CHAPTER ONE

The Forging of Central America

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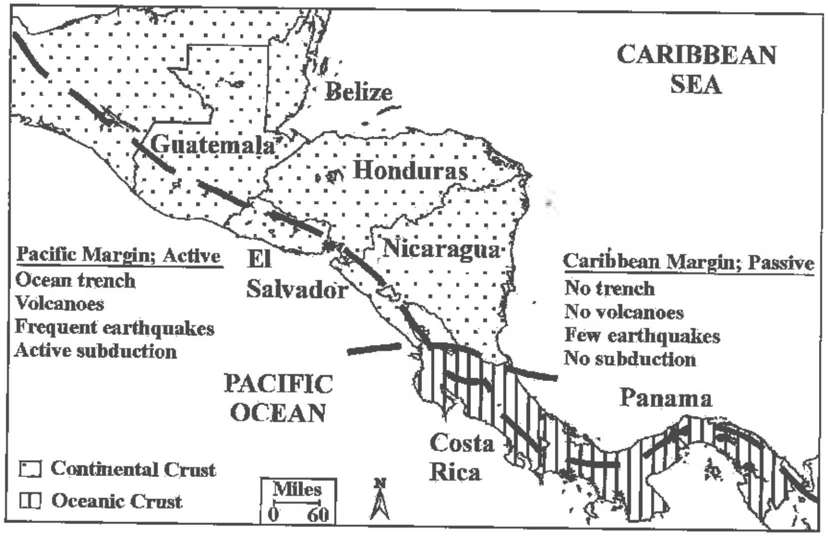
Nowhere in the world does a relatively small sliver of land manifest more dramatically the primal workings of the earth than in Central America. In its geological structure and the variety of its surface expression Central America is one of the most complicated regions on earth. The formation of the Central American isthmus also strongly affected processes operating over a wide area of the surface of the earth. Ocean circulation, climate, and the distribution of plants and animals on land and in the sea were profoundly changed. How and when these changes were triggered by the rise of the Central American isthmus is an area of very active modern research, and the future promises to bring to light new discoveries. For these reasons many scientists believe that the closure of the Central American isthmus was the most important natural event to affect the surface of the earth in the past 60 million years.

Not surprisingly, there is controversy concerning the timing and direction of the complex plate movements that led to the creation of the Central American land bridge. The geological story told here represents the most widely accepted scenario for the geological origins of Central America, but the reader is referred to the references at the end of the book for a discussion of more controversial issues.

The complexity of the geology of Central America is manifest in the variety of its surface terrains, the study of which is known as geomorphology. It is reflected in the asymmetry of geological structure across the isthmus from the Pacific to the Caribbean and in the strong contrasts between the north and south (fig. 1–1). The Pacific side is ge-



1–1. Map showing the distribution of continental crust (northern Central America) and oceanic crust (southern Central America) and the geological contrasts between the Pacific and Caribbean margins of the isthmus.

ologically active and usually the site of the major earthquakes. The ocean crust on this side is buckled downward near the coast into a trench 2000 meters deep; the volcanic chain tends to hug this coast, and there are vast quantities of sediment eroded from the chain and dumped by submarine avalanches into the trench. By contrast, the Caribbean side is mostly stable, with few volcanoes or earthquakes, no trench, and a more continuous and steady transfer of lesser amounts of sediment to a gently sloping marine shelf.

In northern Central America the land is old; hundreds of millions of years of mountain building and the long, slow process of erosion have sculpted the distinctive limestone karst terrains of El Petén and the granites and deformed metamorphic rocks (preexisting rocks transformed by heat and pressure) of the Crystalline Highlands of southern Guatemala, Honduras, and northern Nicaragua. Volcanic activity has come late to these regions and is superimposed on a broad and ancient rock tapestry. But to the south, in southern Nicaragua, Costa Rica, and western Panama, volcanoes dominate and the landscape is new, built in geologically recent times by seismic and volcanic processes. In eastern Panama, along the narrow Darién bridge to South America, where the isthmus rose completely above sea level only 3 million years ago, the volcanic chain ends and the geology takes on the flavor of the continent to the south.

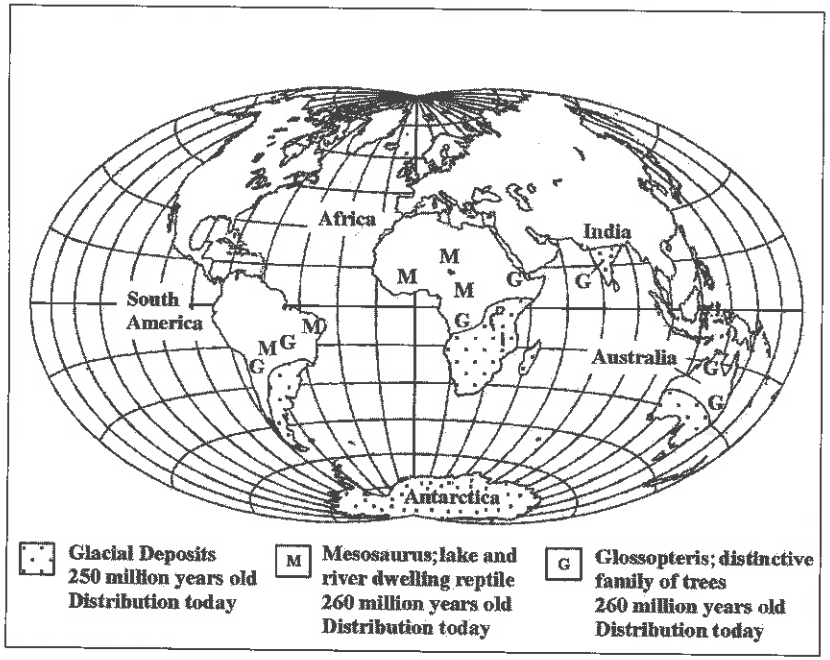
Geology's Unifying Theory: Plate Tectonics

Why is Central America so complicated geologically? What kinds of processes are at work? Geologists now believe that the inexorable movement and fracturing of the surface crust of the earth, as it rides on the hot, flowing mantle below, create the earth's continuously changing surface features. The process, called plate tectonics, suggested a model for the functioning of the earth that revolutionized geological science in the late sixties.

Plate tectonics is the first earth model to provide a coherent explanation for the location of such diverse features as earthquakes, volcanoes, mountain ranges, and deep linear trenches in the oceans. It also helps locate rich deposits of precious metals as well as major reserves of oil and gas. Plate tectonics was broadly accepted as a theory of the earth only in the 1970s, when geologists finally understood the mechanism by which it worked. But years before, some geologists persistently drew attention to the fact that many biological and geological features did not make sense if the continents had always been in their present positions. Identical species of tiny reptiles called *Mesosaurus* that lived in freshwater swamps 260 million years ago are now found as fossils in Brazil and Africa (fig. 1–2). How did they cross the Atlantic? Rocks that are 250 million years old and of glacial origin are now found in India, South Africa, South America, Antarctica, and Australia, as are fossil leaves of a distinctive genus of tree, *Glossopteris*. Scientists know of no mechanism that could form ice only in those locations nor do they understand how a genus of tree could be a native of five continents and live in so many different climatic conditions.

Paleomagnetism

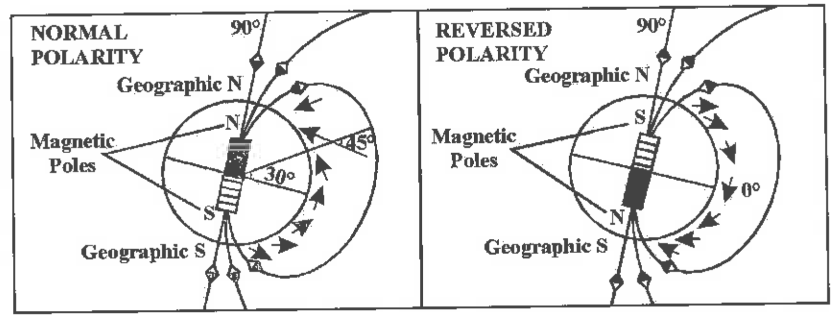
In 1966 two amazing discoveries about the rock record of the earth's past magnetic field were made. The first was that there is a magnetic component imprinted on certain kinds of rocks when they are formed that allows their original location (latitude) to be determined. Minute crystals of magnetite act as miniature compasses that align themselves, while the rock is still molten or the sediments still dropping through the water, to the lines of force of the earth's magnetic field. At the poles, these lines of force are vertical to the surface of the earth; at the equator they are horizontal. For each latitude in between they are at a unique angle (fig. 1–3). Thus, by measuring the angle of the magnetite crystals and allowing for any subsequent tilting of the strata, the original latitude of the rock when it was formed can be determined. These studies



1–2. Map indicating the disjunct and inexplicable distribution of the fossil freshwater lizard *Mesosaurus*, the fossil tree *Glossopteris*, and the glacial deposits of 250–260 million years ago when plotted on a modern global map. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

have shown that most rocks are now far removed from where they were when formed, and in general the older they are, the farther they have moved. Furthermore, measuring of these paleomagnetic angles for rocks of the same age in different continents and then extrapolating where the poles would have been for each continent show that each continent has moved along a different path, that is, each continent produced a different pole position for the same time (fig. 1–4). When continents are moved back so that they have the same pole position for each time interval, for example, 260–250 million years ago, they form a large supercontinent called *Pangea*. The southern contiguous land area within *Pangea* is called *Gondwana*. Here, the rocks with *Mesosaurus* in them occur close together, all the glacial deposits form a single ice sheet covering the pole, and *Glossopteris* occupies a zone at a similar latitude (fig. 1–5).

The second extraordinary discovery about paleomagnetism was that the north and south magnetic poles appear to have reversed themselves erratically during the course of time. At certain times, the paleo-

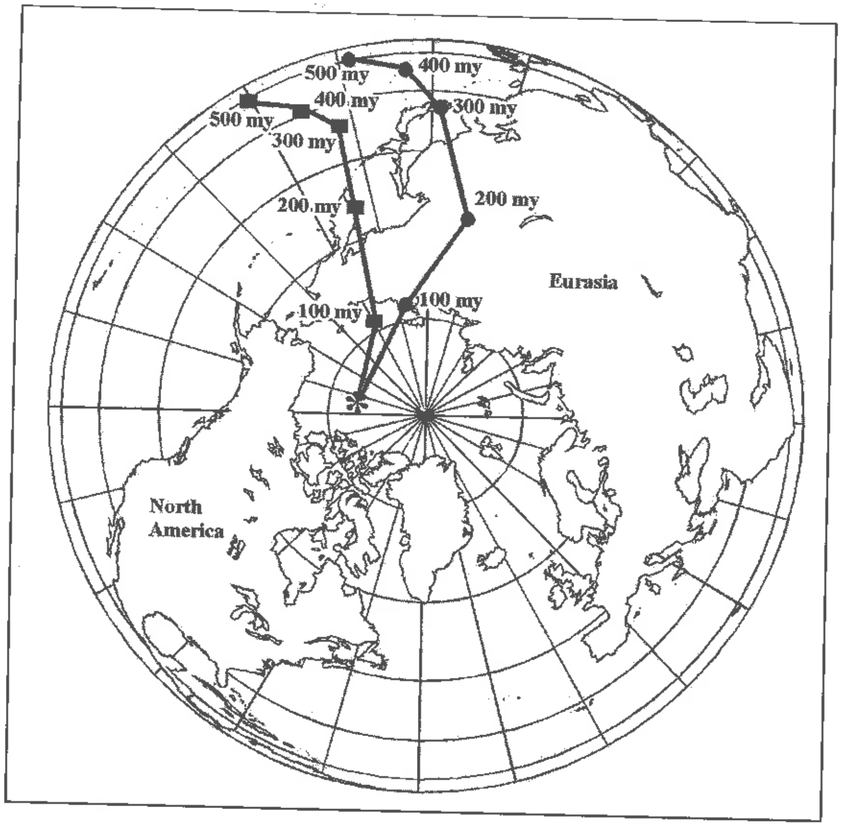


1–3. Diagram of the earth's magnet field during normal and reversed polarities. Directions and polarity of the magnetic lines of force are indicated by arrows. For example, the angle of the magnetic crystals in rocks deposited at 30 degrees of latitude will be 45 degrees.

magnetic measurements of rocks show that the fossil north pole was in the same place as the present one—called normal polarity—and in other cases the fossil south pole was located at the present north pole—called reverse polarity (see fig. 1–3). Thus, the history of the earth is divided into periods of normal and reversed polarity, which vary greatly in duration. The normal and reversed episodes can be recognized most perfectly in the cooled basalt lavas on the floors of oceans, but they are also recorded in many sequences of sedimentary strata on land. Because the earth's magnetic field applies all over the earth, each paleomagnetic episode is imprinted on all rocks that are being formed at the time of its occurrence. When sequences of strata with the same pattern of reversed and normal polarities are identified in different parts of the world, geologists know that they are of exactly the same age even though the sequences may be of different thicknesses in different regions (fig. 1–6). These discoveries were crucial to our understanding of how the plate tectonic model works.

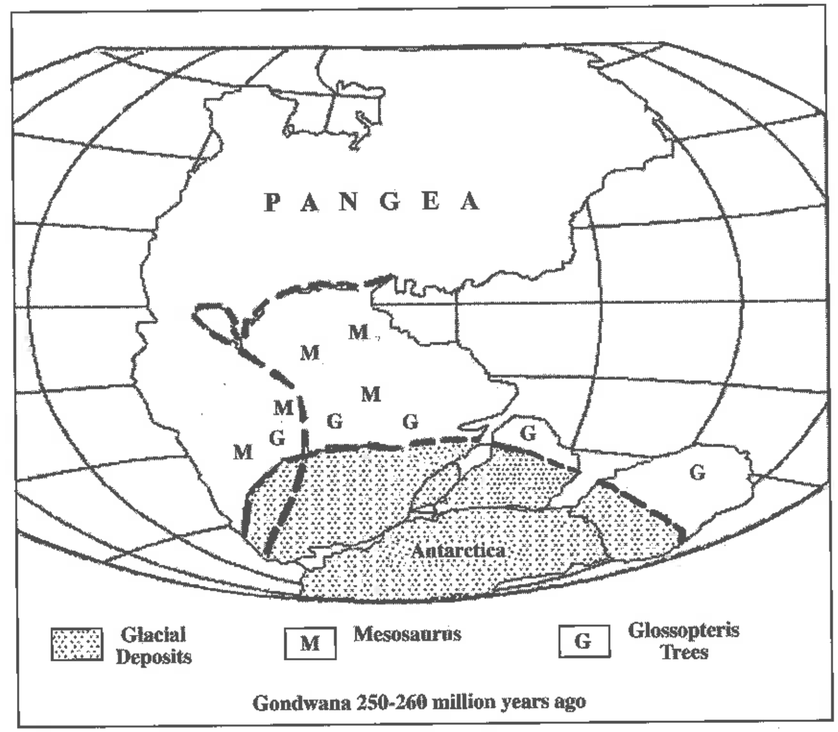
The Plate Tectonic Model

The essence of the plate tectonic model is that the earth has a relatively rigid outer layer called the lithosphere that is about 75–125 kilometers thick (fig. 1–7). The lithosphere, which is capped by a thin crust beneath the oceans and a thicker continental crust elsewhere (see fig. 1–7), is broken up into large and small plates by the plastic flow of the hotter, denser rocks underneath, which, owing to the considerable heat generated in the interior of the earth by naturally radioactive minerals,



1–4. A map showing the various points (connected by a line called the polar wandering curve) at which paleomagnetic measurements predict that the pole would have been for each of the time periods indicated. Note that the rocks measured in Europe (black squares) give a different pole location for each time than the rocks measured in North America (black circles). Because we assume that there could only have been one north and one south magnetic pole at any one time, the two curves prove that each continent has moved in different directions. If the continents are moved to make their different polar wandering curves coalesce, Europe is placed next to North America and the Atlantic Ocean disappears. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

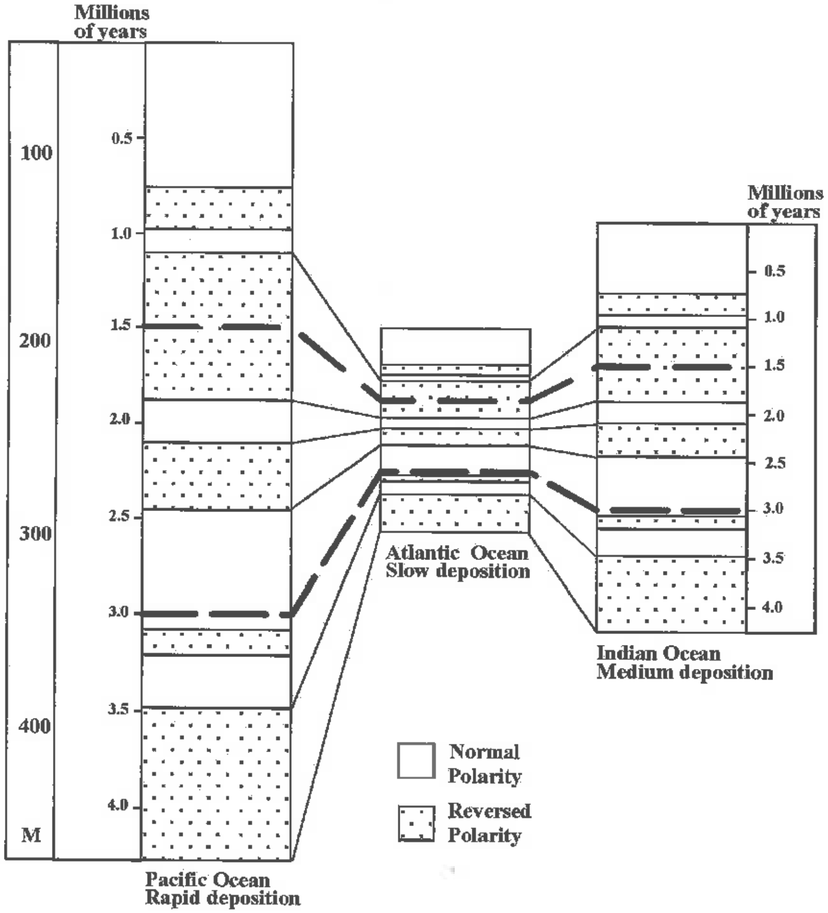
are slowly churning. This deeper layer, 2900 kilometers thick, is referred to as the mantle, and it surrounds the even more dense core of the earth (see fig. 1–7). The flow of the mantle below the lithosphere follows a convecting pattern, so that in some zones in the earth hot liquid rock, called magma, rises to the surface and spreads outward and in others the cooler mantle is sinking (fig. 1–8). The crustal plates are riding passively on the back of this churning mantle. The interaction of



1–5. Using paleomagnetic evidence from rocks 250–260 million years old, geologists have reconstructed a map of the world for that time period, shown here. It shows a unified group of southern continents in one supercontinent named Pangea. The freshwater *Mesosaurus* fossils now cluster together in one region, and the *Glossopteris* trees form a latitudinal belt north of a unified southern polar ice cap. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

these plates as they separate, collide, or pass by each other forms all the major geological features of the surface of the earth.

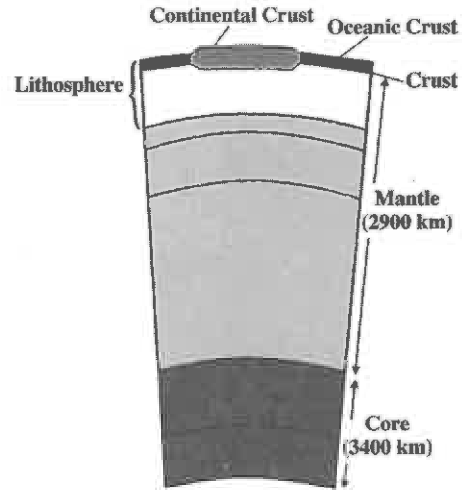
Perhaps the most striking feature of the crust is that it is divided into continents and oceans. To most people, this simply means land versus water. To geologists, the difference is much more fundamental (fig. 1–9). Continental crust is much thicker and on average less dense and structurally more complicated than oceanic crust. The continental crust is made of rocks that have been intensely deformed and chemically and physically altered, including some as old as 3 or 4 billion years. The ocean crust, on the other hand, is thinner, more dense, and relatively unaltered chemically and is nowhere more than about 200 million years old. Furthermore, the oceanic crust is less deformed and carries a record of the strength and polarity of the earth's magnetic field laid out in parallel stripes on either side of long central ridges that are



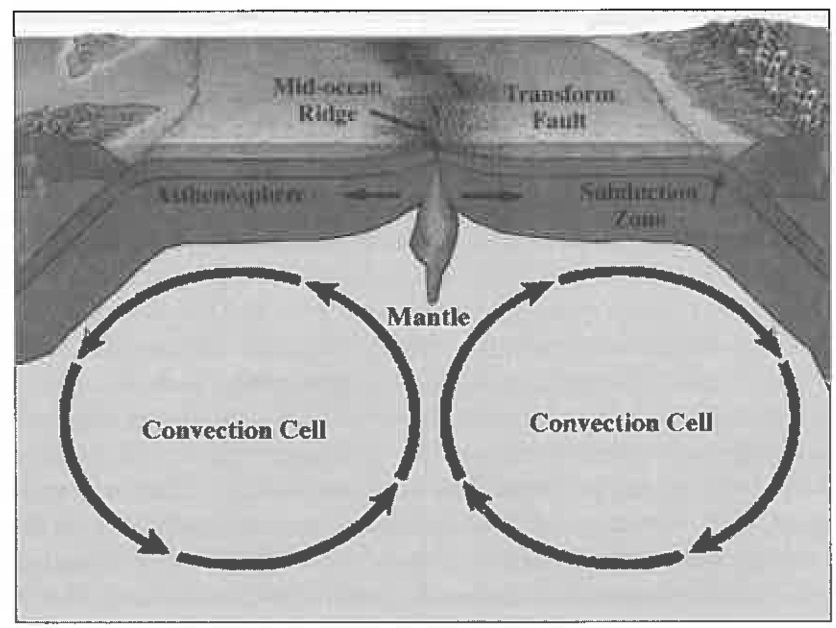
1–6. Three magnetic polarity sequences are shown superimposed on hypothetical cores of sedimentary sequences of the same general age that are of different thicknesses in the Pacific, Atlantic, and Indian Oceans. The sedimentary sections vary in thickness owing to different rates of deposition. In each core, however, the polarity sequence pattern is preserved identifiably, although one is proportionately expanded (rapid deposition) and another is proportionately contracted (slow deposition). The figure indicates lines that can be drawn to identify the same time in each section.

the sites of magma rising to the surface. Each polarity stripe on one side of the central ridge has a mirror image on the other side (fig. 1–10). The reasons for this will become clear below. These geologic differences between continental and oceanic crust are readily explained in the plate tectonic model by the different ways in which the various plates are formed and interact.

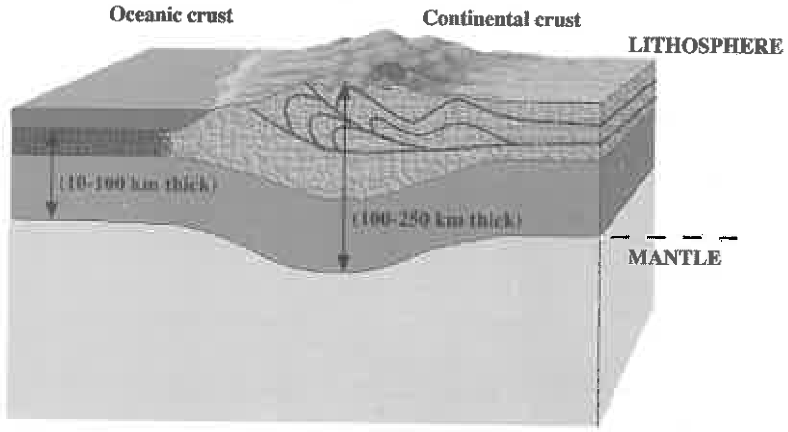
The interactions are of three main types. The first, in which two plates collide, is called a *subduction zone*. There are three possibilities.



1–7. The diagram shows the thicknesses of the different layers that geologists use to define the internal structure of the earth. Note the contrast in thickness of the oceanic and continental crust.



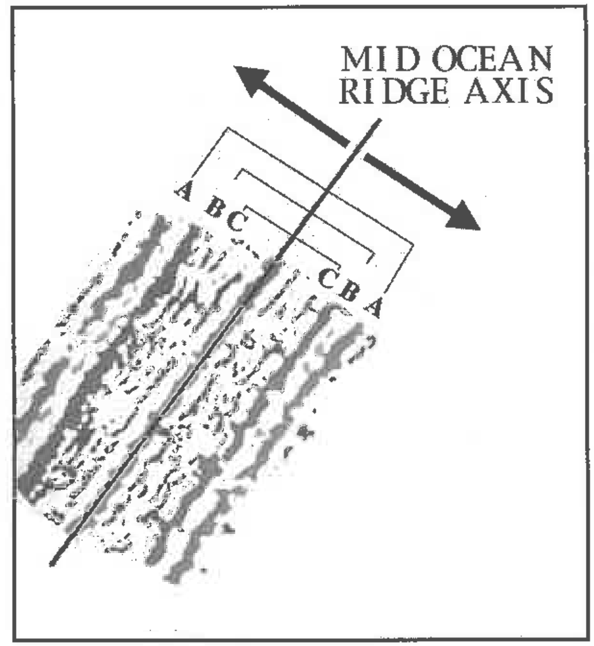
1–8. A schematic cross section of the earth showing the pattern of convecting magma in the mantle, the locations where magma rises to the surface, where the lithosphere is carried laterally, and where magma and the lithosphere sink. This mantle flow drives the movement of surface crustal plates. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.



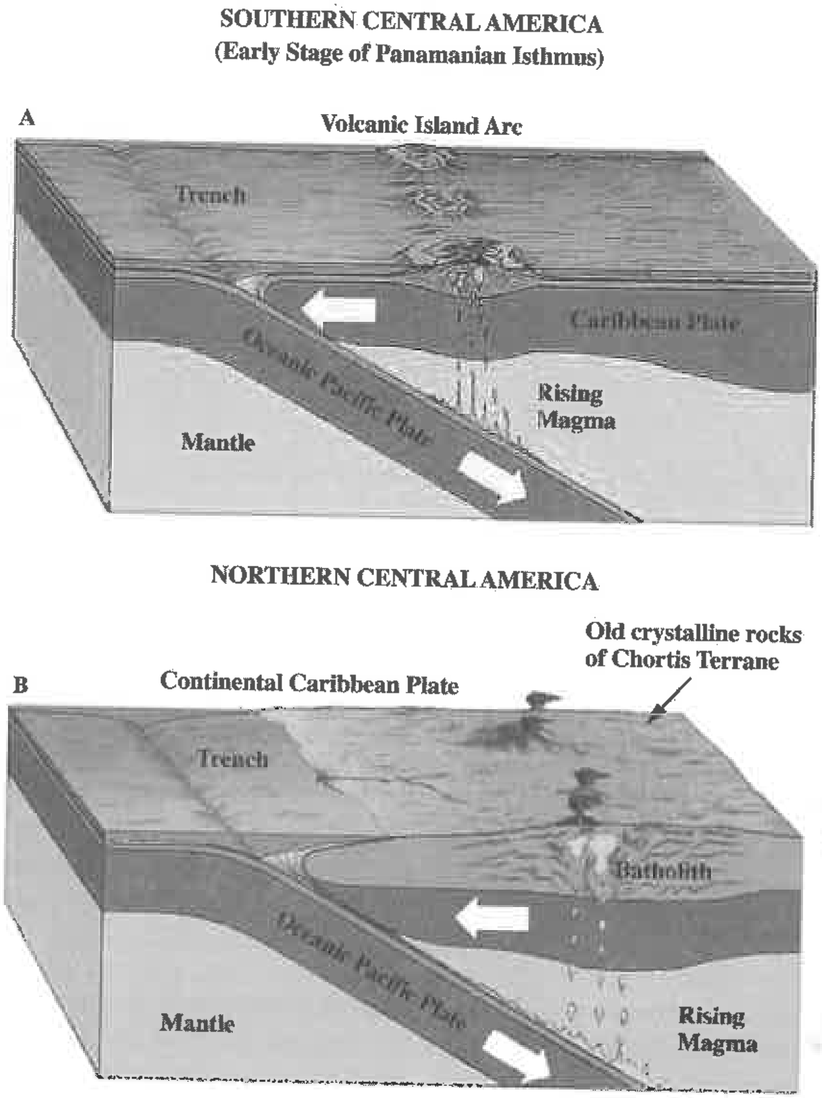
1–9. A schematic cross section of the solid lithosphere showing the differences in thickness and structure of oceanic versus continental crust. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

The two plates may both consist of oceanic crust, or one may be oceanic and the other continental crust, or both may be continental, as in the Himalayas, where India and Asia have collided. In Central America, only the first two possibilities apply. In these collisions, the denser plate sinks beneath the other, usually causing a deep, narrow oceanic trench to form (fig. 1–11). The sinking plate starts to melt at a depth of about 70 kilometers, and the lighter elements of its magma rise to the surface through the overlying plate. If that plate is thin, as in oceanic crust, these magmas pour out as lavas or explode as mixtures of gas, ash, and molten rock fragments called *tephra*, along a curved line of volcanoes that form a volcanic island arc (fig. 1–11A). If the overlying plate is continental and thick, the magma often does not reach the surface and cools to form large bodies of granitelike rocks known as *batholiths* within the upper plate (fig. 1–11B). Eventually, erosion may expose these batholiths at the surface. The compression and buckling up of the overlying plate in subduction, the addition of these lighter magmas, and the scraping off of sediments and other rocks from the sinking plate onto the overriding plate all cause the crust of the upper plate to become thicker and thus more "continental" with time. As a result, the overlying plate subtly changes its chemical composition.

The collisional plate junction, or subduction zone, is where continental crust is mainly generated. Once formed, this lighter, thicker crust will generally not be subducted but will continue to override oceanic crust; it thus continues to accrete material and grow steadily, differentiating into ever larger areas of thicker, lighter crust that now are called continents. Geologists believe that this process has been happening throughout the history of the earth. For this reason, continental crust has expanded in area and become more structurally complicated and more varied in composition than oceanic rocks. Modern subduction zones, involving continental crust, are the location of the world's mountain belts, deep oceanic trenches, zones of major earthquakes, and chains of explosive volcanoes. The same magmas that emplace the granitelike rocks carry with them the fluids from which precious metals are deposited and are thus often the sites of important mining regions, as is the case in much of Central America. Subduction zones in which two oceanic plates interact at first form only a volcanic island arc, such as the Lesser Antilles or the Aleutian Islands, although they are accom-



1–10. A magnetic map of the Atlantic sea floor to the southwest of Iceland shows the parallel stripes of normal and reversed polarity; each one to the east of the mid ocean ridge has a corresponding mirror image to the west as indicated at A, B, and C. The further the stripe is from the mid ocean ridge, the older it is. By dating the stripes radiometrically, via the geomagnetic reversal timescale, the rate of sea-floor spreading can be calculated. Modified from J. R. Heirtzler et al., "Magnetic Anomalies over the Reykanes Ridge," *Deep Sea Research* 13, no. 3 (1966): 427–443, fig. 1, and F. J. Vine, "Magnetic Anomalies Associated with Mid-Ocean Ridges," in R. A. Phinney, ed., *The History of the Earth's Crust, A Symposium*, 1968, fig. 6.



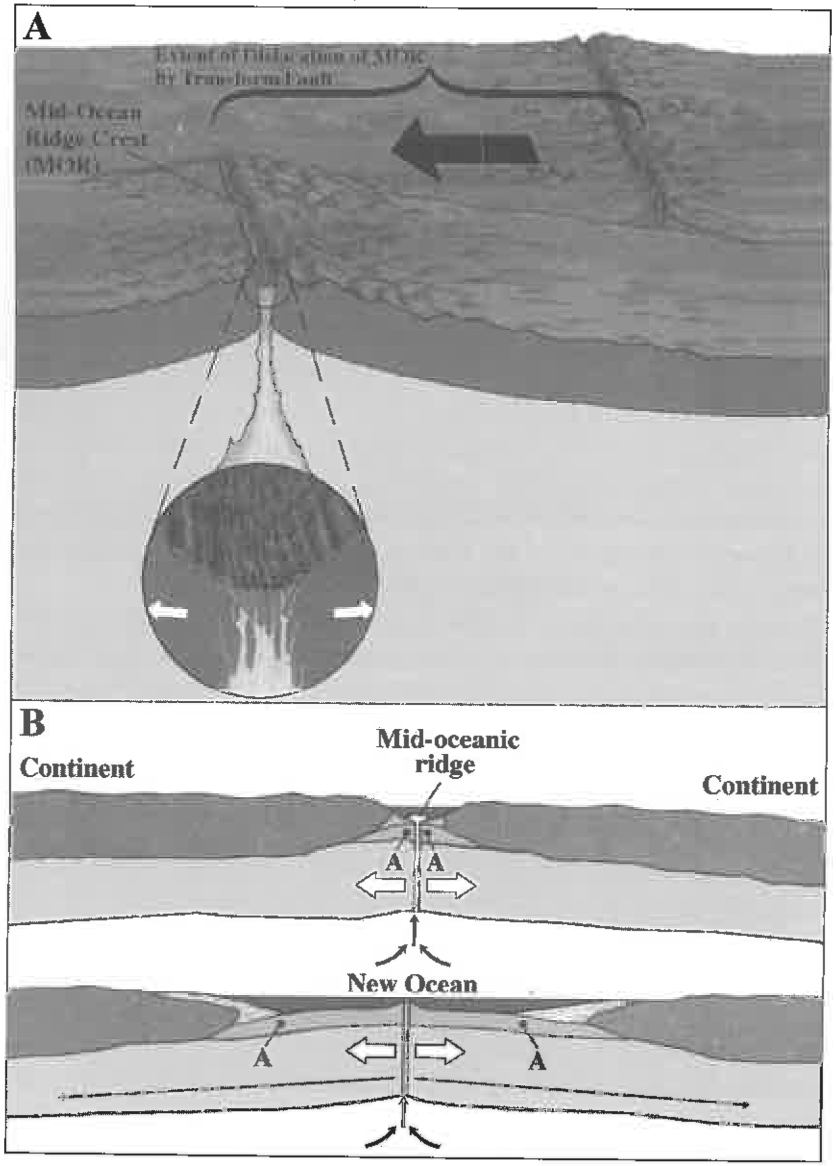
1–11. Cross sections of subduction zones. In (A) each plate is oceanic crust. An island arc of volcanoes represents an early stage in the formation of southern Central America; (B) a subduction zone, where an oceanic crustal plate sinks beneath a continental crustal plate. This is a model for the structure of northern Central America. The batholiths and the surrounding metamorphic sediments, when eroded and exposed at the surface, will form the Central Crystalline Highlands. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

panied by linear ocean trenches and major earthquake and volcanic activity (see fig. 1–11A). Later, they may form a continuous strip of land, as in the Central American isthmus.

The second type of plate interaction occurs where mantle magmas rise and pierce the lithosphere, creating new oceanic crust. This type may take two forms. In the first, the magma rises at a single point on the earth's surface so that a *hot spot* is formed and a very large volcano results, such as Kilauea in Hawaii. Enormous quantities of primal magma pour out. Geologists believe that because hot spots are direct emissions from the underlying mantle they are stationary with respect to the movements of the lithosphere. Thus, as the lithosphere moves over a hot spot, the volcano at the surface will move along the plate through time, leaving a linear track of extinct volcanoes behind in the same way a piece of paper moved steadily over a lit candle would leave a burned trace. The trace of the flame would mark the direction of the movement of the paper, and the track of the extinct volcanoes similarly marks the movement direction of the plate.

More commonly, rising mantle magma wells up along fissures that may be hundreds or thousands of kilometers long. Because hot, dense magma is rising, the surface of the crust is raised into a broad ridge, although the actual line along which the magma reaches the surface and spreads outward is a down-faulted valley or rift (fig. 1–12A). Because these rifted ridges occur in the center of oceans, this type of plate interaction is known as a *mid ocean ridge*. Mid ocean ridges allow geologists to get a glimpse of the rock (called *peridotite*) produced directly from the mantle, although generally the ocean crust forms by decanting of the peridotite magma into the mid ocean ridge, with rapid solidification into hard, black, dense basalt. All of the world's ocean floors are composed of basalt, which has neither mixed with other rocks nor fractionated and been purged of its lighter elements. This explains why the oceanic crust is thinner but denser than the continental crust differentiated in the subduction zones. The fractionated rocks that form continents have the general characteristics of granite and in origin and chemical composition strongly contrast with the typical basalt of oceanic crust. It follows from the differences between oceanic and continental crust that as mid ocean ridges form they will be the sites of new oceans, and as the new crust spreads out the ocean will grow in size (fig. 1–12B).

When the rising magma reaches the surface in the mid ocean ridge and begins to cool, the myriad tiny magnetite crystals within it align themselves with the earth's magnetic field at the angle corresponding to



1–12. A cross section of a typical mid ocean ridge showing the central rift valley where magma (basalt) is extruded to form new oceanic crust: (A) the mid ocean ridge dislocated by a transform fault; (B) a mid ocean ridge slowly creates a new ocean underlain by young oceanic crust. After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc., and Harold Levin, *Contemporary Physical Geology* (Saunders College Publishing Co.), 271, fig. 10–14.

the earth's latitude at that point. They also take on the polarity and the intensity of the earth's magnetic field at the time of cooling. Once the basalt is cooled and hard, the magnetic signal is frozen in place. As the oceanic crust spreads outward in opposite directions on either side of the mid ocean ridge, new magma wells up to take its place. If the earth's magnetic field has changed polarity and intensity during this process, then the new basalt will differ in paleomagnetic signal from the previously formed basalt, which now forms two mirror-imaged stripes on the ocean floor; located on either side of the newly emplaced basalt, the two stripes are identical in polarity, magnetic intensity, and age (see fig. 1–10). As the process continues over millions of years, new mirror-imaged stripes are continuously formed on either side of the mid ocean ridge, and the older ones migrate farther and farther apart. Each stripe, running the length of the opening ocean, has the same age and polarity everywhere. Geologists can establish the age of the stripe by analyzing the amount of decay of radioactive minerals within a piece of basalt at one point, a process called radiometric dating, and thus establishing the age of that stripe anywhere along its length. If the age of the stripe and the distance from the center of the mid ocean ridge are known, then the speed at which the basalt floor is spreading out from the mid ocean ridge can be calculated. About 7 to 8 centimeters per year is a typical rate for these movements. At its current rate of spreading, 2.5 centimeters per year, the sea floor of the Atlantic Ocean has taken 230 million years to reach its present width!

The oceans, then, through their mid ocean ridges, are where new primal crust originates, and this crust, carried outward in both directions, bears a virtual tape recording of the age, width, and paleomagnetic history of the ocean at each stage of its growth. As the same process is taking place in two or three oceans simultaneously, the phased sequences of polarity reversals will enable geologists to correlate stripes formed at the same time in each ocean. Moreover, sediment accumulated in vertical sequences on other parts of the ocean floor and on land records the same episodes of normal and reversed polarity (see fig. 1–6). Within 200 to 300 million years, the spreading ocean floor will eventually arrive at a subduction zone, where it will sink and be melted. For this reason there is no ancient oceanic crust left on earth.

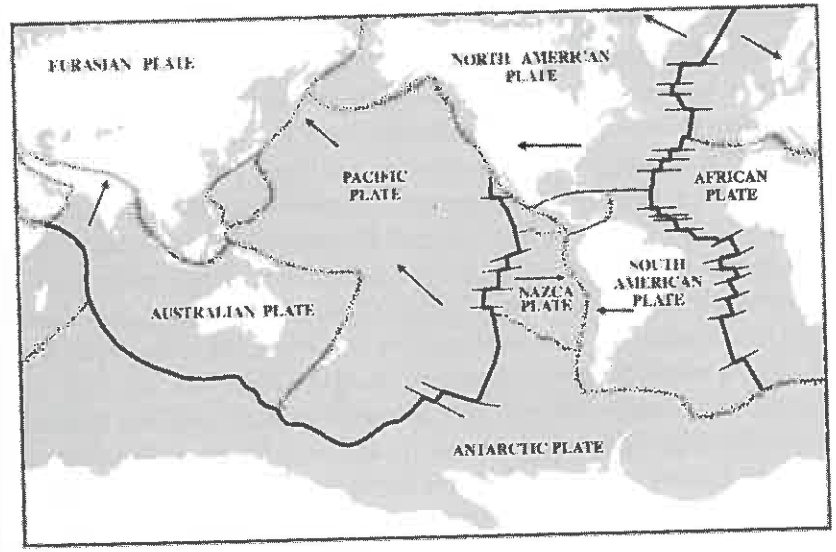
The third and last type of plate interaction is known as a *transform fault*. Plates cannot move away from all mid ocean ridge spreading centers at the same velocity because of the spherical shape of the earth and because lava is generated at varying rates in different places. In order for portions of the crust to move at different velocities, they have to break into segments along faults that transform the motion of the spreading crust into units (plates) with different velocities—hence the term transform fault. Unlike the other two, this interaction does not involve vertical movements and thus little or no volcanic activity and no destruction or creation of crustal material. In transform faults, plates slide by each other, dislocating previous geologic structures (see fig. 1–12A). The most distinguishing feature of a transform fault is intense earthquake activity. Transform faults offset preexisting subduction zones and mid ocean ridges so that the earth's crust is now a mosaic of small and large plates, all of which are interconnected by a web of these three junctions (fig. 1–13).

The plate tectonic model has for the first time allowed geologists to unite, in a single unified theory, the previously unconnected patterns of mountain ranges, volcanic activity, earthquakes, and oceanic trenches, as well as the otherwise inexplicable patterns of fossil and rock distributions in the geologic past. I shall use it to unravel the recent geological history of Central America, which has been dominated by the interactions of a major subduction zone running along its Pacific margin and two transform faults bounding it to the north and south. Central America is affected by the interplay among five different plates, and within its boundaries there are two triple junctions—very complicated points at which three plates intersect. For these reasons its geological history has been complicated and violent.

Assembling Central America

Modern Central America has been geologically recognizable only in the past few million years. Before that, the geological units that form the present isthmus either had not yet formed or were located at other latitudes. A geological unit that has originated in one location and by plate movement has been transported, often large distances, and then accreted onto the edge of another plate during subduction is known as an *exotic terrane*. Several such terranes are now closely united to form modern Central America, but they evolved in very different environments and hence have strikingly diverse rocks and fossils, which testifies to their separate history and genesis. The geologic term *terrane* is distinct from *terrain*, which refers to the nature of the land surface.

Geologically, Central America has been strongly affected by the movements of South and North America. Two hundred fifty million years ago, these two continents were part of the great supercontinent Pangea. About 140 million years ago, at the end of the Jurassic period,



1–13. A map of the major plates of the world. The plates are defined by connecting the mid ocean ridges and transform faults (thick black lines), and the subduction zones (hachured black lines). After "The Theory of Plate Tectonics," Copyright 1994, Tasa Graphic Arts, Inc.

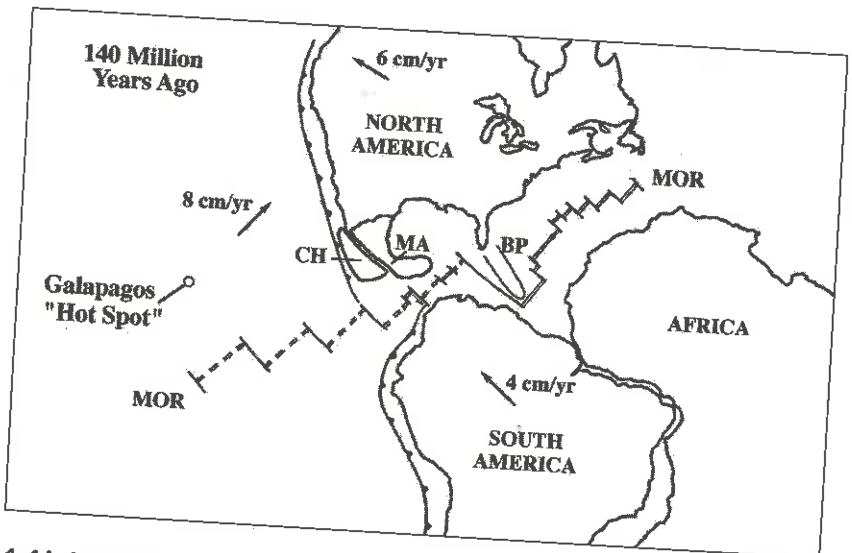
Pangea, through the formation of a mid ocean ridge, began slowly to rift apart. At first, North America separated from Europe, North Africa, and South America to form the fledgling Atlantic Ocean, which connected directly to the Pacific through the present location of Central America (fig. 1–14). On the southern margin of the North American plate, the future Mexico formed a peninsula, to which were attached the Maya and Chortis terranes. Here, more than 300 million years ago, the sediments that would come to form the Crystalline Highlands of northern Central America were deposited. The Maya Terrane was to stay locked to Mexico in a stable position. By contrast, the Chortis Terrane would become detached from western Mexico.

By 80 million years ago, late in the Cretaceous period, the widening Atlantic Ocean had now spread southward and was separating Africa and South America (fig. 1–15). At the same time, the Galápagos hot spot started a vast outpouring of basalt that covered an area 1000 by 3000 kilometers (the gray area in figure 1–15). The Pacific Ocean now had its own mid ocean ridge system, dividing an eastern Farallón Plate from a western Pacific Plate. The eastern margin of the Farallón Plate was now a subduction zone with an accompanying active volcanic arc that stretched along the western coast of North America, including the Chortis Terrane at its southern tip, and the island arc across the site of

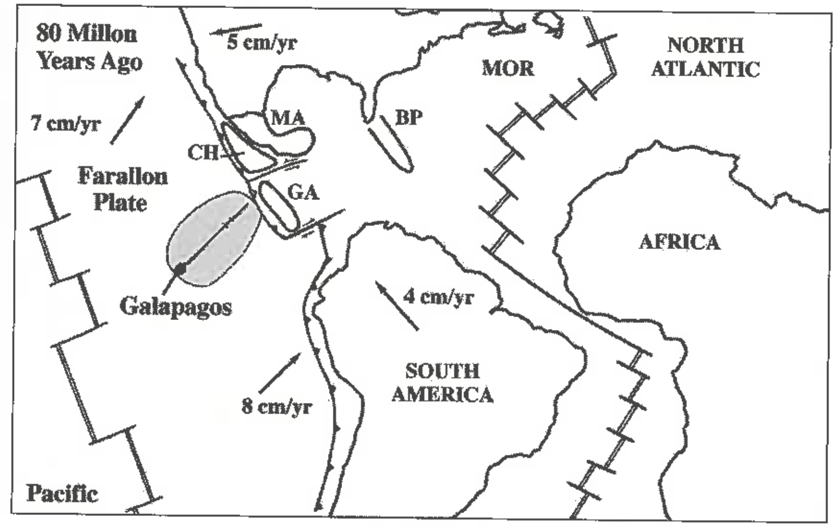
Central America, and down the west coast of South America (see fig. 1–15). The island arc in the location of Central America is labeled *GA* on the figure because subsequent plate movements would carry it far to the northeast, where it would eventually form the islands of Jamaica, Cuba, and Hispaniola (that is, the Greater Antilles).

By the end of the Cretaceous period, about 65 million years ago, the great volcanic arc along the west coast of all the Americas was ruptured in the region of Central America, and a segment of the arc, together with the great basalt sheet poured out by the Galápagos hot spot, had been squirted northeastward as a new small unit—the Caribbean Plate (fig. 1–16). On its western margin a new subduction zone and volcanic island arc had formed—the geological beginnings of modern Central America. The great Galápagos "flood" basalt now floors the Caribbean Sea, and fragments of it in turn have been scraped off in subduction movements and preserved in many terranes that rim the Caribbean.

The future Central America at the end of the Cretaceous period



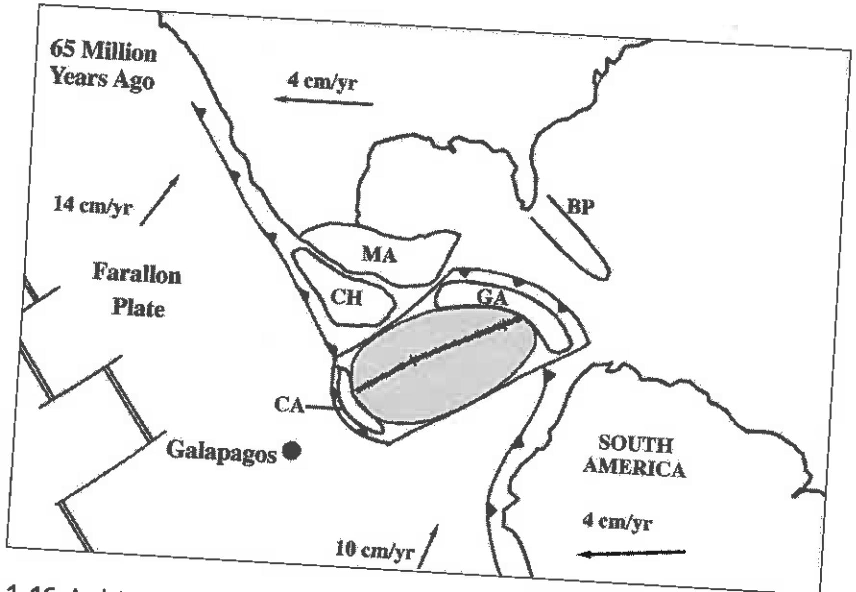
1–14. A reconstruction of the arrangement of plates 140 million years ago, at the end of the Jurassic period. Arrows indicate the direction and speed of relative movement of the plates. Note that only the North Atlantic has opened, connecting with the Pacific Ocean, and that the Chortis Terrane lies largely to the west of the Maya Terrane. BP = Bahama Platform; CH = Chortis Terrane; MA = Maya Terrane; line with black triangles is a subduction zone; double line with offsets is a mid ocean ridge (MOR) with transform faults. (Symbols are the same for figures 1–15, 1–16, 1–17, 1–18, and 1–20.) Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics,* Geological Society of America Memoir 162, fig. 1.



1–15. A plate reconstruction for 80 million years ago, late in the Cretaceous period. The shaded area is a "flood" basalt from the Galápagos Hot Spot, and GA represents a volcanic arc destined to become the future Greater Antilles. Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics,* Geological Society of America Memoir 162, fig. 4.

consisted, then, of a southern extension of the North American Plate forming a continental peninsula, present-day Mexico, with an easterly extension formed by the Maya Terrane, presently underlying the Yucatán, El Petén, and Belize. Sutured onto the Maya Terrane to the south was the Chortis Terrane, newly arrived from the northwest, which now underlies El Salvador, southern Guatemala, Honduras, and Nicaragua (fig. 1–16). The suture between the Chortis and Maya terranes runs along the Motagua Valley in Guatemala, where contemporaneous rocks completely different in character and in original latitudes face each other on opposite sides of the valley. The future Costa Rica and western Panama were a series of oceanic volcanic islands stretching to the south of the Chortis Terrane (labeled *CA* in figure 1–16).

During the Eocene period, about 40 million years ago, the volcanic arc bordering the Caribbean Plate to the northeast finally collided with the Bahamas-Florida Platform, effectively preventing it from moving further northeastward. Cuba and Hispaniola were formed as a result of this collision. After this time, the Caribbean Plate began to move eastward and a new subduction zone was formed, now located along the Lesser Antilles Volcanic Arc (fig. 1–17).

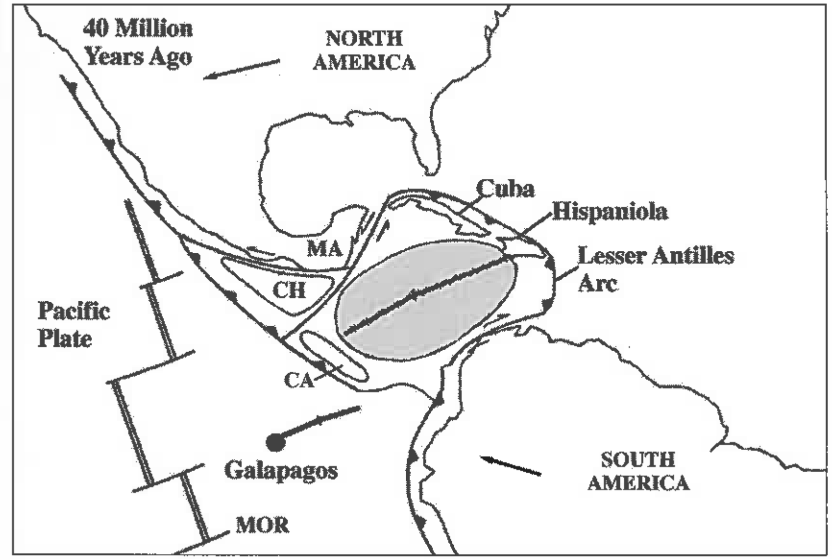


1–16. A plate reconstruction for 65 million years ago at the Cretaceous-Tertiary boundary. Note that the Chortis Block now lies to the south of the Maya Terrane and is fused to it; the Greater Antilles arc has moved far to the northeast, and the new Caribbean Plate (shaded area), floored with the Galápagos "flood basalt," is delimited to the west by a new subduction zone forming the Central American volcanic arc (CA). Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, B. and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics,* Geological Society of America Memoir 162, fig. 5.

Meanwhile, the Farallón Plate in the north had been entirely subducted under the North American Plate, and the Pacific mid ocean ridge system now intersected the coast near the Mexico–United States border. Farther south, the Farallón Plate continued to converge on the Chortis Terrane as well as the proto–Central American arc and South America (see fig. 1–17).

By the beginning of the Miocene period, 20 million years ago, the Caribbean Plate had extended considerably to the east (fig. 1–18). An oceanic gap between the Central American volcanic arc and South America had developed, serving to keep the terrestrial faunas of North and South America separated. In addition, the Farallón Plate had now separated into two units, a northern Cocos Plate and a southern Nazca Plate. Figure 1–19A is a tentative reconstruction of the geography of the isthmus about this time.

As a result of these plate movements, a gradual closing of the deep-water connection of the Pacific and Caribbean started at this time. The proto–Central American volcanic arc extended eastward, and about 12



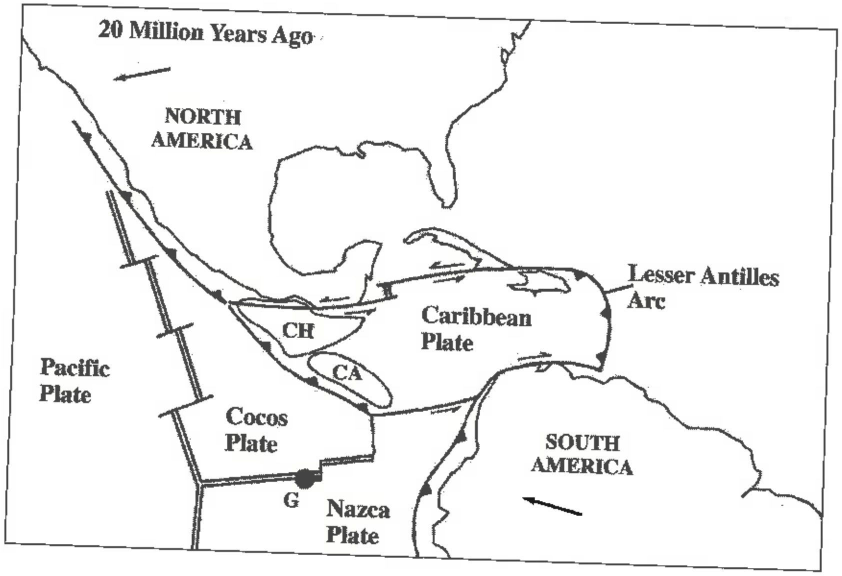
1–17. A plate reconstruction for 40 million years ago, late in the Eocene period. The Greater Antilles volcanic arc has now collided with the Bahama Platform, and the new movement of the Caribbean Plate is eastward along the Lesser Antilles arc. The Americas have overrun the Pacific mid ocean ridge system and much of the Farallón Plate; there is a continuously active volcanic arc the length of the eastern Pacific. Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics,* Geological Society of America Memoir 162, fig. 6.

million years ago finally collided with South America. The future isthmus rose to form a sill some 1000 meters deep.

This momentous event triggered profound changes in both oceans that are still going on today. The first result of the severing of deep-water (2000 meter) connections between the oceans was the disappearance in the Caribbean of microscopic plants (*diatoms*) and animals (*radiolaria*) whose skeletons are made of glass, or silica. In the Pacific, however, this important component of the plankton continues to be abundant to the present time.

By 11 million years ago, islands may have begun to appear in the present location of eastern Panama and the southern half of modern Central America. Over the next few million years the region became an archipelago with many varied marine and coastal habitats. This archipelago further restricted the marine circulation from the Caribbean to the Pacific, but other factors now began to play a role also.

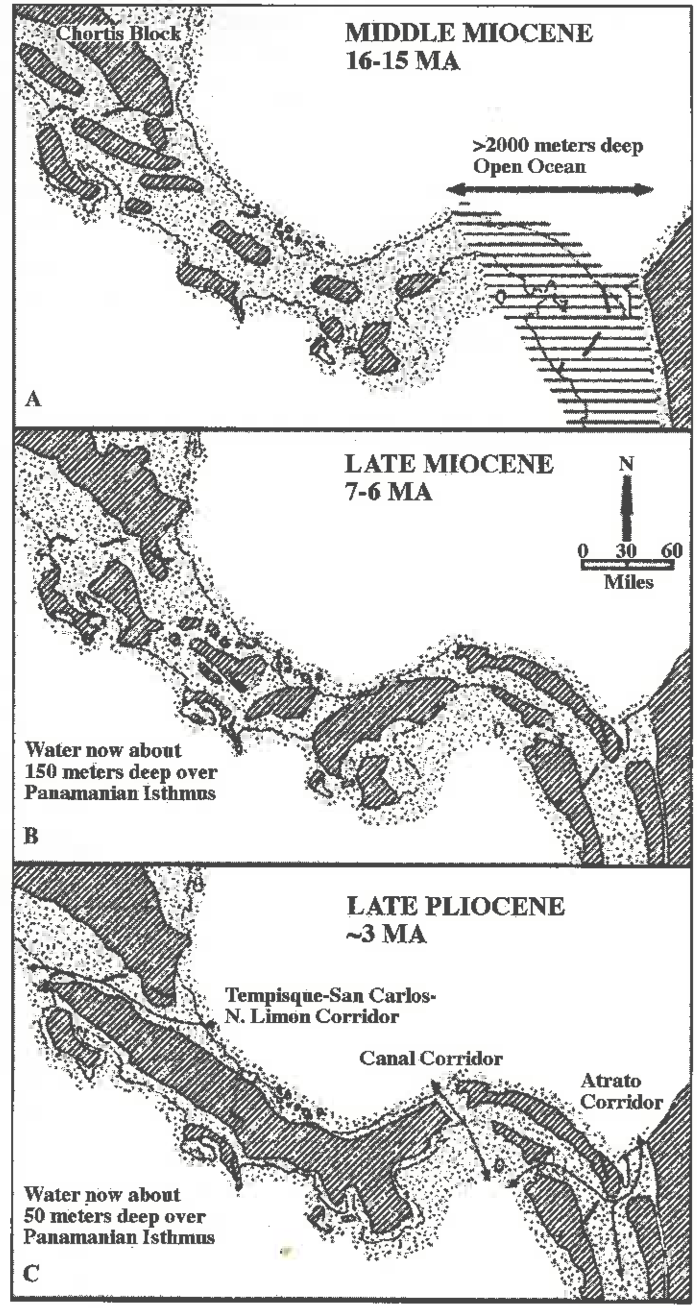
The Antarctic ice cap had began to grow so that sea level dropped as ice was sequestered in the polar caps, and sea temperatures cooled.



1–18. A plate tectonic reconstruction for 20 million years ago. The Farallón Plate is now split into the Cocos and Nazca plates, and the Caribbean Plate continues to migrate eastward, at the same time being squeezed by the relative northwestward movement of South America. Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics*, Geological Society of America Memoir 162, fig. 7.2.

Some geologists believe that this brought the cool, southerly flowing California Current, which is presently restricted to the north, as far south as Guayaquil in Ecuador, effectively isolating the marine species living in the Caribbean from those in the Pacific. Microscopic single-celled animals with calcareous skeletons called *foraminifera* are very distinctive of sediments at the bottom of the sea, different species living at various depths and in diverse sediment conditions. Those typical of the present California Current are known from 11 to about 6 million years ago in sediments along the Pacific coast as far south as Guayaquil. Caribbean forms are not mixed with them. While the marine species were apparently strongly separated at this time, a few island-hopping, swimming animals such as raccoons and sloths were able to migrate between North and South America (see chapter 4) as the isthmus steadily rose and more islands appeared. About 6 million years ago the isthmian sill would have been only 150 meters deep (fig. 1–19B).

Between 6 and 3 million years ago, further dramatic regional changes occurred, culminating in the final closure of the land barrier between the Pacific and the Caribbean. But first, the California Current seems to have retreated northward again so that once more marine



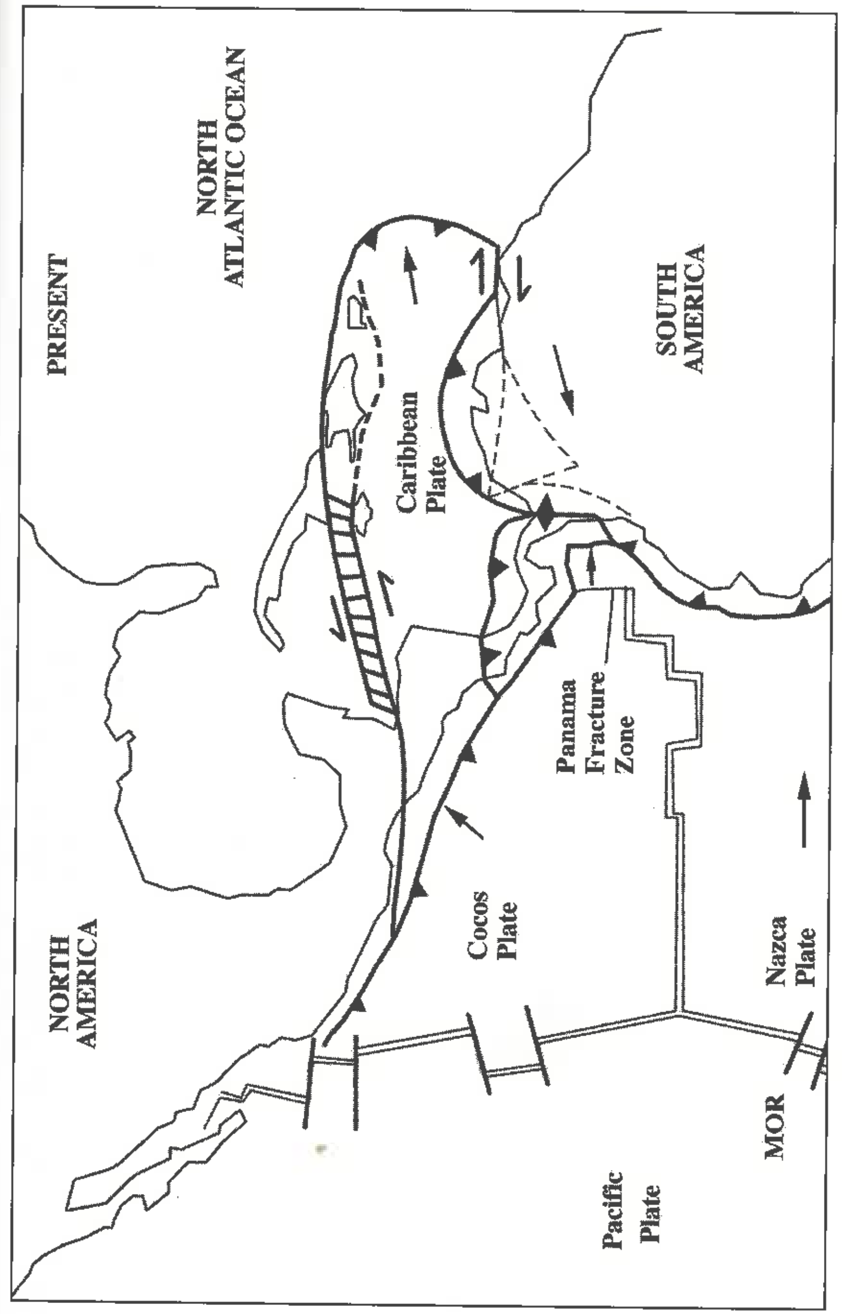
1–19. (A) A schematic paleogeographic interpretation of the Central American isthmus 15 million years ago, in the middle of the Miocene period. The dotted pattern indicates the approximate position of the marine shelf; (B) a schematic paleogeographic interpretation of the Central American isthmus 6 million years ago near the end of the Miocene period. The deepest part of the marine shelf along the isthmus is now about 150 meters; (C) a schematic paleogeographic interpretation of the Central American isthmus about 3 million years ago, at the end of the Pliocene period. The probable last marine corridors connecting the Pacific to the Atlantic are indicated.

species from the Caribbean and the Pacific intermingle. Because of the increasing uplift of the massifs in the San Blas and Majé areas of Panama and in the neighboring South American Andes, huge amounts of sediment, several thousands of meters thick, were eroded from their flanks and rapidly filled up the basins between the rising islands and peninsulas. Thus, about 4 million years ago the deepest water along the isthmian archipelago might have been only 50 meters deep (fig. 1–19C), and after about 3 million years the isthmian barrier was complete. This closing enabled a flood of terrestrial animals to cross the new land bridge between North and South America, as described in chapter 4. The structure and plate movements of the Central American region today are summarized in figure 1–20. The figure shows that the collision of South America with both the Caribbean Plate and the Cocos Plate has produced new subduction zones or overthrusts: one north of the Caribbean coasts of Colombia and Venezuela and one north of Costa Rica and Panama that is buckling up and bending southern Central America.

Southern Central America

The foregoing narrative helps to explain the striking differences of topography and geology between north and south Central America. Figure 1–19C shows the last probable marine corridors between the Pacific and the Caribbean just before final closure. The final strait between South and Central America may have been in the region of the present Atrato Valley of Colombia and the Tuira and Chucunaque valleys of the Darién in Panama. Compression and uplift of this region have only recently brought sediments typical of deep oceans to the surface. The higher areas—for example, the massifs of San Blas, Majé, and Sapo (see fig. 3–4)—that formed the first rising islands and ridges during the early part of the isthmian collision appear to mark the locations of former subduction zones. The intense buckling and resulting compressional thickening, however, as well as a complication in the plate movements to be explained later, have meant a general absence of volcanoes in the Darién of Panama during its later geological history. Today, the great Central American volcanic arc that stretches from Mexico throughout Central America terminates in the apparently quiescent volcano of El Valle in central Panama, although there are very recent lava flows near Panama City.

The volcanic spine of Central America is certainly its most striking physical feature and accounts for the violent explosive activities of



1–20. The plate configurations of the Caribbean and Central American region as they are today. Note the subduction segments north of South America and north of southern Central America, evidence of the collision of the South American and Caribbean plates and the reason for the uplift of the Isthmus of Panama. Modified from Duncan and Hargraves, in W. Bonini, R. B. Hargraves, and R. Shagam, eds., *The Caribbean South American Plate Boundary and Regional Tectonics,* Geological Society of America Memoir 162, fig. 8.

such famous peaks as Fuego, Izalco, Masaya, Arenal, Poas, and many others. As noted above, these volcanoes are the manifestations of the fractionation of the lighter molten elements from the Pacific Plate as it sinks beneath the Caribbean Plate. These powerful compressive and buckling forces have bent the Pacific crust down into the long Middle America Trench, more than 5000 meters deep, and are the cause of the catastrophic, ubiquitous earthquakes that plague Central America from western Panama to Guatemala.

From central Panama tó northern Costa Rica, the Central American isthmus continues to be relatively narrow and dominated entirely by a volcanic arc made up primarily of lavas and rocks formed from volcanic eruptions. Marine sediments are found mostly in marginal basins and on the marine shelves flanking the chain. Some of these, including the basins of Bocas del Toro in Panama and the basins of Limón and Terraba in Costa Rica, have been uplifted and incorporated onto the isthmus, (see fig. 3–4); these basins contain rich deposits of marine fossils that allow the various stages in the uplift of the isthmus to be reconstructed.

Exotic Terranes

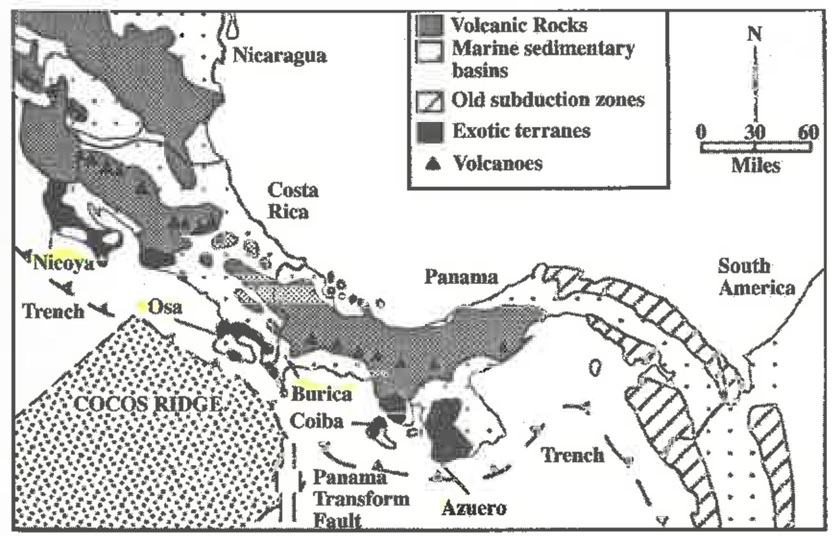
Two other striking geological events have diversified the topography of the lower isthmian volcanic chain in Costa Rica and Panama. First, the continual convergence of the Pacific Plate beneath Central America has swept a variety of *exotic terranes,* such as large hot-spot volcanoes, oceanic ridges that are the traces of hot spots, and ancient mid oceanic ridges, into the mouth of the Central American subduction zone. Because of their thickness and slightly lighter density, the terranes do not subduct easily and so become accreted onto the trailing edge of the Caribbean Plate, where they manifest themselves as promontories: among these are the Azuero, Burica, Osa, and Nicoya peninsulas (fig. 1–21). Each of these regions has at its core rocks that were originally formed perhaps thousands of kilometers to the south and west. Through measurement of the paleomagnetic orientation of the magnetite crystals in rocks from these terranes, the original locations of these far-traveled geological elements are now being established.

The Cocos and Nazca Plates

The second disruptive geological event in the history of the lower Central American volcanic chain and subduction zone requires a close look at the details of the complicated plate movements to the south of Costa

Rica and Panama. When the Farallón Plate split into the Nazca and Cocos plates, the junction between them was a mid ocean ridge system (see fig. 1–20). At its eastern margin, however, the junction is a transform fault known as the Panama Fracture Zone, which intersects the isthmus close to the Burica Peninsula, at the border of Panama and Costa Rica (figs. 1–20, 21)

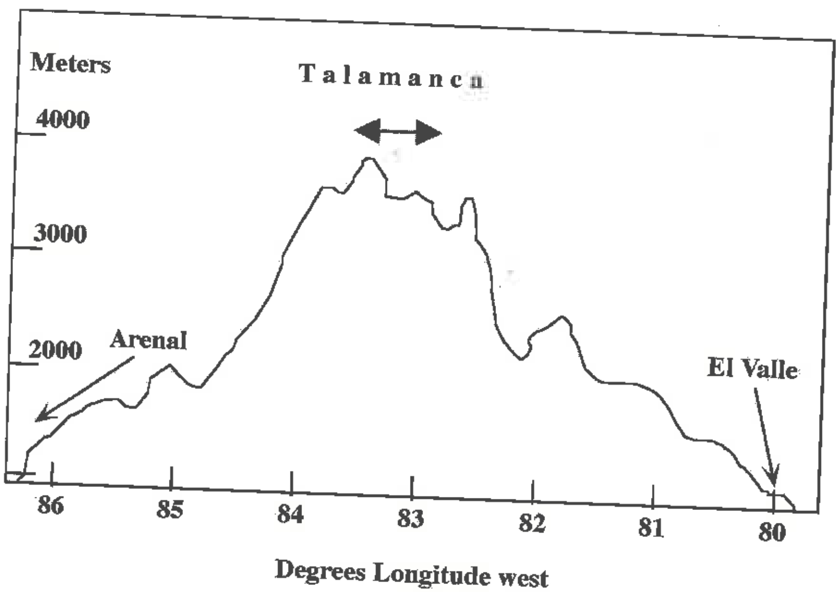
Relative to the Caribbean Plate to the north, the Cocos and Nazca plates move in different directions. The Cocos Plate moves at about 8 centimeters per year to the northeast almost at right angles to the margin of the Caribbean Plate, with the result that subduction is vigorous and volcanoes and earthquakes have always been active, as they still are today. To the east of the Panama Fracture Zone, however, the Nazca Plate appears to move eastward so that for most of the length of Panama there is little difference in direction or speed of movement between the Caribbean and Nazca plates (see fig. 1–20). This may explain the relative quiescence of volcanic activity in eastern Panama and the absence of frequent severe earthquakes. Volcanic activity in Panama is not completely dormant, however, for there is good evidence that there have been lava flows and perhaps some eruptions between Volcán Barú and El Valle in the past few hundred years.



1–21. A geologic map of Central America showing the location of Exotic Terranes and the Cocos Ridge. The Panama fracture zone is a transform fault that separates the Cocos and Nazca plates.

The Cocos Ridge

Also intersecting the isthmus in the region of the Burica Peninsula, but lying to the west of the Panama Fracture Zone, is the Cocos Ridge (see fig. 1–21). It consists of a welt of lighter oceanic crust 2000 meters high and 200 kilometers wide, apparently representing the trace on the Cocos Plate of its passage over the hot spot located at the Galápagos Islands. For the past 3 million years it has apparently been subducted with great difficulty owing to its extra thickness and lightness, and this is having a spectacular effect on the Central American volcanic arc and subduction zone. First, it has uplifted and indented the Middle America Trench, creating a difference in sea floor elevation of more than 3500 meters. Second, it has apparently raised the isthmus to form the Cordillera de Talamanca, at almost 4000 meters, one of the highest points in Central America. Across the Talamanca range all volcanic activity has been choked off, so that while there is normally a volcano every 28–30 kilometers along the isthmian volcanic chain, in the Talamancas there are none for 125 kilometers. Indeed, the whole of the volcanic chain is domed up from El Valle, Panama, in the east (1200 meters) to Arenal, Costa Rica, in the west (1600 meters), a distance of 570 kilometers (fig. 1–22).



1–22. A topographic profile along the southern Central American isthmus from Arenal in northwestern Costa Rica to El Valle in central Panama. The topographic elevation reflects the uplift of the isthmus imposed by the insertion of the Cocos Ridge beneath it in the region of the Talamanca Mountains.

Northern Central America

Northwest along Central America into Nicaragua, the isthmus becomes wider and the age and complexity of the geology correspondingly greater. All of the crust that forms southern Central America, from southernmost Nicaragua to the Darién, has evolved from volcanic activity that generated exclusively oceanic and relatively young crust. To the north, the geologic history centers around the Chortis and Maya terranes, two much larger, older, and more complex regions than any that occur elsewhere in southern Central America.

The Chortis Terrane

The Chortis Terrane is first encountered in central and northern Nicaragua, north of the Nicaragua Depression, and it underlies El Salvador, Honduras, and Guatemala south of the Motagua Valley. The Pacific coastal margin of this terrane is largely dominated by geologically recent lavas and associated volcanic rocks (fewer than 2 million years old) that blanket the region from the coast inland for at least 100 kilometers (see figs. 3–1, 3–3, 3–4) and are a continuation of the volcanic arc that created southern Central America. These volcanoes are still so active that they have poured out a staggering 16 cubic kilometers of lavas and ash along a distance of 1100 kilometers since A.D. 1680.

Although still a striking physiographic feature, the volcanic chain is only one of five distinct geologic regions comprising the Chortis Terrane, several of which long predate the beginning of the Central American volcanic arc.

The other regions making up the Chortis Terrane are the Northern Sierras of southeastern Guatemala and northern Honduras, which represent the intense shearing zone where the northern margin of the Caribbean Plate (the Chortis Terrane) is now moving eastward relative to the southern limit of the North American Plate (the Maya Terrane); the Central Crystalline Highlands of Guatemala and Honduras (see figs. 3–1, 3–3), which contain the most ancient rocks in Central America; the High Volcanic Plateaus, a distinctive region of highlands running inland of the modern volcanic arc from southern Guatemala through El Salvador and Honduras to Nicaragua (see fig. 3–3), formed by volcanic activity 10 to 20 million years ago; and the huge Mosquitia embayment, occupying eastern Nicaragua and the extreme eastern portion of Honduras (see fig. 3–3). Each of these regions has a very different geological history, and they largely correspond to the distinctive physiographic regions of northern Central America described in chapter 3.

The Northern Sierras

The Northern Sierras, which stretch from northeast of Guatemala City in southern Guatemala along the northern coast of Honduras, are a series of east-west trending mountains formed of metamorphic and igneous (formed from molten magma) rocks, partly mantled by younger limestones. The orientation of these mountains is strongly controlled by the powerful and active shearing faults that now delimit the Caribbean and North American plates.

Across these valleys the ancient Maya and Chortis terranes are now facing each other, having become intensely deformed and altered during the plate movements that brought them together at the end of the Cretaceous period. Subsequent eastward movement of the Caribbean Plate, starting at least 40 million years ago, has now caused shearing between the two terranes. Some geologists think that the shearing has caused the two plates to be offset about 120 kilometers; others postulate more than 1000 kilometers of displacement.

The Central Crystalline Highlands

The Central Crystalline Highlands of Honduras form a rugged mountainous core to the Chortis Terrane, and ancient continental basement rocks dating back as far as 500 million years are at their root. These rocks have been subject to intense heat and pressure deep in the crust. Subsequent prolonged erosion finally exposed them so that by 140 million years ago they underlay a shallow marine shelf somewhere on the western margin of the separating and newly formed Atlantic Ocean. Unlike the Maya Terrane, Chortis was migrating south from western Mexico at this time, and its precise location is not known. On its shelf developed a thick sequence of limestones and reefs somewhat like the Bahamas today. Later, the marine shelf was uplifted and began to erode so that rivers and estuaries covered the limestone with gravel and red sand; periodically it would sink beneath the sea, and new reefs and lagoons would form. It then became broken up into fault-fractured valleys, called grabens, and intervening mountains (horsts) and must have looked much like the Basin and Range of Nevada today.

About 90 million years ago, the region was again flooded by the sea, an episode that also flooded large areas of North and South America. Once more a Bahama-like limestone platform was created. The faulted and uplifted elements of these limestones outcrop extensively in the Northern Sierras. From about 75 million years ago, the whole region was penetrated by molten magmas and intensely deformed and uplifted into the highland topography seen today. These granitic and metamorphic rocks underlie the limestones in the Northern Sierras but are extensively revealed in central Honduras and northern Nicaragua, where they give the Crystalline Highlands their name. These intense movements were part of a regional geological event in which Chortis became fused or sutured onto the Maya Terrane (see fig. 1–16). At the same time, the Central American volcanic arc continued subduction and volcanism along the length of the boundary between the Pacific and Caribbean plates, the present sites of western Guatemala, El Salvador, western Nicaragua, Costa Rica, and western Panama.

The High Volcanic Plateaus

The High Volcanic Plateaus are formed by an extraordinary pile of explosive volcanic debris that covers much of southern Guatemala, western Honduras, northern El Salvador, and west-central Nicaragua (see fig. 3–3). They also cap some of the mountains of the western part of the Crystalline Highlands of Honduras. Although there had been continuous if sporadic volcanic activity in this region because of the subduction of the Farallón Plate from the west since the Late Cretaceous more than 80 million years before, there occurred about 20 to 14 million years ago a truly stupendous outburst of volcanic eruptions that covered more than 10,000 square kilometers of Central America. Thousands of cubic kilometers of volcanic deposits were produced, varying in thickness from 700 to more than 2000 meters. During this phase, a special kind of eruption frequently happened wherein molten magma was choked or blocked in the vent of the volcano until it exploded. Gasses not able to be released until the explosion took place (as when a bottle of champagne is shaken before the cork is released) expanded violently, pulverizing the molten magma so that it erupted as glowing hot clouds of foaming gas, ash, and tephra that spewed over the landscape for hundreds of kilometers. These deposits, now faulted and dissected by erosion, form a series of high plateaus that are often capped by younger, more familiar basalt lava flows. On this older volcanic edifice has been built the spectacular line of recent and currently active volcanoes that form the modern Central American volcanic arc in this region.

The Mosquitia

The Mosquitia embayment (see fig. 3–3) in eastern Honduras and central and eastern Nicaragua today is a vast forested lowland, but for much of the past 100 million years it was mountainous. Although probably lying on an as-yet-undetected ancient continental crustal basement, 4500 meters of sedimentary rocks underlay this region, revealed mostly in boreholes. Until 35 million years ago, these deposits indicate a rugged mountainous land mass with active erosion of sediments into intermontane basins, terrain very different from that of the present day. By 35 million years ago the region had become worn down, so that it sank beneath the sea, and marine silt and limestone accumulated. The region rose above sea level again about 10 to 5 million years ago and ever since has oscillated between a shallow, swampy coastal shelf and an emergent coast with extensive estuaries and marginal sea grass beds and coral reefs much like those of today. Even slight changes in sea level now would flood much of this low-lying region.

The Maya Terrane

The most northerly part of Central America lies entirely on the Maya Terrane, part of the North American Plate that underlies Belize and the El Quiché, Alta Verapaz, and El Petén provinces of Guatemala. The Atlantic Ocean began to open about 230 million years ago, and the Maya Terrane formed part of its western continental shelf. Much of the earlier geological record is obscure, but the opening of the Atlantic Ocean was accompanied by geological extension of the crust, which produced fault-bounded rift valleys and intervening mountains, or horsts, along its margin. Erosion of the horsts filled the valleys with gravel and alluvium, and periodic evaporation formed salt and gypsum. These deposits, patchily distributed but distinctive in Central America and Mexico because of their rust-red color, show the Maya Terrane to have been emergent until about 150 million years ago.

For the next 90 million years, the Maya Terrane was submerged, becoming part of a passive (as opposed to subducting) Atlantic continental shelf along which geological conditions were stable and quiet. During this immense amount of time, an enormous reef and lagoon system evolved that generated vast quantities of limestone as well as evaporite deposits such as salt and gypsum. This is the origin of the 3000-meter-thick blanket of limestone that now covers much of the Petén, Belize, and, farther north, the Yucatán.

The limestone cover is largely absent in only two regions of the Maya Terrane (see fig. 3–1). On its southern rim, in the 3000-meter-high ranges that form the Sierras de Chuacús and Las Minas, between the Motagua and Polochic rivers, ancient continental crust is preserved, now intensely folded, sheared, and mineralized as a consequence of the

collision of the Maya and Chortis terranes. At this time also, pieces of an old mid oceanic ridge that formerly lay between the two terranes and that contains samples of the mantle (peridotite) and ocean-floor crust were scraped off during subduction and then squeezed up into this zone where they are now exposed as intrusions into the older crustal rocks. This is the source of much of the jade carved in southern Central America by indigenous peoples (see chapter 6).

The second major breach of the great limestone plateau is in the Maya Mountains of Belize (see fig. 3–1). Here, in a 50-by-90-kilometer window, the 340-million-year-old crust that forms the granite basement of the Maya Terrane has been exposed by uplift and erosion of the overlying limestones.

The collision of the Maya and Chortis terranes at the end of the Cretaceous period signaled the end of the long period of reef growth, as the great limestone bank was raised out of the sea. Limestone terrains are highly susceptible to weathering owing to solution of the rock by rainwater, a process that produces a distinctive topography of circular and vertical-sided limestone towers and intervening basins called karst, as well as immense underground caverns and a general absence of surface drainage. These features give the Petén and much of Belize (as well as the Yucatán) their unique regional character within Central America, as described in chapter 3.

Closing of the Isthmus and the Ice Age

One of the striking consequences of the formation of the Central American isthmus is that the oceans on either side became different. These effects began 15 million years ago, as noted above, when the deep-water circulation between the Pacific and the Atlantic oceans began to be affected and plankton with silica skeletons disappeared from the Caribbean. From 10 to 5 million years ago, an extensive archipelago existed throughout the present region of Central America, forming a more complex and varied marine ecosystem than exists today along the two coasts of the isthmus. From 5 to 3 million years ago, the marine connections across the isthmus would have been narrow and meandering and were probably located in three areas (see fig. 1–19C). First, the Atrato Valley and the Gulf of Urabá were still connected through the San Juan River in Colombia, and the Tuira-Chucunaque rivers in the Darién to the Pacific Ocean. Second, a marine embayment may have connected the Caribbean via the Nicaragua Depression to the Pacific, and third, at least in the early part of this period there are likely to have been connections through the Chagres Valley along the present track of the Panama Canal. The questions of how the barrier of the isthmus was finally completed and whether it was subsequently breached are complicated by the fact that a different set of factors involving global climatic and sea level changes began to play an important role about this time.

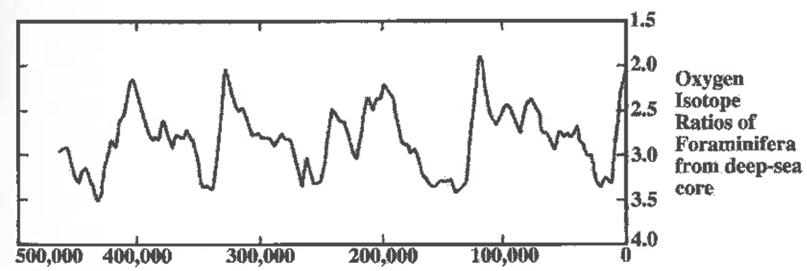
The Effects of the Ice Age

About 3 million years ago, as the isthmus rose to become a shallow barrier forming an extensive archipelago of islands, the Ice Age began to develop as repeated phases of glaciation interspersed by warmer interglacials, in one of which we are now living. There is no reason to suppose that many more such glacial episodes will not come in the future. Starting about 2.5 million years ago, these cold phases became more and more pronounced and showed a remarkably constant frequency of about 100,000 years. In each glacial episode, temperatures got steadily colder and ice accumulated in polar ice caps, causing a fall in sea level. But each time at a given threshold, the process was reversed: temperatures rapidly warmed, the ice melted, and sea level quickly rose. The frequency of these oscillations corresponds very closely to predicted variations in heat coming to the earth from the sun as the distance and orientation of the earth changed during its orbit around the sun. These were predicted by a Yugoslav mathematician earlier in this century and are now called Milankovitch cycles after him. They resulted in changes in sea level that may have been as great as 180 meters, and researchers know that in the past 20,000 years sea level has risen about 135 meters as the modern glaciers have been melting. Thus, the isthmian barrier may have closed and then later been breached during one of these sea level rises. Because the lowest relief of the isthmus is only 45 meters along the Nicaragua–Costa Rica border, further sea level rise as the remaining glaciers melted could still almost breach the isthmus again.

Calculating Paleotemperatures

How do geologists know that temperatures seesawed as predicted by the Milankovitch cycles, and do they have any direct evidence for high and low sea levels? Two lines of evidence strongly point to these conclusions. First, reef corals grow only close to sea level, and by locating and dating corals of this type that are now many tens of meters below the present sea level geologists can calculate the degree of sea level lowering for different times in the past. When a historical sea level curve is constructed using this technique its fluctuations correlate in frequency to the oscillating Milankovitch cycles.

Second, shelled marine animals take up calcium, carbon, and oxygen from the seawater to make their shells. The element oxygen possesses different isotopes, variants of the element that have slightly different atomic nuclei and hence different properties. When certain marine animals secrete their shells, the ratios of oxygen isotopes in the shells change according to the temperature of the seawater. Thus, each shell is a recording thermometer for the temperature of the seawater in which it lived. When paleontologists find, at different stratigraphic levels, well preserved fossil calcareous shells that lived in the floating plankton or in the mud on the bottom of the sea, they can trace the changes in the temperature of the surface and bottom waters of the oceans for different times in the past by carefully measuring the ratio of the oxygen isotopes in the fossil shells. Paleontologists can thus track changes in marine climate as it responds to the glacial cycles, and the clearly oscillating pattern of Milankovitch cycles becomes apparent, as is shown in figure 1–23. Notice that the oscillations are not symmetrical in time but sawtoothlike, indicating that the cold phase built up steadily to a maximum level, then crossed a threshold and rapidly collapsed. Other studies that used different chemical techniques on coral skeletons have shown that the average annual surface sea temperatures in the Caribbean adjacent to Central America dropped 5 degrees centigrade 20,000 years ago, at the height of the last glaciation. Studies of pollen records on land (see chapter 5) show that similar changes in temperature were taking place on land.

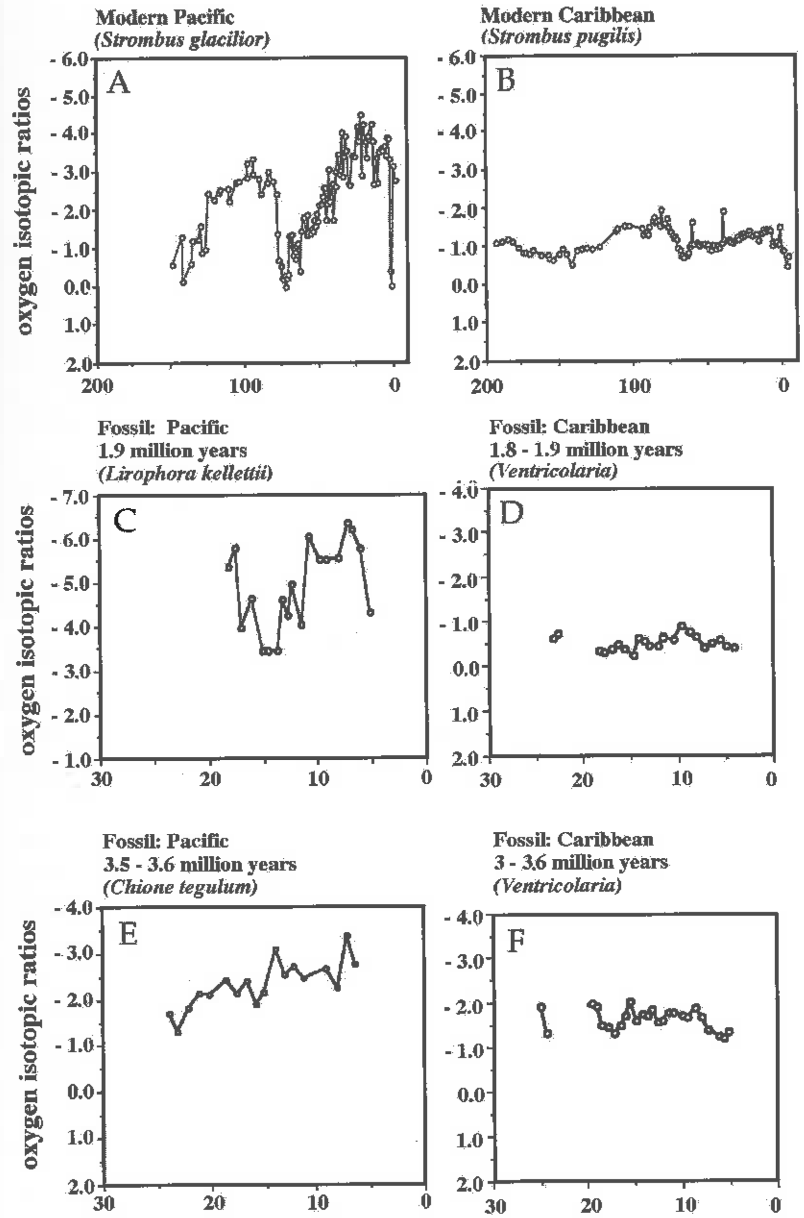


1–23. A diagram of the sawtooth pattern of sea temperatures during the Ice Age. The frequency of the pattern strongly coincides with predicted global heat fluctuations owing to Milankovitch cycles and to rises and falls of sea level. Lower isotope ratios are colder. Modified from J. D. Hays, John Imbrie, N. J. Shackleton, "Variations in the Earth's Orbit: Pacemaker of the Ice Ages," *Science* 194, no. 4270 (1976): 1130, fig. 9.

Isotopes and Upwelling

The final stages in the transformation of the Isthmus of Central America from a complex and extensive archipelago into a more simple isthmus were accompanied, then, by the onset of extensive glaciation in the northern hemisphere with major oscillations of sea level. Reconstructing the final moment of closure is no easy task.

One method is to detect in the fossil record the first evidence of one of the differences that now contrast the Pacific with the Caribbean. A good example is the strong seasonal temperature change in Pacific water in some locations. Trade winds drive surface water away from the isthmus from December to May, causing cold bottom water to rise and take its place—a process called *upwelling*. Animals such as mollusks secrete a layer of shell every month, and so the ratio of oxygen isotopes in each shell layer varies from the warmer wet season to the colder, dry upwelling season. Modern shells from the Pacific show this cycle clearly, whereas the same mollusks in the Caribbean, where there is no upwelling, show no such variation (fig. 1–24). Fossil shells that are 1.8–1.9 million years old (fig. 1–24) show the same contrast as modern shells, strongly suggesting that the isthmus was already formed 2 million years ago. In sediments that are older than 3 million years, however, the curves for the Pacific and the Caribbean are much more similar (fig. 1–24), indicating that there was less seasonality on the Pacific side. This suggests that the isthmus was not yet closed so that the wind-driven Pacific surface water could be replaced by warm Caribbean surface water. Chapter 2 describes in more detail the remarkable series of oceanographic and biological differences that have evolved between the two oceans in these past 3 million years.



1–24. Diagram of the patterns of oxygen isotope measurements for monthly growth of mollusk shells (two-year cycle). The ratios correspond to temperatures of the seawater. (A, B) Living shells from the Pacific and Caribbean; (C, D) fossil shells 1.8–1.9 million years old from the Pacific and Caribbean; (E, F) fossil shells 3 million years or older from the Pacific and the Caribbean. Modified from Jane Teranes, "The Oxygen Isotope Record of Seasonality in Neogene Bivalves from the Central American Isthmus" in *Evolution and Environment in Tropical America*, J. B. C. Jackson, A. F. Budd, and A. G. Coates, eds. (University of Chicago Press, Chicago, 1996).

Central America

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