1 Introduction to Geomorphology

Richard Marston and Randall Schaetzl

Geomorphology is the study of **landforms** – their evolution, shape (morphology), and composition. The word comes from the Greek (*geo*, Earth, *morphos*, referring to form, and *ology*, a branch of knowledge). Landforms come in all types, shapes, sizes, compositions, and ages. There is a landform for everyone, and no two are exactly alike. Understanding Earth's landforms – how they are formed, altered, destroyed, and/or buried by various geologic processes – is at the core of geomorphology. This textbook will teach you the language and concepts that will help you to understand the workings of many of Earth's physical systems. Our goal is to equip you with the vocabulary and toolkit for understanding why Earth's physical landscapes look the way they do. This knowledge will help us all to better manage our fragile natural resources.

The fundamental building blocks of geomorphology are landforms and the sediments that comprised them. Decades of study have taught us that Earth's landforms have formed through various types of surficial and geologic processes, driven by the actions of water, wind, ice, biota, and gravity. These "drivers," and the landforms that result from them, are constantly changing, always evolving. Studying the evolutionary stories of Earth's landscapes are at the very heart of the discipline of geomorphology.

At the core of geomorphology are the depositional and **tectonic processes** that are constantly forming and raising up the land surface, balanced out by the erosional processes that wear it down. The landforms geomorphologists study are caught in the middle of this endless recycling struggle, existing somewhere in between their initial formation and destruction. It is this very cycle that explains why the summit of Mt. Everest is composed of uplifted limestone that had initially formed at the bottom of an ancient ocean, and why this limestone has been glacially carved into jagged peaks. Change at that scale is awesome in the truest sense of the word.

Asking questions about landforms is central to the mindset of every geomorphologist. How did this landform form? Why in this location, formed in this sediment, and in this particular way? Where did the sediment come from and how did it get here? How rapidly did the landform develop, and when did this all take place? Did its formation occur all at once or in a series of depositional and/or erosional events? What did this area look like during the time of formation? What was the climate, and how has it changed? How has the landform been modified since its initial formation? How is it connected to a larger regional story, or to the broader landscape? Answering essential questions like these is what drives, and what fulfills, those who study geomorphology.

Landforms are intricately interconnected with almost every aspect of our daily lives, and as a result, geomorphology is relevant to everyone, everywhere, and at all times. We use sediments from landforms to build roads, to make concrete and pottery, and to construct earthen dams. We ski down glaciated mountains, sunbathe on broad ocean beaches, play golf on glacial moraines, fish in lazy rivers, and explore deep caves. And of course, the soils that feed us have developed in sediments with rich geomorphic histories. Geomorphology lies at the heart of every soil map, and soils sustain our lives. We rely on our knowledge of geomorphology and geology to keep us safe from hazards such as landslides, earthquakes, tsunamis, cave collapses, volcanic eruptions, dust storms, and floods. The water that sustains us is found through our knowledge of the saturated subsurface that we so often take for granted. Most of our drinking water comes from wells set within rock and sediment, or pulled from rivers and lakes that have developed in concert with the local geomorphology. And so, the better we understand the surface and the sediments below it, the better we will be able to manage our hydrological resources. Geomorphology even has extraterrestrial implications! Geomorphic knowledge developed here on Earth helps planetary geologists interpret the geologic past of the many planets and moons within our galaxy. In every part of our everyday lives, and even beyond Earth itself, geomorphology is present, and it is essential.

Landscapes may seem static and unchanging at first glance. But because geomorphologists view landscape development across both short and long timescales, they can see and interpret how landscapes change. Short-term changes are easy to see. In a matter of days, a flood inundates and deposits sediment across large areas. A windstorm uproots thousands of trees, disturbing soils and over the next decade, facilitating a downslope cascade of sediment. Sand dunes, stable for thousands of years, suddenly activate and move swiftly across the landscape, even burying homes and villages. Rockfalls catastrophically wreak havoc with

Figure 1.0 Moraine Lake, in Banff National Park, Alberta Canada, is a classic example of a lake formed in glaciated mountains. Source: Vicki Jauron / Getty Images.

everything below. And then, over longer timescales, landscapes are also constantly changing. Even mountains wear away, their eroded remains washing into the ocean basins. These systems are all unquestionably geomorphology in action – whether we can actually watch it all happen, or not. Geomorphologists work across this range of timescales, expressly *because* landforms change at varying rates.

Geomorphology is both a basic and an applied science. It is a basic science in that landforms and landscapes deserve scientific attention for their own sake. By engaging in geomorphic study, we can improve our understanding of Earth and our place on it. The sheer beauty and wonder of the physical landscape draws many to it, whether in national or state parks, government-managed recreation areas, or private land that we use simply for getaways. Unquestionably, landforms have inherent value simply in their beauty. But geomorphology is also an applied science in that it helps us to understand human impacts on landforms and landscapes, and the impact of landforms on society. Geomorphologists are instrumental in helping to locate important geological resources such as **rock**, **sand**, gravel, **clay**, and **peat**. For example, all societies need sand and gravel, otherwise known as **aggregate**, for their economies to efficiently function. The average American uses, indirectly and directly, five *tons* of aggregate each year. Aggregate is needed for roads, sidewalks, building materials, and myriad other applications! No one is better suited to finding aggregate than a geomorphologist. As mentioned above, geomorphology is also vital to finding and properly managing our water resources – wells, surface water, and wastewater. But perhaps nowhere is geomorphology more applied than in its links to natural hazards (**Fig. 1.1**). Geomorphologists help societal managers keep us safe by studying the hazards (and resources) formed by geomorphic processes, for example, coastal erosion, shifting river channels, cave collapses, landslides, massive floods, sandstorms and dust storms, thawing permafrost, among many others. Geomorphology is a part of our everyday lives – far more than most people imagine.

Recently, humans have become a driving geomorphic force. Many geologists consider today's world to be so uniquely modified (both biologically and physically) by human-caused agents that it deserves its own distinction in the geologic timescale – the **Anthropocene** (see Chapter 4). Although its inclusion as an official segment of geologic time is still being debated, the name refers to the current geologic epoch in which the effects of human activity have been so dramatic that they are overwhelming many "natural" phenomena. Ravaging the planet for resources, draining aquifers, leveling rainforests, driving thousands of species into extinction, and causing unprecedented desertification and soil erosion, not to mention the human-caused changes to the atmosphere that are dramatically changing our climate – there is no doubt that humans are changing the planet in ways and at rates that have never been seen before. Permafrost is thawing, ocean levels are rising, and islands are being flooded, even as large-magnitude weather events are becoming more common. Few specialists are as prepared as geomorphologists are, to assess the impacts of climate change on human societies and systems.

The long history of geomorphology is rich in adventure and discovery of the great outdoors. Geomorphology's blend of lab science and field studies continues to attract scholars even today. The community of geomorphologists is growing ever more diverse and international, working with an increasing variety of field, lab, and analytical tools. Yet, much remains to be done, as our understanding of many landforms and regions is still in its infancy. Armed with the plethora of new, detailed topographic data that are emerging today, and with rapidly increasing options for dating landforms and sediments, the geomorphic community now has

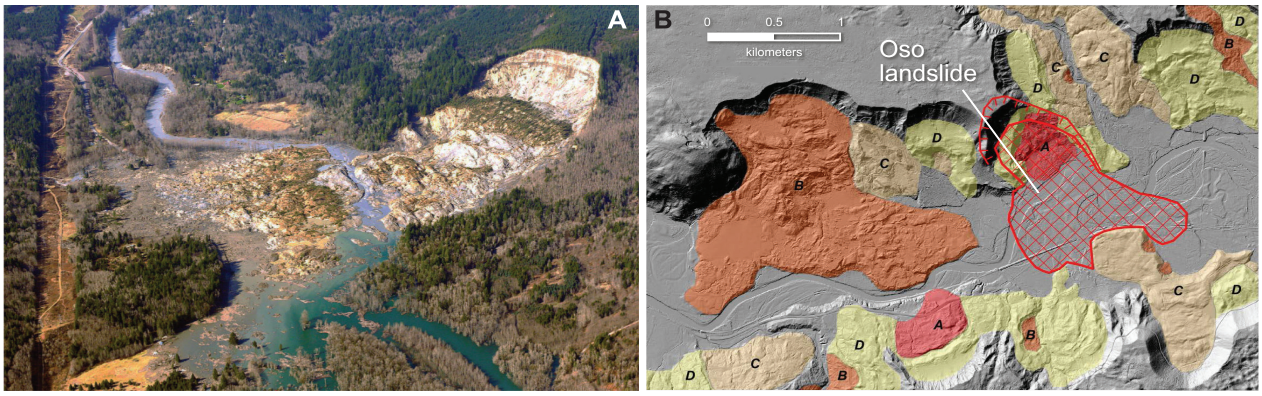

Figure 1.1 The Oso, Washington (USA) landslide is an example of geomorphology in action. **A.** This massive March 22, 2014 landslide resulted in the loss of 47 lives and 49 homes, completely burying a local neighborhood known as "Steelhead Haven." Local residents described the event as a "fast-moving wall of mud." The event was triggered by 200% of normal rainfall over the previous few weeks. **B.** Scientists at the US Geological Survey had predicted that this area could expect to see such events, based on their geomorphic studies of the area. Topographic information for this region clearly shows areas that were affected by similar landslides in the past. Colored areas in this figure indicate older landslide deposits, from youngest (A) to oldest (D). Improved knowledge of geology and geomorphology could have saved many lives. Source: Photo and graphic from the US Geological Survey; in public domain.

the ability to understand and help manage Earth's surface better than ever before. This book might be just the start of your geomorphic journey.

1.1 LANDFORMS AND LANDSCAPES

Landforms are natural features, formed in sediment or rock, that can be observed, described, mapped, and classified. Most landforms possess three fundamental characteristics. They (1) have a distinctive shape and dimensions, (2) occur on a typical position in the landscape, and (3) have formed from distinctive and characteristic materials. Due to their critical importance to the field of geomorphology, landforms are the focus of this book.

Although *Essentials of Geomorphology* contains discussions of hundreds of different types of landforms, for now let's examine just one – an **alluvial fan** (**Fig. 1.2**). As the name implies, the landform is fan shaped. Alluvial fans are typically positioned where steep-flowing, mountain streams deposit sediment from uplands onto the plain below. When the stream emerges from its confined mountain canyon, the channel widens and much of the water infiltrates into the ground, such that the stream loses water and power, leading to sediment deposition and the formation of the fan. Most alluvial fans have lengths of 2–8 km, but can range from a few hundred meters to tens of kilometers long. They are steeper near the apex (where the stream emerges from the mountain canyon), and flatten farther out, resulting in a slightly concave-upward shape from their apex to their distal (far) end. Geomorphologists refer to this as a **longitudinal profile**. Stream channels on the fan shift location frequently, often with each flow event, slowly building up the fan surface over time. Because alluvial fans become larger over time, it is difficult to assign a single age to any particular fan. Rather, we attempt to date the various segments of the fan and in so doing, determine how dynamic its formation has been.

Over time, parts of the fan may be destroyed by river incision, provided the water–sediment mix tips in the favor of more water and less sediment. Streams that traverse the fan may then pick up sediment by cutting into the fan. Other floods may transport large amounts of sediment *onto* the fan, causing it to enlarge and thicken. Geomorphologists have ways of explaining and predicting these various outcomes.

Figure 1.2 An alluvial fan in Death Valley National Park, California, USA. Source: R. Dorn.

Alluvial fans are common on desert landscapes, where they can be a vital source of **groundwater**, which is one reason that agriculture, for example, citrus groves in southern California, have encroached onto so many fans. Many of the western suburbs of Las Vegas, Nevada, and the cities of the San Gabriel Valley in southern California (USA) are built on the outer margins of alluvial fans. However, the same flash floods and debris flows that formed alluvial fans pose potential future hazards for these urban areas. This example points out that the better we understand landforms, the better we can manage land use on them.

An alluvial fan is a landform. **Landscapes** are organized assemblages of genetically interconnected and interrelated landforms, like alluvial fans. To refer back to our example (**Fig. 1.2**), an alluvial fan is but one landform in a desert landscape that might be comprised of a variety of interconnected landforms such as mountain ranges, fans, sand dunes, and desert basins (**Fig. 1.3**). Although each of these landforms has a different geologic history, they are all linked via the processes that have formed them. Water flowing out of (and forming deep valleys in) the mountains helps to form the alluvial fans, which grade into other landforms such as the flat, wet, and salty lake plains at their distal margins (see Chapter 10).

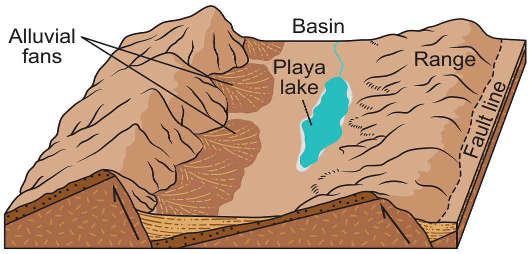

Figure 1.3 Alluvial fans are but one landform in an arid region landscape.

1.1.1 Categorizing Landforms

Landforms come in all shapes and sizes. The largest ones can extend across large regions of Earth's surface, such as mountain ranges or island arcs. These features tend to be formed mainly by **endogenic** processes driven by sources of energy within the Earth, particularly heat left over from when the planet initially formed, and from the decay of radioactive elements. Examples of endogenic processes include crustal uplift, faulting, and deformation, and volcanism. Endogenic processes often are associated with **tectonism**, which refers to deformation of Earth's lithosphere, or crust (**Fig. 1.4A**). These types of landforms also tend to form over long periods of time, or temporal scales (**Fig. 1.4B**) – often millions of years. Local-scale landforms, which form quickly – like ripples in a sand dune – have short temporal scales, on the order of a few hours.

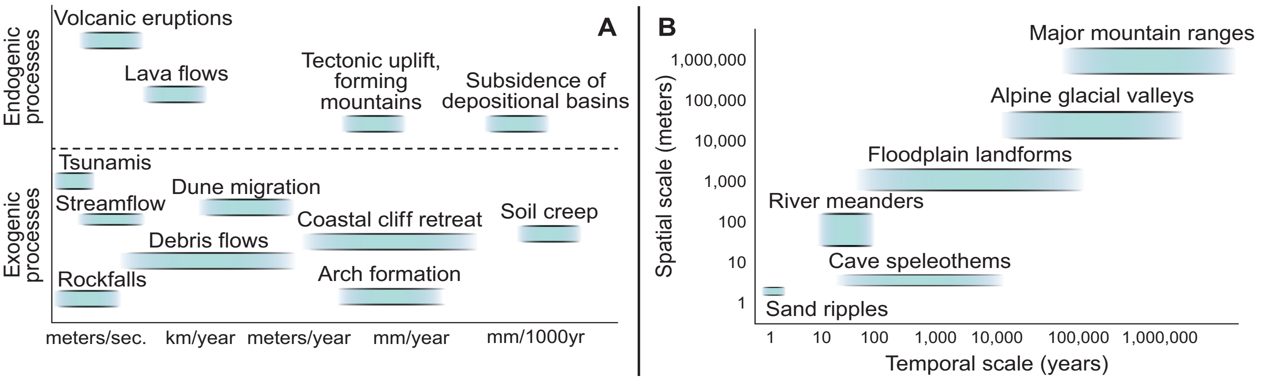

Figure 1.4 A selection of landforms and the timescales over which they may form. **A.** Landforms owe their origins to processes that are along a continuum of forces – from endogenic (from within the crust) to exogenic (at or above the land surface). These forces operate across a wide variety of temporal scales, from the very slow to the extremely rapid. **B.** Landforms vary widely in size, as do the timescales over which they form, as the examples here show. Source: Adapted from *Landscapes and Geomorphology: A Very Short Introduction* by Andrew Goudie and Heather Viles (2010). Reproduced with permission of Oxford University Press through PLSclear.

Landforms are usually shaped by erosion and deposition. They rely on processes driven (ultimately) by solar energy and/or on gravity – think of heavy rain, landslides, flowing **glaciers**, and the frozen/thawing processes of today's Arctic. Collectively these are termed **exogenic** processes because they rely on sources of energy that do not originate within the Earth.

Landforms can also be classified along a continuum ranging from fully *erosional* features, such as a river valley or a glacial cirque, to fully *depositional* features, such as a glacial moraine or a sand dune. Other types of categorizations also exist (**Table 1.1**). Most landforms have a hybrid history of erosion and deposition, which often vary in strength over time. Geomorphic processes also vary in magnitude and frequency. Frequent events occur often, but are usually small in impact, whereas large events can produce substantial change, but occur rarely. On the other hand, moderate events often have the right combination of magnitude and frequency to strongly influence the shape of steady-state landforms.

1.2 DRIVING FORCES, THE RESISTING FRAMEWORK, AND TIME

Landforms result from the interplay, over time, of the **resisting framework** and various **driving forces**. The resisting framework includes mainly (1) rock type (principally, their hardness and resistance to **weathering** and **erosion**), (2) stratigraphy (the layered sequencing of the various rock types), (3) the underlying geologic structure (the geometric arrangement of rock layers, as affected by uplift/subsidence, folding and faulting, intrusion, and emplacement), and (4) biota – the ability of plants and animals to impact erosion rates (**Figs. 1.5**, **1.6**, **1.7**). Driving forces act on these rocks and sediments to create landforms. They are a mix, or balance, of endogenic and exogenic processes, as well as (possibly) forces that originate outside Earth's system (**extraterrestrial processes** such as meteorite and asteroid impacts). Driving forces can either build up (**diastrophism**) or tear down (**denudation**) the landscape. It is the interplay

Table 1.1 End members of some general landform classifications

Classification	Explanation
Depositional (aggradational) vs erosional	Formed by deposition of sediment (depositional) vs those landforms formed by erosion of preexisting sediment or rock (erosional)
Subaerial vs subaqueous	Occurring on dry land (subaerial) vs those landforms occurring underwater (subaqueous)
Stable vs unstable	Exhibiting little change over time due to erosion (stable) vs those landforms that are actively eroding or becoming buried by sediment (unstable)
Bedrock vs unconsolidated	Formed on bedrock vs those landforms that are developed on soil or other loose (unconsolidated) sediment
Relict vs present-day	Formed in the past and have been little-changed since vs those that are currently forming due to erosion or deposition (timescale dependent)

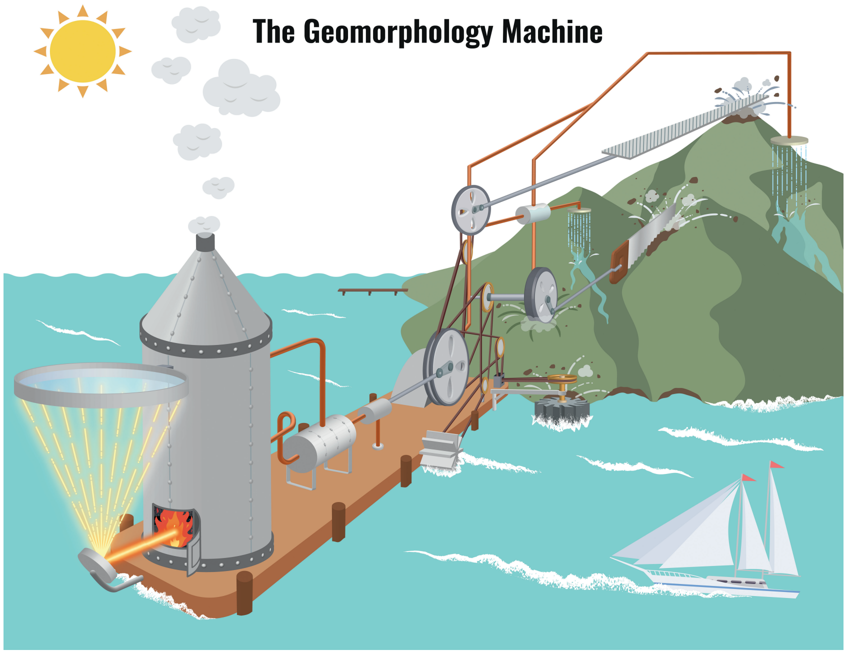

Figure 1.5 The geomorphology we see today represents the long-term actions and balance between the resisting framework and the driving forces, as conceptualized here by the "geomorphology machine," first drawn by geomorphologist Arthur Bloom (1969). The energy for the machine is mainly exogenic – coming from the Sun. The Sun's energy powers the hydrological cycle, which then provides the energy for weather (pressure differences, winds, storms, etc.), thereby forming waves and currents, as well as precipitation. Gravity is also important as an energy source, pulling water, ice, and earth material downward. In this figure, the land represents the resisting framework, whereas the remaining parts of the "machine" are the driving forces that act to wear it down. The driving forces (the geomorphic agents of gravity, water, ice, wind, waves, and currents) abrade, excavate, incise, and then transport any eroded materials from the land to the ocean basins. Source: After Bloom (1969).

Figure 1.6 Illustrations of the role of underlying geology on landform development. **A.** The interesting landforms ("Goblins") in this landscape at Goblin Valley State Park in Utah, USA, are the result of differential erosion. Erosion is more pronounced, and goblin necks are thinner, on the softer rock layers (see Chapter 8). Source: R. Schaetzl. **B.** The Grand Canyon of the Colorado River is an excellent example of how rock structure and stratigraphy, coupled with rock resistance, influence landform development. Some rock layers (limestone and sandstone) form cliffs and spires, whereas the weaker shale beds erode to form broad, flat benches (see Chapter 8). Source: R. Schaetzl. **C.** Rocks in this broad valley, near Vercors, France, have been folded downward into a geologic structure called a **syncline** (see Chapter 9), illustrating the effect of geologic structure on landform development. Source: R. Marston.

of these two opposing suites of processes that create the landforms we see today. Part of a geomorphologist's role is to better understand how this interplay functions, and the rates at which these processes operate.

Although we often cannot see their evolution in real time, landforms are not static and unchanging features. They continually change over time, in response to the interplay between the resisting framework and the various driving

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Figure 1.7 The Chaco River near Farmington, New Mexico, USA, illustrates the interplay between the endogenic forces that operate below the crust and the exogenic forces that operate on and above the surface. The river (the exogenic force) is cutting its valley down into and through the small mountain range, which owes its existence to geologic uplift (an endogenic force). Source: L. Maher.

forces. Most landforms respond very slowly to long-term processes of erosion, which in turn are driven and moderated by climate and vegetation. On the other hand, landforms can also change seemingly overnight in response to disturbances, many of which occur suddenly, like wildfires, but also human-caused activities such as dam construction, urbanization, and coastal development.

The international team of geomorphologists who have collaborated to write this book invite you to explore the world of geomorphology with us. Landforms are everywhere, and never before have geomorphologists had such a wide array of techniques to help us understand them. And of course, every day we have a richer array of literature to assist us in this task. With regard to our knowledge base, we still stand on the shoulders of giants in the field, and every day the pioneering work they have done becomes, in hindsight, more impressive. Together, we can do even more.

REVIEW QUESTIONS

1.1 What is geomorphology and what are the main questions that geomorphologists try to answer?

1.2 How do geomorphologists define the term "landscape"?

1.3 Provide an example of a landform that develops over a short timescale and one that develops over a longer timescale.

1.4 What are the basic characteristics of landforms? As an example, list the characteristics of an alluvial fan.

1.5 Besides time, what are the two other factors that influence the formation of landforms?

1.6 Define exogenic and endogenic factors. How do these factors fit within the scope of geomorphology?

1.7 How do landforms create opportunities and constraints for human activities?

FURTHER READING

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ANOTHER VIEW OF THE GRAND CAÑON.

2 History and Foundations of Geomorphology

Randall Schaetzl and Bruce Rhoads

As defined in Chapter 1, geomorphology is the study of landforms – plain and simple. Whether they are formed on **bedrock** or on loose sediment, by erosion or deposition of sediment, and whatever their age, landforms are the building blocks of Earth's physical landscapes. In essence, *landscapes* are organized and interconnected *assemblages* of landforms. These interconnections may be **temporal**, **genetic**, or **spatial**. With regard to temporal connections, some landforms on a landscape may have all formed at roughly the same time. They may share a similar origin (genetic connections). On many landscapes, however, the landforms may have formed at different times and in different ways. Because geomorphic processes operate over all parts of the landscape, spatial connectivity between the various parts of these landscapes is common – or even expected! Consider the example where the upper part of a hillslope – formed mainly by erosion – merges seamlessly with the lower part of the same hillslope formed in the sediment transported off it (**Fig. 2.1**). The upper and lower parts of this hillslope are connected spatially. Connections like the one in this example are almost always present in landscapes, and geomorphologists strive to better understand them.

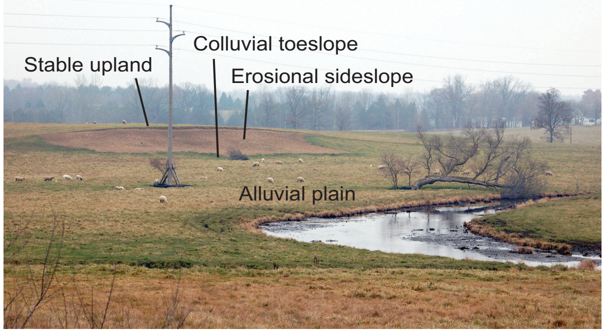

Figure 2.1 Even this low-relief landscape in southern Michigan exhibits interconnectivity among slopes, sediment, and landforms. Source: R. Schaetzl.

The purpose of this chapter is to document and illustrate the basic characteristics of geomorphology as a field of science. Because geomorphology has a colorful history, we also explore some important aspects of how modern geomorphology evolved from its earliest roots. Who first began to think about and explore the geomorphology of landscapes, and what were their contributions? How has the science evolved since then, and what of the future?

Because so many landscapes have been modified by human actions, it is essential that geomorphology also account for anthropogenic impacts. And so, lastly, we will strive to document the importance and utility of the field in the modern world. What can geomorphology contribute to society, and what has it already taught us about the varied ways that surficial processes interact with human activity? Let's begin our brief overview of the field of geomorphology.

2.1 THE SCIENCE OF GEOMORPHOLOGY

Earth's physical landscapes are dynamic and always changing. Geomorphic processes are constantly at work to mold and reshape the land surface. Geomorphologists strive to understand how these processes operate and interact to form landscapes, both today and in the past.

A fundamental principle of geomorphology is that landscapes and landforms are formed by movements of mass. Transfer of mass (sediment) is, in turn, performed by a suite of surficial processes. Often, that movement/transfer is directed downhill, under the influence of gravity, toward a river, a lowland, or a water body. Nonetheless, some processes can move sediment to higher elevations, for example, volcanism, tectonics, or wind. Humans are also capable of moving sediment against gravity, particularly through the use of machinery.

Landscapes are the result of processes that deposit sediment on them or remove sediment from them, coupled with processes that lift up the crust or move it downward. Many of the former (erosional and depositional processes) are driven by flowing water, waves and currents, wind, and/or glaciers. Processes driven by forces within the Earth, such as tectonism, volcanism, and isostasy, are important because they create vertical movements of the land surface. The overall lowering and flattening of a landscape is called **denudation**. Other processes may add **relief** (the elevation difference between high and low points on a landscape). The intricate balance (or lack of balance) between uplift,

Figure 2.0 This nineteenth-century engraving depicts the Grand Canyon, in the southwestern United States, as early geologists saw it. Source: duncan1890 / Getty Images.

additions and removals of mass, and denudation is often a focus of geomorphic study.

Rates of geomorphic change vary widely. Some processes that shape landscapes occur quickly and dramatically, such as landslides, volcanic eruptions, or floods. Many geomorphic processes, though, operate so slowly that changes in landforms are not readily visible across human lifetimes.

To better understand how different surficial processes interact to form landscapes, geomorphologists often link field observations of processes with theoretical models. By doing so, they can better understand how complex interactions among processes change landforms across different scales of space and time. As we shall see below, geomorphic modeling has been around almost since the inception of the field.

Geomorphology is also an applied science, in that it can help (1) identify important resources such as groundwater, surface water, sand, gravel, rock, metals, and clay, and (2) determine how various types of human activities may disrupt geomorphic processes that sustain environmental systems. Geomorphologists are also adept at identifying when and where natural hazards may occur and at helping to mitigate the effects of these hazards.

Soils form the skin of many landforms, and so all manner of soil-based applications rely on geomorphic knowledge and data. The old adage that "Everything we have is either mined or grown" is not only true (think about it!), but also, most of the "mining" and "growing" done on Earth is guided by geomorphology. We mine gravel from glacial and fluvial sediments, pump water from aquifers, grow cotton on coastal plain sediments, and use Earth's deltas to bring foodstuffs of all kinds to market. Geomorphology is the backbone of so much of what we do and have. It is intimately intertwined with our lives.

2.2 AN HISTORICAL VIEW OF THE FIELD OF GEOMORPHOLOGY

Before we discuss the tools and the methods of contemporary geomorphologists, let's examine how the science got to where it is today. Humankind has always been interested in the varied forms of Earth's landscapes. Perhaps it is for this reason that the roots of geomorphology can be found in the science of geology. Geology began to develop in its modern form with the work of Scottish naturalist James Hutton (1726–1797), often called the Father of Geology. Hutton first proposed that the Earth is not static, but changes over time. He also thought that the geologic processes of the past were largely the same processes that we can observe today – a radical proposal at a time when the Biblical flood was thought to have formed many of Earth's landscapes.

Hutton's ideas have since been proven to be both accurate and useful. Thus, we know today that evidence of past processes is preserved in geologic materials, like rocks. As a result, we can use our understanding of modern processes to interpret what caused past changes in the landscape, and estimate how rapidly these changes may have taken place. Because many modern geologic processes operate quite slowly compared to human lifespans, the time required for geologic change can be very long – often many millions of years.

Hutton's way of thinking about the Earth provided the basis for what has become known as the **principle of uniformitarianism**, which, simply stated, is that "the present is the key to the past." Prior to Hutton's work, many people had ascribed the features of Earth's surface to extraordinary occurrences in the past, and which defy modern understanding. These theories, grouped under the term **catastrophism**, asserted that short-lived, violent events of the past were mainly responsible for shaping large parts of the land surface and the rocks below. Proponents of catastrophism attributed Earth's features to divine creation, to the great Biblical flood, or to catastrophes like earthquakes and volcanoes. Alternatively, advocates of uniformitarianism held that surficial processes in the past resembled those that can be observed today. Uniformitarianism helped scientists of the day explain geologic features by studying contemporary processes and understanding their long-term consequences, rather than by invoking some past catastrophe.

Hutton's views inspired his close friend John Playfair (1747–1819) to produce what has become known as **Playfair's Law** – a statement that captures nicely the integrated relations between erosion by rivers and the form of their valleys. In essence, Playfair's Law states that each stream cuts its own valley, and that stream valleys are proportional in size to the streams that cut them.

Hutton's ideas represented a major sea change for the field of geology and laid the foundation for the development of the science of geomorphology. Because he studied rocks near the surface and related their structure to the form of landscapes, his work was very much like that of a geomorphologist. Earth scientists, including geomorphologists, began to extrapolate into the past, to infer the origins of Earth's features, and project the development of these features forward in time – assuming that similar processes will continue to operate in the future.

In the second half of the nineteenth century, several major expeditions were conducted by the United States to explore newly acquired lands in the American West. In 1869, John Wesley Powell (1834–1902) and his fellow explorers bravely floated down the Grand Canyon of the Colorado River, not knowing what lay ahead. During the journey, Powell was struck by how the river had incised into the surrounding rock and by the amount of sediment it carried. Considering the processes associated with this type of erosion, Powell deduced that rivers cannot erode below some lower limit. Thus, he paved the way for the concept of **base level** – the level (elevation) below which a land surface cannot be eroded. Sea level is the ultimate base level, but each river has its own local base level – the elevation at which it enters the next larger trunk stream, or lake.

Other geologists also began to add to the body of geomorphic theory. Clarence Dutton (1841–1912), developed important ideas about **isostasy** – the vertical adjustments

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of the land surface in response to changes in the loading of mass onto it (by water, glacial ice, or sediment). Grove Karl Gilbert (1843–1918), who explored the Henry Mountains in Utah, introduced the notion of a **graded river** – the idea that rivers undergo adjustments in form to efficiently transport the amount of sediment supplied to them by the surrounding watershed. Gilbert's ideas combined geological concepts with those from physics – a development that has led to him being called the Father of Modern Geomorphology. Later in his career, Gilbert also introduced rigorous experimental methods to geomorphology, by using flumes to study the movement of sediment in rivers. In sum, his contributions added to the theoretical advances made by Powell.

Work by Powell, Dutton, Gilbert, and several others not mentioned here set the stage for the scientific exploration and analysis of landform genesis. The term geomorphology was formally introduced immediately prior to the turn of the twentieth century to describe the emerging science of landform study. A theme that became prominent at this time is that landforms may evolve sequentially and predictably over time. This theme would be expanded on by William Morris Davis, who developed it into the overarching geomorphic theory of the early twentieth century.

2.2.1 William Morris Davis' Cycle of Erosion

Any discussion of the history of geomorphic theory must include the **cycle of erosion**, developed and advocated by William Morris Davis, a geologist and geographer at Harvard (**Fig. 2.2**). Davis' model is a simple, yet elegant, visualization of how landscapes evolve. The cycle of erosion, often called the geographic cycle, reigned supreme in geomorphology for several decades from the early to middle twentieth century.

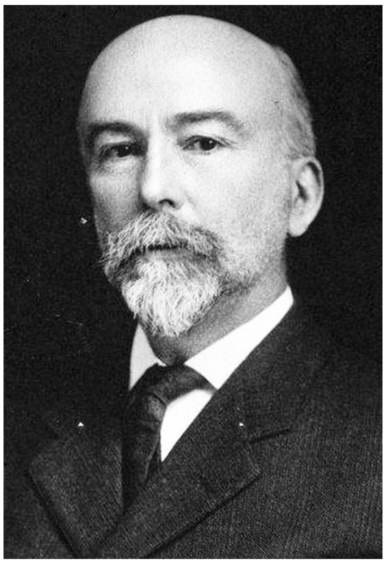

Figure 2.2 William Morris Davis (1850–1934). Source: Universal History Archive / Contributor / Getty Images

Davis was influenced by ideas about sequential development over time, which were prominent throughout the Earth and biological sciences in the late 1800s – when he first formulated his ideas. For example, think of the evolutionary theories of the English naturalist Charles Darwin. Davis travelled widely and was a keen observer. Based primarily on observations in humid-temperate environments in the United States, he conceptualized that landscapes progress through long but predictable cycles. According to Davis, the cycle begins with an uplift event that raises an old, low-relief landscape to heights well above its ultimate base level (sea level). The uplifted landscape then evolves through sequential stages, over long periods of time, until it becomes a nearly flat plain just above sea level. Influenced by ideas about sequential biological development, Davis named the stages that landscapes undergo, as they move through the cycle, in developmental terms – youth, maturity, and old age (**Fig. 2.3**).

The model begins when tectonic forces (assumedly rapidly) uplift a low, poorly drained, nearly flat surface (**Fig. 2.3**). Uplift increases the potential energy of the streams, allowing them to quickly and efficiently incise, forming deep valleys (**Fig. 2.3**). This stage (**youth**) is characterized by broad, flat uplands (remnants of the former, uplifted landscape) with deep, widely spaced canyons, carved by powerful rivers, as they attempt to reach base level (**Figs. 2.3**, **2.4**, **2.5A**). The Colorado Plateau region of the western United States is a classic example of a youthful landscape, having been uplifted in the past, and is now being deeply incised by rivers such as the Colorado and Green.

As the downstream segments of the major rivers transition into lower and lower gradients, that is, as they approach their base level, their capacity to incise decreases. As a result, these sections of the rivers begin to meander laterally, depositing sediment delivered from steep upstream sections of the rivers, and developing floodplains (**Fig. 2.3**). The upper (headwater) reaches of the streams remain steep and, as a result, the rivers develop a concave-upward longitudinal profile. At this time, rivers also "smooth out" their longitudinal profiles, as incision rates decrease. Erosion along hillslopes works to eliminate the remnants of the initial landscape. During this **maturity** stage, most of the landscape is sloping, valleys are broad, the main rivers have well-developed floodplains, and little or nothing of the originally uplifted landscape remains on the uplands (**Figs. 2.3**, **2.4**, **2.5B**). At this stage, **local relief** (the difference in elevation between the local uplands and the nearby lowlands) is greatest. Davis saw this type of landscape at numerous locations worldwide – one of steep slopes, high hills, low mountains, and deep, broad river valleys.

Given enough time and tectonic stability, continued erosion will decrease the relief of the landscape, producing a nearly flat, **old age** landscape as the uplands get worn down, as the lowlands – near base level – gradually fill with sediment. Because hillslopes are gentle and erosion rates small, most of the old age landscape becomes mantled with a thick cover of sediment. Davis famously referred to this