Cambridge University Press
978-0-521-51978-6 - Geomorphology: The Mechanics and Chemistry of Landscapes
Robert S. Anderson and Suzanne P. Anderson
Excerpt
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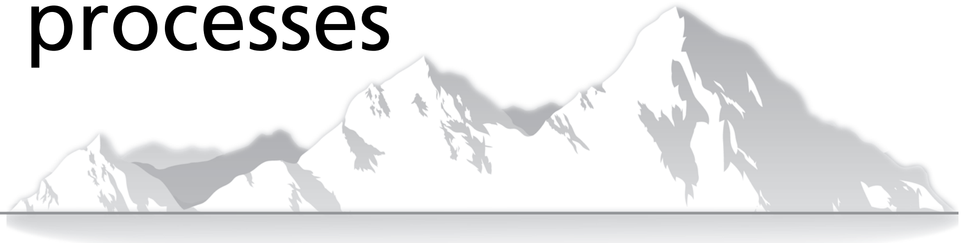
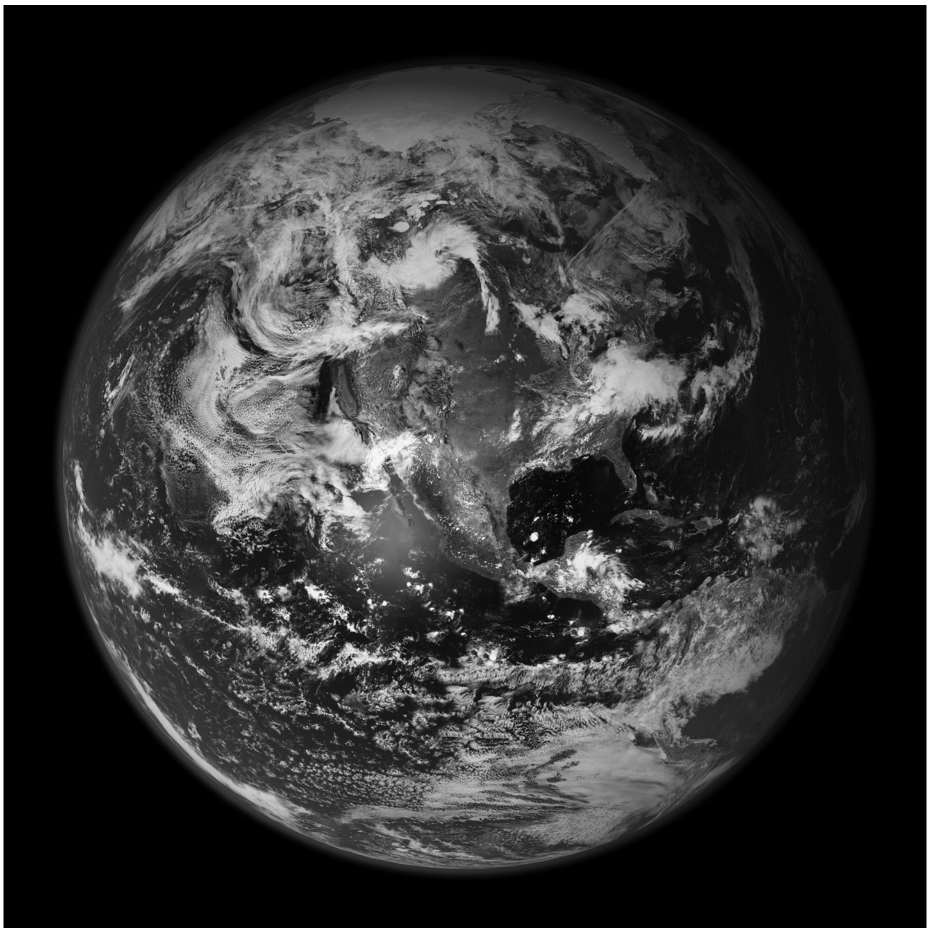
CHAPTER 1

Introduction to the study of surface processes



Suddenly, from behind the rim of the moon, in long, slow-motion moments of immense majesty, there emerges a sparkling blue and white jewel, a light, delicate sky-blue sphere laced with slowly swirling veils of white, rising gradually like a small pearl in a thick sea of black mystery. It takes more than a moment to fully realize this is Earth . . . home.

Edgar Mitchell, American astronaut (quote courtesy Calvin J. Hamilton)



In this chapter

The Earth is a blue and white sphere, spotted with green and brown, spinning through space. Geomorphology is the study of the shape of the Earth's surface and of the processes that are responsible for its evolution. Viewed from space, this may seem a trivial pursuit, given that Earth is nearly a perfect sphere with a very smooth surface. (If we ignore the slight oblateness of Earth, the ratio of surface roughness to radius is very close to the tolerance for roughness of an American billiard ball.) Yet the scale of surface roughness – of mountains and plains, of sand dunes and glaciers – is significant for living organisms. The processes occurring in the surficial zone where rock, water, air, and life interact do more than shape the surface of the Earth; they also drive chemical cycling between rock and atmosphere, influence tectonic motions, and support living systems. This book focuses on landscape evolution processes, but does not neglect connections to large-scale and long-period geologic processes and climate. In this chapter, we briefly outline the specific processes that are responsible for generating topography. We introduce several broad themes that cross-cut the discipline, and that serve as the weft to the process-specific warp in this book. Principal among these themes is the notion that the study of each of these landscapes can be formalized by conserving one or another quantity: sand, ice, water, energy . . .

The Blue Marble image of planet Earth, the most detailed true-color image of Earth to date. Using a collection of satellite-based observations, largely from the MODIS sensor, scientists have generated a true-color mosaic of the entire planet. (From NASA Goddard Space Flight Center. Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).)

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While the principles we address in this book are universal in that they can be applied to the study of any rocky planetary surface, we focus on our own planet and therefore must address why this planet is special. That the surface temperatures of Earth span the phase boundaries of H_2O has not only promoted the evolution of life on the planet, but has led to the diversity of surface processes involved in the evolution of the planet's surface. Ice sculpts landscapes in one way, water as rivers another, water as raindrops another. This diversity is mirrored in the landscapes.

But identifying processes and even formulating mathematical statements about how landscape might evolve in the face of this or that suite of processes is insufficient to capture the essence of the Earth's surface. We must also determine how rapidly or how efficiently these processes are acting. This boils down to the need to document rates – erosion rates, transport rates and the like. While some processes operate at speeds that are measurable over a single field season, or more importantly over the period of a PhD dissertation, most geomorphic rates are very slow. We have needed new tools. In this chapter we touch upon how new tools have emerged to aid the geomorphologist in establishing timing in the landscape.

We introduce the two chief drivers of geomorphic processes. The Earth's surface is the boundary between rock put in motion by deep geophysical processes and the atmosphere put in motion by uneven solar heating. Neither motion is steady. Earthquakes punctuate the motion of the rock. Storms punctuate the motion of the atmosphere. We discuss here the reasons why we must embrace this complexity, and introduce attempts of modern geomorphologists to treat the non-uniformity and non-steadiness of these processes.

The role of the atmosphere is yet more complicated. Even the statistical mean of the weather – the climate – changes on timescales over which landscapes evolve. Any study of the Earth's surface must acknowledge the role of climate history reaching back tens of millions of years. Here we quickly summarize this climate context, focusing on the last few tens of millions of years over which time the majority of the landscapes of the Earth have been rewritten. Discussion of the importance of the climate context sets the stage for the present challenge of addressing how the Earth's surface will respond to climate change induced by anthropogenic changes in the gas content of the atmosphere.

The global context

We live on a blue, white, brown, and green, nearly spherical, spinning, canted planet, 150 million kilometers from a medium-sized 4.5-billion-year-old star (Figure 1.0). One moon adorns the sky and tugs the ocean of its parent planet into a giant moving permanent wave. The moon was born early of a massive collision. That event set the planet spinning on an axis tilted with respect to the plane of the ecliptic, yielding daily and seasonal variations in radiation reaching the surface. The Earth is cooling down. Heat moved efficiently toward the surface by convection of the mantle is more slowly conducted through the outermost, coolest layer, which behaves as a solid on geological timescales, and which is broken into a small number of tectonic plates. The descent of old, cold, thickened plates from the surface also drives a creeping circulation of the mantle, at speeds of several cm per year, and establishes the relative motions of the plates. These motions crinkle the margins of the plates, generating belts of mountains, and drive volcanism that dots the topography with volcanoes where plates descend.

But this topography is subject to attack. That the Earth is both blue and white reflects the fact that water can be found in all three phases at the surface of the planet – blue liquid water, white water vapor (clouds), and ice. This unique aspect of Earth is allowed by being the right distance from the Sun, having an atmosphere that contains gases capable of absorbing long-wavelength radiation, and being large enough to retain these gases. The atmosphere and ocean of the planet are in motion as well; unlike the mantle, motion of fluids of the hydrosphere and atmosphere is turbulent, at speeds up to many meters per second, driven by both the uneven solar heating of the planet and its spin. Water evaporated from lakes and oceans, and transpired by land plants, is transported by storms spawned within the atmosphere, and then precipitates as either rain or snow. It is the motion of these substances, rain immediately and snow more slowly, where it accumulates sufficiently to become a glacier, moving down slopes ultimately generated by crustal processes, that leads to the dissection and sculpting of the land surface. None of these phenomena are steady on geologic timescales. Wind, water, and ice erode, transport and deposit sediment in discrete episodes of activity. Movement of continents on the surface of the planet slowly changes the circulation of atmosphere and oceans. The celestial mechanics of our planet's motion, which includes interactions with other planets in the solar system, leads to variations in the Earth's orbit, which in turn drive variation in the delivery of energy to the Earth. In the last couple of million years, this has resulted in numerous major swings in the climate on the Earth, leading to the growth and demise of huge ice sheets on northern continents. These set the climatic context within which human civilization has arisen and have greatly influenced the landscapes with which we interact.

Our planet supports a tremendous diversity of living organisms, whose activities fundamentally impact the chemical and physical properties of the surface. The green patches on the Earth's surface are evidence of photosynthetic organisms that harvest solar radiation and produce oxygen. Yellow to brown colors are indicative of organic detritus of living systems. Organisms have been found in environments ranging from cold seeps in the dark depths of the ocean, to hot springs on the land surface, encased in rocks in the cold Antarctic Dry Valleys and encrusting deep hot mine shafts. Life harnesses energetic chemical reactions, and the accumulation of products and consumption of reactants of these reactions are capable of changing the chemistry of the surroundings. Living systems build edifices and strengthen soils, and conversely churn soil and break rock. The furtive activities of animals scurrying and digging near the surface, the labor of worms mining the subsurface, the slower actions of roots and plant exudates, the growth of corals and black smoker towers, the protection of the surface by dense canopies of leaves, all of these living systems shape the environment so fundamentally that we struggle to consider what the Earth's surface must have looked like and how it must have behaved before significant life had evolved.

It is on this one planet, whose rocky plates are driven about by an internal heat engine, whose surface is irradiated by a distant Sun, and protected by a cocoon of gases, that now six billion humans strive to extract a living. The landscape serves as the scenic backdrop to this toil, and as a challenge to some who would seek the peaks of the terrestrial landscape and the depths of the oceans. It serves as the generator of catastrophes in the form of floods and landslides. It serves as the interface where atmospheric gases, circulating waters, and rocks of the lithosphere interact. Soil, a consequence of these interactions, both supports the terrestrial biosphere and in turn is modified by that biosphere. The landscape serves as witness to the history of civilization, the fragments of past cultures preserved in deposits. It serves as the signature for any particular civilization, the topography and the climate conspiring to determine the types of plants that can be grown, the transportation corridors, and the landmarks of the culture.

Overview of geomorphology

Earth's landscapes are sculpted by a suite of geomorphic processes that vary with position on the Earth and with time due to changes in the climate. Landscapes contain signatures of the principal active processes that we would like to learn to read.

Terrestrial landscapes consist of hillslopes bounded by channels. Most hilltops are convex upward – they are rounded, not pointy – and are mantled by a layer of soil or mobile regolith. When close enough to the surface, mechanical and chemical weathering processes work on the rock, creating a zone in which the rock is significantly altered, weakened, and broken. When the bits become small enough, they can be transported downhill by hillslope processes. The motion can be either slow (creep) or fast (landsliding), and can involve motion of individual grains or of large masses. The specific processes involved are diverse, and include cold region (periglacial) processes of frost creep and solifluction, the action of burrowing animals, rainsplash, flow of water over the surface, and so on.

Hillslopes deliver water and sediment to streams at their base. Streams naturally and inevitably form a dendritic network that breaks the landscape into drainage basins – these are the quanta of the geomorphic system. Water discharge generally increases downstream, and the size and shape of channels accommodating that discharge change in an orderly fashion. Stream profiles tend to be concave up – they decline in slope with distance downstream. Streams can erode bedrock where tectonic processes are driving rock upward relative to sea level. Outside of these regions, streams are alluvial – sediment mantles the channel floors throughout – and transport the sediment delivered to the river from hillslopes toward the ocean. While natural stream channels can handle the most common annual peak water runoff from rain and snowmelt, every few years the water discharge exceeds the capacity of the channel, and a flood occurs. This delivers water and sediment to the floodplain, which should therefore be considered a part of the river.

Just as streams bound hillslopes, coastlines bound the entire terrestrial landscape. This line of intersection between land and sea varies in time because global sea level changes, because local tectonics raises or subsides rock, and because the coastline either can be eroded by waves or can accrete by deposition. Waves move sediment and erode rock, releasing energy transferred to the water by storms far out at sea.

At high altitudes and latitudes, where winter snow accumulates enough to outpace summer melting, glaciers grow to fill valleys or to overwhelm entire landscapes. A glacier transports ice from a high altitude zone of net accumulation to a zone of net ablation. It accomplishes this transport by movement as a very viscous fluid, and by sliding at the bed. Glaciers can erode the rock over which they slide, sculpting such characteristic forms as cirques, U-shaped valleys, string-of-pearl lakes, and fjords. In the late Cenozoic ice ages, massive ice sheets covered the northern continents, greatly modifying the landscapes of northern North America and Eurasia.

Wind also generates recognizable landforms, some from erosion of rock by sediment but most from deposition of sediment. The sandy deserts are ornamented by ripples on the backs of dunes on the backs of yet larger dunes – these are the poster children of eolian processes. All of these landforms reflect the process of downwind bouncing of sand that we call saltation. Dust, on the other hand, travels different more wiggly paths in a process we call suspension, and can be wafted up to thousands of kilometers by the atmosphere. Loess deposits of far-flung dust mantle a surprisingly large fraction of the Earth's surface.

Guiding principles

How should we organize our thoughts about how the Earth's surface works? What are the guiding principles? What is the connective tissue between the topics or sub-disciplines within geomorphology?

Conservation

One of the strongest organizing principles upon which we found our study of surface processes is the rule of conservation. In most instances one may cast a problem as the conservation of some quantity. The word statement would go something like: "the rate of change of [fill in the blank] within a definable volume equals the rate at which it is produced within that space, plus the rate at which it is transported into the volume across the boundaries, minus the rate at which it is lost across the boundaries." The corresponding generic diagram is shown as Figure 1.1. We will learn to translate this word statement into a mathematical one. The quantity of concern might be heat, or it might be mass of regolith, or the volume of sediment, ice, or water; it might be concentration of a radioactive isotope, or it might be momentum. We will use each of these in developing the major equations in this book.

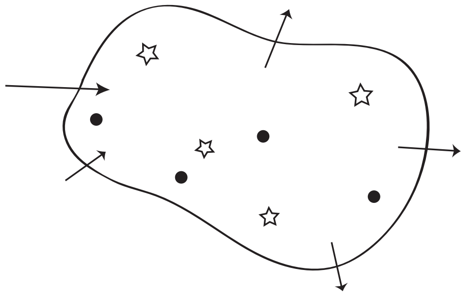

Figure 1.1 Schematic of the concept of continuity we will employ throughout this book. We wish to craft a statement of conservation of some quantity within the control volume represented by the irregular shape. In general, this quantity can be created within the volume (circles), or decay within the volume (stars), or cross into or out of the volume through its boundaries (arrows).

This approach serves to help us parse up a problem, take it apart into pieces we can address individually. For example, in the problem of conservation of heat, heat energy can be produced within a volume by the decay of radioactive elements. We must then know how to constrain how much heat will be generated by these decay reactions, and this will require knowledge of the concentration of such elements in the volume – something that is measurable. In the case of conservation of ice in a parcel of a glacier, we must know how ice moves across the edges of the parcel – we must know the physics that determines the transport rate of ice. This in turn finds us chasing down the physics of deformation of ice, and of sliding of ice against its bed.

To be concrete about it, we catalog here a number of examples in which we employ this approach:

- Conservation of heat in the lithosphere thickness problem
- Conservation of heat in the planetary temperature problem
- Conservation of radionuclides in dating methods
- Conservation of ice in a glacier
- Conservation of heat in permafrost temperature profiles
- Conservation of immobile elements in weathering profiles
- Conservation of regolith in hillslopes
- Conservation of water in overland flow
- Conservation of water in a groundwater field
- Conservation of sediment in bedform profiles
- Conservation of momentum in development of the Navier–Stokes equation
- Conservation of sediment in littoral cells
- Conservation of water in flood discharge calculations

When transformed into mathematical statements, these all look similar. The rates of change are governed by spatial gradients in transport rates, and by any sources or sinks of the quantity of concern.

Transport rules

Material, be it water, ice, or air is moved from one place to another on the Earth's surface by the action of forces that include body forces (usually gravity) and surface tractions, or stresses. The rate of motion is set by the material properties, in particular how a material responds to stresses. The relationship between rate of motion, or strain rate, and an applied stress is called the rheology of the material. In geomorphology, we run into materials with widely differing rheologies. Take the Greenland Ice Sheet for instance. Air cooled near the surface of the ice sheet slides down the surface slope, generating katabatic winds with velocities that can exceed 100 km/hr, while water produced by melting flows down the same surface slopes at velocities rarely greater than 1 m/s. The ice also flows downslope, but at velocities of no more than a few tens of meters per year. Finally, the ice sheet is thick and extensive enough to invoke displacements of the mantle underneath; the mantle is capable of flowing at rates of the order of 1–10 cm/yr. We must become conversant in linear viscous, nonlinear viscous, and coulomb rheologies. More broadly speaking, however, we will find that the transport of a substance is often proportional to the gradients in some quantity. Water and soil move down topographic gradients; chemicals move down chemical concentration gradients; heat moves down thermal gradients. This basic realization serves as connective tissue among many problems; it makes the solutions to many problems conceptually and even mathematically analogous.

Event size and frequency

One of the long-standing discussions in geomorphology is how to accommodate the fact that the geomorphic systems are forced by highly variable environmental conditions. We will find that many of the processes important in the transport of material on the Earth's surface are dependent upon the weather in a complex way. Some of these processes are naturally "thresholded"; for instance, the transport of sand does not occur until the velocity of water or of wind rises above some value. Once above this threshold, the transport increases dramatically with further increase in the flow. We will explore what determines the thresholds, and why the dependence is nonlinear above the threshold. This general characteristic of many transport processes is fundamental to geomorphology in that it bears heavily upon the relative importance of rare, large events. One might ask the question "What is the relative importance of every-day events versus those that occur once every decade, or every century, or every thousand years?" In order to address such a question, we need to know two things: what is the distribution of the sizes of events, and how does the system respond as a function of the size of the event. Weather events are typically distributed such that small events (small wind, small precipitation, etc.) are much more common than large events. We will characterize this more formally, but this is the essence. Note that if the process in which we are interested is thresholded, the little events do nothing – even if they are statistically the most frequent. Conversely, large events will perform a lot of geomorphic work when they occur, given the nonlinear character of transport processes, but they are rare. In essence, this means that there is an inevitable tradeoff between the rarity of an event and the geomorphic work that is accomplished by it. Big events do count, and the more nonlinear the process, the more important they become.

It is in this context that we must assess the principle of uniformitarianism on which much of geology is founded. We acknowledge that the physics and chemistry of the processes acting are indeed immutable; understanding of the present processes is the key to unlocking the past. But we also acknowledge that the external forces acting on the geomorphic system change on a wide variety of timescales. Rates of processes change on timescales of seconds to millions of years. Even the dominance of one process over another has changed. Acknowledgement of the role of major events capable of writing their signature so boldly on the landscape that thousands to millions of years of subsequent Earth history has been incapable of erasing it is part of modern geomorphology. We revel in the stories of these large events. In some sense this leads to something of a neocatastrophist view of the world, one in which the roles of large floods unleashed by glacially dammed lakes, of tsunamis generated by volcano collapse or magnitude 9 earthquakes, and of impacts of 10 km-diameter bolides are acknowledged for the work they can perform in sculpting the Earth's surface.

Establishing timing: rates of processes and ages of landscapes

One of the major advances in our science, one that has allowed us to make significant progress within the last 50 years, is the ability to establish timing in the landscape. The fathers of our field, such greats as Grove Karl Gilbert, Walther Penck, John Wesley Powell, William Morris Davis, and the like, had few tools to employ in dating geomorphic features. There was little constraint on determinations of how fast a landscape evolved, and for that matter on how old the Earth was. We therefore focus in an early chapter in the book on dating methods. While we do not present an exhaustive review, we try to give the reader a sense of the newer techniques. It will not be a surprise to those who know our research that we focus on the utility of cosmogenic nuclides, those rare isotopes of elements formed only by interaction of cosmic rays with atoms in near-surface materials. These have a very short history of use within geomorphology, beginning only in the late 1980s, and evolving rapidly ever since. This method has opened up to quantitative dating the Plio-Pleistocene (essentially the last five million years) during which most of the modern landscape has been developed. We can now date moraines, marine and fluvial terraces, and even caves. Using twists on the same methods, we can now determine the rate of erosion of a point on the landscape, or of a basin, over timescales that are much longer than humans have been around to measure them. While establishment of timing in the landscape is important in telling more precise stories of landscape evolution, its importance goes well beyond this. It has allowed us to test quantitatively models of landscape evolution. We can no longer be satisfied with models that get the shapes of the landscape correct. The models must also evolve at the right rate.

What drives geomorphic processes?

The Earth's surface responds to processes driven from both below and above the surface. We discuss in Chapter 2 how the deep Earth works, and how these processes impact the Earth's surface. The Earth is cooling by both conduction and convection, the former dominating in the lithosphere (and in the inner core), the latter in the lower mantle and outer core. These processes move heat from the interior to the surface of the Earth, arriving at a rate of roughly 40 mW/m^2. This is not much compared to the rate at which solar energy is delivered to the Earth's surface by radiation; in fact it is lower by a factor of about a million! More importantly to geomorphology, however, is the internal engine of the Earth that drives plate tectonics. This has established the context within which we understand the broadest features of the Earth's surface – its ocean basins – and the locations of the different styles of deformation of the Earth's surface. On a smaller scale, the collisions and movements of lithospheric plates drive crustal deformation that results in both faults and folds, and produces earthquakes as these structural elements grow. These processes serve to move rock up or down relative to sea level, delivering rock into harm's way for geomorphic erosion processes driven by the solar engine. Variation in uplift of rock from place to place alters the slope of the land surface. We will see that slopes, both of rivers and of hillslopes, are primary determinants of the level of geomorphic activity in a landscape. This broad topic is the realm of tectonic geomorphology, which is itself the subject of textbooks. Our coverage of this topic is therefore again not exhaustive. While plate tectonics and its crustal manifestation are important in forcing geomorphic processes, it is often the study of geomorphic features that constrains the patterns and the rates of tectonic processes.

The majority of the energy driving the surface system is supplied by the Sun. On average, the incident radiation supplies 1370 W/m^2 of energy to the outer reaches of the Earth's atmosphere, most of which makes its way through the atmosphere to the surface. Spatial variation in solar energy input, and the fact that the Earth is spinning, drives the circulation of the atmosphere. In part, this drives oceanic circulation as well. Solar energy also governs evaporation of water from the surface, which is moved elsewhere by the atmosphere, and precipitates as either rain or snow. This precipitation then moves down gradients, percolates into the ground, runs down hillslopes, and down rivers, or if it becomes ice, flows or slides downhill. It is the motion of these fluids – air, water and ice – that powers many surface processes. While the uplift of rock into harm's way is accomplished largely by tectonic processes, it is the transfer of water from low areas (mostly oceans and lakes) to high ones, that supplies these heavy fluids to the tops of the landscape so that they can do geomorphic work as they travel back down the landscape to the sea under the force of gravity. Tectonics allows local conversion of heat energy to potential energy to raise rock relative to the sea. The atmosphere similarly converts thermal energy into potential energy to raise water above sea level, in a hydrologic cycle with a much shorter timescale.

The surface temperature of the Earth

Ice, clouds, and oceans make the Earth seen from space largely blue and white. This is why the astronauts marveled at the Earth from their trips around the Moon in the 1960s and 1970s. It is made so in large part because the water on or near the Earth's surface exists in solid, liquid, and vapor states. This is unique in the solar system. Why is Earth the "water planet"? Liquid water is stable in only a narrow range of pressure and temperature conditions (Figure 1.2). The mean surface temperature of the Earth is 15 °C above the freezing point of water. This is governed by a radiation balance that we explore in detail in Chapter 5. If the Earth had no atmosphere at all, the radiation balance suggests that the mean temperature of the Earth's surface should be about 255 K, or –18 °C (Figure 5.7).

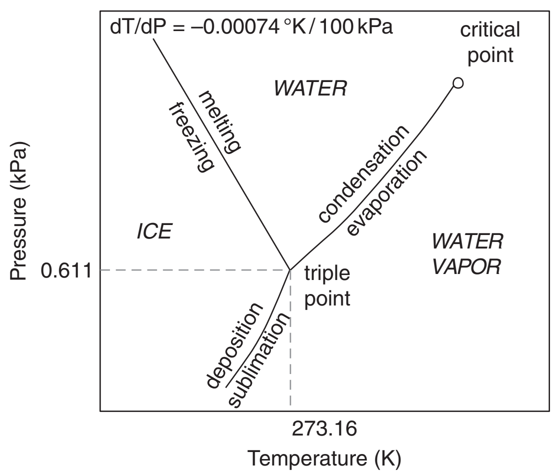

Figure 1.2 Phase diagram $P(T^{\circ})$ for the molecule H_2O. Note the negative slope of the melting curve separating water and ice (redrawn from Lock, 1990, Fig. 2.4, with permission of Cambridge University Press).

Clearly this is not the case. If it were, the Earth's surface would be frozen solid, and water would not exist in liquid and vaporous forms. This calculation does not take into account the chemistry of the Earth's atmosphere, which contains gases, some of them in trace amounts, that are excitable by particular slices of the spectrum of radiation emitted by the Sun and the Earth. The excitation of the gases leads to absorption of some of the energy and alters the simple radiation balance we have just calculated. Gases like H_2O, CO_2, CH_4, O_2, and O_3 absorb energy in specific wavelength bands (Figure 5.8), many of which are around 10 microns, in what we call the infrared band. Light in wavelengths around 0.5 microns, the visible spectrum, is not absorbed by these same gases, meaning that little of the radiation in the visible spectrum is altered by the atmosphere. These so-called greenhouse gases, transparent in the visible (from the Sun) and absorptive in the infrared, are therefore very important for allowing the surface temperature of the Earth to be above 0 °C, rather than well below it. And it is presently the human alteration of the concentrations of these same gases that is forcing the global change of climate in the last hundred years.

The climate context

While the climate varies over all timescales, there is some order to the system. It responds to changes in the Sun's luminosity, variations in the orbit of the Earth around the Sun, variations in the tilt of the Earth's axis of rotation relative to the plane of the ecliptic, and the distribution of continents on the globe. Understanding climate and landscapes is a double-edged sword. On one side, we need a means of deciphering what climate history has been; on the other side, we must know the climate history to understand how a landscape has responded to climate change. Most of the landscapes we see, and most of the geomorphic features we study, are young. This is partly because recent events remove the record of the older history. It is also in part due to the fact that we happen to live in extraordinary times, in the midst of a cycle of ice ages. It is obvious that growth of glaciers and ice sheets affects the areas they override. The climate changes that drove the growth of ice sheets, however, also wrought changes in non-glacial landscapes: increased wetness filled "pluvial" lake basins, withdrawal of water lowered the sea level, regions surrounding ice sheets were locked in permafrost. Because of these events, we generally turn to continuous marine records to provide a history of the climate, and use the knowledge of climate history derived from the marine records to interpret terrestrial landscapes. This approach has its drawbacks, of course. Marine records, while continuous, tend to provide a measure of conditions averaged over a large area – the globe or an ocean basin. To understand a particular landscape, we want to know the local climate, which may be quite different from the global mean or even from the nearby ocean area.

The most commonly used marine climate record is derived from the oxygen isotopic composition of the shells, or tests, of benthic, or bottom dwelling, deep-sea foraminifera. The carbonate shells of these organisms form in isotopic equilibrium with the seawater in which they grew. The ratio of ^{18}O to ^{16}O, expressed as $\delta^{18}O$, in the foraminifera depends on the temperature and the isotopic composition of the seawater. Changes in the temperature of the seawater cause a slight, but known, change in the fractionation of ^{18}O between the carbonate shell and the seawater so that warming reduces $\delta^{18}O$ and cooling raises $\delta^{18}O$ in the foraminifera. The other factor that affects the ^{18}O record of the benthic foraminifera is the growth of ice sheets. Water evaporated from the oceans is much lighter isotopically (−15 to −40 permil (parts per thousand, also written ‰) VSMOW) than mean ocean water (0 permil VSMOW), resulting in a shift in the composition of the ocean. Full Northern hemispheric glaciation and Antarctic glaciation increases the $\delta^{18}O$ of seawater by about 2.4 permil, and hence increases the $\delta^{18}O$ of the foraminifera during glaciations. Many schemes have been devised to separate these two effects in the marine isotopic record.

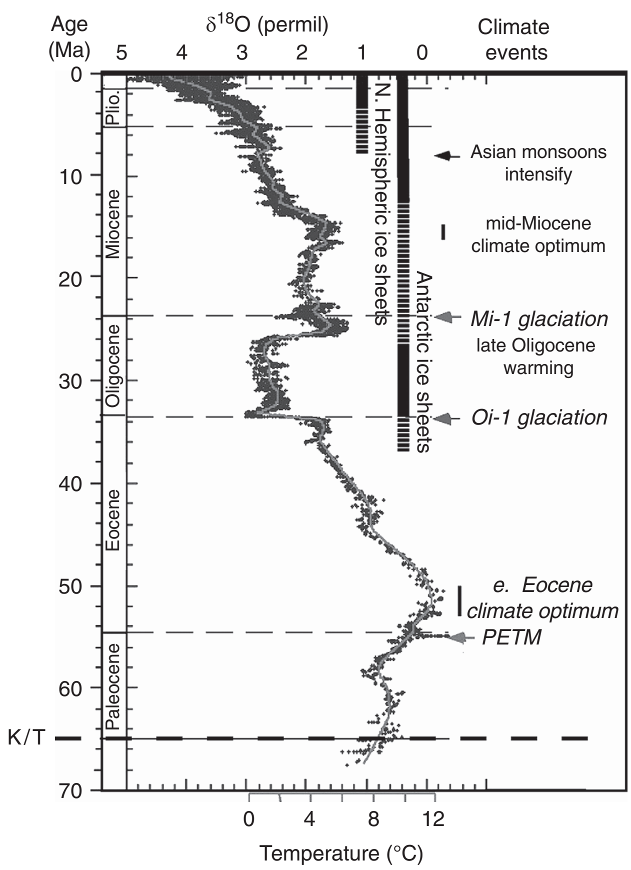

Figure 1.3 Oxygen isotope histories over the Cenozoic derived from deep-sea cores. Climate, tectonic, and biotic events are labeled, as are the occurrences of Antarctic and Northern hemispheric ice sheets. PETM = Paleocene–Eocene Thermal Maximum (after Zachos *et al.*, 2001, Figure 2, with permission from the American Association for the Advancement of Sciences).

A compilation of benthic foraminifera $\delta^{18}O$ composition reproduced in Figure 1.3 shows that Earth's climate has cooled over most of the Cenozoic, following the early Eocene climatic optimum. Several shifts in climate are evident in this general cooling trend, such as a period of full-scale Antarctic glaciation in the Oligocene, from ~34 Ma to ~26 Ma, and the re-initiation of full-scale Antarctic glaciation in the mid-Miocene. The onset of Northern Hemispheric glaciation in the Pliocene, at ~3 Ma, coincides with the deepest cold plunge in the Cenozoic record. These events result from several processes. The slow reorganization

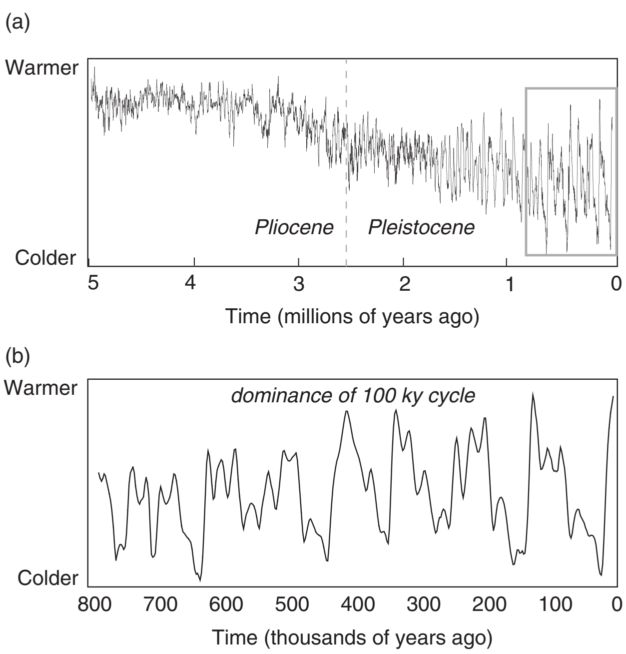

Figure 1.4 Climate history over last 4 Ma from marine isotopic records. (a) 4 Ma to present, showing slow cooling trend starting at roughly 3.5 Ma. The 40 ka (ka = thousands of years, kilo-annum) cycle dominates climate swings until roughly 700 ka, after which the 100 ka cycle dominates. (b) Detail of last 800 ka, showing strong 100 ka cycle. Note also how anomalous the present state of the climate is relative to the mean over the Pleistocene ((a) after $\delta^{18}O$ data in Zachos *et al*., 2001, with permission from the American Association for the Advancement of Science; (b) after Imbrie *et al*. (1984) stacked $\delta^{18}O$ record, with permission from Reidel Press).

of oceanic or atmospheric circulation due to tectonic rearrangements of plates is an important trigger for the onset of glaciations. Antarctic glaciations began when the Southern Ocean opened, isolating the Antarctic plate at high latitudes, and allowing unimpeded circulation of ocean water and atmosphere around it. The onset of Northern Hemispheric glaciation is closely associated with the closing of the Panama seaway. Another strong influence is the variation in the orbital parameters that control the amount, distribution, and seasonal timing of solar radiation on the Earth's surface. These orbital parameters oscillate in predictable ways on timescales of 10^4–10^5 yr, too short to show up in the record shown in Figure 1.3. An examination of the deep-sea foraminifera $\delta^{18}O$ record shown in Figure 1.4 over the last 4 Ma, the period when Northern Hemisphere glaciation began, and the period most relevant to modern landscapes, shows these short-term oscillations in climate clearly. Over most of the record, swings in $\delta^{18}O$ occur at about 41 ky, the period associated with variations in obliquity, or the tilt of the Earth's axis of rotation. Over the last 800–900 ky, however, the period of the dominant oscillations shifts to 100 ky, that associated with variations in eccentricity of the orbit, or the deviation of the Earth's orbit about the Sun from circular. This 100 ky oscillation has dominated the late Quaternary climate, which is marked by glacial–interglacial cycles with this frequency.

Several aberrations also mark the Cenozoic climate record depicted in Figure 1.3. These brief, odd climate intervals are named: the Paleocene-Eocene Thermal Maximum (PETM, also called the Late Paleocene Thermal Maximum, LPTM), the Oi-1 Glaciation, and the Mi-1 Glaciation. Each of these events developed rapidly (10^3–10^5 yr), and cannot be explained by either tectonic plate rearrangements or variations in orbital parameters alone. For instance the PETM may have been triggered by a rapid release of methane to the atmosphere from the vast reservoir of methane stored in clathrates (open-structure ices) on continental margins. These climatic aberrations serve as notice that the climate system is capable of changing rapidly and dramatically in response to triggers that we do not fully understand.

Quite remarkably, a major increase in sedimentation to the world's oceans occurred within the last several million years, coinciding with the onset of the Plio-Pleistocene glacial cycles (Figure 1.5). That this is not a local phenomenon but is rather a global signal has been recently confirmed by analysis of records from many sedimentary basins. One such study documents the 30 Ma history of erosion within the eastern Alps, which we show as the inset to Figure 1.5. Within the Plio-Pleistocene, the geomorphic system appears to have woken up from a mid-Cenozoic stupor. This is a remarkable event, and one that is still crying out for an explanation beyond the simple one that "glaciers are very efficient at eroding the landscapes"; this record includes landscapes not subjected to late Cenozoic glaciation.

While we now know the last few millions of years of global ice volume well from the marine deep sea records, it would have been difficult to deduce this history from the land record alone. Save for a few continuous terrestrial records, such as the massive deposits of silt in China's loess plateau, the terrestrial record is woefully incomplete. In glaciated regions, younger alpine glaciers and ice sheets generally remove the record of older ones by overprinting or