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.

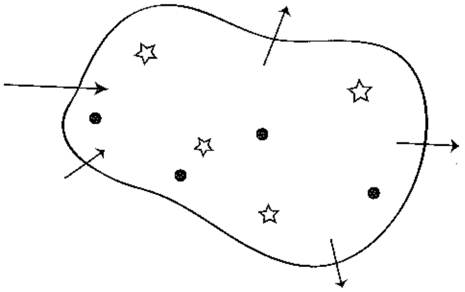

Figure 1.1 Schematic of the concept of continuity we will employ throughout this book. We wish to craft a statement of conservation of some quantity within the control volume represented by the irregular shape. In general, this quantity can be created within the volume (circles), or decay within the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