F1) Our understanding of global geology during the 20th century

There was a fundamental revolution in geology during the twentieth century - beginning in about 1910, and culminating in the 1970s with the widespread acceptance of the **Theory of Plate Tectonics**[1]. The significant points of plate tectonic theory are that:

- the earth's crust is made up of a number of semi-rigid plates,
- these plates move around with respect to each other, largely in response to convection taking place within the earth's interior,
- this process has been going on for much of the earth's history, and
- most of the major geological features of the earth can be explained by processes that take place at plate boundaries.

Geologists are continually learning more about plate tectonics, how the process has affected the earth's crust and mantle, and how it has implications for virtually every aspect of geology. As part of our investigation into plate tectonics we will look first at the history of this scientific revolution, which is an interesting and important lesson in science itself and an insight into how scientific thinking evolves, why this evolution can be so slow and dysfunctional in some cases.

Firstly - it is important to know what was generally believed about global geology before plate tectonics. At the beginning of the 1900s geologists had a reasonable understanding of how most rocks were formed and their relative ages, but there was considerable controversy regarding the origin of mountains, and in particular of mountain belts - such as the Alps. One of the prevailing views on the origin of mountains at the end of the 19th century was known as *contractionism* - the idea that the earth is slowly cooling and shrinking - so that mountain ranges form like the wrinkles on a dried up apple, and in which the oceans were merely submerged parts of former continents.

Another widely held view was described as *permanentism* - in which it was believed that the continents and oceans have always been generally as they are today. This view incorporated a mechanism for creation of mountain chains known as the **geosyncline** theory.

> A geosyncline is a belt of sedimentary deposits that accumulate within the ocean along the margin of a continent - on the continental shelf and slope. The sediments are derived from erosion of the continent (see figure below). Geosynclinal sediments - which eventually turn into sedimentary rocks - can be many thousands of metres thick. As they accumulate they push down the pre-existing crustal rocks. Extenisve geosynclinal deposits exist around much of the coastline of most of the continents. Even into the early 1970's it was widely believed that mountain belts were formed when geosynclines were compressed by forces pushing from either side, although no one was exactly sure what force was to do the pushing.
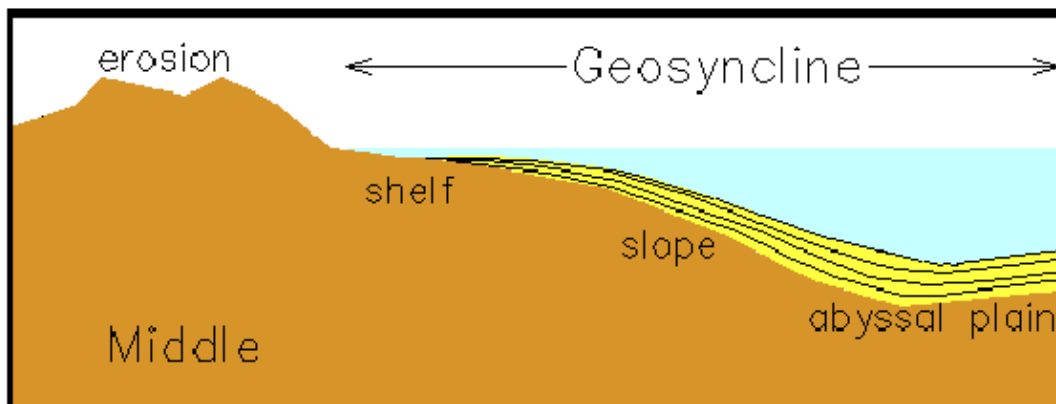
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[1] *Tectonics* is the branch of geology that deals with regional structures in rocks.
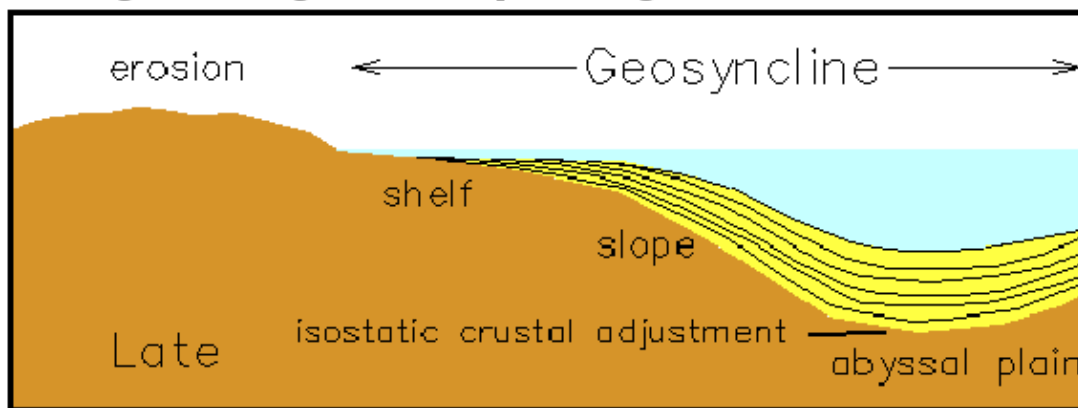
Geosyncline Model

Early stage - Beginning of erosion and deposition

erosion

Geosyncline

shelf

slope

sediments

abyssal plain
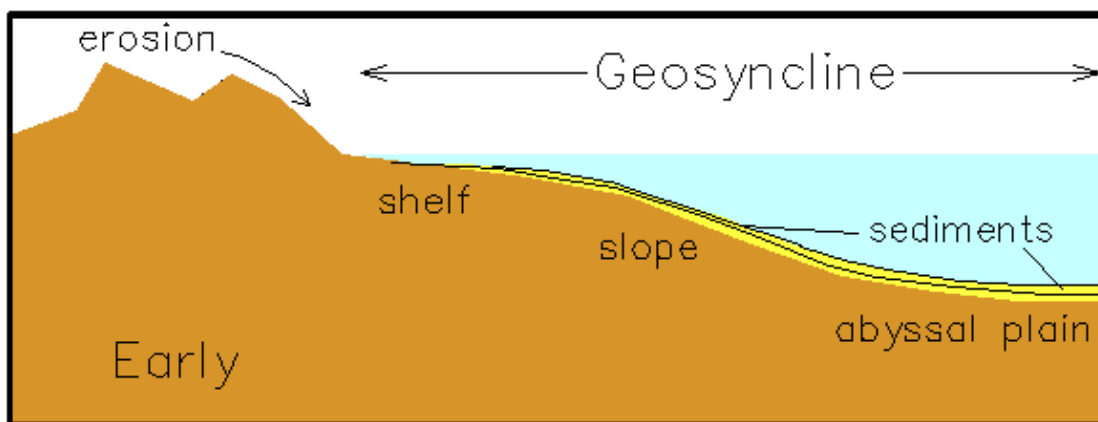
Early

Middle stage - Continuing erosion and deposition - beginning of subsidence

erosion

Geosyncline

shelf

slope

abyssal plain

Middle

Late stage - Continuing erosion and deposition - significant offshore subsidence

erosion

Geosyncline

shelf

slope

isostatic crustal adjustment

abyssal plain

Late

During the 19th century and early parts of the 20th century paleontologists documented several interesting cases of fossil plants and animals which were found only within restricted parts of

both South America and Africa. One famous example of these is the Permian aquatic (freshwater) reptile *Mesosaurus* [as described on p. 14]. There are also several genera of plants (e.g., a type of fern known as *Glossopteris*), fossils of which are found on many of the southern continents, including Antarctica, also snails, earthworms and freshwater fish. Permanentists, who held that the oceans and continents have always been fixed, had some trouble explaining these anomalies. They dreamed up features such as land bridges across the oceans, so that these plants and animals could make their way from one continent to another. Contractionists, of course, merely assumed that the Atlantic Ocean had once been land.

At the start of this century geologists started to uncover evidence that contradicted the existing theories of global geology. Firstly, the data on cooling indicated that too little contraction of the earth could have taken place to support the contractionist theories. For example, in the Alps alone, some 1200 km of strata have been compressed into a space of 150 km. In fact some argued that there had been no significant cooling at all, and hence no contraction. Secondly, the principal of **isostasy** would not allow for sinking continents or land bridges.

Isostasy is based on the principle that the relatively light rocks of the earth's crust are *floating on* and not simply *resting on* the relatively heavy rocks of the mantle [see. p. 338-339]. The continental crust is made up largely of rocks in which **si**licon and **al**uminum are the dominant constituents (such rocks are termed **SIAL**). Sialic rocks are relatively light. The oceanic crust is made up of rocks in which **si**licon, **ma**gnesium and iron are the dominant constituents (such rocks are termed **SIMA**). Simatic rocks are relatively heavy. The mantle is also made of SIMA, but in fact is substantially heavier still than oceanic crust, and mantle material is not completely solid. Continental crust extends above sea level because the relatively light and buoyant continental crust 'floats' high on the heavy mantle. Oceanic crust lies below sea level because the relatively heavy oceanic crust floats low on the mantle. In a mountainous region the crust must be thicker than elsewhere to support the added weight of the mountains. That is, it must extend down farther into the mantle, in the same way that a large ice-berg extends deep into the ocean. Since the crust is floating isostatically on the mantle, and since oceanic crust is compositionally different from continental crust, the continents cannot sink to become ocean, and parts of the ocean cannot rise up to form land.

F2) Alfred Wegener - *The Origin of Continents and Oceans*

Alfred Wegener was born in Berlin in 1880. He was a meteorologist and an academic. In the time around 1910 Wegener encountered two ideas about global geology:

- the strong similarity of the shapes of the western edge of Africa and the eastern edge of South America (the idea originally came from an American named Snider-Pelligrini in 1858[2]) and
- the geological and paleontological match-ups between the continents on either side of the Atlantic Ocean [see p. 12].

Wegener latched on to the idea that Africa and South America had once been joined together, and had since been pushed apart. He pursued his theory with an almost religious zeal - combing the libraries for evidence to support it - largely ignoring the evidence that did not support it. He relied heavily on the matching geological patterns - sedimentary strata in South America matching those in Africa [Figure 1.15], Pennsylvania coal fields matching those in Europe, the mountains of Atlantic Canada matching those of northern Britain. Wegener also referred to the evidence for Permian aged (250 m.y.) glaciation in South America, Africa, India and Australia [Fig. 1.16] and argued that this indicted that these continents were once all connected as a single super-continent that he called *Pangea* ("all land"). He also cited evidence (based on his own astronomical observations) that actually showed that the continents were moving with respect to each other, and determined a separation rate between Greenland and Scandinavia of 11 metres per year, although he admitted that the measurements were not accurate. They weren't - the separation rate is actually about 2.5 cm per year!

Wegener first published his theory in 1915 in a book called *The Origin of Continents and Oceans*. The book was revised several times up to 1929, and translated to French, English, Spanish and Russian in 1924. Wegener died in Greenland in 1930 while trying to obtain better measurements on the spreading rate.

Wegener's ideas were not accepted by the geological community, especially in Great Britain and North America. Much of the criticism was focused not on the theory itself, but on Wegener's methods - on his eager acceptance of evidence that supported his theory, and his tendency to ignore evidence that did not support it. One critic wrote:

> *"My principal objection to the Wegener hypothesis rests on the author's method. This, in my opinion is not scientific, but takes the familiar course of an initial idea, a selective search through the literature for corroborative evidence, ignoring most of the facts that are opposed to the idea, and ending is a state of auto-intoxication in which the subjective idea comes to be considered as an objective fact."*

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[2] If you're interested in more on the history of geology take a look at this website by Ian Johnston of the Liberal Studies Department at VIU: http://records.viu.ca/~johnstoi/darwin/sect2.htm

On the other hand, much of the criticism of Wegener, and of any new theory, was more political than scientific. For one thing, many geologists had spent their lives working on permanentist or contractionist ideas, and they weren't about to give all that up for what seemed like a crazy idea from a meteorologist. Furthermore, there were traditional strong differences of opinion in geology as well as in many other disciplines, between continental Europe on the one hand (especially Germany during and after WW I) and Great Britain and North America on the other.

In fact the fit was not perfect, the geological match-ups were not always consistent, and the separation data were total nonsense - but worst of all - Wegener could not conceive of a good mechanism for moving the continents around. It was understood by this time that the continents were comprised primarily of sialic material (SIAL - silicon and aluminum dominated), and that the ocean floors were primarily simatic (SIMA - silicon and magnesium dominated). Wegener proposed that the continents were like icebergs floating on the heavier SIMA crust, but the only forces which he could imagine to propel continents around were *poleflucht* - the effect of the earth's rotation pushing objects towards the equator, and the lunar and solar tidal forces - which push objects towards the west. It was quickly shown (by a prominent British geologist, Harold Jeffreys), that these forces were far too weak to move continents.

For more on Alfred Wegener's extremely important contributions to earth science, visit this NASA website: http://earthobservatory.nasa.gov/Library/Giants/Wegener/

F3) The internal structure of the earth

Although we can't see into the earth, and the deepest drill-hole is only 13 km, we have a reasonably good picture of its internal structure and composition. Firstly, we can observe material which has been pushed up to surface from great depth - including parts of the ocean floor, and **kimberlitic** material from deep within the mantle[3], the rocks in which diamonds are found. Secondly, we can observe meteorites, most of which are thought to be parts of broken up planets or planetesimals (little planets). Most importantly, however, we can study and understand seismic waves.

Seismic waves are physical disturbances in a body of rock - caused by earthquakes or artificial explosions - which travel through the rock like a wave across a body of water. They are divided into two types:

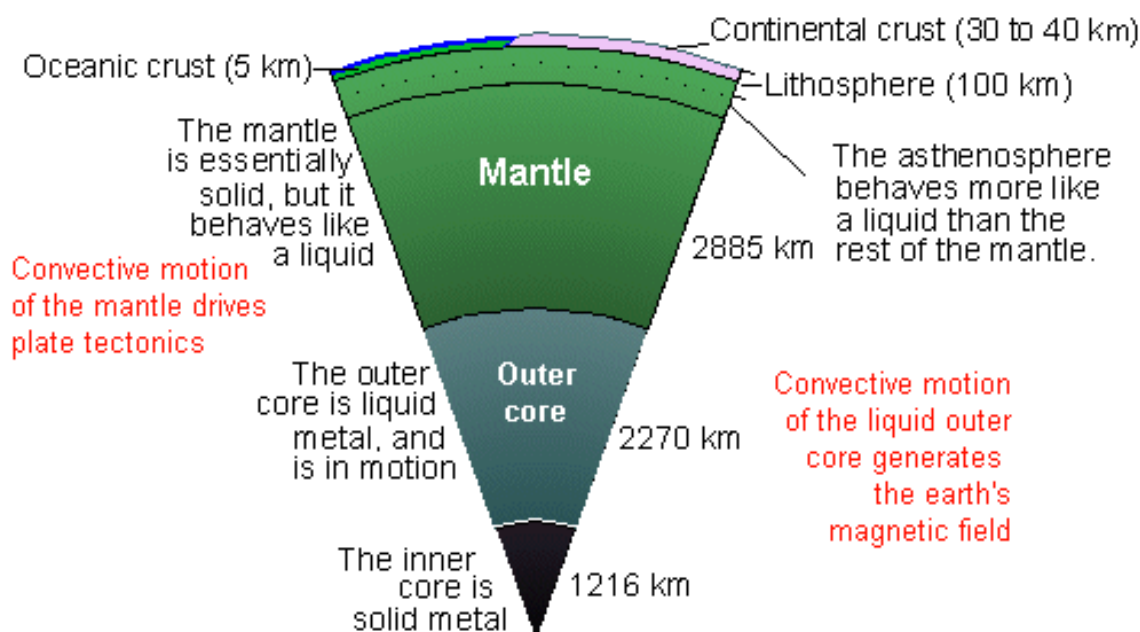| **P** (**P**rimary, com**p**ressional or **p**ush) waves - like a coil spring (or slinky) |
|---|
| **S** (**S**econdary or **s**hear) waves - like a piece of rope which has been flicked |

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[3] A kimberlite is a volcanic eruption with a source deep within the mantle (as opposed to the upper part of the crust for typical volcanoes). Kimberlitic magma travels quickly to the earth's surface and, in some cases, passes through a zone in which diamonds are stable. If some of these diamonds are incorporated into the kimberlite, and if they survive the journey to the surface, a diamond-bearing deposit may form.

Wave velocity depends on density and elasticity of the rock. Seismic wave velocities generally increase with depth because density and elasticity of the rocks increase with depth. There are also some velocity anomalies related to temperature variations and compositional differences. Some of these are discussed below.

P-waves are faster then S-waves[4]. P-waves will travel through a liquid, while S-waves will not. All waves are bent (refracted) at a boundary between rocks of different composition or physical state (e.g., solid versus liquid).

Some important discoveries about the internal characteristics of the earth were made in the early 1900's. For one thing, it was noted that S waves from a large earthquake could not be detected beyond 103° away from the source. This was interpreted as indicating that at least part of the core must behave as a liquid [Figure 10.26]. While P-waves are transmitted through a liquid medium, there is also a P-wave shadow zone extending from 103 to 143° away from the source of a seismic event. Based on an understanding of the refraction of seismic waves, this is also consistent with the idea that part of the core is liquid.

Another important discovery based on seismic data was that there is a significant difference in the seismic velocity - and hence geological properties - between the crust and the underlying

Continental crust (30 to 40 km)

Oceanic crust (5 km)

Lithosphere (100 km)

Mantle

The mantle is essentially solid, but it behaves like a liquid

The asthenosphere behaves more like a liquid than the rest of the mantle.

2885 km

Convective motion of the mantle drives plate tectonics

The outer core is liquid metal, and is in motion

Outer core

2270 km

Convective motion of the liquid outer core generates the earth's magnetic field

The inner core is solid metal

1216 km

material (the mantle). Measurements made at different distances from earthquake epicentres showed that seismic waves that travelled downward, and then were refracted laterally actually moved more quickly than those that just travelled laterally. The dividing line between the crust

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[4] The P stands for *Primary* waves because when there is an earthquake the P waves are first to arrive at a seismic station. S stands for *Secondary*. We'll take another look at P and S waves when we study earthquakes.

and the mantle is known as the **Mohoroviçic Discontinuity**, or **Moho**, after the Yugoslavian who made this discovery.

The layers that make up the earth are shown on the figure above [and on Figure 1.19].

The crust is approximately 5 km thick under the oceans and 30 to 60 km thick on the continents. The average global thickness is about 20 km, which represents 0.3% of the total radius of the earth. This is roughly equivalent to the thinnest layer of skin on the outside of an onion. The **mantle** has a total thickness of 2885 km and comprises more than 80% of earth's volume (the upper part has the composition of the rock peridotite - which includes the minerals olivine and pyroxene). The temperature increases towards the base of the mantle, but not as much as expected - so we conclude that there must be convection within the mantle to transmit some of the internal heat out towards the surface. It is assumed, therefore, that the mantle behaves in a 'plastic' way. We know that it is essentially solid because it can transmit S-waves, but it will 'flow' in response to long-term stress. The uppermost 100 km of the mantle is solid, and this zone, along with the crust, is known as the **lithosphere**. The lithosphere does not participate in the convection, and thus the temperature gradient in this zone is quite steep. Immediately below the lithosphere - from 100 km to 200 km - there is a layer of partial melting - also called the ***low-velocity zone*** because seismic waves are slowed within it (see figure below). As we will see later, the existence of this partially liquid layer is important to the mechanics of plate tectonics. The low-velocity zone makes up part of the **asthenosphere**[5] that is a relatively mobile part of the mantle.

The core has a total radius of 3486 km - and although it comprises only one-sixth of the volume of the earth, it represents almost one-third of its mass. It is predominantly made up of metallic iron along with some nickel and smaller amounts of sulphur and oxygen - the proportion of iron increasing towards the centre. The outer core is liquid, while the inner core (which is actually hotter) is solid. This apparent anomaly can be explained partly by the differences in their composition, but mostly by the difference in pressure. The pressure within the inner core is too great for it to exist as a liquid. The liquid outer

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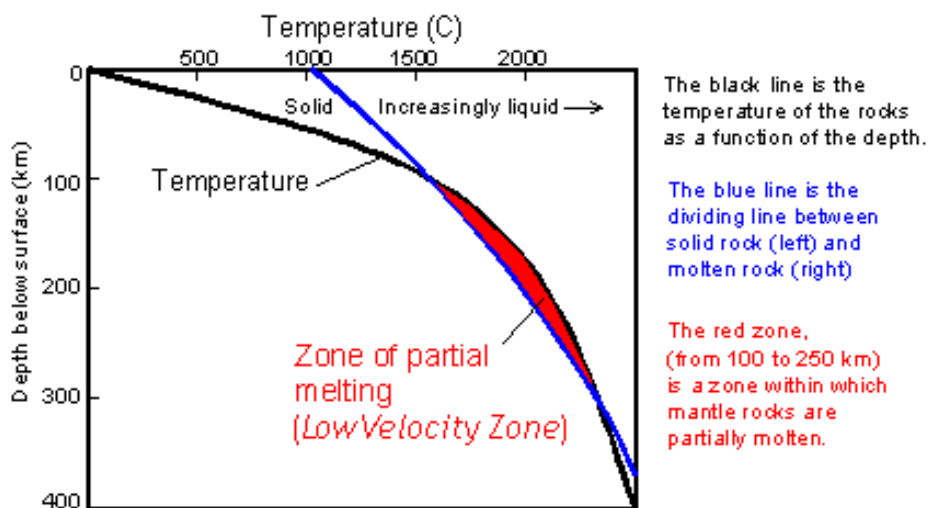
[5] Asthenosphere is from the Greek word *asthene*, which means weak.

part of the core is in motion - and it is this motion - of a material that conducts electricity - that gives the earth its magnetic field.

Seismologists continue to study data from both natural and man-made seismic events using increasingly sensitive instruments and sophisticated data processing methods. With the type of information now available it is possible to generate three-dimensional models of the temperature variations within the mantle. The results provide evidence of where hot material is moving upward from the lower mantle, and where relatively cool material is moving down.
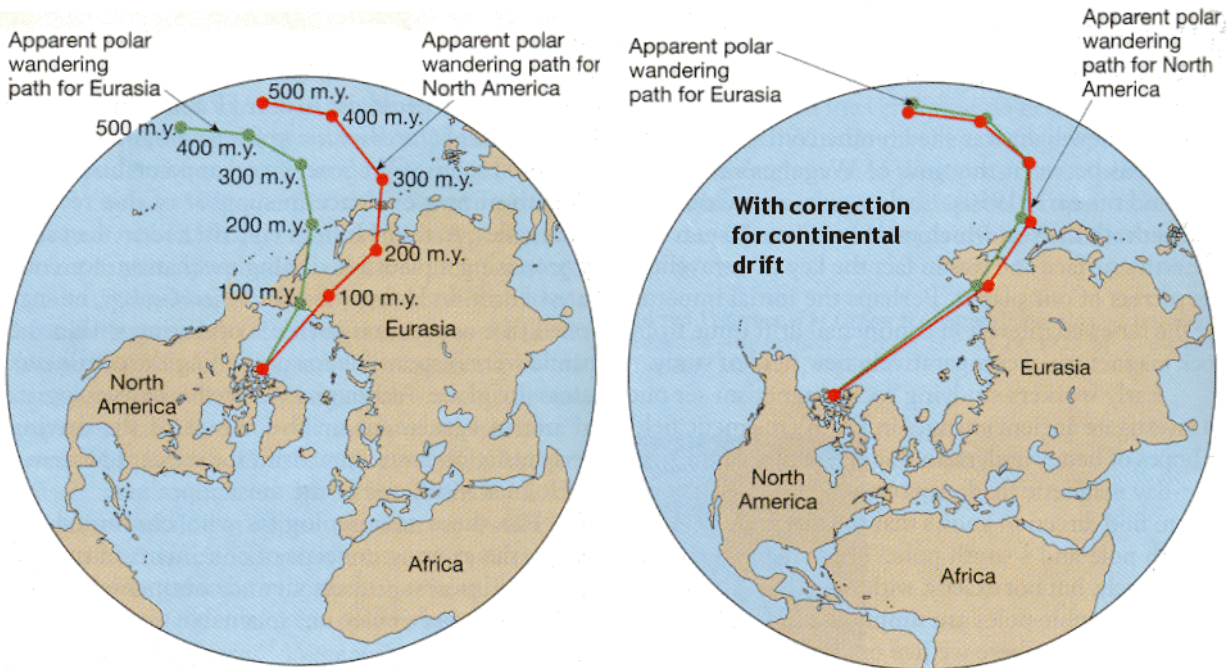
F4) Paleomagnetism

In the middle of the 19th century physicists studying recently cooled volcanic rocks in Italy recognized that they were uniformly magnetized parallel to the earth's magnetic field[6]. As the mineral magnetite crystallizes from magma it becomes magnetized with an orientation parallel to that of the earth's magnetic field at that time [page 312-313]. This is called **remnant magnetism**. Rocks like basalt, which cool from a high temperature and which commonly have relatively high levels of magnetite, are particularly susceptible to being magnetized in this way. By studying both the horizontal and vertical components of the remnant magnetism one can tell not only the direction to magnetic north at the time of the rock's formation, but also the latitude of the sample relative to magnetic north.

In the early 1950s geologists from Cambridge and the University of London started looking at the remnant magnetism of British and European volcanic rocks, and collecting what we call **paleomagnetic** data. To their great surprise, they found that rocks of different ages sampled from generally the same area showed quite different apparent magnetic pole positions. They assumed that this meant that either the earth's magnetic field had departed significantly from its usual position - which is normally close to the rotational pole - or that the rocks (and the continent on which they sit) had moved.

The curve defined by the paleomagnetic data is called a ***polar wandering curve***, although we now know that it defines movement of continents, and not of the magnetic poles. Similar work was soon carried out in North America - and this also showed considerable *apparent* polar wandering, but the results were not consistent with those from Europe. For example the 250 m.y. pole for North America plotted somewhere in China, while the 250 m.y. pole for Europe plotted in the Pacific Ocean. Since there can only have been one pole position 250 m.y. ago, this evidence strongly supported the idea that North America and Europe were not the same distance apart 250 m.y. ago that they are now. Subsequent paleomagnetic work showed that South America, Africa and Australia also have unique polar wandering curves.

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[6] For paleomagnetic work it is necessary to collect samples of a rock, such as basalt, for which the original depositional orientation - in both the vertical and horizontal planes - is known.

"Polar-wandering" curves for Europe and North America. In the diagram to the right the curve locations have been corrected taking continental drift into account.

This paleomagnetic work of the 1950's was the first new evidence in favour of continental drift, and it led a lot of geologists to start thinking that the idea may not be so ridiculous after all. Nevertheless, for a majority of geologists thinking and writing about global geology at the time, this type of evidence was not sufficiently convincing to get them to change their views.

[For more information on the earth's magnetism see page 23.]

## F5) New information from the oceans

During this century our knowledge and understanding of the ocean basins and their geology has increased many times. Before 1900 we knew virtually nothing about the bathymetry and geology of the oceans. By the end of the 1960s we had detailed maps of ocean topography, a clear picture of the geology of ocean floor sediments and the solid rocks underneath them, and more information about the geophysical nature of ocean rocks than we did of continental rocks.

1) **Ocean bathymetry** - Up until about the 1920s the number of soundings in the deep oceans was probably less than 1000[7], and it is not surprising that we knew almost nothing about the

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[7] That is roughly 1 depth sounding for every 350,000 square kilometres of the ocean. To put that in perspective, it would be like trying to describe the topography of British Columbia with elevation data for only a half a dozen points.

topography and nature of the ocean floor. The voyage of the *Challenger* in 1872, and the laying of trans-Atlantic cables had shown that there were mountains beneath the seas, but most geologists and oceanographers still believed that the oceans were essentially vast basins with flat bottoms, filled with thousands of metres of sediments.

Following development of acoustic depth sounders in the 1920s [Figure 11.12] the number of depth readings increased by many orders of magnitude, and by the 1930s it had become apparent that there were major mountain chains in all of the world's oceans. During and after World War II there was a well-organized campaign to study the oceans, and by 1959 sufficient bathymetric data had been collected to produce detailed maps of the entire ocean. See [Figure 11.4] and below.
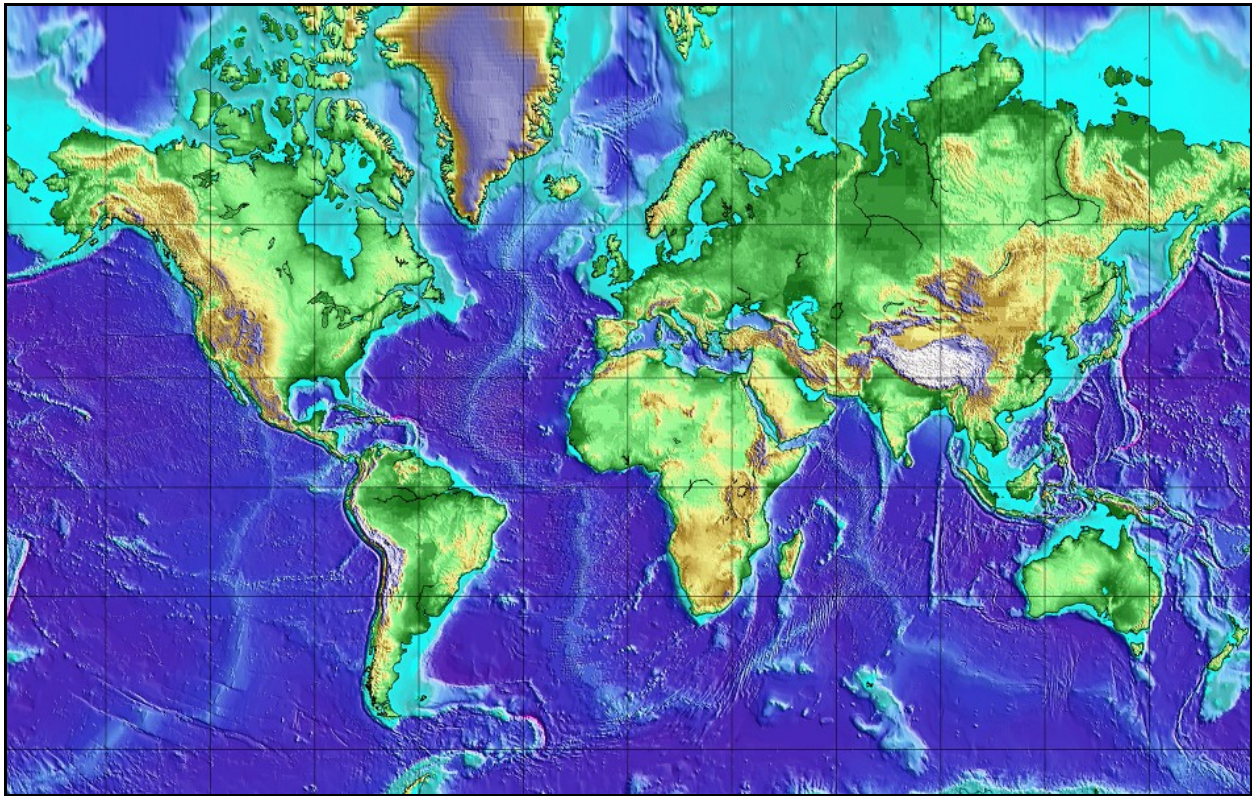
The important physical features of the ocean floor are:

- ridges (commonly in the central parts of the oceans),
- strongly developed trenches perpendicular to the ridges,
- deep ocean plains,
- relatively flat and shallow continental shelves,
- deep trenches (mostly near to the continents), and
- seamounts and chains of seamounts.

2) **Ocean sediments and the oceanic crust -** Seismic sounding[8] was first used to study the ocean floor sediments in the 1930's. As the technique evolved, and the amount of energy was increased, it became possible to see through the sea-floor sediments and to map the bedrock topography and crustal thickness. Hence sediment thicknesses could be mapped - and it was soon discovered that although the sediments were several thousands of metres thick near to the continents, in the ocean ridge areas the sediments were relatively thin - or even non-existent. The seismic studies also showed that the crust is relatively thin under the oceans (5 to 6 km) compared to the continents (30 to 60 km) and geologically very consistent - composed almost entirely of basalt.

3) **Heat flow -** In the 1950's researchers at Cambridge University developed a probe for measuring the flow of heat from the ocean floor[9]. They found the rate to be higher than average along the ridges, and lower than average in the trench areas. These features were subsequently interpreted to indicate that there is convection within the mantle - the areas of high heat-flow being correlated with upward convection of hot mantle material, and the areas of low heat-flow being correlated with downward convection.


4) **Earthquake foci -** With developments of networks of seismographic stations in the 1950's it became possible to plot the locations and depths of both major and minor earthquakes with great accuracy. It was found that there is a remarkable correspondence between earthquakes and both the mid-ocean ridges and the deep ocean trenches. In 1954 Gutenberg and Richter showed that the ocean-ridge earthquakes were all relatively shallow, and confirmed what had first been shown by Benioff in the 1930's, that earthquakes in the vicinity of ocean trenches were both shallow and deep, but that the deeper ones were situated progressively farther inland from the trenches (by several hundreds of kilometres). (see figure to the right)

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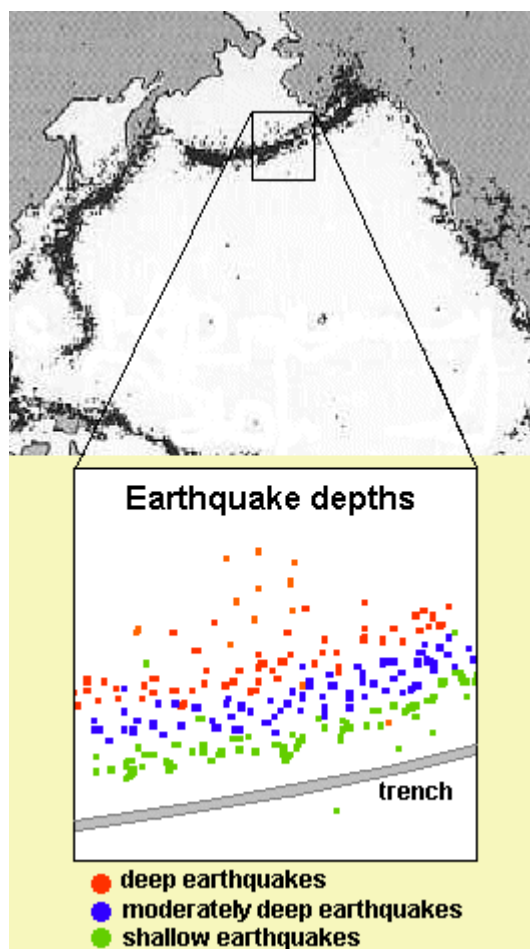
[8] Seismic sounding involves transmitting high-energy sound bursts and then measuring the echos with a series of geophones towed behind a ship. The technique is a little like the *acoustic sounding* used by pleasure-boaters to avoid rocks, and fishermen to find fish; however much more energy is transmitted, and the sophistication of the data processing is much greater.
[9] Ocean-floor heat flow probes measure the temperature within the sediments at two or more depths. These data can then be used to calculate the rate of flow of heat from the underlying rocks.

5) **Magnetic data** - In 1955 scientists from the Scripps Oceanographic Institute persuaded the U.S. Navy to include magnetometer readings in their studies of ocean floor topography. The first comprehensive magnetic data set was compiled in 1958 for an area off of the northwest coast of the US. This survey revealed a bewildering pattern of low and high magnetic intensity in sea-floor rocks. When the data were first plotted on a map nobody understood them - not even the scientists who collected them (see figure below). Although the patterns made about as much sense as the stripes on a zebra, many thousands of kilometres of magnetic surveys were conducted over the next several years.

Juan de Fuca ridge crest
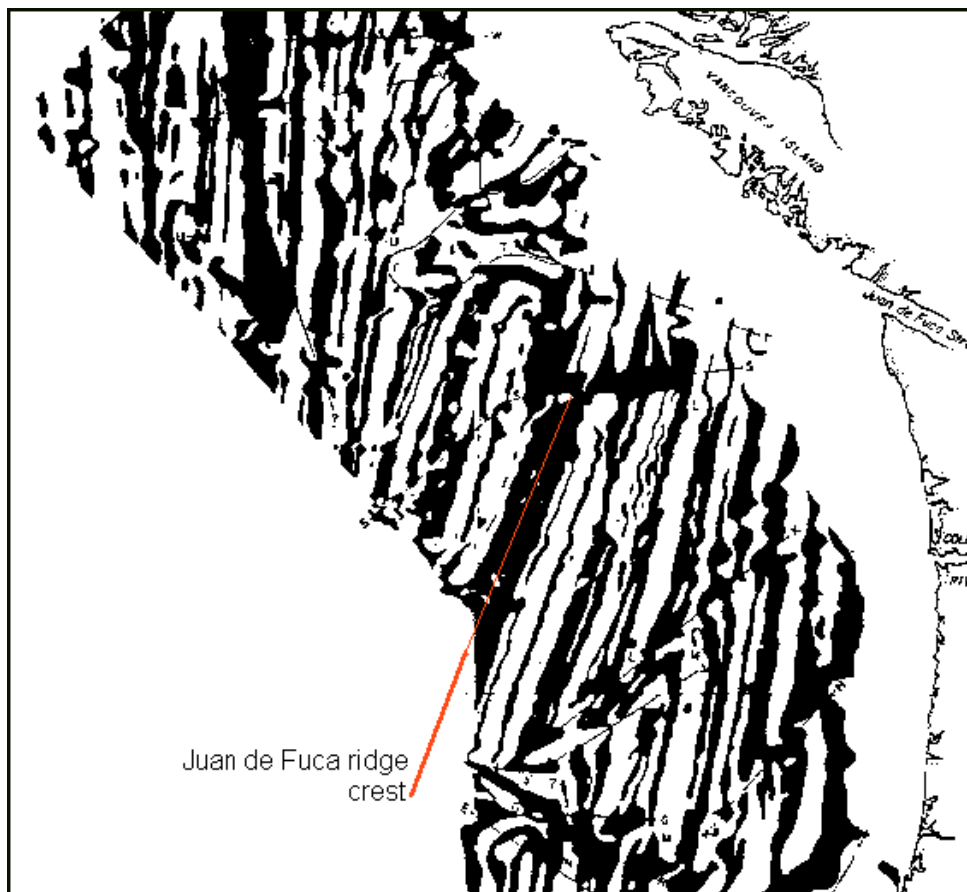
Review questions

1. How were mountains thought to be formed (a) by *contractionists* and (b) by *permanentists*?

2. Geographically, where do geosynclines form?

3. How were the trans-Atlantic paleontological match-ups explained in the 19th century?

4. What are the differences between SIMA and SIAL?

5. In the context of isostasy what would prevent an area of continental crust from becoming part of an ocean?

6. List some of the evidence used by Wegener to support his idea of moving continents.

7. Give three reasons why Wegener's theory was not well received in the 1920's.

8. What was the primary technical weakness with his theory?

9. Which type of seismic waves (S or P) cannot travel through a liquid?

10. Which factors control the speed at which seismic waves travel through rocks?

11. Which of the earth's internal boundaries is represented by the Mohorovicic discontinuity?

12. How did we first find out that part of the earth's core is a liquid?

13. How does the temperature profile of the crust and mantle indicate that part of the mantle must be convecting?

14. What is the "low velocity zone"?

15. Make a sketch of the earth showing the lines of magnetic force, and how the magnetic direction of magnetite within basalt would point at the magnetic north pole, at 45° north and at the magnetic equator.

16. What evidence from the paleomagnetic studies provided support for continental drift?

17. Which parts of the oceans are the deepest?

18. Which parts of the oceans have the greatest accumulations of sediments, and which parts have the least?

19. How was the oceanic heat-flow data related to mantle convection?

20. Describe the relative depths of earthquakes at ocean ridge crests and at ocean trenches.