Plate Tectonics

G1) - New ideas on continental drift

The wealth of new data from the oceans began to significantly influence geological thinking in the 1960s. In 1960 Harold Hess, a widely respected geologist from Princeton University, advanced a theory that had many of the elements that we now accept as **Plate Tectonics**. He maintained some uncertainty about his proposal however, and in order to deflect criticism from main-stream geologists he labelled it *geopoetry*. In fact, until 1962, Hess didn't even put his ideas in writing - except internally to the Navy, which funded his research - but presented them mostly in lectures and seminars. Hess proposed that new seafloor was generated from mantle material at the ocean ridges [see pages 313-314], and that old seafloor was dragged down at the ocean trenches and re-incorporated into the mantle. He suggested that the process was driven by mantle convection currents, rising at the ridges and descending at the trenches. He also suggested that the light continental crust did not descend with oceanic crust into trenches, but that land masses collided and were thrust up to form mountains. Hess's theory formed the basis for our ideas on **seafloor spreading** and **continental drift** - but it did not deal with the concept that the crust is made up of specific **plates**. Although the Hess model was not roundly criticized, it was not immediately accepted, (especially in the US), because it was not well supported by hard evidence.

Collection of magnetic data from the oceans continued in the early 1960s, but still nobody understood the origin of the zebra-like patterns. Most assumed that they were related to variations in the composition of the rocks - such as variations in the amount of magnetite - which is a common explanation for magnetic variations in rocks of the continental crust. The first real understanding of the significance of the striped anomalies was the interpretation of a Cambridge graduate student named Fred Vine. Vine was examining magnetic data from the Indian Ocean and, like others before, he noted the symmetry of the magnetic patterns with respect to the oceanic ridge.

At the same time, other researchers - led by groups in California and New Zealand - were studying the phenomenon of reversals in the earth's magnetic field. They were trying to determine when such reversals had taken place over the past several million years by analyzing the magnetic characteristics of hundreds of samples from basaltic flows. Although the phenomenon is still not well understood, it is evident that the magnetic field of the earth becomes weakened periodically and then virtually non-existent, and then becomes re-established. It is also evident that the re-established field can have the opposite polarity of the pre-existing field[1]. During periods of reversed polarity a compass would point south instead of north.

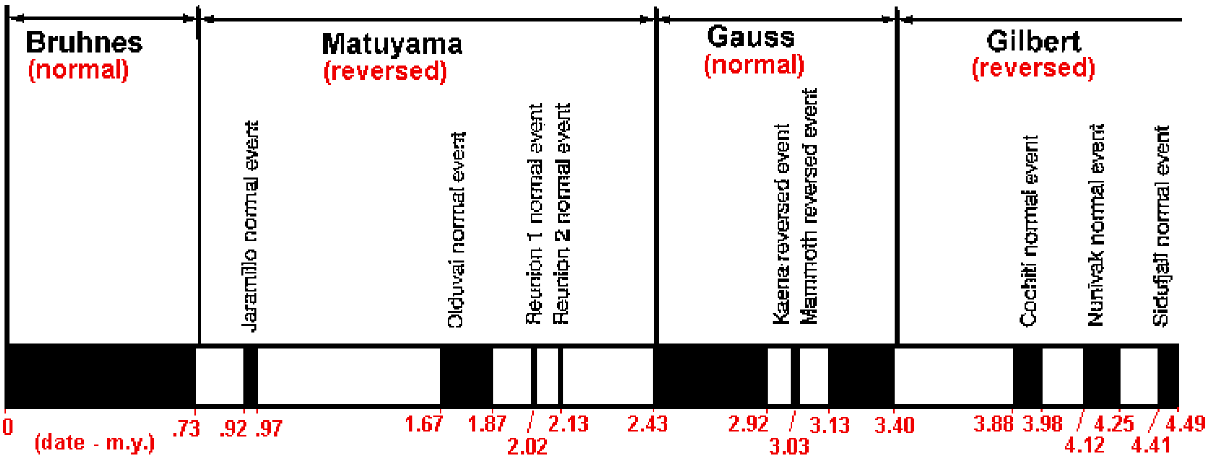
The time scale of magnetic reversals is irregular. For example the present "normal" event has persisted for about 730,000 y. This was preceded by a 190,000 y reversed event, a 50,000 y normal event, and a 700,000 y reversed event (see figure below and [pages 314-315]).

In a paper published in 1963 Vine and his thesis supervisor Matthews proposed that the patterns associated with ridges were related to the magnetic reversals, and that oceanic crust created from cooling basalt during a ***normal*** event would have polarity aligned with the present magnetic

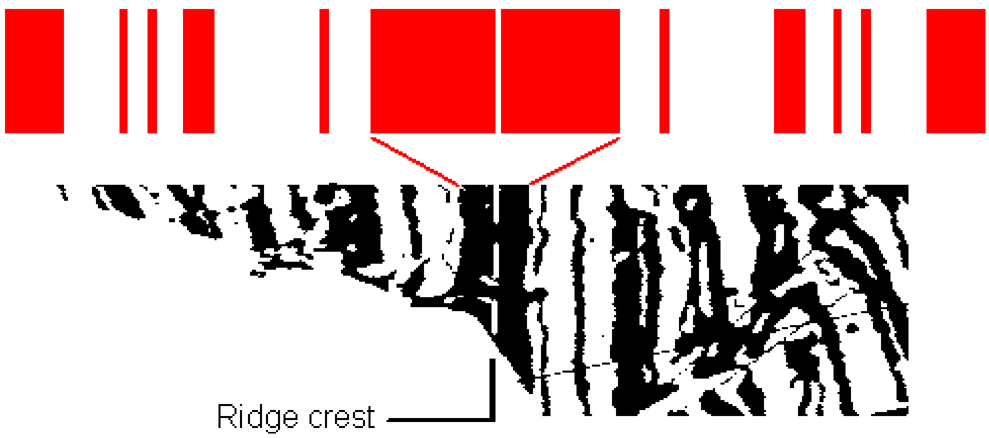
[1] It is probably equally possible that the re-established field could have the same polarity as the pre-existing field. Such events would not show up in the magnetic record.

field, and thus would produce a positive anomaly (a black stripe on the sea-floor magnetic map), whereas oceanic crust created during a ***reversed*** event would have polarity opposite to the present field and thus would produce a negative magnetic anomaly (a white stripe). The same general idea was also put forward at about the same time by a Geological Survey of Canada geologist Lawrence Morley. Many people refer to the idea as the *Vine-Matthews-Morely* hypothesis.

Chronology of magnetic field reversals for past 4.5 m.y.



Vine, Matthews and Morely (VMM) were the first to show this type of correspondence between the relative widths of the stripes and the periods of the magnetic reversals. The VMM hypothesis was confirmed within a few years when magnetic data were compiled from spreading ridges around the world. It was shown that the same general magnetic patterns were present straddling each ridge, although the widths of the anomalies varied according to the spreading rates characteristic of the different ridges. It was also shown that the patterns corresponded with the chronology of the earth's magnetic field reversals. This global consistency provided strong support for the VMM hypothesis and led to rejection of the other explanations for the magnetic anomalies.



The magnetic field reversal chronology is shown here in red and white (red = normal, white = reversed). Part of the magnetic pattern of the Juan de Fuca ridge is shown in black. See if you can correlate some of the magnetic reversal patterns on either side of the ridge crest with the reversal chronology.

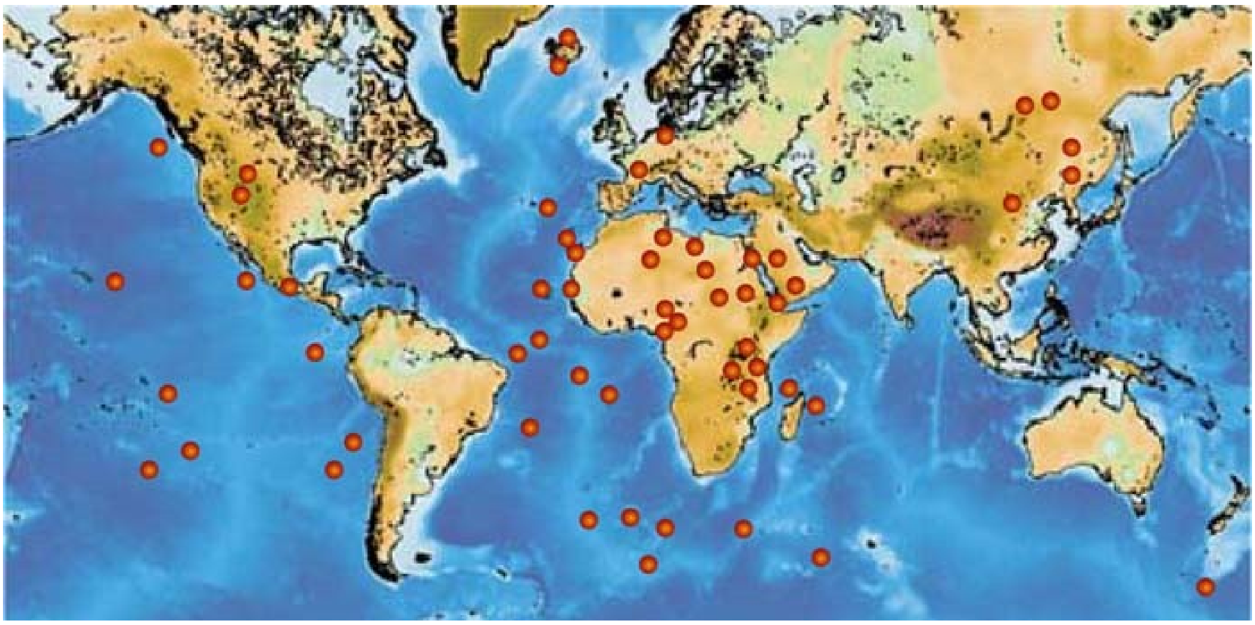
[There is more information on this topic on pages 315-316 of the text.]

G2) Mantle plumes, transform faults and plate tectonics

Mantle plumes

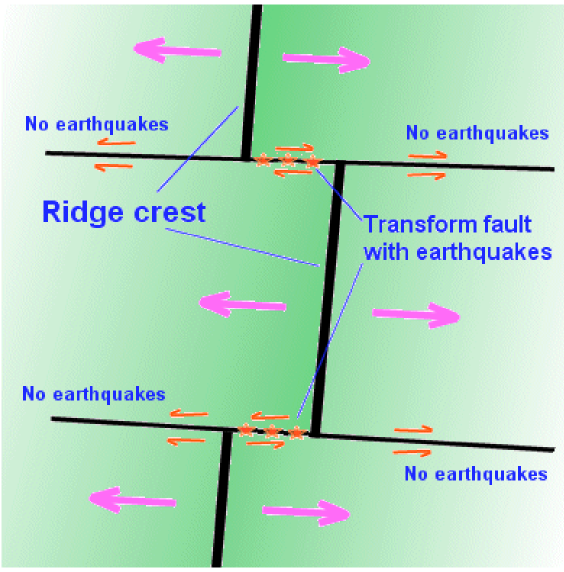
In 1963, J. Tuzo Wilson of the University of Toronto proposed the idea of a **mantle plume** or **hot spot** - a place where hot mantle material rises in a semi-permanent plume, and affects the overlying crust. He based this hypothesis partly on the distribution of the Hawaiian and Emperor Seamount island chains in the Pacific Ocean [Fig. 12.19]. The volcanic rock making up these islands gets progressively younger towards the southeast, culminating with the island of Hawaii itself, which is all less than 1 m.y. old, and in part is much younger. Wilson suggested that a stationary plume of hot upwelling mantle material is the source of the Hawaiian volcanism, and that the ocean crust of the Pacific Plate is moving towards the northwest over this hot spot. Near to the Midway Islands the chain takes a pronounced change in direction, from northwest-southeast for the Hawaiian Islands, to nearly north-south for the Emperor Seamounts. This change is ascribed to a change in direction of the Pacific plate moving over the stationary hot spot - a change which took place about 40 m.y. ago.

There is evidence of many such hot-spots around the world (see map below). Most are within the ocean basins - including places like Iceland and the Galapagos Islands - but some are under continents - an example being the Yellowstone hot spot in the west-central United States, and the hot-spot responsible for the Anahim Volcanic Belt in central British Columbia (west of Quesnel). It is suggested that mantle plumes are very long-lived phenomena, lasting for at least tens of millions of years, probably for hundreds of millions of years. It is also evident that they are typically stationary features with respect to the mantle and core of the earth - while the crust overhead is always moving.

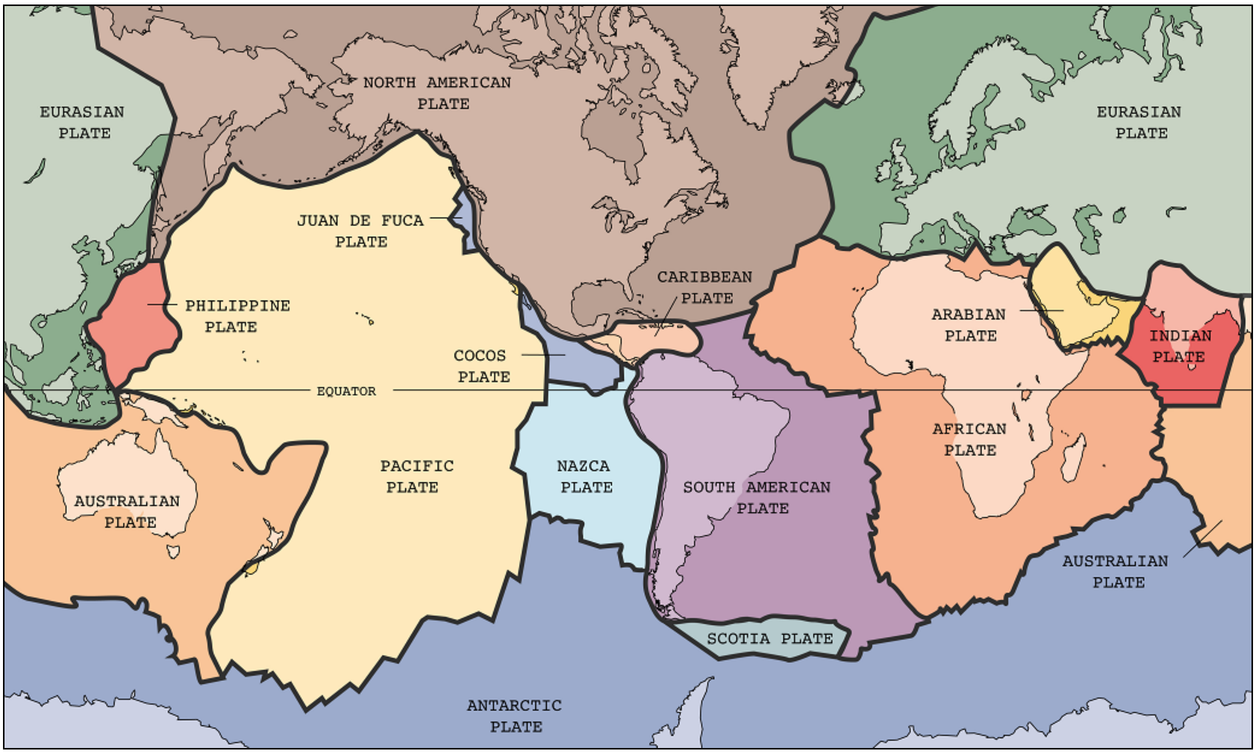


Transform faults

Although oceanic spreading ridges appear to be curved features on the earth's surface, in fact the ridges are composed of a series of straight-line segments, offset at intervals by faults perpendicular to the ridge (see figure to the right). In a paper published in 1965 Tuzo Wilson termed these features **transform faults**. He described the nature of the motion along them, and showed why there is only seismic activity on the section of a transform fault between two adjacent ridge segments [pages 325-326 and Figure 12.15]. The San Andreas Fault is a very long transform fault that links the southern end of the Jaun de Fuca spreading ridge to the series of spreading ridges situated in the Gulf of California. The Queen Charlotte Fault, which extends north from the northern end of the Juan de Fuca spreading ridge (near the northern end of Vancouver Island) towards Alaska, is also a transform fault. In the same 1965 paper Wilson also introduced the idea that the crust can be divided into a series of rigid plates - and thus he is responsible for the term **plate tectonics.**



Continental drift and sea-floor spreading became widely accepted in the mid-1960s as more and more geologists started thinking in these terms. By the end of 1967 the earth's surface had been mapped into a series of plates. [see below and Fig. 1.17 for information on plate motions]. The seven major plates are: **Eurasian**, **Pacific**, **Australian**, **North American**, **South American**, **African** and **Antarctic** - all comprise both oceanic and continental crust. For example, the North America Plate includes most of North America plus half of the northern part of the Atlantic Ocean. (The Pacific Plate is almost entirely oceanic, but it does include the part of California which lies to the west of the Sand Andreas Fault.) There are also numerous small plates (e.g., Jaun de Fuca, Nazca, Scotia, Philippine, Caribbean). Boundaries between these plates are of three types: ***divergent*** *(i.e., spreading),* ***convergent***, and ***transform***. [Fig. 1.17 and 1.18]

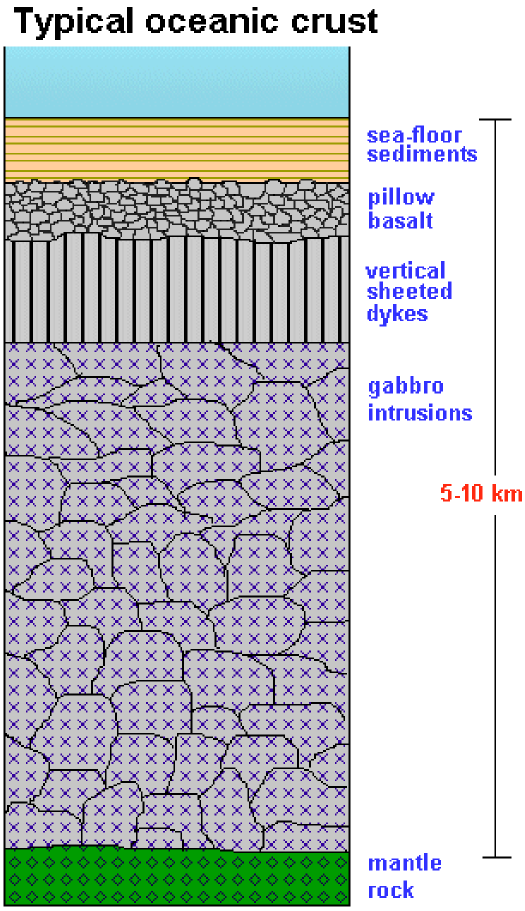


G3) The geology of plate boundaries

The geological processes that take place at different boundaries are described below. Before going there, however, it is important to recognize that plates are not just pieces of continental or oceanic crust, but that, along with the crustal rock, they include a considerable thickness of the rigid upper part of the mantle. Together, the crust and the rigid part of the mantle make up the ***lithosphere*** [Fig. 1.19], which has a total thickness of approximately 100 km. At spreading centres, the lithospheric mantle may be very thin because the upward convective motion of hot mantle material generates temperatures that are too high for the existence of a significant thickness of rigid lithosphere [Fig. 12.9].

The fact that the plates include both crustal material and lithospheric mantle material makes it possible for a single plate to be comprised of both oceanic and continental crust. For example, the North American Plate includes most of North America, plus half of the northern Atlantic Ocean. Similarly the South American plate extends across the western part of the southern Atlantic Ocean, while the European and African plates each comprise part the eastern Atlantic Ocean.

Immediately beneath the base of the lithosphere lies the partial melting zone (the *low velocity zone*) of the upper mantle - which is part of the asthenosphere. It is thought that the relative lack of strength and rigidity of the partial melting zone facilitates the sliding of the lithospheric plates. [see Fig. 1.19]



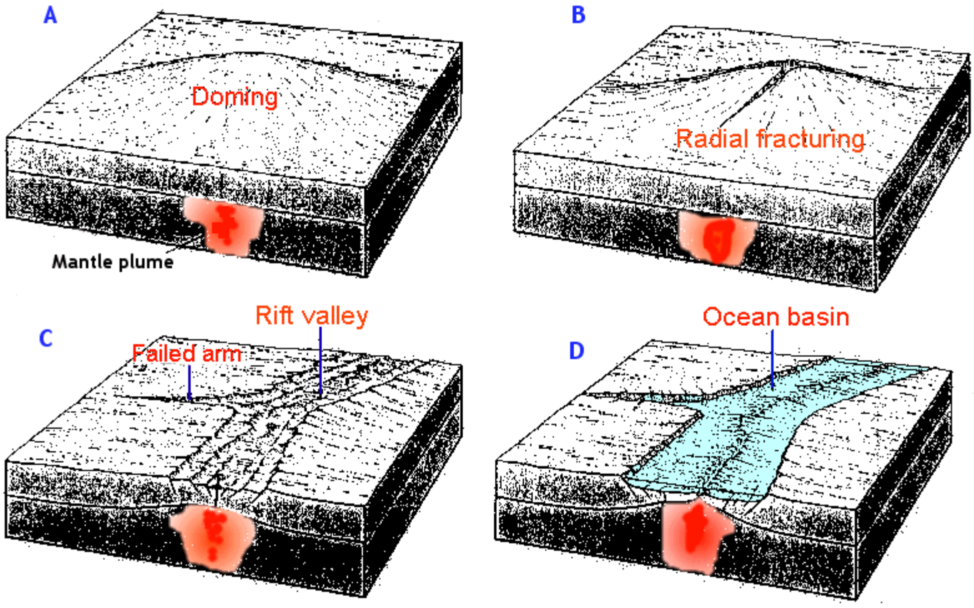
Divergent boundaries

Divergent boundaries are spreading boundaries, where new oceanic crust is created from molten mantle material. Most are associated with the oceanic-ridges, and the crustal material created at a spreading boundary is always oceanic in character[2] [Fig. 12.9].

- Spreading is caused by the convective movement within the mantle, which has the effect of pulling the plates apart.
- Magma from the mantle pushes up to fill the voids left by spreading.
- A variety of volcanic rocks (all of similar composition) are created in the upper part, including **pillow lavas** which are formed where magma is pushed out into sea-water [Fig. 11.5]. Beneath that are **vertical dykes** intruded into cracks resulting from the spreading. The base of the oceanic crust is comprised of **gabbro** (i.e., mafic intrusive rock). (see figure to the right).

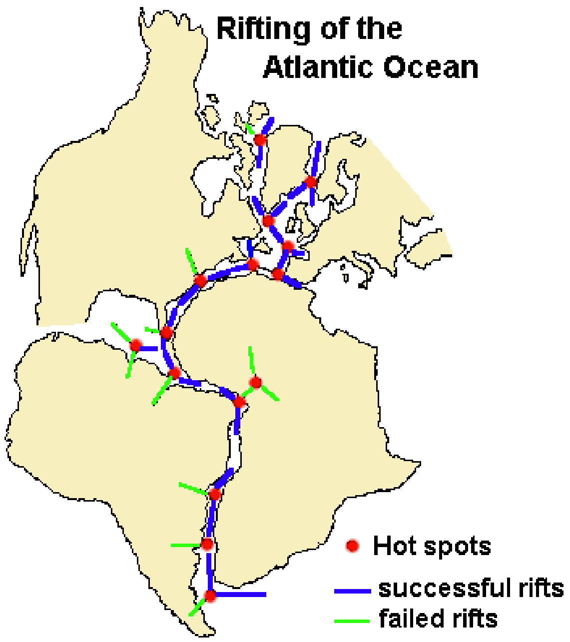
[2] By ***oceanic*** we mean that it is **mafic** igneous rock (e.g., basalt or gabbro, rich in ferro-magnesian minerals) as opposed to the **felsic** igneous rocks (such as granite, which is dominated by quartz and feldspar) which are typical of continental areas. Another term for mafic igneous rock is **SIMA** (**si**licon and **ma**gnesium rich), and another term for felsic igneous rock is **SIAL** (**si**lica and **al**uminum rich).

- Spreading rates vary quite considerable, from 2 to 4 cm/y in the Atlantic, to between 6 and 18 cm/y in the Pacific.



Spreading starts within a continental area with up-warping or doming, fracturing in a radial pattern - with three arms, and formation a rift valley (such as the Rift Valley in eastern Africa). It is suggested that this type of valley eventually develops into a linear sea (such as the present day Red Sea), and finally into an ocean (such as the Atlantic).

A major continental rift is assumed to be initiated by a series of hot spots. Each hot spot has an associated three-arm rift, but in most cases only two of these arms will continue to separate - the third one being termed a "failed arm". Some of these failed arms become major river channels. Rifting along a series of hot spots will then lead to continental rifting. It is thought that some 20 hot spots were responsible for the initiation of spreading along the mid-Atlantic ridge (see figures below).



Convergent boundaries

Convergent boundaries, where two plates move towards each other, are of three types depending on what type of crust is present on either side of the boundary (i.e., ocean-ocean, ocean-continent or continent-continent).

a) **Ocean-Ocean** At an ocean-ocean convergent boundary one of the plates (ocean crust and lithospheric mantle) is pushed under, or **subducted** under the other. There is commonly an oceanic trench along the boundary. The subducted lithosphere descends into the hot mantle at a relatively shallow angle close to the subduction zone, but at steeper angles (up to about 45°) farther down. The significant volume of water within the subducting material (that includes ocean-floor sedimentary rock) mixes with the surrounding mantle. The addition of water to hot mantle lowers its melting point, and leads to the formation of magma. The magma, which is lighter than the surrounding mantle material, rises through the mantle and through the overlying oceanic crust to the ocean floor, to create a chain of volcanic islands known as an island arc. A mature island arc will develop into a chain of relatively large islands (such as Japan, or Indonesia) as more and more volcanic material is extruded and sedimentary rocks accumulate around the islands.

Examples of ocean-ocean convergent zones are: subduction of the Pacific plate south of Alaska (Aleutian Islands), west of Kamchatka and Japan, west of the Philippines and in the northern part of New Zealand; subduction of the India-Australian plate south of Indonesia; and subduction of the Atlantic Plate beneath the Caribbean Plate.

b) **Ocean-continent** At an ocean-continent convergent boundary the oceanic plate is pushed under the continental plate in the same manner as an ocean-ocean collision. Similar geological features apply, and an offshore oceanic trench will normally be present. The mafic magma produced adjacent to the subduction zone will rise to the base of the continental crust and lead to partial melting of the crustal rock. The resulting magma will ascend through the crust producing a chain of largely volcanic mountains.

Examples are: subduction of the Nazca plate under South America (which has created the Andes Range), and subduction of the Juan de Fuca plate under North America (creating mountains like Garibaldi, Baker, St. Helens, Ranier, Hood and Shasta – collectively known as the Cascade Range).

c) **Continent-continent** A continent-continent collision occurs when a continent or large island has been moved along with oceanic crust (which was being subducted under another continent), and then collides with that other continent [Fig. 12.14]. The colliding continental material will not be subducted because it is too light (i.e., because it is composed largely of SIAL rocks), but the mantle convection system continues to operate, so the root of the oceanic plate breaks off and is absorbed into the mantle. There is tremendous deformation of the pre-existing continental rocks, and creation of mountains from that rock, from any sediments which had accumulated along the shores (i.e., within geosynclines) of both continental masses, and commonly also from some ocean crust and upper mantle material.

Examples are: the collision of the Indo-Australian plate into the Eurasian plate, to create the Himalaya Mountains, and the collision of the African plate into the Eurasian plate, to create the Alps in Europe and the Zagros Mts. in Iran).

Transform boundaries

Transform boundaries exist where one plate slides past another, without production or destruction of crustal material. As shown above, most transform faults connect segments of mid-ocean ridges and are thus ocean-ocean boundaries. [See Fig. 12.15] Some transform faults connect continental parts of plates. An example is the San Andreas Fault, which connects the Juan de Fuca ridge with the Gulf of California ridge. Transform faults do not just connect divergent boundaries. For instance the convergent boundary beneath the Himalayas is connected to the subduction zone beneath Indonesia by a transform fault, and the Queen Charlotte Fault connects the Juan de Fuca divergent boundary to the Aleutian subduction zone.

We'll talk more about transform boundaries in the context of earthquakes.

G4) The break-up of Pangea and the Wilson cycle

As originally proposed by Wegener in 1915, the present continents were once all part of a super-continent which he termed **Pangea** (*all land*). More recent studies of continental match-ups and the ages of ocean-floor rocks have enabled us to reconstruct the history of the break-up of Pangea.

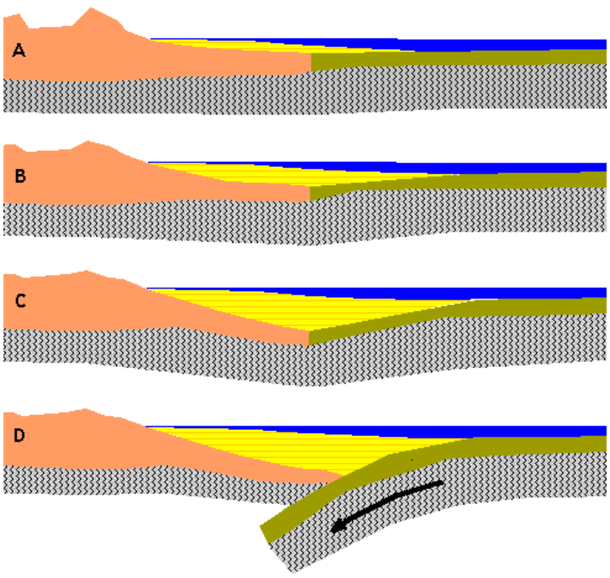
Pangea began to break up along a line between Africa and Asia and between North America and South America between 250 and 200 m.y. ago. During the same period the Atlantic ocean began to open up between northern Africa and North America, and India broke away from Antarctica. [see pages 318-319]

Between 200 and 150 m.y. ago rifting started between South America and Africa and between North America and Europe, and India was moving north towards Asia. By 65 m.y. ago Africa had separated from South America, and most of Europe had separated from North America. A rift began to develop between Australia and Antarctic. India collided into Asia about 45 m.y. ago.

Within the past few million years rifting has taken place in the Gulf of Aden and the Red Sea, and within the Gulf of California. Incipient rifting has begun along the great Rift Valley of eastern Africa, extending from Ethiopia and Djibouti on the Gulf of Aden (Red Sea) all the way south to Malawi.

Over the next 50 m.y. it is likely that there will be full development of the east African rift and creation of new ocean floor. Eventually Africa will probably split apart. There will also be continued northerly movement of Australia and Indonesia. The western part of California (including Los Angeles and part of San Francisco), will split away from the rest of North America, and will eventually sail right by Vancouver Island, en route to Alaska! The Atlantic Ocean is very slowly getting bigger, and the Pacific Ocean is getting smaller - and if this continues without changing for another couple of hundred million years we will be back to where we started, with one super-continent.

There is an interesting animation of continental movements at a Berkeley Geology Department web site. http://www.ucmp.berkeley.edu/geology/tectonics.html.



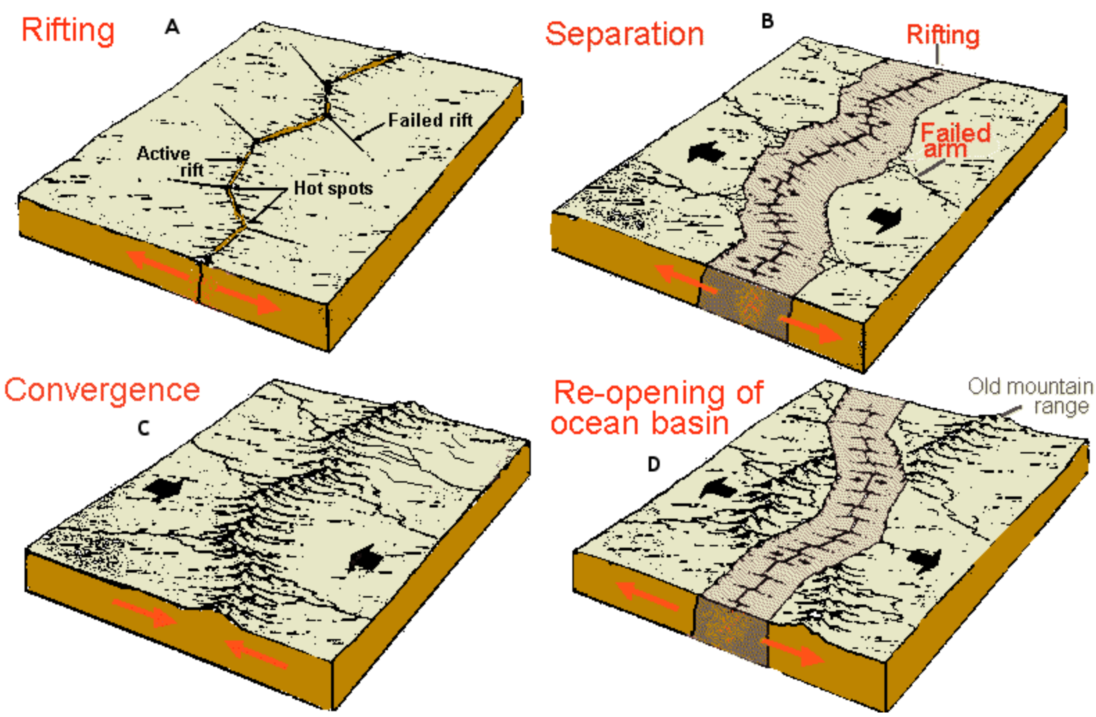
Pangea was not the first super-continent. The super-continent of Rodinia existed from about 1000 m.y. to about 700 m.y. ago.

Wilson cycle

In 1966 J. Tuzo Wilson proposed that there has been a continuous series of cycles of continental rifting and collision. That is, break-up of super-continents, drifting and collision and formation of other super-continents. At present North and South America, Europe and Africa are moving with their respective portions of the Atlantic Ocean. The eastern margins of North and South America, and the western margins of Europe and Africa called **passive margins** because there is no subduction taking place along them.

This situation may not continue for too much longer, however. As the Atlantic Ocean floor gets weighed down around its margins by great thickness of continental sediments (ie. geosynclines), it will be pushed further and further into the mantle, and eventually the oceanic lithosphere may break away from the continental lithosphere (see figure above). A subduction zone will develop, and the oceanic plate will begin to descend under the continent. Once this happens, the continents will no longer continue to move apart because the spreading at mid-Atlantic ridge will be taken up by subduction. If spreading along the mid-Atlantic ridge continues to be slower than spreading within the Pacific Ocean, the Atlantic Ocean will start to close up.

There is strong evidence around the margins of the Atlantic Ocean that this process has taken place before (figure below). The roots of ancient mountain belts, which can be seen along the eastern margin of North America, the western margin of Europe and the northwestern margin of Africa, show that these landmasses once collided with each other to form a mountain chain - possibly as big as the Himalayas. The apparent line of collision runs between Norway and Sweden, between Scotland and England, through Ireland, through Newfoundland and the maritime provinces, through the northeastern and eastern states and across the northern end of Florida. When separation of the northern Atlantic started approximately 130 m.y. ago the fissuring was along a different line from the line of the earlier collision. This is why some of the mountain chains formed during the earlier collision can be traced from Europe to North America and from Europe to Africa.

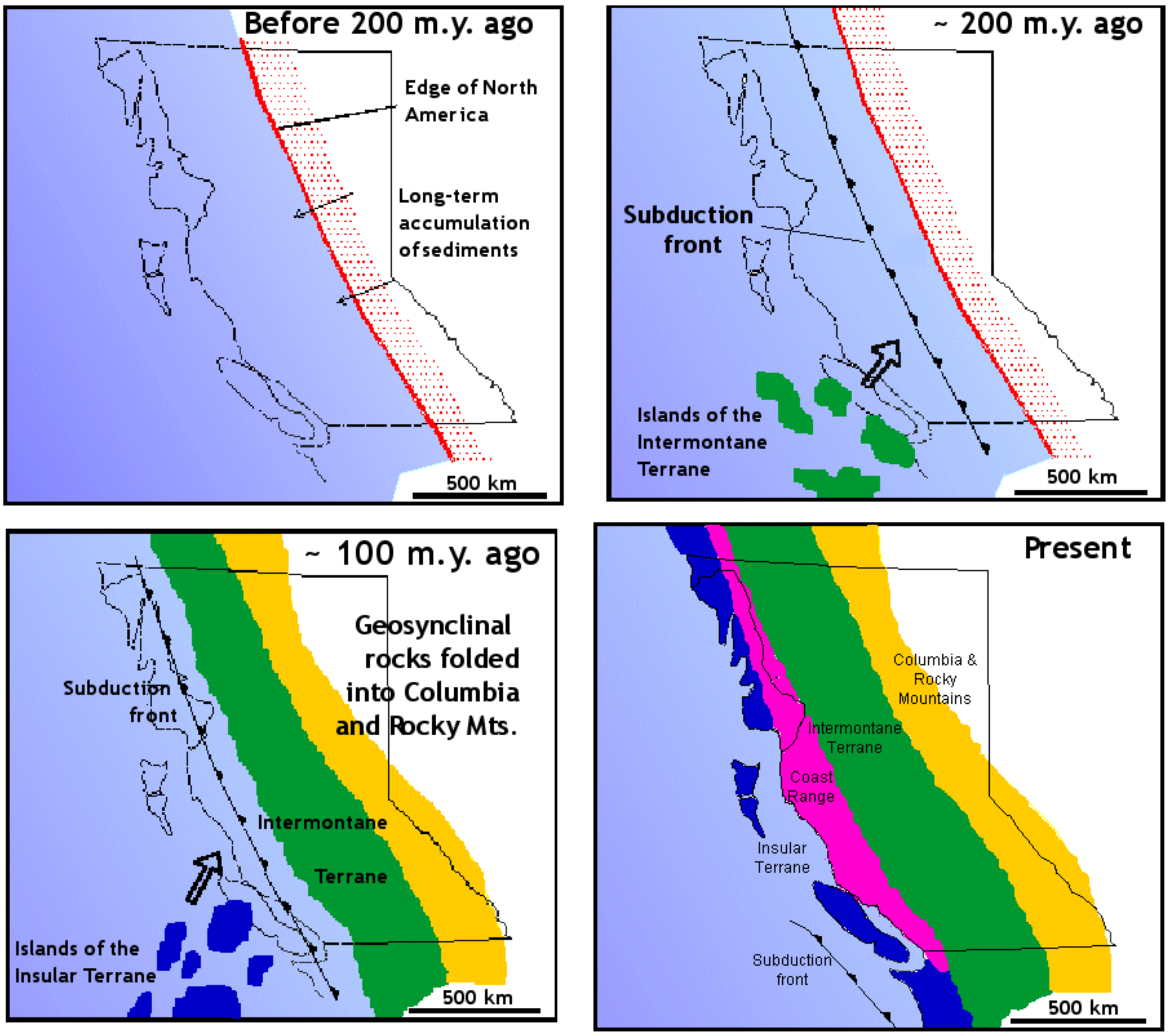


The suggestion that the "Atlantic Ocean" rift may have occurred in approximately the same place during two separate events several hundred million years apart is probably no coincidence. The series of hot spots which has been identified in the Atlantic Ocean may also have existed for several hundred million years, and thus may have contributed to rifting in roughly the same place on at least two separate occasions.

G5) Plate tectonics and the geological history of British Columbia

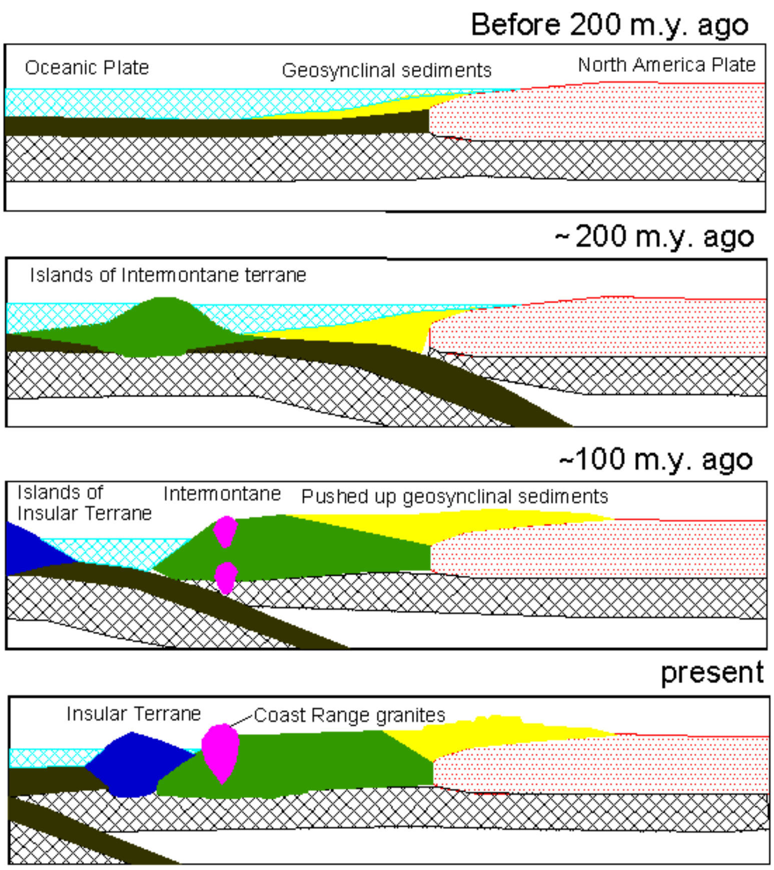
Much of North America is made up of very old rocks. There are large areas of rocks within the shield of central and northern Canada which are all older than 2.5 b.y. The oldest rocks of the world - over 4 b.y. old - are found on the eastern shore of Hudson Bay. In contrast, however, much of British Columbia is relatively young. Up until just a few hundred million years ago most of the area of this province either didn't exist or was under water.

Approximately 700 m.y. ago the super-continent of Rodinia split apart along a line which runs through what is now the eastern part of B.C., and then for the next 500 m.y. (up to 200 m.y. ago) a thick sequence of sandstones, shales and carbonate rocks accumulated within a geosyncline off of the western coast of the continent. These sedimentary rocks were deposited within the area extending as far west as where Kamloops is today (figures below). Originally this was a passive continental margin (like the margins of the Atlantic Ocean), but eventually a subduction zone developed along the coast, with oceanic crust moving towards and subducting beneath North America from a southwesterly direction.



Along with that oceanic crust came some continental crustal material (islands and micro-continents, up to about the size of Japan or New Zealand, and with similar geological features). At around 175 m.y. ago these were ***accreted*** onto the western edge of British Columbia. These rocks are now known as the **Intermontane Super-terrane** (which includes a number of smaller terranes such as the Cache Creek, Quesnel and Stikine Terranes[3]), and they comprise a great diversity of rocks situated between the Rocky Mountains and the Coast Range, extending from just south of the border, through Yukon and into Alaska. The collision of these terranes caused a crumpling and piling up of the existing sedimentary rocks on the edge of the continent to form the Columbia, Omineca and Cassiar Mts., and the western parts of the Rockies[4].

Following these collisions and accretions the earlier subduction zone ceased to be active, and a new subduction zone developed several hundred kilometres to the west. Melting of the descending plate provided much of the magma which is now present as granitic rocks within the Coast Range. At about 90 m.y. ago even more micro continents moved in from the southwest and accreted onto North America to create what we call the **Insular Super-terrane**, including the rocks of Vancouver Island[5] and Haida Gwai (Wrangellia Terrane), as well as most of the Alaska panhandle, and part of southwest Yukon (Wrangellia and Alexander Terranes). This collision contributed to the further pushing and piling up of the Rocky Mt. Main range, the Front Range and the foothills. Within the Rockies, relatively old rocks have been pushed over top of relatively young rocks, and in many cases the rocks on the tops of mountains are older than those underneath (figure below). This collision affected the sedimentary rocks as far east as the foot-hills, just west of Calgary.



[3] Note that the word "terrane" applies to a region of land that has a specific geological origin; it bears no relationship to the word "terrain", which refers to topography.

[4] The process could be likened to a bulldozer pushing its way through a parking lot, with the asphalt being ripped up in sheets and some of those sheets sliding over the top of other sheets. This is not quite the same as the process that led to the formation of the Himalayan Mountains, where a tremendous amount of uplift resulted from the collisions of two huge continental areas.

[5] The Karmutsen basalt, which is exposed on the road cut behind VIU, is an example of these older rocks which have been moved to this area.

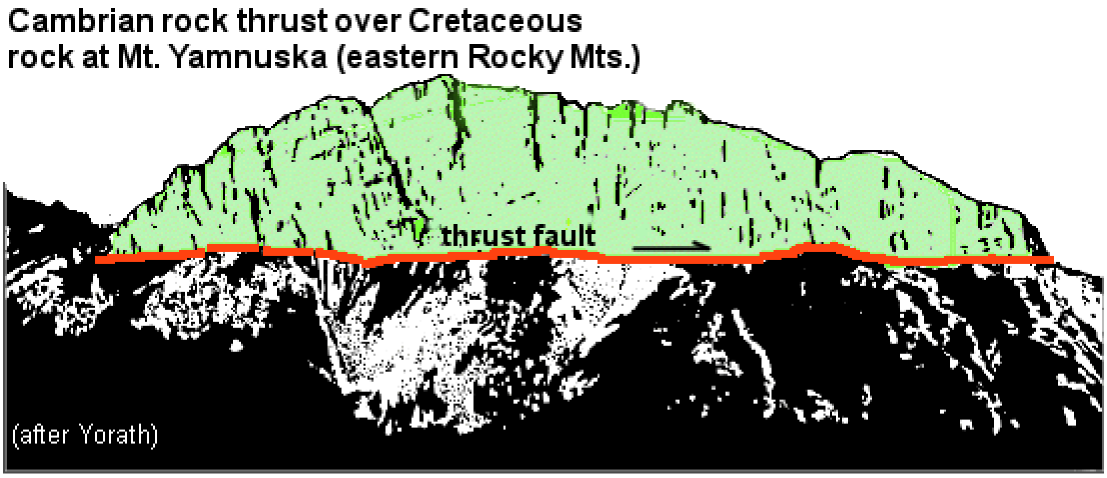
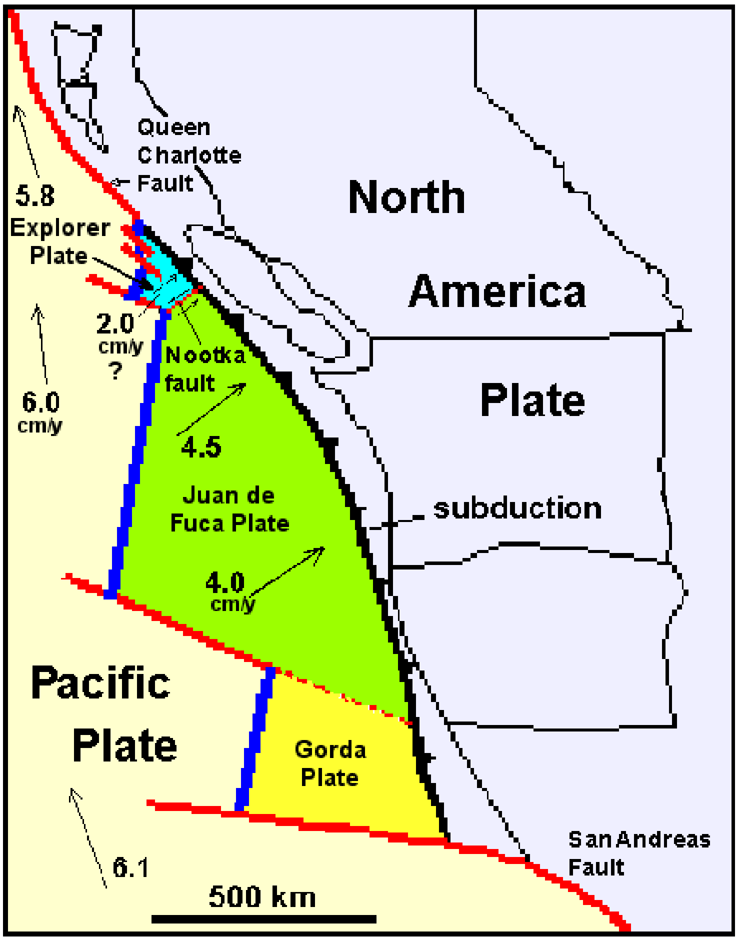


Plate collisions in our area did not end with the arrival of the Wrangellia Terrane which makes up Vancouver Island. At around 55 m.y. ago a small continental block which is termed the Pacific Rim Terrane was accreted onto the west coast of Vancouver Island, and at about 42 m.y. ago another small block - the Crescent Terrane - was accreted onto the southern tip of the island around Sooke. The collisions with these terranes is partly responsible for the current distribution of the Nanaimo Group in our area, and the fact that there are Nanaimo Group rocks at some locations well inland and quite high up on Vancouver Island.



The present the plate distribution in the area to the west of British Columbia and the northwestern USA is quite complex (see figure to the left). Oceanic crust of the **Gorda** and **Juan de Fuca Plates** is being created at the Gorda and Juan de Fuca spreading ridges. The rocks of these plates are moving towards the east at about 4 cm/y and are being subducted underneath southern BC, Washington, Oregon and northern California. Adjacent to, and to the north of the Juan de Fuca Plate, is a smaller plate known as the **Explorer Plate**. This oceanic crustal material is being created at a series of small ridges situated to the northwest of Vancouver Island.

This ongoing plate convergence has implications for the distribution of mountains in British Columbia, including the volcanic mountains of the Garibaldi area, and it has significant implications for the incidence of earthquakes in this area.

Review questions

1. In the model for ocean basins developed by Harold Hess, what took place at oceanic ridges and what took place at oceanic trenches?
2. What aspect of plate tectonics was not included in the Hess theory?
3. How did many geologists originally explain the striped magnetic patterns on the ocean floor?
4. Explain how the magnetic patterns on the ocean floor can be related to reversals in the earth's magnetic field.
5. Magnetic reversal anomalies adjacent to ridges all around the world show virtually the same general patterns. How does this evidence support your answer to question 4 in rather than your answer to question 3?
6. What is a hot-spot and what is its expected life-time?
7. How can we explain the difference in direction of the Hawaiian Island chain versus that of the Emperor Seamounts?
8. Describe the nature of movement at an ocean ridge transform fault (a) between the ridge segments, and (b) outside of the ridge segments.
9. Know the names and approximate extents of the seven major plates
10. How is it possible for a plate to include both oceanic and continental crust?
11. Why is the lithospheric mantle thin at a spreading centre?
12. What is the likely relationship between hot spots and the development of a continental rift?
13. Why is magma produced adjacent to a subducted slab of lithosphere?
14. What geological feature does this magma generate at an ocean-ocean convergent zone?
15. Why does subduction not take place at a continent-continent convergent zone?
16. Make a sketch of a spreading ridge showing how a transform fault can form part of the boundary between two plates.
17. What are typical spreading rates in the Atlantic in cm per year?
18. When did the initial break-up of Alfred Wegener's Pangea begin?
19. What are the most recent sites of continental rifting and creation of new ocean floor?
20. What is likely to happen to western California over the next 50 m.y.?
21. What geological situation might eventually lead to the generation of a subduction zone at a passive ocean-continent boundary such as the eastern coast of North America?
22. What is the evidence that there was once a continent-continent collision between Europe and North America?
23. Which two major super-terranes of British Columbia are thought to have been derived from elsewhere?
24. When did the rocks of Vancouver Island arrive here, and where did they come from?
25. What events led to the formation of the Rocky Mountains?
26. What type of plate boundary exists between the Juan de Fuca Plate and the North American Plate?
27. Why is there some question as to whether the Explorer Plate is actually subducting beneath British Columbia?