Geography and Geology of the San Juan Islands

Chris Comeau

I. Geography of the San Juan Islands

The San Juan Islands mark the geographic center of a dynamic region in northwest Washington which is commonly referred to as **Cascadia** (Figure G.1.). The Cascadia region is characterized by high volcanic peaks, tectonic plate collisions, glacier ice, deep fjords, protected inland seas, and forested islands. The San Juan Islands have been continually shaped and sculpted by these powerful forces of nature and now form a broken land bridge between mainland Washington and Vancouver Island, British Columbia, Canada. The geography of the San Juan Islands is a fascinating and ever-changing story which offers a detailed study of earth processes in progress. It is important to understand that the San Juan Islands that we see and enjoy today are only a temporary manifestation, like a snap-shot in time. The geography of the San Juan Islands will continue to change.

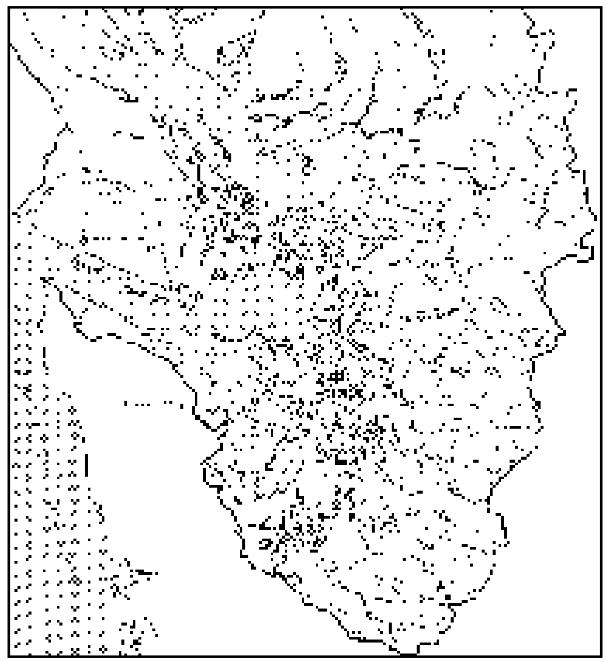


Figure G.1. The San Juan Islands and Northwest Straits within the greater Puget Sound drainage basin. From, Kruckeberg, Arthur R. The Natural History of Puget Sound Country. Seattle, WA: University of Washington Press, 1991. pg. 359. Reprinted by permission of the author.

Across Rosario Strait from the San Juan Islands the Cascade Mountain Range rises from the Skagit River Delta on the eastern and southeastern horizon. On clear days the snow-capped volcanic peaks of Mt. Rainier (14,410 ft.), Glacier Peak (10,436 ft.), and Mt. Baker (10,778 ft.) are easily visible from the islands and serve as dramatic reminders of the dynamic forces which have shaped this entire region. To the south, deep fjords and forested peninsulas mark the entrance to Puget Sound and Hood Canal. The glacially carved peaks of the Olympic Mountains rise dramatically to the southwest, presiding over the Strait of Juan de Fuca which stretches west and into the Pacific Ocean.

The international border between Canada and the United States lies in the center of Haro Strait between the southeastern toe of mountainous Vancouver Island and the San Juan Islands. The Gulf Islands of British Columbia lie to the northwest and are actually an extension of the same island archipelago which comprises the San Juan Islands. The deep channels of Boundary Pass and the Strait of Georgia mark the international border immediately north of the San Juan Islands, as well as the southern entrance of the Inside Passage to southeast Alaska. The rugged, snow-capped Coast Range of mainland British Columbia rises dramatically from the northeastern shores of the Strait of Georgia and merges with the North Cascades at the Fraser River.

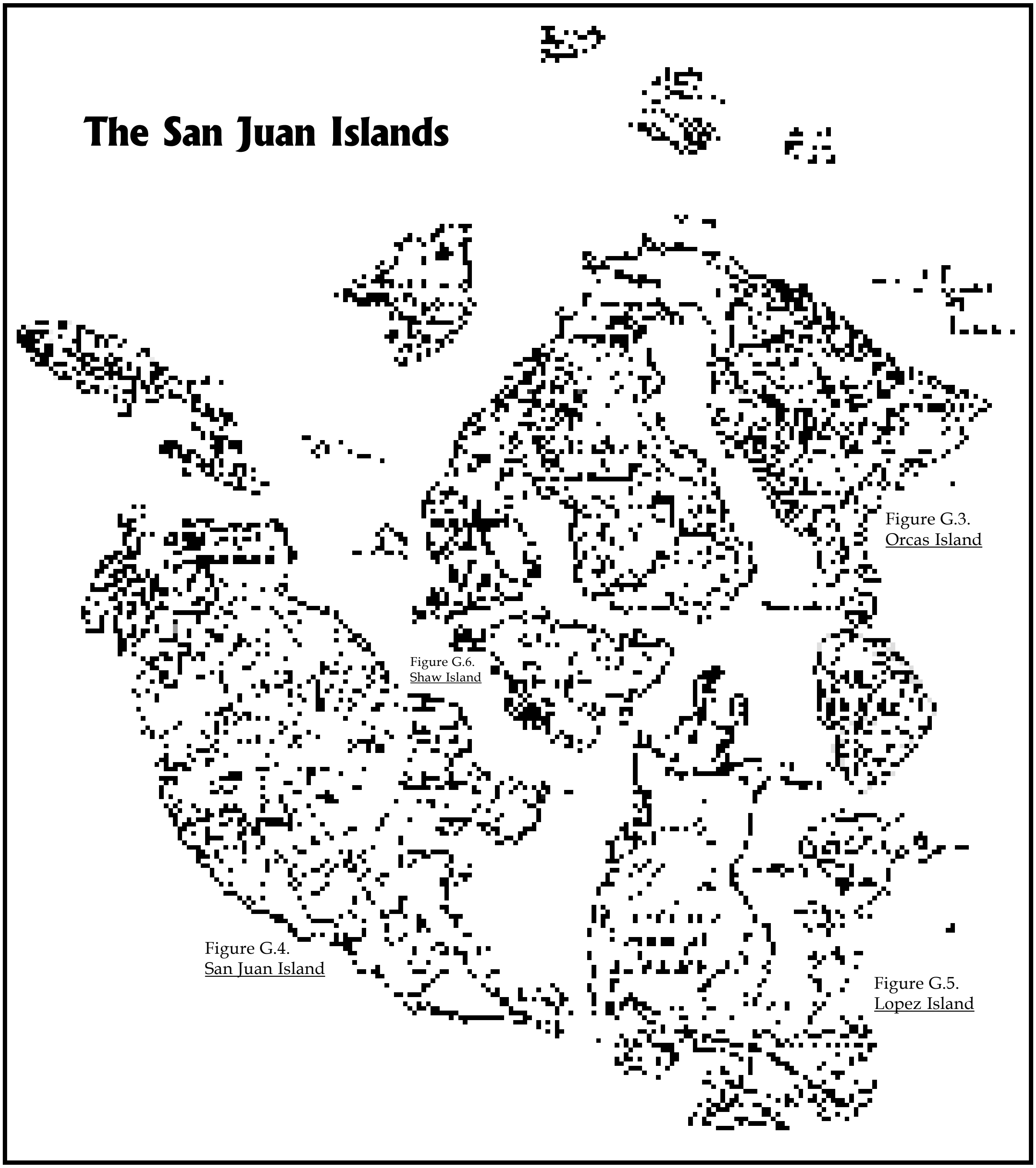


Figure G.2. **The San Juan Islands**
Figure G.3. Orcas Island
Figure G.4. San Juan Island
Figure G.5. Lopez Island
Figure G.6. Shaw Island

Map modified after a section of Speedy Reference Chart No. 3/San Juan Islands by www.evergreen-pacific.com. Reprinted with permission.

Although the San Juan Islands are part of a much larger archipelago, San Juan County, Washington encompasses what is considered to be the San Juan Islands proper (Figure G.2.). The total geographic area of San Juan County measures 265 square miles. Approximately 172 square miles of this total is actually landmass while 93 square miles is sea water. These measurements make San Juan County the smallest county in Washington. However, 385 miles of shoreline can also be measured within the county, which is the most of any county in Washington State. The landmass of the San Juan Islands consists of approximately 430 rocky islands, islets, and rocks which are exposed at high tide. At low tide, it is estimated that perhaps as many as 700 landmasses are exposed. Of these, only 175 islands have been given proper names.

San Juan County also has the distinction of being the only county in Washington that is not connected to any other county by highway. Four of the larger islands are served by Washington State Ferries from Anacortes and are profiled below. Other islands such as Waldron Island (northwest of Orcas Island), Stuart Island (north of San Juan Island), Decatur Island (east of Lopez Island), and Blakely Island (southeast of Orcas Island) are populated but do not have ferry service. Dozens of smaller islands dot the protected waterways and channels of the San Juan archipelago, including 84 islands designated as National Wildlife Refuges.

Orcas Island lies furthest to the north and is the largest island measuring 57 square miles (Figure G.3.). The village of Eastsound, located on the central north coast, is the center of commerce and hosts the largest population center on Orcas Island. Other population centers include Orcas Village, Westsound, and Deer Harbor on the western half of Orcas Island, and Olga, Doe Bay, and Rosario on the eastern half of Orcas. Mt. Constitution, located on the eastern lobe of Orcas Island, rises 2,409 feet above Rosario Strait and is the highest point in San Juan County. Moran State Park is also located on the eastern lobe of Orcas Island and is the largest state park in Washington. East Sound is a long and narrow, glacially-carved fjord which bisects the land mass of Orcas Island, creating a distinctive horseshoe configuration. Turtleback Mountain on the western lobe of Orcas Island, rises 1,519 feet above West Sound and President Channel.

San Juan Island lies furthest west and is second in size measuring 56 square miles (Figure G.4.). The Town of Friday Harbor encompasses one square mile of land area on the central east coast of San Juan Island and hosts the largest population center in the county. Friday Harbor is the only incorporated area in San Juan County, thus serving as the County seat of government. Roche Harbor is also a prominent center of commerce and population on northwestern San Juan Island. Topographic high points on San Juan Island include Mt. Dallas at 1,029 feet and Cady Mountain at 894 feet.

Lopez Island lies furthest to the south and is third in size measuring 29 square miles (Figure G.5.). Lopez Village is located on the northeastern shore of Fisherman Bay on the west coast of Lopez Island and is the center of commerce and population. Lopez Island is relatively flat compared to other islands and the topographic high point is Lopez Hill at 535 feet on eastern Lopez.

Shaw Island lies nestled in between the three larger islands and is fourth in size measuring 8 square miles (Figure G.6.). Shaw does not have a concentrated center of commerce or population. Shaw is also relatively flat with the topographic high point being Ben Nevis Hill at 385 feet located near the center of the island.

II. Weather and Climate of the San Juan Islands

The day-to-day weather in the San Juan Islands is strongly influenced by the surrounding marine environment with mild and humid conditions resulting in a pleasant year-round "Cool Mediterranean" climate. The summer months are normally cool, dry, and sunny with an average July temperature of 60 F degrees, although warm sunny days can produce temperatures in the high 80 F degrees. Winter months are normally mild, wet, and cloudy with an average January temperature of 39 F degrees, although wind chill and cold rain can produce temperatures well-below freezing. Over 75 percent of the yearly precipitation is received between the months of October through March. Weather does fluctuate and sometimes causes extreme drought, fire hazards, thunder storms, high winds and waves, freezing, and snow storms.

The present climate of the San Juan Islands is also affected by the surrounding regional geography. The San Juan Islands lie within the "**rainshadow**" of the Olympic Mountains and, north of the central California region, experience the driest climate on the west coast of North America. During summer months the dominant weather pattern over the region produces southwesterly winds which carry moisture-laden air masses over the northeast Pacific Ocean. These air masses approach the northwest coast and 'come ashore' in the vicinity of the Olympic Peninsula of Washington. The Olympic Mountains rise sharply from the Pacific coast, reaching heights of almost 8,000 feet near Mt. Olympus (7,954 ft.).

When a moisture-laden air mass encounters this wall of rock, it is forced to rise vertically to move over it. This is called **orographic uplift**. Moisture is forced out of the air mass and falls on the western slopes and high peaks of the Olympic Mountains which receive about 200 inches of orographic precipitation every year. The perennial snow fields and glaciers of the Olympics are the direct result of this process and also help to lower the air temperature of approaching air masses. After an air mass has been wrung dry like a sponge by the Olympic Mountains, the resulting cold, dry air descends the northeastern slopes and warms as it moves over the Strait of

Juan de Fuca and the San Juan Islands. San Juan County lies at the heart of this rainshadow (Figure G.7.).

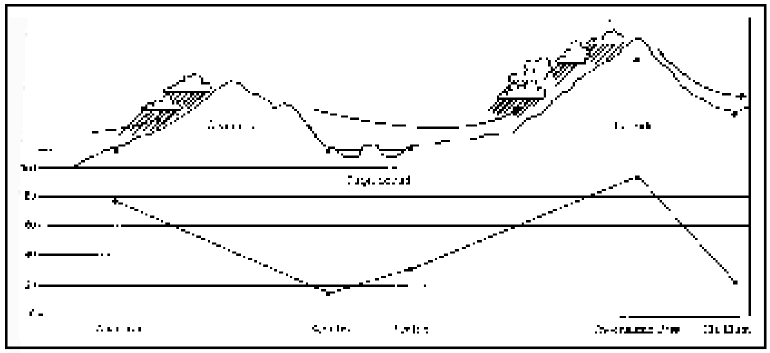


Figure G.7. The Olympic Rainshadow and Orographic Precipitation. From, Kruckeberg, Arthur R. The Natural History of Puget Sound Country. Seattle, WA: University of Washington Press, 1991. pg. 353. Reprinted by permission of the author.

Precipitation varies within the county and increases from southwest to northeast. The southern coasts of San Juan and Lopez Islands receive about 15 inches of precipitation per year; Friday Harbor on the central east coast of San Juan Island receives about 29 inches; and 2,409 foot Mt. Constitution on northeastern Orcas Island can receive up to 45 inches. For comparison: the west slope of the Olympic Mountains can receive up to 200 inches of precipitation per year; the west coast of Vancouver Island can receive up to 300 inches; the west slope of the North Cascades can receive up to 110 inches; the Seattle area receives about 40 inches of precipitation per year. Throughout the year the western slopes of the Olympic Mountains receive about fifty percent of the total regional precipitation, the western slopes of the Cascade Mountains receive about forty percent, and the Puget lowlands between Olympia, WA and Vancouver, B.C. receive about ten percent.

III. Glaciation in Cascadia

The Earth's climate has fluctuated greatly over its estimated 4.6 billion year history. Subtle changes in global temperature have led to great climatic shifts and impacts to the geography of entire regions. Decreases of just a few degrees in global temperature have resulted in '**Ice Ages**'. During these events, glacier ice accumulated in the high latitudes and descended from alpine environments to form '**piedmont**', or regional, ice sheets covering vast area of continents. Recent scientific findings provide evidence that the entire surface of the planet may have been covered with ice on more than one occasion. It is estimated that over the past 2 million years the Cascadia region may have been subjected to as many as 15 major glaciations.

The most recent glacial period affecting Cascadia began approximately 25,000 years before present and is referred to as the **Fraser Glaciation**. The most extensive ice advance, or **stade**, began approximately 18,000 years before present and is referred to as the **Vashon Stade**. A cooler global climate and regional geographic influences allowed great accumulations of snow and ice to form on the western slopes of the British Columbia Coast Range and the North Cascades. Snow and ice also accumulated on the eastern slopes of the Insular Mountains on Vancouver Island. Alpine glaciers flowed downhill and eventually coalesced in the Georgia Depression and Puget Lowland. As glacier ice accumulated in the lowlands and

thickened, a piedmont glacier developed and only the highest mountain peaks remained exposed above the ice as '**nunataks**'. The massive piedmont glacier flowed southward between Vancouver Island and the mainland and completely overrode the San Juan and Gulf Islands. The glacier **scoured** lowland valleys and created the topographic depressions which now exist as Haro Strait, East Sound, and Rosario Strait.

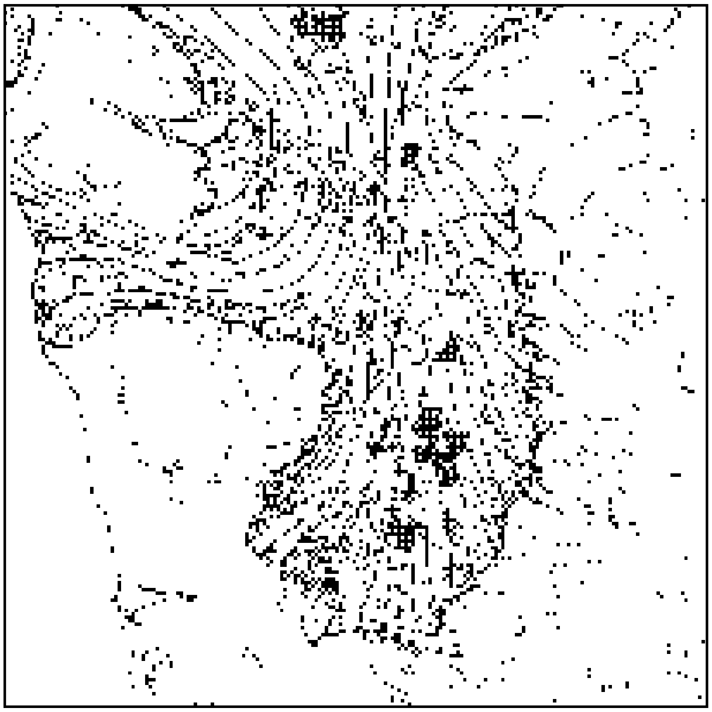


Figure G.8. Full extent of Vashon Stade Glaciation in Puget Lowland Basin, approximately 14,000 years before present. From, Kruckeberg, Arthur R. The Natural History of Puget Sound Country. Seattle, WA: University of Washington Press, 1991. pg. 21. Reprinted by permission of the author.

The piedmont glacier continued to flow south and eventually encountered the Olympic Mountains. Alpine glaciers from the Olympics coalesced with the piedmont glacier and diverted its flow, splitting it into a westward flowing Juan de Fuca Lobe and a southward flowing Puget Lobe. The Vashon Stade glacier was constrained between the Cascade and Olympic Mountains and covered the entire Puget Lowland from the San Juan Islands to an area south of present-day Olympia, Washington (Figure G.8.). It is estimated that at the peak of the Vashon Stade, 14,000 years ago, the area of the present-day San Juan Islands was covered by approximately 4,200 feet of glacier ice. The present site of Bellingham was covered by 5,250 feet, or almost one vertical mile, of ice. The Puget Lobe of glacier ice rose 3,275 feet over the present site of Seattle, 2,500 feet over Tacoma, and 1,400 feet over Olympia.

The maximum southerly extent of the Puget Lobe during the Vashon Stade occurred approximately 13,000 years before present and formed a **terminal moraine** on the lowlands south of Olympia. The global climate had begun to warm and the piedmont glacier ice slowly retreated to the north and to the alpine environments of the surrounding mountain ranges. The modern geography of the San Juan Islands and the Cascadia region became unveiled approximately 10,000 years before present after having been sculpted by ice for 8,000 years.

Physical indications of the presence of this glacial ice can be seen today throughout the San Juan Islands. Non-native granite boulders called '**glacial erratics**' can be found embedded in soils or lying on the surface in forests and fields. These chunks of granite were plucked from the Coast Range of British Columbia and carried to the San Juan Islands in glacier ice. When the glaciers receded, the granite boulders melted out of the ice exactly where they are found today. Thick accumulations of **glacial till** in the form of sand and gravel were deposited in valleys and low-lying places

around the islands. As a result of these many deposits, fresh water from precipitation seeps into the glacial till and forms significant groundwater aquifers.

The sheer weight of 4,200 feet of ice over the San Juan Islands formed a topographic depression in the earth's crust. As the glaciers retreated, the weight of the ice was removed and the surface of the Earth began to rise very slowly in a 'isostatic rebound'. Beaches, deposits of cobble, and **wave-cut benches** were formed by erosion and wave action along the ancient shorelines of the San Juan Islands. These ancient beach lines are slowly being elevated as the islands continue to rebound from the weight of the glaciers (Figure G.9.). Several excellent examples of elevated ancient shorelines can be viewed at Mt. Finlayson, Cattle Point, and South Beach on San Juan Island.

The Vashon glacier generally flowed from northwest to southeast as it rode over the San Juan Islands. Exposed rock surfaces were polished by fine sediments grinding underneath the ice. Boulders and broken rocks transported at the base of the glacier acted as carving tools to gouge deep grooves called '**striations**' in underlying rock surfaces. Glacier ice that moved over the crests of the islands also plucked additional rocks and boulders from the south-facing slopes (Figure G.10.). Evidence of this **glacial plucking** can be seen as steep and ragged, or stepped, south-facing hillsides and coastlines throughout the San Juan Islands.

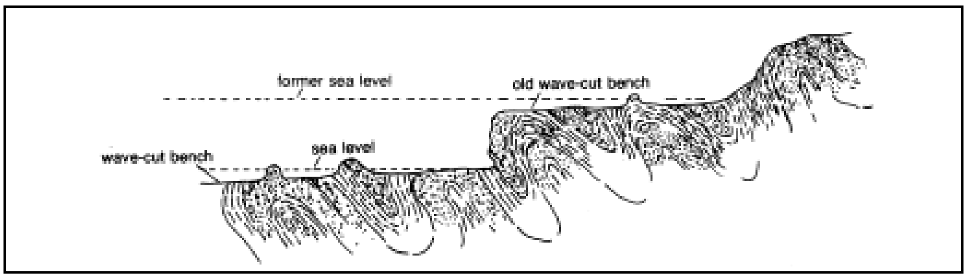


Figure G.9. A coast with a modern wave cut bench and an older one raised above sea level by isostatic rebound, or uplift. © Roadside Geology of Washington, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 256. Reprinted by permission of Mountain Press Publishing Co.

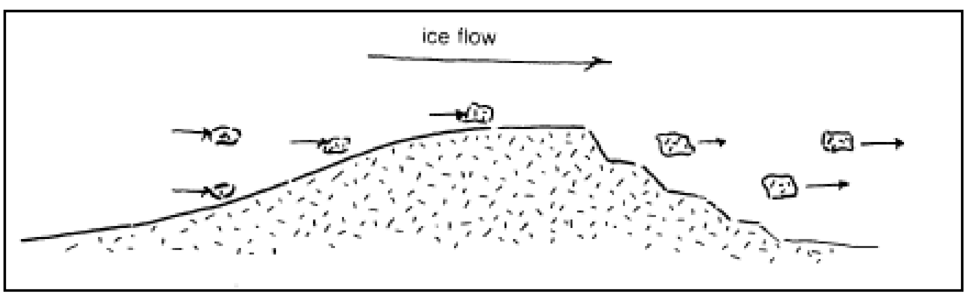


Figure G.10. Example of Glacial Plucking. © Roadside Geology of Washington, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 271. Reprinted by permission of Mountain Press Publishing Co.

IV. Oceanography of the San Juan Islands

Global sea level during the ice ages was much lower than today because much of the surface water on the planet was locked up in ice sheets and glaciers. Approximately 18,000 years before present, at the beginning of the Vashon Stade of the Fraser Glaciation, the global sea level was an estimated 380 feet below present mean sea level. Approximately 14,000 years before present, Puget Sound, the Strait of Juan de Fuca, and Georgia Strait were deep inland seas of ice.

Figure G.11. Bathymetry of San Juan County and the San Juan Islands, Washington. From Puget Sound Environmental Atlas, Vol. 1., Region 2. Reprinted with the permission of the Puget Sound Water Quality Action Team from original prepared by Evans-Hamilton Inc. and D.R. Systems, Inc., Feb. 1997.

As the global climate warmed approximately 13,000 years before present and the glaciers receded, the global sea level began to rise and the deep **U-shaped valleys** that were carved into the Puget Lowland began to fill with sea water. By about 10,000 years ago the entire Puget Lowland was ice free and the global and inland seas were near present levels. The large bodies of water which now surround the San Juan Islands are sometimes called the **Salish Sea**. This term refers to the indigenous Salish people who migrated from interior British Columbia through the Fraser River Valley and into the Puget Lowland after the Vashon glacier had receded. The Straits Salish successfully practiced a semi-nomadic lifestyle in and around the San Juan Islands for thousands of years.

Some localities of the Salish Sea, such as Haro Strait, Boundary Pass, and Rosario Strait, are extremely deep. The vast majority of Haro Strait exceeds 600 feet in depth, as does much of Boundary Pass (Figure G.11.). The deepest water recorded is a sounding of 190 **fathoms**, or 1,140 feet, in Haro Strait approximately one-half mile west of Turn Point on Stuart Island. It is interesting to note that the total topographical relief from this point at the bottom of Haro Strait to the top of Mt. Constitution on Orcas Island is 3,550 feet. The Vashon ice sheet which covered the San Juan Islands 14,000 years ago is estimated to have been 650 feet higher than this!

These deep channels contain vast amounts of sea water which affect the islands in several different ways. The average **tidal range** of the San Juan Islands is approximately 10 feet, but annual tidal extremes can range up to 14 feet. The San Juans experience **diurnal tides**, or two high tides and two low tides per day. A huge volume of sea water is flushed between the deep channels of Haro Strait and the Strait of Georgia. The channels which divide the landmass of the San Juan Islands, such as San Juan Channel,

President Channel and Thatcher Pass, are much shallower on average and, as a result, experience powerful currents, tidal 'rips', and eddylines. Strong upwelling currents from deep channels provide for a thorough mixing of nutrients, oxygen, and temperature. This dynamic marine environment influences climatic conditions, provides ideal conditions for a great diversity of marine life, and is an important erosion and transport mechanism in the ever-changing shape of the San Juan Islands.

V. Geology

The geologic history and formation of the San Juan Islands is an extremely complicated puzzle which is only slowly being pieced together by scientists. The entire western margin of the North American continent, and specifically western Washington, has been assembled over hundreds of millions of years. In fact, most of the landmass between the Rocky Mountains and the Pacific Ocean, including the southern half of Alaska, is considered by geologists to be an intricate compilation of '**exotic**' **terranes** (Figure G.12.). This means that landmasses, or **micro-continents**, have been transported to western North America from other locations and then attached to the continent. Geologic evidence suggests that some of the rock in the San Juan Islands was formed south of the equator on the other side of the Pacific Ocean!

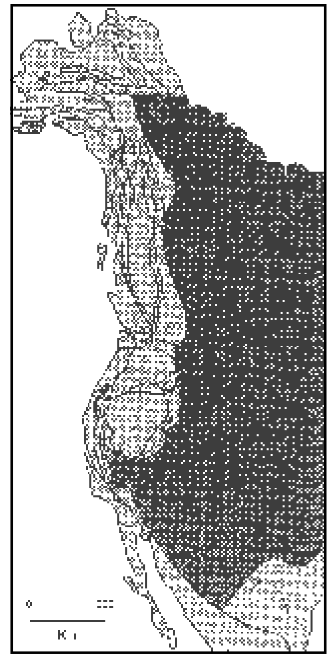


Figure G.12. Exotic terranes which have been sutured onto the western margin of the North American continent. Image modified after figure 16.25 in The Dynamic Earth, 3rd ed. by B.J. Skinner and S.C. Porter © 1995 John Wiley & Sons, Inc. Image appears as figure 9.3, pg. 142 in A Short History of Planet Earth: Mountains, Mammals, Fire and Ice by J.D. Macdougall © 1996 John Wiley & Sons Inc. Reprinted by permission of John Wiley & Sons Inc.

The present geography and topography of the San Juan Island archipelago is primarily due to recent glacial events, but the geological development of Cascadia began more than 350 million years before present. Some rock layers in the San Juan Islands are much older than this. The oldest rock layers of Turtleback Mountain have been **potassium argon dated** at approximately 550 million years before present, but the origin of this rock is somewhat mysterious.

The following narrative traces the assembly of the western margin of the North American continent, Cascadia, and the San Juan Islands in general detail. Significant geologic events are posted on a **geologic time scale** (Figure G.13.).

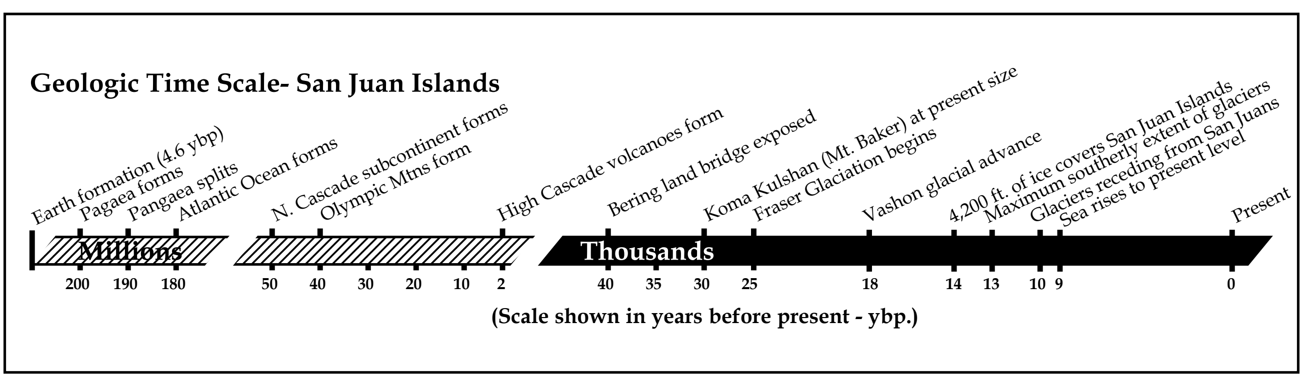


Figure G.13. Geologic Timescale.

Approximately 350 million years ago the western margin of North America closely resembled the broad eastern coastal plain of modern North America. The western continental margin and oceanic crust were coupled together as one **lithospheric**, or crustal, **plate** and were moving away from an **ocean ridge**, or spreading center, far to the west. Eventually, ancient North America merged with other continents to form a supercontinent which scientists refer to as Pangaea (Figure G.14.).

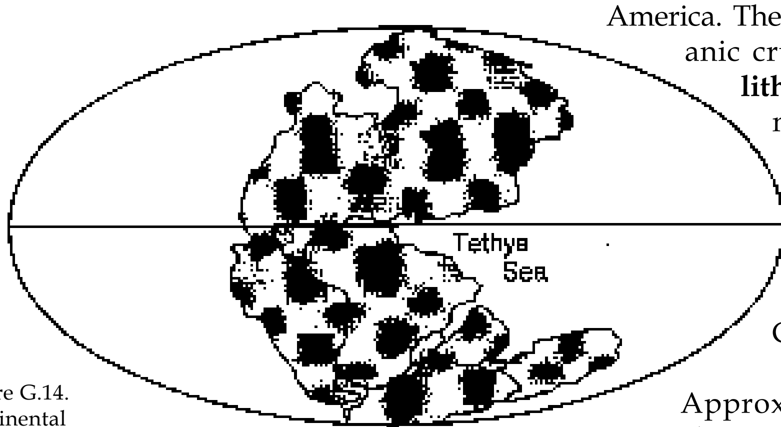


Figure G.14. Continental landmass of Pangaea, approximately 200 million years before present. Image modified after figure 20-17(a) in EARTH 4/E by Press/Siever © 1986 by W.H. Freeman and Company. Used with permission. Image appears as figure 8.4, pg. 130 in A Short History of Planet Earth: Mountains, Mammals, Fire and Ice by J.D. Macdougall © 1996 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

Approximately 200 million years before present this supercontinent began to rift apart and by approximately 180 million years before present the modern Atlantic Ocean was beginning to open along the spreading center of the **mid-Atlantic ridge** (Figure G.15.). As new oceanic crust formed and moved away from the mid-oceanic ridge (Figure G.16.), it pushed the North American continent in a westerly direction and the **Pacific Ocean plate** began compressing against the **North American plate**. Eventually the dense, heavier Pacific plate was **subducted**, or forced, beneath the westward-moving North American plate and created a deep trench along the entire western margin of the North America continent (Figure G.17.). Figure G.18 shows the relative drift of continents following the breakup of Pangaea.

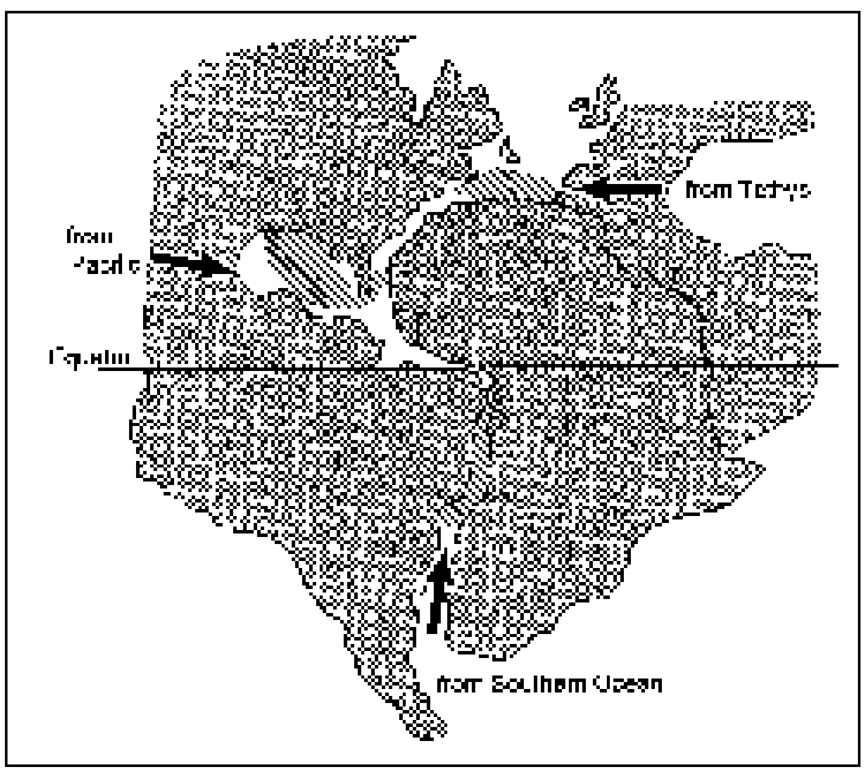


Figure G.15. Pangaea rifting apart, approximately 200 - 180 million years before present. Image modified after Fig. 1 from Geology, Nov. 1975. Modified with permission of the publisher, The Geological Society of America, Boulder, CO, USA copyright © Geological Society of America, 1975. Image appears as figure 9.2, pg. 138 in A Short History of Planet Earth: Mountains, Mammals, Fire and Ice by J.D. Macdougall © 1996 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

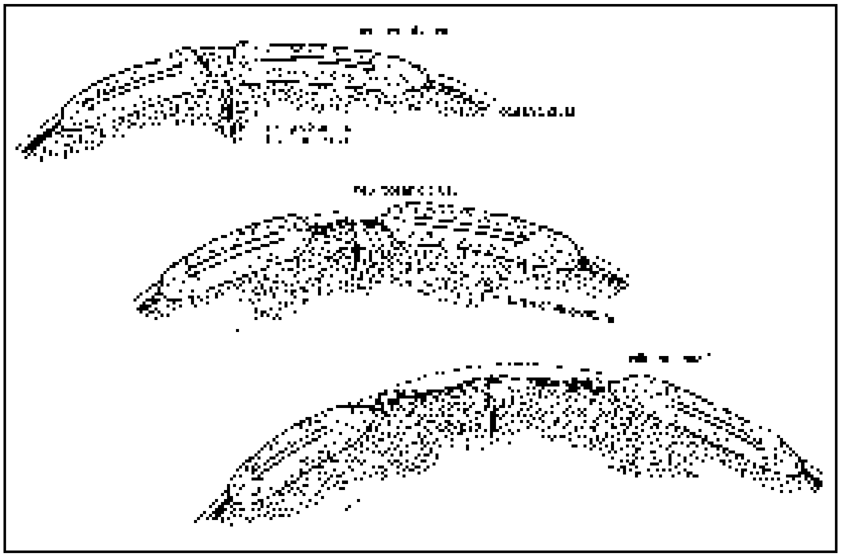


Figure G.16. Example of a continent rifting apart and forming a new mid-oceanic ridge and ocean basin. © <u>Roadside Geology of Washington</u>, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 11. Reprinted by permission of Mountain Press Publishing Co.

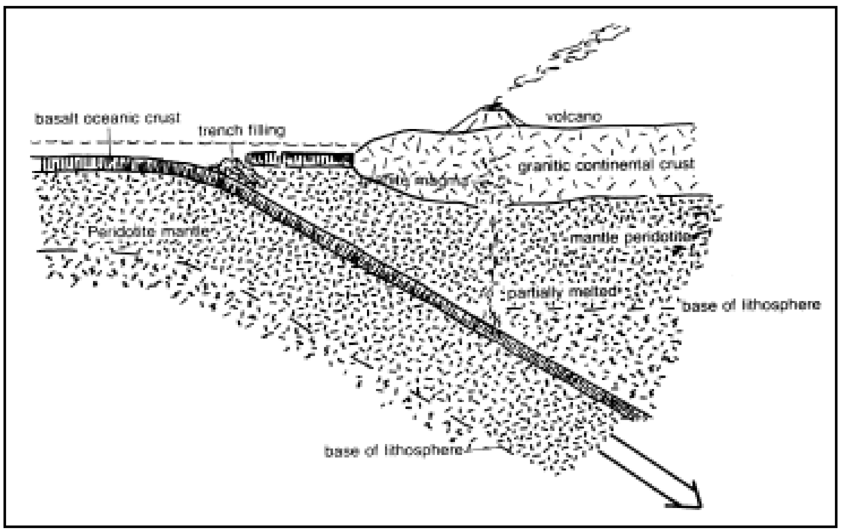


Figure G.17. Example of a typical plate collision boundary. © <u>Roadside Geology of Washington</u>, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 6. Reprinted by permission of Mountain Press Publishing Co.

Figure G.18. Pangaea rifting apart and subsequent continental drift, approximately 170, 120, and 70 million years before present. Images modified after maps in <u>Atlas of Mesozoic and Cenzonic Coastlines</u> by A.G. Smith, D.G. Smith and B.M. Funnell, 1994. New York: Cambridge University Press. Used with permission. Images appear as figure 9.1, pg. 137 in <u>A Short History of Planet Earth: Mountains, Mammals, Fire and Ice</u> by J.D. Macdougall © 1996 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

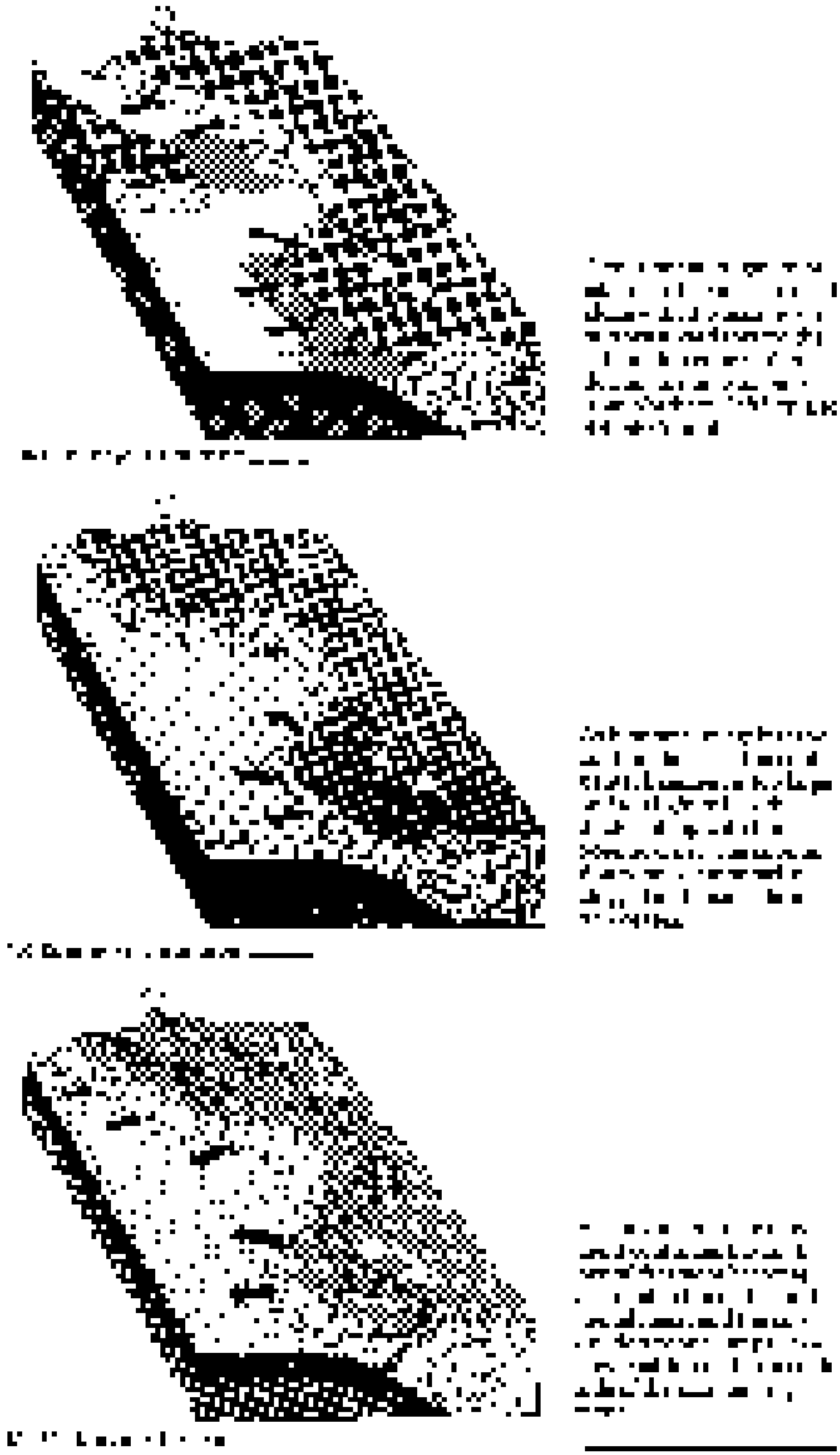


Figure G.19. Accretion of Vancouver Island on North America. From Figure 4.5, pp 32; The Shape and Form of Puget Sound by Robert Burns. Seattle, WA: University of Washington Press, 1985. Reprinted by permission from Washington Sea Grant Program, University of Washington.

Between 160 - 130 million years before present the exotic terrane which now forms modern Vancouver Island docked with and became sutured on to the North American continent (Figure G.19.). Older continental crust, which now forms the San Juan Islands, also arrived at the continental margin during this time and was slowly stuffed into the offshore subduction trench. Basaltic lava flowed from continental volcanoes and collected on top of this older crust along with sediment eroding from the continent (Figure G.20.).

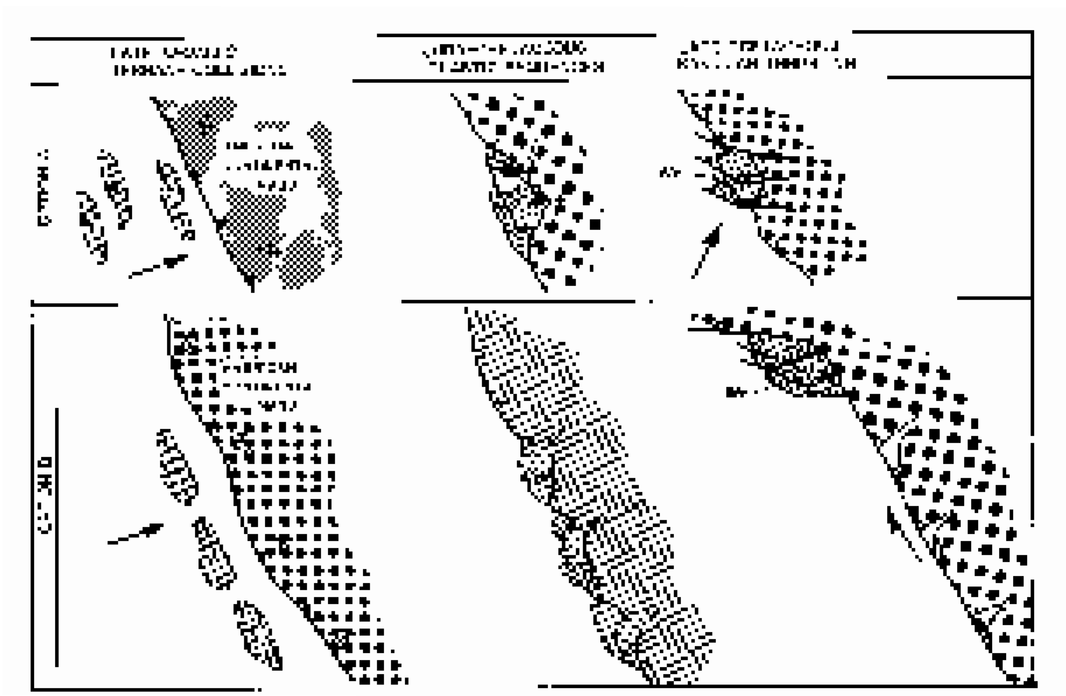


Figure G.20. Two models for the accretionary history of terranes in the vicinity of the San Juan Islands. From Figure 30, pp 44; The Late Cretaceous San Juan Thrust System. Special Paper 221 by M.T. Brandon, D.S. Cowen, and J.A.Vance. Reproduced with permission of the publisher, the Geological Society of America, Boulder, CO, USA copyright © Geological Society of America 1988.

Between approximately 100 - 80 million years before present a very complex series of **tectonic** events occured. Geologists speculate that the layers of bedrock which now form the San Juan Islands were successively downthrust to approximately 12 miles below the surface. The increased temperature and pressure at this depth severely deformed and recrystallized the rock. Over several million years, sequential down-thrusting resulted in the compressional uplift of the San Juan bedrock. As this uplift occurred, overlying rock was removed by erosion and deposited immediately to the northwest (Figure G.21.). Evidence of this can be found as cobble in the **Nanaimo Formation** which makes up many of the Gulf Islands of British Columbia.

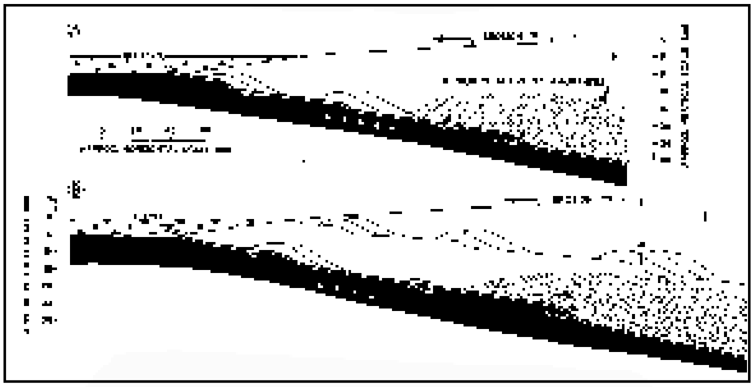


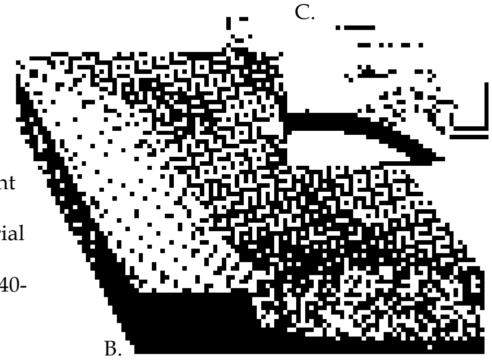
Figure G.21. A model showing the proposed relationship between thrusting and high-pressure metamorphism. From Figure 29, pp 43; The Late Cretaceous San Juan Thrust System. Special Paper 221 by M.T. Brandon, D.S. Cowen, and J.A.Vance. Reproduced with permission of the publisher, the Geological Society of America, Boulder, CO, USA copyright © Geological Society of America 1988.

These tectonic events effectively clogged the existing subduction trench with continental crust and the subduction process temporarily ceased. The continued compressional stress of plate collision resulted in crustal uplift and the formation of the Coast Range from approximately 65 - 40 million years before present (Figure G.22.A.). A new subduction trench eventually formed offshore from the western coast of Vancouver Island and the Pacific plate resumed its slow descent beneath the North American plate. The exotic terrane of the Olympic Peninsula arrived approximately 40 million years before present and by approximately 15 million years ago had sutured itself to the North American continent (Figure G.22.B.). The Olympic Mountains were also formed during this period as **sedimentary** material was continually scraped from the top of the subducting oceanic plate, stuffed into the subduction trench, and slowly thrust up and rotated eastward onto the continent (Figure G.22.C.). More recent glacial and tectonic events are responsible for the present configuration of the Cascadia region (Figure.22.D.).

A.

Fig. A: Accumulations of island arc terrane, seamounts, and sediment of continental origin move toward the northwestern edge of the continent and are scraped off the top part of the slab at the subduction zone 120-65 million years before present. As this process continues, there is additional compressional stress and the continent is deformed and uplifted as the coastal range 65-40 million years before present.

C.



B.

Fig. B & C: The Western margin is finally "straightened' by the emplacement of the Olympic Mountains. Inset: The Olympics have been formed by a complex convergent boundary process of ongoing underthrusting of material that was originally located on the upper surface of the subducting oceanic plate, but is slowly rotated up and eastward toward the continental mass (40-15 million years before present).

D.

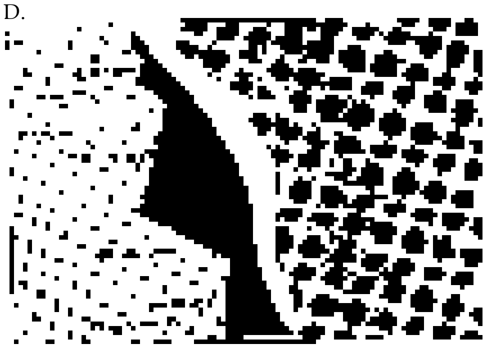


Fig. D: The northwest Coast as it looks today. The Juan de Fuca plate sometimes called the Gorda plate, being formed at spreading centers along Explorer, Juan de Fuca, and Gorda ridges, continues to be subducted along a convergent boundary with the North American plate. Shear boundaries are present along the fracture zones.

Figure G.22. (A/*top* - D/*bottom*) The recent geologic evolution of the Northwest coast. From Figure 4.6, pp 34; The Shape and Form of Puget Sound by Robert Burns. Seattle, WA: University of Washington Press, 1985. Reprinted by permission from Washington Sea Grant Program, University of Washington.

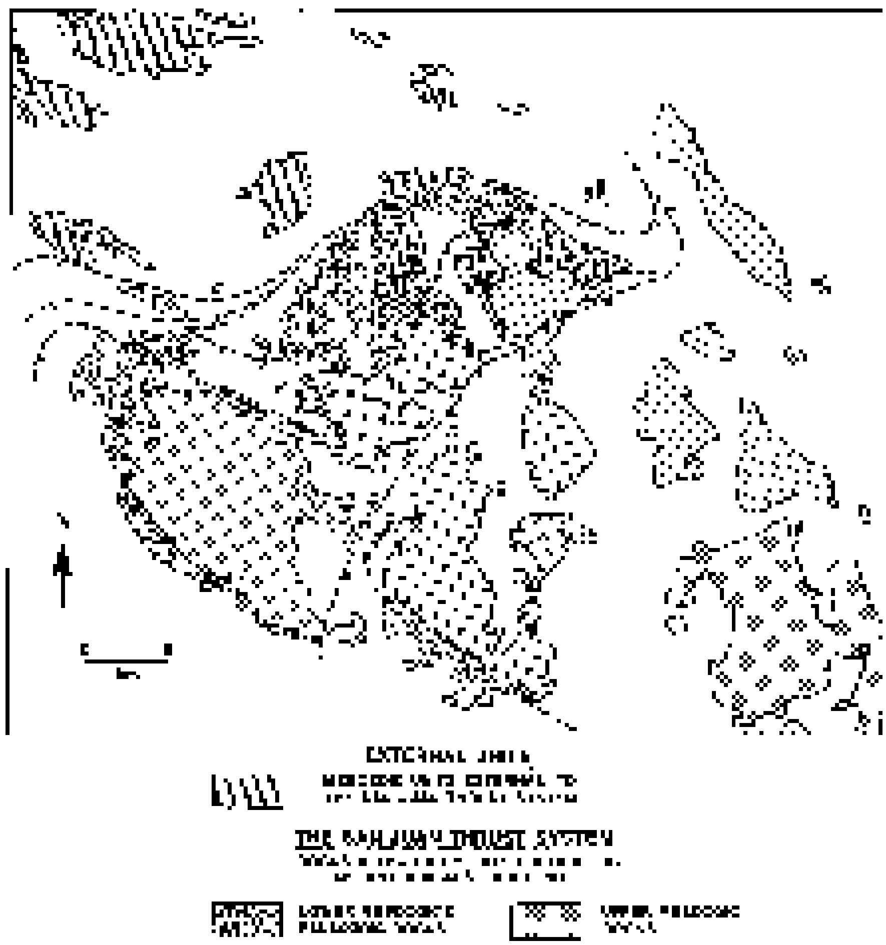


Figure G.23. Major structural divisions in the San Juan Islands. From Figure 5, pp 9; The Late Cretaceous San Juan Thrust System. Special Paper 221 by M.T. Brandon, D.S. Cowen, and J.A.Vance. Reproduced with permission of the publisher, the Geological Society of America, Boulder, CO, USA copyright © Geological Society of America 1988.

The bedrock of the San Juan Islands has been severely compressed and deformed and today is composed of a geologic sequence of thrust faults and stacked **'nappes'**, or tectonic layers. Geologists have identified five separate terranes of varying ages within and peripheral to the San Juan Islands (Figure G.23.). The San Juan Thrust System (Figures G.24. and G.25.) as it is termed, includes in stratigraphic order and ages in millions of years before present: the **Haro terrane** (about 220 - 120); the **Turtleback terrane** (about 540 - 280); the **Deadman Bay terrane** (about 280 - 200); the **Garrison terrane** (about 280 - 240); and the **Decatur terrane** (about 180 - 120).

The geology of the San Juan Islands is sometimes referred to as a '**melange**' to describe the extremely messy combinations and assortment of rock types. These include severely **metamorphosed** sedimentary rocks, limestones deposited in shallow marine environments, mudstones and chert which accumulated on the deep ocean floor, thick sandstone and pebbled conglomerate formations, slate, volcanic basalts, and scraps of oceanic crust. There are excellent examples of most of these rock types at various sites in the San Juan Islands.

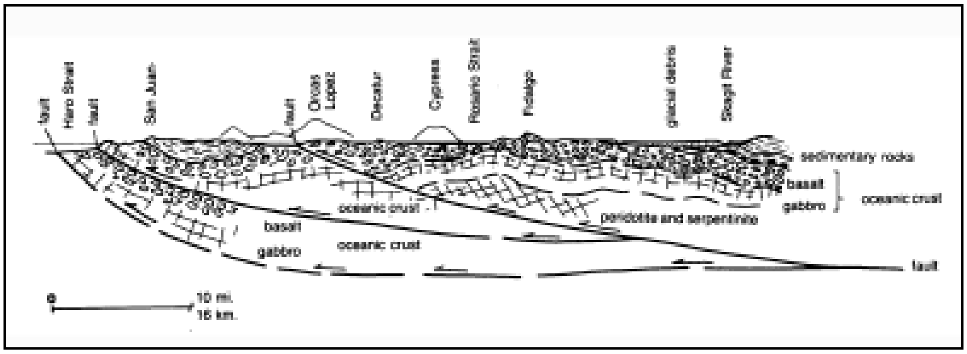


Figure G.24. Geologic cross-section showing the San Juan Islands resting on the Shuksan and related thrust faults which moved them westward over younger rocks beneath. © Roadside Geology of Washington, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 102. Reprinted by permission from Mountain Press Publishing Co.

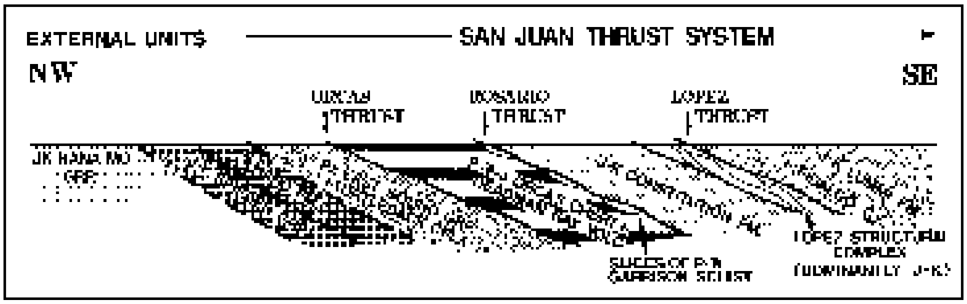


Figure G.25. Geologic cross-section showing the general stacking order of nappes, or related rock layers, in the San Juan thrust system. Figure G.23. Major structural divisions in the San Juan Islands. From Figure 4, pp 7; The Late Cretaceous San Juan Thrust System. Special Paper 221 by M.T. Brandon, D.S. Cowen, and J.A.Vance. Reproduced with permission of the publisher, the Geological Society of America, Boulder, CO, USA copyright © Geological Society of America 1988.

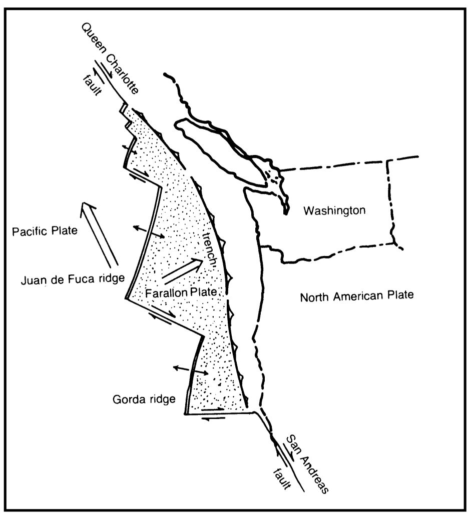


Figure G.26. The Farallon plate and the Juan de Fuca ridge. © Roadside Geology of Washington, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 22. Reprinted by permission from Mountain Press Publishing Co.

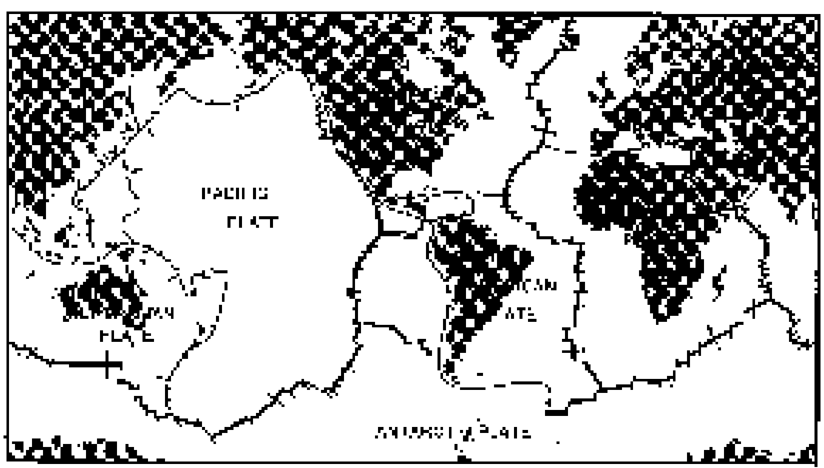


Figure G.27. The East Pacific rise marks the eastern edge of the Pacific plate. From figure 5.2, pg. 64 in A Short History of Planet Earth: Mountains, Mammals, Fire and Ice by J.D. Macdougall © 1996 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

VI. The Geologic Future of Cascadia

A great offshore subduction trench still exists today along the west coast of the Cascadia region. The oceanic **Farallon plate** is being pushed eastward as new ocean crust is formed along the **Juan de Fuca ridge**. As it collides with the continental North American plate at the subduction trench, the Farallon plate is forced down into the mantle of the Earth (Figure G.26.).

The Juan de Fuca ridge is a cutoff remnant of the **East Pacific rise**, which created the present Pacific Ocean basin. This extensive mid-oceanic ridge system stretches from the Queen Charlotte Islands of Canada to Antarctica, with one exception (Figure G.27.). From the southern tip of the Baja Peninsula of Mexico to Point Reyes, California just north of San Francisco Bay, the East Pacific rise disappears. Approximately 45 million years ago this mid-ocean ridge arrived at the continental margin and was subducted beneath the North American plate. The San Andreas **transform fault** was created approximately 35 million years ago to alleviate tectonic pressure and allow continued plate movement between the Pacific and North American plates (Figure G.28.).

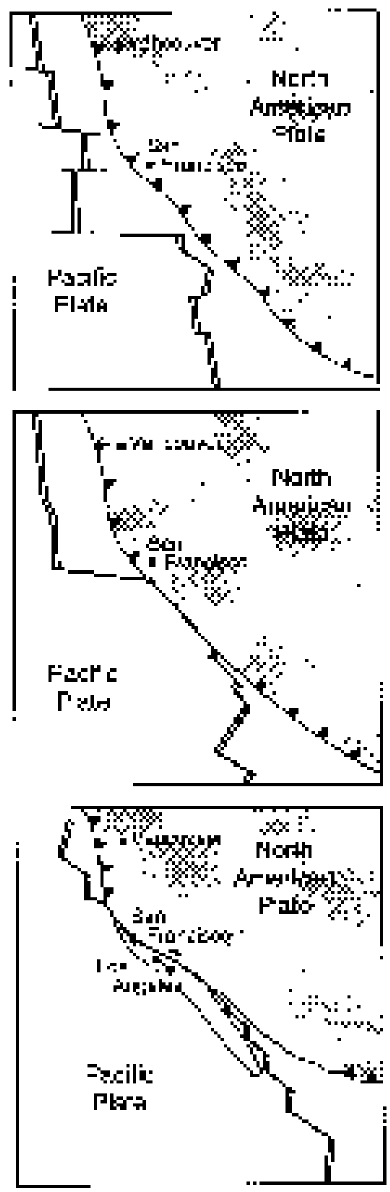


Figure G.28. Subduction of the East Pacific and development of the San Andreas transform fault along western North America. Image modified after figure 16.24 in The Dynamic Earth, 3rd ed. by B.J. Skinner and S.C. Porter © 1995 John Wiley & Sons, Inc. Image appears as figure 5.6, pg. 75 in A Short History of Planet Earth: Mountains, Mammals, Fire and Ice by J.D. Macdougall © 1996 John Wiley & Sons, Inc. Reprinted by permission of John Wiley & Sons, Inc.

The Baja peninsula and southern California lie on the Pacific side of the San Andreas transform fault, called the salinian block, and are slowly travelling to the northwest at the rate of about 2 inches per year. Geologists estimate that the last remnant of the Farallon plate will subduct beneath the North American continent within the next 10 to 15 million years. The mid-ocean spreading center at the Juan de Fuca ridge will disappear and a transform plate boundary will emerge along the entire west coast of North America. The Salinian block will eventually detach from California and move north with the Pacific plate as a long, narrow micro-continent on its way to southern Alaska (Figure G.29.).

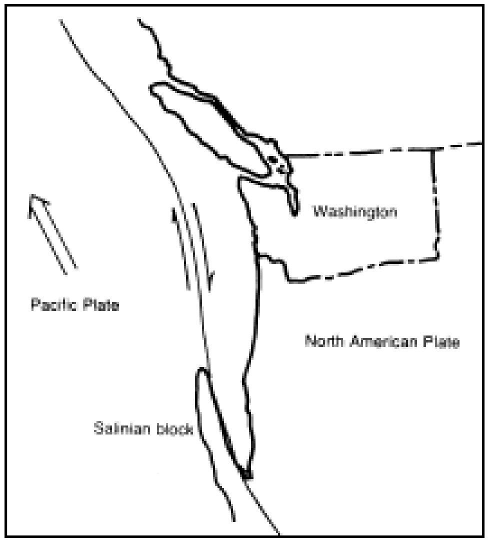


Figure G.29. The future western margin of North America. © Roadside Geology of Washington, by David D. Alt and Donald W. Hyndman, 1984. Mountain Press Publishing Co., Missoula, MT. pg. 23. Reprinted by permission of Mountain Press Publishing Co.

Recommendations For Further Study

The complex nature of the geology of the San Juan Islands cannot be overemphasized. Even the most recent and technological geologic studies remain somewhat inconclusive as to the exact sequence of events which occurred to form the modern San Juan Island bedrock. For the most detailed and recent geotectonic examination of the geology of the San Juan Islands please refer to:

Brandon, M.T., D.S. Cowen, and J.A. Vance. The Late Cretaceous San Juan Thrust System. Special Paper 221. Boulder, CO: Geologic Society of America, 1988.

Alt, David D. and Donald W. Hyndman. Roadside Geology of Washington. Missoula, MT: Mountain Press Publishing Company, 1984. (A more user-friendly and non-technical account of the geologic assemblage of Washington State.)

Gore, Rick. "Cascadia: Living On Fire." National Geographic Magazine, Vol. 193, No. 5, pp 6-37. Washington D.C.: National Geographic Society, 1998. (Excellent color graphics and a contemporary discussion of geologic issues concerning the Pacific Northwest. A double-sided foldout map entitled *Millenium Supplement: Physical World* accompanies this article and is highly recommended for educational purposes.)

Macdougall, J.D. A Short History of Planet Earth: Mountains, Mammals, Fire, and Ice. New York: John Wiley and Sons, Inc., 1996. (An excellent general overview of Earth processes and history.)

References

Alt, David D. and Donald W. Hyndman. Roadside Geology of Washington. Missoula, MT: Mountain Press Publishing Company, 1984.

Brandon, M.T., D.S. Cowen, and J.A. Vance. The Late Cretaceous San Juan Thrust System. Special Paper 221. Boulder, CO: Geologic Society of America, 1988.

Burns, Robert. The Shape and Form of Puget Sound. Seattle, WA: University of Washington Press, 1985.

Kruckeberg, Arthur R. The Natural History of Puget Sound Country. Seattle, WA: University of Washington Press, 1991.

Macdougall, J.D. A Short History of Planet Earth: Mountains, Mammals, Fire, and Ice. New York: John Wiley and Sons, Inc., 1996.

Appendix A.
Basic Physical Geography and Geology Concepts

Students should be introduced to the following concepts to gain a truly comprehensive understanding of earth processes: The close relationship between geography and geology; geologic time; physical earth; crustal material and rock type; plate tectonics; volcanism; and earthquakes. Analogies and demonstration ideas to help teachers make this information more relevant and meaningful to students are provided where possible.

What is Geography?

Geography is the science of describing the Earth. The literal translation of the word 'geography' is from the Greek roots of "geo", meaning Earth, and "graph", meaning description. As such, geography is a multidisciplinary science and incorporates theories and studies from many other physical sciences. A fundamental tenet of geography is that everything is interconnected. Geographic description of the Earth includes the present shape of continental landforms and ocean basins as well as the natural processes that have and will continue to shape Earth from the molten iron core, through the solid outer crust and liquid oceans, to the gaseous atmosphere. Geography also describes the relationships that exist between the natural environment and the biotic organisms that depend on those environments.

What is Geology?

Geology is the science of studying the physical Earth and its internal processes. The literal translation of the word 'geology' is from the Greek roots of "geo", meaning Earth, and "log", meaning study. Geologists are like Earth detectives in that they look for clues in the rocks to explain how they were formed. Reading the rocks allows a geologist to look back to distant times in the Earth's history. Studying the Earth's past allows geologists to better understand the processes which are still shaping the planet and to make predictions about how the Earth will continue to change.

Geologic Time

Earth is a complex and dynamic planet. Scientific studies estimate that the **Earth is 4.6 billion years old**. This number (4,600,000,000) is so great that it is difficult to even comprehend its relevance from a human perspective. According to fossil evidence, human ancestors evolved approximately 4 million (4,000,000) years ago. This may seem like a long time, but human existence represents only 0.0009% of the Earth's total history. So how can a teacher explain geologic time in a way that students can wrap their hands around it? One method is to use relevant analogies that students can un-

derstand. For example, if all of the Earth's history could be compressed into a 3-hour long movie, humans would not appear until the very last second!

Visual and physical display can also help students to comprehend relative geologic time in a meaningful way. For example, one end of a hallway can be marked as the Earth's formation 4.6 billion years ago and the opposite end of the hallway can be marked as the present. A teacher or, better yet, students can divide the hallway into segments and mark meaningful events in between each end. Meaningful events for this learning unit could include: the evolution of fishes and plants; the formation and splitting apart of Pangaea; the evolution of dinosaurs, birds, and mammals; the docking of Vancouver Island to the North American continent, formation of the Cascade Mountains, San Juan Islands, and Olympic Mountains; evolution of humans; recent ice ages; migration of indigenous people to Cascadia; and the arrival of European explorers.

Earth has changed drastically over its long history. Oceans have filled and emptied, mountain ranges have risen and fallen, and continents have changed shape. Earth is changing all around us all of the time and it will continue to do so, with or without human influence. It is important to recognize that Earth is a very dynamic, evolving planet and it supports an incredibly complex array of lifeforms. Fossil and geologic evidence shows that these lifeforms have changed over time to survive in changing natural environments. Dinosaurs were dominant for approximately 180 million years, but could not adapt to rapid changes in the natural environment caused by sudden events, such as meteor impact and extensive volcanism, and so they perished. Humans are but one species in the web of life and are dependent on healthy natural environments. As writer Will Durant so succinctly put it, "Civilization exists by geologic consent, subject to change without notice."

Physical Earth

Geologists divide Earth's physical structure into three major components; crust, mantle, and core. The **crust** is a relatively thin rigid layer, like an outer skin, that ranges in thickness from 2 miles at the oceanic ridges to over 40 miles at extensive continental mountains ranges, such as the Himalaya or the Andes. The rigid crust can become deformed and slowly move. The **mantle** is a mostly solid rocky shell that extends to a depth of about 1,800 miles beneath the surface. It contains over 80 percent of Earth's total volume. Although the mantle is composed of solid rock, it too can become deformed and move very slowly. The **core** lies beneath the mantle and is the Earth's center. It is composed mostly of iron with a density 14 times that of water at the surface. The core can be divided into inner and outer components, based on movement. Geologic theory surmises that the outer core is a liquid that is capable of flow and that the inner core is a

solid. The flow of the outer core is believed to be responsible for generating the magnetic field that surrounds Earth as it rotates and orbits in space. An excellent way for teachers to demonstrate this structure to students is to slice a cantaloupe fruit in half. The outer skin can represent the crust, the orange fruit can represent the mantle, and the hollow seed pit can represent the core. The green section of the rind can represent the important transition zone (asthenosphere) between the crust and the mantle, which is discussed below.

Geologists refer to the crust as the **lithosphere** ("sphere of rock"). Beneath the lithosphere is a relatively soft and weak layer located in the upper mantle that geologists have named the **asthenosphere** ('weak sphere"). The asthenosphere is weak because it is close to the melting point of rock, and some melting does actually occur. A good analogy for the difference between the lithosphere and the asthenosphere is the difference between cold, brittle wax and hot, pliable wax. The soft and weak qualities of the asthenosphere allow the slow movement of lithospheric plates to occur as described in the Plate Tectonics and Boundaries section below.

Crustal Material and the Rock Cycle

Rocks and minerals within Earth's crust occur in numerous varieties and combinations, but are classified into three primary rock types: igneous, sedimentary, and metamorphic. The formation and destruction of these three rock types occurs in a continuous sequence called the **rock cycle**. **Magma** is molten material, which forms inside Earth at the asthenosphere. Eventually magma cools and solidifies in a process called crystallization. Relevant analogies might be liquid wax cooling to brittle wax or water turning to ice. Crystallization can take place beneath Earth's surface or, following a volcanic eruption, at the surface. In either situation, this process forms **igneous rocks**. Igneous rocks at the surface are exposed to the processes of weathering and erosion which break rocks down to smaller sizes, including gravel, sand, and silt. This smaller material is transported by water, wind, glaciers, or waves and accumulates as sediment. As additional layers of sediment accumulate the weight of overlying layers compacts underlying layers in a process called lithification and **sedimentary rock** is formed. Over time sedimentary rock can become buried deep in Earth's surface where it is exposed to heat and pressure. If sedimentary rock becomes deformed by tectonic events involving high pressure and/or heat, such as plate subduction, mountain building, or magma intrusion, it will transform into **metamorphic rock**. If metamorphic rock is subjected to still greater heat and pressure it will melt and form magma, which will eventually crystallize into igneous rock, the completing the rock cycle.

Continental Drift, Plate Tectonics, and Plate Boundaries

Continental drift was a radical hypothesis proposed by **Alfred Wegener**, a German meteorologist and geophysicist, in 1915. Wegener spent a great

amount of time studying the coastlines, ancient climates, soils, and fossils of western Africa and eastern South America. He became convinced that these continents on opposite sides of the Atlantic Ocean had once been joined together in a supercontinent, which he called **Pangaea** (meaning "all land"). Wegener speculated that about 200 million (200,000,000) years ago Pangaea had broken up into smaller continents, which then drifted to their present positions. Unfortunately, Wegener could not provide a logical explanation for a mechanism, which would allow continents to drift across the surface of the Earth and this resulted in extreme criticism of his radical hypothesis from the established scientific community.

By the 1950's technology had greatly improved and new evidence from magnetic alignment of rock layers supported Wegener's continental drift hypothesis. Scientists began to produce sonar maps of the ocean floors and discovered a global oceanic ridge system, including a mid-Atlantic ocean ridge and rift valley system that paralleled the coastlines of both South America and Africa. In the early 1960's a Princeton University scholar named Harry Hess proposed a hypothesis which came to be called **seafloor spreading**. Hess believed that new ocean crust is formed by volcanism at the mid-ocean ridge, which is sustained by upwelling convection currents of magma in the Earth's mantle. As new ocean crust is formed, it moves away from the mid-oceanic ridge and is continually pushed toward the continents where it is then consumed by the deep trenches aligned with the shore. In the mid-1960's an English graduate student named Fred Vine discovered that the oceanic rock layers on each side of the mid-Atlantic ridge showed a symmetrical pattern of stripes showing normal and reversed magnetic orientation. Vine correlated this striped pattern of magnetism with Hess's seafloor spreading theory and the establishment of the scientific community reversed its opinions practically overnight. Wegener's core ideas about continental drift had been correct after all.

By 1968, the ideas of continental drift and seafloor spreading were unified within the theory of **plate tectonics**, which describes all of the dynamic processes involved in the changing shape and location of continents and ocean basins. Earth's crust is segmented into **lithospheric plates**. Some of these plates carry entire continents, such as the North American plate, and some plates carr5y pieces of ocean basins, such as the Pacific plate. Presently there are about seven great lithospheric plates, but there are also six intermediate-sized plates and many small fragments of older plates, such as the Farallon (or Juan de Fuca) plate near the Washington coast. These plates move very slowly, about as fast as human fingernails grow, but are responsible for the continually changing shape of landmasses and ocean basins on the Earth's surface. Important geologic events, such as earthquakes and volcanism, usually occur near the edges of these lithospheric plates or along faults, which are created by the movement of these plates. Generally there are three types of plate boundaries; divergent, convergent, and transform.

Divergent boundaries occur where the Earth is splitting apart, or rifting. A **rift** can occur on land, but usually occurs in the ocean basins and is the primary force involved in lithospheric plate movement. Both Wegener's hypothesis of Pangaea splitting apart and Hess's hypothesis of seafloor spreading, mentioned above, are excellent examples of divergent boundaries and rifting.

Convergent boundaries are found where two lithospheric plates are colliding with each other. Oceanic crust, such as the Pacific plate, is usually composed of a relatively thin, but very dense layer of volcanic and sedimentary rock. Continental crust, such as the North American plate, is usually composed of a relatively thick and light layer of igneous and sedimentary rock. When oceanic and continental plates converge the very dense and thin layer of oceanic crust bends and forms a very **deep-ocean trench** paralleling the continental coastline. The leading edge of the oceanic plate is forced beneath the thicker and lighter continental crust and is thrust downward into the Earth's mantle at an angle in a process called **subduction**. As the dense, saturated oceanic crust slowly descends into the hot mantle it is physically transformed. At a depth of approximately 60 miles below the continental crust the water content at the leading edge of the saturated oceanic crust becomes super-heated and is converted into gases and steam. As it rises, this gas and steam significantly lowers the temperature at which the surrounding and overlying continental crust becomes molten magma. When these super-heated gases, steam, and molten magma reach the surface of the continental crust an eruption occurs. Erupting magma moving across the surface is called a lava flow and as it cools, it forms new continental rock.

Over long periods of time subsequent eruptions and lava flows can create very conspicuous and mountainous structures called **volcanoes**, which mark the active margins of convergent plate boundaries. The Cascade Mountain Range extends in a north to south line from British Columbia, Canada to northern California and has been built by the tremendous force of the Pacific plate converging with the North American plate. The highest peaks in the Cascade Range are the numerous active volcanoes, including Mt. Baker, Mt. Rainier, Mt. Saint Helens, Mt. Adams, Mt. Hood, Mt. Lassen, and Mt. Shasta. These volcanic peaks mark the leading edge of the subducted Pacific plate beneath the North American plate and the point at which oceanic crust melts into magma and rises to the surface to erupt as lava. The volcanoes of the Cascade Mountains are part of the well-known "Ring of Fire" which stretches almost completely around the Pacific Ocean basin.

Transform fault boundaries occur where two plates, or plate fragments, grind past each other in opposite directions without forming or destroying the lithosphere. This type of boundary played an important part in explaining how rigid plates moved across the spherical planet surface. In

1965, a Canadian researcher named Tuzo Wilson proposed that fracture zones, which offset pieces of oceanic ridges, were really transform faults that connect the global active belts into a continuous network that divides the lithosphere into several rigid plates. A simple analogy to demonstrate this continuous belt is the raised red seams of a baseball or softball. The most famous transform fault boundary is the **San Andreas Fault system**. The Baja Peninsula of Mexico and all of coastal California south of Point Reyes, near San Francisco is actually part of the Pacific plate. This landmass is grinding in a northwesterly direction relative to the North American plate and as it does it sometimes causes great earthquakes.

Earthquakes

An **earthquake** is the vibration of Earth produced by rapid releases of energy within the lithosphere. Most earthquakes occur when lithospheric plates or faults grind into each other or past each other. Tremendous waves of energy are generated at the earthquake's **focus**, or point of origin in the lithosphere, and travel through the crust for hundreds or even thousands of miles. A good demonstration of this effect is to drop a pebble into a large container of water, such as a bathtub. The waves generated by the pebble's contact with the water are analogous to the seismic waves of energy that radiate through the crust from the focus of an earthquake. The power generated by an earthquake is hard to even imagine. The most powerful earthquakes ever recorded released the equivalent energy of several hundred human-manufactured atomic bombs in a just a few seconds. Earthquakes can be very hazardous, especially when they occur in areas, which are densely populated by humans, such as coastal California, Mexico, Japan, and India. Entire cities have been destroyed in minutes by earthquakes. In 1556 an earthquake in Shensi, China killed over 830,000 people in just a few minutes. Catastrophic earthquakes have occurred throughout Earth's 4.6 billion (4,600,000,000) year history and will continue into the unforeseeable future.