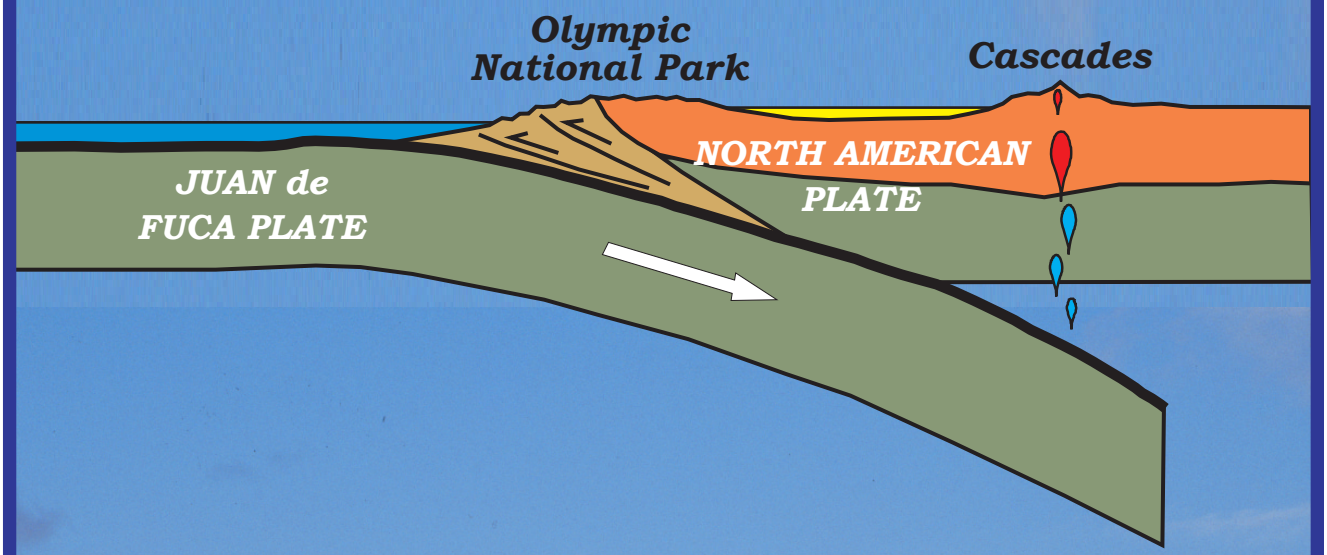
SUBDUCTION IN THE PACIFIC NORTHWEST

Geology Training Manual for Olympic National Park



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Cover: ***The Olympic Mountains are the result of convergence between the Juan de Fuca and North American plates.*** *(The Needles viewed from southeast side of Obstruction Peak. Photo by R. J. Lillie).*

SUBDUCTION IN THE PACIFIC NORTHWEST:

Geology Training Manual for OLYMPIC NATIONAL PARK

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PREFACE

Close your eyes and imagine you're an eagle flying high over Olympic National Park. The jagged peaks below extend westward to the waters of the Pacific Ocean. On the east is Puget Sound, and then the snow-capped volcanic giants – Mount Baker and Mount Rainier. If we could have that eagle's perspective we'd see laid out before us a landscape that has an incredible story to tell of the way the Olympic Mountains formed in the distant past, and continue to form today.

Resource Education Rangers commonly engage visitors in situations ranging from a couple of minutes (visitor information desk; trail roves) up to an hour or so (walks, talks, evening programs). This manual has one "bottom line" objective: **after an encounter with a Resource Education Ranger, a visitor can walk away with a basic understanding of the composition and history of development of the Olympic Mountains**. In a sense the manual could be written as one sentence:

> ***"The rocks of the Olympic Mountains were manufactured in the sea, but are now uplifting and eroding as the ocean floor descends beneath North America."***

The first part of the sentence relates to the materials that comprise the mountains: hard crust of the ocean (basalt) and younger sedimentary layers (sandstone and shale). The second part hints at the process responsible for uplifting the materials out of the sea: subduction of one plate beneath another.

The manual presents aspects of the geologic materials and evolution of Olympic National Park that should be mastered by all Resource Education Rangers. Simple concepts of the materials (rocks) found in the park are presented, along with the process (plate subduction) that led to uplift of the mountains**.** ***All rangers should be able to answer basic questions about the formation of the Olympic Mountains — to explain, for example, how and why the Olympics differ from the volcanic peaks in the Cascades.*** While not all rangers may wish to present entire programs on geology, they might begin some programs by developing the Olympic landscape as the stage upon which biological, ecological, or historical events are played.

In places the manual discusses more advanced concepts. Subtleties of rock materials, plate tectonics, and other geologic processes

are presented so that rangers with special interest in geology might develop programs and answer questions in detail. Parts of the manual touches on more elaborate geological ideas, including some complexities and controversies that may be important to scientists and other curious folks. Those details could be useful when engaging some visitors one-on-one.

This manual is thus designed to help rangers convey to park visitors that the landscape seen by the eagle is typical of a subduction zone: a ***coastal range*** composed of material lifted out of the sea (Olympic Mountains), and a ***volcanic range*** where hot fluids rise from the top of the subducting plate (Cascade Mountains).

> "Do not try to satisfy your vanity by teaching a great many things. Awaken people's curiosity. It is enough to open minds; do not overload them. Put there just a spark. If there is some good inflammable stuff, it will catch fire."
>
> *Anatole France*

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THE GIANT RECYCLING MACHINE

The Edge of the Sea

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

Rachel Carson, *The Edge of the Sea*, © 1955, Houghton Mifflin, Company.

A grain of sand erodes from a lofty peak in the Olympic Mountains. It's carried by a stream, perhaps one similar to today's Quinault River, to the shores of the Pacific Ocean. There it's swept 100 miles out to sea and settles with other particles of sand, silt, and mud onto the ocean floor. Gradually it's covered by a mile or more of younger sedimentary layers, until our sand grain is no longer free. Through time it's cemented to other grains and is now part of a layer of sandstone, and the surrounding mud has hardened to shale.

But those layers are not standing still. They're carried on top of the Juan de Fuca Plate, back toward the North American continent, as if on a giant conveyer belt. Moving about 2 inches per year, they return to near the coast in about 3 million years, where the plate begins a downward plunge. As the plate relentlessly grinds away, the layers are transported still farther eastward and deeper and deeper beneath the edge of North America. After another 2 million years they lie 10 miles beneath the central part of the Olympics. Way down there the temperature and pressure are so great that the sandstone and shale layers harden into metamorphic rocks called metasandstone and slate.

Now something different happens. Instead of continuing their journey eastward and deeper into the Earth, the layers are scraped off the top of the Juan de Fuca Plate and rise upward. The scraping is accompanied by huge earthquakes that rattle the surface above. At the same time, overlying rock is worn away by the actions of wind, water, and ice. In another 15 million years our grain of sand finds itself once again a mile above the sea. Only briefly it experiences the sunlight and stars, wind and snow and rain, before being once again eroded

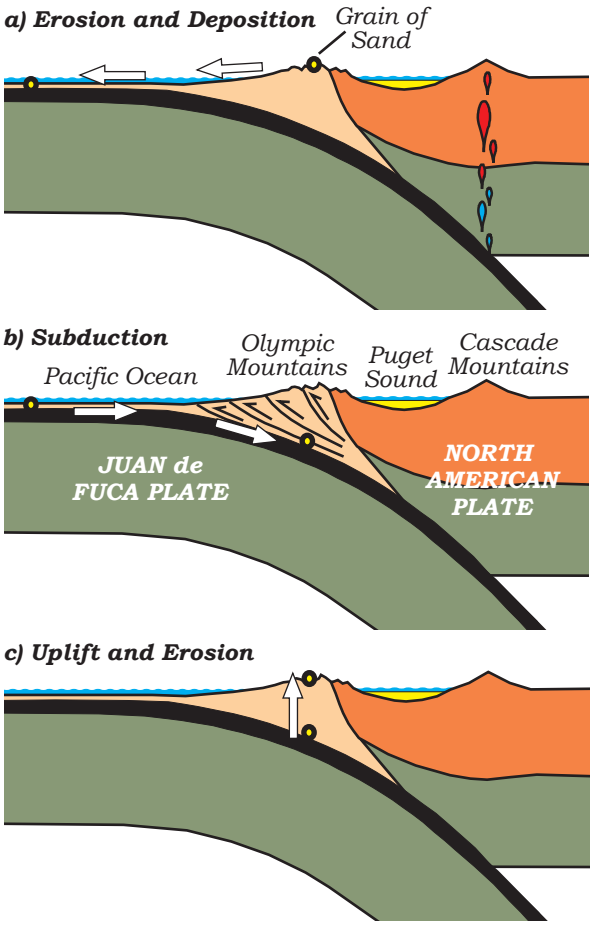


Fig.1. ***The Olympic Mountains are a giant recycling machine!*** *a) A grain of sand eroded from high in the Olympic Mountains is transported by streams out into the Pacific Ocean, where it settles on the sea floor. b) The grain, now imbedded in a layer of sandstone, is carried eastward on top of the Juan de Fuca Plate. In 5 million years it lies 10 miles beneath the Olympics. c) The sandstone layer is scrapped off the top of the plate and squeezed upward. 15 million years later the sand grain once again erodes from the surface of an Olympic Mountain peak.*

and carried to the sea.

The Olympic Mountains are a giant recycling machine (Fig. 1). Over a period of about 20 million years a sand grain might be eroded, carried to the sea and buried; then moved eastward back beneath the mountains and shoved upward, to be eroded again and carried back to the sea. You can engage the public on the geology of Olympic National Park by having them visualize such processes responsible for the development of the Olympic Mountains. The recycling nature of the range can further enhance appreciation of the renewable aspects of an ecological system.

The recycling model highlights four aspects of geology that should be in the toolbox of Resource Education Rangers at Olympic National Park:

1) the subduction of one plate beneath another in the Pacific Northwest (***plate tectonics***);
2) the formation of the igneous, sedimentary, and metamorphic rocks found in the Olympic Mountains (***petrology***);
3) the development of folds, faults, and unconformities within the uplifting rocks (***structural geology***); and
4) the development of mountains, valleys, and other landforms through the interactions of subduction, uplift, and erosion (***geomorphology***).

Deep Thought

The Surface Water Recycling Machine

Like our grain of sand, a drop of water goes through a similar cycle, from high in the mountains, down a stream, and out into the ocean. The difference is that, instead of being shoved a few miles down into the Earth, the water droplet evaporates and rises a few miles upward into the air, is carried eastward by wind, and falls back on the Olympics as mist, rain, or snow. And the water cycle is a few weeks rather than 20 million years!

PRESENTING OLYMPIC GEOLOGY TO PARK VISITORS

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

There are many places in Olympic National Park that might inspire visitors to think about geological processes (Fig. 2). At high vantage points, like Hurricane Ridge, rangers can have visitors imagine the Juan de Fuca Plate descending beneath their feet, causing the Olympic Mountains to rise from the sea as sediment and hard rock are scraped from the top of the plate. On beaches Olympic visitors can examine sedimentary layers that were tilted as they were lifted out of the ocean.

Have You Listened to the Earth?

"Yes, the Earth speaks, but only to those who can hear with their hearts. It speaks in a thousand, thousand small ways, but like our lovers and families and friends, it often sends its messages without words. For you see, the Earth speaks in the language of love. Its voice is in the shape of a new leaf, the feel of a water-worn stone, the color of evening sky, the smell of summer rain, the sound of the night wind. The Earth's whispers are everywhere, but only those who have slept with it can respond to its call."

Steve Van Matre, *The Earth Speaks*, © 1983, The Institute for Earth Education.

Five Questions about the Geology of Olympic National Park

As Resource Education Rangers it is our responsibility to paint a picture of the forma-

a

b

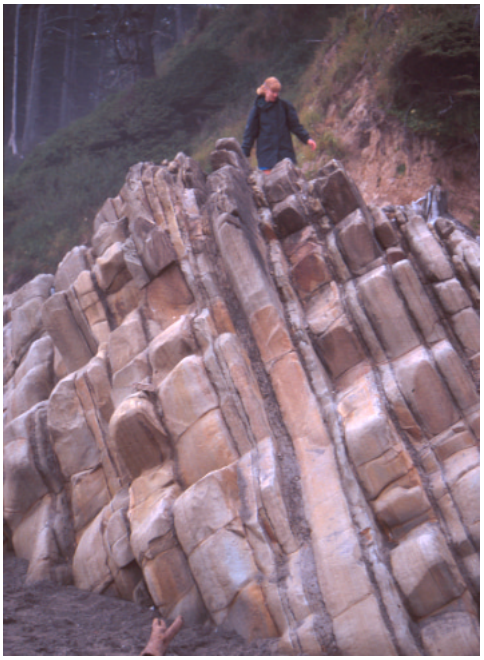


Fig. 2. ***Examples of places in Olympic National Park where visitors can be engaged in discussions of geology.*** *a) View to the southwest from* **Hurricane Ridge**. *The dramatic topography is still forming as the Juan de Fuca Plate subducts beneath the Olympic Peninsula. b) Beach 3 north of* **Kalaloch**. *Sandstone and shale layers were lifted out of the sea and tilted to a nearly vertical position. (Photos by R. J. Lillie).*

tion of the Olympic Mountains with a level of detail that visitors can understand. We've done our job well if visitors ask us to expand upon what we've said. Below is a list of questions about Olympic National Park and the development of mountain ranges and other features that form the foundation of Olympic geology. The remainder of this manual provides the background and details behind the brief answers.

1. Why are the Olympic and Cascade mountain ranges so different?

Both the Olympic and Cascade mountain ranges are products of plate convergence as the Juan de Fuca Plate subducts beneath North America (Fig. 3). But the ranges form at different parts of the subduction zone: one is volcanic, the other a product of crustal deformation. The Cascade Mountains lie above the position where the Juan de Fuca plate is about 50 miles (80 km) deep. It's so hot at that depth that fluids, primarily water, begin to "sweat" from the ocean crust and its cover of sediments. As the hot water rises it melts rock in its path, producing magma. Some of the magma reaches the surface as lava flows and other volcanic products of Mount Baker, Mount Rainier, Mount St. Helens, and other ***Cascade Mountain*** peaks. Farther west the top of the Juan de Fuca plate is not nearly so deep. Its rocks are still pretty cold, so that it does not sweat fluids and hence produces no volcanoes. Instead, some of the hard ocean crust and sedimentary layers are scraped off the top of the plate and squeezed upward as coastal ranges, including the ***Olympic Mountains***.

2. Why does an oceanic plate subduct beneath a continental plate?

Earth's crust is less dense than the underlying mantle. Although both crust and mantle are solid, crust can be thought of as "floating" on the mantle (Fig. 4). The crust of continents is thicker, and hence more buoyant, than crust of the ocean. If one envisions Earth's mantle as a swimming pool, continental crust might be thought of as a soccer ball, which sticks up higher out of the water than a smaller tennis ball (oceanic crust). A swimmer might

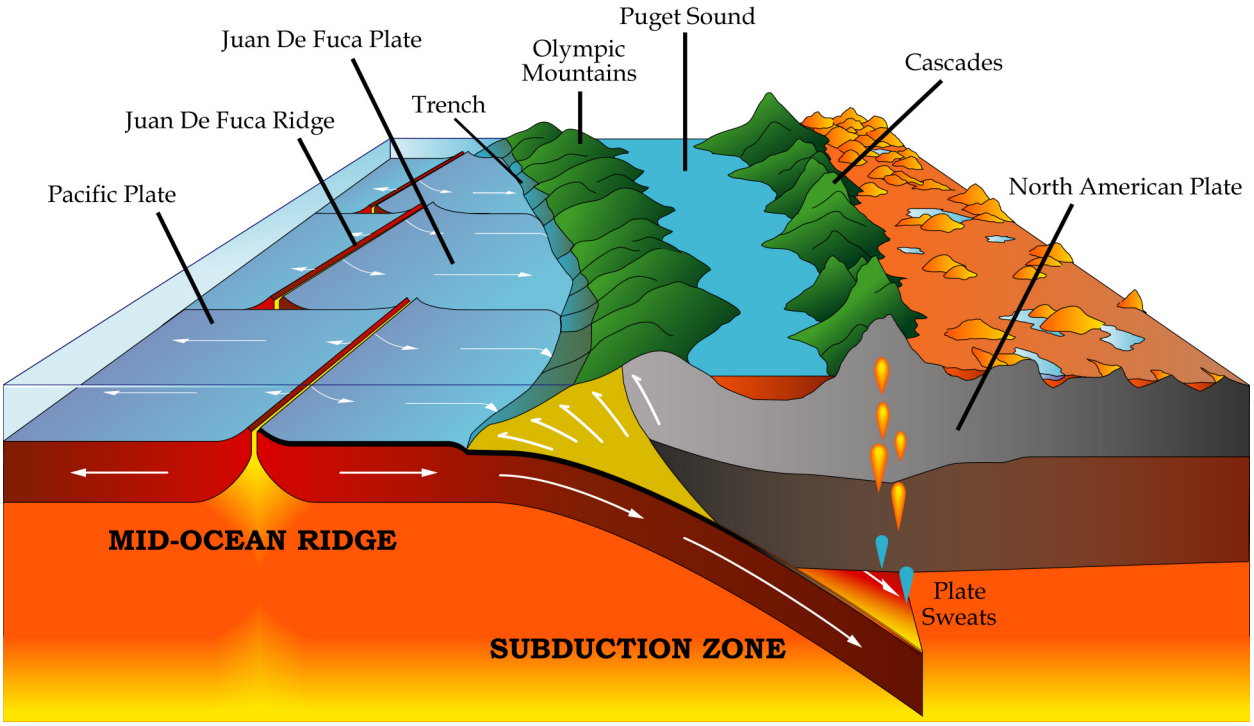


Fig. 3. ***Three-dimensional view of the tectonics of the Pacific Northwest.*** *As the Juan de Fuca Plate subducts beneath North America, two parallel mountain ranges form. Coastal mountains, like the* **Olympics**, *are rock and sediment uplifted from the ocean. The* **Cascades** *are volcanoes above the zone where the top of the plate gets so hot it sweats water and other fluids. Puget Sound is the area that remained near sea level as the two mountain ranges developed. (Illustration by Bernard Garcia).*

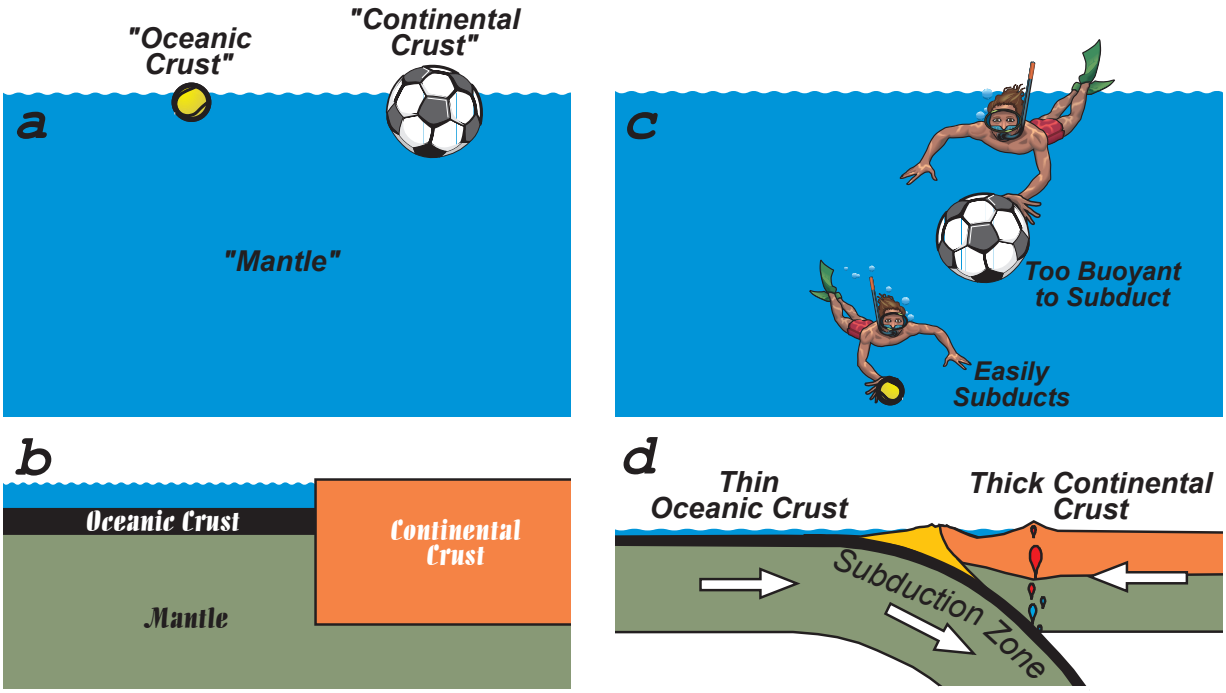


Fig. 4. ***Why an oceanic plate subducts beneath a continental plate.*** *a) A bigger, more-buoyant soccer ball sticks up higher, and rests lower, in a swimming pool than a smaller, less-buoyant tennis ball. b) Thick (more-buoyant) continental crust "floats" up higher on the mantle than the thin (less-buoyant) oceanic crust. c) A swimmer could easily "subduct" the tennis ball to the bottom of the pool, but would have a more difficult time with the soccer ball. d) Likewise, where plates converge, the plate with the thinner oceanic crust will subduct beneath the one with the thicker continental crust.*

easily bring the tennis ball to the bottom of the pool, but it would be more difficult to "subduct" the larger soccer ball. Similarly, a plate capped by thin oceanic crust can easily subduct, while one with thick continental crust is too buoyant. As plates converge in the Pacific Northwest, the oceanic Juan de Fuca Plate thus subducts beneath the continental North American Plate.

3. *Why are the lava-flow rocks in Olympic National Park so dark and heavy?*

The volcanic rocks on the Olympic Peninsula were not formed in the subduction zone, but are most likely products of plate divergence. As the edge of North America ripped away, hot mantle rose from below and began to melt as pressure dropped. Lava flows that poured out on the ocean floor formed minerals rich in iron, making dark-colored ***basalt*** (Fig. 5).

Fig. 5. ***Basalt "pillows" are evidence that rocks of the Olympic Mountains formed beneath the ocean.*** *As a pulse of lava poured out and struck the cold water, it cooled quickly and hardened into a pillow form that settled on the sea floor. Other pulses created pillows that piled up on, and filled the gap between, previously formed pillows. (Hurricane Ridge Road just beyond tunnels. Photo by R. J. Lillie).*

4. Are the Olympic Mountains getting higher or lower?

It's thought that the Olympic Mountains are in a topographic steady state (Fig. 6). The amount of uplift, caused by layers added to the base of the mountains by the Juan de Fuca plate as it subducts, is roughly balanced by erosion due to wind, water, and ice. As more and more layers are added from below, the range continually rises. But erosion on the surface keeps the

mountains at about the same maximum elevation of 1 to 1½ miles (1.5 to 2.5 kilometers). The general height of the mountains is thus maintained as the Olympic Mountains recycle themselves!

It's no coincidence that uplift and erosion are in balance. This is often the case where mountains are actively forming, because erosion increases as topography gets higher and steeper. When mountains begin to form the erosion rate is low, so that uplift exceeds erosion. But if the mountains were to get really high, then the rate of erosion would exceed uplift. So a natural topographic height is established where uplift and erosion rates are equal.

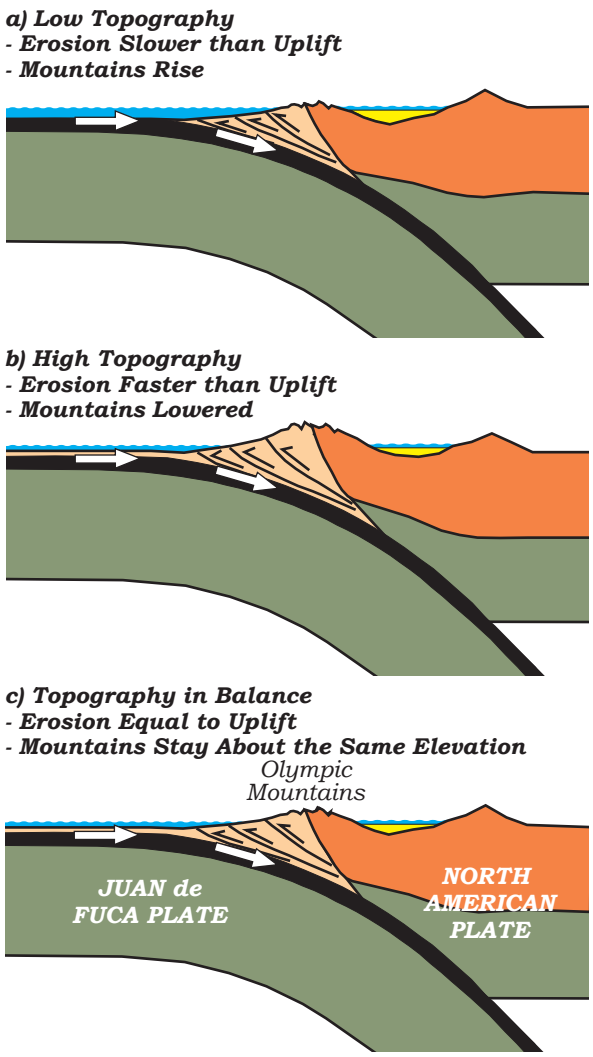


Fig. 6. ***A developing mountain range commonly reaches a steady topographic state.*** *a) Coastal mountain range (like the Olympics) begins to form due to plate subduction. When elevations are low, the erosion rate might be 0.01 in/yr, while the uplift rate is 0.04 in/yr. The net effect is that the topography rises by 0.03 in/yr (0.04 - 0.01 in/yr). b) If the mountains were to grow to great height, the erosion might accelerate to 0.06 in/yr, so that the net effect would be to decrease topography by 0.02 in/yr (0.04 - 0.06 in/yr). c) The mountains find a natural height where the rate of erosion equals the uplift rate. The uplift/erosion rate of 0.04 in/yr in the Olympic Mountains thus produces topography about 5,000 to 8,000 feet above sea level.*

5. Why is a devastating earthquake likely to occur in the Pacific Northwest?

Subduction zones are where the largest earthquakes occur, such as the 1960 Peru-Chile earthquake and the 1964 earthquake in Alaska. The situation is analogous to a stuck dresser drawer. You can pull and pull on it and it won't budge, until finally you pull so hard that the drawer suddenly jerks open. Likewise, converging plates can lock together for decades or centuries, until accumulated stress is so great that the plates suddenly let go and snap along their boundary as a devastating earthquake (Fig. 7). Much evidence, including sudden downdropping of coastal areas,

Deep Thought

The Origin of Deep Canyons

Ice and water have carved canyons deep into the interior of the Olympic Mountains. But why are the Olympic canyons so deep? Why is any canyon deep? Consider the Grand Canyon in Arizona. The Colorado Plateau, 7000 feet (2000 meters) above sea level, is being eaten away by the Colorado River a mile below in the canyon. You might think of the river as a knife carving downward into a wedding cake. But there's another way to look at it. ***Hold the knife steady and move the cake upward.*** Thus the Colorado River has been holding steady at 2000 feet elevation while the Colorado Plateau moves slowly upward. Likewise, rivers like the Elwha want to be near sea level, yet the Olympic "plateau" continues to move upward as material is added from below.

Fun Factoid!

Material added to the base of the Olympic Mountains uplifts the range at a rate of about 4 hundredths of an inch per year (0.04 inches/year; 1 millimeter/year). From a depth of 10 miles (16 kilometers), it thus takes about 15 million years to elevate above sea level. If it were possible for uplift to continue at that rate with no accompanying erosion, then ***in 15 million years the Olympics would have peaks twice as high as Mount Everest!***

great "tsunami" waves, and rapid deposition of sediments offshore, suggests that the last giant earthquake in the Pacific Northwest occurred about 300 years ago. The geological evidence also suggests that equally-large earthquakes occurred 1100, 1300, and 1700 years ago. In fact, it appears that at least seven great earthquakes occurred in the past 3000 years, separated by intervals of 200 to 1000 years. Native American stories and archaeological sites also suggest that the Pacific Northwest was periodically hit by devastating earthquakes. The most straightforward interpretation is that the downgoing Juan de Fuca Plate has been locked against the North American Plate for the past 300 years and that a great earthquake is likely to strike the Northwest during the next one to two centuries, when the plates suddenly let go.

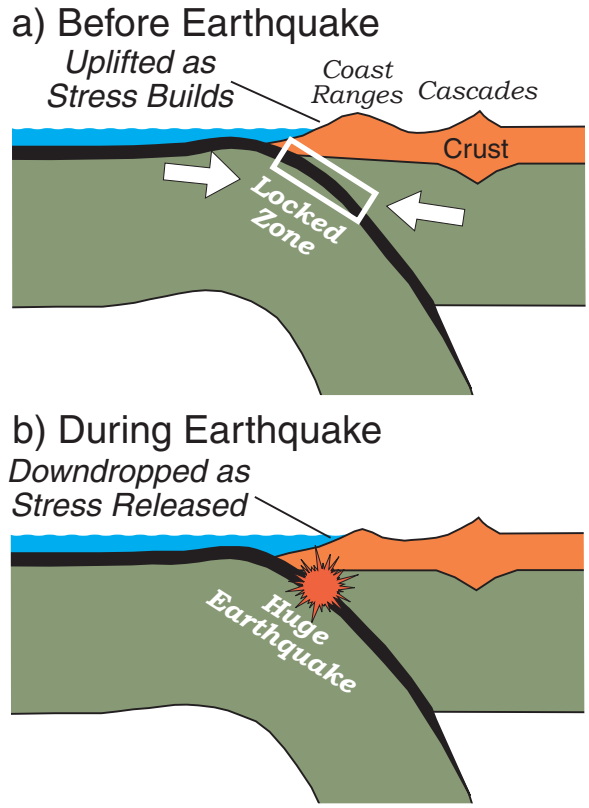


Fig. 7. ***Uplift and downdrop of coastal region due to great subduction zone earthquake.*** *a) Plates lock together. The region above the locked zone is contorted and slowly uplifts, because the plates continue to converge but have no place to go. Shallow bay areas may rise a few feet out of the sea and develop into marshes. b) Plates suddenly unlock. After a few centuries, stress builds to a level where the plates snap apart and the energy is released as a giant earthquake. The uplifted areas drop down abruptly, again becoming shallow bays.*

PLATE TECTONICS: BUILDING THE LANDSCAPE

The geological landscape is the stage upon which episodes of natural and cultural history are played.

The Pacific Northwest is an exciting place to observe geologic processes in action. As the Juan de Fuca Plate plunges beneath North America, sediment and hard rock from the ocean floor are scrapped off and squeezed upward as the spectacular mountains of Olympic National Park. Farther east the deepening plate becomes so hot that it releases fluids that melt their way to the surface, forming the beautiful but dangerous volcanoes in the Cascade Mountains. And as time ticks on, the entire region awaits sudden release of energy locked between the converging plates as a devastating earthquake.

The term ***tectonics*** originates from the Greek word "tektōn," referring to a builder or architect. ***Plate tectonics*** suggests that large features on Earth's surface, such as continents, ocean basins, and mountain ranges, result from interactions along the edges of large plates of Earth's outer shell, or ***lithosphere*** (Greek "lithos," hard rock). The plates, comprised of Earth's crust and uppermost mantle, ride on a warmer, softer layer of the mantle, the ***asthenosphere*** (Greek "asthenos," lacking strength). Earth's lithosphere is broken into a mosaic of seven major and several minor plates (Fig. 8). Relative motions between plates define three types of boundaries: ***divergent***, where plates rip apart, creating new lithosphere; ***convergent***, where one plate dives beneath the other and lithosphere is destroyed; ***transform***,

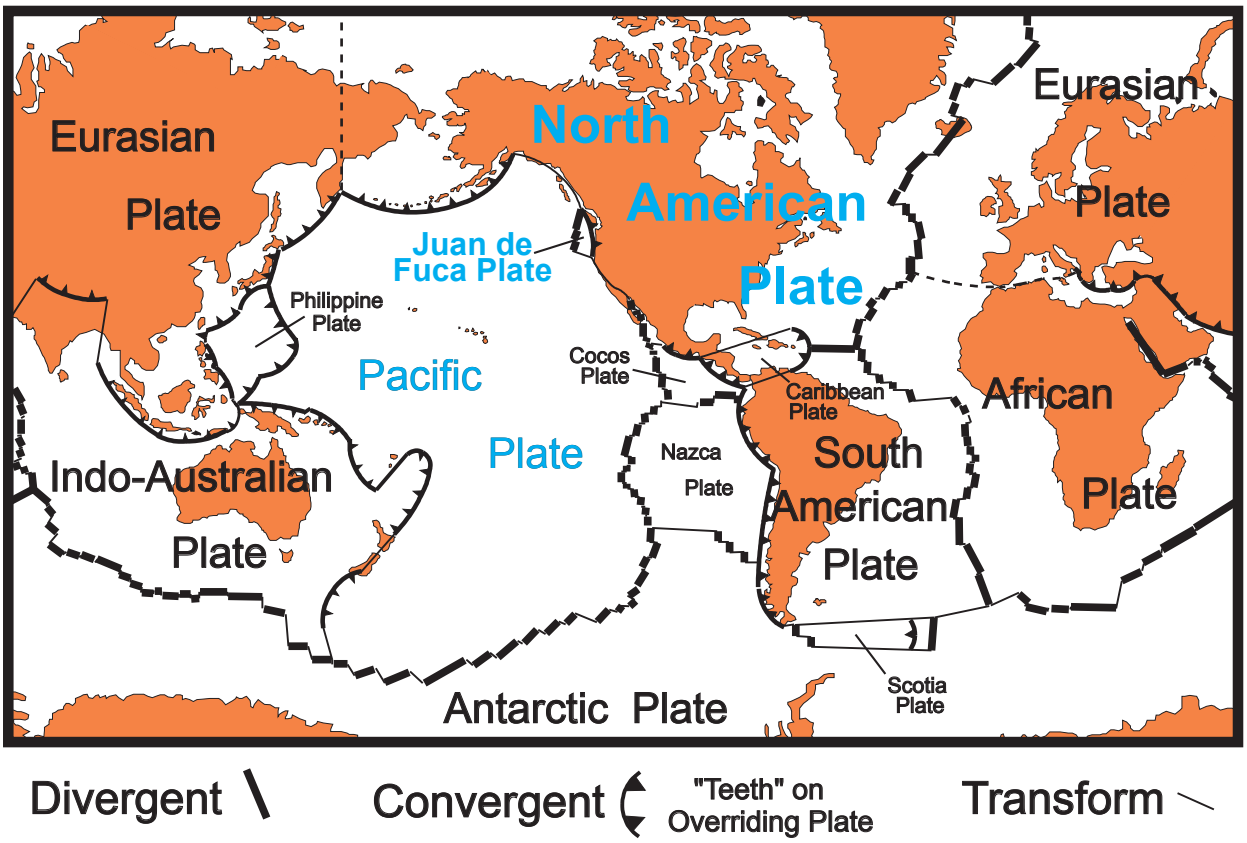


Fig. 8. ***Plate tectonic map of the world, showing the three types of plate boundaries.*** *The Pacific Northwest is a convergent plate boundary where the small Juan de Fuca Plate subducts beneath the North American Plate.*

where plates slide past one another, neither creating nor destroying lithosphere (Fig. 9). Another large-scale feature is a ***hotspot***, where a plate rides over a fixed "plume" of hot mantle, creating a line of volcanoes. Distinct patterns of mountains, earthquakes, and volcanoes are associated with each type of plate boundary and with hotspots.

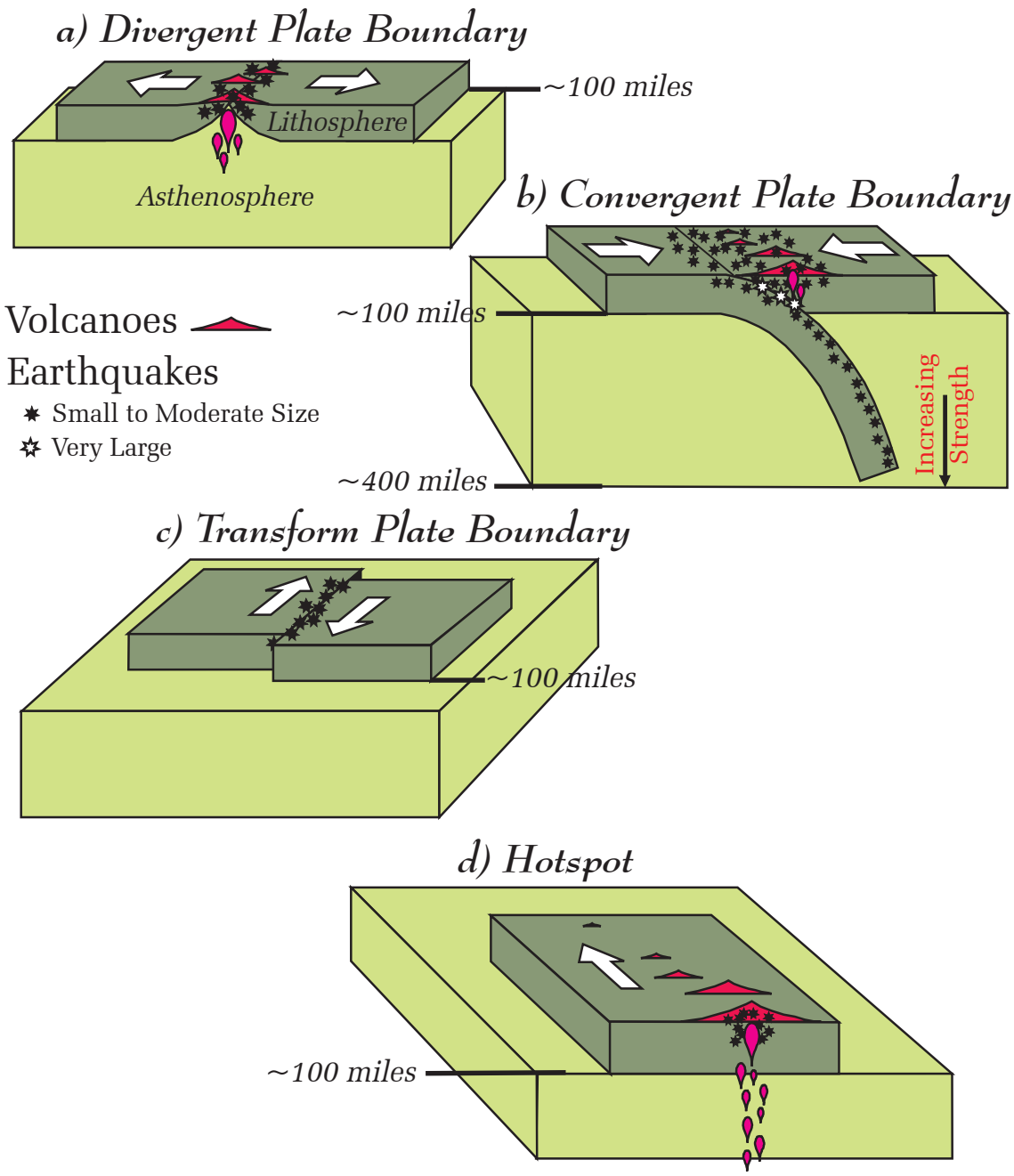


Fig. 9. ***Tectonic activity occurs at the three types of plate boundaries and at hotspots.*** *Volcanoes erupt in the zone where plates diverge, on the overriding plate where plates converge, and along a line where a plate rides over a hotspot. Only shallow earthquakes, of small to moderate size, occur at* **divergent** *and* **transform** *boundaries and at* **hotspots**. *The cold, brittle lithosphere may extend to great depths at* **convergent** *boundaries, accompanied by a dipping zone of shallow to very deep earthquakes; the largest earthquakes occur at convergent boundaries where the two plates lock together for many years, then suddenly let go.*

The Whole Earth

Soon after it formed 4.6 billion years ago, the molten Earth settled into three layers (left side, Fig. 10). Dense material, mostly iron, fell toward the center to form the ***core***. Lighter compounds of silicon and oxygen (silicates) remained closer to the surface. Silicates rich in iron and magnesium formed the ***mantle***, overlain by a thin ***crust*** of silicates containing light elements (aluminum, calcium, potassium, and sodium). This classical division, based on chemical composition, was discovered in the early 1900's by analyzing earthquake seismic waves that penetrated the entire Earth.

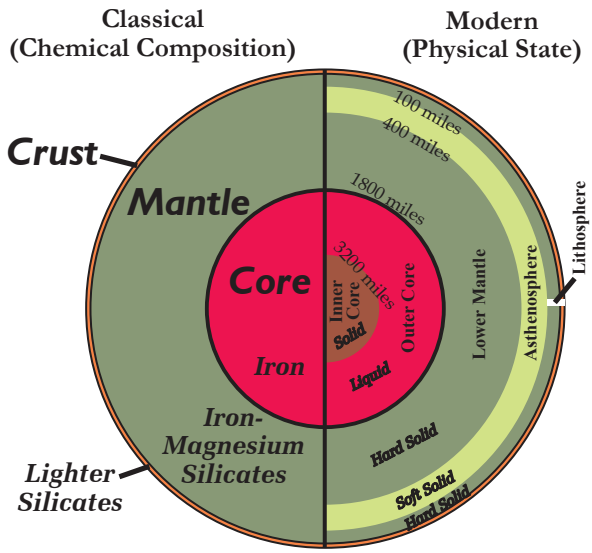


Fig. 10. ***Gross layers of the Earth.*** *Left: The classical division of the Earth is according to* **chemical composition**, *the heavier materials concentrated toward the center. Right: In modern times the three chemical divisions are divided into five zones according to* **physical state**, *caused by temperature and pressure changes within the Earth.*

By the mid 20th century detailed seismic observations made it possible to study Earth's interior in finer detail. In modern times the three chemical layers are differentiated into five zones based on physical state (right side, Fig. 10). Changes in physical state occur because both temperature and pressure increase downward in the Earth. Temperature is hot enough at depths of 1800 to 3200 miles (2900 to 5100 kilometers) that the iron of the ***outer core*** is liquid. Below that, however, to a depth of 4000 miles (6400 kilometers) at Earth's center, pressure is so great that the ***inner core*** is solid.

The iron/magnesium silicates of the mantle also show stratification due to the increasing temperature and pressure (Fig. 11). The outermost mantle and crust are cold and hard (like butter in a refrigerator), forming the rigid ***lithosphere***. Below about 100 miles (150 kilometers) depth the mantle is warmer, so that the ***asthenosphere*** is a softer solid (like butter left on a dinner table). Still deeper, from 400 to 1800 miles (700 to 2900 kilometers), pressure is so great that the ***lower mantle*** is again a hard solid. These changes in strength of the mantle create a unique situation where plates of lithosphere ride over the softer zone of asthenosphere, similar to sliding a hard Oreo® Cookie over the creamy filling (Fig. 12).

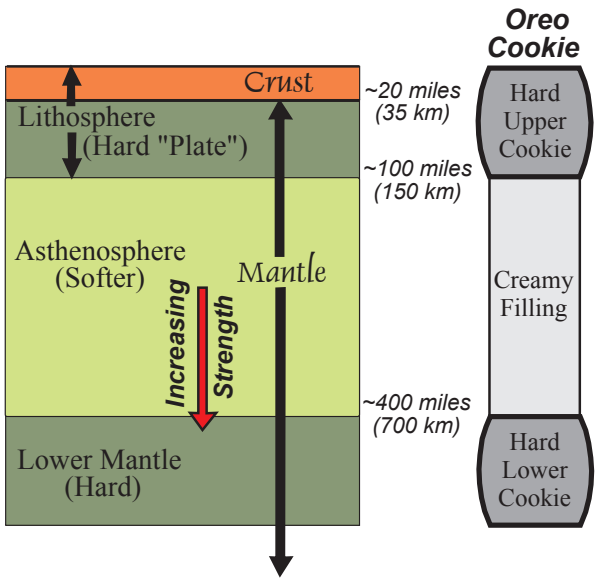


Fig. 11. ***Cross section of the upper 600 miles (1000 kilometers) of the Earth, including the crust and part of the mantle.*** *Increases in temperature and pressure with depth cause the mantle to exist in three different states. The uppermost mantle and crust comprise the cold, rigid plates of lithosphere. Hotter mantle below forms the somewhat softer asthenosphere. Pressure increase with depth causes the asthenosphere to gradually increase in strength, to the more solid lower mantle. Lithospheric plates can be compared to a hard Oreo® cookie, riding on the soft, creamy filling (asthenosphere). The lower cookie (lower mantle) does not move.*

Sliding a Plate over the Asthenosphere

a) Divergent Plate Boundary

b) Convergent Plate Boundary

c) Transform Plate Boundary

Fig. 12. ***Simulating lithospheric plate boundaries with Oreo® cookies.***

Fun with Food!

Sliding Plates and Oreo® Cookies

The three types of plate boundaries (Fig. 9) can be demonstrated with Oreo® cookies (Fig. 12). The upper cookie is the ***lithosphere***, the creamy filling the ***asthenosphere***, and the lower cookie the ***lower mantle*** (Fig. 11). (Be sure to get the "Double Stuff" variety, which has adequate asthenosphere)! First, carefully remove the upper cookie (a "twisting" motion is required). Slide the upper cookie over the creamy filling to simulate motion of a rigid lithospheric plate over the softer asthenosphere. Next, break the upper cookie in half. As you do so, listen to the sound it makes. What does that sound represent? (An earthquake. Message: it takes cold, brittle lithosphere to make earthquakes – earthquakes do not occur in the soft, flowing asthenosphere).

- To simulate a ***divergent plate boundary***, push down on the two broken cookie halves and slide them apart. Notice that the creamy filling between the two broken "plates" may tend to flow upward, similar to the rising, decompression, and partial melting of hot asthenosphere at mid-ocean ridges.
- Push one cookie piece beneath the other to make a ***convergent plate boundary***. Note that this is the only situation where the cold, brittle lithosphere extends to great depths, and hence the only place where deep earthquakes occur. The very largest earthquakes are at subduction zones where two plates get stuck together for centuries, then suddenly let go (Figs. 7 and 9b).
- Simulate a ***transform plate boundary*** by sliding the two cookie pieces laterally past one another, over the creamy filling. You can feel and hear that the "plates" do not slide smoothly past one another, but rather stick then let go, stick then let go. The cracking sound you hear each time is like an earthquake occurring along the San Andreas Fault in California.

Tectonics of the Pacific Northwest

The Pacific Northwest is a region where a plate capped by thin oceanic crust is subducting beneath North America. The coastal ranges of Vancouver Island, Washington, Oregon, and northern California contain rugged mountains of rocks that were manufactured in the ocean, then scrapped off the plate and lifted out of the sea. But the Cascade Mountains – within the same subduction zone – are dramatically different. They contain explosive volcanoes formed as hot water rises from the top of the subducting plate and generates magma as it melts its way to the surface.

Rangers can set the stage for programs on the ecological, biological, and geological aspects of Olympic National Park by first describing the broad landscape of the region and explaining how it developed. The large-scale topography and other geologic features in the Pacific Northwest result, to a large degree, from the interaction of two plates of Earth's rigid outer shell (Fig. 13). The ***Cascadia Subduction Zone*** is the region of convergence between the Juan de Fuca and North American plates. The convergence results in two parallel mountain ranges (Fig. 14): an ***accretionary wedge*** due to uplift of material from the sea (the Olympics and other coastal ranges), and a ***volcanic arc*** (the Cascade Mountains). The ranges are separated by a "forearc basin" filled with sediment and sometimes water (Puget Sound in Washington, the Willamette Valley in Oregon, the Great Valley in California). Park Service sites in the coastal ranges (Olympic National Park, Oregon Caves National Monument, Redwood National and State Parks) are thus sedimentary layers and hard crust lifted out of the sea, while national parks in the Cascades (Mount Rainier, Crater Lake, and Mount Lassen) are on active volcanoes.

WARNING!!

Buzzword Alert!

Terms like "accretionary wedge" and "volcanic arc" convey, concisely, information about a portion of the Earth to those trained in geology. Such buzzwords are given here so that you might understand their meaning when you run across them in readings or in conversations with some scientists. If you use these words, be sure to explain them clearly and avoid overusing them.

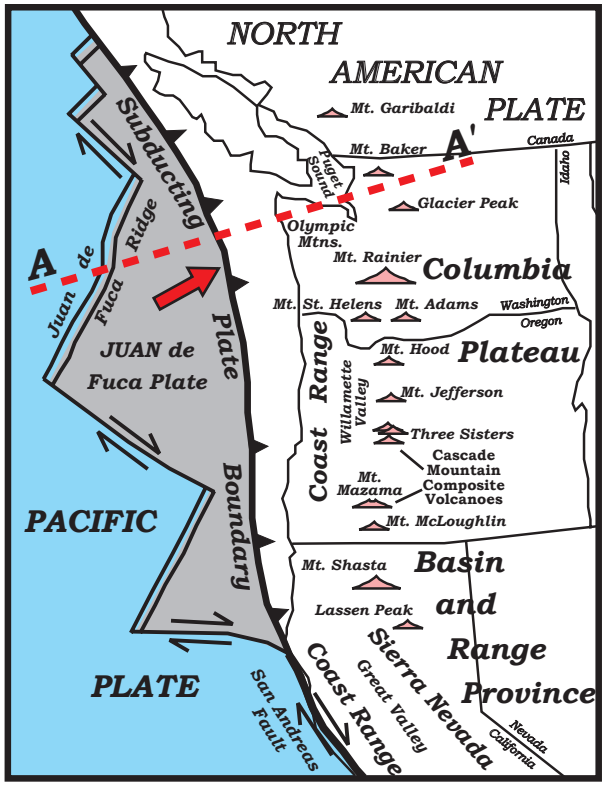


Fig. 13. ***Tectonic elements of the Pacific Northwest.*** *The broad landscapes are due to interactions along three types of plate boundaries.* **Divergent Plate Boundary:** *The small Juan de Fuca plate is manufactured where it diverges from the Pacific Plate along the Juan de Fuca Ridge system.* **Convergent Plate Boundary:** *Two parallel mountain ranges form where the Juan de Fuca plate is subducting northeastward beneath the North American Plate: coastal ranges (including the Olympic Mountains) near the plate boundary, and the Cascade volcanoes farther inland. Puget Sound in Washington, the Willamette Valley in Oregon, and the Great Valley in California are the low areas between the two ranges.* **Transform Plate Boundary:** *The San Andreas Fault is the boundary where the Pacific Plate is sliding north-northwestward past the North American Plate. Other tectonic features include the Basin and Range Province (a continental rift zone where the North American plate is ripping apart), the Columbia Plateau (perhaps the place where the Yellowstone "Hotspot" originally surfaced), and the Sierra Nevada Mountains (the eroded remnants of an extension of the Cascade volcanic arc). A-A' is the line of the cross section shown in Fig. 15.*

Juan de Fuca Ridge (Divergent Plate Boundary)

The Juan de Fuca Plate is one of Earth's smaller plates (Fig. 8). It is actually being created about 200 miles (350 kilometers) off the coast of the Pacific Northwest, where the ocean floor is ripping apart along the Juan de Fuca Ridge (Fig. 15). At such a ***divergent plate boundary*** hot mantle rises, elevates the sea floor, and begins to melt. New plate material is thus added to the edges of the Pacific and Juan de Fuca Plates as they move away from one another. Lava pours out on the ocean floor, cooling to form pillows of basalt. As the Juan de Fuca Plate moves toward North America, sediment from the eroding continent covers the basalt and hardens into layers of sandstone and shale.

Cascadia Subduction Zone (Convergent Plate Boundary)

The North American Plate is capped by continental crust, which is thicker and therefore more buoyant than the oceanic crust of the Juan de Fuca Plate (Fig. 4). Plate convergence thus results in subduction of the Juan de Fuca Plate beneath the edge of North America (Figs. 14, 15).

Deep-Sea Trench (Not!). As the top of the Juan de Fuca Plate begins its downward plunge about 50 miles (80 kilometers) offshore, it creates a depression on the sea floor. In other areas where an ocean plate subducts, as off the west coast of South America, a deep-sea trench forms. In the Pacific Northwest, however, two factors inhibit trench development. First, the Juan de Fuca Plate converges with North America at a relatively slow rate of only about 2 inches (5 centimeters) per year. Second, the wet climate means that an enormous amount of sediment is deposited off the coast. The depression in the sea floor fills up with sediment just about as fast as it forms, so that no deep-sea trench is evident. But the thick accumulation of sediment is important, as it supplies new material that is added to the base of the Olympic and other coastal ranges and maintains their high topography.

Olympics and other Coastal Mountain Ranges ("Accretionary Wedge"). Near the Pacific coast the top of the Juan de Fuca Plate is less than 10 miles (16 kilometers) deep, where it is still cold and rigid. As the plate descends sediment, and occasionally some of the basaltic ocean crust, are scraped off its top and squeezed upward along folds and faults. The

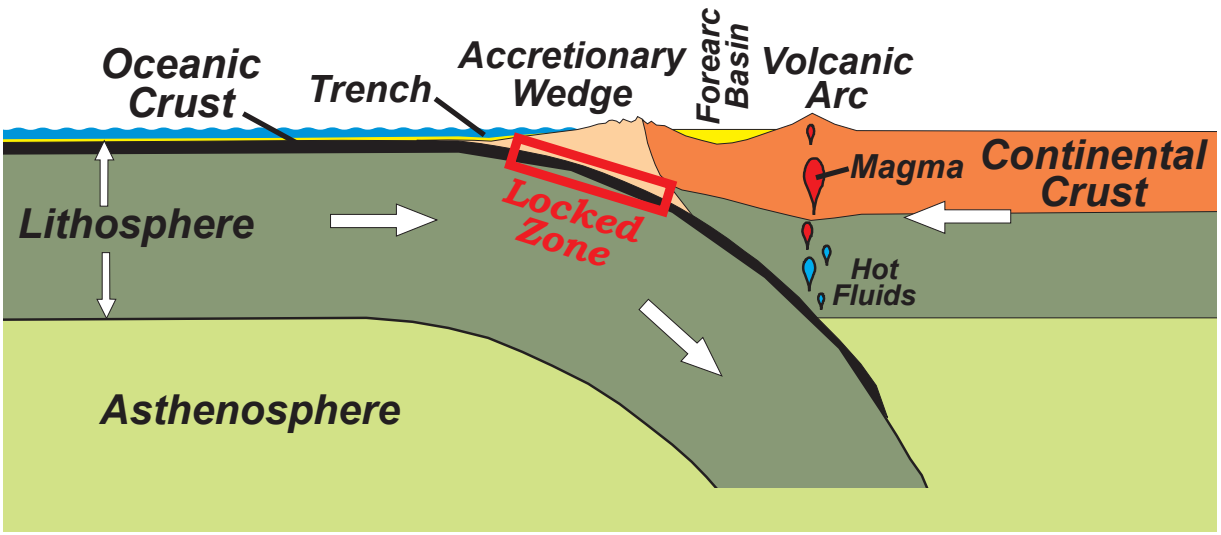


Fig. 14. ***Ocean-continent subduction zone at a convergent plate boundary.*** *The plate with thinner (less-buoyant) oceanic crust descends (subducts) beneath the plate with thicker (more-buoyant) continental crust, depressing the ocean floor at a* **deep-sea trench**. *Two parallel mountain ranges form on the overriding plate: an* **accretionary wedge**, *where material scrapes off the cold plate; and a* **volcanic arc**, *above the region where the plate gets hot enough to "sweat" fluids. The sediment-filled depression between the two ranges is the* **forearc basin**. *The* **locked zone** *is where the two plates may stick together for centuries, only to suddenly let go as a devastating earthquake.*

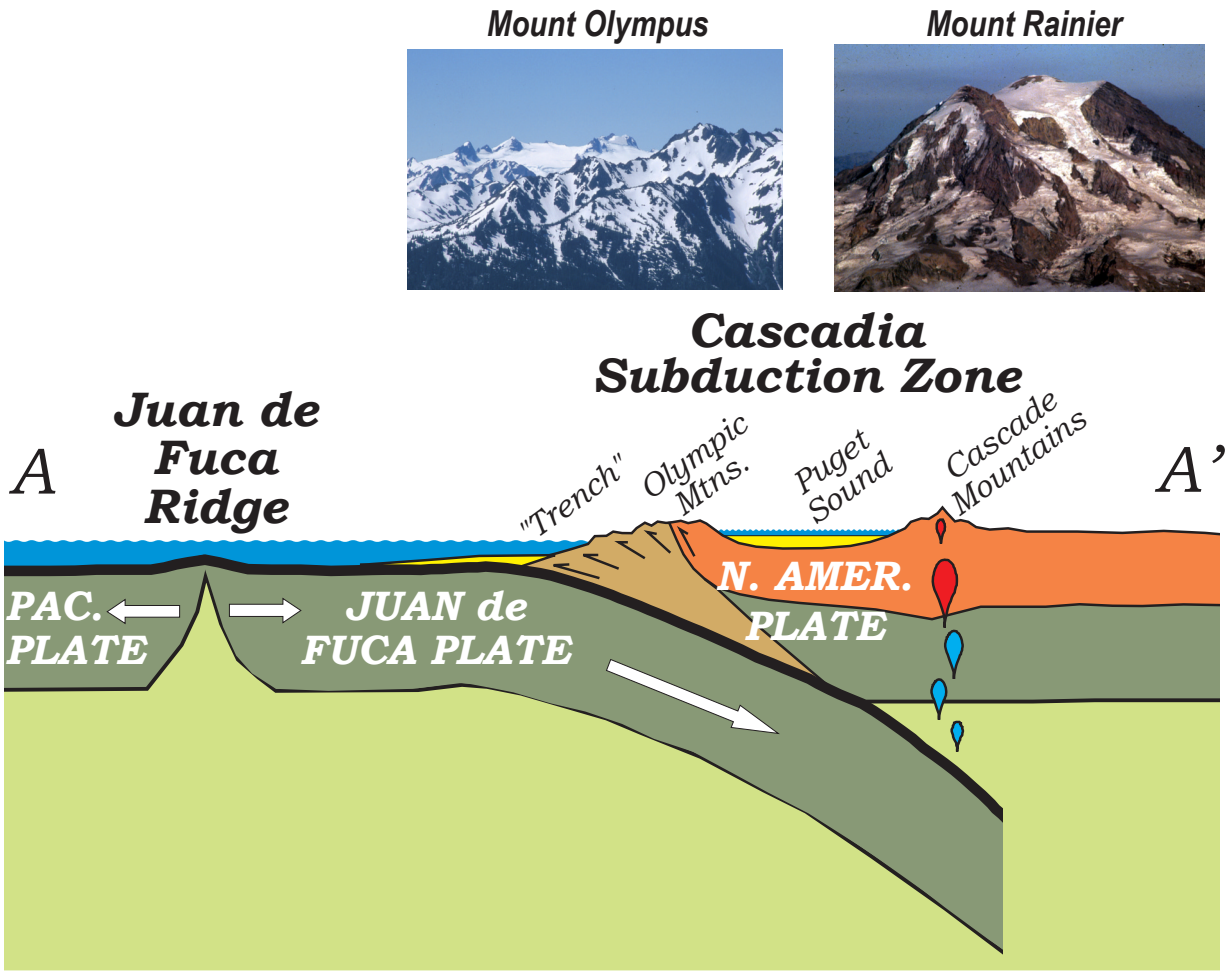


Fig. 15. ***Subduction in the Pacific Northwest results in two parallel mountain ranges.*** *(Cross-section A-A' from Fig. 13). The Juan de Fuca Plate forms at the Juan de Fuca Ridge, where it moves away from the Pacific Plate. Ocean sediments are scraped off the top of the Juan de Fuca Plate as it subducts beneath the edge of North America, piling up as the* **Olympic Mountains** *("accretionary wedge"). Hot fluids sweat from the top of the plate farther east, rising and melting rock to form the* **Cascade Mountains** *("volcanic arc"). Puget Sound is part of the low area ("forearc basin") between the structural (Olympic) and volcanic (Cascade) mountain ranges. Mount Olympus and Mount Rainier illustrate the contrasting appearance of mountains in each range. (Photos by R. J. Lillie).*

material attaches (or "accretes") to the overriding North American Plate, assuming an overall wedge shape. The Coast Range Mountains of Vancouver Island, Washington, Oregon, and California thus comprise an ***accretionary wedge***.

Puget Sound and other Lowlands ("Forearc Basin"). Puget Sound in Washington, the Willamette Valley in Oregon, and the Great Valley in California are lowlands between the uplifted (coastal) and volcanic (Cascade) mountain ranges. These regions lie in front of the volcanic are (Cascades) and collect sediment, and are thus the ***forearc basin***.

Cascade Mountains ("Volcanic Arc"). About 150 miles (250 kilometers) inland from the coast, the top of the Juan de Fuca plate is about 50 miles (80 kilometers) deep, where the sedimentary layers and hard crust are subjected to high temperatures and pressures and metamorphosed. A by-product of the metamorphism is the release of hot fluids, especially water and carbon dioxide. Being lighter than the surrounding rock, those hot fluids rise and melt rock in their path. The melting produces silica-rich magma that is so thick and

Fun Factoids!

• The Juan de Fuca Plate moves northeastward, toward and under the North American Plate, at a rate of about 2 inches (5 centimeters) per year. ***Your fingernails grow at about the same rate!***

• Even though it's moving so slowly, given enough time the plate covers a significant distance. Every one million years the plate moves about 30 miles (50 kilometers)!

• In 8 million years, crust of the Juan de Fuca Plate makes the entire journey of 200 miles (350 kilometers) from where it is manufactured at the Juan de Fuca Ridge to where it plunges downward at the Cascadia Subduction Zone.

pasty that it sometimes traps gasses under high pressure. The magma erupts through the Cascade Mountain volcanoes in a variety of ways. Occasionally it explodes if pressure on the trapped gasses is released suddenly, as occurred at Mount St. Helens in 1980. More often it pours out on the surface and hardens to gray-to-pink colored rocks called andesite, dacite, and rhyolite. The high gas content can cause frothy particles of pumice to spew forth, or fine particles of ash to rise high in the air. Hot magma can release water or melt large amounts of glacial ice; when steep parts of a volcano collapse as landslides, mudflows can roar down valleys, freezing into layers as hard as concrete. And at times very hot clouds of gas roar down the mountain slopes, devastating everything in their paths. The layer-upon-layer of different materials have built the Cascade Mountains into "strato" or "composite" volcanoes reaching elevations over 14,000 feet (4300 meters). Their steep profiles are due to the high-silica lava, which tends to stick to the sides rather than flow long distances.

It may seem remarkable that the Cascade volcanoes lie along a fairly narrow line extending northward from Mt. Lassen in northern California to Mt. Garabaldi in southern British Columbia (Fig. 13). But the reason becomes clear when you realize that the line of volcanoes is directly above the magic depth of 50 miles (80 kilometers), where the top of the Juan de Fuca Plate begins to "sweat" (Fig. 3).

Earlier Tectonic Events

The basic Olympic story involves subducting the Juan de Fuca plate, scraping sedimentary strata off its surface, and the resulting uplift and erosion that produce the spectacular mountains. Subduction also helps us understand why some of the rocks are metamorphosed, how certain structures developed, and the potential for large earthquakes. The fact that subduction is an ongoing process makes it easy to appreciate that the rocks and structures of Olympic National Park formed through processes similar to those happening today. The subduction story is thus a simple and effective way for Resource Education Rangers to help visitors contemplate how the Earth operates in the Pacific Northwest.

But the Olympic story also involves events that occurred before the modern subduction zone was established. It includes gradual growth of the North American continent westward, formation and uplift of the Crescent Terrane that now rims the park, then development of the modern accretionary wedge that forms the core of the Olympics.

Westward Building of the North American Continent

The Olympic and Cascade mountain ranges represent only the very latest of the events that have been shaping the landscape of the Pacific Northwest. In fact, 100 million years ago the edge of the North American continent was in the far eastern portion of Washington state (Fig. 16a). Much like the modern situation, oceanic crust was subducting eastward, building a volcanic arc and accretionary wedge (Fig. 16b). Over time fragments of thick continental crust and oceanic islands were added to the continental edge. Rocks of North Cascades National Park are not volcanoes like the modern Cascades; instead they are much older materials (an "exotic terrane") that crashed into North America. With addition of more and more material, the subduction boundary progressively jumped westward. Its present position developed about 50 million years ago.

As subduction zones jumped westward, mountain ranges were added to the Pacific Northwest. Over time, the mountains eroded downward as the continent grew westward.

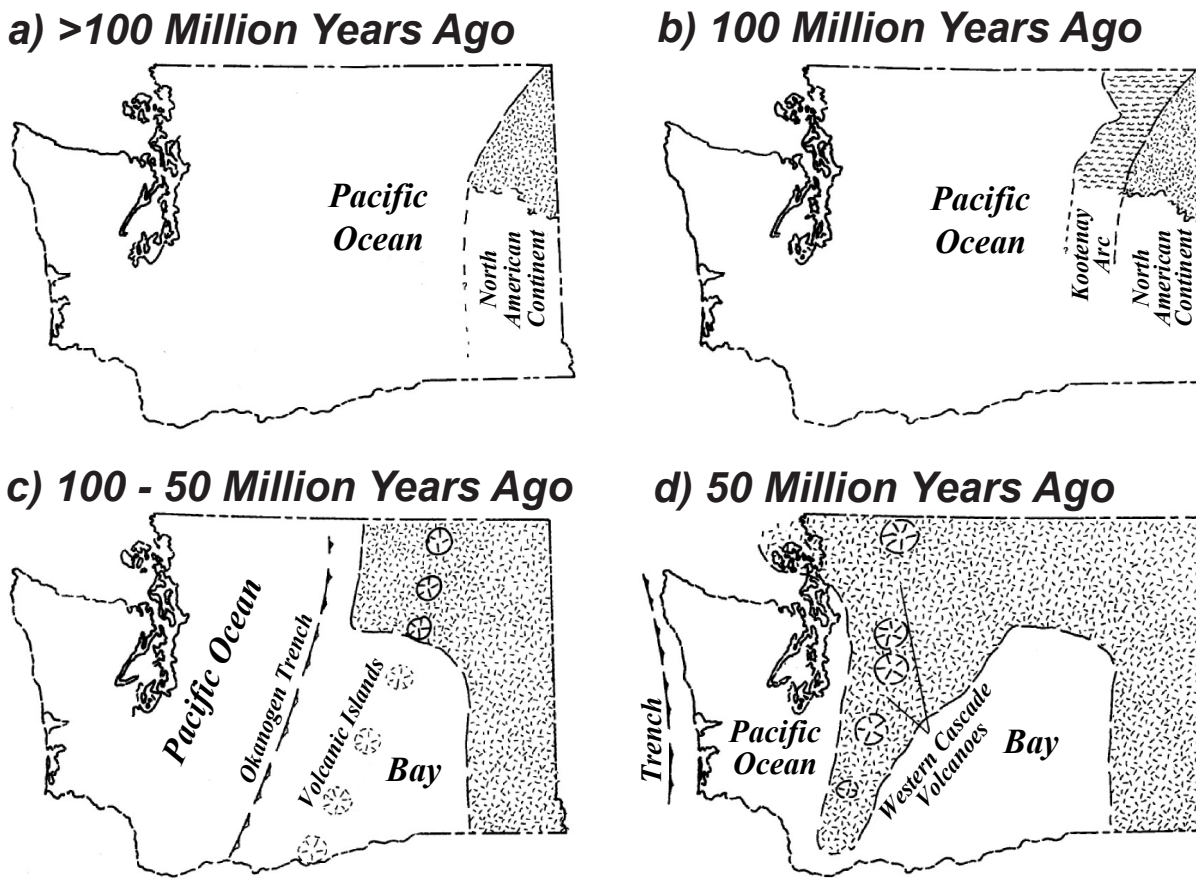


Fig. 16. ***Westward growth of North American continent.*** *a) The west coast of North America was in the position of eastern Washington prior to 100 million years ago. b) The Kootenay arc, a volcanic mountain chain similar to today's Cascades, developed along the continental edge. c) Subduction off the west coast (Okanogan Trench) resulted in another volcanic arc and added more material to North America. d) After "exotic crust" of the North Cascades crashed into the continent, the trench jumped farther westward. The Olympics and Cascades are the latest in a series of subduction-related mountain ranges that comprise the Pacific Northwest. (From D. D. Alt and D. W. Hyndman, "Roadside Geology of Washington," Mountain Press Publishing Company, 1984).*

Mountain ranges in western Idaho and eastern Oregon and Washington thus become progressively younger as you travel westward; their rocks are the deep portions of the volcanic and coastal ranges that formed along the ancient subduction zones. The Coast Ranges and Cascade Mountains are the youngest set of subduction-related mountain ranges; in time the subduction zone might again jump westward, stranding remnants of those mountains as new mountains form in the region that is currently offshore.

Origin of the Crescent Terrane

It's important when interpreting to the public to convey the idea that science is constantly evolving and that different theories may exist to explain the same phenomena. The Crescent Terrane is part of a series of basalt outcroppings that extend from southern Oregon to Vancouver Island (Fig. 17). The rocks formed between 56 and 47 million years ago, then were uplifted and permanently attached to the edge of North America about 30 million years ago. They consist mainly of oceanic basalt, as evidenced by pillows (Fig. 5), but ancient soils and the development of cracks ("columnar joints") suggest they occasionally poured out on land. Earlier interpretations suggested that the basalt terranes formed along a mid-ocean ridge or hotspot and were rafted in from oceanic plate movement. But they may have developed much closer to the edge of North America.

Plate divergence can literally tear a continent apart. Such continental rifting is happening today in the Gulf of California where Baja is ripping away from the rest of North America. Although the origin of the Crescent Terrane is still uncertain, a number of geologists now believe that earlier plate movements may have ripped apart the edge of the continent. Massive amounts of basalt, as much a 24,000 cubic miles (100,000 cubic kilometers) flowed into the ocean water along the continental shelf and built up seamounts and emerging islands. This theory is supported by recent structural, geochemical, and paleontological studies. The word "terrane" is also being questioned, as the basalts may have formed in place along the continental margin instead of being rafted in on an oceanic plate from farther out to sea. A hotspot plume near the continental margin, such as the one that is now under Yellowstone National Park, may also have been involved.

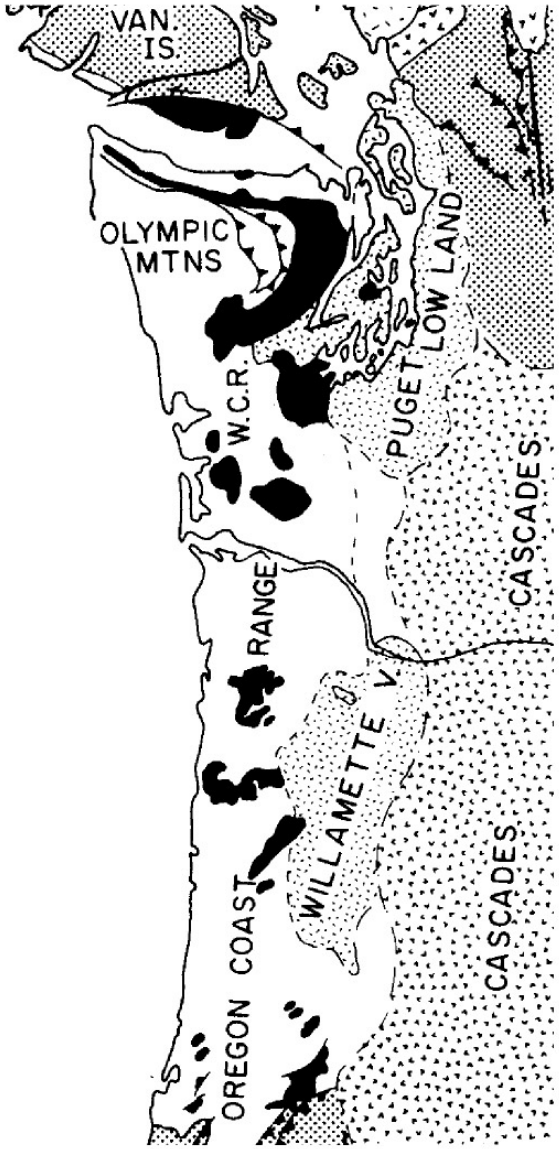


Fig. 17. ***Exposures of 49 to 62 million year old basalt in the coastal ranges of the Pacific Northwest.*** *The rocks, shown in black, include the* **Crescent Terrane** *on the Olympic Peninsula and the* **Metchosin Formation** *on the southern tip of Vancouver Island. (From R. A. Duncan, 1982, "A captured island chain in the Coast Range of Oregon and Washington," Journal of Geophysical Research, vol. 87, p. 10827-10837, 1982).*

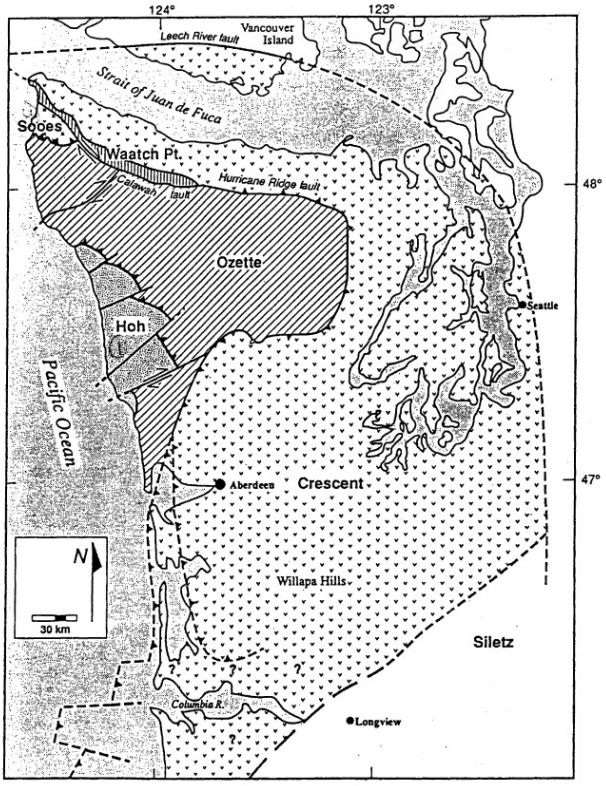


Fig. 18. ***Simplified map of major bedrock units in northwestern Washington.*** *Basalt of the Crescent Terrane underlies not only portions of Olympic National Park, but also much of the Puget Sound area and regions south of the park ("v" pattern on map). (From R. S. Babcock, C. A. Suczek, and D. C. Engebretson, "The Crescent 'Terrane,' Olympic Peninsula and southern Vancouver Island," Washington Division of Geology and Earth Resources, Bulletin 80, p. 141-157, 1994).*

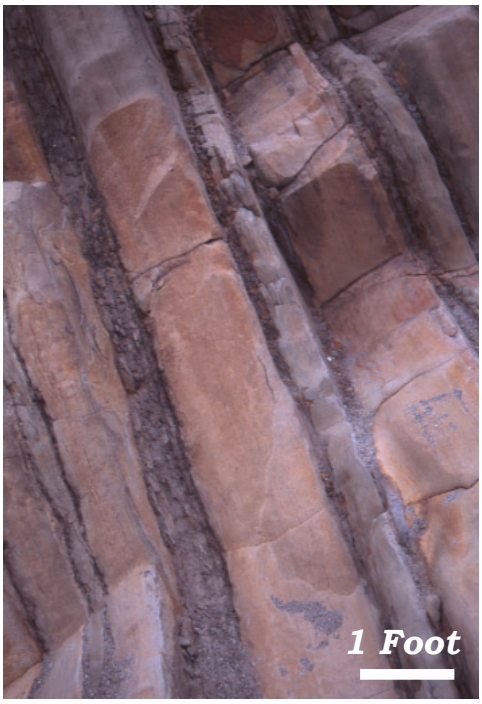
THE MATERIALS OF OLYMPIC NATIONAL PARK

Resource Education Rangers at Olympic National Park have a relatively easy task identifying rocks because most of the rocks in the park are ***basalt***, ***sandstone***, ***shale***, or ***slate*** (Fig. 19). But what luck! Just those four examples represent the three basic types of rocks: basalt is igneous rock; sandstone and shale are sedimentary rocks; slate is metamorphic rock. Rangers can educate the public by emphasizing the vastly different processes responsible for forming each type: hot, molten liquid cools and solidifies to form igneous rock; ice, wind, and water erode and transport particles of rock that settle and harden into layers of sedimentary rock; pre-existing rocks re-crystallize in a solid state to form metamorphic rock.

You can weave Earth's materials into the Olympic story of subduction and recycling (Fig. 1). The basalt rocks are relatively old, manufactured somewhere off the coast of North America about 50 million years ago and later uplifted as a result of plate convergence. Sand and mud eroded from the continent has been continuously deposited on the Pacific sea floor. The sandstone and shale layers now exposed in the Olympic Mountains formed from 45 to 20 million years ago. But some of those layers were pushed down to depths of 7 to 10 miles

a) Igneous Rock

b) Sedimentary Rock



c) Metamorphic Rock

Fig. 19. ***The three basic types of rocks are represented by the four most common rocks in Olympic National Park.*** *a) Igneous*. **BASALT** *just beyond the tunnels on the Hurricane Ridge Road. b) Sedimentary*. **SANDSTONE** *interbedded with thin layers of* **SHALE** *on Beach 3 north of Kalaloch. c) Metamorphic*. **SLATE** *two miles up the Obstruction Point Road. (Photos by R. J. Lillie).*

(11 to 16 kilometers) and changed to metamorphic rock like slate. The rock cycle continues today as new basalt is forming at the Juan de Fuca Ridge, particles of exposed rock erode from the Olympic Mountains and are deposited on top of the new basalt, and older sedimentary layers are being metamorphosed beneath the mountains.

Besides the four dominant rock types, other rocks are found in Olympic National Park. ***Gabbro***, a rock similar to basalt but containing larger mineral crystals formed deeper within the Earth, is found on The Needles in the northeastern part of the park, as well as at Point of Arches on the coast. Layers of ***limestone*** are in places interbedded with the older sedimentary strata on Hurricane Ridge. There are also very young sedimentary layers that were deposited by melting glacial ice and water in stream valleys. And a wide variety of rock types are found in large boulders called ***glacial erratics***, manufactured in Canada and brought to the Olympic area by great continental ice sheets during the height of recent ice ages.

Rocks and Minerals

Sometimes the terms "rock" and "mineral" are confused. A ***mineral*** is a substance that has the following properties. 1. It is a naturally-occurring, inorganic solid. 2. It has a definite chemical composition. 3. It has a specific crystalline structure. 4. It has definite physical properties that result from the chemical composition and crystalline structure. Take for example, the mineral ***quartz***. Its chemical composition is SiO_2, meaning the crystal molecules have two atoms of oxygen (O) for every one atom of silicon (Si). Quartz forms long, six-sided crystals that come to a point. One of its physical properties is that it has hardness of 7, meaning it can scratch the mineral orthoclase (hardness 6), but not topaz (hardness 8).

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

Three Basic Types of Rocks

Rocks are classified according to the way they formed. An ***igneous rock*** is an aggregate of interlocking minerals, formed by the cooling and solidification of molten magma. A ***sedimentary rock*** is an aggregate of fragments eroded from older rocks, or minerals precipitated through chemical or biological activity. A ***metamorphic rock*** is an aggregate of interlocking minerals, formed by re-crystallization of some or all of the minerals in an existing rock; the re-crystallization occurs when the rock is subjected to elevated temperature or pressure, but while the rock is still solid.

Igneous Rocks

Igneous rocks solidify from ***magma***, which is molten rock that may contain gases and suspended solid material. The terms "magma" and "lava" are often used interchangeably, but have important differences. All melted Earth material is magma, while ***lava*** is magma that poured out on Earth's surface, forming ***extrusive*** (***"volcanic"***) rocks. When magma solidifies below Earth's surface, ***intrusive*** (***"plutonic"***) rocks result.

Igneous rocks are classified according to two parameters, texture and chemistry (Table 1). ***Texture*** refers to the ***size of the mineral grains***, which is a function of how quickly the magma cooled (Fig. 20). Intrusive rocks are coarse-grained because they cooled very slowly within the Earth, where mineral crystals had time to develop. Magma that encounters air or water at Earth's surface cools very quickly, so that extrusive rocks have fine-grained minerals that you generally cannot see with your naked eye.

The ***chemistry*** of igneous rocks is commonly related to the ***amount of silica*** (silicon and oxygen) contained in the rock minerals (Table 1). Silica is the same material that makes up window glass and, in its pure form, is the mineral quartz (SiO_2). Rocks with high silica content thus tend to be light-weight and light in color. Coarse-grained (intrusive) ***granite*** and fine-grained (extrusive) ***rhyolite*** are pink-to-white-colored igneous rocks that are high in silica (≈ 70% of the total rock mass).

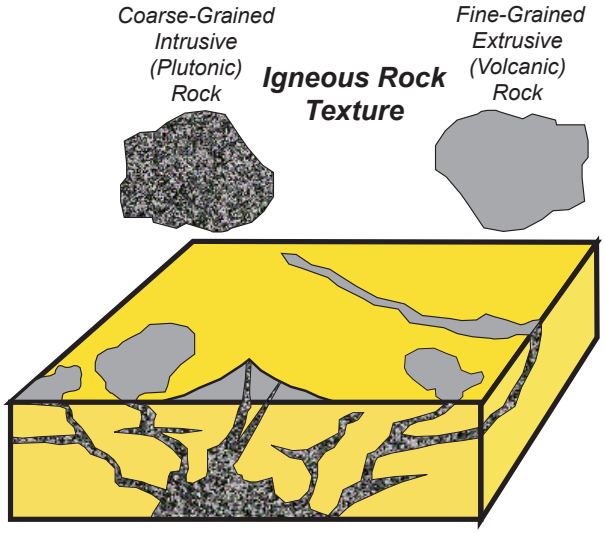


Fig. 20. **Texture of igneous rocks.** *Magma may cool below Earth's surface, forming coarse-grained,* **intrusive** *(plutonic) rocks. Fine-grained,* **extrusive** *(volcanic) rocks form where magma pours out on Earth's surface as lava flows or other eruptive material.*

As the silica content goes down, minerals generally have higher percentages of heavier elements like iron, forming rocks that are darker and more dense. Intermediate-silica (≈ 60% SiO_2) rocks are coarse-grained ***diorite*** and fine-grained ***andesite*** that are commonly gray in color. Low-silica (≈ 50% SiO_2) igneous rocks are black, including intrusive ***gabbro*** and extrusive ***basalt***. When rock is very low in silica (< 40% SiO_2) it has a lot of iron and magnesium, so that it forms olive-green colored ***peridotite***, the very heavy, coarse-grained rock that makes up Earth's mantle. Crust has more silica and less iron, and is thus less dense, than the mantle. Oceanic crust, made of gabbro and basalt, is somewhat heavier than continental crust, which has rocks closer to the composition of granite.

Igneous Rocks in Olympic National Park. Most of the igneous rocks found in Olympic National Park were manufactured in the ocean and are thus basalt. The low-silica and high-iron content combine to make basalt dark and heavy. In places the basalt layers have weathered to a red color, because the iron reacted with water to form iron oxide (rust).

The presence of spectacular "pillows" in lava flows is evidence that much of the basalt formed underwater (Fig. 5). Silica is the "thickening agent" in lava, much like flour added to pancake batter. High-silica lava, the kind that makes rhyolite and andesite, is thick and pasty and cannot flow very far — Cascade "composite" volcanoes, like Mt. Baker and Mt. Rainier, have steep slopes because they were built up by such pasty lavas. Conversely, basalt lava is thin and runny and will flow for miles and miles. It makes up low-profile "shield" volcanoes like those found in Hawaii. But if basalt lava spills out from beneath the sea floor, it immediately encounters the cold water and hardens quickly. A pulse of lava assumes a globular shape that flattens into a pillow form as it flops onto the sea bottom. Successive pulses deposit more pillows between the gaps and on top of earlier pillows. The spectacular pillows of basalt seen on the road up Hurricane Ridge

Table 1. CLASSIFICATION of IGNEOUS ROCKS

		CHEMICAL COMPOSITION			
		% Silica			
		70%	60%	50%	40%
TEXTURE	Fine-Grained Extrusive ("Volcanic")	*Rhyolite*	*Andesite*	***Basalt**	
	Coarse-Grained Intrusive ("Plutonic")	*Granite*	*Diorite*	*Gabbro*	*Peridotite*

*** Common igneous rocks in Olympic National Park.**

(Fig. 19a) thus indicate that some of the 50 to 60 million-year-old Crescent Formation developed on the sea floor and was later uplifted.

The Crescent Formation comprises much of the hard bedrock of the Olympic/ Puget Sound region (Fig. 18), and are one of many uplifted "terranes" of basalt in the coastal ranges of the Pacific Northwest (Fig. 17). Some of the basalt must have spilled out above sea level, as shown by ancient soils and a cooling pattern that resulted in vertical cracks (columnar "joints") along Hood Canal.

Table 2. CLASSIFICATION of SEDIMENTARY ROCKS

			HOW FORMED	
			Eroded Rock Particles ***("Clastic")***	**Biological or Chemical Activity** ***("Non-Clastic")***
GRAIN SIZE	**Coarse**	**Gravel**	*Conglomerate*	
		Sand	***Sandstone**	
		Silt	*Siltstone*	
	Fine	**Mud**	***Shale**	*Limestone*

*** Common sedimentary rocks in Olympic National Park.**

Sedimentary Rocks

Most sedimentary rocks form through the cycle of: 1) erosion or chemical or biological activity that forms particles (sediment); 2) transportation of the sediment by water, wind, or ice; 3) deposition of the sediment in oceans, lakes, or streams; 4) compaction and cementation of the sedimentary particles as they are buried beneath more sediment. Eroded particles of rocks are known as clasts. ***Clastic sedimentary rocks*** (like sandstone and shale) are composed of such particles, while ***non-clastic sedimentary rocks*** (like limestone and rock salt) result from particles that precipitate out of solutions during biological or chemical activity.

Types of sedimentary rocks are best understood by imagining their environments of deposition (Table 2). Gravel is found on the beds of fast-moving streams. When buried and cemented, it forms the sedimentary rock ***conglomerate***. ***Sandstone*** is made of sand-size

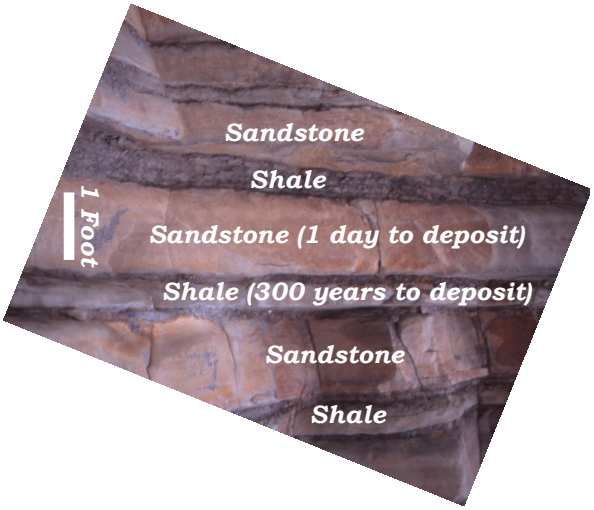


Fig. 21. ***Turbidite sequence on Beach 3 north of Kalaloch.*** *Today the rock layers are nearly vertical (Fig. 19b); the photo is rotated to show the original horizontal orientation, with the older layers on the bottom, the youngest on top . (Photo by R. J. Lillie).*

It's About Time

The layers within a ***turbidite*** sequence represent drastically different rates of deposition that may tell us about huge earthquakes in the Pacific Northwest (Fig. 21).

- ***Sandstone*** layers are commonly one to five feet thick. They were each deposited in about one day, as a turbidity flow reached the flat ocean floor and slowed down.
- The thin ***shale*** layers are only a few inches thick but each took hundreds of years to be deposited, as fine mud settled out of the calm ocean water.
- Turbidity flows are thought to be submarine landslides caused by severe shaking of the continental shelf during earthquakes. The thin shale layers thus represent the time it took for stress to build between large earthquakes (Fig. 7).

Uplifting Thoughts

A basic tenet of geology is that "the present is the key to the past," known as ***uniformitarianism***. This concept is apparent on beach walks at Mora and Kalaloch. Rangers can have visitors examine the towers of hard sandstone. They can see and feel the coarse grit in the 20 million year old rock, and compare its color and texture to that of the sand on the modern beach. Both were deposited by the sea.

Look out to sea where sand is still being deposited out there today, on the Juan de Fuca Plate. Twenty million years ago similar sand was also deposited in layers. The layers were carried along on top of the plate, shoved down a bit, and then up, where we see them today as the hard rock on the beach.

grains, mostly quartz, that were deposited in stream beds or on beaches. In lakes or deeper parts of the ocean, where water is quieter, finer particles of silt and mud accumulate. Burial, compaction, and cementation turns them into ***siltstone*** and ***shale***. In warm climates shell fragments of marine organisms dissolve in seawater, precipitating out as calcium carbonate. This fine lime mud eventually turns into the sedimentary rock ***limestone***.

Sedimentary Rocks in Olympic National Park. Most of the sedimentary rocks in Olympic National Park result from sand and mud deposited in huge fans beneath the ocean. Such layers of thick sandstone and thin shale are called ***turbidites*** because they were deposited by fast-moving undersea flows of water known as turbidity flows (Fig. 21). The flows are often triggered by earthquakes. The high volume of sediment makes turbidity flows dense, so they move quickly down the edge of the continental shelf. As a turbidity flow reaches the flat bottom of the deep ocean it begins to slow down, first dropping the coarse, heavy sand, then gradually the finer silt. The very fine particles continue farther out to sea as mud. During the time between turbidity flows, the ocean water is quiet, so that a thin layer of mud is deposited on top of the sand and silt. A turbidite sequence thus commonly has thick layers of sandstone (deposited quickly by a turbidity flow) interbedded with thin shale layers (slowly deposited over the long time period between turbidity flows). From above such flows have a "fan-shaped" pattern, reflecting the flow of water from the mouth of a river. The modern Astoria Fan spilling off the continental shelf near the mouth of the Columbia River is an excellent example of this pattern.

Besides sandstone and shale, Olympic National Park has layers containing large rock fragments. The term ***breccia*** is used to describe these layers, because their particles are quite angular, unlike the more rounded appearance of pebbles and cobbles found in conglomerate (Table 2).

There are also sedimentary deposits from streams, lakes, and glaciers in the park. In fact, glacial deposits are far more widespread in the Olympic region than just the present,

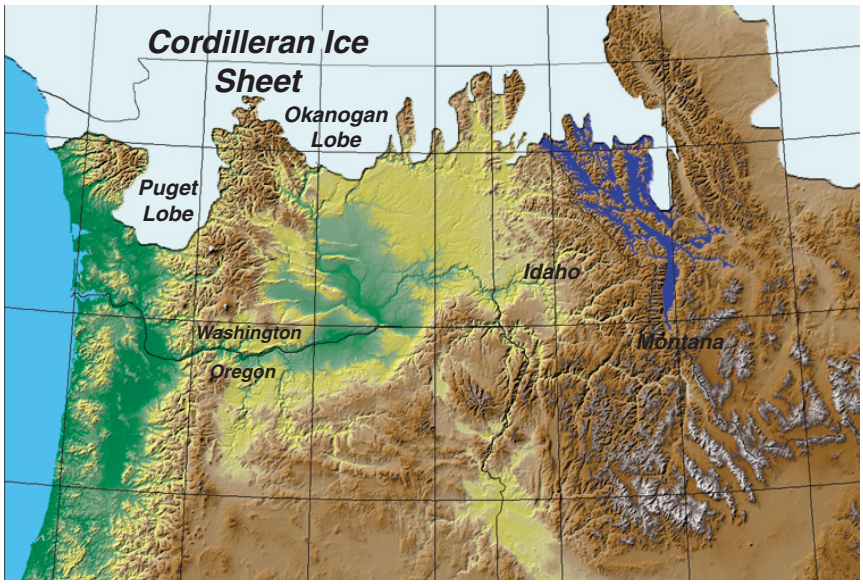


Fig. 22. ***Extent of glacial advance in the Pacific Northwest at the height of the last Ice Age (18,000 years ago).*** *Lobes of ice extended southward from Canada, across the Straight of Juan de Fuca, and into the lowlands surrounding Puget Sound. Glacial deposits thus occur in the northern and northwestern parts of Olympic National Park, as well as along Hood Canal. (Topographic data from GTOTO30. Ice sheet data from R. W. Waitt, Jr., "Case for periodic, colossal jökulhlaups from Pleistocene Lake Missoula," Geological Society of America Bulletin, v. 96, p. 1271-1286, 1985. Map compiled by David A. Strausz).*

high-altitude glacial valleys. Very young deposits of cobbles, sand, and silt on the northern and northwestern sides of the Olympic Peninsula reveal that continental ice sheets extended far down from Canada during recent ice ages (Fig. 22).

Metamorphic Rocks

There are three general factors that determine what type of metamorphic rock forms: 1) the original ("parent") rock; 2) the heat and pressure the rock endured, and 3) the presence (or absence) of fluids within the rock. The classification of metamorphic rocks is thus extensive and technical. Metamorphism, nonetheless, can be understood on a simple level if one imagines what happens to a specific parent rock as it is buried deeper and deeper within the Earth (that is, as it encounters increasing temperature and pressure). For example, as the sedimentary rock ***shale*** is initially buried, it begins to compress and heat up, forming the low-grade metamorphic rock ***slate*** (Table 3). With deeper burial larger crystals develop (especially the flaky mineral mica), forming intermediate-grade ***phyllite*** and then ***schist***. Finally, at great depth where the temperature and pressure are high, large crystals of blocky minerals like quartz and feldspar form, resulting in a high-grade metamorphic rock called ***gneiss***. If the rock is buried deeper it becomes so hot that it melts, forming ***magma***.

Metamorphic Rocks in Olympic National Park. The degree to which a rock has been metamorphosed provides a clue to how far a rock was pushed below the surface, and for how long. Some of the rocks in the park, especially along the coast, are still clearly sandstone or shale, indicating that those rocks were never more than about 5 miles (8 kilometers) below the surface. But in other places, particularly in the core area of the mountains, rocks were pushed down 7 to 10 miles (11 to 16 kilometers). Those shales developed to slate and phyllite, but never to higher-grade schist (Table 3).

The sandstone and shale layers experienced the same high temperatures and pressures, but the effect is not as noticeable in the sandstones (Fig. 23a). Technically rangers could use the term "metasandstone," but it may not be useful because the rocks still look basically like sandstone. Had they been metamorphosed to higher-grade quartzite, the re-

Table 3. CLASSIFICATION of METAMORPHIC ROCKS

Parent Rock:	Shale	Sandstone	Limestone	Basalt
Increasing Temperature and Pressure ↓	***Slate**	***Meta-Sandstone**	↓	↓
	***Phyllite**			
	Schist	*Quartzite*		
	Gneiss		*Marble*	*Eclogite*
	Rock Melts, forming MAGMA			

*** Common metamorphic rocks in Olympic National Park.**

Very Deep Thoughts!

What's it like beneath the Olympics?

• As you go deeper into the Earth, the temperature rises by about 60° F per mile (20° C per kilometer). At a depth of 10 miles (16 kilometers) the temperature is thus around 600° F (320° C).

• The amount of pressure exerted by the air column at sea level is about one atmosphere (15 pounds per square inch). Scuba divers know that for every 30 feet (10 meters) they descend into water, the pressure increases by about one atmosphere. Rock is about 2 to 3 times as dense as water. "Rock divers" would experience a pressure increase of about one atmosphere for every 10 feet (3 meters) of depth in the Earth. At 10 miles (16 kilometers) depth, the pressure is about 5,000 times the air pressure at Earth's surface!

Cascade Sauna

Why the Juan de Fuca Plate Sweats

Metamorphism of the rocks on the top part of the Juan de Fuca Plate is ultimately responsible for the Cascade volcanism. The crust of the ocean is mainly basaltic (the igneous rocks basalt and gabbro). As the plate descends to greater and greater depths and encounters higher temperatures and pressures, the crustal rocks on top of the plate are metamorphosed to eclogite. Eclogite is a much denser rock, formed as the rock is compressed and hot fluids (mostly water) are driven off. That hot water rises and melts rock of the overriding North American plate, forming magma.

crystalization would obscure the original grains of sand.

The high pressure caused some of the metamorphic rocks to develop preferred directions of cracking, know as ***cleavage***. This effect is especially noticeable in slate, which shatters along the perpendicular cleavage planes into long, skinny blocks, an effect know as ***pencil cleavage*** (Fig. 23b).

a) Metamorphosed Turbidite Sequence

b) Pencil Cleavage in Slate

Fig. 23. ***Metamorphic rocks in Olympic Olympic National Park.*** *a)* **Sandstone** *and* **shale** *layers on Hurricane Hill Trail have changed to* **metastandstone** *(light color) and* **slate**. *b) The* **slate** *on Obstruction Point Road has well developed planes of weakness, so that the rock shatters into long "pencils." (Photos by R. J. Lillie).*

GEOLOGIC TIME

Geology's most important contribution to human thought may be that, according to scientific observation, the Earth is about 4.6 billion years old. The great length of geologic time is difficult to appreciate, given that the span of a human life is only a few decades. For perspective, consider that by some accounts, based on cultural and religious beliefs, the Earth is only about 6,000 years old. Consider that 4.6 billion years is about ***one million*** times as long as 6,000 years. With only 6,000 years available it is necessary that processes happen very quickly in order for continents, oceans, mountains, valleys, and other features to form. With a million times as much time to work with, however, those features could develop through slow processes acting over long periods of time. Whether one accepts that Earth is very old (4.6 billion years) or relatively young (6,000 years), the controversy affects thinking far beyond geology and other sciences. The debate encompasses history, philosophy, and religion, involving ideas at the very heart of the nature of people and the universe.

Geologic Time Scale

Table 4 is the geologic time scale, showing the names of the divisions of geologic time as well as the span of years represented by each division. The divisions generally relate to forms of life that occurred at various times in the geologic past. The 4.6 billion years of Earth history are first broken into four ***eons***. In the Hadean and Archean eons, spanning nearly half of geologic time (from 4.6 to 2.5 billion years ago), there were only very primitive bacteria and algae. The Proterozoic Eon, from 2.5 billion to 570 million years ago, saw the development of primitive aquatic plants. In the Phanerozoic Eon, beginning 570 million years ago, life suddenly flourished and evolved to the complex plants and animals we know today. The Phanerozoic Eon is broken into finer divisions called ***eras***, in turn divided into ***periods*** and ***epochs***. The first period of the Phanerozoic Eon is the Cambrian. Rocks older than the Phanerozoic (that is, older than the Cambrian Period) are thus collectively termed ***Precambrian***.

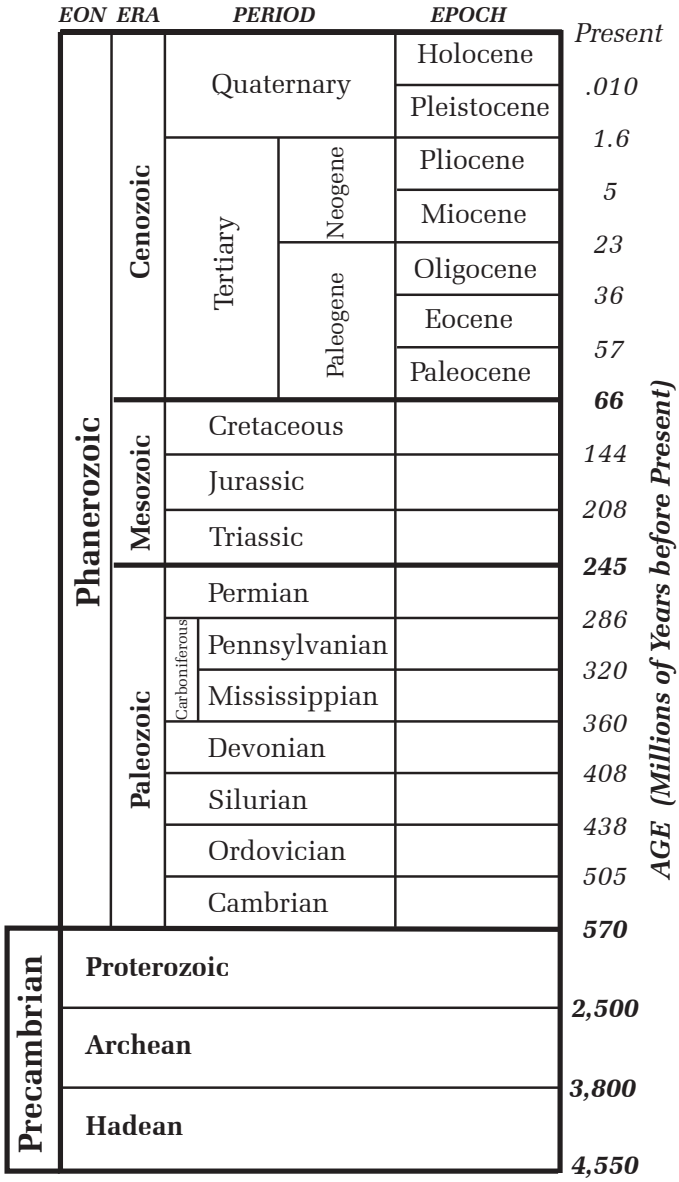


Table 4. ***Geologic Time Scale.*** *Figure courtesy United States Geological Survey. From Decade of North American Geology (DNAG), 1983.*

At the beginning of the Paleozoic Era (meaning "time of early life") marine invertebrates suddenly flourished, followed progressively by the development of fish and early land plants. In the Mesozoic Era ("middle life") trees

Deep Time

Like distance, time is difficult to imagine. Our bodies occupy about one square foot of space, and five or six feet of height. We can relate that to the dimensions of our house and the town we live in. But distance becomes harder to grasp when we consider a trip across the country or to Europe — our bodies and homes seem so small. We've traveled to the moon and may think it's far away, yet a lunar round trip is only 500,000 miles, equivalent to going around the Earth 20 times (some of those 57' Chevy's and Volkswagen Busses have done that!). But think about Mars. A round trip journey there would be about 1,000 times as far as a moon excursion. And a trip to the nearest star (Alpha Centauri) is about 100,000 times the Mars journey, or 100 million moon trips. Imagine going to the nearest galaxy (Andromeda) , equivalent to 10 trillion moon trips! It is clear that, based on the size of our bodies and our living space, we cannot begin to envision such distance. The concept of ***deep space*** thus sums up our inability to comprehend distances so large.

Likewise it is difficult to imagine geologic time. We can understand a day of our lives, and maybe even the idea that our lifetimes cover about 30,000 days. We might be surprised to find that the 6,000 years of recorded history is only equivalent to about 75 of our lifetimes. That we can imagine. But what about 5 million years ago, when our human-like ancestors first came on the scene? That would be equivalent to 60,000 lifetimes. And what about the heyday of the dinosaurs 200 million years ago, roughly equivalent to 2,000,000 of our lifetimes. Now consider that the 4.6 billion years since the Earth formed spans about 50,000,000 lifetimes. So, analogous to our inability to imagine large distances, we can think of ***deep time*** as symbolizing the futility of trying to comprehend how long the Earth has been around.

appeared, along with dinosaurs and the first birds and mammals. The Cenozoic Era ("modern life") saw the rise of mammals and, very recently, humans.

Geologic Time at Olympic National Park

The enormous span of geologic time, and where our own lives fit in, can be visualized by putting the 4.6 billion years between the goal lines of a 100-yard long football field (Fig. 24). The span of only very primitive life (Precambrian) stretches all the way across mid-field to the opponents 12 yard line! Extinction of the dinosaurs (end of the Mesozoic, 66 million years ago) would be between the 1 and 2 yard lines. The appearance of the earliest human ancestors (5 million years ago) would be 4 inches from the goal line. The beginning of recorded history (about 6,000 years ago) would be 5 one-thousandths of an inch (.004 inch) from the goal line, less than the thickness of the "dimples" on the leather ball!

According to the football analogy, nearly all the rocks you see at Olympic National Park would have formed less than 1 1/2 yards from the opponents goal line. They include basalt formed 57 to 45 million years ago, during the Eocene Epoch. The 45 to 18 million year ages for the sedimentary rocks means that they were

Ponderances on Time

Olympic High School

The youngest hard sedimentary rocks at Olympic National Park are 18 million years old. This is rather curious, considering what we figured out earlier about the Olympic-sized recycling machine — that the cycle covers a similar span of time, about 20 million years (Fig. 1). So where are the rocks that are younger than this? The answer is that they are going through earlier parts of the cycle. They are either still on the Juan de Fuca Plate and headed toward North America (Fig. 1b), or they are beneath the Olympics and haven't yet made it back up to the surface (Fig. 1c).

So the youngest (18 million year old) rocks exposed on Olympic beaches are like the (18 year old) students about to graduate from "Olympic High School." We know there are younger students, but we don't see them at the graduation ceremonies because they are in earlier grades and haven't yet risen to the highest level where they are about to enter the real world!

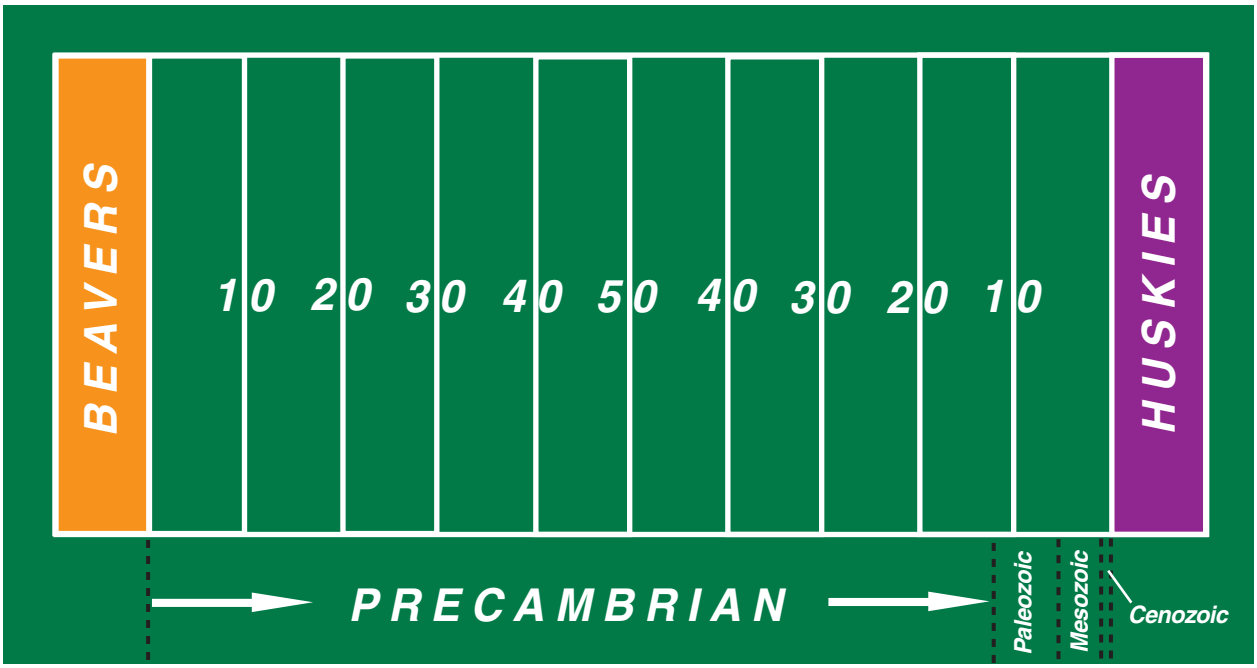


Fig. 24. ***The Geologic Time Scale (Table 4) compared to the length of a football field.*** *Virtually all the rocks at Olympic National Park were formed during the Cenozoic, within 1 1/2 yards of the opponents goal line!*

deposited from the Eocene to the Miocene. Glacial stream deposits of sand, silt, and gravel are Pleistocene and Holocene in age, having been deposited less than a million years ago.

There are two occurrences of somewhat older rocks at Olympic National Park. Point of Arches, near the extreme northwestern tip of the peninsula, has rocks as much as 144 million years old. And boulders and cobbles scattered about in the northern portions of the peninsula are various types of rock of many ages, including some Precambrian, that were carried by continental ice sheets extending from Canada during Pleistocene ice ages (Fig. 22).

GEOLOGIC STRUCTURES

The Sides of the Mountains

"Mountains should be climbed with as little effort as possible and without desire. The reality of your own nature should determine the speed. If you become restless, speed up. If you become winded, slow down. You climb the mountain in an equilibrium between restlessness and exhaustion. Then, when you're no longer thinking ahead, each footstep isn't just a means to an end but a unique event in itself. THIS leaf has jagged edges. THIS rock looks loose. From THIS place the snow is less visible, even though closer. These are things you should notice anyway. To live only for some future goal is shallow. It's the sides of the mountains which sustain life, not the top ....."

Robert Pirsig, *Zen and the Art of Motorcycle Maintenance*, ©1974, William Morrow and Company

The geologic map of Olympic National Park indicates where various types and ages of rocks are found on the surface (Fig. 25). The general pattern reveals the "core area" of 18 to 45 million year old sedimentary and metamorphic strata surrounded by 45 to 57 million-year-old

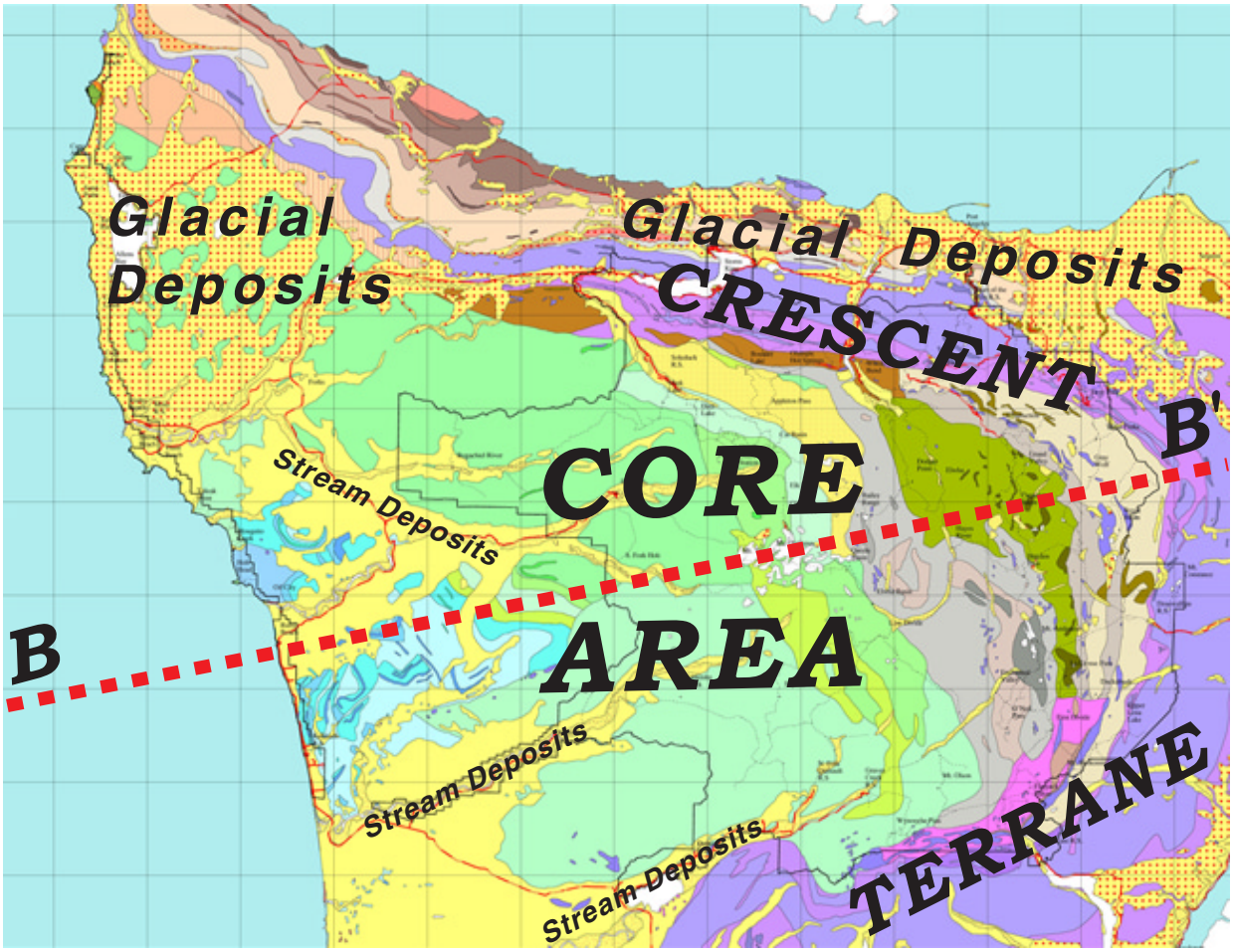


Fig. 25. ***Geologic Map of Olympic National Park.*** *The basic pattern is older layers of* **basalt** *(Crescent "Terrane") forming a "horseshoe" around younger layers of* **sandstone**, **shale**, *and* **slate** *in the "Core Area" of the Olympics. The hard rocks are covered by very young layers of* **gravel**, **sand**, *and* **silt** *that were deposited by continental ice sheets in the northern and northwestern parts of the Olympic Peninsula, and by streams and mountain glaciers in other areas. B-B' is the cross-section shown in the next figure. From geographic information systems (GIS) data compilation, Olympic National Park Staff.*

basalt known as the Crescent Terrane. The core strata are mainly turbidite sequences that were subjected to various degrees of metamorphism during subduction.

The overall structure of the range can be viewed as the development of two large structures (Fig. 26). First, the older rocks of the Crescent Terrane were pushed over the younger layers along a gigantic ***thrust fault***. Then, as the layers uplifted they were folded into a large, plunging ***anticline***. Much of the basalt of the Crescent Terrane has been eroded away, so that the sedimentary and metamorphic rocks from beneath now form the core area of the Olympics. The basalt that remains forms a large "horseshoe" pattern around the north, east, and south portions of the park (Fig. 25). The rocks were also deformed along numerous smaller faults and folds as they were caught in the vice between the converging North American and Juan de Fuca Plates. They were often tilted to such an extent that layers now have near-vertical orientations (Fig. 27).

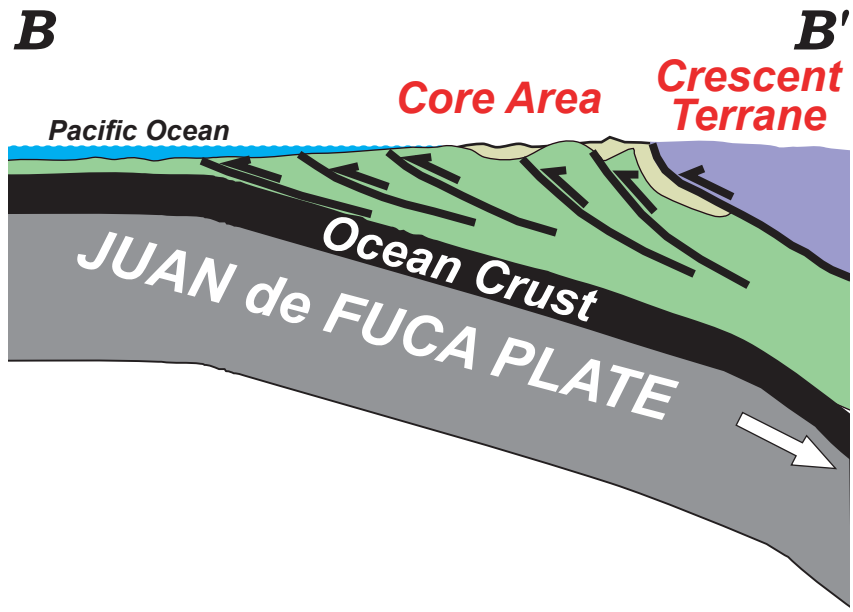


Fig. 26. ***Schematic cross-section along line B-B' shown in previous figure.*** *Basalt rocks of the Crescent Terrane are thrust over younger sedimentary and metamorphic rocks exposed in the Core Area. (Modified from Brandon and others, 1998).*

Fig. 27. ***Turbidite sequences in the Core Area of Olympic National Park are often tilted to such an extent that layers are vertical.*** *(Hurricane Hill Trail; photo by R. J. Lillie).*

Basic Types of Structures

Geologic structures, like the breaking of rocks along faults or buckling into folds, commonly form where rocks are subjected to huge forces along plate boundaries. And disruptions in the normal sequence of rock layers, known as unconformities, testify to profound geologic events that occurred in the region.

Faults

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

There are three main types of faults, described by how one fault block moves relative to the other. The type of faulting can be described by envisioning the layers of rock before and after faulting (Fig. 28). In the 19th century, coal miners in Pennsylvania recognized faults offsetting the strata along the walls of mine shafts. They described the type of fault motion by standing across the sloping fault surface. The block in back of their head they called the ***hanging wall***, at their feet the ***foot wall***.

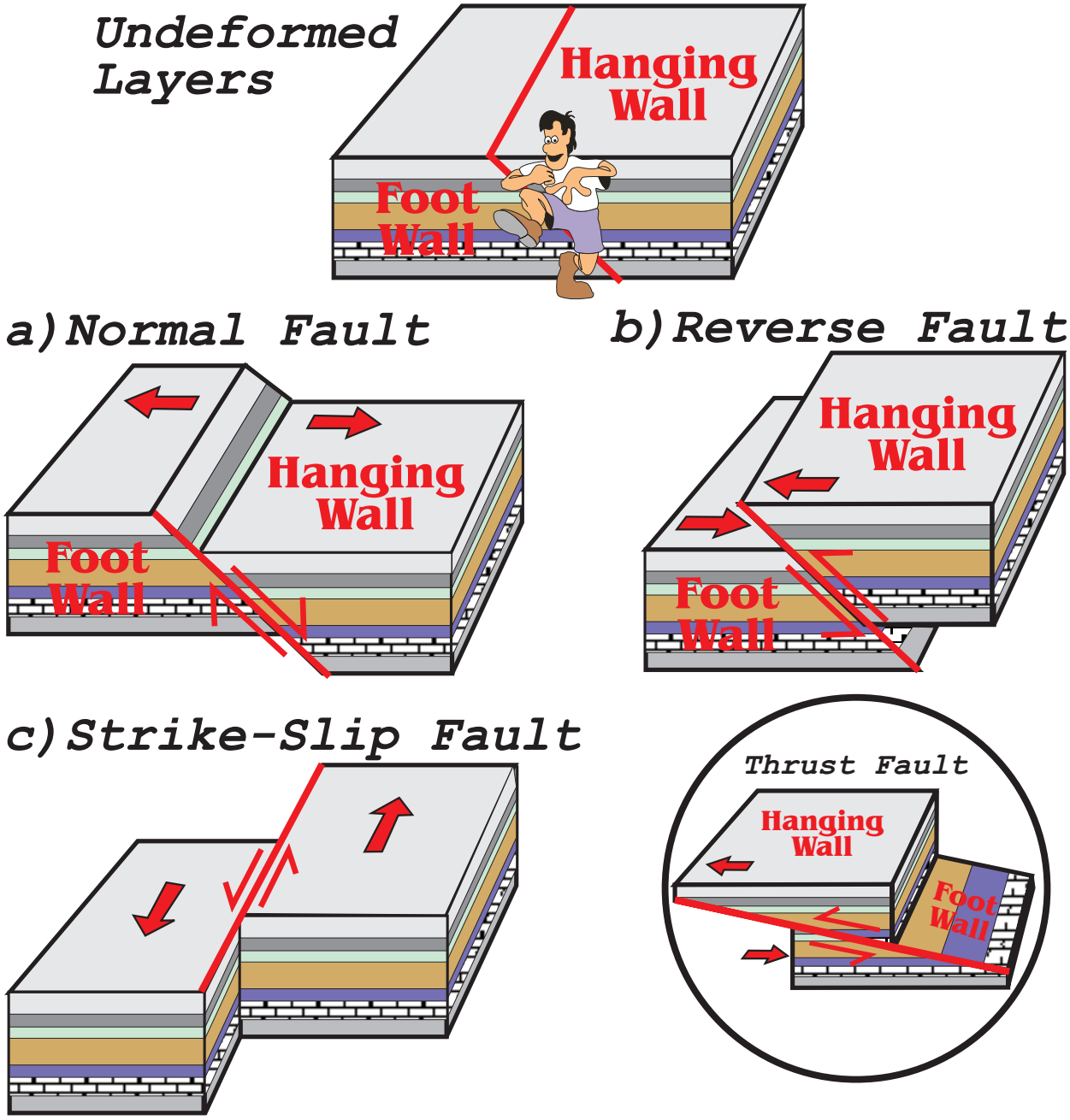


Fig. 28. ***Types of faults.*** *When a person stands across the fault, their head is next to the hanging wall, their feet next to the foot wall. a)* **Normal fault.** *The hanging wall moves down, relative to the foot wall. b)* **Reverse fault.** *The hanging wall moves up, relative to the foot wall. (A* **thrust fault** *is a low-angle reverse fault). c)* **Strike-slip fault.** *One block slides laterally past the other.*

A fault where the hanging wall block moved downward, relative to the foot wall, was termed a ***normal fault*** (Fig. 28a). A ***reverse fault*** occurred where the hanging wall moved upward, relative to the foot wall (Fig. 28b). A special kind of reverse fault, where the fault surface slopes at a low angle, is called a ***thrust fault***. The term ***strike-slip fault*** was later applied to the situation where one block slid laterally past the other (Fig. 28c).

The type of faulting often relates to the type of stress that occurs at a plate boundary (Fig. 9). Plates tend to ***pull apart*** at divergent boundaries, forming normal faults. They ***compress*** at convergent boundaries, so that blocks are thrust over one another along reverse

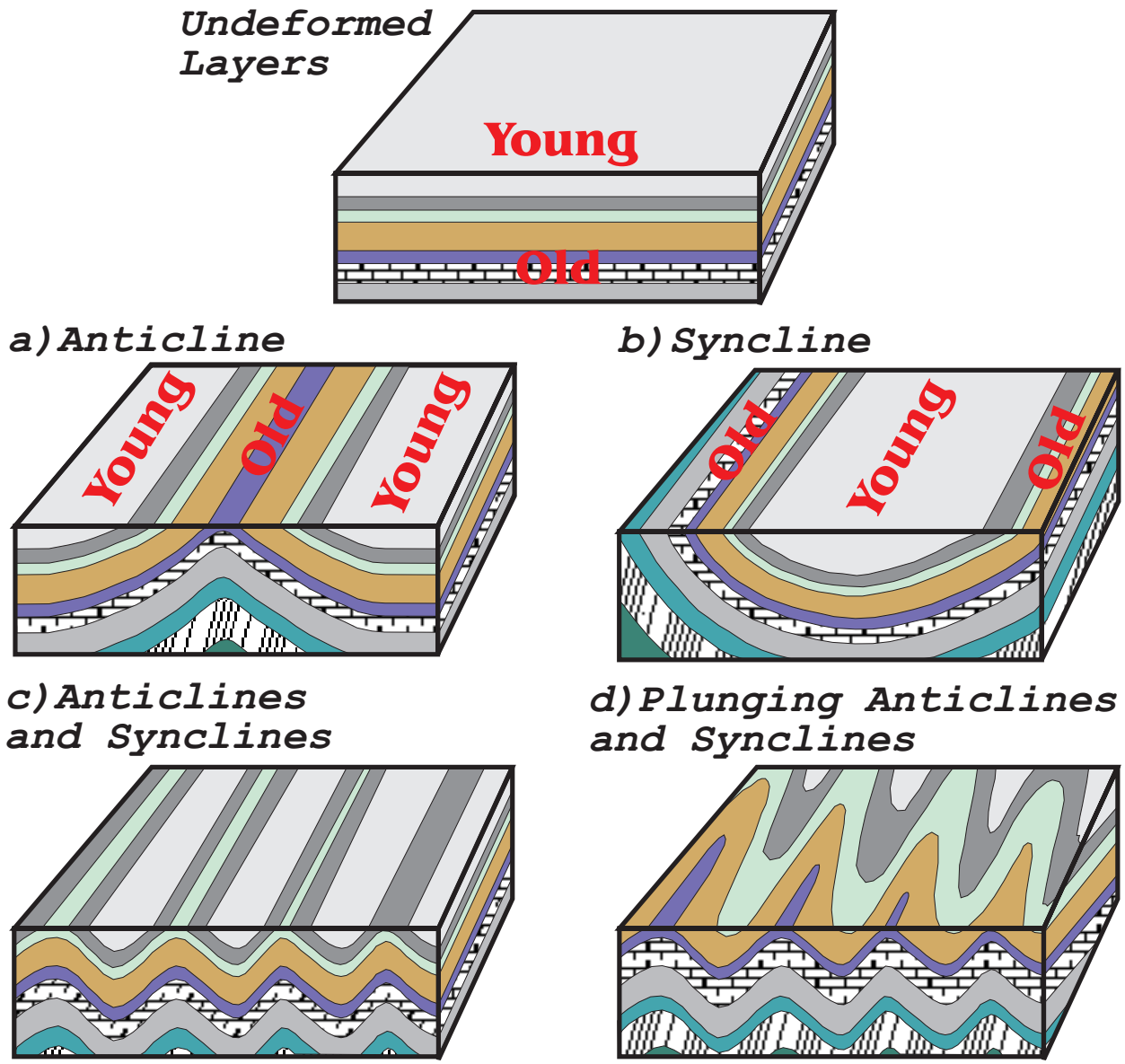


Fig. 29. ***Types of folds.*** *a)* **Anticline.** *The layers are bent upward so that, on the eroded surface, the older rocks are at the center. b)* **Syncline.** *Layers bent downward, exposing younger rocks at the center. c)* **Series of anticlines and synclines.** *d)* **Series of plunging anticlines and synclines.**

faults. Where plates ***shear*** past one another along transform boundaries, faults are predominately strike-slip. While this simple pattern generally rings true, stress patterns are often complex, so that all three types of faults might be found along a given plate boundary.

Folds

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

As with faults, it helps to envision rock layers before and after folding (Fig. 29). In a normal sequence of rocks, the older layers are at the bottom, the youngest on top. An ***anticline*** is where the layers are folded upward; after some surface erosion, the older layers are at the center of the anticline, the younger ones toward the flanks (Fig. 29a). Where rock is bent downward, at a ***syncline***, the younger layers appear at the center (Fig. 29b). Rock layers are often buckled into a ***series of anticlines and synclines***, the same pattern you get when you

push on a rug (Fig. 29c). In some places, such as the Valley and Ridge Province of the Appalachian Mountains, rock layers are folded in a more complex fashion, forming ***plunging anticlines and synclines*** (Fig. 29d). After erosion, distinct "V-shaped" patterns develop on the ground surface.

Unconformities

Layers of sediment can be viewed as pages of a book, telling a continuous geologic story. But in places some of the pages may never have been written, or they may have been ripped out of the book. Likewise, there are places where the geologic story is incomplete because of non-deposition or erosion. An ***unconformity*** is the surface that represents the missing part of the geologic record.

The coastal areas of Olympic National Park contain some spectacular ***angular unconformities***. That is, the strata below the unconformity surface are tilted at an angle, while those above are nearly horizontal (Fig. 30). The angular unconformities in Olympic illustrate that older sandstone and shale layers were tilted as they were lifted out of the sea, then partially eroded. Flat-lying glacial deposits later covered some of those truncated layers. The angular unconformities thus represent the missing time interval between deposition of the sandstone and shale layers (about 20 million years ago) and the glacial material (less than a million years ago).

Fig. 30. ***Angular Unconformity.*** *The tilted sandstone and shale layers below the unconformity are about 20 million years old, while the glacial gravel layers above are less than 1 million. Beach 3 north of Kalaloch. (Photo by R. J. Lillie).*

Structures in Olympic National Park

The convergence between the Juan de Fuca and North American plates results in compression. Reverse faults are therefore common in Olympic National Park, especially the low-angle thrust variety (Fig. 28b). In fact, the Cascadia Subduction Zone can be thought of as a gigantic thrust fault, where the North American Plate is the "hanging wall" that is being shoved over the Juan de Fuca "foot wall" (Fig. 15). A large thrust fault in the park is the curved zone where the older Crescent Terrane has overridden younger strata that form the core area of the mountains (Figs. 25, 26). This fault zone has different names along its length, including the Calawah and Hurricane Ridge faults on the north. Numerous other reverse faults are found throughout the park, offsetting strata from scales of miles to inches.

The broad structure of Olympic National Park is an upfold, like an anticline, but with an interesting twist (Fig. 31). For a normal stratigraphic sequence, with younger layers deposited on top of older layers, anticlinal folding would produce a structure with the oldest strata in the center (Fig. 29a). But the sequence of rock layers in Olympic National Park is not normal; older basalt rocks of the Crescent Terrane were thrust over the younger sedimentary layers (Fig. 31a). When the strata were deformed into a broad anticline, tilted eastward, and the older rocks eroded from the top, a "window" into the younger rocks was established (Fig. 31b). So the Olympic Mountains are an unusual type of anticline, with the younger layers exposed in the middle.

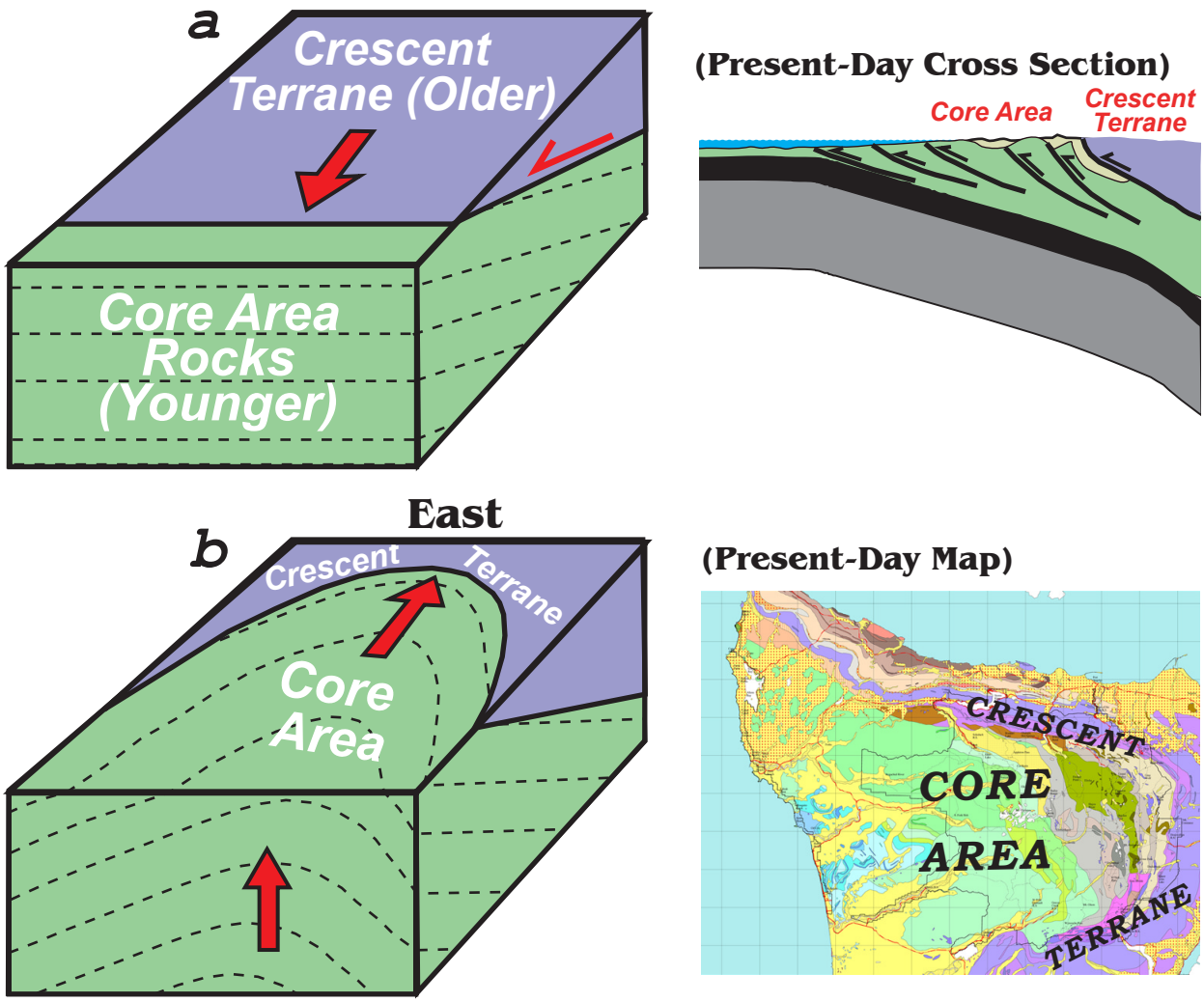


Fig. 31. ***Structural development of Olympic Mountains.*** *a)* **Thrust fault.** *The Cresent Terrane basalt was thrust westward over younger sedimentary and metamorphic layers that now form the Core Area of the Olympics. (Compare side panel with present-day cross section). b)* **Eastward-Plunging Anticline.** *The region was folded into an anticline and tilted eastward. The underlying, younger Core Area rocks were exposed as some of the Cresecent Terrane was eroded from the top of the anticline. (Compare eroded surface with present-day map).*

EARTHQUAKES

Earthquakes in the Pacific Northwest and the vicinity of Olympic National Park are of four varieties, each in some way related to the convergence of the Juan de Fuca and North American plates. As the cold Juan de Fuca Plate descends its brittle upper portion contorts and cracks as earthquakes (Fig. 32a). The largest and most devastating earthquakes occur where the two plates lock together for centuries, then suddenly let go (Fig. 32b). Smaller events occur within the overriding North American Plate, where plate convergence causes compression and breaking along shallow fault lines (Fig. 32c), or where magma rises beneath the Cascade Mountains (Fig. 32d). Resource Education Rangers can have visitors gaze over the landscape and imagine their position relative to the subducting plate. Where, and to what extent, might each of these types of earthquakes affect their lives?

What Causes Earthquakes?

Believe it or not, rocks are elastic – they behave like a rubber band or rubber ball. Under a small amount of stress (compression, pulling, or shearing), they gradually deform (compress, stretch, or bend). When the stress is removed, the rocks return to their original size and shape. But so much stress might be applied to a rock that it deforms permanently, either by ***ductile*** flow (like silly putty) or ***brittle*** cracking (like breaking a pencil). The level of stress where the material begins to flow or

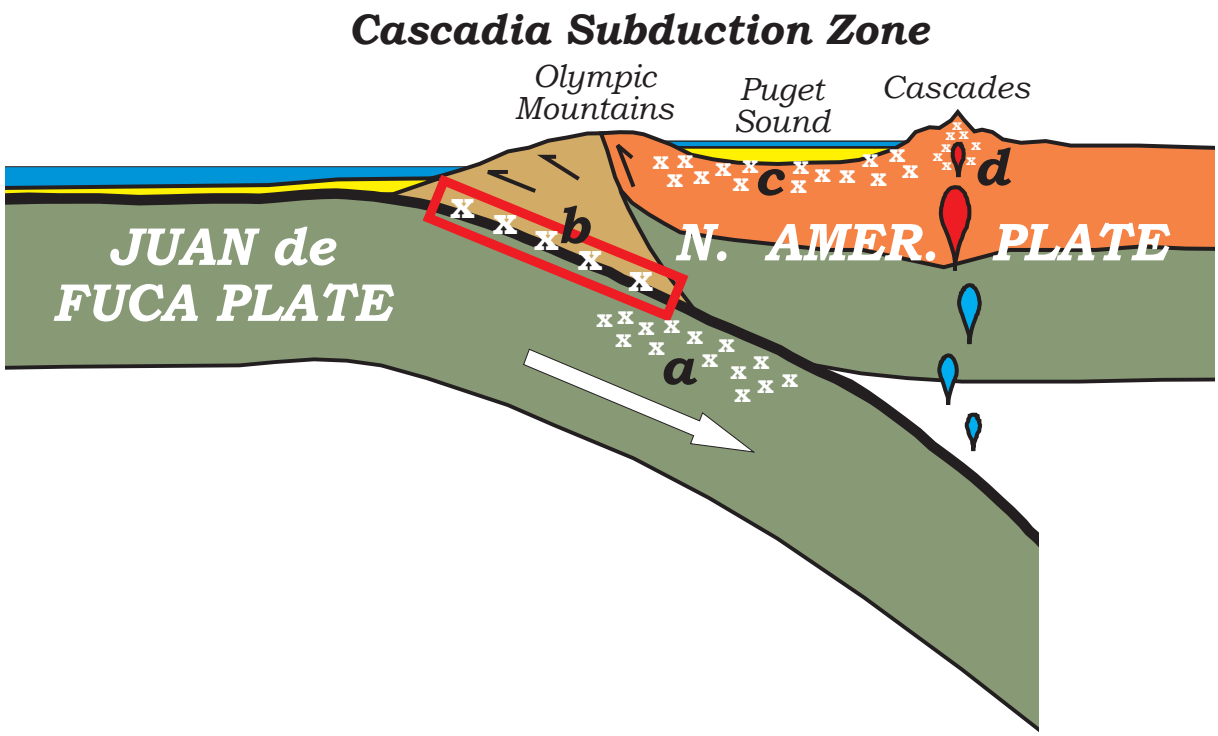


Fig. 32. ***Types of earthquakes occurring in the Pacific Northwest.*** *a)* **Within Juan de Fuca Plate.** *The top portion of the Juan de Fuca Plate stays cold and brittle for some time as it subducts, so that "subduction slab" or "Benioff Zone" earthquakes occur to depths of about 30 miles (50 kilometers) beneath the Olympic/ Puget Sound region. The Magnitude 6.8 earthquake of February 28, 2001 was of this type.* *b)* **Between Juan de Fuca and North American plates.** *Beneath the offshore, Olympic, and Puget Sound regions the plate boundary is less than 20 miles (30 kilometers) deep, where rocks are still cold and brittle. A devastating earthquake can occur if the plates lock together for centuries, then suddenly let go (Fig. 7).* *c)* **Within North American Plate.** *The overriding plate is compressed as it converges with the subducting plate. The Seattle area is one of many regions of shallow earthquakes that result.* *d)* **Rising magma beneath the Cascades.** *The colder, brittle rock above cracks as small earthquakes and earthquake swarms.*

crack is called the elastic limit.

Rocks that are cold and brittle undergo ***elastic rebound*** when they are stressed beyond their elastic limit (Fig. 33). That is, the layers of rock initially bend in an elastic fashion, like stretching a rubber band or winding a clock spring. But when the elastic limit is reached, they suddenly break along a fault line and snap to new positions. The sudden snapping is an ***earthquake*** that releases energy in the form of seismic waves.

Fig. 34 shows earthquakes over a 10-year period, plotted without geographic reference. As you compare the map with Fig. 8, notice that the earthquakes not only outline the boundaries of plates, but their depths reveal the distribution of cold, brittle material (Fig. 9). Only shallow earthquakes occur at divergent boundaries (Mid-Atlantic Ridge), transform boundaries (San Andreas Fault), and hotspots (Hawaii). But at convergent boundaries (western South America), earthquakes extend to great depth. Why is this so?

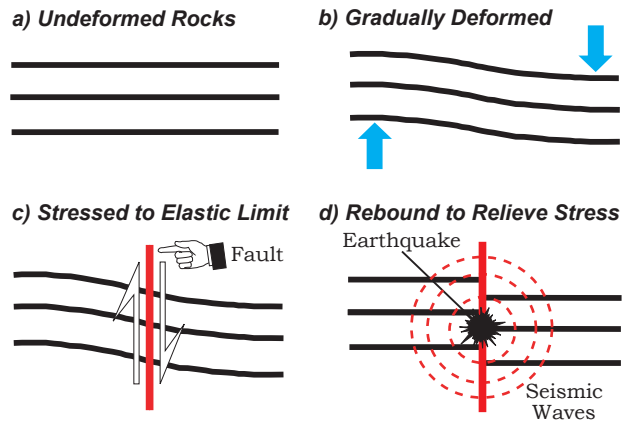
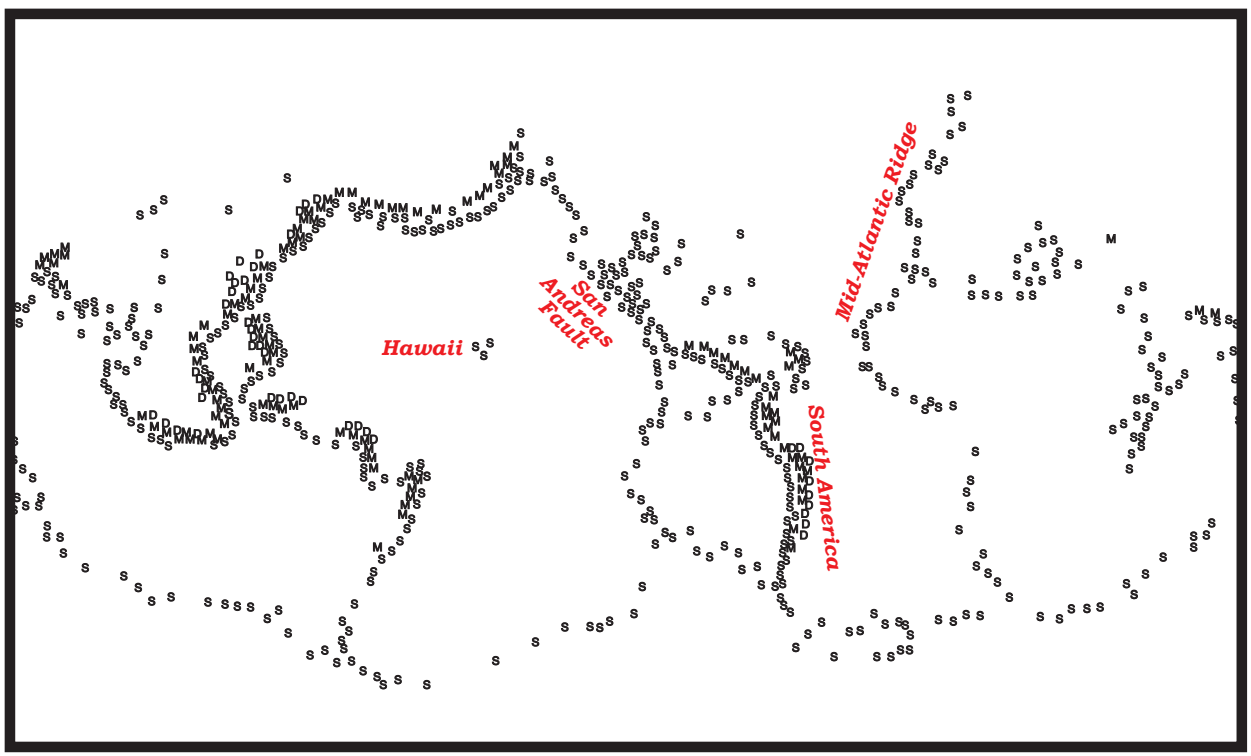


Fig. 33. ***An earthquake occurs due to elastic rebound.*** *a) Cross-sectional view of undeformed rock layers. b) Stress causes layers to bend elastically. c) When elastic limit is reached, the rocks break along a fault. d) Earthquake seismic waves radiate from the broken rock as it suddenly snaps to new positions across the fault.*



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

Fig. 34. ***Locations of large earthquakes recorded over five-year period, plotted without geographic reference.*** *Data from Barazangi and Dorman (1969); figure modified from Hamblin and Christianson (1995). The earthquakes outline the plate boundaries shown in Fig. 8. Only* **shallow** *earthquakes occur at divergent boundaries (Mid-Atlantic Ridge), transform boundaries (San Andreas Fault), and hotspots (Hawaii). Zones of earthquakes dipping from* **shallow**, *to* **intermediate**, *to* **deep** *outline subducting plates at convergent boundaries (western South America).*

Location of Earthquakes

There are two conditions necessary for earthquakes to occur: 1) motion within the Earth so that material is stressed beyond its breaking point (or "elastic limit"); and 2) material that deforms in a sudden (***brittle***), rather than flowing (***ductile***), manner. Practically the only region of the Earth that can produce earthquakes is the lithosphere (Figs. 9, 10). In fact, earthquakes are generally confined to the cold, upper portion of lithospheric plates, which break like peanut brittle. The lower, warmer regions of plates tend to bend easily without breaking. Earthquakes at divergent, transform, and hotspot settings are therefore only shallow, within the upper 20 or so miles (30 kilometers) of Earth's surface (Fig. 9a,c,d). Shallow earthquakes also occur due to compression and other stresses as plates converge (Fig. 9b). If convergence is fast enough, the plate remains cold and brittle to considerable depth, much like a cube of ice remains cold and brittle for some time when it is pushed to the bottom of a cup of hot coffee. Earthquakes therefore can occur to considerable depth (down to 400 miles; 700 kilometers) as the rigid top portion of a subducting plate is stressed and contorted. The biggest earthquakes ever recorded, beneath Chile in 1960 and Alaska in 1964, occurred in regions where one converging plate had been locked against another for centuries, building enormous stress (white stars, Fig. 9b).

Focus and Epicenter

The location of an earthquake can be described by its latitude, longitude, and depth. The ***focus*** is the actual "point" (relatively small volume) within the Earth where the earthquake energy was released (Fig. 35). The ***epicenter*** is the point on Earth's surface directly above the focus. The ***focal depth*** is the distance from the epicenter to the focus.

Focal depths relate to the type of plate boundary (Figs. 9, 34). Most earthquakes are shallow focal depth, from the surface to 40 miles (70 kilometers) depth; shallow focus earthquakes occur at all types of plate boundaries. Most intermediate (40 to 200 miles; 70 to 300 kilometers) and virtually all deep (up to 400 miles; 700 kilometers) earthquakes occur at convergent boundaries, where lithosphere subducts to great depths.

Strength of an Earthquake

There are two terms used to describe the strength of an earthquake: ***magnitude*** is quantitative, related to the amount of energy released by the earthquake; ***intensity*** is qualitative, describing the severity of shaking at a given location.

Magnitude

The strength of an earthquake is commonly reported to the public in terms of the familiar ***Richter Scale***, which measures earthquake magnitude. Magnitude is based on precise measurements of the amplitude of seismic waves, at known distances from the epicenter, using seismographs. It is expressed according to a logarithmic scale, whereby an increase in magnitude by one unit corresponds to a 10-fold increase in amplitude of the seismic waves. For example, consider a magnitude 6 earthquake, compared to a magnitude 7 earthquake, occurring in exactly the same place (Fig. 36a). At the same seismic station, the ground moves up and down 10 times as high for the magnitude 7 event as it did during the magnitude 6 ($10^7/10^6 = 10^1 = 10$). Now consider a magnitude 8 earthquake, which produces waves that are 10 times as large as the magnitude 7 earthquake. Compared to the magnitude 6 earthquake, the magnitude 8 would thus produce waves 100 times as large ($10^8/10^6 = 10^2 = 10x10 = 100$).

Now let's consider how magnitude re-

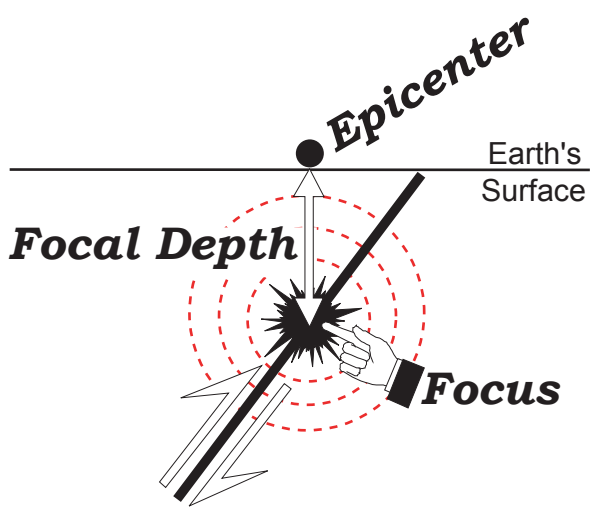


Fig. 35. ***Cross-sectional view of a rupturing fault, illustrating terms used to describe the location of an earthquake.***

lates to the amount of energy released by an earthquake. ***It takes a 30-fold increase in the amount of seismic energy to make the amplitude of seismic waves grow by a factor of 10.*** It would therefore take about 30 magnitude 6 earthquakes to equal the energy released by a single magnitude 7 earthquake (Fig. 36b). And about 900 (30 x 30) magnitude 6 earthquakes would have to go off all at the same time to equal a magnitude 8 earthquake.

The energy released by an earthquake relates to three parameters: 1) the surface area of the ruptured fault; 2) the amount of movement along the fault during the earthquake; and 3)

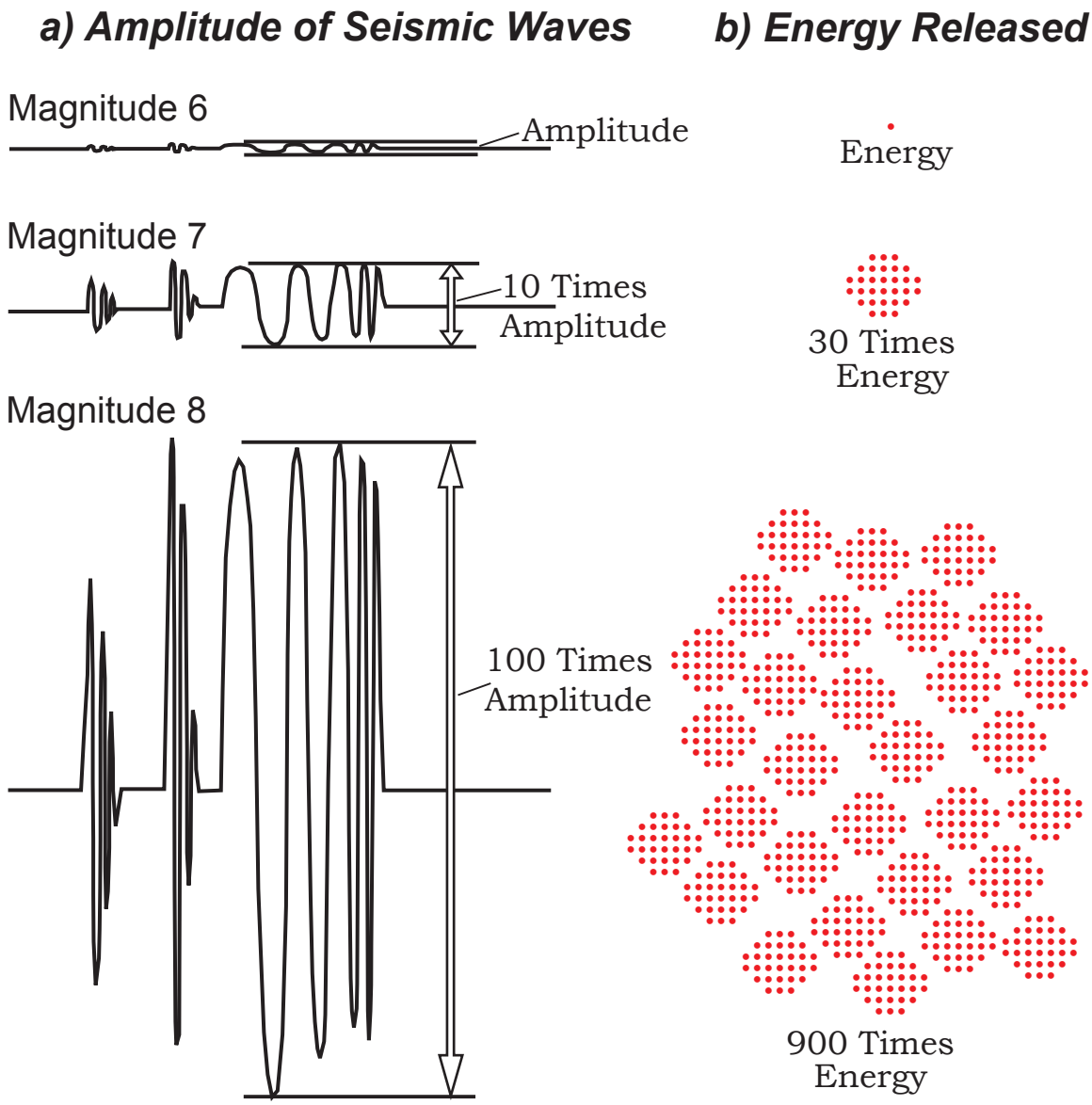


Fig. 36. ***Earthquake magnitude is measured according to the size (amplitude) of seismic waves, which relates to how much energy was released by the earthquake.*** *a) Consider three earthquakes occurring on the San Andreas Fault in Los Angeles and recorded on the same seismograph in Seattle. The waves from a* **Magnitude 6** *earthquake would be recorded with a certain amplitude. Waves would appear 10 times that amplitude if the second earthquake were* **Magnitude 7**. *Waves from a* **Magnitude 8** *earthquake would be 10 times as big as the Magnitude 7, meaning 10 x 10, or 100 times as big as the waves from the Magnitude 6 earthquake. b) It would take about 30* **Magnitude 6** *earthquakes, all going off at the same time, to make the amplitude of the seismic waves grow by a factor of 10. Thus 30 times as much energy is released by a* **Magnitude 7** *earthquake compared to a* **Magnitude 6**. *And it would take about 900 (30 x 30) Magnitude 6 earthquakes to equal the energy released by a* **Magnitude 8***!*

the amount of friction along the fault zone. Thus the larger the area of rupture and fault displacement, the larger the earthquake. Where hot asthenosphere shallows, the overlying plate is hot and only brittle enough to break along small faults. Earthquakes at divergent plate boundaries and hotspots are therefore only up to about magnitude 7.5 (Fig. 9a,d). The region is generally colder where plates slide past one another at transform plate boundaries, so that rocks break along bigger faults (Fig. 9c). Earthquakes as large as magnitude 8.5 can therefore occur in western California, when hundred-mile long segments of the San Andreas Fault suddenly snap. A cold, brittle plate can be forced against another where plates converge (Fig. 9b). The plates may lock together and build stress for centuries, only to break along a fault zone up to 1000 miles (1500 kilometers) long. The resulting earthquakes can reach magnitude 9.5, close to that of the largest ever recorded in South America in 1960 and Alaska in 1964. As we'll see later, our own Cascadia Subduction Zone may be capable of producing earthquakes nearly as large.

Sobering Soliloquies

- At 2 inches per year, in 300 years the Juan de Fuca Plate should slip about 600 inches (50 feet) beneath North America. But if the two plates have been locked together for the past three centuries, then suddenly let go, the North American Plate would lunge 50 feet over the Juan de Fuca Plate!
- The energy released by a huge (magnitude 9) earthquake in the Pacific Northwest would be equivalent to about one million atomic bombs exploding all at once.
- The great subduction zone earthquake scenario is especially scary, because such an earthquake would cut off roads and disable emergency response systems throughout the Northwest. From where would the help come?

Intensity

Intensity of an earthquake is based on effects at the surface, as witnessed by people. For a given location, intensity is reported as Roman Numerals according to the ***Mercalli Scale*** (Table 5). Three factors that tend to increase intensity at a given location are: 1) magnitude of the earthquake; 2) proximity to the earthquake focus; and 3) loose soil as opposed to firm bedrock.

During an earthquake, people often report "hearing" the ground rumble a bit, like an approaching train, then "feeling" the ground shake violently. The reason is that there are three types of seismic waves generated by an earthquake, and the waves travel at different speeds. The fastest are ***compressional waves,*** which are really sound waves traveling in the rock of the Earth. They move as the material compresses and expands, compresses and expands. Moving at about half the speed are ***shear waves***, which contort the Earth in sideways motions, and then ***surface waves*** that roll the land surface up-and-down and back-and-forth. People thus sense vibrations of the compressional waves, which commonly have smaller amplitudes and less severe ground motion than the later shear and surface waves. The more intense shear and surface waves therefore cause the bulk of the damage.

Immediately after an earthquake, survey forms are circulated to residents of the affected region to determine what people actually observed during and after the quake. Based on those surveys, intensities can be inferred for specific areas. Contour maps are drawn showing the observed intensity relative to the location of the earthquake epicenter (Fig. 37). Seismic wave amplitudes get smaller with increas-

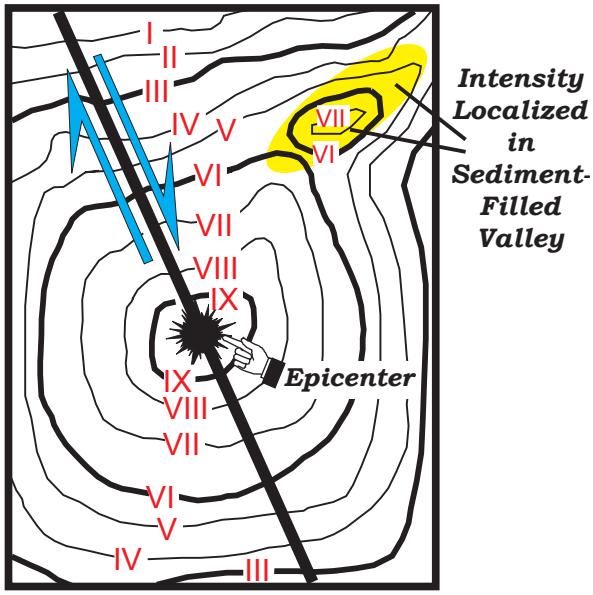


Fig. 37. ***Earthquake intensity states how severe the ground shaking was at a given location.*** *It depends on the* **magnitude** *of the earthquake, the* **distance** *from the focus, and the* **local soil conditions**. *The contour map shows that intensity is generally highest near the epicenter, but can be enhanced in areas built on loose material.*

Intensity	Observed Effects
I	Not felt except by very few people, under special conditions. Detected mostly by instruments.
II	Felt by a few people, especially those on upper floors of buildings. Suspended objects may swing.
III	Felt noticeably indoors. Standing automobiles may rock slightly.
IV	Felt by many people indoors, by a few outdoors. At night, some are awakened. Dishes, windows, and doors rattle.
V	Felt by nearly everyone. Many are awakened. Some dishes and windows are broken. Unstable objects are overturned.
VI	Felt by everyone. Many people become frightened and run outdoors. Some heavy furniture is moved. Some plaster falls.
VII	Most people are in alarm and run outside. Damage is negligible in buildings of good construction.
VIII	Damage is slight in specially designed structures, considerable in ordinary buildings, great in poorly built structures. Heavy furniture is overturned.
IX	Damage is considerable in specially designed structures. Buildings shift from their foundations and partly collapse. Underground pipes are broken.
X	Some well built wooden structures are destroyed. Most masonry structures are destroyed. The ground is badly cracked. Considerable landslides occur on steep slopes.
XI	Few, if any, masonry structures remain standing. Rails are bent. Broad fissures appear in the ground.
XII	Virtually total destruction. Waves are seen on the ground surface. Objects are thrown in the air.

Table 5. ***Mercalli Scale of earthquake intensity.*** *(From Hamblin and Christiansen, 2001).*

ing distance from the earthquake source; intensities generally decrease with distance from the epicenter. Exceptions occur due to local ground conditions. Seismic waves are amplified in areas where there is unconsolidated sediments or landfill, locally increasing the intensity.

Earthquakes in the Pacific Northwest

The boundary between the Juan de Fuca and North American plates is similar to other regions where a plate with oceanic crust descends beneath one with continental crust, but with one remarkable exception. Like other ocean/continent subduction zones, the overall morphology of the Cascadia Subduction Zone consists of a coastal mountain range (Olympic Mountains), volcanic arc (Cascades), and depression in between (Puget Sound; Fig.32). But unlike the other regions, there is no written record of a large earthquake (magnitude ≥ 8) occurring in the Pacific Northwest, even though written records have been kept for the past 200 years. There is geological evidence, however, that large earthquakes resulted in subsidence of coastal areas and flooding by tsunami waves at various times in the past. The last four occurred about 300, 1100, 1300, and 1700 years ago. The explanation is that stress builds as the Juan de Fuca and North American plates lock together along their boundary (Fig. 7). After 200 to 800 years of continued convergence the stress becomes so great that the plates suddenly unlock, sending off shock waves as a giant earthquake. If this interpretation is correct, it is a sobering thought, because the last great earthquake apparently occurred 300 years ago!

Maximum intensities that might be expected at Olympic National Park depend on which type of earthquake occurred, and the specific observation sites in the park. Subducting Juan de Fuca Plate earthquakes (Fig. 32a) can be up to magnitude 7. Their foci are generally beneath the Puget Sound/Seattle region, at depths of about 30 miles (50 kilometers). Thus they originate about 100 miles (150 kilometers) from the park, so that their maximum intensities would reach about V in areas of firm bedrock like Hurricane Ridge, but could get up to intensity VII or so in areas with looser soil, like around Lake Crescent. A “locked zone”

(Fig. 32b) earthquake of magnitude 8 or 9, however, could have far greater consequences. If it were centered beneath Washington state, it might produce intensities up to XII in the park.

Geological Evidence for Locked Zone Earthquakes

There are two lines of evidence for large Cascadia Subduction Zone earthquakes. The first relates to what happens when converging plates lock together. To try to absorb the stress, Earth's surface slowly bends upward (Fig. 7a). In 300 years the land can move up about 6 feet (2 meters). But if the plates suddenly unlock, the surface will abruptly drop down the same amount (Fig. 7b). In many areas along the Washington, Oregon, and northern California coasts there are marsh plants, including small trees, that were suddenly killed and partially buried by deposits of sand. Above the sand are bay muds and then more marsh and sand deposits. This sequence repeats itself at least seven times over the past 3,000 years. Each sequence is thought to indicate the time between large earthquakes. As the plates lock and the surface rises, shallow bay areas rise up and become marshes. Then, when the earthquake occurs as the plates suddenly unlock, the surface abruptly drops below sea level and is covered by sand from the resulting giant "tsunami" wave. Over the next few hundred years the area slowly rises up again until the next big earthquake.

The second line of evidence is the age of large turbidity flow deposits off the coast ("turbidites;" Fig. 21). A big earthquake rattles the region so much that large pieces of the edge of

The February 28, 2001 Earthquake

The earthquake that struck near Olympia, Washington, on February 28, 2001 was of the ***subduction slab*** variety. That is, it occurred at about 32 miles (52 kilometers) depth, within the top part of the subducting Juan de Fuca Plate (Fig. 32a). Its epicenter was 11 miles (18 kilometers) NE of Olympia, or about 15 miles (24 km) WSW of Tacoma and 36 miles (58 km) SSW of Seattle – it has thus been name the **Nisqually Earthquake**. Its magnitude was 6.8, and intensities as high as VIII were felt near the epicenter, especially along stream valleys.

Such quakes are common in subduction zones, sometimes showing that a cold slab extends to as much as 400 miles (700 kilometers) depth (Fig. 9b). But the Juan de Fuca Plate that is subducting beneath Washington is young and relatively hot, having formed at the Juan de Fuca Ridge within the last 10 million years (Figs. 3, 13, 15). The region of the plate that is still cold enough to be brittle is shallow, extending only beneath the Olympic Mountain/Puget Sound area (Fig. 38). Subduction slab earthquakes beneath Puget Sound therefore occur only to about 35 miles (55 kilometers) depth. But in fact they are useful to geologists because they help to outline the geometry of the subducting Juan de Fuca Plate.

The Nisqually Earthquake resulted in intensities only as high as VIII because it occurred 32 miles (52 kilometers) below the surface. It caused about two billion dollars in property damage. But that number would have been much higher had the earthquake been shallower or of larger magnitude. Seismic waves lost energy as they travelled the 32 miles from the focus to the surface, much as your voice looses volume as it travels from the front of an auditorium to the back rows. Intensities were therefore not nearly as severe as they would have been for a shallower quake.

As destructive as the February 28 earthquake was, two of the other varieties that occur in the Pacific Northwest could be far more severe. A ***locked zone*** earthquake (Figs. 14; 32b) would occur at a similar depth, but its magnitude (about 9) would release seismic energy equivalent to 1,000 Nisqually earthquakes occurring all at once (Fig. 36b). And a quake within the ***overriding, North American Plate*** would have magnitude similar to the February 28 event, but it would be very shallow (Fig. 32c). There are many active faults of that nature in the Seattle/Puget Sound area. The Magnitude 6.9 earthquake that struck Kobe, Japan on January 17, 1995, occurred on a similar type of shallow fault, with a focal depth of only 1 mile – it resulted in the loss of over 3,000 lives, and 200 billion dollars damage.

It is thus clear that the February 28, 2001 earthquake in the Puget Sound region was only a "wake-up" call, reminding us that we need to prepare for far greater events!

the continental shelf break up and travel down the continental slope as turbidity flows. Drilling and carbon age dating has documented 14 such turbidites for the past 7,700 years, many that correlate with age dates obtained from the buried marshes.

The buried marsh and turbidite evidence suggests that great earthquakes struck the Pacific Northwest at intervals ranging from 200 to 800 years, with an average "recurrence interval" of about 300-500 years. In other words, it takes a few centuries for enough stress to build between the two converging plates so that they suddenly unlock as a devastating earthquake.

Evidence for the Last Great Pacific Northwest Earthquake

The last huge earthquake is thought to have struck the Pacific Northwest on January 26, 1700. Without direct observation, how is it possible to date such an event so precisely? Carbon dating of stumps in buried marshes suggests the trees died about 300 ± 10 years ago. Written records from Japan indicate that a giant tsunami wave hit that country on January 27, 1700. The pattern of when and where the waves struck suggests that the tsunami was generated in the Pacific Northwest of the Untied States. Traveling about the speed of a jetliner, it takes about 12 hours for such a wave to cross the Pacific Ocean. The carbon age-dating and tsunami data are consistent with a Cascadia Subduction Zone earthquake occurring on January 26, 1700.

Evidence is thus quite good that giant earthquakes occur along the Cascadia Subduction zone about every 300 to 500 years and that the last one was 300 years ago. So the next one might be today, or 200 years from now, or anytime in between. Stress has built up along the plate boundary for three centuries, so we better be aware and prepared when the locked boundary suddenly lets go!

Explaining a Great Subduction Zone Earthquake to Park Visitors

Olympic National Park provides an exceptional setting to make the public aware of the danger and likelihood of a major earthquake. Visitors can imagine the Juan de Fuca Plate beginning its downward plunge about 50 miles (80 kilometers) out in the Pacific Ocean (Fig. 38). The plate encounters higher and higher temperatures as it extends at a shallow angle, deeper and deeper into the Earth. Far to the east the top of the plate, at 50 miles (80 kilometers) depth, is so hot that it sweats hot fluids that rise and make the Cascade volcanoes. Very large earthquakes will not occur along the plate boundary near there because the rocks are so hot that they deform in a ductile fashion, like pulling taffy. The taffy will deform, but it will do so silently. Beneath the Olympics and Puget Sound, however, the situation is quite different. The top of the plate is only 5 to 15 miles (8 to 25 kilometers) deep. Rocks at those depths are still relatively cold, so that they break in a brittle manner. Imagine bending a piece of peanut brittle. When it finally breaks it gives off a snapping sound. Thus you can imagine what happens if the subducting Juan de Fuca Plate is locked against the North American Plate for centuries. The "snapping" sound that occurs when the plates suddenly let go is seismic waves that travel to the surface

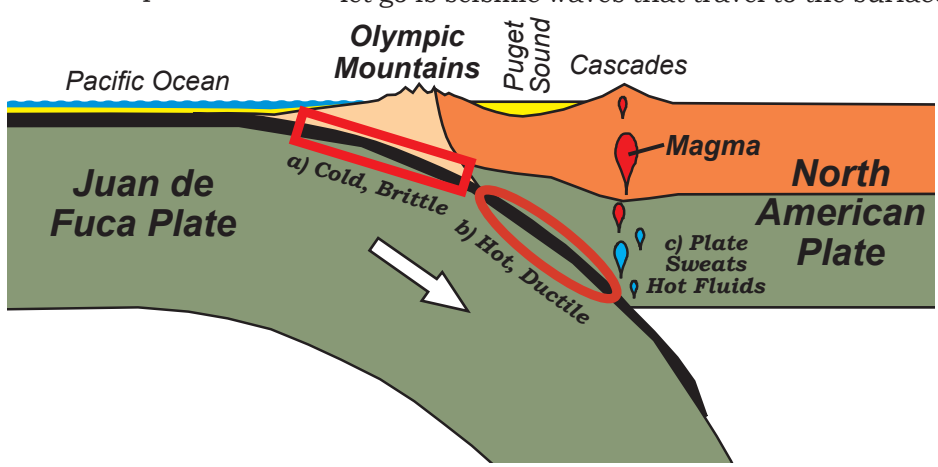


Fig. 38. ***Behavior of Juan de Fuca/North America plate boundary.*** *a) Where the boundary is shallow, the rocks are relatively cold - they fail in a* **brittle** *fashion. This is the "locked zone" where huge earthquakes occur. b) Farther east the plate boundary is deeper and thus hotter. Rocks fail in a* **ductile** *fashion, flowing instead of snapping as earthquakes. c) The Juan de Fuca Plate gets still hotter where it extends deeper.* **Hot fluids rise**, *forming the Cascade Volcanoes.*

and severely shake the region.

Rangers at Olympic National Park can have visitors look down and imagine the cold, brittle "locked zone" about 10 miles (16 kilometers) beneath their feet (about the same as the lateral distance from the top of Hurricane Ridge to Port Angeles). The locked zone extends from about 30 miles (50 kilometers) offshore, completely beneath the Olympics to the Puget Sound area (Fig. 32b). And the two plates may be locked all along the subduction zone boundary from Vancouver Island to northern California (Fig. 13). A sudden unlocking could produce an earthquake every bit as big as the one that occurred in Alaska in 1964, when a similar plate boundary snap occurred. Even if only one-tenth of the length of the boundary suddenly lets go, the resulting earthquake would be as big as the magnitude 8.3 earthquake that rattled San Francisco in 1906 (the largest earthquake to strike the lower 48 states during the 20th Century!).

PARTING THOUGHTS: FINDING CONNECTIONS

Geologic processes have built, and continue to build, the landscape of Olympic National Park. That landscape is an important component of both the natural and cultural histories of the region. Resource Education Rangers can develop programs focused on geological processes that formed some of the spectacular features of the park and surrounding areas:

"Natural Processes in Balance: The Olympic Mountains as a Giant Recycling Machine"

"Commotion in the Ocean: Formation of the Olympic and Cascade Mountain Ranges"

"The Present is the Key to the Past: The Loose Sand and Rocky Spires on Olympic Beaches"

"Can You Stand the Heat, Can You Stand the Pressure: Development of the Igneous, Sedimentary, and Metamorphic Rocks of Olympic National Park"

Rangers can also weave themes that relate the landscape to other physical and cultural aspects of the Olympics:

"Steady-State Subduction and Weather: The vastly different climates of the Olympic Peninsula"

"Earthquakes, Tsunami, and People: Native American accounts of Natural Disasters in the Pacific Northwest"

"Seattle awaits The Big One: How Olympic Geology Presents Clues to the Potential for Devastating Earthquakes in the Pacific Northwest"

However you chose to educate the public about the geology of Olympic National Park, the important thing is that visitors come away with a greater appreciation of the role of the physical Earth in the ecosystem. You could begin most any program by explaining how the Olympic landscape developed, and how that landscape influences aspects of natural or cultural history highlighted in your program.

The Ground Beneath Your Feet

"You must teach your children that the ground beneath their feet is the ashes of our grandfathers. So that they will respect the land, tell your children that the Earth is rich with the lives of our kin. Teach your children what we have taught our children — that the Earth is our mother. Whatever befalls the Earth, befalls the sons of the Earth. If men spit upon the ground, they spit upon themselves.

"This we know. The Earth does not belong to man; man belongs to the Earth. This we know. All things are connected like the blood which unites one family. All things are connected.

"Whatever befalls the Earth befalls the sons of the Earth. Man did not weave the web of life; he is merely a strand in it. Whatever he does to the web, he does to himself ....."

Chief Seattle

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GLOSSARY

accretionary wedge – A mountain range formed as sedimentary strata and hard crust are scraped off the top of a subducting plate.

andesite - A fine-grained, light-to-dark colored **igneous rock** with about 60% **silica**.

angular unconformity – An **unconformity** in which the underlying strata are tilted at a different angle than the overlying strata.

anticline – A **fold** in which the rocks layers are bent upward.

asthenosphere – Relatively soft portion of Earth's upper **mantle**. The rigid plates of **lithosphere** drift about over the flowing asthenosphere.

basalt – A fine-grained, dark-colored **igneous rock** with about 50% **silica**.

breccia – 1. A **sedimentary rock** made up of very coarse, angular fragments. (A similar rock with rounded, coarse fragments is a **conglomerate**). 2. A **volcanic rock** with coarse, angular rock fragments encased in finer volcanic particles. 3. A zone of angular rock fragments resulting from grinding between fault blocks.

brittle – Failure of material by discrete cracking and breaking (like peanut brittle or cold plastic).

cleavage – The breakage of a rock or mineral along planar faces.

columnar jointing – Cracks formed due to the shrinking of a lava flow as it cools. If cooling is uniform, the cracks commonly result in vertical, six-sided (hexagonal) columns.

conglomerate - A **sedimentary rock** formed from the compaction and cementation of sediment containing a lot of pebbles or cobbles. (If those particles are angular, the rock is called **breccia**).

continental drift – The theory that continents are not stationary, but rather move about relative to one another.

continental rift zone – A region of mountain ranges and long valleys formed as a plate capped by thick continental crust is pulled apart by plate divergence.

convergent plate boundary – Region where two slabs of Earth's outer shell (**lithosphere**) move toward one another, destroying lithosphere. **Subduction zones** and **continental collision zones** are common manifestations of convergent plate boundaries.

core – The central region of the Earth made mostly of iron.

crust – The outermost part of the Earth composed mostly of light silicate minerals.

diorite - A coarse-grained, light-to-dark colored **igneous rock** with about 60% **silica**.

divergent plate boundary – Region where two slabs of Earth's outer shell (**lithosphere**) are pulling apart from one another, creating new lithosphere. **Mid-ocean ridges** and **continental rift zones** are common manifestations of divergent plate boundaries.

ductile - Failure of material by flowing (like silly putty or hot plastic).

earthquake – A sudden movement within the Earth that releases vibrations (seismic waves).

eclogite - A metamorphic rock formed from a pre-existing rock (generally **basalt** or **gabbro**) that experienced high pressure, yet relatively low temperature.

extrusive rock - An igneous rock that solidified from magma that erupted on Earth's surface, forming fine-grained mineral crystals (**volcanic rock**).

fault – A break in the Earth along which the blocks on either side have moved parallel to the break.

fold – A structure formed as rock layers are bent.

foot wall - When a person stands across a fault plane, the block of rock that is next to their feet.

forearc basin – A depression between the uplifted (**accretionary wedge**) and volcanic (**volcanic arc**) mountain ranges formed above a **subduction zone**.

formation – A mass of rock with recognizable characteristics that make it distinguishable from surrounding masses of rock. Usually applied to a layer or sequence of layers of sedimentary rock.

gabbro - A coarse-grained, dark-colored **igneous rock** with about 50% **silica**.

geomorphology – The study of landforms, like mountains, valleys, and shorelines, and the processes that created them.

glacier – A naturally-formed mass of ice that moves gradually downslope under the influence of gravity.

gneiss - A **metamorphic rock** formed from a pre-existing rock that underwent extreme increases in temperature and pressure. (Greater amount of metamorphism than **schist**).

granite - A coarse-grained, generally light-colored **igneous rock** with about 70% **silica**.

hanging wall – When a person stands across a fault plane, the block of rock that is next to their head.

hotspot – Plume of hot material that rises from Earth's deep **mantle**. Chains of volcanoes form on the surface of a plate that rides over a hotspot.

igneous rock – A rock that solidified from molten fluid (**magma**).

intrusive rock - An **igneous rock** that solidified from **magma** that cooled within the Earth, forming coarse-grained mineral crystals (**plutonic rock**).

joint – A crack in a rock, with slight opening but no significant lateral movement of the blocks of rocks on either side of the crack. (A crack involving significant lateral movement is a **fault**.)

lava – Hot, molten rock (**magma**) that poured out on Earth's surface or beneath the sea.

lava flow – 1. Molten material (**magma**) pouring out on Earth's surface. 2. Hard rock formed from magma that erupted from the summit of a volcano, or from fissures along its sides.

limestone - A **sedimentary rock** formed from the compaction and cementation of calcium carbonate precipitated out of water.

lithosphere – The rigid outer shell of the Earth, composed of the outermost **mantle** and **crust**. The lithosphere is broken into plates that move over the underlying, softer **asthenosphere**.

magma – Hot, molten rock that may contain some amounts of gas and solid material.

mantle – The portion of the Earth between the **crust** and **core**. Made of **silicates** rich in iron and magnesium.

marble - A **metamorphic rock** formed from a **limestone** layer that underwent extreme increases in temperature and pressure.

metamorphic rock – A rock formed through the re-crystallization of a preexisting rock, while the rock was still solid.

metasandstone - A metamorphic rock formed from a **sandstone** layer that experienced relatively small increases in temperature and pressure. (Lesser amount of metamorphism than **quartzite**).

mid-ocean ridge – An undersea mountain range formed from volcanic activity where lithospheric plates diverge.

mineral – A naturally occurring, inorganic solid with specific chemical composition and crystalline structure.

moraine – Rock and other sedimentary material deposited on the sides or at the terminus of a **glacier**.

normal fault – A break in the Earth along which the **hanging wall** has moved up, relative to the **foot wall**. Formed when the rocks are subjected to tension (pulled apart).

pencil cleavage – A property of some **slate** whereby it breaks along **cleavage** planes and original bedding planes, resulting in long pieces of rock that look like pencils.

peridotite - A coarse-grained, olive-green colored **igneous rock** with about 40% **silica**.

phyllite - A **metamorphic rock** formed from a **shale** layer that experienced moderate increases in temperature and pressure. (Metamorphism between that of that of **slate** and **schist**).

pillow lava – A rock layer (**lava flow**) with globular structures formed when magma erupted through the sea floor or flowed into the ocean.

plate tectonics – The theory that large features on Earth's surface result from the movement of large plates of Earth's outer shell.

plunging fold – An **anticline** or **syncline** that is tilted so that it dips into the ground.

plutonic rock – An **igneous rock** that solidified from **magma** that cooled within the Earth (**intrusive rock**).

quartz – A **mineral** composed of pure silicon and oxygen (chemical formula SiO_2).

quartzite - A metamorphic rock formed from a **sandstone** layer that underwent extreme increases in temperature and pressure. (Greater amount of metamorphism than **metasandstone**).

reverse fault - A break in the Earth along which the **hanging wall** has moved down, relative to the **foot wall**. Formed when the rocks are subjected to compression (pushed together).

rhyolite - A fine-grained, generally light-colored **igneous rock** with about 70% **silica**.

rock – A mixture of **minerals** that are cemented together in some natural way.

sandstone – A **sedimentary rock** formed from the compaction and cementation of eroded rock particles the size of sand.

schist - A **metamorphic rock** formed from a pre-existing rock that experienced relatively large increases in temperature and pressure. (Greater amount of metamorphism than **slate**).

sedimentary rock – A rock formed from the burial and cementation of eroded rock fragments, or from material precipitated through biological or chemical activity.

seismology – The study of **earthquakes** and the waves they generate.

shale - A **sedimentary rock** formed from the compaction and cementation of fine mud.

silica – An ion consisting of the elements silicon and oxygen that combines with other elements to form most of the **minerals** in Earth's **crust** and **mantle**.

silicate – A compound that contains the elements silicon and oxygen.

siltstone - A **sedimentary rock** formed from the compaction and cementation of eroded rock particles finer than sand.

slate – A **metamorphic rock** formed from a **shale** layer that experienced relatively small increases in temperature and pressure. (Lesser amount of metamorphism than **schist**).

slaty cleavage – A property of some **slate** whereby it breaks along planes at different angles than the original sedimentary bedding.

strike-slip fault - A break in the Earth along which the blocks on either side of the break slid horizontally past one another. Formed when the rocks are subjected to shearing stresses.

subduction zone – A **convergent plate boundary** where one plate slides beneath another.

syncline - A **fold** in which the rock layers are bent downward.

tectonics - The study of large features on Earth's surface and the internal processes that led to their formation.

terrane – An extensive region with distinctive geology that is considerably different than the geology of surrounding regions.

thrust fault – A low-angle **reverse fault**.

till – Poorly-sorted and poorly-stratified rock fragments and other sedimentary material carried by a glacier.

transform plate boundary – Region where two slabs of Earth's outer shell (**lithosphere**) slide laterally past one another.

(deep sea) ***trench*** – A depression on the ocean floor formed where one lithospheric plate subducts beneath another.

tsunami – A giant sea wave caused by movement of the sea floor due to an earthquake, landslide, or volcanic flow.

turbidite – A sequence of thick sandstone and thin shale layers deposited by a **turbidity flows**.

turbidity flow – A current of water saturated by sediment that rushes down a continental slope, dropping the sediment on the deep floor of the ocean.

unconformity – A surface representing the disruption of the normal deposition of sedimentary strata. The disruption could be because strata were never deposited, or because they were deposited but were later eroded away.

volcanic arc – The chain of volcanoes that forms on the overriding plate at a subduction zone.

volcanic rock – An **igneous rock** that solidified from magma that erupted on Earth's surface (**extrusive rock**).

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USEFUL WEBSITES

National Park Service **http://www.nps.gov/**

Olympic National Park http://www.nps.gov/olym/index.htm
Mount Rainier National Park http://www.nps.gov/mora/index.htm
Geological Resources Division http://www2.nature.nps.gov/grd/
Geologist-in-the-Parks Program http://www2.nature.nps.gov/grd/geojob/index.htm
Park (Virtual) Geology Tours http://www2.nature.nps.gov/grd/tour/index.htm

U. S. Geological Survey **http://www.usgs.gov/**

Earthquake Information http://earthquake.usgs.gov/
Volcano Information http://volcanoes.usgs.gov/
Cascade Volcano Observatory http://vulcan.wr.usgs.gov/
Geology of National Parks http://www2.nature.nps.gov/grd/usgsnps/project/home.html

State of Washington **http://access.wa.gov/**

Department of Natural Resources http://www.wa.gov/dnr/
Division of Geology and Earth Resources http://www.wa.gov/dnr/htdocs/ger/
Geographic Information System (GIS) Data http://www.wa.gov/dnr/base/gisdata.html

University of Washington **http://www.washington.edu/**

Geophysics Program (Earthquake Information) http://www.geophys.washington.edu/SEIS/

Oregon State University **http://osu.orst.edu/**

Department of Geosciences http://osu.orst.edu/dept/geosciences/
College of Oceanic and Atmospheric Sciences http://www.oce.orst.edu/

Others

National Association for Interpretation http://www.interpnet.com/
National Center for Science Education http://www.ncseweb.org/