“Common people marvel at the unusual; wise people marvel at the common.”

-Confucius

Introduction

Geology along the C&O Canal

Welcome to the Himalayas! Welcome to the bottom of the ocean! Welcome to the beach! Welcome to the Great Rift Valley! Welcome to Indonesia! Welcome to a magma chamber ten miles underground! Welcome to Alaska! Welcome to the neighborhood of trilobites, sharks, dinosaurs…

Welcome, in short, to the C&O Canal.

Along the length of the C&O Canal are rocks that tell stories of all these dramatic episodes. The Canal itself is merely the latest chapter in an epic story of mountains, oceans, volcanoes, and extinct creatures. In the geologic past, the rocks of this homely Canal was at the center of a supercontinent, then deep in the ocean, then in the center of another supercontinent.

So, congratulations! You've picked one of the best places in the world to learn about geology. Sure, it doesn't have the flagrant geological *obviousness* of the Grand Canyon, but the C&O Canal is actually a much better place to learn about the history of the Earth.

The Canal (and its surrounding parkland) cuts across all the key geologic regions of the eastern United States, in one line. As such, it offers a 185-mile-long "transect" across eastern North America, from the tidal reaches of the Atlantic Ocean, through the Appalachian Mountains, and into the stable interior of the continent. The C&O Canal is unique in this way. No other park traverses so much varied terrain; not even the Grand Canyon.

The rocks along the Canal tell a story over a billion years old: the growth of our continent from smaller predecessors, the creation and demise of several supercontinents, the opening and closing of several oceans, the building of enormous mountains, rise and fall of sea level, the evolution and extinction of weird beasts and crazy critters, and the cutting of one of the nation's great rivers. The Potomac's path in turn decided where the Canal would be located, and that decision ultimately brings us here today, you with this book in your hand, in a narrow but lengthy national historical park. It really is a *historical* park – but that history goes back much further than most people realize.

This book tells the story of eastern North America from the perspective of Canal rocks, and it will show you how to figure out this history for yourself (in other words, not just *what* we know, but also *how* we know it). It is my hope that readers will find their experiences in the park enriched by this new knowledge. By viewing the world through "geology-colored glasses," I will help you to discover a wealth of fascinating information about the planet's antiquity, and give you a new perspective on your place here on Earth.

Chapter 1: The twisted logic of geologists

Reading the story in the rocks

What is geology?

Geology is the study of the Earth. Most people associate geology only with "rocks," but in truth it encompasses rocks, volcanoes, earthquakes, oceans, meteorites, climate, the atmosphere, and ancient life. Every natural object, every natural process on the entire planet falls within the purview of this branch of science. Collectively, and rather unimaginatively, all these different aspects are called "The Earth System." While that's a totally boring name, it emphasizes the interconnectivity of rocks with the oceans, the atmosphere with life, and everything with everything else. The Earth is a system, a system of parts that trade matter and energy back and forth between them.

About ten years ago, there was a trend for "ecospheres," little glass orbs full of seawater. (Remember these? Great conversation pieces! Good office décor! They were bigger than Cabbage Patch Kids! …Okay, maybe not.) To refresh your memory, these sealed containers contained algae (simple, one-celled "plants") and tiny shrimp. When you paid $200 for your ecosphere, you were told to bring it home and put it in the sunlight. Once bathed in a nice sunbeam, the algae then used the light's energy to make food through that biochemical wonder known as photosynthesis. One of the waste products of photosynthesis is the element oxygen. Shrimp, being animals, need oxygen to live, so they would breathe it in, and exude their own waste product, the gas carbon dioxide. Carbon dioxide is one of the necessary products for the algae's photosynthesis. In this way, this simple little ecosystem mirrored the planet's overall commerce in simple gases: plants need carbon dioxide and give off oxygen; animals need oxygen and give off carbon dioxide. A neat trade, all things considered: If you don't think so, take a deep breath. You've got to admit: it works out rather well.

Just as the ecosphere is a simple system, so the Earth is a complex one. Rather than just three players (shrimp, algae, and seawater), the planet has a multitude of players interacting in countless ways. Rocks trade matter with the oceans and the atmosphere, water's energy transports grains of rock, animals breathe and reproduce and die, bacteria metabolize nitrogen, snow reflects incoming sunlight, volcanoes spew ash into the upper atmosphere, meteorites impact, bonds break, heat flows, chemistry happens, things change. John Muir put it best: "When we try to pick out anything by itself, we find it hitched to everything else in the Universe."

Geology is the discipline that bothers paying attention to all of that.

And geology is a *science*. Think "science" and you'll likely conjure up an image of white coats, bubbling beakers of colored liquids, maybe some smoke and a stray bolt of lightning or two, all set in a laboratory. Think "geologist" and perhaps the image is different: a rugged individual trekking through some wilderness, hitting rocks with a hammer and taking notes in a little yellow notebook. In truth, neither of these stereotypes hits the mark precisely. Though laboratory experiments figure less in geological investigations than they do in say, biology or chemistry, the scientific method guides geology as surely as it guides physics.

But the main thing that sets geology apart from the other sciences is its historical nature. By this, I mean that geologists are concerned with telling a story: the story of the planet Earth. Like all stories, the Earth's history has characters (rock, atmosphere, ice, oceans, life). Like all good stories, the Earth's history is full of drama. When was the last time you enjoyed a movie where nothing happened? A complex plot is always intriguing, and the Earth is no exception. The Greek philosopher Heraclitus summarized this when he said "Πάντα ῥεῖ καὶ οὐδὲν μένει." In case that's Greek to you, it can be translated, "Change is the only constant." In other words, nothing stays the same. The fundamental nature of the world is *change*, not stasis.

If you're a geologist, it's your job to figure out *what* changed, *when* it changed, *how* it changed, and *why* it changed. In a way, this is a bit like Sherlock Holmes' job: From simple, basic clues, the great detective made inferences that allowed him to deduce how a crime had taken place. In a similar way, geologists make observations, and then interpret those observations using "geologic logic," a system of thinking derived from run-of-the-mill common sense. This book will help you make observations about what you see along the C&O Canal, and once you have done that, you can interpret what you see.

Geologic logic

The Earth is quite old, and the peculiar human beings known as geologists have only been around to wonder about it for a relatively short time. Given that no people were around to observe Earthy happenings for most of geologic time, how the heck are we supposed to figure out what happened?

On the television show *C.S.I.* (and its countless spin-offs), the detectives approach a crime scene with a method for getting the maximum amount of information about what might have transpired. If we're going to tease out the history of the planet, then we too need some sort of clues to work from. Unlike *C.S.I.*, we have no DNA, so stray fibers, bloodstains, or fingerprints. Instead, it turns out that Earth processes leave clues in rocks. In this sense, the Earth's accumulated rocks represent a record of events, as assuredly as a newspaper is a record of events. The only difference between the two is that they're written in different languages. In order to appreciate the C&O Canal from a geologic perspective, we are going to need a crash course in speaking Rock.

First off, there's about a gazillion different kinds of rocks, but right now, you only need to be concerned with three of the broadest categories: Igneous, Sedimentary, and Metamorphic. This rocky triumvirate has been memorized by countless schoolchildren, and so it loses some meaning simply because few bother to think about what these three words imply. They describe *how* a specific rock formed. Consider this:

Igneous rocks are rocks that form from the cooling of liquid (molten) rock. There are few earth substances that are comfortable being liquids at the temperatures which reign at the Earth's surface. Notice how similar the word "igneous" is to "ignite," or "ignition." Igneous rocks start off *hot*. The processes of plate tectonics, which I discuss later in this chapter, bring these hot rocks to the surface of the planet. They either erupt as liquid and then cool on the surface (like lava from a volcano), or they cool underground, and are later brought to the surface in solid form (like a granite). Examples include basalt, granite, and andesite.

Sedimentary rocks are rocks that form from the bits and pieces of other rocks. Sediments are produced when Earth-surface processes (like rainfall, wind, and the flow of rivers) break pre-existing rocks apart. Picture a mountain, any mountain. As the weather works on the mountainside's exposed rock, big chunks get broken off, small chunks get broken off, chemical reactions transform some of its less-stable components, and maybe some of its mass even dissolves into water. Wind or water carries all of these particles (or solutions) off somewhere else. Eventually, the sediments get dropped in a pile, and that pile might get glued together into a sedimentary rock. Examples include shale, sandstone, and limestone.

Metamorphic rocks start off as some kind of pre-existing rock, but then they undergo a transformation. Kind of like how a caterpillar's transformation into a butterfly is termed a "metamorphosis," (literally, a "change in shape") so too is the transformation of a mudstone into a schist. When the original rock is exposed to conditions of heat and pressure beyond its "comfort zone," it undergoes a series of chemical reactions which make it more stable at the hot, pressurized conditions. Certain substances are destroyed, and new ones are formed in their place. When you toast a bagel, you're committing metamorphosis. Nature "toasts her rocks" especially in situations of mountain-building. Examples include slate, schist, gneiss, and marble.

I'll give you some more details on what individual rocks mean in Chapter 2, but for now, chew on this: If we find igneous rocks somewhere along the C&O Canal today, that means that lava (or magma) existed in that spot in the past. If we find sedimentary rocks somewhere along the C&O Canal today, it means that loose sediments were deposited in that area sometime in the past. Ditto for metamorphic rocks: if we find them poking out of some rocky cliff today, as we do at Great Falls, this implies that hot temperatures and high pressures cooked some pre-existing rocks, at some time in the past.

Wearing the uniform

This approach to reading the rock record goes by the unwieldy name "uniformitarianism." The essential part of that word is the root "uniform." The idea behind uniformitarianism is that the laws of nature are *uniform* over time. James Hutton, a Scottish geologist, developed this idea in geology's early years (the late 1700s). He is often paraphrased via the catchphrase "The present is the key to the past." Though individual rocks can get abraded, melted, metamorphosed, or whatever, the processes that do these things to modern rocks are the *same* processes that worked on ancient rocks.

The band Talking Heads tapped into this timeless truth in their 1980 hit "Once in a Lifetime." In that song, frontman David Byrne belted out these uniformitarian lyrics: "Same as it ever was, same as it ever was."

A couple of examples would serve us well here: take sandstone, a sedimentary rock. Sandstone is made of sand. Sand accumulates today in certain areas of the world, beaches and sand dunes in particular. Natural processes like waves and wind concentrate sand in these settings. If we find a sandstone, then we assume that waves or wind must have deposited a bunch of sand in a suitable setting (say, a beach or a dune) in the geologic past. Furthermore, in the time since the sand was deposited, the grains were "glued together" to turn it from loose sand into solid sand*stone*. This interpretation is strengthened when we focus on particular features of sediments that form only in certain settings, like little burrows that clams dig into beach sands – if we find those same features in ancient sands, preserved as sandstones, then we can be confident that it indeed formed at a beach.

Let's take granite, a common igneous rock, as our second example. If we find a granite exposed along the C&O Canal, like we do along the Billy Goat Trail, we might well wonder what processes put it there. In other words, what processes give rise to granites today? (And therefore what processes must have happened here in the past?) Well, it turns out that granites form from magma, or else they wouldn't qualify as igneous rocks.

More specifically, granites are light in color, meaning that they come from magmas of a certain composition (enriched in chemical elements like silicon and potassium), and they have big crystals. Crystals take time to form and grow, so when we find big, visible crystals in igneous rocks, we infer that they cooled down very slowly. Lava erupted onto the surface of the earth cools rapidly and makes small crystals, so geologists infer that large crystals indicate slow cooling in a nice, insulated environment: that is, underground. When the magma is surrounded by warm rock, it loses heat less rapidly, and so crystals have more time to grow large. Think about between decanting a pot of hot soup, fresh from the stovetop. You pour half of it in a Thermos, and then pour the other half into a bowl and set it on the windowsill. One loses heat rapidly, and thus cools rapidly; the other takes a lot longer. Translate this into crystal growth, and you've got a coarse grain size in the resulting rock.

Granites form today due to the partial melting of other rocks. When you have a rock made of many different "ingredients" and you subject it to a lot of heat, some of those ingredients are going to act one way, and some are going to act differently. Think about the difference between putting butter and onions in a frying pan. As the heat rises, the butter melts, but the onion just cooks. Better yet: imagine a chunky chocolate-chip cookie (my favorite kind): it's loaded with nuts, chocolate chips, maybe some coconut shavings and oatmeal flakes, too. Now put this cookie in the toaster: as you do, the chocolate softens and liquefies, running out of the cookie as a liquid, but the rest of the cookie just burns. A similar sort of process gives rise to a granite: Say you have a sedimentary rock that is getting heated up. The "ingredients" in that sedimentary rock with the lowest melting points will liquefy first. Because liquids are generally less dense than solids, the liquid will rise upwards, taking these low-melting point ingredients away from a higher-melting point "residue" which is left behind. Voila! You now have a magma that is of a different composition than its "parent" material: this is what is meant by *partial* melting.

So that's *how* granites form today – but *where* do granites form today? It turns out that they only seem to be generated where continents bump into each other. Think of dents in your car door – those annoying divots that get created when somebody bumps their grocery cart into your Porsche (*you have a Porsche*, right?), and it impacts your brand-new paint job. Those dents don't just happen by themselves: it takes another object impacting your vehicle to make them. Similarly, partial melting of the Earth's crust (the raw source material for granite) only occurs when continents collide with one another. Thus, when we find a blob of granite alongside the C&O Canal, it's not only evidence for a magma chamber cooling slowly underground, it's also an indication that continents have plowed into one another at or near that spot! Granites are the calling cards left behind by continental collisions (Figure 1.1).

Wayward continents

The science of geology got a shot in the arm in the late 1960s and 1970s. A revolutionary new idea, the notion of plate tectonics, changed the way that geologists looked at the world. **Plate tectonics** is a unifying theory of geology: it knits together all kinds of disparate observations into a cohesive story. Plate tectonics explains earthquakes, volcanoes, mountain ranges, and even the most basic fact about the surface of the Earth: we have continents and we have oceans.

This fact may seem extraordinarily obvious to you, because we humans are land-dwellers, and we don't often think about the bottom of the sea. We live on the outermost layer of the Earth, the crust. But 70% of the crust is in Davey Jones' locker. The ocean is where it is because that's the crust's lowest spot. Water always flows downhill, and fills in the low spots, so ocean water covers up the entire oceanic portion of the crust. If you were to vacuum all the water out of the world's oceans and view the planet dry, you would be struck by what a precise dichotomy there is between continents and ocean basins. Continents are big, thick rafts of crust, stitched together of many disparate rocks. Oceanic rocks, on the other hand, are uniform and monotonous, thin and wrinkly. They appear to be cut from different cloth.

Add in a perspective on the age of these two actors, and their differences are even more profound: The oldest oceanic crust is a mere 200 million years old. That may sound like a lot to a human being, but to geology it's small potatoes. The oldest continental dates to over 4 billion years old. In other words, the continents have rocks that are *two thousand times* older than the *oldest* oceanic rocks.

Why this enormous discrepancy? We get a hint if we turn our attention away from the oldest rocks in the ocean and towards the youngest: there are oceanic rocks are being generated today at the mid-ocean ridges. The mid-ocean ridge (Figure 1.2) is the world's longest mountain range, and it's almost entirely drowned beneath the sea. Like the seams on a baseball, the mid-ocean ridge wraps around the planet, over 50,000 kilometers long. It's got an odd shape, a sort of stair-stepping zig-zag pattern of high ridges occurring in segments, separated laterally by large cracks. Furthermore, along the crest of the ridge, there's something unexpected: a valley! If the ocean were drained, and you were able to get a sense of how the mid-ocean ridge compares to everything else on the globe in shape and in size, you would certainly declare it the most distinctive topographic feature on Earth.

Let's return now to the issue of the age of the oceanic crust. As Figure 1.2 shows, the oceanic crust is youngest right there at the mid-ocean ridge! It gets progressively older as you travel away from the ridge in both directions, reaching its maximum elderly status right at the edge of the continents which bound the ocean. The implication is that somehow the mid-ocean ridge is *making* new oceanic crust, and that the more it makes, the further the continents get pushed apart!

This realization is backed up by two further lines of evidence: the oceanic crust right at the mid-ocean ridge is not only young, it's *hot*. The further away from the ridge you get, the colder the crust gets. Second, the crust right at the mid-ocean ridge is thin. As we've seen with the other trends, the further away you get from the ridge, the thicker the crust gets, until it's about ten kilometers thick at "maturity." (Figure 1.3) This makes sense if it's true that new oceanic crust is being produced at the mid-ocean ridge: the oceanic crust is made of basalt, an igneous rock. It forms from lava. Lava is hot. As it gets older, it cools down, and as it cools, additional hot rock underneath congeals onto it, building up the thickness from the top down.

No one knew about the existence of the mid-ocean ridge until the Second World War, when the U.S. government spent a lot of money mapping the ocean floor. Their motivation was to figure out how to defeat German submarines (U-boats), but the big payoff came when the data was made public after the war. It was then that geologists around the world came to recognize the reality of **sea-floor spreading**.

Oceans get wider over time. As continents move further apart, it's like opening up a partly-healed wound. The scab tears open, and fresh blood wells to the surface, congealing into a new, younger strip of scab. Repeat the process for several million years, and you'd have a heckuva scar. The Earth is the same way: the continents move apart, and lava wells up in between, sealing the crack with fresh oceanic crust.

All well and good, you might be thinking. But the planet isn't getting any larger, so if you open up new ocean basins by moving continents and spreading the sea-floor, then you have to get rid of seafloor somewhere else to compensate. You're right, and I congratulate you on your insightful thinking! There is indeed a means of getting rid of old oceanic-crust. It's called **subduction**.

Subduction is the recycling of oceanic crust back into the mantle. Another observation made in the World War Two surveys of the seafloor was that there are exceptionally deep areas of the world's ocean basins: **trenches**. The deepest of these, the Marianas Trench in the south Pacific, is about 11 kilometers deep! Trenches mark the spot where oceanic crust sinks back down into the mantle. Interestingly, the world's trenches are inevitably paralleled by chains of volcanoes (Figure 1.4). Geologists interpret this remarkable correlation to the oceanic crust melting as it plunges into the mantle. It's hot down there, and a slab of oceanic crust that's cold and solid at the bottom of the ocean won't be once it's 50 kilometers into the mantle. When it melts, the magma doesn’t stick around. Being a fluid, magma is less dense than solid rock, and so it rises, as do the blobs in a lava lamp. If these blobs of magma find their way to the surface, they will build up an erupting volcano (Figure 1.5).

Oceanic crust can be subducted underneath other oceanic crust, as shown in Figures 1.4 and 1.5). But it can also be subducted under the continent’s thicker crust. Figure 1.6 shows this scenario: this is what gives rise to the long series of volcanoes paralleling South America’s west coast (the Andes): subduction of Pacific Oceanic crust eastward underneath the edge of South America. Note that not all the magma makes it to the surface. Some of it lodges in pockets that stay at depth. These magma chambers cool slowly to form **plutons**: solid bodies of coarse-grained igneous rock, like granite. (Later, through uplifting to higher levels in the crust, these plutons may become exposed at the surface.)

Now that we’ve taken a close look at the ocean floor, let’s re-examine the continents with our new perspective. Figure 1.6 shows how different the continents and ocean basins are. The crust they are made of is totally different. Whereas the oceans were floored by a 10-kilometer thick slab of the dark igneous rock **basalt**, the continents are on average 40 kilometers thick, and have an average composition that’s approximately granitic. As a result, you could think of continents as “fluffy” – they’re thick “rafts” of crust, floating higher in the mantle than the oceanic crust. Basalt is dense, granite is more buoyant. When the two encounter one another, as in Figure 1.6, the continents always win, and the oceanic crust gets shoved down the hatch. Continents are survivors; oceanic crust is cheap, disposable. Over time, continents persist like heirlooms, while oceanic crust is trashed whenever it proves inconvenient.

This explains the disparity in ages between our planet’s two major surface features: the continents are so ancient because every time they crash into the oceanic crust, they come out on top (literally). The oceanic crust is so young because it’s been subject to perpetual recycling for 4.5 billion years.

The recognition of sea-floor spreading caused geologists to take a fresh look at an old suggestion: the notion of **continental drift**. Without knowing anything about the oceanic floor, a German meteorologist named Alfred Wegner made a bold suggestion in the early 1900s. Wegner suggested that continents are not as permanent as they might seem at first glance. Rather, they skid around the surface of the Earth like bumper cars, occasionally crashing into each other, and at other times drifting apart. Wegner assembled a wealth of evidence supporting his conjecture, but it was such a radical idea that he was insulted and made fun of. The poor guy was ahead of his time.

Wegner noticed that if you traced out major fossil distributions, glacial deposits, lava flows, desert sands, coal layers, and other features of the continents, they frequently dropped off the eastern edge of one continent only to pick up again on the western edge of another continent, like a photograph ripped in half. Furthermore, all the major mountain belts seemed to be aligned parallel to the edges of these continents. Even the shapes of the continents themselves suggested that they could fit together like the pieces of a jigsaw puzzle!

Wegner's evidence was correct, but it wasn't until sea-floor spreading came along that scientists realized how continents could drift. As we see it now, each of the continents is surrounded by a "skirt" of oceanic crust. Roughly, this shape is similar to that of a flying saucer (Figure 1.7). The continent is thickest in the middle, and the oceanic crust around it is quite thin. Both types of crust move together as one unit, a **tectonic plate**. Just like a person can change their clothes, so too can a continent shed its skirt of oceanic crust and later develop a new one in its place.

As these tectonic plates drift around the surface of the Earth, subducting oceanic crust, occasionally the continents will run into one another. Figure 1.8 shows how this happens. As two tectonic plates move towards one another, the oceanic crust between them is subducted. After the entire ocean basin has been shoved down the hatch, the two continents come into direct contact. They collide, with the same result as a collision between two cars: there's a lot of violent shaking, and a lot of destruction. The leading edges of both continents get mangled, with huge masses of rock shoved up into the air. This is how mountain ranges are formed, an event geologists call an **orogeny**. The Himalayas, in central Asia, are a modern example of an orogeny, as the Indian Plate plows into the Eurasian Plate.

Along the C&O Canal, we find rocks that record two major episodes of orogeny: one during the Proterozoic Eon, about a billion years ago (the Grenville Orogeny), and another during the Paleozoic Era, between 460 and 300 million years ago. This latter episode had three pulses: the Taconian, Acadian, and Appalachian Orogenies, which collectively formed the Appalachian Mountains. This one-two-three event was like running into a raccoon with your car, then a Volkswagen bug, and then a Mack Truck. The eastern edge of North America ran into a volcanic island chain, then into a small continent the size of Madagascar or Japan, and then into Africa. (We had already hit part of the Mack Truck before: the Grenville Orogeny is thought to be partly due to collision with the part of Africa that today makes up the Congo region.)

As plates drift, they not only move towards each other; they can also move apart. If this happens, we get an episode of **continental rifting** (Figure 1.9). Continents are good at insulating the heat of the layer of the Earth beneath them. This layer, the mantle, will heat up to unstable levels if insulated too well for too long. If it gets too hot in the mantle, it will get more fluid, and flow faster. This flow in the mantle is what drives plate tectonics: the plates are carried along on top of mantle currents, just like a whitewater raft is carried along by the river underneath it. If the currents in the mantle get strong enough, they will rip the continental "raft" into several pieces. Figure 1.9 shows how this works: as the overlying continental plate gets stretched, it breaks along faults. Some blocks of crust drop downward into the mantle: this is happening today underneath the Great Rift Valley of east Africa. These rift valleys fill in with sediments from the continent, and they also get choked with voluminous eruptions of dark lava. This is the variety called basalt. It's tapping the mantle below, drawing up the most mobile minerals in molten form. Recall that basalt is also the stuff we earlier learned formed the oceanic crust. All you have to do is keep stretching open that rift valley, keep sealing the crack with basalt, and eventually the sea will come pouring in. At that point, you no longer have a rift valley. Instead, you have a new ocean basin. (If you head north from the modern Great

Rift Valley, you'll find young, skinny ocean basins in the Red Sea and the Gulf of Aden. These are nothing more than flooded rift valleys, but someday they could be as wide as the Pacific. At the bottom of each, you will find a mid-ocean ridge. See Chapter 6, Figure 6.8)

These tectonic plates don't move fast by human standards – they skid along at about the same rate at which your fingernails grow – a couple of inches per year. In a human lifetime, a tectonic plate will move only a dozen feet or so. Doesn't sound like much, until you take into account the vast stretch of geologic time. Keep moving the plates at that rate, and within 250 million years, you can open up an ocean the size of the Atlantic.

The big picture for the planet, then, is something like we see in Figure 1.10. The Earth has more layers than an onion! Outermost, as we've seen, is the crust. We now know that the crust comes in two varieties: continental and oceanic. Continents are about four times as thick as oceanic crust, reflecting their lower density. Oceanic crust will subduct under a continent if the two collide, generating volcanoes (V.). Continents are too buoyant to subduct, so if they collide, it causes an orogeny and they raise up a mountain range (M.).

Notice that the uppermost layer of the mantle rides along with the crust. Together, these two top layers are known as the **lithosphere** (Greek for "rock sphere"). Each tectonic plate is made of lithosphere: crust of one or two varieties, plus the lithospheric mantle directly underneath. Below the lithosphere is the **asthenosphere**, the "sick, weakly" layer of the mantle ("asthmatic" comes from the same root). Remember all the flow we talked about earlier: the currents which drag the tectonic plates around? That's all happening in the asthenosphere, which is partially (but not totally) molten. Below the asthenosphere is another layer of mantle which also behaves as a solid.

The core is made of the densest stuff on the planet: iron and nickel. Because of variations in temperature and pressure, the **outer core** is liquid (this is the source of the Earth's magnetic field) and the **inner core** is solid.

Surface processes versus plate tectonics

Consider the phrase "Two competitors are battling for dominance over the surface of the Earth." It sounds like the plot of a movie like *Godzilla vs. King Kong*, right? As far as geology goes, it's quite true for the constant competition between plate tectonics and the surficial forces of erosion and deposition. By "surficial," I mean the forces operating on the Earth's *surface*: wind and rain, freezing and warming by the sun, ice and gravity. These surficial processes endeavor to tear down the Earth's mountains and hills. The sediments they generate are deposited elsewhere, in low-lying areas that act as basins.

One way to visualize this would be to examine Figure 1.11: it shows a buckled sidewalk in Washington, DC. This buckled sidewalk serves as an analogy for the different situations operating in uplifted and down-dropped areas of the Earth's surface. Note that even in this small example, the sidewalk panels which are uplifted (on the right) are deeply incised by water, and they have been stripped clean of sand and dirt by the energy of rain washing over them (not to mention the constant scuffing they endure at the feet of pedestrians). On the left, the down-dropped sidewalk panels have been buried by layers of sediment, washed off of neighboring areas. These buried panels are protected from erosion by the overlying blanket of sediment. The geologic record is more "complete" in the sedimentary basin on the left, and an unconformity is being produced in the uplifted "mountainous" region on the right.

Plate tectonics shoves rock up in the air (uplift), and erosion tears them down again. Plate tectonics is willy-nilly about its uplift – it's not a prime purpose, merely a symptom. Plates move because they're dragged around by currents deep in the Earth's mantle. The only "goal" here is the release of heat from the mantle. All the action seen as chunks of the Earth's crust careen around is a consequence of that deep heat release. Occasionally, these chunks will ram into one another. When this happens, mountains get shoved upwards. Then the plates drift apart again, and the mountains are abandoned.

Surficial processes, by comparison, are slow and methodical. They are constantly at work breaking rocks into smaller pieces, rotting out the less stable constituents of the rocks, and pulling the various pieces downward under the influence of gravity. If this suite of surficial processes had a goal, it would be to resurface the entire surface of the planet into a smooth sphere. Surficial processes tear down the bits that stick up, and they fill in the nooks and crannies. It's simply a question of trying to reach equilibrium: redistributing rock mass to minimize potential energy.

So, there's a conflict here: a set of processes (mantle movement, and the resulting plate motions above) creates a bumpy landscape, and another set of processes (rainfall, gravity, hurricanes, landslides) seek to smooth the landscape out. As you can tell by looking around you, here at the C&O Canal or anywhere else, neither of these players has won yet. As long as there is heat being vented from the Earth's mantle, plate tectonics keeps operating, and as long as plate tectonics keeps shoving rock up into mountains, the forces of erosion will keep tearing them down.

Recipe for a rock: ingredients

You're in the kitchen, baking cookies. Let's say you're baking a batch of cookies for me, and you know my favorite cookies are the over-the-top, everything-but-the-kitchen sink chunky kind. So you open the cupboard, pull out the flour, the brown sugar, the white sugar, some eggs, a stick of butter, some chopped walnuts, maybe a handful of raisins, a dash of vanilla extract, and (of course) *lots* of chocolate chips. You mix these ingredients together in a bowl, and then put spoonfuls of the dough on a cookie sheet. Then you slip the sheet onto the oven rack, and set the timer for fifteen minutes.

When the timer buzzes, out comes the cookie sheet. The smell is fantastic! You use a spatula to pry the cookies onto a cooling rack, but you can't help nibbling on one of the crumbs. Delicious! Maybe just one more… Maybe two more…

Once you've eaten your fill and start feeling sick, take a good long look at one of your cookies. You've got an entity in your hand, The Cookie, which did not exist before you put the ingredients together and followed the recipe to make it. Consider a single chocolate chip in the middle of your cookie: its physical properties distinguish it from the walnuts and the raisins. By means of color, texture, hardness, and taste, it's pretty easy to differentiate these chunky ingredients. Each is distinct, and yet altogether, they comprise the total cookie. Figure 1.12

Similarly, rocks have ingredients. These simpler building blocks which make up the rock are known as **minerals**. They are as distinct from one another as chocolate chips are from walnuts, and for the same reasons. You can tell minerals apart on the basis of their physical characteristics. Different minerals have different colors, textures, hardness, and, yes, even different tastes (salt is a mineral, for instance, and you know how distinctive it tastes).

What qualifies as a mineral? Not chocolate chips! Minerals have to meet certain criteria. They must be: (1) solid, (2) inorganic – that is, not produced by living processes, (3) chemically distinct – in other words, made up of a certain set of ingredients, without too many variations or impurities, (4) naturally occurring, and (5) have a crystalline internal structure – on a molecular level, minerals have a geometric lattice.

This roster of qualifications excludes many substances, and includes some surprises. Coal, for instance: though a natural geological product, and commonly referred to as a rock, coal does not qualify as a mineral. Coal is derived from plant matter – it is literally the compressed remains of ancient swamps, and as such is organic. Glass, too, is out. On a molecular level, glass has no crystal lattice; it is "amorphous" on the finest scale. Evidence of this may be found in the tremendous malleability of glass: just heat it up a little bit, and it can be bent and blown into all sorts of shapes. This is a property which makes it very useful to those of us who appreciate fine sculpture and bottled beer, but it's not the property of a mineral. Ceramics, like your toilet or a dinner plate, meet four of the criteria, but they're artificial, and so don't count as minerals. Lastly and somewhat unexpectedly, ice *does* count as a mineral! It's solid, inorganic, chemically distinct (only H_2O in there!), occurs naturally, and has an internal crystal lattice (which you can observe as you watch ice crystals grow, perhaps in the winter waters of the C&O Canal!). It meets all the criteria. So ice is a mineral, but liquid water isn't.

Minerals are the basic constituents of the Earth; individual mineral growths are **crystals**. When most people think of a "crystal," they think of a great big gleaming prism of sparkling transparency, the sort of thing displayed in New Age stores or the gem exhibit in a museum like the Smithsonian. A thing of beauty, in other words. While some crystals are indeed beautiful, most are not. Picture a granite countertop. (Perhaps you have one in your kitchen at home, or perhaps they have one at your local bank.) The granite has probably been polished down to a smooth surface, but that lets us get a good look at the shape of the crystals inside. Figure 1.12 Fitted together like the pieces of a jigsaw puzzle are strange shapes of pink, grey, black, and white. Each of these different colors is a different mineral "species" and each of the puzzle-pieces is an individual crystal of that mineral. The pink, for instance, is the mineral **potassium feldspar**, a very common constituent of the Earth's crust. The grey one is **quartz**, also very common. The white is another kind of feldspar, the variety with the almost unpronounceable name “**plagioclase**” (*pladj-ee-oh-clayz*). And, depending on its shape, the black could be either **biotite mica**, which looks like a stack of tea saucers, or long blade-like lathes of **amphibole**.

A mineral’s comfort zone

Minerals are configurations of elements which are stable at the time of their formation. Another way of putting this is to say they’re “comfortable” or “happy.” Consider yourself: you would not happy if you were being crushed under tremendous pressure, or if you were roasting on a blazing summer day, or freezing because you’re only wearing a tee-shirt and a blizzard rolls in. Depending how pressing your state of discomfort is, you’ll take action to get yourself comfortable again. Minerals are the same way: their internal configurations of elements are only stable under certain conditions. Each mineral has its own “happy place,” when it is at **equilibrium** with its environment. Outside of this comfort zone, it’s edgy and unstable – a situation which won’t last long. In order to re-attain equilibrium, the mineral crystal either changes to a different crystal form, or it reacts to form a stable substance – perhaps a new mineral.

Usually, the minerals we find at the Earth’s surface are stable, at least within the range of human experience. At the surface, certain minerals are more stable than others. Quartz, for instance, is exceptionally well-suited to the conditions prevailing on the surface of the planet. Minerals like hematite, or biotite mica, are less stable, and if they are exposed to the weather for any length of time, they will begin to rust. This rust is a chemical effect, the reaction of the element iron in the mineral with oxygen in the air. We start off with two different substances, iron and oxygen, and we end up with a new substance that wasn’t there before: rust (iron oxide). Anyone who has ever left his or her bicycle outside in the rain is familiar with the fact that water helps this rusting process to happen. Rusting is an example of **chemical weathering** (Figure 1.13 A).

Chemical weathering is one of the two ways in which the processes operating at the Earth’s surface break down rocks and minerals. The other variety of weathering is **physical weathering**. This amounts to nothing more than breaking something large into smaller pieces. When you grind pepper onto your Caesar salad, you’re physically weathering the peppercorns. When you drop a teacup on the floor and it explodes into hundreds of shards, that too is physical weathering (Figure 1.13 B). In both cases, you start off with a large piece, and you end up with many small pieces *of the same substance*. A chunk of limestone bouncing down a hillside impacts and breaks into several pieces: though each resulting piece is smaller than the original, it’s still made of limestone. With physical weathering, nothing new is being created; pieces of a shattered window are still made of glass. Compare this to the previous example of a rusty bicycle. You start off with steel on the bike and oxygen in the air, (and a little rainfall to catalyze the reaction), but you end up with something new: rust. This is what differentiates chemical weathering from physical weathering.

As you might expect, the two processes complement each other quite nicely. Physical weathering cracks open fresh surfaces for chemical weathering to attack. Likewise, when chemical weathering degrades some of a rock’s stock of minerals, the rock is weaker, making it more susceptible to physical weathering (Figure 1.14). The C&O Canal offers great examples of both of these relationships. The Monocacy Aqueduct, a "bridge of water" that used to float Canal barges over the Monocacy River at its confluence with the Potomac, is built of quartzite from nearby Sugarloaf Mountain. Walking across the Aqueduct (it has since been drained of water), you can examine the blocks of stone used to construct it. Many of these blocks have their corners worn away preferentially. Contemplating such a repetitive pattern, you would likely ask yourself why the corners, more than any other part of the block, get so worn away? The answer is that the corners have the most surface exposed to the elements (Figure 1.15). Think of smaller cubes of stone within the block. A cube without any surface exposure at all is completely shielded from the corrosive effects of the weather. A cube in the middle of one of the block faces has one of its six sides exposed, and so will experience chemical weathering on that face only. Along the edges of the block, a cube would have two of its faces exposed to the weather, and in a corner position, the poor little cube has half of its surface area (three out of six sides) exposed to chemical attack. With more area to work on in the corners, chemical weathering is more effective.

For this same reason, when a chef cooks potatoes in boiling water, he cuts them into small pieces. The amount of potato is the same pre- and post-chopping. But the collection of smaller pieces of potato will cook faster than if the whole potato were to be tossed unchopped into the pot. Again, the reason is surface area. The more pieces the potato is cut into, the more surface area is exposed, and the faster it will cook.

At Great Falls, we see a situation where chemical weathering paves the way for more intensified physical weathering. If you hike the Billy Goat Trail, or walk from the Great Falls Tavern visitor center out to the observation deck on Olmstead Island, you will pass numerous holes in the rock. These are potholes, a natural feature causing by the river's waters carving into the rock. (More on pothole formation in Chapter 8.) The rock they are drilled into is a metamorphic rock made of several different minerals. As you look at it, you will notice a platy banding in the rock, where dark layers alternated with light-colored layers. The layers are mostly upright (vertical). Now get up close and personal with one of the potholes (there are some nice ones just downstream of the bridge that leads from the Towpath to Olmstead Island). First making sure there are no spiders inside, run your hand over the inside surface of the pothole. There will be a fine-scale variation between the dark and the light layers. The dark layers will be depressed into the rock, and the light-colored layers will bulge upwards against your fingertips, standing out in high relief.

What's going on here is that physical weathering (the drilling of the potholes in the river) is opening up access to minerals that were previously ensconced safely in the middle of the rock. Now that they're all exposed to the air, the light-colored and the dark-colored minerals can attempt to stand up to chemical weathering. They will do this with various degrees of success: the light-colored ones are stable at Earth surface conditions, but the dark ones aren't. As a result, the dark-colored minerals will "rot" (chemical decompose) but the light-colored ones won't. The next time the river water swirls a mix of sand and grit in that pothole, it will etch away the dark-colored minerals and leave the light-colored ones behind.

The rock cycle

Rocks are great: they can serve as a window into former ages, they can be sculpted into fantastic forms (whether by Michelangelo or by the Potomac River), and sometimes their textures and colors are just plain old beautiful. But, like all of life's pleasures, rocks are ephemeral. They get formed, they last awhile, and then they get destroyed. The processes of plate tectonics generate igneous and metamorphic rocks, and the processes of sedimentation generate sedimentary rocks, but the processes of weathering and erosion break rocks down, effectively recycling them by generating pieces of rock ("sediments") and then laying those sediments down elsewhere, perhaps to become new sedimentary rocks. The longer a rock exists, the more likely it is to be weathered and eroded. This is why we have so many rocks from recent geologic history, and so few from the misty beginnings of geologic time.

The word "recycling" is entirely appropriate to describe this process. The forces of plate tectonics raise up mountains, which are then attacked by ice, rain, and wind, which generates sediments, which are deposited in broad sheets adjacent to the mountains, which are then the materials to be crumpled up into the mountains of tomorrow. Over and over, the process creates rock and destroys it and creates it anew using the same materials: this is the rock cycle. Figure 1.16 shows this tangled knot of relationships. Sedimentary rock gets metamorphosed. Metamorphic rock melts. It re-solidifies into igneous rock. Exposed to the surface conditions of rain and weather, the igneous rock is weathered into small grains, and those eventually are deposited a hundred miles away, becoming new sedimentary rocks… On and on it goes. It never ends.

Chapter 2: Getting to know your neighbors

The main types of rock seen along the C&O Canal

As noted earlier, the three main "families" of rocks are designated on the basis of *how they form*. Sedimentary rocks form from sediments. Igneous rocks form from molten rock. Metamorphic rocks form from the chemical alteration of pre-existing rocks.

Let's now take a closer look at the specific varieties found in each family, and see what they can tell us about the past.

Sedimentary rocks: documenting ancient environments

Sedimentary rocks are made of bits and pieces of other rocks. These bits and pieces may be rock fragments, individual mineral grains, or chemical residues like rust, or minerals that have dissolved in water. Regardless of the individual specifics, all of these sedimentary raw materials are produced when other, older rocks are exposed at the surface of the planet, weathered, and eroded.

Some stuff dissolves in water, some reacts with other substances, and some remains as solid chunks (collectively called "clasts," from the Greek for *broken*). The clasts are easiest to visualize: everyone has seen sand, everyone has flung a pebble into a pond. Pebbles and grains of sand are both sediments, as are boulders, cobbles, silt, and clay. The difference between these? Merely their size: Boulders are big, with cobbles a bit smaller, gravel a bit smaller still, sand smaller yet (but still big enough to see with the naked eye). Below our unaided vision's ability to discern are silt and clay, and these may be distinguished by the sense of touch. Take a pinch of the mystery powder between your fingers, and rub it back and forth. Silt grains feel gritty in the hand, but clay feels smooth, because its particles are smaller than our nerves can discriminate.

These clasts get weathered out of a source which is part of the solid Earth (the bedrock): a cliff, perhaps, and then they are **eroded** away from that source area, **transported** some distance, and (sooner or later) **deposited**. After they are deposited, they may or may not be turned into rock, a process called **lithification**. Each of these steps along the clast's path leaves its mark, like a hero accumulating battle scars on an epic journey. The job of a sedimentary geologist is to read the odyssey from the resultant sedimentary grains.

Each detail of a sediment tells us something about its history. Like a connoisseur elucidating a wine's *terroir* from the details of its taste, a geologist can tease out a sediment's finest details. Whether it's wine or mud, the good news is that you and I can also develop the sophistication to appreciate these subtle differences. (And just as learning about wine helps you appreciate it more, so does learning about sediment!)

Let's start off by focusing on how big the grains are that make up a given sedimentary rock. In geology as in life, size matters. To get these particles of rock (clasts) to move, they must be pushed, pulled, carried, or rolled. It will be obvious to you that it is easier to move small particles than large ones. Blow on a pile of silt and it will poof up into the air. A boulder, however, will not respond to your exhalation, even if you're the Big Bad Wolf. All the huffing and puffing in the world won't move large boulders. (A really big flood or a glacier can move them, however!)

So, we have a correlation here: the larger the particles a sedimentary rock is made of, the stronger the energy of the wind or water which deposited it. (In most cases, water is the prime mover of sediment; wind plays only a supporting role.) Coarse-grained sedimentary rocks, therefore, were deposited by high-energy water. The coarsest we will see along the C&O Canal are **conglomerates** (Figure 2.1), where the individual particles range in size between pebbles and boulders. Medium-sized grains, like sand, were deposited by medium-energy waters, and make **sandstones**. Fine-sized grains, like silt or clay, were deposited by the calmest, lowest-energy waters, and make up sedimentary rocks like **shales** and **siltstones**. (The difference between a shale and a siltstone is that a shale will split easily into flakes, whereas siltstone is more blocky and solid in every direction. A shale is shown in Figure 2.1.)

The second thing a sedimentary geologist will check for is the roundness of the grains. Like stamps in a passport, how rounded the clasts are tell us something about how far they have traveled. Think about the history of an individual clast: weathering cracks it off from its parent rock, and sets it loose in the world. Then the forces of wind, water, gravity, maybe even glacial ice go to work on it. As the clast is tumbled along, the sharp parts stick out and are more likely to impact its neighbors. As a result, the sharp bits don't last long. (Figure 2.2 A) The further the clast travels, the more likely it is to have its rough and angular parts smoothed away. The further the clast travels, the rounder and smoother it becomes.

If these clasts become stuck together into a rock, we can still tell how far they traveled before they were united into a rock. If the clasts are big enough to see easily (that is, gravel sized or larger), the resulting sedimentary rocks are called **breccia** (rhymes with "getcha"; composed of angular pieces) and **conglomerate** (composed of rounded pieces). (Figure 2.2 B and C)

After size and rounding, the next aspect of a sedimentary deposit or sedimentary rock to catch a geologist's eye is how well sorted it is. **Sorting** is how well the various sizes in a batch of sediment compare to one another: Are they all sand-sized? Is it clay-sized? Is it a mix of sand and clay? Is it sand, clay, gravel, cobbles, and boulders all mixed together? (Figure 2.3) Sorting shows us how systematically these sediments were deposited: the more uniform a "population" of sedimentary clasts is, the more uniform the energy of the water that deposited it. The more varied the sizes are, the more chaotic the original deposition must have been.

In examining sorting, the question we are asking ourselves is: was this sediment dumped all at once, or was it systematically deposited? If it is dumped all at once, like by a flash flood, we would expect to find large grains like gravels and cobbles mixed in with smaller grains, like sand and silt. If it is systematically deposited, we would expect to see that the sediment is "winnowed out": as the current slows down, large particles are deposited, and smaller ones continue traveling in the water. The current slows a bit more, and medium-sized particles drop to the bottom. The currents slows even further, and slightly smaller material gets deposited, and the water can only carry the finest clasts any further. Eventually, when the current's forward momentum ceases entirely, even the finest sediments drop out of suspension, and settle over the bottom. Such a process yields a series of well-sorted sedimentary deposits: big grains in one area, medium grains downstream, and finer ones still beyond that. It's *methodical*. Compare this again to the poorly-sorted example given above: In a flash flood, the water strength quickly builds up, gathering all manner of particles, and then just as quickly subsides, dropping everything together. It's *sloppy*.

Compare Figure 2.3 B and C: the sandstone (B) is well sorted because it is composed of entirely sand-sized grains. Nothing too big, nothing too small. Like Goldilocks amongst the three bears, it's juuuuuuuust right. The conglomerate (C), on the other hand, is a mix of grain sizes: pebbles are jumbled together with sand, and even with silt. Obviously, this is sloppy deposition: I'm reminded less of Goldilocks, and more of the Tasmanian Devil!

Lastly, geologists can read part of a sediment's tale from its composition. The minerals present in a sedimentary rock tell us something about the conditions it was deposited under. Sandstones offer a good example. (Figure 2.4) Sandstone 2.4A is a quartz sandstone, which implies it's almost entirely quartz. Quartz is one of the most common minerals in the Earth's crust. More importantly, it one of the most stable minerals at Earth surface conditions of temperature, pressure, and humidity. Whereas nine out of ten minerals will decay (chemically weather) into other substances at the Earth's surface (Figure 1.13), quartz is happy the way it is.

Consider a Snickers™ bar, which is composed of peanuts, nougat, caramel, and chocolate. Imagine eating a bite of Snickers™, but instead of chewing it, simply let it dissolve in your mouth. As the candy bar equilibrates to conditions inside your mouth, the various ingredients will adjust. The first to go will be the chocolate, which probably started dissolving on your fingers, before it even got into your mouth. Next to go will be the caramel, with the nougat lingering on your tongue for a while longer yet. But the peanuts, no matter how long you suck on them, will not dissolve away. The peanuts are at chemical equilibrium sitting on your tongue. (Start *physically* weathering them by chewing, however, and it's a different story.)

The peanuts in the Snickers™ bar are like the mineral quartz. While everything else around it reacts, dissolves, or chemically weathers away, quartz is solid and inert and stable. The result is that as a diverse suite of minerals are rendered into sediment at the Earth's surface, only the toughest last. As time goes by, quartz gets more and more common in a mature batch of sediments. This term "maturity" refers to the sum total of a sediment's characteristics: Is it angular, poorly-sorted, and made of many different minerals? Then it's **immature**. Is it rounded, well-sorted, and made only of quartz? They it's **mature**. Somewhere in between? We call those **submature**, a term that might be better reserved for some teenagers I know…

So Sandstone 2.4A is a quartz sandstone, and is therefore mature. It's made of sand like the sand we find at the beach. Beaches are one of the last stops on the sedimentary train, far removed as they are from their source areas. Sandstone 2.4B has a variety of minerals making it up, and we can see the grains are somewhat coarser. Particularly obvious are the large, angular feldspar grains (pinkish in the photo). These feldspars would weather to clay minerals if they were exposed to Earth surface conditions for any significant amount of time, and so when we find them in a sandstone, our inference is that they are close to their source. This interpretation is backed up by the angular shape of the grains: they haven't traveled very far if they still have sharp corners. Sandstone 2.4B is an **arkose**, an immature sandstone that was deposited in continental settings, often very near the mountains which supplied the sediments.

Sandstone 2.4C is something else again. We can see a mix of both sand-sized grains and mud. It's dark grey in color. This is a **greywacke** ("grey wacky"), an immature sandstone that is deposited in deep ocean basins, adjacent to a continent's steady supply of clastic sediments. We see greywacke-type sands being deposited today off the coasts of places like the Andes in South America, or up in the Gulf of Alaska. In both places, rapid weathering of an uplifted range of mountains drops a tremendous load of sediment a short distance away, in the deep ocean. The short distance traveled by these grains gives them little chance to mature. Furthermore, the mix of both sand- and mud-sized grains says this sandstone is poorly sorted, which means it was dumped all at once, rather than being winnowed out.

Indeed, these modern greywacke-depositional areas are frequently subjected to large storm-runoff deposits which tumble down the bottom of the sea in big cloudy packages called "turbidity currents". Because of the tremendous load of sediment, these turbidity currents are quite dense, and flow along the bottom much like an avalanche (Figure 2.5 A and B). As this cloud of mixed-up sediment slows down, it settles out its grains in order of their size. Because they're the heaviest, the biggest clasts settle out first. Medium-sized grains settle out next, and the finest constituents of the turbid cloud are the last to settle out. The result is a distinct package of sediments that is coarsest at the bottom, and finest at the top: **graded bedding** (Figure 2.5 C and D). Each package of graded bedding represents one depositional event: one surge of sediment-thickened water tobogganing down the submarine slope.

Another aspect of composition that can be insightful is color. Oxygen is a common component of our modern atmosphere, and it's a good thing, too! Without oxygen, you and I would have a difficult time with that whole breathing thing. But oxygen does more than simply allow us to live: it's a restless, troublesome element, forever seeking out mischief in unlikely places. Oxygen likes to react with many different compounds, from organic material like wood to metals like iron (fire and rust are oxidation reactions). Fortunately for geologists, oxygen's activities are recorded in the sedimentary record by means of two distinctive colors. When oxygen reacts with iron, it leaves behind reddish-brown rust (Figure 2.6). Geologists call the rust "hematite," but pay them no mind: It's rust. So when we find reddish sedimentary rocks, often the individual grains are coated with rust, or glued together with rust. This tells us those sediments accumulated in contact with high concentrations of oxygen (**oxic** conditions).

Similarly, unoxidized organic material is distinctly black, so when we find very dark sediments, it indicates a high proportion of organic material that accumulated under very low concentrations of oxygen. Sedimentary environments that are low in oxygen (**anoxic** conditions) include deep sea basins and stagnant bodies of water like swamps. As a result, sedimentary rocks found from these areas (like coal or the black shale in Figure 2.6) are black in color.

So, to sum up what we can learn from attention to the subtle details of clastic sediments, Figure 2.7 presents a compilation – a sort of cheat sheet, if you will, to help you run a background check on any suspicious-looking sediment you come across.

Okay, now we know a lot about these clasts. But we haven't yet addressed the essential question of how these loose sediments get turned into rock-solid sedimentary rocks. As usual, we can find the answer by baking up a batch of cookies. This time, before you mix in the chocolate chips, take a handful of them. If you want to stick this chocolate chips together, there are two ways to do it. The first is to squeeze them in your hot little hand. The individual chocolate chips will deform and wrap around one another, filling in all the little air gaps. Open up your fist and take a look: you now have a solid chunk of chocolate in your hand. You've generated a chocolate-chip-stone from **compressing** the loose chocolate chips. The same thing happens with real sediments: pressure causes them to knit themselves together into a solid chunk.

The second major way to get all those chocolate chips stuck together is to glue them together with something else. I recommend cookie dough. Squirt some cookie dough in between all those chips, throw the little wads of dough + chips into the oven, and in twelve minutes or so, you'll have your "sedimentary rock." This time, however, you'll have created it by **cementing** them together. Real sediments can get cemented into rock with natural mineral deposits: hematite, silica, calcite.

If these methods of sticking loose sediments together into sedimentary rock aren't too violent, they may preserve structures that formed in the sediment at the time it was formed. The most obvious sedimentary structure is bedding, also called stratification. This is the original layering of the rock, reflected the horizontal order it was laid down in. An individual layer is called a bed, or a stratum. Multiple beds are typically called **strata**.

Let's take a look at two examples more exotic than bedding that frequently appear along the C&O Canal (Figure 2.8). **Ripple marks** are linear ridges of sand or mud that form when a current is moving over top of them. Typically, ripple marks form perpendicular to the current direction, and they move (downstream) over time. Sand dunes are basically just great big ripple marks. In cross-section, ripple marks look like the cross-beds seen in Chapter 5's Figure 5.9. **Mudcracks** form when wet mud dries out. As the mud loses water to evaporation, it shrinks a bit in volume. As it contracts, cracks open up to accommodate the shrinkage. Because the contractional force is the same in every direction on top of a drying mud puddle, the cracks are usually in a polygonal arrangement. You can observe this process for yourself after a rainstorm: go find a mud puddle and watch it crack. (*It's marginally more fun than watching paint dry.*) Later, the mudcracks can get filled in with a younger deposit of sediment. In the photo, that infilling sediment was sand, producing a very obvious crack pattern. (It's not as obvious when the mudcracks are filled in with more mud.)

Besides this wealth of clastic examples, there are two other kinds of sedimentary rocks we should get to know. Some sedimentary rocks are produced by chemical processes, and still others are produced by living things. Limestone is an example of a chemical sedimentary rock, and coal is an example of a sedimentary rock that owes its origins to living things. Let's take a quick look at each:

When rocks are weathered, we mentioned that not only are they broken into smaller pieces, but some minerals are actually dissolved. When minerals dissolve, the various elemental components of the mineral dissociate from one another and jump into solution in the surrounding water. In so doing, the water becomes slightly "salty" with dissolved minerals. Table salt, also known by the mineral name **halite**, is one substance that easily dissolves in water. **Calcite**, the mineral that forms stalactites, is another. When we get water running through our pipes that has minerals dissolved in it, we call it "hard" water; it can clog pipes and create unsightly deposits (Figure 2.9).

Sedimentary rocks that are deposited when dissolved minerals recrystallize from solutions of "hard water" are called chemical sedimentary rocks. Rock salt is perhaps the easiest to imagine: As rocks on the continents are weathered, they lose ions of sodium (Na) and chlorine (Cl) to the water that runs over them. The rivers and streams carry these ions in solution down to the oceans. There, the water can be evaporated away, but the ions cannot. Left behind by the ever-flowing rivers and ever-evaporating seas, the ions become more and more concentrated. The solution that we call the ocean is a rich broth of dissolved minerals. In some situations, like in tidal lagoons, seawater circulation is restricted, and so more water leaves the lagoon via evaporation than enters it from the sea. In these circumstances, the dissolved salts become too concentrated to stay in solution. The Na combines with the Cl to make NaCl, a tiny bit of salt. Joined together with more sodium and more chlorine, the minerals precipitate out from the solution, settling as thin flakes to the floor of the lagoon, or else grow new layers onto pre-existing crystals.

Thus do deposits of **rock salt, rock gypsum**, and **limestone** build up into "chemical" sedimentary rocks. Of these, limestone is by far the most important along the C&O Canal: it makes up close to half the stack of sedimentary rocks in the Valley and Ridge Province (Figure 2.1). Even silica, the material that makes up quartz, can dissolve in solutions and settle out as a rock called **chert**. Of these four, limestone is by far the most common along the C&O Canal. Whether it's studded with fossils, or carved into caves, limestone is made up of the minerals calcite ($CaCO_3$), which fizzes when weak acid is dripped on it.

Lastly, there is a group of sedimentary rocks which have living things as their origins. These "biochemical" sedimentary rocks are 100% composed of the remains of organisms. When you compress the plant matter from an ancient swamp, you compact it into **coal** (Figure 2.11). As we've seen earlier, coal is black because most of its abundant organic components have not reacted with oxygen due to immersion in the anoxic waters of the swamp. Other components of living critters which can be transformed to rock include shells which accumulate into **coquina** (Figure 2.11), and planktonic organisms (itty-bitty floaters with shells made of either silica or calcite). **Chalk** is the most famous of these; it is made up of the shells of dead plankton of a sort called coccolithophores. The chalk your teacher uses to write with is made up of hundreds of thousands of little coccolithophores, deceased organisms whose shells crumble and smear out as they are dragged across the blackboard. (*Brutal, isn't it? We should outlaw school!*)

So where does a biochemical sedimentary rock stop and a fossil begin? **Fossils** are the remains of (or the traces of) ancient life. Fossils are only found in sedimentary rocks, because the fossils themselves act as sedimentary grains. Whether we call it a fossil or not largely depends on size: can we see the critter with our unaided eye, or do we have to use a microscope? If the former, it's a fossil. If the latter, there's a tendency to just call it a biochemical sedimentary rock.

Living things could never survive at the incredible temperatures and pressures that give rise to metamorphic reactions, nor in molten magma. Sometimes we find distorted fossils in metamorphic rocks that have had sedimentary rocks as their precursors, but even a small amount of distortion will frequently deform a fossil beyond all recognition. In sedimentary rocks, clastic grains (or chemical precipitates) accumulate around a dead organism or a piece of an organism (the molted shell of a trilobite, for instance, or a single bone from a many-boned dinosaur), and may preserve it for the future. Sometimes we even find fossils of organisms that appear to have been alive at the time they were surrounded by sediment: buried alive, in other words.

Fossilization is rare. When organisms die, they are rarely in a position where they are likely to be preserved as fossils. Instead, they rot. Vultures descend, bacteria begin to putrefy the corpse, and vagaries of weather (or coyotes) break the body up into small pieces and scatter it hither and yon. Consider your backyard squirrel. When he dies, the odds are not good that that he will be preserved as a squirrel fossil. Even if the squirrel were to fall into a sedimentary basin and be quickly buried in mud, what are the odds that that mud will be turned to mud-stone? What are the odds that the mudstone will avoid erosion and weathering through the ages? What are the odds that it will be again returned to the surface of the Earth where you and I might find it and ask paleontological questions about it? The odds are slim. Very slim indeed.

But… even rare events happen sometimes. We *do* find fossils. Like the Lottery, this rare concatenation of circumstances will occur, given enough time. Who wins this fossil lottery? Those who study fossils, the paleontologists, do. Using fossils, we can reconstruct the history of life on Earth, and how it has changed over time. Because only sedimentary rocks host fossils, they are essential to teasing out the history of life on Earth.

Ch-ch-ch-ch-changes

It's worth pointing out here that the fossil record shows an epic tale of changes in the community of living things through time. Organisms today aren't the same as organisms in the geologic past. Trilobites and dinosaurs are two of the fossil critters who no longer roam the planet: finding fossils of them shows us evidence for past extinctions. Other times, we will find fossils that aren't present in any previous (older) sediments: these indicate evolution of a new species from related ancestors. **Evolution by natural selection**, a theory as important to biology as plate tectonics is to geology, has been getting a bad rap lately among some circles in America. I think that's a shame: it's a beautiful, simple theory, well supported by over a hundred year's worth of testing, and I encourage readers to learn more about it. This public misunderstanding is often characterized as a "debate," but there's no debate whatsoever among scientists.

The gist of it is this: in any population of organisms, different individuals have different traits. These traits are controlled by genes (encoded by DNA in the cells of your body). Some traits are more useful than others. Periodically, the environment will offer challenges to the population of organisms, and only the best-equipped individuals will survive. Because they survive, and the poorly-equipped ones don't, the best-equipped individuals get to reproduce, thereby passing on their genes to another generation. Sex shuffles the deck of genetic cards, and no child is exactly like their parents (*recent laboratory clones excepted*). Over time, this series of challenges followed by reproduction among the survivors will tend to make the population better and better equipped for survival. The population changes to be better "fit" in its environment.

That's all evolution says: populations change over time. (*Change being the only constant, just like Heraclitus said!*) Not especially radical, really, unless it comes up against established religious orthodoxy. If it seems hard to reconcile this common sense with scriptural literalism, you might ask for some evidence. The fossil record is that evidence. It shows us a series of frames from the long-running movie of organic evolution. Referencing the public discussion of evolution, the comedian Lewis Black said, "We have the fossils. We win." If there is anyone open-minded enough to consider the validity of the scientific method and the overwhelming evidence in favor of evolution, I have faith that the theory's beautiful simplicity will eventually convince them.

Igneous rocks: distillations of the Earth

When a volcano erupts, lava pours out onto the surface of the Earth and cools off. As it cools, it loses energy, and its constituent molecules can no longer jump around all willy-nilly and disorganized. Instead, they settle into a sedate, steady formation: knitting themselves into mineral crystals. These crystals grow until they interlock with one another, and the lava is transformed into a solid rock. Think Hawai'i: smooth, runny lava glows orange, trickling over the surface. After a day or so of cooling, it's the solid black rock called **basalt**.

All igneous rocks cool from molten rock, but not all of them follow the above scenario. Perhaps you have a granite countertop in your kitchen at home. This **granite** is an igneous rock too, but it's different from the basalt in two important ways. First, the granite is much lighter in color. Sometimes granites are pinkish, sometimes whitish, but regardless of subtle differences in shading, they are always lighter in color than basalts. This difference in color reflects a difference in **composition**: that is, the actual minerals that the two rocks are made from differ. Granite is made up of quartz, potassium feldspar, sodium plagioclase feldspar, muscovite, and maybe a little biotite. Basalt is made up of calcium plagioclase feldspar, pyroxene, hornblende, and small amounts of quartz and the other light-colored minerals. These different "ingredients" make for rocks of not only different colors, but also different properties. Density is one important property: Granites are less dense than basalts. The average granite is about 2.6 times as dense as an equal volume of water. Basalts, on the other hand, are more like 2.9. Though this may seem insignificant now, but remember that it has huge implications for plate tectonics. As discussed in the last chapter, the oceanic crust is made of basalt, and the continental crust is, on average, granitic in composition. Dense crust (basalt) subducts, but buoyant crust (granite) doesn't. The continents always win in an encounter with oceanic crust, and result is that the continents have grown to a ripe old age. Basalt lives fast and dies young.

The second major difference you can see between basalt and granite is their **crystal size**. The basalt's crystals are tiny, invisible to the naked eye. On the other hand, the granite has large, chunky crystals, ranging from the size of chocolate chips to the size of keyboard keys. Some granites have really big crystals that are the size of a stick of butter! The difference in size is purely a function of the speed at which the granites cooled from molten rock: the longer it takes an igneous rock to cool (and thereby transition from all liquid to all solid), the more time its crystals have to grow. The more time the crystals have to grow, the bigger they will be. So, crystal size in an igneous rock tells us about how quickly the rock cooled. Granites (with their big, chunky crystals) cooled slowly. Basalt (with its itty-bitty crystals) cooled quickly.

Why do some igneous rocks cool quickly, and others more slowly? It all has to do with insulation. Think about a winter day. You're warm at home, but there's a blizzard raging outside. You need to run an errand outside, and you're faced with a choice: Do you put on a coat or not? If not, you will lose heat very rapidly to the cold conditions. If you do put on a coat, the coat will insulate your body heat, and you will lose heat less rapidly. You'll still be losing heat – just not as fast as without a coat. Molten rock can be insulated too, but the insulation isn't a down parka: it's other rocks. Igneous rocks that cool from magma deep underground are surrounded by miles of rock insulation in every direction, which means they lose heat slowly, and thus cool over a long period of time. (Some estimates suggest that certain bodies of granite have cooled over several *million* years; now *that's* slow!) We've already seen the opposite: when lava gets burped out onto the Earth's surface by a volcano, that lava is chilled by the surrounding air. It loses heat quickly, and so it cools to solid rock in a short period of time. Some lava cools instantaneously: perhaps by being quenched by cold water; this allows no time at all for any crystals to form, and the result is volcanic glass, **obsidian**. (Glass has no crystal structure: on a molecular level, it is amorphous.) In between these extremes, there are pockets of molten rocks cooling at various depths in the Earth's crust: some just below the surface, some many miles down. Each will record its rate of cooling through the size of the crystals that it produces.

Figure 2.12 summarizes the differences between the main varieties of igneous rocks. You can see that there are four main categories of composition – that is, which minerals the igneous rock is made of. These make up the columns of the chart. Conveniently, the lighter colored ones are at one end of the chart, and dark ones towards the other. The official geologic term for "light" is **felsic**, meaning the rock is enriched in feldspars and silica (another name for quartz). Likewise, "dark" igneous rocks are really **mafic**, meaning that the rock is enriched in magnesium and iron (chemical symbol Fe). In between these two are **intermediate** compositions, which have 50% mafic minerals and 50% felsic ones. Beyond mafic is a fourth category, **ultramafic**, which has exceptionally low amounts of silica, and is so dark it's green. That's a little counterintuitive, but there you have it: *darker than dark = green*. Ultramafic rocks are rich in olivine and pyroxene: dense, dark green minerals. The mantle, the layer of the Earth below the crust, is made of ultramafic rocks.

There are also two rows in Figure 2.12 describing the rock's **texture**, or crystal size. The upper row are all the igneous rocks with small crystals, which indicates rapid cooling. They cooled quickly because they had no insulation, which means they were erupted onto the Earth's surface by volcanoes. These produce lava flows. The lower row is the coarse-grained igneous rocks, the ones that cooled over a long period of time, an indication that they were well-insulated, deep down in the Earth's crust. These produce plutons (solidified magma chambers).

Using these two criteria, we can determine the appropriate name for each igneous rock. You'll see our old friends granite and basalt there: granite is at the intersection of felsic and coarse-grained, whereas basalt is fine-grained and mafic. But notice that if you took that same granitic magma, and erupted it from a volcano instead of cooling it slowly underground, you would end up with a **rhyolite** instead. Likewise for the basalt: that same blob of lava, if it never made it to the surface, would have cooled slowly, and thus grown large crystals. We would therefore have to call it a **gabbro**. (The Vietnam Veteran's Memorial on the National Mall in Washington is made of gabbro.)

Similarly, if the magma is of intermediate composition and cools slowly, it yields a **diorite**. If it erupts and cools rapidly on the surface, it will solidify into an **andesite** (named for the Andes Mountains in South America, where andesitic volcanoes are common). These intermediate rocks have some quartz, some feldspars (both the calcium-based variety and the sodium-based variety), and also some amphibole, a black blade-shaped mineral.

Lastly, the ultramafic rocks need names: **peridotite** is the coarse, green rock which makes up much of the Earth's mantle, and the uncommon **komatiite** is what happens when molten mantle erupts right at the Earth's surface (an infrequent occurrence, and therefore a very rare rock).

Now note the trends across the bottom of Figure 2.12: ultramafic rocks have the highest melting point / cooling temperature. Felsic rocks have the lowest. In other words, if you're cooling a magma down, the first minerals to form will be the darkest ones. The last minerals to crystallize will be those on the felsic end of the chart. The sequence would go something like this: You have a 100% liquid magma, which begins to cool. As the temperature drops, first mafic minerals like olivine and pyroxene form. They would appear as dark green crystals swirling in the magma. Then calcium plagioclase feldspar.

Then amphibole, in thin black needles. You've now got 50% solid crystals in 50% liquid; a "crystal mush." Keep cooling the magma down. Biotite mica makes little black "books." Sodium plagioclase feldspar forms little white chunks. Then comes the potassium feldspar, looking like pieces of bubble gum. The magma's getting colder and colder, and it's 80% solidified. Cool it a bit more, and the final 20% crystallizes into muscovite mica (thin translucent sheets) and quartz (clear or grey). Now you have 100% solid rock – but in the path to get there, we crystallized the mafic minerals first, and the felsic ones last.

Now, instead of cooling a magma, think about heating up a solid rock. This is the reverse of the thought experiment we ran in the previous paragraph. The first minerals to melt out of that rock will be the felsic ones (quartz, potassium feldspar, sodium plagioclase feldspar, muscovite mica). They make the transition from solid to liquid between 600º C and 700º C. The mafic minerals, in contrast, stay solid unless the rock gets heated up to very high temperatures (over 1000º C).

At first this may all sound trivial, but it's a big deal when you consider the rocks we find at the outer layer of the planet. Though the mantle is our ultimate source for all our igneous rocks, we see gobs more granite on the surface than we do peridotite. **Partial melting** is the incomplete melting of a rock: in other words, some of the minerals turn to liquid and trickle out, and other minerals stay solid and are left behind. When you take an igneous rock that has both mafic and felsic minerals in it, and you subject it to, say, 800 º C, the felsic minerals will melt, but the mafic ones won't (Figure 2.13). The end result of partially melting such a rock will be that you are left with two products: a magma of felsic composition, and a solid residue that is mafic in composition.

(You can also get a rock to partially melt by releasing its pressure. Some rocks, like the rocks of the mantle, are already quite hot, and would easily melt if they were at the Earth's surface. However, the tremendous weight of the overlying rock mass keeps them compressed into a solid. If that pressure is released, then the already-hot rock can melt. This is what happens at a mid-ocean ridge: **decompression** of the mantle by moving the lithosphere off of it causes partial melting. The resulting lava is basaltic, which rises to seal the open crack between the plates above.)

What we are observing with partial melting is similar to the process of distillation. You may not be a whiskey drinker, but you're no doubt aware that whiskey is strong stuff. It didn't start off strong: the original "mash" is only about as alcoholic as beer is. But through multiple cycles of distillation, makers of whiskey can concentrate the alcohol, and leave the extra water and other ingredients behind. The same thing is happening in the Earth: by partially melting an ultramafic rock, you distill a mafic magma from it. (*Like we observed in the previous paragraph, partially melting the ultramafic mantle generates the mafic rocks of the oceanic crust*.) By partially melting a mafic rock, you distill an intermediate magma from it. (*Such as is happening today where the Nazca Plate is being subducted underneath the South American Plate, giving rise to the Andes' andesite.*) And – you guessed it – by partially melting an intermediate rock, you end up with a felsic magma. (*Such as happens when intermediate-composition continents collide*.) Each time, the more mafic constituents are abandoned, and the melt gets more and more felsic: that is, it's getting to be higher and higher "proof". Igneous rocks are distillations of the Earth, and felsic rocks like granite are most distilled of all. Ultramafic rocks like peridotite are closest to being "sour mash," the source from which the rest are derived.

Metamorphic rocks: cooking under pressure

Breakfast time! What to have this morning? A cup of coffee, some bacon, perhaps a bagel. Ahh yes, and an egg or two. Let's have them sunny-side up. The cracked eggshell yields a fluid gel, clear with an orangey yolk. When it hits the hot frying pan, however, a change takes place. The clear albumen becomes opaque, white, and solid. The translucent fluid of the yolk also yields to the heat. It becomes solid and more yellow. As you set down to your morning repast, you probably don't think much about it, but the fact is: you've just committed **metamorphism**.

Metamorphism via heat is easy to imagine. When rocks get hot, they cook, just like eggs. Chemical components rearrange themselves to be more "comfortable" under the elevated temperatures. Minerals that were stable under cooler conditions find they can no longer hack it under in these new circumstances. They literally can't take the heat. And so they react, their component elements recombining to form new minerals that are "happier" with the hot situation.

Metamorphic rocks that form due to heat are called "contact" metamorphic rocks, because they come into contact with heat. Most frequently, this is due to burial deep in the Earth, or due to magma intruding into the vicinity of the rock. **Marble** is a classic example of a metamorphic rock (Figure 2.14). Marble starts off as limestone, a chemical sedimentary rock made mainly of the mineral calcite. When it gets cooked, the calcite merges into larger and larger crystals. These large crystals give marble its characteristic "sugary" appearance on a fresh surface.

A quartz-rich sandstone can undergo contact metamorphism too. When it gets heated, the same thing happens as with the marble: small crystals merge to give rise to sugary-textured larger crystals. The only difference is the mineral involved: a limestone is made of calcite, and so is the resulting marble, whereas a sandstone gives rise to a **quartzite** (Figure 2.14), which is of course predominantly quartz.

Picturing how *pressure* causes metamorphism might not be as easy as visualizing the way heat makes it happen. But it's just as important. The deeper a rock is buried in the Earth, the more pressure it is subjected to. Consider the difference in pressure on your head when you dive down to the deep end of a swimming pool. Or when your ears pop driving up a mountain road: both of these are manifestations of pressure change. And these are modest ones, indeed: compare them to the pressure change of piling a mile-thick layer of rock on your head. Some metamorphic rocks show evidence of having been down hundreds of kilometers into the Earth, at pressures millions of times higher than those you experience in your daily life.

Different minerals have their "happy places" at higher temperatures and pressures, so one of the changes we see as we get deeper in the Earth is that certain minerals form which only form under high temperatures and pressures. Because we know the conditions under which these minerals reach a stable equilibrium, we can interpret their presence in terms of metamorphic conditions. When we find these minerals, like garnets (Figure 2.15), in rocks exposed at the surface today, they tell us "I used to be much, much deeper down below the surface." There's a whole spectrum of different minerals which can tell us "I was shallowly buried," or "I was 40 kilometers down," or "I got cooked at 800º C." As you can imagine, this is *good stuff*, as far as geologists are concerned. We love it that little mineral nuggets can give us such valuable information. These metamorphic index minerals are critical to determining the history of a metamorphosed area, like the Piedmont section of the C&O Canal.

There's another, more important kind of pressure that we also need to talk about; a kind of pressure that's going to be very important in making the rocks of the C&O Canal look the way they do. This is **differential pressure**, pressure that's different in one direction than it is in other directions. Consider our earlier example of ambient pressure: diving to the bottom of the swimming pool. As your ears pop, you know your head is being subjected to greater pressure than it was up on the surface. But, that pressure is the *same in all directions*. As a result, your head is the *same shape* at the bottom of the pool as it was up on the diving board. Now consider another example: getting punched in the nose. When someone lands a punch on your face, they too are subjecting your shnozz to high pressures, but this time all the pressure is *coming from one direction*. The unlucky result is that your nose *changes shape* as it is compressed from front to back.

For a less violent example, consider a beach ball being squeezed between two bumper cars (Figure 2.16). As the two cars (driven by such handsome chauffeurs) get nearer to one another, the ball is squeezed *inwards* from the sides. To compensate for this indignity, it bulges *upwards*, trying to stay the same overall volume by changing its shape.

Rocks do the same thing. When rocks are squeezed in a tectonic "vise", they change shape. Certain minerals will get squished into new, flattened shapes. Others will change their orientation, rotating into a position that is most stable relative to the squishing. Consider cookie dough: in baking the cookies that I showed you in Figure 1.12, I conducted a little experiment. I sliced open a ball of cookie dough to get a look at the orientations of the various ingredients inside. Then I squashed a second ball of cookie dough, and cut it open, too. I then compared the arrangement of nuts, raisins, oat flakes, and chocolate chips. (Figure 2.17) As you can see, the different ingredients responded in different ways to me flattening the cookie dough. The nuts and chocolate chips didn't seem affected at all. The raisins, however, flattened out into "pancake" shapes. The oat flakes rotated until they were approximately perpendicular to the direction in which I was applying differential pressure. All in all, the dough of the cookie changed shape. I pushed down on it from the top, and it flattened out from left to right. Experiment concluded, I popped the dough in the oven and waited as it baked into a delicious snack.

Rocks subjected to differential pressure change their shape just like the cookie dough does. Along the C&O Canal, and in particular in the Piedmont area, we see rocks that have experienced “regional” metamorphism (as opposed to the “contact” metamorphism mentioned earlier in this section). Regional metamorphism occurs where two tectonic plates crash into one another. Because the crash is directional, it ends up producing **foliated** metamorphic rocks. Foliation results from a parallel alignment of mineral grains, often mica minerals in particular. A notebook is foliated, because all its pages are oriented in the same direction. A wadded-up ball of newspaper is not foliated; its surface is oriented in a hundred directions, none more preferentially than any other. The original ball of cookie dough in Figure 2.17 was non-foliated. The squashed one developed foliation. Figure 2.18 gives examples of three of the more important foliated metamorphic rocks you will encounter along the C&O Canal.

Which rock is which?

There’s a big obstacle to trying to do geology out in the real world: Regardless of whether they’re metamorphic, igneous, or sedimentary, most rocks can’t be seen in their entirety. If we’re lucky, we have really good exposures, like out in the desert where there’s no plants covering up the rocks. Another example would be a freshly glaciated landscape, where glaciers have scraped off all the concealing layers of dirt and revealed the rocks underneath. But most places aren’t the desert, and aren’t fresh out from under the glaciers. So we get a grab bag of rock exposures. Some places have decent exposures, like in river beds (Mather Gorge comes to mind as an excellent example of an excellent exposure). Other places are built up, paved over, buried under dirt, flooded by lakes, or similarly inaccessible. We’re stuck piecing together the bigger picture from small, uncommon exposures. **Stratigraphy** is the branch of geology which correlates rock units from one location to another.

The basic tenets of stratigraphy are mere common sense. First off, there’s the idea that sedimentary layers (strata) or lava flows on the surface of the Earth are originally deposited horizontally. This makes sense: if you pour sand on the floor, it spreads out into a horizontal layer of sand. If you pour sand on the wall or ceiling instead, the sand will fall down onto the floor and spread out into a horizontal layer of sand. This concept, dubbed **original horizontality**, is key to making sense of sedimentary layers that aren’t horizontal. If you find tilted sandstones, or shales, or basalt lava flows (like we do along the entire C&O Canal west of Point of Rocks), then you can assume that they were originally horizontal, and then at some time after they were deposited, they were tilted up into some other position.

Second, there’s the idea that in a stack of sedimentary strata, the oldest layer is on the bottom. Think pancakes: you’ve got the griddle going, and you’re fixing up a mess of flapjacks for the whole family. As you prepare the pancakes, you pile them up on a plate. The first one done will be on the bottom, and the last one to come out of the skillet will land on the top of the stack. This basic fact is the idea called **superposition**. Simply put, the youngest is on top; strata get older the deeper you go. Figure 2.19 shows this relationship, both in terms of a jar of lentils and a cartoon stack of sediments. The light-colored lentils went into the jar first, followed later by the dark-colored lentils. In the block diagram, the orange layer is younger than the brown layer, but older than the blue layer.

Third is the notion of **lateral continuity**, which is to say that sedimentary strata were originally deposited in one continuous sheet, though we might not find them still connected today. Part of the layer may be folded up, or part might be hidden from view, or a river might have cut a canyon through the layer, breaking it into two pieces. Lateral continuity says if you find Permian-age limestone on top of sandstone on the south side of the Grand Canyon, and you find Permian-age limestone on top of sandstone on the north side of the Grand Canyon, that's one continuous sheet of sandstone (older) topped by one continuous sheet of limestone (younger), and the material that used to connect the two has simply been removed by the erosion of the Canyon. Figure 2.20 shows an example: there's no reason to think that the orange layers on opposite sides of the canyon are different, since they're in the same position on both sides. Geologists make the assumption that they were once connected, and only later bisected by the river.

The fourth principle of stratigraphy explores the idea of figuring out which rock is older by virtue of their **cross-cutting relationships**. Sometimes rocks aren't deposited in nice flat sheets: granites, for instance, cool in blob-shaped magma chambers underground, and they are younger than the rocks that they intrude into. Oftentimes, magma will find its way into a crack in the rock and solidify there, forming a big tabular zone of igneous rock called a dike. These dikes cut across older rock units. Imiagine baking a birthday cake. It's my birthday, and by now you figure I've got to be sick of eating cookies. So you bake a nice cake in the oven. But as you're pulling it out to cool, it breaks in half. *Oh no!* you think, *it's ruined!* Not so: all you have to do is "glue" the crack shut with a nice seam of icing. The icing is like a dike that cuts across the cake. For a visual example, see Figure 2.21: an igneous pluton rises up from below and intrudes into our familiar stack of sediments. The magma chamber cracks open the surrounding rock and squirts magma into the crack; this cools into a dike. Because the dike cuts across the orange layer, we know that the orange layer must be older, and the dike is therefore younger.

Fifth and last, the principle of relative dating by **inclusions** rounds out our toolbox of stratigraphic techniques. Another glance at Figure 2.21 reveals little chunks of the sedimentary host rocks present in the magma chamber. These inclusions also show us relative ages of the two rock units. There's no way you can break off chunks of something unless it already exists. So when we find inclusions, we know that the rock which makes up the inclusion is older, and the one doing the including must be younger. It's like a crumb in the cake icing we mentioned in the previous paragraph. Figure 2.22 shows an example from rocks along the C&O Canal. Here, we see fragments of the Swift Run Formation sandstone (purplish chunks) included in a lava flow of the Catoctin formation (green background rock). The Swift Run must be older, and the Catoctin lava must be younger. (The Catoctin's metamorphosis to that sickly green color – the mineral epidote – came even later.)

Isotopic dating

For a most of the history of geology as a science, geologists had only two sets of tools to determine how old a rock was: the fossil record showed changes in life as recorded in sedimentary rocks, and the preceding five stratigraphic principles allowed "relative dating" of rocks. This is similar to me saying "I am older than my brother," but without telling you exactly how old I am, or how old my brother is.

When I give you a date in this book, that a certain rock is a specific number of millions of years old, that number is coming from measuring the amount of certain chemicals in that rock. By measuring them through the techniques of isotopic dating, we can get actual ages for some rocks. This would be the geologic version of me saying, "I'm 32 years old; My brother is 28."

A brief synopsis of how this works: Some chemical elements come is a few varieties. These varieties differ by their weight. The heaviest ones are least stable, and they will break down over time through the process of radioactive decay. Each elemental variety, called an **isotope**, breaks down at a specific rate. This rate is constant, and never varies so far as we can tell. That's the essential thing about isotopic dating, the thing that makes it so useful. It is the only process we know of which does not change its rate, no matter what.

When the unstable heavy isotope breaks down, it produces a lighter-weight stable isotope (and releases some energy in the form of radioactivity). Uranium, for instance, breaks down to become lead. We usually call the starting isotope the **parent**, and the stable end-product the **daughter**. The more time passes for a given rock, the less parent it has, and the more daughter it has. It's like an hourglass: you can tell how much time has passed by comparing the amount of sand at the top to the amount of sand at the bottom.

It is through measurement of these isotopes that we have come to our appreciation for the immense age of our planet. By quantifying the amount of three lead daughter products, each produced through a different isotopic decay system, and comparing them to one another, it was determined that the Earth is about **4.6 billion years old**. Each of the three different isotope systems gives exactly the same age for the Earth. Each system corroborates the other, and furthermore, all three agree with the age of the Earth predicted from studies of meteorites. (It appears the planet coalesced from meteoritic starting material, and the meteorites we encounter today are remnants of the early solar system.) All four lines of evidence agree: we live on a 4.6 billion-year-old planet.

Let's pause a moment for reflection on this age. 4.6 billion years is a very, very long time. The portion of geologic history we will see along the C&O Canal is less than a quarter of that, and most of it is far younger still. If you squeezed the entire history of the Earth into a single calendar year, so that the Earth began on January 1 at midnight, and today was December 31 at midnight, here are the dates of some key events along the C&O Canal:

March 20 – first fossils (bacteria)
October 20 – Grenville Orogeny sutures together the supercontinent Rodinia
November 14 – Rodinia rifts apart; Iapetus Ocean basin opens

November 18 – Cambrian period begins; North America flooded with shallow sea
November 24 – Taconian Orogeny: volcanic island chain is added to North America
December 3 – Acadian Orogeny: a small continent is added to North America
December 8 – Appalachian Orogeny sutures together the supercontinent Pangea
December 13 – Pangea rifts apart; Atlantic Ocean opens
December 26 – Coastal Plain sediments deposited
December 29 – Meteorite impact in the Chesapeake Bay
December 31, 11:48pm – oldest human (*Homo sapiens*) fossils
December 31, 12:00pm – you pick up this book and start reading

Time after time

Everything I discuss in this book takes time. The insight provided by isotopic dating provides us a clearer perspective on the enormous depths of geologic time. Compared to your age, or mine, a thousand years is a long time. Compared to a million years, a thousand is hardly worth mentioning. Compared to a billion years, even a million seems small.

Geologists had hints that geologic time must be immense by examining the geologic record even before they figured out how to date rocks using radioactive decay. In those pre-isotopic days, fossils were the timepieces of geology. The succession of fossils through geologic time – different critters in different-aged rocks – provided a stunning accurate way of figuring out how old rocks were relative to one another. These fossils not only show changes through time (evolution), but they can be used as tools to match up rock strata in widely separated localities. For instance, the presence of the trilobite *Olenellus* in the Antietam Sandstone of the Blue Ridge Province (Figure 6.16) signals to us that the Antietam must be Cambrian in age, for *Olenellus* is only found in Cambrian-age rocks around the world. (It evolved early in the Cambrian, and went extinct before the Cambrian ended, and so if it's present in a rock, that rock can only be Cambrian in age.) By comparing the fossil content of each rock layer, careful geologists were able to establish a robust **geologic time scale** (Figure 2.23), establishing the *relative* age (but not *absolute* ages) of different rock layers.

The geologic time scale can seem intimidating at first: a big stack of boxes, divided into incomprehensibly large-sounding units. "Eon," "era," "period," and "epoch" might strike you as unwieldy at first, but they have a relation to one another as seconds do to minutes, and minutes to hours, and hours to days. An eon is the largest unit of geologic time. It is subdivided into eras, of which the three most important to us are the most recent: the Paleozoic, Mesozoic, and Cenozoic.

Furthermore, all of the units of geologic time are labeled with bizarre names. A few of those names seem to match up with something real (Mississippian, for instance), but where the heck did words like "Cambrian" and "Triassic" come from? All of these period names have some root in the early days of geology as a science (late 1700's – early 1800's). "Cambrian" comes from the Roman name for Wales, where rocks of this age were first described. "Triassic" comes from a triad (threesome) of distinctive strata in Germany: red beds, chalk, and black shales. Each of the others has similar eponymous origins, but it’s trivial to list them all here. Needless to say, there are Triassic rocks in other places besides Germany, and there are Cambrian rocks in more places than Wales.

The eras, on the other hand, are named for their fossil content: “Paleozoic,” “Mesozoic,” and “Cenozoic” mean “ancient life,” “middle life,” and “recent life,” respectively. The Paleozoic is characterized by ancient sea life like trilobites. The Mesozoic is well known for its charismatic dinosaurs. The Cenozoic, our own era, is known for the diversification and dominance of mammals, including ourselves.

The boundaries between each unit of geologic time do not occur at regular intervals, and that is because they are due not to the metronymic progression of time. Rather, we can tell one period from the next by changes in the collection of living things. Extinctions change the make-up of the species present in the rocks, and so the major boundaries between geologic timescale units are actually the times when many species went extinct, and were replaced by newly-evolved forms. Mass extinctions mark the most important boundaries – like the end of the Paleozoic, or the dinosaurs’ demise at the conclusion of the Mesozoic. Only later was the isotopic dating system able to put specific numbers on the boundaries between different geologic time units.

Evolution’s rhythm is irregular and sporadic; it has no steady pulse. Animals go extinct and evolve in response to environmental conditions, not the simply chronological accumulation of time. The fossil record shows these changes in stunning detail, and our geologic time scale is a reflection of this fact.

Interlude: Go west, young man

The nature of physiographic provinces

Viewed broadly, the East Coast of the United States can be divided up geologically into physiographic provinces. Each physiographic province is a region which has a distinctive appearance to its landscape. It can be readily distinguished from its neighboring provinces. In all cases, the appearance of the landscape is directly due to the rocks underneath: the type of rock (igneous, sedimentary, or metamorphic), as well as their configuration (whether flat-lying, folded, or faulted).

Along the C&O Canal, traveling from the Atlantic coast westward into the heart of the North American continent, we pass through six physiographic provinces: the Coastal Plain, the Piedmont, the Culpeper Basin, the Blue Ridge, the Valley and Ridge, and the Alleghany Plateaus (Figure I.1). In the next six chapters, we will follow this westward journey along the northern banks of the Potomac. We're faced with a tough decision here: do we go in chronological order, or in geographic order? I've chosen the latter. Because this is a spatially-linear path, it will jump around in geologic time. If we instead listed the physiographic provinces in order of the age of their rocks, we would have a very different order:

Blue Ridge (*oldest*)

Piedmont

Valley and Ridge + Alleghany Plateaus

Culpeper Basin

Coastal Plain (*youngest*)

This order doesn't match up with what we find on the ground, but such is life.

The Coastal Plain and the Alleghany Plateaus serve as neighbors to the C&O Canal, but the Canal doesn't really traverse either of them. They are key to the geologic history of the area, however, and so they are included here. Otherwise, it would be as if we presented a biography of a person without mentioning their adolescence and their final years.

In general, the North American continent is analogous to an old sofa (Figure I.2). The oldest rocks in North America (the "crystalline basement" rocks) are the original sofa. Over time, the sofa accumulates wear and tear, and so does our continent. Someone may spill coffee on the sofa; this is similar to an outpouring of lava across the continent. To cover up the coffee stain, the sofa's owner may throw a slip cover over it. The slip cover is like the blanket of sediments which overlays the crystalline basement of North America. A rip may develop in the sofa when your fat Uncle Louie sits on it too suddenly, and loose change may fall into the hole. Similarly, the North American continent has rifted open, and sediment has filled the resulting gash. Some padding might soften this gash, and so a pillow is added to the sofa. Likewise, new material is added to North America in the form of terranes; blocks of crust that started off elsewhere. A pet cat may scratch up the sofa, leaving gouges in its sides. Similarly, glaciers have gouged into the northern portion of our continent, scraping deep grooves in the basement rock, and peeling away the covering sediments. Another slip cover may be added to cover the damage, like the youngest layer of sediments which are draped on the lowest elevations of the North American coast.

As we can read the history of the sofa from this hodgepodge of scars, stains, and additions, so too can we deduce North America's past by the geological accumulations of sediment, lava, terranes, and deformation.

Each of the physiographic provinces we can examine along the C&O Canal bear a unique combination of rocks types and arrangements. The Coastal Plain, for instance, is flat-lying young sedimentary rocks. The Piedmont is the metamorphosed rocks of an ancient ocean, shot full of granite injections. The Blue Ridge is a chunk of the crystalline basement, broken off from far below and shoved upwards. The Valley and Ridge is wrinkles in Paleozoic sedimentary layers. The Alleghany Plateaus are these same sedimentary layers, only not as folded-up as they are in the Valley and Ridge.

Chapter 3: East of Eden

The Coastal Plain Province

When early settlers first arrived in the mid-Atlantic, the first part of North America they saw was the broad, flat land that today we call the Coastal Plain. It was buggy, but it was lush. To their ears, it sang with promise. Sailing up the rivers of the eastern seaboard, the settlers' boats penetrated the Coastal Plain Province easily. The bottom of the river was loose sediment, and even though they were sailing against the current, it was a smooth passage.

Eventually, however, no matter which river they were in, the boats' progress was stymied by the appearance of hard rocks poking up from the river bottom. As the river water tumbled over ledges of these rocks, it created rapids and waterfalls. The boats could pass no further, at least not safely. On the James River, the settlers encountered rapids at the site of present day Richmond. On the Rappahannock River, the rocks stopped inland passage at the spot we today call Fredericksburg. This is no accident: these cities are where they are almost purely because of the geology. They wanted to be as far in to this fresh new continent as they could (the better to extract its resources, and be protected from the vagaries of the Atlantic Ocean's weather), and they needed navigable rivers for ease of trade. Where the river ceased to be navigable, they stopped and settled.

Settlers traveling up the Delaware River founded Philadelphia where they were forced to stop. Ditto for New York. Baltimore too owes its location to the presence of hard rock underneath its waters.

If you were on one of those early vessels, sailing up the Potomac River from the Chesapeake Bay, you would be sailing over mud until you passed Alexandria on the left, and Haines Point to starboard. The first outcropping of hard bedrock can be found at the upstream end of Theodore Roosevelt Island. Your boat might dodge the toothy Three Sisters Islands, visible upstream from modern-day Key Bridge, but your hull would start scraping bottom shortly thereafter. This would signal that you had entered the Piedmont, the hard metamorphic rocks beneath the Coastal Plain (subject of Chapter 3).

But you needn't risk shipwreck in order to figure out where the Coastal Plain stops. As this transition is taking place beneath the water, it is also being reflected in the landscape on shore. Abruptly, as you sail past the Kennedy Center and Rosslyn, you will notice that the country is no longer flat on either side of the river. Instead, Georgetown rears up to your northeast, and the tall cliffs of Arlington loom to the southwest. If you have ever driven on the George Washington Memorial Parkway, you experience this transition as a steep uphill climb right after the Spout Run exit. On the DC side of the river, try walking up Wisconsin Avenue from K Street to Georgetown's main drag on M Street. It's no Everest, but it is a steep hill – a fact that is entirely due to the fact that M Street is on hard rock, and K Street is on loose sediment. K Street is Coastal Plain; M Street is Piedmont.

Richmond, Fredericksburg, Washington, Baltimore, Philadelphia, New York: now extend the series by adding Atlanta to the southwest, and Boston in the northeast. Collectively, if you compare these cities to the directions of the compass, they all line up on a common trajectory. This line of waterfalls is called the Fall Line, and it is one of the most basic and important geological features of the East. (Figure 3.1) The Fall Line is more properly referred to as the Fall Zone, because in actuality the location of Coastal Plain deposits varies back and forth in more of a Wiggle than a Line. In some areas, it is a discrete boundary; in other areas, it is more diffuse.

The Fall Zone is the boundary between two physiographic provinces. It separates Coastal Plain on the east from Piedmont on the west. It is at this boundary that the Canal begins, or ends, depending on how you want to measure it. Some would say that the Canal should be more properly measured from the spot where it first draws water. This upstream end is the one at Cumberland, Maryland. Others would suggest that the Canal's "starting point" should be the spot where it, as a structure, originated. Canal excavation began on the eastern end in 1828. It didn't get to Cumberland until 1850. The mile marker system of measuring distances along the Canal reflects this fact: the bottom of the Canal, MM 0, is in DC, a few meters away from the Pennsylvania Avenue and Rock Creek Parkway.

The first actual shovelful of dirt wasn't an easy one to turn over. The man wielding the shovel was President John Quincy Adams, and the day was July 4, 1828. He was attempting to dig on the Piedmont side of the Fall Zone (near Little Falls, a mile or so east of the DC-Maryland boundary). He quickly realized it was tough stuff to dig through. The sweating president stumbled through three attempts to turn over a shovelful of the hard, rocky soil, and was thoroughly embarrassed by the task's difficulty. This humiliating opening episode presaged the rest of the Canal's construction, which would be fraught with difficulty.

Why was it so hard? After all, just three years previously, the Erie Canal had opened to barges traveling from the New York's Hudson River, to Lake Erie. The builders of the C&O Canal had every reason to expect a similar degree of ease, right? Wrong. The underlying geology was totally different. In New York, the route went through loose, unconsolidated glacial deposits, an auspicious geologic circumstance which made the Erie Canal easier to dig, and therefore ultimately more profitable. The C&O Canal was doomed from the start: hard rocks sealed its fate as much as competition with nascent railroad lines.

Downstream of the Fall Zone, the Canal is no longer needed because the Potomac River has carved a navigable route on its own. At the eastern limit of Georgetown, the C&O Canal debouches into Rock Creek, and a few yards downstream into the Potomac itself. This is Foggy Bottom. In the shadow of the Watergate complex, the wayward canal water returns to the river from which the Canal diverted it.

Though it's easiest to think of as a line on a map (Figure 3.1), this boundary between the Piedmont and the Coastal plain is really a three-dimensional feature. Let's attempt to alter our perspective from that of the bird's eye view high above the landscape, to a "gopher's eye view": that is, looking at the Fall Zone sideways, in cross-section. (Figure 3.2) Re-imagining the physiographic boundary as a surface, you can see this: the hard, folded-up, metamorphosed crystalline rocks of the Piedmont lie below; flat lying, loosely-held-together deposits of the Coastal Plain lie above. The Coastal Plain, therefore, overlaps onto the Piedmont Province. The Coastal Plain is a blanket, tucking the Piedmont into bed for the night. Some of the deposits of the Coastal Plain cannot be called "rock" per se, because they haven't been glued together or otherwise lithified. Recall the chocolate chips of Chapter 2: when it comes to Coastal Plain deposits, the chocolate chips are still loose, rattling around in their bag. These are the youngest rocks anywhere along the Canal. They haven't experienced the intense pressures or temperatures which have hardened other rocks into tougher units.

The sedimentary cover is thinnest at the Fall Zone, but it thickens rapidly the closer to the ocean you go. By the time you get out to the current Atlantic coast, Coastal Plain sediments are 8000 feet thick.

There are two major environments which deposited the sediments of the Coastal Plain: **rivers** and **the ocean**. Together, they have draped the edge of the North American continent in a thick drapery of sediment. The marine deposits are intimately tied to the river deposits, because they formed a continuous system which advanced towards the oceans when sea level was low, and then retreated towards the center of the continent when sea level was higher.

By far, the oceanic deposits cover much more territory, but these sediments cannot be seen in C&O Canal National Historical Park. You'll have to venture off the Towpath if you want to see them. Ocean-deposited Coastal Plain rocks can be seen in Calvert Cliffs State Park in Maryland, for instance, where there are thick exposures of Miocene (about 30 million years ago) rocks chock-full of fossil shells, shark teeth, and whale bones.

Two of the most distinctive of these fossils are the state fossils of Maryland and Virginia, both of which are found in Coastal Plain deposits. *Ecphora gardnerae* (Figure 3.3) is a rusty-colored snail with four distinctive protruding ribs. It is the official state fossil shell of Maryland. *Ecphora* can be found in the St. Marys Formation in places like Calvert Cliffs. The St. Marys Formation is one of the ocean-deposited Coastal Plain units. *Chesapecten jeffersonius* (Figure 3.4) is a large grey scallop shell from the Yorktown Formation, a younger package of rocks (Pliocene in age, about 4 million years ago) well exposed in its namesake Yorktown, Virginia, as well as along tidal rivers along the eastern seaboard. *Chesapecten* is the state fossil of Virginia. It also holds the distinction of being the first fossil described from the New World, published in 1687 by Martin Lister, an English naturalist who dreamed up the idea of national geologic surveys. Along with these shelly mollusks, the Coastal Plain yields fossils of vertebrate animals too: whales in particular, though an occasional walrus is found.

Speaking of vertebrates, Maryland also has a state fossil dinosaur, *Astrodon johnstoni*, a vegetarian sauropod, which is known from Coastal Plain deposits in Maryland and the District of Columbia. Other dinosaurs found in the same sediments, collectively known as the Potomac Formation, include "*Capitalsaurus*" an unofficially-named giant raptor. *Capitalsaurus* is the official dinosaur symbol of Washington, DC Further into the Maryland Coastal Plain lie exposures of the Severn Formation, which has yielded fossils of duck-billed dinosaurs (hadrosaurs), as well as large marine reptiles. The marine reptiles lived exclusively in the oceans, and are not dinosaurs. They include mosasaurs (essentially Komodo dragons on steroids, with flippers), plesiosaurs (looking like the mythical Loch Ness monster), and giant turtles and crocodiles.

Swimming alongside these giant beasts were sharks, which haven't changed much since they first evolved 370 million years ago. Fossils of the largest shark, *Carcharocles megalodon* appears in younger Coastal Plain sediments of Miocene age (about 20 million years old).

These exotic fossil-bearing layers are found deeper in the Coastal Plain than the edge of the province immediately adjacent to the Park. Along the C&O Canal, we're more likely to see something like Figure 3.5: On high terraces above the Potomac River, there are deposits of coarse gravels and sands, patches of the Potomac Formation. This is the same formation that elsewhere bears dinosaur fossils, but these gravels are far too coarse to provide any decent fossil deposits. Remember that large sedimentary grains indicate fast, turbulent water: not the ideal conditions for preserving fossils.

The individual cobbles are well rounded, indicating that they have traveled a long distance. This suggests that these deposits were deposited by a river, and indeed geologists interpret these deposits as river deposits. You can't date them using isotopes, because the date rendered from a particular cobble would be the age of its source rock, not the age of the deposit it ended up in. (This would be like approaching a jet-lagged American in the Tokyo airport and asking for the time, even though he hasn't yet reset his watch to the new time-zone.) Fossils in the deposits suggest a Cretaceous age (about 100 million years old) for the oldest. The Potomac Formation is interpreted to be deposited by the ancient Potomac River, or a similar predecessor. Imagine this river coursing down from the Mesozoic Appalachian highlands: a swift torrent of water with dinosaurs swimming in it! These river deposits are capped with Miocene (about 030 million years old) deposits of the oceanic Calvert Formation on the highest hills of DC, Virginia, and Maryland.

These deposits are unlithified, meaning that they have not been stuck together into rocks. The river cobbles are loose, as loose as the day they were deposited. You could dig up Cretaceous river gravels by the shovelful, if you owned hilltop property along the Potomac River. (Too bad President Adams didn't try to dig into them: He would have had a much easier time of it!)

Because the C&O Canal stays low in the Potomac's valley, the Towpath never bypasses these hilltop terrace deposits if you stick directly alongside the Canal. So it's time to venture away from the water, and into the woods. On the Virginia side of the river, Glade Hill in Great Falls Park showcases a suite of large cobbles and boulders that were deposited on top of the hill there by the ancestral Potomac River (Figure 3.6). Because Glade Hill has an elevation of 200 feet, and the river is at about 75 feet above sea level (at Mather Gorge), these rocks were deposited when the Potomac was at least 125 feet higher up than it is now. That intervening 125 feet of rock has been cut away by the river since the time it dropped those boulders in its bed: a bed that is now the top of the highest hill in the Great Falls area! (See Chapter 8 for more details on this cutting process)

You will occasionally see loose cobbles rolling around near trails, where they have rolled after being eroded out of higher exposures. A good many can be seen on the Berma Road trail between the Stop Gate at mile marker (MM) 13.7 and the Anglers Inn parking area at MM 12.4. Getting further off-Canal, on the woodland trails east of the Great Falls Tavern visitor center, hikers will see more of these ancient riverbed deposits. One particularly interesting clast to keep an eye peeled for is rounded cobbles of sandstone containing *Skolithos* worm tubes (Figure 3.7).

These are small chunks of the Antietam sandstone. The tubes, which appear like thin soda straws running through the rock, are the dwellings of Cambrian worms, which dug holes in loose beach sands. The worms' abilities to dig holes indicates that they had vascular pressure in their bodies. By altering the pressure in various segments of their body, they could move forward or dig holes. Think of how a worm moves forward: it stretches out the front half of its body to a new location, grabs hold with tiny hairs, and then contracts and thickens. The rear half of the body is pulled forward as a result. This same technique can dig a hole: the stretched-out, skinny portion of the worm wiggles in between the sand grains, then it inflates through vascular pressure. The hole is enlarged, and the worm can repeat the trick to dig further down. These *Skolithos* tubes only appear in the geologic record starting in the Cambrian, indicating that vascular bodies had developed by that point in Earth history. (Previous to this advance, worms probably more closely resembled *Planaria*, the flat worm you may be familiar with from 7th grade life science class: It glides everywhere on a thin layer of mucus-slathered tiny hairs. Without a vascularized body, it cannot pump or thrust the way a modern earthworm can.)

After the worms dug their holes, the sand was buried and lithified into sandstone. The sand grains were compacted and cemented together, and the worms' burrows were preserved even though the worms themselves had long since rotted away. The cobbles were broken off from their source rocks far up the Potomac River valley by forces of weathering and erosion in the aftermath of the Appalachian Orogeny. We currently find exposures of the Antietam Sandstone at its namesake Antietam, which is about fifty miles up the river from Great Falls. So each little cobble you find in the woods above Old Anglers Inn was tumbled downstream for fifty miles, dulling its sharp edges every time it impacted the bottom or another rock (remember Figure 2.2). After they had traveled a long ways, they were worn to their current rounded state.

Other Coastal Plain sediments record a very different environment. Underneath the shallow Coastal Plain of downtown Washington, DC, workers excavating for major buildings like the Mayflower Hotel and the Ronald Reagan Building have dug down to swamp deposits. These dark-colored (low-oxygen) layers include some huge fossils: petrified cypress trees. Cypress is a typical species of tree that grows in swampy areas today; there's a lot of cypress in Florida. It appears that our swift-moving rivers and their round crew of cobbles over-ran at least one big wetland, condemning these cypress trees to the fate of being fossilized.

Of all the rocks along the C&O Canal, these Coastal Plain sediments accumulated most recently, between the Cretaceous and now. Because they are so young, they haven't had a chance to be deformed in any major way. They simply represent a time when the land surface was higher (that is, the Potomac hadn't yet cut in as deeply as we find it today), and when sea level was higher too. These rocks speak of the calm of a passive continental edge: no volcanoes, no violent upthrusting of mountains; just gentle flow of rivers and lapping of waves, depositing sediments all the while.

The only exception to the peace was an event that occurred in the late Eocene, about 35 million years ago. On one bad day, the peaceful calm was shattered when a large chunk of rock came hurtling out of the sky and slammed into the shallow ocean off the coast. Though we are not sure whether it was a meteorite (rock) or comet (ice), it left quite a wound in the Earth's crust. It formed a massive crater which now lies underneath the Chesapeake Bay (Figure 3.8).

This Chesapeake Bay impact, similar to the one that likely killed off the dinosaurs, was much more recent than its more famous cousin. The dino-exterminating impact took place 65 million years ago, just off the Yucatán Peninsula of Mexico.

The Chesapeake Bay impact crater is half that age. It is the largest known crater in the United States, about 80 miles in diameter. But it is invisible to human eyes. Buried beneath 35 million years' worth of Coastal Plain sedimentary deposits (over 300 meters thick!), it is detectable only with advanced technology. A 1983 drill core, taken off the coast of New Jersey showed small glass spheres and a peculiar variety of the mineral quartz (called "shocked quartz"), both of which are key indicators of an extraterrestrial impact. Seismic soundings in 1993 and later gravity anomaly surveys revealed its presence in fine detail, located beneath the mouth of the Chesapeake Bay running from underneath the tip of the Delmarva Peninsula across the Bay to Norfolk, Virginia (Figure 3.8).

A cross-section of the crater (Figure 3.9) shows that the meteorite (or comet) penetrated the surface cover of pre-35-million-year-old sediments, like the Potomac Formation, and lodged in the bedrock beneath.

The moment of impact would have been spectacular. The energy released by the collision is estimated to be about equivalent to two million megatons of TNT. Quartz that was present got "shocked" into its distinctive structure by this tremendous force. Some rock melted, formed droplets, and quickly recongealed as beads of glass. Water, displaced by the sudden splashdown, would have roared away in all directions in massive tsunamis, devastating the eastern seaboard. If the impact were to happen today, Norfolk, Richmond, Williamsburg, Baltimore, and Washington would all be destroyed. Under the sea, blocks of sedimentary strata next to the crater were suddenly unsupported on their sides facing the crater, and they slumped inwards, effectively expanding the diameter of the hole. Chaotically disorganized blocks of rock rained back down into the hole, filling it with a massive pile of angular blocks, a **breccia**.

Later, after the violence of the impact had faded away, the seas returned to normal, and passive continental margin sedimentation began anew. These new layers of sediments, younger than the impact, draped over the mixed-up rocks below. Over time, as more sediments accumulated, the overlying weight compacted the breccia. This subsidence caused a second generation of faulting in the overlying layers. Strata over the impact breccia dropped downwards. The depression that resulted is the site of the modern Chesapeake Bay.

Chapter 4: Exotic terrain

The Piedmont Province

An ancient ocean

The rocks of the Piedmont Province are found along the C&O Canal from MM 0 in Georgetown upstream to Seneca, MM 22.8. They are hard rocks: metamorphic and igneous. The metamorphic rocks were mainly sedimentary before they were metamorphosed, though there are some meta-igneous rocks in there too. These **meta-sedimentary** (metamorphosed sedimentary) and **meta-igneous** (metamorphosed igneous) rocks have been intruded by magma, which has cooled to form granites, lamprophyre, and other igneous rocks which have not been metamorphosed.

The story of the Piedmont begins about 700 million years ago (the Neoproterozoic period) with an ancient ocean, an ocean that no longer exists. Because this ocean occupied roughly the same place that the Atlantic Ocean would later occupy, it is named in relation to the Atlantic. It is called the **Iapetus Ocean**, for Iapetus was the father of Atlas (for whom the Atlantic is named). Some people just call it the "proto-Atlantic Ocean," indicating its status as the ocean that came before the Atlantic. The Iapetus Ocean was created when an early supercontinent, Rodinia, broke apart in an episode of rifting. (The story of this rifting is well recorded in Blue Ridge rocks, so we will save it for Chapter 6.)

Once established, though, the Iapetus Ocean would have looked a lot like a modern ocean: basaltic crust at the bottom, with sediments on top of that, and then a heck of a lot of water. It would have had small blocks of continental crust, sometimes called "micro-continents," as well as islands of various sizes. The Iapetus would have looked different from a modern ocean only on close examination. If we dove beneath its surface, we wouldn't see any fish, any reptiles, any sharks, or even any trilobites. Instead, there would have been strange jellyfish-like creatures, soft and pliable. Some would have been rooted to the bottom, like a modern sea anemone or a coral is. Others would have been floaters, or perhaps they crawled along the bottom. Some would look like a sculpture of a feather, carved from Jell-O. Others resembled a pineapple upside-down cake. These oddballs are the first multicellular creatures, collectively called the Ediacaran fauna after the spot where their first fossils were found, in the Ediacaran Hills of Australia. Fossilization is unlikely for soft animals like the Ediacaran critters, as well as modern jellyfish, worms, and sea cucumbers. Hard parts like teeth, shells, and bones are far more stable than mushy flesh, and so hard parts dominate the fossil record. It takes exceptional circumstances to preserve something as delicate as an Ediacaran, and so they are rare.

We don't find <u>any</u> Ediacaran fossils in the rocks of the Piedmont, for two reasons. First, these rocks aren't sedimentary any more. They have been metamorphosed, in some places quite a lot. This metamorphosis destroys any fossils that might have been there. Second, the depositional environment wasn't right for these fossils to be preserved. Sediments accumulate in a variety of locales, some of which are conducive to living things, some of which are not. Unlike the beach sandstones of the Ediacaran Hills, the sediments that make up the Piedmont's rocks were deposited in the deep ocean, where fewer animals live.

One thing you'll notice as you stroll along the Canal from Georgetown westward is that the rocks are dark-colored. As we've learned before, dark color is a sign that they were deposited in anoxic (low oxygen) conditions, such as those that dominate the deep ocean. You'll also notice a grain size that is mostly sandy, though in some places it edges towards silt-sized. This makes it a greywacke (Figure 2.4 C), a muddy sandstone. Greywacke is deposited in large piles of sediment called deep-sea fans. These fans funnel a mixed package of sediment off the continents, which tumbles downward as a dense turbidity current (like we saw in Figure 2.5). As we learned in Chapter 2, turbidity currents settle out in order of their weight. This leaves behind a characteristic deposit called graded bedding (Figure 4.1): each bed has a layer of coarse grains at the bottom, a layer of medium-sized grains in the middle, and a layer of fine grains at the top. Each layer grades subtly into the next, and the graded beds are stacked up on top of one another in a zebra-striped pattern. If the greywackes of the Piedmont were deposited in a similar style, we should find graded bedding along the C&O Canal today. Most of the graded bedding has been destroyed by later metamorphism, but in a few places, it survives. The best examples are found on the Great Falls observation decks on the Virginia side of the river, although folded stacks of graded bedding can be found in many places along the Billy Goat Trail (Figure 4.2)

It's easy to get distracted by the spectacular modern scenery: Great Falls' roaring torrent, the uncanny straightness of Mather Gorge; but make no mistake about it: the real show is in the rocks. Welcome to the bottom of the ocean.

A modern analogue for the environment where these sediments accumulated would be the Gulf of Alaska, where muddy torrents pour off the seaside mountains into the deep ocean. The uplifted mountains directly adjacent to the deep ocean provide a source of lots of mud and sand. This sediment would have traveled only a short horizontal distance before coming to rest in the cold, low-oxygen waters of the deep ocean.

Another feature of the modern Gulf of Alaska would also likely have been present in the Iapetus Ocean 700 million years ago: icebergs. These floating "islands of ice" are actually fragments of glaciers. Glaciers course along over the continents, scraping up rock and entraining a mess of sediment in the ice. When pieces of the glacier break off and float away in the ocean, they often contain chunks of rock. Out at sea, the ice melts, and the rocks drop out – some of them quite large. These "dropstones" plummet to the bottom of the sea and settle into the finer-grained muddy sands already there. They look out of place, because they are so much larger than the other sediments. Later, the dropstones will be buried by further turbidity currents.

There is substantial evidence around the whole planet from deposits of this age that suggests an Ice Age period unlike any other. The rocks suggest that the ice came down from the poles almost to the equator. In other words, the whole planet froze over. Dubbed "Snowball Earth," because of what such a glaciated planet would look like from space, this cold period is recorded by dropstones and other lines of evidence from every continent except Antarctica.

It's not certain that the clasts we find in the greywacke along the C&O Canal are Snowball Earth dropstones, but in Loudon County, Virginia (the Blue Ridge Province), the Faquier Formation, another Iapetus-deposited rock unit, has been identified as a Snowball Earth deposit.

Figure 4.3 shows some larger clasts present in the greywacke exposed along the Potomac near Chain Bridge (MM 4). There's quite a variety of chunks in there: many sizes, many colors. Some of these clasts are recognizably cobbles of granite, or gneiss. The gneissic ones have foliations which differ from the foliation in the rest of the rock, so we know they are derived from some other, pre-greywacke deposit of gneiss. It's hard to tell whether these clasts are glacial dropstones or not, because the greywacke has been so metamorphosed (at a later time). The deck has been shuffled. The metamorphosis makes it difficult to get a precise picture of conditions at the time the sands and mud (and dropstones?) were deposited. In fact, I really shouldn't be calling them "greywacke" at all. A better descriptor would be "meta-greywacke."

The meta-sedimentary rocks of the Potomac Piedmont go by many names: some people call them part of the Wissahickon Schist, focusing in on their metamorphic textures. Other geologists refer to them by names like "Sykesville Formation," "Laurel Formation," and "Mather Gorge Formation." For our purposes, I think it's enough to call them **meta-greywacke**. That summarizes what we know about their origins, while also acknowledging that they were later cooked and squashed by metamorphosis.

Mixed in with the meta-greywacke, and especially well exposed along the Billy Goat Trail are large tabular zones of very dark rock with a texture like alligator skin. These rocks are **amphibolite**, an intrusive igneous rock dominated by the mineral amphibole. Amphibole, as you can tell from Figure 4.4, is mafic. What are these big slabs of amphibolite doing amongst all this meta-greywacke? There are two possibilities. One is that the amphibolite is a **sill**, which is a thick mass of magma that gets inserted between sedimentary layers. Sills are essentially a thin, flat variety of plutons. Imagine inserting the nozzle of a tube of toothpaste in between two slices of bread. Squeeze the tube, and toothpaste squirts into the thin gap between the slices of bread. It pushes the slices apart, and spreads out into a big pancake-shape mass. The ultramafic magma could have squirted in between greywacke layers like the toothpaste. The second possibility is that this amphibolite cooled into rock from magma deep in the oceanic crust. According to this second possibility, it was only later, when all these rocks were deformed, that the amphibolite was shoved into the midst of all this meta-greywacke. Therefore, this amphibolite would be a slice of the oceanic crust, a fragment of the floor of the Iapetus Ocean. I favor this latter interpretation of the amphibolite. Regional geology backs this up: similar slivers of mafic and ultramafic rocks extend up and down the East Coast in a northeast-southwest line, essentially paralleling the Appalachian Mountains. Connecting these dots shows us the line that used to mark the shore of ancient North America. That's where the Iapetus Ocean used to be; all that's left are a few telltale slabs of ultramafic rocks.

Not all packages of marine sediments and ultramafic slices are the same. By comparing variations in the various rocks, geologists have established that the Piedmont rocks consist of a series of chunks of crust, shoved on top of each other in a series of "tectonic shingles." Each of these slabs of crust is distinguishable from its neighbors, but all are part of the Iapetus Ocean basin. It would be as if you took modern-day Indonesia, and its thousands of islands, and swept them up. Slathering them onto the edge of the Asian continent, you would now have a series of mushed-up islands (and the oceanic rocks which once separated them) clinging to the edge of a larger and older continent.

Geologists call these chunks **terranes** (Figure 4.5). ("Terrain" means the lay of the land, the landscape. "Terrane" is a displaced chunk of crust.) The Potomac Terrane, the only terrane exposed along the C&O Canal, is interpreted as being an accretionary wedge. Accretionary wedges form when a plate of oceanic crust gets subducted underneath a continent. As the oceanic slab goes down the trench, all the sediment on its back, plus assorted knobs and plateaus of oceanic crust get scraped off by the leading edge of the continent. This pile of scrapings is kind of like what would pile up on a bulldozer's blade if it were driven along the bottom of the ocean – only much bigger (Figure 4.6). As you can imagine, the internal coherency of these sediments is all jumbled up by this method of accumulation: as a result, geologists call it a "mélange," the French word for "mix."

The fact that greywacke and other sediments would have been scraped off indicates that things are changing with our friend the Iapetus Ocean. Rather than the calm, stable situation that prevailed during the Cambrian and early Ordovician (from, say, 545 until 470 million years ago), the development of an accretionary wedge indicates that subduction has initiated. The Iapetus Ocean is shrinking, it's underlying crust being subducted, and the loose sediments on top with no choice except to pile up.

Of course, what's another symptom of subduction? Volcanoes! There's plenty of evidence along the C&O Canal for volcanic activity about 470 million years ago, the middle Ordovician. This is the **Taconian Orogeny**, the first of three pulses of mountain-building that eventually generated the Appalachian Mountains.

Far upstream from the Piedmont, in the Valley and Ridge Province, Ordovician-age sedimentary rocks start changing. They loose their "clean limestone" look and start recording an influx of dirtier sediments from the east. The average Joe will look at these layers of rock and see merely a change in rock type. "Yeah, so what?" he might intone, "Limestone below, shale above, then red sandstones and conglomerates on top of that." A sedimentary geologist looks at the same package of rocks and sees an increasing influence of land-derived sediments, and therefore decreasing water depth. The land is getting closer, these sediments tell us. They also include packages of volcanic ash, which has weathered over time to beds of **bentonite**, a clay mineral. This tells us the approaching landmass was volcanic in nature, probably a chain of volcanic islands similar to the modern Aleutians, or Indonesia. One of these bentonite layers goes by the nickname The Big Bentonite, because it is such a huge deposit. (Technically, the Big Bentonite is a European moniker, and it's officially dubbed the Millburg Bed in the U.S.) 1140 cubic kilometers of volcanic ash were belched into the air in what must have been the mother of all eruptions. The ashfalls of the Big Bentonite covered a wide swath of three continents, and likely fell into the Iapetus Ocean too. All in all, it’s estimated to have covered millions of square miles with ash several meters thick. Studies of the minerals in the ash suggest that it was a single sustained eruption lasting a couple of weeks. It is the largest single volcanic eruption we know of, ever. It was 454 million years ago.

In the Piedmont, we don’t find this coarsening sediment, nor nice fat layers of volcanic ash. The Piedmont was in a very different place during the Taconian Orogeny. The accretionary wedge, that mélange of deepwater sediments and oceanic crust that North America had bulldozed off the bottom of the Iapetus, was getting squeezed. The volcanic island chain was now encountering the subduction zone, but islands don’t fit down a trench very well. Picture a shoelace getting caught in the gap at the end of an escalator: It clogs the system briefly, but soon the shoelace breaks and the overlying shoe (volcanic islands) is left on the boundary between the moving escalator (oceanic crust) and the solid floor (continental crust). In this manner, terranes were added to the eastern edge of the North American continent.

Just as the conveyor belt at the grocery store moves boxes of cereal, cartons of milk, and bunches of celery ever forward towards the cashier, so too does oceanic crust move islands and micro-continents ever forward towards the subduction zone, where they are scraped off and added to the edge of the continent. Once added on, or “accreted,” we call them terranes.

While the Potomac Terrane and its neighbors were feeling the squeeze from being caught in this tectonic vise, its rocks began to change. Not only were they all jumbled-up from being shuffled in the accretionary wedge, now they began to metamorphose too. Heat and pressure increased as the islands shoved inwards onto the continent. Greywacke and ultramafic rocks of the Potomac Terrane warmed and started developing metamorphic foliation. Think back to the cookie dough that I squished in Figure 2.17: The minerals align themselves perpendicular to the direction they are being squeezed from. So as North American continent and the island arc pushed on the sediments from both sides, the foliation developed in a vertical direction. Mica flakes rotated until they stood on end, and quartz ribboned itself out into upright pancake shapes. After this event, it was no longer greywacke: now the rocks of the Potomac Terrane became meta-greywacke.

Estimates of the conditions our Piedmont rocks were subjected to are based on the metamorphic minerals we find grown in them. The garnets of Figure 2.15, for instance, speak to elevated temperatures and pressures for an extended period of time. Along the Billy Goat Trail, where these rocks are best exposed in C&O Canal National Historical Park, it’s thought that the rocks were at about 14 kilometers depth (about ten miles). That’s a lot of overlying rock mass. Imagine the weight of ten miles of rock balanced on your head. As you can imagine, it would have been hot down there: temperature estimates are that it heated up to somewhere around 700º C.

This is really hot, even for a subduction zone. It was hot enough to trigger partial melting of the meta-greywacke. Remember partial melting, the Earth's own distillation process? When rocks made of many different minerals (like greywacke) are heated up, the lighter-colored, lower-melting-temperature minerals turn into liquids, but they leave the darker-colored, higher-melting-temperature minerals behind (Figure 2.13). You can see this process frozen in action along the Billy Goat Trail. There you will find terrific exposures of **migmatite**, a partially-melted rock (Figure 4.7). Migmatite is a weird rock in terms of classifying it: it's so metamorphosed that it's not even metamorphic anymore. It has started to melt, and therefore part of the rock is igneous. It's on the cusp between these two major families of rocks.

When we find it exposed in places like the Billy Goat Trail, it offers us insight into the way that granites are formed. A close examination of the migmatite shows us wispy strands of dark minerals surrounded by a clotted network of pink-and-white granite (Figure 4.7 B). I'm reminded here of the cheese-making process: To make a hard cheese, the raw cheese is pressed in a device that uses cheesecloth to separate the solid curds from the liquid whey. These dark strands are the mafic remnants of the greywacke, the tough fibers that wouldn't melt, and the surrounding granite is the magma that resulted. Because we see the dark strands in a variety of orientations within the granite portion of the migmatite, we know that their foliation preceded the melting event. (If foliation was imparted *after* melting instead, all the foliated strands would parallel one another.)

Eventually, enough felsic magma was generated by this partial melting that the molten granite mobilized, and cut through the semi-molten migmatite. Its natural buoyancy as a hot, liquid, felsic mass drove it upwards, seeking a place where its low density would allow it to stay. As a result, we see granite dikes cutting across the semi-granitic migmatite (Figure 4.8). These dikes also cut across the meta-greywacke and the amphibolite, as we saw back in Figure 1.1. Some of the granites in the Great Falls area have been isotopically dated to be about 469 million years old.

Where did this granite end up? Higher up in the crust, but as you can see if you look up from the Billy Goat Trail, there's nothing above you but empty sky and turkey vultures. There's been a lot of overlying rock removed by erosion, so we won't find the granites hanging over our heads. Further to the east, in the Piedmont rocks underlying Georgetown, similar granites can be found. There, the Georgetown Intrusive Suite, a series of plutons that were injected into the crust one after another, show us what it looks like when granites lodge themselves in the crust. They crack open surrounding rocks with dikes both large and small (Figure 4.9), and settled into the pocket that they've muscled open for themselves. Isotopic dating on the Georgetown Intrusive Suite gives ages of about 464 million years ago.

Amid all this heat and collisional pressure, the rocks behaved differently than you and I are used to seeing rocks behave. We're accustomed to rocks breaking when they're stressed too much, but these hot rocks didn't break so much as *flow*. Conditions were so hot and pressurized that the rocks behaved in a ductile manner: more like warm wax than cold wax. As a result, we see numerous signs in the modern Piedmont that showed us the Ordovician Piedmont was flowing in a goopy, oozy way. For instance, examining rocks in the parking area adjacent to Pennyfield Lock shows a swervy, __ texture that indicates they have flowed (Figure 4.10). Some of the original layering is preserved, but you can see how it has been shoved over its neighbors, thinning some areas, and thickening others. Taken to extremes, this stretching of the rock yields sausage-shaped segments of slightly-more-solid rock. Figure 4.11 shows how lightly-less-solid rock has flowed around these segments, known as **boudins** (from the French word for sausage).

We also get more prosaic examples of rock flow: folding. You can't spit on the Billy Goat Trail without hitting a folded rock of one kind or another. Figure 4.12 shows two of the myriad examples exposed along the C&O Canal between Georgetown and Seneca: folded meta-greywacke, and folded migmatite. It's axiomatic that it's not easy to fold rocks at Earth surface temperatures and pressures, so this is just one more line of evidence indicating how far down these Piedmont rocks once were. During the Taconian Orogeny, towering mountains once sat on these rocks, causing them to squish and smear.

All of these effects – metamorphism, intrusion of granites, and deformation like folding, boudinage, and smearing – are all symptoms of orogenic activity. Though it would be a tough sell to call the Piedmont "mountainous" today, it bears all the traits of a mountain belt. The only thing it's missing is the peaks themselves, and of course they have been removed through erosion over the past 300 million years.

Let's now take a look a quartz veins. Similar to dikes, we see many quartz veins through the Piedmont Province. Like the icing sealing together the fragmented pieces of cake, these quartz veins seal cracks in the rock. Unlike dikes, however, they are made of quartz only, deposited by hot solutions of silica-bearing water. (Dikes, on the other hand, are filled in with igneous rock instead.) You can see several generations of quartz veins in the Great Falls area: older, folded ones (some of them folded twice), and a younger set that were emplaced after the folding episode was over. Because they missed the folding, the youngest quartz veins are straight.

This younger generation of straight quartz veins aren't 100% pure quartz – they also contain smidges of **gold**. These veins were intensively mined for gold by the National Gold Mining Company in the 1860s. The company was started by a group of Union veterans of the Civil War. Remnants of their Maryland Mine can be seen at the entrance to the Great Falls Tavern visitor center, near MacArthur Boulevard. There, mine shafts penetrated to a maximum depth of 230 feet, pulling some 5000 ounces of gold out of a six-foot-wide vein. The gold was extracted by a protracted purification process: the vein quartz was crushed into sand-sized powder, and then rolled across a copper plate that was coated with mercury. Gold stuck to the mercury, while the quartz sand rolled on by. This amalgam was heated until the mercury vaporized – oddly enough, usually with a potato nearby to absorb the toxic mercury vapor. This process took time, though, and they hadn't worked through all the ore when the mine was shuttered in 1936, in advance of World War II. When MacArthur Boulevard got a layer of asphalt (macadam), a nearby pile of 6 tons of unprocessed gold ore was used as fill for the asphalt.

Like these gold-bearing straight quartz veins, another tabular structure in the Piedmont is undeformed and unfolded. Again, this indicates that it was emplaced *after* the rocks had cooled down and the mashing stresses of tectonic collision were but a distant memory. These are the **lamprophyre dikes** which will be so important in our discussions in the last chapter of this book (Figure 4.14). Lamprophyre is an igneous rock, and like the granite dikes we saw earlier, it injected itself as magma into a crack in the older host rocks. Lamprophyre, however, is a dark rock: its most common components are amphibole, biotite, and pyroxene; mafic minerals one and all. Biotite from these lamprophyre dikes has been dated isotopically to be about 360 million years old.

360 million years ago, elsewhere in our Canal rocks, further to the west, a significant change was happening. We return here to the Valley and Ridge Province's thick stack of sedimentary rocks. These sediments, you will recall, started getting dirty during the Taconian Orogeny. After the orogeny ended, the sediments' younger layers show a cleaner aspect: they go from sandstones and shales (derived from the shedding of Taconian Mountain sediments) to clean carbonate rocks: limestones that were deposited far from the influence of any dirty mountain range. But, about 360 million years ago, they return to clastic grime once again. Like before, the huge influx of dirty sediment indicates uplift of mountains which must be the source of that sediment. These clastics are the ground-up remains of the Acadian Mountains. Like we saw with the Taconian Orogeny, we find volcanic ash (weathered to bentonite) interspersed with the shales and sandstones. One of these ash layers, the Tioga Bentonite, is evidence of a 380 million-year-old volcanic eruption. The source was a volcano somewhere in Virginia, to judge from the way that the ash layer thickens in that direction.

This batch of sediments (+ volcanic ash) in the Valley and Ridge, as well as the lamprophyre dikes back in the Piedmont, are both symptoms of a new orogeny. This second pulse of Appalachian mountain-building is called the **Acadian Orogeny**. The continued subduction of the Iapetus Ocean's underlying crust brought a micro-continent called Avalonia, about the size of modern Japan, slamming into the eastern edge of North America (Figure 4.13). Avalonia has been demoted to the "Avalon terrane" today, and you can find it making up the coast of Maine and Newfoundland. There may be scraps of it hidden under the Coastal Plain's blanket of sediments, too, but they're likely to be small if they exist. The Acadian Orogeny was much more of a big event in New England than it was at the latitude of the C&O Canal: around here, all we got were a few lamprophyre dikes and a dozen layers of sediments and volcanic ash.

Missing time

The rocks of the Piedmont Province are much older than the loose deposits of the Coastal Plain which lie on top of them. The physical boundary between these two rock units of such disparate ages is an ancient erosional surface. We've learned three things that can help us tease out the timing relationship between these two rock units: First, the rocks of the Coastal Plain lie on top of the rocks of the Piedmont. According to the principle of superposition, the Coastal Plain rocks must be younger, and the Piedmont rocks must be older. Second, the Coastal Plain rocks contain fossils of more recent organisms (dinosaurs, whales, shellfish that resemble modern shellfish). Third, though they were originally quickly deposited in an oceanic setting, the rocks of the Piedmont do not contain any fossils, a fact which suggests that they are pre-Cambrian in age.

So there is a big gap in the geologic record here: all the time between the pre-Cambrian and the Cretaceous is missing, about 400 million years. If we were trying to read a complete story from these Fall Zone rocks, we would be disappointed. It would be as if you began reading a 500-page novel, and got to page 5, only to find that the bulk of the book's pages had been ripped out, up until page 430. The final seventy pages of the book are present, pressed right up against page 5, but it's hard to make the transition between the introduction of the novel and its thrilling conclusion. You would know *something* had happened in there, but you wouldn't know *what*. It would make it rather difficult to figure out what's going on.

This is the nature of the geologic record: it's full of gaps, riddled with so-called "missing time." This record of geologic time might be absent for one of two reasons: it may have been "written" (deposited) and then later "erased" (by erosion and the relentless action of the rock cycle), or it may never have been recorded in the first place. There's no rule that says all of geologic time must be recorded in the rock record. Certainly no single location records the totality of geologic history, and perhaps we don't have a complete record even over the entire planet's surface. Even the Grand Canyon, which appears to be as complete a geologic record as we could hope for, is hopelessly riddled with these gaps, where "pages" from the geologic book have been ripped out. (It's estimated that if you were to add up all the missing time at the Grand Canyon, it would exceed all the time which is well recorded there!)

These gaps in the geologic record can be somewhat informative, though: **Unconformities** are what geologist call ancient erosional surfaces. So finding and identifying an unconformity is useful, because in order to produce such a gap, there must have been erosion (the "ripping out" of the geologic "pages"). When we examine areas around the modern world that are subject to incisive erosion, we find that uplifted areas are more susceptible to the tearing down effects of the Earth's surface than areas that are at or below sea level.

Recall the buckled sidewalk of Figure 1.11. The up-thrust section of sidewalk is much more susceptible to scuffing by people's feet. The down-dropped area might have a complete sedimentary record, but not its neighbor the "mountain range." So, then: unconformities aren't a complete mystery: they indicate uplift and erosion, the sort of thing that is typical of a mountain belt. In fact, this is how orogenies (mountain building events, initiated by tectonic collisions) were first identified: an unconformity in one area, and a thick deposit of clastic sediments in an adjacent area. How do you identify a mountain range that is no longer mountainous? Look for the sediments it shed off. Keep in mind that the Earth's surface processes are constantly battling plate tectonics in an effort to smooth out the planet's surface. Parts that poke up get worn down, and parts that poke down get filled up.

So, to bring us back to the C&O Canal, we are reminded of the immense span of time that is missing between the rocks which make up the Piedmont Province (pre-

Cambrian) and those which make up the Coastal Plain (Cretaceous and younger). There is an unconformity surface separating these two distinct packages of rock, and that unconformity marks the site of an ancient mountain range. At the Canal's easternmost terminus, where it debouches back into the Potomac River, there are several spots in Washington, DC, where the unconformity may be observed. You know you're out of the Piedmont and into the Coastal Plain when you stop seeing hard grey rocks, and start seeing round cobbles and pebbles of a light tan color (Figure 4.15). These pebbles and cobbles will be loose; you can pick them up in your hand. Unlike the rocks below them (or any of the other rocks along the Canal), they are not glued together into a rock. These are the Cretaceous river gravels described in Chapter 3.

One excellent place to observe the relationship between these rock units is two miles north of the C&O Canal's zero mile marker. At the intersection of Adams Mill Road and Clydesdale Place NW, outside the National Zoo's service entrance in the Adams-Morgan neighborhood, is a small sheltered display that looks something like a batting cage (Figure 4.16). Inside this "cage" is an outcrop showing both the Piedmont rocks (below) and the Coastal Plain gravels sitting on top of them. In addition, both units are cut by a fault! The fault shoves Piedmont rock up and on top of Coastal Plain deposits, an excellent demonstration that (a) the Coastal Plain is younger than the Piedmont (according to the principle of superposition), and (b) that the fault is younger than them both (according to the principle of cross-cutting relationships).

Setting aside for the moment the full story of this fault, let's reflect a moment on how we know there is a fault there at all: it's the difference in appearance between the Piedmont rocks below (hard, dark, metamorphic) and the Coastal Plain deposits above (loose, coarse, light-colored). The line that divides the two is not in the same place on opposite sides of the fault line – and so it's that discrepancy, the unconformity surface, which alerts us to the presence of a fault.

The unconformity is the final sign of a mountain range that used to tower above what today is merely rolling hills… Welcome to the Himalayas.

Chapter 5: A big ditch

The Culpeper and Gettsyburg basins

After the fresh, flat deposits of the Coastal Plain, the youngest rocks transected by the C&O Canal are those found in the Culpeper Basin, a big hole that was created, and filled in, during the Triassic and Jurassic periods. The Canal traverses these rocks between MM 22.8 (Seneca) and 48.2 (Point of Rocks).

The basin opened up about 200 million years ago. Just north of the C&O Canal, the Culpeper Basin narrows to a thin waist at Frederick, Maryland, and then expands again to the northeast as the similarly-sized Gettysburg Basin. Separating the Piedmont on the east from the Blue Ridge on the west, these Triassic basins are evidence of continental rifting. These two are not the only ones of their type: in fact, there are about a dozen of these large sedimentary basins that run up the east coast from Georgia to Newfoundland (Figure 5.1). They are collectively named the “Newark Group” after the largest example, to be found nowadays in Newark, New Jersey.

These are *rift* basins. They opened up as rift valleys between two chunks of continental crust headed in opposite directions, as the supercontinent Pangea ripped itself apart. Pangea had just been assembled in the Pennsylvanian and Permian periods by a massive collision between two continents: Africa and North America. Once sutured together, these two, plus most of the world’s other landmasses, comprised Pangea. This supercontinent was a massive thing: a landmass that stretched from one pole to the other, roughly shaped like the letter C, with a huge sea (the “Tethys”) starting at the equator and opening to the east.

Eventually, this “supercontinent” situation proved unstable. Continental crust is thick, and like a thick jacket, it’s very good at insulating. That is to say: it stops heat flow. If you wear a down parka on a day that gradually warms up, at some point you are going to start overheating. You will rip that jacket off even if I offer you a hundred dollars to keep it on: you’re rifting apart from the sweaty thing!

Similarly, supercontinents restrict the amount of heat that can flow out of the Earth’s interior towards its surface. That heat builds up underneath in the mantle, accumulating into a hotter and hotter mass that eventually has no choice but to rise up and bust on through! As this release of heat happens, it rips apart the restrictive continent above it. The result is that the continent rifts apart, splitting into two pieces. In between is the site of a new ocean basin.

A similar rift valley system can be observed today in modern East Africa, where the African Plate is ripping into two smaller plates. These sub-plates aren’t sticking together: the Somali Plate is headed east, and the Nubian Plate is headed west. The Great Rift Valley is the gap between the two, dropped down a half a mile in some places, and a terrific trap for any sediment in the area.

This copious influx of sediments, washed off the adjacent highlands on both sides, is a boon to studies of early human history. Our ancestors walked in that Rift Valley, and the constant dumping of sediments has preserved their bones for us to marvel at. Even transitory phenomena like footprints get archived by a constant torrent of sediments. The trackway at Laetoli, Tanzania is only the most stunning example of this: there, two hominids (one big, one small) walked side by side through wet volcanic ash about 3.6 million years ago. Like you and I, they walked on two feet, and their tracks show this. It's likely that earlier hominids did not restrict their strolls to the valley floors, but that is the only place we will ever find footprints like these. Why the valleys rather than the peaks? If they had left a similar chain of footprints on the side of a mountain, those tracks are thousands of times more likely to be destroyed soon after by the forces of weather and gravity. They are exposed, and unstable. Recall Figure 1.11: the uplifted areas are preferentially subjected to erosion, and the down-dropped areas are preferentially buried in sediment.

So what would it have looked like here in America? Can we imagine the scene in the Triassic, when these valleys formed? Well, start with your mental image of the Great Rift Valley in Africa. Now take away the elephants and zebras, and replace them with raptor dinosaurs and other large reptiles. Airbrush out the acacia trees, and plant seed-ferns in their place. Now, the biggest difference of all: Put a big range of mountains right next door to the rift valley. In the Triassic, eastern North America would have looked fresh and rough-hewn, a lot like the modern Alps. The young Appalachian Mountains were shedding incredible amounts of fresh sediments off their flanks. Some went west, and coursed over West Virginia and Ohio. Some went east, and clogged up the yawning gulf formed by the Newark Group basins.

Because the sediments had only a short distance to travel from their source in the hills to their resting place in the basin, they did not have much time to be modified by the sedimentary portion of the rock cycle. I refer here to the processes of weathering, erosion, and transportation. Deprived of these formative experiences, the sediments that filled the Triassic rift valleys are described by geologists as "immature": they're not as well-developed as they could be.

Take arkose, for instance. Arkose is a variety of sandstone that is typical of continental basins. Characterized by a substantial proportion of large, angular feldspar grains (Figure 5.2), arkose shows us sediments which have traveled only a short distance. As you will recall, the further a batch of sediment travels down the pipeline, the more concentrated its quartz content becomes (unstable minerals like feldspars are chemically weathered into clay minerals), and the rounder its grains get. Arkose is neither compositionally mature, nor texturally mature. To the geologist, arkose practically screams with adolescent frustration. It thinks it's a big, bad adult sandstone, but even a quick glance shows it has a long way to go.

If you would like to take a quick glance at some arkose, to see what I'm talking about, check the river side (west) of the Towpath between MM 34 and 35, south of White's Ferry and just north of the Turtle Run campsite. There are some nice examples of arkose present in boulders on the side of the path. If you look closely, you will see transparent reddish, grayish, and purplish quartzes, all identifiable as *quartz* because of their translucence (in spite of their variegated colors). But there are also numerous little chunks of white in there, solid opaque white, some of it tending towards pink or grey. These are the *feldspars*, the characteristic minerals of the arkose. Just as you can tell a teenager by their petulant attitude, so you can tell an arkose by its petulant feldspars.

If the Great Rift Valley of Africa doesn't do it for you as an analogy for a continental basin, we can shift our attention to the west. The Basin and Range Province (which occupies most of Nevada, plus portions of adjacent Utah, California, and even a smidge of Idaho) is a great place to go to see rift basins in action. There, as the North American continent widens from east to west, we have a series of hundreds of north-south-trending mountain ranges separated by hundreds of north-south-trending valleys. The geologist Clarence Dutton famously quipped that the Basin and Range looked like "an army of caterpillars marching north." As Figure 5.3 shows, the mountains are separated from each other by chasms filled with sediment eroded off the mountains. This striking pattern is due to the crust stretching out in an east-west direction, like the opening of a paper fan. The Basin and Range is smoothing itself out over time: rock gets eroded off the tops of the mountains, and then tumbles down-slope to fill in the concave sink at a lower elevation. If tectonics ceased refreshing the topography, Nevada would soon be as smooth as Kansas. Endlessly pouring into those Basins of the Basin and Range are uppity young arkoses, still wet behind the ears. They are only a few miles removed from, and a few thousand feet below, their ancestral homelands.

Though they're not as dry as Nevada, the sediments in the Newark Group rift valleys reflect the same trend. They show us terrestrial scenes, far from the influence of the ocean. The down-dropped basin mainly filled with lakes and streams.

Along the C&O Canal, one of the best places to see these rocks is west of Seneca Quarry (MM 23), where the Canal traverses Seneca Creek on an aqueduct. You'll notice that the Towpath turns red in the vicinity of Seneca. Just west of the aqueduct, a small trail diverges from the Towpath, and heads into the woods. A short walk along this trail brings you to the abandoned Seneca Quarry (Figure 5.4), which operated between 1774 and 1898. The sandy grain size and distinctive deep red color will be instantly familiar to anyone who has walked any distance along the Canal, for this is where much of the stone used in Canal locks was gathered. Seneca Sandstone was also used to construct the Smithsonian Castle on the National Mall, as well as numerous less celebrated structures along the Canal's route. For instance, examine the lockhouse downstream of the Seneca Aqueduct.

Recall that the Culpeper Basin and the Gettysburg Basins are not alone: they are part of the larger chain of basins called the Newark Group. A more northerly counterpart to the Seneca Sandstone, quarried from the Newark Basin, was the building material used to construct New York City's famous brownstones. It's essentially the same rock, just not as red.

The red color is due to copious amounts of oxidized iron (Figure 2.6). Oxidation is rusting, and the reddish color you see in the Seneca Sandstone is the same as the reddish smear that comes off on your fingers after you touch rusty metal. The color red is used by sedimentary geologists as an indication that the sediments were deposited in a continental location: that is, above sea level, exposed to the air.

There is other evidence that the Seneca Sandstone was exposed to the air too: Just beyond the quarry is a small unpaved parking area where a few dozen large blocks of stone have been piled up. A quick examination of the surfaces of these blocks reveals some interesting features. When sediments are deposited, they frequently are imparted with distinctive structures that tell us something about conditions at the time of deposition. Note that these "primary sedimentary structures" do not get created during transport of the sediment, nor during lithification: they occur when the sediments have been dropped, when they are still loose and malleable. Later, they are preserved when the sediment gets turned into sedimentary rock.

The blocks of Seneca Sandstone adjacent to the parking area show three distinctive types of structures: mudcracks, raindrop impressions, and trace fossils.

Mudcracks form when fine-grained wet sediments are dried out (Figure 5.5). As they lose water to evaporation, they contract, and crack open in a series of polygonal shapes. Fossil mudcracks like these tell us that the sediments must have been exposed to the air, for it's impossible to dry out underwater. Later, the sediment-carrying water returned, and filled in the cracks with a fresh load of sediment, burying the mudcracks for the future.

Raindrop impressions tell a similar tale: Each drop of rain, when it falls through the air, carries enough velocity to punch a small crater in fine sediments. If there is just a smattering of rain, individual raindrop craters can be created, and preserved (Figure 5.6). Again, this sedimentary structure indicates to geologists that the sediment must have been exposed to the open air, at least for a short period of time. After all, raindrops impacting on the surface of a lake will not affect the shape of the sediments at the bottom of the lake.

Trace fossils are indications left in sediments showing that living organisms were there when the sediments were deposited. Trace fossils come in a hundred varieties, from burrows to footprints, gnaw marks to resting places. Even fossilized poop counts as a special kind of trace fossils. In the red sandstones of the Seneca Quarry, we find horizontal trails or burrows that meandering within the plane of bedding. Shortly after viewing these fossils one day, I walked a short distance down to the Potomac River, and noticed a snail making its way through the mud there (Figure 5.7). Separated by only 200 feet, and a 200 million years, here were two traces that looked virtually identical! We don't know whether it was a snail or a worm, or some other creature that left the little red ridges in the Seneca sandstone, but they tell us that *something* crawled through the mud a long time ago.

Another trace fossil that's distinctive and reasonably common in Triassic and Jurassic rocks of the Culpeper Basin is the footprint of a dinosaur. These sediments were deposited when dinosaurs had begun their domain over the planet, and they walked in wet mud as they did. The most distinctive track is of a three-toed bipedal dinosaur (Figure 5.8), like an ostrich with scales. An unexpected location where these tracks turn up is in Montpelier, the home of President James Madison. There, a series of this dinosaur tracks can be seen in the red sandstone floor of his living room.

Elsewhere, parts of a similar group of rocks, the Bull Run Formation, were evidently deposited by streams. The rocks bear evidence of a current of water pushing sand along the bottom. When we saw this before, in Figure 2.8, we had a top-view, and we called it "ripple marks." Compare that image with Figure 5.9, where we get a glimpse at the same process, but this time from the perspective of a side-view. A distinct feathery shape shows us the direction that the water current was pushing the sediment. As Figure 5.9 C shows, the water picked up sediment on the upstream side of the migrating ripple, and tumbled it over the crest. Over time, new layers built up on the front side of the ripple only, moving it downstream. What we see preserved in this sample is **cross-bedding**, evidence of water that was moving steadily from right to left.

Perhaps the most distinctive rock in the Culpeper Basin is the Leesburg Conglomerate (Figure 5.10). It is only found along the western edge of the down-dropped basin, and it's the coarsest sedimentary rock we will find in this area. The large size of its grains serves as a reminder it was deposited by water strong enough to move those big clasts, and that means high energy. Probably the conglomerate was deposited as a debris flow. The limestone's big rounded cobbles of in a variety of hues make it an attractive rock, and it stands out like a neon sign when you drive by it on many roadside exposures along Route 15 from Point of Rocks south towards Leesburg. When the U.S. Capitol was under construction, someone got the notion to use the Leesburg Conglomerate as columns in the Statuary Hall. What a bone-headed idea! Though it's patriotic to use local U.S. stone in such a project, conglomerate is a notoriously difficult stone to work. Every subtle, artisanal attempt to carve and smooth the stone fought against the conglomerate's knobbly nature. There were a great many broken or pocked columns tossed on the scrap heap for each of the smooth, polka-dotted ones which grace the Capitol today.

The cobbles are of limestone, the Leesburg Conglomerate is often mistakenly called a "marble," but unlike a marble, it does not have that distinctive "sugary" appearance when freshly broken (Figure 2.14). Along the C&O Canal, the Leesburg Conglomerate pops up between MM 38 and the Marble Quarry campground.

Another odd sediment that shows up only rarely in the Culpeper Basin is black shales. Remember that black indicates low oxygen, and everything else we've seen so far here has been well-oxygenated and rusty. There were evidently small pockets of anoxic waters, perhaps in swamp environments or deep lakes. Figure 5.11 is from just such a deposit. Note how instead of seeing a trace fossil here, we're seeing a real body fossil – this is another indication of low oxygen conditions when these sediments were deposited. Only if oxygen levels were low could this fish's body avoid decay while lying at the bottom of the water.

Let's go back to our modern analogue for the Culpeper and Gettysburg Basins again: the Great Rift Valley of East Africa. Not only is the Great Rift Valley being filled in by sediments shed off the highlands to its east and west, it's also subject to periodic influxes of lava and ash. This is because the rifting releases pressure on the mantle far below, and that allows it to partially melt. The resulting mafic magma ascends along the fracture network that developed when the crust stretched out. We already mentioned an example where ashfalls have preserved a stroll early in humanity's history (Laetoli, Tanzania). Figure 5.12 shows fresh basaltic lava, the same stuff that makes up the oceanic crust, welling to the surface and spreading out over the Afar Triangle region in northern Ethiopia. This is what a flood basalt looks like at the moment it happens, but keep in mind, that lava is coming from somewhere: it has a plumbing system of feeder dikes beneath the surface, funneling the lava upwards. In the Culpeper Basin, we see some basalt flows, but most of the overlying rocks have been stripped away by erosion, leaving only the deeper feeder dikes behind. These occur in a variety of shapes and sizes, and are more often the igneous rock **diabase** than basalt. Diabase is essentially the same composition as gabbro and basalt (that is, mafic), but it's intermediate between them in crystal size (Figure 5.13). This indicates the shallow depths at which the diabase cooled, not too fast and not too slow.

These diabase intrusions are harder than the shales and sandstones of the Culpeper Basin. As a result of recent weathering attacking them both, the diabase stands up as hills – high spots in the local topography. The weaker sedimentary rocks are carried away by the streams, and the ancient magmas now rise above the landscape.

So our overall picture of the Culpeper Basin is something like Figure 5.14: down-dropped continental crust (Piedmont and Blue Ridge rocks), filled in with clastic sediments generated by weathering of the adjacent highlands. Magma and lava intrude from below, and cool to become basalt and slightly-coarser-grained diabase. The coarsest sediments are at the edges of the basin, and the middle hosts fine sediments deposited in the calm waters of ancient lakes. Through it all, dinosaurs walked about, going about their dinosaur business.

Once the rifting process really gets going, the igneous rocks take over, far outpacing the sedimentary inputs in the basin. Rather than filling with immature sandstones and conglomerates, they widen and widen, with lava welling up from beneath to accommodate this extension. Decompression of the underlying mantle generates a mafic-composition magma, which can cool to become new oceanic crust (if the rift basin is wide enough).

Of course, it should be evident that the Newark Group rift basins were failures. They never opened up to be new oceans. Instead of deepening to the point where ocean water rushed in and created a narrow ocean like the modern Red Sea or the Gulf of Aden, they simply widened a bit, got choked with sediment, and then died. Other rift basins, a few dozen kilometers to the east, got the prize. They were the ones to connect together in a long chain, forming the brand spankin' new Atlantic Ocean. Think about pulling on a thick wad of pizza dough. If you and I play tug-of-war with the dough, it will start to develop numerous small rips as it stretches. Eventually, some of those small rips will connect up, and they will suddenly grow much larger. This is the dough's weakest link, the rip that will end up taking up all the strain and dividing the dough in two. The smaller rips are the Culpeper Basin and its ilk. The big rip is the Atlantic Ocean (Figure 5.15).

If the Newark Group rifts had won instead, the Atlantic Ocean would have opened up here. Point of Rocks would be the Atlantic coastline. Frederick, Maryland would be the northeast shore of Morocco, and the cities of DC and Baltimore would be somewhere in the Atlas Mountains!

Chapter 6: Crystalline basement

The Blue Ridge Province

The C&O Canal runs through the Blue Ridge Province from Point of Rocks (MM 48.2) to just past Harpers Ferry, at Fort Duncan Bend (MM 63). The Blue Ridge itself, the mountain ridge for which the province is named, occupies a portion of this stretch, but the province is bigger than its namesake alone. Regardless of mountain or valley, for those 15 miles, the Canal traverses the oldest rocks it sees along its entire route. The story of the Blue Ridge is a great place to take a step back, and look at the general way that mountains get formed, with the mountains here offering examples of not just one but *two* distinct cycles of mountain-building.

The processes of mountain-building in the Proterozoic Eon made the very oldest of the Blue Ridge rocks: the granites that were intruded in the continental collision that built up the oldest supercontinent, **Rodinia** (from the Russian *родина*, meaning "homeland"). These granites, which originally were inserted into the crust as pockets of liquid magma, are about a billion years old (that's *billion*, with a *b*). This date, derived from radiometric dating of minerals in the granite, gives us the timing of the Grenville Orogeny, a period of mountain-building experienced by young North America a very long time ago.

However, the igneous rocks are not all *exactly* the same age: Some of these granites were intruded earlier than others, and thus were subject to deformation as the orogeny continued. Thus they metamorphosed from granites into granite-gneisses. These bear the characteristic banding of regional metamorphism ("foliation") – a trait that distinguishes a gneiss from a more even-grained granite. Thus the really old rocks (intruded at the beginning of Grenvillian mountain-building) will have "stringers" of dark and light minerals in them, and the slightly-less-old rocks (intruded towards the end of the orogeny), will lack these stripes, and will instead have light and dark minerals that appear evenly-speckled throughout the mass of rock. (Figure 6.1)

These granites, like all granites, are derived from partial melting of other rocks. Their sources were probably a variety of things, but we do find some intriguing clues about what some specific source rocks may have been. They contain beet-red garnets, aluminum-rich metamorphic minerals that grow on the chemical remains of sedimentary predecessors. (Garnets come in several colors, each indicative of the composition of the pre-metamorphic source rocks.) More interesting, shiny dark grey patches in these granites are deposits of **graphite**, the same stuff that makes up pencil "lead." Graphite is pure carbon, and the source for this carbon was likely organic matter. A billion years ago is long before recognizable multi-cellular fossils show up in the geologic record, so the organic material source is likely to be the remains of bacteria and their kin: single-celled, small, but extraordinarily prolific organisms. We have plenty of bacterial fossils from early Earth history, some as old as 3.5 billion years old. So we know there was life on Earth at the time of the Grenville Orogeny (indeed, it had been around for 2.5 billion years at that point!), so it's not hard to imagine accumulations of organic matter that could have been melted to generate these old Grenvillian granites. They probably looked like the black shale we saw in the last chapter (Figure 5.11), minus the fish fossil.

The Grenville was not one of the pulses of Appalachian mountain-building; it's almost three times as old as those younger mountains. During the orogeny, the eastern edge of North America collided with the nuggets of continental crust that would go on to become the ancient centers of the Congo and Amazonia (Figure 6.2). The Congo craton would have been most likely to be directly "offshore" from the C&O Canal at that point, while the Amazonia craton would have been further north – about where Newfoundland is today. (A **craton** is a platform of really old, really stable rocks, usually located in the interior of a continent.) Sandwiched between these cratons and North America was a block of land which was smeared out in the collision. For a gruesome analogy, you could imagine an auto wreck where a poor critter, a raccoon for instance, gets caught between two trucks. Of course, the late raccoon is in a new, different shape after the collision as compared to what he looked like before. When the wreck is over, and the trucks are pulled apart, a bit of the roadkill sticks to each of them. Similarly, the Grenvillian landmass was smeared out from its original shape into a long line paralleling the east coast. This line can be traced from Newfoundland to North Carolina.

When continents collide, things heat up. Partial melting (like we saw in the migmatite described in Chapter 4) results in felsic magma, which lodges in the orogenic mountain belt as granites. Granites that were intruded early in the orogeny will be deformed by later collisional stress and will develop metamorphic foliation, whereas the later granites will cool after these "squashing" stresses impact older rocks, and so they won't bear the scars. It's kind of like September 11th: If you were around on that day, you'll remember how scared we all were; you'll bear the emotional "foliation" from that event. Kids born after that day won't be directly scarred by the episode.

So now we've got our granites and our gneisses. Lying atop these ancient igneous rocks is a thin, patchy veneer of sediments: stream gravels and sandstones. These sediments (now transformed to sandstone and conglomerate) record the erosion of the Grenville Mountains in Proterozoic time. The mighty Grenville Mountains were built up by the forces of tectonics, but once the orogenic forces waned, the everyday forces of rainfall and gravity started their slow, methodical work. The higher up a landmass is thrust into the sky, the more susceptible it is to wearing down caused by weathering and erosion. Rain falls, gravity pulls it inexorably downhill. As it flows, this runoff carries the mountains down to the sea, sand-grain by sand-grain, over millions of years. During storms, more sediment would have tumbled down the valleys; During dry times, there would have been less. As streams gouged into the hillsides, steep cliffs formed, and then collapsed under the force of gravity. Piles of boulders were gradually reduced during periods of intense rainfall – and almost *all* rainfall would have produced powerful scouring floods then, since there was no soil to absorb the downpour. (Land-dwelling organisms, like plants, had not yet evolved.)

Eventually, these surficial process wore the mountains down to stumps, with cobble-choked streams meandering amongst them. These streambeds are preserved as the Swift Run Formation, named for exposures in Shenandoah National Park, further south along the Blue Ridge. Because the streams and their sedimentary debris would only be found in low-lying areas (and not on hill-tops), the Swift Run is a patchy formation. It's not found everywhere, but it is distinctive when seen (Figure 6.3).

Let's imagine visiting this ancient landscape, perhaps in your time machine. (You *do* have a time machine, right?) Exiting this imaginary craft, picture the scene. Standing on one of these bare hills, surveying the scene, your view would have been unobstructed – for this was in the Proterozoic, say about 700 million years ago, and therefore a long time before plants would have colonized the land surface.

You would have been in the middle of a vast continent of bare rock; Rodinia would stretch off for thousands of miles in every direction. If you had walked from west to east across this weird, empty landscape, you would have crossed from North America proper over the mangled remains of the Grenvillian micro-continent, and onto the Congo crust. Though the mountains have been reduced to mere hills, the *mountain belt* remains. This belt of "roadkilled" micro-continent, and the granites which intrude it, would have been the only remaining evidence of the ocean which once bounded North America's eastern shore.

As you're standing there pondering this, a sudden jolt would have knocked you off your feet. An earthquake! Something was happening to Rodinia: it was beginning to rip apart.

Another earthquake, and a huge crack may have opened up at your feet. Not wanting to be separated from your time machine, you jog back across the Grenville mountain belt. Behind you, the Congo craton is pulling away from North America, and the crack enlarges. A large block of crust rotates downward, sliding in to fill the gap.

It might occur to you to wonder why Rodinia, stable for 300 million years, should suddenly start ripping itself asunder: Why supercontinents break apart is as important a question as why they form in the first place. Think of putting a potato in the microwave: you forget to poke holes in it with a fork, but set it to cook regardless. After a minute or two, the potato gets hotter and hotter, and then explodes. It's essentially the same trick a popcorn kernel pulls, except a bit bigger. The excess heat in these foods causes water to vaporize, and water vapor takes up a lot more volume than liquid water does. It expands violently, ripping open its container as it does. Continents act the same way: if they are heated up for too long, the heat will rip them apart.

Continental crust, which is about four times as thick as oceanic crust, is a very effective insulator. Because it doesn't give heat a chance to vent like thinner crust would, heat builds up and eventually reaches uncontainable levels. This heat "inflates" the crust, as most substances expand in volume when they get hotter. This thermal expansion reduces the density of overlying crust, and makes it easier to rip apart. And rip apart it does, the crust extending laterally, and thinning out as a result. Earthquake by earthquake, the supercontinent begins to rift.

We've seen this before, in Chapter 5: The much younger rocks of the Culpeper Basin record a similar episode of continental rifting. C&O Canal rocks show *two* episodes of continental rifting and the birth of a new ocean. The first time was this Proterozoic chapter, and then the Triassic rift basins followed (They also show two episodes of mountain building: first the Grenville Orogeny, and then 600 million years later, the one-two-three collisions that collectively built the Appalachians.)

As the crust stretches, it fractures, and some of these fractures act as pipes. Below the crust, the mantle is being decompressed by this rip opening up overhead. The mantle rocks are already quite hot, but up until now, they were kept solid by the overlying pressure. Now, however, the mantle rocks can melt because of the release of pressure. Basaltic magma is formed through partial melting of the ultramafic mantle. The cracks which you would have seen forming on the surface reach far downward, like a tree root seeks out water. The fractures tap the newly molten rock far below, and conduct it to the surface.

Let's pretend all these earthquakes and yawning chasms haven't scared you out of Proterozoic Rodinia yet. You're standing there at the door of your time machine, snapping pictures of this continental rifting. Perhaps you're thinking how much it looks just like the rifting happening today in East Africa, minus the giraffes and warthogs. Then you hear a hissing sound, and you soon see lava welling up from one of the cracks in the Earth. It flows out of the ground like blood from a wound. The flow burbles out, glowing incandescent orange. It spreads in all directions, getting deeper and deeper. It fills the valleys, burying the stream sediments there. The water of the streams themselves vaporizes as soon as the lava touches it. Again, this is just like East Africa (Figure 5.12). With your time machine parked atop a small hill, you don't have to worry about being flooded by lava…yet. Soon the lava flows stretch to the horizon, and only a few small hills (like the one you're parked on) stick up above the sea of molten rock. You would have been struck by what a *gentle* eruption this was: not violent like Mount Saint Helens or Vesuvius. It would have been more like the lava eruptions in Hawai'i, an eruption that you can walk right up to without fear.

If you had been observing this scene, you might have started feeling a bit light-headed at this point. As you shut the door of the time machine and prepare to depart, you would have noticed bubbles on the surface of the lava flow: these bubbles pop, and they release carbon dioxide gas. Aha! That explains the light-headedness: the lava is releasing gas as it gently erupts over the surface. Below the surface of the lava, other bubbles were forming in much the same way that bubbles form in a bottle of soda when it is uncapped. Gases like carbon dioxide are dissolved in the liquid lava or the liquid soda, and stable *so long as they are kept under pressure*. When that pressure is released (by opening the soda or by erupting the lava), the dissolved carbon dioxide comes out of solution, and creates bubbles.

In the rift-zone lava, these bubbles are making their way to the surface (bubbles are less dense than lava), as the lava congeals all around them. Soon the lava is the consistency of honey, and the bubbles' ascent slows. Then the lava cools completely, and solidifies into solid rock. Because this is mafic lava, the resulting volcanic rock is a basalt, fine-grained and dark colored. When basalt cools, some bubbles are preserved in the middle of the rock, just like the holes in Swiss cheese (Figure 6.4).

As you sit and watch from the safety of your time machine, you see something else happening. As the lava cools and solidifies, it contracts. Again, here is that relationship between heat and volume, playing out before your eyes. Picture what happens to mud as it dries out: it loses water, and thus contracts in volume. The result? As we've seen in the Culpeper Basin, mudcracks form – the mud accommodates its shrinkage by breaking open in a series of polygonal cracks. Cooling lava acts the same way (Figure 6.5). Although the shrinkage caused by cooling isn't as large as the shrinkage caused by drying, a series of polygonal cracks form at the surface, and then extend from the top down into the lava flow as the deeper portions cool.

You're in your time machine, thinking that maybe you'd like to get out and grab a sample of this holey rock for a souvenir, when yet another earthquake shakes the ground, and a fresh crack opens up, instantly oozing another outpouring of lava. The second flow covers the first. You decide not to stick around after all, and it's a good decision. Other flows will keep erupting as long as the crust continues to stretch. Each flow blankets the last, and eventually the entire landscape would have looked like eastern Washington State, where the Columbia River cuts through a younger series flood basalts. Iceland is a modern analogue; another spot on the modern Earth where tectonic rifting is triggering eruptions of basalt.

This stack of thick lava flows, preserved today as the Catoctin Formation, was the result of crustal stretching – Rodinia being ripped apart. North America headed one direction, and the Congo craton (and assorted other continental chunks) headed off in another direction.

We can tell the direction of crustal stretching by looking at clues hidden in the rocks. Just as the north-south orientation of the mountains in the Basin and Range Province (Figure 5.3) indicates that the crust is stretching in an east-west direction, the rifting of Rodinia left perpendicular "stretch marks" in the crust. In our case, the clues can be found in the plumbing that fed the lava flows. That lava was percolating upwards along fractures, and the fractures themselves tell us the direction of stretching. These fractures are preserved today as dikes cutting across older rocks (Figure 6.6). The dikes are filled with basalt, and the older rocks are the granites and gneisses left over from the Grenville Orogeny. Though these dikes are harder to see along the C&O Canal (a few are visible east of Sandy Landing, near MM 60), Figure 6.7 shows their orientation in nearby Shenandoah National Park. The dikes are oriented northeast-southwest, which indicates that the Congo craton was pulling away from North America in a southeasterly direction. North America was headed to the northwest.

Ultimately, as the two continents pulled apart, one crack got deeper than the others, and that crack became a new ocean basin. Imagine stretching some bread dough between your hands. As you pull on it, you can see it elongating, and numerous small rips form. However, once one rip gets torn open a little wider than the others, then all the strain is concentrated there: the small rips stop tearing, and the big rip opens up completely. The result is you're left with two blobs of dough where there was once one. Tectonically, the result is the same: the continental crust separates into two blobs, and fresh oceanic crust is created in the gap between them. The failed rips, being open holes, quickly fill with sediments. The Blue Ridge hosts failed rift valleys that are the Proterozoic equivalent of the Culpeper Basin. However, some different sediments are found: one of the most important is the glacial debris of the Faquier Formation, evidence of the Snowball Earth episode mentioned in Chapter 4: a very cold period in Earth's history when glaciers may have extended all the way to the equator! A "puddingstone" of multiple-sized fragments is found there – black in color due to the low oxygen conditions that occur when a layer of ice prevents water from mixing with the atmosphere. These dark beds grade upwards into red beds, which indicate post-glacial well-oxygenated conditions. There has even been a suggestion that the rifting of Rodinia (and the eruption of the flood basalts) may have been the decisive factor that ended the Snowball Earth glaciation. When volcanoes erupt, they release lots of carbon dioxide (like we saw with the soda-pop-esque bubbling earlier). This carbon dioxide acts as a greenhouse gas, then and now. If enough of it built up in the atmosphere, it could have warmed the planet enough to melt back the glaciers.

As the continents continue to diverge, the mantle generates dark, dense magma which wells up to cool into oceanic crust. This is the process that is happening today at mid-ocean ridges (Figures 1.2 and 5.15): the plates consist of both continental crust in their interiors, but are fringed with a skirt of oceanic crust out at their boundaries (Figure 1.7). As two plates pull apart, a slight gap opens between them, and magma squirts in to seal that crack shut. A year or two later, another earthquake opens the gap again, and again it is sealed shut from below by an upwelling of magma. This process – continental rifting transitioning to mid-ocean rifting – is how oceans are born.

When Rodinia broke apart, it gave birth to the Iapetus Ocean. At first, this fledgling ocean would have looked like the modern Red Sea, between Africa and Arabia (Figure 6.8): a skinny little ocean basin. As time passed and seafloor spreading continued, the ocean basin would have widened and widened until eventually it would have looked like the modern Atlantic Ocean, at least in general dimensions. Incidentally, the reason we call the post-Rodinia ocean "Iapetus" is because it is the predecessor of the modern Atlantic Ocean. The Atlantic Ocean is named for Atlas, the Titan of Greek mythology who held the world on his back. The father of Atlas was Iapetus, and so the ocean that came before the *Atla*ntic goes by this name as well. (Iapetus was himself the son of Gaia, the goddess of Earth, and Uranus, the god of the sky.)

The rifting of Rodinia stranded some fragments of the continent as islands our stranded in the Iapetus ocean crust, much as modern Madagascar "floats" off the east coast of Africa. Later, during the orogenies which closed the Iapetus Ocean, these islands would become re-attached to North America. The Goochland Terrane (Figure 4.5) is one example.

Okay, so you don't have a time machine of your own. But fear not; you have geology. Today you can see these ancient lava flows exposed along the C&O Canal at Point of Rocks and Lander (MM 51). The whole mass of rock, known as the Catoctin lava flows for exposures on Catoctin Mountain in Maryland, has been turned green by later metamorphism. However, the stacked sequence of lava flows is still discernible, as are original features like columnar jointing. You can see the preserved gas bubbles too, though they have since been filled in with mineral deposits – imagine your Swiss cheese studded with olives instead of empty holes (Figure 6.9).

The geologic history of the Blue Ridge doesn't end here, though: its rich saga has only just begun. Stacked on top of the Catoctin's lava flows are some sedimentary rocks, which in sequence tell how the Iapetus Ocean overflowed the continent in a shallow sea. Remember that the stratigraphic principle of superposition informs us that the higher up in a stack of depositional layers a particular sedimentary rock is, the younger it must be. So by looking at a sketch of the stratigraphic "column" for the Blue Ridge (Figure 6.7), then we can see that on top of our Catoctin lavas, we have a sequence of distinctive sedimentary rocks: (from oldest to youngest) the Weverton sandstones & conglomerates, the Harpers shales, the Antietam sandstone, and then on the very top limestones of several flavors, starting with the Tomstown Formation.

When you think about it, these sediments (gravel, sand, silt, and carbonate) represent a spectrum of relative distance to the sedimentary source (Figure 6.8). In this case, the source is North America, with its uplifted lands adjacent to the new ocean basin. As time goes by, the edge of the continent, which had been heated by the Rodinia rifting build-up, cools down. As it cools, it decreases a bit in volume, and therefore in density. The edge of the crust subsides, and as it sinks, it makes room for sediment to pile up on top of it. At the same time the edge of the continent was cooling, there was a whole lot of hot, buoyant oceanic crust being produced at the new Iapetus mid-ocean ridge. This hot, fresh crust displaced a lot of ocean water, and so sea-level rose. With sea level rising even as the shore of North America dropped down in elevation, conditions were ripe for accumulating a thick batch of sedimentary rocks.

So the uplands of North America are shedding sediments, and these sediments come in all sizes: big boulders, medium-sized cobbles, small sand grains, and eensy-weensy grains of silt. As they get washed away from their source area and downhill towards the ocean, these sediments get deposited in order of their mass. The heaviest ones are least able to be carried by the water, and so the water drops them first. The sand makes it a little bit further, but eventually that gets dropped too, and only the silt remains suspended in the water. Eventually, offshore a mile or two, the ocean water is calm enough to deposit even the silt. Beyond that, there are no more sediments derived from the land, and the ocean will deposit only what it can supply from its own waters: chemical sedimentary rocks like limestone and dolostone – carbonate rocks, in other words, that precipitate directly from ions in the seawater.

So, then, the size and type of sedimentary deposit can tell us how far away we are from the shoreline. Particles larger than sand size get deposited on the continent, at higher elevations than the beach: river deposits, for instance. The beach, as we all know, is sandy. Particles smaller than sand (like silt) get deposited offshore from the beach, in calmer water like the lagoons found at Assateague Island National Seashore (Figure 6.9). And beyond that, there are no little chunks of sediment being brought *directly* offshore, though some may be drifted up from further down the coast. If so, this makes a barrier island, like the modern Outer Banks of North Carolina. Far, far away from the landmass's dirty sedimentary input, we get carbonates being generated from ions dissolved in the ocean water itself. If we find a carbonate like a limestone, then, it tells us that it could not have been deposited too near to the shore.

So now reconsider the sequence of rocks atop the Catoctin lava flows (Figure 6.10). Note that this list is in stratigraphic order, with the oldest strata at the bottom, and the youngest deposited last, on the top:

> **Tomstown Formation (and other carbonates):** far from the shore, far from land. No dirt!
>
> **Antietam (Hampton) sandstone:** beach environment, but separated from land by a body of calmer water. Probably a barrier island beach.
>
> **Harpers (Erwin) shale:** off-shore in the ocean, but still in the "aura" of sediments being shed off the continent. Calm water, probably a lagoon-type setting.
>
> **Weverton conglomerate and sandstone** (Figure 6.13)**:** Inland, higher elevation than the shore, in river channels leading from the mountains to the beach.

What's the overall trend here? At the bottom of the stack (and therefore at the earliest time), we have "shallow" water deposits. As we work our way up through the stratigraphic dogpile (and as time therefore passes), we find deposits that indicate the shoreline is getting further and further away, and therefore the water is getting deeper and deeper. This stack of sediments, collectively called the Chilhowee (pronounced "Chill Howie") Group, tells us a story of deepening seas during the Cambrian period of geologic time (beginning about 545 million years ago).

If the order of sediments were reversed, with the limestone at the bottom and the coarsest conglomerates at the top, the story would be reversed: it would tell about sea level dropping, rather than rising. It's not just the sediments themselves, but their position relative to one another, that spin this tale for us.

Think about strapping on a SCUBA apparatus, and wading into a river like the modern Potomac (Figure 6.11). Once you're fully submerged, start walking downstream: at first you'll be banging your ankles on boulders and cobbles at the bottom of the river, but by the time you exit the Chesapeake Bay, the river's forward momentum will have been dulled by the fact that the water's already at sea level. Without gravity to propel it forward, it doesn't move as fast. The boulders are left behind, and then the cobbles. Your ankles will be grateful that you're now walking in sand. As you head further away from the coast, and deeper into the Atlantic, you'll find the water calming further, and while waves might by crashing far above your SCUBA tank, at the bottom you'll find the water calm enough to deposit its smallest particles. Further offshore still, and you'll rise out of a lagoon and crest a barrier island. More sand. Wade in again on the other side, and continue your submarine trek. Go far enough, and perhaps you'll walk into the carbonate sediments surrounding the Bahamas. Under your feet will be granules of calcite, and perhaps limey mud. Both of these deposits are precipitated directly from the seawater's rich broth of dissolved minerals: you've now walked out of the continent's sphere of sedimentary influence. You may find the water getting shallower, and your head would pop up above surface in the Bahamas: Time to go find a beach-towel and a drink with a little umbrella sticking out of it!

If walking along the ocean floor to the Bahamas seems like too much effort, then you have another option: sit still and let the Bahamas come to you! Again, strap on your SCUBA gear, but this time, wade into the river and stand still. Wait (Figure 6.14). As geologic time passes, and sea level rises, the shoreline will move up over your position. The river will be drowned, and the beach will move its sands over your head. With the passage of more time, the shoreline transgresses further onto the continent, and the beach heads inland. The water calms; you are draped in silt. This is the lagoon that deposited the Harpers Formation. More time, more sea level rise, and the barrier islands tack inland, following the retreating shoreline. You recognize this from your sedentary position as a linear hill of sand nearing, passing over your head, and heading towards the continent. The coast is now far, far away. Little flecks of calcite get precipitated out of the seawater, and settle all around you. That's what the Chilhowee Group shows us: a deepening sea.

It is in these sediments that we find our only fossils in the Blue Ridge Province. In some of the beach sandstones, we find thin, soda-straw-sized tubes which extend vertically downward from the bedding surface. These are *Skolithos* tubes, a trace fossil left behind by an oceanic worm in the Cambrian (Figure 6.15). They are particularly common in the Antietam Formation's sandstones. Those Cambrian beaches were crawling with little worms. These worms dug burrows in the sand, and likely poked their heads up into the open water to feed. As they dug, they lined their burrows with a thin veneer of mucus. Grains of silt stuck to the mucus, and later when the burrows were filled in with sand, this mucus/silt layer prevented the interior of the burrow from annealing with the exterior. The result is the distinctive tubes we see today. (We also see fragments of the Antietam sandstone far downriver, broken off by erosion and tumbled down the ancient Potomac, yielding the distinctive cobbles seen in Figure 3.7.)

Elsewhere in the Antietam sandstone, there were little creepy-crawlies, organisms called trilobites (Figure 6.16). Related to horseshoe crabs, trilobites are hard-shelled creatures that crawled on the bottom. Like modern-day pillbugs (also known as roly-polys or woodlice), the trilobites could roll themselves up into a tight ball for protection against predators. Their back is a series of overlapping plates of armor. Underneath, they would have had jointed legs to crawl with, though these don't fossilize very well. Jointed legs are a feature that unites trilobites with all arthropods, organisms that include insects and scorpions as well as lobsters and shrimp. The shells of trilobites are very common fossils in rocks throughout the Paleozoic era. One of the reasons for this profusion is that trilobites molted in order to grow, much like modern crabs or spiders do. In molting, the arthropod jettisons its old exoskeleton, and then puffs itself up while the new exoskeleton hardens. (We eat soft-shelled crabs when they are mid-way through this molting process.) For paleontologists, molting organisms are great because they leave many traces of themselves behind. For most of us, we leave only one skeleton when we die, but trilobites could have left twenty or more.

Particularly prolific fossils that are widespread around the Earth and limited to a short period of geologic time are useful as tools. They allow us to determine the relative age of a sedimentary rock. Remember, this is how the geologic time scale was determined in the first place – not with isotopic dating, but with the succession of fossil critters. The presence of *Olenellus*, a trilobite from the Antietam Formation in Pennsylvania, is the reason we know that the Antietam is a Cambrian-age deposit.

So, do these fossils end the story of the Blue Ridge? Not by a long shot. Though our Chilhowee Group sediments are pretty much the youngest rocks we find exposed in the Blue Ridge Province, there is yet more action to come. Geology is a palimpsest endeavor: continually reworking what's already there. And so, as various events overprint pre-existing rocks with their signatures, the nature of Blue Ridge rocks changes.

All the rocks we have so far discussed (from the oldest granite gneisses to the youngest Cambrian limestones) were reworked by an event that crumpled them all up: the **Appalachian Orogeny**. An orogeny, as we have already seen, is a mountain-building event, like the one that built up the Grenville Mountains a billion years ago. In the Appalachian Orogeny, Africa slammed into North America about 300 million years ago, closing the Iapetus Ocean for good and buckling up a terrific range of mountains (Figure 6.17). The runty little Congo craton that we encountered 700 million years previously (during the Grenville Orogeny) had grown! Now it joined together with several other continents into Africa, and not only that, but also the rest of the southern continents, into a massive linebacker of a continent, Gondwana. Now he was back, ready for revenge… and North America got a pounding.

The orogeny was also the cause for a general increase in temperature (to about 350 º or 400º C) and pressure – resulting in the metamorphism of the pre-existing rocks. The Weverton and Antietam sandstones fused into metamorphic quartzites; the Harpers formation became compressed into a slate (or a shinier version of a slate called a "phyllite"). But the most stunning transformation of all was with the Catoctin Formation: there, metamorphic grains of chlorite and epidote grew in profusion, imparting a green color to the basalt flows. Chlorite is sort of "forest green" in hue, whereas epidote is a pistachio-colored green. This is how we went from the staid black of un-metamorphosed basalt (like in Figure 6.4 and 6.6) to the weird verdigris of Figures 6.5 and 6.9.

Recall from Chapter 4's discussion of the Piedmont that two smaller orogenies had already happened in the early Paleozoic: the Taconian Orogeny, which was the docking of a volcanic island arc with North America, and the Acadian Orogeny, which added the Avalonia micro-continent to the east coast. Those two narrowed the Iapetus Ocean somewhat. But they were the opening acts for the biggest tectonic collision of all. When Africa plowed into North America, it caused a terrific amount of damage and destroyed the Iapetus Ocean basin.

The Appalachians, at their height, would have been fully comparable to the modern Himalayas (the tallest mountains in the world, caused by India ramming into Asia). These mega mountains would have stretched across *three* of our physiographic provinces: not just the Blue Ridge, which today is the most "mountainous" of the bunch, but also the

Valley and Ridge to its west and the Piedmont to the east. (And probably several provinces on the northwest coast of Africa too!) The topographic height of these mountains that we see today does not necessarily reflect their ancient elevations when the Appalachian Mountains were at their peak.

Figure 6.18 shows what mountain belts look like when they are young and fresh, middle-aged and fading, and completely worn down to their nubs. Note a couple of things about this figure: First, on the fringes of the mountain belt, you have lots of folding and thrust faulting of surficial sedimentary strata. Imagine shoving a big sheet cake across a table: as the bottom of the cake sticks to the table, the top is able to go a little bit further than the bottom, and so it folds upwards. Eventually even this upward buckle isn't sufficient to take up all the strain the cake is experiencing, and so the cake breaks. It keeps traveling in the same direction (away from the center of the mountain belt), but now its buckled form is thrust over the cake next door. The same thing happens with rocks. The buckled and thrusted rocks go on to form the Valley and Ridge Province.

Second, notice that further in towards the center of the mountain belt, the compressive forces are stronger, and they have uprooted rocks even deeper than the layer cake of the sedimentary strata: here we see basement rock is also fractured, thrust upwards, and bent into large folds. To continue our previous analogy, this is like shoving so hard on the cake that you end up breaking the table beneath it, and shoving large splinters of wood up and over the imbricated cake thrusts. Because these rocks are deeper in the mountains than the Valley and Ridge rocks, we would expect to see a greater degree of metamorphism in them. These uprooted basement rocks go on to form the Blue Ridge Province.

Lastly, notice that the center of the mountain belt, the part of the range directly under the most massive Everest-like peaks, is the remnants of the former ocean basin that separated the continents. In this location, you would expect to find oceanic sediments (like greywacke), islands that have been mashed between the continents (remember the poor raccoon between the trucks), and slices of the ultramafic rocks of the ocean crust. Because of their great depth under the rocks of the mountain range, and their proximity to the orogenic heat, we would expect to find these rocks to be the most metamorphosed of the bunch. Indeed they are; these metamorphic rocks will become the Piedmont Province.

The Blue Ridge is thus a vast, buckled slice of the crust of North America. Unlike the sedimentary rocks to the west, which are merely veneer by comparison, or the squashed ocean basin to the east, the rocks of the Blue Ridge have come up from the deep. They are the compound fracture North America sustained when Africa rammed it: a chunk of continental "bone" poking up through the "skin" of sediments. Figure 6.19 shows the overall nature of the Blue Ridge Province: it's one big fold, lopsided towards the west. At the base of it is a fault. It's been shoved from an original position in the east over towards the west, and up on top of much younger rocks. The purpose of a fold is to let a rock take up some strain – it shortens the rock in one direction (horizontal), and compensates for that shortening by piling up in another direction (vertical). Think of a carpet lying on the floor at home: if you shove on one end of the carpet, it moves towards the other end of the rug. But as the two edges get closer to one another, folds develop in order to accommodate the shortening. These folds poke up in the air, since they can't very well poke down into the floor. So, the folds not only allow the carpet to *shorten*; they *thicken* it as well.

Figure 6.19 also shows well the relationship between the Blue Ridge Mountains and the Blue Ridge Province. In the Mountains, the edges of the vast fold poke up higher than the surrounding landscape, forming low, linear mountains to the east: ridges like Catoctin Mountain and South Mountain in Maryland, and Short Hill Mountain and Bull Run Mountain in Virginia. And on the west, the province's namesake rises, the Blue Ridge itself. Taller than the surrounding ranges on both sides, the Blue Ridge mountain range stands out as a key topographic feature of the east coast.

So, traversing the Appalachians west to east, we are traveling today from the edges of the great mountain belt towards its dark center, getting "deeper" in the Earth's crust and closer to the mangled remains of the Iapetus Ocean. Consider now which of these three provinces has the most pronounced topographic majesty today: the Blue Ridge is by far the tallest, with the Valley and Ridge providing a corrugated landscape of limited relief, and the Piedmont being reduced to mere "rolling hills." Here's the kicker: the Appalachians ain't what they used to be. The mountains we see today, the actual high points in the landscape that stick up in the air are more the results of *erosion* than they are the result of tectonic uplift (Figure 6.20).

The reason the Blue Ridge sticks up so high? It's tougher than the rocks on either side of it. The granites and granite gneisses and lava flows resist erosion. And for the past 250 million years, erosion is the only force that's been working on these mountains. Tectonics abandoned their uplift after the Appalachian Orogeny, but it's been raining ever since. While rainwater can dissolve away the limestones that make up the valleys of the Valley and Ridge, it can't do the same to these igneous rocks. Likewise, even though the Piedmont was in the center of the ancient Appalachians, that doesn't mean it's well suited to standing up tall in the modern world. The Piedmont was heavily metamorphosed, and metamorphic minerals that are comfortable ten miles deep in the Earth's crust are not generally well-suited to conditions at the surface. Up here, mica minerals get broken down, and that makes it easier to slough away the Piedmont landscape.

The Piedmont, once the tallest of these three, is ironically now the lowest.

Chapter 7: A great washboard

The Valley and Ridge Province

From the Blue Ridge escarpment westward to the Canal's terminus in Cumberland, the C&O traverses the Valley and Ridge Province (MM 63 to MM 184.5). The Valley and Ridge is a massive stack of sediments which record the conditions at the time of their deposition. Like pages in a book, some layers tell us of Bahaman-type seas, while others describe being buried in debris from neighboring pre-Appalachian mountains. All of these layers have then been folded up, telling yet another story: the crumpling of the pages.

Fuel from fossils

The main purpose of the C&O Canal was to bring coal from the Appalachian Mountains to the thriving economies downstream, in particular Washington, DC. So, right off the bat, we know there must be coal "in them thar hills." Indeed, Appalachian coal is the original "fossil fuel." Oil did not emerge as a useful commodity until the drilling of the first well in northwestern Pennsylvania in 1859. Coal, however, had proven itself to be a useful resource long before the Industrial Revolution, and the best place to get coal in the young United States was the Valley and Ridge Province.

Coal (Figure 2.11) is a rock made of the element carbon. It is literally a fossil fuel, because it is made from the compressed remains of ancient swamps. The swamps existed in the latter half of the Paleozoic era, in the period aptly dubbed "Carboniferous" by British geologists (Here in the U.S., we divide the Carboniferous into two periods: the earlier Mississippian, and the later Pennsylvanian.)

Plants living in these bygone backwaters died and keeled over. Submerged in anoxic water, the plants didn't rot like they would have in well-oxygenated waters. The carbon in the woody, leafy tissues stayed put, whereas the process of decomposition would have oxidized it into carbon dioxide (among other compounds). Once buried, these swamp deposits were compressed and heated. Many of the unstable compounds were driven off by this pressure-cooker effect, but the carbon was left behind. It became more and more pure the longer it was compressed and cooked. These changes are really a series of metamorphic reactions: chemical alterations and recombinations that turn swamp plants into coal. Each coal "seam" mined in the Appalachians is a single ancient swamp: dozens of feet thick of mushy brown mulch, compacted into a few inches of solid carbon.

These ancient swamps are what powered the Industrial Revolution. Without them, it's hard to imagine the United States attaining the superpower status it now enjoys. These thin black seams are what separate the lucky from the unlucky: they have tremendous importance to the modern history of our country. (If only we were so blessed with oil…)

When we burn coal, we oxidize it. We take that solid chunk of carbon, and combine it with oxygen to create carbon dioxide. The reaction, of course, releases heat, which is why we bother doing it: that heat can warm a house or boil water to turn a steam turbine. The energy we release when we burn coal was originally sequestered by photosynthesis in primeval plants in a Paleozoic swamp. We are effectively reversing the photosynthesis reaction when we use a fossil fuel: liberating sunlight energy that has been in deep storage for hundreds of millions of years.

Oil is much the same as coal. In the case of oil, however, the photosynthesis is not being accomplished in a swamp by ferns and strange-looking trees. Instead, tiny single-celled organisms called plankton were floating in an ancient sea, conducting photosynthesis in the sun-dappled uppermost waters. These plankton pulled CO_2 out of the Paleozoic atmosphere and fixed it as carbon in their bodies, giving off O_2 as a waste product. When the plankton died, their single-celled bodies drifted down to the bottom of the sea, accumulating in thick layers that were rich in carbon. The bottom of the sea is much colder than the bottom of a swamp, but it has similarly low levels of oxygen. Eventually, buried and heated to the temperature of a cup of coffee (about 100º C), metamorphic reactions commenced which created a new substance, petroleum.

If you consider a bottle of vinaigrette salad dressing, you'll quickly realize that newly-generated oil would not want to stay put at its place of generation. Oil is less dense than water, whether it's extra virgin olive oil or jet-black petroleum. As a result, your salad dressing will quickly segregate itself into two layers based on their respective densities: the water (or vinegar) is more dense, and so it will pool on the bottom of the bottle. Rising up higher because of its lower density will be the oil. You shake up your vinaigrette before pouring it on the salad so that you get an equal proportion of these two tasty ingredients.

Now let's return to the deep, to this simmering planktonic cemetery: as oil and its vaporous cousin natural gas are formed, they quickly look for a way out. Less dense than the surrounding water, the oil wants to migrate upwards. It burbles upwards through the surrounding water-saturated sediments, forming bubbles like the exhalations of a diver under the ocean. These bubbles of oil rise up and up, until they cannot rise any further.

What stops them? More often than not, the answer is *folds in the rocks above them*. Some rocks are permeable to fluids like oil or water flowing through them. Sandstone, for instance, acts a lot like a giant sponge. It is full of holes which are well connected, so fluids can percolate through it, passing from one little pore to the next along microscopic channels. Other rocks, like shale, are made of such fine particles that they have no "pores" between those particles, and are therefore essentially watertight. As oil seeks its way up, it finds easy passage through sandstone, but is blocked by layers of shale. When shale is bent upwards into a big bulge, oil can pool under that bulge. It stays put in that location because its buoyancy keeps it pressed up against the shale "ceiling," which won't let it through. Natural gas, being a gas, is even less dense than the oil, and so it settles into a third layer, up at the top of the folded rocks.

As an analogy, consider two boats, side by side in the water. One boat is right-side-up, but its neighbor is up-side-down, submerged in the waves (Figure 7.1 A). From below, buoyant droplets of oil and natural gas rise upwards. When they reach the boats, the droplets follow two different paths depending on which boat they encounter. Droplets that reach the keel of the right-side-up boat are diverted off to either side of the hull. The keel of the up-side-down boat sticks up in the air, however, and when droplets of oil or natural gas find their way into this boat, the shape of the vessel funnels them upwards towards the keel. The right-side-up boat might be good for rowing around in, but it is lousy at collecting oil. The up-side-down boat, on the other hand, serves as an excellent oil collector and storage system.

When geologists look for natural reservoirs of oil underground, what they are looking for are the geologic equivalent of up-side-down boats: upfolded rock layers called **anticlines** (Figure 7.2 B). Anticlines are the most common oil "traps," and they are the simplest constructions: an alternating series of permeable (sponge-like) and impermeable (waterproof) layers of rock, bent upwards into an "A"-shape. Neighboring the anticline of Figure 7.2 B on the left is a **syncline**: a down-folded series of rock layers with an overall "U"-shape in profile. Note that the syncline and the anticline share the same rock layers; they are merely different geometric aspects of the same fold system.

When you're searching for oil, and you drill down to the top of an oily anticline, you're set for life. The natural buoyancy of the fossil fuels will push them up to you.

Other geologic resources

Oil and gas aren't the only resources that Mother Nature yields in the Valley and Ridge Province. Solid rock has also been used for a couple of economically-important reasons.

Iron ore is found outcropping in areas of hematite-rich sedimentary rocks along the Canal. Hematite, you might recall, is the geologist's mineral word for rust. Reddish-colored sandstones and shales can be used as a source of iron. This ore was heated in a special building called a foundry to turn it into iron. Chunks of limestone and coal were added as a flux, and when the combination of the three rocks were hot enough, the iron liquefied and ran out into little hollow grooves to harden into pig iron. Pig iron is hard iron, rich in carbon (from the coal), and cannot be bent or hammered. Rather it would have to be melted and poured into molds to make equipment. It took additional refining to remove the excess carbon, and get flexible iron that could be worked by a blacksmith. Iron is heavy, and so the Canal was a key factor in keeping these iron foundry's alive. It was much easier to ship heavy iron implements on the water than over rutted dirt roads. In turn, the foundries supplied iron tools for the Canal – fittings and valves for the locks, mainly.

Another important resource mined along the Canal was a prosaic one: cement. Like iron, cement is heavy stuff, and the Canal made it much easier to extract this dense load to towns where it could be used. The Round Top Cement Mill, located three miles north of Hancock, is the best preserved of these cement-producing operations. From 1863 to 1909, this mill produced a dry combination of limestone, sand, and gravel that, when mixed with water, would set to produce cement. Kilns used to produce the cement and portions of the mill are still visible today.

Folding and thrusting: edge of an orogeny

The folding that makes the Valley and Ridge Province so useful in trapping oil and exposing coal is the same reason that the terrain appears as a gigantic washboard to us: valley after ridge after valley after ridge after valley. This repetitious folding of sedimentary rock layers makes riding a bicycle across the Appalachians hard work. It is also what gives us that "classic Appalachian" view: endless mountain ridges repeating off into the distance, valleys filled with mist. You can almost hear the bluegrass music drifting up from the coal miners' camps.

These long, linear mountain ridges and the long, linear valleys which separate them are the westernmost portion of the ancient Appalachians, a region called the "fold and thrust belt" (Figure 6.18). All the rocks in the Valley and Ridge Province have been folded up by the Appalachian Orogeny. Some of them have been scrunched so much that the folds themselves break open and a folded package of rocks will be thrust to the west over its neighbors.

The folds come in all sizes: state-sized, hill-sized, person-sized, and peanut-sized. Compare Figure 7.2 and Figure 7.3. The aerial view of Figure 7.2 shows what folds look like in map view, from the bird's eye perspective. Individual rock layers can be traced long distances in sinuous zig-zag configurations. These layers were originally deposited horizontally, and were folded into these extreme shapes by the Appalachian Orogeny. Figure 7.3 shows a more traditional look at a fold, the neat cross-section. Combining these two views should help us come to an understanding of folds as three-dimensional features. Picture a crumpled carpet that has skidded across a floor. From the side-view, you see snake-like wiggles, but from above the wrinkles look straight and linear.

The orientation of these wrinkled strata is perpendicular to the direction they were compressed in. Africa came plowing in and mashed up the sedimentary layers, wrinkling them in a northeast-southwest orientation, indicating that Africa's force was directed from the southeast towards the northwest. Wrinkle one of the pages of this book, and you'll see the same phenomenon on a smaller scale: push it towards the spine, and a wrinkle develops parallel to the spine.

Near the Round Top Cement Mill is a great anticline, nicknamed the "Devil's Eyebrow." Here, the Bloomsburg Formation is folded up into a distinctive arch, with the calcite-rich rocks at the core of the fold weathered away to form a shallow cave. These limey rocks were mined for raw materials for the Round Top Cement Mill, an easy job at the Devil's Eyebrow, because the calcite-rich layers could be "peeled" off the inside of the fold, like taking an onion apart from the inside, out.

Recall from Chapter 6 that some of these folded layers aren't just folded, they're thrusted too. So the rocks have deformed by flowing up to a point, but then they just couldn't take it anymore, and snapped. Slabs of rock rode along weaker layers (shale, in particular) and coasted westward, pushed along like a barge before a tugboat. As a result of all this deformation, it goes without saying that the rock layers are no longer in the same position as where they started. Walking from the east towards the west along the

Canal, we are in general walking from older rocks (Cambrian) into successively younger and younger layers. You will walk through the Ordovician and through the Silurian, getting into the Devonian before Cumberland. The rocks of the Valley and Ridge elsewhere show younger strata, but that's the limit of what we find so close to the Appalachian Mountains (the younger, higher layers have been removed by subsequent erosion.)

Raw rock, wrinkled but uncooked

The rocks of the Valley and Ridge have not been metamorphosed nearly as much as the rocks that make up the provinces at the core of the ancient Appalachians: the Blue Ridge and the Piedmont. Rather, the strata of the Valley and Ridge are *bona fide* sedimentary rocks (as opposed to "meta-sedimentary"). Their structure is distinctive (the folds – anticlines and synclines) but rather monotonous. The real story is in the stack of sediments, and what we can infer from the different conditions they represent.

The really important thing about Valley and Ridge rocks is that they record what was happening next door as the first two phases of Paleozoic mountain-building commenced (the Taconian and Acadian Orogenies). This is a good thing: long before geologists were able to radiometrically date the metamorphic rocks of the Piedmont or the granites which intrude them, they were able to read the evidence of orogenic activity from sediments deposited elsewhere. (Orogenies shed lots of dirty sediment.) The "Appalachian Basin" therefore filled up with sediments that reflected varying conditions throughout the Paleozoic, until 300 million years ago it too became folded up on the edge of the great ancestral Appalachians.

Mudcracks tell us that the sediments were exposed to the air (Figure mudcracks). Graded bedding tells us about turbidite flows. Ripple marks can help us deduce the directions in which ancient stream currents flowed. These, together with the size and type of sediments, often speak eloquently of a particular environment where they formed.

There are dozens of formations (distinct depositional rock units) layered one atop the other in the Appalachian Basin. If you unfolded it all, it would look like Figure 7.4 A. Each one can be distinguished from its upstairs and downstairs neighbors by some virtue of composition, thickness, grain size, sedimentary structures, color, or fossil content. The stack varies between sandstones, shales, mixed sandstones and shales, red-colored sandstones and shales, black shales, and limestones. There's a couple of layers of weathered volcanic ash (bentonite) thrown in too. As the paleontologist Richard Fortey put it, these rocks are "a succession of ancient seafloors," each piled on the next.

If you're wondering how there could be seafloor overlying western Maryland, consider that sea level does not stay put. It rises and it falls. Sea level is rather low in the modern world because much of the world's water is locked up in glaciers and icecaps (particularly in Antarctica and Greenland). When there is no Ice-Age-ish glacial buildup, sea level is about 70 meters higher than it is now. If the continental crust is cold and devoid of orogeny, then it can subside below sea level, with the result that the continent gets flooded. These shallow seas atop the continents are a frequent theme of Paleozoic

North America. Most of the rocks underlying the central portion of our country were deposited by shallow continental seas.

As you can see, these seas were prolific in the strata they deposited. There's far too many formations to bother spending time getting to know them each individually. Let's take a step back, and look at the overall trends.

Figure 7.4 B gives us the bigger picture of the Valley and Ridge's sequence of sedimentary strata. The forest for the trees, if you will. The Precambrian basement rocks are old friends: we've met them in Chapter 6, on the Blue Ridge. Atop them is our Cambrian sequence of rift-related layers. After that, a thick stack of limestones tell us that things were tectonically calm: the ocean water was clean and deposited only chemical sedimentary rocks.

In the Ordovician period, however, that pattern changes. Suddenly we see layers of clastic sediments, which must have uplifted land as their source. Whether shales or sandstones, these layers tell us, "Somewhere, mountains are being eroded." The mountains, of course, are the Taconian Mountains, off to the east. We know there were volcanoes erupting at this time too, because of the ash layers included in these sediments. One of these layers, the Big Bentonite, is an ash deposit from the largest known volcanic eruption ever. It turns out if you measure the thickness of these clastic layers, they thin out towards the west, and get thicker (and coarser-grained) towards the east. Like a bloodhound following a scent, these thickening sediments lead us to their source in the east.

You can imagine these great piles of sediment, often called **wedges** because of their tapered shape in profile, spreading westward as the Taconian Mountains were being thrust up to the east. The stain of dirty mountain-shed sediments would have oozed into the clean Bahamas-like shallow sea, like a mug of coffee spilled across a clean bedspread. The more the mountains rose up, the more sediment they shucked off, and the more dirt piled into the Appalachian Basin.

Above the Taconian stack in Figure 7.4B, we see another period of calm must have settled in, for the limestones return. But it's a short-lived reprieve: soon the clastic sediments return, again spiked with volcanic ash. This time the wedge is much thicker, a great big fan-shaped avalanche of sand, silt, and gravel pouring off of the Acadian Mountains to the east. Again, we find that the thickness of the beds (and the size of the grains within them) increases the further east we go, until we run into the mountain belt itself. This would be the spot from which the sediments were shed, and it is marked by an unconformity. Erosion generated sediments in uplifted areas, and then those same clasts were rolled downriver to the lowest spots, where they were dropped. Remember that the goal of surficial processes is to smooth down the surface of the globe to a smooth sphere: under the influence of raindrops, peaks become reduced to valley-fill.

At this point, the geologic record as written in Valley and Ridge sedimentary layers ends. Younger strata may not have been deposited in this spot, or more likely they were deposited, but later removed by erosion of the great mountain chain. They do record one final event, but it’s not written in the *composition* of the strata. Instead, it is their configuration – the fact that they are all folded-up. This is one more symptom of the great collision between North America and Africa during the Appalachian Orogeny.

Meanwhile, back at the Bat Cave…

Limestones underlie both the Frederick and Shenandoah Valleys, a fact that has two important effects on the landscape. First, because limestone is soft and easily eroded, the Frederick and Shenandoah Valleys are valleys, not mountains. If they were instead carved from sandstone or granite, we would expect to see them sticking up into the sky, rather than down into the Earth. Limestone doesn’t stand up to Earth surface conditions very well. The reason is that limestone dissolves in acid (Figure 7.5). Even a weak acid like vinegar will wreak havoc on the delicate structure of the calcite mineral. It splits apart into two ions: calcium and carbonate, and these ions dissolve into the acid. You might not think this would be much of a problem for limestones – after all, giant vats of acid are the sorts of things only found in James Bond movies, right? Surely such corrosives don’t exist naturally?

Well, it’s unlikely to find super-strong acids in large natural concentrations, but we do find a very widespread acid that, though weak, can dissolve away limestone if given enough time. This insidious acid I speak of is… rain.

Yes, rain. As raindrops fall through the atmosphere, they pick up a small amount of carbon dioxide. This CO_2 dissolves in the raindrop, and makes a very weak carbonic acid. When the rain falls on the limestone, the carbonic acid dissolves away a little bit of the calcite, carrying it away with the rainwater.

It’s ironic that we frequently choose limestone when constructing our most elegant buildings: the buildings look white and gleaming when first constructed, but then, like any limestone, they begin to dissolve away over time. The years and the acid rain take their toll, and the Washington Monument weights less than it used to as a result; molecule by molecule dissolution is carrying the Washington Monument down into the Tidal Basin, and out into the Potomac River. The river totes the dissolved ions to the Chesapeake Bay and the Atlantic Ocean, where they may encounter water warm enough to concentrate them to over-saturated levels. The Bahamas are shallow, sun-warmed water where these conditions are met. As the water evaporates, the calcium and carbonate ions hook together, and settle to the ocean floor as minute flecks of calcite: the limestone of the future.

The second major consequence of limestone on the landscape is the formation of caves. The same dissolving we see on limestone exposed at the surface also happens underground. Rainwater, weakly acidic with carbon dioxide, trickles into the ground along fractures. As it flows beneath the surface as groundwater, it dissolves the limestone, making the fractures bigger. Let this go on for a long enough period of time, and the fracture is enlarged enough to qualify as a cave.

We have already met a small cave in the Devil's Eyebrow, near Round Top. There are thirteen natural caves along the C&O Canal, in addition to eight mines. Other caves include Two Locks Cave, near Two Locks, and Howells Caves, near McMahons Mill (Figure: cave photo). These are not commercial caves, and should only be entered by trained cavers with proper equipment.

Carbonates, Carbon dioxide, and Katrina

Though they might not look like much, limestones themselves are of critical importance in regulating the Earth's atmosphere.

The deposition of limestones is one of the most important natural mechanisms of removing excess carbon dioxide from the atmosphere. By combining calcium ions (Ca) in seawater with dissolved carbon dioxide (CO_2), calcite ($CaCO_3$) is formed. Volcanoes and animals both exhale CO_2 into the atmosphere, and limestones and photosynthetic plants both pull it out. Naturally, these four players keep the level of CO_2 approximately stable over geologic time. It's an example of how the Earth's different elements – rock, atmosphere, and living things – trade matter back and forth in a single System.

Humans have altered the balance of this system by taking oil, coal, and natural gas (fossil fuels) out of the Earth and burning them. To burn oil is to oxidize its carbon. When you put oxygen and carbon together, you get CO_2. By driving gasoline-powered cars, heating are homes with oil, and burning coal to generate electricity, we are currently dumping far more CO_2 into the atmosphere than the limestones and the plants can keep up with. To make matters worse, in the past 150 years, we've cut down about a third of the planet's forests, which means we have crippled one aspect of our carbon-removal system. (It doesn't appear that we've affected the rate at which limestone gets deposited, however.)

Geologic records show that as CO_2 increases, so does the average global temperature: this is the so-called "greenhouse effect." CO_2 is a greenhouse gas – the more of it there is, the hotter the planet gets. The ten hottest years in human history have all occurred in the last fourteen years. The hottest year observed by humans was 2005. This was also the same year that saw record melting of the world's great ice sheets in Greenland and Antarctica, and the most powerful hurricane season ever. The fuel that powers hurricanes is nothing more complex than hot water. Not surprisingly, the hotter the atmosphere gets, the hotter the oceans get.

The limestones and the trees will keep doing what they can to keep CO_2 levels down, but we've stacked the deck against them. If we want sea level to stay where it is, we need to examine whether we want to alter the rate we're putting CO_2 into the air.

Life of another era

Because the rocks of the Valley and Ridge are true sedimentary layers, free of the damaging effects of metamorphism, they do an excellent job of recording changes in fossil life. They are like the Coastal Plain in this respect, only folded up, and covered a much longer span of geologic time, the Paleozoic Era.

Some of the simplest fossils in the Valley and Ridge are also the oldest. **Stromatolites** (Figure stromatolites) are layered mounds of limestone made by photosynthetic "algae". These "algae" (technically, they are cyanobacteria) are simple organisms, single cells arranged in filamentous strands. As they grow, these microscopic strands tangle up grains of calcite, forming the layers of the stromatolite. (The word "stromatolite" itself actually means "layered rock.") The stromatolites are ancient; they are our oldest readily-visible fossils. (Some bacteria fossils are older, but microscopic.) Stromatolites date back to the Archean Eon, with the oldest ones pegged at being 3.46 billion years in age. There are none this old along the Canal in the Valley and Ridge Province – our rocks are all Paleozoic in age, roughly between 400 and 250 million years old. Shortly after life originated on this planet, stromatolites was thriving in shallow, sunny ocean water, where the little green strings of cyanobacteria were photosynthesizing, building up dome-like structures a layer at a time. These domes bulge upwards, towards the sun, burying older layers under a fresh green veneer of living cyanobacterial filaments. Living stromatolites can be found today in a few isolated environments on Earth – they are rare, because unprotected cyanobacteria are easy pickings for snails and other grazers. Stromatolites only survive where it's too salty for the snails to get at them, or the water currents are too strong, scouring away snails and their kin.

Corals are also found in Valley and Ridge rocks – though they are unlike the individuals we find in coral reefs today. Early on, corals came in two shapes: honeycomb-like tabulate corals, or the horn-shaped rugose corals. Both forms were common throughout the Paleozoic.

Trilobites are frequent fossil finds in Valley and Ridge rocks that were originally deposited in the oceans. Trilobites are joint-legged animals (like insects or crabs) that lived exclusively in the oceans throughout the Paleozoic era. They went extinct at the end of the Permian period. Just like insects and crabs, trilobites shed their shells, resulting in each individual trilobite being able to leave many traces of his body throughout his life. Trilobites had the ability to roll up in a ball, much as a "pill bug" will if you disturb the log he is hiding under.

Another joint-legged creature, the **ostracode**, is also found in C&O rocks. These creatures were like shrimp that wore two big shells around their body. At first glance, they look like beans, but when the bean is split open, a bunch of hairy legs stick out. Ostracodes are still alive in modern oceans, though they are microscopic. Ancient ostracodes were much larger, some up to a centimeter long.

Another denizen of the Paleozoic seas was the **crinoid**. Related to sea urchins and starfish, crinoids are sometimes called "sea lilies" because they stand up like flowers above the sea floor. After death, their stalks break into many small Lifesaver-shaped pieces. These are common fossils in several C&O Canal limestones.

Conodonts are little toothy-shaped bits of calcite that were originally the gill-support structures for a primitive group of eel-like creatures. With big eyes and big mouths, the conodont creatures swam much as modern fish do, with flicks of their tapered tails, but they lacked backbones. In fact, the only hard part in their soft little bodies were these distinctive conodont structures. Conodonts are very distinctive in their shape and geologic age, and so they are excellent tools for correlating strata in far-flung locations.

Similarly useful fossils for stratigraphic correlation are the **graptolites**, colonial animals that floated in mat-like wads on the ocean surface. Their strands are distinctly saw-toothed in appearance, an indication of the individual animals (the "teeth" of the saw) which collectively made up the colony (the whole line of "teeth"). Each graptolite animal lived in a little cup, from which he reached out and filtered the water for food.

Another filter feeder is the **brachiopod**. At first glance, brachiopods superficially resemble clams, but they are totally unrelated. Though both organisms have shells, the brachiopods shell stood at the end of a fleshy stalk. It opened the shell and filtered out nutritious bits from the water using a special organ shaped like a curled feather. Brachiopod shells are some of the most common fossils from the Paleozoic, and may be found in huge numbers in the Helderberg Group of limestones, for instance.

There are clams, too, though not many. Related to clams are snails and cephalopods like the modern octopus and squid. All of these animals are **mollusks**, and many mollusks have shells that preserve well as fossils. Ancient cephalopods had either straight shells (like a cone) or coiled shells (like a ram's horn).

Useful tools

These fossils are beautiful and fascinating of their own account, but they are also useful as tools to geologists. Geologists can use fossils not only to tell them about the evolution of life, but also about a host of other things.

To start with, certain organisms only like to live in certain places. For instance, siliceous sponges (sponges who make their skeleton out of silica rather than calcite) only like cold, deep water. If we find fossils of a siliceous sponge in a sedimentary rock, it tells us that those sediments were originally deposited in cold, deep water. That's a useful thing to know – another sentence in the geologic story, another piece of the puzzle.

Another thing fossils can tell us is which way is up. If sedimentary layers are still in their original horizontal position, like in the Coastal Plain, this isn't so critical. But in the Valley and Ridge Province, we have seen the layers have been crumpled up like so many wet lasagna noodles. Oftentimes, geologists can't see the whole fold – they're limited to a small piece of the larger structure. They want to determine whether the particular rock layers they are looking at are right-side-up or up-side-down. Certain fossils are useless at this: fish, for instance. When fish die, they flop down however they happen to land. But other fossils grow in a certain set position, and if they are buried alive, that position stays with them Sponges, for instance, grow upwards, as do many corals. Even the simplest fossils, stromatolites, have this sort of paleo-up / paleo-down information: they bulge upwards, and are concave downwards. If you find a stromatolite that's bulging downwards, chances are your sedimentary layer has been flipped upside down by tectonics.

As we saw in Chapter 6's discussion of the Blue Ridge, certain fossils are great time-keepers. Think about the Ford Mustang, a classic car that changes its look every couple of years or so. If you're familiar with Mustangs, you can instantly tell what year a particular one was made by some combination of its hubcaps, headlights, tail fins, grill, or number of windows. The same thing applies to fossils. Trilobites like *Olenellus* (Figure 6.16) are terrific chronometers for the Paleozoic Era. Trilobites change regularly throughout the Paleozoic, and if a diagnostic individual species is widespread enough during its reign, then it allows us to correlate sedimentary layers at far-flung locations. Because *Olenellus* had been established as a Cambrian species from rocks in Europe, and because we found it in the Antietam Sandstone in the Blue Ridge, we were able to determine that the Antietam was also a Cambrian-aged rock. Such fossils are called **index fossils**, because they serve as indexes to the passage of geologic time.

Finally, groups of fossil organisms can tell us about the past distribution of the continents, and therefore the motions the plates have made over time. If you look around the world today, this shouldn't be too surprising: if you find a kangaroo skeleton, chances are that you're in Australia. Elephants are limited to Africa and Asia. The fossils tell you something about where they came from, in the past as well as in the present. For instance, if you examine all the Cambrian-aged fossils from around North America and Europe, you will find that most of them match up into one of two groups: a North American Group and a European group. However, there is some overlap: Fossils of northern Scotland match up with the "American" fossil group. Fossils of the southeastern United States match up with the "European" group. What gives? It appears that the land which now makes up northern Scotland started off on this side of the pond, and was later ripped off from its homeland to hitch a lift to the northeast Atlantic. Likewise, the rocks that now underlay Florida started off on the other side of the Iapetus Ocean. They were brought into contact with North America during the Appalachian Orogeny, but when Pangea broke apart, they stuck to North America, and let Africa leave without them.

Undeformed uplands: the Alleghany Plateau Province

To the west of the Valley and Ridge Province is another physiographic province. West of the C&O Canal's western terminus in Cumberland, we find the Alleghany Plateau, sometimes pluralized as the Alleghany Plateaus. There's no real distinction here between the stratigraphy of this province and the Valley and Ridge Province. It's the same stack of rocks, further removed from the sources of massive sedimentary input of the Appalachians, but certainly continuous with the strata of the Valley and Ridge. True, there are a few more layers stacked on top, younger in age than those they rest atop. Some of them are as young as Permian, but below these are the familiar multitudinous cast of characters we met in the Valley and Ridge.

However, the Plateau isn't folded or faulted in the way that so characterizes its neighbor to the east. Its rocks are flat, or nearly so. That old phrase, coined by Nicolas Steno, comes back into play here: *original horizontality*. These layers were deposited in a flat, horizontal layer just like their extensions to the east. Those eastern ones got mangled in the Appalachian Orogeny, forming the Valley and Ridge. The Plateau, on the other hand, was far enough away from the impact site that it wasn't crumpled in the collision.

There are some moderate up-warpings and down-warpings, including moderate anticlines which have concentrated oil and gas deposits.

Because it hasn't been folded like its neighbor to the east, the Alleghany Plateau hasn't been thickened vertically. (Recall that when rocks are squeezed from the sides, they bulge upwards to compensate, like the beach ball in Figure 2.16). If they weren't shoved upwards, that means that the uppermost (youngest) layers of Alleghany Plateau were less susceptible to the forces of weathering and erosion. And that, my friends, means that we see more layers stacked on top, layers that were either destroyed in the Valley and Ridge or else they were never deposited in the first place. Many of these upper-Paleozoic layers are the ones with coal in them. The coal seams are buried swamps that were at the end of rich river deltas, much like the modern Mississippi delta. The rivers which supplied them were mighty, fully the equal of the modern Mississippi. They carried millions of tons of sediment westward, off the slopes of the Himalaya-sized Appalachians. These huge rivers stretched across the entire continent, from east to west, and deposited the eroded detritus of the Appalachians all over the west. The Petrified Forest, in Arizona? That's buried under sloughed-off Appalachian sediments. You can go and find individual zircon minerals in the sands around those stone trees, and the zircons will tell you that they were formed in Maryland.

When the rivers met the ocean, their forward momentum ceased, and they dropped their load of dirt. Where this happens today, we find deltas – large fan-shaped swaths of mud at the end of major rivers. The Ganges, the Mekong, the Okavango, the Nile: the great deltas of the world are the dumping grounds for their continents' unwanted debris. Frequently these rich, wet deltas are host to lively swamps. A slight rise in sea level, only a few meters or so, can drown a delta's swamps, preserving them as coal. This fluctuation repeated many times throughout the Pennsylvanian period and the Permian. It's thought that glaciers in the southern supercontinent Gondwana froze water and re-melted in cycles, causing sea level to rise and fall in similar cyclic waves.

It is uplifted, however. The flat-lying strata of the Alleghany Plateau are high up in the air. As rivers have bitten down into them, trying to cut their way to sea level. The more we shove a package of rocks up into the air, the more the rivers on top of that package want to slice down into it. What these rivers are trying to do is reach the lowest point they can flow to. Most of the time, this lowest elevation is sea level. As a result, terrific canyons like New River Gorge have been opened up. The terrain must be described as mountainous, even if the underlying rocks are horizontal. Such is the power of rivers: it can make a mountainous landscape out of flat rocks (Alleghany Plateau) and make a flat landscape out of mountainous rocks (Piedmont).

When you start think about it, the Alleghany Plateau and the Coastal Plain look more and more alike. They are similar in several major ways: each is a flat-lying deposit of the ocean, made of many individual layers. Each is studded with fossils and gritty with sand. In each case, the layer-cake has been cut into by the grinding action of rivers, resulting in a similar pattern of geologic outcrops. There are a couple of big differences, of course: the Alleghany Plateau's sediments have been lithified (stuck together into rock), something we can't say for the Coastal Plain. Also, the Alleghany Plateau has been *more* uplifted than the Coastal Plain. But the similarity is undeniable: the sedimentary cycle which was wrought upon eastern North America during the Paleozoic is repeating itself again now. Change is the only constant, sure: but some things never change.

Chapter 8: Scalpel, please

The cutting of the river and the making of the Canal

The Potomac River drainage basin encompasses 14,670 square miles of Virginia, Maryland, West Virginia, Pennsylvania, and the District of Columbia. It is one of the most important rivers to drain into the Chesapeake Bay.

In this chapter, we will examine the processes that put the Potomac where it is, and therefore determined the course of the C&O Canal. This is different from the previous six chapters, which examined the story of the bedrock underneath the river. Now we're talking about sculpting that bedrock – this is the same distinction as talking about the Carrera Marble as being a nice white marble, and then talking about Michelangelo carving a block of that marble into the *David*.

The sculptor here, though, is water. The tools it wields are nothing more than grains of sand and silt.

The Potomac River has existed, draining eastward off of the Appalachians, for a very long time. Perhaps the Potomac's early days were as a vigorous mountain freshet, tumbling down from the great heights of the young Appalachians. We don't know about that stage in this specific river's history, but we know that rivers of this type must have existed at that time. Most of these rivers drained westward at first, not to the east. These rivers transported the Appalachians westward, a grain of sand at a time. These sand grains today can be found as far west as Arizona and Wyoming. Together, both eastward- and westward-directed rivers contributed to the wearing down the Appalachians from Everest-like proportions to nubs even smaller than the mountains we observe today.

The landscape went from Himalayan to Minnesotan in about 200 million years. Without the forces of tectonic thrusting to keep them tall, the peaks succumbed to relentless erosion. The result was a flat landscape worn down to near sea level. The rivers draining that landscape responded to the flatness by stopping with their erosion, and started deposition instead. The Potomac and others started to lay down the gravels that form the base of the Coastal Plain sequence, and the great rivers began to meander. Meandering is a slow, sinuous dance performed by mature rivers. When the landscape is level, there's little incentive to cut downward, and so rivers move sideways instead. Water coming around a bend in the river hits the outside edge of the river bed with extra force due to its momentum.

Think about the forces you feel when you round a corner too fast in your car: you're pulled towards the outside of the curve. Water does the same thing, pummeling the outer edge of the curve with extra force. It erodes the curve outward, into a bigger loop. Meanwhile, on the inside of the curve, the water is moving slowest of all, and it deposits sediment there (like our Cretaceous river gravels). By meandering back and forth across the landscape, mature rivers build up big loops like overenthusiastic cursive. Some of these loops even curve back on themselves and connect. The river flows through the cut-off, abandoning the loop. Meanders are dynamic things: they loop and curve, grow and shift over time. The U.S. border with Mexico is defined near Brownsville, Texas by the Rio Grande, which meanders as it flows towards the Gulf of Mexico. This means that the nation's borders aren't in the same place today as they were yesterday! (If you compare maps of the Rio Grande in the 1920s with today, you'll see how severe this shifting can be over a century.)

Rivers at this stage stick to their channel most of the time, but overflow in times of flood. The floodwaters flow out over a wide floodplain, bounded by less eroded lands on both sides of the river valley. This whole level – the channel plus the floodplain – is a terrace that shows the rivers' width at some point in the past. When the river cuts down deeper at a later time, it abandons these old floodplains to higher elevations. In the Culpeper Basin, these terraces can be seen easily on both sides of the Potomac from the Turtle Run campsite, between MM 34 and 35. To walk down to the shore of the river from the Towpath, you walk down a set of three giant steps: each representing the river's edge at a higher, wider time in its past.

Recall that we learned in Chapter 3 that due to the C&O Canal's position low in the Potomac valley, it's difficult to see the hilltop terrace deposits directly unless you get off the trail. Remember that Glade Hill on the Virginia side of the river hosts a collection of large cobbles and boulders that were deposited there when the summit of Glade Hill was merely the bottom of the Potomac River.

During the Cretaceous, rivers were dropping sediments on the Coastal Plain. In the Miocene, sea level rose, and the flooding of the edge of North America allowed oceanic sediments to pile on top of the gravels that were already there. Thicker and thicker, this blanket of young sediments built up, some of them chock full of fossils.

At the end of the Pliocene, something happened far, far away that would disrupt the Potomac River's stability. This event is a beautiful example of how the various parts of the Earth system interact: subduction of the Cocos Plate underneath the Caribbean built up a narrow strip of land that connected North America to South America. The Isthmus of Panama was formed by volcanic eruptions about 3.5 million years ago. When the layers of lava and ash built up, they cut off the flow of ocean water between the Atlantic and Pacific Oceans. This innocuous buildup of igneous rock shunted off the Gulf Stream, a major current in the Atlantic, which now flowed northward, up the east coast of North America, towards Iceland. The Gulf Stream brought lots of water vapor up to the North Atlantic. Evaporation of this water vapor triggered greater-than-normal amounts of snowfall. After this change in currents, more snow fell on the Northern Hemisphere in the winters than could melt in the summers. Snow accumulated and got deeper. The bright reflectivity of the snow bounced sunlight back into space, and so conditions got colder. Colder conditions meant more snow piled up on the continents – both North America and northern Europe. Eventually, by about 2 million years ago, the snow had gotten packed into ice sheets several miles thick, and it began to flow south, as glaciers. The Ice Age had begun.

Which brings us back to the Potomac. When glaciers build up on the continents, they take water from the oceans to make into ice. It's all water, of course: liquid in the oceans, solid in glacial ice. There's only a finite amount of water on the Earth, so if we're adding water to the continental ice sheets, it's got to come out of the oceans.

And so sea level dropped, which meant that the Potomac River was no longer "happy" at its new, higher elevation. Rivers want to cut down to the lowest level possible – in most cases, that's sea level. When land is uplifted, or sea level drops, rivers at no longer at equilibrium, and they respond by cutting in. Figure 8.1 shows the effects of continued drop in sea level: the river incises to deeper levels, and its floodplain is narrower and narrower. Older levels are left behind as terraces above the river. Furthermore, new levels are cut into the solid rock. Unlike terraces, which are made from loose sediment deposited by the river, these gouges in the bedrock go by a different name: **straths**.

A cross-section of the Potomac Gorge (Figure 8.2) shows that the Potomac has numerous straths – higher, wider shadows of the Potomac's past. Note the riverbed deposits abandoned on top of Glade Hill, a terrace deposit, as well as the narrow strath – a notch, really – of the current river.

Now, if we take this same cross-section and rotate it to get a three-dimensional view, we see that each of these straths is shaped something like a rowboat (Figure 8.3). The straths are like the gunwales, which lead up to the pointed bow of the boat, where the river flows over a waterfall from a higher level (old strath) to a lower level (younger strath).

Figure 8.4 shows a satellite view of the Great Falls area, where we see that the bow end of each of these straths points up to Great Falls itself. It's actually like we've got a series of boats of different sizes, nested one inside another like Matryoshka dolls (you know, those Russian ones that fit inside one another), all of their bows tied up at Great Falls. The large size and impressive grandeur of the Falls is due to the "bunching up" of river levels at this one spot. Great Falls would be much less striking if it were spread out over fifteen miles.

Let's take a step back and recall that the river is cutting down because it wants to get to sea level. If sea level keeps dropping, the river keeps cutting down in a smooth arc. But sea level drops sporadically, and with each drop the river tries to adjust itself. Before it can get re-stabilized however, the darn sea level drops again. And so the river cuts in some more. This pattern, repeated many times, gives us our many different terrace levels, and waterfalls between them. The essential idea is that a waterfall is a "nick point" in a river's overall profile. The river loses elevation gradually over many miles, then all of a sudden it drops, ka-pow, and then resumes its gradual slope. The rock under the waterfall is the **nickpoint** (Figure 8.5). New nickpoints form when sea level drops, and the river manages to cut in right at the sea level. A waterfall is created at the shore. Over time, this water fall undermines its own geologic underpinnings, and the rocks which make it up are eroded away. The nickpoint, and the waterfall above it, retreat upstream. If you do this for a long enough period of time, it leaves a gorge behind. This gorge is a strath in the act of being cut. The nickpoint is the tip of the "bow" of the strath's overall rowboat shape. As it gets older, the nickpoint takes the bow further upstream, but the river also widens the strath at the same time. Drop sea level again, and a new nickpoint forms, and a new "boat" of erosion starts sailing upstream. The Grand Canyon formed in this way, as did Niagara Falls. Nickpoints on the march: Great Falls is heading west, marching inexorably upstream.

How fast does this process occur? Science provides a useful way of testing the age of the Potomac Gorge by measuring how long its rocks have been exposed to the sun and air. A special form of isotopic dating examines a rock's "sun tan" – how long it has been exposed to UV rays. Just as you can gauge whether a person has been in the sun a long time or a short time by examining their tan lines, so can geologists examine a rock's "tan" by measuring amounts of Beryllium-10 in the rock. Beryllium-10 is an isotope of the chemical element beryllium, which forms when UV light hits the oxygen atoms in quartz. Beryllium usually has an atomic weight of 9, so any Beryllium-10 present is the result of the breakdown of oxygen by UV light. If the rock has been exposed to the sun for only a few years, most of its oxygen will still be oxygen. If the rock has been exposed to UV light for millions of years, a matching number of its oxygen atoms will have been altered to Beryllium-10.

Taking samples of rock at each of the straths that emanate from the Potomac's nickpoints, geologists have determined that the entire Potomac Gorge has been carved since the last Ice Age. Our best estimates indicated that both the Potomac and the Susquehanna Rivers both incised their gorges beginning about 35,000 years ago, and concluding about 13,000 years ago. Overall, then, the Gorge has been cut down only about a millimeter per year. Another way of expressing this is to say that every thousand years, the Gorge is cut another meter (about 3 feet) deeper into the Earth.

Because the Susquehanna's drainage basin includes a large area that was under Ice Age glaciers, but the Potomac was never glaciated, it's interesting to note that both rivers show similar ages for their gorges. Because the timing and the rates of incision are so similar, glacial melt water is no longer the prime suspect in carving out these gorgeous gorges. Instead, it seems more likely that regional changes in climate and crustal uplift were responsible for this buzzsaw-like burst of down-cutting.

But how exactly does the river cut into the bedrock below? Rock is harder than water, so in what way (or *ways*) does this nickpoint form? Observing the rocks along the Canal, we can come up with three major ways that the river removes rock: quarrying, abrasion, and drilling. Quarrying is the removal of large blocks of rock by water pressure. When the water comes pummeling over the falls, it hits bottom hard. The high-pressure water squeezes into cracks in the rock, forcing it apart and sometimes lofting it upwards. Quarrying is really effective at removing big chunks of rock, but it doesn't happen all that often, mainly during times of high water – floods.

That the river fluctuates widely between low flow and flooding is obvious from geologic signs. Figure 8.6 shows a "bathtub ring" at low water levels, and deposits of clam shells and sand high above Mather Gorge show that the river level can crest above even those heights at flood times. Because the Canal draws its water directly from the river at many points along its length, it is susceptible to flooding. When the river rises, it seeps over into the Canal. Flooding is most frequent in spring, with the combination of winter snowmelt and spring rain showers. Flooding ultimately doomed the Canal, as damage sustained during flooding was too expensive to repair. 1889, 1924, 1936, 1942, 1985, and 1996 were all years when exceptionally high river levels flooded adjacent areas. The 1889 flood, often called the "Johnstown Flood," for a town in Pennsylvania that was destroyed by the high water, began the Canal's decline by breaching it in several places, and scattering Canal boats willy-nilly over the landscape. Economic realities made it hard to recover from these damages, and the 1924 flood inflicted such ruin that it put the Canal out of business for good. More recently, the 1996 flood wiped out a section of the Towpath south of Widewater, near the downstream entrance to the Billy Goat Trail.

The second major way that the river carves into the rock is through abrasion, basically sandpapering its way down into the rock. Abrasion happens all day, every day, but it's not especially effective at removing large amounts of solid rock. Just as you would choose a chainsaw if you had to cut down a tree rather than a sheet of sandpaper, the river uses quarrying for its big jobs, and sandpaper for the finishing touches.

But there's a third tool in the toolbox: the drill. Rivers drill into the rock, creating a distinctive feature that's quite prominent along Mather Gorge: potholes. Figure 8.7 shows two typical potholes from along the Billy Goat Trail. One is open and smooth; the other is clogged with a large block of rock. The river drills these circular holes using a suspended grit of sand and silt, swirled in a vortex like a watery tornado. The gritty tornado abrades into the rock, most effectively at times of high (and therefore fast) water flow. There's an old myth in geology that these potholes are carved out by larger rocks, cobble-sized round hunks of stone. But it's unlikely that's the case: if you run your hand around the inside of a pothole, you'll find there is a difference in the relief between light-colored minerals (quartz) and dark-colored minerals (biotite mica). Biotite is much softer than quartz, and so it's easier to etch away. But a big cobble can't make that distinction. The only way you're going to carve out a millimeter-width flake of mica is with a tool smaller than it. So sand and silt must be our culprits here – which brings us to the question of how they get swirled in such a perfectly cylindrical pattern.

As you walk around the Great Falls area, you'll notice plenty of large lumps of meta-greywacke rock. These lumps are roughly the same shape as loaves of bread, with their long sides apparently controlled by the fracture systems that run though the bedrock. (It's easier to break rock along a fracture than across one.) In addition to these parallel, steep sides, these "bread loaves" have rounded ends, especially the ends that face upstream. Also, they frequently wear a necklace of potholes. You may be able to walk around them now, checking out these dry potholes, but when the Potomac River reaches flood stage, many of these rock loaves are surrounded by water. It is then that we see how the holes form (Figure 8.8).

As flood water flows around these rocky obstacles, it rushes past further away, but is slowest near to the surface of the rock. This difference in flow speeds results in turbulence, and circular eddies form as water flows from fast towards slow. These circular currents, clockwise on the Maryland side of the loaf and counter-clockwise on the Virginia side, are grit-charged vortexes that drill into the rock. One thing you will almost always notice about potholes is while they are cylindrical, they are not vertical. Instead, most potholes tilt: their foot is towards the upstream, while the head tilts downstream. This too can be explained by Figure 8.8: As the river flows, it drags the top of the spinning "drill" downstream. The bottom is safely anchored in the pothole, but the overall vortex tips due to this discrepancy. So the drill is now oriented differently, and it drills in an upstream direction. Estimates of the rate at which potholes get drilled are surprisingly fast: about an inch per year. This is an average, of course: Most of the drilling is accomplished during times of flooding, when the water is moving with more power past the potholes.

A bunch of potholes may develop in a line, like perforations on a sheet of notebook paper. Of course, a perforated sheet of paper is easier to rip than a sheet without perforations, and the same is true for rock. Over time, potholes enlarge and inter-connect, providing a larger slot which the hydraulic pressures of quarrying can go to work on. All three processes of river incision work together to move nickpoints upstream, and widen straths that already exits.

Is it the fault's fault?

An additional factor which may have helped to carve out the Potomac River is the presence of faults. Faults, as we've seen before, are breaks in the rock, where the opposite sides have slid past each other. On the fault surface itself, rock gets pulverized as if it were pepper being ground onto your Caesar salad. As far as rivers are concerned, the result is that it's easier to cut into the rock

Anyone who hikes along the Mather Gorge section of the Potomac River, downstream of Great Falls, will be struck by how incredibly straight that section of the river is (Figure 8.4). Straight and narrow, Mather Gorge may be a spot where the Potomac River carved into the softer rocks along a linear fault zone.

One of the main pieces of evidence supporting this idea is the lamprophyre dikes we saw in Figure 4.14. These lamprophyre dikes are not in the same place on the Virginia side of the river as they are on the Maryland side! Looking at them from the Billy Goat Trail, it appears that they have been offset by several meters to the right. While dikes don't have to be perfectly straight (they can open up as jagged cracks), this is pretty compelling evidence. However, do we need a fault? Couldn't the arrow-straightness of Mather Gorge be explained by the foliation in the rocks alone? A recent study by an undergraduate student at the University of Maryland measured the orientations of the foliation in Mather Gorge rocks as well as all the many cracks that run through it. She found that these structures grouped themselves into five sets, and that *none* of those sets aligned with Mather Gorge. This lends increasing credence to the fault hypothesis.

When faults move, the Earth quakes. Though the C&O Canal is no longer as seismically active as it once was, we know that earthquakes do occur in this region, though less frequently than, say, California. A December 2003 event near Goochland, Virginia registered a 4.5 on the Richter Scale, for instance. Several magnitude-3 events have occurred near Hancock, Maryland. As we saw in Figure 4.16, thrust faulting has occurred sometime since the Miocene, cutting across the unconformity that separates Piedmont below and Coastal Plain above. So faulting has happened in the recent past, and it continues to happen today – it's plausible that one such fault might lay beneath Mather Gorge.

Mountains made modern

As a consequence of the youth of Coastal Plain deposits, it's easy for the Potomac to saw into them, and it has cut down all the way to sea level through them. However, it's tougher for the Potomac to cut into hard Piedmont rocks, and it has managed only a relatively small amount of incision to the west of the Fall Zone. Using the techniques of quarrying, abrasion, and drilling, our Potomac sculptor began digging in to Piedmont rocks by creating a series of waterfalls. These have retreated upstream, leaving the Potomac Gorge in their wake.

We've been talking a lot in this chapter about the effects of the Potomac River on cutting its gorge through the rocks of the Piedmont. But the effects in the provinces upstream have been just as dramatic. At Harper's Ferry, the scenery is quite striking: a large water gap has formed where the Potomac (joined at that point by the Shenandoah, flowing up from the south), cuts *across* the Blue Ridge Mountains (Figure 8.9). Actually, there are two water gaps here, because just east of Blue Ridge Mountain is South Mountain, and the Potomac cuts across that one too! We typically think of rivers flowing around obstacles such as mountains, so this "water gap" presents us with a conundrum: How does a river cut through a mountain? (The Potomac is not alone in pulling off this trick: the Susquehanna has several water gaps along its course through Pennsylvania: See Figure 7.2 for views of several of them.)

Water gaps form when rivers cut down. The tricky thing to visualize is not the river cutting into rock as it chews its way down to sea level. Rather, the tricky thing is picturing what this landscape looked like before that happened. Recall that the Appalachian Mountains had been severely eroded by the time the Cretaceous rolled around. They might not have been as flat as a pool table, but that landscape was definitely scoured down to a gentle topography. Rivers like the Potomac, flowing back and forth over this plain, deposited their loads of gravel and sand. Underneath this veneer of sediments were the varied members of the bedrock: granite under the Blue Ridge, folded sedimentary layers under the Valley and Ridge, metamorphics under the Piedmont. All is well and good, and stable. But then sea level dropped, and the Appalachians were resurrected. As the Potomac cut down towards sea level, it cut down through everything: first the loose gravels (easy!), then the bedrock beneath (tougher, but not that tough). As the Potomac cut its groove deeper, mountains appeared to rise on either side of it.

Add to this the fact that some rocks are easier to erode than others: limestone dissolves away, shale is soft, sandstone is stable, granite is hard. When we look around the C&O Canal today, we find invariably that the hardest rocks make up the tallest mountains, and the softest rocks make up the lowlands and valleys. Limestone adjacent to granite: the limestone goes on to be the Shenandoah Valley, and the granite goes on to be the Blue Ridge. The Piedmont rocks were at the core of the ancestral Appalachian mountains: their high degree of metamorphism and partial melting tell us that. But minerals stable ten miles under a mountain aren't stable at the Earth's surface, and so it has been relatively easy for rivers to erode the Piedmont. Surprisingly, the rolling hills we see there today are the legacy of the mountains' former heights.

So as the rivers cut down in the regions where we find water gaps today, the water removes everything *except* the hardest rocks. The hard rocks: granite, diabase, sandstone, quartzite, stick up high because they have proved themselves resistant to erosion. These are mountains that grew as raindrops stripped away the neighboring rock. At Harpers Ferry, the mighty Potomac's slow grind kept pace with the granite of the Blue Ridge, but smaller rivers with less "bite" got shunted off to the side (like the Shenandoah). Instead of grinding against granite, the Shenandoah River found it was easier to cut into limestone. It was limited to the valley from an early age.

So this is a new perspective: we often think of mountains as old, since they are solid. Rivers, on the other hand, are liquid, and so they must be young, right? Wrong. Here we have clear example of a river being much older than a mountain – a return to our analogy of the Potomac as a sculptor, freeing the statuesque landscape that was trapped in the bedrock below.

It is because the Potomac is so much older than the modern Appalachian Mountains that the C&O Canal is so special. The fact that the river pre-dates the high topographic relief of the modern topography has allowed it to cut across all the many different physiographic provinces of the east coast. Because the C&O Canal parallels the river, it too manages to traverse an extraordinary variety of geology. Instead of *paralleling* the geology, as does the Shenandoah River or the coastline, the C&O slices *across* four physiographic provinces, with an additional two flanking it on either end: six different chapters of the geologic epic, arrayed in a shuffled sequence.

Further west, in the Valley and Ridge Province, also had some striking effects due to sea level drop and Potomac erosion. There, a section of the Potomac where it had reached a comfortable stage of meandering, the Paw Paw Bends, suddenly turned violent, and bit down into the rock beneath. Though its shape speaks of the leisurely life, its depth speaks of an upstart go-getter. The Potomac at the Paw Paw Bends (Figure 8.10) are a classic example of a rejuvenated river. The elderly river, dawdling back and forth with little better to do, is suddenly inspired to hew downward, and it is made young again. The Bends themselves are called "incised meanders," a geologic oxymoron that only makes sense if the height of the land changes relative to sea level. When the Ice Age dropped the bottom out, the Potomac immediately began grinding downward.

Many glaciers melted at the end of the last Ice Age, causing sea level to rise again. The deeper waters flooded coastal stream valleys like that of the Susquehanna / Potomac / Rappahannock / James / York (which all ran over a low spot – the relict of an impact crater 35 million years old), producing the Chesapeake Bay. Meanwhile, elsewhere on the Potomac watershed, the nickpoints were still marching up-river, floods kept widening the valley, and the exhumed Appalachians became mountainous again.

It is because the Potomac is so much older than the modern Appalachian Mountains that the C&O Canal is so special. The fact that the Potomac River pre-dates the modern topographic high relief allowed the river to cut across all the many different physiographic provinces of the east coast. Because the C&O Canal parallels the river, it too manages to traverse the same extraordinary variety of geology. Instead of *paralleling* the geology, as does the Shenandoah River or the coastline, the C&O slices *across* the geology. It transects four physiographic provinces, with an additional two flanking it on either end. These are six different chapters of the geologic epic, arrayed along the Canal in a shuffled sequence.

The shortest chapter of geologic history

The rocks underneath the surface made problems for a stalwart group of humans who decided to create a canal along the north banks of the Potomac.

When the Canal was constructed, between 1828 and 1850, the engineers followed the course of the Potomac River. This proved to be the easiest route to follow, for the river had done much of the hard work of carving already. Where the river had left soft deposits as terraces, Canal engineers had an easier time of it. Sometimes they would use old, abandoned channels of the Potomac River, like at Widewater along the Piedmont stretch of the Canal. On the other hand, where the river had gouged into naked bedrock, it took some dynamite and sweat to make the Canal. Recall President Adams' tough time turning over the first ceremonial shovelful of Canal dirt. Event that embarrassing episode paled in comparison to the challenges of building a Canal around waterfalls, or through mountains. In certain areas near Great Falls, like at Mary's Wall (MM 14), the Canal hangs precipitously above the Potomac Gorge, teetering on a balustrade resembling a house of cards.

In other places, the Potomac's protracted course made the Canal's engineers look for a shorter route. The *ne plus ultra* can be found along the Paw Paw Bends, those incised meanders we met in Figure 8.10, where the Canal engineers abandoned the loop-de-loops, and spent fourteen years cutting a tunnel through the adjacent mountain instead. I'm not sure this was the brightest of decisions, but it's a stunning example of man's ability to cope with natural barriers. Almost a kilometer long, the tunnel conducts the Canal past the sinuous Bends.

Water gaps presented a particularly difficult situation for the builders of the Canal. At places like Point of Rocks and Harpers Ferry, the Potomac is hemmed in by vertiginous walls of bedrock on either side. Where do you put a Canal when you have so little room to work with? More to the point, where do you put both a Canal and a railroad? The Baltimore and Ohio (B&O) Railroad was also using the Potomac River corridor for its westward route, and the limited space offered at Point of Rocks resulted in a protracted legal battle over who had the right-of-way. At Point of Rocks, the Railroad lost, and was forced to dig a tunnel through Catoctin Mountain there. At Harpers Ferry, it's astonishing to see how engineers managed to fit not only the railroad and the Canal on the north side of the river, but *also* a two-lane road. These three strands of transportation wind around one another like fibers in a piece of rope, intertwining through bridges and tunnels until they pass safely through the water gap: Once in the softer rocks of the Valley and Ridge, the three entities can spread out again.

Potomac palimpsest

In constructing the Canal, humans modified a landscape that was itself modified by the Potomac River. Before the river, there were the rocks: of different ages and strengths, some deformed, some not. Collectively, the rocks, the river, and the Canal tell a story a quarter the age of the Earth, and including the contributions of our own species. We are an industrious lot, and it shows. The stories revealed by the C&O Canal give us perspective on our own time here. If you compared all of geologic time to the height of the Washington Monument, the Earth would have formed at the base of the obelisk, but a great deal of nothing would have happened for a long time. The pyramid on top represents the Phanerozoic Eon, the time since the Cambrian began 543 million years ago (when lots of animals start showing up in the fossil record). The dinosaurs occupy a period of time less than the height of the observation windows, and the human presence on Earth is of such short duration it could be represented by the thickness of a sheet of paper laid atop the Monument's highest point.

Compared to the age of the Earth, humans have been here for an incredibly short time. Yet in that time, we have accomplished much, and changed some of the fundamental aspects of the planet's processes. The C&O Canal is a testament to what humans can do, but it is also a testament to what we cannot. Underneath the Canal, the rocks speak of forces that can only be accomplished by nature, planet-scale happenings that dwarf our own scratchings at the surface.

The rocks of the C&O Canal show us that the Earth is a dynamic place, constantly changing. Sea level rises, falls, and rises again. Glaciers come and go. Currents in the mantle drag tectonic plates around, colliding them (building mountain ranges) or dragging them apart (opening ocean basins). Volcanoes erupt, solidify, get worn away to sand. Life evolves, lasts a while, and goes extinct. Molecules get traded between rocks, magma, ocean water, the air, and living creatures. The carbon in your body might once have been included in a limestone, a stromatolite, or a dinosaur. With every event, the geologic record is written over, added to. This stunning pageant has been going on for a long, long time.

Like dipping our toes in the ocean, we have only begun to read the Earth's history. We've gotten an important sample, but it's much deeper than we will ever be able to fully plumb. Realizing this, some people might feel small and helpless. They compare their own lives to their massive planet and its epic tale, and find their own stories insignificant by comparison. Other observers will find themselves entranced by the enormous story. These geologically-enlightened souls will not feel alienated, because they will recognize their part in the Earth's story. The more you learn about this stuff, the more you realize it's all one big system. We are not visitors to this planet, nor separate from it. You and I are *part* of the Earth, as surely as are the rocks beneath our feet, the air in our lungs, and the water in our Canal.

Chapter 1

These pictures are reduced in size and quality: **Do not use in the book.**
Use large files (in chapter folders) instead.

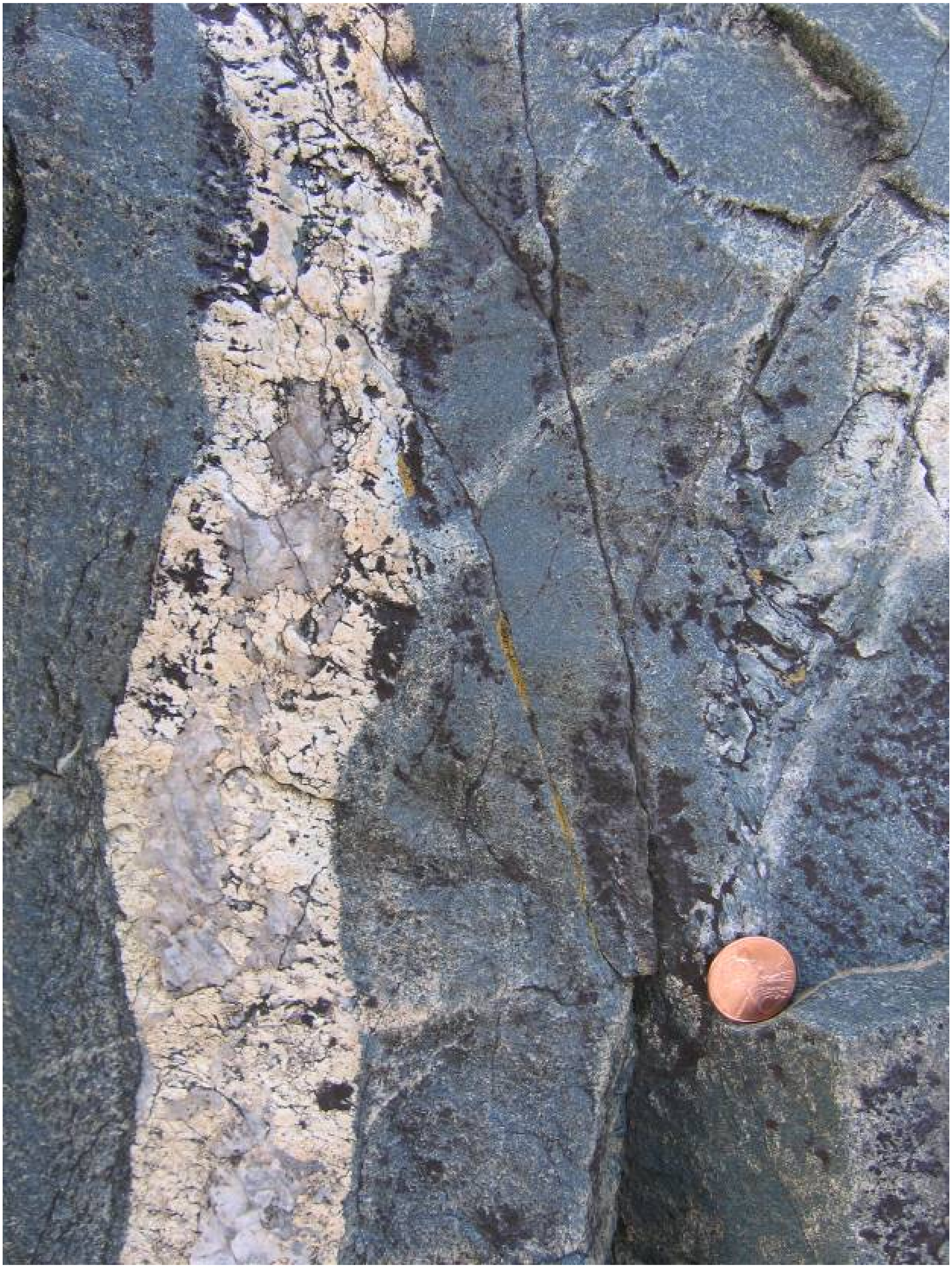

Figure 1.1 A dike of granite cuts across darker amphibolite rocks along the Billy Goat Trail, downstream from the Great Falls Tavern Visitor Center. Granites are a symptom of mountain-building activity. *Penny for scale.*

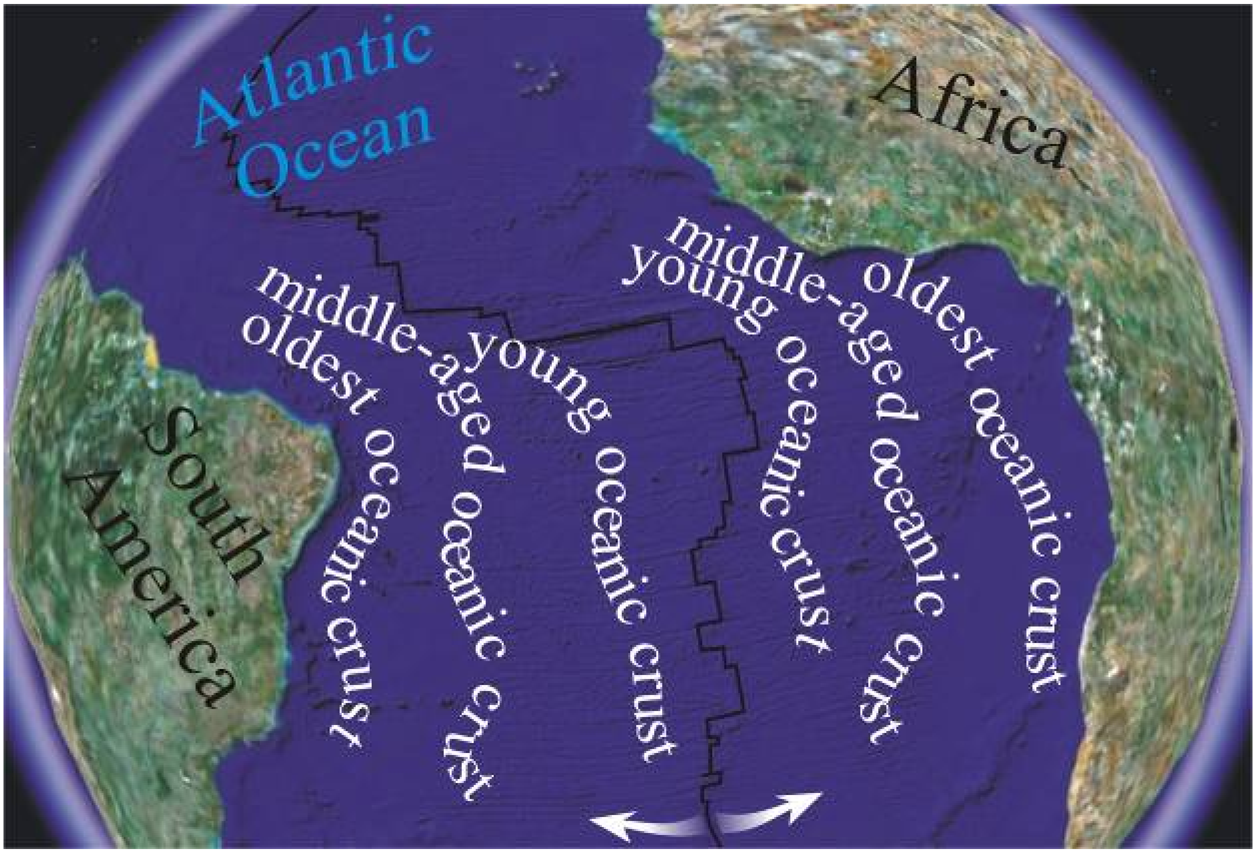

Figure 1.2 The mid-ocean ridge in the South Atlantic. As South America and Africa have spread apart, new oceanic crust has been generated to fill the gap between them. This oceanic crust is oldest at the continents' margins, and gets younger towards the mid-ocean ridge. The fact that the mid-ocean ridge is equidistant from both landmasses indicates that it produces oceanic crust at roughly the same rate in both directions. *Modified from a Google Earth image.*

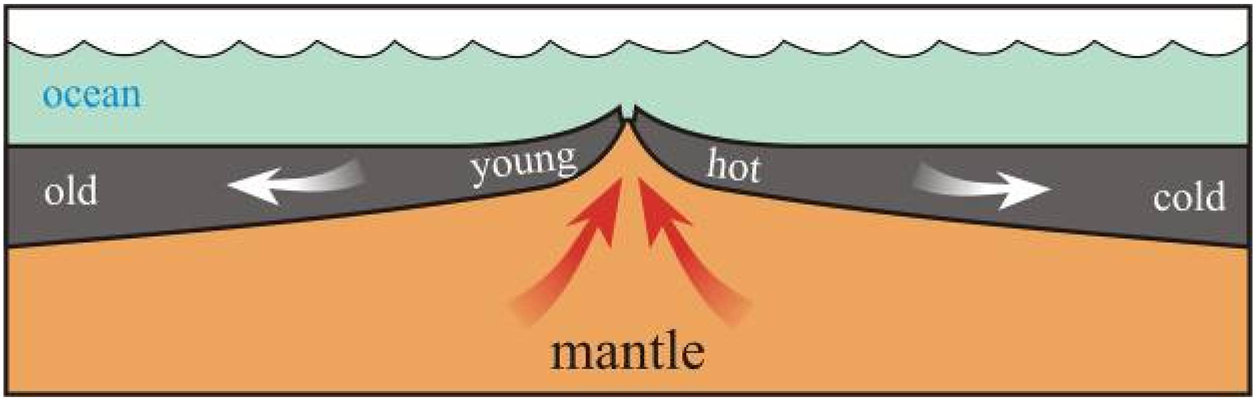

Figure 1.3 Oceanic crust and the mid-ocean ridge. New oceanic crust is produced directly under the ridge, where the hot mantle is decompressed, allowing it to partially melt. The resulting lava surges upwards, where it cools into crust. When first formed, the oceanic crust is hot, and therefore buoyant. It sticks up above the ocean floor. After it ages, it cools down (getting more dense), thickens, and sinks deeper into the mantle. The cooling process takes about 80 million years.

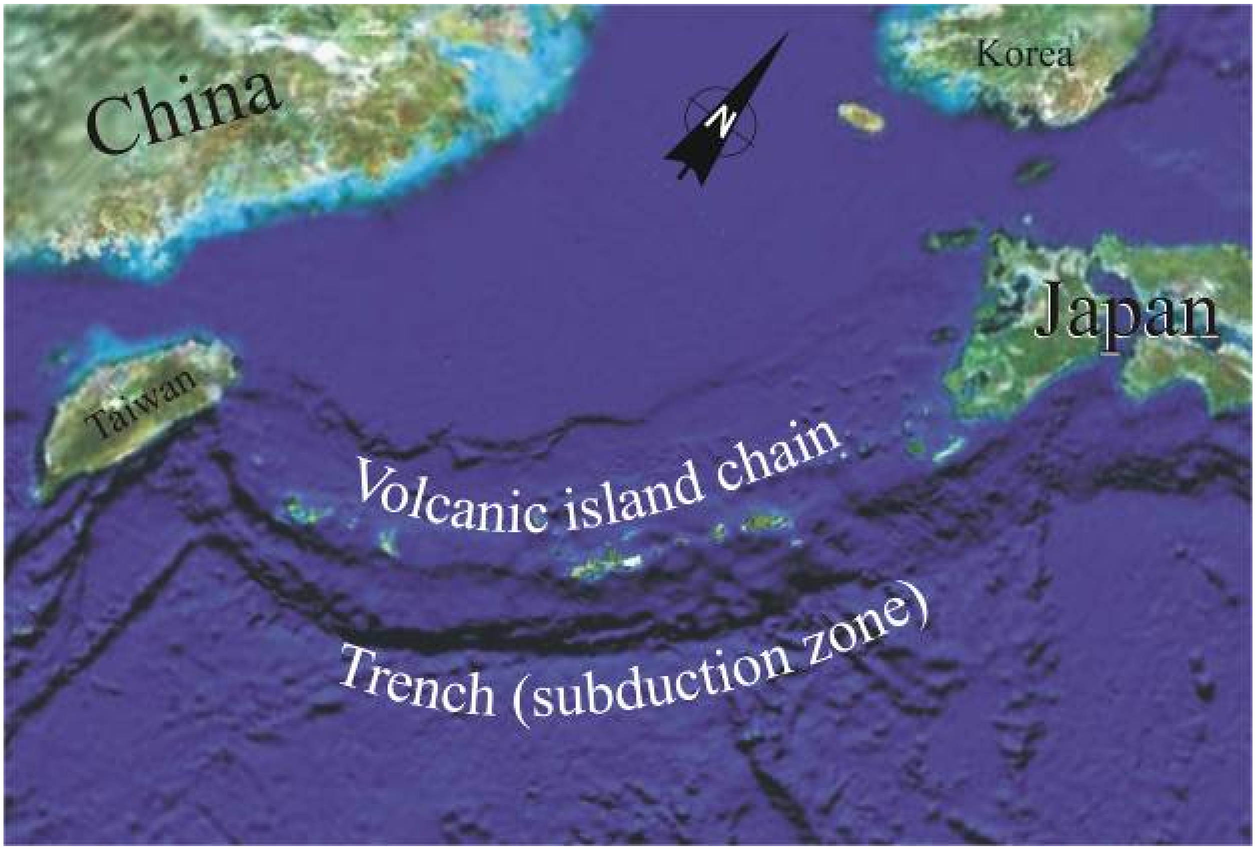

Figure 1.4 The remarkable parallelism between oceanic trenches and chains of volcanic islands. The Ryukyu Islands between southern Japan and Taiwan illustrate this nicely, though the pattern is repeated dozens of times at subduction zones around the planet. *Modified from a Google Earth image.*

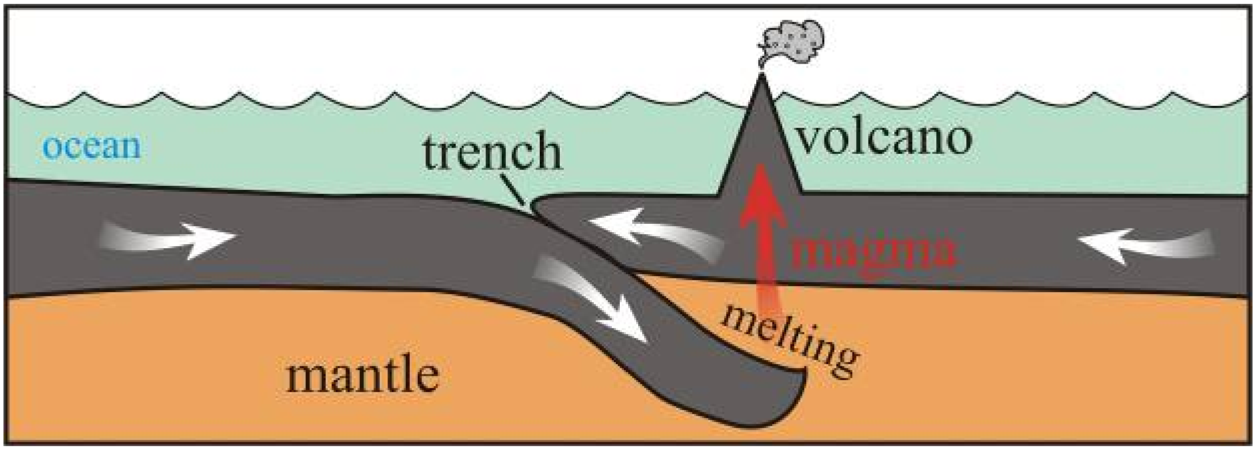

Figure 1.5 Subduction of oceanic crust under other oceanic crust. When two plates of oceanic crust converge, the older and colder of the two subducts (because it is more dense). As it plunges into the mantle, it heats up, causing it to partially melt. The molten magma travels upwards through the overlying plate to create a volcano.

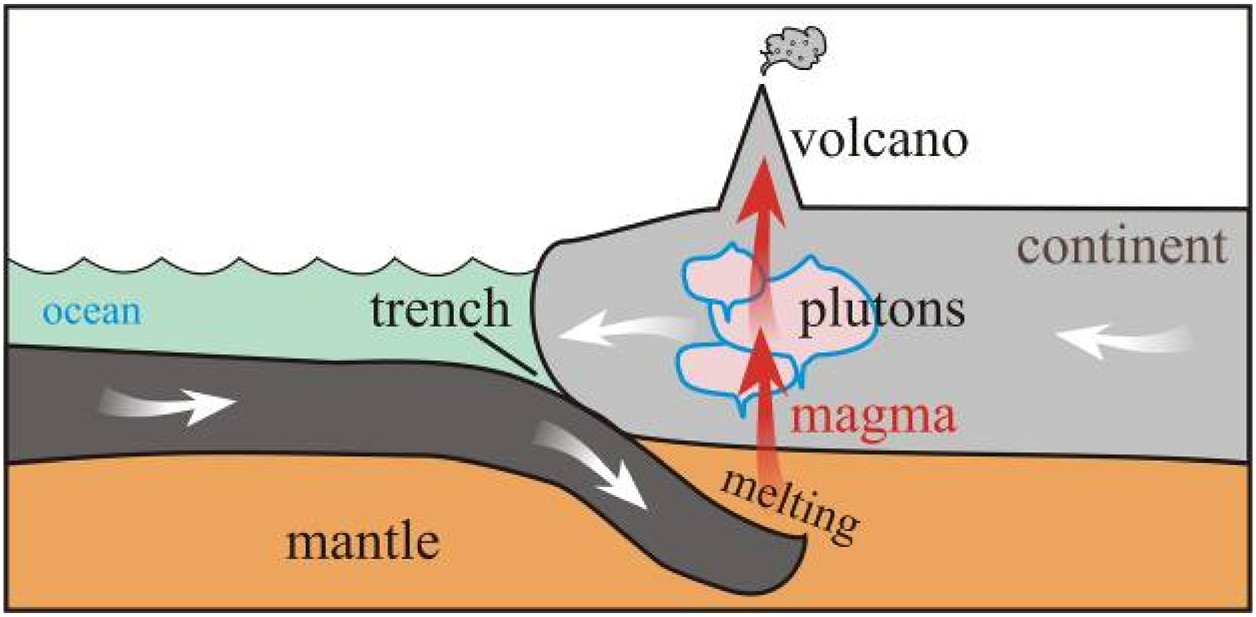

Figure 1.6 Subduction under a continent. When thinner, denser oceanic crust butts heads with thicker, more buoyant continental crust, the oceanic crust always loses. It sinks into the underlying mantle in a process called subduction. At the surface, this is marked by a deep furrow called a trench. As the subducted slab sinks, it gets hotter. This causes it to partially melt. The liquid rock, called magma, is buoyant, and so it moves upwards through the overlying rocks. If it stops before it gets to the surface, it cools and becomes a pluton. If it makes it all the way to the surface, the lava erupts from a volcano. This basic fact of geology is the reason for the stunning discrepancy between the ages of oceanic crust and continental crust. While there are continental rocks as old as 4 billion years in age, there is no oceanic crust in the world that is older than 200 million years.

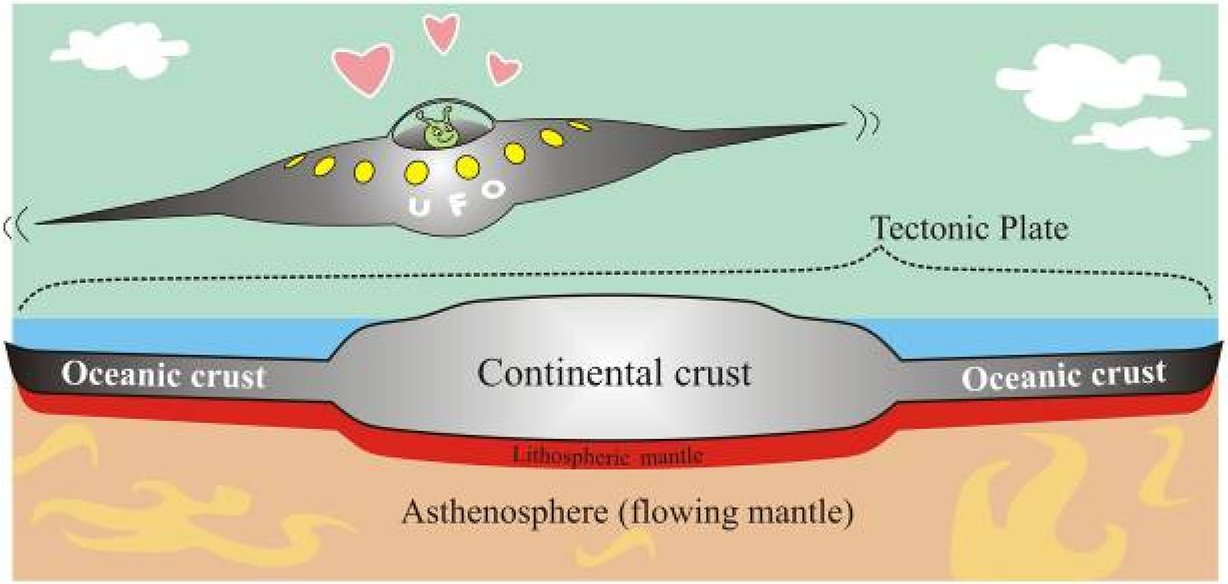

Figure 1.7 Tectonic plates as UFOs. Tectonic plates can consist of both continental crust and oceanic crust. Typically, the arrangement is as shown above: a thick central portion that is the continent, surrounded by a fringe of oceanic crust, which is much thinner in profile. This is reminiscent of the classic shape of flying saucers, only there don't appear to be any little green men at the controls of the continents.

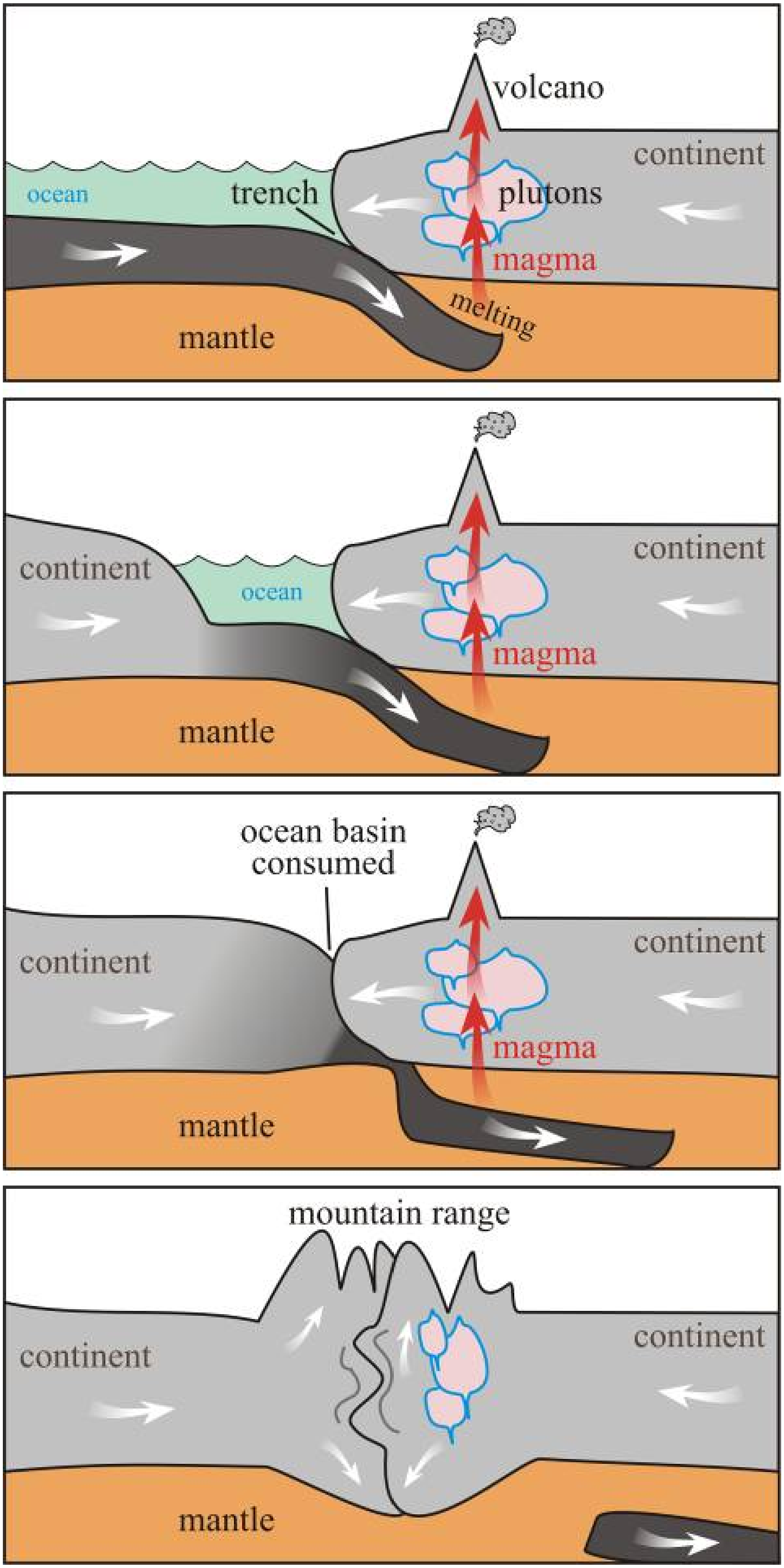

Figure 1.8 Continental collision. When plates containing continents move towards one another, the intervening oceanic crust is destroyed through subduction. Eventually, when the oceanic crust is completely subducted, the two continents come into contact. Because continents are too buoyant to subduct, they crash into one another, raising up a large range of mountains. In the modern world, Africa and Europe are experiencing such a collision, and the Alps are the result. Elsewhere, India is colliding with Asia, raising the Himalayas.

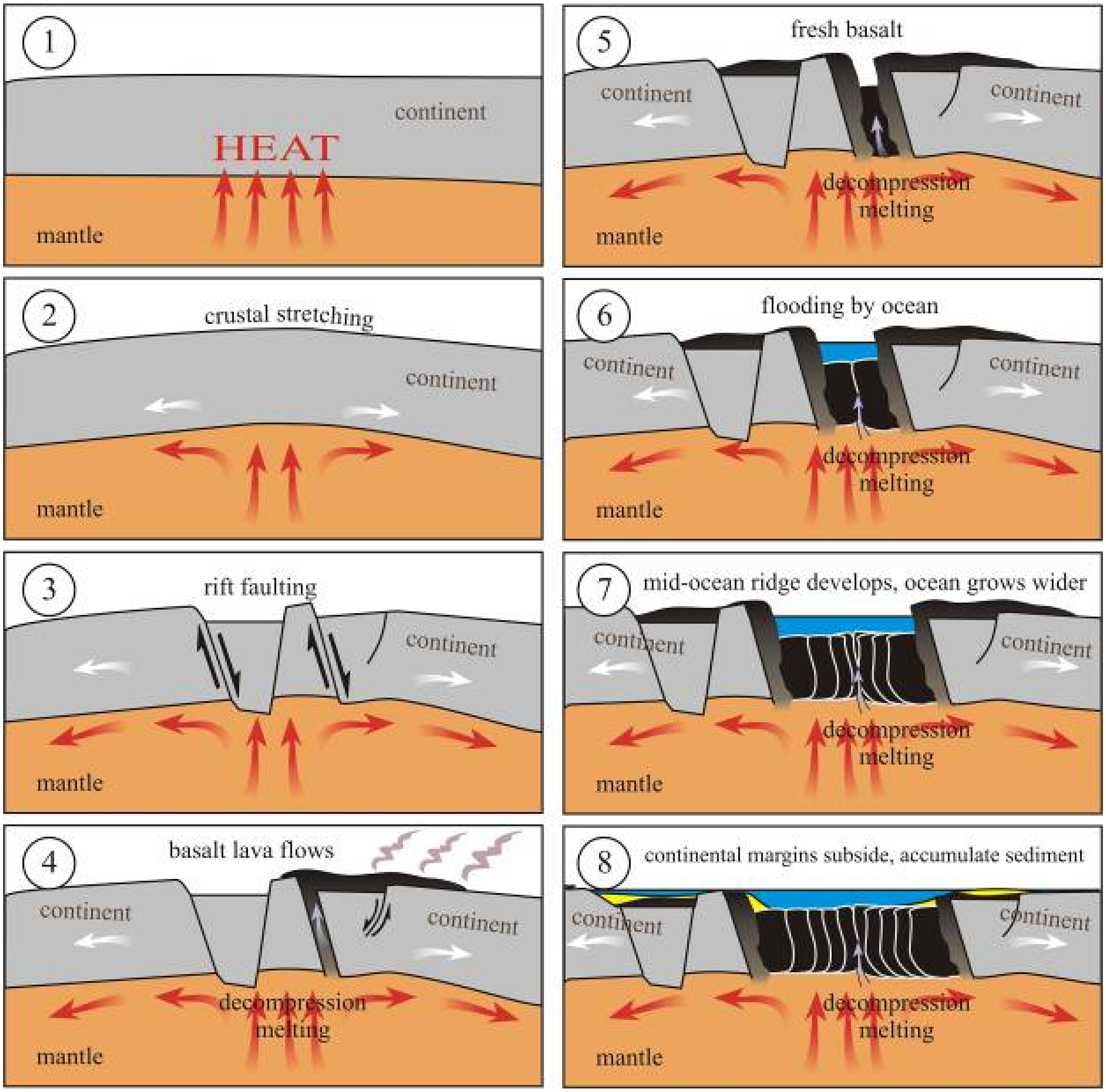

Figure 1.9 Continental rifting. Continents' thickness allows them to be effective insulators of the underlying mantle. If they're too good at this task, the mantle hits up and begins to vigorously stir about. As it circulates, it drags the continents apart. As the continents begin to rift, extensional faulting develops, and blocks of crust drop down, creating basins (3). Meanwhile, pressure is released on the underlying mantle; it partially melts. Some of the faults serve as conduits for magma to travel upward, like a set of pipes. Dark lava flows of rock develop at the surface (4). As the crust continues to stretch, one fracture will get wider and wider, and soon be filled with dark lavas (5). Eventually, the ocean finds its way in (6), and a narrow ocean basin is born. Continued spreading creates a mid-ocean rift (7), which produces new oceanic crust as the ocean widens. Meanwhile, the once-heated continental margins cool off and subside, allowing sediments to accumulate on top of them (8).

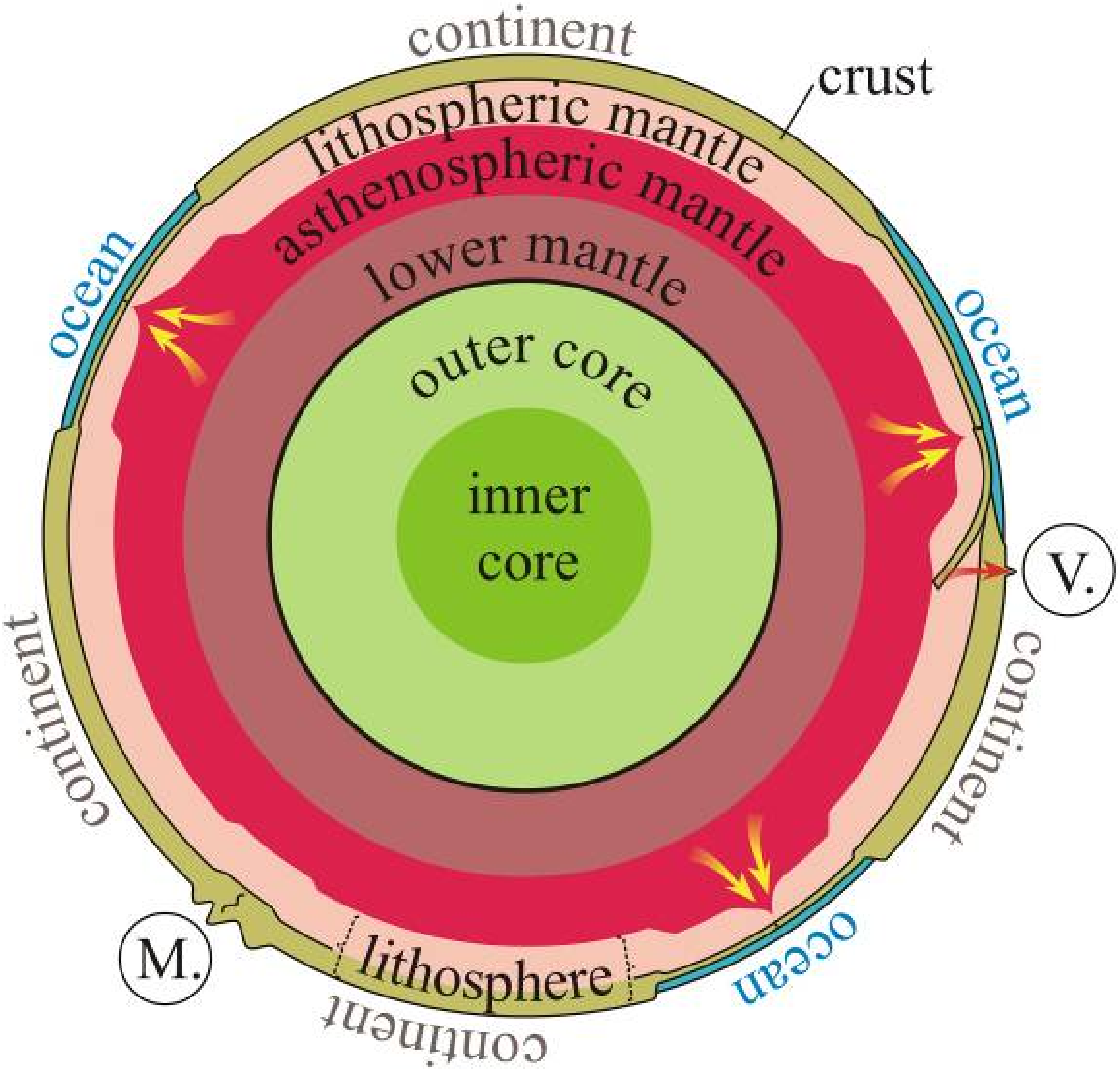

Figure 1.10 Layers of the earth. The earth's densest materials are at its center, pulled there by the force of gravity. Iron and nickel make up the core. The inner core is solid because of the immense pressure it is under, while the slightly-less-pressurized outer core can circulate as a liquid (generating the Earth's magnetic field). Surrounding the core is the mantle, which can be subdivided into a lower mantle layer, a "weak" layer called the asthenosphere, which is partially molten, and an upper solid layer which is annealed to the overlying crust. The crust and the uppermost mantle together make up the lithosphere, which is broken into tectonic plates. Plates can include continental crust and/or oceanic crust. Oceanic crust is dense, and so it sinks to a lower level in the mantle, making it the lowest spot on the surface. The result is that ocean water sits on it. Rise of warm asthenospheric mantle generates new oceanic crust at mid-ocean ridges. When oceanic crust is subducted, volcanoes result (V.). When continents collide, mountains result (M.).

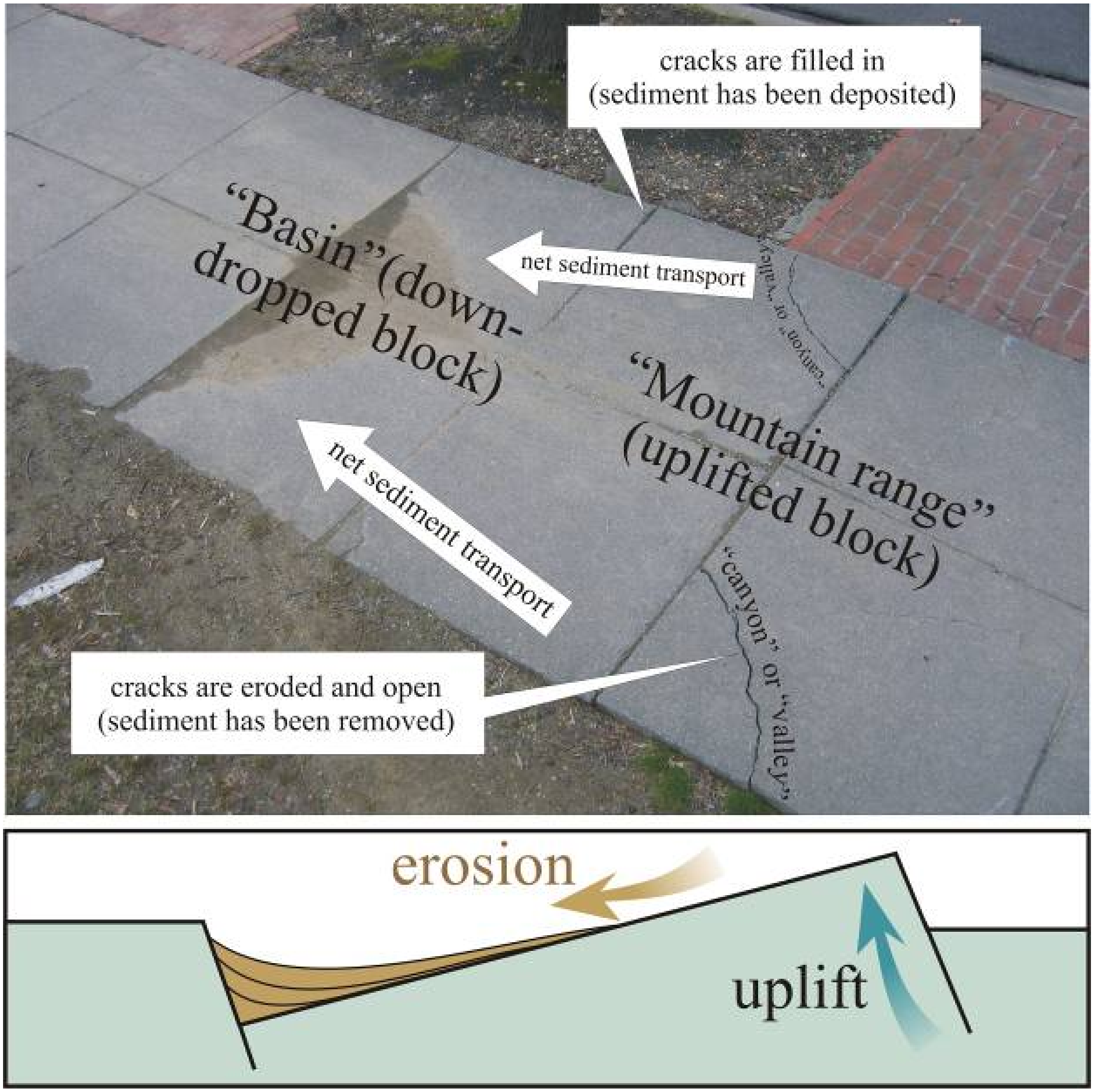

Figure 1.11 A buckled sidewalk as an analogy for uplift, erosion, and deposition. When a sidewalk gets buckled up, it resembles the relationship between mountains and adjacent basins. When mountains are shoved upwards, they are more susceptible to erosion: they get more rain, streams run faster off their high relief, and landslides remove large amounts of material that is unstable. Sediment runs downhill, whether carried by water or gravity alone; it settles in the lowest spot it can find. If this process continues without further uplift, the rock material making up the “mountain” will eventually be entirely redistributed to the “basin.”

Figure 1.12 Foods and rocks both have ingredients. Cookies, for instance have a variety of tasty and distinct nuts and sweet things. Rocks have a variety of minerals which are equally distinct, though not as tasty.

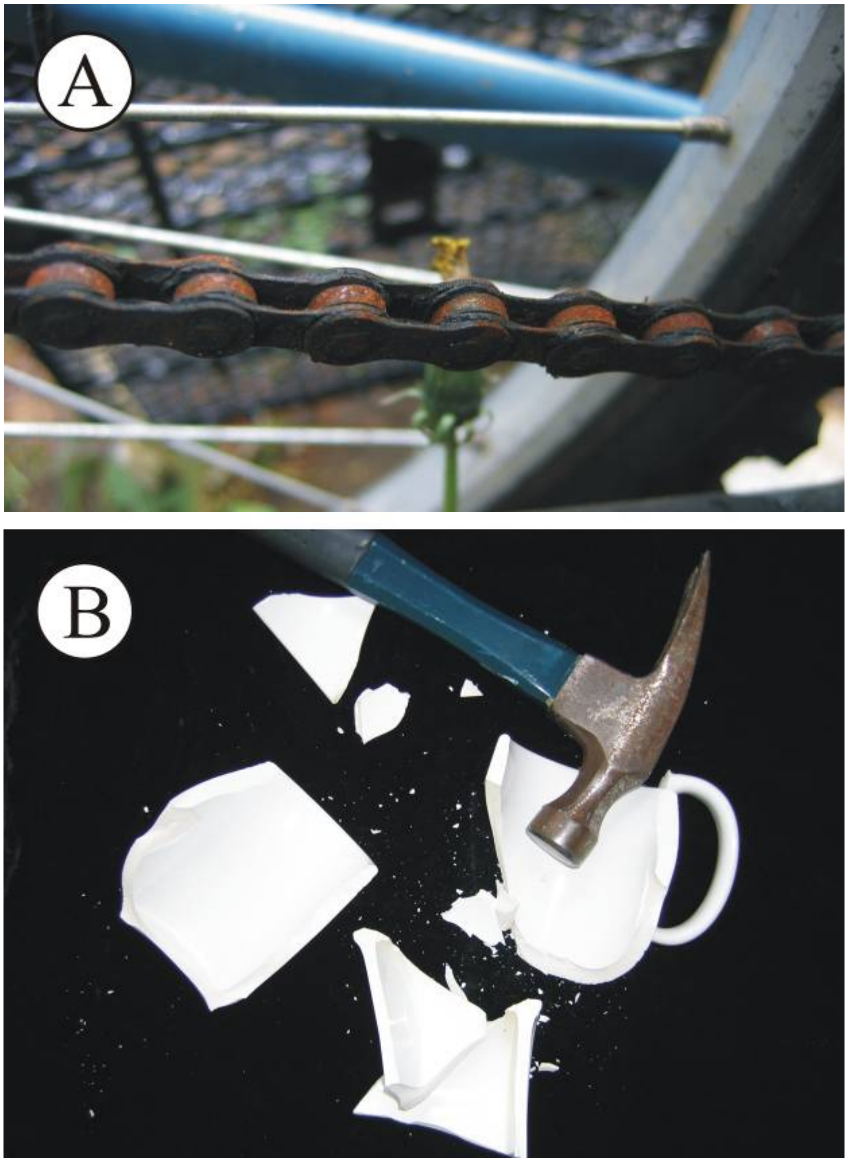

Figure 1.13 Weathering in every-day life. (A) Chemical weathering yields a new substance which did not previously exist, as is the case with rust forming on a bicycle chain. (B) Physical weathering does not produce any new substance, but simply reduces one substance, in this case a coffee mug, into smaller pieces of that same material.

(need a bigger one!)

Figure 1.14 Corner weathering at the Monocacy Aqueduct of the C&O Canal. These blocks of quartzite from nearby Sugarloaf Mountain (not the “white granite” described in the Canal Company proclamation posted at the parking area nearby) show preferential weathering at their corners. Why?

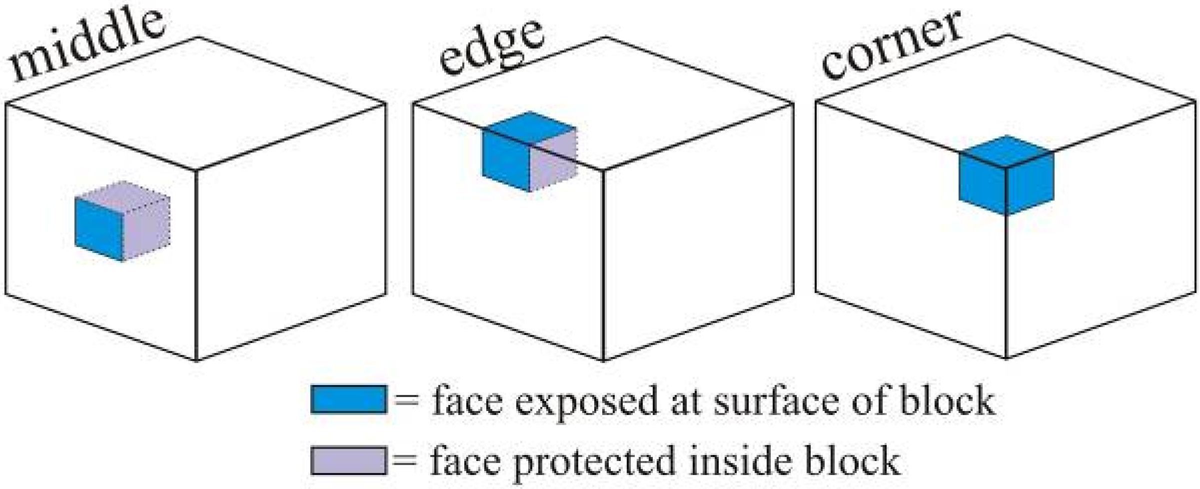

Figure 1.15 The importance of surface area to weathering. Three tiny blocks of rock are embedded at several positions within a larger block of stone. If the little block is in the center of the large block, it will not be exposed to the elements, and will not weather (not shown). If it is exposed in the middle of a face on the large block, it will experience some weathering. If it is located along the edge between two faces of the large block, it will get twice as much weathering. If the little block is located at the corner of the large block, three of its six sides will be exposed to the surface, and it will experience three times as much weathering as the llittle block in the middle of the big block’s face (first drawing).

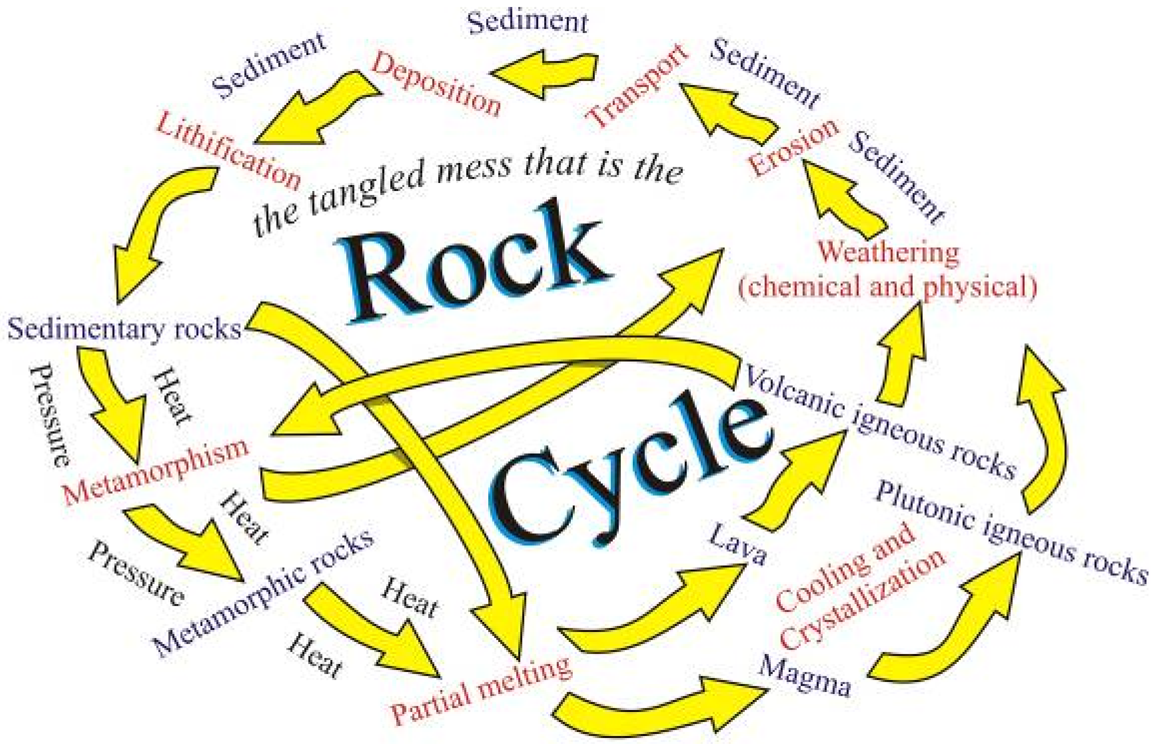

Figure 1.16 The Rock Cycle. Any pre-existing rock can be turned into a sedimentary rock by weathering it, eroding the resulting grains (sediments), transporting them, and depositing them. Once deposited sediments may be lithified (stuck together) into sedimentary rocks. Any pre-existing rock can be turned into a metamorphic rock by subjecting it to high temperatures and pressures for an extended period of time. Any pre-existing rock can be turned into an igneous rock by melting it, then cooling it down again. If it cools quickly, if forms a volcanic igneous rock. If it cools slowly, it forms a plutonic igneous rock.

Chapter 2

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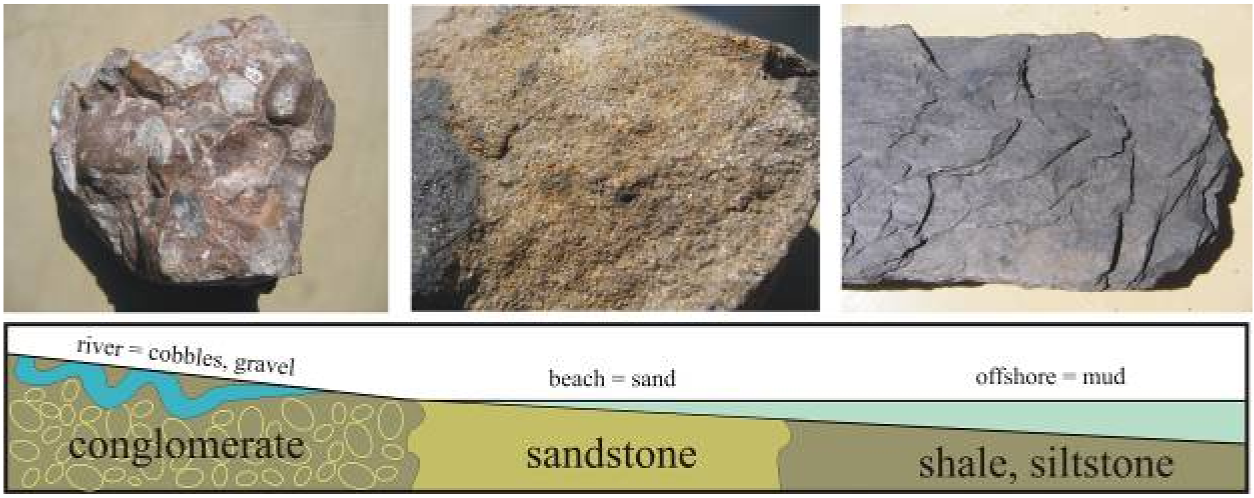

Figure 2.1 Sediment size and its relation to water energy. Rivers flow quickly, sometimes down steep gradients. Because their currents have a lot of energy, they can carry large particles like cobbles or gravel. These large particles get dropped as soon as the river flows into the ocean. At the beach, waves endlessly pound the shoreline, carrying away finer materials, but depositing lots of sand. Out to sea, where waves are not as energetic, finer grains like silt and clay settle out, leaving mud on the bottom. The rocks these various sediments can become are (respectively) conglomerate, sandstone, and shale (or siltstone).

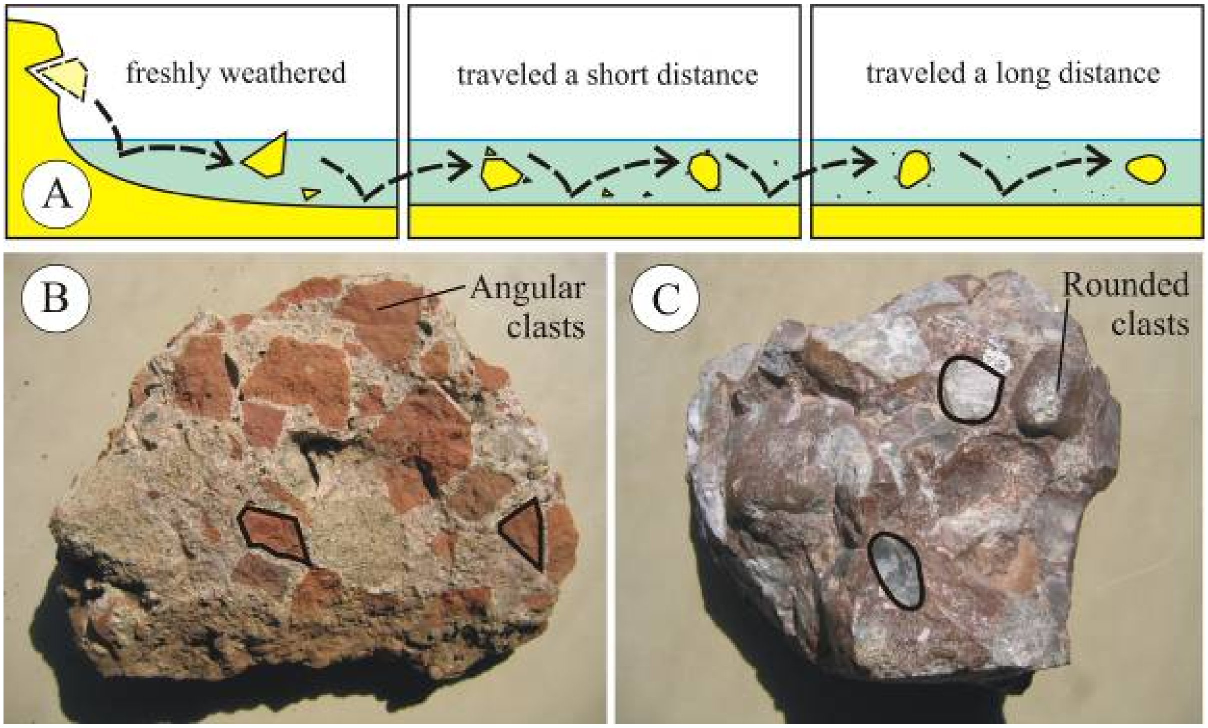

Figure 2.2 Rounding of sedimentary grains. (A) When chunks of rock (sedimentary clasts) are freshly broken off from their source area, they are sharp and angular in shape. As they are tumbled down a stream, the sharp edges are the first thing to be abraded away: they are easiest to snap off. As the clast tumbles along, rough edges get burnished away, and the clast becomes smoother and more rounded. When it has traveled a long distance, it shows its journey's toll by its egg-like shape. (B) A rock made of large angular clasts is a breccia. (C) A rock made of large rounded clasts is a conglomerate.

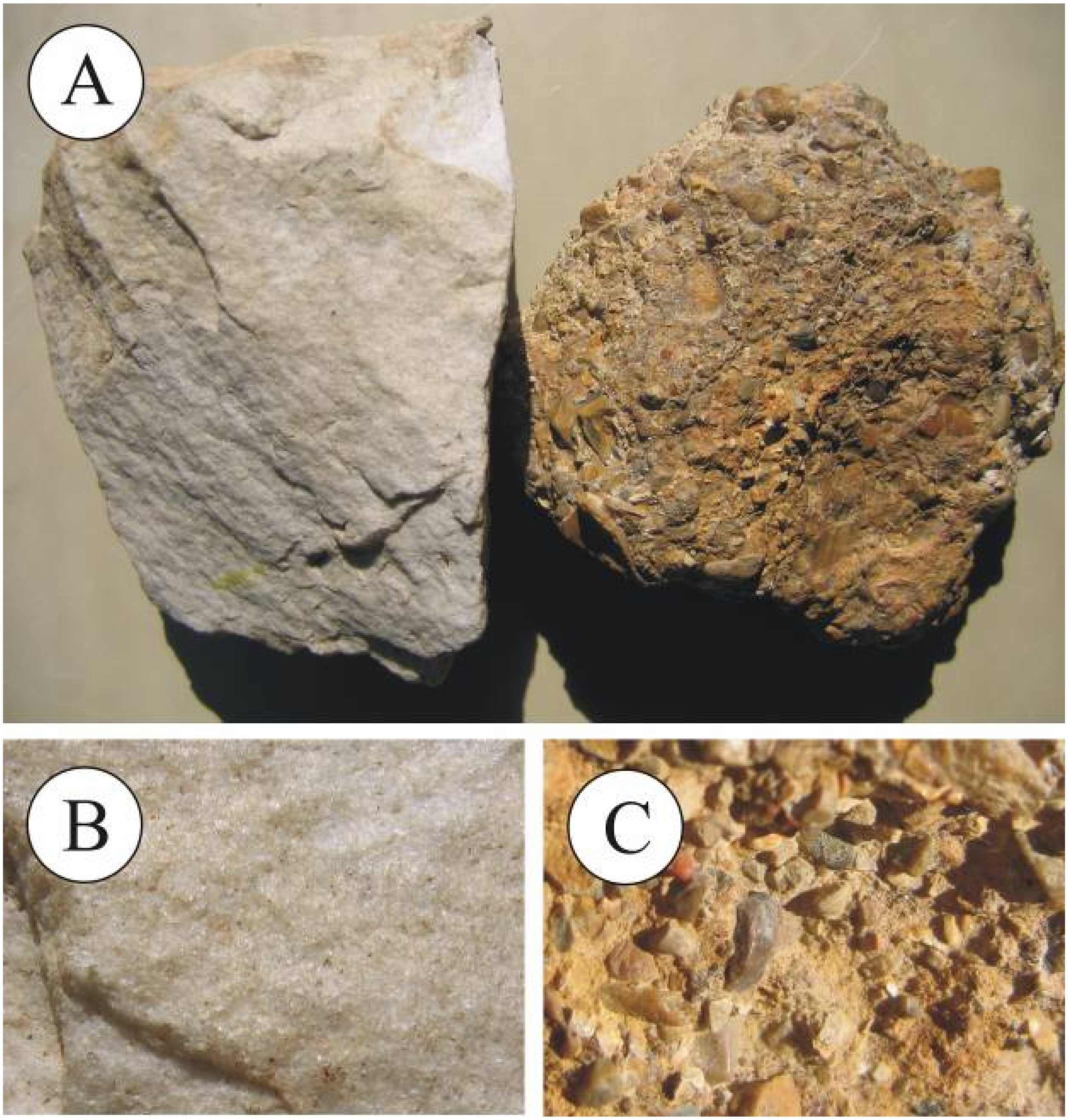

Figure 2.3 Sorting in sedimentary rocks. (A) A comparison between a quartz sandstone on the left and a conglomerate on the right. (B) and (C) Close-ups showing the different "populations" of grains in each rock. In the quartz sandstone, the grains are all about the same size: sand. In the conglomerate, there is a variety of sizes, ranging from pebbles to sand to silt. These differences reflect the slackening of the water which deposited them. The quartz sandstone is well "winnowed out," meaning it has been removed from larger grains by gradually slackening water, and had the smaller grains removed from it. The conglomerate, on the other hand, was dumped in a hurry, and the grains show it. If we interpret the environments these two rocks were deposited in, we would assign (B) to a beach, and (C) to a stream's flash flood deposit.

Figure 2.4 Composition of three common sandstones. (A) Quartz sandstone is almost entirely made of sand-sized grains of the mineral quartz. It is deposited in beaches and sand dunes. (B) Arkose is poorly sorted, often reddish, and contains large, angular grains of feldspar. It is deposited in locations not too far removed from its source area, like continental rift basins. (C) Greywacke is a mix of sand and mud, often dark grey in color due to low oxygen conditions. It is deposited in deep ocean turbidity currents (see Figure 2.5).

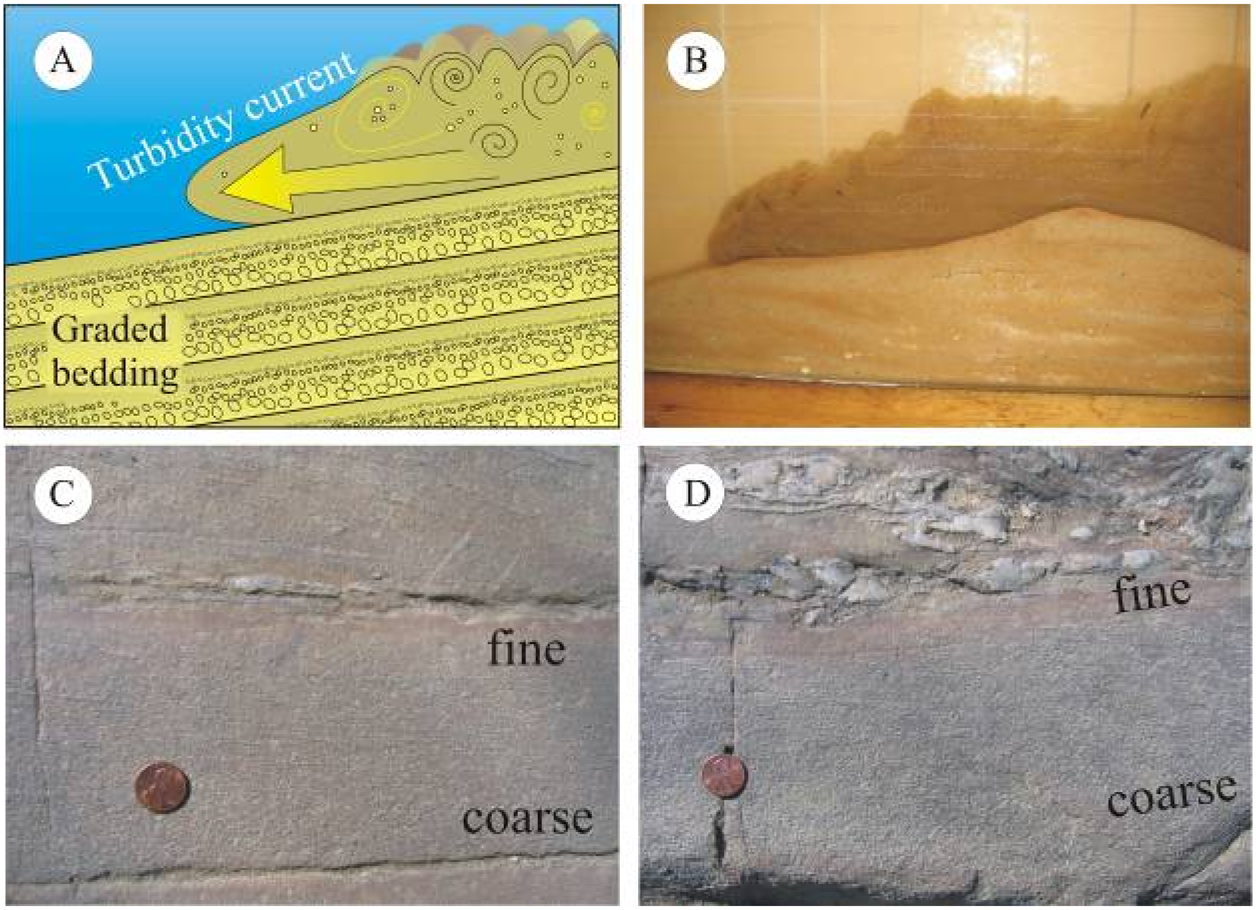

Figure 2.5 Turbidity currents and the graded bedding that they leave behind. (A) Turbidity currents are dense packages of suspended sediment and water that roll down a submarine slop in a turbulent cloud. As they settle out, the heaviest grains drop out first – these are the coarse layers at the base of each bed. The coarse deposits grade upward into medium-grained sediment, and fine-sized sediment at the top, reflecting the gradual calming of the turbid cloud. (B) A turbidity current produced in an experimental sedimentation tank. (C) and (D) Examples of graded bedding in the meta-greywacke rocks of the Mather Gorge Formation, photographed at the Great Falls overlook, Virginia side of the river. *Penny for scale.*

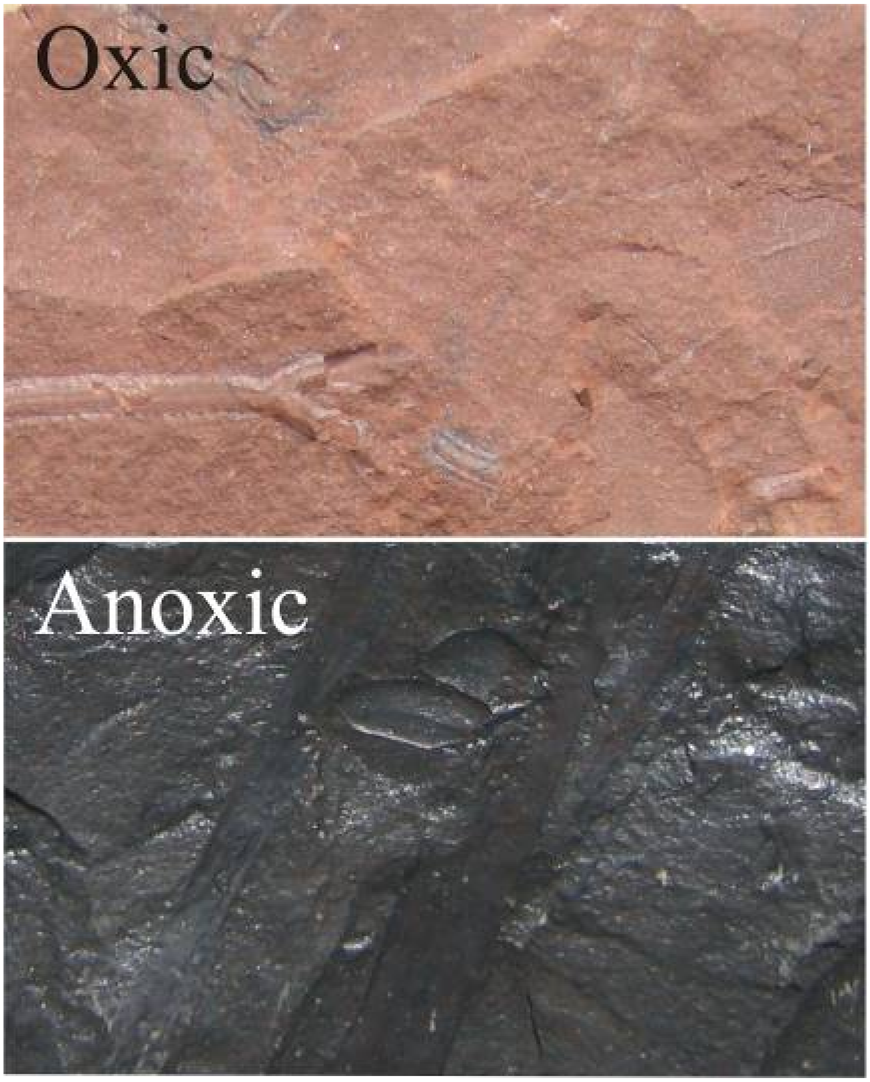

Figure 2.6 Color as a clue to a sediment's environment of deposition. Oxic conditions (high levels of oxygen) completely decay organic material and produce the oxidation of iron (rust), coloring the sediments red. This is a classic "red bed," like the Seneca Sandstone. Anoxic conditions (low levels of oxygen) prevent the decay of organic material, causing the sediment to be black. If iron is present, it is unoxidized.

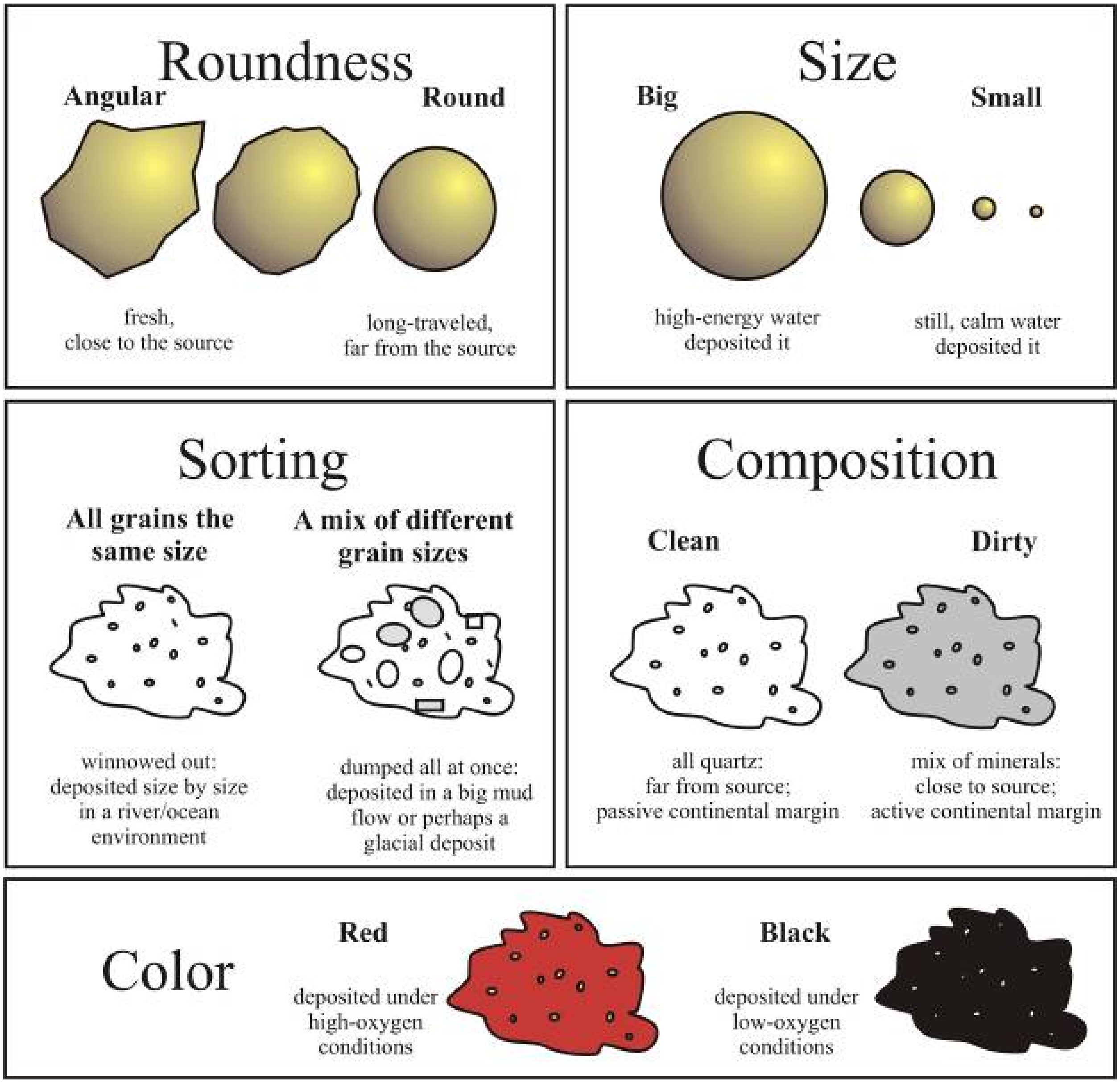

Figure 2.7 Clues from sediments. A summary of the important types of information we can learn from paying close attention to the details of a sedimentary rock.

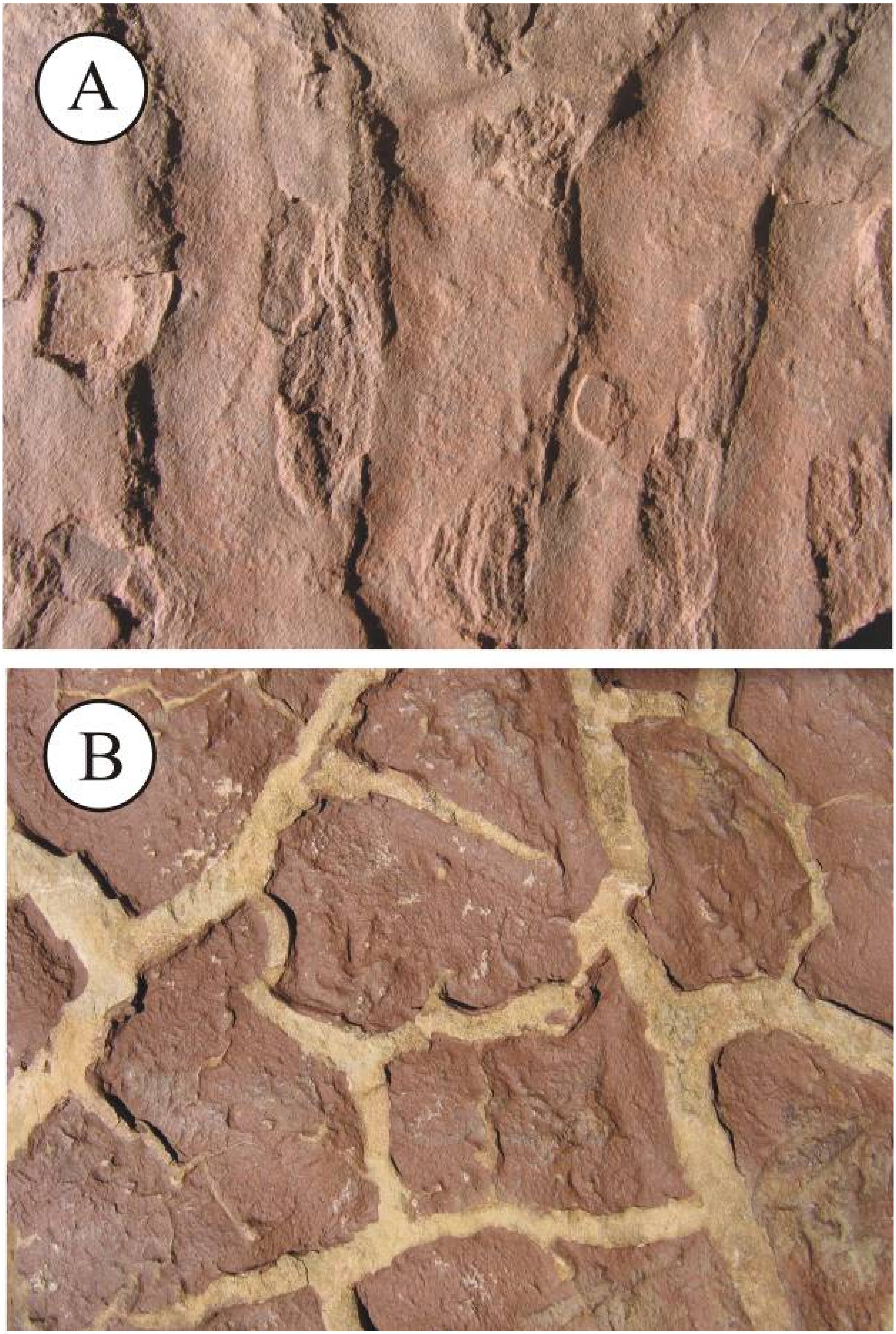

Figure 2.8 Sedimentary structures. (A) Ripple marks. (B) Mud cracks infilled by sand.

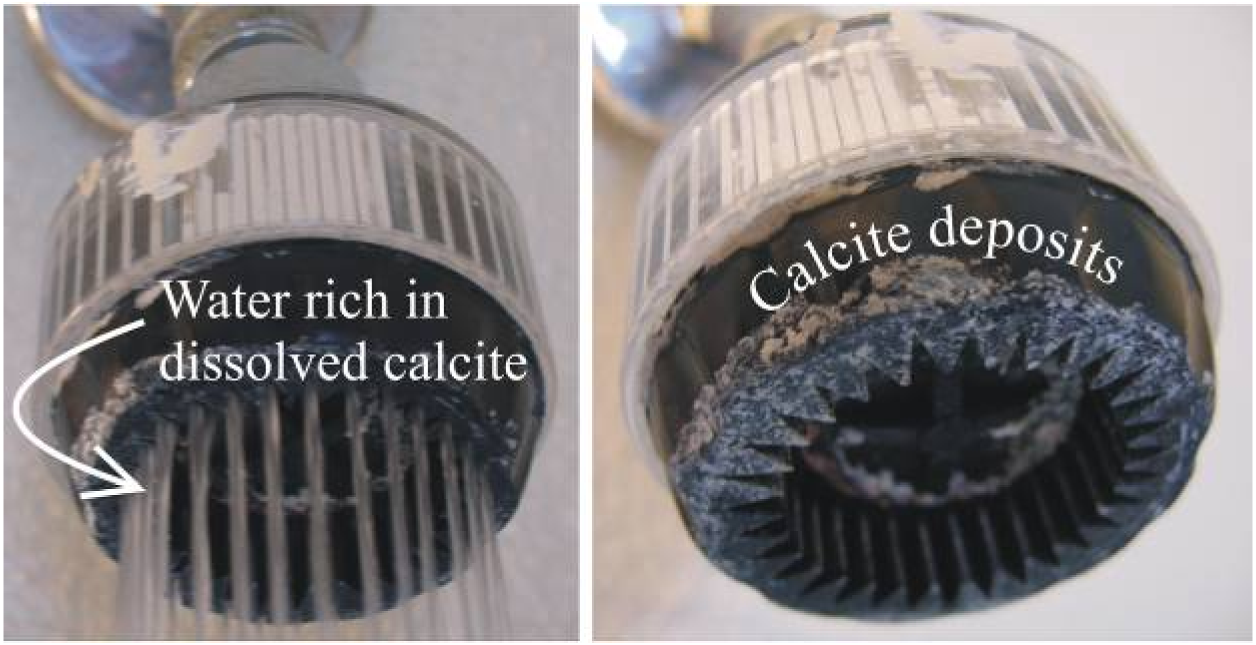

Figure 2.9 Calcite deposition in a domestic shower. “Hard” water contains dissolved calcite ions. When the water evaporates, these ions re-attach, and precipitate calcite crystals, a small deposit of limestone.

Figure 2.10 Limestone, most important of the chemical sedimentary rocks. Like in the showerhead example of Figure 2.9, fine flecks of calcite precipitate directly from seawater, settling to the ocean floor in a “lime mud.” This sample is highly rich in fossils, mainly pieces of crinoids (“sea lilies,” a variety of echinoderm), shown in fine detail thanks to the fine texture of the lime mud.

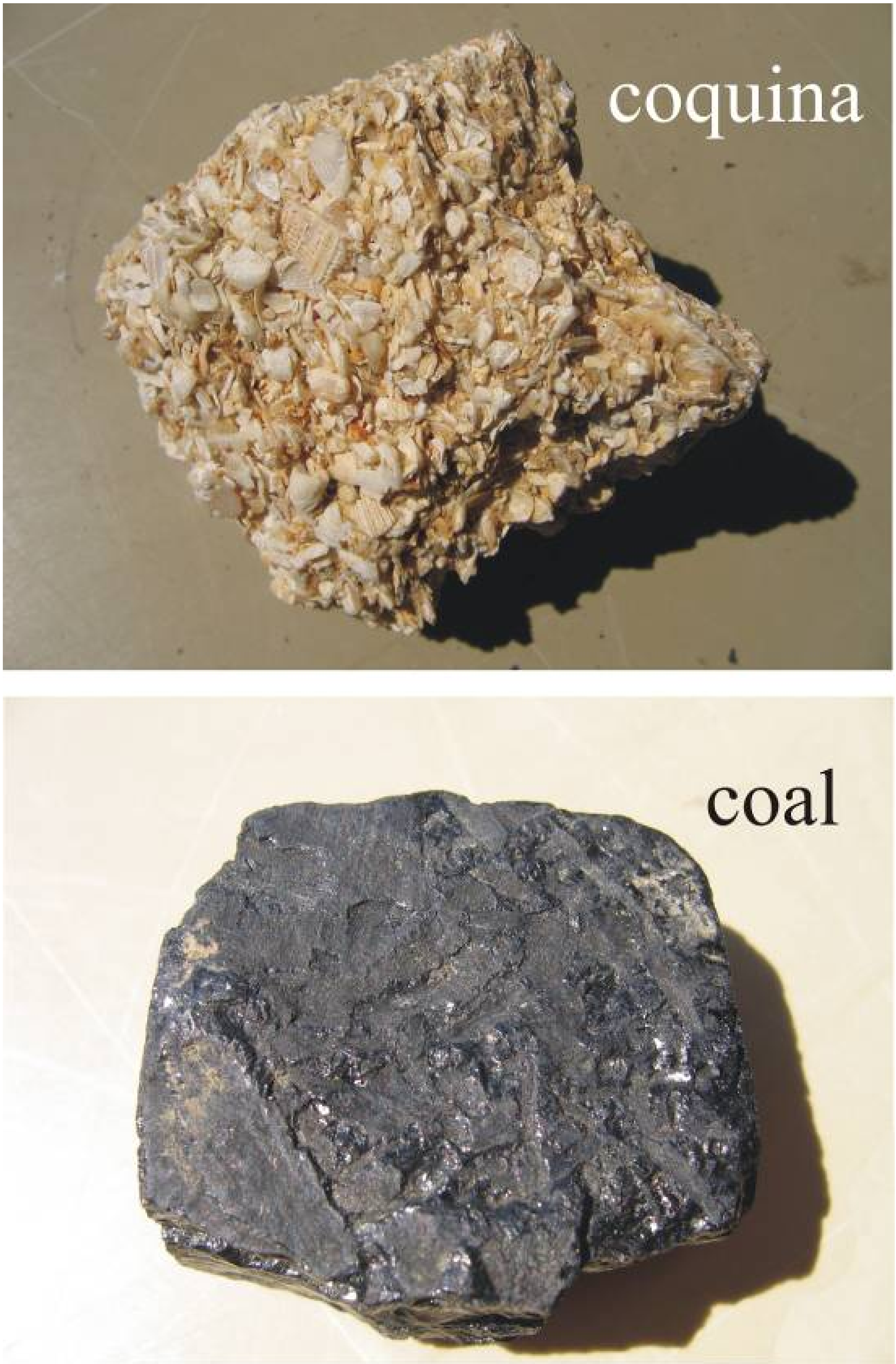

Figure 2.11 Biochemical sedimentary rocks. Coquina is has the texture of a granola bar, but it's made from shell fragments, glued together with a calcite cement. Coal is the carbon-rich remains of the plants that lived in an ancient swamp.

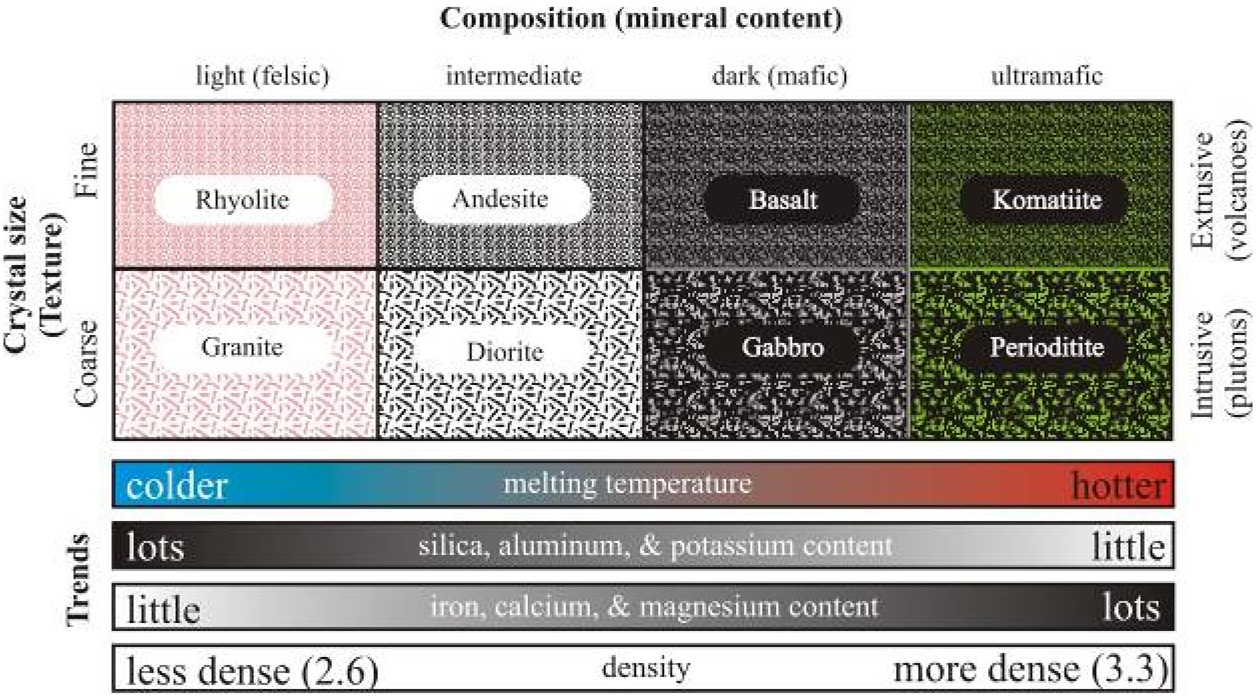

Figure 2.12 Classification of igneous rocks. Compositional variations are shown in the four vertical columns; textural variations are shown in the two horizontal rows. Major (and fundamentally important) trends are shown across the bottom of the chart.

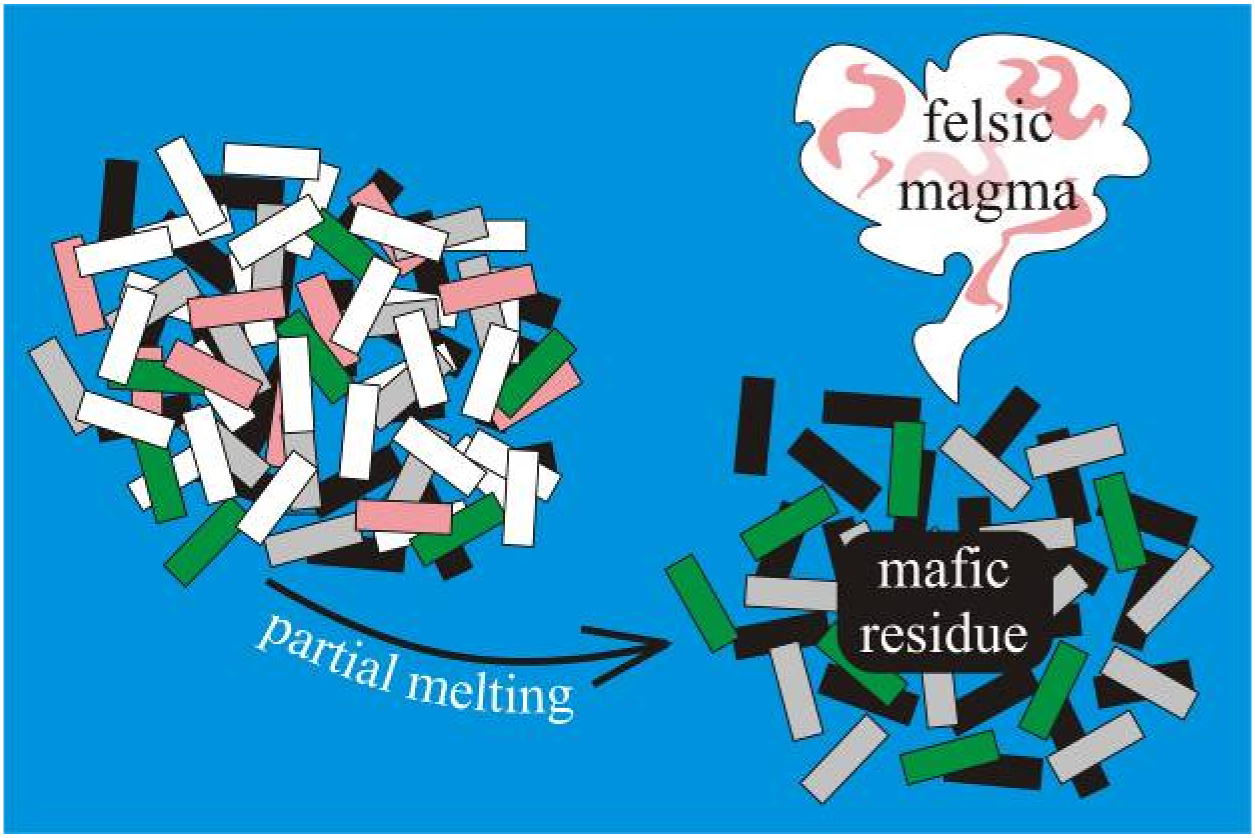

Figure 2.13 Partial melting of a rock with five minerals. When heated up, the felsic minerals (like quartz, mica, and potassium feldspar) will melt, but the mafic minerals (like olivine and amphibole) will remain as a solid rock. The magma escapes, drive upwards by its low density.

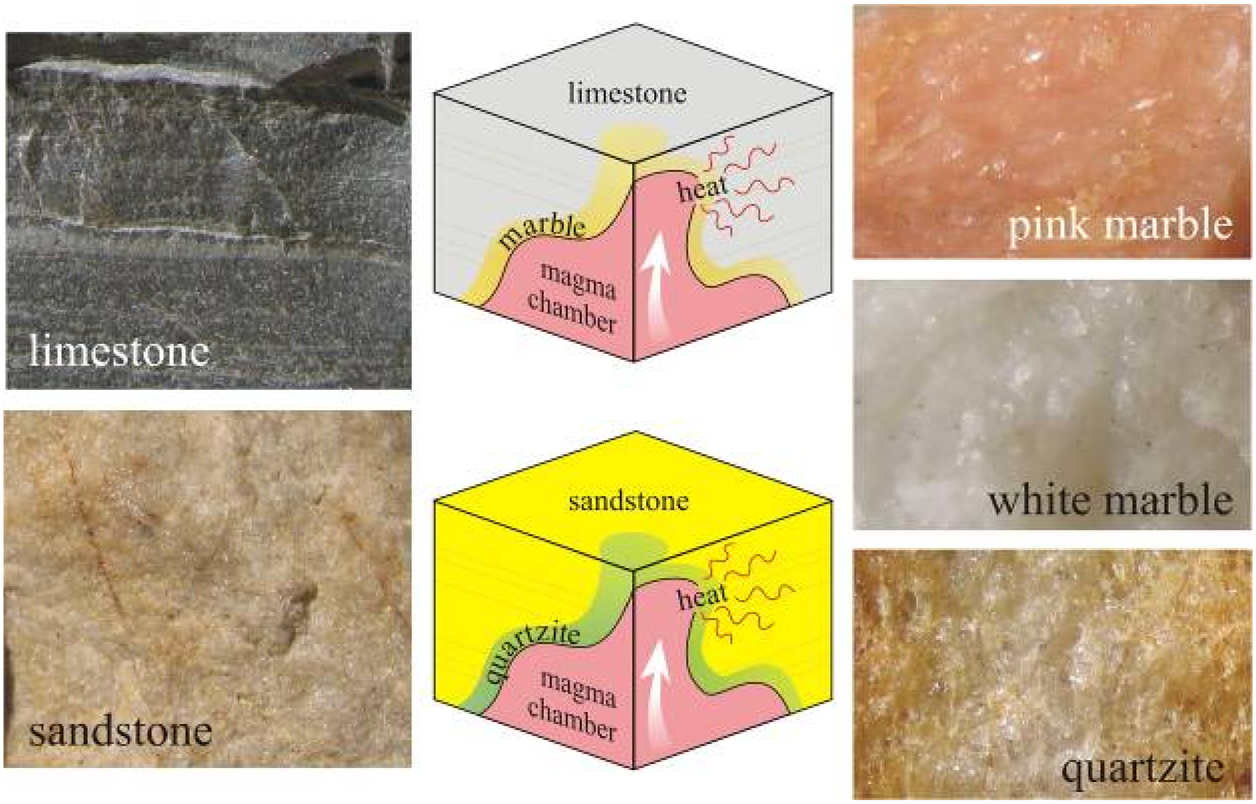

Figure 2.14 Contact metamorphism. Parent rocks like limestone or sandstone (left) will fuse into coarser “sugary” crystals as a result of being cooked by heat from a nearby magma chamber (center). The resulting metamorphic rocks, marble (two varieties) and quartzite have a distinctive appearance as compared to their starting rock, even though they are composed of the same minerals.

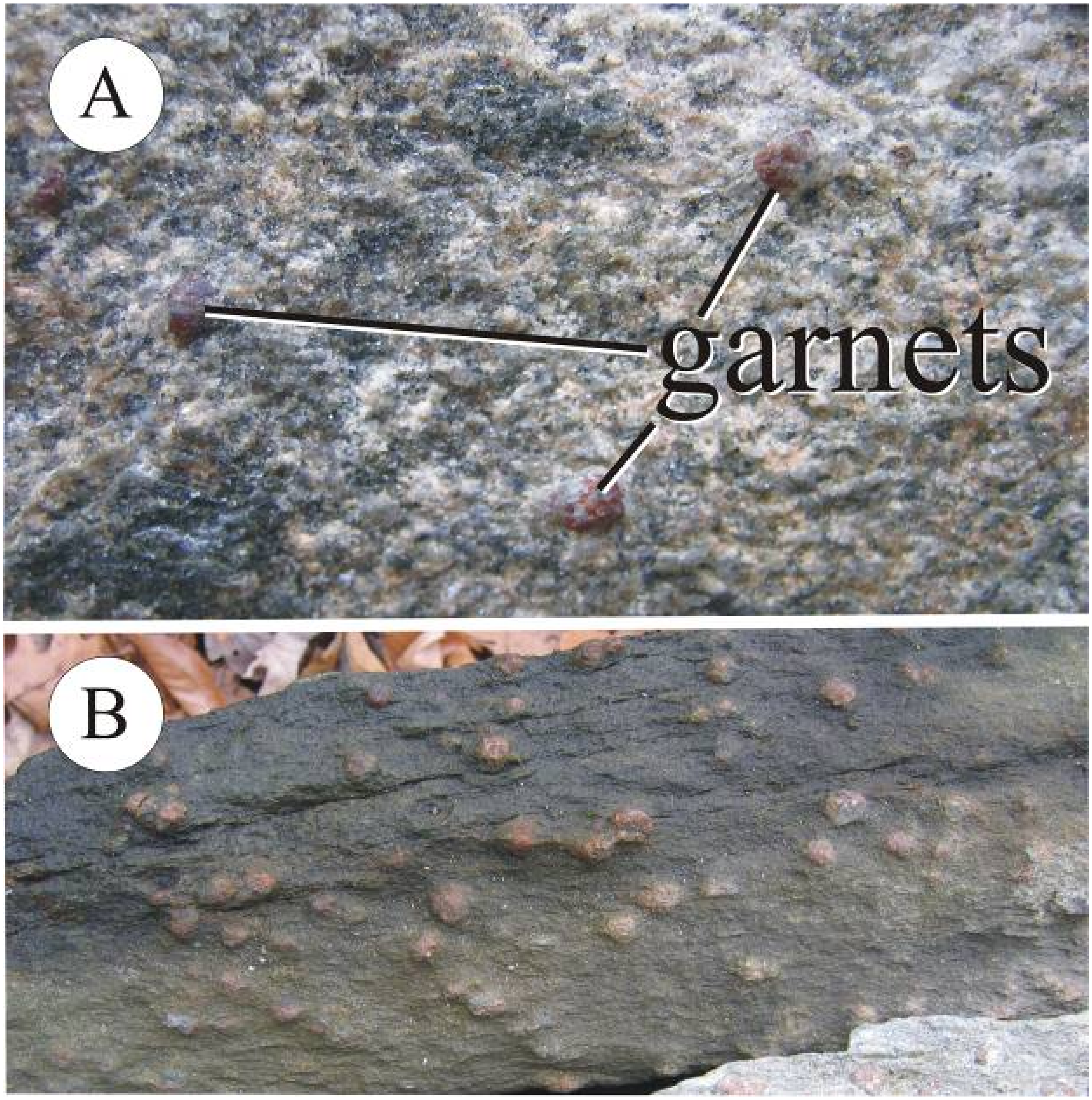

Figure 2.15 Garnets growing in meta-greywacke of the Piedmont Province. These large cranberry-colored minerals grow in place as a result of metamorphic conditions. When the temperature and pressure increased, the garnets grew, and now they stand in mute testament to the depths in the Earth where they once visited. Note also how the garnets bulge out of the meta-greywacke. In spite of being chemically unstable at Earth surface conditions, they are at least *hard*, and stand up well to physical weathering – at least better than the mica that surrounds them.

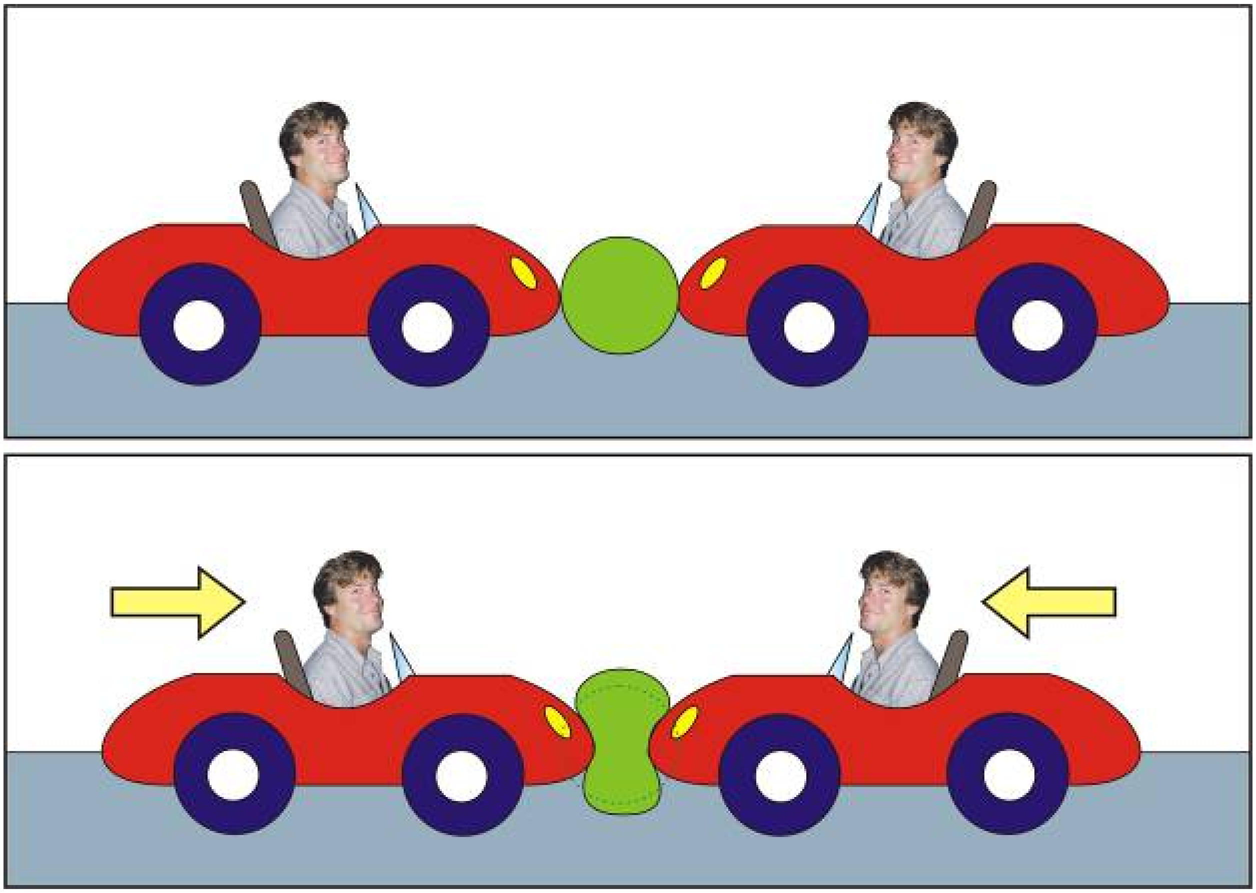

Figure 2.16 Differential pressure. Two bumper cars squeeze a green beach ball. As a result of being compressed from the sides, the ball bulges upwards and downwards. It changes its shape due to being stressed. We see a similar effect at convergent plate boundaries. When two continents collide, the rocks caught between them attain a vertical orientation.

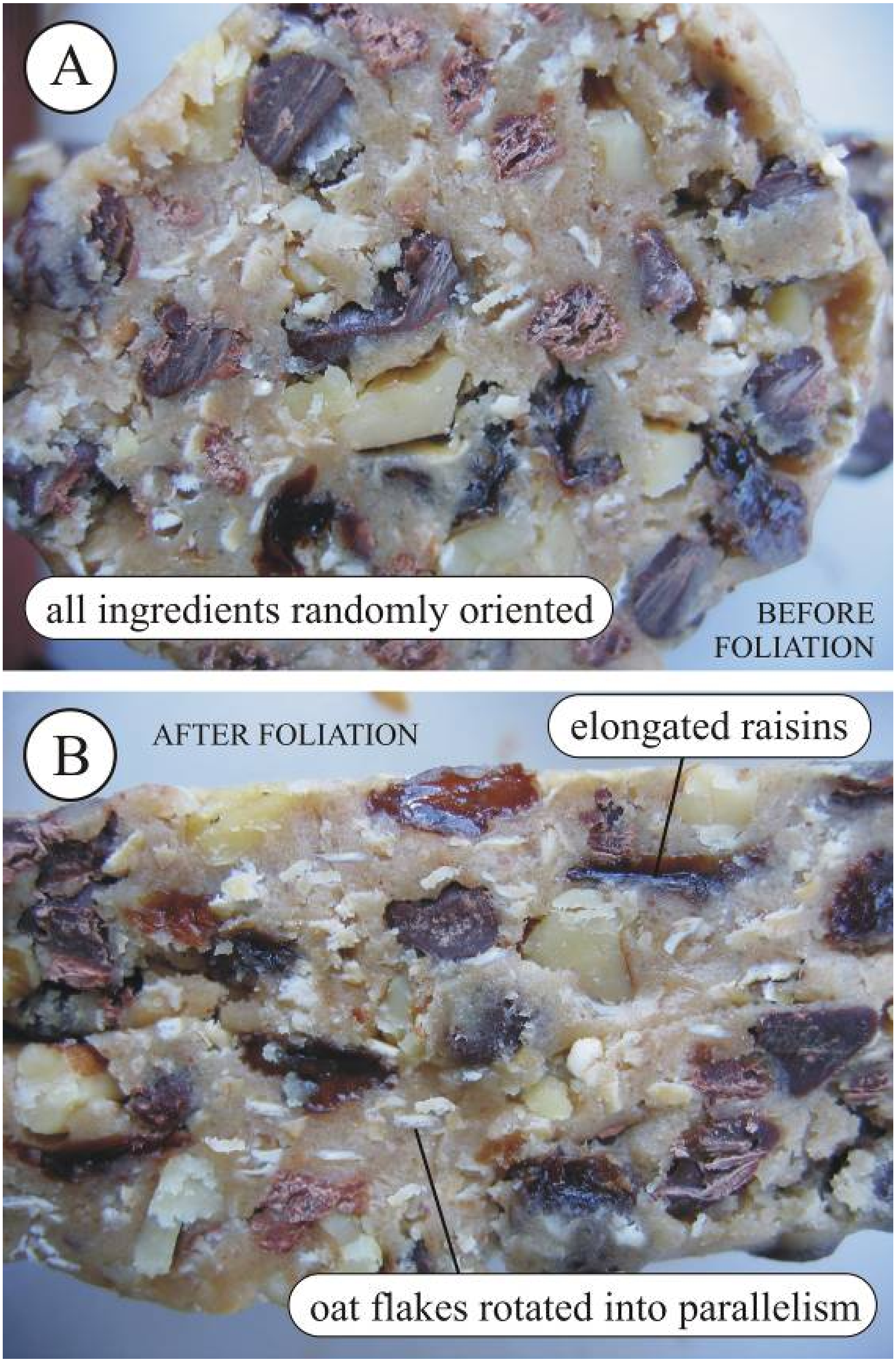

Figure 2.17 Chunky cookie dough before and after being squashed by the cookie baker. (A) All ingredients are randomly oriented in the absence of differential pressure. (B) After being squashed, the cookie has attained foliation. Its stiff oat flakes have all rotated to face the same direction (perpendicular to the direction of compression) and the raisins have “ribboned” themselves out in the same direction (again, at 90° to the direction they were squished from).

Figure 2.18 Foliated metamorphic rocks. Slate splits into flat sheets – good for blackboards or roofing tiles. Schist has a scaly, shiny appearance due to the presence of large crystals of mica. Gneiss is characterized by coarse bands or “stringers” of alternating light and dark minerals.

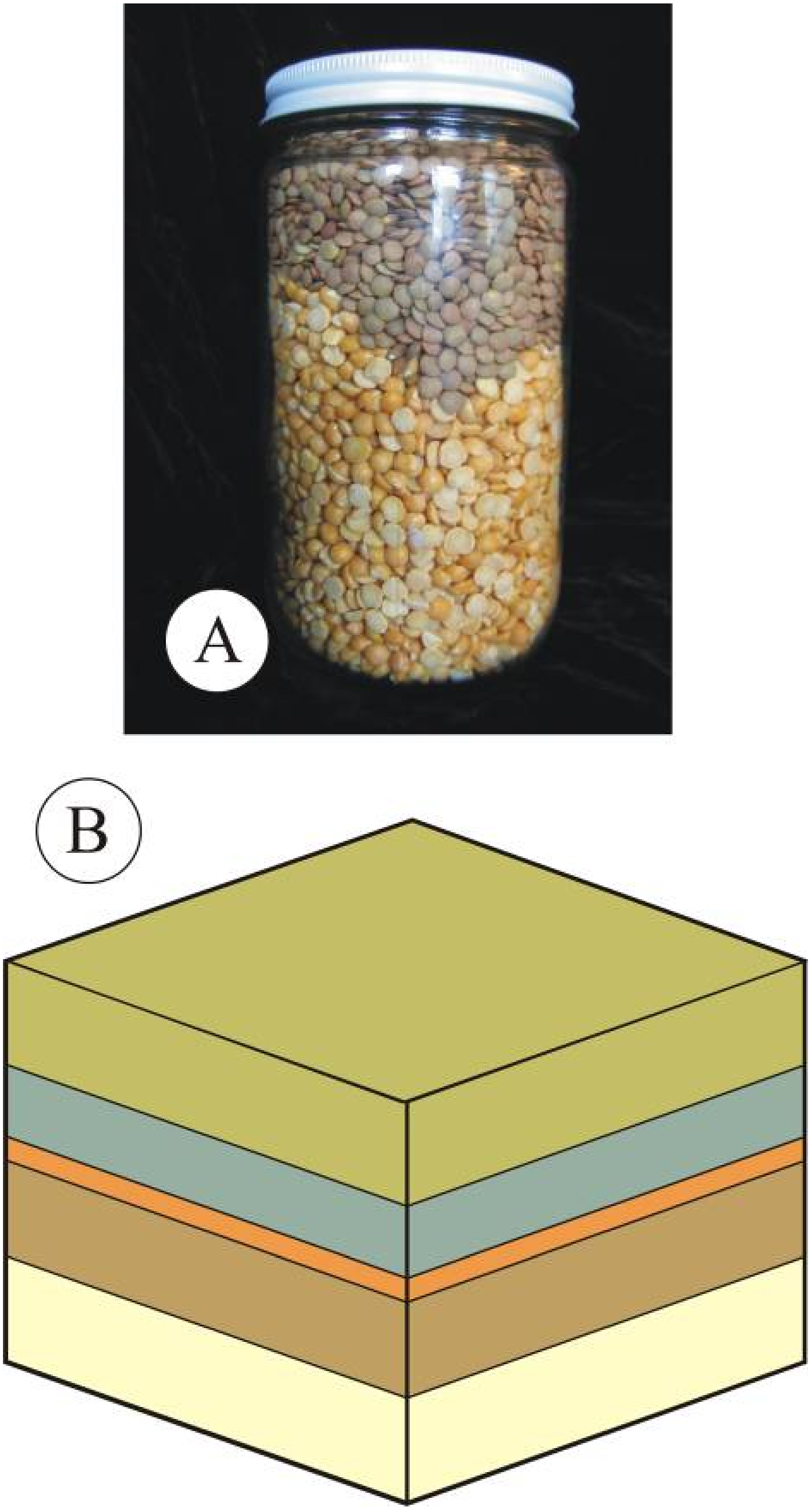

Figure 2.19 The principle of relative dating by superposition. In any stack of materials, be it (A) lentils in a jar or (B) a series of cartoon sedimentary rocks, the oldest layers are the ones that were deposited first, and we find them at the bottom. More recently added layers get stacked on top of pre-existing layers. In the jar, the yellow lentils were poured in first; brown lentils later.

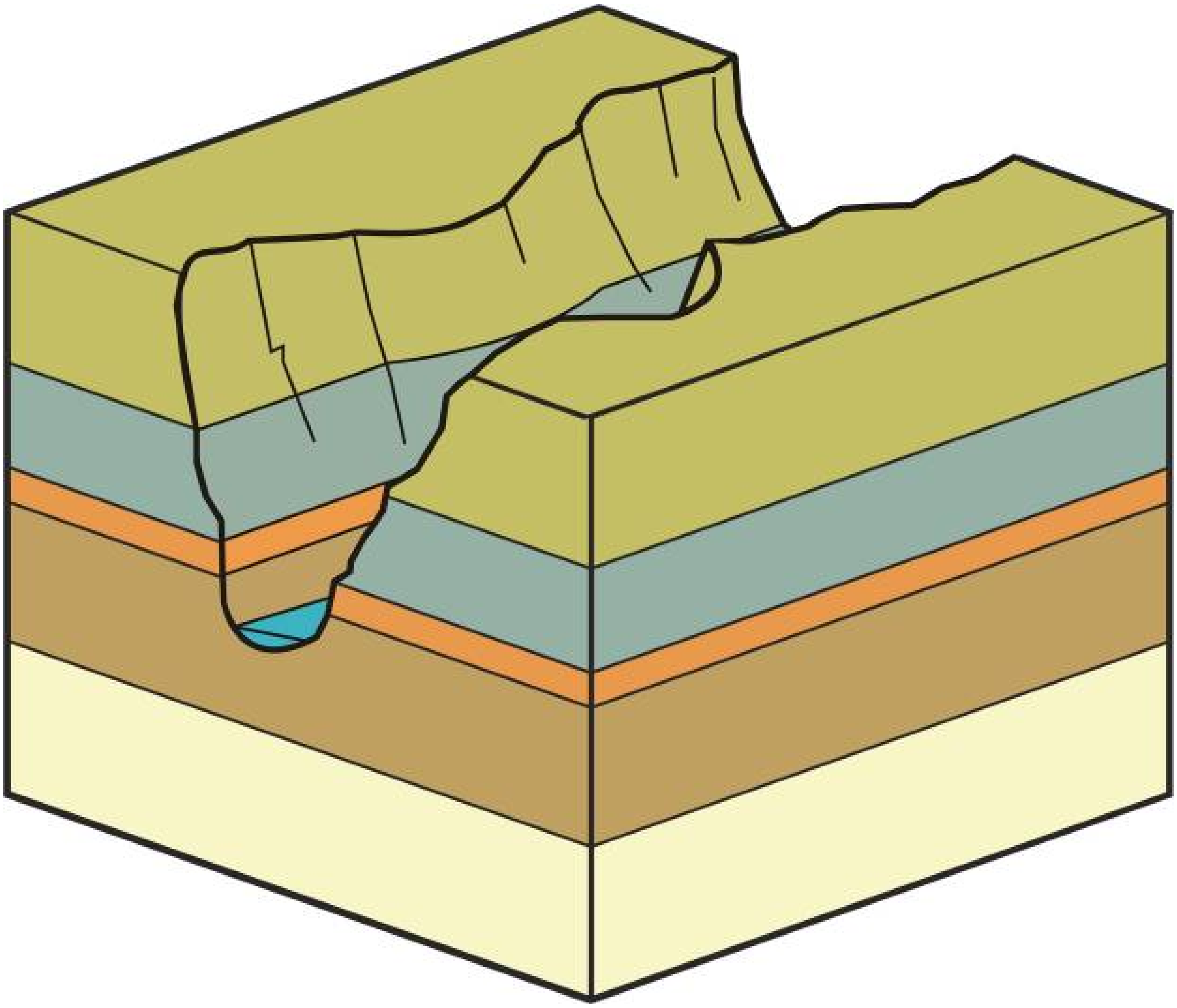

Figure 2.20 The principle of lateral continuity. Geologists see a situation like this note that we have a stack of brown-orange-blue on one side of a canyon, and the same stack on the opposite side of the canyon. Therefore, they make the assumption that the strata were once continuous – the orange layer was one big flat sheet of orange, and later the canyon cut down into the stack and separated it into two pieces.

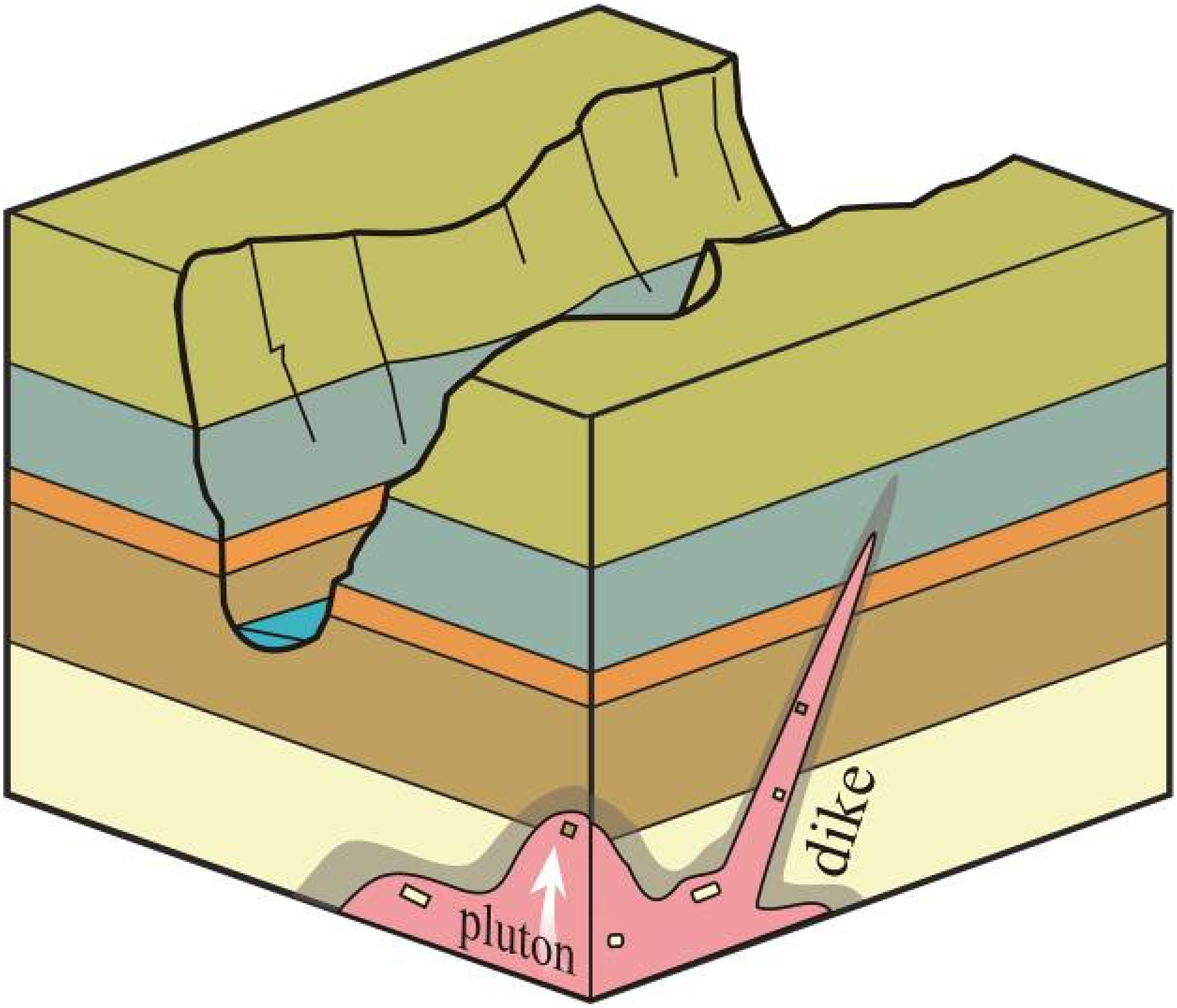

Figure 2.21 The principle of relative dating by cross-cutting relationships. A body of magma (pluton) intrudes into a stack of sedimentary layers. It extends a dike of molten rock into a fracture. Eventually the magma cools into igneous rock, and we get a look at it. The dike must be younger than the orange layer, because it cuts across it. If the dike were older, the orange layer would cut across the dike. Even the aureole of contact metamorphism which surrounds the hot pluton "overprints" the sedimentary rocks, telling us that the sediments are older, and the pluton is younger. Also, note the fragments of the sedimentary rocks which have fallen into the magma chamber. These inclusions are known as "xenoliths" – alien rocks.

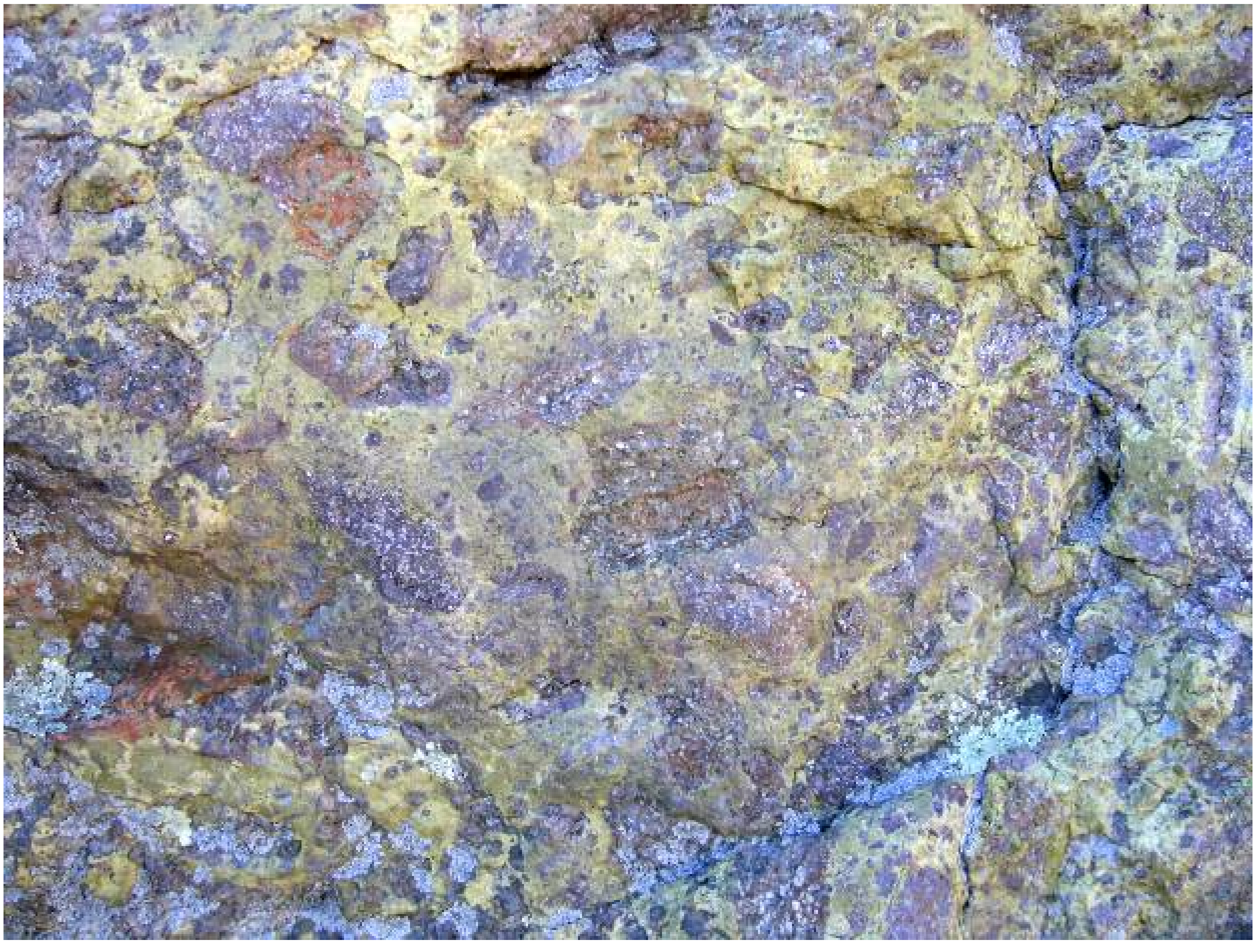

Figure 2.22 Inclusions as a tool for relative dating. This outcrop of a volcanic breccia (from Shenandoah National Park) shows bright green meta-basalt surrounding inclusions of purple and white sandstones. The sandstone must be older than the basalt in order for it to be broken up into pieces, and have those pieces included in the basalt.

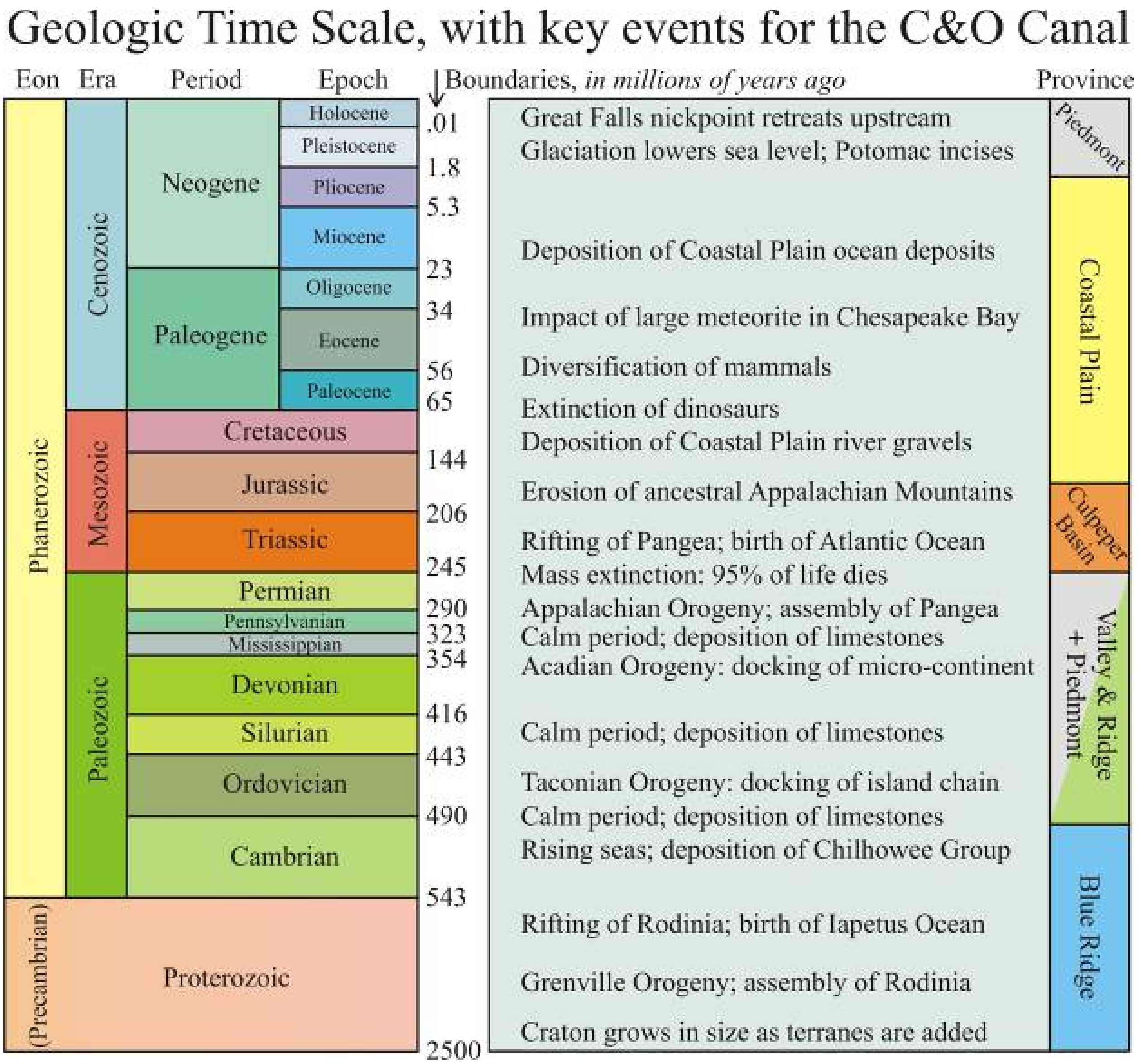

Figure 2.23 The geologic timescale, emphasizing the portion of geologic history well recorded by rocks along the C&O Canal. Key events are noted for each period, and the physiographic provinces that best record those events are noted at the far right.

Interlude

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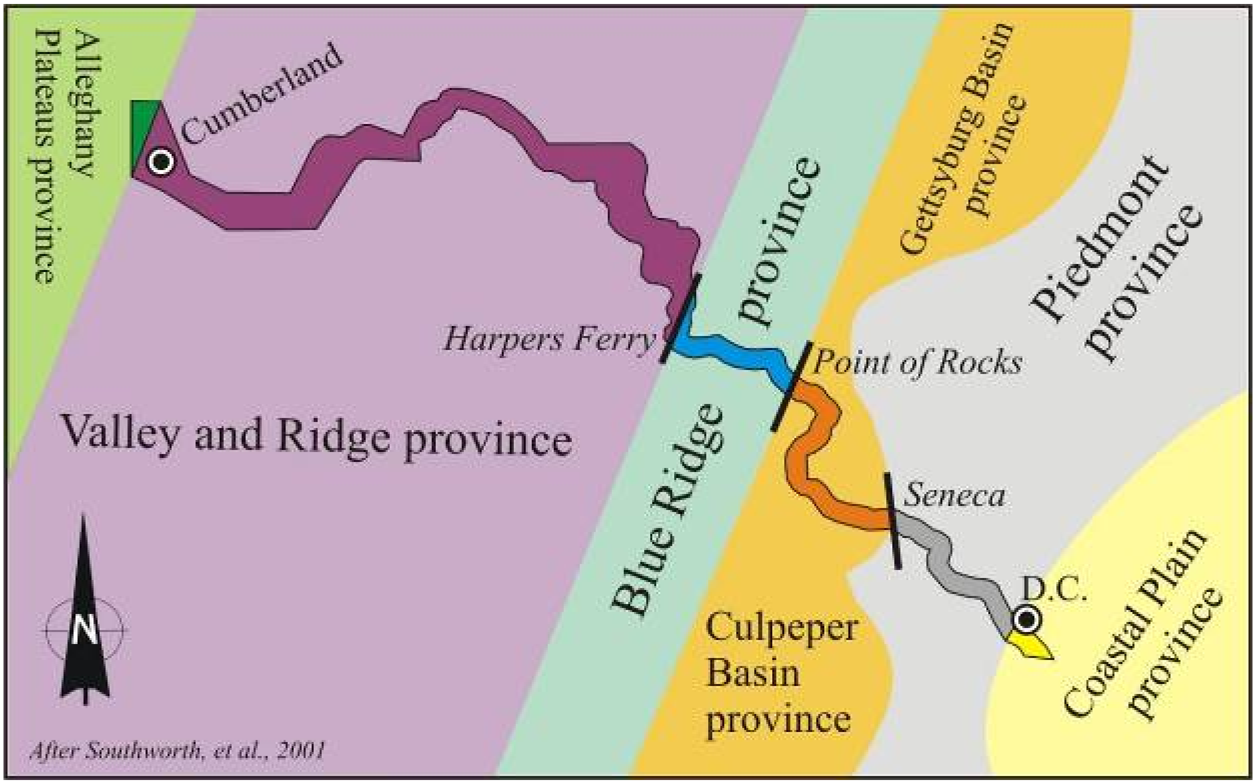

Figure I.1 Physiographic provinces along the C&O Canal.

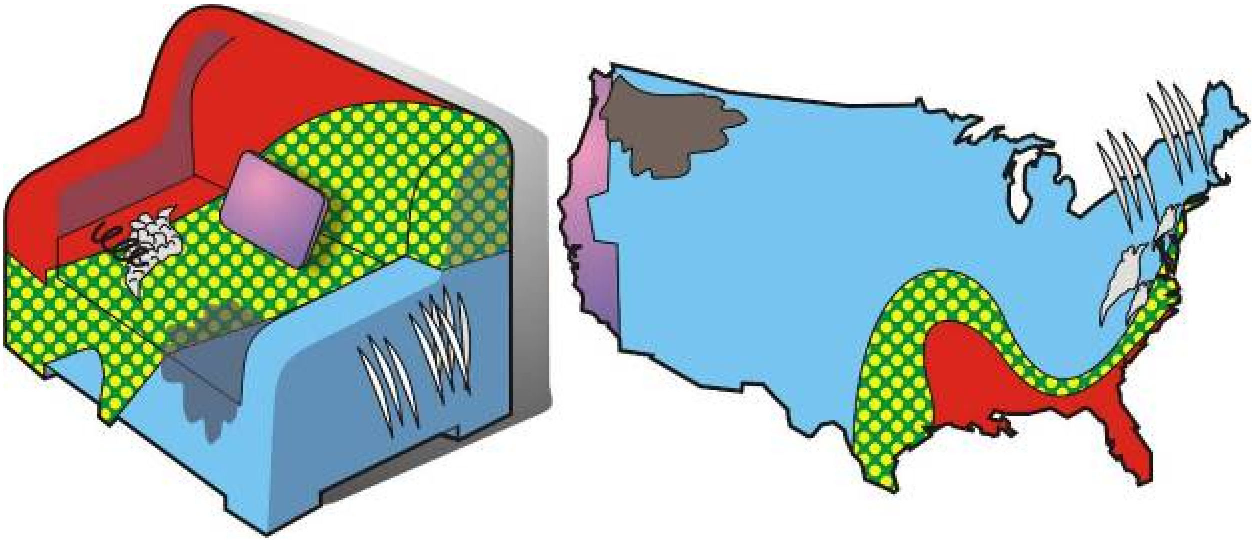

Figure I.2 An old sofa as an analogy for the North American continent: ripped, scuffed, stained, and draped in slipcovers and pillows, the sofa reminds us that continents change over time: they get torn by rifting, scratched by glaciation, and new material gets added in the form of terranes, lava flows, and sedimentary strata.

Chapter 3

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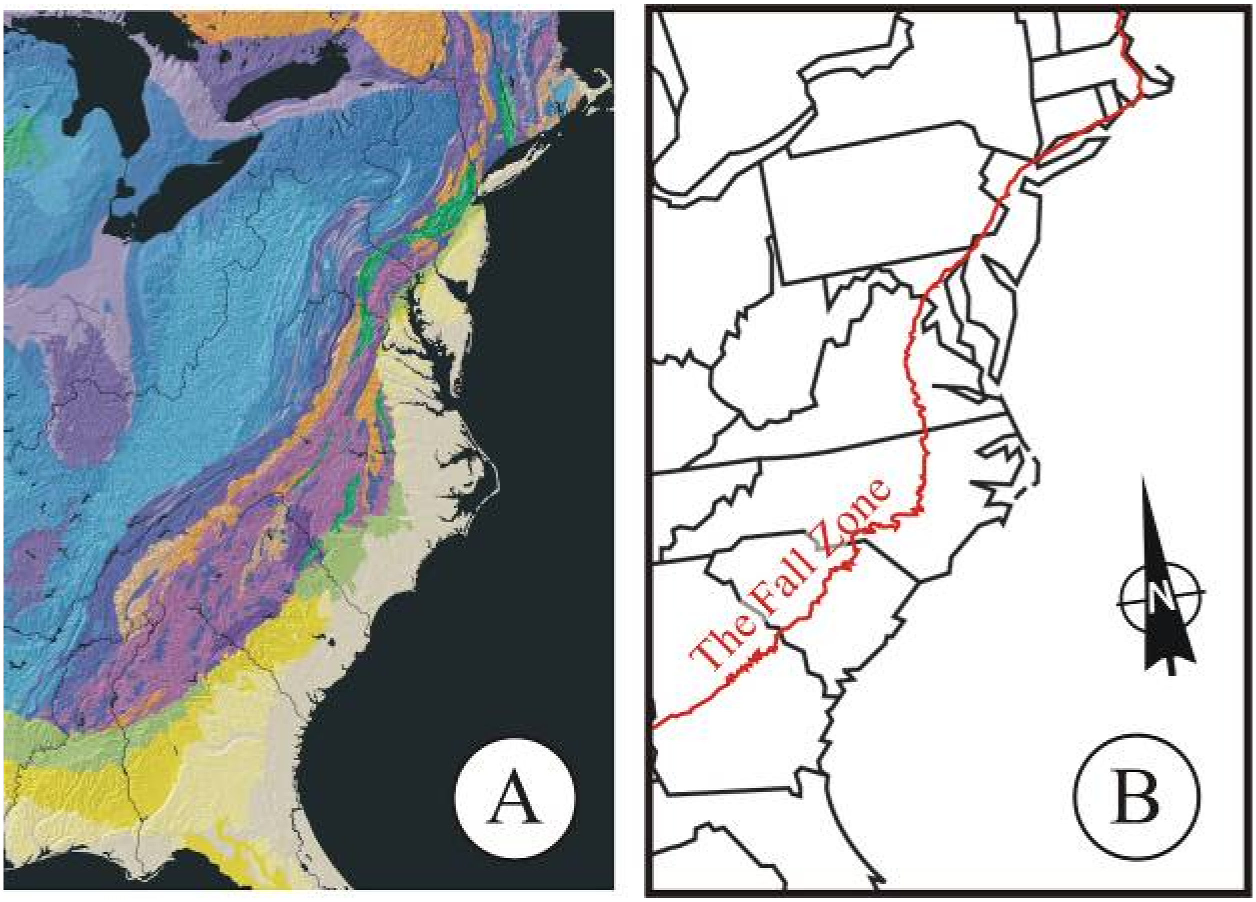

Figure 3.1 The Fall Zone. (A) The east coast of the United States as shown in an image from the USGS's beautiful "Tapestry of Time and Terrain," a continent-sized combination map that shows both topographic relief and the age of geologic formations. Note that the darker colors (older rocks) are fringed with several layers of younger rocks (light green, yellow, and grey) from Cape Cod down through the centers of the Carolinas and Georgia, and wrapping around to become the lower reaches of the Mississippi Valley. (B) The same area, with the boundary shown in red between the harder underlying rocks and the softer overlying rocks of the Coastal Plain.

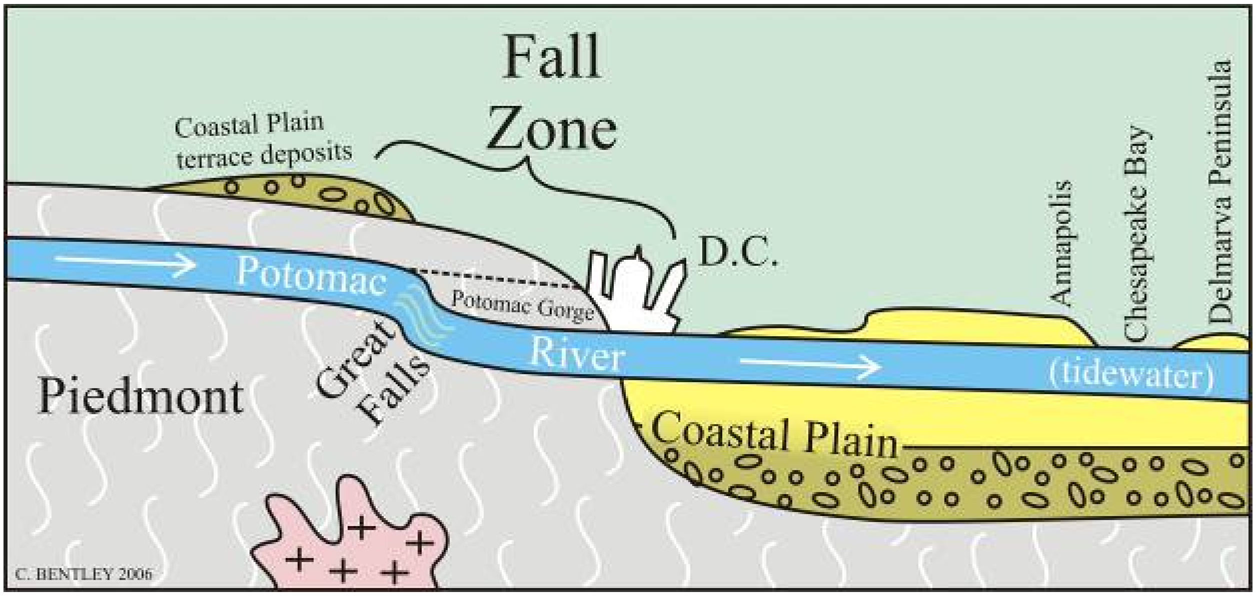

Figure 3.2 The Fall Zone in cross-section, showing the incision of the Potomac Gorge, which extends from Washington, DC, upstream to Great Falls. Terrace deposits of gravel high above the modern river are related to similar deposits at the base of the Coastal Plain sequence of strata.

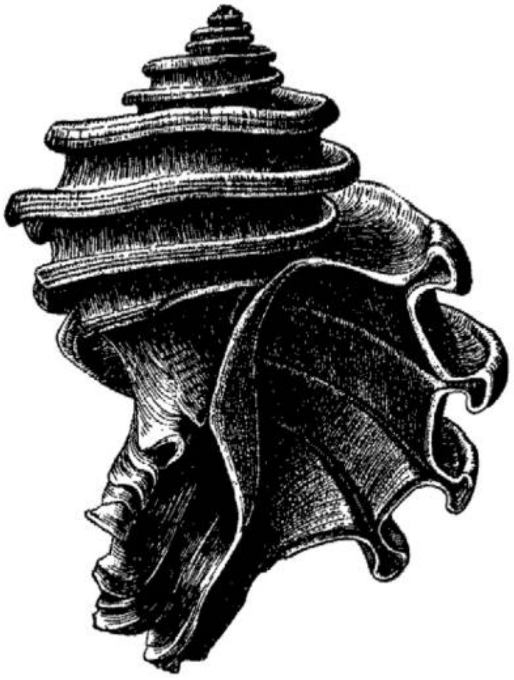

Figure 3.3 *Ecphora gardnerae*, state fossil shell of Maryland. A snail with a corrugated shell (the four ribs impart extra strength), *Ecphora* is found in Miocene-age Coastal Plain deposits along the Atlantic Coast. It is about two inches long. *Modified from Plate 25, Volkes, Glaser and Conkright, 2000.*

Figure 3.4 *Chesapecten jeffersonius,* the state fossil of Virginia. A large scallop from Pliocene (~4 million year old) Coastal Plain sediments, *Chesapecten* has the distinction of being the very first fossil described from the New World. It is about 4 inches wide.

Figure 3.5 River cobbles… on a hill top. These terrace deposits of well-rounded pebbles, gravel, and cobbles occupy the peaks of many of the highest hills in the Potomac Piedmont. They are interpreted as being deposited by the ancestral Potomac River at a time when sea level was higher, and the river meandered back and forth across a flat landscape. Later, when sea level dropped, the river cut into the bedrock below, and abandoned its gravels on higher, inaccessible ground. Photo from Prince William Forest Park. *Keys for scale.*

Figure 3.6 Rounded boulders of sandstone on top of Glade Hill, Great Falls Park, Virginia. Rounding of clasts is an indication of how far they have been transported, and so these must have come from a respectable distance, 20 miles or more. The type of rock backs up this interpretation as well: sedimentary rocks like these are found far upstream in the Valley and Ridge Province, and only the strength of a Potomac-sized river could have toted them down to the Piedmont. The large size of these (and thousands of other) boulders indicate they were deposited by very strong water currents, and so the *top* of Glade Hill is interpreted as being the *bottom* of the ancestral Potomac River, long since abandoned as the river has incised into the metamorphic Piedmont rocks below. *Pen for scale.*

Figure 3.7 *Skolithos* trace fossils in a cobble of the Antietam sandstone. The soda-straw shaped tubes in this cobble were originally dug in loose sand by worms on a Cambrian beach. The original orientation of the tubes would have been vertical, poking down into the sand. The sand was fused into sandstone, and eventually a piece of that sandstone was broken off and carried downstream by the ancestral Potomac River, which rounded the cobble as it transported it. *Length of cobble is about six inches.*

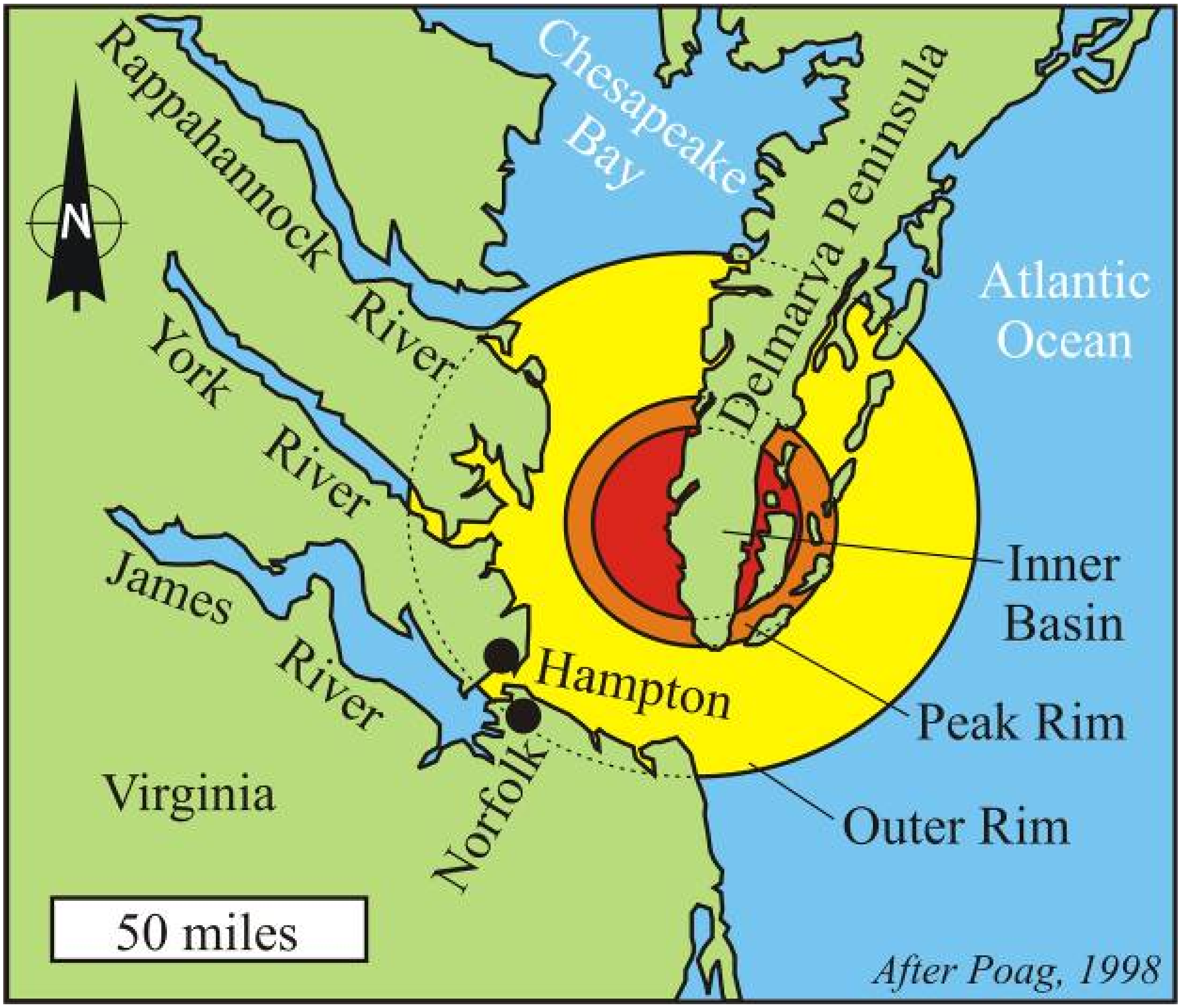

Figure 3.8 Location map of the Chesapeake Bay impact crater, at the tip of the Delmarva Peninsula and the mouth of the Chesapeake Bay. Buried under the subsequent 35 million years' worth of muddy sediments, the crater is invisible to human eyes today, but can be detected through a number of geologic techniques. It has an inner basin, punched into the underlying bedrock, and an outer rim, showing where blocks of loose sediment slid downward and inward, partially filling the bedrock crater at the same time they expanded the diameter of the crater in the pre-35-million-year-old Coastal Plain sediments.

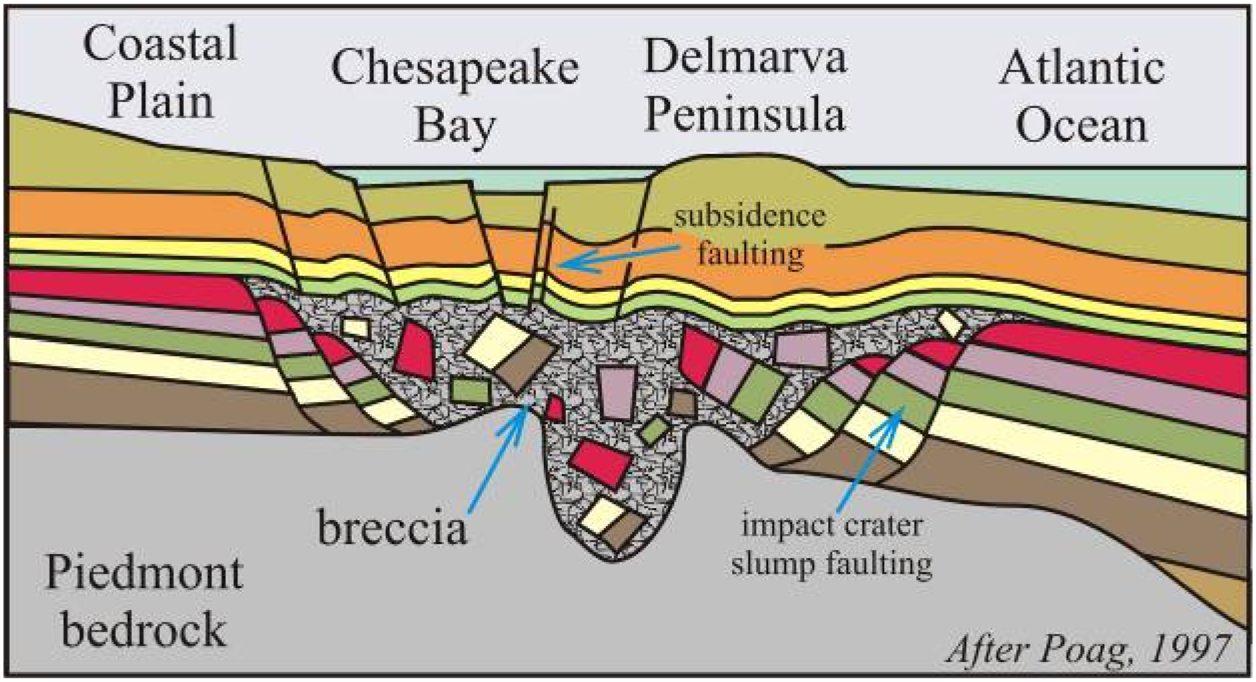

Figure 3.9 Cross section of the Chesapeake Bay impact crater, showing the disruption of sedimentary layers that pre-existed the impact (lower five layers), the penetration of the meteorite (or comet) through those layers and into the Piedmont bedrock beneath, the infill of the crater with a jumble of large and small blocks of debris (impact breccia), slumping of adjacent sedimentary layers into the hole, thereby widening the crater into adjacent Coastal Plain strata, and then later deposition over top of the whole mess (upper four layers). Later compaction of the breccia has caused the layers above to subside, causing some faulting.

Chapter 4

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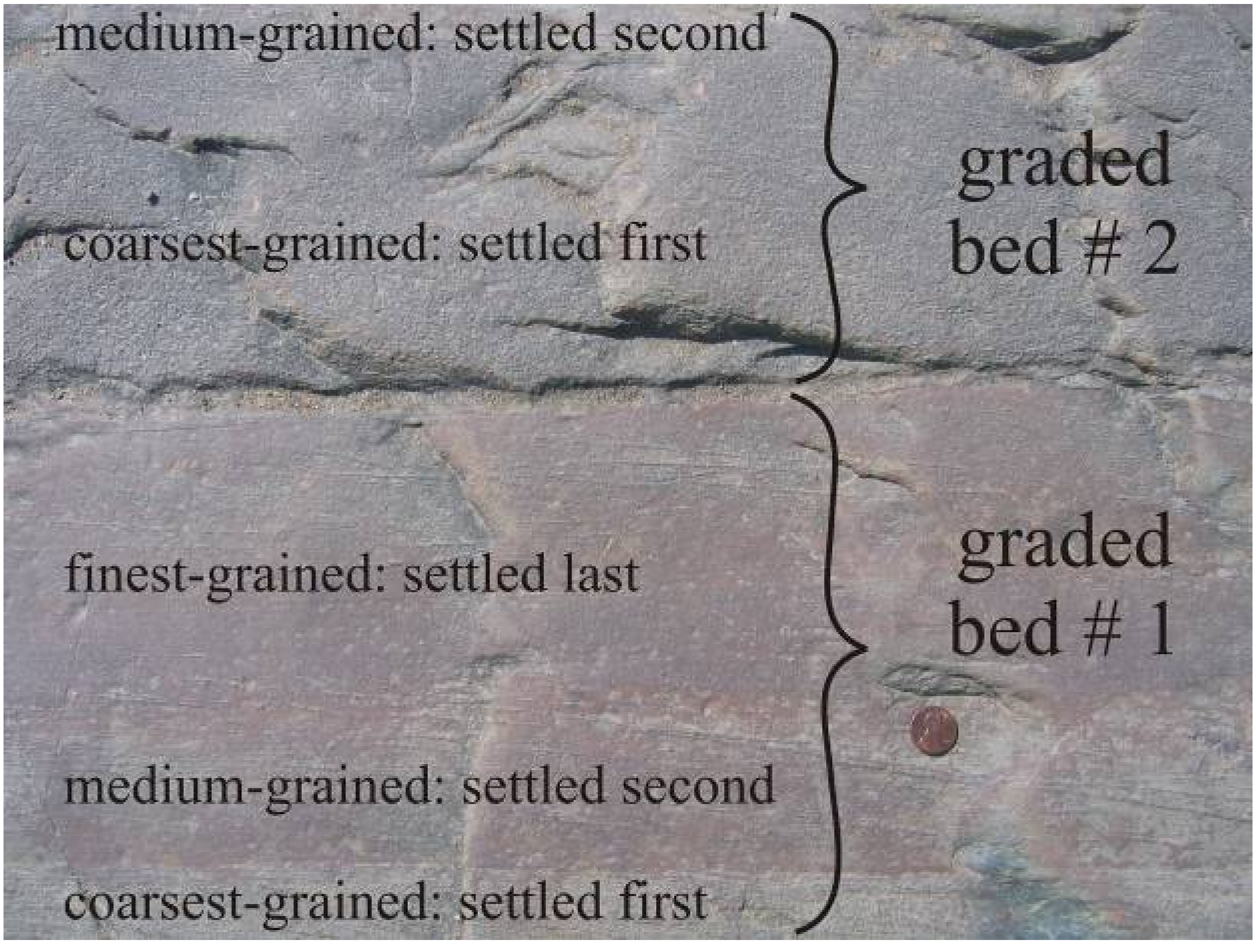

Figure 4.1 Graded bedding in the Mather Gorge Formation, exposed at Great Falls overlooks on the Virginia side of the river, at Great Falls Park. The graded beds are interpreted to be turbidite deposits. Recall how these graded beds form (Figure 2.5): with the heaviest grains settling out first, followed by progressively smaller and smaller particles. *Penny for scale.*

Figure 4.2 A folded stack of meta-greywacke layers in Mather Gorge, along the Billy Goat Trail. Palimpsest exposures like this tell us of two geologic events: the initial deposition of the greywacke in graded beds (distinguishable near the fold's "elbow"), and later folding of those layers into a bent configuration. *Penny for scale.*

Figure 4.3 The variety of clastic inclusions in the meta-greywacke along the Potomac Gorge. Fine, grey-colored sand and mud (since metamorphosed) include larger clasts that range from pebble to boulder in size. They come in a variety of compositions, ranging from almost entirely mafic (dark clasts) to 100% quartz (whitest clasts). Others, like the large chunk in the lower right, appear to be cobbles of gneiss and granite, with distinct textures that differ from the surrounding rock. *Hand-lens for scale.*

Figure 4.4 Amphibolite, an ultramafic rock made from the mineral amphibole. This specimen is a nice, clean exposure along the Billy Goat Trail. *Penny for scale.*

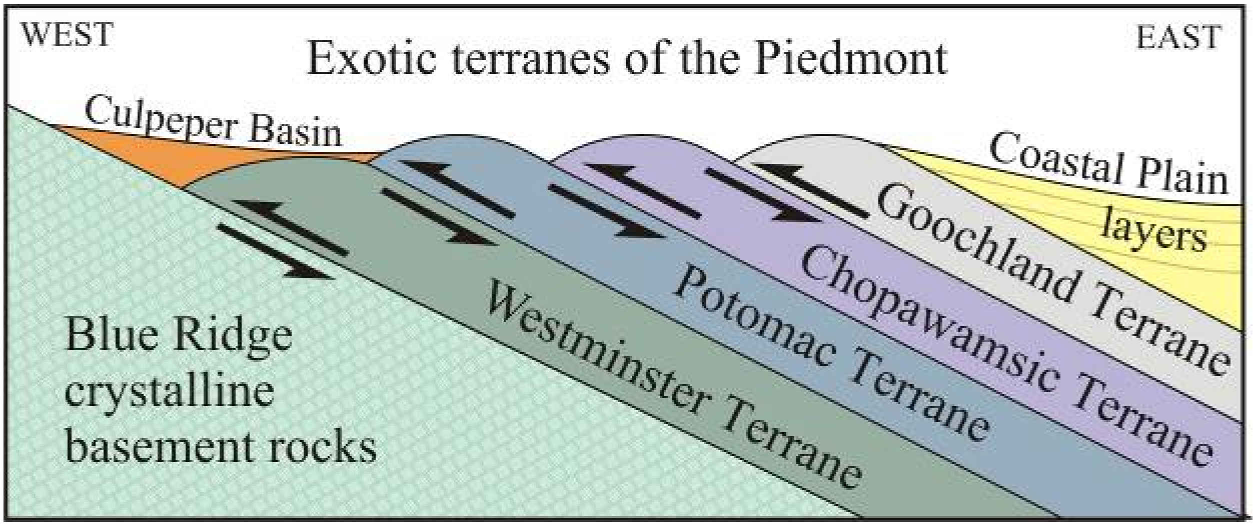

Figure 4.5 Exotic terranes of the Virginia Piedmont. Though not all of these package of rock are exposed along the C&O Canal, elsewhere in the Piedmont this “shingled” overlapping relationship has been determined. The Westminster Terrane is rocks that were in the Iapetus Ocean immediately adjacent to ancestral North America; The Potomac Terrane is turbidite deposits from further offshore. The Chopawamsic Terrane is a volcanic island chain that used to be in the Iapetus Ocean; the Goochland Terrane is a chunk of pre-Iapetus continental crust which was rifted away from North America, stranded for a while out in the ocean, and later re-attached when the ocean was closed during the three orogenies of Appalachian mountain-building. Along the C&O Canal, only the Potomac Terrane is well exposed.

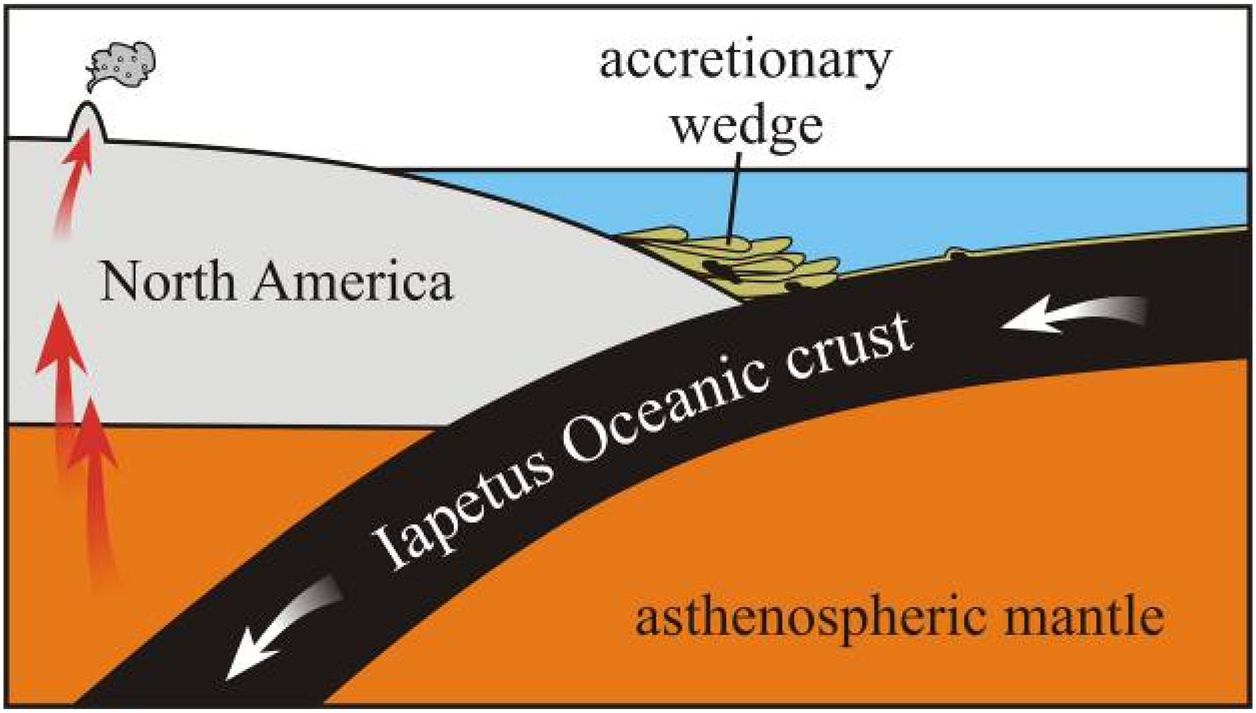

Figure 4.6 When oceanic crust is subducted beneath a continent, the leading edge of the continent acts as a bulldozer, scraping off the sediments that have accumulated on the ocean floor, plus any stray knobs or protuberances of basalt. This pile of scrapings is known as an accretionary wedge.

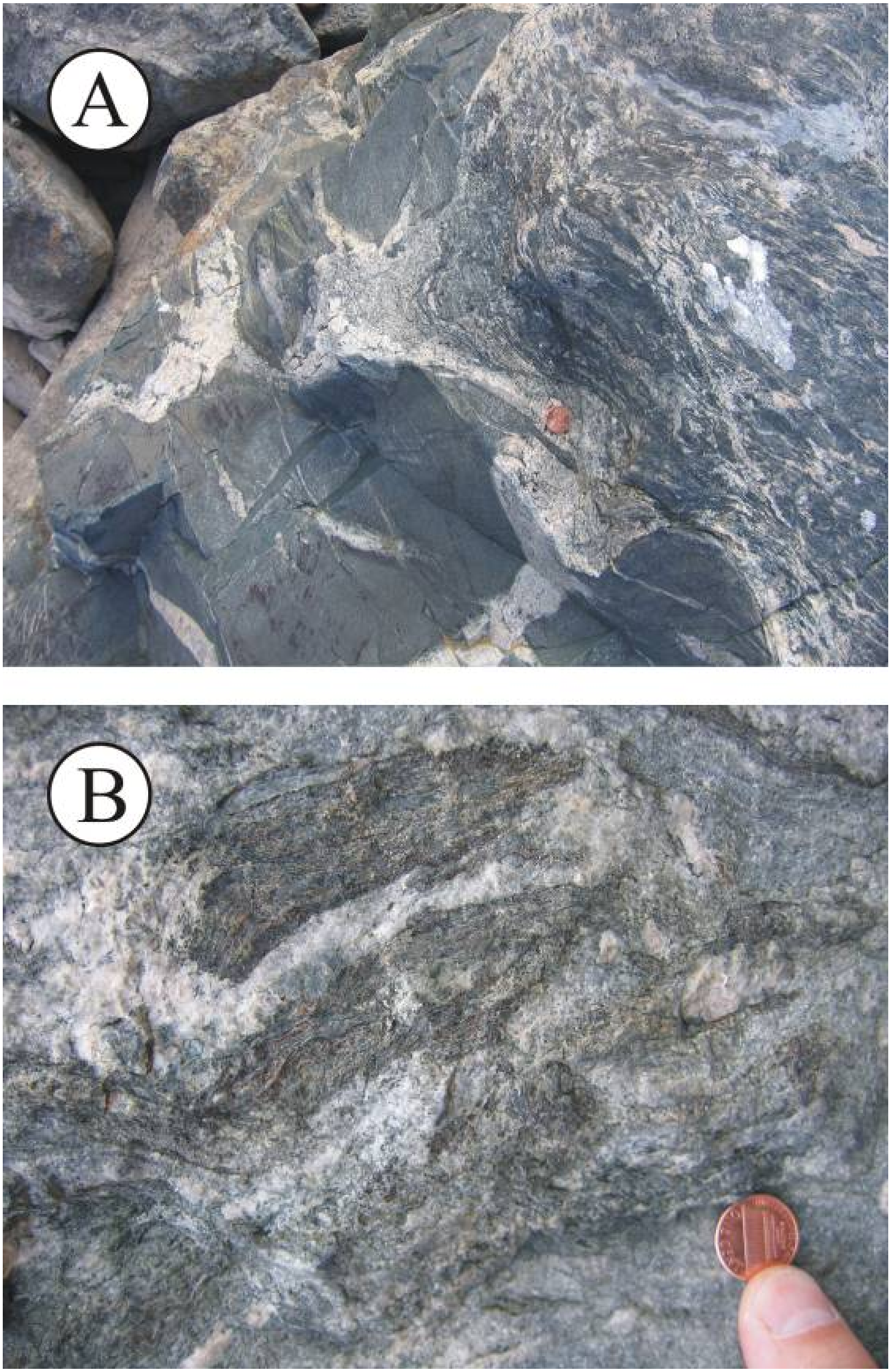

Figure 4.7 Migmatite, a rock that preserves evidence of partial melting. (A) When greywacke is heated up to high levels (probably about 700º C), the minerals which have low melting points turn to liquid: quartz, potassium feldspar, and muscovite mica melt. However, it's not hot enough to melt minerals with high melting points (amphibole, biotite mica, calcium plagioclase feldspar). Those minerals remain solid as the dark strands you see in (B). *Penny for scale.*

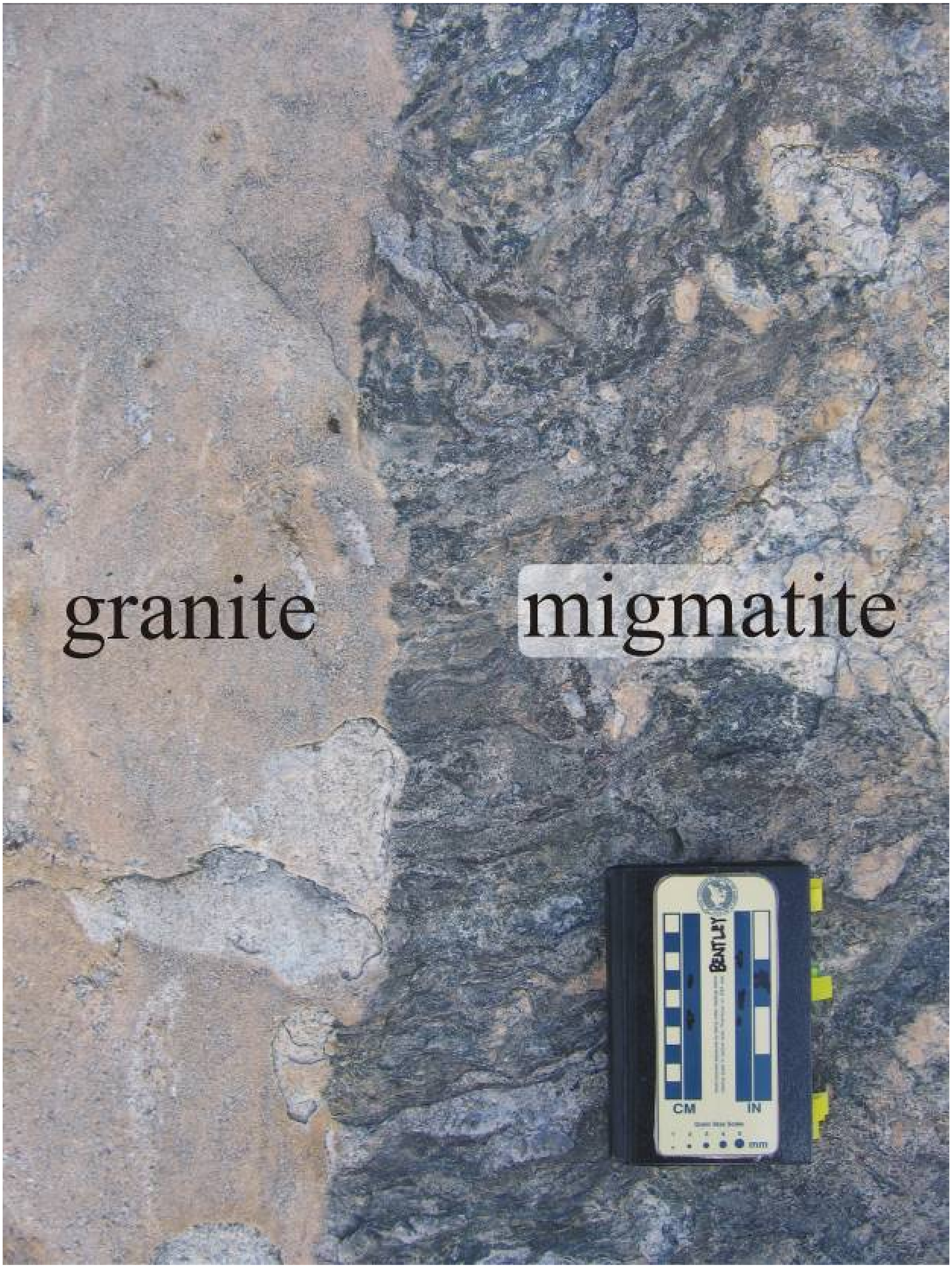

Figure 4.8 Like an butterfly emerging from its cocoon, a dike of mobilized, relatively pure granite cuts across its source rock, the migmatite.

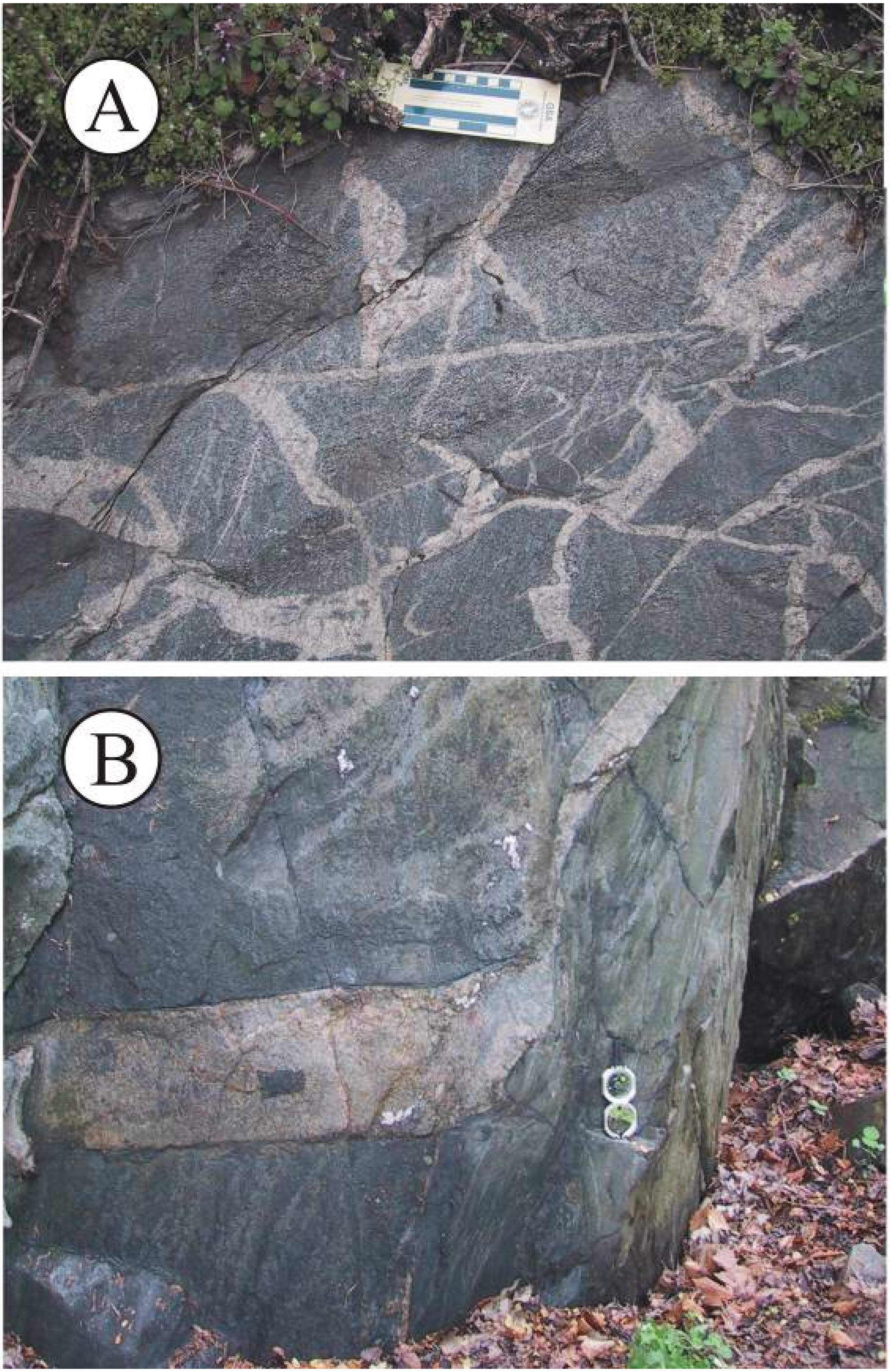

Figure 4.9 Rocks of the Georgetown Intrusive Suite. (A) Gabbro, an early intrusive, is fractured and intruded by lighter-colored granite. Rock Creek Parkway. (B) Dike of granite (with rectangular dark xenolith) cuts across older gabbro. The granite dike was later boudinaged – stretched into a thinner, sausage-shaped link. *Brunton compass for scale.*

Figure 4.10 Flow in metamorphic rocks. The distinctive wavy texture in this metamorphic rock shows ductile flow in heavily-metamorphosed meta-greywacke. It has been smeared out like hot wax. *Field of view is about one foot wide.*

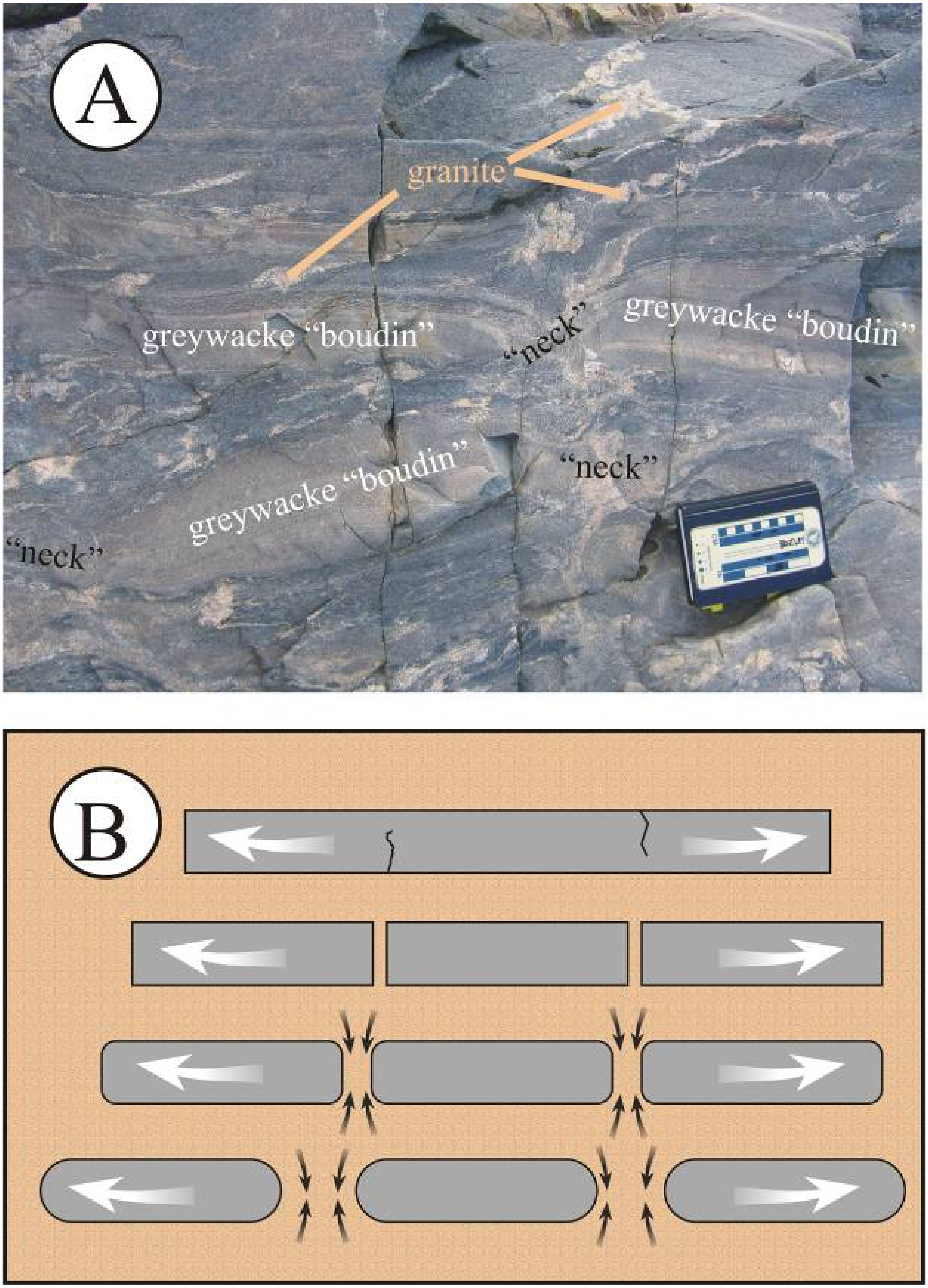

Figure 4.11 Boudinage. When relatively stiff layers are stretched in a matrix of mushier stuff, the stiff layer breaks into segments and the mushy stuff flows into to fill the gaps. The end result is a feature that looks like a string of hot dogs (hence the term *boudin*, French for sausage). In this case, greywacke has become stretched and broken into pods, and migmatite granite has flowed into the “necks” between segments.

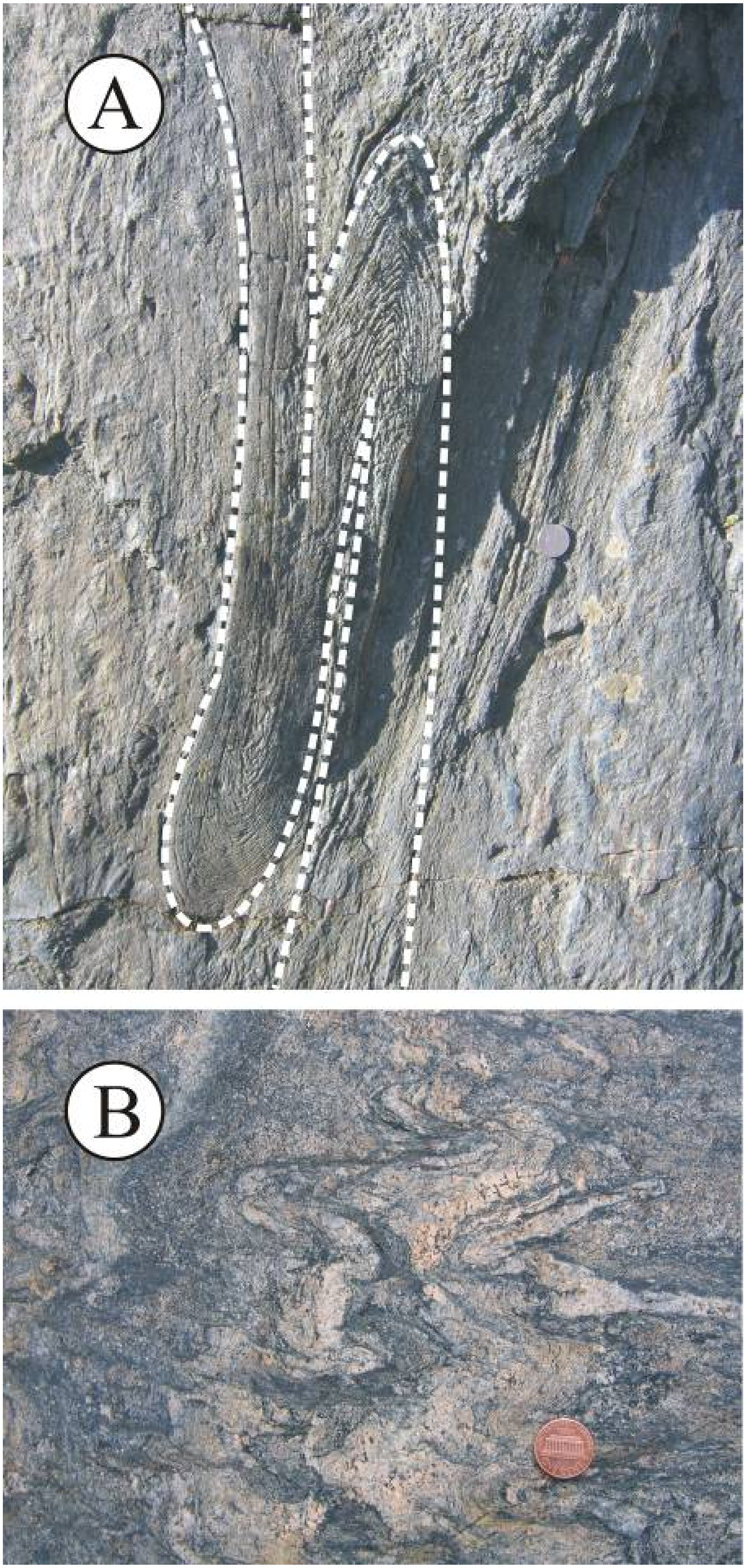

Figure 4.12 Folding in Piedmont rocks. (A) a very tight fold in meta-greywacke of the Mather Gorge Formation, along the downstream entrance to the Billy Goat Trail. *Dime for scale.* (B) Smaller-scale folds in migmatite, along the Billy Goat Trail. *Penny for scale.*

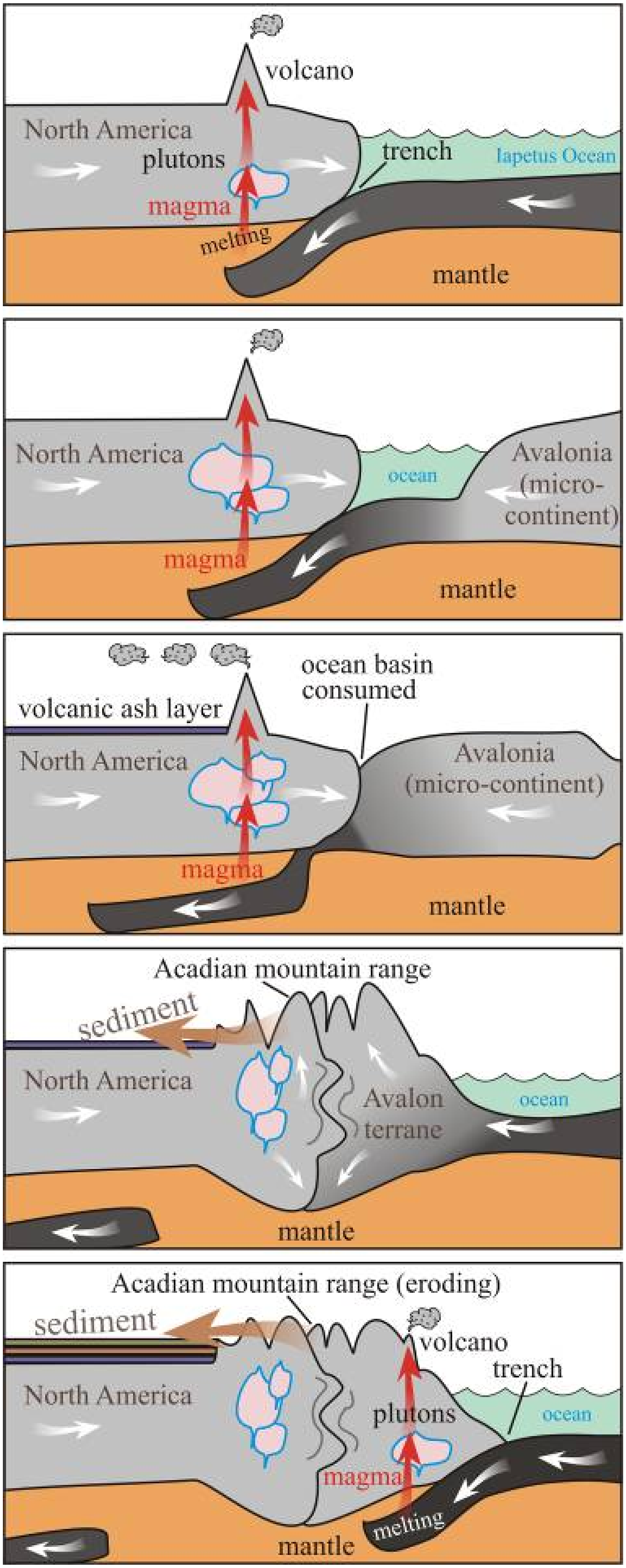

Figure 4.13 The Acadian Orogeny. After the docking of a chain of volcanic islands in the Taconian Orogeny 460 million years ago, subduction of the basaltic crust of the Iapetus Ocean resumed. This subduction closed the Iapetus Ocean until it brought a micro-continent called Avalonia directly to North America's shore about 360 million years ago. The two collided, raising up the Acadian Mountains range. While the Acadians were weathered away, subduction resumed further to the east, closing the final segment of the Iapetus Ocean.

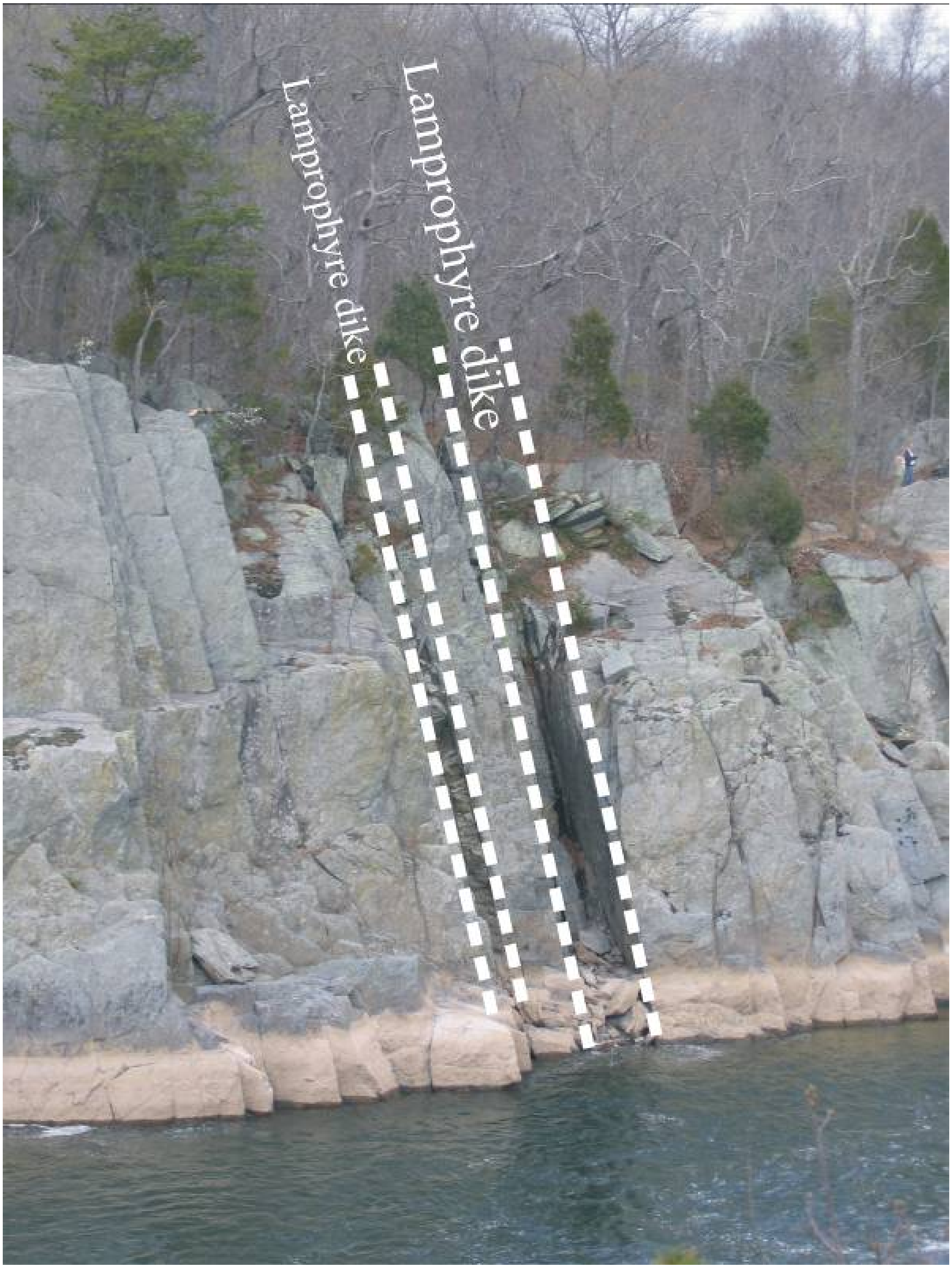

Figure 4.14 Lamprohyre dikes along Mather Gorge. These dikes are straight and unfolded, unlike older dikes which experienced deformation during the Taconian Orogeny. This lack of deformation, plus the isotopic age (360 million years old) indicate these dikes are part of the Acadian Orogeny.

Figure 4.15 Cretaceous river gravels exposed on a hilltop in Washington, DC. The round shape of the cobbles indicates they have been transported a long distance. Their Cretaceous age indicates a huge amount of missing time between them and the rocks they sit on: the Precambrian meta-greywacke.

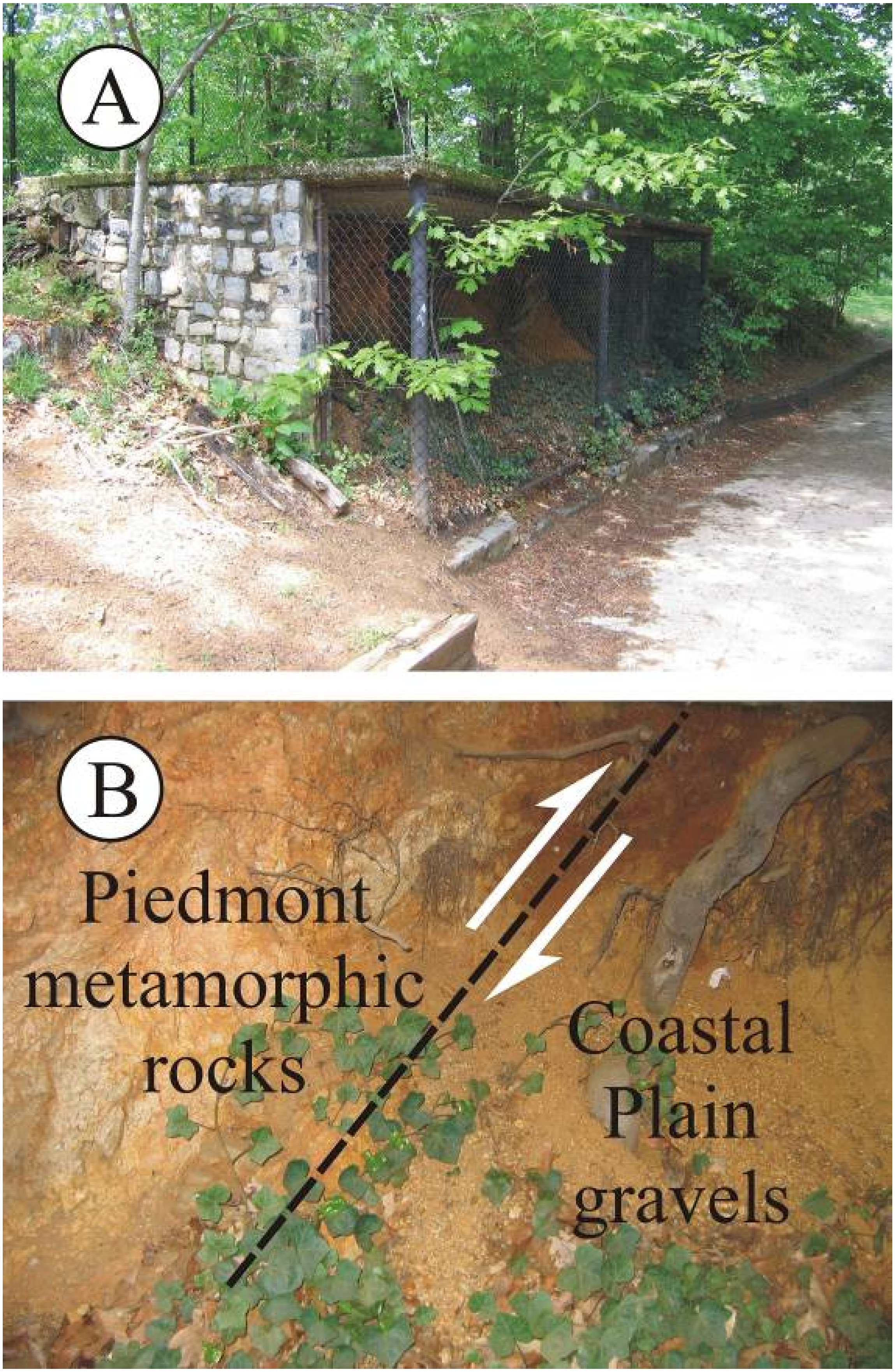

Figure 4.16 Thrust fault display in Adams-Morgan, at the intersection of Adams Mill Road and Clydesdale Place. (A) The cage-like structure is very distinctive. (B) Inside, you can clearly see meta-greywacke of the Piedmont shoved up over much younger river gravels.

Chapter 5

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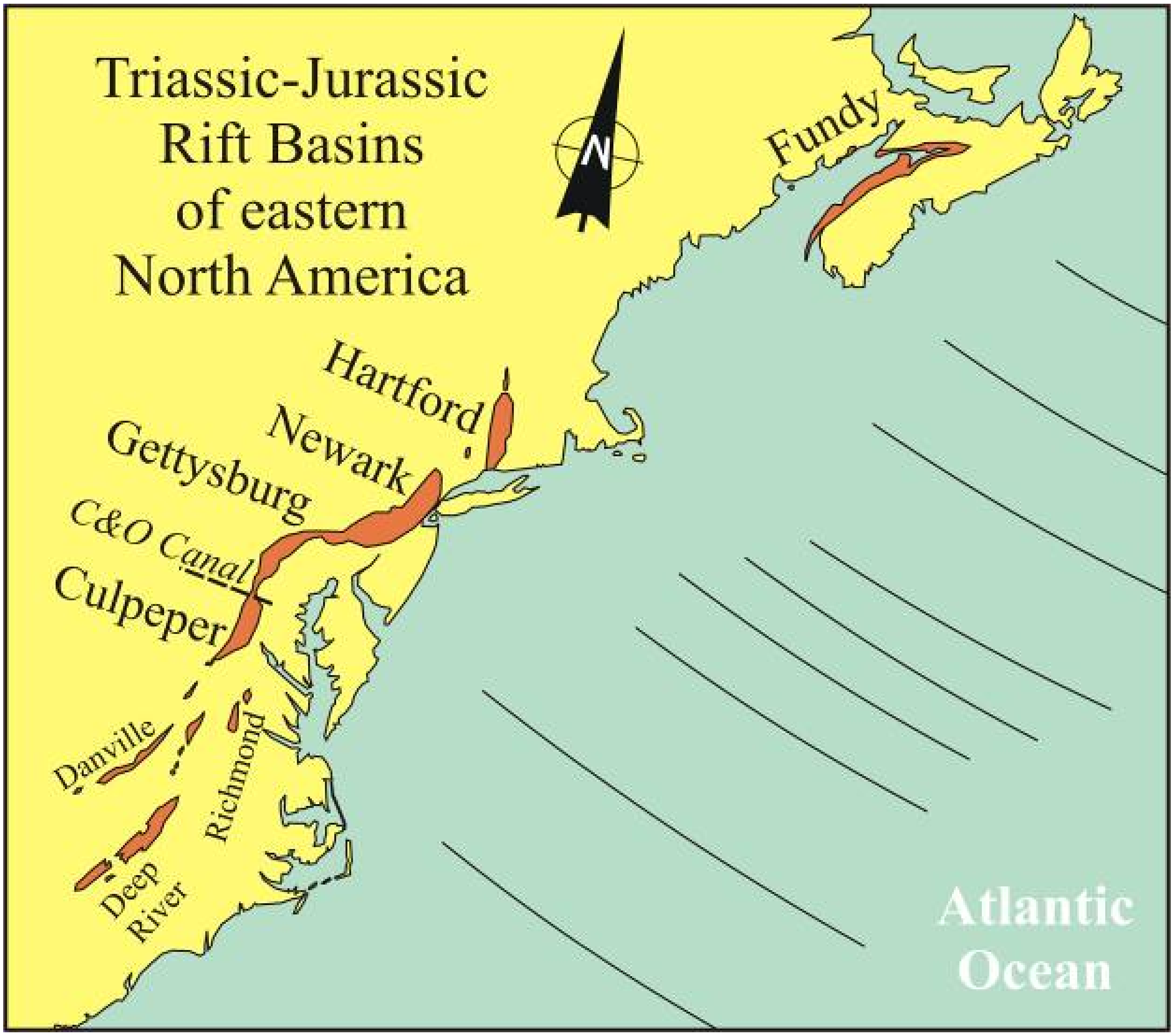

Figure 5.1 The Triassic rift basins of eastern North America. Collectively dubbed the "Newark Group" for the large basin exposed at Newark, New Jersey, these basins are the Triassic equivalent of the modern Basin and Range Province (Figure 5.3). These basins opened up as Pangea began tearing apart during the Triassic, and they continued to fill during the Jurassic, when another series of rifts, further offshore, ended up linking together and tearing the supercontinent open completely, creating the Atlantic Ocean. Lines in the Atlantic show major transform fractures, oriented about 90º (perpendicular) to the linear rifts. The C&O Canal crosses only one of these rift valleys, the Culpeper Basin.

Figure 5.2 Arkose, an immature sandstone that accumulates in continental rift basins. Characterized by large, angular feldspar grains, arkose shows us sediments which have not traveled a very long distance from their source are to their depositional area.

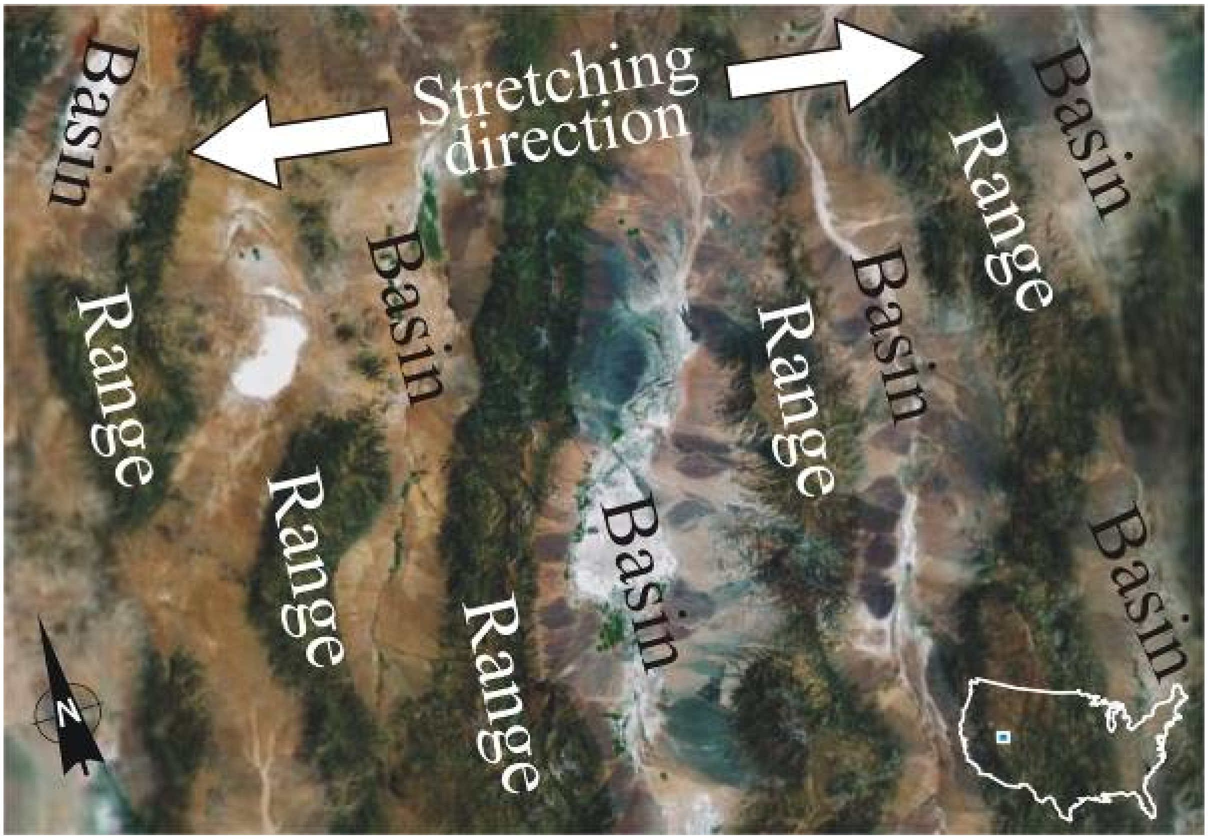

Figure 5.3 The Basin and Range Province of Nevada, showing how crustal extension in an east-west direction creates a faulted landscape of north-south-trending mountain ranges separated by down-dropped basins. *Modified from a Google Earth image.*

Figure 5.4 Seneca Quarry, built of the same red sandstone that was quarried here for 124 years. The red color of the sandstone indicates that it was deposited under well-oxygenated conditions. This was the source of the stone used in many locks along the C&O Canal, as well as the Smithsonian Castle and many “brownstones” in Washington, DC. Note in photograph (C) the dangers of exploring this area: the natural forces of weathering and erosion are reducing the old quarry facility back into the sediment that it once was.

Figure 5.5 Mud cracks in a finer-grained layer within the Seneca Sandstone, indicating it was exposed to the air for a period of time, letting the mud dry out and crack.

Figure 5.6 Raindrop impressions in the Seneca Sandstone. When raindrops impact damp sediment, they create a miniature crater, which can be preserved in the resulting rock. These bumps bulge out of the face of the rock at us, which indicates we are look at *casts* of the original divots: it other words, we are looking at the bottom of a later deposit of sediment which filled in those raindrop impressions, which is why the bulge out from, rather than sink into, the rock face.

Figure 5.7 Aquatic snail leaving a trace of its passage through the river-bottom silt. Little trails like these are frequently preserved in the fossil record, showing us a glimpse of an animal's activity during its life. Snail is about half an inch long; *reflection of camera on the water surface provides a sense of scale*.

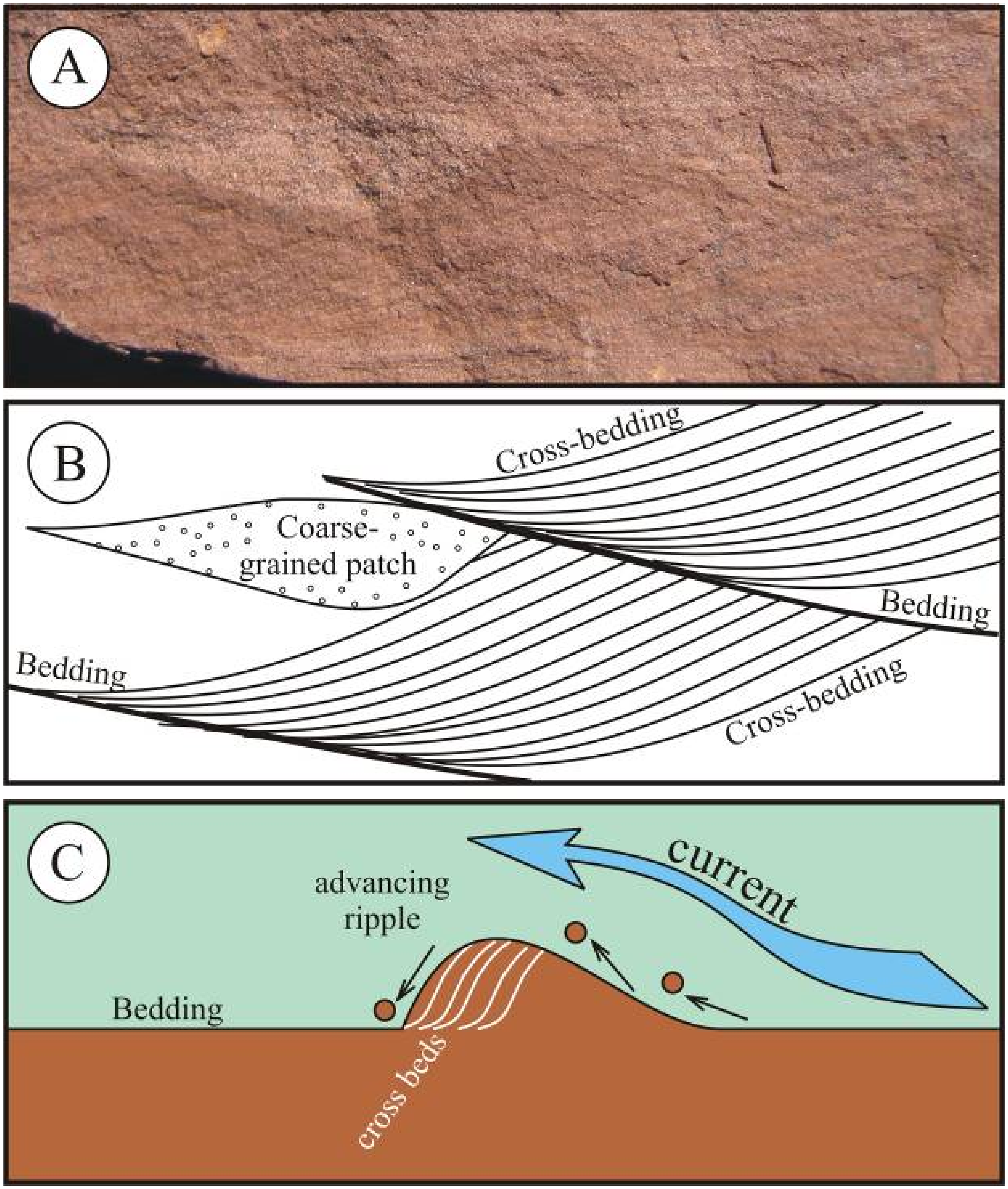

Figure 5.9 Cross-bedding in the Bull Run sandstone. Cross-beds can tell us the direction a current was moving, since they pile up on the downstream side of migrating ripples.

Figure 5.8 Dinosaur footprints in the Culpeper Basin. These three-toed footprints, of a shape called *Grallator*, are reasonably common in the sediments of the Triassic rift basin. Photograph courtesy of Ken Rasmussen. *Pen for scale.*

Figure 5.10 The Leesburg Conglomerate, a sedimentary deposit of rounded limestone cobbles. It is found along the western edge of the Culpeper Basin, closest to source rocks in the Appalachian Mountains. This outcrop is on Route 15, two miles north of Leesburg, near the intersection with Whites Ferry Road. This rock was quarried for the “puddingstone” columns of Statuary Hall in the U.S. Capitol Building in Washington.

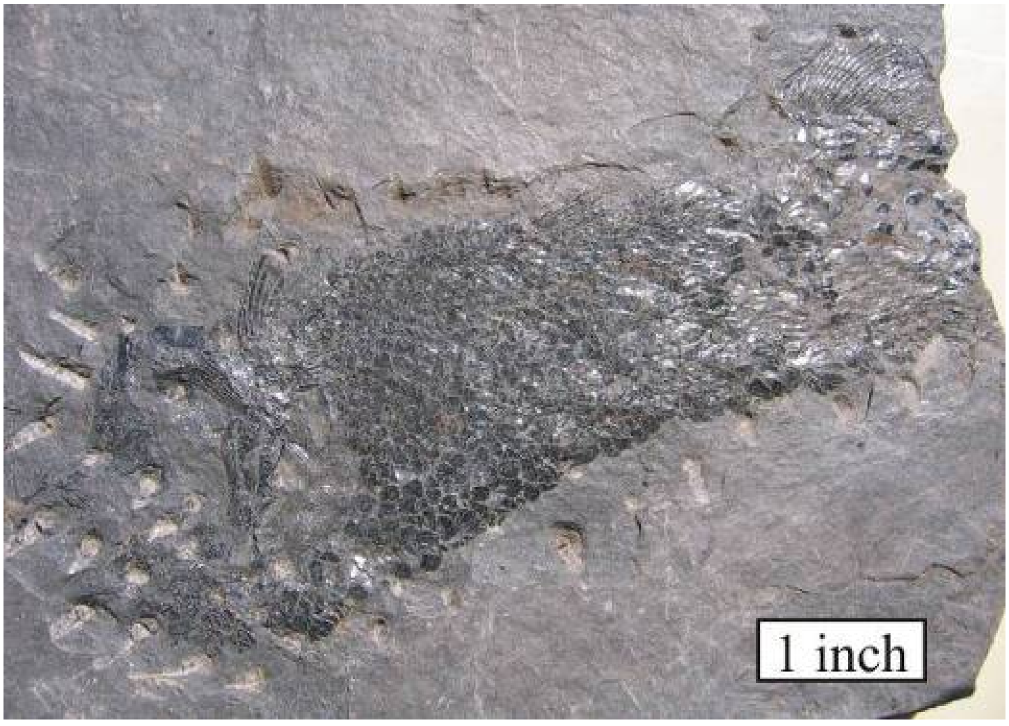

Figure 5.11 Fossil fish preserved in black shale from the Culpeper Basin. Though most of the Culpeper Basin’s sediments show us well-oxygenated environments of deposition, there were a few low-oxygen spots, perhaps deep lakes or swamps. This fish is preserved as a carbon film, the remnants of its body after volatile compounds were driven off by compression and heating. Fossil courtesy of Ken Rasmussen.

Figure 5.12 Modern rifting in the Afar Triangle region, northern Ethiopia. This northerly extension of the Great Rift Valley shows fresh basalt erupting at the surface, as well as a large influx of continental sediments from the adjacent highlands – both features associated with the Culpeper Basin during the Triassic and Jurassic. *Modified from a Google Earth image.*

Figure 5.13 Diabase, a shallow intrusive rock of mafic composition, very common in the Culpeper Basin as dikes of various shapes. Basalt, which is finer-grained, is also present in the Triassic rift valley, though less common. *Keys for scale.*

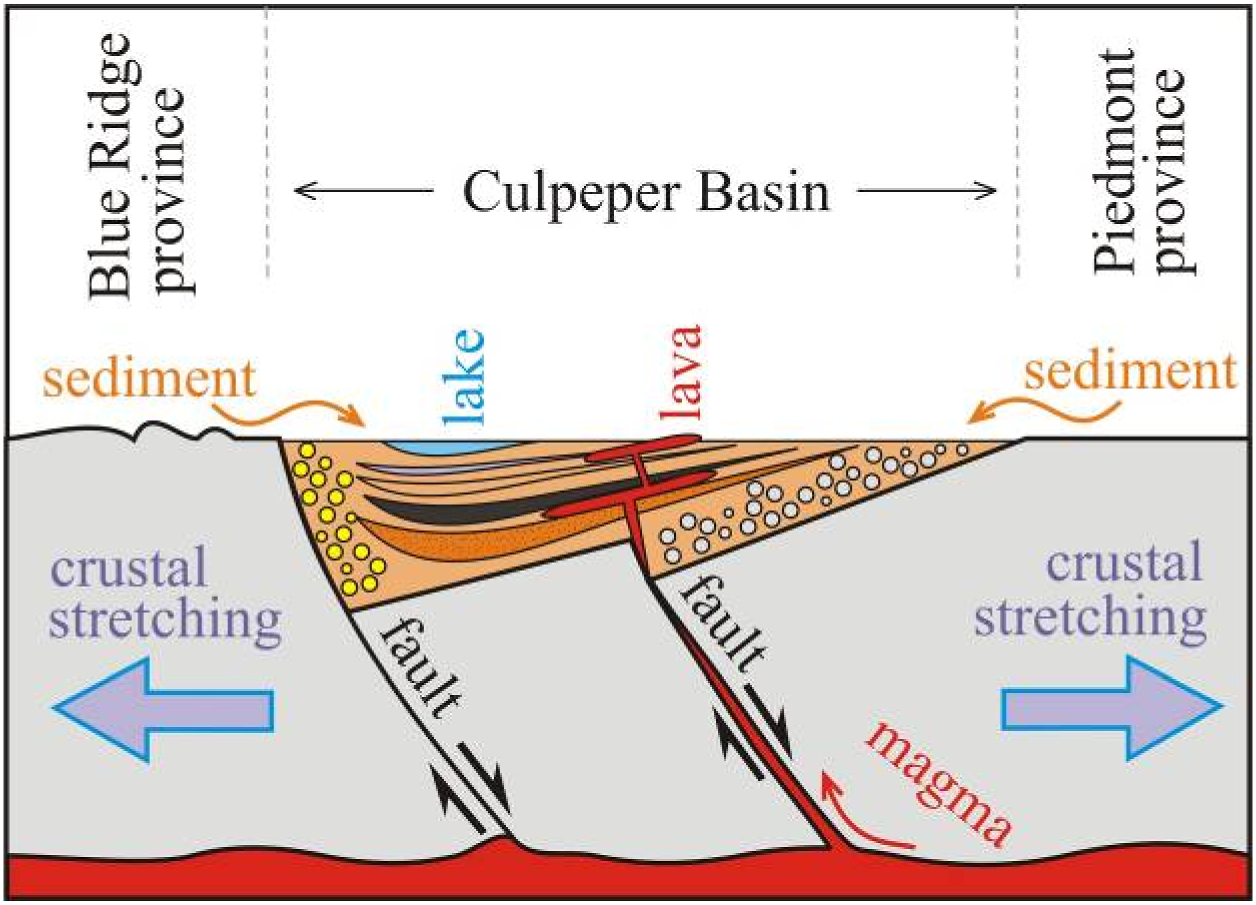

Figure 5.14 Schematic cross-section of the Culpeper Basin. Down-dropped blocks of Piedmont and Blue Ridge rocks accommodate crustal extension by sliding along faults. These faults also conduct magma upwards from decompression-induced partial melting of the mantle. The lava mixes with continental clastic sediments. The sediments are coarsest (conglomerates) on the eastern and western margins of the basin, while lakes in the center of the basin accumulated finer grain sediments like silts.

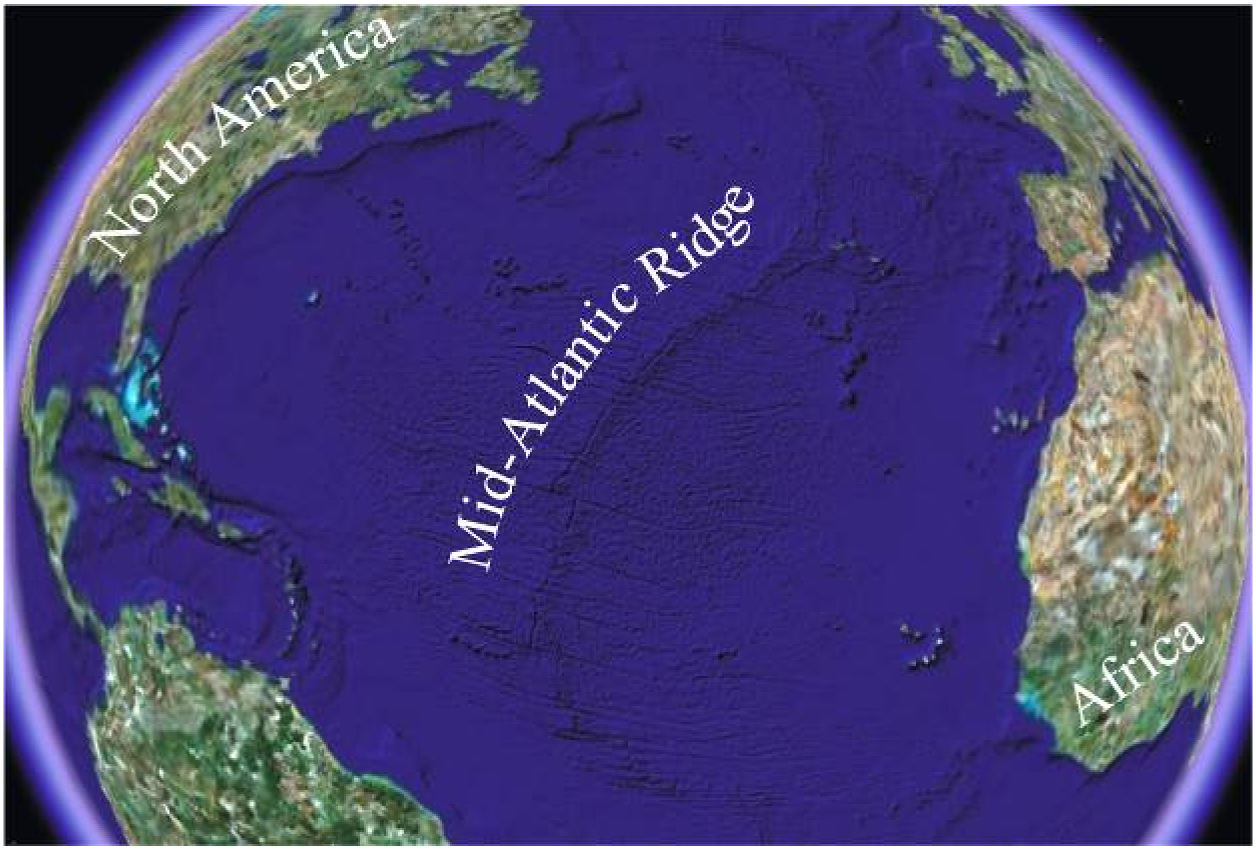

Figure 5.15 The Atlantic Ocean, born through the rifting of Pangea into the modern continents of North and South America, Eurasia, and Africa. Separated down the middle by the Mid-Atlantic Ridge, the Atlantic Ocean is oldest at the continental margins, where basalts date to shortly after the rifting of the Culpeper Basin. The Atlantic's linear shape parallels the linear trend of the Newark Group rift basins, emphasizing their common cause. *Modified from a Google Earth image.*

Chapter 6

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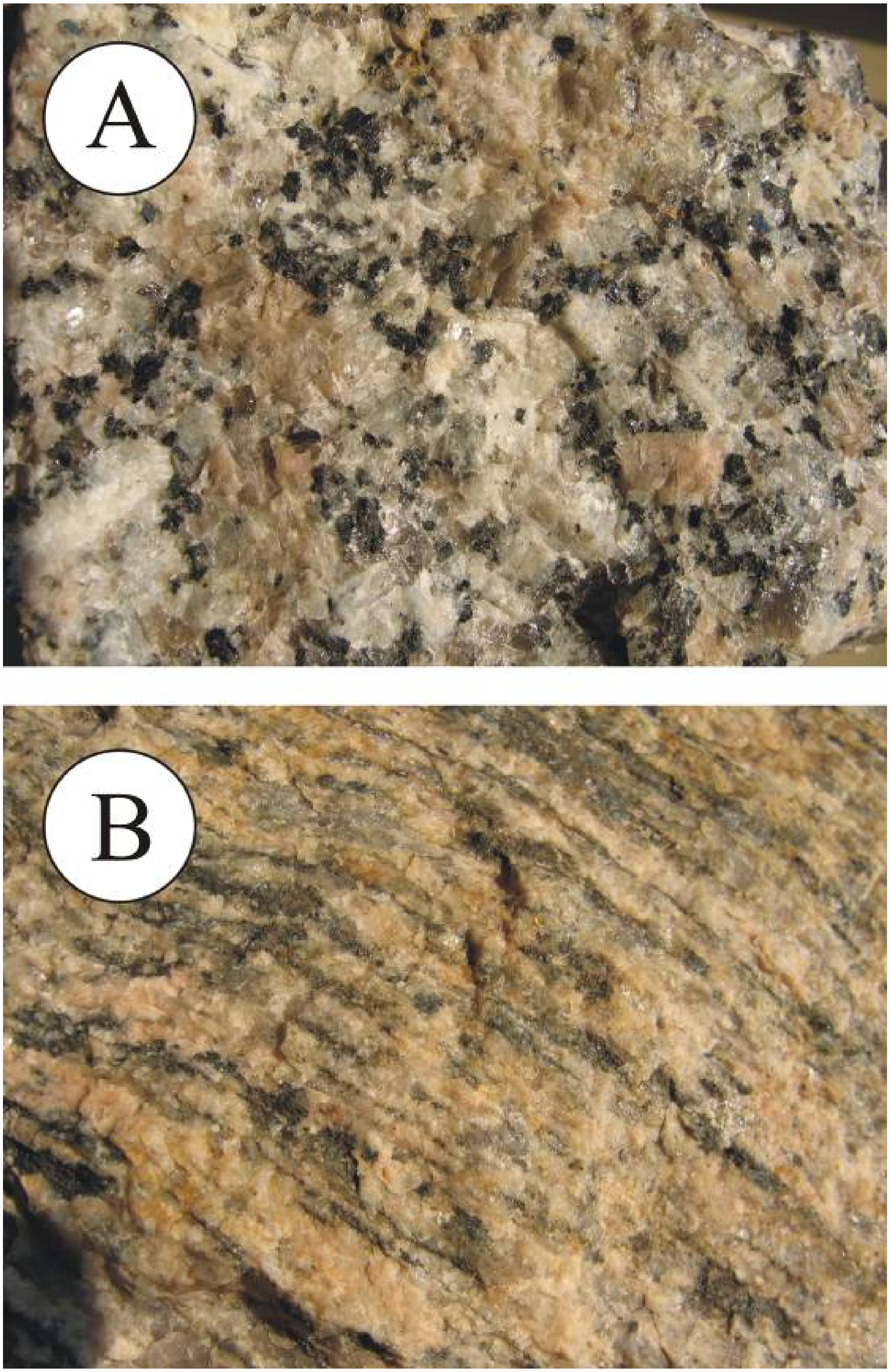

Figure 6.1 Granite versus granite gneiss. When granite first cools from magma, its mineral grains are randomly oriented. If it is deformed after it has cooled, it develops bands or “stringers” of minerals, qualifying it as a gneiss. *Field of view is about three inches wide.*

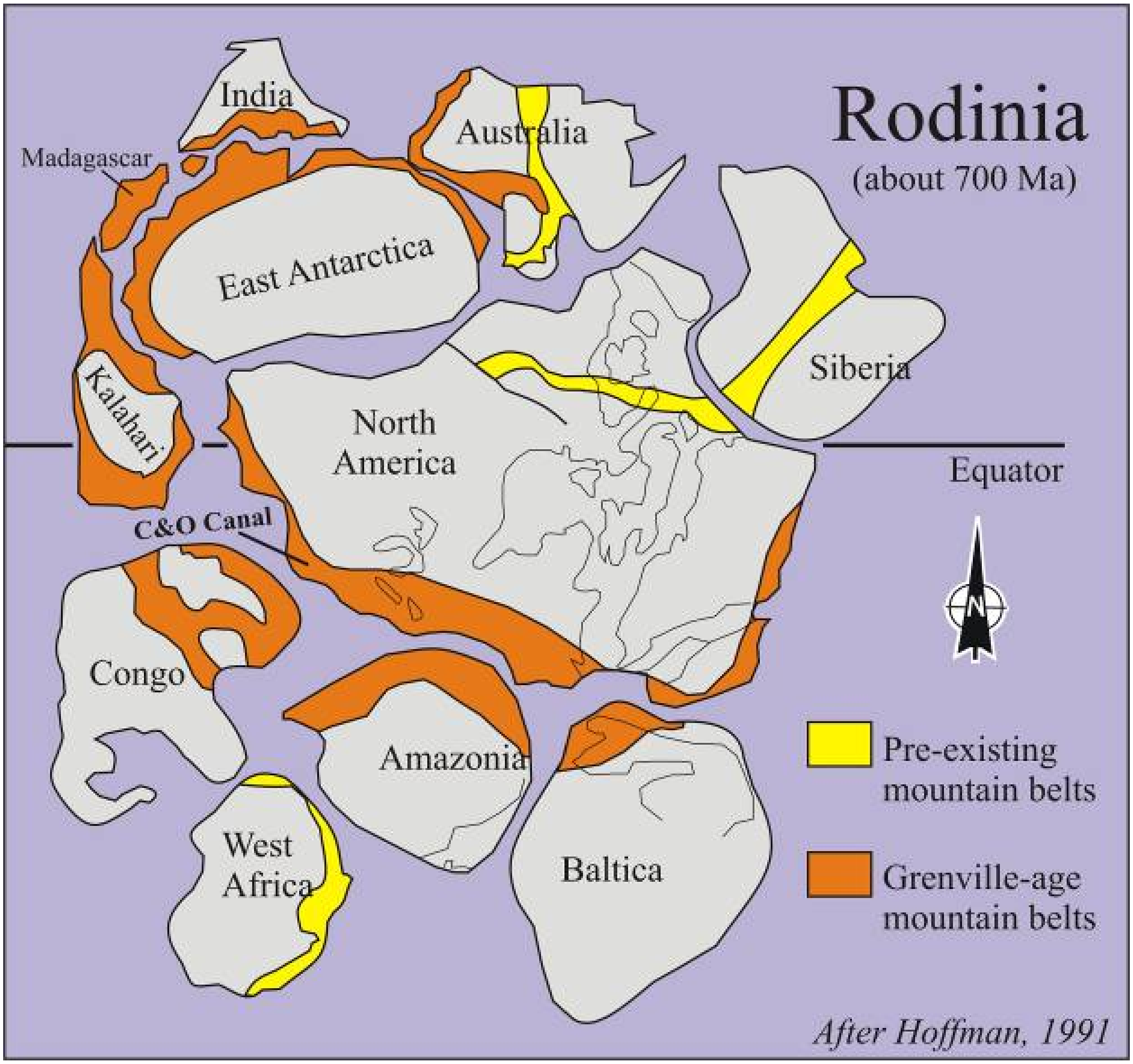

Figure 6.2 Rodinia, the first supercontinent recorded along the C&O Canal. (Pangea is the second; it comes later.) Ancestral North America was the core of this giant landmass, which was assembled from smaller fragments around 1.1 billion years ago. Notice that North America is not only located on the equator, but also rotated over 90° from its modern position.

Figure 6.3 The Swift Run Formation, a sandstone and conglomerate that appears to be the eroded remains of the Grenvillian Mountains Because the Swift Run is not a nice thick layer, and is instead patchy and discontinuous, it appears to have been deposited in stream valleys between rounded hillocks of granite. *Field of view is about six inches wide.*

Figure 6.4 Vesicles in basalt (holes) are formed when the lava erupts and releases gases from solution. This release, called degassing, is triggered by a release of pressure. It’s very similar to opening a bottle of soda, causing it to begin release carbon dioxide from solution, only here the bubbles are trapped in stone. *Each sample is about four inches in diameter.*

Figure 6.5 Columnar jointing in basalt. When basaltic lava cools, in contracts, forming polygonal cracks (B) which extend downward into the flow as 5- or 6-sided columns (A). *Pencil for scale.*

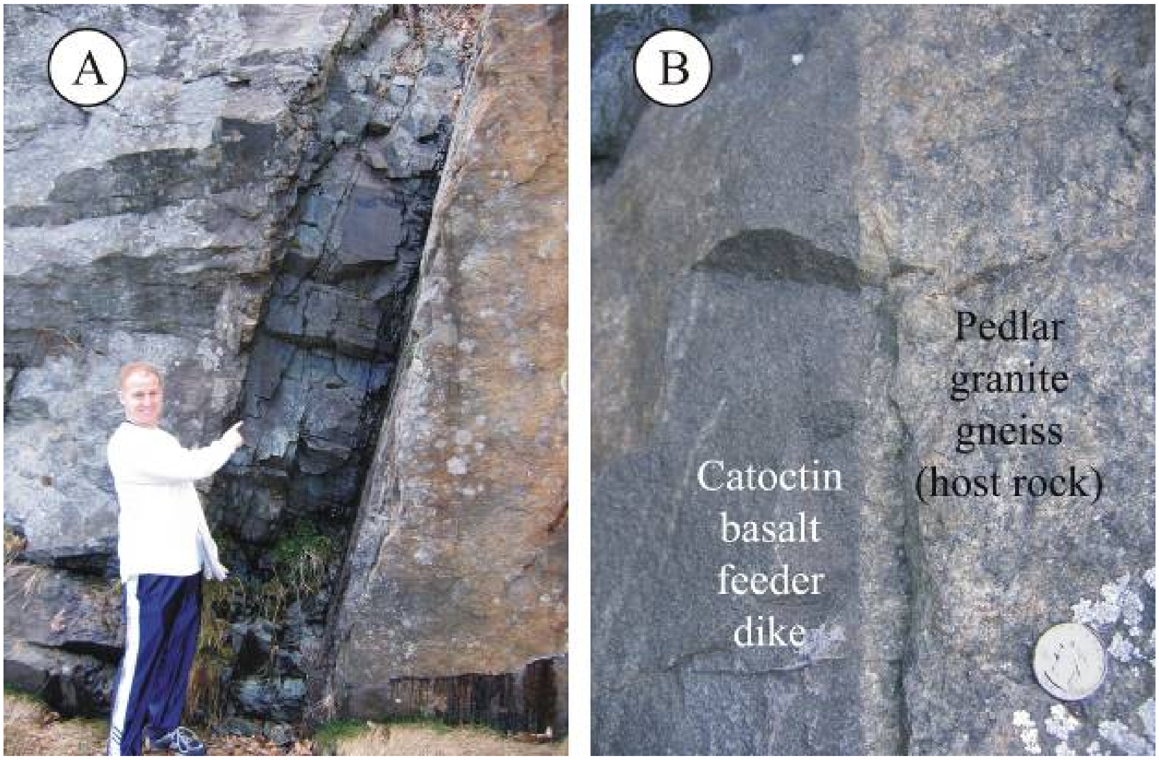

Figure 6.6 Dikes of basalt cut across the older granites and granite gneisses. It is thought that these dikes were the "plumbing" that fed the flood-like eruptions above. (A) Mike Nelson points out a dike along Skyline Drive in Shenandoah National Park. (B) Close-up of the contact between the dike and its granite gneiss host rocks. *Quarter for scale.*

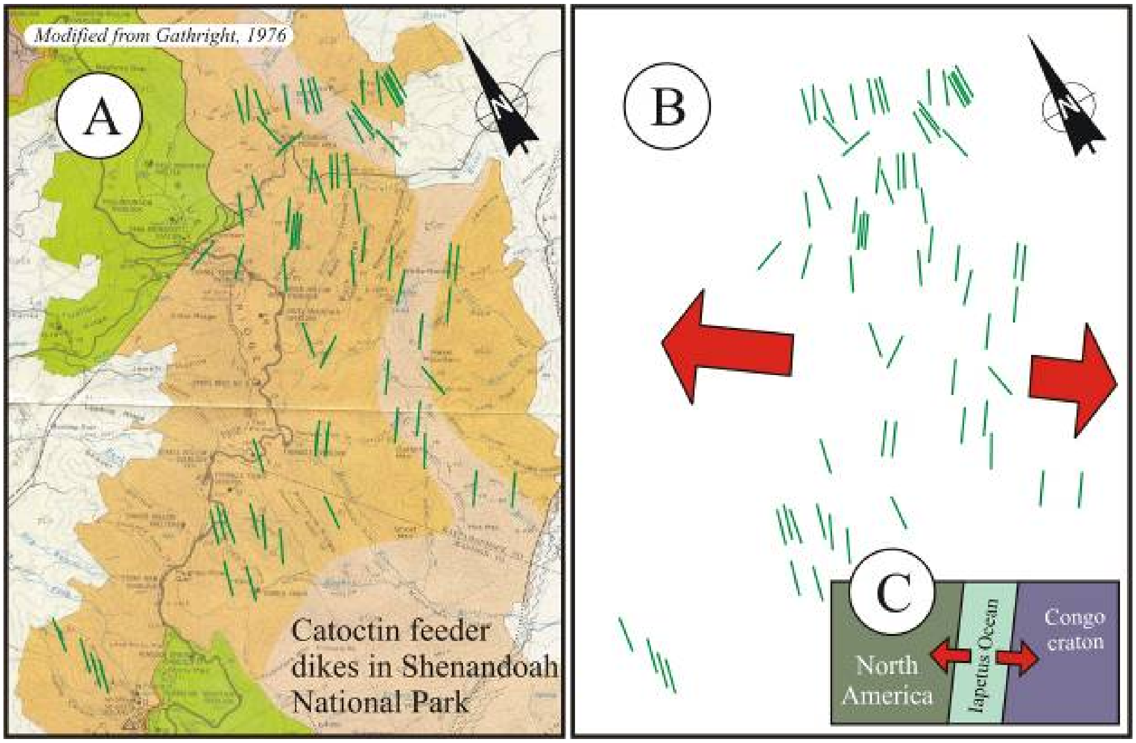

Figure 6.7 The orientation of feeder dikes (like those in Figure 6.6) can tell us the direction in which the crust was being stretched (direction of Rodinia's rifting). The dominant northeast-southwest orientation of the extensional dikes (A) tells us the crust was being stretched perpendicular to that, from the northwest to the southeast (B). The tectonic interpretation is that the Congo craton pulled away to the southeast (C), opening the Iapetus Ocean.

Figure 6.8 The modern Red Sea and Gulf of Aden, analogues for the Proterozoic Iapetus Ocean as it was "born" through the rifting between North America and the Congo craton. Here, the Arabian Plate has rifted away from the African Plate, opening up a narrow ocean, complete with its own mid-ocean ridge.

Figure 6.9 Amygdules in meta-basalt (greenstone of the Catoctin Formation). Amygdules are vesicles (degassing bubbles) that have been filled in at a later time by hydrothermal deposits of minerals.

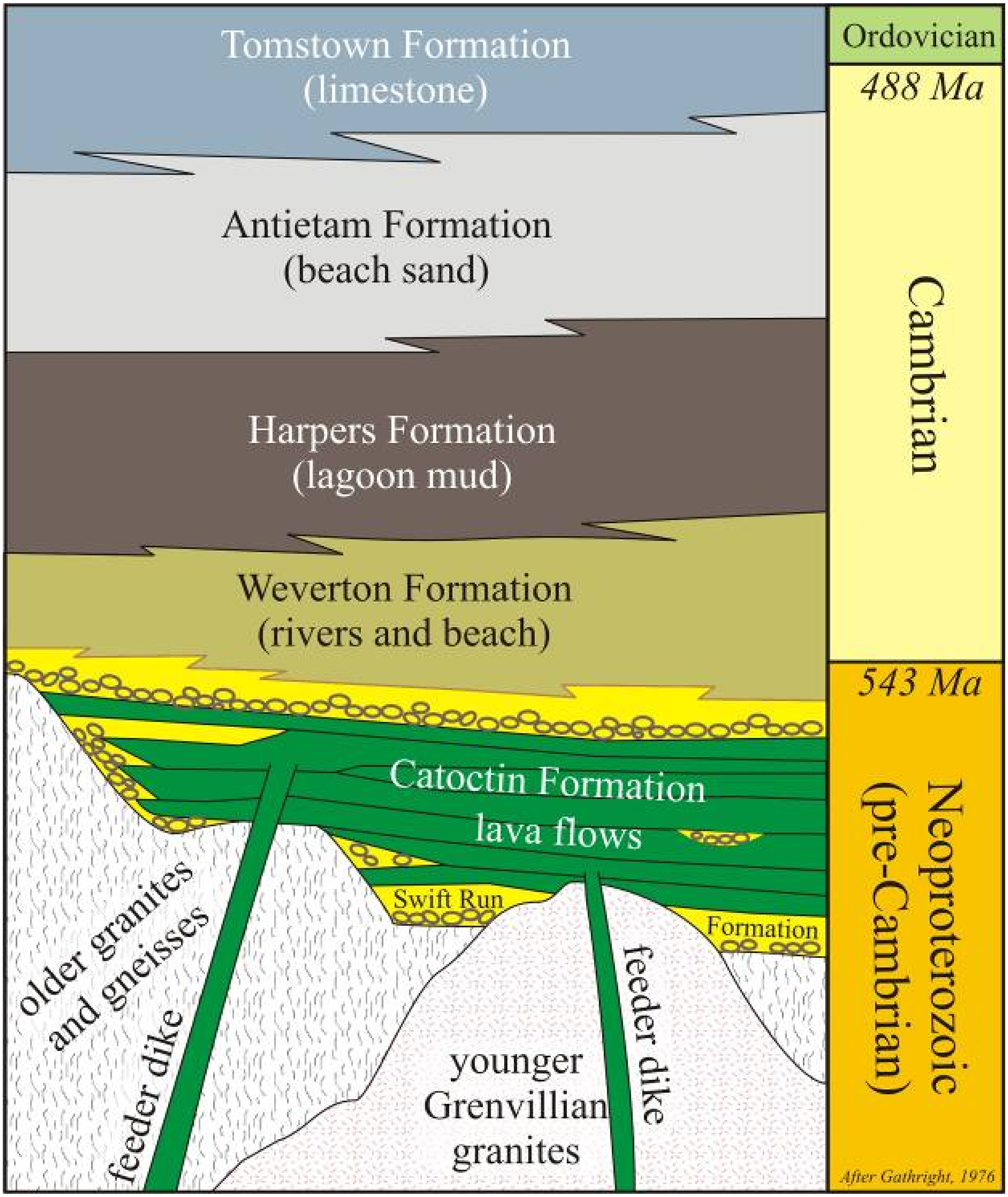

Figure 6.10 A generalized sequence of rock units in the Blue Ridge Province. Older granites are foliated into gneisses; younger granites lack this foliation. The Swift Run Formation lies on top of both in low spots. Basaltic dikes cut across these rocks to feed the flood basalts of the Catoctin Formation (later metamorphosed to greenstone). On top of these, the Chilhowee Group (Weverton, Harpers, and Antietam Formations) record deepening sea levels through the Cambrian. The Tomstown Formation and other carbonates take over after that, showing us a Bahamas-like environment that lasted until the Taconian Orogeny.

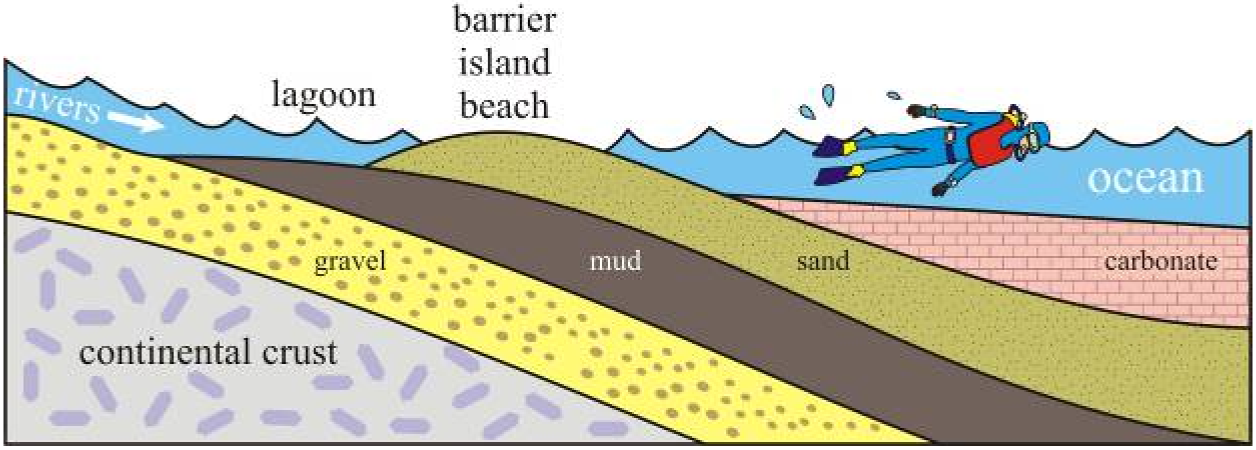

Figure 6.11 The offshore pattern of sediment types. Highest-energy water is found in rivers flowing off the continents, so that's where the biggest grains of sediment (gravel) are. Coastal lagoons are low-energy environments, and deposit mud. Barrier islands are sandy, and then fat out to sea, there is no more input (large or small) of sediments derived from the land. Instead, the ocean water precipitates carbonate rocks like limestone.

Figure 6.12 A coastal lagoon, at Assateague Island National Seashore, the sort of environment where the Harpers Formation was probably initially deposited, minus the plants (land plants had not evolved yet in the Cambrian).

Figure 6.13 The Weverton Sandstone, the petrified remnants of a Cambrian beach. *Field of view is about three inches.*

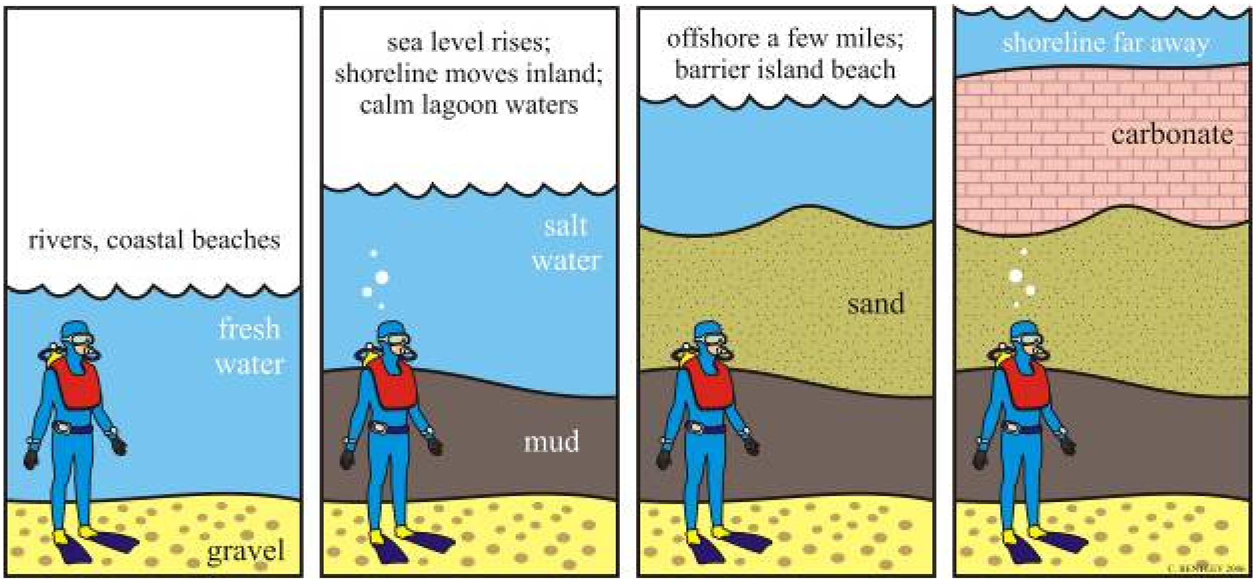

Figure 6.14 Deepening sea levels as observed by a patient SCUBA diver (and recorded in the sediments for the rest of us).

Figure 6.15 Large *Skolithos* tubes in sandstone. Top view, looking down on the “bullet holes” in the top of the block. This view is very similar to the view we would have had if we swam over the shallows off the coast of Cambrian North America. Below us, in the wet sand, industrious little worms would be digging their burrows.

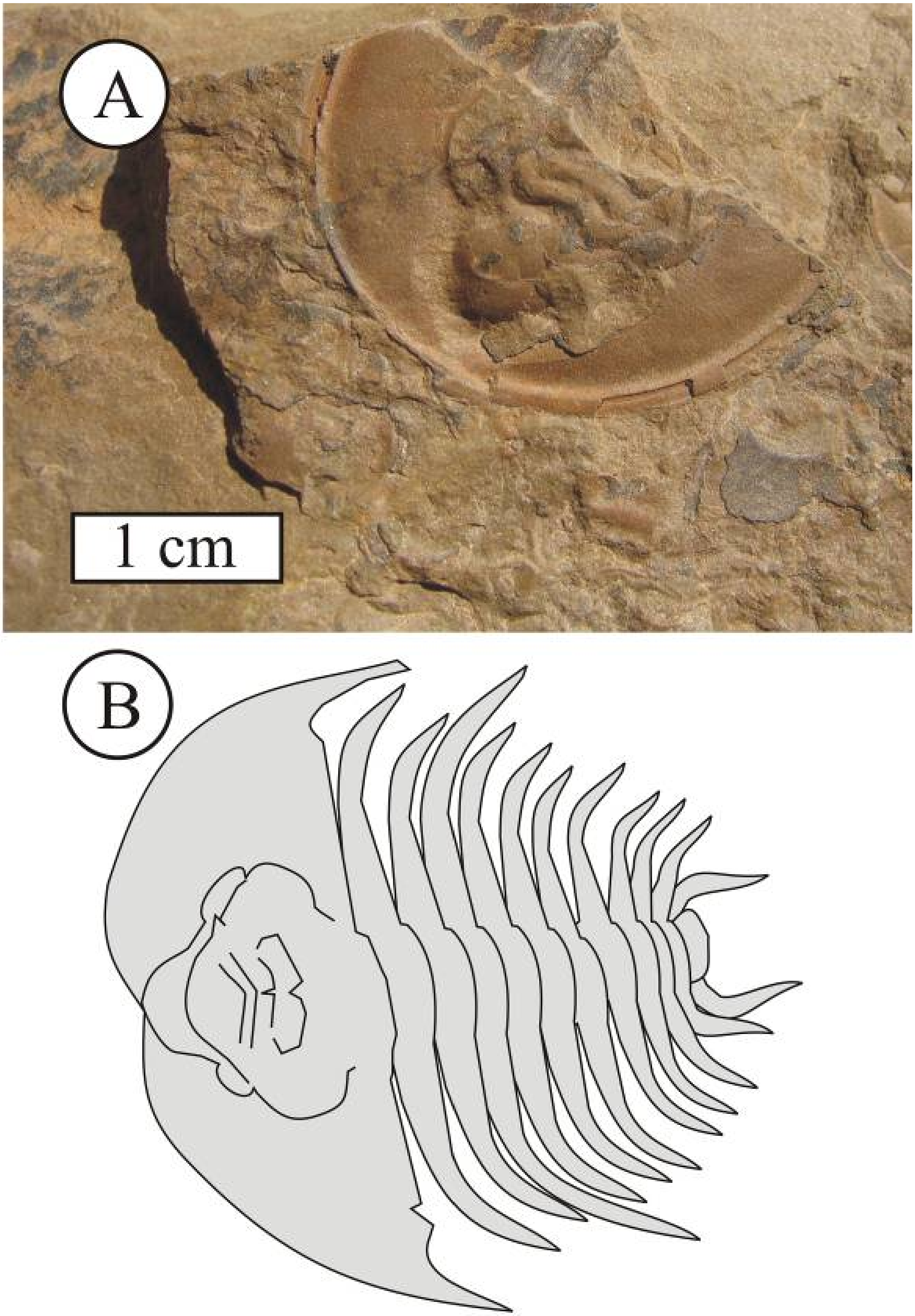

Figure 6.16 The trilobite *Olenellus*, an important fossil that allows us to decisively place the Antietam Formation was deposited in the Cambrian period of geologic time. (A) Olenellus head shield fragment in siltstone. (B) Reconstruction of the whole animal, now extinct but distantly related to horseshoe crabs.

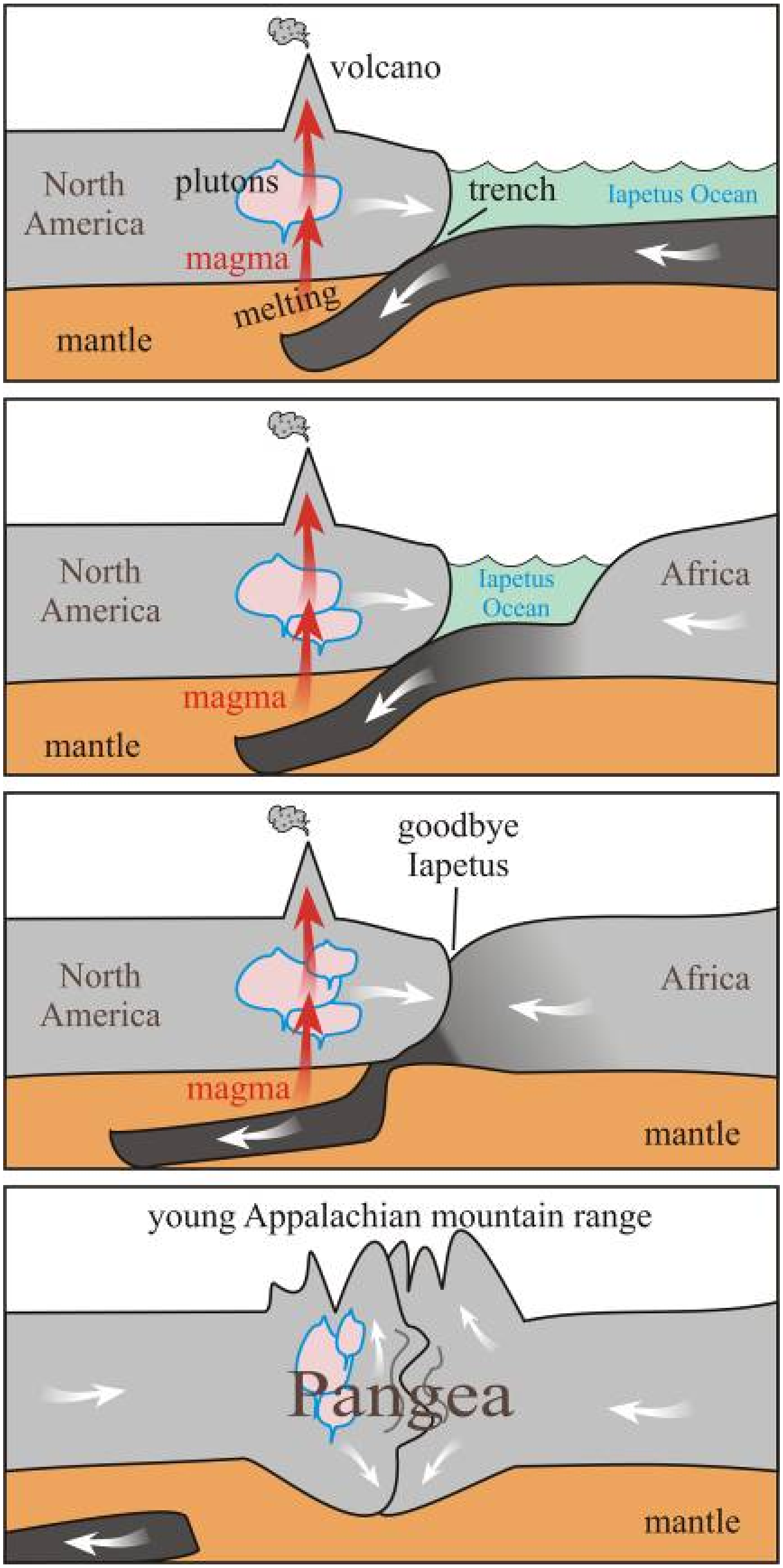

Figure 6.17 The Appalachian Orogeny. As continued subduction of oceanic crust narrowed the Iapetus Ocean, it brought two plates of continental crust crashing into each other. (North America and Africa, at least at the latitude of the C&O Canal) The collision raised up the young Appalachian Mountains which would have resembled the modern Himalayas.

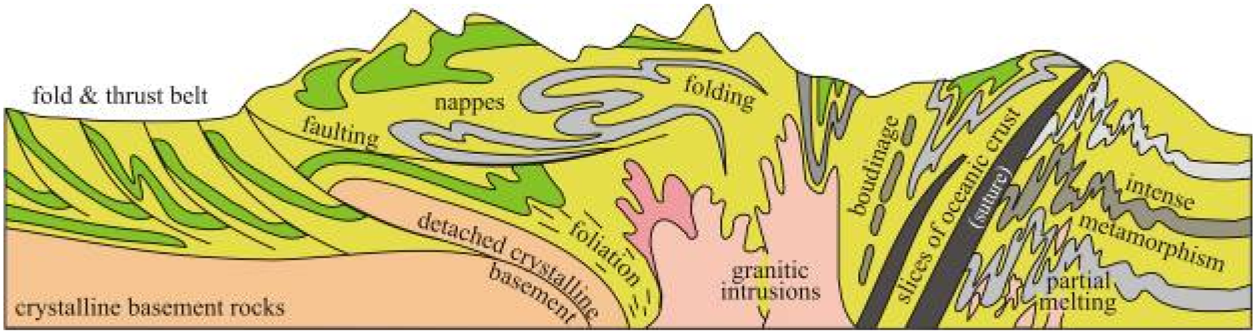

Figure 6.18 The typical anatomy of a mountain belt when first formed. The suture zone is marked by intense metamorphism of oceanic sediments and slices of oceanic crust. Partial melting occurs at depth, giving rise to intrusions of granite. Huge slices of rock are thrust upward and folded over, including fragments of the "crystalline basement" rocks, and their overlying sedimentary strata.

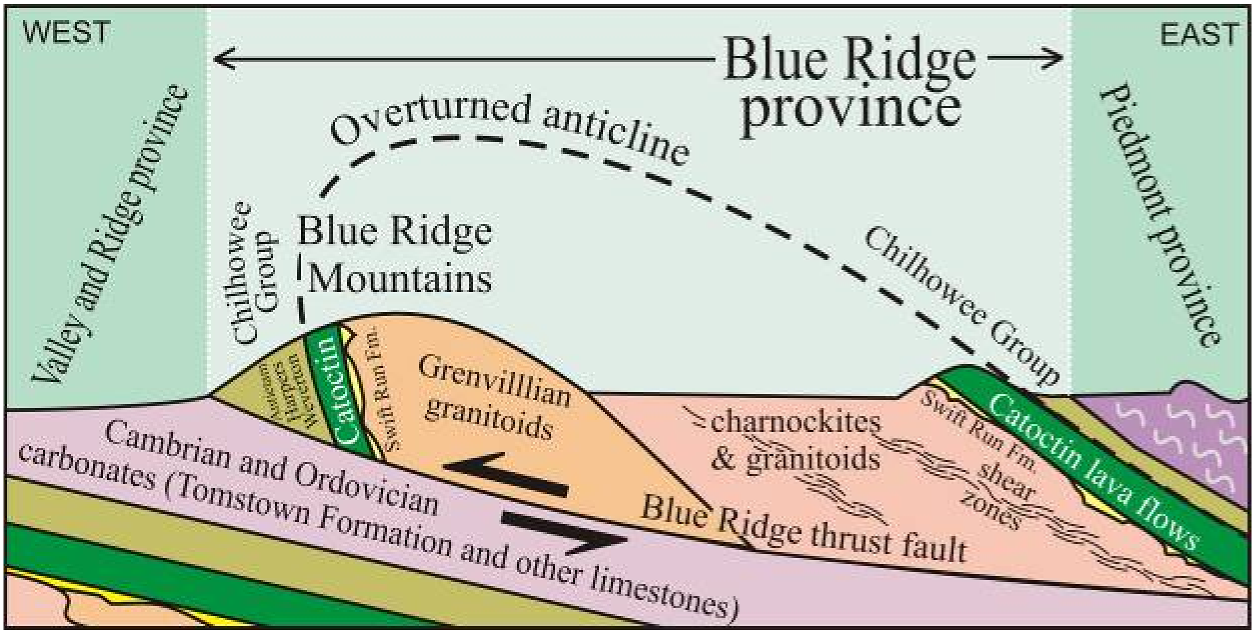

Figure 6.19 A simplified cross-section of the Blue Ridge province, showing its structure as an overturned fold, skewed westward along a large fault that underlies the province. The rocks of the Blue Ridge used to be deeper in the crust, and further to the east, before the collision of North America and Africa during the Appalachian Orogeny snapped it off and shoved it to the west over much younger rocks.

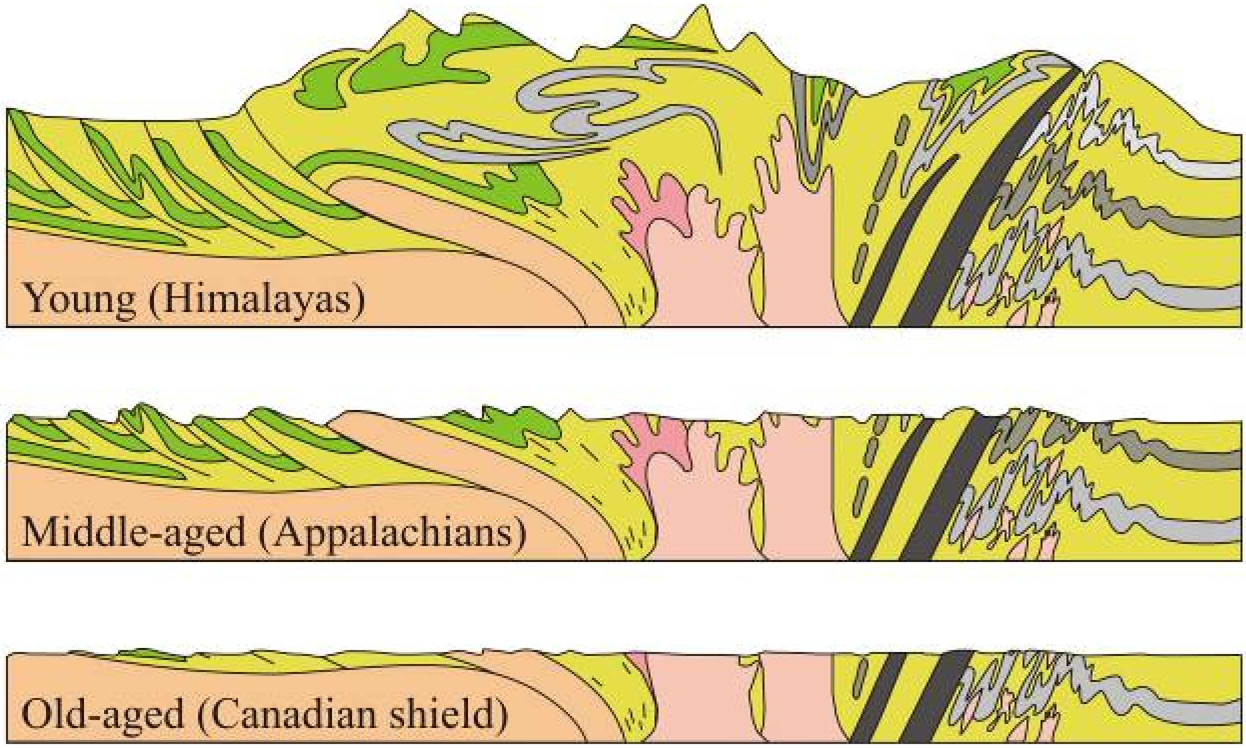

Figure 6.20 The erosion of mountain belts over time. When first formed, mountain belts are truly mountainous, on the same scale as the modern Alps or Himalayas. When middle-aged, mountain belts are worn down to lower levels, revealing rocks that used to be located in their interiors. In general, the topography at this point is gentle, akin to the modern Urals or the Appalachians. When mountain belts get elderly, the forces of weathering and erosion have burnished them down to their roots, and though the mountains themselves are gone, a suite of evidence (metamorphism, deformation, granite intrusions) shows us that the mountain belt remains.

Chapter 7

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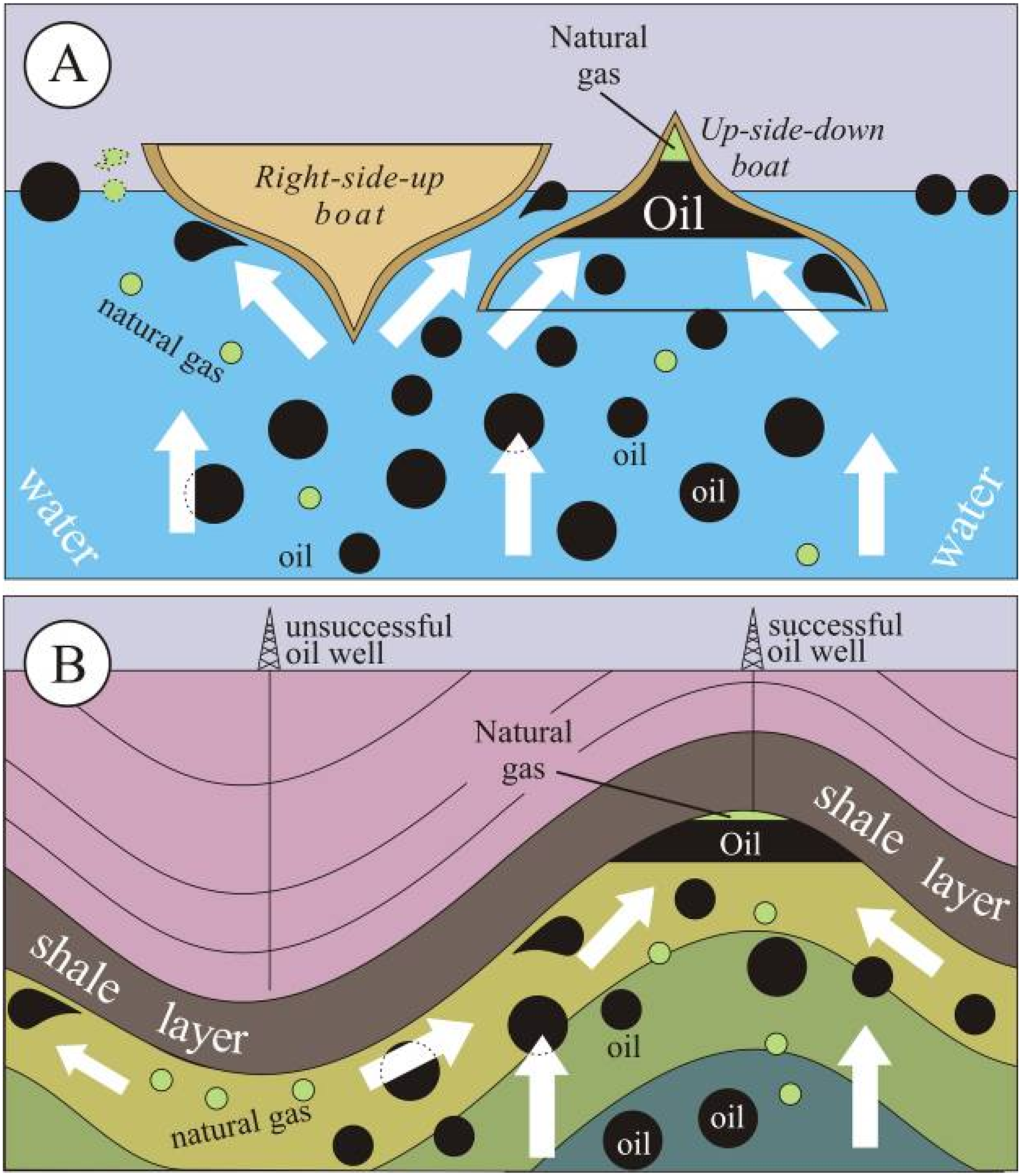

Figure 7.1 Two boats as an analogy for the oil-trapping properties of up-turned folds (anticlines) versus down-turned folds (synclines). Oil rises due to its lower density as compared to water. Natural gas has an even lower density than oil. They will both travel upwards until something halts their progress, like an upside-down-boat, or an anticline made of a layer of shale. Oil and natural gas then pool in a bubble under this high point, and stay there until we pump them out.

Figure 7.2 The extreme scale of folding in the Valley and Ridge Province is evident in this image of the Susquehanna River's path across the Pennsylvanian Valley and Ridge. Individual formations which stand up well to weathering and erosion are topographically high, and they mark the folds lying beneath the surface. *Modified from a Google Earth image.*

Figure 7.3 A syncline in the Rose Hill Formation near Round Top.

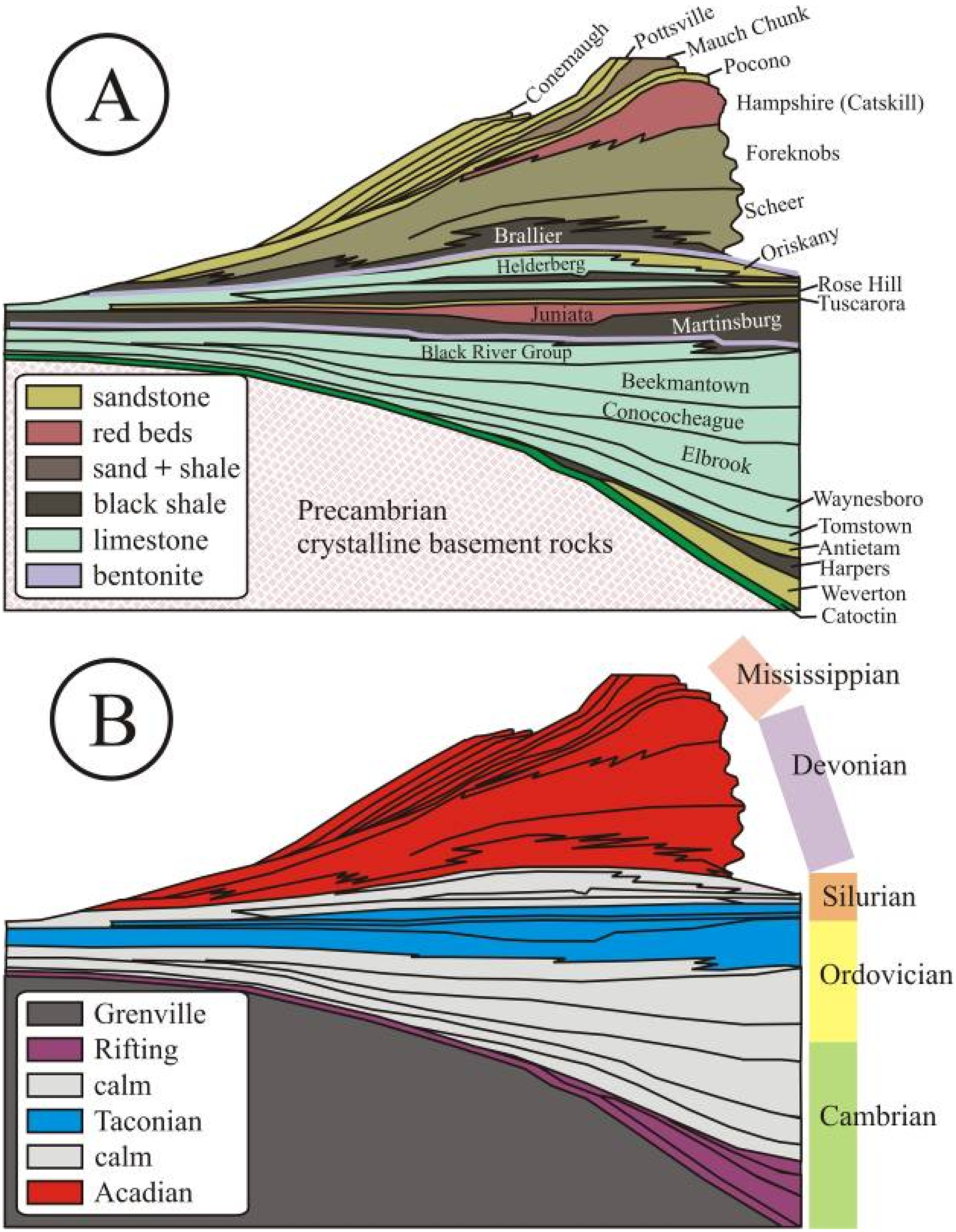

Figure 7.4 (A) The stratigraphic sequence in the Valley and Ridge Province, a mind-numbing stack of dozens of formations. (B) The larger patterns shown by this sequence: rifting of Rodinia, calm waters between tectonic events, the Ordovician Taconian Orogeny shedding sediments westward, another (shorter) period of calm, and then a further influx of land-derived sediments, this time from the Devonian Acadian Orogeny.

Figure 7.5 Limestone reacts with acid, even weak acid. Here, diluted hydrochloric acid is dripped on a block of limestone, causing it to fizz (carbon dioxide is being released).

Other photos still to come: Sideling Hill
Figure 7. x

Other photos still to come: Devil’s Eyebrow
Figure 7. x

Other photos still to come: caves
Figure 7. x

Other photos still to come: ripple marks
Figure 7. x

Other photos still to come: mud cracks
Figure 7. x

Other photos still to come: stromatolites
Figure 7. x

Chapter 8

These pictures are reduced in size and quality: **Do not use in the book.**
Use large files (in chapter folders) instead.

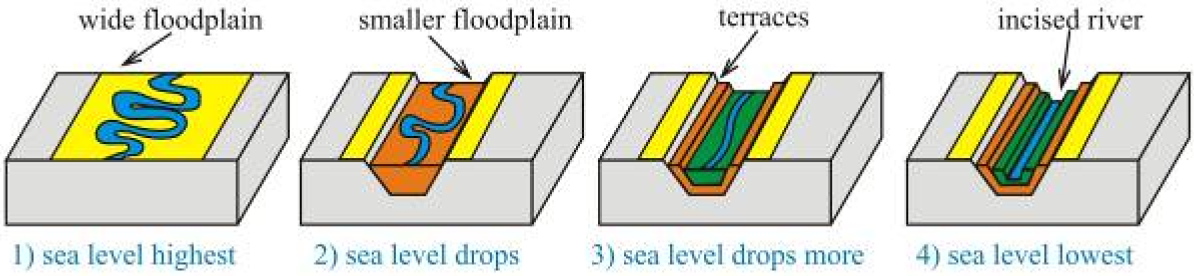

Figure 8.1 Incision of a mature river with progressive drops in sea level. Over time, the river becomes restricted to narrower and deeper valleys with smaller floodplains. Older levels are abandoned as terraces (if carved from loose sediment) or straths (if carved into bedrock).

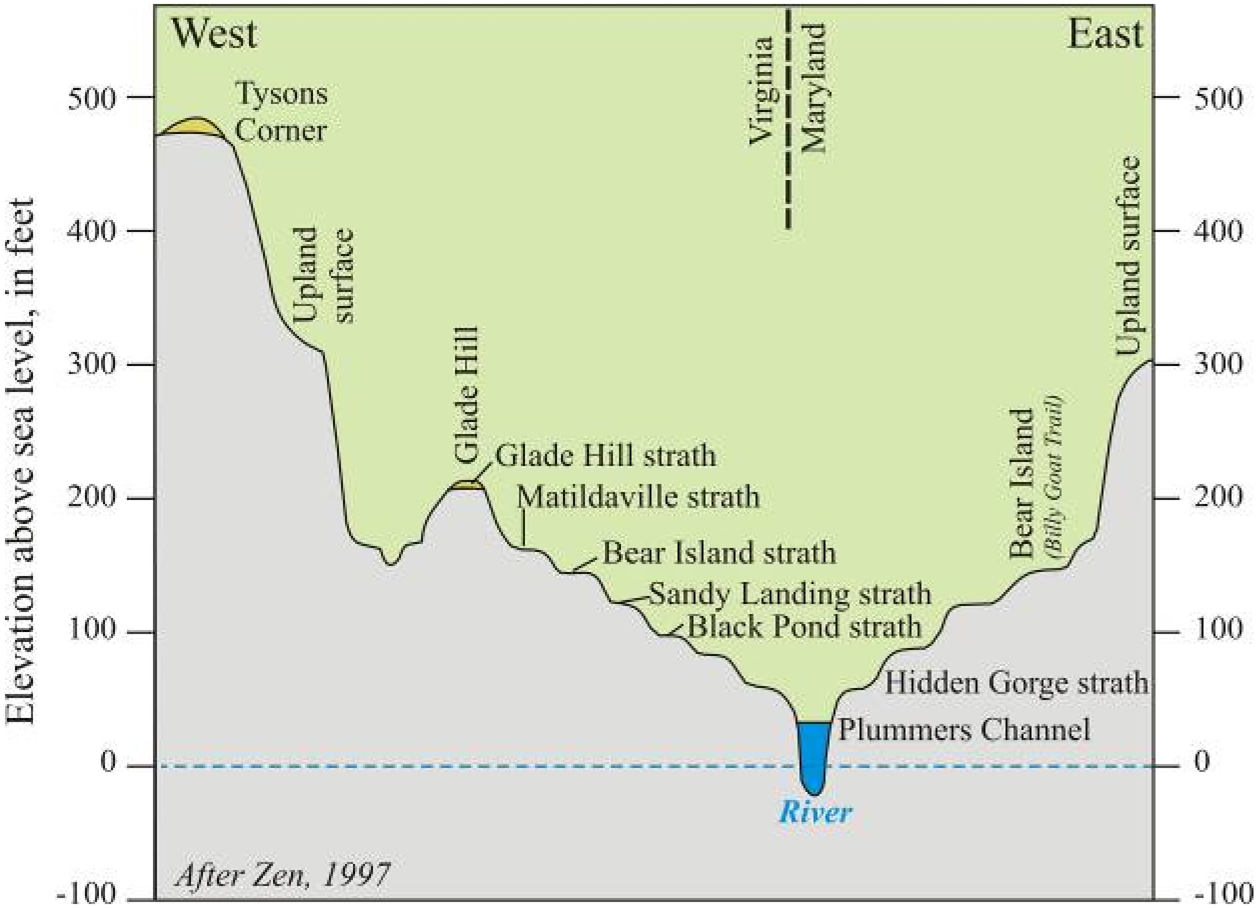

Figure 8.2 A cross-section of the Potomac Gorge at Mather Gorge, along the Billy Goat Trail. The elevations of major land surfaces are shown, including the six major straths.

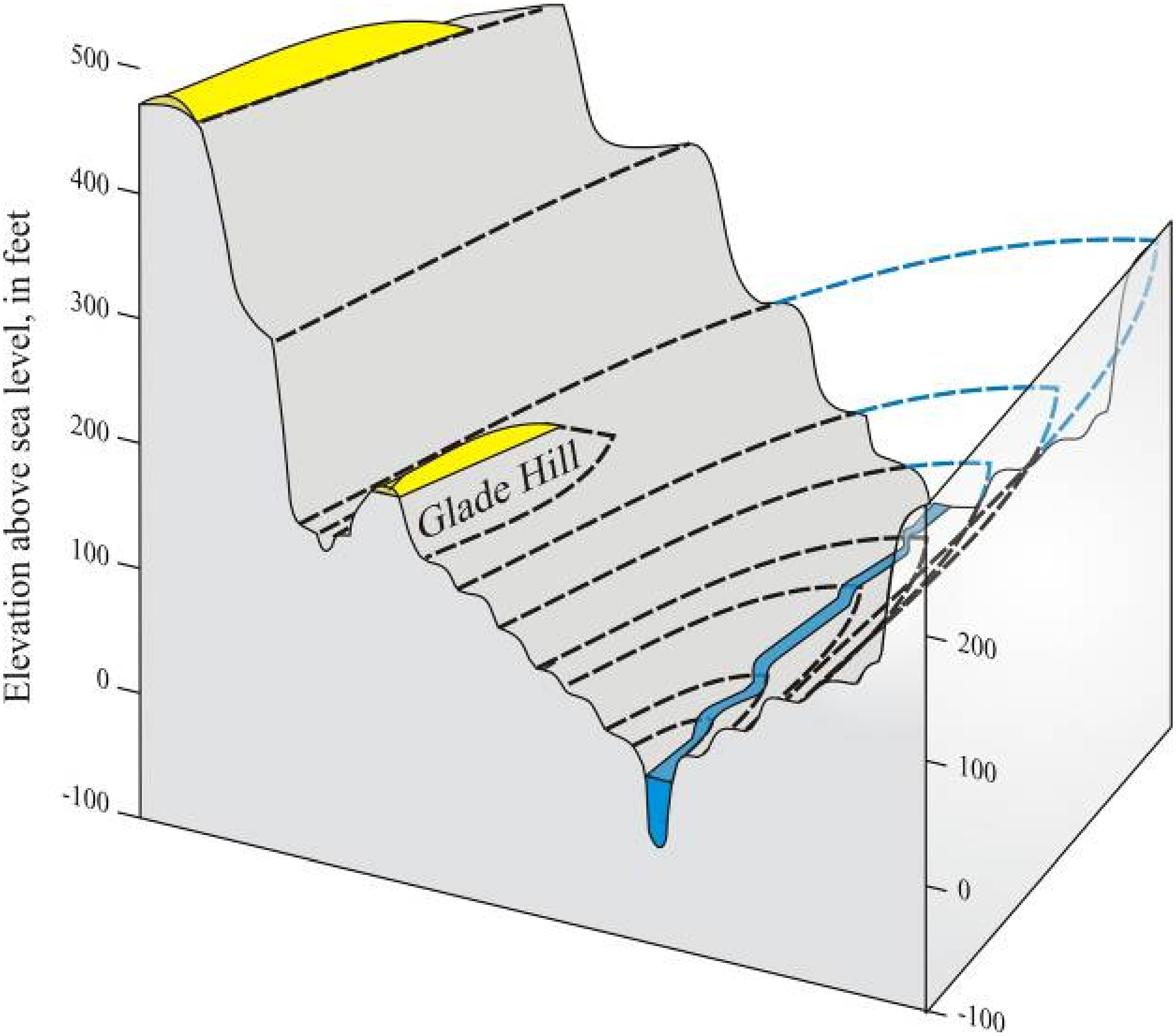

Figure 8.3 From a three-dimensional perspective, straths appear less like stair-steps, and more like rowboats: widest at the downstream end, narrowing to a pointed bow at the upstream end.

Figure 8.4 Aerial view of the Great Falls area, where the pointed upstream ends of several straths are "bunched up" together at the same point, now the site of an amazing waterfall. Note also how straight Mather Gorge is in this view. *Modified from a NASA satellite photo.*

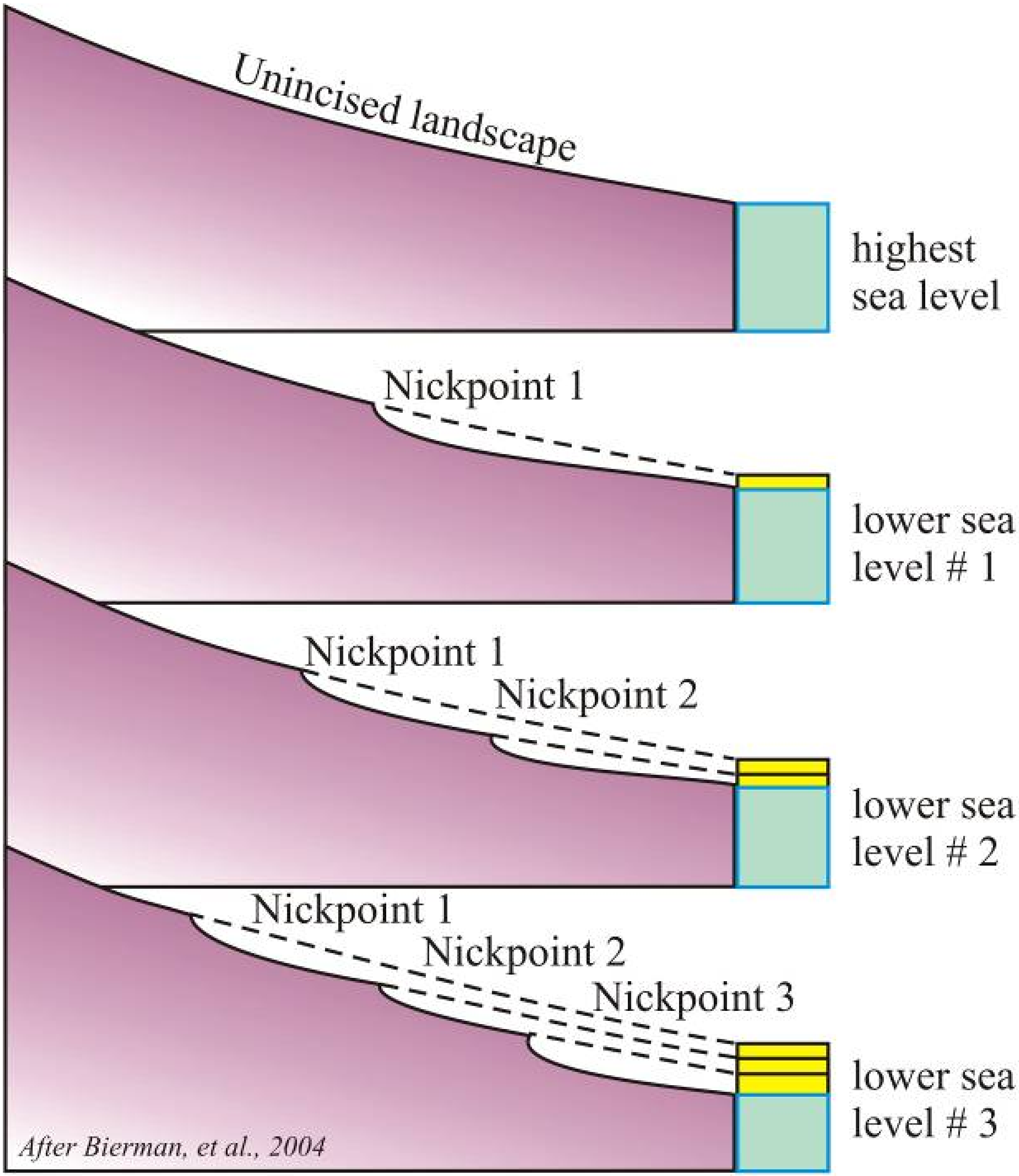

Figure 8.5 Nickpoint development with dropping sea level, and propagation upstream over time.

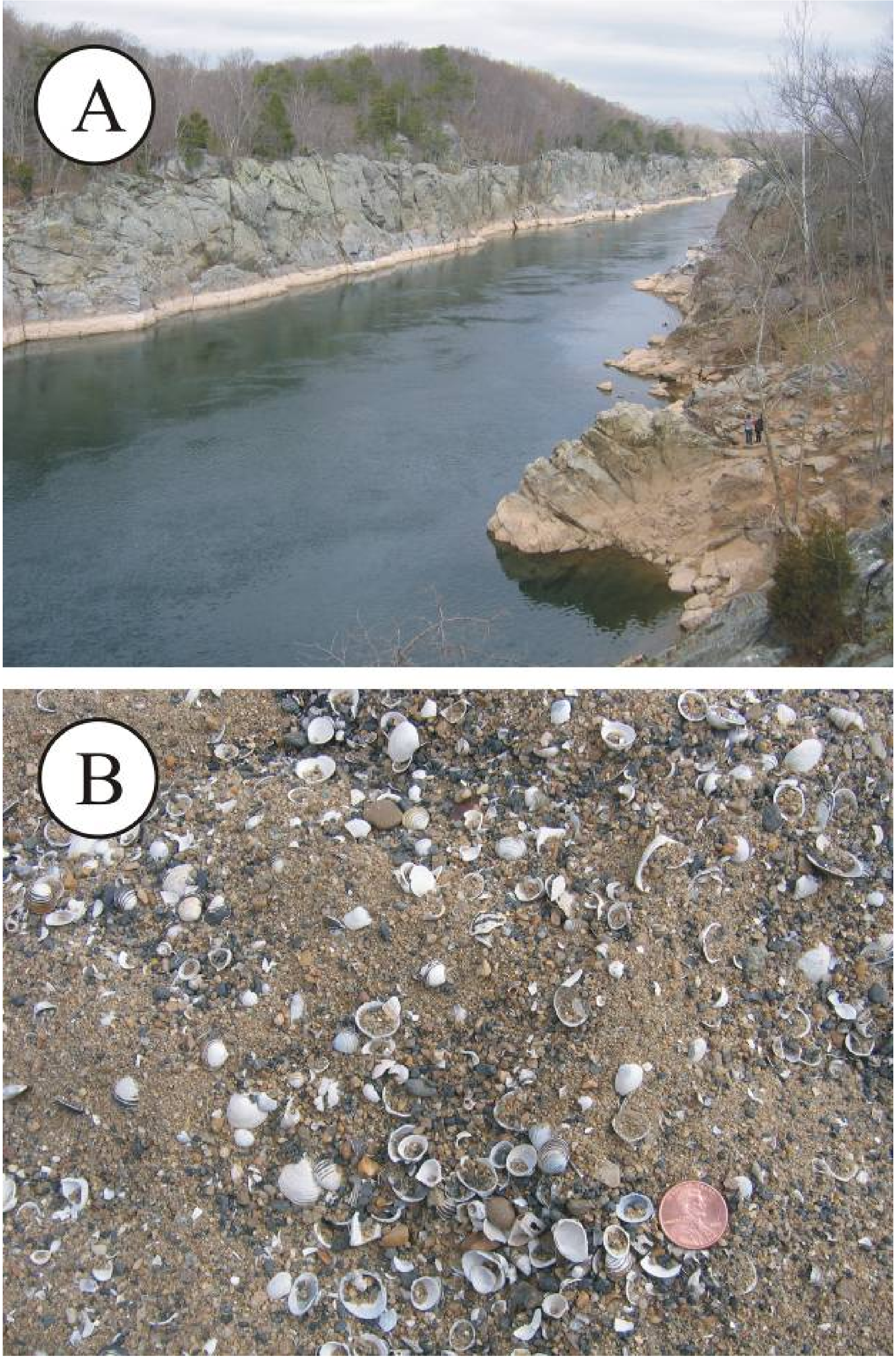

Figure 8.6 Evidence of changing river levels in the Potomac Piedmont. (A) A “bathtub ring” of silt (tan/orange stripe above river level) shows that the river has fallen to lower than normal levels. (B) Deposits of freshwater clam shells and sand, dozens of feet above the river, indicate that in flood stage, the river reaches great heights. *Penny for scale.*

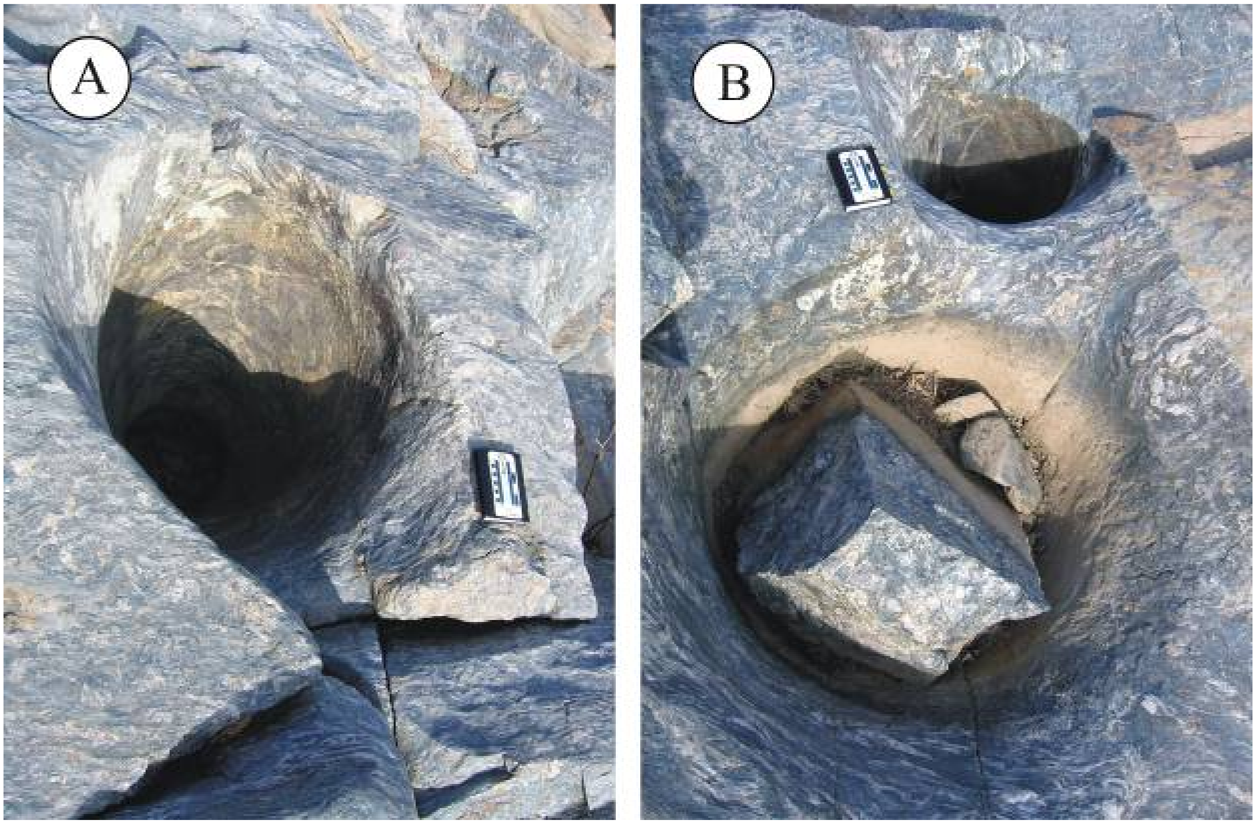

Figure 8.7 Several potholes drilled into migmatite along the Billy Goat Trail. (A) Empty (and therefore still active) pothole. (B) A pothole whose drilling days are over: the hydraulic vortex has been shut down by a large block of rock dropping into the hole. Notice the layer of silt annealed to the rear wall of this pothole – a sure indication it hasn't been successfully scoured in some time. *Scale is in inches and centimeters.*

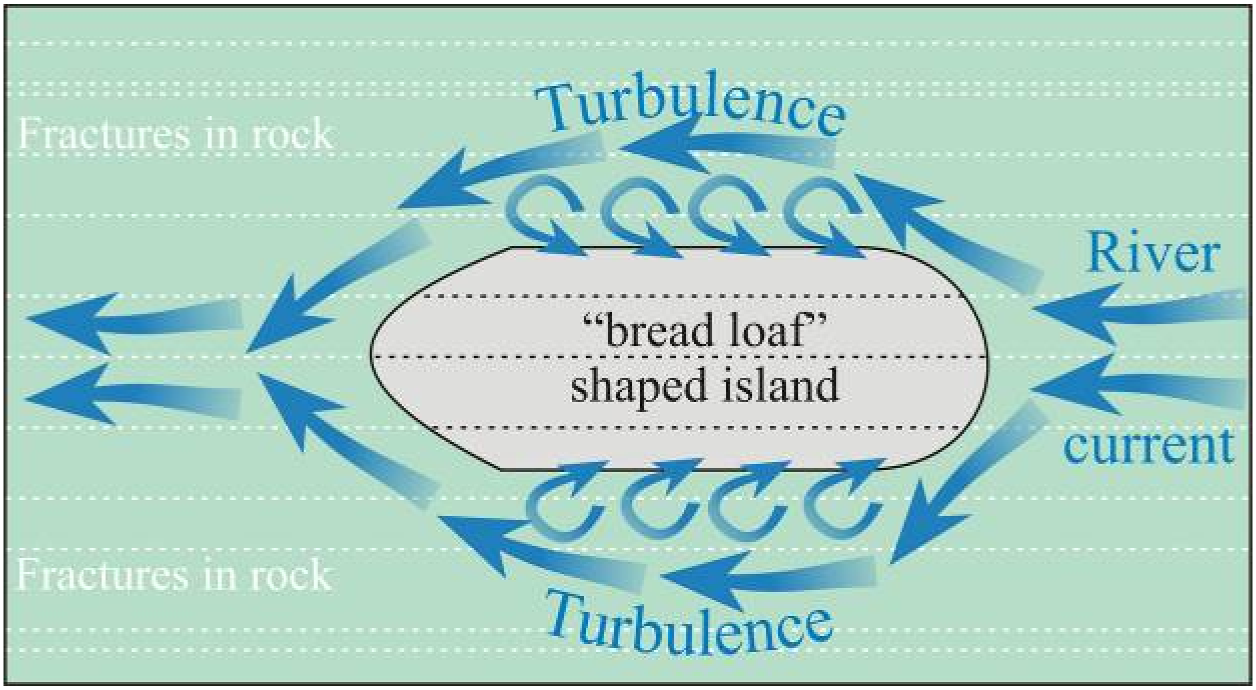

Figure 8.8 Formation of potholes drilled into the sides of "bread loaf"-shaped rock masses. During times of high water, the current splits to go around this obstacle, which creates clockwise and counter-clockwise vortexes along the side of the rock. These twisting vortexes can bore into the rock, provided they are full of sand and silt.

Figure 8.9 The water gaps at Harpers Ferry. At its confluence with the Shenandoah, the Potomac cuts across two linear mountain ranges, the Blue Ridge and South Mountain. The river is older than the mountains, and it has removed all the (softer) rock that was surrounding them. *Modified from a Google Earth image.*

Figure 8.10 Incised meanders at the Paw Paw Bends. An old age river, with its looping meanders, bit down when sea level dropped, trapping it in curves that no longer move. *Modified from a Google Earth image.*