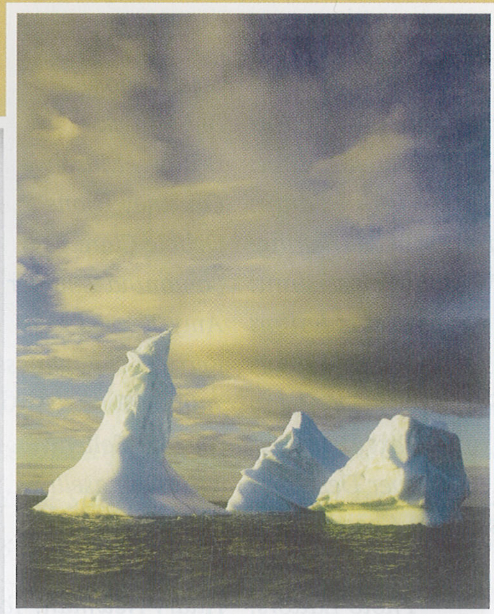

Earth's Climate

PAST AND FUTURE

Third Edition

WILLIAM F. RUDDIMAN

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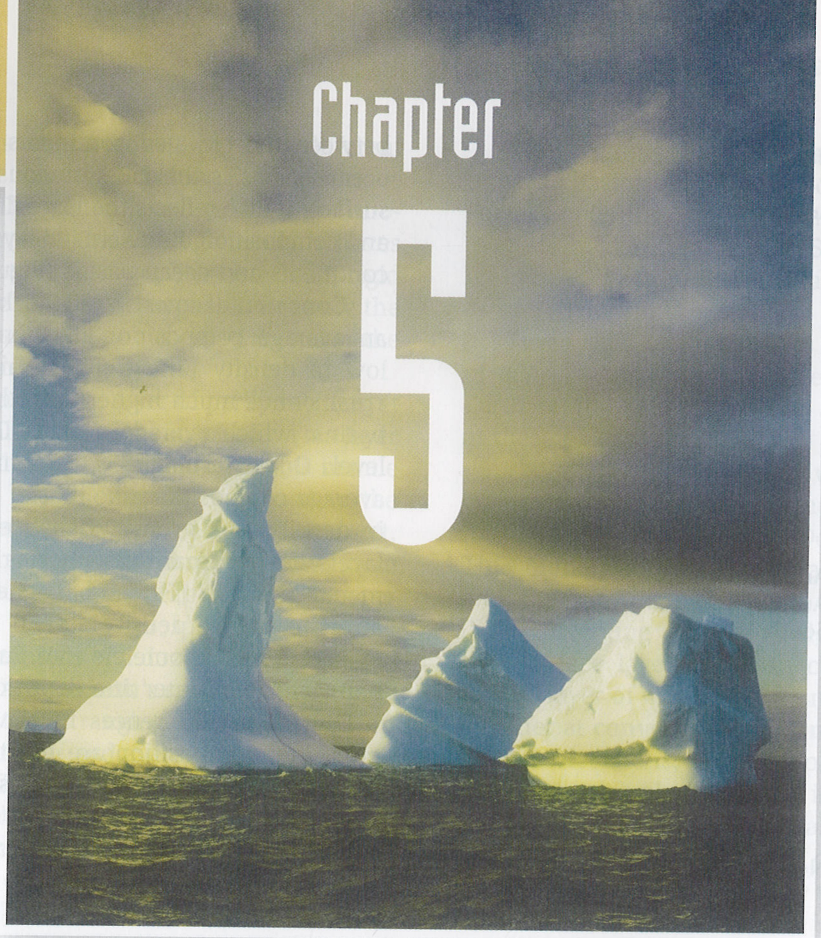

Chapter 5

Plate Tectonics and Long-Term Climate

The last 550 million years of Earth's history are far better known than the first 4 billion years. From this time forward to the present, the locations of the continents and the shapes of the ocean basins become progressively clearer. Better-preserved sedimentary rock archives also hold more abundant evidence of past climates, including alternations between icehouse intervals with large ice sheets present and greenhouse intervals without ice on land (Figure 5-1). These fluctuations are the focus of this chapter.

First we examine how plate tectonic processes work. Next, we explore the possibility that icehouse intervals occur when plate tectonic motions shift continents across cold polar regions. Then we use climate models to investigate the factors that controlled climate 200 million years ago, a time when all landmasses on Earth existed as a single giant continent. These investigations reveal that changes in atmospheric CO_2 levels are needed to explain the sequence of changes from icehouse to greenhouse conditions over the last half-billion years. Finally, we evaluate two hypotheses that link changes in plate tectonic processes to changes in CO_2 levels.

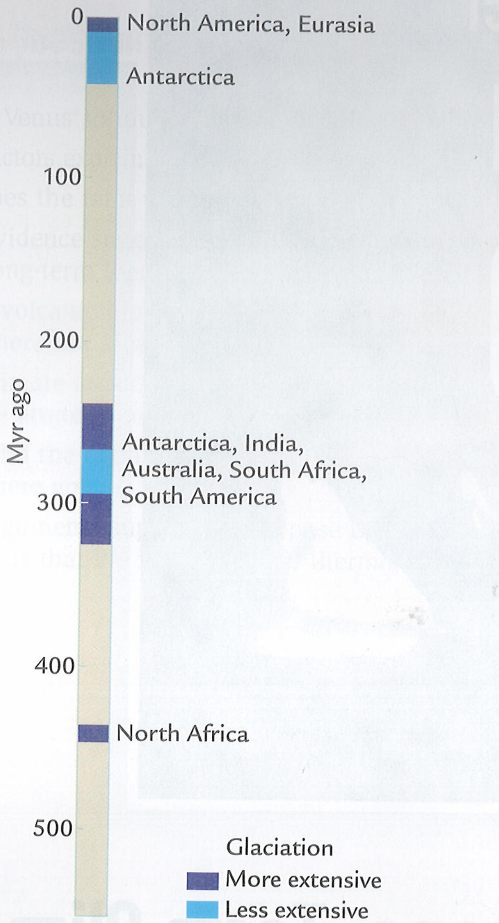

FIGURE 5-1
Icehouse intervals
Three intervals of major glaciation occurred during the last 500 Myr.

Plate Tectonics

In 1914, the German meteorologist Alfred Wegener proposed that continents have slowly moved across Earth's surface for hundreds of millions of years. He based his hypothesis in part on the obvious fact that continental margins such as those of eastern South America and western Africa fit together like pieces of a jigsaw puzzle. Research in the last half of the twentieth century showed that Wegener was correct in claiming that these continents were once joined and have since moved apart, but that he underestimated the mobility of Earth's outer surface. In fact, *all* of Earth's surface is on the move.

5-1 Structure and Composition of Tectonic Plates

Wegener's assumption that continents move in relation to ocean basins had a reasonable basis. The contrast between the elevated continents and the submerged ocean basins is the most obvious division on Earth's surface. It also reflects the large difference in thickness and composition of the crustal layers that comprise the continents and ocean basins (Figure 5-2).

Continental crust is 30–70 kilometers thick, has an average composition like that of granite, and is low in density (2.7 g/cm^3). This thick, low-density crust stands much higher than the floor of the ocean basins, which average near 4,000 meters below sea level. **Ocean crust** is 5–10 kilometers thick, has an average composition like that of basalt, and is higher in density (3.2 g/cm^3). Below each of these crustal layers lies the **mantle**, which is richer in heavy elements like iron (Fe) and magnesium (Mg) and has an even higher density (> 3.6 g/cm^3). The mantle extends 2,890 kilometers into Earth's interior, almost halfway to its center at a depth of 6,370 kilometers.

But these differences in elevation, crustal thickness, and composition are not the primary explanation for the fact that continents (and ocean basins) move. Instead, the critical reason for this mobility lies in the way different layers of rock behave.

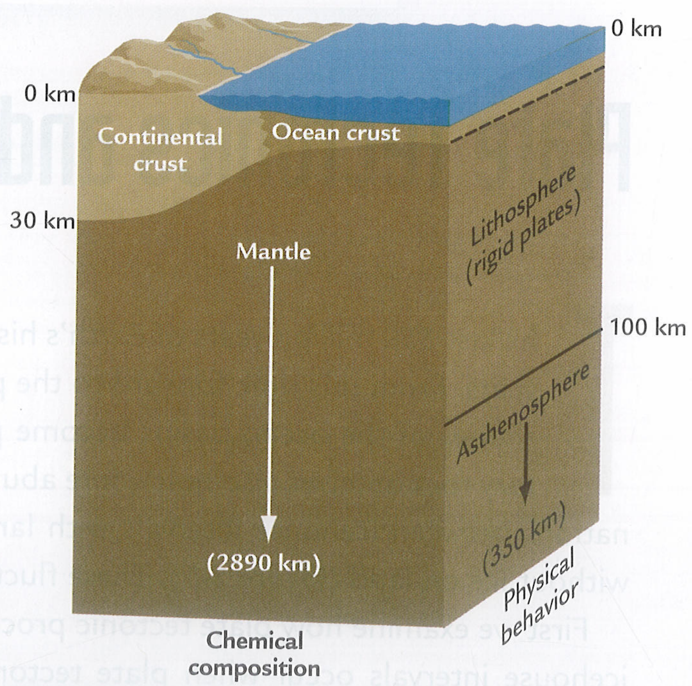

FIGURE 5-2
Earth's structure
Earth's outer layers can be subdivided in two ways. The basalts of ocean crust and the granites in continental crust differ from each other and from the underlying mantle in chemical composition. The other division is physical behavior: the lithosphere that forms the tectonic plates is hard and rigid, whereas the underlying asthenosphere is softer and capable of flowing slowly.

Two rock layers characterized by very different long-term behavior exist well below Earth's surface (see Figure 5-2). The outer layer, called the **lithosphere**, is 100 kilometers thick and generally behaves just the way the word "rock" implies: as a hard, rigid substance. The lithosphere encompasses not only the crustal layers (oceanic and continental) but also the upper part of the underlying mantle.

Below the lithosphere is a layer of partly molten yet mostly solid rock called the **asthenosphere**. This layer lies entirely within the upper section of Earth's mantle at depths of 100 to 350 kilometers. Compared to the rigid lithosphere, this deeper layer behaves like a soft, viscous fluid over long intervals of time, and flows more easily. It is the viscous behavior of this "softer" deeper layer that allows the overlying lithosphere to move.

The lithosphere consists of a dozen **tectonic plates**, each drifting slowly across Earth's surface (Figure 5-3). These plates move at rates ranging from less than 1 up to 10 centimeters per year and average about the same rate of growth as a fingernail. Over a time span of 100 million years, even slow plate motions of 5 centimeters per year add up to shifts of 5,000 kilometers, enough to create or destroy an entire ocean basin.

Most tectonic plates consist not just of continents or ocean basins but rather of combinations of the two. For example, the South American plate in Figure 5-3 consists of the continent of South America and the western half of the South Atlantic Ocean, all moving as one rigid unit.

These rigid tectonic plates have three basic types of edges, or margins. Most tectonic deformation on Earth (earthquakes, faulting, and volcanoes) occurs at these plate margins (Figure 5-4).

Plates move apart at **divergent margins**, the crests of ocean ridges like the one that runs down the middle of the Atlantic Ocean (see Figure 5-3). This motion allows new ocean crust to be created, and the new crust spreads away from the ridge. Plates diverging at ocean ridges carry not just the near-surface layer of ocean crust but also a much thicker layer of mantle lying underneath. Plates come together at **convergent margins** (see Figure 5-4 left). At these locations, the lithosphere (ocean crust and upper mantle) plunges deep into Earth's interior at ocean trenches in a process called **subduction**.

Some convergent margins occur along continent-ocean boundaries, such as the western coast of South

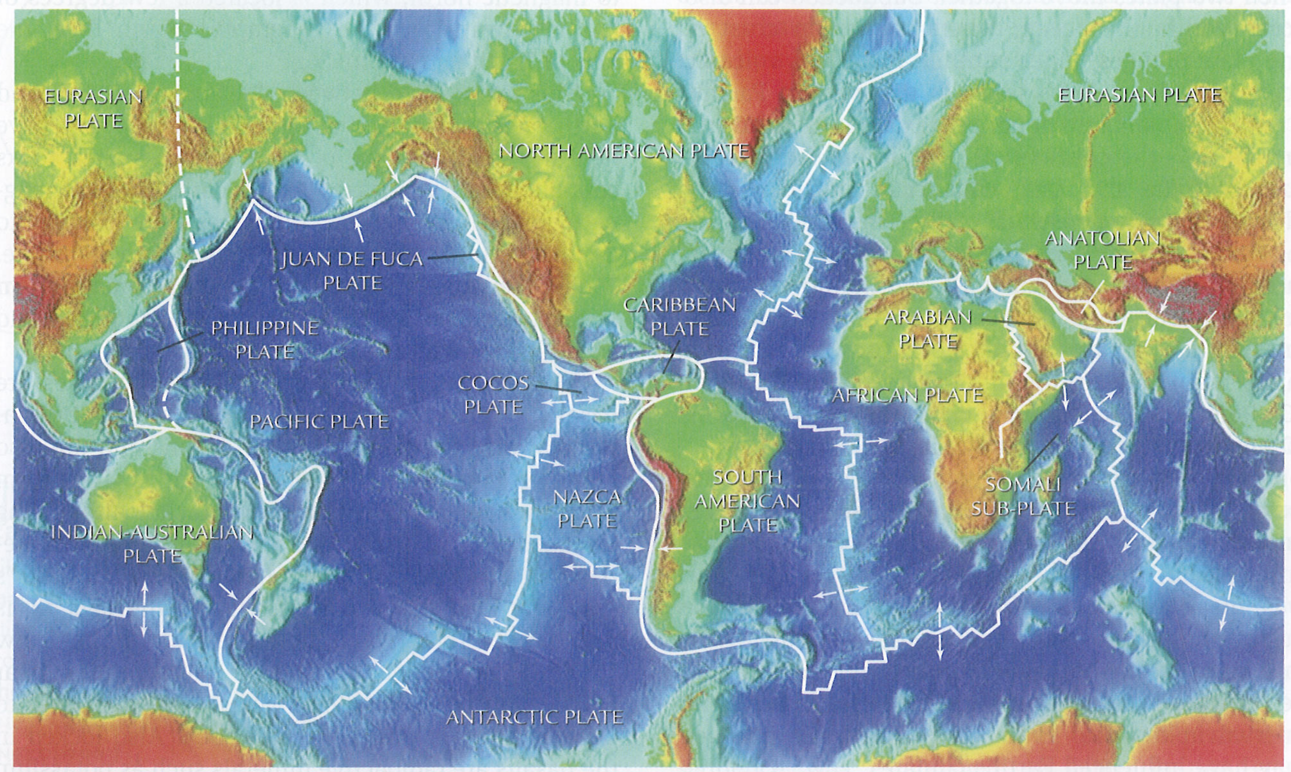

FIGURE 5-3
Tectonic plates
Earth's lithosphere is divided into a dozen major tectonic plates and several smaller plates, which move as rigid units in relation to one another, as the arrows indicate. (COURTESY NATIONAL GEOPHYSICAL DATA CENTER, NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, U.S. DEPARTMENT OF COMMERCE.)

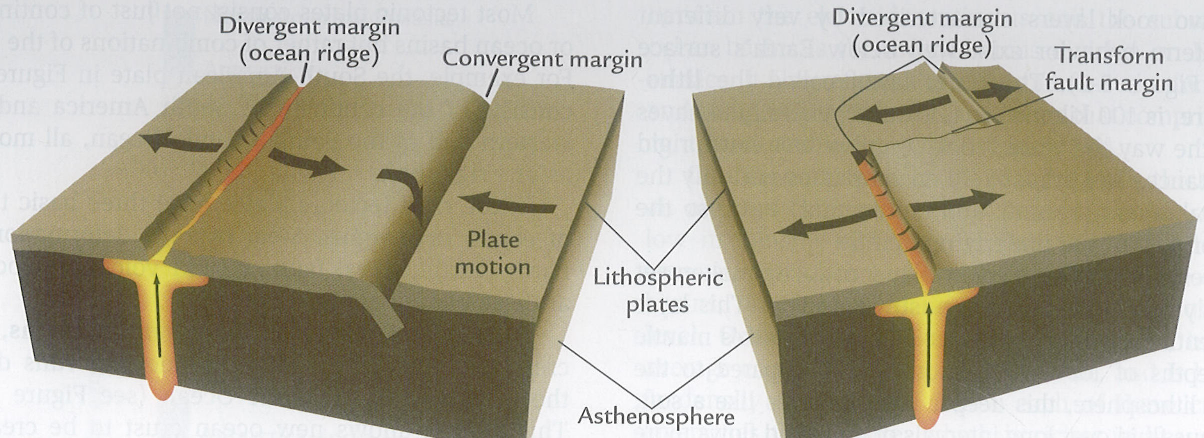

FIGURE 5-4
Plate margins
Earth's tectonic plates move apart at ocean ridges (divergent margins), slide past each other at faults (transform fault margins), and push together at convergent margins. (MODIFIED FROM F. PRESS AND R. SIEVER, *UNDERSTANDING EARTH*, 2ND ED., © 1998 BY W. H. FREEMAN AND COMPANY.)

America. In this case, narrow mountain chains such as the Andes form on the adjacent continents because of the compressive (squeezing) forces produced when two plates move together. Subduction can also occur within the ocean, where the ocean crust of one plate plunges under another and forms volcanic ocean islands, such as those in the western Pacific. A less common but important example of converging plates is the **continental collision** of landmasses such as India and Asia, which can create massive high-elevation regions such as the Tibetan Plateau.

Plates also can slide past each other at **transform fault margins** (see Figure 5-4 right), moving horizontally along faults such as the San Andreas Fault in western California. Sliding of plates at transform faults again involves the lithosphere—both the upper 30 kilometers of continental crust and the underlying 70 kilometers of upper mantle.

Even though geoscientists do not yet know the exact balance of forces that have caused past movements of plates and eventually produced their present distributions, they can accurately measure the way these processes have changed Earth's surface during the last several hundred million years. With this knowledge, the history of tectonic changes can be compared with changes in climate over the same interval in order to evaluate how tectonic changes may have influenced Earth's climate.

5-2 Evidence of Past Plate Motions

The past effects of plate tectonics in rearranging Earth's geography can be assessed from a broad range of evidence, the most important of which starts with the fact that Earth has a **magnetic field**. Molten fluids circulating in Earth's liquid iron core today create a magnetic field analogous to that of a bar magnet (Figure 5-5). Compass needles today point to magnetic north, which is located a few degrees of latitude away from the geographic North Pole, the axis of Earth's rotation.

This close link between "magnetic north" and Earth's north-polar axis of rotation is assumed to have held in the past. Some of Earth's once-molten rocks contain "fossil compasses" that record their past magnetic field. These natural compasses were frozen into the rocks shortly after they cooled from a molten state. Today, they give scientists studying **paleomagnetism** a way to reconstruct past positions of continents and ocean basins with respect to the pole of rotation.

The best rocks to use as ancient compasses are basalts, which are rich in highly magnetic iron. Basalts form the floors of ocean basins and are also found on land in actively tectonic regions. They form from molten lavas, which cool quickly after being extruded onto Earth's surface. As the molten material cools, its iron-rich components align with Earth's magnetic field like a compass. After the lava turns into basaltic rock (when its temperature drops below 1,200°C), continued cooling to temperatures near 600°C allows the "fossilized" magnetic compasses to become fixed in position in the rock. Also locked in the basalts are radioactive minerals such as potassium (K). Their slow decay (see Chapter 3) can date the time when the basalt layers cooled and acquired their magnetic compasses.

Paleomagnetism is used to reconstruct changes in the configuration of Earth's surface in two ways. (1) Back to about 500 million years ago (and in some cases earlier), paleomagnetic compasses recorded in

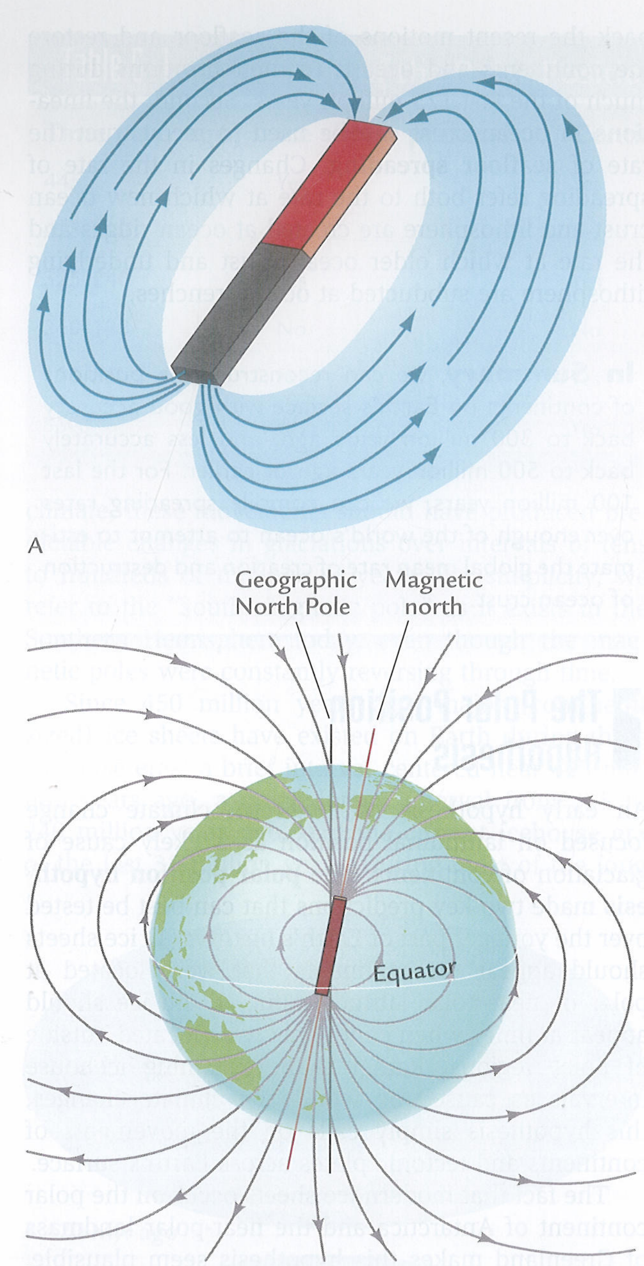

FIGURE 5-5
Earth's magnetic field
Like the magnetic field indicated by iron filings around a bar magnet (A), Earth has a magnetic field that determines the alignment of compass needles (B). Basaltic rocks contain iron minerals that align with Earth's prevailing magnetic field shortly after the molten magma cools to solid rock. (B: F. PRESS AND R. SIEVER, *UNDERSTANDING EARTH*, 2ND ED., © 1998 BY W. H. FREEMAN AND COMPANY.)

continental basalts can be used to track movements of landmasses with respect to latitude. (2) Over the last 175 million years, paleomagnetic changes recorded in basaltic oceanic crust can be used to reconstruct movements of plates and (over part of that interval) rates of spreading of the seafloor.

PALEOMAGNETIC DETERMINATION OF PAST LOCATIONS OF CONTINENTS Because ocean crust is constantly being destroyed at convergent plate boundaries, no ocean crust older than 175 million years survives except as highly altered fragments crumpled along continental margins. For older intervals, paleomagnetism must rely on basalts deposited on the continents. The orientations of the magnetic compasses frozen in these basalt layers are used to determine the past latitude of that rock (and of the portion of continental crust in which it is embedded) in relation to the magnetic poles.

In molten lavas that cool at high latitudes, the internal magnetic compasses point in a nearly vertical direction because Earth's magnetic field has that orientation at high latitudes (see Figure 5-5B). In contrast, lavas that cool near the equator have internal compasses oriented closer to horizontal, nearly parallel to Earth's surface. After they form, the basaltic rocks may be carried across Earth's surface by plate tectonic processes, but the angle of dip of their embedded magnetic compasses still records the latitude at which they formed. Rocks older than about 500 million years are less reliable for these studies because of the increasing likelihood that their magnetic compasses have been reset to the magnetic field of a later time by subsequent tectonic activity.

PALEOMAGNETIC DATING OF OCEAN CRUST Paleomagnetism is also used to trace the movement of the seafloor during the last 175 million years because of an entirely different aspect of Earth's magnetic field: the fact that it has repeatedly reversed direction. Compasses that today point to magnetic north in the present "normal" magnetic field would have pointed to magnetic south (a position very near the South Pole) during times when the field was in a "reversed" orientation.

Past changes in the magnetic field are recorded in fossil magnetic compasses in well-dated basaltic rocks from many regions. Because widely dispersed basaltic rocks have yielded the same sequence of reversals through time, the magnetic-reversal history they record must be a worldwide phenomenon. The reversals occur at irregular intervals ranging from as long as several million years to as short as a few thousand years.

Soon after this worldwide magnetic reversal sequence was established on land, marine geophysicists found stripe-like magnetic patterns called **magnetic lineations** on the ocean floor (Figure 5-6). Ships surveying the ocean towed instruments that measured Earth's regional magnetic field. To the surprise of most scientists, these magnetic lineations along the flanks of the mid-ocean ridges were found to be symmetrical around the ridge axis.

Even more surprisingly, the mapped pattern of horizontal highs and lows measured in the magnetic lineations at sea closely matched the pattern of normal and reversed intervals defined by the magnetic-reversal history from basalt sequences on land. Because of this match, scientists realized that the time framework that had been developed on land could be transferred directly to the lineations in the ocean. Based on this remarkable link, ocean crust could be dated in any region where ships measured the magnetic lineations.

This unexpected match of magnetic patterns on land with those in the ocean proved that new (zero-age) ocean crust is constantly being formed at the crests of the ocean ridges and that the ocean crust and underlying lithosphere then slowly move away from the ridge axis in both directions. As a result, the age of the ocean crust steadily increases with distance from the ridges (see Figure 5-6).

Scientists have now used this information about the age of existing ocean crust to evaluate causes of past climate changes in two ways. First, the dated magnetic lineations on the seafloor can be used to roll back the recent motions of the seafloor and restore the continents and oceans to their positions during much of the last 175 million years. Second, the lineations in ocean crust can be used to reconstruct the rate of **seafloor spreading**. Changes in the rate of spreading refer both to the rate at which new ocean crust and lithosphere are created at ocean ridges and the rate at which older ocean crust and underlying lithosphere are subducted at ocean trenches.

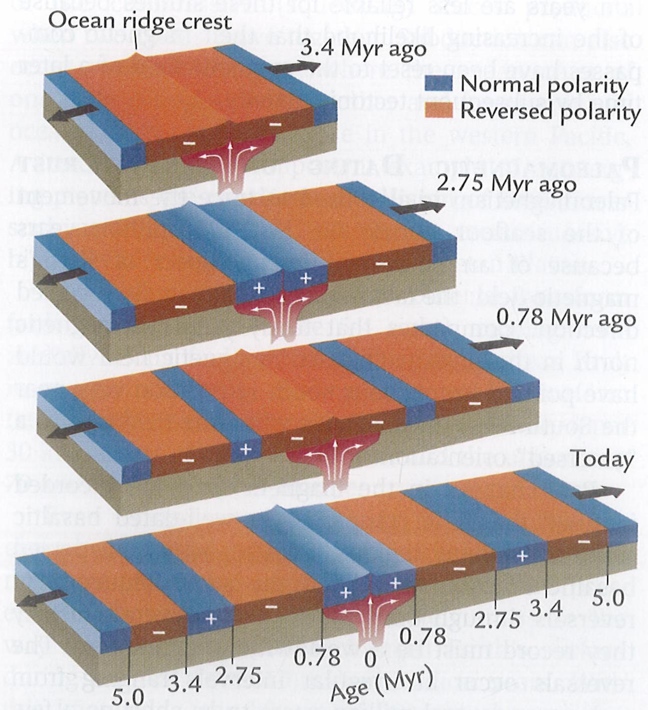

FIGURE 5-6
Magnetization of ocean crust
As molten lava erupts at the seafloor, cools, and solidifies, successive bands of ocean crust form and are magnetized in the normal or reversed polarity prevailing at the time. As the plates move apart, equal amounts of magnetized crust are carried away from the ridge axis in both directions and can be used to date the seafloor. (MODIFIED FROM F. PRESS AND R. SIEVER, *UNDERSTANDING EARTH*, 2ND ED., © 1998 BY W. H. FREEMAN AND COMPANY.)

In Summary, we can reconstruct the positions of continents on Earth's surface with good accuracy back to 300 million years ago, and less accurately back to 500 million years ago or earlier. For the last 100 million years, we can compile spreading rates over enough of the world's ocean to attempt to estimate the global mean rate of creation and destruction of ocean crust.

The Polar Position Hypothesis

An early hypothesis of long-term climate change focused on latitudinal position as a likely cause of glaciation of continents. The **polar position hypothesis** made two key predictions that can best be tested over the younger part of Earth's history: (1) ice sheets should appear on continents that were located at polar or near-polar latitudes, but (2) no ice should appear at times when continents were located outside of polar regions. Rather than explaining icehouse intervals as caused by worldwide climate changes, this hypothesis simply calls on the movements of continents and tectonic plates across Earth's surface.

The fact that modern ice sheets occur on the polar continent of Antarctica and the near-polar landmass of Greenland makes this hypothesis seem plausible. Modern ice sheets exist at high latitudes for several reasons: cold temperatures caused by low angles of incident solar radiation, high albedos resulting from the prevalent cover of snow and sea ice that reflect most solar radiation, and sufficient moisture to replenish the ice despite melting along their lower margins (see Chapter 2).

5-3 Glaciations and Continental Positions since 500 Myr Ago

We can directly test the polar position hypothesis against evidence in the younger geologic record. Over the last 450 million years, seafloor spreading has slowly moved continents across Earth's surface between the warmer low latitudes and colder high latitudes (Table 5-1). If latitudinal position alone controls climate, these movements should have produced predictable changes in glaciations over intervals of tens to hundreds of millions of years. For simplicity, we refer to the "south magnetic pole" as it exists in the Southern Hemisphere today, even though the magnetic poles were constantly reversing through time.

Since 450 million years ago, major (continent-sized) ice sheets have existed on Earth during three icehouse eras: a brief interval centered near 445 million years ago, a much longer interval from 325 to 240 million years ago, and the current icehouse era of the last 35 million years. During most of the long intervening intervals (430–325 Myr and 240–35 Myr ago), large ice sheets do not seem to have existed.

Near 420 million years ago, small landmasses that were later to form modern North America and the northern part of Eurasia lay scattered across a wide range of latitudes (Figure 5-7A). The other land areas, equivalent to modern Africa, Arabia, Antarctica, Australia, South America, and India, were combined in a much larger southern supercontinent called **Gondwana**. Gondwana was located on the opposite side of the globe from North America, but it had begun a long trip that would carry it

Table 5-1 Evaluation of the Polar Position Hypothesis of Glaciation

Time (Myr ago)	Ice sheets present?	Continents in polar position?	Hypothesis supported?
445	Yes	Yes	Yes
425–325	No	Yes	No
325–240	Yes	Yes	Yes
240–125	No	No	Yes
125–35	No	Yes	No
35–0	Yes	Yes	Yes

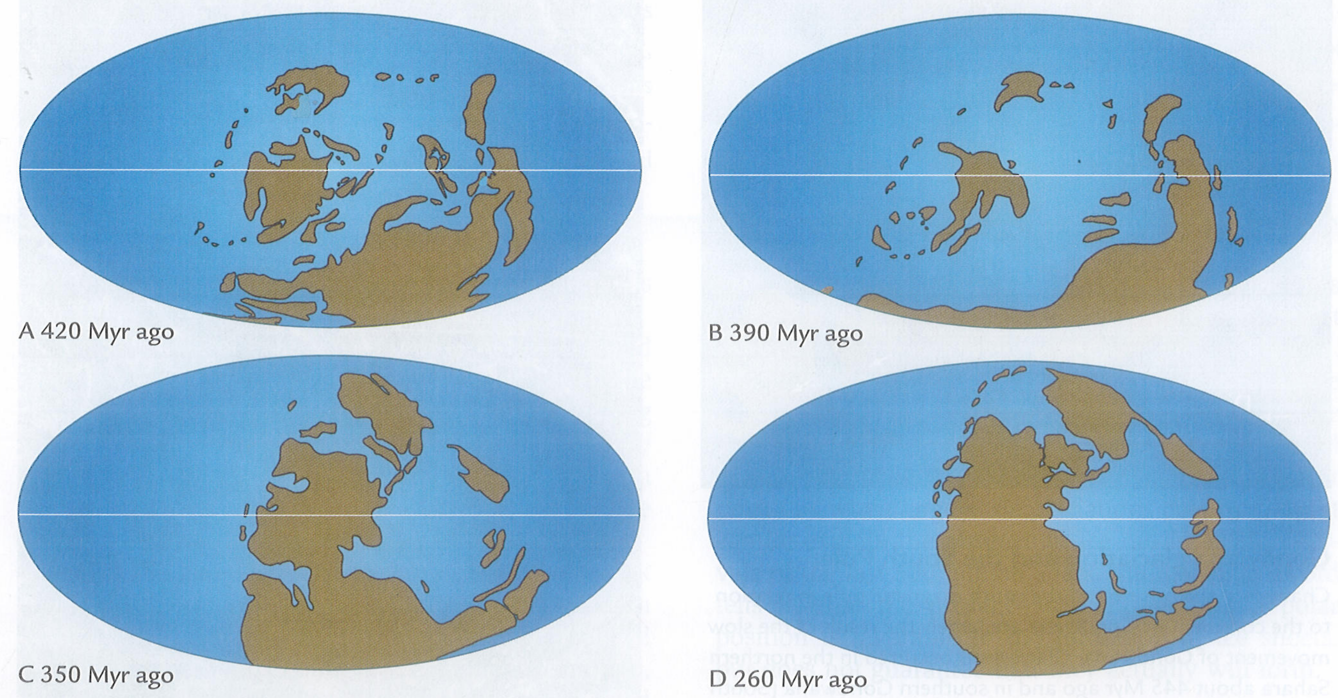

FIGURE 5-7
Moving continents
After 450 Myr ago, plate tectonic activity carried the southern continent of Gondwana across the South Pole on a path headed toward continents scattered across the Northern Hemisphere (A–C). Subsequent collisions formed the giant continent Pangaea (D). (ADAPTED FROM S. STANLEY, *EARTH SYSTEM HISTORY*, © 1999 BY W. H. FREEMAN AND COMPANY.)

across the South Pole and then northward to a collision with the northern landmasses, creating the giant supercontinent **Pangaea**, meaning "All Earth" (Figure 5-7B–D).

This motion is conveniently represented by plotting the changing position of the magnetic south pole in relation to the land (Figure 5-8). But this convention makes it look as if the south magnetic pole moved southward across Gondwana. Instead, the Gondwana continent was moving across the pole.

How well does the pattern shown in Figure 5-8 explain the intervals of glaciation and nonglaciation listed in Table 5-1? The position of the south magnetic pole 445 million years ago agrees with the evidence of glaciation in the area of the modern Sahara Desert. The weight of the ice pressing down on the loose rubble carried in its base left striations (grooves) cut into bedrock (Figure 5-9).

At first glance, this match is consistent with the polar position hypothesis, but closer inspection raises problems. One problem is that this glacial era near 445 million years ago was very brief in terms of geologic time. Although its duration was once thought to be about 10 million years, new evidence suggests that large amounts of ice may only have been present for a million years or less. That brief a glaciation is not easily explained by the slow motion of Gondwana across the South Pole (Box 5-1).

A far more perplexing problem is the lack of glaciations between 425 and 325 million years ago, even though the Gondwana continent was still continuing its slow transit across the pole (see Figures 5-7 and 5-8). Somehow land existed at the South Pole for almost 100 million years without major ice sheets forming. This observation argues against the hypothesis that a polar position is the *only* requirement for large-scale glaciation.

From 325 to 240 million years ago, Gondwana continued its slow journey across the South Pole, and a huge region centered on the south-central part of the continent was glaciated (see Figure 5-8). These ice sheets were centered on modern Antarctica and South Africa, and they spread out into adjoining regions of South America, Australia, and India. Because of the correspondence between the area of Gondwana that was glaciated and its position at or near the south magnetic pole, this long interval of glaciation is consistent with the polar position hypothesis.

By 240 million years ago, Gondwana had moved farther northward and the glaciation had ended. The lack of ice after that time agrees with the positioning of major landmasses away from the South Pole. By that time, the northern part of Gondwana had begun to merge with the northern continents and form the even larger supercontinent Pangaea.

After 180 million years ago, Pangaea began to break up. Its southernmost part, which included the modern continents of Antarctica, India, and Australia, moved back over the South Pole by 125 million years ago, yet no major ice sheet developed. Antarctica remained directly over the pole but largely free of ice from 125 million years ago until 35 million years ago, when significant amounts of ice reappeared. Here again we face the mystery encountered earlier: How could a landmass centered on a pole have remained ice-free (or largely so) from 125 to 35 million years ago?

Clearly, the polar position hypothesis accounts for part of Earth's glaciation history during the last half-billion years (see Table 5-1). During that interval, ice sheets developed only on landmasses that were at polar or near-polar positions, consistent with the presence of ice at the South Pole today. This general correlation confirms that continents occupied polar positions when large-scale glaciations occurred, but it cannot explain the absence of ice during some intervals of the last 500 million years. The geologic record tells us that the presence of continents in a polar position is favorable to the formation of ice sheets, but does not guarantee that they actually will form.

In Summary, the polar position hypothesis is part of the explanation of Earth's glaciations, but not the entire story. Some other factor must also be at work, a factor that allows ice sheets to form over polar continents during some intervals and prohibits them from doing so during others.

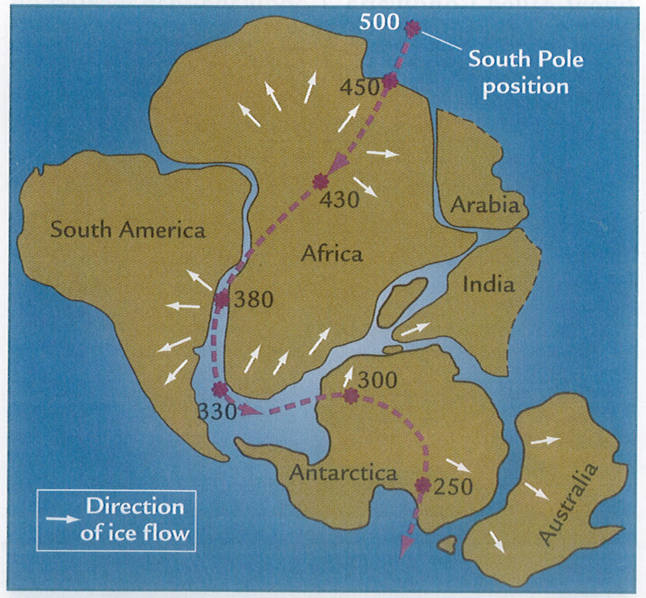

FIGURE 5-8

Gondwana glaciation and the South Pole

Changes in the position of the south magnetic pole in relation to the continent of Gondwana are largely the result of the slow movement of Gondwana. Glaciations occurred in the northern Sahara about 445 Myr ago and in southern Gondwana (South Africa, Antarctica, India, South America, and Australia) 325–240 Myr ago. The (shallow) water shown between the modern continental outlines was land during Pangaean times. (ADAPTED FROM T. J. CROWLEY ET AL., "GONDWANALAND'S SEASONAL CYCLE," *NATURE* 329 [1987]: 803–7, BASED ON P. MOREL AND E. IRVING, "TENTATIVE PALEOCONTINENTAL MAPS FOR THE EARLY PHANEROZOIC AND PROTEROZOIC," *JOURNAL OF GEOLOGY* 86 [1978]: 535–61.)

FIGURE 5-9

Glacial striations

Bedrock with grooves cut into the surface by glacial scouring and gouging. (LEONARD LEE RUE III/SCIENCE SOURCE.)

Looking Deeper into Climate Science

Box 5-1

Brief Glaciation 445 Myr Ago

An ice sheet comparable in size to that on modern Antarctica covered the North African part of the Gondwana continent near 445 million years ago. This glaciated interval has been thought to have lasted for 10 million years or more and has been attributed to a combination of factors: the general cooling effect from a Sun that was 4% weaker than today, the positioning of the North African part of Gondwana directly over the South Pole, and a reduction of atmospheric CO_2 values, caused by some combination of slower CO_2 input by volcanoes and faster chemical weathering. Faster weathering may have been caused by small continental collisions prior to the ones that later formed the supercontinent Pangaea, perhaps aided by the first appearance of vegetation on land and its effect in enhancing weathering (see Chapter 3).

More recent dating of the geologic record suggests that the peak expression of this glaciation may have lasted for only a million years—very brief in comparison with the 35 million years of the present glacial era and the glaciation that lasted from 325 to 240 million years ago. If this glaciation was indeed only a million years long, neither seafloor spreading nor chemical weathering seems likely to have changed the CO_2 concentration in the atmosphere fast enough to explain it. Volcanoes and chemical weathering rates can gradually drive CO_2 levels low enough to produce glaciation, but this episode appears to require a mechanism capable of dropping and then raising CO_2 values within a million years.

One mechanism under consideration is an abrupt increase in the rate of burial of organic carbon. The organic carbon subcycle (see Chapter 4, Box 4-1) meets several requirements for explaining a large but rapid climate cooling. Because it carries one-fifth of the total flow of carbon through the upper parts of Earth, this subcycle has the potential to alter the global carbon balance and atmospheric CO_2 levels. Also favoring this explanation is the fact that large amounts of organic carbon can be quickly buried in the sedimentary record, causing a rapid reduction of CO_2 levels.

Several kinds of changes can cause rapid burial of organic carbon: changes in wind direction that cause increased upwelling along coastal margins; an increase in the amount of organic carbon and nutrients delivered to the ocean; a change toward wetter climates on continental margins, where low relief naturally favors formation of vegetation-rich swamps; or the isolation of small ocean basins in regions of high rainfall that generates carbon-rich river runoff.

Modeling Climate on the Supercontinent Pangaea

One fortunate aspect of studying the history of Earth's climate on tectonic time scales is the number of natural experiments Earth has run by altering its geography in major ways. Because the locations of continents are accurately known for the past 300 million years, climate scientists can use general circulation models (GCMs) to evaluate the impact of these geographic factors on climate. Here we examine a time near 200 million years ago when collisions of continents had formed the giant supercontinent Pangaea. Because this configuration differs considerably from the more dispersed continents today, Pangaea provides climate scientists with a very different and yet a real Earth for testing the performance of climate models.

5-4 Input to a Model Simulation of the Climate on Pangaea

Chapter 3 showed that GCM runs require the major physical aspects of a past world to be specified in advance as *boundary-condition inputs* in order to run simulations of past climates. The most basic physical constraint is the distribution of land and sea. Pangaea remained intact from the time it had formed (250 Myr ago) until it broke up after 180 million years ago. The focus here is on this long interval of relatively stable land-sea geometry. The only tectonic change of significance during this time was a very slow northward movement of Pangaea.

Around 200 million years ago, Pangaea stretched from high northern to high southern latitudes and was almost symmetrical around the equator (Figure 5-10A). The landmasses of Gondwana (Antarctica, Australia, Africa, Arabia, South America, and India) formed its larger southern part. The somewhat smaller northern part of Pangaea, sometimes referred to as Laurasia, consisted of North America, Europe, and north-central Asia. A wedge-shaped tropical seaway formed an indentation deep into the east coast of Pangaea, while the west coast had a smaller seaway in the north. This single landmass represented almost one-third of Earth's surface. It spanned 180° of longitude across its northern and southern limits near 70° latitude, and one-quarter of Earth's circumference (90°) at the equator.

Modelers have simplified this configuration for use as input to climate simulations by making the land distribution symmetrical around the equator (Figure 5-10B). This simplification requires relatively small changes in the way Pangaea is represented by the model grid boxes, which were large in size at the time this experiment was run (1994). A benefit of this simplification is that each seasonal model run in each hemisphere is the exact mirror image of the same season in the other hemisphere because the seasons simply switch back and forth between hemispheres. This symmetry effectively doubles the number of years the model simulates.

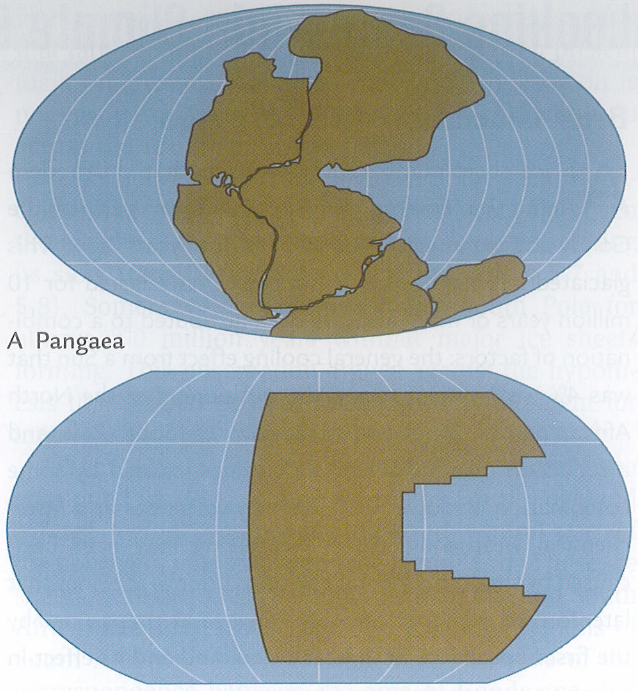

FIGURE 5-10
The supercontinent Pangaea
Geographic reconstructions of the interval around 200 Myr ago show all the continents joined in a single landmass called Pangaea (A). Climate modelers have simplified this configuration into an idealized continent symmetric around the equator (B). (A: ADAPTED FROM J. E. KUTZBACH AND R. G. GALLIMORE, "MEGAMONSOONS OF THE MEGACONTINENT," *JOURNAL OF GEOPHYSICAL RESEARCH* 94 [1989]: 3341–57; B: FROM J. E. KUTZBACH, "IDEALIZED PANGEAN CLIMATES: SENSITIVITY TO ORBITAL CHANGE," *GEOLOGICAL SOCIETY OF AMERICA SPECIAL PAPER* 288 [1994]: 51–55.)

A second important decision on input to the model is global sea level. Evidence from rocks on Pangaea indicates that global sea level 200 million years ago was comparable to its present level. As a result, sea level was placed close to the structural edges of the continents, where it lies today.

A third important decision is the distribution of elevated topography on the continents, but this aspect of Pangaea is not as well known and has to be approximated. In the simulation examined here, all land in the interior of Pangaea was represented as a low-elevation plateau at a uniform height of 1,000 meters, with its edges sloping gradually down to sea level along the outer margins of the continents.

Another important boundary condition that needs to be specified is the CO_2 level in the atmosphere, but the CO_2 concentration for 200 million years ago is not certain. Although long-term CO_2 levels are determined by tectonic factors, they are also an integral part of the climate system. Because the choice of CO_2 concentration will have a direct impact on the climate simulated by the model, the danger of circular reasoning caused by choosing the wrong CO_2 level is present.

Fortunately, other considerations help climate modelers constrain the CO_2 level, if only by inference. Astronomers know that the Sun had not yet reached its present strength and was still about 1% weaker than it is today (see Chapter 4). By itself, this weaker Sun should have made Pangaea significantly colder than the modern world, with snow and ice closer to the equator than today.

Yet evidence from Pangaea refutes a colder world. No ice sheets existed on Pangaea 200 million years ago, even though its northern and southern limits lay within the Arctic and Antarctic circles (see Figure 5-10A). Today, landmasses at similar high latitudes are either permanently ice-covered (Greenland) or alternately ice-covered and ice-free through time (North America, Europe, and Asia). The absence of polar ice suggests that Pangaea's climate was somewhat warmer than today's climate.

Fossil evidence of vegetation on Pangaea supports this conclusion. Except for a few surviving tree types such as the ginkgo (Figure 5-11), Earth's vegetation has evolved to different forms since Pangaean times, and comparisons between plant types now and then have to be based on types with similar appearances rather than on actual species composition. Several kinds of palm-like vegetation that would have been killed by hard freezes existed on Pangaea to latitudes as high as 40°. This suggests that the equatorward limit of hard freezes on Pangaea was 40°, slightly higher than the modern limit (30° to 40°).

The most likely reason for a warmer Pangaea is that a higher CO_2 level 200 million years ago compensated for the weaker Sun. The model experiment examined here assumed a CO_2 level of 1,650 parts per million, almost six times the recent preindustrial value of 280 parts per million. As we will see, this choice not only produced temperature distributions consistent with the evidence from the lack of permanent ice and frost-sensitive vegetation, but it also simulated other climatic features that match independent evidence from the Pangaean geologic record. These other features, particularly precipitation and evaporation, are the main focus here.

With the critical boundary conditions specified, the model simulation is ready to run. After 15 years of simulated time to allow the model climate to come to a state of equilibrium, the results shown are based on the last 5 years of simulated seasonal changes.

FIGURE 5-11
Pangaean trees
Modern gingko trees are descended from similar forms that first evolved some 200 Myr ago. (COURTESY OF MICHAEL BOWERS, BLANDY FARM, BOYCE, VA.)

5-5 Output from the Model Simulation of Climate on Pangaea

Because of its huge size and the reduction of the moderating influence of oceanic moisture, we might anticipate that the interior of Pangaea would have had an extremely dry continental climate. The climate model simulation confirms this expectation.

The model simulates widespread aridity at lower latitudes, especially in the Pangaean interior. Simulated mean annual precipitation and soil moisture levels are very low across vast expanses of interior and western Pangaea between 40°S and 40°N (Figure 5-12). Precipitation values of 1–2 millimeters per day in these regions are equivalent to annual totals of 15–25 inches (35–70 cm) per year, comparable to those in semi-arid grassland areas such as the western plains of the United States today.

This pervasive aridity reflects two factors: (1) the large amount of land at subtropical latitudes beneath the dry, downward-moving limb of the Hadley cell, and (2) the large amount of land in the tropics, causing trade winds to lose most of their ocean-derived water vapor before reaching the continental interior

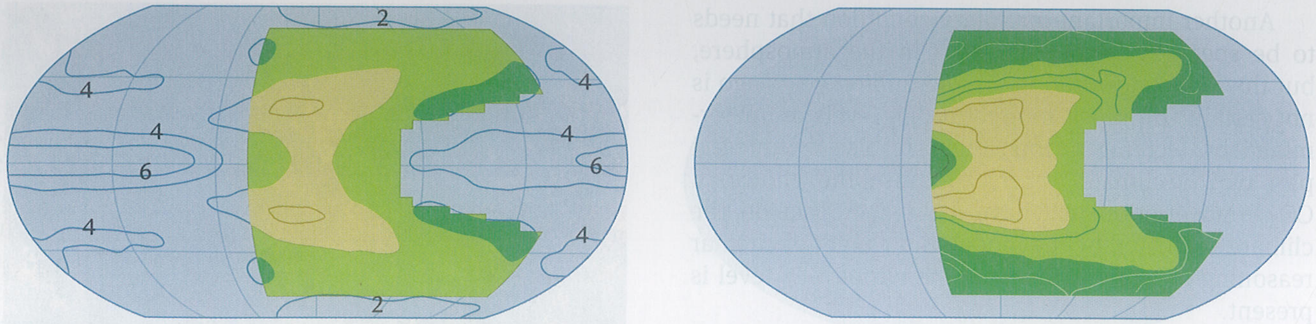

FIGURE 5-12
Precipitation on Pangaea
Climate models simulate patterns of annual mean precipitation (A) and soil moisture (B) on Pangaea. Broad areas of the tropics and subtropics were very dry. (ADAPTED FROM J. E. KUTZBACH, "IDEALIZED PANGEAN CLIMATES: SENSITIVITY TO ORBITAL CHANGE," *GEOLOGICAL SOCIETY OF AMERICA SPECIAL PAPER* 288 [1994]: 41–55.)

(see Chapter 2). In contrast, the simulated ocean around Pangaea received far more rainfall than the land, and considerably more than it does today.

Geologic evidence supports the model simulation of widespread Pangaean aridity. The clearest evidence is the presence of **evaporite** deposits, salts that precipitated out of water in lakes and coastal margin basins with limited connections to the ocean. Evaporite salts form only in arid regions where evaporation far exceeds precipitation. More evaporite salt was deposited during the time of Pangaea than at any time in the last several hundred million years (Figure 5-13). These evaporite deposits occurred in regions the model simulates as having been arid.

Because the moderating effects of ocean moisture failed to reach much of Pangaea's interior, the continent was left vulnerable to seasonal extremes of solar heating in summer and cooling during winter. As a result, the model simulates a large seasonal temperature response (Figure 5-14). In some mid-latitude regions, summer daily average temperatures of +25°C (77°F) alternated with winter daily temperatures of −15°C (+5°F).

This wide range of seasonal temperatures could explain the lack of ice sheets on Pangaea. The simulated winter temperatures were cold enough to provide the snowfall needed for ice sheets to grow, but the hot summers on Pangaea, even along the poleward margins of the sun-warmed landmass, caused rapid melting of the snow and thereby prevented glaciation. Ice sheets form more readily on smaller continents where summer temperatures are kept cooler by moist winds from the nearby ocean.

The model simulation also indicates that average daily land temperatures in winter would have reached the freezing point as far equatorward as 40° latitude (see Figure 5-14), close to the low-latitude limit of frost-sensitive vegetation on Pangaea indicated by geologic evidence. But with winter nights likely to have been considerably colder than daily mean

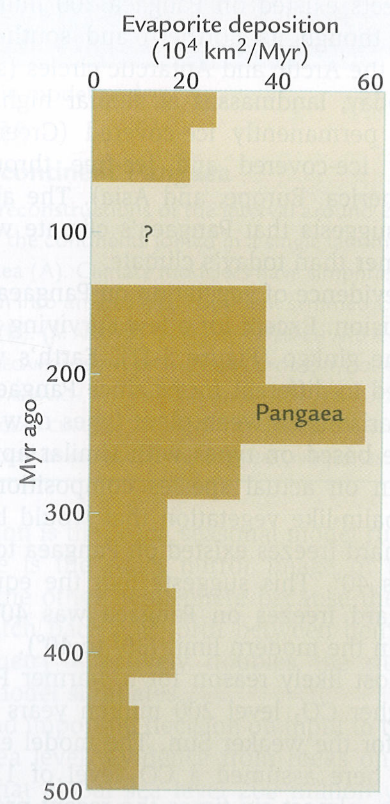

FIGURE 5-13
Pangaean evaporites
The volumes of rock salt deposits (evaporites) formed about 200 Myr ago were larger than at any other time in the last 500 Myr, indicating very dry conditions on Pangaea. (ADAPTED FROM W. A. GORDON, "DISTRIBUTION BY LATITUDE OF PHANEROZOIC EVAPORITES," *JOURNAL OF GEOLOGY* 83 [1975]: 671–84.)

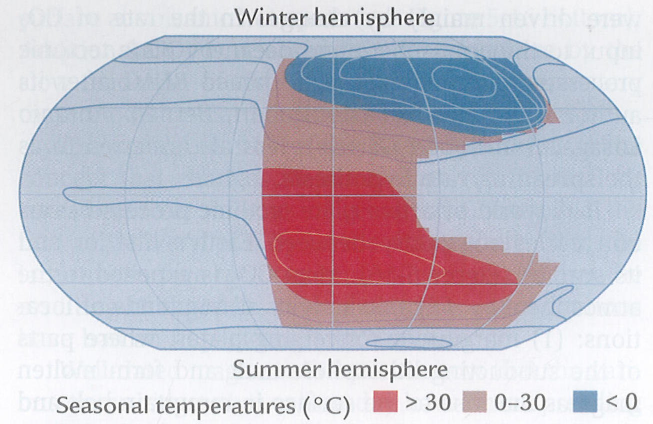

FIGURE 5-14
Temperature on Pangaea
Climate model simulations show very large seasonal temperature contrasts on Pangaea between the summer hemisphere, which was warmed by solar radiation, and the winter hemisphere, which lost heat by longwave back radiation to space. (ADAPTED FROM J. E. KUTZBACH, "IDEALIZED PANGEAN CLIMATES: SENSITIVITY TO ORBITAL CHANGE," *GEOLOGICAL SOCIETY OF AMERICA SPECIAL PAPER* 288 [1994]: 41–55.)

temperatures, the model results disagree to some extent with the ground-truth evidence. Despite the high CO_2 values used as input to the simulation, freezing occurs closer to the equator in the model simulation than the evidence from past vegetation indicates.

Another fundamental characteristic of the climate of Pangaea was the strong reversal between summer and winter monsoon circulations. Monsoon circulations are driven by the different rates of response of the land and the oceans to solar heating in summer and radiative heat loss in winter (recall Chapter 2). The large seasonal swings in land temperature and smaller seasonal changes in ocean temperature reflect these contrasting responses of land and ocean.

Strong solar heating over the part of Pangaea situated in the summer hemisphere (alternating between north and south) caused heated air to rise over the land. This upward motion of heated air created a strong low-pressure cell at the surface (Figure 5-15A), which produced a net inflow of moisture-bearing winds from the ocean. This moist inflow brought heavy rains to the east coast, especially in the subtropics (Figure 5-15B).

The situation in the winter hemisphere was the reverse. Weak seasonal heating from the Sun and strong heat loss by longwave back radiation caused cooling over the interior of Pangaea. This cooling caused air to sink toward the land surface, built up high pressures over the continent, and pushed cold, dry air out over the ocean. As a result, precipitation over the land was greatly reduced.

Note that the winds on the eastern margins of Pangaea from 0° to 45° latitude reversed direction between the seasons: warm, wet, summer monsoon winds blew from the sea onto the land, but cold, dry, winter monsoon winds blew from the land out to sea. The subtropical margins of Pangaea were places of enormous contrasts in seasonal precipitation, alternating between very wet summers and dry winters.

Geologic evidence of seasonal moisture contrasts on Pangaea comes from the common occurrence of **red beds**, sandy or silty sedimentary rocks stained various shades of red by oxidation of iron minerals. Red-colored soils accumulate today in regions where the contrast in seasonal moisture is strong. Red beds were more widespread on Pangaea than during other geologic intervals, consistent with the model simulation of highly seasonal changes in moisture between wet summer monsoons and dry winter monsoons.

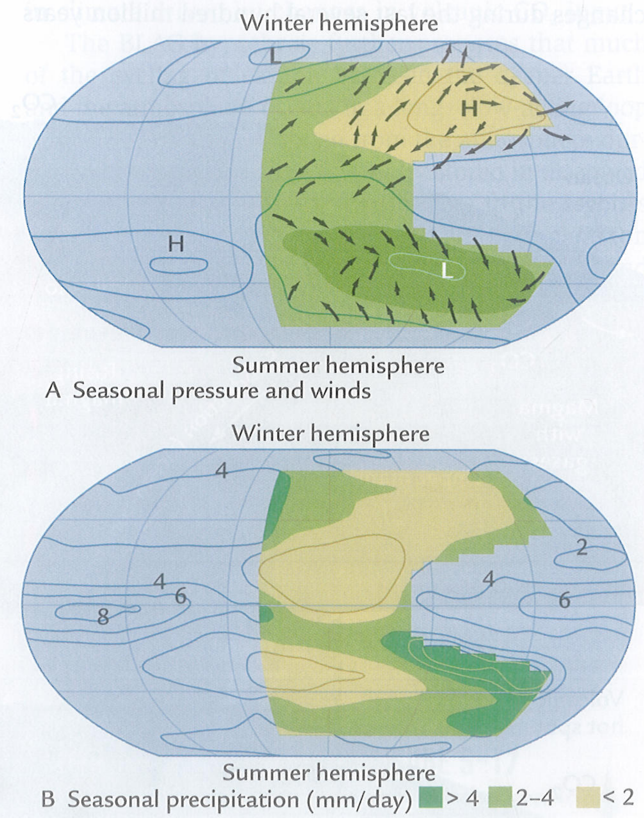

FIGURE 5-15
"Supermonsoons" on Pangaea
Climate models simulate very large seasonal changes in surface pressure and winds (A) and monsoonal precipitation (B) on Pangaea. Summer heating creates a low-pressure region (L) and draws in moist oceanic winds, which drop heavy precipitation along the subtropical east coast. Winter cooling creates a high-pressure cell (H) that sends dry air out from land to sea and reduces precipitation. (ADAPTED FROM J. E. KUTZBACH, "IDEALIZED PANGEAN CLIMATES: SENSITIVITY TO ORBITAL CHANGE," *GEOLOGICAL SOCIETY OF AMERICA SPECIAL PAPER* 288 [1994]: 41–55.)

Tectonic Control of CO_2 Input: The BLAG (Spreading Rate) Hypothesis

Our examinations of both the polar position hypothesis and the climate of Pangaea suggest that changes in Earth's geography alone cannot explain the variations between warm greenhouse climates and cold icehouse climates during the last 500 million years and that variations in the CO_2 concentration in the atmosphere played a role. In the remainder of this chapter, we examine two hypotheses that attempt to explain why CO_2 has changed over very long intervals of time. One hypothesis emphasizes changes in CO_2 input by volcanoes; the other focuses on changes in CO_2 removal by weathering.

5-6 Control of CO_2 Input by Seafloor Spreading

In 1983, a new hypothesis proposed that climate changes during the last several hundred million years were driven mainly by changes in the rate of CO_2 input to the atmosphere and ocean by plate tectonic processes. This hypothesis is named BLAG after its authors, the geochemists Robert **B**erner, Antonio **L**asaga, **A**nd Robert **G**arrels). It is also referred to as the **spreading rate hypothesis**.

In a world of active plate tectonic processes, carbon cycles constantly between Earth's interior and its surface (Figure 5-16). Most CO_2 is expelled to the atmosphere by volcanic activity at two kinds of locations: (1) margins of converging plates, where parts of the subducting lithosphere melt and form molten magmas that rise to the surface in mountain belt and island arc volcanoes, delivering CO_2 and other gases from Earth's interior; and (2) margins of divergent plates (ocean ridges), where hot magma carrying CO_2 erupts directly into ocean water.

Some volcanoes also emit CO_2 at sites distant from plate boundaries, where thin plumes of molten material rise from deep within the interior and reach the surface at volcanic **hot spots** (see Figure 5-16 bottom). Additional CO_2 is released to the atmosphere by the slow oxidation of old organic carbon in sedimentary rocks eroded at Earth's surface (recall Chapter 4).

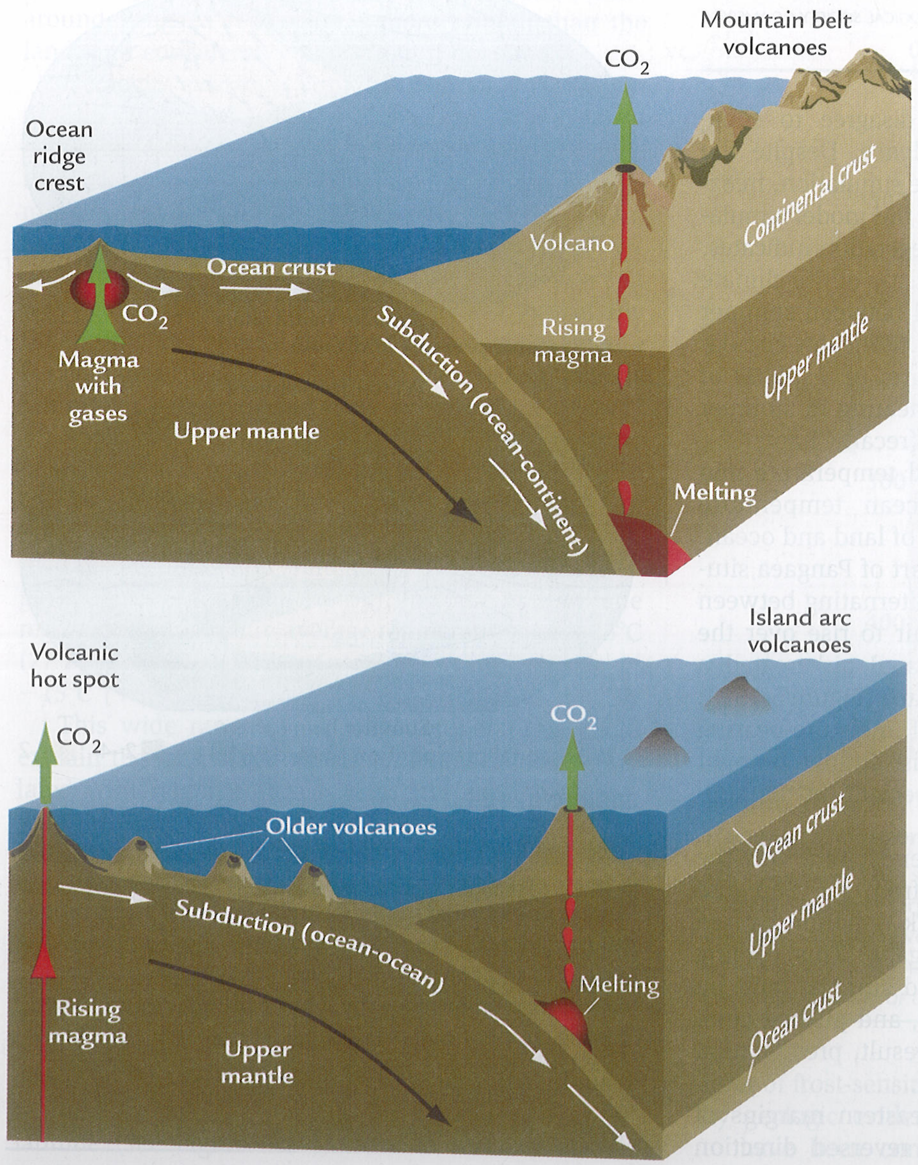

FIGURE 5-16
CO_2 input
CO_2 is transferred from Earth's interior to the atmosphere-ocean system primarily at ocean ridges (top left) and subduction zones (top and bottom right). Lesser emissions of CO_2 occur when volcanoes erupt at hot spots in the middle of plates (bottom left).

The central feature of the BLAG hypothesis is the concept that changes in the average rate of seafloor spreading over millions of years have controlled the rate of delivery of CO_2 to the atmosphere from the large subsurface rock reservoir of carbon and that the resulting changes in atmospheric CO_2 concentrations have had an impact on Earth's climate.

Well-dated magnetic lineations show that the various ocean ridges that exist today have been spreading at different rates for millions of years (Figure 5-17). For example, the ridge in the southern Pacific Ocean spreads as much as ten times faster than the one in the Atlantic Ocean.

The BLAG hypothesis is based on the concept that the *globally averaged* rate of seafloor spreading has also changed over time. Changes in the mean rate of spreading should alter the transfer of CO_2 from Earth's rock reservoirs to its atmosphere at ocean ridges and subduction zone volcanoes because these plate margins are vital participants in the process of seafloor spreading (see Figure 5-16).

Faster rates of spreading at ridge crests create larger amounts of new ocean crust and more frequent releases of magma, which deliver greater amounts of CO_2 to the ocean (Figure 5-18). Faster spreading also causes more rapid subduction of crust and sediment in ocean trenches and delivers larger volumes of carbon-rich sediment and rock for subsequent melting and CO_2 release through volcanoes. Conversely, slower spreading reduces both kinds of CO_2 input to the atmosphere.

Although the BLAG hypothesis focuses on changes in spreading rates as a driver of long-term climate change, it also calls on chemical weathering for negative feedback to moderate these changes (see Chapter 4). Increased volcanic emissions caused by faster seafloor spreading lead to higher atmospheric CO_2 levels and a warmer climate (see Figure 5-18 top). This initial shift toward a greenhouse climate then activates the combined effects of higher temperature, greater precipitation, and more vegetation to speed up the rate of chemical weathering and draw CO_2 out of the atmosphere at a faster rate. The resulting CO_2 removal opposes and reduces some of the initial warming driven by faster spreading rates and higher CO_2 concentrations. Similarly, chemical weathering feedbacks work to offset some of the impact of cooling caused by slower volcanic input of CO_2 (Figure 5-18 bottom). In effect, the BLAG hypothesis relies on chemical weathering to moderate any fluctuations in climate driven by changes in volcanic CO_2 input.

The BLAG hypothesis further proposes that much of the cycling of carbon between the deeper Earth and the atmosphere occurs in a long, slow-acting loop (Figure 5-19). Carbon taken from the atmosphere during chemical weathering is initially stored in dissolved HCO_3^{-1} ions that are carried by rivers to the sea. As we have seen (recall Chapter 3), marine plankton use this dissolved carbon to form $CaCO_3$ shells, and the shells are deposited in ocean sediments when the organisms die. The movement of carbon through this surface part of the cycle is rapid, occurring in just a few years.

The $CaCO_3$-bearing sediments are then carried by seafloor spreading toward subduction zones at

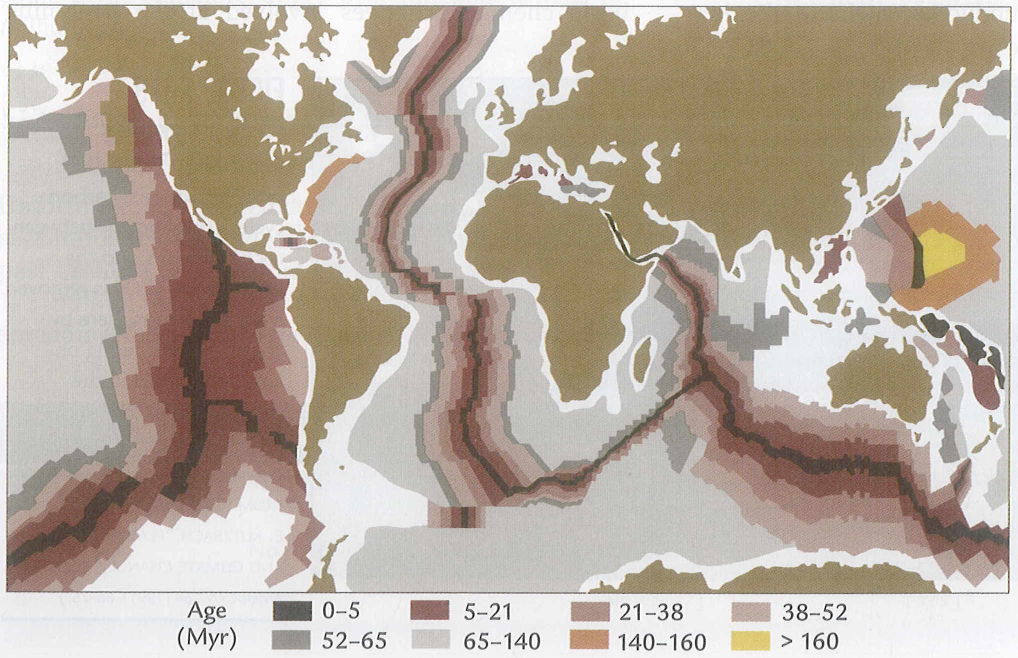

FIGURE 5-17
Age of the seafloor
Some ocean crust dates as far back as 175 Myr ago. Modern spreading rates are as much as ten times faster in the Pacific than in the Atlantic. (MODIFIED FROM S. STANLEY, *EARTH SYSTEM HISTORY*, © 1999 BY W. H. FREEMAN AND COMPANY, AFTER W. C. PITMAN ET AL., MAP AND CHART SERIES MC-6 [BOULDER, CO: GEOLOGICAL SOCIETY OF AMERICA, 1974].)

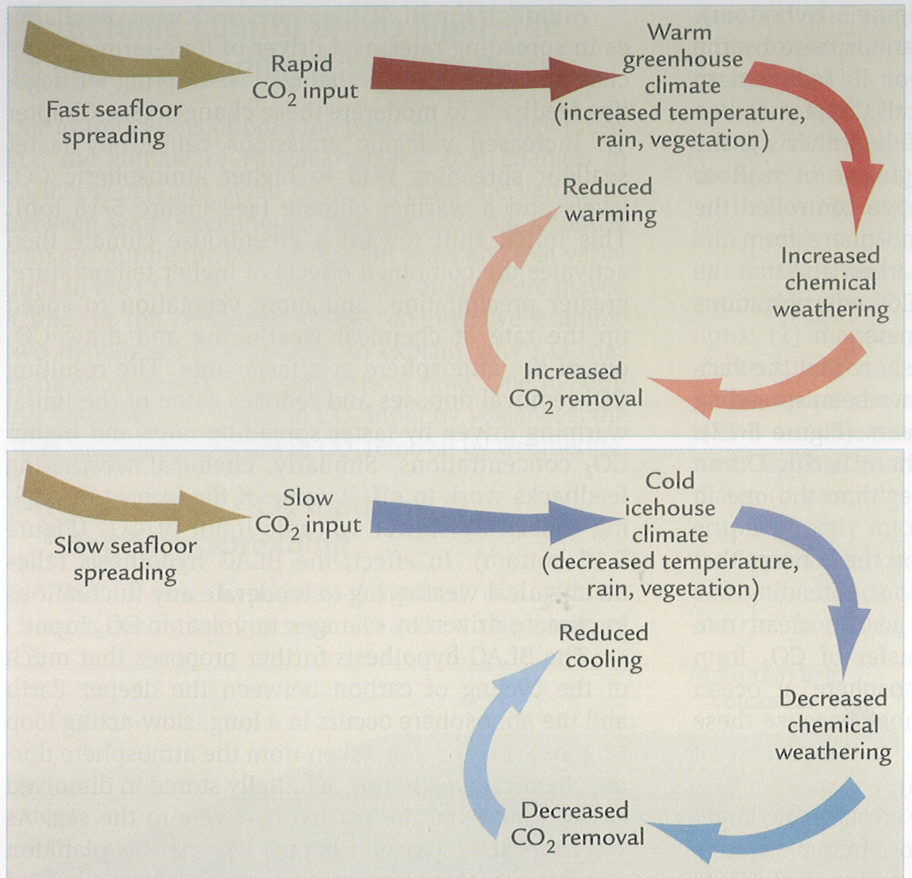

FIGURE 5-18
The BLAG (spreading rate) hypothesis
This hypothesis predicts that atmospheric CO_2 concentrations and global climate are driven by the global mean rate of seafloor spreading, which controls the rate of CO_2 input at ocean ridge crests and subduction zones. The spreading rate hypothesis also invokes chemical weathering as a negative feedback that partially counters changes in atmospheric CO_2 and global climate initiated by varying rates of seafloor spreading.

continental margins. Some sediment is scraped off at the ocean trenches, and some is carried downward in the subduction process (see Figure 5-19). This slow journey of carbon-bearing sediments across the ocean floor and down into the trenches and beyond takes tens of millions of years.

Most of the $CaCO_3$ (and other carbon) carried down into Earth's interior by subduction melts at the hot temperatures found at great depths or is transformed in other ways. These processes eventually return CO_2 to the atmosphere through volcanoes and complete the cycle. Almost none of the subducted carbon is carried deep into the mantle. Movement of carbon through this deep part of the cycle takes tens of millions of years.

The two chemical reactions that summarize the basic chemical changes involved at the beginning and end of this tectonic-scale carbon cycle are mirror opposites:

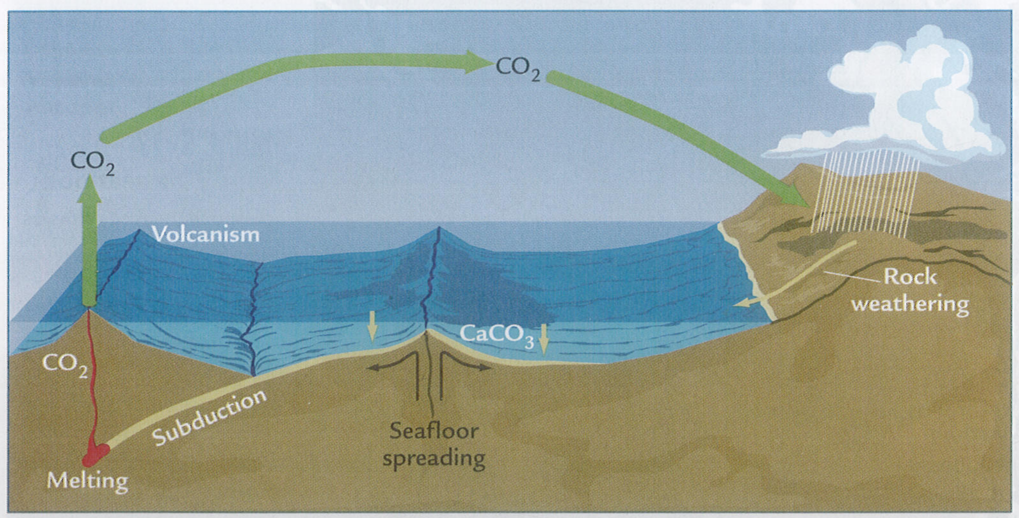

FIGURE 5-19
Carbon cycling
In the BLAG (spreading rate) hypothesis, carbon cycles continuously between rock reservoirs and the atmosphere: CO_2 is removed from the atmosphere by chemical weathering on land, deposited in the ocean, subducted, and returned to the atmosphere by volcanic activity. (ADAPTED FROM W. F. RUDDIMAN AND J. E. KUTZBACH, "PLATEAU UPLIFT AND CLIMATE CHANGE," *SCIENTIFIC AMERICAN* 264 [1991], 66–75.)

Chemical weathering on land

$$\underset{\text{Silicate rock}}{CaSiO_3} + \underset{\text{Atmosphere}}{CO_2} \rightarrow \underset{\text{Plankton}}{CaCO_3} + \underset{\text{Plankton}}{SiO_2}$$

Melting and transformation in subduction zones

$$\underset{\text{Ocean sediments}}{CaCO_3 + SiO_2} \rightarrow \underset{\text{Silicate rock}}{CaSiO_3} + \underset{\text{Atmosphere}}{CO_2}$$

Together, the two reactions form a complete (closed) cycle with no net chemical change over tens of millions of years. The longest part of the cycle is caused by the slow spreading and subduction of the seafloor, the slow transformation of $CaCO_3$ in the lower crust and upper mantle, and the slow delivery of CO_2 to the surface through volcanic action. In contrast, changes in spreading rates can alter the rate of melting and CO_2 release to the atmosphere with little or no delay because carbon-bearing sediment is already "in the pipeline." At any interval in time, carbon-bearing sediments are in the process of being subducted into Earth's interior, and changes in the average rate of subduction will soon result in different rates of melting of this down-going material.

The BLAG hypothesis proposes that this cycling of carbon provides long-term stability to the climate system by moving a roughly constant amount of total carbon back and forth between the rocks and the atmosphere over long intervals of time. As a result, atmospheric CO_2 levels are constrained to vary only within moderate limits. But the long delays between carbon weathering and burial permit small imbalances to occur between the rate of carbon burial and the return of CO_2 to the atmosphere. These imbalances could drive climate changes over intervals of tens of millions of years.

5-7 Initial Evaluation of the BLAG (Spreading Rate) Hypothesis

Unfortunately, the predictions of the BLAG hypothesis cannot be directly tested over most of the geologic past because no undeformed ocean crust older than 175 million years exists to use for calculating past spreading rates. All older crust has been subducted in ocean trenches. Half of the crust that formed 50 million years ago has already been destroyed by rapid subduction under western South America (see Figure 5-17) and by the total disappearance of ocean crust in the former tropical seaway (called Tethys) by subduction and collision along the southern coast of Asia.

Most reconstructions have inferred that the global mean spreading rate was faster near 100 million years ago than it is at present. If this conclusion holds up to future scrutiny, the BLAG hypothesis would predict that the rate of input of CO_2 to the atmosphere should have been higher 100 million years ago than it is today (Table 5-2). This prediction would agree with geologic evidence of a warmer climate 100 million years ago, and with the absence of large polar ice sheets. We will revisit this important issue in the next two chapters.

Tectonic Control of CO_2 Removal: The Uplift Weathering Hypothesis

A second hypothesis that attempts to explain how plate tectonic processes control atmospheric CO_2 levels emerged from work by the marine geologist Maureen Raymo and colleagues in the late 1980s. Parts of this concept date back to work by the geologist T. C. Chamberlain a century ago. The **uplift weathering hypothesis** proposes that chemical weathering is an active driver of climate change, rather than just a passive negative feedback that moderates climate.

5-8 Rock Exposure and Chemical Weathering

The BLAG hypothesis emphasizes changes in CO_2 delivery to the atmosphere by seafloor spreading, and it assumes that removal of CO_2 by chemical weathering responds only to climate-related changes in temperature, precipitation, and vegetation. Although these factors certainly affect chemical weathering (see Chapter 4), they are not the only processes that do so.

The uplift weathering hypothesis starts from a different perspective. It asserts that the global mean

Table 5-2 Evaluation of the BLAG Spreading Rate (CO_2 Input) Hypothesis

Time (Myr ago)	Ice sheets present?	Spreading rates	Hypothesis supported?
100	No	Faster (?)	Yes (?)
0	Yes	Slower (?)	Yes (?)

rate of chemical weathering is mainly affected by the availability of fresh rock and mineral surfaces for weathering to attack, and it proposes that this exposure effect can override the combined effects of the climate-related factors (temperature, precipitation, and vegetation) on a global basis.

Figure 5-20 shows a simplified example of the importance of rock exposure. This simplification starts with a large boulder-sized cube of rock with six surfaces consisting of squares 1 meter across, each having a surface area of 1 m^2. This rock cube has a total surface area of 6 m^2, calculated from the total area of all six sides.

Now we slice this cube into halves along each of its three axes. This slicing creates eight smaller cubes, each 0.5m on a side, with each side having a surface area of 0.25m^2. The total surface area of these eight smaller cubes is 12m^2:

$$(8 \text{ cubes}) \times (6 \text{ sides each}) \times (0.25\text{m}^2 \text{ of surface area per side})$$

Note that simply cutting the large cube into smaller cubes has doubled the exposed surface area of the rock without changing its volume, at least for the imaginary (idealized) laser-sharp cut assumed in this example. The fragmentation has created more exposed surface area for weathering to attack.

This idealized process can be continued to progressively finer grain sizes, with similar results. Ten sequential halvings of the rock's dimensions will produce over 1 billion cubes each 1 mm on a side, about the same size as grains of sand on a beach. Together these tiny cubes have a total surface area 1,000 times larger than the original block, yet they still retain the same total volume. Fragmentation to even smaller sizes will expose still more surface area.

With over 1,000 times more surface area to act on, chemical weathering would increase by a factor of 1,000 or more. The huge increase of weathering in this hypothetical example far exceeds the combined changes estimated from changes in temperature, precipitation, and vegetation (see Chapter 4). Based on this analysis, climate-related factors are not the only processes to consider in evaluating chemical weathering.

5-9 Case Study: The Wind River Basin of Wyoming

Direct evidence of the importance of rock exposure in chemical weathering comes from studies of a drainage basin in the Wind River Mountains of Wyoming. Because all the bedrock in this basin consists of granite, the kind of silicate rock that is most typical of continental crust, this watershed is reasonably representative of the average response of continental rocks to weathering.

The Wind River Mountains have been glaciated repeatedly over the last several hundred thousand years, and each glaciation has left deposits of unsorted debris (glacial moraines) in the valley and foothills below. Because some older deposits have not been overridden by later glacial advances, undeformed moraines ranging in age from 200 to 130,000 years are present in the same valley.

These Wind River moraines provide an opportunity to quantify the amount of weathering of ground-up debris that is identical in composition but widely varying in age. The extent of weathering can be determined by analyzing the soils that have subsequently developed on the moraines. These soils gradually lose their major cations (Mg^{+2}, Na^{+1}, K^{+1}, Ca^{+2}, etc.) to the chemical

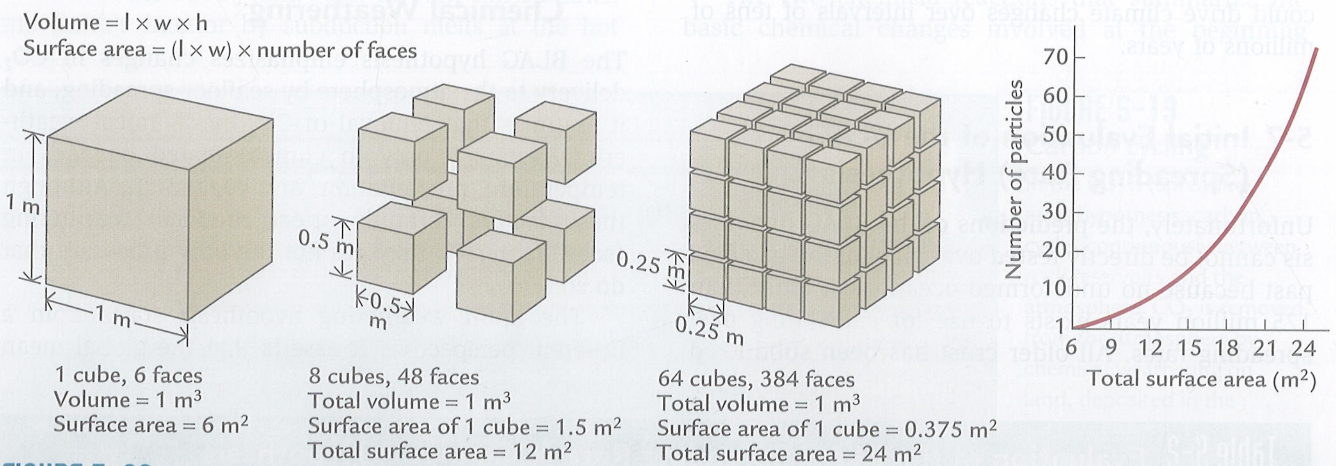

FIGURE 5-20
Fragmentation of rock
Each time a cube-shaped rock is sliced into smaller cubes (with each side half as long as before), the total surface area of rock doubles, even though the volume remains the same. (D. MERRITTS ET AL., *ENVIRONMENTAL GEOLOGY*, © 1997 BY W. H. FREEMAN AND COMPANY.)

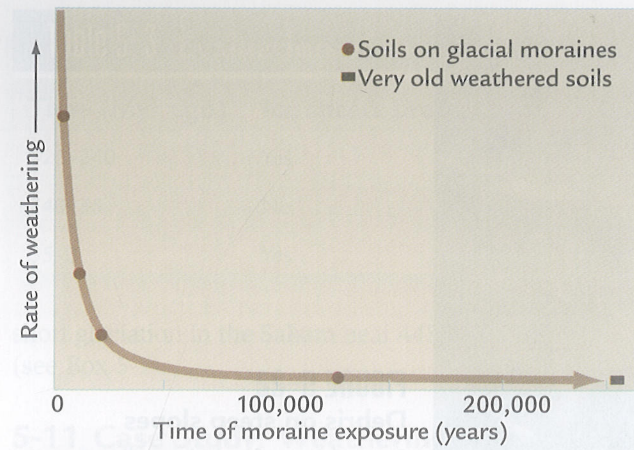

FIGURE 5-21
Weathering and exposure time
Glacially eroded and fragmented granite weathers quickly soon after deposition, but much more slowly 100,000 years later. (ADAPTED FROM J. D. BLUM, "THE EFFECT OF LATE CENOZOIC GLACIATION AND TECTONIC UPLIFT ON SILICATE WEATHERING RATES," IN *TECTONIC UPLIFT AND CLIMATE CHANGE*, ED. W. F. RUDDIMAN [NEW YORK: PLENUM PRESS, 1997].)

weathering process. The cumulative amount of chemical weathering that has occurred since each moraine was deposited can be determined by measuring the total loss of these weathering-sensitive cations. Dividing the total amount of weathering since the moraine was deposited by the time elapsed yields the *average* rate of chemical weathering over that entire interval.

The Wind River deposits show a rapid (exponential) decrease in the mean rate of cation weathering with time of exposure (Figure 5-21). The younger moraines have average rates of weathering that are at least a factor of 100 faster than the older ones. The older moraines presumably also went through a phase of fast weathering during the tens of thousands of years soon after their deposition, and then weathered much more slowly later on. But why would younger glacial deposits weather so much faster?

The most likely explanation is that freshly ground rock has far more weatherable material—more of the kinds of fresh, unweathered silicate grains that are most vulnerable to the weathering process. As these vulnerable minerals are preferentially removed through time, only more resistant minerals are left, and rates of weathering slow.

Another part of the uplift weathering hypothesis relates to the effect of grain sizes on weathering (see Figure 5-20). Finer grain sizes expose more mineral surface area and cause faster weathering early in the process, but the finer sizes of eroded material disappear earlier as weathering consumes them. The coarser grain sizes that remain weather more slowly because they expose less surface area per unit of volume. Coarser fragments may also develop an outer coating, or "rind," of weathering-resistant material that protects fresher material in their interiors and slows the weathering attack.

5-10 Uplift and Chemical Weathering

The uplift weathering hypothesis focuses on evidence that exposure of fragmented and unweathered rock is a key factor in the intensity of chemical weathering. It then links this evidence to the fact that freshly fragmented rock is exposed mainly in regions of tectonic uplift.

Several factors increase rates of exposure of fresh rock in uplifting areas. Mountains and plateaus have steep slopes both on their margins and in valleys between high peaks. Erosional processes known as **mass wasting** are unusually active on such slopes. Mass-wasting processes include rock slides and falls, flows of water-saturated debris, and a host of other processes that dislodge everything from huge slabs of rock to loose boulders, pebbles, and soil. Every event that removes overlying debris exposes fresh bedrock and unweathered material. Many high-mountain slopes consist almost entirely of fresh debris moving downslope (Figure 5-22).

Another important factor is earthquakes. Mountains and high plateaus are built by tectonic forces that push together and stack huge slivers of faulted rock at the margins of converging plates. This stacking process is accompanied by earthquakes that generate large amounts of energy, shake the ground, and dislodge debris. Even more fresh rock is exposed as a result.

A third important characteristic of steep slopes is that they are focal points for orographic precipitation (see Chapter 2). When warm air is forced up and over high terrain and then cooled, water vapor condenses and precipitation occurs. High but narrow mountain belts in the tropics and mid-latitudes capture much of the moisture carried by winds. In addition, large plateaus such as the Tibetan Plateau create their own wet (monsoonal) circulations by pulling moisture in from adjacent oceans. Major erosion events also occur in high-mountain areas when heavy rain falls on snow. Heavy precipitation favors chemical weathering.

Glacial ice also enhances chemical weathering in high terrain. Uplift can elevate rock surfaces to altitudes where temperatures are cold enough for mountain glaciers to form. Mountain glaciers pulverize blocks of underlying bedrock and deposit the debris in moraines at lower elevations. As we saw in the case study of the Wind River Range, glacial grinding greatly enhances rates of chemical weathering.

All these factors (steep slopes, mass wasting, earthquakes, heavy precipitation, and glaciers) are present in high mountains and plateaus. The uplift weathering

FIGURE 5-22
Debris on steep slopes
Steep slopes of actively eroding mountains consist of highly fragmented debris periodically dislodged downslope. (PHOTOSPHERE IMAGES/PICTURE QUEST.)

hypothesis proposes that uplift accelerates chemical weathering through the combined action of these processes (Figure 5-23). Faster weathering draws more CO_2 out of the atmosphere and cools global climate toward icehouse conditions. Conversely, during times when uplift is less prevalent, chemical weathering is slower, and CO_2 stays in the atmosphere and warms the climate, producing greenhouse conditions.

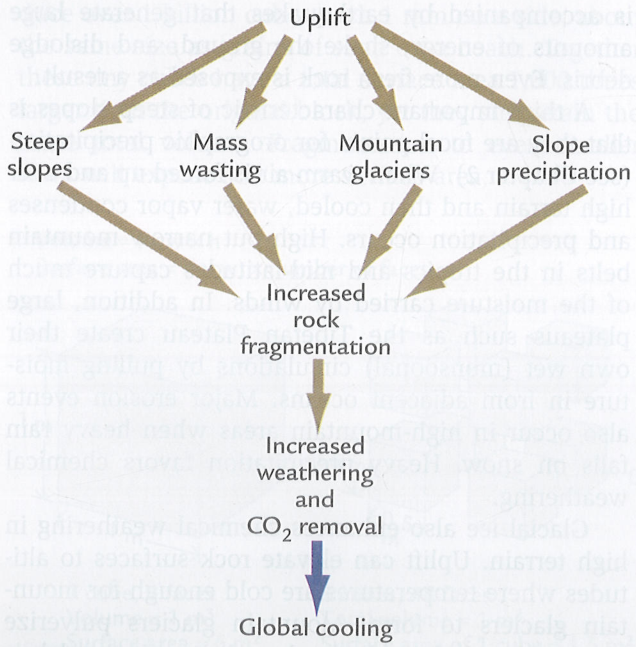

FIGURE 5-23
Uplift weathering hypothesis
Active tectonic uplift produces several tectonic and climatic effects that cause strong weathering of freshly fragmented rock. This process removes CO_2 from the atmosphere and cools global climate.

The two major kinds of plate tectonic processes that cause uplift have different implications for the uplift weathering hypothesis. The first process, subduction of ocean crust underneath continental margins, is an integral part of plate movements and a process that is continually active in many regions on Earth. Because subduction occurs relatively steadily over time, the total amount of high mountain terrain on Earth is likely to be relatively constant through time, even though the locations and heights of individual mountain ranges vary considerably.

The second process that creates high terrain is the collision of continents, and these events are far less common. Collision between India and Asia over the last 55 million years created the Tibetan Plateau in southern Asia, but no plateau-like feature remotely close in size to Tibet existed on Earth between 240 and 55 million years ago because no major continental collision of this kind occurred during that interval. Earlier, between 325 and 240 million years ago, the collisions between Gondwana and other continents that created the supercontinent Pangaea also formed a plateau of moderate size in east-central Europe, as well as high mountain ranges in eastern North America (the Appalachians) and in northwestern Africa.

The uplift weathering hypothesis focuses mainly on plateaus created by occasional collisions of continents, rather than on the ever-present mountain belts. As Table 5-3 indicates, times of continental collisions that created plateaus match times of glaciations over the last 325 million years. Like the BLAG hypothesis, the uplift weathering hypothesis is consistent with the icehouse-greenhouse-icehouse climatic sequence. But if recent discoveries prove correct, neither the uplift weathering hypothesis nor the BLAG hypothesis nor the polar position of Gondwana is a complete explanation for the

Table 5-3 Evaluation of the Uplift Weathering (CO_2 Removal) Hypothesis

Time (Myr ago)	Ice sheets present?	Continents colliding?	Hypothesis supported?
325–240	Yes	Yes	Yes
240–35	No	No	Yes
35–0	Yes	Yes	Yes

short glaciation in the Sahara near 445 million years ago (see Box 5-1).

5-11 Case Study: Weathering in the Amazon Basin

The effect of uplift on chemical weathering can also be evaluated by examining the drainage basin of the Amazon River of South America (Figure 5-24). This region can be divided into two major units: (1) the

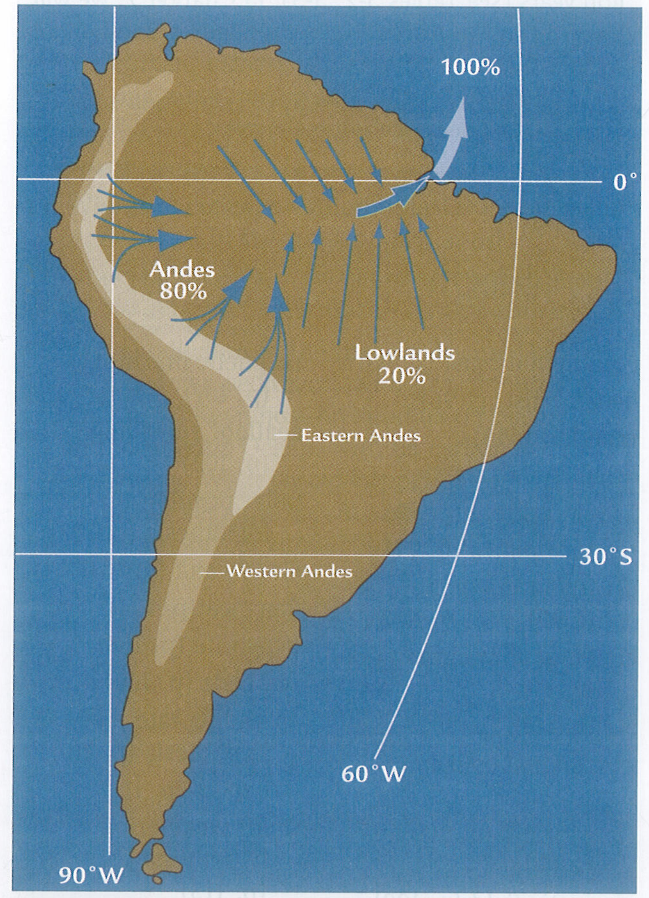

FIGURE 5-24
Weathering in the Amazon Basin
Almost 80% of the chemically weathered ions that reach the Atlantic Ocean from the Amazon River come from the small area of the eastern Andes, and just 20% from the extensive lowlands of the Amazon Basin.

low-lying Amazon Basin, where trade winds blowing westward from the Atlantic Ocean bring frequent precipitation to the rain forests of Brazil, and (2) the high-elevation eastern slopes of the Andes Mountains, which collect most of the rest of the incoming Atlantic precipitation.

Scientists have determined the regional distribution of chemical weathering in this drainage basin by sampling the amount of chemically weathered ions flowing down to the Amazon River in dissolved form. They found that the upper tributaries of the Amazon emerging from the foothills of the Andes carry almost 80% of the total dissolved chemical load discharged by the river when it enters the Atlantic. Despite its vast size and warm moist environment, the lower Amazon Basin adds only the remaining 20% of the total. Most of the chemical weathering in the Amazon drainage basin occurs in the Andes, at rates per unit area that are a factor of 40 higher than those in the lowlands.

How can this be so? This evidence seems at odds with what the eye actually sees in the two regions. In the lower Amazon rain forest, highly weathered clays that are the end products of intense chemical weathering dominate. In the Andes, rock debris produced by strong physical-mechanical weathering dominates, with little apparent evidence of intense chemical weathering.

The answer to this mystery is deceptively simple. The lower Amazon Basin is a place where chemical weathering does indeed dominate in percentage terms, but in which the fresh minerals have long since been "used up" in the weathering process. The only fresh, unweathered bedrock remaining in the lowlands lies buried hundreds of meters beneath a protective cover of highly weathered clays, out of reach of intense weathering processes. These older clays at and near the surface are the end products of slow bedrock weathering over many tens of millions of years, and they have little weatherable material left. As a result, the average rate of chemical weathering in this region is extremely low.

In contrast, the physical impacts of active uplift in the Andes (steep slopes, earthquakes, mass wasting, heavy precipitation, and glacial erosion) combine to generate a continual supply of fresh, finely ground rock debris for weathering. Some of this weathering occurs on the steep upper slopes of exposed high terrain even in the absence of much vegetation or soil cover. Much of it occurs in basins on the lower flanks of the mountains, where soils and vegetation have gained a foothold yet the supply of fresh unweathered rock debris from higher-elevation streams and rivers is continuous.

The lack of obvious visible chemical weathering in the Andes has two explanations. First, chemical weathering products such as clays are continually overwhelmed by the much larger supply of physically fragmented debris cascading down the steep slopes. Second, the fine clays and other products of weathering are soon removed from the steep slopes by fast-flowing streams and rivers and carried away to the Amazon lowlands or the ocean.

The Amazon Basin studies confirm that the rate of chemical weathering is rapid in the Andes, and presumably in many of Earth's other high-elevation regions as well, even though the visible effects of chemical weathering are not apparent. These studies also show that some warm, wet, vegetated regions may be places of surprisingly slow chemical weathering.

5-12 Weathering: Both a Climate Forcing and a Feedback?

The original uplift weathering hypothesis left an important issue unresolved. It did not specify a negative feedback that would act as a thermostat and moderate the climatic effects that uplift and weathering produce. Without such a thermostat, what would stop rapid uplift from accelerating chemical weathering to the point where Earth would freeze? As we have seen in Chapter 4, this nearly happened some 700 million years ago. And why wouldn't Earth overheat during times when uplift was minimal?

One possible mechanism that could moderate the degree of uplift-induced climate change is the total amount of fresh rock exposed at Earth's surface. Plate tectonic processes that cause uplift only affect the relatively small areas actively involved in subductions and collisions. The small size of these areas in turn limits both the amount of exposure of fresh rock at any one time and the intensity of cooling caused by uplift.

In addition, the effects of the uplift weathering processes are probably opposed by the chemical weathering thermostat. Uplift of geographically limited regions (perhaps 2% of Earth's total land area) could drive climatic cooling by promoting increased chemical weathering and CO_2 removal from the atmosphere, but chemical weathering on the other 98% of the continental area might well slow with the onset of cooler, drier climates and the reduction in vegetation cover. A slowing of the rate of CO_2 removal would leave more CO_2 in the atmosphere and moderate the overall cooling. In the end, the uplift-induced weathering increase would succeed in causing a net global cooling, but not nearly so large a cooling as would have occurred without the negative weathering feedback.

In Summary, both the BLAG (spreading rate) hypothesis and the uplift weathering hypothesis seem to provide plausible explanations of the icehouse-greenhouse changes of climate over the last 325 million years (see Tables 5-2, 5-3). In Chapter 7, we will revisit both hypotheses by examining in greater detail the sequence of changes that transformed the warm greenhouse climate of 100 million years ago to the later (and present) icehouse climate.

Key Terms

continental crust (p. 98)
ocean crust (p. 98)
mantle (p. 98)
lithosphere (p. 99)
asthenosphere (p. 99)
tectonic plates (p. 99)
divergent margins (p. 99)
convergent margins (-p. 99)
subduction (p. 99)
continental collision (p. 100)
transform fault margins (p. 100)
magnetic field (p. 100)
paleomagnetism (p. 100)
magnetic lineations (p. 101)
seafloor spreading (p. 102)
polar position hypothesis (p. 102)
Gondwana (p. 103)
Pangaea (p. 104)
evaporite (p. 108)
red beds (p. 109)
spreading rate hypothesis (p. 110)
hot spots (p. 111)
uplift weathering hypothesis (p. 113)
mass wasting (p. 115)