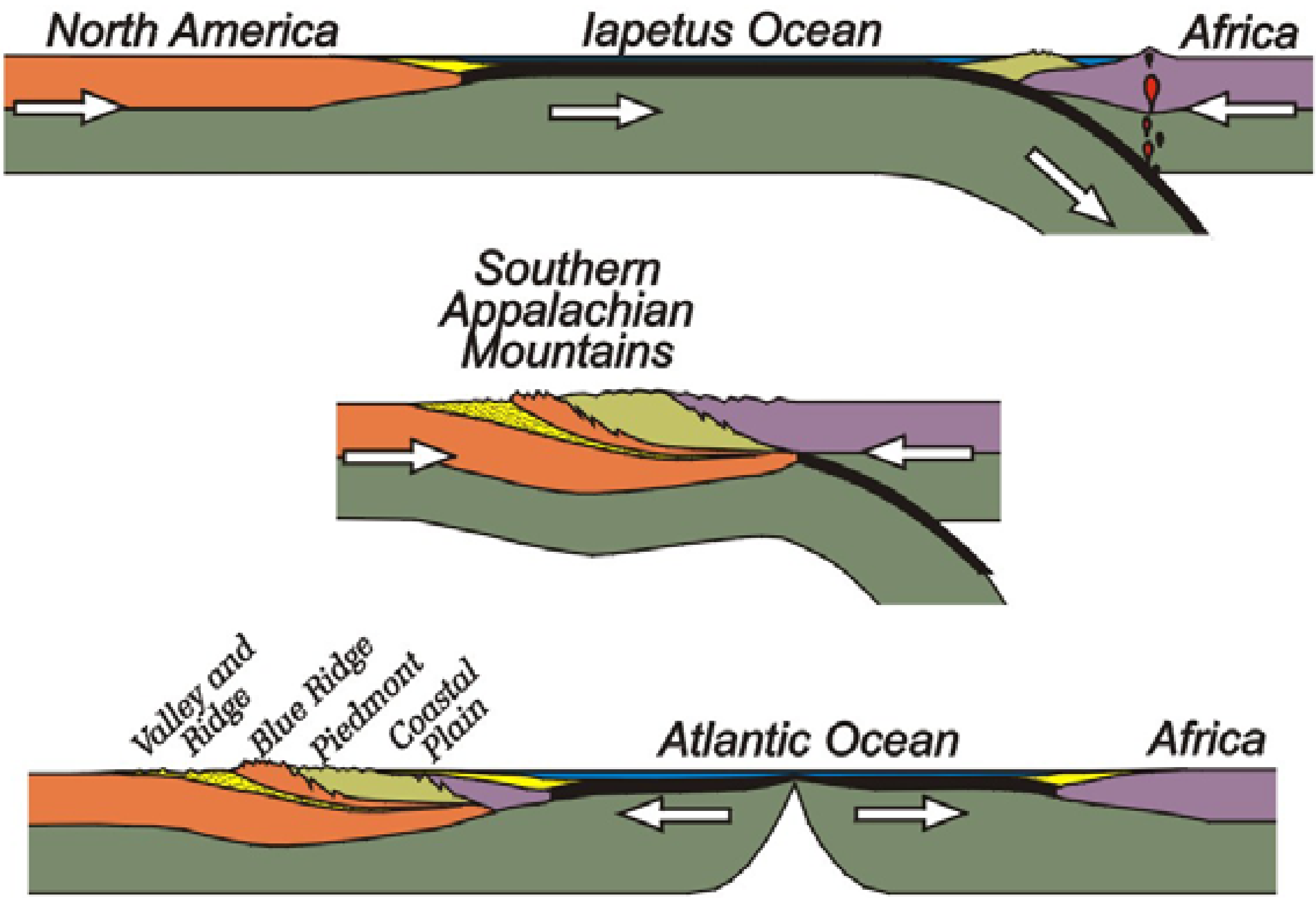
BLUE RIDGE PARKWAY

Geology Training Manual

(Plate Tectonics and the Grandfather Mountain - Linville Falls Region)



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PREFACE

This manual is an overview of concepts important to understanding the geology of a portion of the Blue Ridge Parkway. 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 Southern Appalachian Mountains to park visitors.

The Blue Ridge Parkway is an exciting place to "seize the moment," to help visitors learn while they are relaxed, on vacation in a beautiful and fascinating place. There are few places on Earth where so many people can ascend to the crest of a mountain range formed by the collision of continents; no other where they can drive the length of the crest in their car! We can use viewpoints on the Parkway to explain to visitors how the Appalachians formed, how the Blue Ridge evolved during the uplift and erosion of the mountains, and how the mountains affect the people and plants of the region.

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INTRODUCTION

WHY MAKE A BIG DEAL ABOUT GEOLOGY?

Geology is the study of the Earth. It incorporates more than just the identification of a bunch of rocks. Geology involves the study of processes occurring on or within the Earth that make the Earth come alive. Processes within the Earth include those responsible for ***earthquakes***, ***volcanoes***, the ***metamorphism of rocks***, and the ***formation of mountains***. The actions of wind, water, and ice occur at Earth's surface, resulting in ***erosion***, ***exposure of older rocks***, and ***deposition of sedimentary strata***. Park rangers can observe features at Earth's surface and explain them to the public in terms of Earth's internal and external processes.

The ***Blue Ridge*** is an old piece of the North American continent that broke off and was pushed westward over younger rocks when Africa came crashing in about 300 million years ago. The Parkway lies entirely on the surface of the Blue Ridge, but near other provinces related to the formation of the Southern Appalachian Mountains. From viewpoints along the parkway, rangers can explain the surrounding landscape in terms of the continental collision that formed the Appalachians. With this background, it is easier to understand the types of rocks and geologic structures found along the Parkway, and to incorporate them into programs on the natural history of the region.

PRESENTING BLUE RIDGE GEOLOGY TO PARK VISITORS

Background in three areas of Geology is important to appreciate the Blue Ridge Parkway: tectonics, petrology, and geologic structures. ***Tectonics*** is the study of large features on Earth's surface and processes within the Earth that resulted in their formation. A modern view of tectonics is that Earth's outer shell is rigid and is broken into large plates that move about relative to each other (hence, ***plate tectonics***).

The other two areas of geology relate to interactions along the boundaries of moving plates. ***Petrology*** is the study of rocks and the processes that form them. Plate boundaries are generally where: 1) heating or decompression generates magma that forms igneous rocks; 2) erosion and deposition result in sedimentary rocks; and 3) increases in temperature and pressure cause existing rocks to re-crystallize as metamorphic rocks. ***Geologic structures***, like the breaking of rocks along faults or buckling into folds, commonly occur where rocks are subjected to huge forces along plate boundaries.

What to Present?

The geology of the Blue Ridge Parkway lends itself to presentations on two different scales. From overlooks one can stand atop the Blue Ridge and see the Piedmont to the east and the Valley and Ridge to the west. These features originate from processes that occurred on a very large scale, the scale of plate tectonics. ***On a clear day, park rangers can have visitors gaze far to the east and imagine Africa rafting in as the ancient Iapetus Ocean closed***; the resulting collision folded strata of the Valley and Ridge, uplifted the Blue Ridge, and squeezed in earlier ocean material (the Piedmont).

On a more local scale, visitors can examine rocks and geologic structures that formed due to plate tectonic interactions. In the Grandfather Mountain area, all three types of rocks occur: sedimentary and igneous rocks formed along the ancient continental margin when Iapetus opened half a billion years ago; metamorphic rocks developed as Iapetus closed and the continents collided. At Linville Falls visitors can see various types of geologic structures, including a fault where older rocks were thrust over younger ones, folds in the rock layers, and vertical cracks ("joints") along which eroding rocks break away and fall into the gorge.

A guide to the geology observed along the southern portion of the Blue Ridge Parkway has recently been published by the North Carolina Geological Survey and will be available at Parkway visitor centers (***A Geologic Adventure along the Blue Ridge Parkway in North Carolina***, by Mark Carter, Carl Merschat, and Bill Wilson). It explains geology observed from overlooks and at rock outcroppings, all keyed to Parkway mileage markers. Rather than duplicate that material, this training manual provides the "big picture" of geology (plate tectonics) that can help rangers explain detailed observations of rocks and structures found in the road guide.

Ten Questions about the Blue Ridge

The type of questions one is able to ask can often 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 Blue Ridge and the two local areas covered in this manual. The purpose of the 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 given here constitute the rest of the manual.

Large Scale

1. ***How did the Appalachians form?***

   About 300 million years ago an ancient ocean closed and Africa crashed into North America.

2. ***How high were the Southern Appalachians at the time of collision?***

   They were probably at least as high as the Alps and maybe even the Himalayas; these are mountain ranges where continents are currently colliding.

3. ***Why were the Southern Appalachians so high?***

   As the ocean closed the edge of the North American continent was pushed beneath the colliding continent, like northern India extending beneath Asia today. Continental crust is thick and buoyant like a beach ball. A broad region, similar to the Himalayas and Tibetan Plateau, was therefore uplifted.

4. ***After 300 million years of erosion, why is there still an Appalachian mountain range?***

   Even after that amount of time the crust is somewhat thicker than the crust of surrounding regions. Like an iceberg sticking out of water, thick crust rises up higher out of the mantle than thin crust.

5. ***How deep were the rocks that are now exposed at the surface in the Blue Ridge?***

   The deeper you go into the Earth the higher the temperature and pressure. Some of the rocks of the Blue Ridge are metamorphosed to such a degree that they must have been about 5 to 15 miles (10 to 25 kilometers) below the surface.

6. ***Where did the geologic provinces that now comprise the Southern Appalachians originate?***

The Piedmont is sediments, crust, and islands formed in the ancient ocean between North America and Africa. The Blue Ridge is hard crust and sedimentary and volcanic strata deposited along the ancient continental margin of North America. Rocks of both the Piedmont and Blue Ridge were metamorphosed as the ocean closed and the continents collided. The Valley and Ridge is sedimentary strata of the continental margin that were folded, faulted, and shoved westward during the collision.

Local Scale

7. ***Where did rocks around Grandfather Mountain and Linville Falls originate?***

The oldest are rocks that were metamorphosed during an ancient mountain building episode over a billion years ago. They were overlain by sedimentary and volcanic strata deposited in fault-bounded valleys as the ancient continent rifted apart about 650 million years ago. As the ancient ocean opened, slightly younger sediments deposited along the continental margin overlay these rocks.

8. ***What happened to these rocks when the continents collided?***

Older rocks were thrust over them, so that they were buried within the Earth and metamorphosed. The metamorphism was generally not too severe; sedimentary grains and layering are still apparent.

9. ***Why do we see these rocks exposed at the surface today?***

As the topography eroded, weight was taken off the thick, buoyant crust. It thus continued to rise, eroding away a hole (or “window”) through the older rocks.

10. ***Why are the walls of Linville Gorge so steep and straight?***

Pressure was released as rock overlying the metamorphosed sandstones eroded away. During uplift the decompressed sandstones expanded, forming tiny vertical cracks, called joints. As water seeps into the cracks and freezes it expands, prying the rock apart; slabs of rocks thus break off along the vertical joints.

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 general geology background of Park Service interpreters. It is hoped that the information will enable interpreters to design their own programs on the tectonic history, rocks, and structures observed along the Blue Ridge Parkway. 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.

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, at overlooks, 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 in the Appalachians: ***practically everything is covered with trees or some other type of vegetation!*** Rock outcroppings may be considerably weathered, covered with rust, lichens, and other material, to the extent that rocks all appear the same. On national parkland, you can't simply take out a rock hammer and wack off a fresh piece! A suggestion would be to take along rock samples with fresh faces exposed, to show visitors during the program. Similarly, plate tectonic theory is background information critical to understanding how and where various types of landscapes form, but trees obscure those landscapes. But plate tectonic concepts can be worked into programs if visuals, like those developed in this manual, are used at scenic overlooks.

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 Parkway and a few specific observations along the Parkway, 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.

TECTONIC EVOLUTION OF THE SOUTHERN APPALACHIANS

Earth scientists had just discovered something fascinating about the continent Patty Keene was standing on, incidentally. It was riding on a slab about forty miles thick, and the slab was drifting around on molten glurp. And all the other continents had slabs of their own. When one slab crashed into another one, mountains were made. (Breakfast of Champions by Kurt Vonnegut, Jr., © 1973, Delacorte Press).

The Southern Appalachian Mountains result from the collision of continents. In their prime they were probably as high as mountains in the current zone of continental collision stretching from the Himalayas to the Alps. But in the 300 million years since the Appalachians formed, the Atlantic Ocean opened and the mountains eroded down considerably (Fig. 1).

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. 2). 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. 3). The sutured continents later ripped apart, opening the Atlantic (Fig. 4). 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).

APPALACHIAN – OUACHITA - MARATHON MOUNTAIN BELT

The mythological metaphor is a vivid representation of the events that shaped the Appalachian Mountains and adjacent coastal plain. In reality, the story is far more complex and the mountain range 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. 4). 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 (Fig. 4). 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. 3). The highest mountain in the Appalachians today is Mt. Mitchell, lying just off the Blue Ridge Parkway and rising 6,684 feet (2,037 meters) above sea level. But in its prime, the Blue Ridge may have had peaks as high as Mt. Everest.

The Appalachian story is one of continents ripping apart, then crashing together as whole oceans open and close. 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 rocks and structures found along the Blue Ridge Parkway.

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. 5). 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. 6). 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 volcanism are associated with each type of plate boundary and with hotspots.

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.

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 6300 kilometers (3900 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 refrigerator), 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. 6).

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 kilometers (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. The effects of the buoyancy difference between the two types of crust can be envisioned by considering a tennis ball and a soccer ball in a swimming pool (Fig. 10). 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; areas underlain by thick continental crust likewise stand above sea level, while those with thin oceanic crust sag below. 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; lithosphere with thin oceanic crust is readily consumed (subducted) when plates converge, while buoyant continental crustal blocks collide rather than subduct.

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. 11). The configuration of 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 (Figs. 2-4).

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 a vast new amount of 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. 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 (Fig. 12).

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. 13). 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 instead passive "passengers" at the tops of plates comprised mostly of stiff mantle (lithosphere). The plates move about on the softer mantle beneath (asthenosphere, Fig. 8). The observations of narrow zones of earthquakes and their depths provides clues to the distribution of deforming, brittle material, and thus outline the lithospheric plate boundaries (Figs. 5, 6).

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. 14). 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. 14a); and 2) hot material that was solid because of enormous pressure rises and decompresses (Fig. 14b,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 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.

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. 15a), form on the overriding plate where one plate "subducts" beneath another (Fig. 14a). 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. 12). Plate divergence produces vast amounts of volcanic material (Fig. 14b), creating interlocking volcanoes that form long, submerged mountain chains like the Mid-Atlantic Ridge (Fig. 15b). The Hawaiian Islands and their sub-sea extension, the Emperor Seamount Chain (Fig. 15c), are a classic example of mountains developed over a hotspot (Fig. 14c).

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. 6), stresses buckle the rocks into folds or break them along faults, creating topography like the Valley and Ridge Province (Fig. 16a). The second way is less obvious but can have dramatic results. The highest region on Earth, the Himalayas and Tibetan Plateau (Fig. 16b), was created not so much by folding and faulting, but by the thick, buoyant crust of India sliding underneath (Fig. 10c). (Imagine the swimmer in Fig. 10b 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 (Fig. 9), 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.

GEOLOGIC STRUCTURES

Two types of geologic structures, folds and faults, are important components in the development of a collisional mountain range like the Southern Appalachians. In addition, as the mountains eroded and the pressure released on the rocks below, small cracks called joints developed. At Linville Falls, eroding rocks break in slabs along the joints, creating the spectacular vertical walls of the gorge.

Folds

A ***fold*** is the bending of rock layers along a recognizable pattern. Folding can occur where rocks are cold and brittle, accompanied by cracks and small faults that allow the rock to bend. Folds also form in hot, ductile rock, as the rock flows and bends instead of cracking.

The type of fold can be described by envisioning the layers of rock before and after folding (Fig.17). In a normal sequence of rocks, the oldest layers are at the bottom, the youngest on top. An ***anticline*** is where the layers are folded upward; after some surface erosion, the older layers are at the center of the anticline, the younger ones toward the flanks (Fig. 17a). Where rock is bent downward, at a ***syncline***, the younger layers appear at the center (Fig. 17b). As Africa came crashing in 300 million years ago, it buckled the sedimentary layers of the Valley and Ridge Province into a series of anticlines and synclines (Fig. 17c). In many places the Appalachian rocks are folded in a more complex fashion, so that the anticlines and synclines plunge into the ground (Fig. 17d). After erosion, the result is spectacular "V-shaped" patterns on the eroded surface (Fig. 16a).

Faults

A ***fault*** is a break between two blocks of rock, along which there is relative movement between the blocks. Faulting is ***brittle*** deformation of rock, occurring primarily in the cold, upper portion of the crust. The warmer, lower crust, like the asthenosphere, tends to fail in a ***ductile*** fashion, slowing flowing rather than breaking.

There are three main types of faults, described by how one fault block moves relative to the other (Fig. 18). In the 19th Century, coal miners in Pennsylvania recognized faults offsetting the strata along the walls of mine shafts. They described the type of fault motion by standing across the sloping fault surface. The block in back of their head they called the ***hanging wall***, at their feet the ***foot wall***. A fault where the hanging wall block moved downward, relative to the foot wall, was termed a ***normal fault*** (Fig. 18a). A ***reverse fault*** occurred where the hanging wall moved upward, relative to the foot wall (Fig. 18b). Later, the term ***strike-slip fault*** was applied to the situation where one block slid laterally past the other (Fig. 18c).

Normal, reverse, and strike-slip faults form due to specific kinds of stresses, which generally relate to the three types of plate boundaries. When a block of rock is subjected to ***tension***, as at divergent plate boundaries (Fig. 6a), it is pulled apart along normal faults. At convergent plate boundaries (Fig. 6c), where there is ***compression***, blocks are pushed (or thrust) over other blocks, forming reverse faults. Most of the faults in the Appalachians are a special kind of reverse fault, where the fault surface slopes at a low angle; they are thus called ***thrust faults*** (inset, Fig. 17b). There are ***shearing stresses*** concentrated along transform plate boundaries (Fig. 6b), so that faults are predominately strike-slip. While this simple pattern relating the kind of faulting to the type of plate boundary generally rings true, it should be noted that stress patterns are often complex; all three types of faults may be found in various places along a given plate boundary.

Joints

As the Appalachians were uplifted and pressure relieved, small cracks, called ***joints***, formed. The joints are vertical and form two perpendicular sets (Fig. 19a). The Linville Falls area is a spectacular place to observe joints. The Linville River follows joints, first one set then the other, flowing in a "zigzag" pattern (Fig. 19b). The lower falls flow over quartzite of the Chilhowee Formation, carving a deep gorge. The walls of the gorge are nearly vertical because erosion has removed slabs of rock along joints (Fig. 19c). Right-angle turns in the walls form because of the perpendicular joint sets.

ROCKS AND MINERALS

Virtually all the rocks found along the Blue Ridge Parkway are ***metamorphic***, one of the three basic kinds of rocks. They are rocks that formed previously through igneous and sedimentary processes, but were later "cooked" by heat and pressure within the Earth. Like earthquakes, volcanoes and mountain ranges, most rocks are products of the processes that occur at the boundaries of lithospheric plates.

Sometimes the terms "rock" and "mineral" are confused. A ***mineral*** is a substance that has the following properties. 1. It is a <u>naturally-occurring, inorganic solid</u>. 2. It has a <u>definite chemical composition</u> (or a specific range of compositions). 3. It has a <u>specific internal (crystalline) structure</u>. 4. It has <u>definite physical properties</u> that result from the chemical composition and crystalline structure of the mineral. For example, a common mineral found in rocks along the Blue Ridge Parkway is ***quartz***. It occurs naturally as clear white "veins" intruding rocks, as rounded grains in sandstone, or as interlocking crystals if the sandstone was metamorphosed to quartzite. Its chemical composition is SiO_2, meaning its molecules have two atoms of oxygen (O) for every one atom of silicon (Si). It forms long, six-sided crystals that come to a point. One of its physical properties is that it has a hardness of 7, meaning that it can scratch the mineral orthoclase (hardness 6), but not topaz (hardness 8).

A ***rock*** is an <u>aggregate of minerals</u>. Generally (but not always), it's a mixture of more than one kind of mineral. The mineral grains are held together as a rigid solid; either they become interlocked as they form, or the particles are cemented together in some natural way. For example, after sediment is deposited and buried, silicon and oxygen atoms can precipitate from groundwater, gluing grains of quartz and other minerals together as ***sandstone***.

The three general types of rocks relate to the manner in which the rock formed. An ***igneous rock*** is an aggregate of interlocking minerals, formed by the cooling and solidification of molten magma. A ***sedimentary rock*** is an aggregate of fragments eroded from older rocks, or minerals precipitated through chemical or biological activity. A ***metamorphic rock*** is an aggregate of interlocking minerals, formed by re-crystallization of some or all of the minerals in an existing rock. The re-crystallization occurs when the rock is subjected to elevated temperature or pressure, but while the rock is still in a solid state.

<u>Igneous Rocks</u>

Igneous rocks solidify from ***magma***, which is molten rock that may contain gasses and suspended solid material. When magma cools slowly below Earth's surface, large mineral crystals have time to form. Coarse-grained ***intrusive*** rocks thus result. (They are also called ***plutonic*** rocks, after *Pluto*, the Roman god of the underworld). The terms "magma" and "lava" are often used interchangeably, but have important differences. All melted Earth material is magma, while ***lava*** is magma that poured out on Earth's surface. Because it is in contact with the air, lava cools quickly, forming fine-grained, ***extrusive*** (or ***volcanic***) rocks. (***Volcanism*** refers to the fiery action at Earth's surface caused by the Roman god *Volcanus*).

Igneous rocks are classified according to two parameters, texture and chemistry. Texture refers to the ***size of the mineral grains***, which is a function of ***how quickly the magma cooled***. Intrusive rocks are coarse-grained because they cooled very slowly within the Earth, where mineral crystals had time to develop. Magma that encounters air or water at Earth's surface cooled very quickly, so that extrusive (volcanic) rocks have fine grains that you generally cannot see with your naked eye.

The ***chemistry*** of igneous rocks is commonly related to the ***amount of silica*** (silicon and oxygen) contained in the rock minerals. Silica is the same material that makes up window glass and, in its pure form, is the mineral quartz (SiO_2). Rocks with high silica content thus tend to be light-weight and light in color. Coarse-grained (intrusive) ***granite*** and fine-grained (extrusive) ***rhyolite*** are thus pink-to-white-colored igneous rocks that are high in silica (≈ 70% of the total rock mass). As the silica content goes down, minerals generally have higher percentages of heavier elements like iron and magnesium. With decreasing silica content, igneous rocks therefore tend to be heavier and darker. Intermediate-silica (≈ 60%) rocks are coarse-grained ***diorite*** and fine-grained **andesite** that are commonly gray in color. Low-silica (≈ 50%) igneous rocks tend to approach black in color, as intrusive ***gabbro*** and extrusive ***basalt***. When rock is very low in silica (< 40%) it has a lot of iron and magnesium, so that it forms the olive-green colored ***peridotite***, the very heavy, coarse-grained rock that makes up Earth's mantle. Crustal material isn't as heavy as mantle (Fig. 9) because crust has more silica and less iron and magnesium. Oceanic crust, made of gabbro and basalt, is somewhat heavier than continental crust, which has rocks closer to the composition of granite.

Most of the igneous rocks found along the Grandfather Mountain – Linville Falls corridor of the Parkway relate to continental rifting 700 million years ago that opened the Iapetus Ocean. The extrusive rocks are of both high-silica ***rhyolite*** and low-silica ***basalt*** composition, while intrusive rocks of varying compositions also occur. Some of the much older rocks are ***granites*** that were subjected to high temperatures and pressures, forming the metamorphic rock gneiss.

Sedimentary Rocks

Most sedimentary rocks form through the cycle of: 1. erosion, chemical, or biological activity that forms particles (sediment); 2. transportation of the sediment by water, wind, or ice; 3. deposition of the sediment in oceans, lakes, or streams; 4. compaction and cementation of the sedimentary particles as they are buried beneath more sediment.

Types of sedimentary rocks are best understood by imagining their environments of deposition. Gravel is found on the beds of fast-moving mountain streams. When buried and cemented, it forms the sedimentary rock ***conglomerate***. ***Sandstone*** is made of sand-size grains, mostly quartz, that were deposited in stream beds or on beaches. In lakes or deeper parts of the ocean, where water is quieter, finer particles of silt and mud accumulate. Burial, compaction, and cementation turns these materials into ***siltstone*** and ***shale***. The shell fragments of marine organisms dissolve in warm seawater, precipitating out as calcium carbonate. This fine lime mud eventually turns into the sedimentary rock ***limestone***.

The sedimentary rocks around Grandfather Mountain formed when an ancient continent (Laurentia) ripped apart about 700 million years ago. They are primarily conglomerates, sandstones, and shales deposited in lakes and streams within continental rift valleys. The Iapetus Ocean then opened, forming a broad continental shelf off the eastern edge of ancient North America. Sandstones around Linville Falls, as well as the dolomite (a rock similar to limestone) in Linville Caverns, were deposited on the subsiding shelf about 550 million years ago.

Metamorphic Rocks

A specific type of metamorphic rock results from the original ("parent") rock, the amounts of heat and pressure the rock endured, and the presence (or absence) of fluids within the rock. The classification of metamorphic rocks is therefore quite extensive and technical. Metamorphism, nonetheless, can be understood on a simple level if one imagines what happens to a specific parent rock as it is buried deeper and deeper within the Earth (that is, as it encounters increases in temperature and pressure). In fact, the Grandfather Mountain – Linville Falls areas are quite useful for that purpose. In those areas there are rocks that have been subjected to only low degrees of metamorphism so that the sedimentary grains and layering of the parent rocks are still evident, as well as older rocks that are so altered that the parent rocks cannot be determined.

Around Grandfather Mountain, a small amount of metamorphism has changed the conglomerate to ***metaconglomerate***. The sandstone has recognizable layers and mineral grains, so that it is ***metasandstone***. Where sandstone was almost pure quartz grains, as around Linville Falls, metamorphism altered the quartz to denser, interlocking crystals; the metamorphic rock is called ***quartzite***.

Shale shows a metamorphic progression that goes from ***slate***, to ***phyllite***, to ***schist*** , to ***gneiss*** ("nice") with increasing temperature and pressure. Shale metamorphism in the area has commonly progressed to phyllite. The older rock at Linville Falls is gneiss that has been metamorphosed to such a high degree you cannot tell what the parent rocks were. Other metamorphic rocks in the area include the igneous rocks basalt and rhyolite that have been slightly changed to ***metabasalt*** and ***metarhyolite,*** and limestone and dolomite that are now ***marble.***

THE SOUTHERN APPALACHIAN STORY

The tectonic history of the Southern Appalachian Mountains involves opening an ancient ocean along a divergent plate boundary (Fig. 2), closing the ocean through plate convergence (Fig. 3), followed by divergence that opened the Atlantic Ocean (Fig. 4). Tracing this large-scale development helps us understand the place of origin of the various geologic provinces of the Southern Appalachians, as well as the rocks and structures observed along the Blue Ridge Parkway. The discussion below illustrates that coastal Carolina was originally part of Africa, the Piedmont contains rocks formed in the Iapetus Ocean, the Blue Ridge is an uplifted part of North America's ancient continental margin, and the Valley and Ridge is sediments from the margin that were folded and faulted (Fig. 20). The Grandfather Mountain - Linville Falls corridor contains rocks of the ancient continental margin that were overridden by older rocks during the collision, then metamorphosed and pushed upward as the overlying rocks eroded away.

LAURENTIA

Long before the Appalachians were around, deep rocks of the region were part of an old continent, but it was nothing like the North America we know today. About 1.1 billion (1,100 million) years ago, a very ancient ocean closed. The old continent collided with another, forming a supercontinent known as ***Laurentia***. This mountain building, know as the Grenville Orogeny, deformed and metamorphosed rocks that are now buried beneath younger layers in the Valley and Ridge Province, and exposed at the surface in the Blue.

CONTINENTAL RIFTING AND THE OPENING OF THE IAPETUS OCEAN

Ancient North America did not extend nearly as far east as it does today (Fig. 2). In fact, the Appalachian Mountains are roughly in the position of the earlier continental margin. Rocks to the east of the Blue Ridge formed within the Iapetus Ocean, or were part of Africa (Figs. 1, 3).

About 750 million years ago the supercontinent Laurentia began to rip apart. As a continent pulls apart it stretches, thinning the crust and entire lithosphere (Fig.21a). The resulting ***continental rift zone*** 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 elevated mountain ranges, separated by down-dropped valleys. The rift valleys fill with up to 5 miles (8 kilometers) of sedimentary and volcanic strata as they subside.

If a continent completely rips apart, the two fragments can drift away as parts of different lithospheric plates (Fig. 21b). 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. 21c). The plate boundary is then at the mid-ocean ridge, far from the margins separating continental from oceanic crust; such margins are termed ***passive continental margins***.

Fig. 22 shows different stages of divergent plate margin development in the region of northeast Africa and Saudi Arabia. Active continental rifting (Fig 21a) is occurring in East Africa. Many of the rift valleys have lakes because the valley floors are dropping faster than sediments 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 (2^{nd} deepest; 4708 feet, 1435 meters), Lake Malawi in East Africa (4^{th} deepest; 2316 feet, 706 meters), Issyk Kul in central Asia (5^{th} deepest; 2297 feet, 700 meters), and Lake Tahoe in the Basin and Range Province (8^{th} deepest; 1685 feet; 514 meters). The Red Sea is an early-stage ocean basin (Fig. 21b), with passive continental margins bordering Africa and Saudi Arabia and a mid-ocean ridge down the center. The Gulf of Aden is more advanced (Fig 21c), including a mid-ocean ridge that extends into the Indian Ocean.

Have visitors imagine the Grandfather Mountain area 700 million years ago. The region was in the zone where Laurentia was ripping apart***. Like East Africa (Fig. 22), rift valleys subsided and were filled with sand, mud, and gravel deposited in rivers and lakes.*** At times volcanoes erupted, so that the sedimentary deposits were inter-stratified with lava flows. Some of the erupting material solidified before reaching the surface as intrusive dikes. The sequence of rocks known as the ***Grandfather Mountain Formation*** is the remnants of these rift-valley deposits, after they were deformed and metamorphosed during the later continental collision (Fig. 23). The bulk of the Grandfather Mountain Formation is coarse ***sandstone***, but in places it contains pebbles, hence it is a ***conglomerate***. Inter-layered volcanic flows include light-colored, high-silica ***rhyolite***, as well as dark, low-silica ***basalt***.

After an ocean completely opens, the region subsides, developing a continental shelf, slope, and rise (Fig. 24). Beneath the shallow water of the shelf, sedimentary layers, such as ***sandstone*** of the ***Chilhowee Formation*** at Linville Falls, cover the older rift valleys and their sedimentary and volcanic deposits. Farther out to sea, in much deeper water, the continental slope and rise are covered by mud. The ***Ashe Formation***, exposed along a much of the Parkway south of Linville Falls, results from such mud that was first turned into ***shale***, then metamorphosed to phyllite and schist during subduction and continental collision.

CLOSING OF IAPETUS AND CONTINENTAL COLLISION (PANGEA)

Where lithospheric plates converge, the plate with thinner, less buoyant crust commonly descends beneath the other plate. The region where a lithospheric plate descends deeply within the mantle is called a ***subduction zone*** (Fig. 25). Two chains of mountains, one structural and one volcanic, form parallel to the ***deep-sea trench*** at the surface juncture of the plates. Just landward of the trench, where the top of the plate is shallow and cold, some of the sediments and underlying rock are scraped off and deformed into a wedge-shape. These materials attach (or "accrete") to the overriding plate; portions of this ***accretionary wedge*** may rise above sea level as the sediments and rock are compressed, folded, and faulted, forming long ridges and valleys.

Farther from the trench the top of the descending plate may reach depths of 60 to 100 miles (100 to 150 km), where it is so hot that fluids are driven from its crust. The fluids rise, melting silicate minerals from the mantle and crust of the overriding plate. Magma that makes it to the surface erupts as a (straight or curved) chain of volcanoes, at sea called an ***island arc*** (Fig. 25a), on land a ***volcanic arc*** (Fig. 25b). The Andes Mountains in South America and the Cascade Mountains in the Pacific Northwest (Fig. 15a) are active volcanic arcs erupting above subduction zones.

From about 500 to 300 million years ago the Iapetus Ocean gradually closed through subduction (Fig. 20a,b). In the process island arcs, continental fragments, and finally the African continent, collided with the ancient continental margin of North America. ***Pangea*** is the name for the huge continent that resulted (Fig. 11b). In the western part of the Appalachians, the rocks were originally part of North America. The ***Valley and Ridge Province*** is thus folded and faulted sedimentary strata of the continental margin, while the ***Blue Ridge*** is a piece of the deeper, hard crust that was uplifted and shoved westward. Farther east, however, the rocks formed elsewhere and were attached (or “accreted”) to the edge of North America as the ocean closed. The 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 formed quite a bit east of the zone of “suturing” between the continents. Rocks beneath young sediments on the Coastal Plain of Florida and the eastern parts of Georgia and the Carolinas are thus stranded pieces of Africa, left behind when the Atlantic opened (Fig. 20c).

During the late stages of continental collision the sedimentary rocks of the Valley and Ridge Province were detached from the hard rocks underneath and pushed westward. The strata were compressed, deforming in two different ways. Analogous to a rug pushed across a floor (or squeezing an accordion), a series of anticlines and synclines developed (17c,d). The rocks were also cut by east-dipping thrust faults (inset, Fig. 18b), stacking up like roof shingles. The overall structure is commonly packages of folds separated by thrust faults. The term ***Valley and Ridge*** originates from the pattern of erosion that occurs in the folded and faulted strata. Erosion cuts downward into the folds and thrust blocks, but not uniformly. Sandstones are commonly very hard to erode, so they remain high as ridges. The valleys are soft shales and limestones that dissolve in the wet climate. From airplanes or satellites, the plunging anticlines and synclines make an amazing pattern of elongated ridges that sometimes end in "V's" (Fig. 16a).

Grandfather Mountain Window

The Blue Ridge Parkway crosses unusual terrain between Gillespie Gap and Boone, North Carolina. Most of the Parkway lies on old rocks that were metamorphosed to such a degree that the original rocks are difficult to identify. Between Parkway mileposts 286.4 and 316.8, however, there are relatively young rocks that are clearly sedimentary and igneous in origin. Cades Cove, in the northwest portion of Great Smoky Mountains National Park, is another such "***window***," where limestones are completely surrounding by harder, older rocks.

In the ***Grandfather Mountain Window*** older, overthrusted rocks have been worn through by erosion, exposing younger rocks beneath (Figs. 26). The older rocks are ***gneiss***, metamorphosed deep within the Earth 1.1 billion years ago during the Grenville Orogeny. As Africa came crashing into North America 300 million years ago, they broke off along a thrust fault and were pushed westward (Fig. 27a). They came to rest over younger rocks of ancient North America's continental margin, including rift-valley sediments and lava flows of the ***Grandfather Mountain Formation***, and shelf deposits of the ***Chilhowee Formation*** and ***Shady Dolomite*** (Fig. 27b). After thrusting, the region was bowed upward as a large anticline. Erosion wore through the old rocks on top, allowing a peep through the "window" at the younger rocks beneath (Fig. 27c).

In the Linville Falls area you can actually see the rocks above and below the thrust fault, as well as the fault itself (Fig. 28). The fault is exposed to the left of the Upper Falls Overlook. Beneath an overhang is a three-foot (one-meter) wide zone of ***mylonite***, rock that was pulverized during thrusting. The overhanging rock is ***gneiss*** that was thrust over younger rocks of the Chilhowee Formation (Fig. 27b), sandstones that were metamorphosed to ***quartzite***.

What's Beneath the Appalachians?

Prior to the 1980's there was debate about the nature of reverse faults in the Southern Appalachian Mountains. Where they cut the surface, the faults commonly dip eastward, at fairly steep angles. One school of thought, know as "thick-skinned," suggested that faults continue at that angle, cutting the old igneous and metamorphic rocks beneath. A "thin-skinned" group, however, suggested that the steep angles of the faults do not persist with depth. Instead, the faults flatten and merge into a flat zone above the old, hard rocks.

Debate over "thick-skinned" vs. "thin-skinned" was not so much about the Valley and Ridge Province, where it was reasonable to imagine that the softer sedimentary rocks could have been detached from the underlying, rigid basement and thrust westward. Argument in the 1970's centered around the nature of uplift and lateral transport of rocks farther east, namely the Blue Ridge and Piedmont. How far had these rocks moved westward over the North American continent? The thick-skinners felt strongly that the rocks moved mostly vertically along steep faults; they had not moved very far westward over North America. The thin-skinners, however, thought it possible that the low-angle detachment zone extended entirely beneath the Valley and Ridge and continued eastward beneath the Blue Ridge, and perhaps even farther. The implication of this interpretation was that hard rocks at the surface were pushed westward tens, and maybe even hundreds, of miles over North America.

The thick- vs. thin-skinned thrust debate paralleled (and was part of) the overall controversy of plate tectonics. Did mountain ranges result from downwarping and vertical uplift (Geosynclinal Theory), or were they products of large horizontal displacements (Plate Tectonic Theory)? In the late 1970's the Southern Appalachian Mountains served as a natural laboratory to test the two hypotheses. Seismic reflection profiles were recorded from the Valley and Ridge Province eastward, all the way to the Atlantic Coastal Plain. The profiles revealed that thrust faults merged with a nearly horizontal (detachment) zone above basement rocks in the Valley in Ridge Province. Strong reflections from the detachment zone were traced eastward, entirely beneath the Blue Ridge and part of the Piedmont. It was thus demonstrated that the Blue Ridge and Piedmont were thrust westward in a thin-skinned fashion over the North American continent (20b).

CONTINENTAL RIFTING AND THE OPENING OF THE ATLANTIC OCEAN

The final events in the Appalachian story occurred over the last 250 million years, ripping apart Pangea, opening the Atlantic, and wearing down the Appalachians through erosion. The story that unfolded earlier, during the formation and breakup of Laurentia (Fig. 21), were thus repeated as Pangea was created (Fig. 3), then destroyed (Fig. 4). Sedimentary and volcanic strata are found in rift valleys in the eastern part of the Piedmont, relics of the rifting of Pangea 250 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. New oceanic crust is being created as the Atlantic Ocean widens at the current plate boundary, the Mid-Atlantic Ridge.

EROSION OF THE SOUTHERN APPALACHIANS

The Southern Appalachian Mountains appear to have 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). The ongoing collision between India and Asia is uplifting the Himalayas and Tibetan Plateau, a region over 1,000 miles (1,500 kilometers) wide, averaging over 15,000 feet (4,500 meters) above sea-level (Fig. 16b).

Like the Alps and Himalayas, the Southern Appalachians owed their overall height to the great thickness of crust resulting from the collision (Fig. 10). That great thickness cannot last for long, however, because the topography erodes, taking the 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 Mountain, Mt. Mitchell, stands 6,684 feet (2,037 meters) above sea level. Grandfather Mountain, due to its resistant sandstone and conglomerate remains at 5,964 feet (1,818 meters) elevation.

The erosion and accompanying isostatic rebound means that 10 to 15 miles (15 to 25 kilometers) of material was removed from portions of the Southern Appalachian Mountains. At such depths within the Earth, rocks were subjected to high temperatures and pressures. Medium-to-high-grade metamorphic rocks, like schist and gneiss, are thus found in places along the Blue Ridge Parkway.

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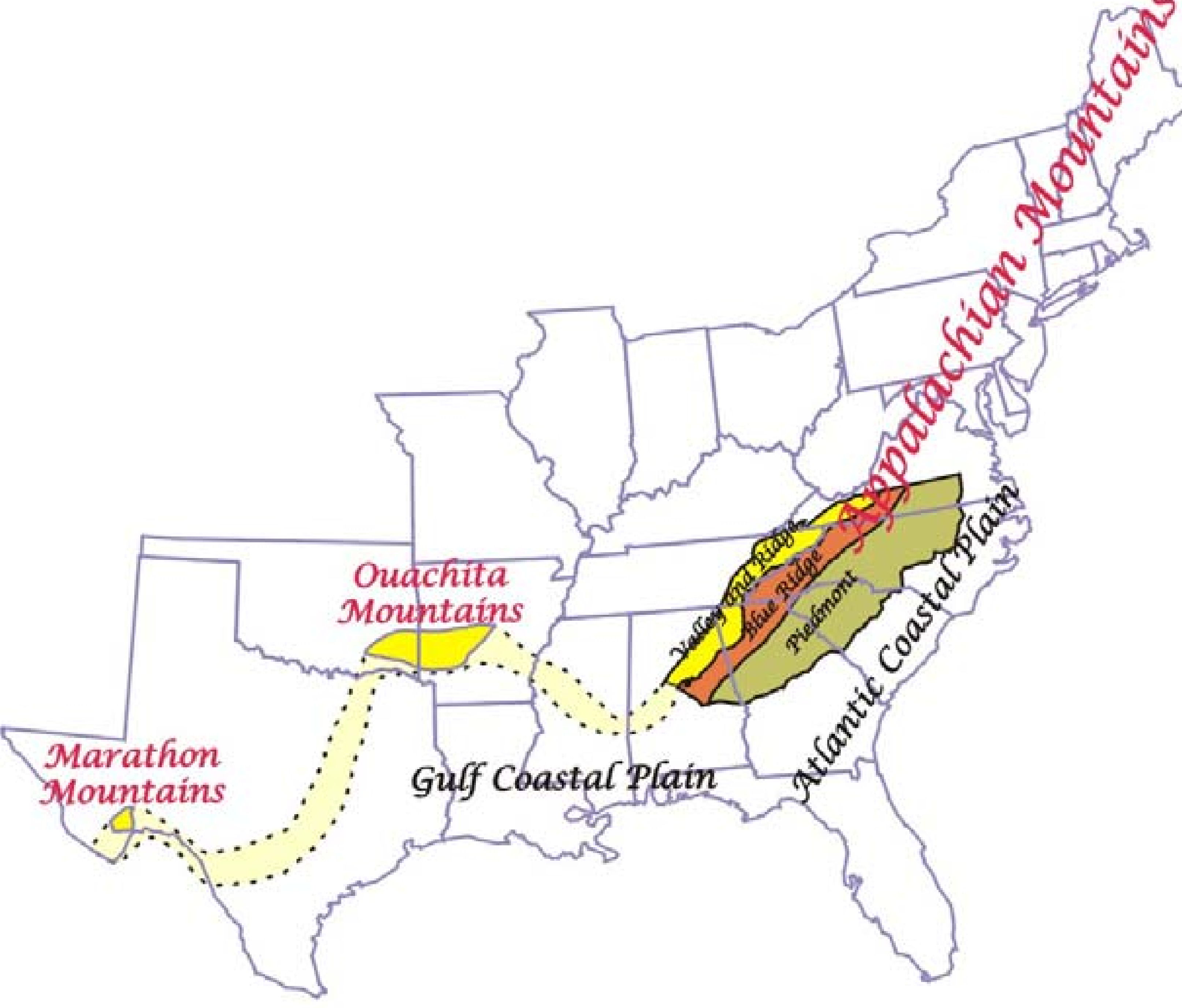


<u>Fig. 1</u>. **Appalachian - Ouachita - Marathon Mountain Belt.** *The Appalachian Mountains are actually part of a much larger chain that includes the Ouachita Mountains of Arkansas and Oklahoma, and the Marathon Mountains of west Texas. After 300 million years the mountains have been deeply eroded and covered in places by young sediments of the Atlantic and Gulf coastal plains. The Blue Ridge Parkway follows the highest part of the chain in North Carolina and Virginia.*

600 MILLION YEARS AGO
(Iapetus Ocean Opens)

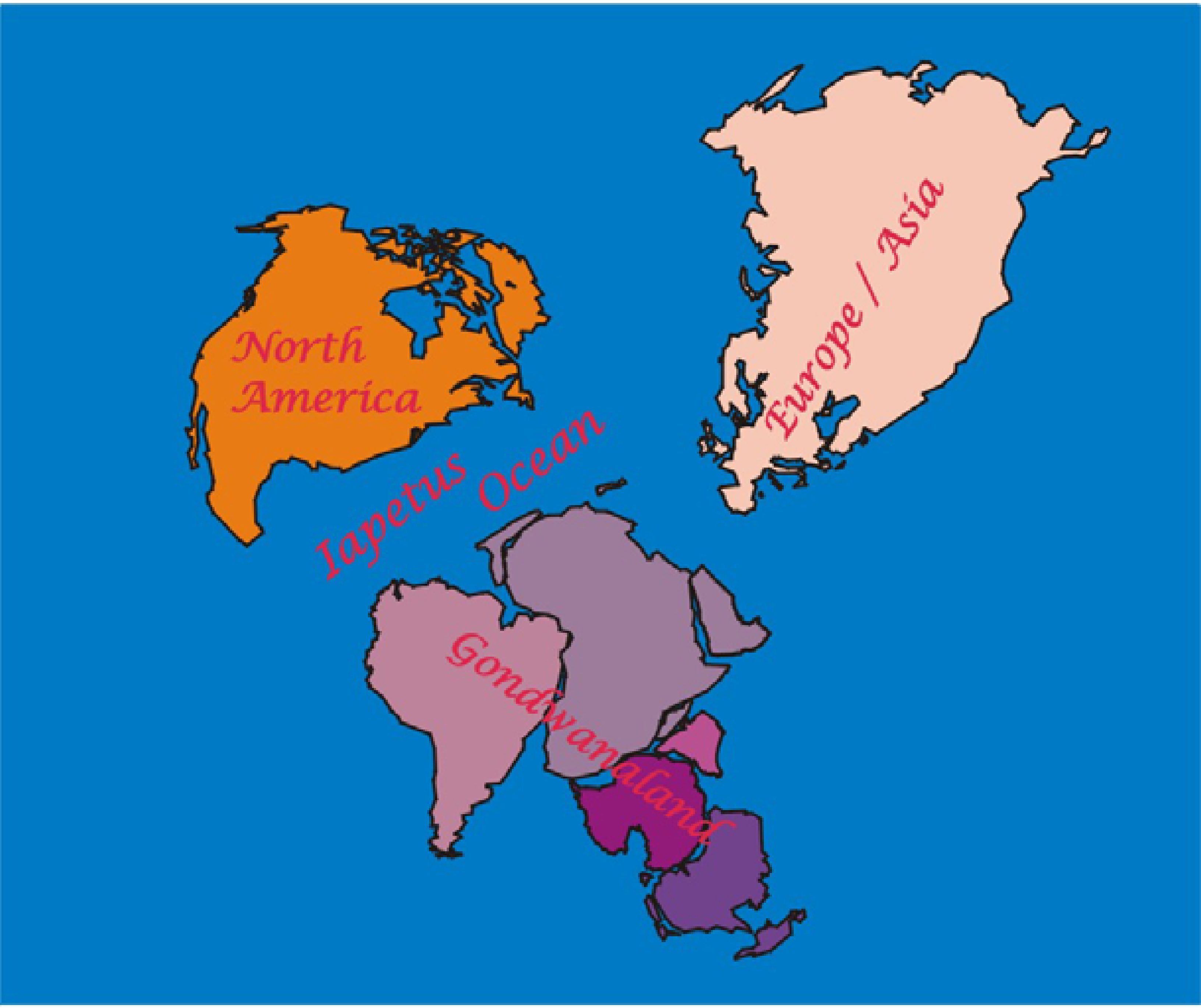
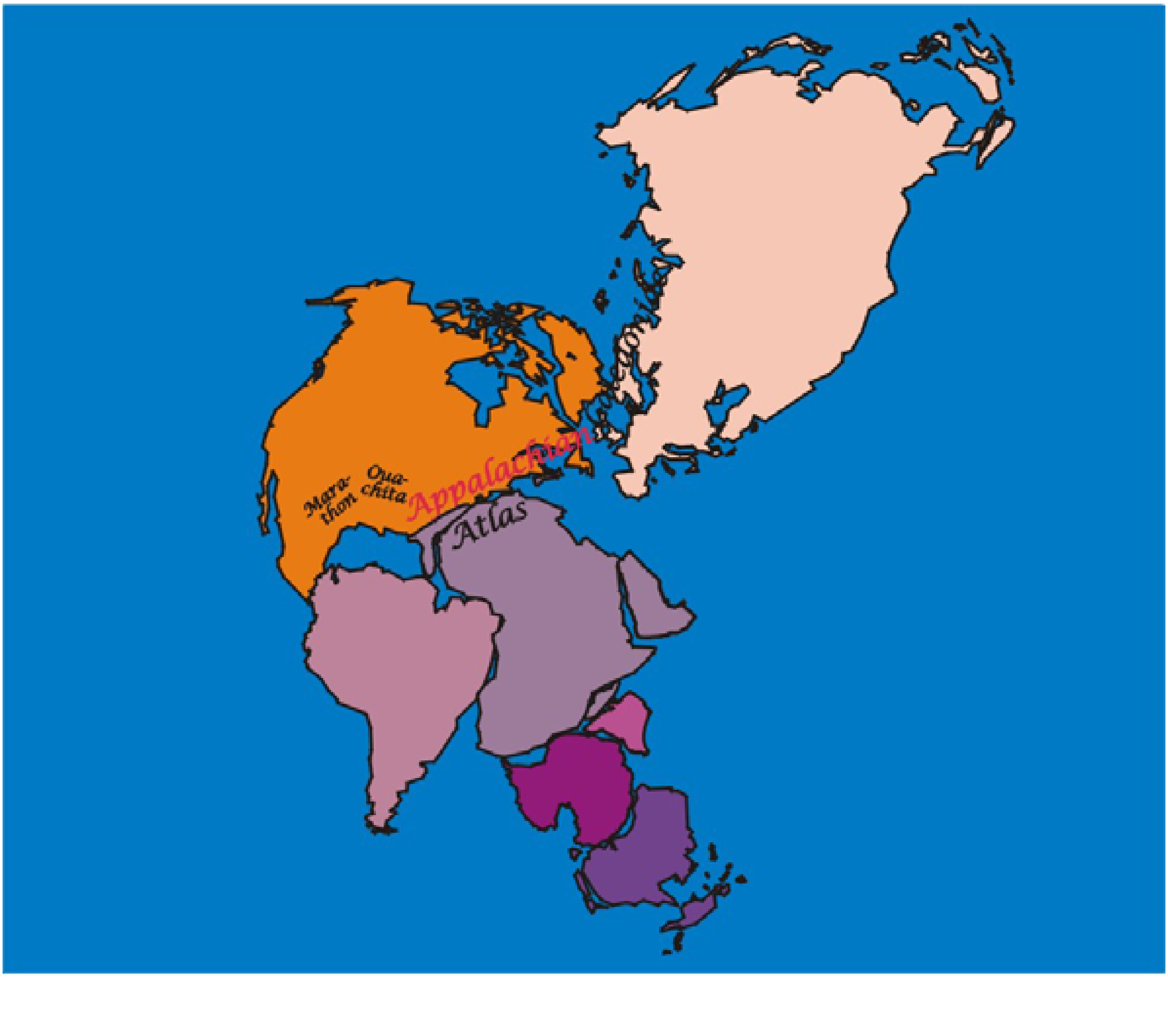


Fig. 2. ***Positions of continents after opening of the Iapetus Ocean.*** *Notice that the land that will later become Florida and the coastal Carolinas is part of Africa at this time.*

300 MILLION YEARS AGO
(Iapetus Ocean Closes)



*<u>Fig. 3</u>. **Positions of continents after the closure of the Iapetus Ocean.** Notice that 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.*

TODAY
(Atlantic Ocean Opens)

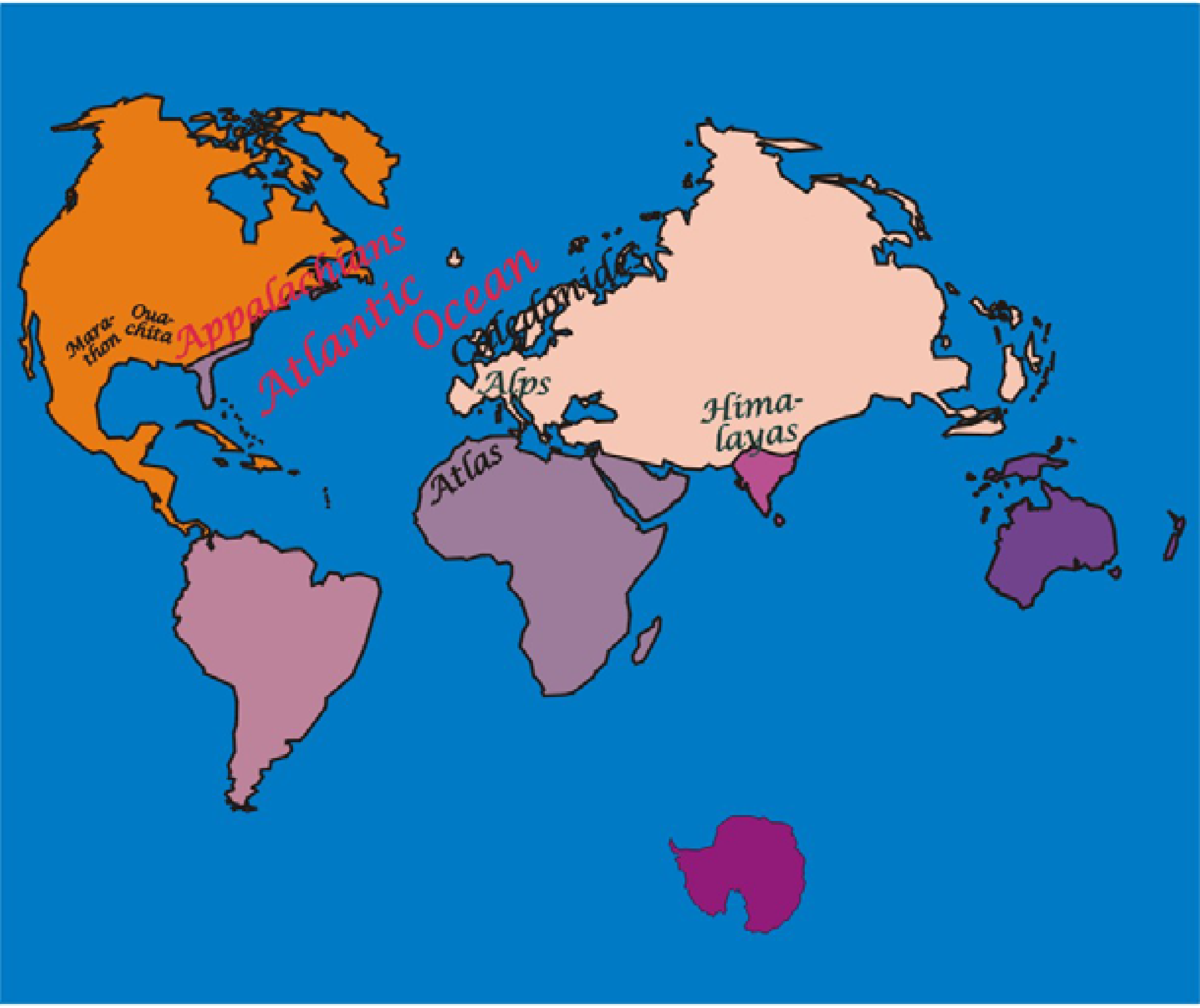


Fig. 4. **Positions of continents today.** When the Atlantic Ocean opened, fragments of the collision zone were left on three different continents: the Appalachians in North America, the Atlas in Africa, and the Caledonides in Europe. Another continental collision is occurring today, where Africa and India ram into Europe and Asia, forming the chain of mountains from the Alps to the Himalayas.

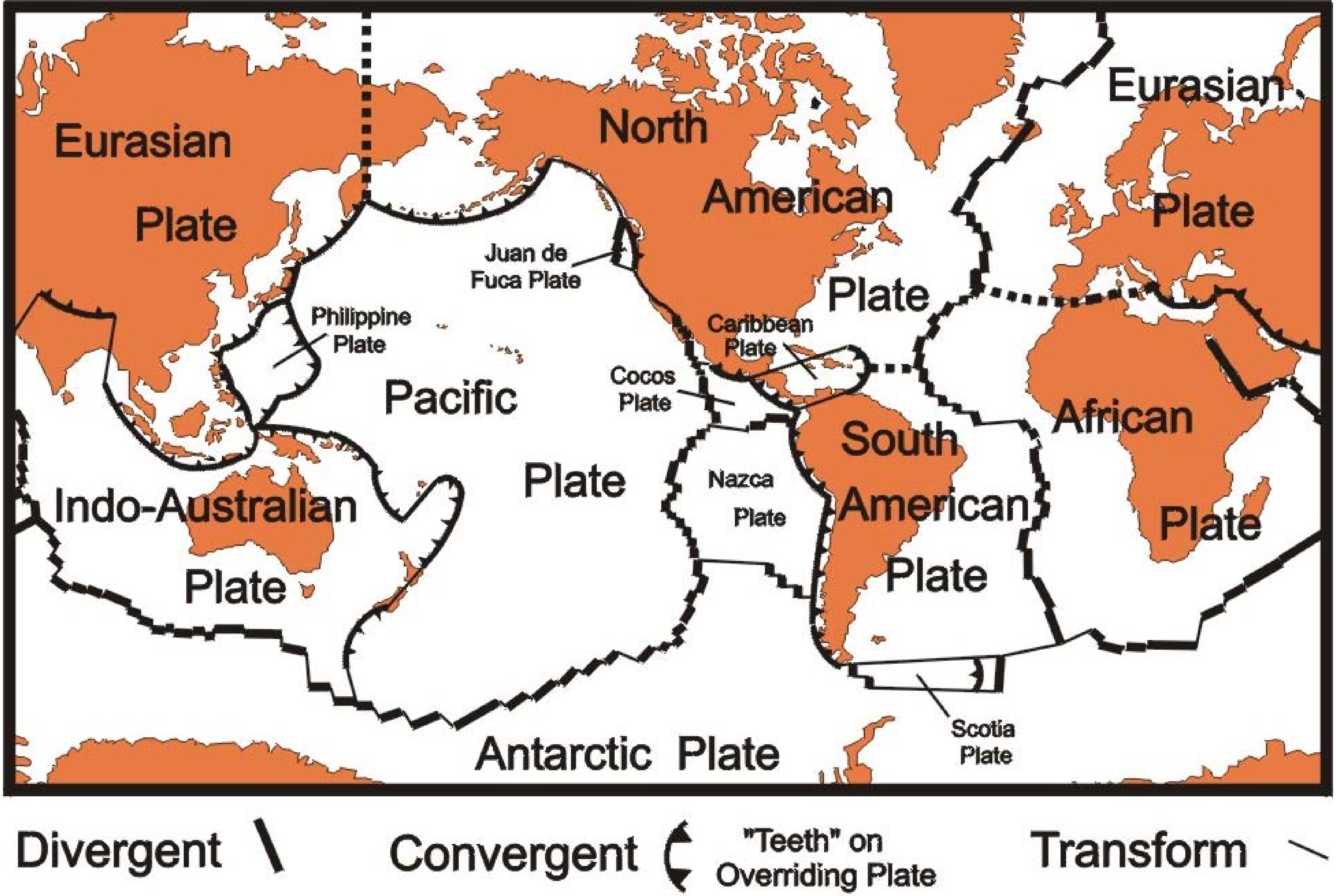


Fig. 5. Plate tectonic map of the world, illustrating the three types of plate boundaries. Note that the locations of plate boundaries correlate strongly with the narrow zones of earthquakes in Fig. 13.

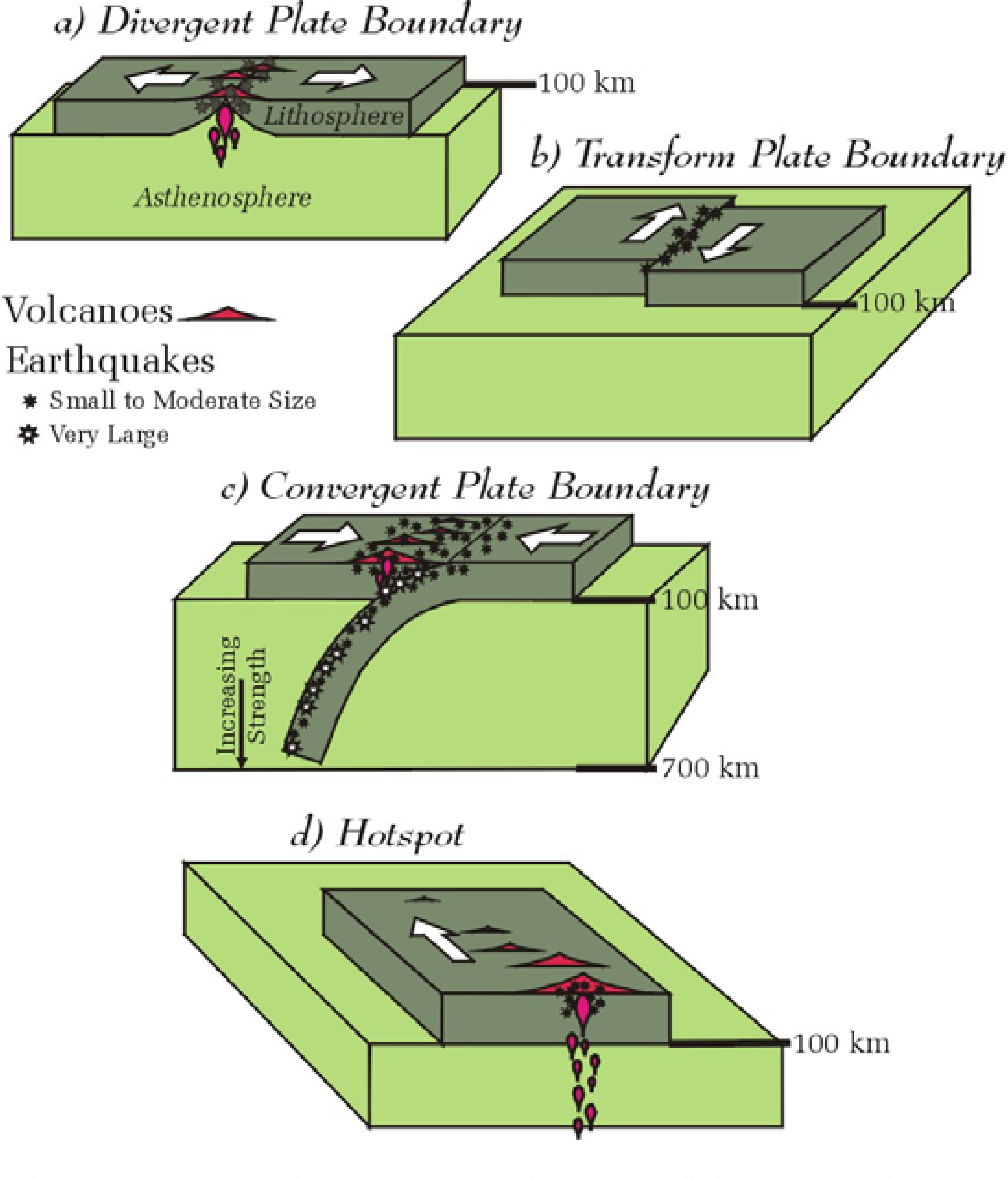


Fig. 6. Tectonic activity occurs at the three types of plate boundaries and at hotspots. ***Volcanoes*** *erupt in the zone where plates diverge, on the overriding plate where plates converge, and along a line where a plate rides over a hotspot. Only* ***shallow earthquakes****, of small to moderate 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.*

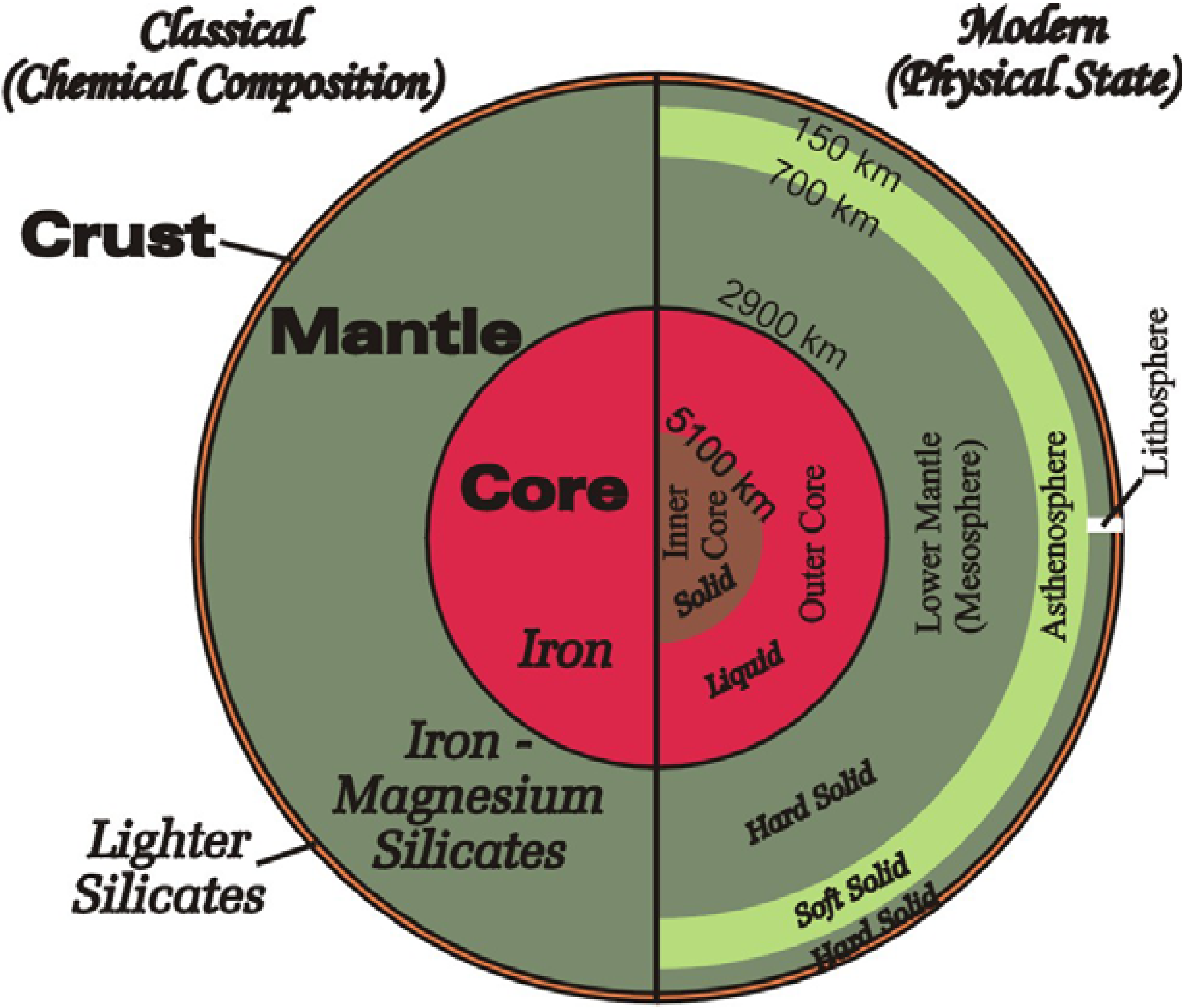


Fig. 7. Left: The classical division of the Earth is according to **chemical composition**, *the heavier materials concentrated toward the center. Right: In modern times the three chemical divisions are broken into five zones according to* **physical state**.

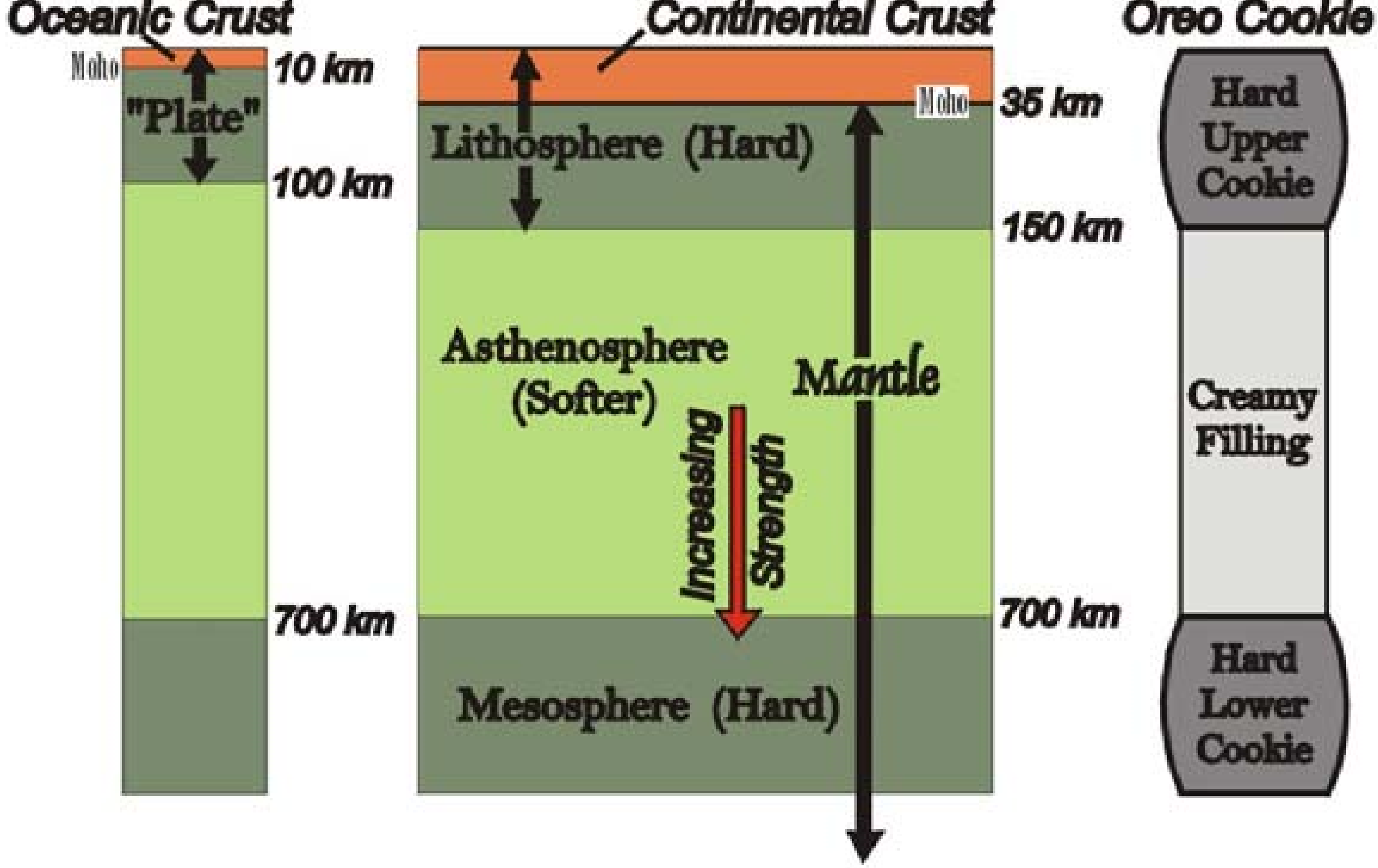
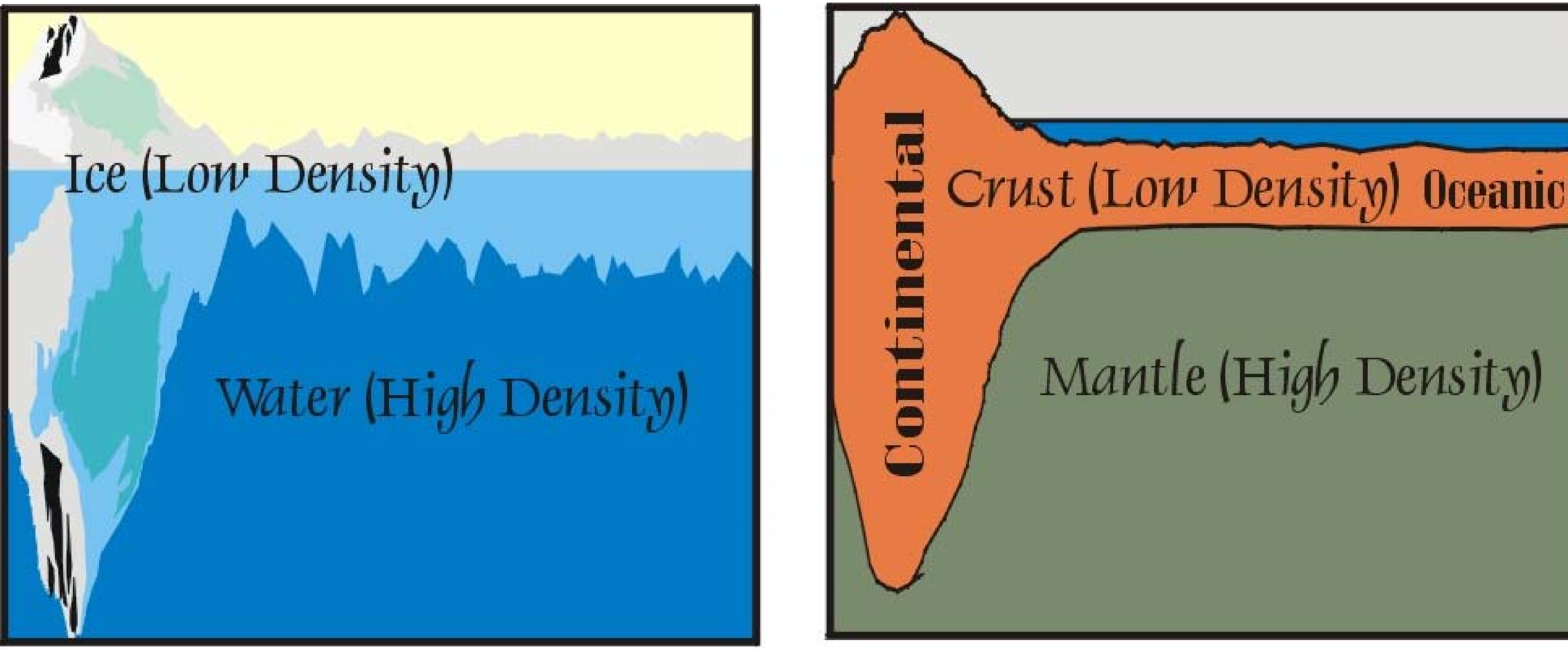


Fig. 8. *Cross section of the upper 1000 or so kilometers of the Earth, including the crust and part of the mantle. Increases in temperature and pressure with depth cause the mantle to exist in three different states. The uppermost mantle and crust comprise the cold, rigid plates of* ***lithosphere****. 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.*



<u>Fig. 9</u>. ***Continental crust*** *is much <u>thicker</u>, and therefore <u>more buoyant</u>, than* ***oceanic crust****. Crustal blocks can be thought of as "floating" on the underlying, denser mantle. Much like icebergs floating on water, the topography of thicker continental crust sticks up much higher that that of thinner oceanic crust. Notice that, analogous to the thicker iceberg, continental crust also sticks down farther into the denser mantle than the thinner oceanic crust.*

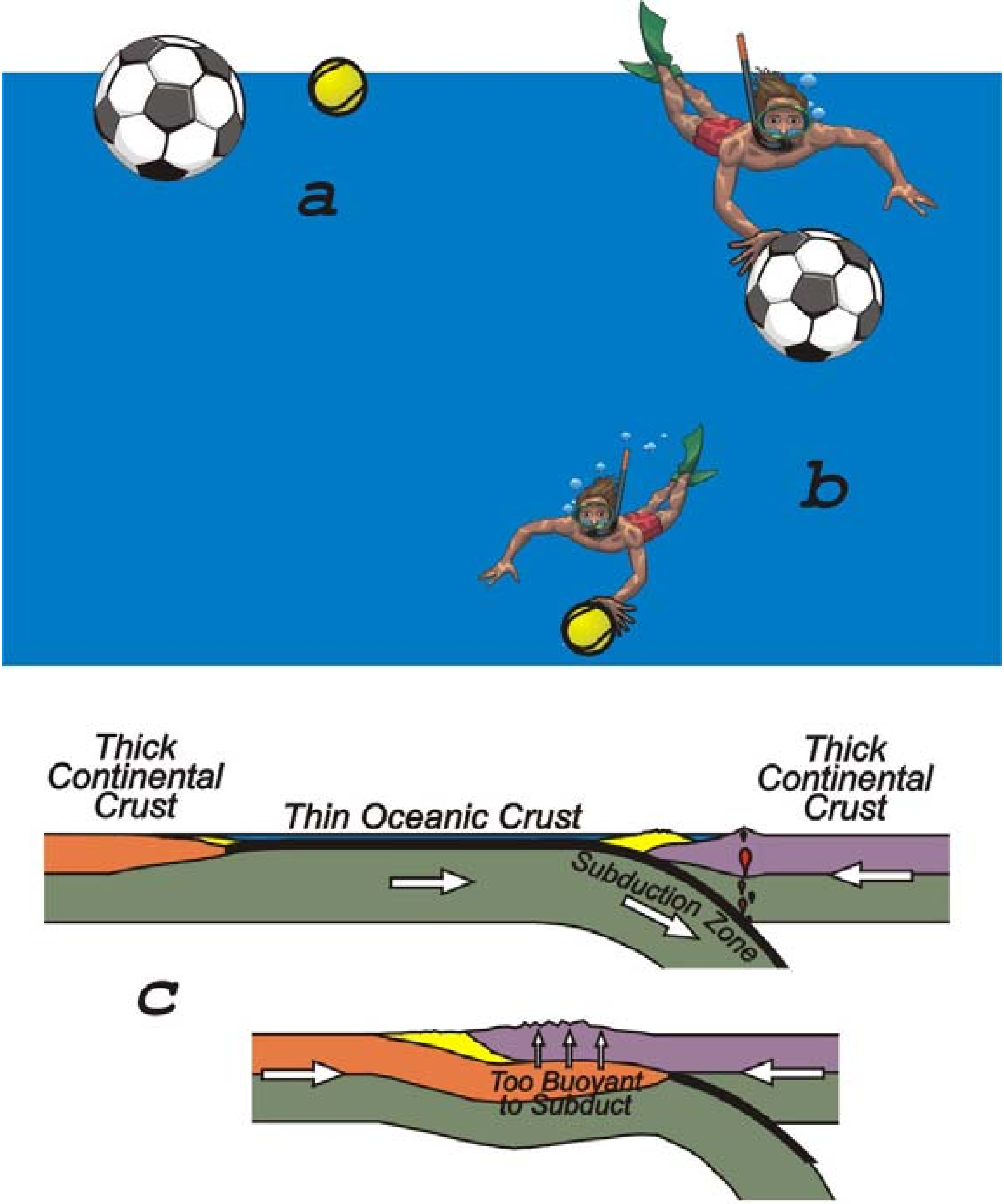
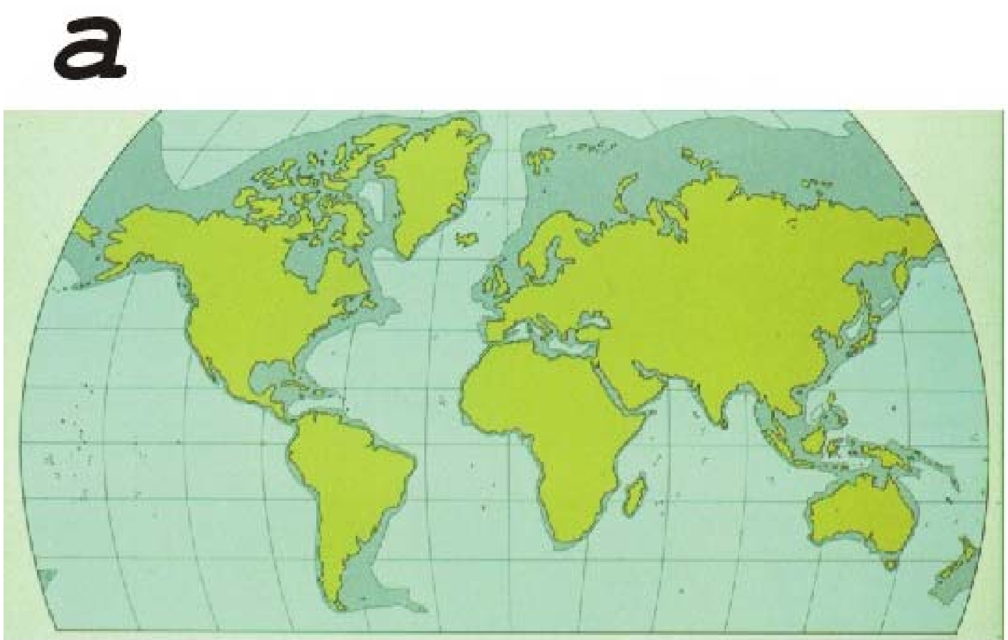


Fig. 10. a) The bigger, more-buoyant soccer ball sticks up higher, and rests lower, in the water than the smaller, less-buoyant tennis ball. b) A swimmer can easily "subduct" the tennis ball to the bottom of the pool, but not the soccer ball. c) Thin (less-buoyant) oceanic crust can subduct, while thick (more-buoyant) continental crust cannot.



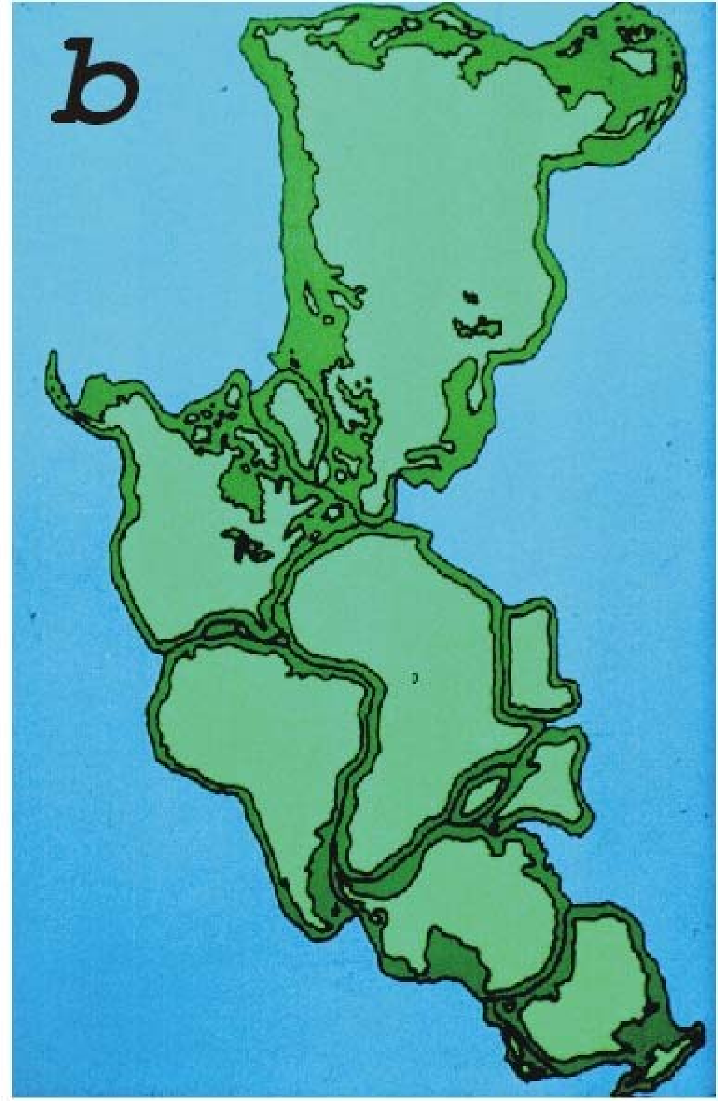
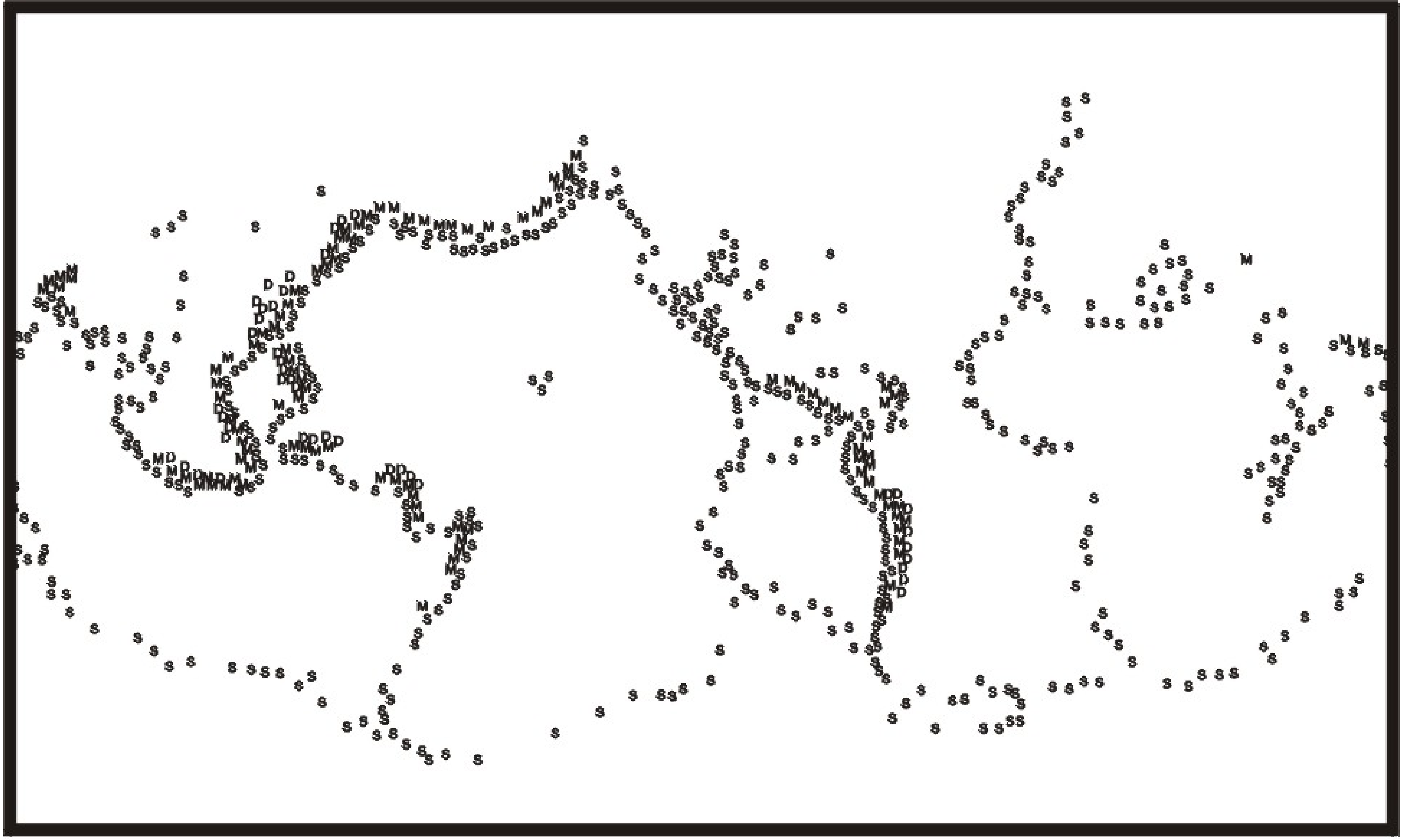


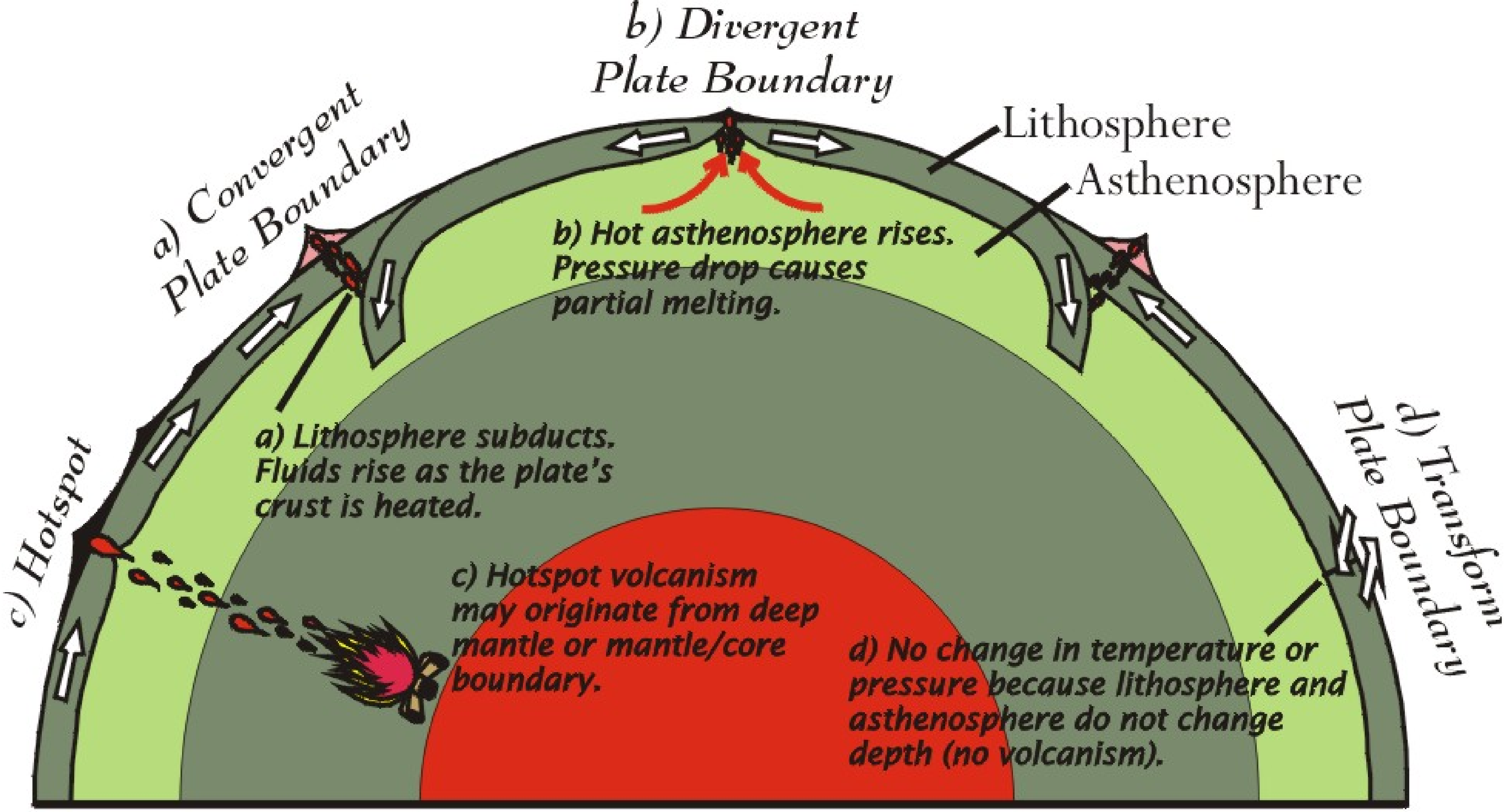
Fig. 11. *a) Thick continental crust includes not only regions above sea level (yellow), but also the* ***continental shelves*** *(gray) that lie beneath shallow water. (From Skinner and Porter, 1989). b) Continents joined together at their continental shelves to form the supercontinent of* ***Pangea****. (From Atwater, 1986).*

<u>Fig. 12.</u> World map showing features of the ocean floor. 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****. (From Marie Thorpe, 1977).*



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

Fig. 13. Locations of large earthquakes recorded over five-year period, plotted without any geographic reference. The earthquakes outline the plate boundaries shown in Fig. 5. 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. Data from Barazangi and Dorman (1969); figure modified from Hamblin and Christiansen (1995).



<u>Fig. 14</u>. *Volcanism occurs due to: a)* ***heating*** *of the crust of the descending plate at a <u>convergent boundary</u>; b)* ***drop in pressure*** *on hot asthenosphere as it rises at a <u>divergent boundary</u>; and c) deep mantle material rising and* ***decompressing*** *at a <u>hotspot</u>. At a <u>transform boundary</u> (d) material stays at about the same depth; there is no appreciable rise in temperature or drop in pressure and hence no volcanism.*

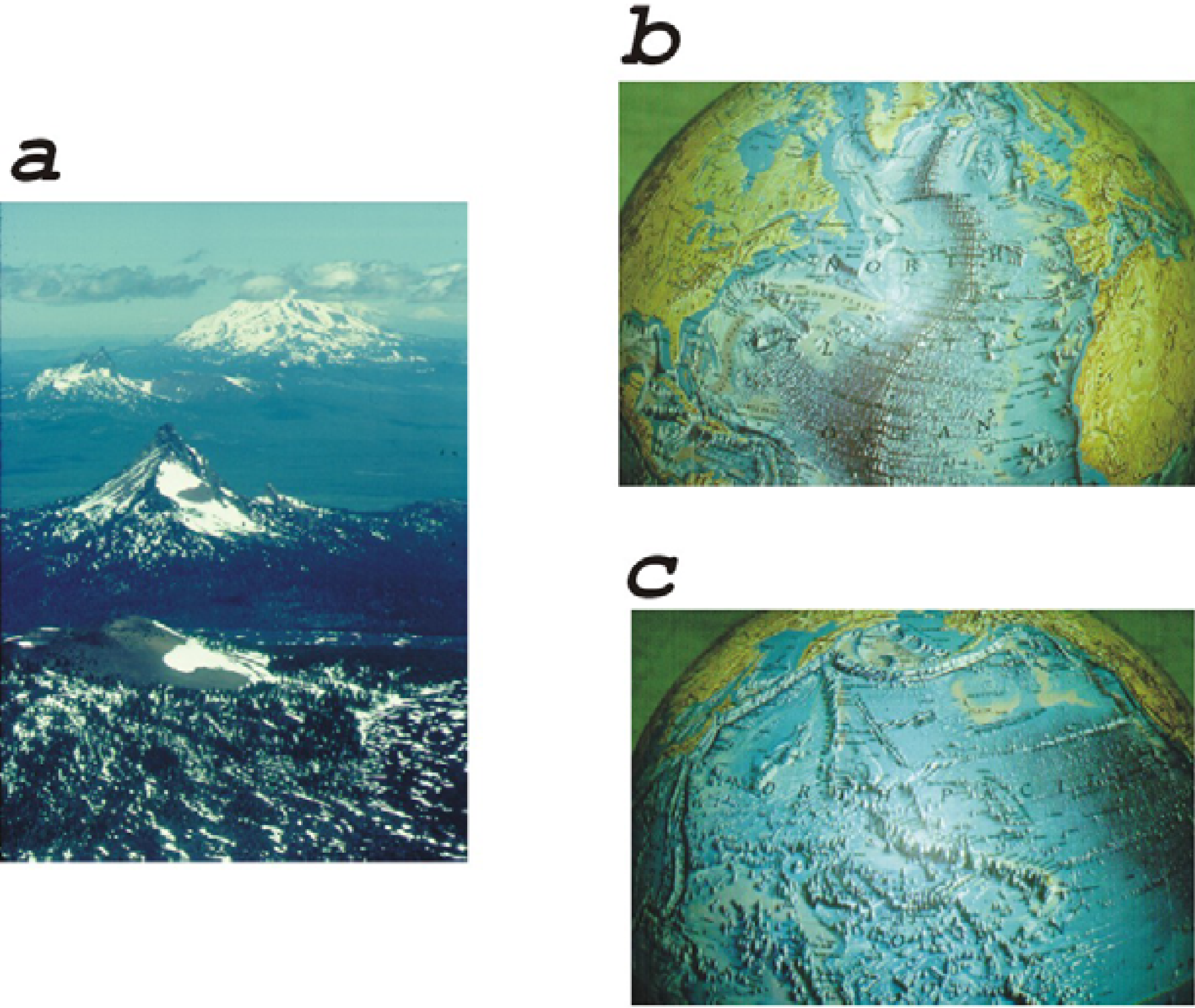


Fig. 15. **Types of volcanic mountain chains.** *a) A* **volcanic arc** *is a chain of composite volcanoes that forms above a subduction zone (Cascade Mountains). b) At a divergent plate boundary with oceanic crust, a* **mid-ocean ridge** *is a mountain range of submerged, interlocking shield volcanoes (Mid-Atlantic Ridge). c) Plate motion over an* **oceanic hotspot** *leaves a chain of shield volcanoes that are youngest at a hotspot, older away from it (Hawaii-Emperor Seamount Chain).*

a

b

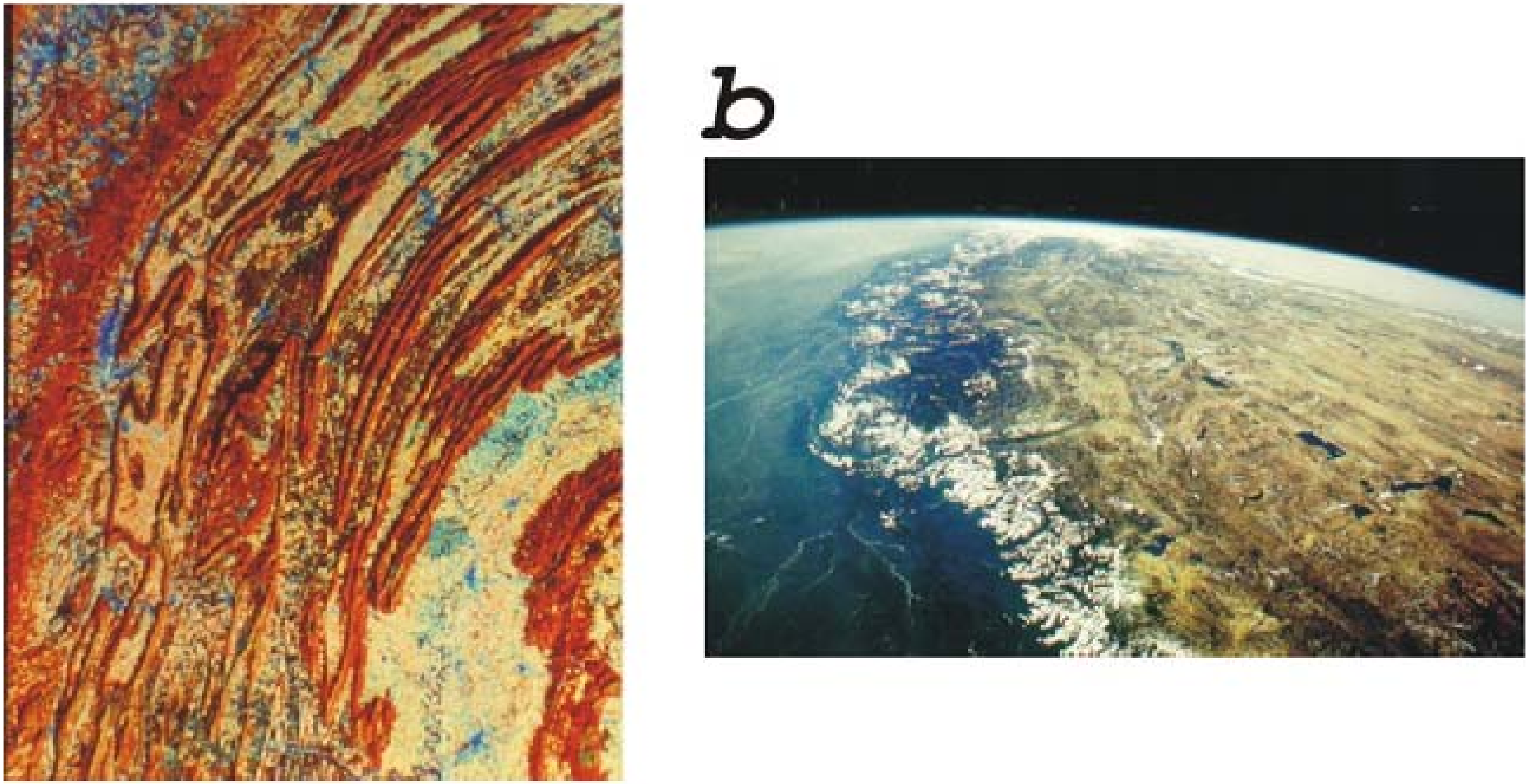


Fig. 16. ***Satellite images of mountain ranges formed by crustal deformation***. *a) Valley and Ridge Province of the Appalachian Mountains. Sedimentary strata of the ancient continental margin of North America have been folded into plunging anticlines and synclines. b) Active continental collision zone in northern India, Nepal, and Tibet. On the left (south) is 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.*

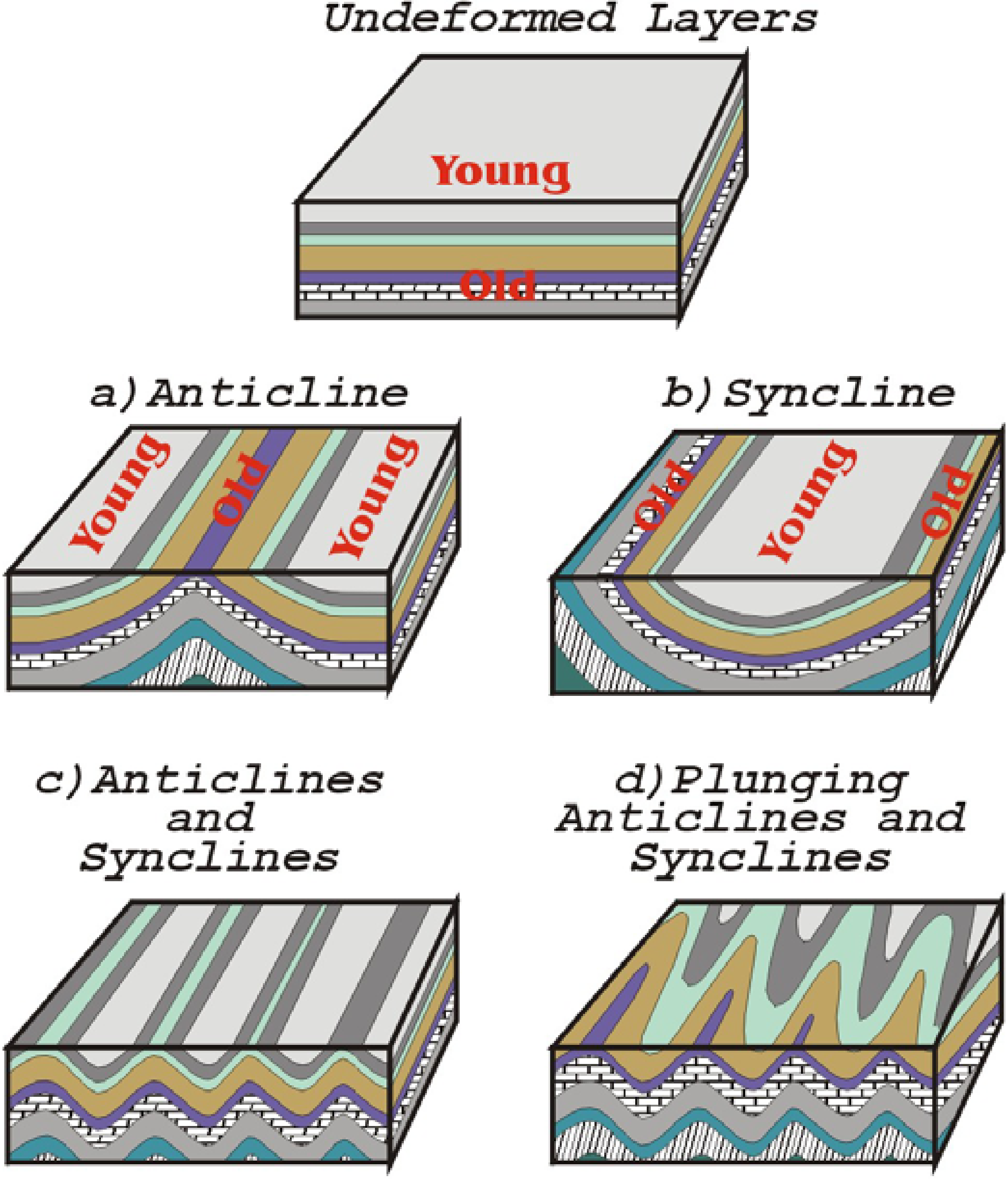


Fig. 17. **Types of folds.** *a) Anticline. The layers are bent upward so that, on the eroded surface, the older rocks are at the center. b) Syncline. Layers bent downward, exposing younger rocks at the center. c) Series of anticlines and synclines. d) Series of plunging anticlines and synclines.*

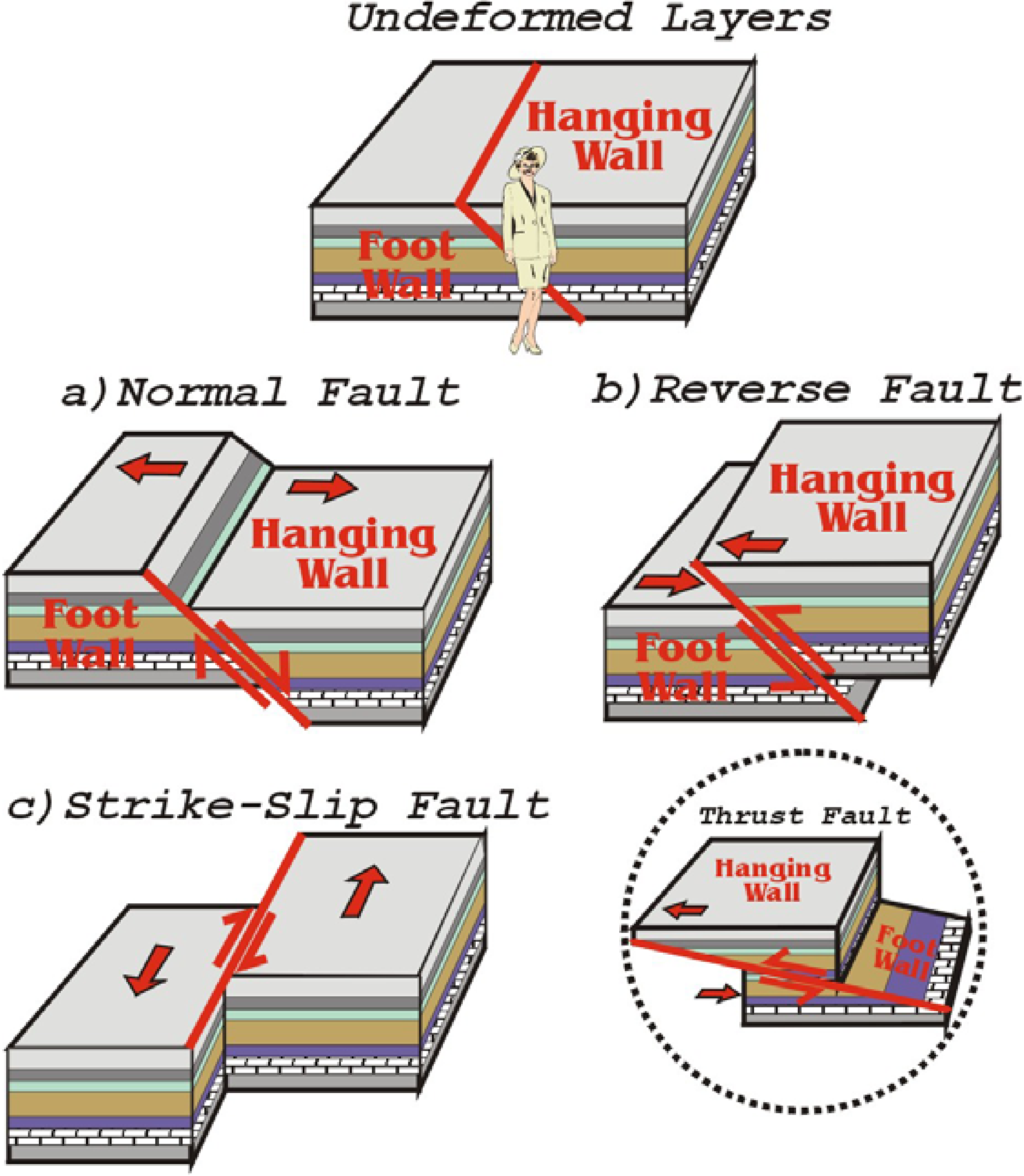


Fig. 18. **Types of faults.** *a) Normal fault. The hanging wall moves downward, relative to the foot wall. b) Reverse fault. The hanging wall moves upward, relative to the footwall. (A thrust fault is a low-angle reverse fault) c) Strike-slip fault. One block slides laterally past the other.*

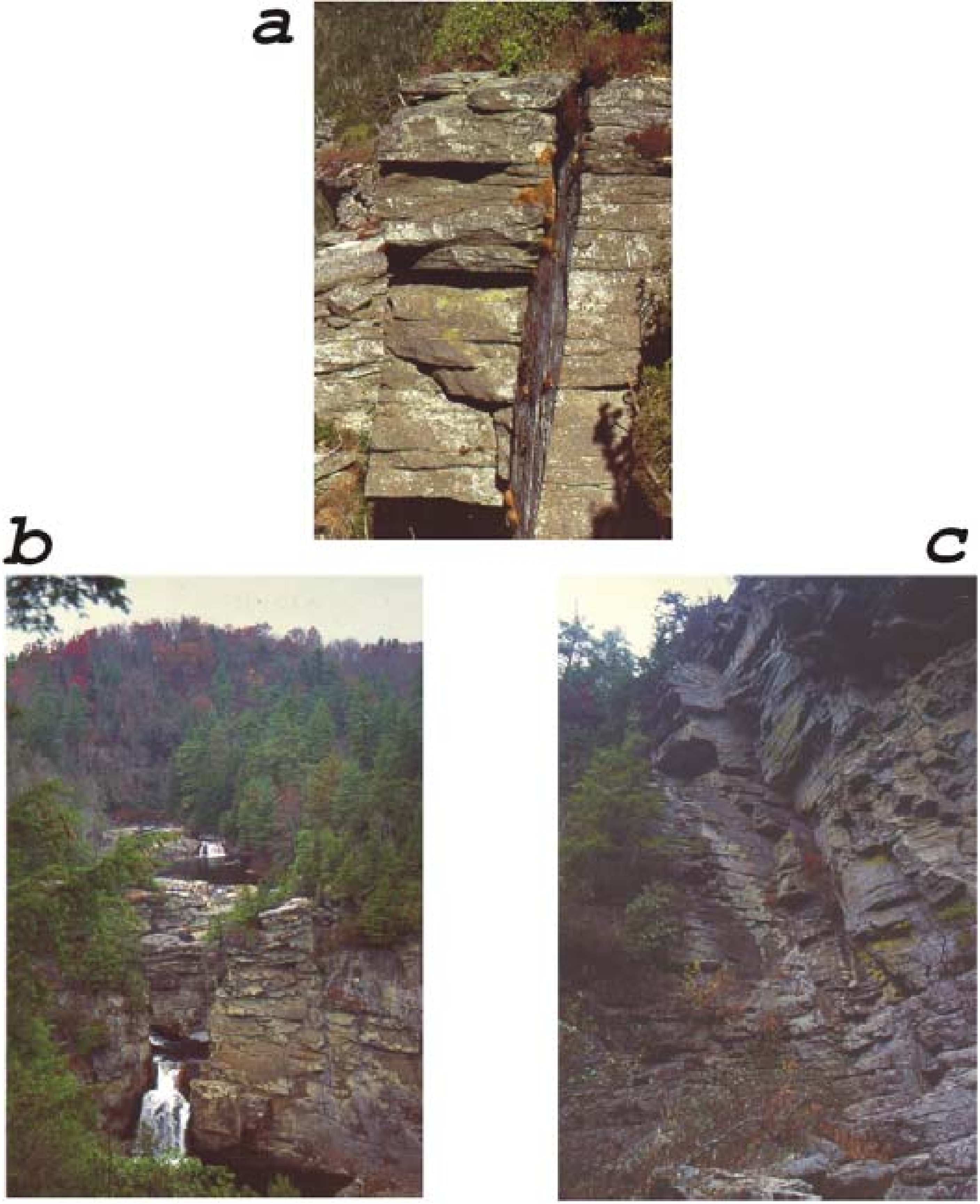


Fig. 19. ***Joints are cracks formed in rock as pressure is released.*** *a) Vertical joints in conglomerate on Grandfather Mountain. There are two sets of joints that are nearly perpendicular, so that rock slabs break off as rectangular blocks. b) Linville Falls flows through cracks carved along similar sets of joints. c) The walls of Linville Gorge are vertical because slabs of rock break off along the perpendicular joint sets.*

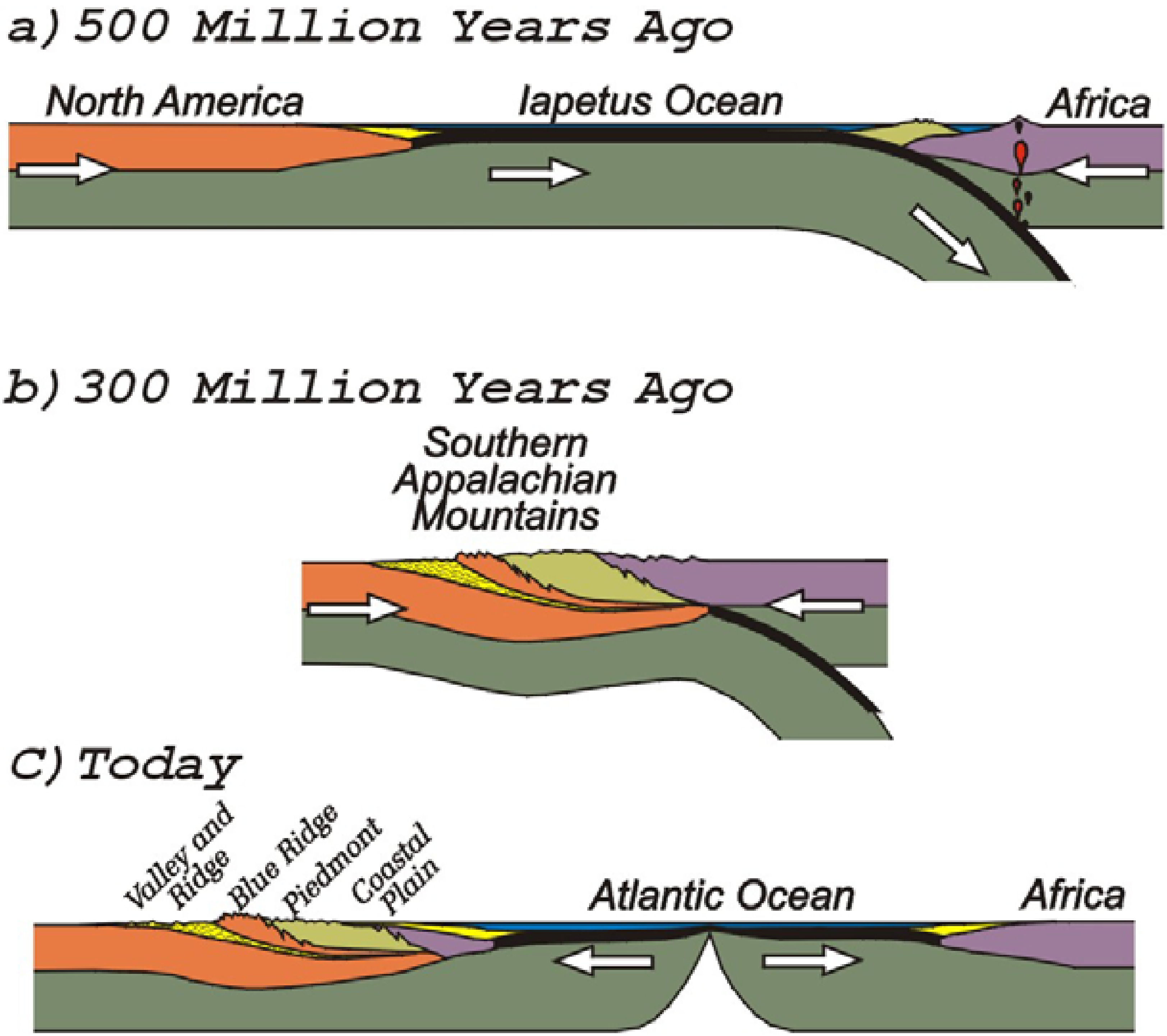


Fig. 20. **Plate tectonic evolution of the Southern Appalachian Mountains.** *a) Iapetus Ocean between North America and Africa begins to close about 500 million years ago. b) The Southern Appalachians form as the Iapetus ocean completely closes and Africa crashes into North America about 300 million years ago. The Blue Ridge is part of North America's ancient continental margin. c) The Atlantic Ocean opens, leaving the remnants of Iapetus as the Piedmont, along with a sliver of Africa as coastal Carolina and Florida.*

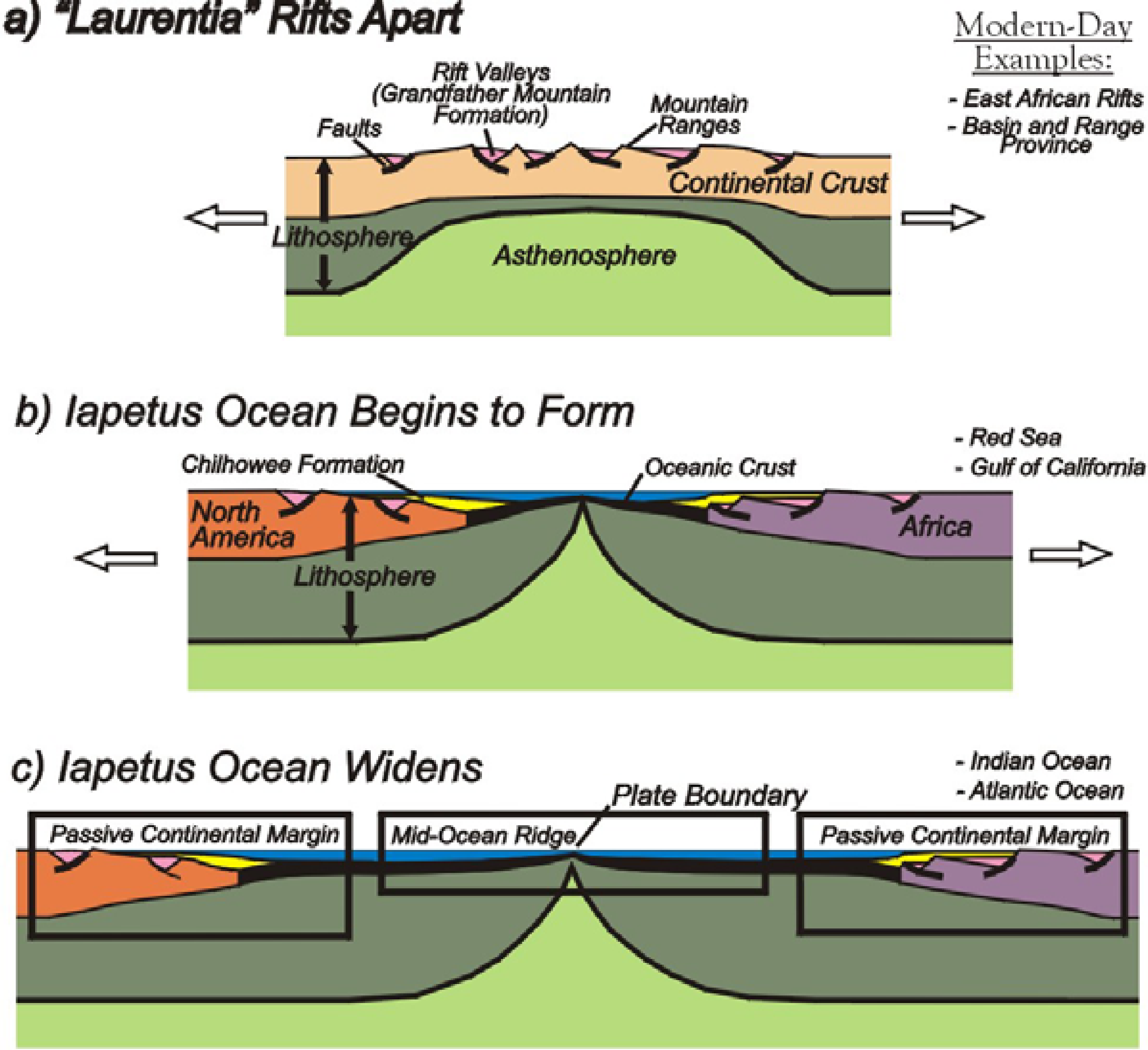


Fig. 21. **Plate divergence resulted in continental rifting and opening of the Iapetus Ocean.** *a) As the ancient continent ("Laurentia") rifted apart about 750 million years ago, gravel, sand, mud, and lava flows were deposited in rift valleys, like those in East Africa today. These sedimentary and volcanic strata became the conglomerate, sandstone, shale, basalt, and rhyolite that comprise the Grandfather Mountain Formation. b) As the continents completely ripped apart, the narrow ocean was much like the Red Sea today. c) As the Iapetus Ocean widened, sand, silt, and mud were deposited on North America's continental margin about 600 million years ago. Some of these layers hardened into rocks of the Chilhowee Formation.*

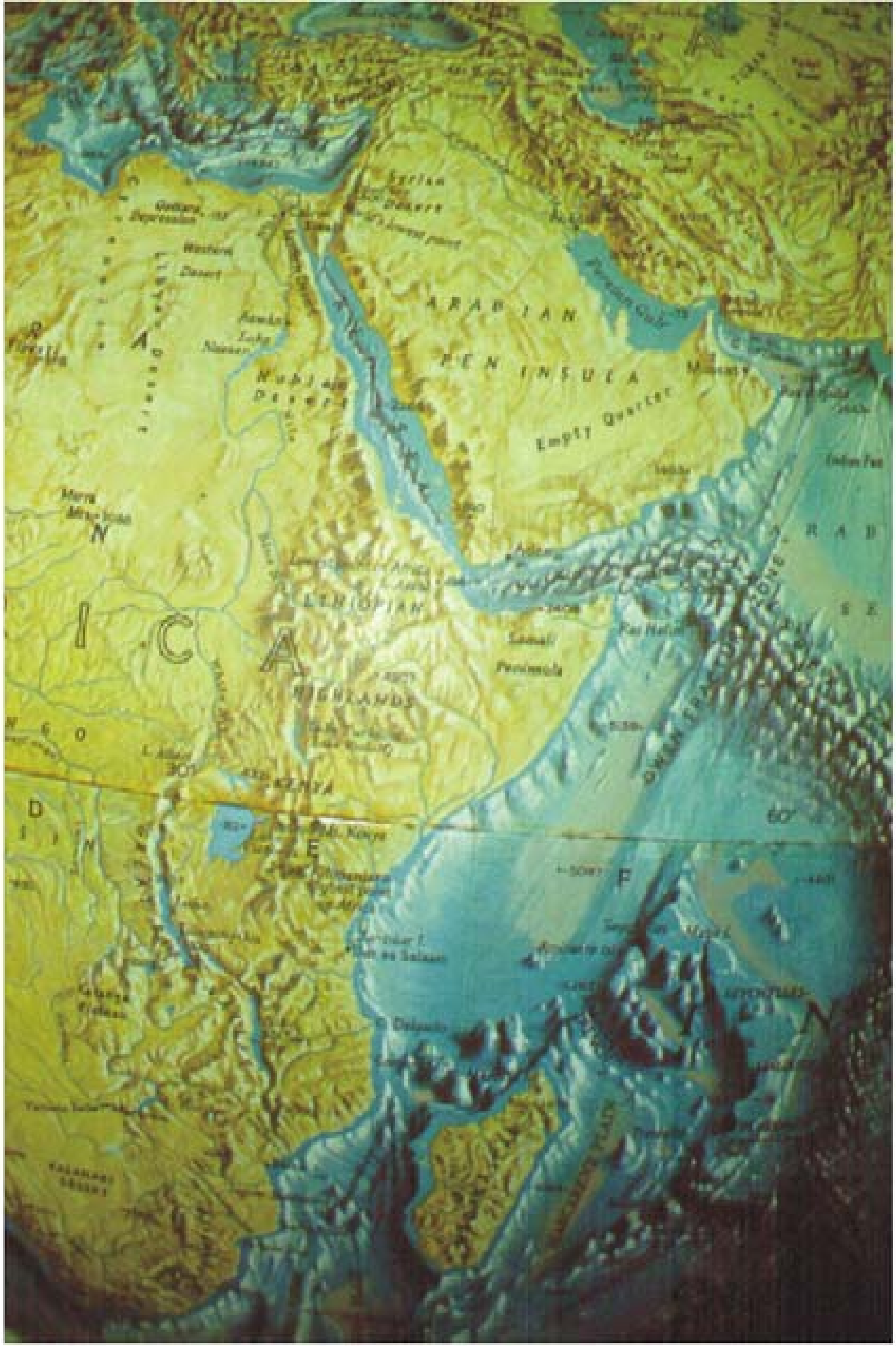


Fig. 22. Divergent plate boundary development shown on National Geographic Society, Physical Globe. East Africa is an active continental rift zone (Fig. 21a), the Red Sea an early ocean basin (Fig. 21b), and the Indian Ocean a more advanced ocean (Fig. 21c). The sedimentary and volcanic strata of the Grandfather Mountain Formation were deposited in rift valleys in an environment much like East Africa. The Chilhowee Formation is continental shelf deposits, similar to sedimentary layers forming today off the east coast of Africa.

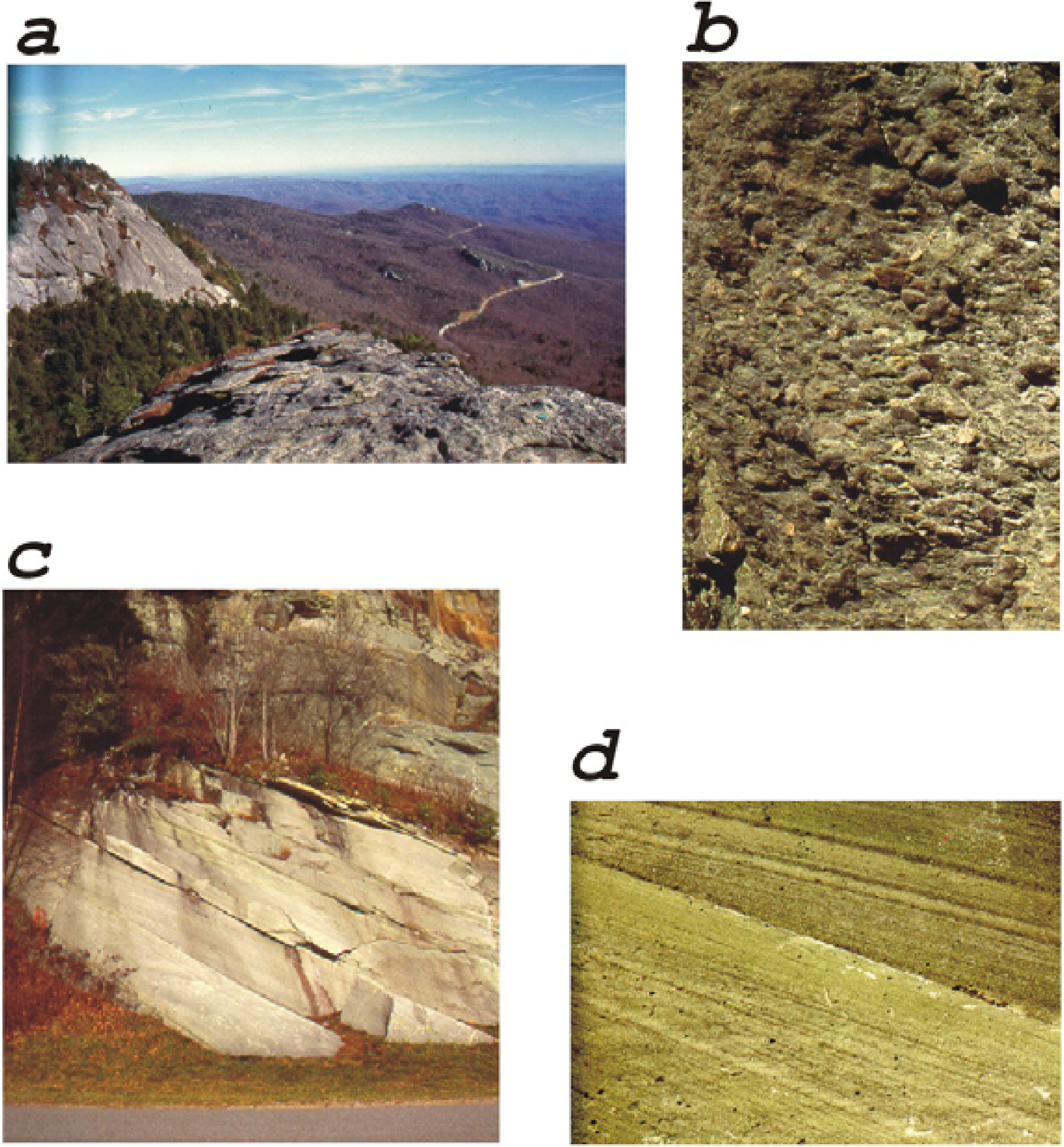


Fig. 23. ***Rift valley strata in Grandfather Mtn. area.*** *a) View of Linn Cove Viaduct area of Blue Ridge Parkway (approx. milepost 300 to 303). Rock in foreground is conglomerate of Grandfather Mtn. Formation. Its resistance to erosion is shown by prominence of MacRae Peak (middle left), along the high ridge of Grandfather Mtn. b) The conglomerate has pebbles deposited by mountain streams flowing into the rift valley. c) Tilted sandstone layers near Parkway milepost 302. d) Layers and crossbeding in the sandstone still evident after slight metamorphism.*

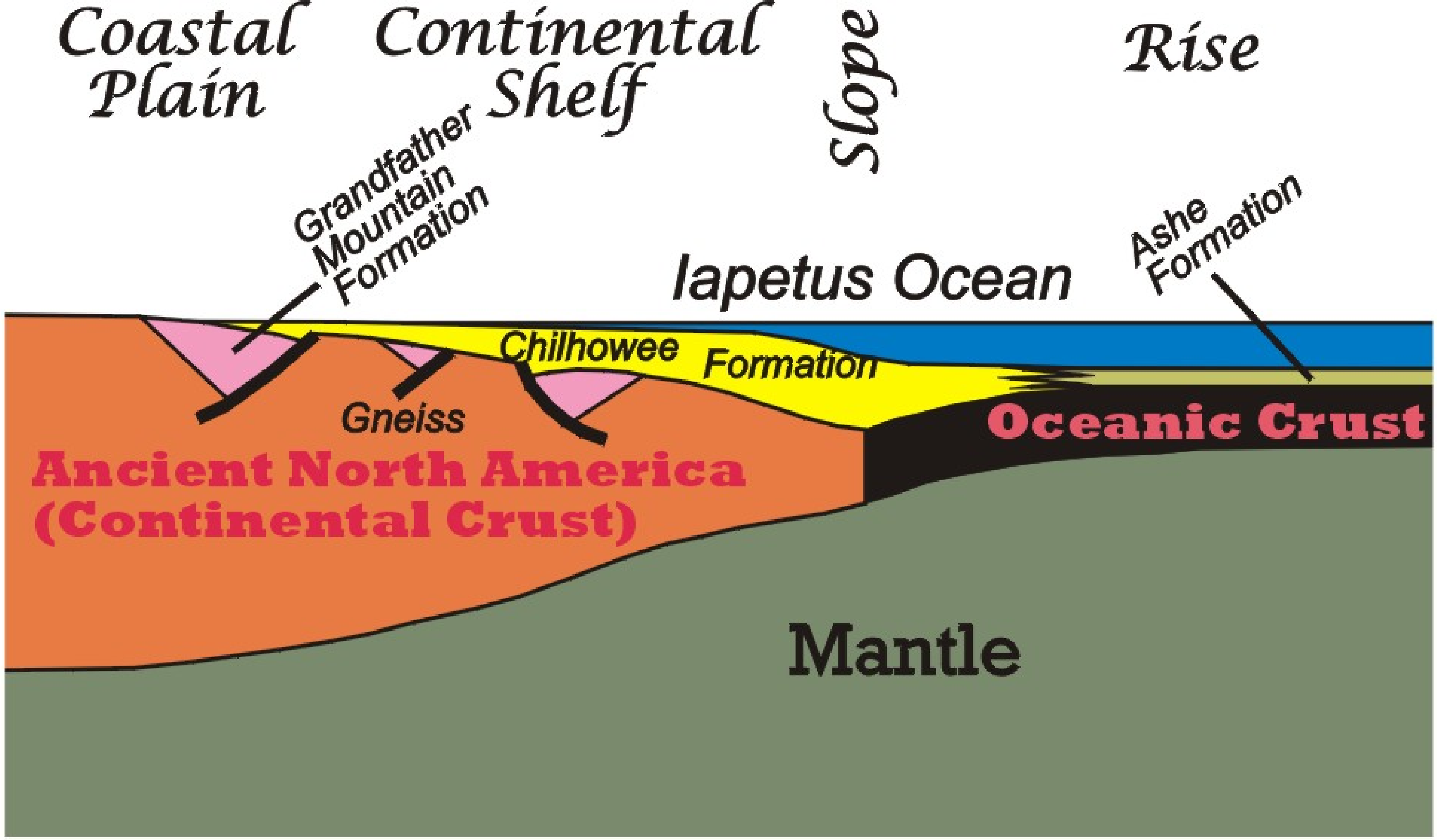
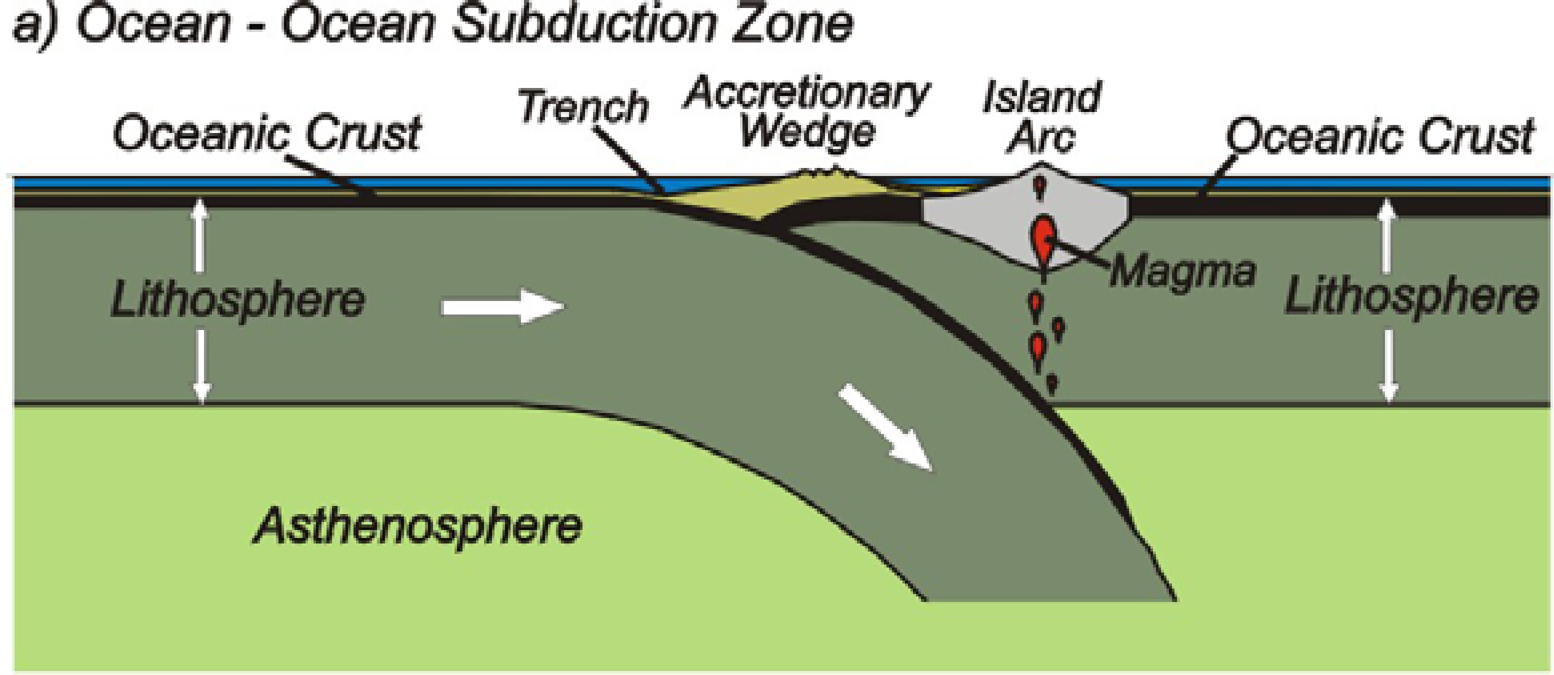


Fig. 24. ***Passive continental margin of ancient North America****. During breakup of a larger continent (Laurentia), the 1.1 billion year old gneiss was cut by normal faults and overlain by younger strata. The* ***Grandfather Mountain Formation*** *is sedimentary and volcanic layers filling continental rift valleys (Figs. 21a, 23). Sediments deposited on the continental shelf include sandstone, siltstone, and shale of the* ***Chilhowee Formation*** *(Fig. 21b). Shales of the* ***Ashe Formation*** *formed in much deeper water of the Iapetus Ocean.*



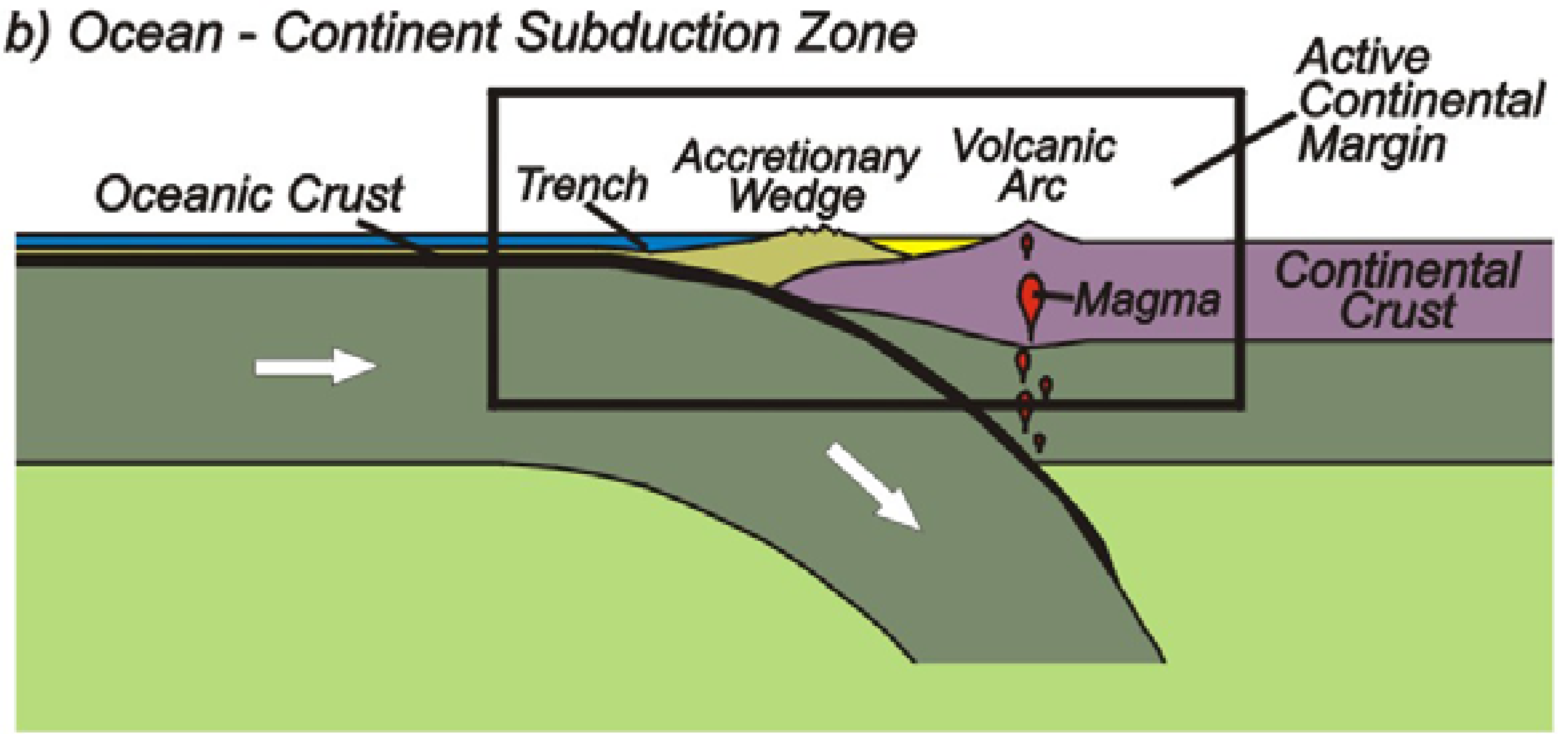


Fig. 25. **Subduction zones at convergent plate boundaries.** *At about 100 miles (150 kilometers) depth the top of the downgoing plate becomes so hot that it "sweats." The hot fluids rise, melting rocks in their path and erupting as volcanoes on the overriding plate. a) Where both plates are capped by oceanic crust, an* **island arc** *forms above the subduction zone. b) Oceanic crust subducts beneath more buoyant continental crust, forming a* **volcanic arc** *along the edge of the continent. An example is the Cascade Range in Oregon (Fig. 15a). The* **Piedmont** *in the Southern Appalachians consists of islands arcs, deep-ocean sediments, and accretionary wedge sediments that were part of the Iapetus Ocean between North America and Africa.*

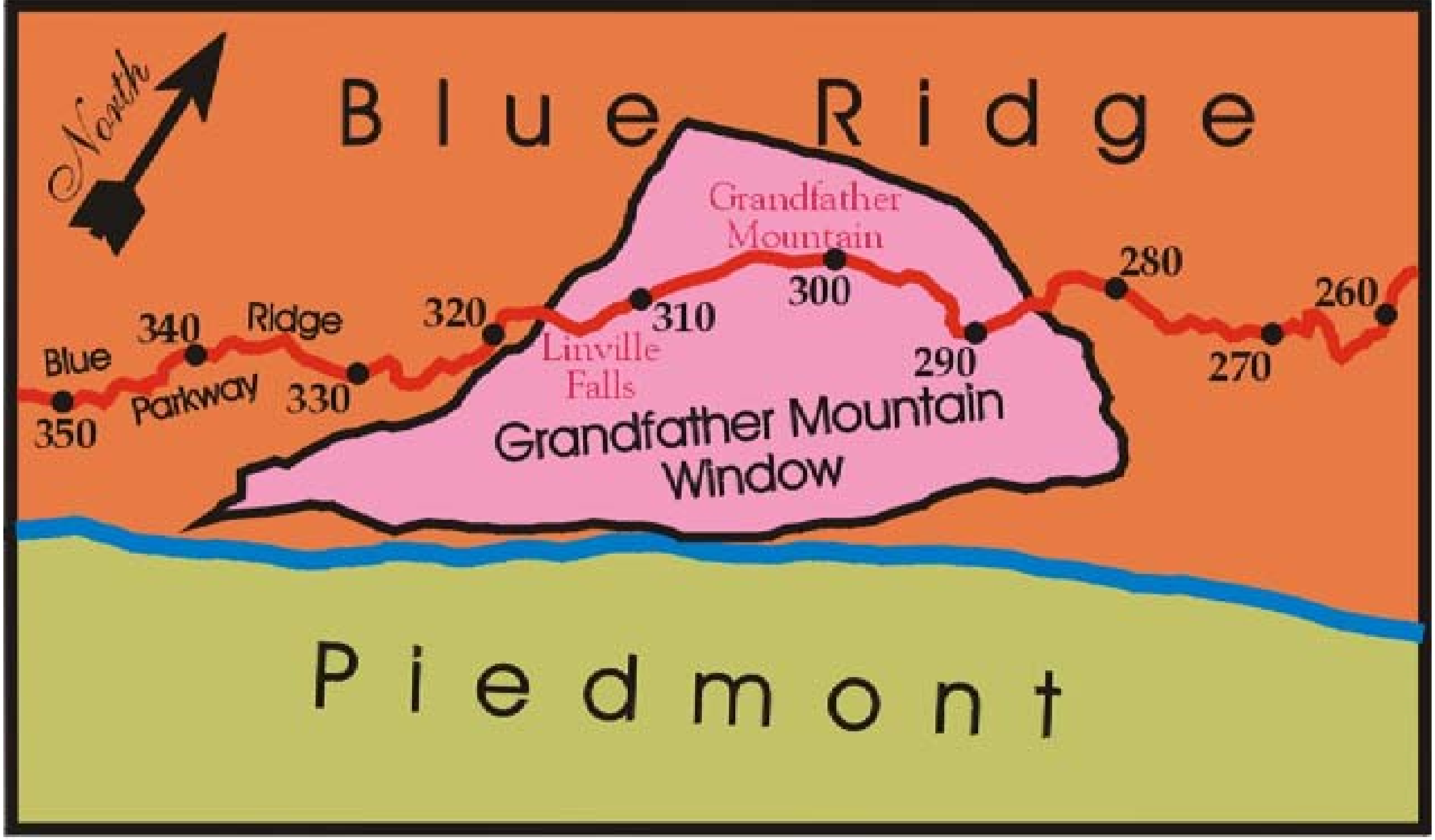


Fig. 26. **Grandfather Mountain Window**. *Most of the Blue Ridge is metamorphic rocks, a billion years old or older, that were thrust over younger strata (Fig. 27a,b). In the Grandfather Mountain area the overthrusted rocks have eroded through, so that the younger rocks can be seen as if looking through a "**window**" (Fig. 27c). Rocks in the window are evidence that the Blue Ridge is part of the ancient continental margin of North America: rift-valley strata of the Grandfather Mountain Formation (Fig. 23); continental shelf deposits of the Chilhowee Formation (Fig. 19b,c) and the dolomite (rock similar to limestone) at Linville Caverns.*

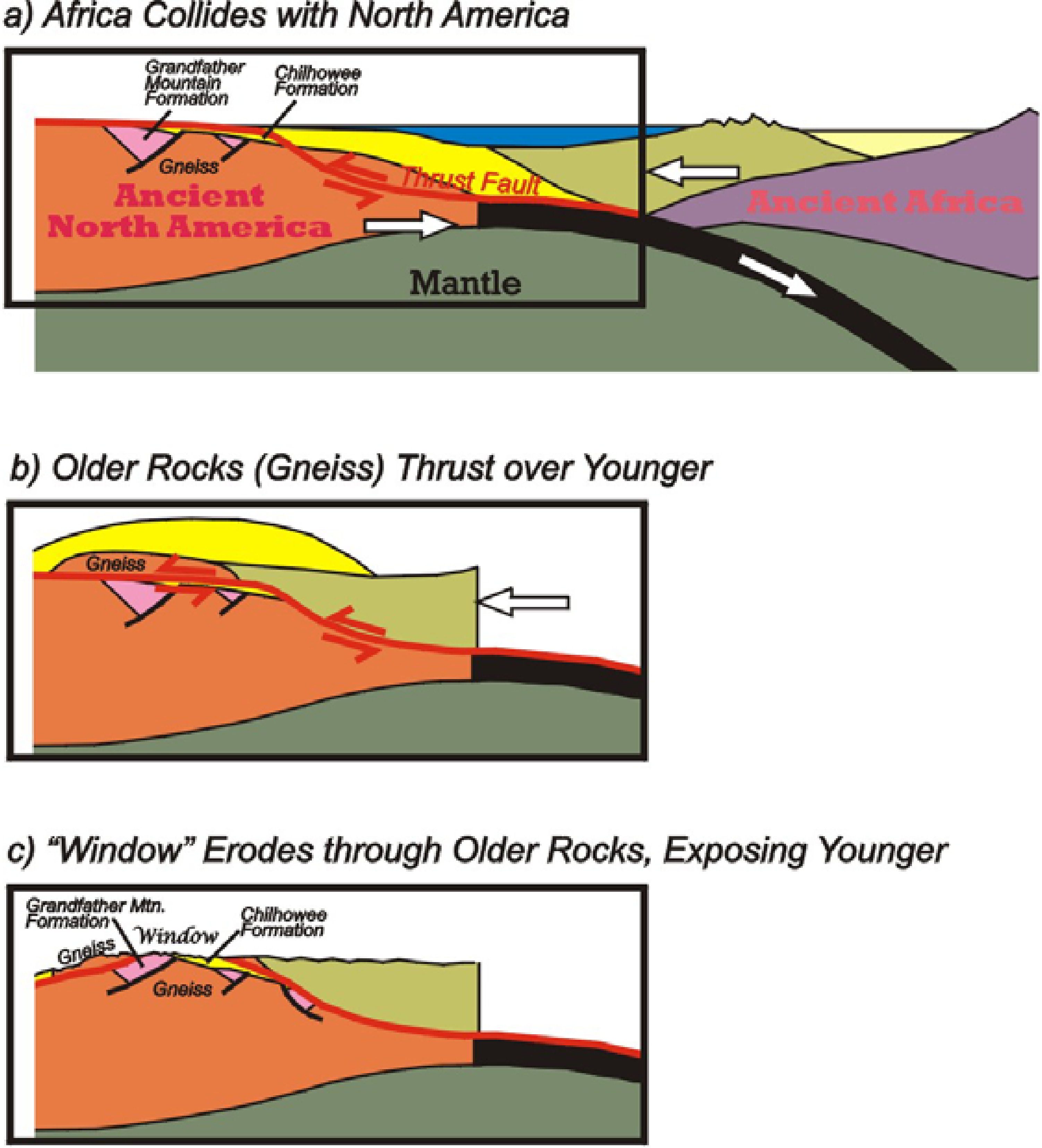


Fig. 27. **Development of Grandfather Mountain Window**. a) As Africa came crashing in (Fig. 20b) a piece of the North America's continental margin broke off along a thrust fault (Fig. 18b). b) Older metamorphic rocks (**gneiss**) were pushed westward over younger rift-valley deposits (**Grandfather Mountain Formation**) and continental shelf strata (**Chilhowee Formation**). c) After the sequence was bent upward into an giant anticline (Fig. 17a) the top eroded away, exposing a "**window**" to view the younger rocks.

Fig. 28. **Thrust fault at Upper Linville Falls.** *In the background, the falls flow over 1.1 billion (1100 million) year old, high-grade metamorphic rock (gneiss). The rock in the foreground is 550 million year old sandstone of the Chilhowee Formation, metamorphosed to quartzite. The older rocks were pushed over the younger ones along a low-angle reverse fault (thrust fault, Fig. 18b). The fault, which is the boundary of the Grandfather Mountain Window (Figs. 26, 27), is approximately in the position of the pool of water.*