This natural bridge in California was carved from the rock by the action of ocean waves.

CHAPTER 15 Erosion

You will know something about the process of erosion if you can:

1. Distinguish between a transported soil and a residual soil and relate the formation of both types of soil to weathering and erosion.
2. Explain the role of gravity in the erosional process.
3. Develop a generalized model of the erosional process, with particular emphasis on the role of running water as an agent of erosion.
4. Name some other agents of erosion and describe their effects on the earth's surface.

The weathering of solid rock is often the first in a series of related changes that alter the face of the earth. What happens to the smaller rock particles that are produced as a result of weathering? Many, perhaps most, of these smaller particles are transported—often great distances—from their point of origin. Thus, the final change in this series may occur hundreds of kilometers from the place where it all started.

EROSION

It is a common occurrence for a homeowner to order a load of topsoil. The soil is delivered by a truck, and if a large area is involved, it may be spread by a bulldozer. Suppose you dug down into such a spot at a later time and examined the soil profile. You would be able to see that the characteristics of the top layer were quite different from those of the layers underneath, for example, in color, mineral composition, and organic content. The differences would be more than could be explained by weathering alone. You could therefore infer that the top layer had been brought in from someplace else.

Natural soil profiles often show this same condition. They differ so much from the bedrock underneath them that it is not likely that they formed from that bedrock and must have been carried in from someplace else. The rock particles in this type of soil are called *transported sediments*. If, on the other hand, it can be shown that the soil particles have been weathered from the original bedrock, they are called *residual sediments* (meaning that they have always "resided" there).

Earth scientists have found that transported sediments are far more common on the earth than residual sediments. This indicates that there are forces on the earth that can move rock particles from one place to another. Any natural process that removes sediments from one place and carries them away to another is called *erosion*. In this chapter we will examine various ways in which erosion is brought about.

As in so much of earth science, we will have to be detectives in many cases of erosion. Just as a bulldozer may leave tread marks as evidence that it has been in an area, so the natural agents of erosion also leave telltale signs. However, there are also many situations in which we can actually observe erosion occurring. So we do not have to rely entirely on inference. Let us then see what we can discover about the forces and agents of erosion.

Gravity—The Driving Force of Erosion. Everything on the earth is continuously being pulled toward the earth's center by the force of gravity. Any particle of matter that is free to move is going to move downward unless some other force interferes. The atoms, molecules, and mineral crystals in a solid rock are, of course, not free to move in response to gravity. So mountains stand tall, resisting the force of gravity.

However, the forces of weathering are constantly attacking the surfaces of the mountains, weakening and loosening bits and pieces of all sizes. These pieces of rock *are* free to move, and when they do move, they move downward in response to gravity. In almost all cases, they also move horizontally away from their original location. Gravity is the driving force of this movement. And as rock particles move down and away from where they were, there is a loss of potential energy. As we will see, all erosion is powered by a conversion of the potential energy of gravitation to other forms, particularly kinetic energy.

Gravity can thus work alone as an

Figure 15-1. Rocks on a slope. Pieces of bedrock, which have broken off as a result of weathering, are found on most slopes.

agent of erosion, tending to pull all loose particles down along every slope. Figure 15-1 shows a common sight wherever the land has rocky slopes. We see sediments that have accumulated near the bottom of a hillside. A study of these rock pieces would show that they are very similar in composition to the solid bedrock of the hillside. They have apparently been weathered from the bedrock and have rolled down the slope. However, most of them have not fallen all the way down. They are resting on the slope, even where the slope is rather steep. This observation agrees with common daily experience. Objects on a slope do not necessarily roll or slide down it.

Angle of Repose. If you put a marble on a glass plate, and lift one end of the glass the slightest amount, the marble will roll downward. But if you put a block of wood on a board, you can lift one end of the board to a considerable angle before the block begins to slide. If you cover the board and the block with sandpaper, you have to tilt the board even higher before the block will move. The force of friction accounts for these observations. This force can resist the effect of gravity—up to a point. What is that point?

The full force of gravity is directed straight downward. If an object is resting on a horizontal surface, 100% of its weight is directed at right angles to the surface (that is, straight down) and none of it is directed along the surface. If, however, the surface is tilted, only a fraction of the force of gravity acts at right angles to the surface. This part of the force presses the object against the surface and produces the frictional force that tends to keep the object from sliding down. Another fraction of the gravity acts downward along the slope. This is the force that tends to make the object slide or roll down the slope. These two parts of the force of gravity on a slope can be shown by diagrams like those in Figure 15-2.

Notice that as the angle increases, the fraction of gravity that causes friction becomes less and the fraction that is pulling the object down the slope becomes greater. At some angle, then, the force down the incline will become greater than the resisting force of friction, and the object will slide or roll down. For a given kind of loose material resting on a given kind of surface, there is some angle at which the effective force of gravity down the slope becomes greater than the resisting force of friction. The material will then move down the slope.

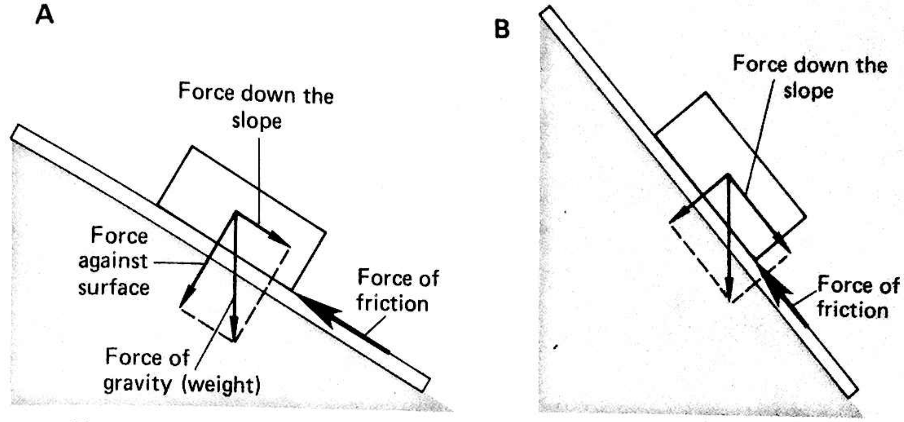


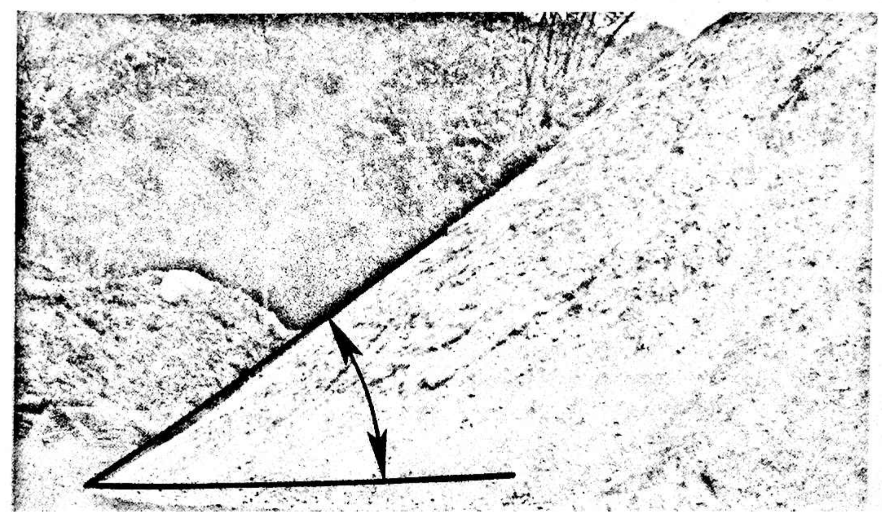
Figure 15-2. Force of gravity on a tilted surface. On a tilted surface the force of gravity is divided into two components. One component acts at right angles to the surface. The second acts downward along the slope.

The greatest angle at which loose material will rest on a surface is called the *angle of repose* (or rest).

You can find the angle of repose for earth materials quite easily. Just make a pile of the material on the ground and measure the angle of the cone that is formed (see Figure 15-3). For most earth materials you will find that this angle is about 35°. This is the angle you are likely to see in piles of sand and gravel at construction sites or in gravel supply yards. On slopes any greater than this, you are not likely to see much loose material, unless it is resting on other sediments below it.

Some Effects of Gravity. On slopes that are close to the angle of repose, the shock of a slight earthquake may send a sudden rush of rocks and soil down the slope in a *landslide*. The reason for this is that the force of friction is greater when an object is at rest on a surface than after it starts mov-

Figure 15-3. Angle of repose. The angle of repose is the greatest angle at which loose material will rest on a surface.



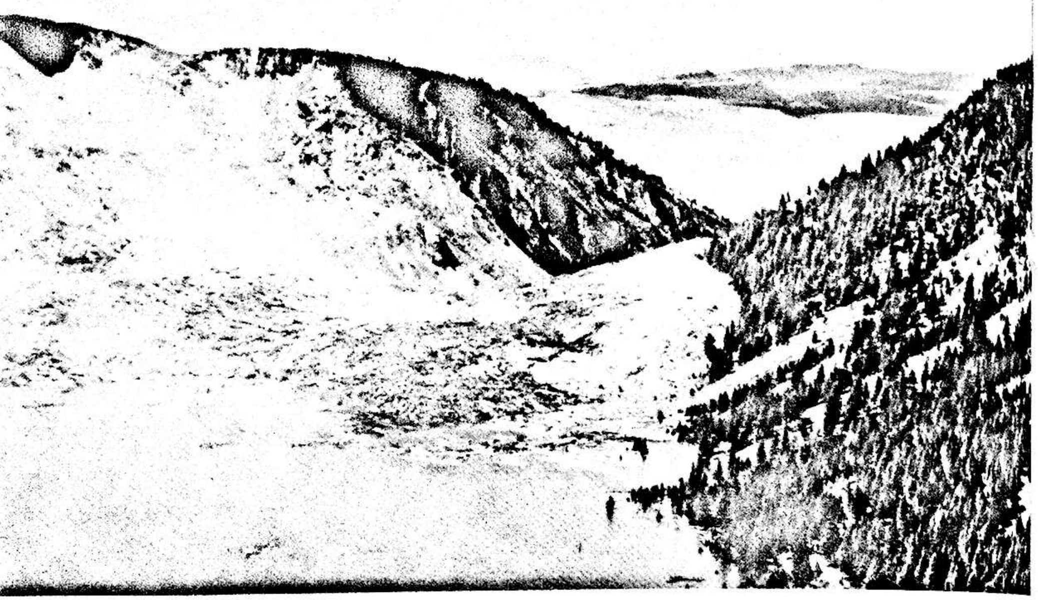


Figure 15-4. Landslide in Madison Canyon, Montana.

ing. Therefore, once a mass of sediments begins to slide down a slope, it tends to keep going and even to build up speed. The effects of one famous landslide are shown in Figure 15-4. In other cases, a heavy downpour may soak the ground and reduce the friction between the soil particles. Again, there may be a landslide, or a kind of slipping of material called *slumping*.

Landslides are not a very common occurrence. They can occur only where the land is steep enough. And even when it *is* steep enough for a landslide to occur, there may not be enough loose material to form one. Sediments may have moved down the slope one piece at a time as they formed.

Near the beginning of this section we said that solid mountains can resist the force of gravity. There is evidence, however, that whole hillsides *can* be affected by gravity over a period of time. On many hillsides you can see fence posts, telephone poles, tombstones, and other objects that were once set vertically, but are now tilted. Sometimes, layers in the bedrock are also seen to be curved downslope. What these observations indicate is that the whole hillside is slowly slipping downward. This is a process called *hillside creep*. It is believed to be caused in many cases by alternate swelling and contracting of the surface during wet and dry seasons. The swelling loosens and separates the soil particles slightly. When they settle back, they also settle down a little lower. Over the course of the years, the upper layers of the soil and rock slowly move downhill.

Agents of Erosion. Landslides, falling rock, slumping, and hillside creep need a fairly steep slope to occur. Where slopes are not very steep, the downslope effect of gravity is just not great enough to move the sediments. Most of the earth's land surfaces have

slopes of less than 5°! So, if gravity were the only agent of erosion, most sediments would remain where they formed. But we began this chapter by observing that most sediments appear to have been transported. What, then, are the agents of erosion that transport sediments down these very gradual slopes?

Running water is a rather obvious agent of erosion. In any muddy river you can see the sediments being carried along. In rushing mountain streams, you can see and hear the sand and pebbles being rolled and bounced along the bottom. On a world-wide basis, running water moves far more material than any other agent of erosion. We will therefore concentrate our attention on erosion by running water in the rest of this chapter. But we will consider some other agents, also.

SUMMARY

1. Sediments that have been moved into a region from another place by natural processes are called transported sediments.
2. Sediments that formed in their present location are called residual sediments.
3. The removal and transport of sediments is called erosion.
4. Transported sediments are much more common than residual sediments and are evidence of erosion over large portions of the earth's surface.
5. Gravity is the main driving force of all erosional processes.
6. Gravity may act alone as an erosional agent, producing such effects as landslides, slumping, and hillside creep.
7. Running water is the predominant agent of erosion on the earth.

STREAMS

Imagine yourself on a slope near the top of a mountain range. There is the splash of a raindrop at your feet. Then another. Soon the rain is pelting down. The dry dirt softens as the pore spaces fill with water. Mud forms. The water that was rain begins to trickle downhill across the earth. Tiny dirt particles are carried along. As the dirt moves away, spaces are left in the soil. More and more dirt particles move downhill with the water, following the most direct route downward. Gradually a pathway develops. Particles are picked up from the bottom of this pathway and carried downhill with the water. Other dirt particles slip from the top of the pathway when the support is removed from below. They tumble into the water and are washed along downhill.

The rain stops. The trickles of runoff dry up or infiltrate the soil. But permanent streams continue to flow downward. They are supplied by ground water seeping into the stream bed from the surrounding layers of saturated soil. Where two streams meet at a common low point, they join to form a single larger stream. More

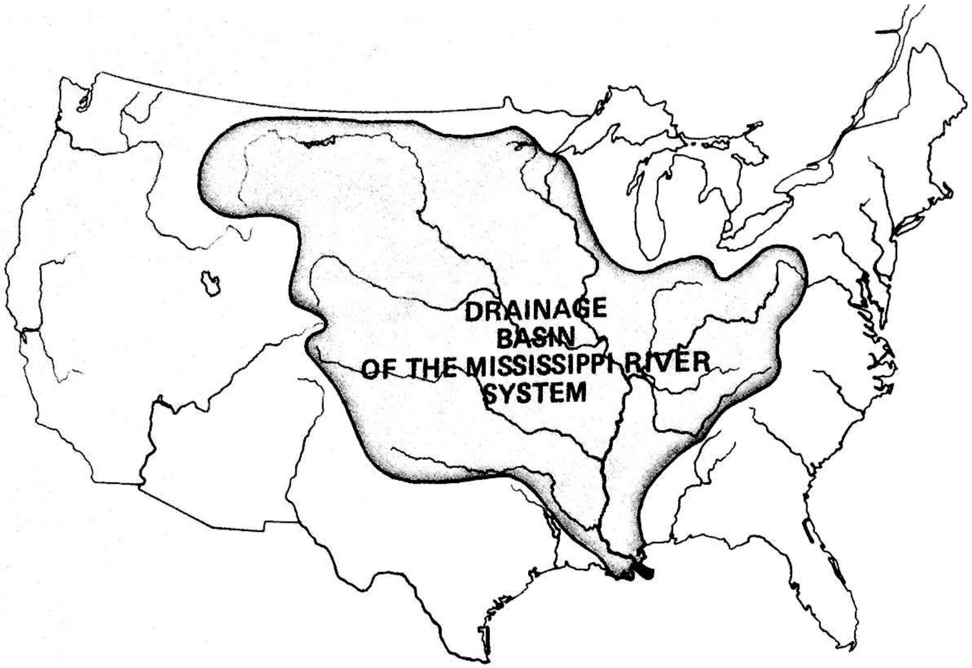


Figure 15-5. Drainage basin of the Mississippi River system. All streams within this drainage system empty into the Mississippi River.

and more small streams join the main stream as the running water descends to lower levels.

Drainage Basins. Follow this growing stream downward. The volume of water it is carrying—its discharge—keeps getting larger. The stream becomes deeper and wider in order to move this growing volume of water. Finally, the stream may become a broad, majestic river like the Mississippi. Near its mouth at New Orleans, the Mississippi River may carry as much as 50,000 cubic meters of water per second down to the Gulf of Mexico.

Now let us retrace our steps. Follow a river like the Mississippi upstream along each of its branches. As you do this, you climb to higher and higher ground. Eventually you reach the source of any branch you are tracing—a point where its flow begins. This may be a pond or lake fed by ground water, or it may be a spring in the ground where the water table reaches the surface. Beyond the source, the ground continues to rise for a while. Then it reaches a peak or ridge and starts to drop again. Soon you reach the sources of other streams that are flowing down on the other side of the ridge into another river system.

Look at the map in Figure 15-5. A continuous line has been drawn along the high ground above the source of each stream that flows into the Mississippi River. This line is called a *divide,* because it divides the Mississippi River system from all neighboring systems. It completely encloses the Mississippi River and all its branches. There is no stream inside this region that does not flow into the Mississippi or one of its tributaries.

This enclosed area is called the *drainage basin* of the Mississippi

River system. Every drop of the water that flows down the river originally fell as precipitation within that drainage basin. A similar basin can be traced for every river in the world.

Stream Systems. Some drainage basins are very large, like that of the Mississippi system (see Figure 15-5). Others are short and narrow, like those of the rivers flowing down the eastern slopes of the Appalachian Mountains. Whatever its size or shape, each drainage basin contains a single stream system that branches like a tree. All the running water within the basin ends up in the same stream that empties into a large body of water, such as a sea or ocean.

A stream system consists of more than running water. It includes all the land surface drained by the system and all the sediment being transported by the system. The potential energy of gravity that drives the system should also be considered a part of it. We have used the word "system" several times in this section, and we have used it many times before in referring to such things as the solar system, high and low pressure systems, etc. In each case the word means something made of many interrelated parts that work together as a unit. You may recall that we also mentioned "closed" systems (see page 128). In a closed system, nothing enters or leaves the system. A stream system is clearly not this kind. It is an open one. The precipitation that provides the water enters from the atmosphere. The water eventually leaves the system through the mouth of the stream or by evaporation. Some of the sediments also leave through the mouth of the stream. And finally, the potential energy used by the system is lost to the environment as heat. (We will consider energy relationships in a stream system in greater detail in the next chapter.)

SUMMARY

1. Every stream and its branches make up a single system that collects all the runoff within a definite area called the drainage basin of the system.
2. A stream system consists of running water, the land surface it drains, the sediment it transports, and the potential energy used to drive it.

CHARACTERISTICS OF STREAMS

While it is true that no two streams are ever exactly alike, there are certain characteristics that are common to all streams. These characteristics, in turn, affect the "life history" of the stream and the valleys that are carved out by it. Although every stream has branches, we can begin by examining a theoretical stream that does not have any. What we discover about such a simple stream can then be applied to each branch. Then by combining the effects of all the branches, we can put together a picture of the action of the system as a whole.

Velocity. Like the rocks and sediments on a hillside, water on a hillside is pulled downward by the force of

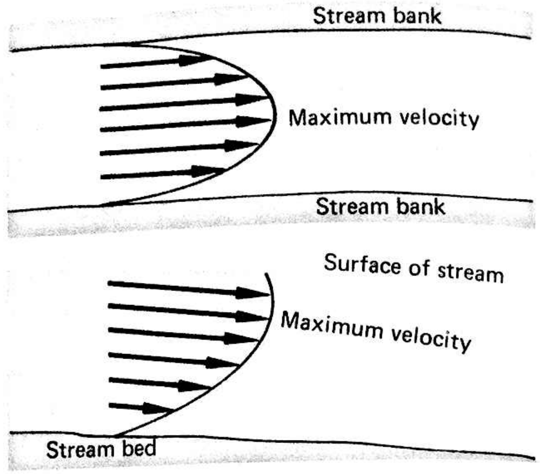


Figure 15-6. Water velocity in a stream. The velocity of the water varies with location in the stream. It is greatest near the surface and least along the bottom and sides of the stream.

gravity. Sediments may be held on a slope by friction, but no force of friction acts on water unless the water is moving. Therefore, water always flows downhill on even the slightest of slopes. However, the speed of its flow does depend on the slope. As the slope increases, the effective force of gravity down the slope also increases. So the velocity of the flowing water increases, too.

As soon as the water starts to flow, forces of friction develop. There is friction between the moving water in a stream and the bed of the stream. There is also friction between the layers of water in the stream as they slide over one another, and between the surface layer and the air. As the velocity of the stream increases, all these forces of friction also increase. There is, then, some velocity at which the force of gravity driving the water down the slope is just balanced by the resisting force of friction. This is the average velocity at which the stream will be moving.

The velocity will not be the same everywhere in the stream. Near the bottom and sides of the bed, it will be least, because that is where the friction is greatest. The velocity will increase as the distance of the water from the bed increases, except near the surface, where friction with the air will slow the water again. Figure 15-6 is a model of the velocity patterns that would be found in the cross section of a typical stream.

Effect of Discharge. As the discharge of a stream increases, the stream becomes deeper and wider in order to move the greater quantity of water being supplied to it. As a result, relatively less of the water is in contact with the bed, and the frictional resistance to the flow has less of an effect on the stream as a whole. The average velocity of the stream therefore increases when its discharge increases. A deep river flowing over a gentle gradient may, then, have a greater average velocity than the same stream near its source, where the gradient is much steeper. However, the velocity of flow *along the bed* will be greater where the gradient is steeper. This is an important factor in the ability of a stream to produce erosion, as we will see later.

Ability to Transport Sediments. In the discussion of gravity as a force of erosion, we pointed out that gravity by itself cannot move sediments very

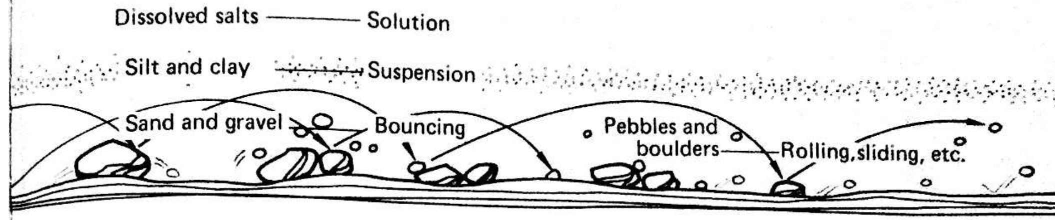


Figure 15-7. Movement of sediments in a stream.

far because most land slopes are not steep enough. The force of gravity acting down a gentle slope is not great enough to overcome the friction between the sediments and the ground. Moving water, however, can provide the additional force needed to move sediments down gradual slopes. Moving water does this in various ways, depending on the size of the sediments (see Figure 15-7).

The smallest sediments—ions—are carried in solution. Colloids, other clays, and silt are kept suspended in the water by its turbulent motion. Sand and small pebbles in a fast-moving stream will be moved by bouncing along the bottom. Larger sediments may be too heavy to be lifted off the bottom by the moving water, but they may be moved by sliding and rolling. Remember that gravity is always pulling these sediments downward. What the water is really doing is making it easier for the particles to respond to gravity by helping to overcome the resistance of friction.

A large pebble will need more force to start it moving than a particle of sand or silt. If you have ever waded across a stream, you know how much harder it is to keep your footing in a swift part of the current than where the water is moving slowly. The faster a stream is moving, the greater the force it exerts, and the larger the sediments it can move. Figure 15-8 is a graph that shows the average velocity

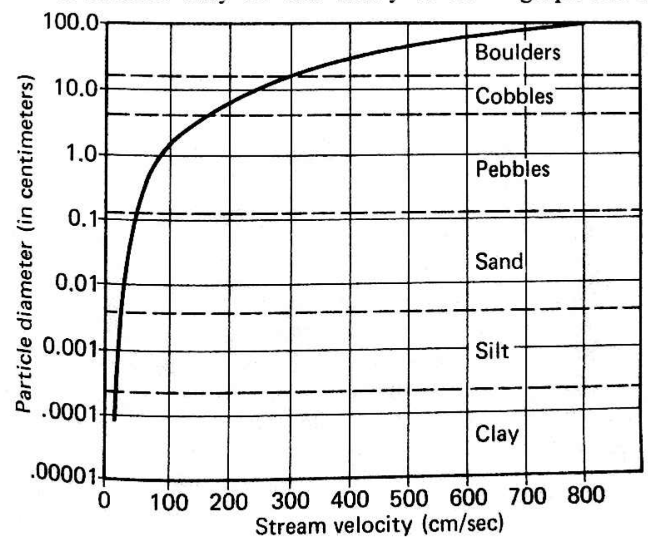


Figure 15-8. Relationship of water velocity to size of sediments transported.

of water that is needed to keep sediments of different sizes moving. This graph confirms what we would expect to find in any stream that is transporting sediment. Where the flow is rapid, we can expect to see sand, gravel, and even rather large stones being moved downward to lower elevations. We expect the water to be quite cloudy or muddy with suspended sediments. Where the stream is moving slowly, we expect to see sand and gravel resting on the bottom, while the finer sediments go drifting by above them.

Quantity of Sediment Transported. The velocity of the water determines the maximum size of the sediments that the stream can move. But that doesn't tell us anything about how *much* sediment the stream will transport. This depends mainly on the discharge of the stream—the amount of water passing a point each second. A river may be carrying enormous quantities of sediment if its discharge is large, even though none of the sediment is coarser than clay or silt. A mountain stream may be moving large boulders, but only a few at a time. So the total mass of sediments moved by the small stream may not be very great.

We may think of erosion as the work that a stream does. In terms of measurable earth changes, it is not just the size of the sediments moved that counts, or the amount of sediments passing a particular point. What is important is the total work of erosion that an entire stream does. In the next section of this chapter we will consider a stream as a total erosional system and see what its effects on its environment may be.

SUMMARY

1. As the slope of a stream bed increases, the average velocity of the stream increases,
2. An increase in the discharge of a stream increases its average velocity.
3. Streams transport sediments as ions in solution, as suspended matter, and by the bouncing and rolling of particles along the stream bed.
4. The size of the sediments that a stream can transport increases as the stream velocity increases.
5. The total amount of sediment that a stream can transport increases as its discharge increases.

EROSION BY STREAMS

Picture in your mind a well-established stream high on a mountainside. Slopes, or gradients, of the surface are steep up here. Imagine, too, that it is spring, and melting snows have saturated the ground. Runoff into the stream is at a seasonal peak, and so is the discharge of the stream. Steep slopes combine with heavy discharge to give the stream a high velocity. It is therefore capable of moving most of the sediments that

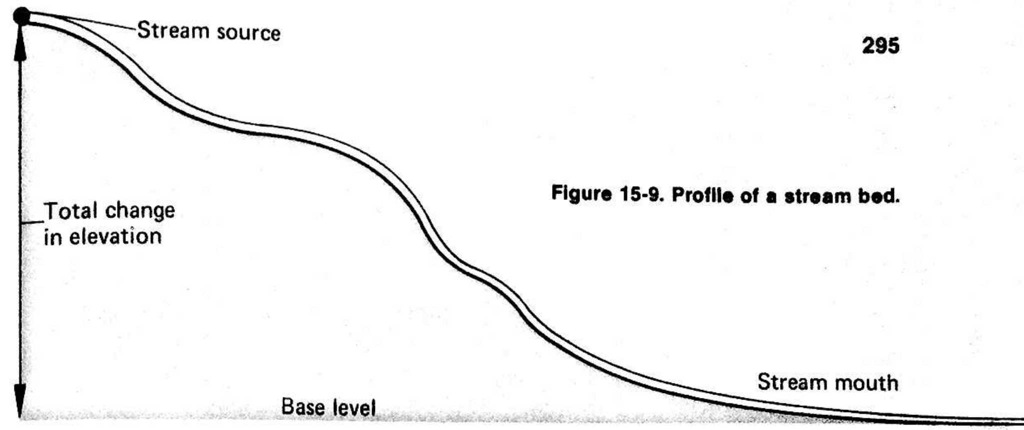


Figure 15-9. Profile of a stream bed.

may be in it—certainly all the sand and gravel, probably all the larger stones, and perhaps even some boulders.

Where will these sediments come from? Some will be broken loose from the stream bed, but most will come from the bedrock of the surrounding slopes. As weathering breaks the rock into pieces of various sizes, they slide and roll down the steep slopes into the stream. As the stream flows along, it gradually accumulates a greater and greater load of sediments. Irresistibly the stream drags, rolls, bounces, or carries these sediments to ever lower levels.

Is this the only effect of the stream—to transport sediments of weathered rock? Let us see what else the stream may be doing.

The Work of a Stream. Figure 15-9 is a profile of the bed of a stream like the one we have been talking about. The water anywhere along the stream has potential energy due to its elevated position in the earth's gravitational field. When it reaches the lowest point of the profile, it will have lost that potential energy. The amount of potential energy it loses depends only on the difference in height. Whether the water falls straight down over the edge of a cliff, or runs down a sloping stream bed, the total potential energy lost is the same.

The lowest level to which a stream can flow is called its *base level.* In most cases, this is sea level, although a large lake may act as the base level for a portion of a stream above the lake. The total potential energy of a stream varies with its height above its base level.

Energy, you will recall (page 119), is the capacity to do work. Some of a stream's potential energy may be used to do work. What work may a stream do? Look at Figure 15-10. This is a cross section of the Grand Canyon of the Colorado River in Arizona. Note the V-shape of the canyon with the river at the bottom of the V. Could the stream have cut through the solid rock to carve this canyon? If so, that would certainly be an impressive piece of work. By what process could water cut rock?

First of all, the rushing water can pry loose any grains of material that are projecting into its path. It can also lift flakes of rock that have been weakened by chemical weathering. Most important, however, is the load of sediments being dragged and bounced along the bed. Just as you

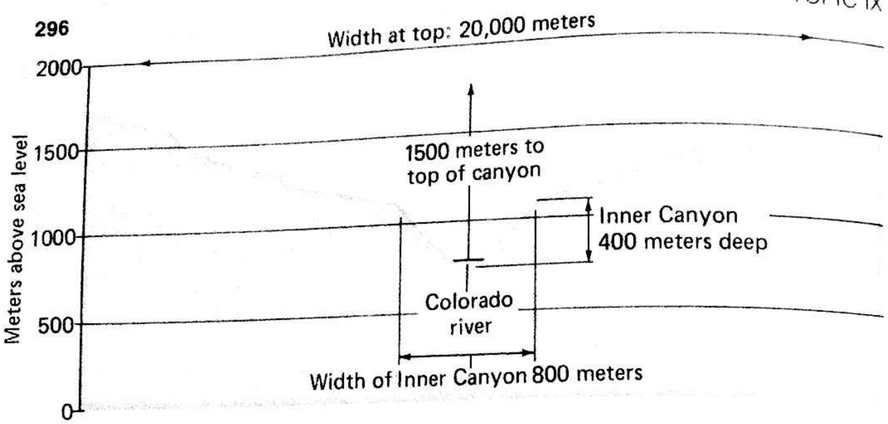


Figure 15-10. Cross section of the Grand Canyon of the Colorado River.

can scrape a hollow into a board with a piece of sandpaper, so a stream can use its sediments to scrape the bottom and sides of its bed. It may take thousands of years for these processes to cut down through a meter of rock. But in the history of the earth, there is time enough for Grand Canyons to be cut many times over.

Youthful Streams. The streams we have been examining are streams with steep gradients, and they have rough sediments flowing rapidly down from high elevations. Such streams usually have V-shaped cross sections. The sharpness of the V will vary, depending on the resistance of the walls to weathering. In some cases, the walls of the canyon are nearly vertical, as in Ausable Chasm along the Ausable River in the Adirondack Mountains of New York (see Figure 15-11). Because of the high velocity of these streams, especially at flood periods, all loose material on their beds is constantly being moved along. Their beds are therefore continuously exposed to erosion and downcutting by the streams. A stream at this stage in its life is called *youthful*. Its actual age in years is not important. One "youthful" stream may be millions of years older than another. It is still youthful if it is still cutting through bedrock.

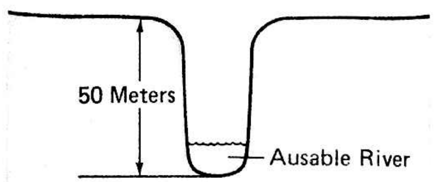
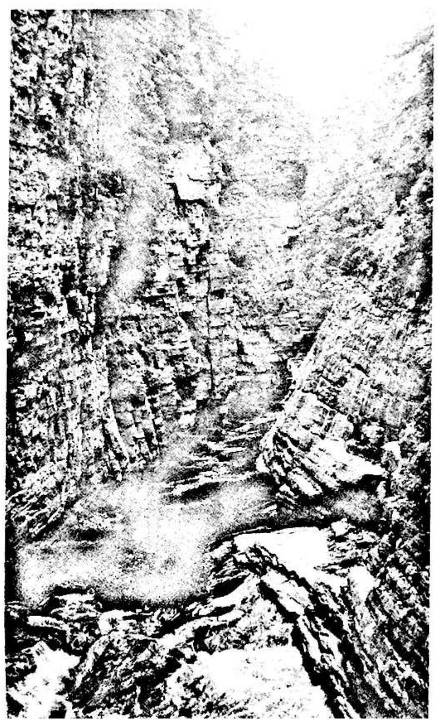


Figure 15-11. Ausable Chasm along the Ausable River in New York State. The Ausable River is an example of a youthful stream.



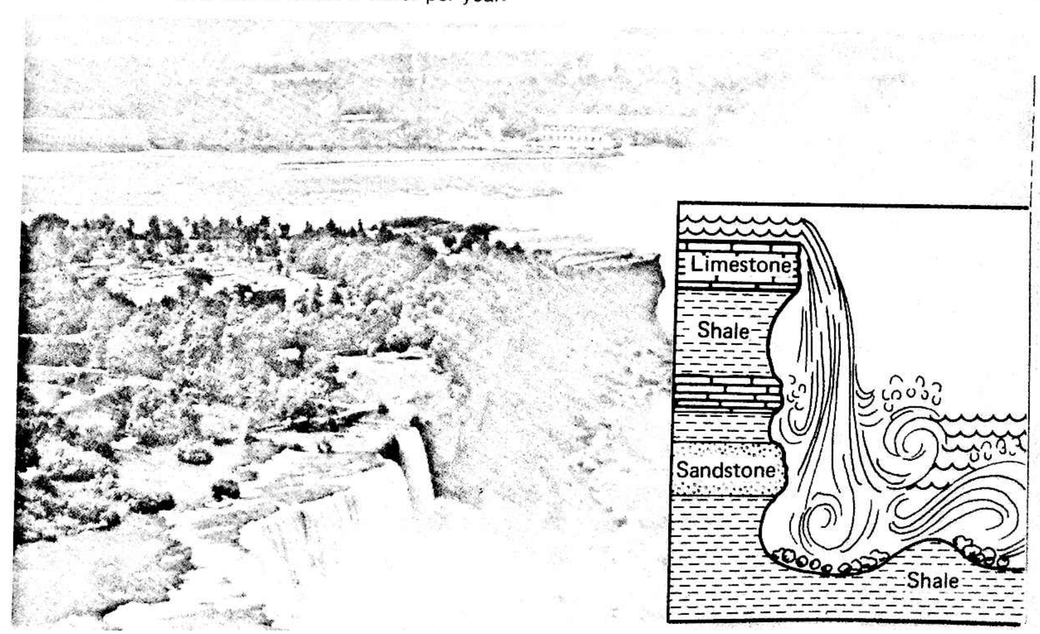
In this early stage of development, it is quite common to find rapids, where sharp increases in the gradient result in high velocity. Waterfalls are also likely to occur, with the stream dropping almost vertically to a lower elevation. These irregularities in the profile of the stream bed occur because of variations in resistance of the bedrock to erosion. Where the stream runs over a less resistant rock, it will downcut more rapidly, producing the sharp changes in slope that we have mentioned.

These features last only a relatively short time. The very increase in velocity that these features produce gives the stream more cutting power. It therefore tends to remove these steep sections by eroding them away (see Figure 15-12).

Mature Streams. As a youthful stream continues to cut its bed downward, it approaches closer to its base level. Its potential energy for the work of cutting and removing rock becomes less. As a result, its average gradient also decreases. So its velocity near its bed becomes less. It loses the ability to move the larger sediments it has been transporting. The stream bed now becomes covered with this loose material, thus protecting it from further erosion. Only at times of peak flow can the stream move these sediments. Cutting action of the stream becomes very slow, or stops altogether. Meanwhile, weathering and the action of tributary streams have widened the base of the V and formed a valley with gentle slopes, as shown in Figure 15-13.

In its youthful stage, the stream had enough energy to move obstacles or destroy irregularities in its bed. Now

Figure 15-12. Niagara Falls. The stream is eroding the shale more rapidly than the more resistant limestone. Because of undercutting of the falls, they are being moved upstream at a rate of about 1 meter per year.



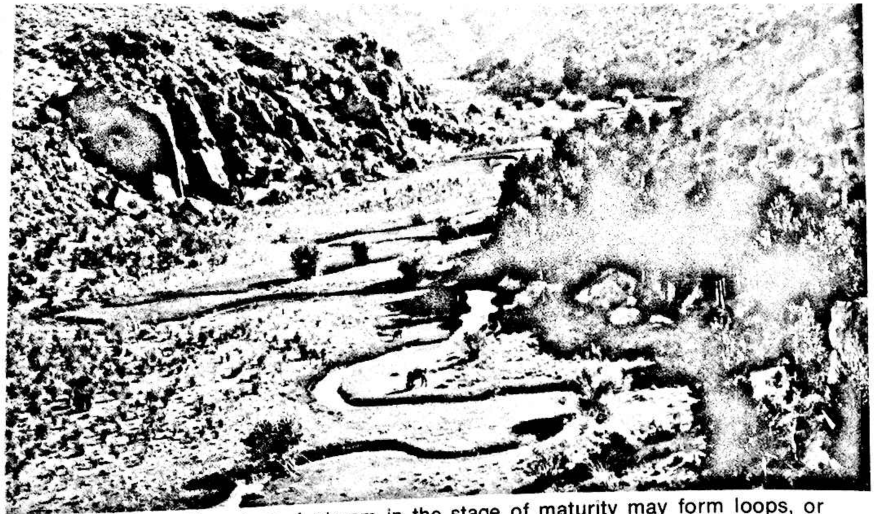


Figure 15-13. Meanders. A stream in the stage of maturity may form loops, or meanders, that swing back and forth across the valley.

the stream is affected more by the obstructions it meets. It goes around them and begins to swing to one side or the other, forming loops called *meanders* and traveling back and forth across its widening valley (see Figure 15-13).

Although the stream is traveling more slowly along its bed than when it was youthful, and therefore cannot transport the larger sediments, this does not mean that its ability to carry sediment has decreased. By now, tributary streams are feeding large volumes of water and sediment into the main stream. Because of the increase in the volume of water, and therefore in its total kinetic energy, a greater mass of sediment can now be carried. But the transported sediment is mostly silt and clay.

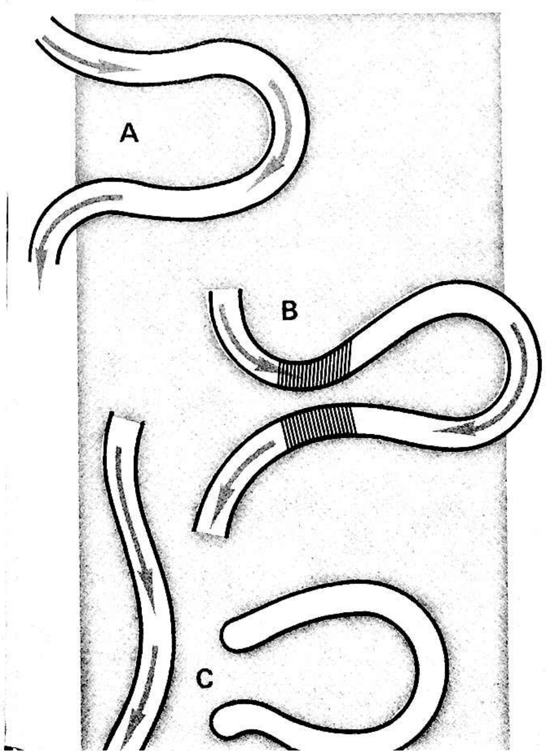
The stream is now said to have reached the stage of *maturity*. As in the case of a youthful stream, maturity is not a matter of age in years, but depends only on the characteristics of the stream and its valley.

Old Streams. Finally, the gradient of the stream bed becomes so small that the stream cannot move any but the finest of its sediments. During periods of peak flow, such a stream will usually overflow its banks and flood the nearby portions of its valley. When the flow subsides, a layer of silt and clay is left on the valley surface. This area is called a *flood plain*. The well-sorted sediments of flood plains soon become rich soils.

A stream or river at this stage is considered *old*. One of the features of a river in old age is the shape and behavior of its meanders. A typical pattern for a stream in old age is seen in Figure 15-14. The meanders are strongly looped. From time to time they become cut off from the stream and are left behind as water-filled depressions called *oxbow lakes*. The reason for this is that the water on the outside of a curve has to move faster than that on the inside in order to make the turn. The faster-moving water on the outside of the curve erodes the bank and extends the curve further in the same direction. On the inside of each curve, where the water slows down, sediment tends to be deposited. Figure 15-15 shows how this process leads to the cutting off a loop

Figure 15-14. Stream in old age.

Figure 15-15. Formation of oxbow lakes.



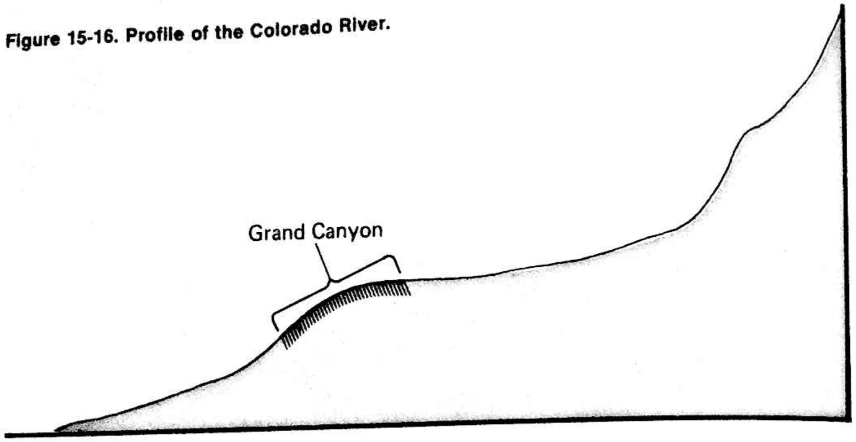
and the forming of an oxbow lake.

The process also causes a stream in old age to weave back and forth across its flood plain, from the base of the hills on one side to the hills on the other. In the course of time (which may be thousands of years), the stream crosses every part of its plain. Wherever it happens to be, it leaves its deposits of silt and clay after every flood. Thus the entire plain acquires a deep cover of soil.

The Life History of a Stream. In this explanation of the life cycle of a stream, we have focused on each stage separately, as if the entire stream changed from one phase to the next as a unit. It is very unlikely that any stream is at the same stage of development throughout its entire length. In fact, most streams tend to have the characteristics of youth near their source and of old age near their mouths, and to be in the mature stage somewhere in between.

The pattern, however, is not often that simple. Look at Figure 15-16, the profile of the Colorado River. Judging by its gradient, the river is almost surely in the youthful stage near its source high in the Rocky Mountains. Near its mouth at the Gulf of California, it is approaching the stage of old age. But the river is certainly in the youthful stage where it is cutting the Grand Canyon, and this is about two-thirds of the way to the river's mouth. The noticeable increase in gradient where the river enters the Grand Canyon explains its "youthfulness" here. We can infer that local conditions can greatly affect the development of a stream all along its course. We will return to this subject in the final chapters of this book.

Figure 15-16. Profile of the Colorado River.



Story Without End. How does the life of a stream end? Theoretically, the stream and its branches should eventually reduce its entire drainage basin to a flat plain nearly at sea level. We don't know what such a land would look like because there are no such places on earth. Although weathering and erosion are constantly acting to level the land, other forces seem to be constantly pushing it up again. So a stream in very old age may find itself youthful again as its valley rises. With a fresh supply of potential energy, it begins to repeat its life story.

SUMMARY

1. Youthful streams carrying sediments down steep gradients can cut through solid bedrock.
2. When youthful, streams have V-shaped valleys.
3. In the stage of maturity the valley of a stream widens. The stream ceases to cut through the bedrock.
4. In old age, the stream develops a wide flood plain, across which it wanders in a series of curves, or meanders.

OTHER AGENTS OF EROSION

As we stated earlier in this chapter, running water is by far the leading agent of erosion on a worldwide scale. For those of us who have lived our lives in the humid sections of the United States, running water is the eroding agent that we are most aware of. But there are places in the world, such as the Sahara Desert, where streams almost don't exist. If you lived in such a region, you would be most conscious of the power of the wind to transport sediment. In very cold climates, running water is also seldom seen. Here we would be conscious of the presence of ice and the

erosional effects it can produce. You don't have to leave the United States to find places where wind and ice are important agents of erosion. So it will be useful to compare the action of these agents with that of water and to consider briefly the similarities and differences in their effects.

Erosion by Ice. Masses of frozen water on land are called *glaciers*. They are most likely to form in the cold temperatures at high elevations, and fill up the valleys and depressions on mountainsides, somewhat the way water would. Glaciers of this kind are sometimes called "rivers of ice" or "frozen rivers" because they look like rivers that have frozen in place (see Figure 15-17). In some ways they act like very slowly moving water. However, there are some important differences in the way these *valley glaciers* interact with the surface of the land.

Glaciers may also cover vast areas of the earth's surface in the form of sheets of ice, called *continental glaciers*. Long-term changes in the earth's average temperature may cause such ice sheets to extend themselves toward lower latitudes during cooling periods and then to retreat during warmer periods. There is evidence nearly everywhere in the Northern Hemisphere that such an advance and retreat occurred rather recently (in geological terms), ending only about 10,000 years ago.

For our purposes we need not be concerned with the differences between the valley glaciers that resemble rivers and the continental ice sheets that are more like vast seas. Both types have similar transporting properties and both types produce and leave similar results.

Glaciers form by the steady accumulation of snow that falls on their

Figure 15-17. A valley glacier.

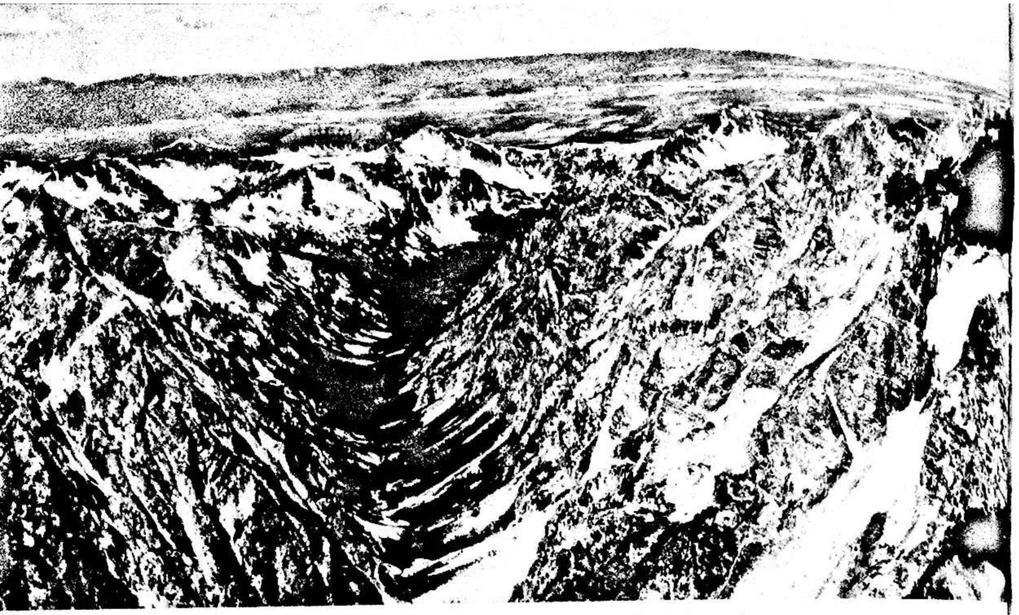


Figure 15-18. U-shaped valley formed by glacial erosion.

surfaces. As the snow piles up, its weight compresses the lower portions and turns them to solid ice. If you have ever made a snowball, you may have personally experienced this "icing" effect. The enormous weight of a glacier causes it to move slowly down its valley. The movement of a glacier is like that of a river in very slow motion. The velocity is least at the bottom and sides where the ice is in contact with the valley floor. It is greatest near the center of the top surface of the mass of ice.

When the lower edge of a glacier reaches elevations where the air temperature is above the freezing point, the advance of the ice stops. Streams of water then flow continuously from the melting ice front. The erosional action of these streams will be basically the same as that of any stream.

Where a valley contains a glacier, weathered rock particles continually slide and roll down the slopes, just as they do where the valleys have running streams. However, the sediments that fall onto a glacier remain on the surface of the ice for a time. Gradually they are covered by fresh snow, and gradually they sink through the ice to the bottom of the mass. Thus the bottom and sides of a glacier become studded with sediments. Unlike the sediments in fast streams, which become rounded and smooth by constant friction among themselves, sediments in a glacier are often sharp and irregular. This is a result of their being ground against the bedrock as the glacier moves. As the glacier moves steadily downslope, it drags these sharp sediments along the surface of the bedrock. The bedrock is thus scratched, torn, and broken, and the surface is eroded wherever the ice is in contact with it—on the sides of the valley, as well as on the bottom. One result of glacial erosion, then, is the carving out of U-shaped valleys, rather than the V's cut by narrow streams (see Figure 15-18).

When, because of climate changes, a glacier is advancing, it pushes a large load of unsorted sediments ahead of it like a bulldozer. When a warming interval causes the glacier to retreat, it leaves these piles of sediments behind. Thus the remains of glacial erosion are much different from those of stream erosion. These effects will be considered in more detail in later chapters.

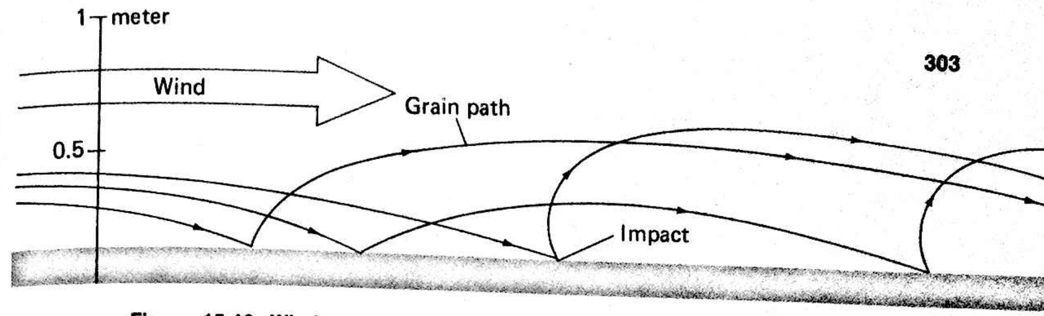


Figure 15-19. Wind erosion. Sand grains carried by the wind generally bounce along the ground. From hitting against other grains, the grains become rounded and their surface frosted.

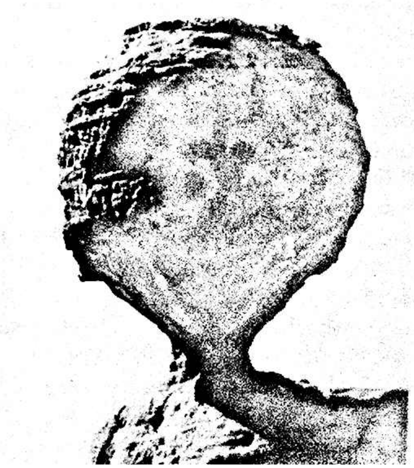
Erosion by Wind. If you have ever had a particle of dirt blown into your eye, you know that moving air can transport sediments. For wind erosion to occur, however, there must first of all be a wind, and second, there must be loose, dry particles available for the wind to move. You wouldn't expect a dust storm in a forest, even with winds of 100 km/hr.

Wind erosion is most noticeable in desert regions. Here, weathering has reduced the bedrock to fine particles, mostly of sand size. When a wind blows, the sand grains move in a series of bounces, similar to the movement of sand along a stream bed (see Figure 15-19). Note that the sand grains seldom rise as much as a meter off the ground. However, small piles of windblown sand tend to build up into forms called *dunes*. Sand dunes, which may be 50 meters or more in height, are a common feature of desert regions. They also occur along sandy beaches.

Particles that have been moved by wind erosion have certain noticeable characteristics. They are well rounded by the repeated impact of grain against grain. When examined with a magnifier, their surfaces are seen to have a frosted appearance.

Wind can also erode solid rock, somewhat the way water does, by the grinding action of windblown sand. Such effects of wind erosion are seen in many arid regions that have outcrops of bedrock. Since sand particles blown by wind remain near the ground, their erosional effects are observed only near the base of rocks. An undercutting of a rocky cliff in a des-

Figure 15-20. Erosion of a rock by wind. Because the particles transported by the wind remain close to the ground, the base of the rock undergoes the greatest amount of erosion.



ert region is usually evidence of wind erosion. A striking example of what wind erosion can do is seen in Figure 15-20.

Erosion by Waves. Anyone who has stood on an ocean beach when large waves are rolling in must be aware that enormous forces are at work. There is a constant churning of the sand as the waves break, crash down, ride up the slope, and then fall back. But is erosion going on? There seems to be a constant back-and-forth movement, but is anything being carried *away?* A study of beaches over a period of time shows that transport of the sand does occur. Most of the time there are currents of water flowing parallel to the beach. Although these cannot be seen, their effects are often noticed by swimmers who find themselves being carried down the beach in one direction or the other. Often there are currents flowing in toward the shore at one place and away from the shore at others. These currents have erosional effects that change the shape of the beach and the kinds of sediments on it.

Waves also erode bedrock that is exposed to their action. Weathering produces sediments that are then washed and scraped away by the impact of the waves. So wherever there are rocky slopes along an ocean shore, they are being worn away by the waves. Wave action is another instance of erosion by water—moving water, if not actually "running" water.

Density Currents. The erosional activity of water and wind—and even ice—may be familiar to you. You may have seen their effects in your environment, even if you were not conscious of the process at work before you started this course. There is another erosional agent that is seldom observed and whose existence has only recently been discovered. Much is still to be learned about it. This agent is called a *density current*. It can form and operate wherever two materials of different densities are in contact and one material is able to flow over or under the other. One detailed example will serve to illustrate some of the properties and effects this erosional agent may have.

In 1935 Hoover Dam was completed, creating a lake (called Lake Mead) almost 130 km long in the original channel of the Colorado River. It was well known before that time that the Colorado carries over a hundred billion kilograms of sediment each year. It was expected that this sediment would gradually accumulate and spread out over the floor of the lake.

Soon after the completion of the dam, scientists began to record a sediment flow along the floor of the lake of an unexpected kind. Once or twice a year, a thick flow of clay and water moved down the lake. This flow might take a week or more to travel the entire 130 km. When the flow reached the dam, the rise in lake floor level was sometimes as much as 10 m, settling out over a period of time to less than 6 m.

These flows were examined in detail in this natural laboratory. Figure 15-21 shows the results of this study. The mechanism of this flow is now understood to be associated with a density difference. The clay-laden water that arrives at the new mouth of the Colorado as it enters Lake Mead settles at first. Soon, however, the balance is upset, usually by a heavy flow of new sediment-laden water.

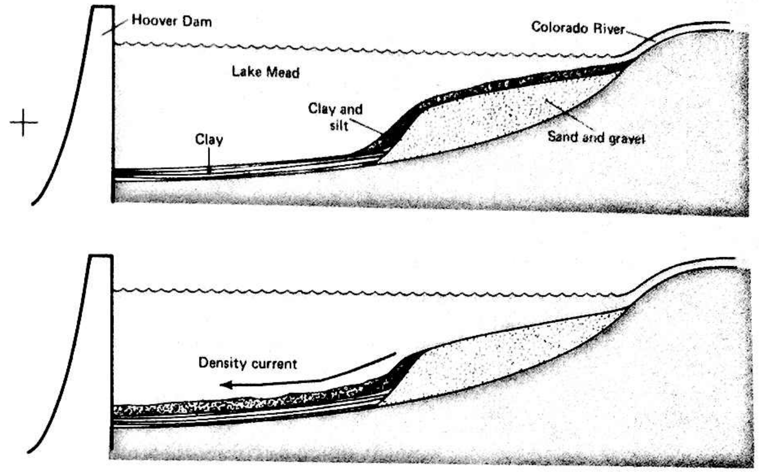


Figure 15-21. Density currents in Lake Mead.

This triggers the flow of a density current—the flow of the denser mixture of water and sediment down under the less dense, clearer water above.

Recent research indicates that this specialized type of transport may be of even greater importance than was first realized. Density flows have been observed along the margins of the continental shelf in the ocean. This may be an important mechanism for moving sediment to the deep ocean floor.

Effects on Sediments. If we review the processes of erosion that have been described in this chapter, we can see that each agent of erosion produces different effects on the sediments it transports. Erosion by running water rounds and smooths the particles it moves. Sediments moved by glaciers tend to retain their original irregular and sharp outlines. Wind-driven particles are well-rounded, but tend to have a frosted or finely pitted surface. These different effects are of importance to the earth scientist because they help him infer the process that brought sediments to where they are found. This, in turn, helps him infer the conditions that existed in the environment at the time the transport occurred. Very often, these conditions are quite different from those of the present environment. In later chapters we will see how some of these inferences can be applied.

SUMMARY

1. Moving ice, called glaciers, can erode rock and transport sediments.
2. Wind can transport sediment of sand size or smaller and can produce distinctive erosional effects, such as sand dunes.
3. Wave action has erosional effects on shoreline rocks and on beaches.
4. Density currents can transport sediments along underwater slopes.
5. Each agent of erosion produces distinctive changes in the material it transports.

REVIEW QUESTIONS

Group A

1. What are *transported sediments*?
2. What are *residual sediments*?
3. What is *erosion*?
4. Are transported sediments or residual sediments most common? Which type provides evidence of erosion?
5. What is the main driving force of all erosional processes?
6. What effects are produced by gravity acting alone as an erosional agent?
7. What is the predominant agent of erosion on the earth?
8. What is meant by the *drainage basin* of a stream system?
9. Name all the parts of a stream system.
10. What is the relationship between the slope of a stream bed and the average velocity of the stream?
11. How does an increase in the discharge of a stream affect its average velocity?
12. Describe the ways in which streams transport sediments.
13. What is the relationship between stream velocity and the size of the sediments that the stream can transport?
14. What is the relationship between the discharge of a stream and the amount of sediment that the stream can transport?
15. What type of stream is most effective in cutting through bedrock?
16. What is the shape of the valley of a young stream?
17. Describe the valley of a stream in the mature stage.
18. Describe a stream in old age.
19. What is a *glacier*?
20. What is the role of wind in erosion?
21. What causes erosion on shoreline rocks and on beaches?
22. How are sediments transported along underwater slopes?

Group B

1. a. Explain what observations would be needed to decide if a soil is residual or transported.
   b. Which is more important, weathering or erosion, in the formation of a residual soil? Explain.
   c. Which is more important, weathering or erosion, in the formation of a transported soil? Explain.
2. Why do earth scientists usually consider gravity to be necessary for erosion to occur?
3. a. The velocity of the water in a stream varies at different points across the stream's width and at different depths. Describe these differences and explain what causes them.
   b. Describe the various types of particles that may be eroded by running water.
   c. Explain what causes a stream to pass from youth to maturity and from maturity to old age.
4. List the observations that would lead you to believe that the following agents of erosion had been active in a particular area: (a) ice, (b) wind, (c) waves, (d) density currents.

REVIEW EXERCISES

1. In the study of weathering of tombstones in Connecticut (page 259), the investigator found that the surface facing west was most weathered and the surface facing north was least weathered. Present an hypothesis that explains this pattern of weathering.
2. Examine the outside walls of several old stone or brick buildings in your area. Determine which wall of each building shows the most weathering.
   a. Is the direction in which the most weathered wall faces the same for every building studied?
   b. In which direction do the walls showing the least weathering face?
   c. Are the results of your investigation the same as the results of the study of Connecticut tombstones? If so, do you think that the causes of the weathering pattern are the same in your area as in Connecticut?
   d. Examine several buildings that are either made of wood or have wooden parts. Can you observe the same kinds of weathering effects in the wood as you saw in the brick or stone? Is the order of weathering (by direction) the same for wood as for the stone or brick?
   e. Are the weathering effects that you have observed caused by physical or chemical weathering?
3. Figure 14-8 (page 269) shows the relationship between climate and weathering (Point *A* in that illustration is Middletown, Connecticut).
   a. What climatic changes would have to occur in the Middletown area for the type of weathering to change?
   b. Referring to Figure 14-8, find which type of weathering occurs in your local area. (To do this, you will have to have some idea of the average annual precipitation and average annual temperature of your area.)
   c. What would happen to the weathering pattern in your area if the average annual temperature increased over long periods of time by 5°C? What would happen if the average annual temperature decreased by 5°C?
4. Below are graphs showing average monthly temperatures and rainfall for locations in five different types of climates. Using information from the graphs and from Figure 14-8 (page 269), describe the type of weathering that would occur at each location.