GEOLOGIC PERSPECTIVES • HOW MOUNTAINS ARE FORMED • MOUNTAIN STRUCTURES • MOUNTAIN MATERIALS • WHERE TO GET GEOLOGIC INFORMATION

CHAPTER 26

MOUNTAIN GEOLOGY

Geology is essential knowledge: climbing success—or even your life—can depend on your understanding the form and substance of mountains. Climbers learn from experience that different types of rock affect what different routes are like, ranging from sheer walls to those having cracks and ledges galore. Climbers also discover that some kinds of rocks are very durable, whereas others crumble under pressure. This knowledge is important for the safe and well-rounded mountaineer.

GEOLOGIC PERSPECTIVES

Climbers can gain a better understanding of mountains by examining them on three scales: as an overall landscape, as a single outcrop, and as a close-up view of a single specimen of rock. Each perspective contributes to a broad comprehension of the mountain environment.

Landscape. The wide-angle landscape view examines the mountain as a whole, sometimes from miles away. Observing geology at this scale helps climbers find a viable route to the summit. Using photos or binoculars, look for routes with strong, supportive rock, or identify areas where rock may be weak and unreliable—in other words, places to trust and places to treat with caution. Ridges may follow a layer of resistant rock. Sets of fractures may offer a zigzag route to the summit. Sudden changes in slope may indicate a *fault* (a fracture along which movement has occurred) or an abrupt change in rock type.

Outcrop. The midrange perspective focuses on specific outcrops from 10 to 100 feet (3 to 30 meters) away. Here climbers can see features that could help—or hinder—an ascent. For example, a regular pattern of cracks is probably a good bet for chock placements, and a reliable avenue upward may be found in a *resistant dike,* which forms when the intrusive magma that has filled a fracture has cooled to form rock harder than the host rock.

Rock. At arm's length from the outcrop or closer, the details of the rock itself are more apparent. At this scale, climbers can identify rock types and recognize textures that might be difficult to climb or that might provide advantageous holds.

HOW MOUNTAINS ARE FORMED

The ultimate landscape view is the whole earth. When we look at mountain ranges on a global scale, we can see a clear pattern of their occurrence, and this pattern can be explained by plate tectonic processes. According to the theory of plate tectonics, the outermost layer of the earth (the *lithosphere*) is composed of plates that are slowly but constantly moving.

Most mountain ranges are formed by immense forces that squeeze rock masses together or pull them apart. Where tectonic plates move toward each other, their edges (*margins*) are called *convergent*. Where tectonic plates pull away from each other, their margins are called *divergent*. Along what are called *transform margins*, blocks of lithosphere move side by side and mountains rarely form. The sections below describe the two types of mountain-forming plate margins.

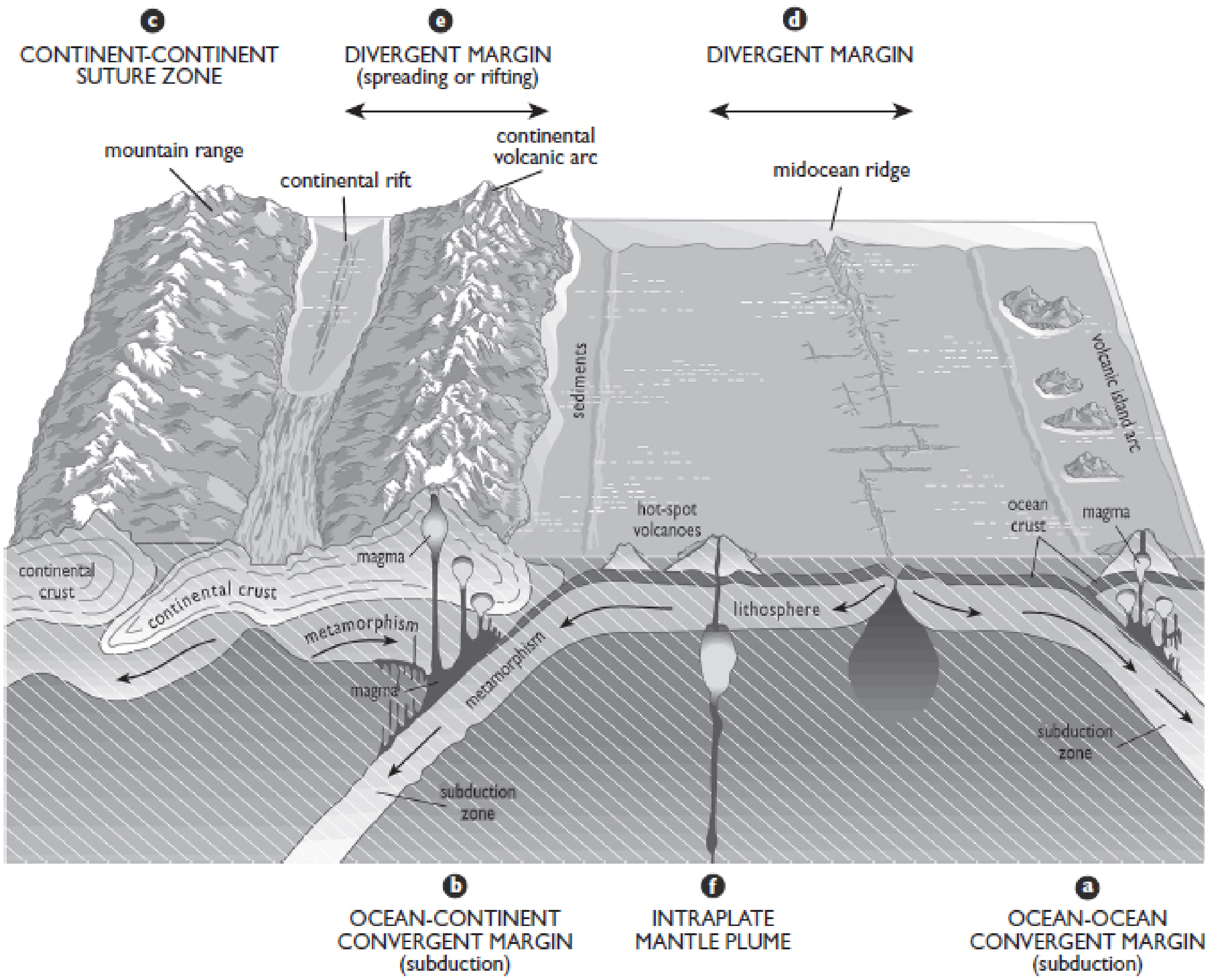

Fig. 26-1. Characteristic features of various types of convergent and divergent plate margins: a, ocean–ocean convergent margin producing a volcanic island arc; b, ocean–continent convergent margin producing a continental volcanic arc; c, continent–continent convergent zone producing a suture zone mountain range; d, oceanic divergent margin producing a midocean ridge; e, continental divergent margin producing a continental rift; f, intraplate mantle plume producing a chain of seafloor hot-spot volcanoes.

CONVERGENT PLATE MARGINS

Three varieties of convergent margins each produce a somewhat different type of mountain.

Ocean–Ocean Margins

Where two plates of oceanic lithosphere converge is called an *ocean–ocean margin* (fig. 26-1a). The older, colder slab forms a *subduction zone* by sinking beneath the younger, warmer slab. Deep within the subduction zone, 55 to 60 miles (90 to 100 kilometers) below the earth's surface, abundant *magma* (molten rock beneath the earth's surface) is formed and rises buoyantly. Over time, much of the magma makes its way to the surface, where a chain of oceanic island volcanoes grows. The island mountains of the Aleutians and Indonesia are two examples.

Ocean–Continent Margins

Subduction can also occur where oceanic lithosphere is subducted beneath the edge of a continent (fig. 26-1b). This produces a chain of volcanic mountains on land. Three types of volcanoes can be formed.

Shield volcanoes. Great conical stacks of basalt flows with gentle slopes, such as Belknap Crater in the Cascade Range of central Oregon, are shield volcanoes, which are uncommon.

Stratovolcanoes. Most of the climbing destinations along ocean–continent convergent margins are stratovolcanoes (also known as *composite volcanoes*), composed mainly of andesite and having steep slopes, such as Washington State's Mount Rainier and Mount Baker or Japan's Mount Fuji.

Cinder cones. Composed of pyroclastic fragments, cinder cones are generally only a few hundred feet high. Examples include the Black Buttes near Bend, Oregon, and Wizard Island in Oregon's Crater Lake.

As tectonic plates move, they cause various stresses—faulting, folding, and uplift—that create mountain structures (see "Mountain Structures" later in this chapter). These movements, as well as erosion, expose deeper layers of the earth's crust. For example, the schist and gneiss exposed in Washington's North Cascades originated as clay and silt on the seafloor 250 million years ago. During plate convergence, this material was buried as much as 100,000 feet (30,000 meters) beneath the earth's surface, where it was metamorphosed by heat and pressure into schist and gneiss. Continued plate convergence has now moved these rocks back to the surface in the northern part of the North Cascades range. To the south, volcanism has buried the metamorphic basement yet again and has built a chain of large stratovolcanoes that extends from British Columbia to northern California. Mountain ranges of similar origin include the Andes of South America and the Japanese Alps.

Suture Zones

Many of the major mountain ranges of the earth are found where continental plates or island arcs have smashed together as they have converged (fig. 26-1c). For example, the Himalayan range has been uplifted by the collision of India and Asia, Europe's Alps were created by Africa's northward push into Europe, and the Rocky Mountains were uplifted by the collision of numerous microplates that extended the edge of North America hundreds of miles westward over the past 170 million years. In these mountain ranges, faulting may thrust one part of the range over another. These huge thrust-faulted structures are well exposed in the Alps, the Canadian Rockies, and the North Cascades (see Figure 26-3).

DIVERGENT PLATE MARGINS

Where lithospheric plates diverge, the lithosphere is stretched and ultimately breaks apart, as when taffy is pulled too quickly. The most extensive divergent margins are the submarine mountain ranges of the midocean ridges (fig. 26-1d), but these are obviously inaccessible to climbers. Divergent margins also develop within continents (fig. 26-1e), and these definitely produce terrain of interest to mountaineers.

Continental rifts. As the lithospheric plates move apart along continental rifts, vertical faults break the crust into huge block-shaped mountains with nearly vertical faces on one side and gentler slopes on the other. These form great escarpments, such as East Africa's Great Rift Valley. Some mountains of the western United States, including Utah's Wasatch Range and California's Sierra Nevada, are fault-block ranges associated with stretching (extension) within the North American Plate rather than along its margin (see Figure 26-2).

Mountains created by extension generally have less *relief* (contrasting elevations) than those created by convergent margins, but not always. Mount Whitney, part of the Sierra Nevada, is the highest peak in the contiguous United States, at 14,494 feet (4,400 meters); Wheeler Peak of the Snake Range in eastern Nevada rises above 13,000 feet (4,000 meters).

Volcanism also affects the topography of rifted margins. Magma from the upwelling mantle beneath the rift can rise through faults to the surface, where over time it builds up both shield volcanoes and composite volcanoes, such as Africa's Mount Kilimanjaro.

INTRAPLATE HOT-SPOT VOLCANOES

The tallest mountain on Earth is not Mount Everest but, rather, the island of Hawaii, where the summit of Mauna Kea is 30,000 feet (9,000 meters) above the seafloor. Hawaii is part of a chain of volcanic islands and underwater sea-mounts that extend from the mid-Pacific nearly to Japan. These gigantic islands of basalt are the surface expression of thermal plumes, called *hot spots* (fig. 26-1f), that rise from the lower mantle toward the overlying lithosphere like a cumulus cloud building toward the stratosphere on a warm summer day. These plumes burn through the moving lithosphere, creating a chain of volcanoes built upward from the seafloor.

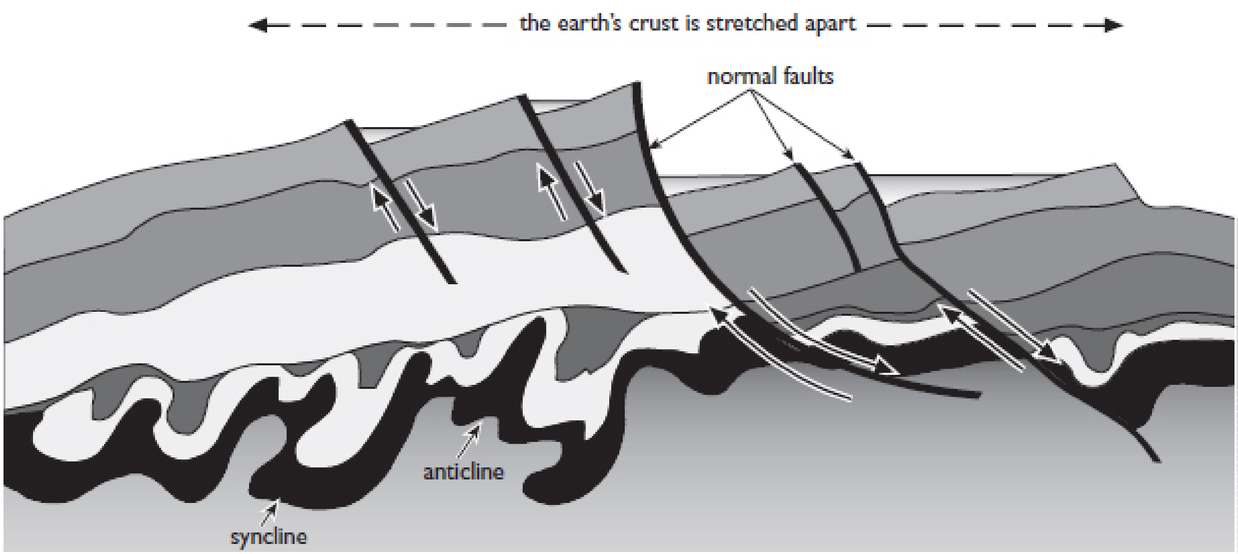

Fig. 26-2. Typical structures of a continental divergent plate margin, such as the Basin and Range of the western United States or the East African Great Rift Valley; note steep escarpment formed due to normal faulting.

Hot spots are also located within the continents—an example is the chain of volcanoes and lava flows (*lava* is rock that is molten at the surface of the earth) that extend across the Snake River Plain from near Boise, Idaho, northeast to Yellowstone National Park, where the plume is currently located. Because hot spots produce mainly shield volcanoes with gentle slopes, technical climbing is rarely required to ascend them. However, one of the most interesting traverses in the world is the trail to the summit of Mauna Loa on the island of Hawaii.

MOUNTAIN STRUCTURES

The slowest tectonic plates move at about the same velocity as fingernails grow, and the fastest move at about the same velocity as hair grows: a range of about 2 to 7 inches (5 to 17 centimeters) per year. Such slow movements cannot be seen, but the effect on the earth's surface can be profound. Slow as it is, this movement of the tectonic plates stresses rocks, and the results are the varying structures known as mountains. These stresses move mountains up, down, or from side to side and break them up into pieces. Near the earth's surface the rock layers are brittle, so they fracture into joints or move along faults. At greater depths, where the temperature and pressure are higher, the rocks tend to bend into folds rather than breaking.

FOLDS

Most sedimentary rocks are originally deposited in horizontal layers known as *beds*. However, in mountains such as the Front Range of Colorado, it is common to see beds that dip steeply or are even vertical. These rocks have been compressed into *folds*. This movement can be simulated by laying a napkin flat on a table and pushing its sides together, producing a series of archlike *anticlines* and troughlike *synclines* (fig. 26-2). Folds range in size from microscopic to a mile or more high. In some cases, such as the Ridge and Valley Province of the United States' Appalachians, the shape of the range is dictated by the underlying fold structure. The patterns of folds create ramps, overhangs, and resistant ridges that can be crucial factors in planning a route to a summit.

JOINTS AND VEINS

Joints are cracks that develop when rock masses expand or contract. Contraction joints are formed when hot rock shrinks during cooling. The only common kind of pure contraction jointing is the columnar structure of lava flows. The result is an array of roughly hexagonal columns that are typically 10 feet (3 meters) in height. Exceptionally high columns such as Devils Tower in Wyoming provide spectacular climbing opportunities.

Joints also develop when erosion exposes rocks that were once buried deeply within the earth, and as the overlying rocks are stripped away, fracturing can result from the once-buried rocks expanding upward. If the expansion joints develop parallel to the exposed surface (as at Half Dome in California's Yosemite National Park), rocks peel off in layers that are called *exfoliation joints* (fig. 26-3). Sets of joints commonly occur at angles of 30, 60, or 90 degrees to each other—and these joint angles tend to be persistent as long as the rock type is the same. Recognition of joint patterns is essential for routefinding, especially on vertical faces in granitic rocks, where joints could be the only path to the summit without aid climbing.

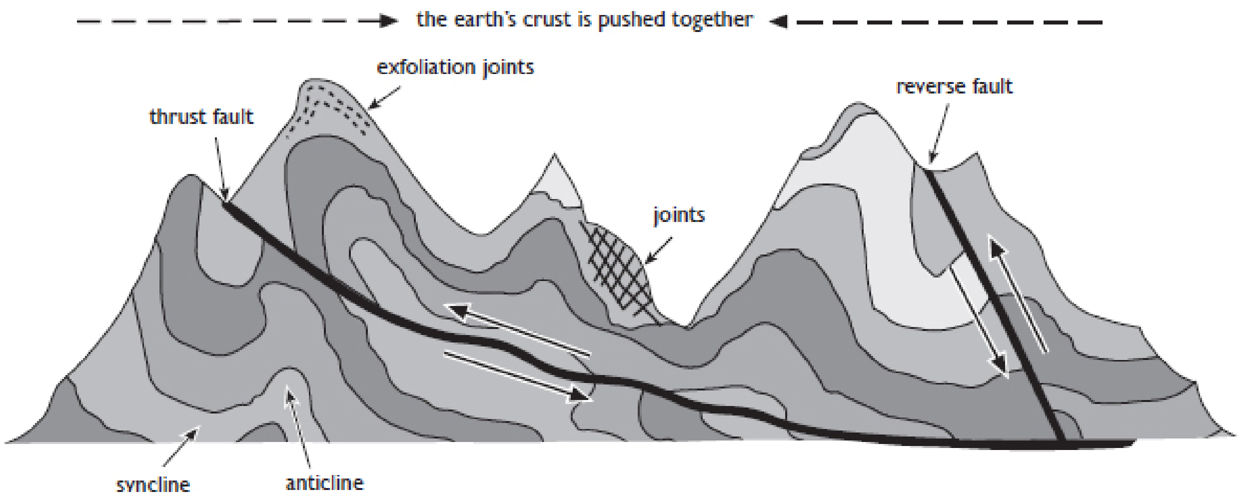

Fig. 26-3. Typical structures of a continental convergent margin, such as Europe's Alps, the Himalaya, and North America's Rocky Mountains.

Veins are fractures that have been filled by minerals, most commonly quartz or calcite. Veins can have an important effect on the texture of weathered rock surfaces. Quartz veins tend to project out as resistant ridges, whereas softer calcite veins are recessed. On some sheer faces, these can provide the only holds available, so the pattern of fractures determines where climbers should look for the next hand- or foothold.

FAULTS

Faults are fractures along which movement has occurred. The discernible movement may be only a fraction of an inch, or the movement can uplift a whole mountain range, such as Wyoming's Teton Range. Climbers need to know about faults because they can bring blocks of very different rock together. Fault zones also can consist of very weak, ground-up rock called *gouge* that may present a hazard to climbers.

Faults are classified according to their relative movement. *Normal faults* involve vertical movement that occurs when the earth's crust is stretched to the point of breaking (see Figure 26-2), as in the Basin and Range region of Nevada, Utah, and California. Vertical movement also occurs along *reverse faults* and along *thrust faults*, which are reverse faults with an angle of less than 20 degrees (as shown in Figure 26-3). Here the fault is caused by compression due to the collision of lithospheric plates; examples are Europe's Alps and the Himalaya.

Strike-slip faults (for example, the San Andreas Fault in California) move the lithosphere in a horizontal plane, rather than up and down. This can move mountains from place to place but generally does not cause uplift.

MOUNTAIN MATERIALS

The rocks that compose mountains are the foundation of the climbing experience. Each type of rock has a different fracture pattern, surface texture, and durability. The strength of rocks, as well as their resistance to erosion and weathering, depends on the minerals of which they are composed. This in turn determines the reliability of holds and the overall climbing strategy for different rock types.

MINERALS

Minerals (crystals that are solid and inorganic) have unique properties by which they can be identified: color, hardness, *cleavage* (the tendency to split along definite crystalline planes), luster, and crystal shape. Only seven minerals compose most rocks of the earth's crust. Six of these are silicate minerals: feldspar, quartz, olivine, pyroxene, amphibole, and biotite. Except for biotite, these silicates are generally hard, durable materials. Only one common mineral, calcite, is soft and soluble. Calcite is composed of calcium carbonate, the major ingredient in many antacid tablets. It is resistant and stable in arid climates but dissolves readily in humid climates—and in acid rain.

Feldspar and quartz are the most resistant to breakdown under the constant assault of weathering. They are also the most abundant rock-forming minerals, composing most granites and sandstones. The other silicates—olivine, pyroxene, amphibole, and biotite—are dark, iron-rich minerals. Pyroxene is commonly found in basalt and gabbro. Amphibole and biotite are familiar as the black crystals in granite, granodiorite, and diorite, as well as in many schists and gneisses.

ROCKS

Rocks are classified into three categories: *igneous* (crystallized from a melt), *sedimentary* (deposited as particles, precipitates, or organic matter), and *metamorphic* (recrystallized by heat and/or pressure). A mountain climber does not need to be an expert in classifying rocks. However, it is very useful to be able to recognize a few general categories, because different rock types call for very different climbing strategies.

The first thing climbers need to know is that rocks are like a box of chocolates: you cannot tell what "flavor" they are until you look inside each one. Weathering, lichens, and biofilms (groups of microorganisms that grow together and stick to a surface) obscure the surface of many rock outcrops. To identify a rock's true color and appearance, look for a fresh surface that has recently broken open. Beneath a brown exterior there may be a black basalt, a white rhyolite, or even a glassy obsidian.

The following sections contain a few generalities about what kinds of climbing are effective on some of the most common rock types.

Igneous Rocks

Igneous rocks (from the Latin *ignis*, meaning "fire") crystallize from magma or lava. They can be either *volcanic* rocks (named for Vulcan, the Roman god of fire), which form from lava that is extruded at the surface, or *plutonic* rocks (named for Pluto, the Roman god of the underworld), which form underground from magma. See Table 26-1.

Volcanic rocks. The two types of volcanic rock are *lava flows* and *pyroclastics*. Most lavas crystallize rapidly under conditions of supercooling, so they commonly consist mainly of very tiny mineral grains that are invisible without magnification. However, they often include large crystals that formed in magma chambers underground before eruption. The composition of lava flows is essentially the same as their plutonic counterparts, the granitoids—in others words, rhyolite has the same chemical composition and minerals as granite, andesite matches diorite, and basalt matches gabbro (see Table 26-1). Most lava flows make very good climbing rock. Exceptions are lavas that are full of small cavities formed by gas bubbles and flows that have been chemically altered (*alteration zones*) by corrosive volcanic gases. This type of lava flow, which is composed of crumbly rock that is hazardous to climb, can be found on most volcanoes.

Pyroclastics are deposits of volcanic rock fragments produced by explosive eruptions. These include outcrops of ash and pumice that tend to fail unpredictably and therefore should be avoided on climbing routes if possible. Many pyroclastics also show some degree of chemical alteration. Anyone climbing stratovolcanoes from the Aleutians to the Andes should be aware of this potential hazard.

TABLE 26-1. CLASSIFICATION OF IGNEOUS ROCKS

Color and Mineral Content	**Volcanic (extrusive):** fine-grained rock erupted as lava or ash; cools quickly; may contain small holes or crystals	**Plutonic (intrusive):** coarse-grained rock that cools and crystallizes slowly underground
Light-colored; very little iron content	Rhyolite or dacite (black, glassy = obsidian)	Granite or granodiorite
Usually gray; moderate iron content	Andesite	Diorite
Dark (black to green-black); high iron content	Basalt	Gabbro or peridotite (rare)

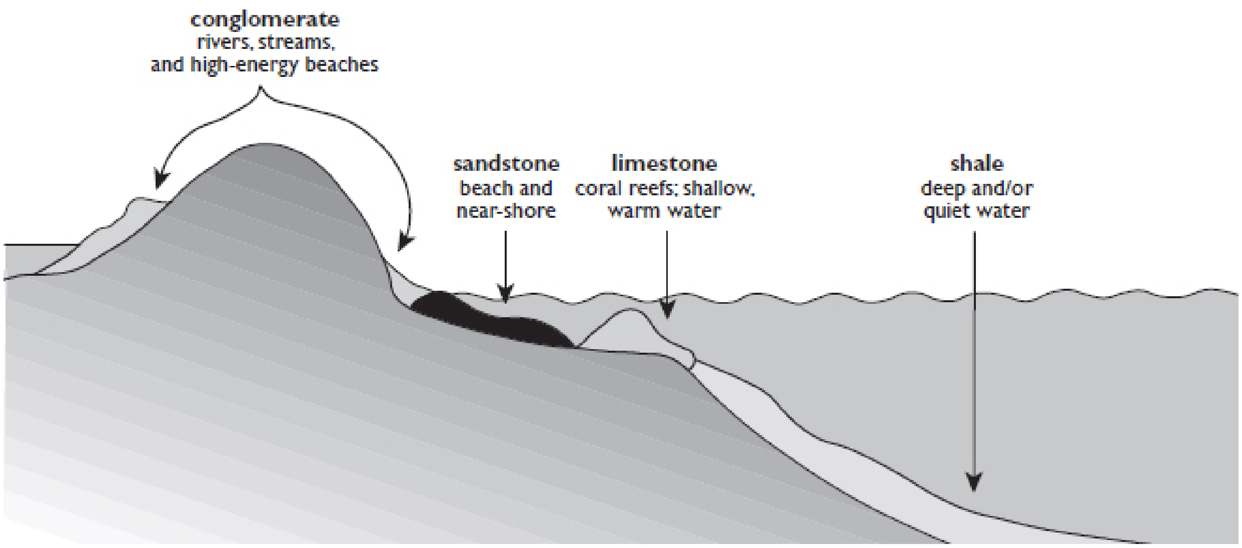

Fig. 26-4. Environments of deposition of various kinds of sedimentary rocks.

Plutonic rocks. The most common plutonic rocks are the coarse-grained granitoids—granite, granodiorite, and diorite. Granitoids are very durable unless highly weathered. They tend to have multiple fracture planes that define crack systems toward the summit or chimneys if accentuated by weathering. A good way to check the reliability of protection in granitoid rock is to hit it with a hammer. If it rings, it is good rock; if it makes a dull thud, be careful.

Sedimentary Rocks

Most sedimentary rocks are made of three types of material: fragments (*clastics*) of preexisting rocks, *precipitates* from solution (chemical), or organic material. Clastic rocks are classified according to the size of fragments in the rock. Fine-grained rocks, including thinly bedded *shales*, are the products of deposition in quiet, low-energy environments such as lakes or the seafloor. Coarse-grained clastic rocks, including *sandstones* and *conglomerates*, are transported and deposited in higher-energy regimes such as stream channels and beaches washed by waves crashing onshore (fig. 26-4).

Sandstone with silica cement (*gritstone*) is, for many, the most desirable rock to climb. It has continuous fracture systems, as do granitoids, coupled with high friction from its sandpapery surface formed of quartz and feldspar grains. Sandstone outcrops are commonly slabby, with many reliable hand- and footholds. Sandstone provides good protection unless it is highly weathered or poorly cemented. Note that sandstone can be weak when wet.

Shale is also slabby, but because it is composed chiefly of soft clay, it crumbles just as easily as do altered pyroclastics. The best protection is probably a long, thin blade driven between layers, but nothing should be trusted. Avoid shale if possible, but be aware that it is commonly found in layers between sandstones.

Limestones, composed of chemical precipitates or organic material, are deposited in warm equatorial seas. Routefinding on limestone can be challenging because crack systems are far less continuous than on granitoid rocks. Also, limestone is composed of the soft mineral calcite, so if protection points are stressed during an ascent, as in the event of a leader fall, they can degrade and fail. Where limestone has been below the water table before uplift, it can have many solution cavities, caves, and overhangs that make climbing interesting.

Metamorphic Rocks

Metamorphic rocks are igneous or sedimentary rocks that have been recrystallized by heat and pressure. The most distinctive change is *foliation*, wherein minerals are aligned like the grain in wood; foliation is found in slates, phyllites, schists, and gneisses. Foliation is a plane of weakness in the rock, from a rock climber's viewpoint. This weakness dominates in slate, which is fine-grained. If you try to drive a piton parallel to the foliation, a slab of rock will easily split off that looks like a piece of blackboard. *Schist*, which has mineral grains coarse enough to be visible, has more resistance to splitting, but protection is still poor if it is placed parallel to the foliation. Most *gneisses* are similar to granitoids in strength, but climbers should still be aware of the foliation plane.

There are also several nonfoliated metamorphic rock types, including quartzite, marble, and hornfels. *Quartzite*, like sandstone, is a climber's favorite. It is slabby, with long, continuous fractures, and forms very solid outcrops, but it lacks the friction of sandstone, especially when wet. Note that in the alpine zone, where extensive freezing and thawing occur, quartzite slabs can sluff off, but not as easily as sandstone does. *Marble* is similar to limestone in that it is composed of soft calcite that is easily degraded and soluble in humid climates. It tends to have more continuous fractures than limestone, but expect unusual topography. *Hornfels* is a rock formed by heat along the margin of granitoid plutons. It is very hard and brittle. Chocks and cams work well in this rock, but the acts of driving pitons and placing bolts can splinter it.

Climbers should be aware of metamorphic changes along fault zones. In the shallow part of faults, movement shatters or grinds rock into *gouge.* Decomposition can also occur if hot fluids circulate through the fractured rock. Both the gouge and decomposed rock are very weak and are unreliable for protection. Deeper in the fault zone, rocks tend to flow rather than break. This produces *mylonites*, which have an intense foliation and are generally as unreliable as schist for protection points.

WHERE TO GET GEOLOGIC INFORMATION

The primary provider of geologic maps and information in the United States is the US Geological Survey (USGS); its website is the gateway to a cornucopia of geologic data for the entire world (see Resources for all websites mentioned here). Check out links to the USGS map finder—a clickable set of maps showing the name and location of all available 7.5-minute topographic maps. Another useful service of the USGS is the National Geologic Map Database. A new venture of the USGS is the Geology in the Parks program, which provides information via a website and brochures in cooperation with the National Park Service.

Other federal agencies that dispense geologic data are the US Forest Service and the US Bureau of Land Management. Nearly all of the state geological surveys also maintain websites with abundant geologic information; links to state geological surveys are listed online.

Another useful tool for planning climbing trips, Google Earth is a virtual mapping program that displays satellite images. The free program can be downloaded or accessed online. It allows climbers to easily see the terrain and specific features for almost any mountain on Earth, facilitating route planning.

Many mobile applications today provide accessible and useful information via phones and other mobile devices. The caveat to this is not all backcountry areas have data access, so climbers must download this information ahead of time for offline access in the field.

To get a site-specific geologic map or details on the geology of a chosen climbing route, there is no better place than the nearest college geology department. Many have websites with a lot of local geologic information, and all have faculty and students who are avid climbers and know exactly what rocks and structures they have seen on different routes.

Better still, start looking carefully and making detailed notes on the geologic features of the routes that you climb. Climbers are in effect practicing geologists, interpreting rock types and structures as they ascend. Personal observations are the best way to learn how to read the rocks for future climbs.