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Part I
Introduction

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1 Definitions, rationale, and scope of the book

Definition of terms

Earth surface processes include weathering; sediment production by weathering and biochemical or chemical precipitation; erosion, transport, and deposition of sediment under the influence of gravity, flowing water, air, and ice; earthquakes and Earth surface motions; volcanic eruptions and movement of volcanic ejecta. Study of the landforms (morphology) of the Earth's surface, including the processes responsible for such landforms, is called *geomorphology*. The study of sediment, specifically the nature and origin of unconsolidated sediments and consolidated sedimentary rocks, is called *sedimentology*. *Stratigraphy* strictly means the description of (sedimentary) strata, which, by definition, is another aspect of sedimentology.

Importance of Earth surface processes

Earth surface processes are important for scientific, engineering, environmental, and economic reasons, as explained below.

Shaping of the Earth's surface

Many of the Earth surface processes responsible for landforms involve the formation, erosion, transport, and deposition of sediment (Figure 1.1). It is impossible to understand the formation of depositional landforms (such as deltas and beaches for example) without knowledge of the sediments that compose them. Furthermore, the nature of sedimentary deposits is likely to be related to the processes of sediment production and erosion in the source area. Therefore, the disciplines of geomorphology and sedimentology are intimately related.

Interpretation of ancient surface processes, landforms, and sedimentary deposits

The only rational way of interpreting the origin of ancient sedimentary deposits (Figure 1.2) is to compare them with modern sedimentary deposits, or with theoretical models based on knowledge of modern sedimentary processes. Then, the sedimentary record can be interpreted in terms of past Earth surface processes and landforms, leading to reconstruction of the geography, tectonics, and climate of the past (i.e., Earth history). Evolution of life on Earth and the habitats and lifestyles of past organisms are also reconstructed from the fossil evidence preserved in sedimentary deposits.

Knowledge of Earth surface processes, landforms, and sedimentary deposits is being used increasingly to interpret the present and past surface environments on other planets (e.g., Mars), and such interpretation requires particular care in view of the different physical, chemical, and biological conditions on other planets.

Engineering, environmental, and public-safety issues

Many Earth surface processes involve engineering, environmental, and public-safety issues, including landslides and debris flows; river floods; storm surges; riverbank and beach erosion; sedimentation in navigation channels; ground movements, landslides, and tsunamis associated with earthquakes; eruptions of volcanic ash and lava, and their effects on climate, river floods, and sediment gravity flows (Figure 1.3). Earth surface processes must be understood when constructing anything on the Earth's surface: buildings, roads, railways, canals, dams, coastal barrages

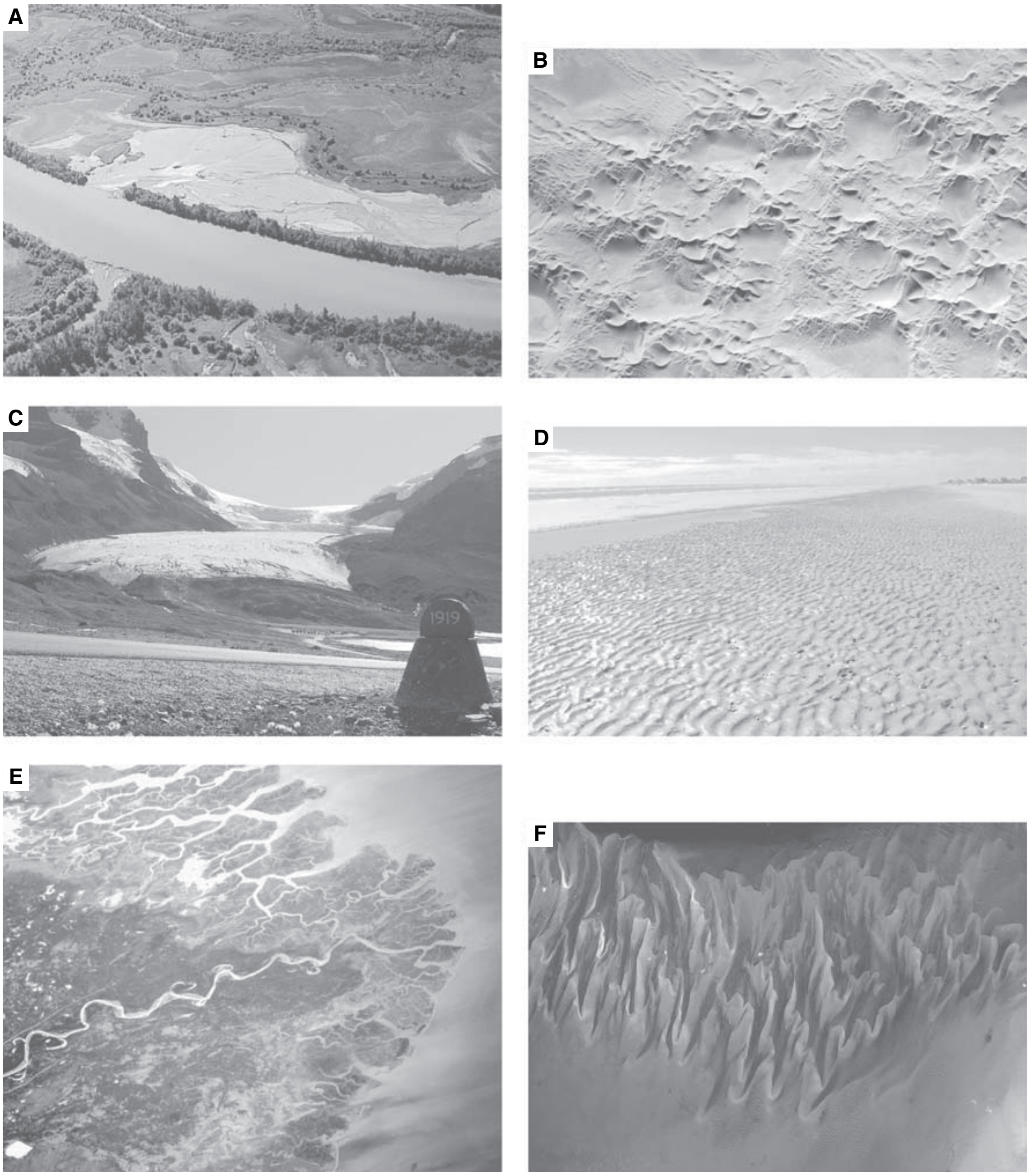

FIGURE 1.1. Depositional landforms. (A) Channels, levees, and crevasse splays on the Columbia River, BC, Canada. Photo courtesy of Henk Berendsen. (B) Issaouame sand sea in eastern Algeria. From NASA Earth from Space. (C) Athabasca Glacier, Canada, showing marginal deposits and the position of the terminus in 1919. Photo courtesy of Henk Berendsen. (D) Beach with ridge and runnel, Galveston Island, Texas. Photo courtesy of Robert Tye. (E) The Indus River delta. From NASA Earth from Space. (F) Carbonate-sand tidal sand shoals from the Bahamas. From Earth Science World Image Bank. (See Plate 1 for color versions.)

(Figure 1.4). Earth surface processes must also be understood when repairing human damage to Earth's surface environment: e.g., restoration of natural ecosystems; remediation of polluted water and air.

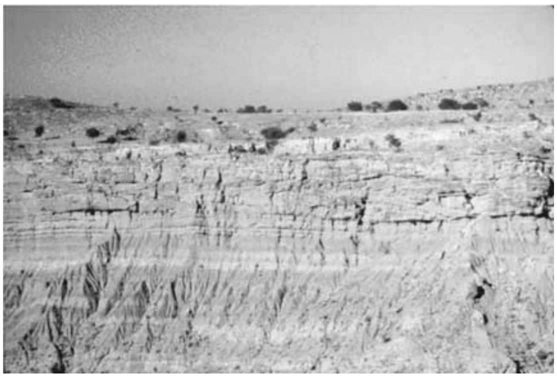

FIGURE 1.2. A large outcrop of sedimentary rocks from the Miocene Siwalik Group, northwest Pakistan. (See Plate 2 for color version.)

Economic resources in sedimentary deposits

Knowledge of sedimentary deposits is essential for the exploration, development, and management of economic resources that they contain: water, oil, and gas in their pore spaces; stone, sand, and gravel for building; clay for pottery and bricks, and as a source of aluminum and iron; limestone for cement; evaporite minerals; coal and lignite; placer minerals such as gold (Figure 1.5).

Rationale and scope of the book

It is clear that Earth surface processes, landforms, and sedimentary deposits are intimately related. They have a fundamental bearing on understanding Earth history; modern engineering, environmental, and public-safety issues; and exploitation and management of economic resources in sedimentary deposits. Geomorphologists, sedimentologists, environmental

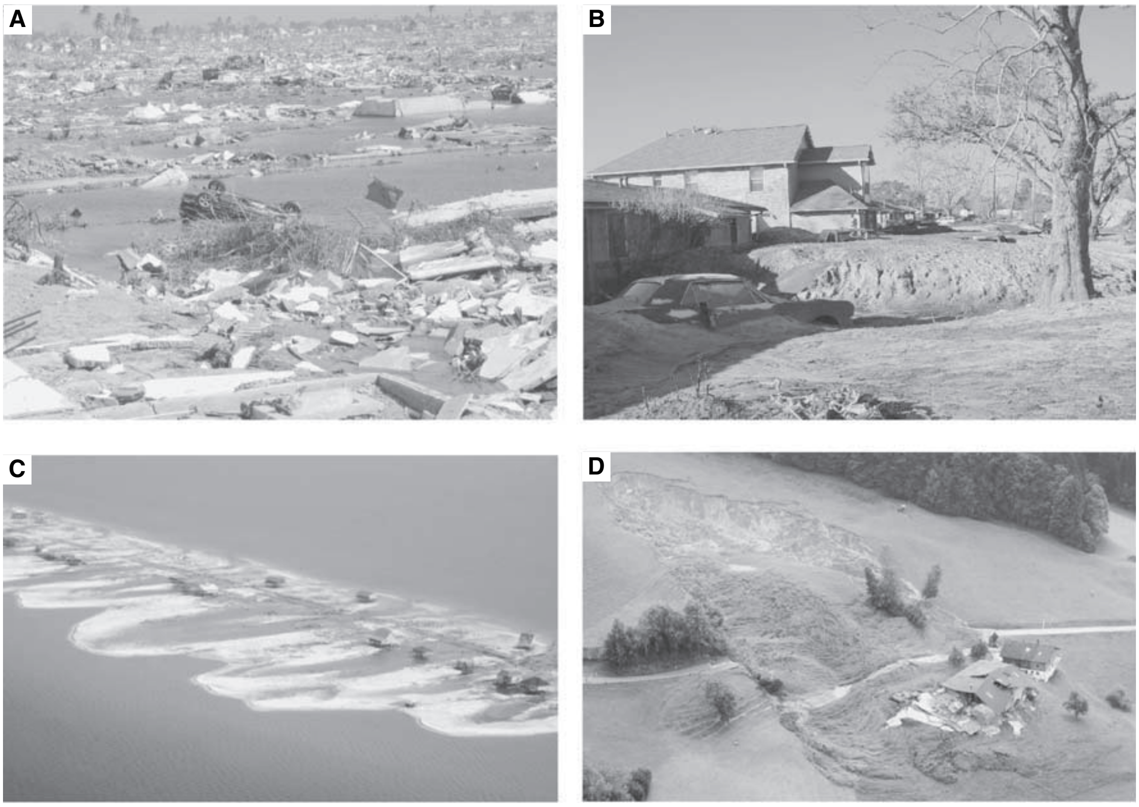

FIGURE 1.3. (A) Tsunami damage in Banda Aceh, Sumatra, 2004. Photo courtesy of Guy Gelfenbaum of the US Geological Survey (http://walrus.wr.usgs.gov/tsunami/sumatra05/). (B) Sand deposits in New Orleans associated with levee breaches during Hurricane Katrina in 2005. Photo courtesy of Suzanne Leclair. (C) Beach erosion, Dauphin Islands, Alabama, following Hurricane Katrina in 2005. Photo courtesy of Robert Young. (D) A slump and landslide, northern Austria. Photo courtesy of Henry Posamentier. (See Plate 3 for color versions.)

FIGURE 1.4. (A), (B) River engineering in the Netherlands: levees and groins. Photos courtesy of Henk Berendsen. (C) The storm surge barrier across the Oosterschelde Estuary, Netherlands. Photo courtesy of Robert Hoeksema. (D) Beach replenishment in Palm Beach County, Florida. Photo from http://www.pbcgov.com/erm/enhancement/nourishment.asp. (See Plate **4** for color versions.)

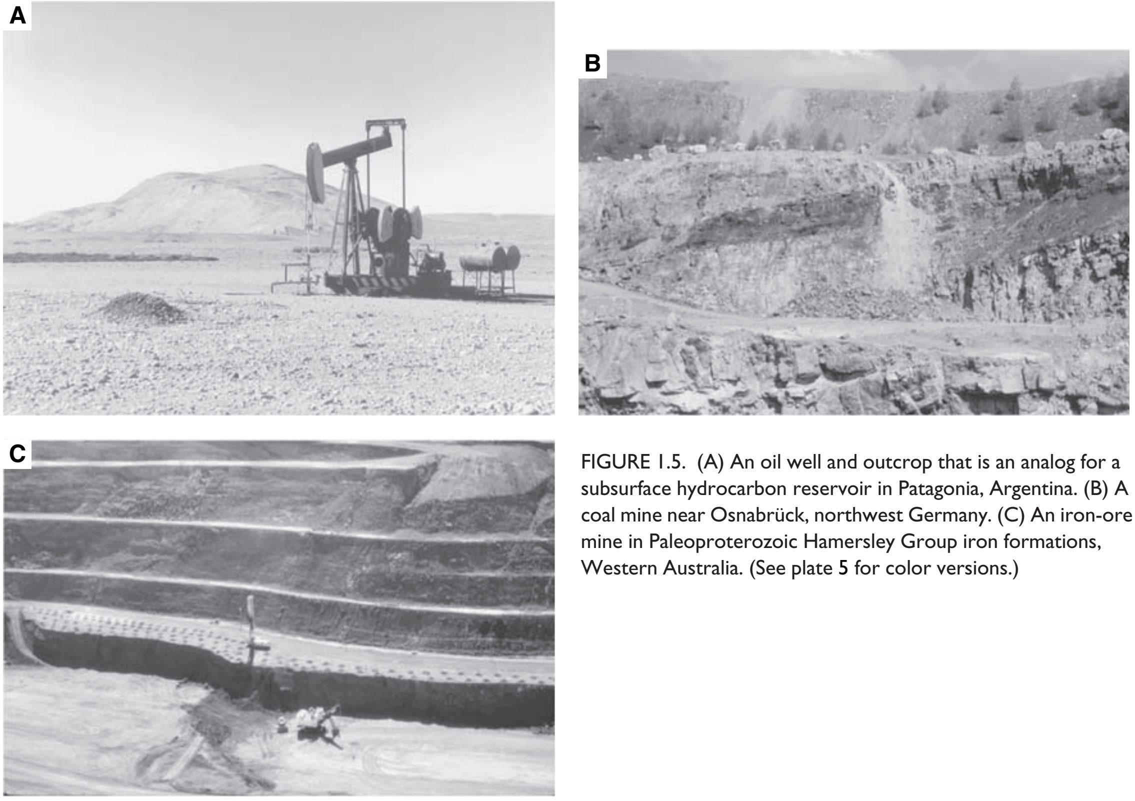

FIGURE 1.5. (A) An oil well and outcrop that is an analog for a subsurface hydrocarbon reservoir in Patagonia, Argentina. (B) A coal mine near Osnabrück, northwest Germany. (C) An iron-ore mine in Paleoproterozoic Hamersley Group iron formations, Western Australia. (See plate **5** for color versions.)

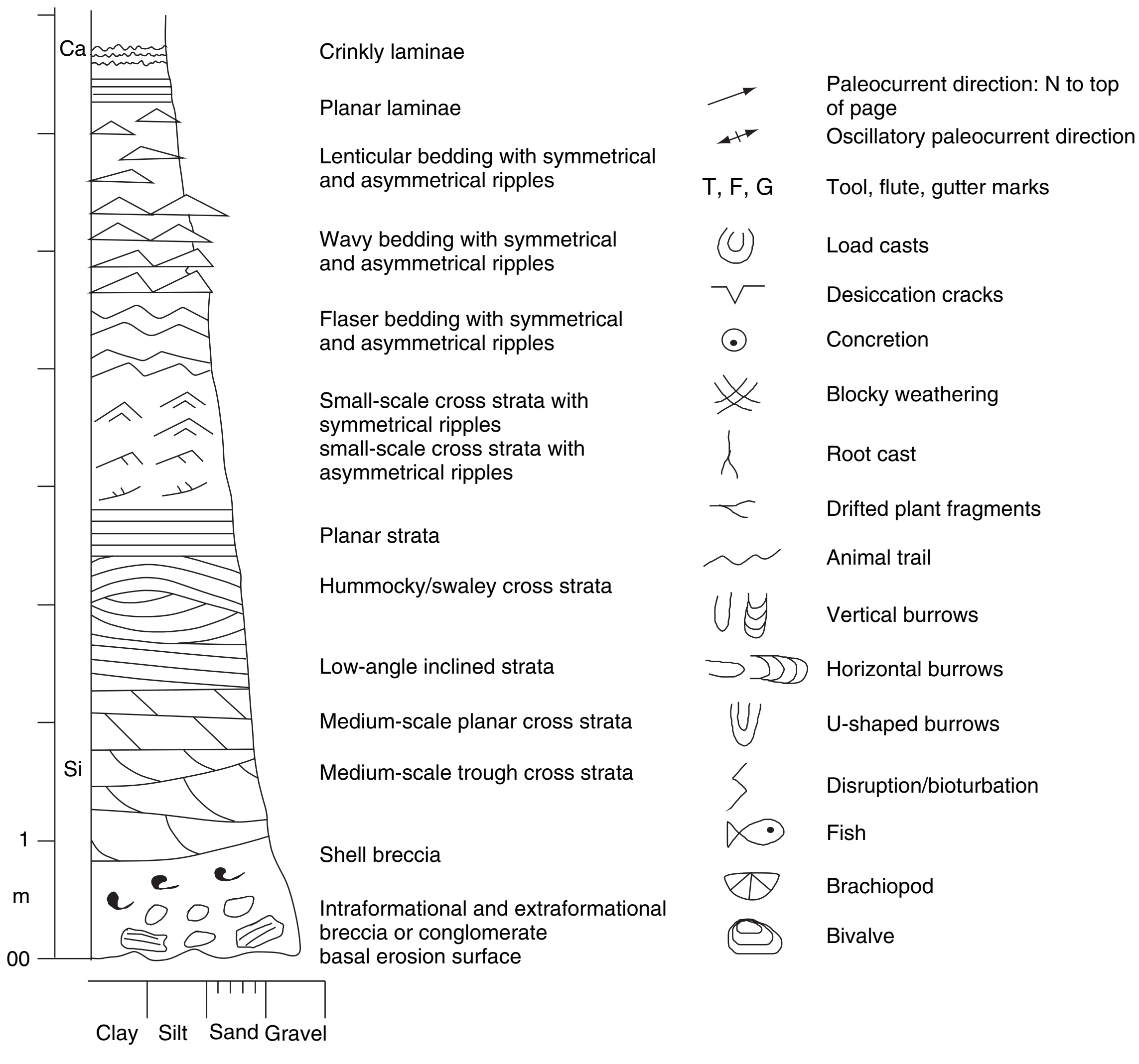

FIGURE 1.6 Typical (recommended) legend used for sedimentological logs. The leftmost column can be used for describing sediment composition (e.g., siliciclastic, calcareous). The grain-size scale is normally subdivided (e.g., very-fine, fine, medium, coarse, very-coarse sand). Additional symbols can be used as necessary. Symbols used should ideally look something like the features they represent.

scientists, and engineers traditionally study different aspects of Earth surface processes, landforms, and sedimentary deposits, commonly in different academic departments of institutions of learning. A more integrated view should enhance our appreciation of these topics. In particular, it is being realized that, in order to understand the nature of sedimentary deposits in subsiding basins, it is necessary to understand the generation of sediment in the source area and the nature of erosion and transport through the drainage network to the place of deposition. These processes are dependent upon tectonism and climate in the uplands and in the depositional basins, which are most likely all interrelated.

This book links Earth surface processes, landforms, and sedimentary deposits in a way that has not been attempted before. The book is divided into six parts. The first, introductory, part includes an overview of the Earth's lithosphere, hydrosphere, atmosphere, and biosphere, and their evolution through time, in order to set the stage for the main part of the book. Part 2 deals with the physical, chemical, and biological processes at and near the Earth's surface that cause the breakdown of rocks (weathering) into sediments (including soils), modify the chemical composition of water and air, form sediments by chemical or biochemical precipitation, and produce characteristic landforms. Part 3 is concerned with the physical processes of fluid flow, sediment transport, erosion, and deposition associated with the movement over the Earth's surface of water, air, ice, and sediment–fluid mixtures. Such movements are typically due to the effects of gravity, wind, volcanic eruptions, and earthquakes. Chemical and biological processes of erosion and deposition are also considered. These different types of processes are commonly associated with distinctive landforms (e.g., ripples, dunes) and types of sedimentary strata (called *lithofacies*, as manifested in stratal thickness, orientation, grain size and shape, and sedimentary structures). Part 4 considers environments of erosion and deposition on the Earth's surface. An *environment* is a part of the Earth's surface where erosion and deposition are proceeding that has a distinctive association of physical, chemical, and biological landforms and processes, and hence sediment deposits (*lithofacies associations*). Examples of environments are rivers on floodplains, glaciated regions, deserts, lakes, coasts, continental shelves, coral reefs, and ocean basins. In some texts, certain processes (e.g., ice flow) are treated together with the environments (e.g., glaciated areas) in which they are generally active. However, we have deliberately not done this, because it is common for several different processes to occur in a given environment (e.g., glaciated environments may include processes of ice flow, river flow, wind, wind waves, and sediment gravity flows). Parts 5 and 6 deal with the largest-scale (in terms of space and time) processes and landforms on the Earth. Part 5 concerns the transformation of loose sediment into sedimentary rock (*diagenesis*) as sedimentary strata are buried beneath the Earth's surface. Part 6 is about the accumulation of large-scale sequences of sedimentary strata in sedimentary basins, and the associated formation and erosion of mountains. These processes are controlled by large-scale tectonics, and by changes in climate and sea level. Thus, the discussion of the various Earth surface processes, associated landforms, and sedimentary deposits in Parts 3–6 progresses from relatively small-scale and short-term to large-scale and long-term. Throughout the book, there is frequent reference to engineering, environmental, and economic issues. An appendix (located on the book's web page) contains information on methods for studying Earth surface processes, landforms, and sediments in the field, in the laboratory, and using theoretical models. Figure 1.6 is a legend for the sedimentological logs which appear throughout the text.

The subject areas of this book are developing and changing rapidly, and the quantity (if not the quality) of published literature in these areas is growing exponentially. The task of critically examining and summarizing this literature and keeping up to date has been challenging, and is a never-ending process. Obviously, most of the content of this book is not based on our own original research. The main reference books that we have used (and are therefore considered important) are listed at the beginning of each chapter, and it will be noticed that we have declined to make subjective comments about the relative merits of these books. Citations throughout the text are kept to a minimum in the interests of flow and clarity. We had to be very selective in choosing the published work that is cited in the list of references. We apologize in advance if we have missed or misrepresented important work of others, and encourage any offended parties to complain to us about this.

The book is designed for all levels of undergraduate students and beginning graduate students with interests in Earth surface processes, physical geography (geomorphology), sedimentology, stratigraphy, Earth history, environmental science, and engineering geology. Modest but realistic background knowledge of mathematics, physics, chemistry, and biology is assumed. There is enough material in this book to support the traditional undergraduate courses in Earth surface processes (geomorphology) and in sedimentology–stratigraphy. We have tended to lean towards more in-depth information rather than less, on the premise that it is easier to skip some information in a book than to look elsewhere for it.

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2 Overview of the Earth

Introduction: spheres of the Earth

This chapter is an overview of the nature of the Earth's lithosphere, atmosphere, hydrosphere, and biosphere, and the interactions among them at the Earth's surface today. The long-term evolution of these "spheres" throughout Earth's history is also discussed briefly. The material in this chapter forms the basis of the more detailed information in the remainder of the book.

The Earth's shape closely approximates an oblate spheroid with a polar radius of 6,357 km and an equatorial radius of 6,378 km. A sphere with the same volume as the Earth has a radius of 6,370 km. The center of the Earth comprises a spherical core with a radius of approximately 3,470 km. Outside the core are several more or less concentric spheres. From inside out, these spheres are the mantle, lithosphere (composed of the uppermost mantle and overlying crust), hydrosphere (mostly the liquid ocean), and gaseous atmosphere (Figure 2.1). In addition, the biosphere is concentrated at the boundaries between the crust, ocean, and atmosphere. The biosphere extends down into the underlying crust for as much as 5 km, and to some as yet unknown depth into the crust beneath the oceans. The biosphere also extends up into the atmosphere. Coincidently, the surface of the Earth discussed in this book corresponds more or less to the distribution of the biosphere. The masses of the various spheres of the Earth are given in Table 2.1.

All of the spheres of the Earth are in motion. Fluid motions in the outer core produce the Earth's magnetic field. Convection cells comprising creeping motions in the mantle are manifest at the Earth's surface most noticeably as volcanoes and earthquakes, but also as the relative motions of a dozen or so rigid, tectonic *plates* (Figure 2.2). The plates extend laterally for hundreds to thousands of kilometers, and are up to 200 km thick. The plates are composed of the crust and upper portions of the mantle that together comprise the lithosphere (Figure 2.1). The velocities of convection currents in the mantle, and lateral velocities of lithospheric plates, are on the order of a few tens of millimeters per year. The atmosphere and hydrosphere are fluid, and spatially variable solar heating of these fluids ultimately produces fluid motions that range in scale from millimeters up to tens of thousands of kilometers. Currents of air (wind) in the atmosphere may have velocities on the order of tens of meters per second, whereas currents and oscillatory motions of liquid water typically range up to meters per second. The more important large-scale circulation patterns of the atmosphere and hydrosphere are outlined briefly below. Motions of the atmosphere and hydrosphere, and how these motions interact with the loose granular material (sediment) at the Earth's surface, are major topics of this book.

The lithosphere, hydrosphere, atmosphere, and biosphere interact physically as they move relative to one another, and interact chemically by exchanging materials that are stored for varying time spans. The most obvious manifestations of these chemical interactions are chemogenic and biochemogenic particles that are precipitated out of the atmosphere and hydrosphere and accumulate as sediment at the surface of the Earth. The hydrosphere, atmosphere, and biosphere are the main arteries of material exchange on the Earth, whereas the lithosphere and hydrosphere act as the main storage regions. The mantle is also important in interchange of materials in the Earth.

The long-term evolutionary histories of the lithosphere, atmosphere, hydrosphere, and biosphere are intimately interlinked as materials are interchanged among the different spheres. Changes in the storage of material among the various spheres have led to changes in the composition of the atmosphere, hydrosphere, and lithosphere throughout Earth's history.

Materials such as fossil fuels may be sequestered in the crust for up to hundreds of millions of years. The lithosphere is subject to recycling as lithospheric plates are subducted back into the mantle. Some of the subducted material may be transferred back into the crust and atmosphere as igneous magmas and associated volcanic gases. Some material may be completely removed from the Earth as gases escape into space.

Much of the material in this chapter is covered in standard introductory geoscience text books such as Grotzinger *et al.* (2007), and Turcotte and Schubert (2002) provide advanced treatment of the lithosphere dynamics. Additional information on the oceans can be found in Chester (2003), Open University (1989), Pernetta (1994), Pinet (2006), Summerhayes and Thorpe (1996), Thurman and Trujilo (2004), and Weaver and Thomson (1987), whereas Hartmann (1994) provides a comprehensive treatment of climatology and atmospheric circulation. The biosphere is covered in Campbell *et al.* (1999); early life on Earth is covered in Schopf (1983) and Bengtson (1999). Earth science textbooks that emphasize interactions among the spheres include Berner and Berner (1996), Ernst (2000), and Kump *et al.* (2004). Stanley (2005) provides a comprehensive history of the lithosphere, atmosphere, hydrosphere, and biosphere.

TABLE 2.1. Masses of the "spheres" of the Earth (Faure, 1991)

	Mass ($\times 10^{20}$ kg)
Core	18,830
Mantle	40,430
Crust	236
Hydrosphere	15
Atmosphere	0.0053
Biosphere	0.00003

The lithosphere

Composition

The core of the Earth probably consists mostly of iron, nickel, and sulfur. The elemental compositions of the mantle, continental crust, and oceanic crust are given in Table 2.2. The upper 660 km of the mantle is mostly composed of the mineral olivine. Various high-pressure polymorphs of olivine with closer packing structures predominate below this level. The crust of the Earth is composed of various aluminosilicate minerals, the most important of which are (1) the plagioclase feldspar solid-solution series ($CaAl_2Si_2O_8 \leftrightarrow NaAlSi_3O_8$); (2) the olivine solid-solution series ($Fe_2SiO_4 \leftrightarrow Mg_2SiO_4$); (3) pyroxene ($(Mg,Fe,Ca)Si_2O_6$); (4) amphibole (hydrous Na, Ca, Fe, Mg aluminosilicates); (5) biotite mica ($K(Mg,Fe)_3(AlSi_3O_{10})(OH)_2$); (6) quartz ($SiO_2$); (7) potassium feldspar ($KAlSi_3O_8$); and (8) muscovite mica ($KAl_2(AlSi_3O_{10})(OH)_2$). Continental crust and oceanic crust have slightly different elemental and mineralogical compositions (Table 2.2). Approximately 95% of the mass of the continental crust is composed of granitic igneous and metamorphic rocks, mostly made up of Na-rich plagioclase, pyroxene, amphibole, quartz, biotite, muscovite, and K-feldspar. The ocean crust is

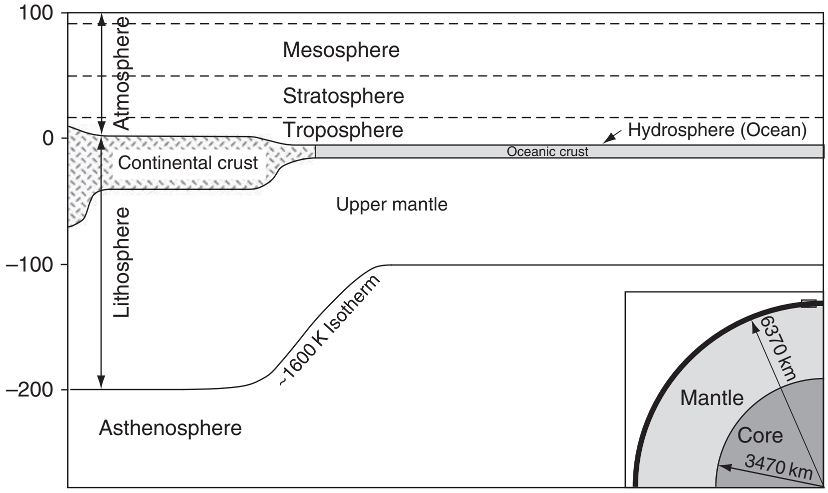

FIGURE 2.1. The spheres of the Earth. Inset on the lower right is a section of the Earth showing the core and mantle. The outer rind comprises the lithosphere, hydrosphere, and atmosphere, shown in the main panel.

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dominantly composed of gabbros and basalts, igneous rocks mostly made up of Ca-rich plagioclase feldspars and pyroxenes.

TABLE 2.2. Elemental composition of Earth's rock shells in percentage by mass (Faure, 1991)

	Mantle	Continental crust	Ocean crust
O	44.3	45.5	44.1
Si	21.5	26.8	23.1
Al	1.9	8.4	8.1
Fe	6.3	7.1	7.8
Ca	2.2	5.3	8.9
Mg	23.0	3.2	4.5
Na	0.4	2.3	1.0
K	0.1	0.9	0.3
Ti	0.1	0.5	0.8
P	0.0	0.1	0.08
Everything else	<0.2	<0.1	<1.3

The outermost crustal rocks are generally covered by loose, granular material (sediment) that originates from chemical and physical breakdown of pre-existing rocks. Sediments are unconsolidated, whereas sedimentary rocks are their consolidated counterparts. Sediments and sedimentary rocks comprise only approximately 5% of the mass of the crust, but cover approximately 75% of the land surface area and perhaps 95% of the sea floor. Sedimentary rocks up to 15 km thick accumulate in local depressions called sedimentary basins (see the section on plate tectonics below). However, sediments and sedimentary rocks also occur as a widespread veneer (less than 1 km thick) over many continental interiors and oceanic basin plains. The proportions of the various kinds of common sedimentary rocks on the continents are given in Table 2.3.

Physical properties

Important physical properties of the lithosphere include density, pressure, temperature, and rheological

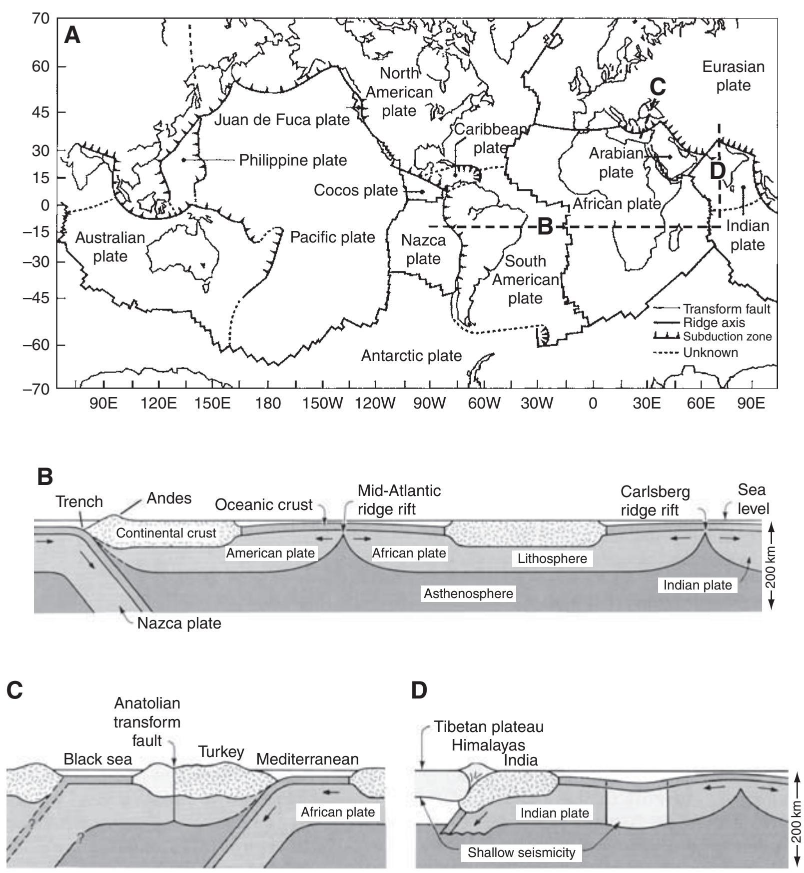

FIGURE 2.2. Elements of plate tectonics. (A) The distribution of major tectonic plates of the lithosphere. Spreading ridges (accretionary boundaries), subduction zones (convergent boundaries), and transform boundaries are indicated. Modified from Turcotte and Schubert (2002). The positions of schematic cross sections through the lithospheric plates and underlying asthenosphere (B), (C), and (D) are indicated. The cross sections emphasize the plate movements. Modified from Press and Siever (1978).