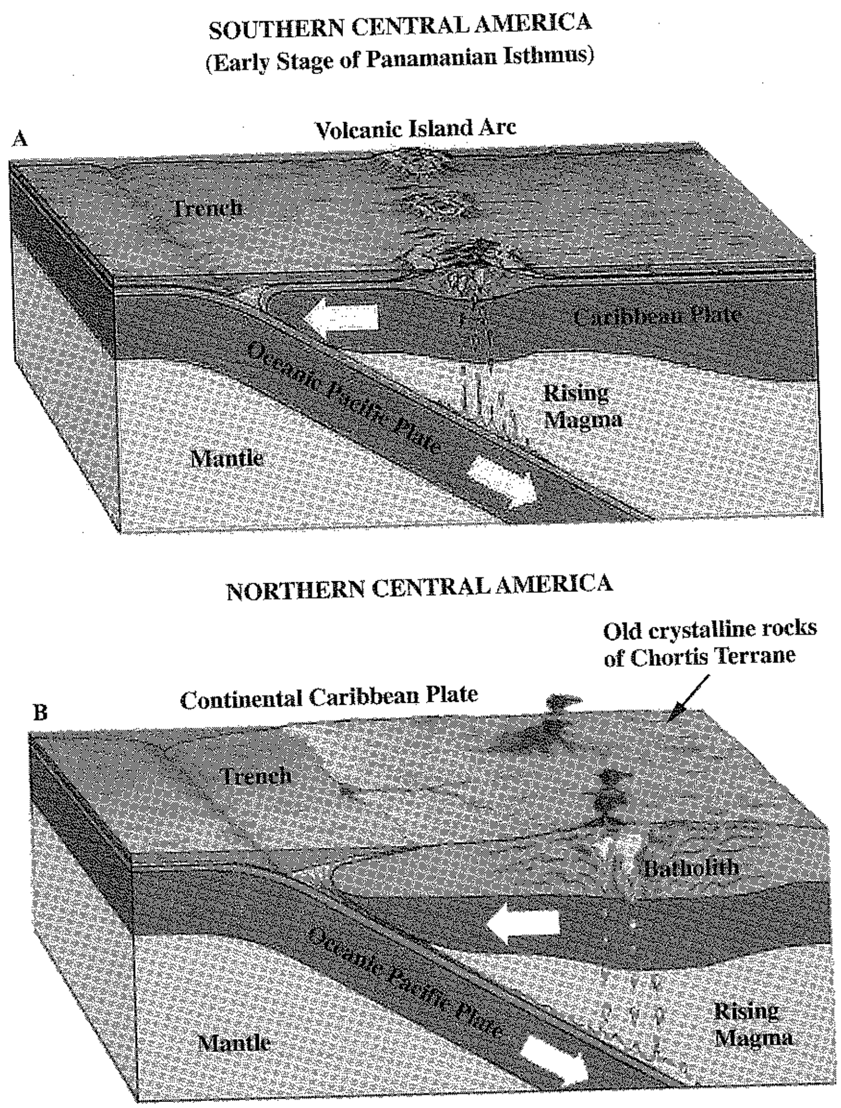
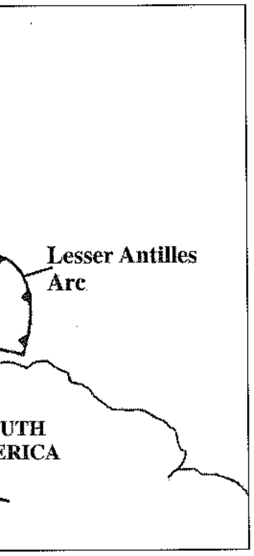


1–11. Cross sections of subduction zones. In (A) each plate is oceanic crust. An island arc of volcanoes represents an early stage in the formation of southern Central America; (B) a subduction zone, where an oceanic crustal plate sinks beneath a continental crustal plate. This is a model for the structure 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.



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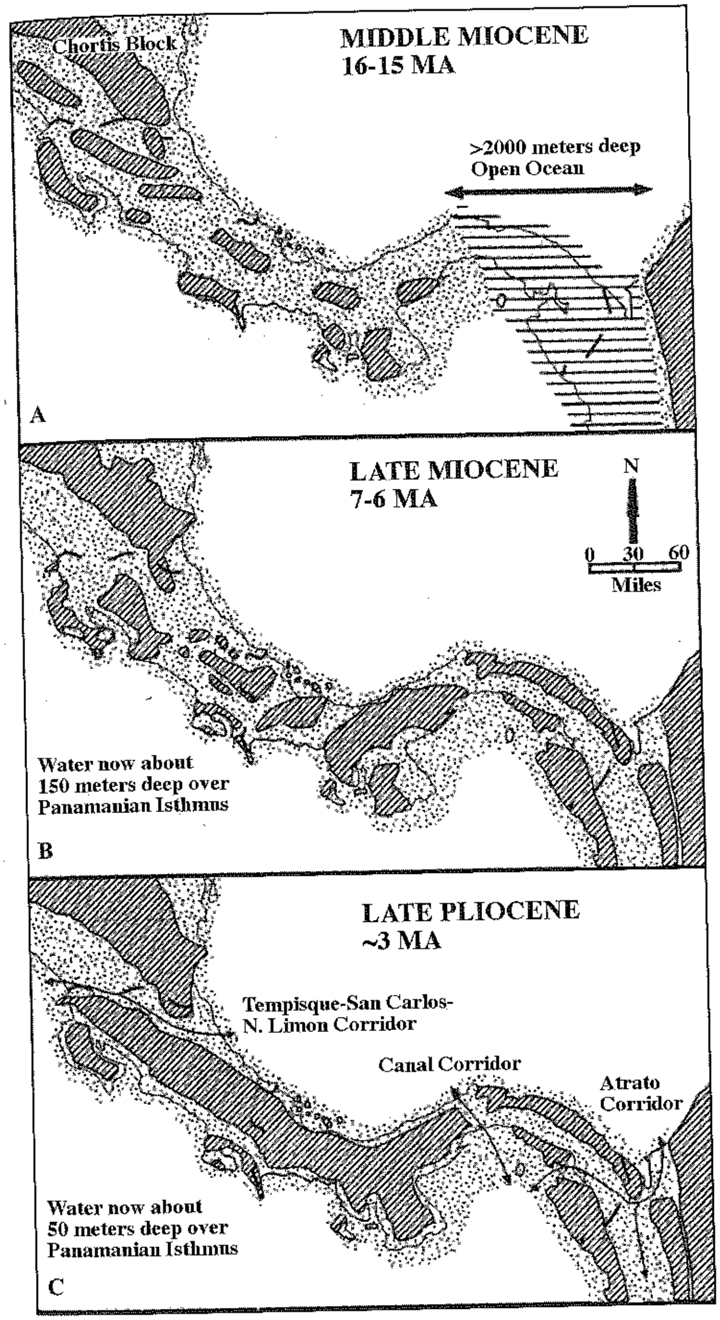

1–19. (A) A schematic paleogeographic interpretation of the Central American isthmus 15 million years ago, in the middle of the Miocene period. The dotted pattern indicates the approximate position of the marine shelf; (B) a schematic paleogeographic interpretation of the Central American isthmus 6 million 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.

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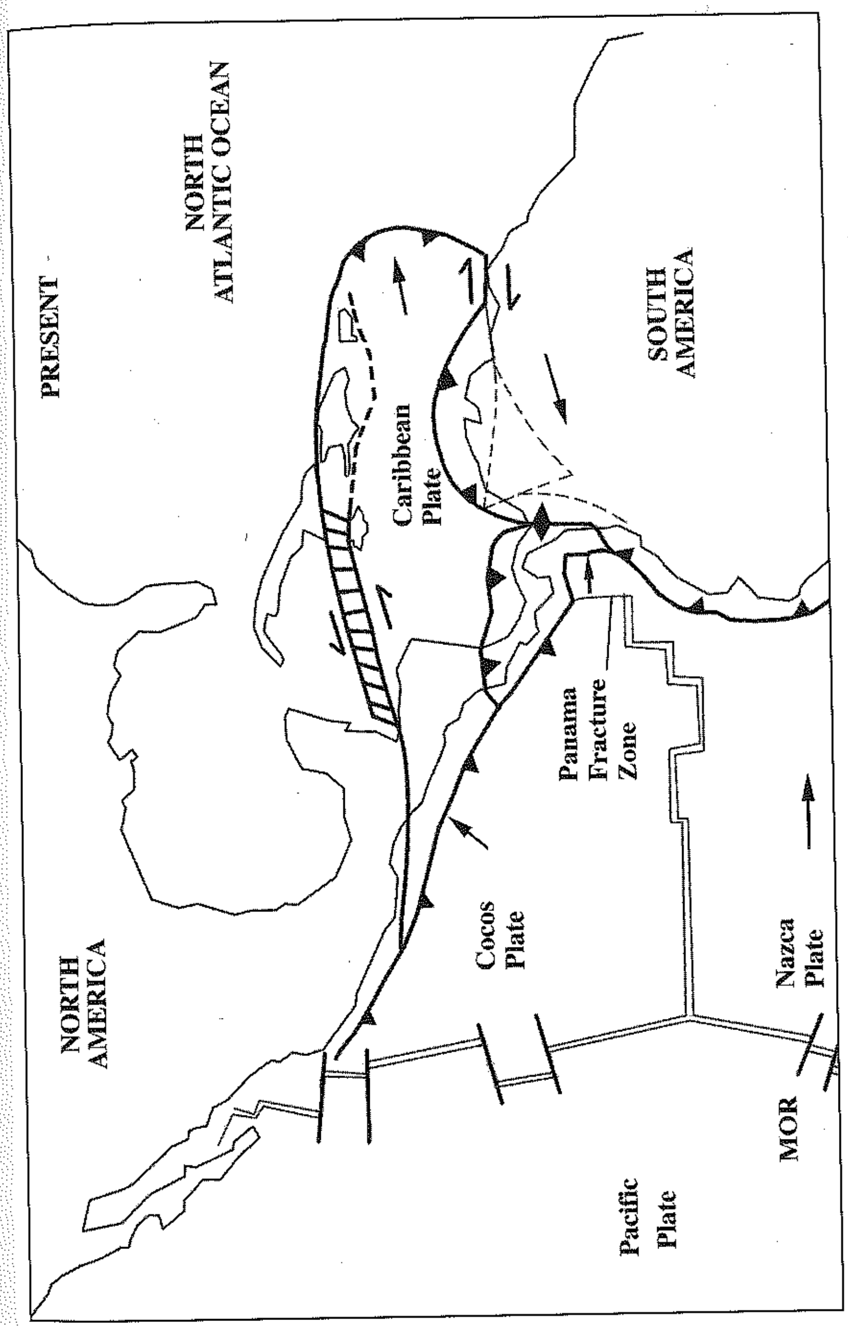


1–20. The plate configurations of the Caribbean and Central American region as they are today. Note the subduction segments north of South America and north of southern Central America, evidence of the collision of the South American and Caribbean plates and the reason for the uplift of the Isthmus of 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.

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.

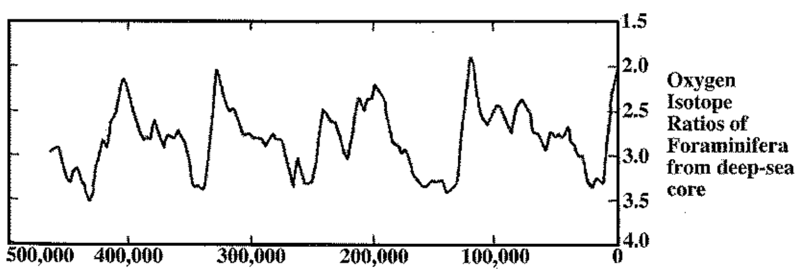
The Effects of the Ice Age

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.

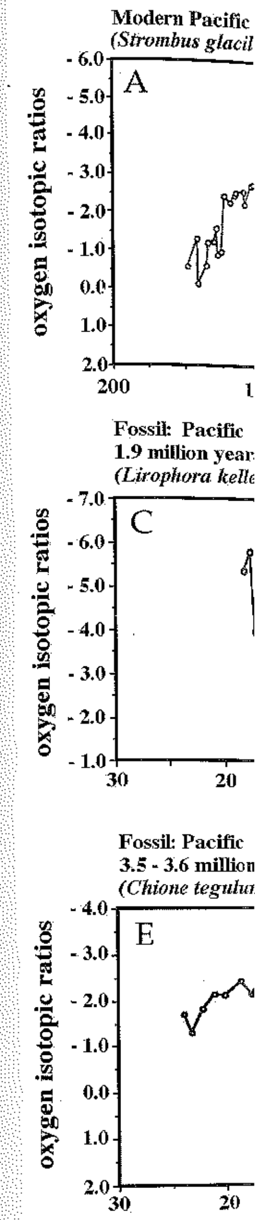


1–23. A diagram of the sawtooth pattern of sea temperatures during the Ice Age. The frequency of the pattern strongly coincides with predicted global heat fluctuations owing to Milankovitch cycles and to rises and falls of sea level. Lower isotope ratios are colder. Modified from J. D. Hays, John Imbrie, 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
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