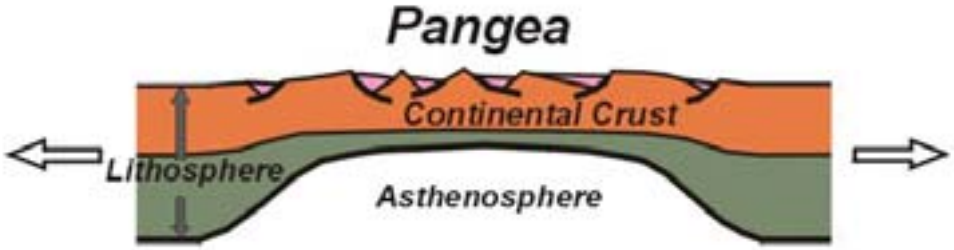
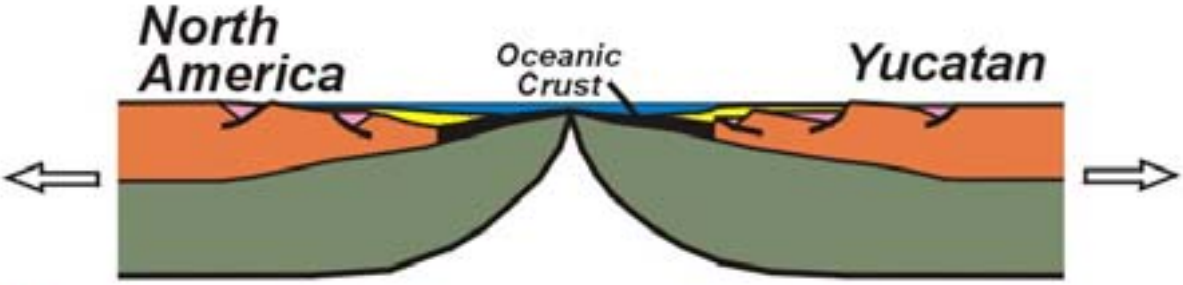
Gulf Islands National Seashore

Geology Training Manual

Plate Tectonics and Formation of the Northern Gulf of Mexico





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GULF ISLANDS NATIONAL SEASHORE
Geology Training Manual

(Plate Tectonics and Formation of the Northern Gulf of Mexico)

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PREFACE

This manual is an overview of concepts important to understanding the geology of Gulf Islands National Seashore. It is intended as part of the training of permanent, seasonal, and volunteer workers in Park Service Interpretation. The manual is written primarily for non-geologists, to give them grounding in basic geologic concepts; the concepts discussed are those that will help explain the structure and evolution of the northern Gulf of Mexico to park visitors.

Gulf Islands National Seashore is an exciting place to "seize the moment," to help visitors learn while they are relaxed, on vacation in a beautiful and fascinating place. America's national seashores are along the transition zone where crust thins dramatically from the continent to the ocean. We can use seaside panoramas to explain to visitors how the Gulf of Mexico formed when continents ripped apart, how the coastal plain and continental shelf relate to the crust thinning seaward, and how positions of the shoreline and barrier islands are sensitive to changes in sea level, sediment supply, and ocean currents.

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Ten Questions about the Northern Gulf of Mexico

The types of questions one is able to ask can gauge mastery of a subject. As interpreters we know this - we've done our job well if visitors ask us to expand upon what we've said. Below is a list of questions about the Gulf Coast and the development of coastlines and barrier islands. The purpose of this manual is to give interpreters enough background in the three areas of geology so that they can ask similar questions. Details explaining the brief answers constitute the rest of the manual.

1. ***How did the Gulf of Mexico form?***

About 300 million years ago Europe, Africa, and South America collided with North America, forming the supercontinent of Pangea. As Pangea ripped apart 200 million years ago, South America and the Yucatan Peninsula pulled away from the southern part of North America, opening the Gulf.

2. ***Why is North America above sea level, the Gulf of Mexico below?***

Like other continents, North America has thick crust, compared to surrounding ocean basins, like the Gulf of Mexico. Crust is light material that "floats" of the underlying, heavier mantle. Continental crust is thick and buoyant like a beach ball; it therefore sticks up higher than the surface of thin oceanic crust.

3. ***Why don't large earthquakes or other tectonic activity occur along margins of the Gulf of Mexico?***

Tectonic activity commonly occurs along the boundaries of large, moving plates of Earth's outer shell. The Pacific coast of the United States coincides with plate boundaries and is thus an <u>active continental margin</u>, with earthquakes, volcanoes, and developing mountain ranges. The Atlantic and Gulf coasts, however, are <u>passive continental margins</u>, far away from plate boundaries and accompanying tectonic activity.

4. ***What is the overall topography of the northern Gulf of Mexico?***

The Gulf Coast shows the classic morphology of a <u>passive continental margin</u>: a low-lying <u>coastal plain</u>, broad <u>continental shelf</u>, then a steep <u>continental slope</u>, gentle <u>continental rise,</u> and flat <u>abyssal plain</u>. This topography is a consequence of the transition from continental to oceanic crust. Like an iceberg sticking out of water, thick crust rises up higher out of the mantle than thin crust. The high areas (coastal plain and shelf) are thus underlain by continental crust, while relatively thin continental and oceanic crust underlies low regions (continental rise and abyssal plain).

5. ***Why is the coastline of the northern Gulf of Mexico so far from the edge of the continental shelf?***

Widths of continental shelves are sensitive to <u>changes in sea level</u>. When worldwide temperatures are low, much of the water is frozen in the polar ice caps, so that sea level drops. During those times the northern Gulf shoreline is near the edge of the continental shelf, more than 100 miles (160 kilometers) to the south of its current position. If Earth's atmosphere were to warm up sea level would rise, flooding coastal areas to as far as 70 miles (110 kilometers) to the north, to the cities of Baton Rouge, Hattiesburg, and Augusta.

6. ***Besides sea level change, what other factors influence the position of the coastline?***

The north-south position of the coastline in also sensitive to subsidence and sediment supply. When the continents ripped apart their crust was stretched and thinned, eventually subsiding below sea level as the Gulf opened. Sediment eroded from North America was continuously deposited in the depression. The supply of sediment is enormous compared to the rate of subsidence, so that over the very long term the northern Gulf Coast and continental shelf have been building southward.

7. ***How thick are the sedimentary deposits of the Gulf coastal plain and continental shelf, and why are they such thickness?***

In places the sedimentary layers approach a thickness of 10 miles (16 kilometers). Subsidence accompanying crustal thinning created a basin as the Gulf of Mexico opened 200 million years ago. Shortly before the Atlantic and Gulf basins developed, the flanking Appalachian mountains were very high, perhaps as high as the Alps or Himalayas are today. Erosion of the mountains to their current, more modest heights supplied a tremendous volume of sediment as the basin continued to subside.

8. ***Why are the beaches in Gulf Islands National Seashore so white, yet so brown farther west?***

Sediment reaching the Gulf along the Florida Panhandle, Alabama, and Mississippi coasts is almost entirely form erosion of hard rocks in the southern Appalachian Mountains. Quartz, a hard, durable mineral, survives transport by fast-moving streams, while softer minerals break down and dissolve, or remain suspended in the water. Sedimentary particles available for deposition along the northeastern Gulf Coast are thus pure white quartz. Sediment deposited along the Louisiana and east Texas coasts is from the Mississippi River system, which drains a large portion of North America, including areas rich in clay. The material thus has lots of fine mud and silt mixed in with the sand, resulting in the "chocolate brown" appearance of beaches from the Mississippi delta westward.

9. ***Why are the barrier islands so elongated?***

As rivers bring in sediment from the eroding Appalachians, the ocean current sweeps the sand particles westward, parallel to the coast. Wave action from the Gulf keeps the sand concentrated along a ridge, so that the islands are long and narrow.

10. ***How do the barrier islands change through time?***

The westward longshore current erodes islands on their east sides and deposits sand on the west. The barrier islands are thus temporary features that migrate gradually westward through time. On a longer time scale the islands also migrate in north-south directions, due to the changes in subsidence, sediment supply, and sea level discussed above.

What Should Interpreters Know About Geology? What Should Interpreters Explain to Visitors?

The level of technical detail presented in this manual is that thought appropriate for the geology background of Park Service interpreters. It is hoped that the information will enable interpreters to design their own programs on the tectonic history, sedimentology, and geomorphology of Gulf Islands National Seashore. The

detail of the programs, however, should be at a level somewhat different than that presented here. In other words, present a program with language and explanations the public can understand, but have in your toolbox more in-depth information to field questions.

It is not suggested that rangers at Gulf Island National Seashore routinely present whole programs on the tectonics of the region. Rather, talks on many topics that involve the physical setting of the Seashore can begin with a 2 to 5 minute explanation of the formation of the northern Gulf of Mexico. The positions of the coastal plain and continental shelf, slope, and rise can be related to the crustal structure that developed as the passive continental margin formed. Positions of the coastline and barrier islands in the past can then be explained in terms of changing sea level over the low-lying coastal plain and shelf. Interpreters can thus start big by talking about plate tectonics and regional geology, then gradually zero in on details of geomorphology, ecology, biology, archaeology, history, or other topics that require appreciation of the physical setting.

DOs and DON'Ts

DOs:

- Present information at a level the public understands.
- Talk about things you truly understand.
- Talk about things that the people are actually seeing, along beaches, during boat tours, in visitor centers, and on slides during evening programs.

DON'Ts:

- Use "buzzwords."
- Talk over people's heads.
- "Parrot" information or concepts you don't really understand.
- Talk about things the visitors aren't looking at.

About "Buzzwords"

Technical terms, or "buzzwords," are both a godsend and a curse. They are useful because they are concise; they can convey a lot of information with a minimum of verbiage. For example, instead of "the relatively soft part of Earth's mantle, between about 100 and 400 miles depth, sandwiched between harder mantle above and below," we can simply say "asthenosphere." Buzzwords are not useful, however, when the intended audience does not have sufficient technical background. How many people know what Earth's mantle is, much less that it has a relatively soft zone called the "asthenosphere?" Park Service interpreters should be familiar with buzzwords, because they enable the interpreter to explore concepts in greater depth when communicating with experts or researching material for programs. When explaining things to the public, however, it may be best to avoid buzzwords. Why not explain the concept in simple English, even if it takes a few more words? At the very least, define a buzzword the first time you use it in a program, and give a real-life analogy (preferably one involving food!).

If you can't see it, then take it along!

There is a fundamental problem in explaining geology along the Gulf Coast: ***the nearest rocks are ten miles away (straight down!)***. The presence of the thick sediment, though, attests to plate tectonic processes that resulted in a transition from thick continental to thin oceanic crust. Rangers can draw on the lack of visible rocks, as well as on the thick accumulation of sediment, as testimony to the tectonic processes that opened the Gulf of Mexico. During talks you can take along Gulf Coast beach sand and rocks from the Appalachian Mountains, to show visitors the nature of the sand particles and their place of origin.

Plate tectonic theory is background information critical to understanding how and where various types of landscapes form. We can see landforms within the transition from land to sea, but the underlying crustal structure responsible for the transition is not visible. Plate tectonic concepts can be worked into programs, though, if visuals (like those developed in this manual) are used on beaches and during boat tours, slide presentations, and other programs.

Developing a Knowledge Gap

Interpretation is possible when your general knowledge of the park resource is somewhat more than that of a typical visitor. The "knowledge gap" does not have to be great! If you know some basic geologic concepts and familiarize yourself with the tectonic setting of the Seashore and a few specific observations along the Seashore, then you can begin to relate geology to the public. Even more important is that you know enough to explain how geology relates to plants, people, and other things that visitors see in the park. This Geology Training Manual thus gives information and insight to help you expand the knowledge gap between you and the visitors.

PLATE TECTONICS AND THE ORIGIN OF CONTINENTAL MARGINS

> *"Now I hear the sea sounds about me; the night high tide is rising, swirling with a confused rush of waters against the rocks below …. Once this rocky coast beneath me was a plain of sand; then the sea rose and found a new shore line. And again in some shadowy future the surf will have ground these rocks to sand and will have returned the coast to its earlier state. And so in my mind's eye these coastal forms merge and blend in a shifting, kaleidoscopic pattern in which there is no finality, no ultimate and fixed reality - Earth becoming fluid as the sea itself." (The Edge of the Sea, by Rachel Carson, © 1955, Houghton Mifflin, Company.)*

The Gulf of Mexico resulted from the rifting of continents about 200 million years ago. Since then South America and the Yucatan Peninsula have moved away as the Gulf widened and the southern edge of North America subsided and was covered by a large thickness of sediment. The coastlines and barrier islands of Gulf Islands National Seashore lie above the zone of crustal thinning on the edge of the ripped-apart continent (Fig. 1).

Earth's dynamic forces are commonly manifest along the boundaries of large, moving plates of Earth's outer shell. The edges of continents may or may not coincide with the edges of plates (Fig. 2). The West Coast of the United States is an ***active continental margin***; earthquakes occur in California as one plate slides past another,

volcanoes in the Pacific Northwest as an oceanic plate descends beneath the continent. The Atlantic and Gulf coasts are far from plate boundaries and hence do not have volcanic or large earthquake activity; they are thus ***passive continental margins***.

The Gulf of Mexico story is part of one that involves continents crashing together then ripping apart as whole oceans open, close, then re-open through time. Plate tectonics explains how it is possible for such massive pieces of Earth's crust to move about, and provides a framework to understand the large-scale geology of regions surrounding Gulf Islands National Seashore.

PLATE TECTONICS

The term ***tectonics*** originates from the Greek word "tekton," referring to a builder or architect. ***Plate tectonics*** suggests that large-scale features on Earth's surface, such as continents, ocean basins, and mountain ranges, result from interactions along the edges of large plates of Earth's outer shell, or ***lithosphere*** (Greek "lithos," hard rock). The plates, comprised of Earth's crust and uppermost mantle, ride on a warmer, softer layer of the mantle, the ***asthenosphere*** (Greek "asthenos," lacking strength). Earth's lithosphere is broken into a mosaic of seven major and several minor plates (Fig. 3). Relative motions between plates define three types of boundaries: ***divergent***, where plates rip apart, creating new lithosphere; ***convergent***, where one plate dives beneath the other and lithosphere is destroyed; ***transform***, where plates slide past one another, neither creating nor destroying lithosphere (Fig. 4). Another large-scale feature is a ***hotspot***, where a plate rides over a fixed "plume" of hot mantle, creating a line of volcanoes. Distinct patterns of mountains, earthquakes, and volcanoes are associated with each type of plate boundary and with hotspots (Figs. 5, 6).

The Whole Earth

Soon after it formed 4.6 billion years ago, the molten Earth settled into three layers (left side, Fig. 7). Dense material, mostly iron, fell toward the center to form the ***core***. Lighter compounds of silicon and oxygen (silicates) remained closer to the surface. Silicates rich in iron and magnesium formed the ***mantle***, overlain by a thin ***crust*** of silicates containing light elements (aluminum, calcium, potassium, and sodium). This classical division, based on chemical composition, was discovered in the early 1900's by analyzing earthquake seismic waves that penetrated the entire Earth. ***The clean, white sand in Gulf Islands National Seashore is testimony to the silicate nature of Earth's crust. The grains of sand are almost entirely quartz, which is silica in its purest form*** (chemical formula SiO_2).

By the mid 20th Century detailed seismic observations made it possible to study Earth's interior in finer detail. In modern times the three chemical layers are differentiated into five zones based on physical state (right side, Fig. 7). Changes in physical state occur because both temperature and pressure increase downward in the Earth. Temperature is hot enough at depths of 2900 to 5100 kilometers (1800 to 3200 miles) that the iron of the ***outer core*** is liquid. Below that, however, to a depth of 6400 kilometers (4000 miles) at Earth's center, pressure is so great that the ***inner core*** is solid. The iron/magnesium silicates of the mantle also show stratification due to the increasing temperature and pressure (Fig. 8). The outermost mantle and crust are cold and hard (like butter in a freezer), forming the rigid ***lithosphere***. Below about 150 kilometers (100 miles) depth the mantle is warmer, so that the ***asthenosphere*** is a

softer solid (like butter left on a dinner table). Still deeper, between about 700 and 2900 kilometers (400 and 1800 miles), pressure is so great that the lower mantle (***mesosphere***) is a harder solid. These changes in strength of the mantle create a unique situation where plates of lithosphere can ride over the softer zone of asthenosphere (Fig. 4), similar to sliding a hard Oreo® Cookie over the creamy filling.

Blocks of crust actually ride passively at the top of plates of lithosphere, 75 to 200 kilometers (50 to 120 miles) thick, composed mostly of mantle (Fig. 8). There are two types of crust: relatively high-silica ***continental crust***, about 20 to 75 kilometers (10 to 50 miles) thick, and lower-silica, 2 to 8 kilometer (1 to 5 mile) thick ***oceanic crust***. The underlying mantle is denser than both continental and oceanic crust; crustal blocks can thus be thought of as "floating" on the denser mantle, much as icebergs on water (Fig. 9). Continental crust is more buoyant than oceanic crust, mainly because it is thicker. Relatively thick crust underlies not only the continents but also their surrounding shelves (Fig. 10a). The surface of those areas is therefore above, or just barely below, sea level. The surface of oceanic crust, on the other hand, lies about 3 miles (5 kilometers) below sea level.

Continental Drift and The Development of Plate Tectonic Theory

Ever since the first maps of the Atlantic Ocean were made in the 16th Century people noticed how Africa and South America fit together like pieces of a giant jigsaw puzzle. The fit is even more impressive if continents are joined together at the edges of their continental shelves (Fig. 10b). That huge landmass, called ***Pangea***, represents only a brief glimpse in time, about 250 million years ago. At that time, during the Permian Period, most of the continental crust happened to be joined together. Prior to that time the continents were apart; since then they have drifted apart (imagine bumper cars being stuck together for a while, then flying apart).

The theory of continental drift met with skepticism in the early 20th Century, because it was thought impossible for blocks of crust to plow their way over mantle, which was known to be much more rigid and dense than crust. Two situations resulted in new information critical to acceptance of continental drift and plate tectonics. First, the topography of the ocean floor was mapped in great detail during and after World War II (Fig. 5). It was discovered that the floors of the ocean basins are not flat. A continuous mountain chain circumscribes the globe near the center of oceans and, in places, the ocean floor descends abruptly into deep trenches.

Secondly, a network of seismographs was installed around the world in the early 1960's, to detect nuclear tests during the Cold War. It was then possible to accurately locate earthquakes and to map the speed at which seismic waves pass through various regions of the Earth. The seismic data revealed startling observations. 1) Earthquakes are not scattered throughout the oceans, but instead are confined to narrow, rather continuous bands (Fig. 6). 2) Only shallow earthquakes occur along the mid-ocean ridges, but they extend along dipping zones from the surface downward at deep-sea trenches. 3) Within the upper mantle, there is a zone where seismic waves travel slowly. The last observation is the "Rosetta Stone" for plate tectonic theory. It provides a means by which continents can drift apart. Instead of having to plow their way through stronger mantle, the continents are passive "passengers" at the tops of plates comprised mostly of stiff mantle (lithosphere). The plates of crust and stiff mantle move about on the softer mantle beneath (asthenosphere, Figs. 7, 8). The observations of narrow zones of earthquakes and their depths provides clues to the distribution of deforming, brittle lithosphere, and thus outline the plate boundaries (Figs. 3, 4).

Volcanism

Contrary to popular conceptions, molten Earth material (magma) does not originate from the molten core of the Earth. The source of almost all magma is much shallower, at depths of the lower crust and upper mantle (Fig. 11). The melting of rock occurs under two circumstances: 1) material that was cold and solid near Earth's surface is pushed to depths where it is much hotter (Fig. 11a); and 2) hot material that was solid because of enormous pressure rises and decompresses (Fig. 11b,c). The first situation is the normal way we envision melting. At room temperature and pressure, for example, putting a match to plastic will cause it to melt. The top of a plate thus "sweats" fluids as it encounters higher temperature during subduction. The second situation can be understood in the context of a pressure cooker. Under high pressure, water in the cooker remains liquid at temperatures considerably above its normal boiling point (212°F; 100°C). Removing the lid from the cooker suddenly releases the pressure, causing the hot water to flash to steam. Similarly, hot mantle material that is solid under high pressure will begin to melt ("flashes to liquid") when the material rises and decompresses at divergent plate boundaries and hotspots.

Formation of Mountains

Mountain ranges generally form due to volcanism or deformation of the crust. The type of volcanism (and hence type of volcanoes) depends on the type of plate boundary (or hotspot) and type of crust (oceanic or continental) on each plate involved. Likewise, forces that deform the crust into mountains depend on the type of plate boundary present, and whether oceanic or continental crust caps the plates involved.

Considering Earth's topography both above and below the sea, most mountain ranges result from volcanic activity. Chains of steep-sided volcanoes, such as the Cascade Range in the Pacific Northwest (Fig. 12a), form on the overriding plate where one plate "subducts" beneath another (Fig. 11a). The chains of volcanoes are often curved, so that they are called ***volcanic arcs*** (for example, notice the Andes Mountains and Aleutian chain in Fig. 5). Plate divergence produces vast amounts of volcanic material (Fig. 11b), creating interlocking volcanoes that form long, submerged mountain chains like the Mid-Atlantic Ridge (Fig. 12b). ***The oceanic crust of the Gulf of Mexico formed as a similar mid-ocean ridge gradually moved away from North America***. The Hawaiian Islands and their sub-sea extension, the Emperor Seamount Chain (Fig. 12c), are a classic example of mountains developed over a hotspot (Fig. 11c).

Mountain ranges form in two important ways through deformation of Earth's crust. The first is obvious. As plates rip apart, crash together, or shear by one another (Fig. 4), stresses buckle the rocks into folds or break them along faults, creating topography like the Valley and Ridge Province of the Appalachian Mountains (Fig. 13a). The second way is less obvious but can have dramatic results. The highest region on Earth, the Himalayas and Tibetan Plateau (Fig. 13b), was created not so much by folding and faulting, but by the thick, buoyant crust of India sliding underneath (Fig. 14). The effects of the buoyancy difference between oceanic and continental crust can be envisioned by considering a tennis ball and a soccer ball in a swimming pool (Fig. 14a). The balls are about the same density, but the soccer ball sticks farther out of the water because it is bigger and hence more buoyant. A swimmer can easily bring the tennis ball to the bottom of the pool, but might have difficulty doing that with the more buoyant soccer ball (Fig. 14b). Similarly, lithosphere with thin oceanic crust is readily consumed (subducted) when plates converge, while buoyant continental crustal blocks

collide rather than subduct (Fig. 14c). (Imagine the swimmer in Fig. 14b putting a very large beach ball under his belly and rising part way out of the water). Mountain ranges thus rise upward as crust thickens, an effect known as ***isostasy***. Like the Himalayas, continental collision formed the Appalachian Mountains not only through folding and faulting, but also through isostatic uplift as the crust thickened. In fact, the Southern Appalachians remain prominent because their crust is still somewhat thicker than the crust of surrounding regions.

Continental Margins

The margins of continents reflect the zone of transition from thick continental to thin oceanic crust (Fig. 9). Some continental margins lie along plate boundaries and thus display active features like volcanoes, earthquakes, and mountain building (Fig. 2a). In other areas the continent-to-ocean transition zone is passive because it lies a long distance from the nearest plate boundary (Fig. 2b).

Active Continental Margins

The Pacific Coast of the United States has two types of active continental margins. Western California lies along a transform plate boundary where the Pacific Plate slides north-northwest, relative to the North American Plate. The San Andreas Fault, a surface manifestation of the plate boundary along much of its length, is thus the site of earthquakes. Farther north the Juan de Fuca Plate subducts beneath North America, producing the Cascade volcanic mountain chain (Fig. 12a). The active continental margin is thus associated with a convergent plate boundary (Fig. 2a).

Passive Continental Margins

Lithospheric plates are not normally capped by just continental or just oceanic crust. Rather, they commonly have both crustal types, so that transitions from thick continental to thin oceanic crust lie imbedded within the plate (Fig. 3). Along the Atlantic Coast of the United States the nearest large earthquake and volcanic activity is along the Mid-Atlantic Ridge, 2000 miles (3000 kilometers) from the continental margin. The Gulf Coast of the southern United States is a similar passive continental margin, imbedded within the North American Plate and thus lacking tectonic activity (Fig. 2b).

CONTINENTAL MARGIN OF THE SOUTHERN UNITED STATES

Gulf Islands National Seashore lies along the passive continental margin of the southern United States. The nature of the margin and its position, however, are only the current product of a long history of continental margin development that is still occurring. The history involves an earlier edge of North America that was some 500 miles (800 kilometers) to the north, a margin that now lies roughly beneath the Appalachian and Ouachita mountains (Fig 1). That earlier margin was deformed as Africa and South America came crashing in, forming the mountains. When continental rifting later occurred it left behind rocks representing the closed ocean, as well as

pieces of Africa and South America. Appreciation of the plate tectonic history of the southern margin of the United States therefore helps to understand the current structure, sedimentation, and geomorphology of the northern Gulf of Mexico.

DEVELOPMENT OF PASSIVE CONTINENTAL MARGINS

Passive continental margins form during divergent plate motion as continents rift apart and an ocean basin opens (Fig. 15). Where plates move away from one another the lithosphere thins, so that the underlying, buoyant asthenosphere elevates a broad region (Fig. 15a). The elevated regions are ***continental rift zones*** or ***mid-ocean ridges***, depending on whether the lithosphere is capped by continental or oceanic crust. If a continent completely rips apart, the two fragments drift away as parts of different lithospheric plates (Fig. 15b). New oceanic lithosphere is created between the continents, at a mid-ocean ridge. If the process continues long enough, a large ocean basin forms (Fig. 15c). The plate boundary is then at the mid-ocean ridge, far from the margins separating continental from oceanic crust; the margins are thus ***passive continental margins***.

Continental Rift Stage

As a continent rips apart it stretches, thinning the crust and entire lithosphere (Fig. 15a). The region is raised to high elevation because the underlying asthenosphere is hot and buoyant. The upper part of the crust deforms in a cold, brittle fashion, causing earthquakes and mountain ranges, separated by down-dropped valleys. The ***rift valleys*** fill with up to 5 miles (8 kilometers) of sedimentary and volcanic deposits as they subside, forming basins. A broad region of continental rifting in western North America, including all of Nevada and portions of Oregon, Idaho, California, Utah, Arizona, New Mexico, west Texas, and Mexico is thus termed the Basin and Range Province.

Fig. 16 shows stages of divergent plate boundary development in northeast Africa and Saudi Arabia. Active continental rifting (Fig. 15a) is occurring in East Africa. Many of the rift valleys have lakes because the valley floors are dropping faster than sediment can fill them. In fact, most of the world's deepest lakes form in continental rift valleys, including Lake Baikal in Siberia (deepest; 5369 feet, 1637 meters), Lake Tanganyika in East Africa (2nd deepest; 4708 feet, 1435 meters), Lake Malawi in East Africa (4th deepest; 2316 feet, 706 meters), Issyk Kul in central Asia (5th deepest; 2297 feet, 700 meters), and Lake Tahoe in the Basin and Range Province (8th deepest; 1685 feet; 514 meters).

Continental Drift Stage

Continental rifting can progress to a point where the crust breaks into two separate fragments (Fig. 15b). Each fragment includes a zone of transition from normal thickness ***continental crust***, to crust that was stretched and thinned during rifting (***transitional crust***), to thin ***oceanic crust*** formed at the new mid-ocean ridge. As the ocean expands the continental fragments move farther and farther from the ridge (Fig. 15c). The transitions from continental to oceanic crust (passive continental margins) are eventually imbedded in the two separate lithospheric plates, far from the plate boundary (the mid-ocean ridge).

The center of the Red Sea has a very narrow zone of newly-formed oceanic crust (Fig. 16). It's surrounded progressively by the crust that was thinned during rifting, then the full-thickness continental crust. Northeast Africa and southwest Saudi Arabia are thus passive continental margins that formed very recently (Fig. 15b). An older passive margin is evident along the southeast coast of Africa, which is now distant from the current mid-ocean ridge within the Indian Ocean (Fig. 15c).

Sedimentation and Morphology

Sedimentary basins are relatively low areas of Earth's surface where eroded rock particles (sediments) accumulate. Most sedimentary basins form due to subsidence at plate boundaries or on passive continental margins.

At divergent plate boundaries sedimentation occurs during continental rifting and continues as the ocean basin opens and the continents drift away (Fig. 17). ***Syn-rift strata*** (sedimentary deposits from eroding mountain ranges, along with lava flows) initially collect in rift valleys (Fig. 15a). Passive continental margins later subside below sea level during the continental drift stage, because the lithospheric plates cool as they move away from the mid-ocean ridge (Fig. 15b). ***Post-rift strata*** then cover the syn-rift strata and older continental rocks, as surrounding mountains erode and the margin continues to subside (Fig. 15c).

The crust that lies beneath post-rift strata shows evidence of the earlier phase of continental rifting and mid-ocean ridge development (Fig. 17). Beneath coastal plain and continental shelf regions there are rift valleys filled with sedimentary and volcanic strata, very much like those forming today in East Africa (Fig. 16) and the Basin and Range Province. Farther out to sea, the continental slope, rise, and abyssal plain are underlain by oceanic crust that formed as the mid-ocean ridge drifted away from the continent.

The sedimentary layers on a passive continental margin can reach enormous thickness because they are deposited on continental crust that was thinned during the rifting stage, or on even thinner oceanic crust. (Normal continental crust is too thick and buoyant to subside very much, and therefore cannot develop very deep basins). Beneath the continental shelves of the Atlantic and Gulf of Mexico the post-rift strata thus reach up to 10 miles (16 kilometers) thickness.

The morphology of a passive continental margin is a consequence of sedimentation over crust that thins seaward (Fig. 18). Continental crust is thick, so that its buoyancy makes it stick up high; conversely, thin oceanic crust sits down low (Fig. 9). The thickness difference results in the top of oceanic crust lying about 3 miles (5 kilometers) lower than normal-thickness continental crust (Fig. 18a). A crust of tapering thickness would cause the gradual change in water depth depicted in Fig. 18b. The situation is further changed by the fact that, as the margin moves away from the mid-ocean ridge it cools, subsides, and is covered by sediment eroding from the continent (Fig. 18c). This subsidence and sedimentation results in a thin veneer of sediment lying just above sea level at the ***coastal plain*** and a thickening wedge of sediment beneath shallow water along the ***continental shelf***. Farther out to sea, as thin oceanic crust is encountered, the water deepens abruptly along the ***continental slope***, then more gradually along the ***continental rise***, to the flat ***abyssal plain*** (Fig 19).

TECTONIC HISTORY OF THE GULF AND ATLANTIC COASTS

Early Appalachian geologists had classic educations. They envisioned the evolution of eastern North America as a metaphor based on Greek mythology. Iapetus was the son of Gaia, and the father of Atlas. An ancient sea bordering eastern North America was termed the Iapetus Ocean (Fig. 20). As the ocean closed, Europe, Africa, and South America collided with North America, forming a mountain range that was, in places, as lofty as the Himalayas (Fig. 21). The sutured continents later ripped apart, opening the Atlantic (Fig. 22). Thus the Greek mythology: Gaia (Mother Earth) gave birth to Iapetus (an ocean), who in turn fathered Atlas (both the Atlantic Ocean and the Atlas Mountains).

Following the Greek mythology, the tectonic history of the southeastern United States involves opening an ancient ocean along a divergent plate boundary, closing the ocean through plate convergence, followed by divergence that opened the Atlantic Ocean and Gulf of Mexico (Fig 23). Tracing this large-scale development helps us understand the history of the Gulf of Mexico as well as the origin of the various pieces of crust beneath the coastal plain and the mountains to the north. The discussion below illustrates that most of Florida was originally part of Africa; the southern portions of Alabama, Mississippi, and Louisiana may have been part of South America; and the southern Appalachian and Ouachita mountains are rocks of the Iapetus Ocean that were thrust over the ancient edge of North America.

Development and Destruction of the Ancient Continental Margin

Ancient North America did not extend nearly as far east and south as it does today (Fig. 20). In fact, the Appalachian and Ouachita Mountains are roughly in the position of the earlier continental margin (Fig. 1). That margin, formed about 600 million years ago, was a passive continental margin, similar to the modern Atlantic and Gulf coasts. It formed as an even earlier continent ripped apart, opening the Iapetus Ocean. Rocks to the east of the Appalachians and south of the Ouachitas formed within the Iapetus Ocean, or were part of Africa or South America (Figs. 1, 23).

From about 500 to 300 million years ago the Iapetus Ocean gradually closed through subduction (Fig. 23a). In the process volcanic islands, continental fragments, and finally the African and South American continents, collided with the ancient continental margin of North America (Fig. 23b). ***Pangea*** is the name for the huge continent that resulted (Figs. 10b, 21).

The mountain range formed as the Iapetus Ocean closed is far more extensive than just the Appalachians. From northern Georgia and Alabama, the zone of continental collision continues southwestward, buried beneath sediments of the Gulf coastal plain. In places it pokes through as small mountains, the Ouachitas of Arkansas and Oklahoma, and the Marathon Mountains in the Big Bend area of west Texas (Fig. 1).

In a modern continental collision zone, thick crusts of India, Saudi Arabia, and Africa crash into Asia and Europe (Fig. 22). The result is a continuous chain of mountains, 6,000 miles (10,000 kilometers) long and as much as 1,000 miles (1,500 kilometers) wide. From west to east the chain includes the Pyrenees, Alps, Carpathians, and Caucasus mountains of Europe, then the Anatolian, Zagros, Makran, Sulaiman, Pamir, Karakorum, and Himalayan ranges in Asia. The later three ranges have most of the highest mountains in the world, including Mt. Everest at 29,028 feet (8,848 meters).

The closing of the Iapetus Ocean and collision of continents that led to the Appalachian Mountains was every bit as impressive as collisions forming the Himalayan - Alpine mountain chain today. Reconstruction of the continental configuration 300 million years ago shows that, besides the Marathon - Ouachita - Appalachian chain, the ancient collision zone also included the Atlas Mountains of West Africa and the Caledonides in southern Greenland, the British Isles, and the Scandinavian portion of Europe (Fig. 21). The highest mountain in the Appalachians today is Mt. Mitchell, rising 6,684 feet (2,037 meters) above sea level. But in their prime, the Appalachians may have had peaks as high as Mt. Everest.

In the western part of the Appalachians, the rocks were originally part of North America. The ***Valley and Ridge Province***, as well as the ***Ouachita*** and ***Marathon*** mountains, are folded and faulted sedimentary strata of the continental margin, while the ***Blue Ridge*** of the Appalachians is a piece of the deeper, hard crust that was uplifted and shoved westward. Farther east and south, the rocks formed elsewhere and were attached (or "accreted") to the edge of North America as the ocean closed. The Appalachian ***Piedmont*** is therefore an array of volcanic islands, sedimentary rocks, and crust of the Iapetus Ocean that were caught up in the collision. In places the Atlantic Ocean and Gulf of Mexico formed quite a bit east and south of the zone of "suturing" between the continents. Rocks and young sediments of the ***Coastal Plain*** beneath most of Florida and the eastern parts of Georgia and the Carolinas are thus stranded pieces of Africa, left behind when the Atlantic opened (Fig. 22c). Similarly, as the Gulf of Mexico opened, parts of South America and the Yucatan were stranded and now constitute the southern parts of Alabama, Mississippi, Louisiana, and east Texas (Fig. 23c).

Continental Rifting and the Opening of the Atlantic Ocean and Gulf of Mexico

The Gulf of Mexico story culminates with events that occurred over the last 250 million years, as Pangea ripped apart, opening the Atlantic and Gulf, and wearing down the Appalachians and Ouachitas through erosion (Fig. 23c). The story that unfolded earlier, as the ancient continental margin of North America formed, was repeated as the Atlantic and Gulf coasts developed. Sedimentary and volcanic strata are found in rift valleys beneath the coastal plains, relics of the rifting of Pangea 200 million years ago. The Coastal Plain sediments are younger, the landward part of the passive margin sequence that extends offshore across the continental shelf, slope, and rise (Fig. 17). New oceanic crust is being created as the Atlantic Ocean widens at the current plate boundary, the Mid-Atlantic Ridge. ***The rifting and continental drift that opened the Gulf of Mexico ceased about 150 million years ago, so that current activity involves subsidence, sedimentation, and sea level changes that shift the coastline through time***.

Erosion, Subsidence, Sedimentation and Development of the Northern Gulf Coast

The Southern Appalachian Mountains evolved to the stage of a very hard continental collision. Individual mountains may have attained heights comparable to Mt. Blanc in the Alps (15,781 feet; 4,810 meters) or even Mt. Everest in the Himalayas (29,028 feet; 8,848 meters). Like the Alps and Himalayas, the Southern Appalachians owed their overall height to the great thickness of crust resulting from the collision (Figs. 9b, 14c). That great thickness cannot last forever, however, because as the topography erodes, it takes weight off the buoyant crustal root. Rebound of the root then occurs, rebuilding just

enough topography to maintain isostatic equilibrium. With each step in the process, the crustal root is a little shallower and the overall topography a bit lower. After 250 million years the result is that the overall height of the crest of the Southern Appalachians is about 3,000 feet (1,000 meters) and the highest peak, Mt. Mitchell, stands 6,684 feet (2,037 meters) above sea level. The fact that isostatic rebound accompanies erosion, however, means that 10 to 15 miles (15 to 25 kilometers) of material was removed from portions of the Southern Appalachian Mountains. Much of that material was deposited in the northern Gulf coastal plain and offshore areas, accounting for the enormous thickness of sediment observed today (Fig. 24).

The types of sedimentary layers deposited along a passive continental margin depend on the nature, height, and proximity of the source area, the climate of the margin, openness of the ocean basin, and depth of water. When the Gulf of Mexico originally developed it was a narrow trough between North and South America, with only a small opening to the Atlantic and Pacific oceans. It was also at very low latitude, near the equator. Those two factors meant that there was restricted water circulation; salt water could flow into the narrow trough, but the hot climate meant that there was a lot of evaporation. Consequently, an enormous thickness of salt precipitated out of the water. The salt was overlain by sand and mud deposited by streams from the flanking Ouachita and Appalachian mountains, which were much higher than they are today. In places lacking streams to bring in continental sediment, such as the shallow shelf surrounding the Florida peninsula, shell fragments from marine animals were dissolved then deposited as lime mud. The layers of sand, mud, and lime compacted and hardened into the rocks sandstone, shale, and limestone, respectively. The thick salt layer below, however, could not compact so easily. Through time the overlying sedimentary layers compacted to higher density material than the salt below. Like a "lava lamp" (or oil rising through water), the less-dense salt rose up through the overlying layers, forming salt domes (Fig. 24).

GULF ISLANDS NATIONAL SEASHORE

The eastern and southern coasts of the United States are parts of the passive continental margins that formed as the Atlantic Ocean and Gulf of Mexico opened when Pangea ripped apart. Nine national seashores lie within the broad zone of transition from continental to oceanic crust (Fig. 25). Development of the coastal plain and continental shelf, slope, and rise on the eastern seaboard is a function of change from thick continental to thin oceanic crust (Fig. 18). Understanding plate tectonic processes that lead to continental rifting and passive margin development is thus important to understanding the current position and geologic history of our national seashores.

Gulf Islands National Seashore contains beaches along the coastlines of Florida and Mississippi, as well as barrier islands on the low-lying continental shelf (Figs. 26, 27). The coastlines and barrier islands are features that, geologically speaking, change positions rapidly, depending on global sea level, sediment supply, and rate of subsidence of the continental margin. All nine of the national seashores lie along the very gentle slope that extends hundreds of miles from the landward edge of the coastal plain to the seaward edge of the continental shelf (Figs. 1 and 17-19). Over this large distance, elevation changes by only about 1000 feet (300 meters), from 400 feet (120 meters) above sea level to 600 feet (180 meters) below. The average slope is thus only about 0.03 degrees, or 3 feet per mile (0.6 meters/kilometer)!

Sea Level Changes and Shoreline Migration

In recent times, as Earth's climate fluctuated, sea level dropped when water was concentrated in polar ice caps, then rose as the ice melted. The shoreline has thus migrated back and forth, from near the edge of the continental shelf during the peak of ice ages, to somewhere landward of its current position when climate was warmest (Fig. 28). During the peak of the last ice age, for example, when sea level was about 400 feet (120 meters) lower, the Gulf coastline was about 100 miles (160 kilometers) to the south (Fig. 29). Lands that currently make up the national seashores were therefore high and dry at that time, developing their current morphology as the Earth warmed and the coast migrated to its current position over the last 18,000 years. At other times, during warmer climate, the coast was 70 miles (100 kilometers) farther north. Nowadays the concern is that people are forcing the issue by spewing hydrocarbons and other materials into the atmosphere, perhaps causing Earth's atmosphere to warm through the "greenhouse effect." If that is the case, then over a period of only a few decades water could flood the Gulf Coastal Plain and flood the cities of Baton Rouge, Hattiesburg, and Augusta.

Source of White Sands

The type of sediment deposited along a coastline depends of the source of the sediment and the water currents that move and deposit the sediment. The sizes and locations of the drainage areas for the streams that supply the sediment (Fig. 30) heavily influence deposition along the northern Gulf Coast. The sediment that reaches Gulf Islands National Seashore comes from a very small drainage area. In fact, virtually all the particles are from erosion of the southernmost portion of the Appalachian Mountains (Fig. 31a). The fast moving streams bring mostly grains of clear white quartz the short distance across the coastal plain to the Gulf. The westward longshore current deposits it as pure white sand along the coast and barrier islands of the seashore (Fig. 31b).

To the west and east the sedimentary supply is quite different. The Mississippi River system drains an enormous portion of the North American continent, through slow-moving streams that bring in a lot of mud and silt, in addition to sand. Beaches of Louisiana and east Texas are therefore a "chocolate brown" color. Along the west coast of Florida streams bring in dissolved limestone from the peninsula, but very little sand, silt, or mud. The material deposited is mostly fragments of sea shells; the beaches are white, but not nearly as sparkling as the those of Gulf Islands National Seashore!

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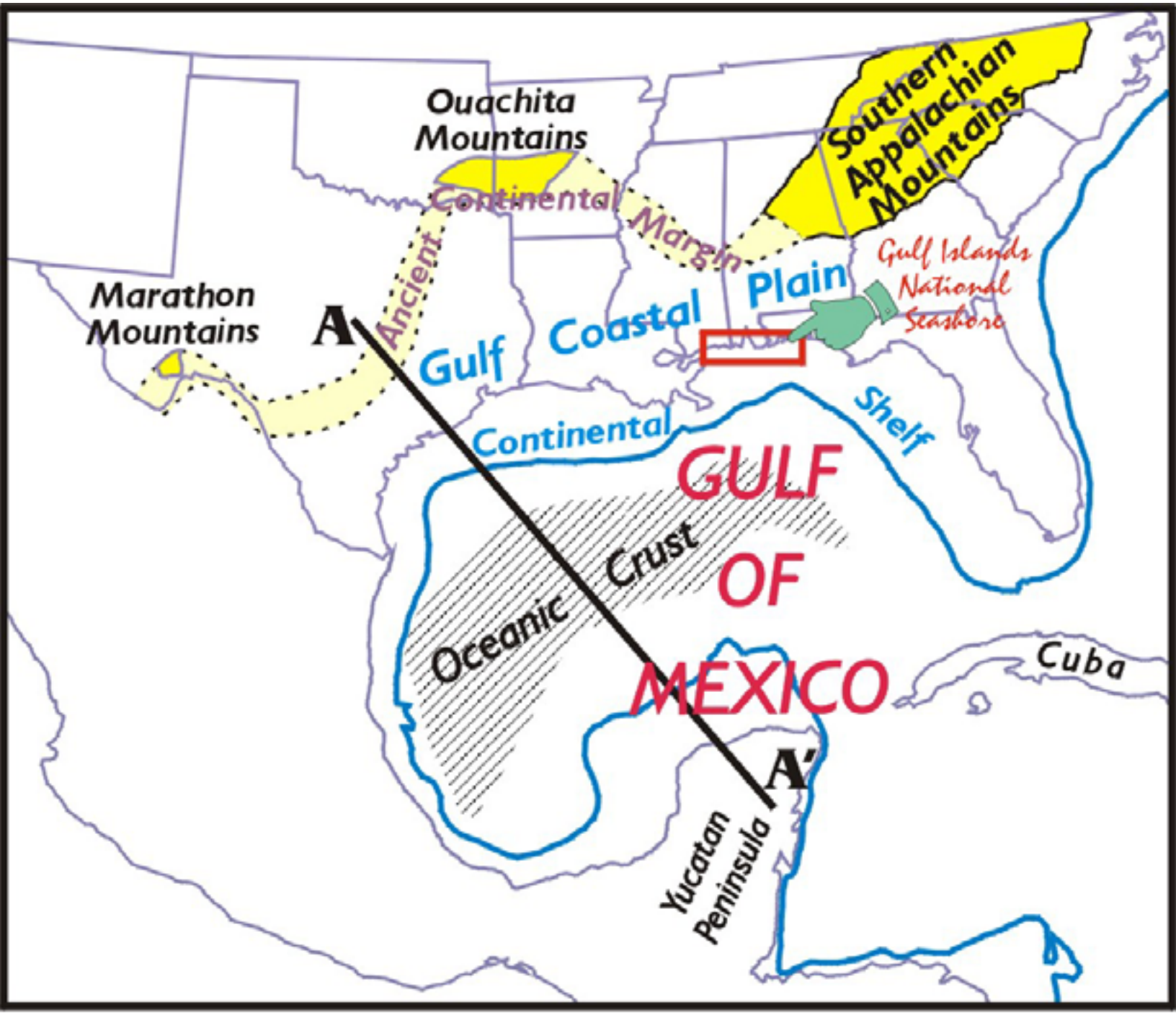


Fig. 1. ***Map of Gulf of Mexico, showing location of Gulf Islands National Seashore.*** *The Gulf coastal plain and continental shelf mark the transition from thick crust of North America to thin crust of the Gulf of Mexico. True oceanic crust underlies only the central and western Gulf. An earlier continental margin of North America is now covered by the Appalachian - Ouachita - Marathon mountain chain. The mountains eroded and supplied sediment as the Gulf of Mexico opened. A-A' is the line of the cross section shown in Fig. 24.*

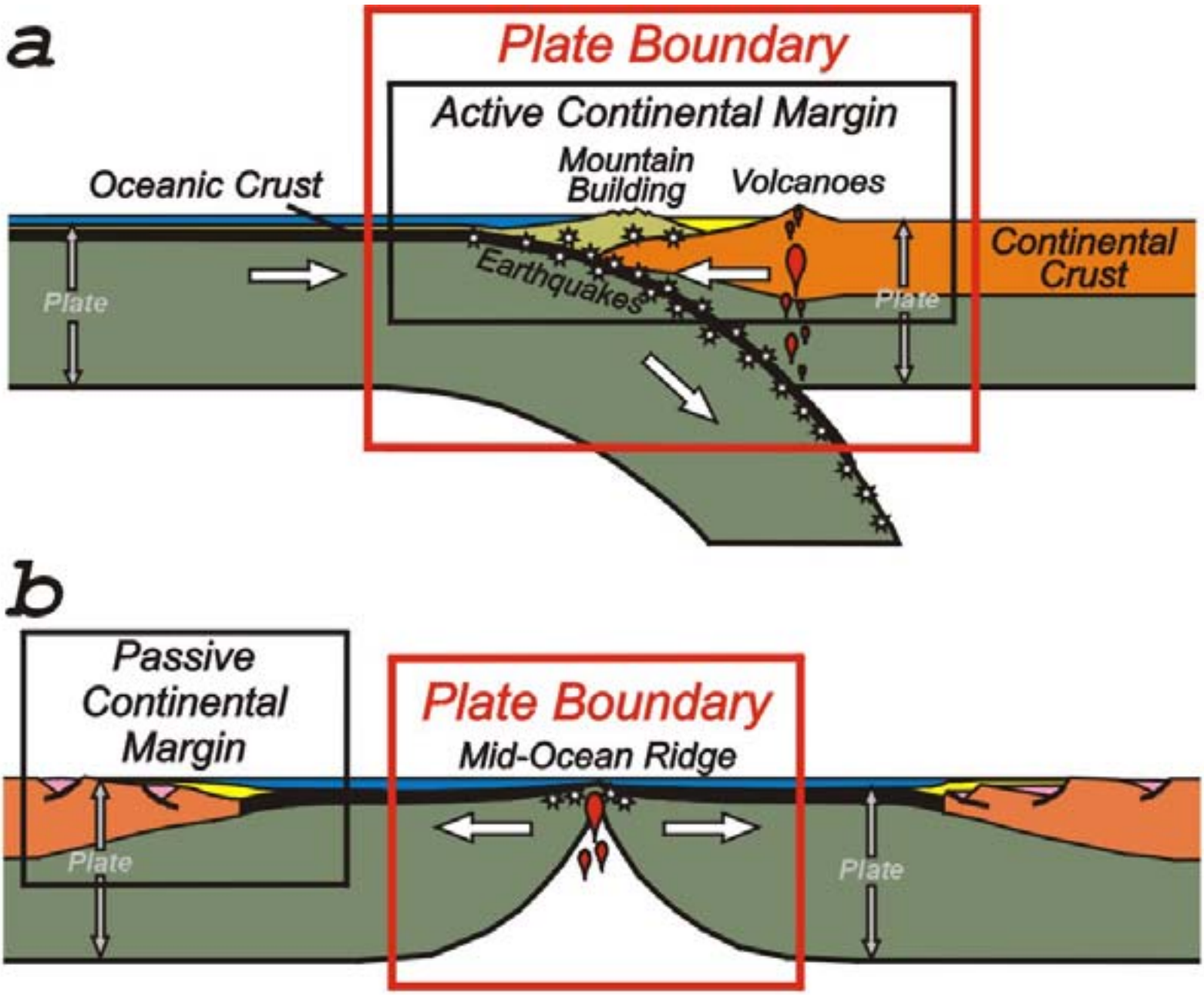


Fig. 2. ***Active and passive continental margins***. *Continental margins are zones of transition between thick continental crust and much thinner oceanic crust. a) A continental margin is active if it lies at or near an active plate boundary, where earthquakes, volcanoes, and mountain building occur. b)A continental margin is passive if it lies a great distance from an active plate boundary and its associated tectonic activity.* ***The National Seashores on the Atlantic and Gulf coasts lie along a passive continental margin.***

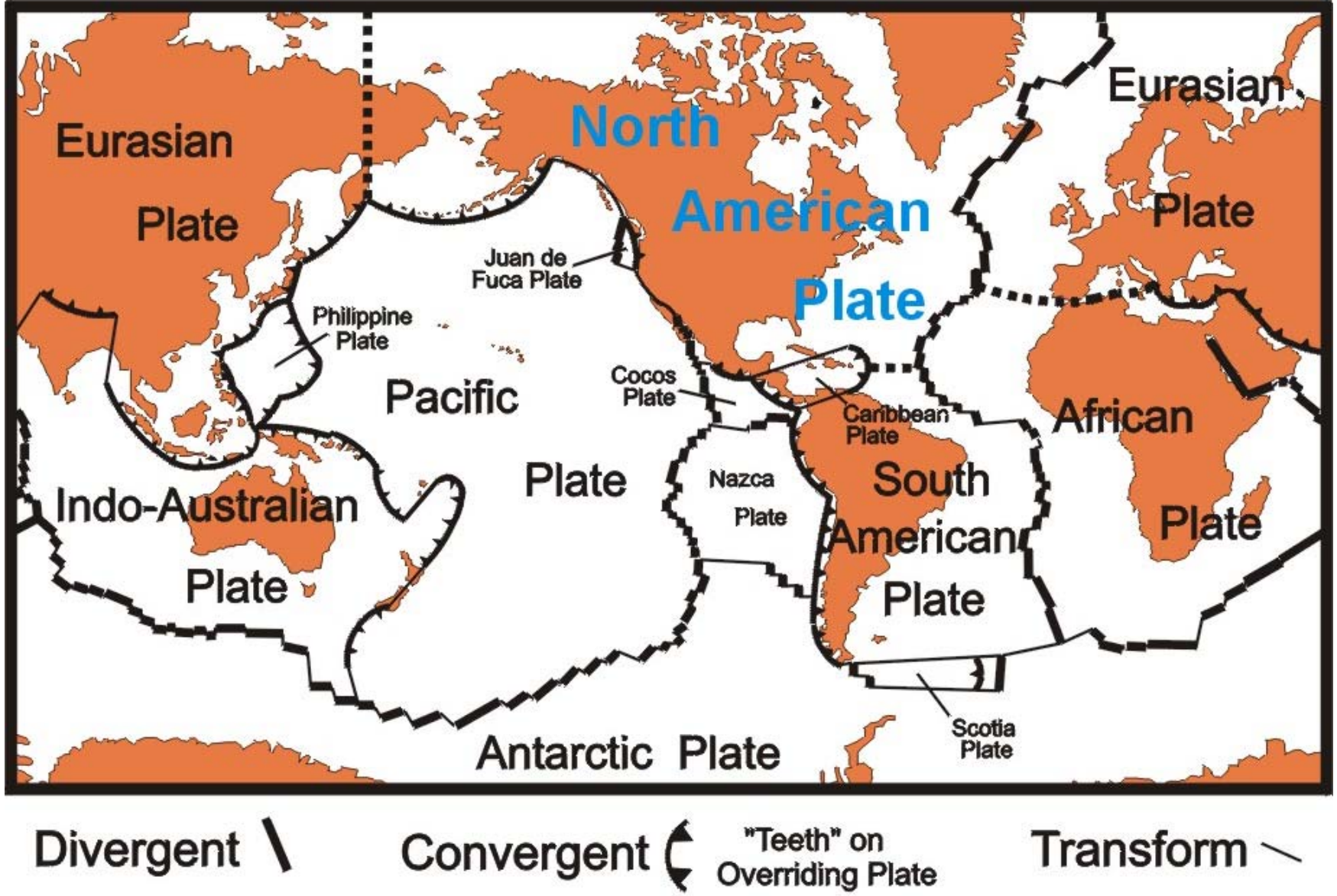


Fig. 3. ***Plate tectonic map of the world, illustrating the three types of plate boundaries***. *Note that the locations of plate boundaries correlate with the narrow zones of earthquakes in Fig. 6. The Pacific Coast of the United States is an active continental margin, lying along transform and convergent plate boundaries.* ***The coasts of the Atlantic Ocean and Gulf of Mexico are passive continental margins; they are imbedded within the North American Plate, far from its boundaries.***

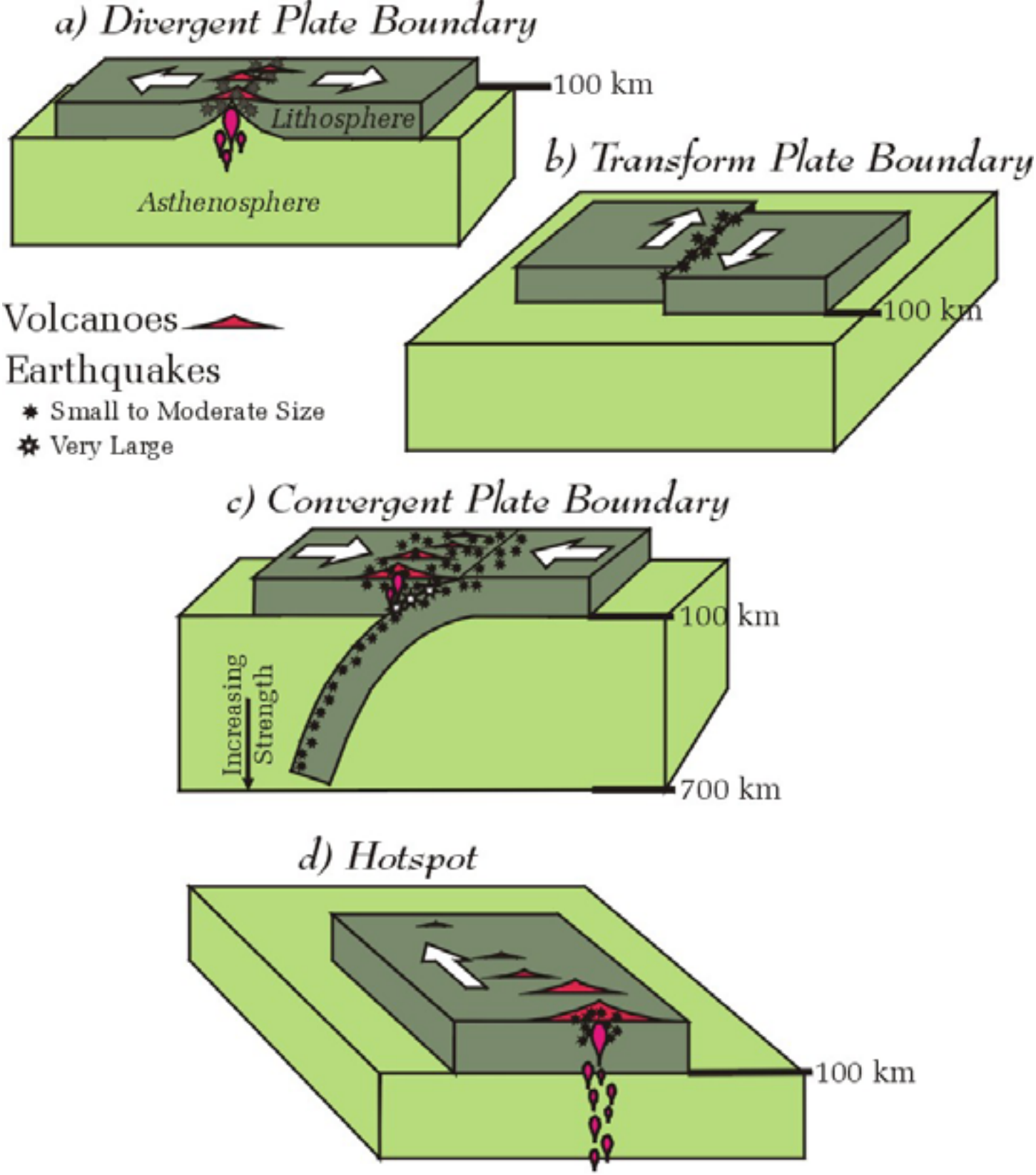
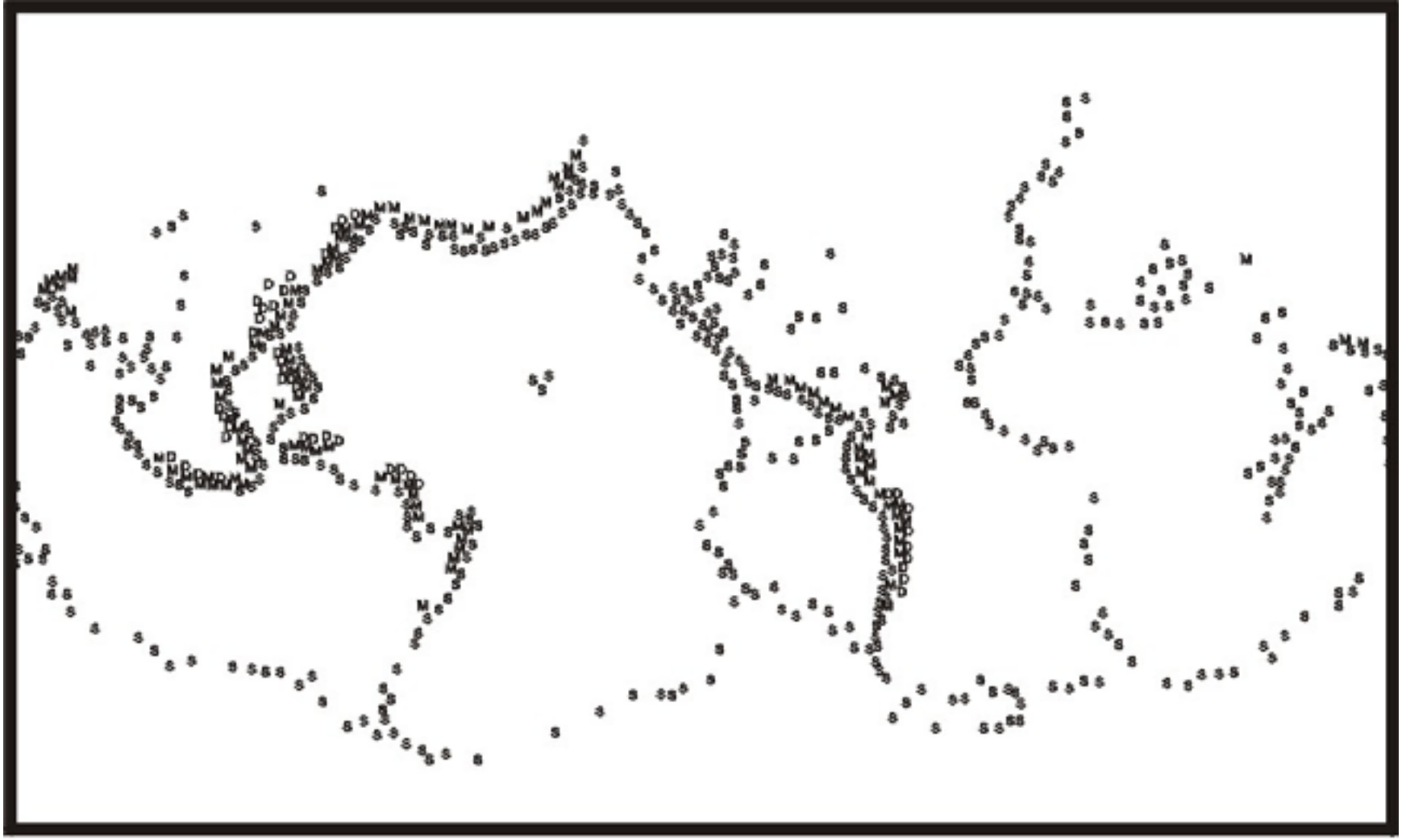


Fig. 4. ***Tectonic activity occurs at the three types of plate boundaries and at hotspots.*** *Volcanoes erupt in the zone where plates diverge, on the overriding plate where plates converge, and along a line where a plate rides over a hotspot. Only shallow earthquakes, of small to moderate size, occur at divergent and transform boundaries and at hotspots. The cold, brittle lithosphere may extend to great depths at convergent boundaries, accompanied by a dipping zone of shallow to very deep earthquakes; the largest earthquakes occur at convergent boundaries where the two plates lock together for many years, then suddenly let go.*

Fig. 5. ***World map showing features of the ocean floor***. *(From Marie Thorpe, 1977). A system of mid-ocean ridges forms the broadest and longest mountain chain on Earth. Continental shelves extend outward to where the water deepens abruptly on continental slopes. On the edges of some oceans, as well as in some places within oceans, narrow deep-sea trenches occur. Lines of volcanic islands form long chains on the ocean floor, deepening progressively as underwater seamounts.* ***Note the prominent continental shelves off eastern North America, along the passive continental margins of the Atlantic Ocean and Gulf of Mexico.***



S = Shallow (< *70 km*) M = Intermediate (*70 - 300 km*) D = Deep (>*300 km*)

Fig. 6. ***Locations of large earthquakes recorded over five-year period, plotted without any geographic reference***. *Data from Barazangi and Dorman (1969); figure modified from Hamblin and Christiansen (1995). The earthquakes outline the plate boundaries shown in Fig. 3. Only shallow earthquakes occur at divergent and transform plate boundaries and at hotspots. Zones of earthquakes dipping from shallow, to intermediate, to deep outline subducting plates at convergent boundaries.* ***The Atlantic and Gulf coasts of the United States lack earthquake activity because they are passive continental margins, far removed from active plate boundaries.***

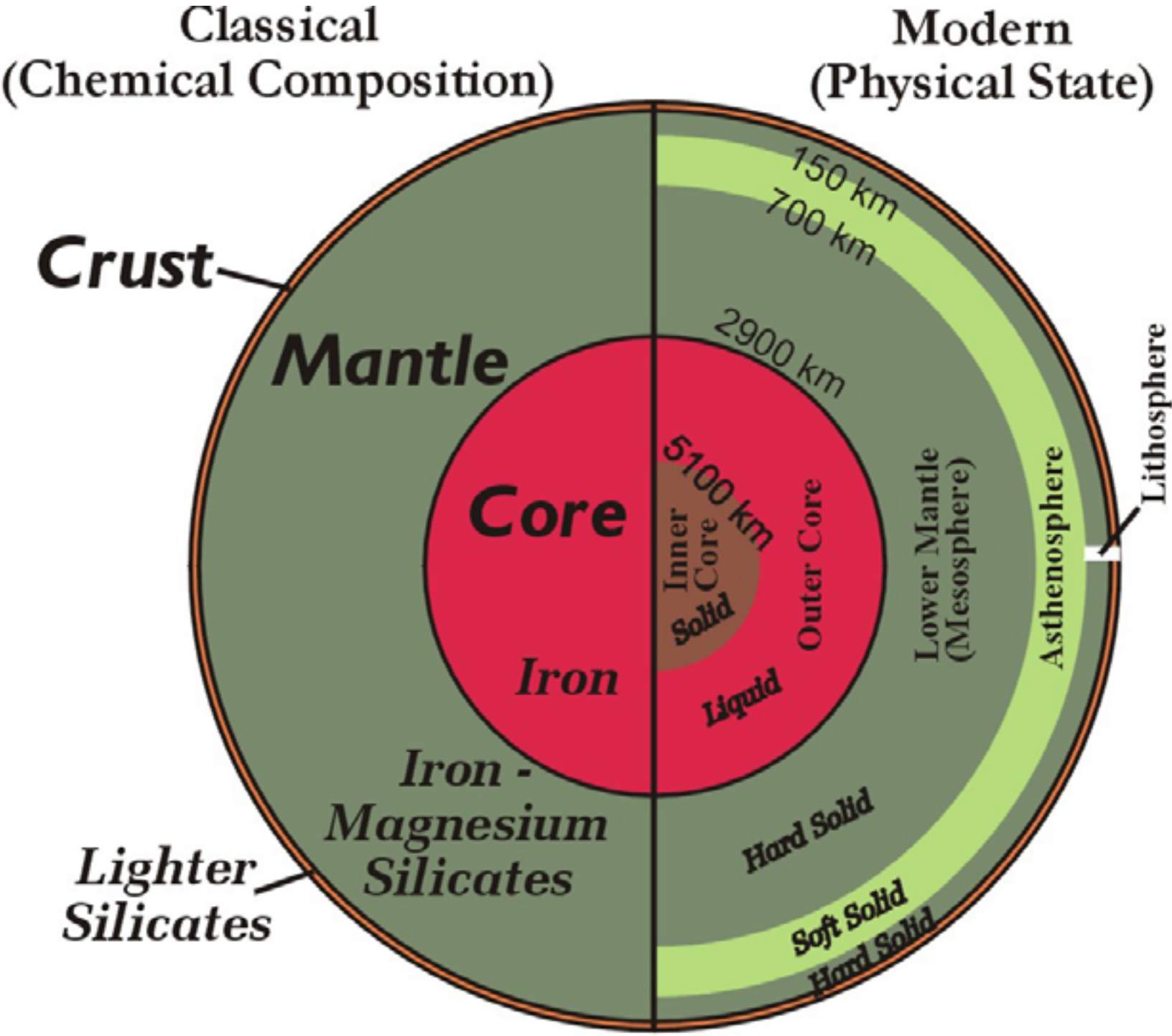


Fig. 7. ***Gross layers of the Earth***. *Left: The classical division of the Earth is according to chemical composition, the heavier materials concentrated toward the center. Right: In modern times the three chemical divisions are broken into five zones according to physical state.*

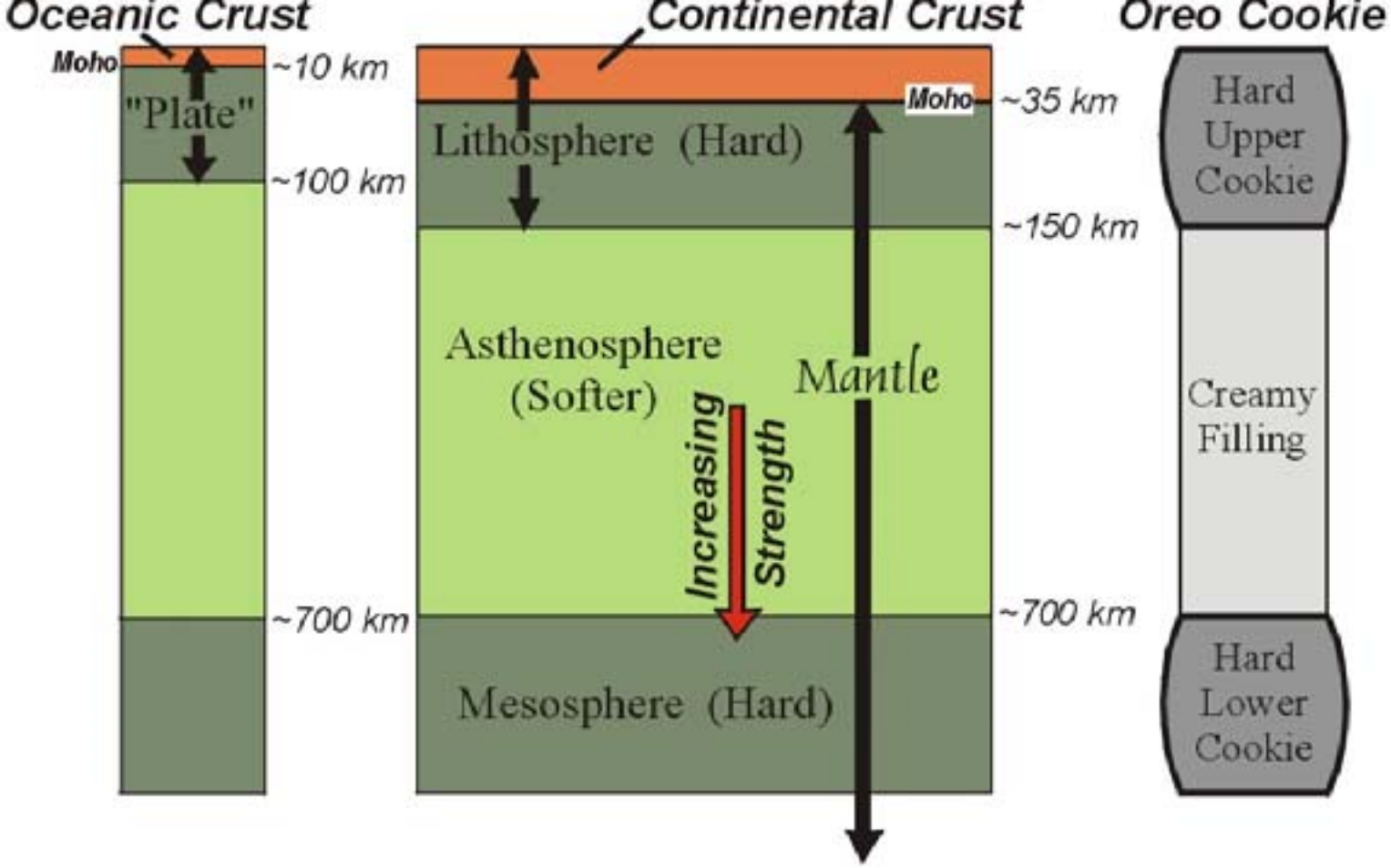


Fig. 8. ***Cross section of the upper 1000 or so kilometers of the Earth, including the crust and part of the mantle.*** *Increases in temperature and pressure with depth cause the mantle to exist in three different states. The uppermost mantle and crust comprise the cold, rigid plates of lithosphere. Hotter mantle below forms the somewhat softer asthenosphere. Pressure increase with depth causes the asthenosphere to gradually increase in strength, to the more solid mesosphere. Lithospheric plates can be compared to a hard Oreo® cookie, riding on the soft, creamy filling (asthenosphere). The lower cookie (mesosphere) does not move.*

Fig. 10. ***Buoyancy of thick (continental) compared to thin (oceanic) crust***. *a) Relatively thick crust includes not only regions above sea level (yellow), but also the continental shelves (gray) that lie beneath shallow water. (From Skinner and Porter, 1989). b) Continents joined together at their continental shelves to form the supercontinent of* ***Pangea***. *(From Atwater, 1986). Note that there is a gap between North and South America that was filled with continental crust of the Yucatan Peninsula and other fragments now in the Caribbean region. The peninsula of Florida lies at the juncture where North America, South America, and Africa later rifted apart.*

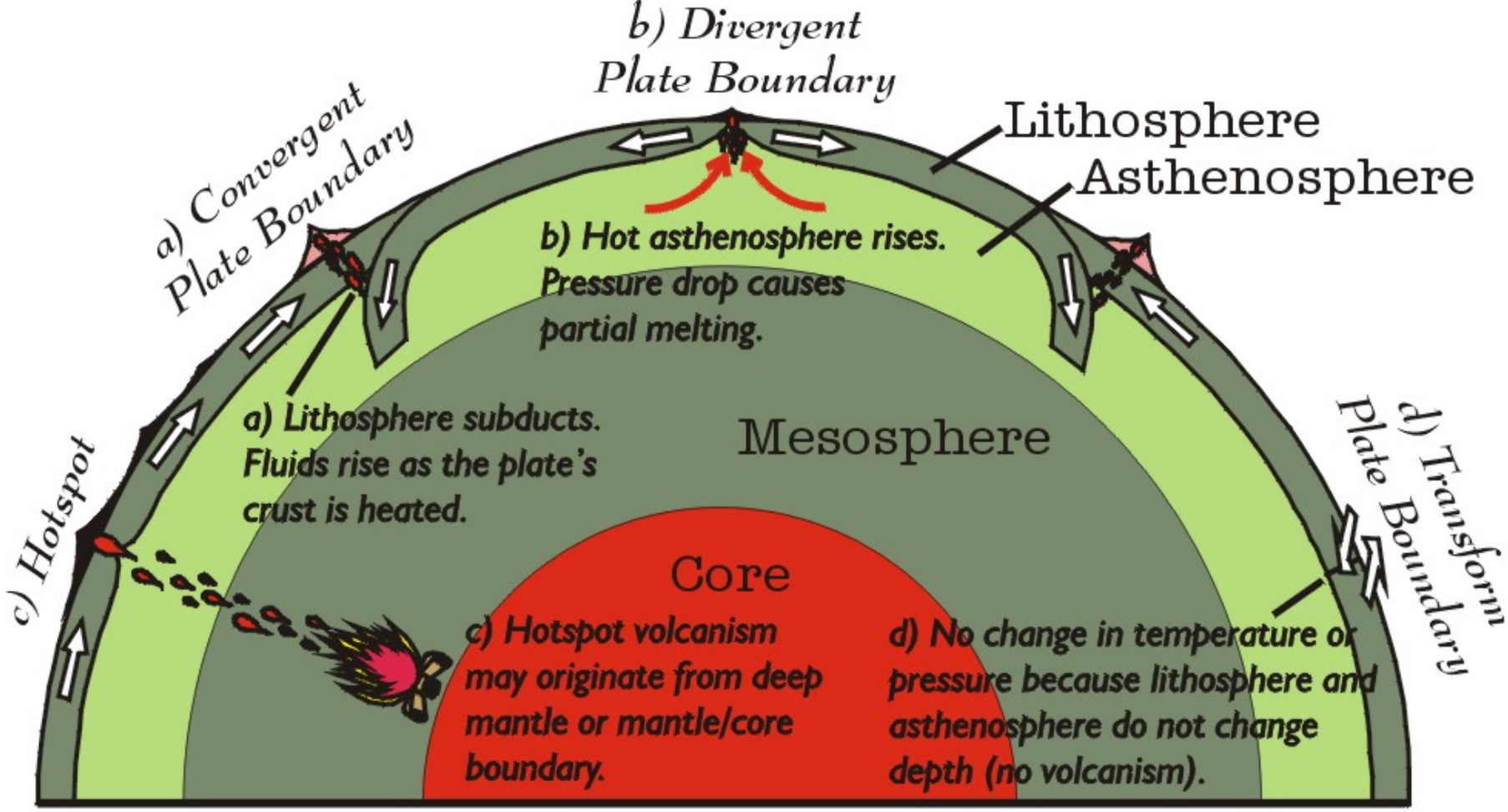


Fig. 11. **Reasons for volcanism**. *a) Heating of the crust of the descending plate at a* **convergent plate boundary**. *b) Drop in pressure on hot asthenosphere as it rises at a* **divergent plate boundary**. *c) Deep mantle material rising and decompressing at a* **hotspot**. *d) At a transform plate boundary material stays at about the same depth; there is no appreciable rise in temperature or drop in pressure and hence little or no volcanism.* ***The Gulf Coast has no volcanism because it is far from any plate boundary or hotspot***.

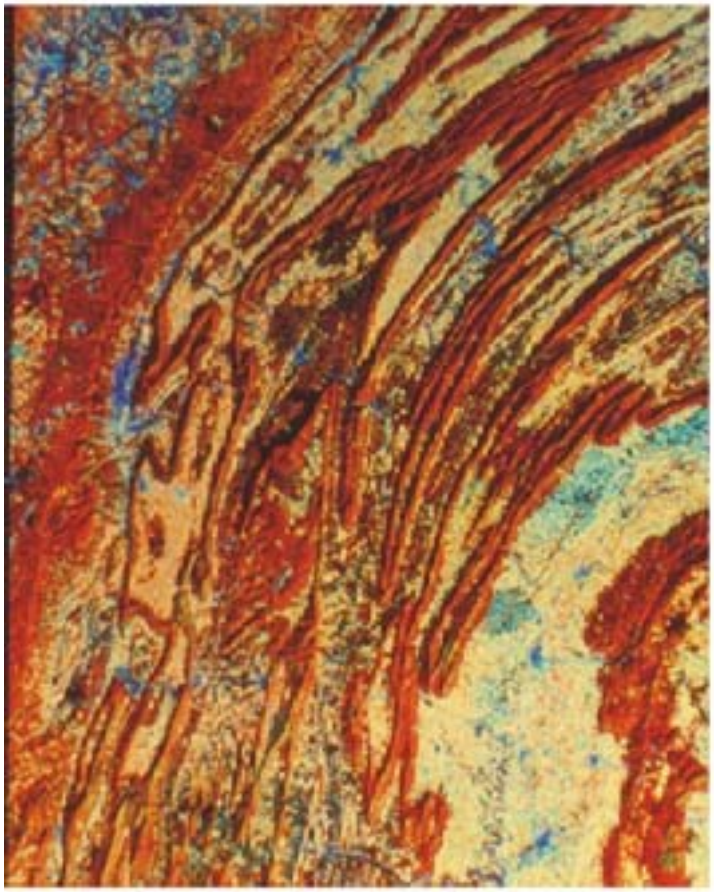
a

b

c

Fig. 12. ***Types of volcanic mountain chains.*** *a) A volcanic arc is a chain of steep composite volcanoes that forms above a subduction zone (Cascade Mountains; Figs. 2a, 11a). b) At a divergent plate boundary with oceanic crust, a mid-ocean ridge is a mountain range of submerged, interlocking shield volcanoes (Mid-Atlantic Ridge; Figs. 2b, 11b). c) Plate motion over a hotspot leaves a chain of broad shield volcanoes that are youngest directly above the hotspot, older away from it (Hawaii-Emperor Seamount Chain; Fig 6d, 11c). Photo in (a) by R. J. Lillie; (b) and (c) from National Geographic Society Physical Globe.*

a



b

Fig. 13. ***Satellite images of mountain ranges formed by crustal deformation***. *a) Valley and Ridge Province of the Appalachian Mountains (Landsat photo). During plate convergence, sedimentary strata of the ancient continental margin of North America were folded like a rug pushed across a floor. b) Active continental collision zone in northern India, Nepal, and Tibet (Skylab photo). On the left (south) are the undeformed plains of India. The snowcapped peaks are the folded and faulted Himalayas. To the north, the Tibetan Plateau is a vast region of high topography because the thick, buoyant crust of India extends underneath (Fig. 14c).*

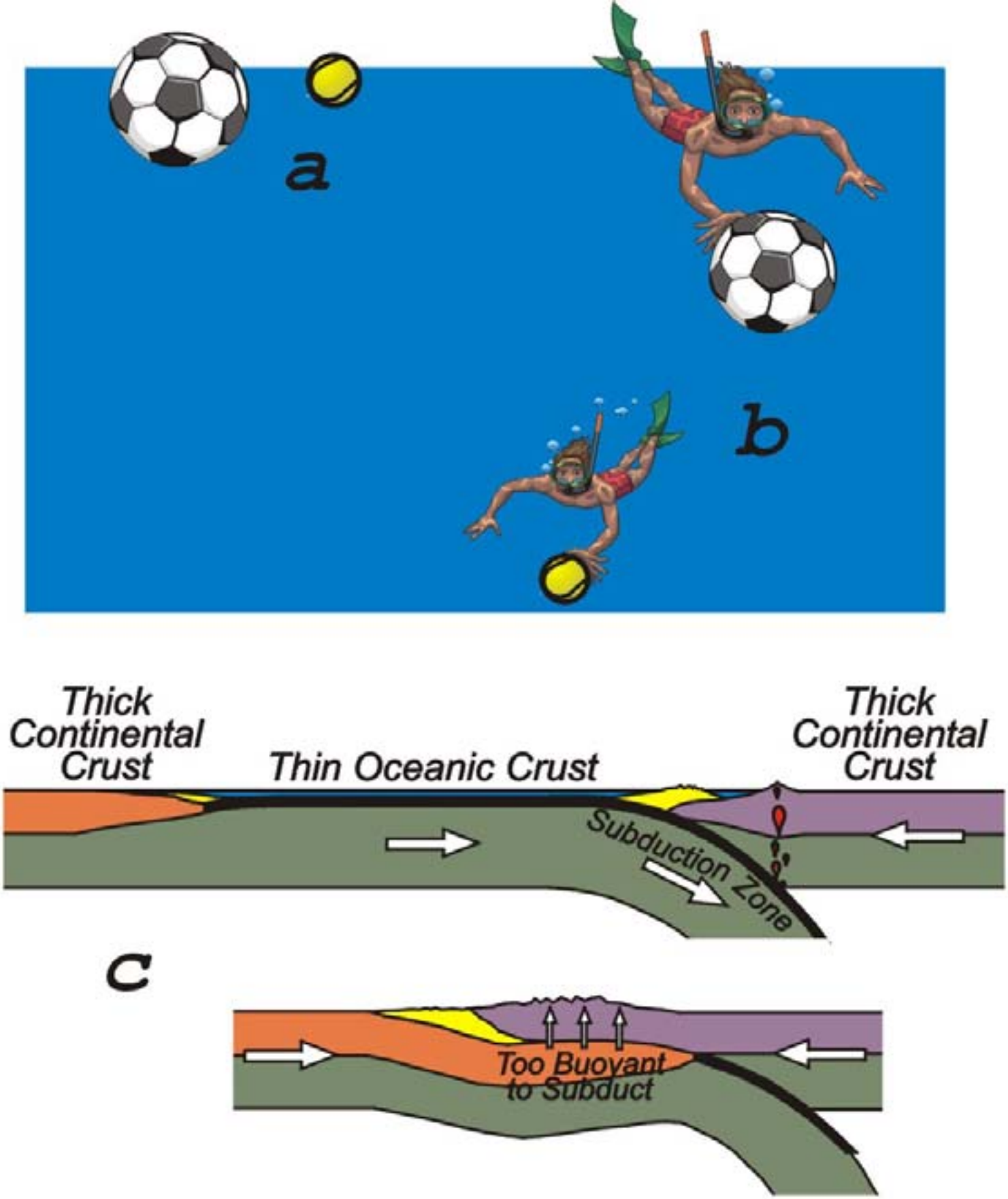


Fig. 14. ***Effects of crustal buoyancy***. *a) The bigger, more-buoyant soccer ball sticks up higher, and rests lower, in the water than the smaller, less-buoyant tennis ball. b) A swimmer can easily "subduct" the tennis ball to the bottom of the pool, but not the soccer ball. c) Thin (less-buoyant) oceanic crust can subduct, while thick (more-buoyant) continental crust cannot. Continental collision therefore results in a broad region of uplifted topography (Fig. 13b).*

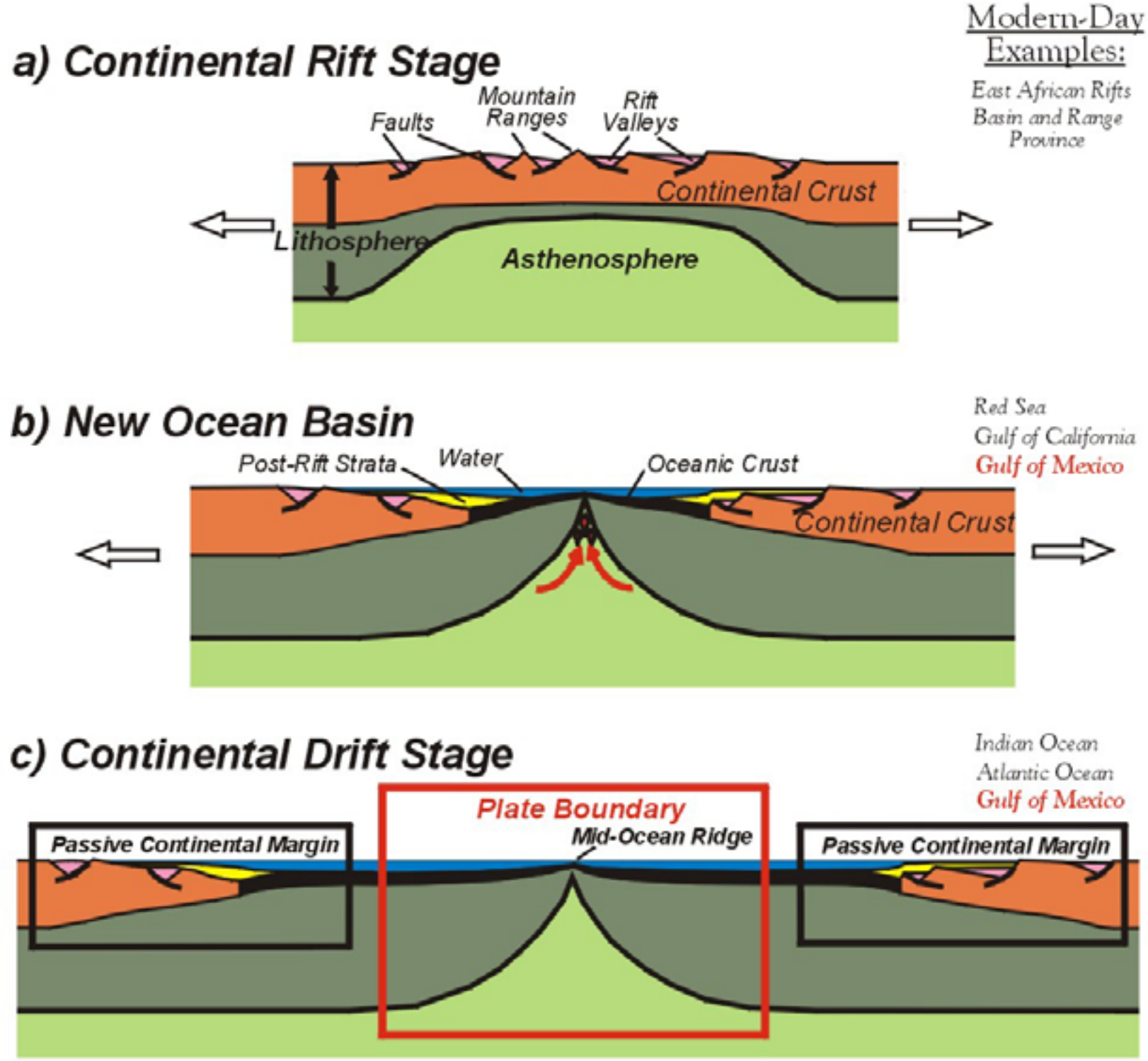


Fig. 15. ***Plate divergence results in continental rifting and the development of a mid-ocean ridge separating passive continental margins.*** *a) Continental rift stage. Rift valleys form as the crust rips apart and thins. b) New Ocean Basin. A narrow basin, with thin oceanic crust, develops as the two continental fragments completely rip apart. c) Continental drift stage. The continents move away from one another as parts of different lithospheric plates. The transitions from thick continental to thin oceanic crust are* ***passive continental margins*** *because they are far away from the active plate boundary at the mid-ocean ridge. Thick sedimentary deposits develop as the continental margins cool and subside.* ***Opening of the Gulf of Mexico ceased between stages (b) and (c), before a lot of continental drift occurred.***

Fig. 16. ***Divergent plate boundary development in eastern Africa***. *(National Geographic Society Physical Globe). East Africa is an active* ***continental rift zone*** *(Fig. 15a), the Red Sea an* ***early ocean basin*** *(Fig. 15b), and the Indian Ocean a more* ***advanced ocean*** *(Fig. 15c).* ***The Gulf of Mexico developed to a stage between that of the Red Sea and the Indian Ocean.***

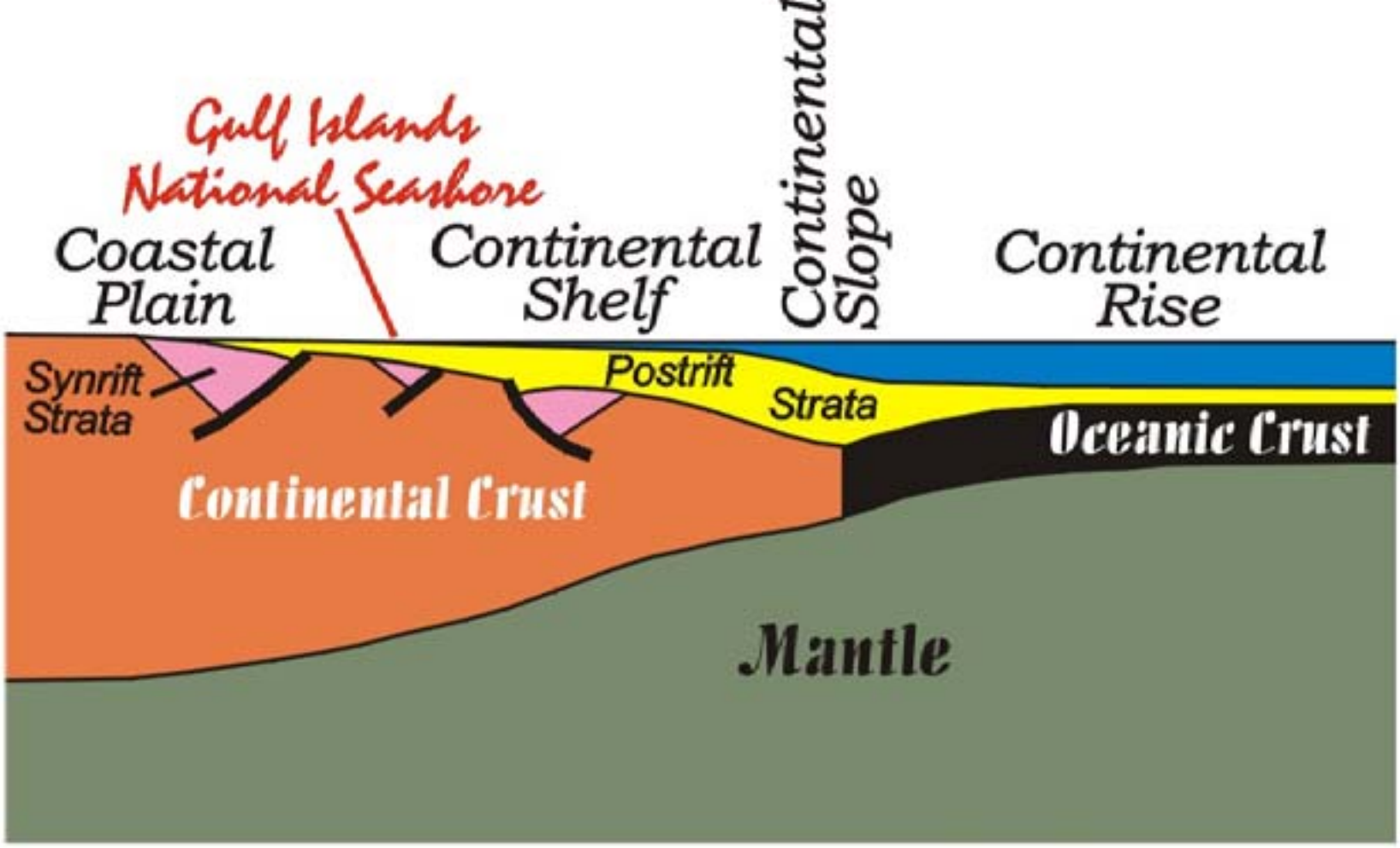


Fig. 17. **Crustal structure of passive continental margin**. *Older, sedimentary and volcanic layers (**synrift strata**) fill the former rift-valleys (Fig. 15a). Because the oceanic crust is thinner (and hence less buoyant) than continental crust, its surface is lower (Fig. 9b). As the ocean basin floods with water, **postrift strata** (sandstone, shale, and limestone) accumulate along the margin. The morphology of the top of the wedge is a function of crustal thickness changes, sediment supply, and margin subsidence (Fig. 18). The ocean water is shallow over the thicker continental crust, forming a broad **continental shelf**. It deepens along the **continental slope** to the **continental rise**, which overlies the thinner oceanic crust. Barrier islands and coastlines on the continental shelves of the Atlantic and Gulf of Mexico coasts are the sites of several National Seashores.*

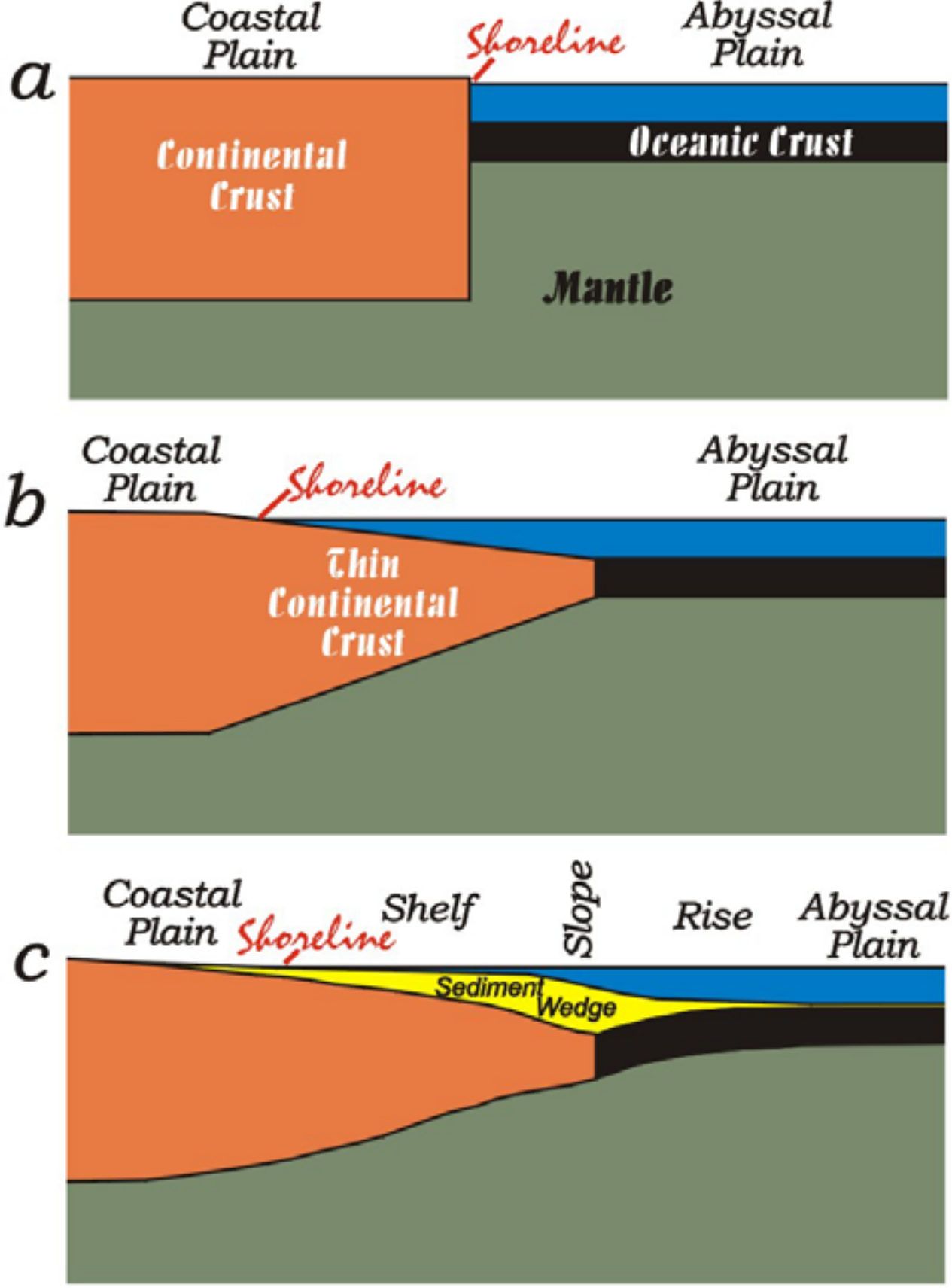


Fig. 18. ***Evolution of coastal plain; continental shelf, slope, and rise; and abyssal plain along passive continental margin***. *a) Simple model with blocks of continental and oceanic crust. The greater buoyancy of the thick continental crust makes it stick up higher than the thin oceanic crust (Figs. 9, 13a). Only a* ***coastal plain****, near sea level, and* ***abyssal plain****, about 3 miles (5 kilometers) below sea level, would form. b) Model including a tapered zone of continental crust that thinned during rifting (Fig. 15). A zone of deepening water would develop between the coastal and abyssal plains. c) Model incorporating a wedge of sediment draped over the continental margin ("postrift strata," Fig. 17). A* ***continental shelf*** *develops; beyond its edge is a relatively steep sea-bottom, the* ***continental slope****, then a more gentle* ***continental rise****.*

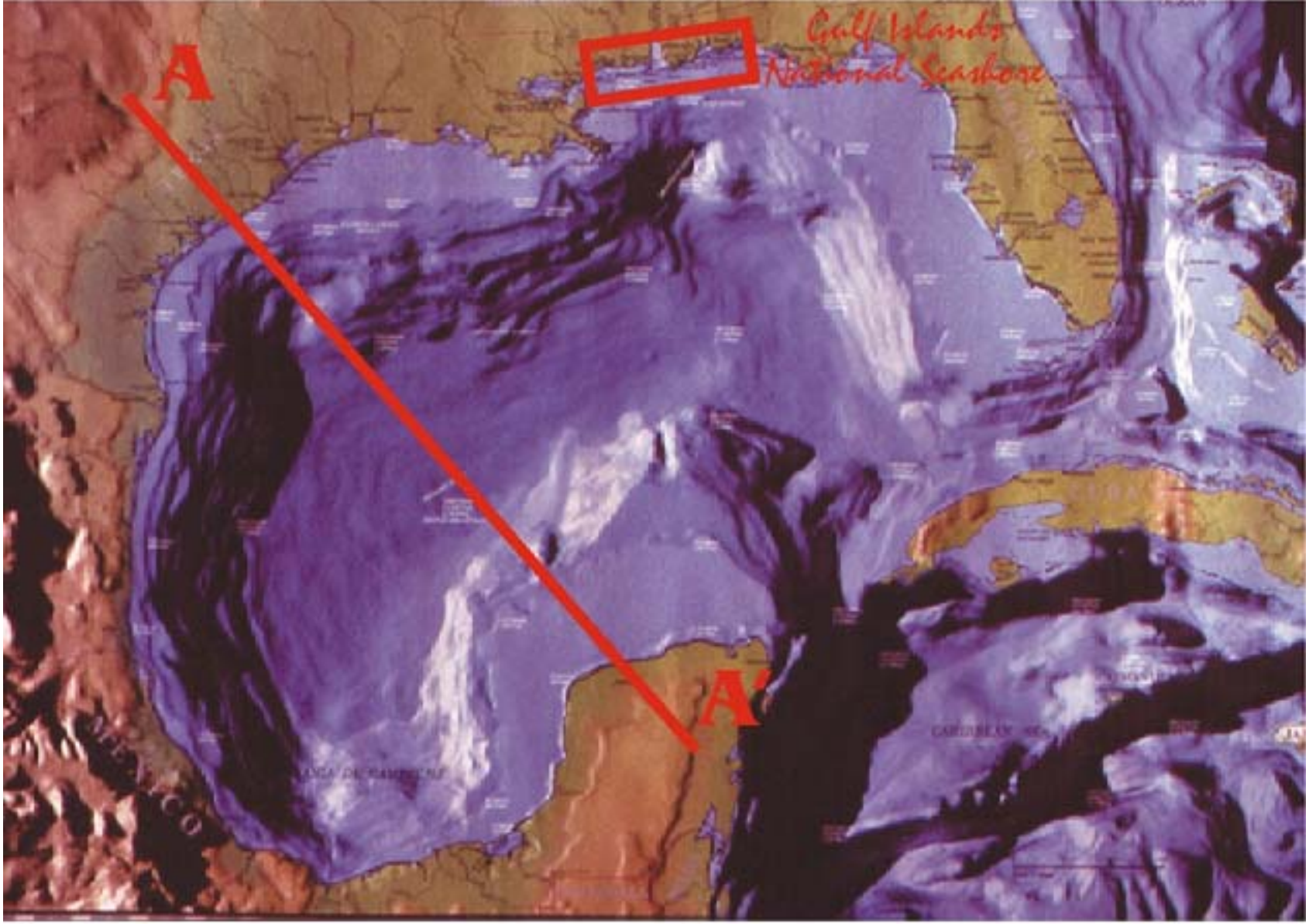


Fig. 19. ***Relief map of the seafloor of the Gulf of Mexico.*** *(From GLORIA seafloor images. Copyright 1995, FOTOFLITE / PORT Publishing Company). Note the broad continental shelves off western Florida and the Yucatan Peninsula. The only true oceanic crust lies in the western and central Gulf (Fig. 1). Gulf Islands National Seashore lies about 100 miles north of the shelf edge. Deep canyons cut into the edge of the shelf when sea level was much lower (Figs. 28, 29). Cross section A-A' is shown in Fig. 24.*

600 MILLION YEARS AGO (Iapetus Ocean Opens)

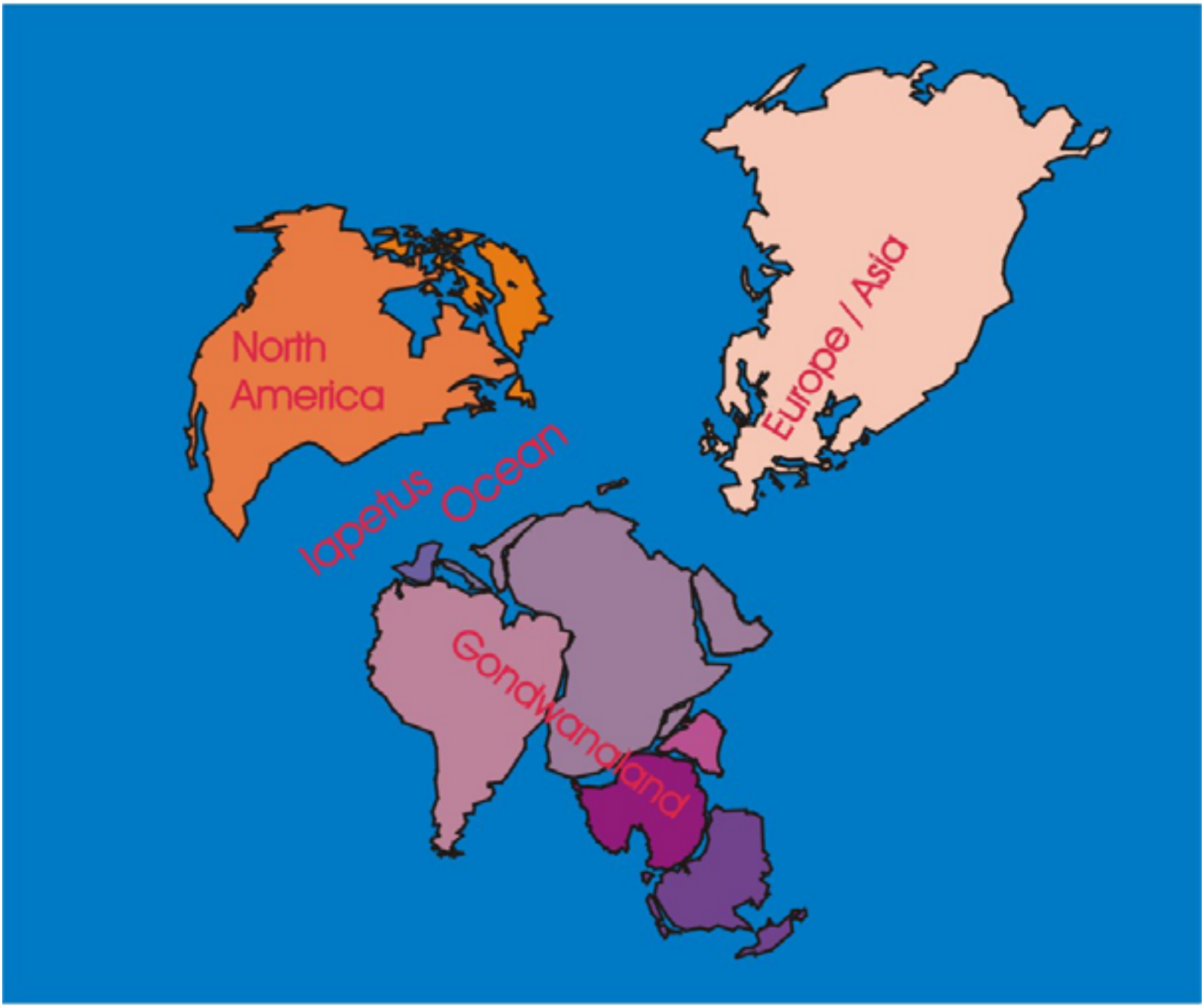


Fig. 20. ***Positions of continents after opening of the Iapetus Ocean.*** *Notice that the land that will later become Florida and the coastal plain of Georgia and the Carolinas is part of Africa. The Yucatan Peninsula and Cuba may have been on the northern side of South America.*

300 MILLION YEARS AGO
(Iapetus Ocean Closes)

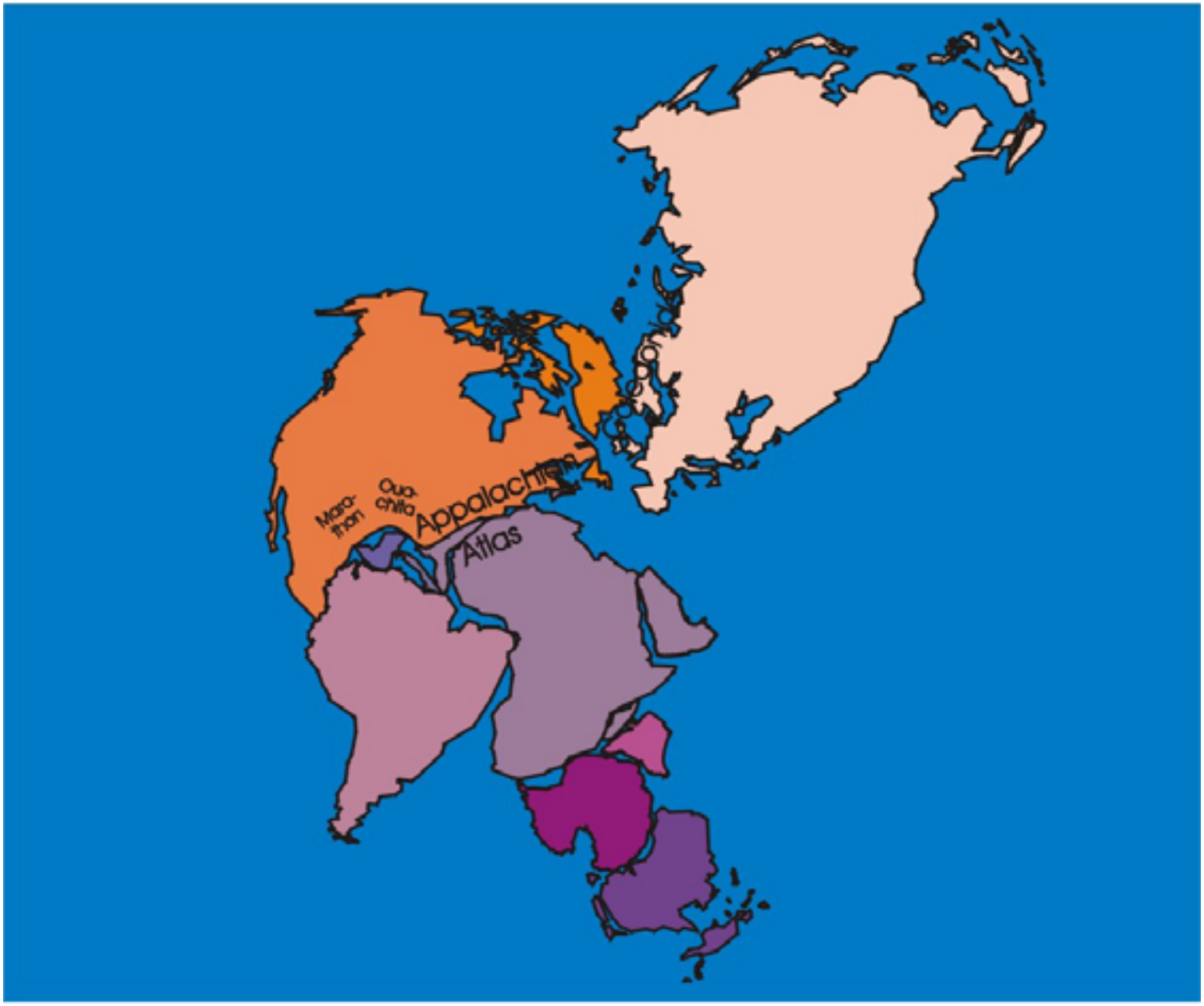


Fig. 21. ***Positions of continents after the closure of the Iapetus Ocean.*** *The supercontinent of Pangea (Fig. 10b) formed as the continents collided. The Appalachian Mountains are part of a much larger zone of continental collision that includes the Marathon and Ouachita Mountains in the southeastern United States, the Atlas Mountains in Africa, and the Caledonide Mountains in Greenland, the British Isles, and Scandanavia. Crustal blocks that later became the Yucatan Peninsula and Cuba lie between North and South America.*

TODAY
(Atlantic Ocean and Gulf of Mexico Open)

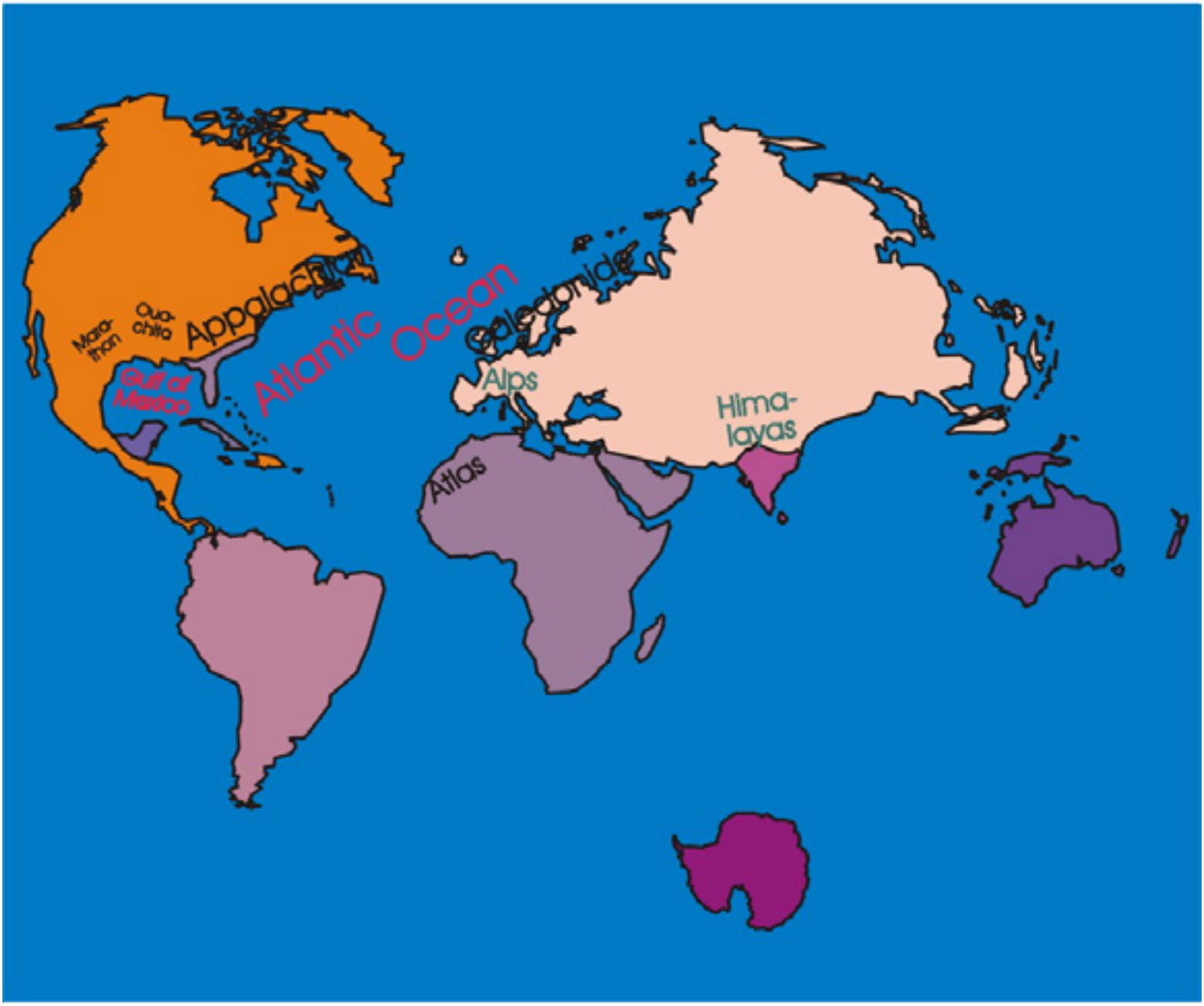


Fig. 22. ***Positions of continents today.*** *When the Atlantic Ocean opened, fragments of the collision zone were left on three different continents: the Appalachians in North America, the Atlas in Africa, and the Caledonides in Europe. Another continental collision is occurring today, where Africa and India ram into Europe and Asia, forming the chain of mountains from the Alps to the Himalayas. The Gulf of Mexico opened as the Yucatan Peninsula, Cuba, and South America ripped away from North America. The Gulf ceased opening when tectonic activity shifted to the Caribbean region, as South America continued drifting southward. Much of Central America and the Caribbean Islands formed from recent volcanic activity.*

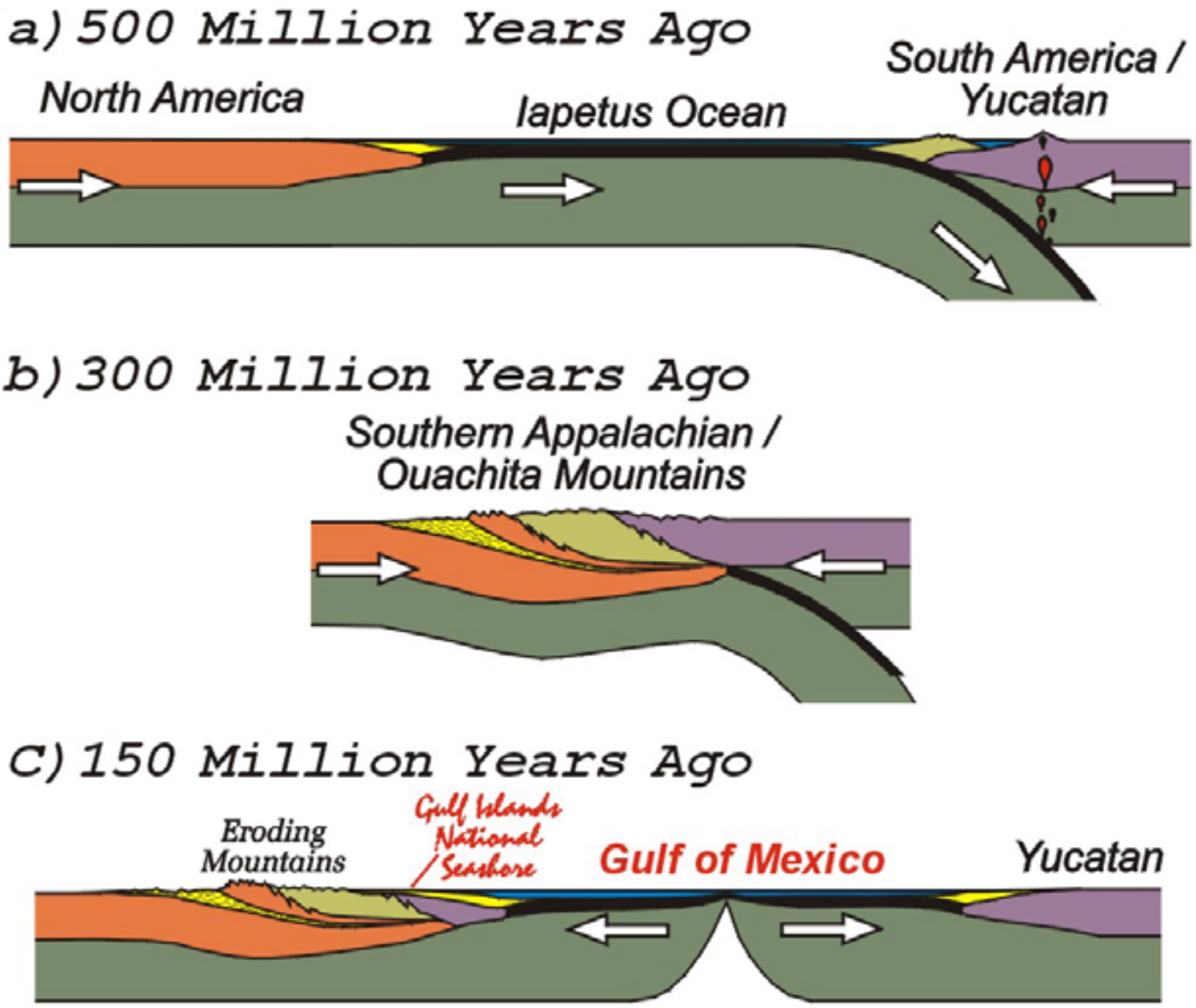


Fig. 23. **Plate tectonic evolution of the Southern Appalachian - Ouachita Mountain Chain and the Gulf of Mexico**. *a) Iapetus Ocean between North and South America (Fig 20) begins to close about 500 million years ago. b) The Southern Appalachian and Ouachita mountains form as the Iapetus ocean completely closes and South America (along with Africa and the rest of Gondwanaland) crashes into North America about 300 million years ago (Fig. 21). c) The Gulf of Mexico opens, leaving pieces of Gondwanaland behind. Opening of the Gulf ceased after only a small amount of oceanic crust developed (Fig. 1); South America then moved away from the Yucatan (Fig. 22).*

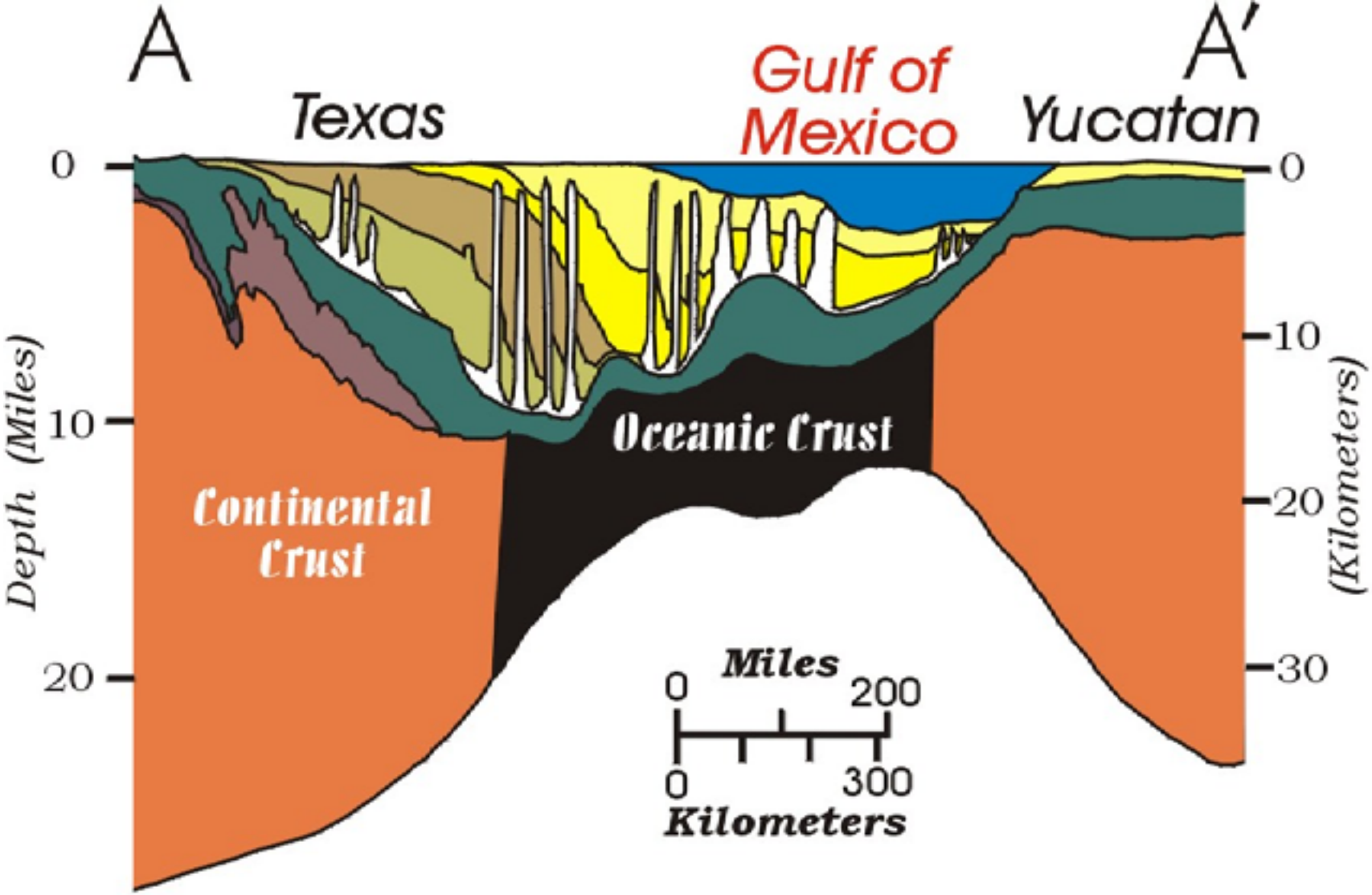


Fig. 24. **Crustal-scale cross section of the Gulf of Mexico**. *(A-A' in Figs. 1 and 19; modified from Walper and others, 1979). Note that only the very central part of the Gulf has oceanic crust (Fig. 1). The northern Gulf of Mexico is underlain by continental crust that was thinned during rifting (Figs. 15, 17). The thin crust is covered with up to 10 miles (16 kilometers) of sedimentary strata. In Florida and Mississippi, Gulf Islands National Seashore lies on top of the thick pile of sediment. The layer of salt (white) was deposited when the Gulf was narrow and water circulation restricted; it later formed salt domes that penetrated the overlying sedimentary layers.*

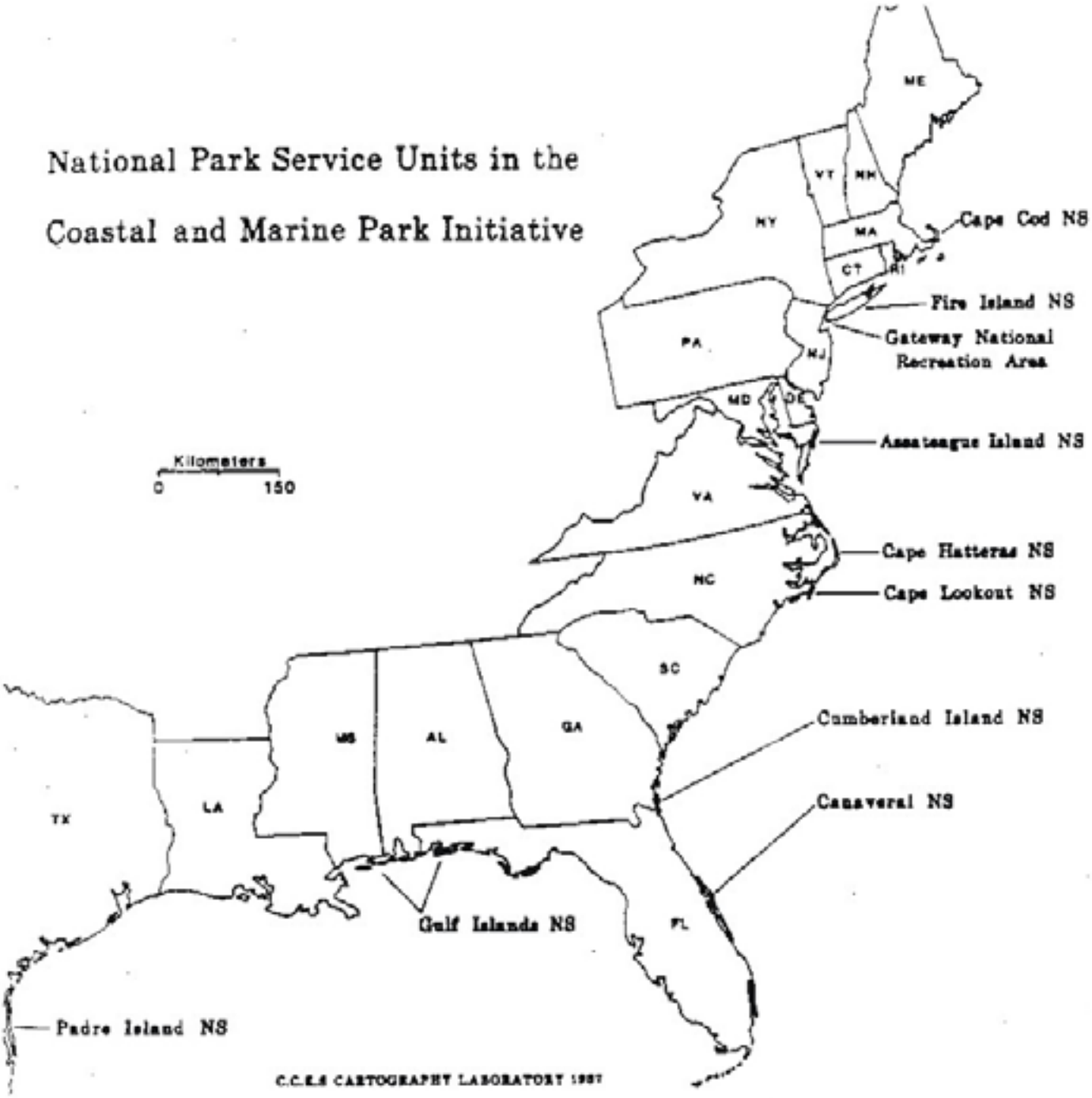


Fig. 25. ***Nine National Seashores on the Atlantic Ocean and Gulf of Mexico.*** *The coastlines and barrier islands lie on the very gently-sloping surface of the coastal plain and continental shelf (Fig. 18c), and are thus sensitive to changes in sea level, subsidence, and sediment supply.*

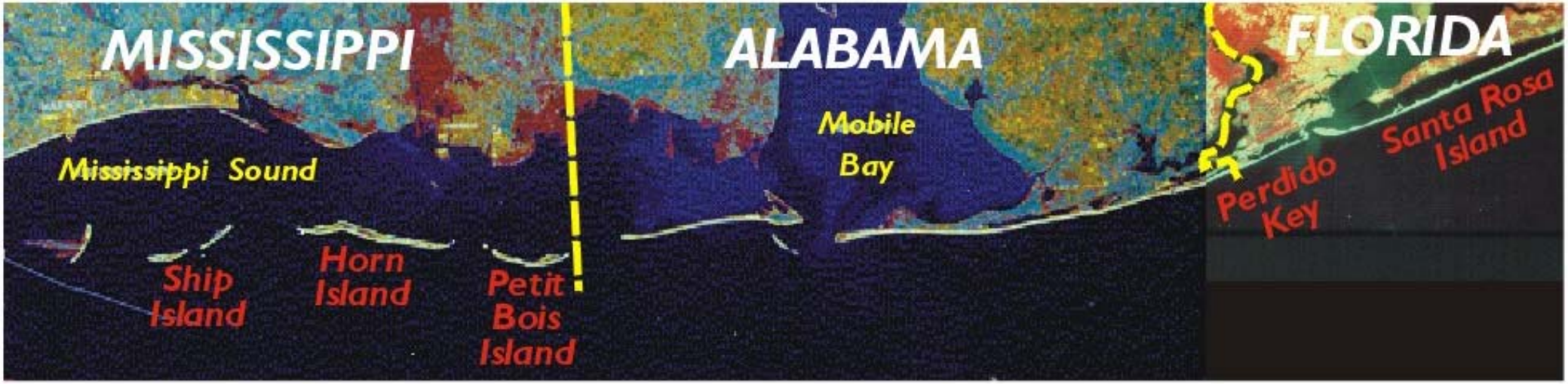


Fig. 26. ***Landsat image of Gulf Islands National Seashore***. *The Seashore includes all of the islands in Mississippi labeled in red, parts of those labeled in Florida, and coastal areas onshore in both states.*

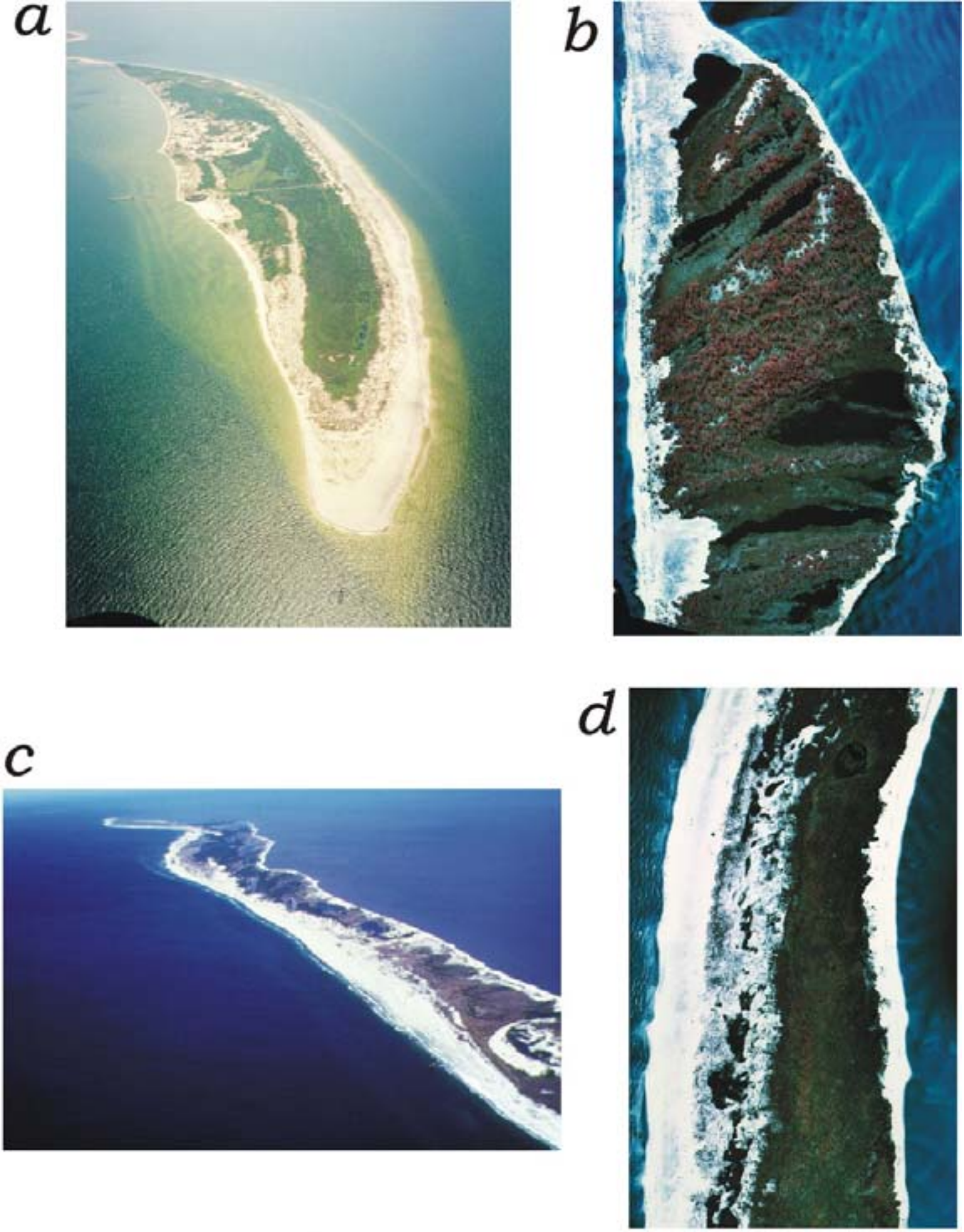


Fig. 27. ***Areal Photographs of barrier islands in Gulf Islands National Seashore, showing startling contrast between white sand and blue sea.*** *(Photos by Mike Hobbs??) a) West Ship Island. B) East Ship Island. c) Horn Island. d) Petit Bois Island.*

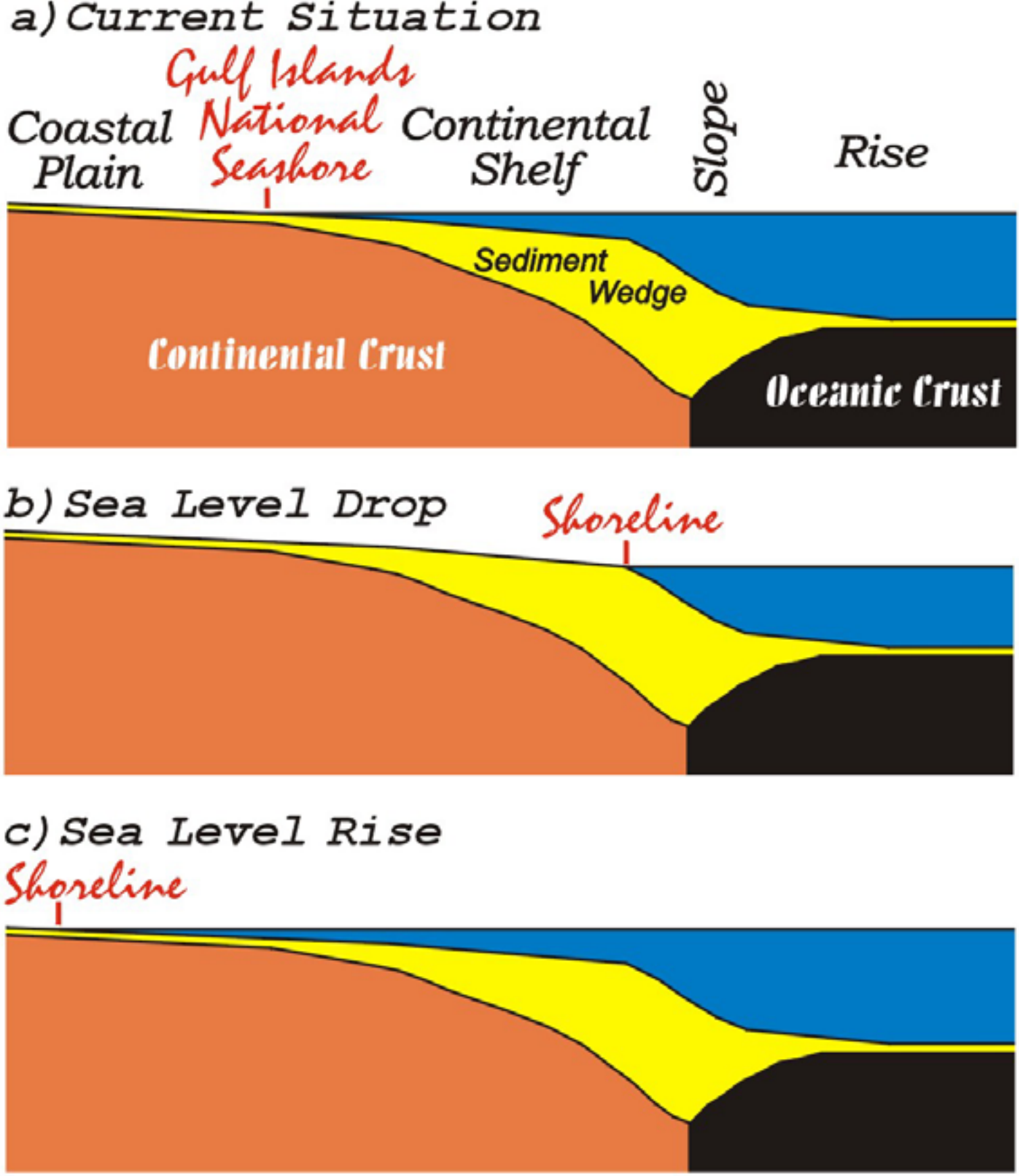


Fig. 28. ***Migration of coastline as sea level changes along passive continental margin.*** *The surface of the coastal plain and continental shelf tilts seaward at only about 3 feet per mile (0.6 meters per kilometer), or 0.3 degrees. a) A thin layer of water covers the continental shelf, so that Gulf Islands National Seashore lies about 100 miles (160 kilometers) landward of the edge of the continental shelf. b) When Earth's atmosphere is cold a lot of water is concentrated in the polar icecaps, causing sea level to drop. The shoreline and barrier islands along the Atlantic and Gulf of Mexico would then be near the edge of the continental shelf (Fig. 29). c) Warmer temperatures cause melting of the icecaps and a rise in sea level. Coastlines migrate inland as coastal plains flood.*

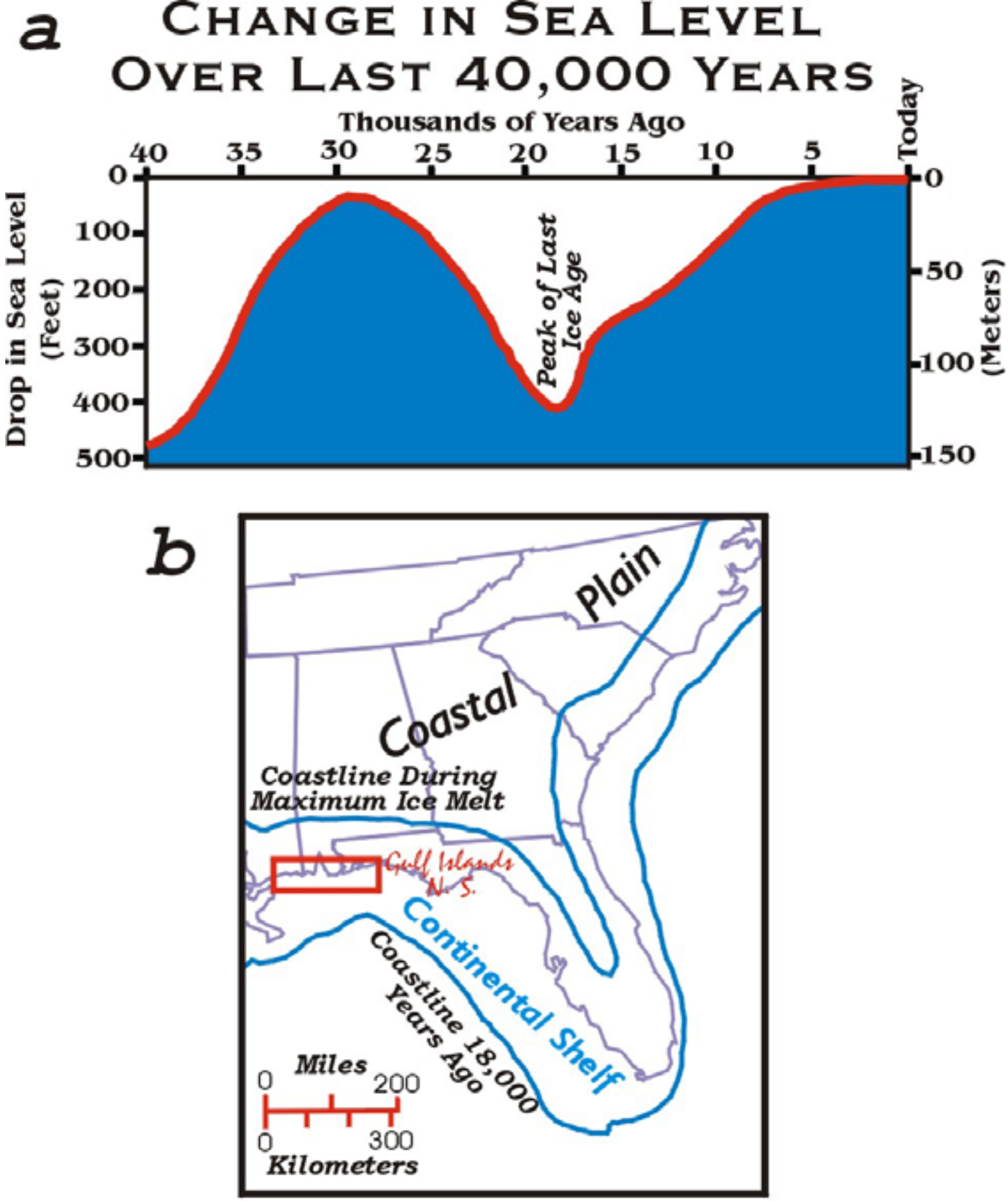


Fig. 29. **The position of the coastline is sensitive to changes in sea level.** *a) Sea level has been more than 400 feet (120 meters) lower than its present position twice in the past 40,000 years. (From Stone, 1981; after Curray, 1965). b) During the peak of the last ice age, about 18,000 years ago, the coastline was near the edge of the continental shelf (Fig. 28b). At other times during the past 5 million years, sea level was higher than today, so than areas of the coastal plain were flooded (Fig. 28c). (From Schmidt, 1997; after Williams and others, 1990).*

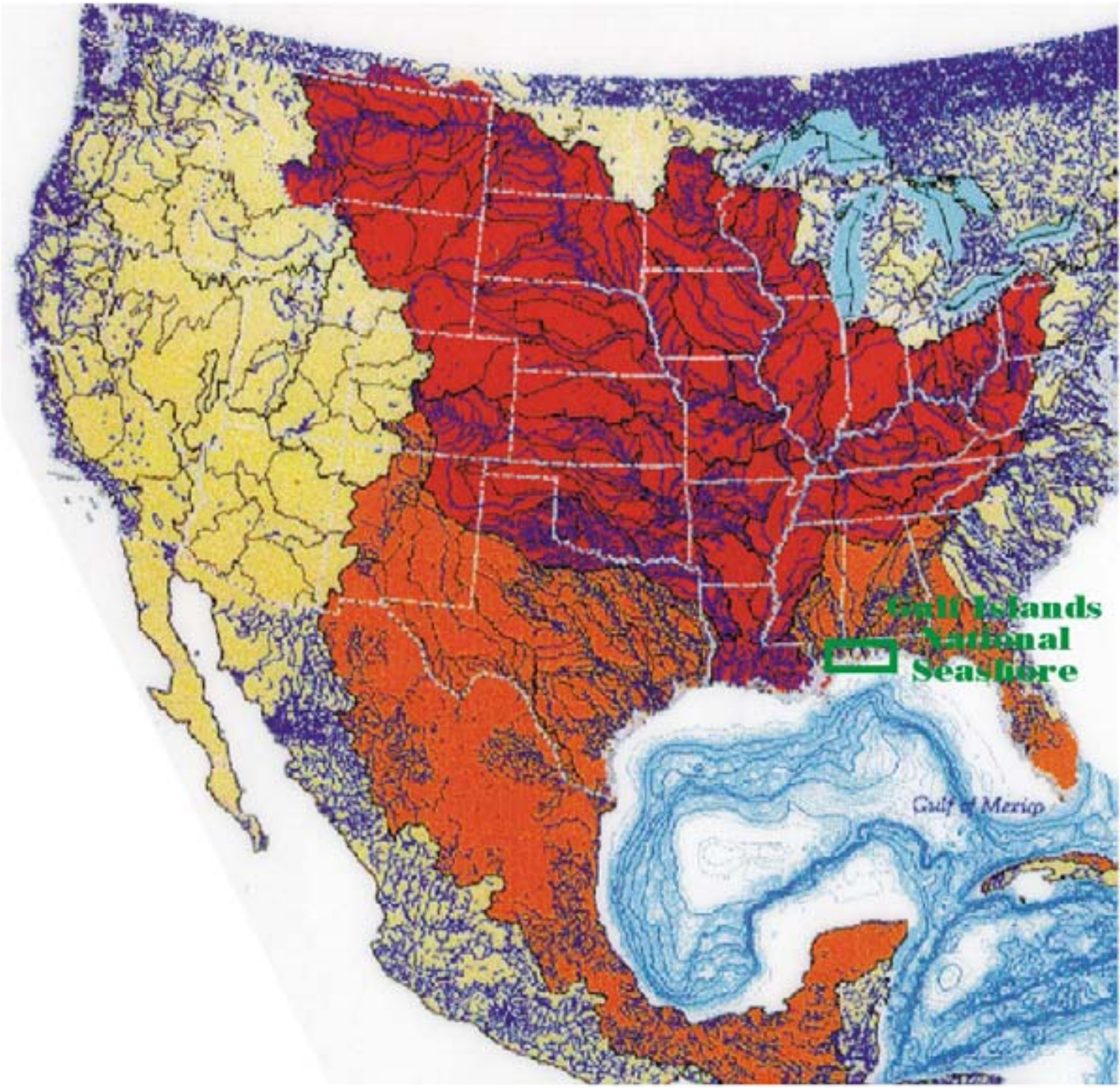


Fig. 30. **Drainage into the Gulf of Mexico**. *(From data compiled by U. S. Environmental Protection Agency, Water Quality Division, Dallas, Texas). Orange region on right: The eastern Gulf has a small drainage area, so that sedimentary particles that reach most of Gulf Islands National Seashore are from erosion of a small part of the Southern Appalachian Mountains (Fig. 31a). Red region: The coasts of Louisiana and east Texas receive a lot of mud from erosion and drainage of a large portion of the North American continent by the Mississippi River system.*

a

b

Fig. 31. ***Source and deposition areas for the white sands of Gulf Islands National Seashore***. *a) The sedimentary particles originate from the erosion of rocks in the Southern Appalachian Mountains. (Grandfather Mountain region along the Blue Ridge Parkway, North Carolina). b) Clear grains of quartz survive the journey to the Gulf of Mexico and are deposited as the white sand beaches. (Fort Pickins area, Santa Rosa Island, Florida). Photos by R. J. Lillie.*