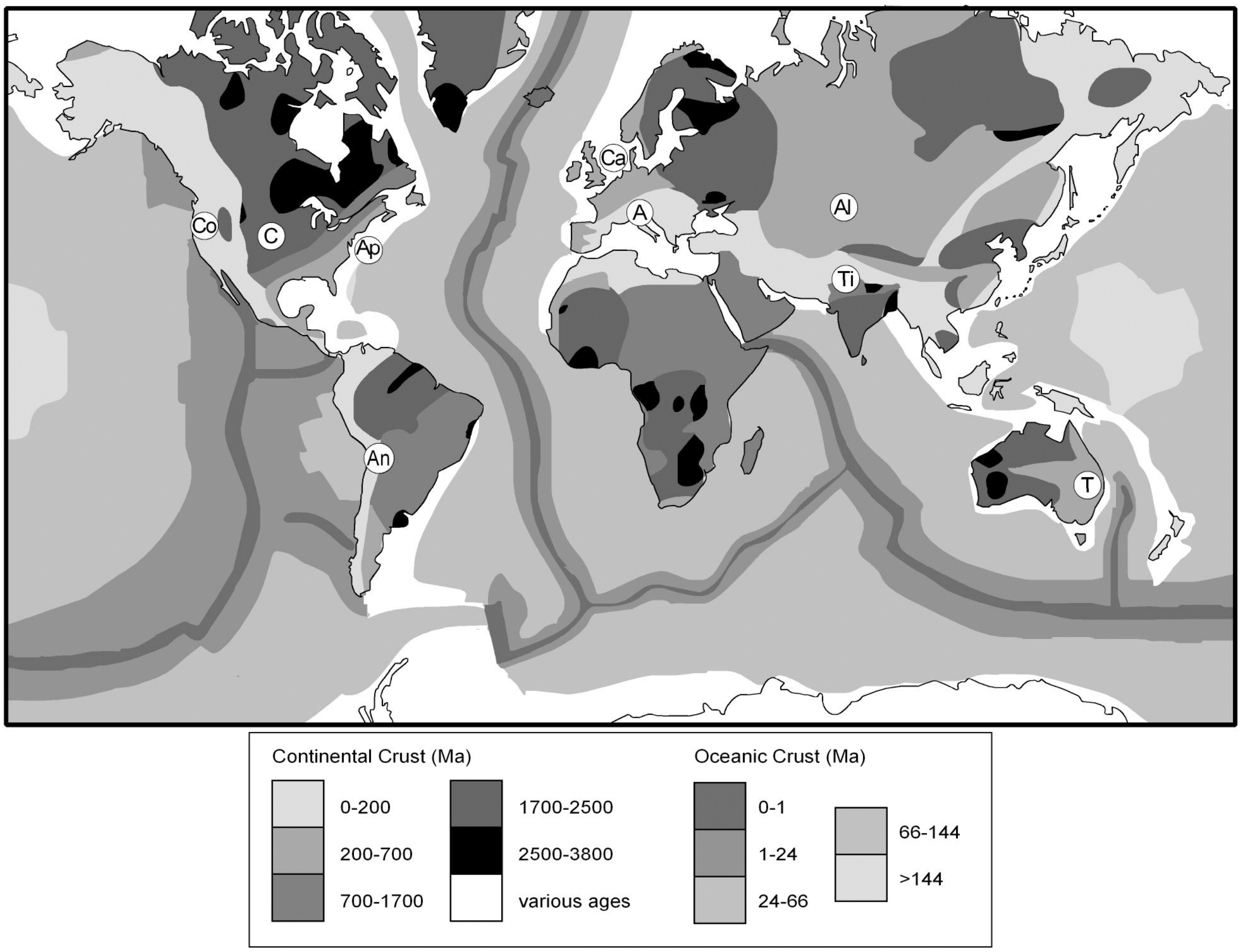

FIGURE 20.2 Areas of the world that were deformed during various geologic periods. In most continents the oldest deformed rocks (basement) are covered by younger sedimentary rocks (cover). Also shown are continental rocks on margins as in oceanic plateaus. Areas that are described in the essays are European Alps (A), Himalaya/Tibet (Ti), Altaids, North American Cordillera (Co), Andes (An), Caledonides (Ca), Appalachians (Ap), Tasmanides (T), Precambrian North America, and North American cratonic interior (c).

much less well understood, and its tectonic history is quite speculative. This temporal pattern of knowledge merely reflects the situation that, as rocks become sparser and have more complex histories with age, our ability to study ancient tectonics diminishes. Yet, the pursuit of this understanding poses new challenges to field and laboratory geologists alike.

20.3 WHAT CAN WE LEARN FROM REGIONAL PERSPECTIVES?

The next several pages contain a lot of information, as you will see. Each essay in turn condenses even more information in only a few pages. So the answer to the question posed in the header of this section would be: *a lot!* But it makes no sense to just read all the essays and memorize the respective histories of these areas. The essays should be used as a first introduction to the continental geology of the world, but they may serve several other purposes. We identify just a few.

- The essays get you rapidly acquainted with fundamental geologic aspects of some area of the world. This probably means that you will concentrate on one or two essays as a basis for a more in-depth study of a region.
- The essays show the various approaches that may be taken in the study of (ancient) mountain belts. When you look beyond the details of individual areas, you will find that stratigraphy, geochronology, geo-

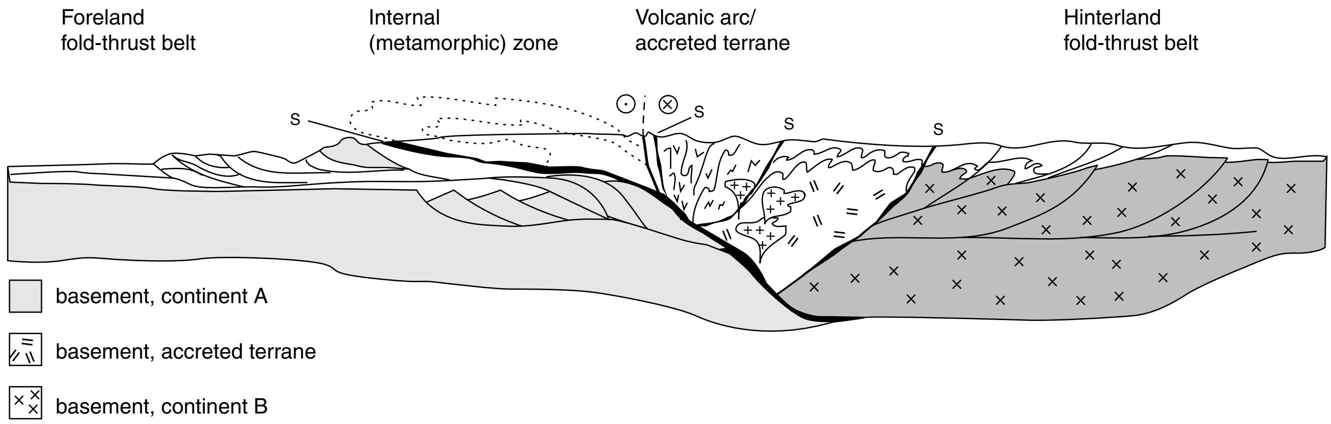

FIGURE 20.3 Idealized section through a collisional orogen, showing foreland fold-thrust belt, metamorphic hinterland (with nappes), inverted passive margin, strike-slip plate boundary, accreted volcanic arc, accreted microcontinent, and sutures (S). Most if not all mountain belts contain several of the features shown in this ideal section, but none probably contains all of them. The diagram is based on observation in Phanerozoic mountain belts; most Precambrian belts preserve only the deeper crustal levels.

chemistry, geophysics, and other earth science disciplines need to be integrated to obtain an understanding of a region's tectonic history.

- The essays allow you to recognize fundamental features that are common to most areas. We will next look at orogenic architecture as an example of one of these features.

Orogenic architecture describes the broad geometry of a mountain belt (Figure 20.3). Whereas the details of each individual mountain belt differ, they have many features in common. Generally you will find a deformed, originally wedge-shaped sedimentary sequence that was deposited at the stable continental margin. This sequence may contain marine carbonates if the area was located in the equatorial realm. Slivers of **ophiolite,** a rock assemblage containing ultramafic (mantle) rocks, gabbros, dikes, and pillow basalts, are remnants of ancient ocean floor[1] that are also preserved in an orogen. In fact, ophiolites are critical evidence for the activity of modern-day plate tectonics in ancient mountain belts. Granites, associated with volcanic arc formation or the melting of overthickened crust, are variably present. As the orogen evolves, marine clastics (sometimes called **flysch**) that are derived from the eroding mountain belt are deposited in foreland basins and at the waning stages of orogenic activity coarse continental clastics (sometimes called **molasse**) are laid down. In young orogenic belts we find that isolated slivers of basement rocks (also called **crystalline basement**) have become exposed by faulting. In some cases, mantle rocks are similarly exposed. In ancient orogens this basement component significantly increases, and the sedimentary sequence is mainly preserved in metamorphosed and highly deformed rocks (called paragneiss). The oldest mountain belts consist nearly entirely of deformed mid-crustal to lower-crustal rocks of magmatic origin (called orthogneiss). In a way, these ancient orogens expose the roots of deeply eroded mountain belts and, in combination with modern regions, they provide a fairly complete section through orogenic crust.

Deformation is usually polyphase and each phase can contain several fold generations. Within a single orogenic phase, the deformation sequence may look something like the following: Early structures are thrusts that repeat stratigraphy, or large recumbent folds that repeat and locally invert stratigraphy (called **nappes**). These thrusts often root in a **detachment zone** (or **décollement**) at depth. In metamorphic regions this stage has produced widespread transposition**.** These early structures are overprinted by upright folds that may contain an axial plane foliation, and later fold generations are commonly present as kinks and crenulations. These contractional features locally overprint evidence of an initial rifting stage (normal faulting) that formed at the passive plate margin. In addition to early rifting, extensional structures often

[1]Geochemical evidence suggests that most ophiolites in mountain belts are obducted backarc basin oceanic lithosphere rather than main ocean basin.

form during the later stages of mountain building and during unroofing (**synorogenic** and **postorogenic extension,** respectively; not shown in Figure 20.3).

Orogens are often curved in map view, which may reflect the shape of the original plate margin, may be a result of rotation by indentation **(oroclinal bending),** or may represent differential displacements along trend. Blocks with distinct lithologies and deformation history (lithostratigraphic blocks, nowadays called **terranes**) may be incorporated in the mountain belt, reflecting the accretion of oceanic plateaus, ocean islands, or fragments of disrupted continents to the active plate margin. The boundaries of these blocks are called **sutures** and they may be marked by ophiolites, indicating that ocean floor originally separated the blocks. Other deformation characteristics, such as progressive outboard-younging of deformation, may be present and you are encouraged to search for them in the essays that follow. While you may at first be interested in the geology of only one area, a knowledge of other areas often leads to understanding your own particular region and offers alternative views; that is why we need to study the literature and that is why we offer these regional perspectives.

20.4 SOME SPECULATION ON CONTRASTING OROGENIC STYLES

Most geoscientists accept the notion that earlier in Earth's history the mantle was hotter overall than it is today, because the young Earth held more of its primordial heat and had a greater concentration of radioactive elements than it does today. For example, decay of radioactive elements produced three times as much heat at the beginning of the Archean and about 1.8 times as much heat at the beginning of the Proterozoic as it does today. Thus, **mantle convection** in the younger Earth was probably more vigorous than it is today; but whether a hotter, more vigorously convecting mantle caused young continents to be warmer than those of today remains a point of debate. If excess heat of the Earth's interior was lost, in part, by conduction through the continents, then the continents must have been warmer. However, if the additional heat of the young Earth was lost through convection involving oceanic lithosphere (because spreading rates were faster, or spreading occurred at a greater number of ridges, or there were a greater number of hot spots), then the continental crust may not have been substantially hotter. Researchers who argue in favor of the idea that the crust was not substantially hotter in Precambrian times, point out that young continents lay above a thick lithospheric root and thus would have been insulated from the convecting asthenosphere. Uncertainty over the stability of the mantle beneath continents complicates interpretation of the thermal conditions of continents. The deep root of thickened, cooler mantle that formed beneath collisional orogens may **delaminate,** at which time hot asthenosphere flows against the base of the continent, causing an increase in heat flow into the continent. Delamination would be more likely in the Archean if mantle convection was more vigorous, which may explain the prevalence of high-temperature metamorphism in Archean terranes.

The height of a mountain range on Earth depends largely on the strength of the crust, because crust collapses and spreads laterally under its own weight if the gravitational load of the elevated region exceeds the strength of rock at depth, and exceeds the magnitude of the horizontal tectonic forces that hold up the range. Thus, a decrease in crustal strength would mean that a mountain range could not grow as high during contractional orogeny, because a weak crust would allow the range to collapse and undergo lateral spreading before it built up as high mountains. Since the strength of the crust decreases as temperature increases due to the temperature dependence of deformation mechanisms, then crust with a higher geotherm will be weaker than crust with a lower geotherm. This contrast would imply that the width and height of Precambrian orogenic belts would be less than those of Phanerozoic orogenic belts for a given amount of horizontal convergence (Figure 20.4). Thus, the cross-strike geometry of mountain ranges might have been different in the past—Archean and Early Proterozoic orogens may have contained wider belts of plastically deformed rock.

In addition to geometric observations, geologists increasingly recognize interconnections between the atmosphere, climate, erosion, and tectonics. Can changes in environmental conditions affect regional geology over time? If **atmospheric circulation** and **climate** were significantly different in the past, then ancient orogenic belts may have been different, both morphologically and structurally, from modern orogens. Earth's early atmosphere may have been more corrosive than the modern atmosphere, because of the greater concentration of volcanic gases. If so, rainfall might have caused chemical weathering at faster rates than today. If the Archean and early Proterozoic atmosphere was richer in CO_2 than the Phanerozoic atmo-

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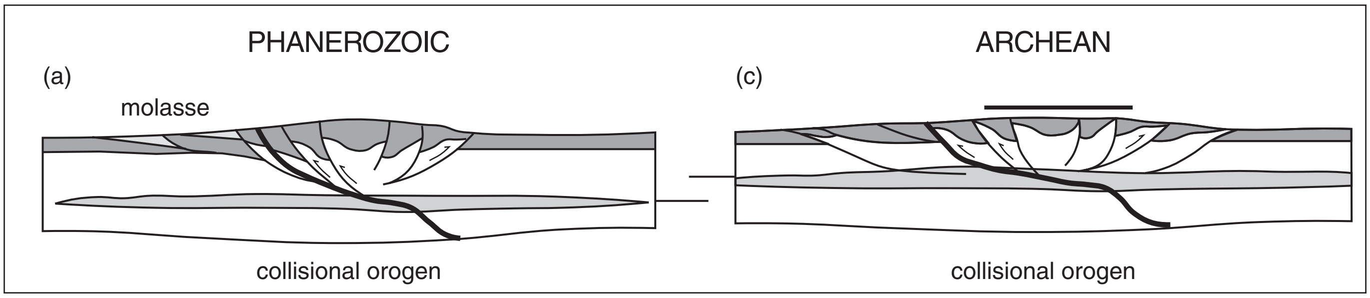

FIGURE 20.4 Schematic cross-sections that contrast collisional orogens of Archean/Paleoproterozoic time with those of Phanerozoic time. The shaded layer represents supracrustal rocks, the white layer represents basement, and the patterned lens represents a mid-crustal weak zone. (a) Phanerozoic collisional orogen with adjacent foreland basin. (b) Archean/Paleoproterozoic collisional orogen. The thin horizontal line above the orogen defines the comparative height of the Phanerozoic orogen.

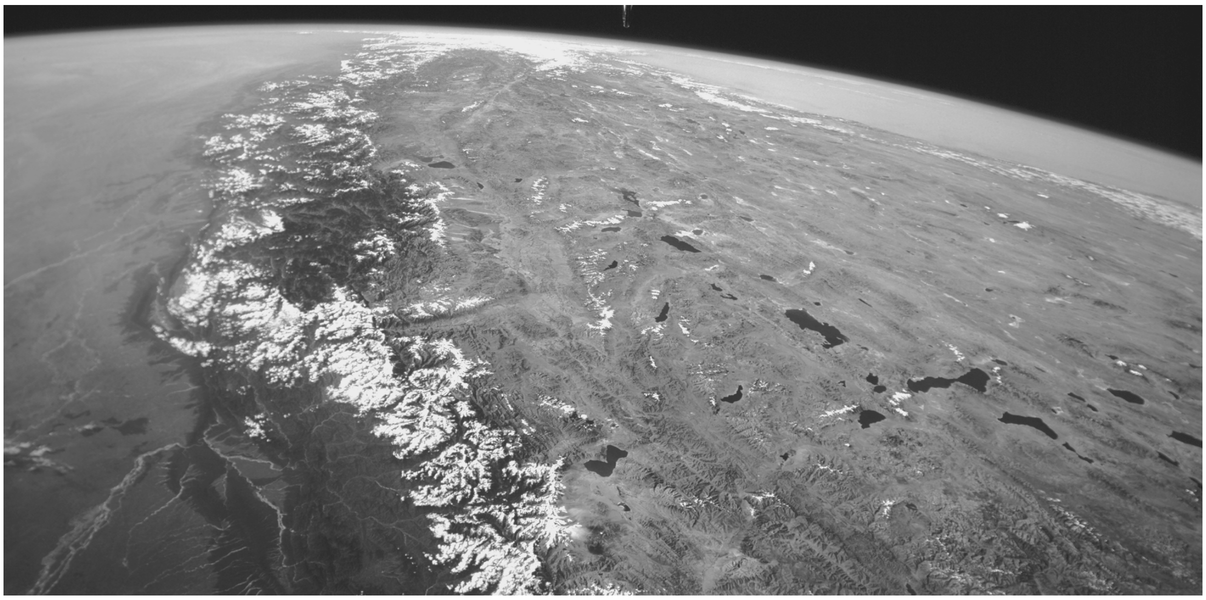

FIGURE 20.5 View from space of the eastern Himalayas and the Tibetan Plateau.

sphere, the Earth was probably warmer most of the time, so atmospheric circulation and oceanic evaporation might have been faster, leading to greater rainfall. Because continents were smaller in Earth's early history, storms would not be calmed by movement over broad areas of land. Thus, weathering and erosion may have been faster during Earth's earlier history than they are today. So exhumation rates would be faster and isotherms in the crust would rise significantly. To replace the mass deficit resulting from erosion, rocks metamorphosed at great depth would be rapidly brought to the surface, producing wide metamorphic belts as relicts of orogens. When tectonism eventually ceased, the next succession of supracrustal rocks would be deposited directly on high-grade gneiss. Further, foreland fold-thrust belts would be smaller, basement structures would be reactivated in the foreland (because uplift of isotherms would bring hot rocks to the surface in the foreland), and deep foreland basins would not develop. Although far from proven, these speculations offer an interesting framework for exploring ancient orogens and past tectonic activity. Try to keep them in mind when reading the essays.

20.5 CLOSING REMARKS AND OUTLINE

The splendor of mountain belts has long attracted the interest of geologists and the general public both as objects of scientific investigation and for their natural beauty (Figure 20.5). You can imagine that a vast body of literature exists on regional deformation after some 150 years of regional mapping and associated laboratory work. The advent of the unifying concept of plate tectonics in the 1960s also coincides with a publication explosion in the Earth sciences (all sciences, in fact). In the Preface, we have already mentioned the enormous volume of current literature. Mercifully, each of the following essays lists only some of the more informative references and makes no attempt to offer a comprehensive reading list. To these references we only add general textbooks in this chapter, which complement the information in the essays and include many areas and topics not covered here. With all this information in hand you should not find it too difficult to explore the literature on your particular area or topic of interest.

Of course, there are many other regions of interest in the world beyond those described in the essays that follow; our choices merely represent a sampling of some reasonably well understood areas. New insights continue to be discovered everyday in these already well-studied regions, and many are waiting to be discovered in lesser known areas. As every scientist will tell you, our increasing knowledge (in our case, of deformation and tectonics) is usually accompanied by an increase in the number of unanswered questions. This ensures a continued challenge for future generations of geologists. Happy reading!

ADDITIONAL READING

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