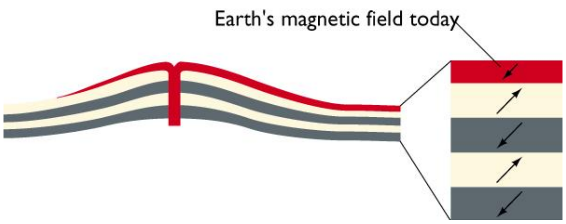
210D4: Paleomagnetism

D4.1 Introduction to paleomagnetism

1797 Alexander von Humboldt noticed that rocks could be magnetized by lighting strikes.

1906 Bernard Brunhes reported reversely magnetized lavas from ancient lavas in the Massif Central in France.

1929 Motonori Matuyama noted that Quaternary lavas had remnant magnetization that was in the same direction as the present day magnetic field. Older quaternary and Pleistocene lavas had reversed magentization direction. Matuyama suggested that these reversely magnetized rocks were caused by reversals of the Earths magnetic field.



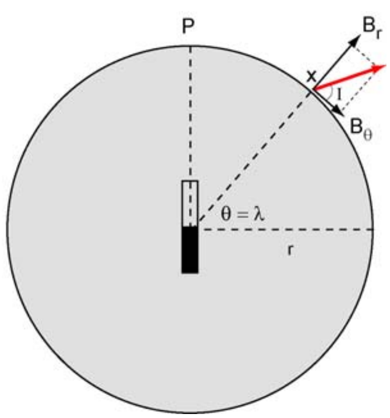
1930+ Louis Neel and John Graham : Spontaneous self reversals observed in some lava flows during cooling and this suggested that the observed magnetic field reversals may be artefacts.

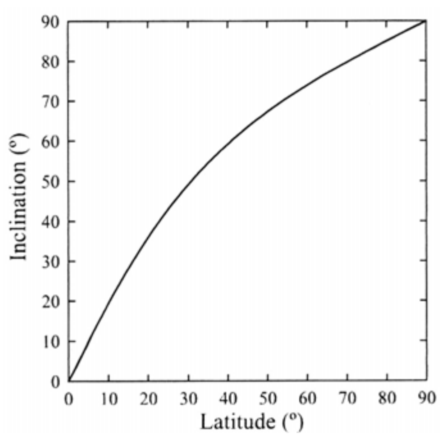
1951 Jan Hospers' detailed study of basalts in Iceland and elsewhere showed that magnetic reversals are likely real.

1956 Evidence for polar wandering presented by Keith Runcorn. Showed that magnetized rocks of differing ages record a variable position for the geomagnetic pole. When combined with studies on other continents, it was noted that each continent had a different polar wandering path. The simplest solution to this apparently complicated situation was that the pole had not moved, but the continents had moved independently.

D4.2 Determining the location of the magnetic pole from a paleomagnetic sample

D4.2.1 Determine paleolatitude

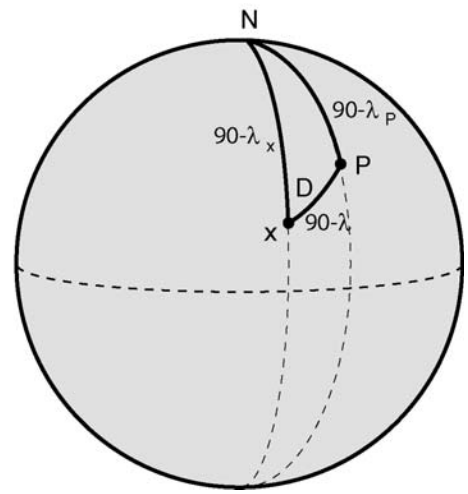




- Measure I from the rock sample
- Compute the paleolatitude (λ) from $\tan I = 2 \tan \lambda$

D4.2.2 Determine the location of virtual geomagnetic pole (VGP)

- Sample is collected from location X
- Present magnetic pole is located at N
- The previous calculation is only part of the solution because it assumes that no rotation of the sample has occurred since the rock was magnetized.
- From the sample can measure the declination angle D
- The angles D and λ are now known
- This allows the apparent polar position (P) to be computed



- P is the virtual geomagnetic pole (VGP)

Consider spherical triangle PNX and apply the cosine law. Details of spherical triangles and trigonometry on page 20 of the textbook.

$$\cos(90-\lambda_P) = \cos(90-\lambda_x)\cos(90-\lambda) + \sin(90-\lambda_x)\sin(90-\lambda)\cos D$$

This simplifies to

$$\sin\lambda_P = \sin\lambda_x \sin\lambda + \cos\lambda_x \cos\lambda \cos D$$

Next stage is to compute the longitude of point P. Let the longitude of P and x be Φ_P and Φ_x.

The angle PNX is the difference in longitude, Φ_P-Φ_x so some more spherical trigonometry gives

$$\frac{\sin(\Phi_P - \Phi_x)}{\sin(90-\lambda)} = \frac{\sin D}{\sin(90-\lambda_P)}$$

which simplifies to

$$\sin(\Phi_P - \Phi_x) = \frac{\sin(90-\lambda)\sin D}{\sin(90-\lambda_P)}$$

Depending on the size of the angles λ, λ_x and λ_P this equation has two possible solutions. Details on page 53 of the textbook.

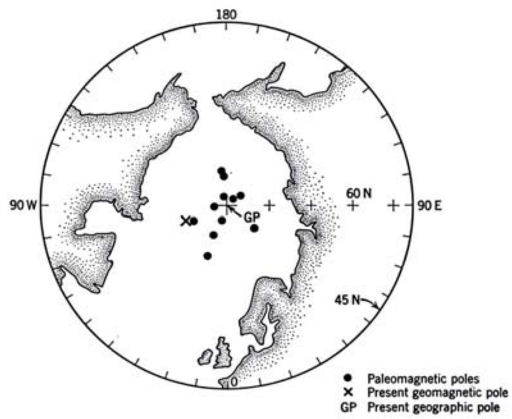
Note that we can only find the relative longitude (Φ_P-Φ_x)

D4.2.3 Assumptions made in paleomagnetism

Geocentric axial dipole (GAD) hypothesis. This assumes that the main field has always been a dipole field oriented with the rotation axis.

Evidence to support this hypothesis

- Paleomagnetic pole positions. For example figure on right from Irving (1964) shows pole positions for last 7000 years. When averaged over 10,000 years, the geomagnetic and geographic poles are coincident. Currently these two poles differ by 11°

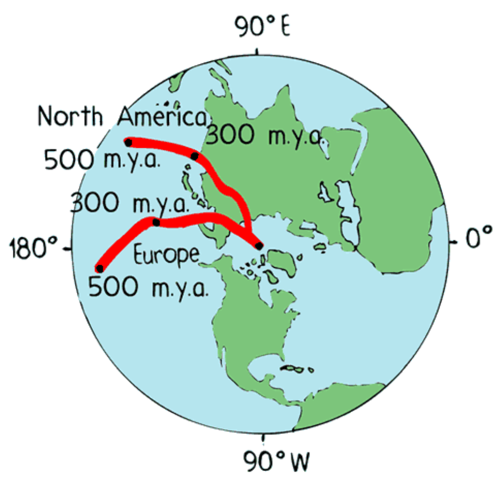


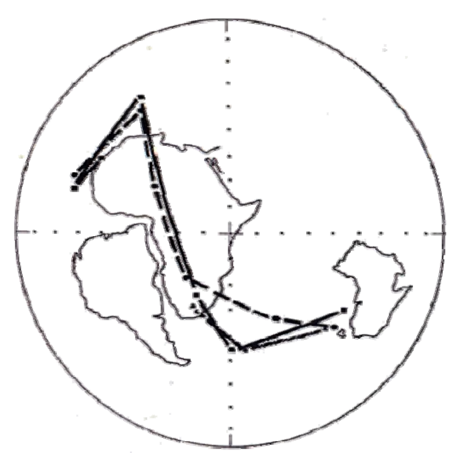
- Paleointensity studies consistent with a predominantly dipole field in the past.

- Measurement of the inclination angle recorded by deep sea sediments. Consistent for last 5 million years.

<u>D4.3 Apparent polar wander paths</u>

- If multiple VGP locations can be determined from rock formations that can also be dated, then the apparent polar wander (APW) path for a continent can be reconstructed.
- These were found to be different for different continents. e.g. left hand panel below showing relative motion of Europe and North America. See Fowler Figure 3.6
- These observations can be reconciled if the continents have moved relative to each other.
- Right panel shows the APW paths during the Paleozoic for Africa (solid), South America (dashed) and Australia (hatched). The curves are very similar and this shows that the continents moved together as part of Gondwanaland.

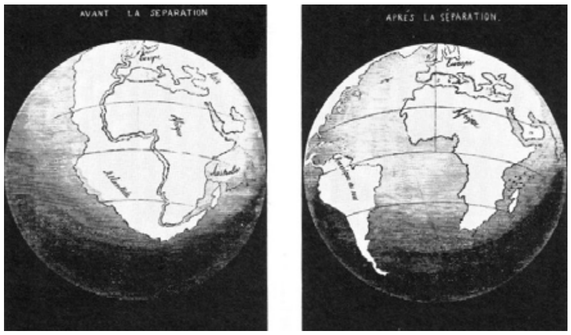




- Also note that this shows that these southern continents were in the polar region at this time. From McElhinny, reproduced in Stacey (1969).

D4.4 Paleomagnetism and evidence for plate tectonics

1620 Francis Bacon noted the '*conformable instances*' along the east and west coastlines of the Atlantic Ocean.



1858 Antonio Snider-Pellegrini suggested that continents were linked during the Carboniferous Period, because plant fossils in coal-bearing strata of that age were so similar in both Europe and North America. His book was called "*Création et ses mystères dévoilés*"

1885 Geologist Edward Seuss described similarities between plant fossils from South America, India, Australia, Africa and Antarctica. Proposed that they once formed a super continent named **Gondwanaland**. Named after the Gond people of north-central India.

1915 Alfred Wegener suggested the idea of continental drift. Developed previous ideas of the fit of continents and matching patterns of fossils and plants.

Wegener made some reconstructions of the location of the continents in the past.

He envisioned continents made of lighter material floating in a denser mantle. This was (possibly) inspired by ideas of the continents floating that were derived from the isostacy hypothesis of Airy. However, Wegener had no viable mechanism to move the continents and he proposed the unlikely idea of a polar-fleeing centrifugal force (*polfluchkraft*).

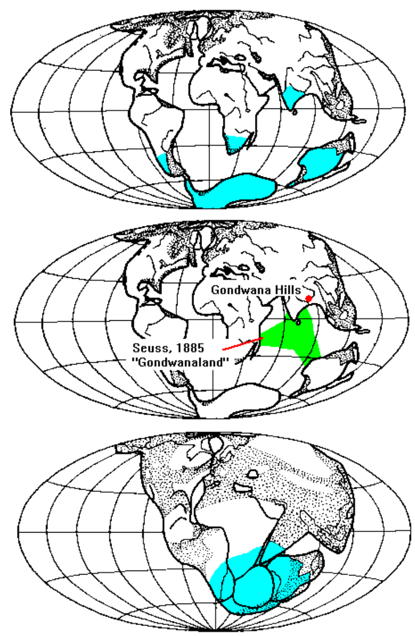
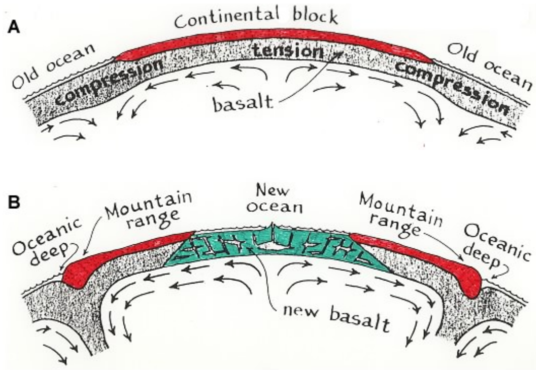
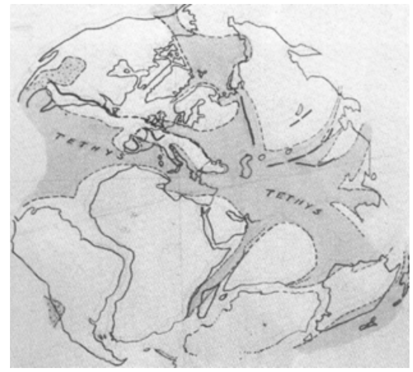


Figure from Wegener (1929) showing positions of continents at 300, 55 and Ma before present. Figure annotated by Steve Dutch (UWGB). Blue shows the extent of Permian glaciation. This figures and excellent notes found at http://www.uwgb.edu/DutchS/EarthSC102Notes/102PlateTectonics.htm

1930-40 Opposition to idea of continental drift from Sir Harold Jeffreys and other geophysicists, mainly because of a lack of a mechanism for the huge forces needed to move continents through the mantle. These seismologists viewed the Earth as solid, based on observations of seismic wave propagation.



Arthur Holmes idea of mantle convection



du Toit (1937)

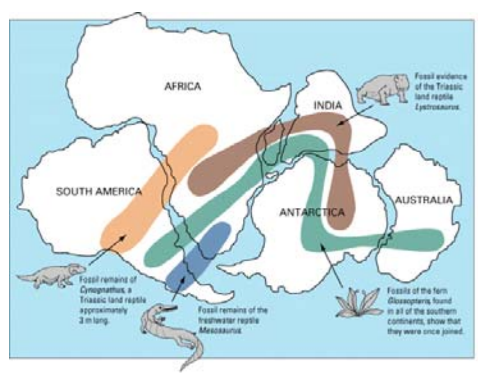
Arthur Holmes suggested the idea of mantle convection. This provided a mechanism for moving the continents across the surface of the Earth.

Alfred Wegener died in Greenland in 1930

South African geologist Alexander du Toit suggested that there had been a northern supercontinent called **Laurasia** made up from North America, Greenland, Europe and Asia. This provided a unifying explanation for the distribution of the remains of equatorial, coal-forming plants, and thus the widely scattered coal deposits (1937).

1950's Convincing evidence that the magnetic field had reversed, and that continents recorded the fact that their distance from the magnetic pole had changed over geological time.

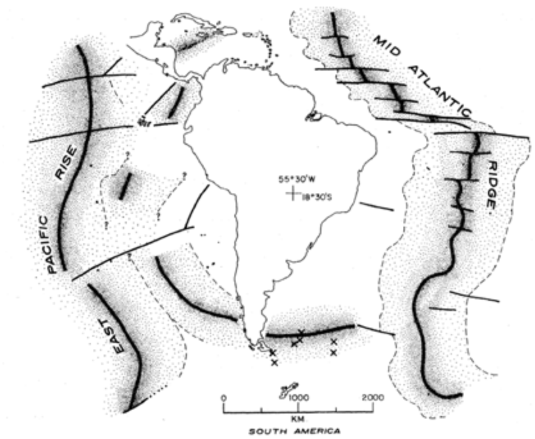
- This polar wandering could be explained simply by continental drift.
- Also explained other observations that suggested that the continents had changed latitude over geological time. e.g. coal seams in the Arctic at Svalbard and evidence for glaciation in sub-tropical South Africa.



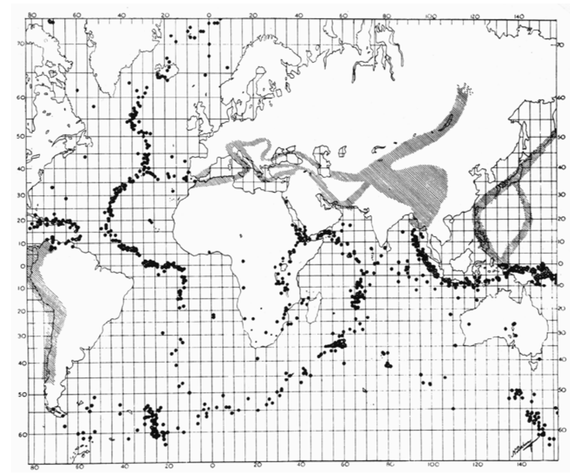
http://pubs.usgs.gov/gip/dynamic/exploring.html

D4.5 Seafloor magnetic anomalies

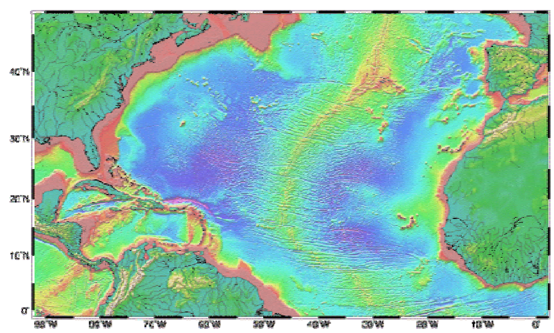
- In 1855, a bathymetric chart published by U.S. Navy Lieutenant Matthew Maury revealed the first evidence of underwater mountains in the central Atlantic (called "Middle Ground").
- These mid-ocean ridges were clearly volcanic (Azores, Iceland etc) and associated with a narrow belt of many earthquakes (Rothe, 1954). It was inferred that these ridges must be geologically active.
- Important evidence to support the hypothesis of continental drift came from observations of magnetic fields measured by survey ships on profiles that crossed the world's oceans.
- In the late 1950's new magnetometers became available for geophysical studies in the oceans. Magnetic stripes of alternating positive and negative polarity were discovered.

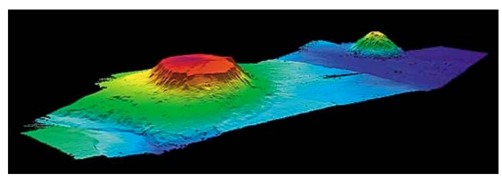


Menard (1965)



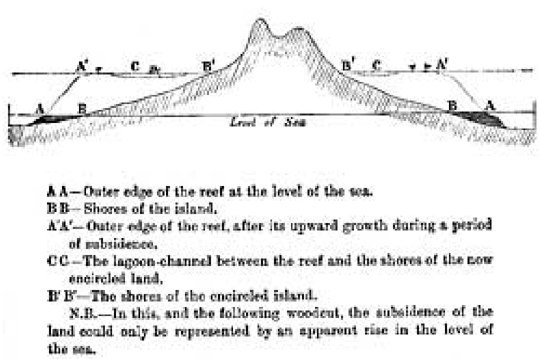
Earthquake locations from Rothe (1954)

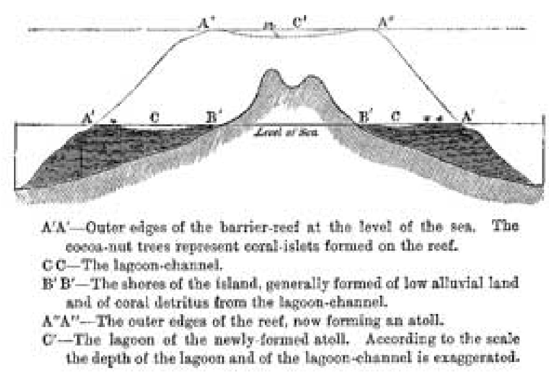




- Lack of sediments in deep ocean and on crests of mid-ocean ridges showed they were the youngest parts of the oceans (not the oldest part as once thought).

- Atolls are rings of coral reef that have developed above volcanos in the deep ocean. Their origin was first described by Darwin (1842).





- Once they are submerged the coral dies and they become a flat topped seamount. These were found to be widespread in the Pacific by Harry Hess during his service on submarines during WWII. He named these features guyots.

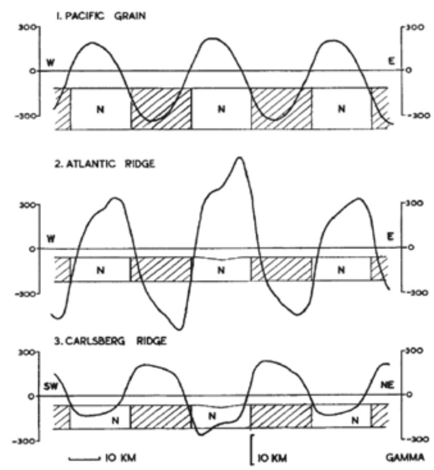
- Can show that the ocean floor subsides as it ages and moves away from the mid-ocean ridge.

- This can be explained by simple thermal arguments that model a change in density with plate age.

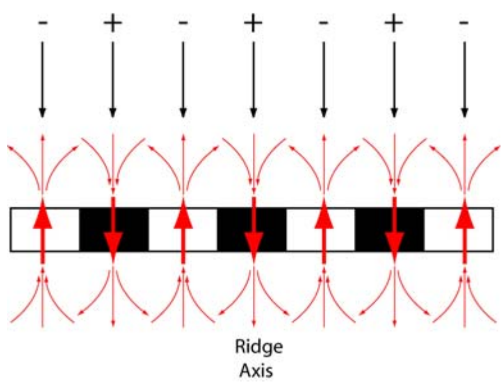
- 1959-1962 Ideas of seafloor spreading suggested Harry Hess, Robert Dietz and others. Lack of knowledge of deep oceans prevented confirmation of these ideas.

- 1962 Lawrence Morley. Suggested explanation for the magnetic stripes, assuming oceanic crust was magnetized as it was erupted. Magnetization recorded changes in polarity of the geomagnetic field. These ideas were rejected for publication by *Nature* and *Journal of Geophysical Research* as too speculative.

- Vine and Matthews (1963) independently suggested the same idea and published their results in the journal *Nature*.

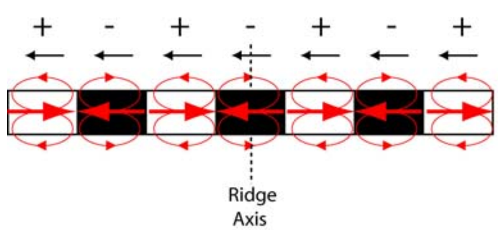


Magnetic stripes at High magnetic latitudes



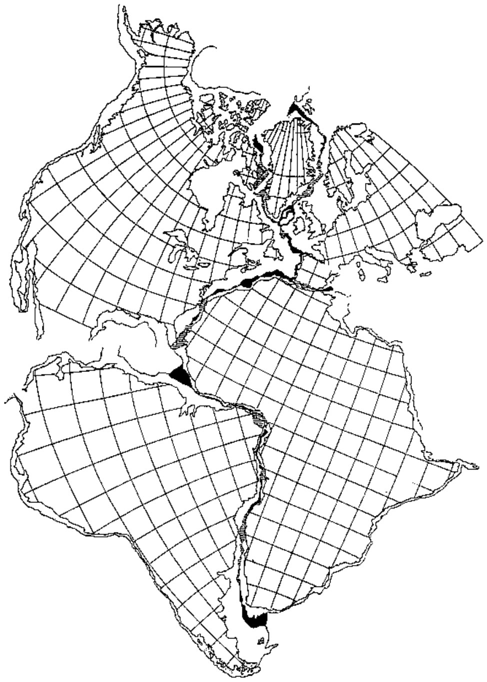
- In high magnetic latitudes the Earth's magnetic field is close to vertical.
- The remnant magnetization at the ridge is in the same direction as the Earth's field.
- The ridge crest is a **positive** magnetic anomaly.

Magnetic stripes at Low magnetic latitudes

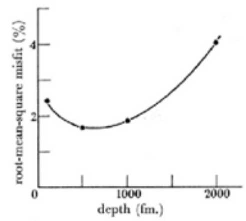


- In low magnetic latitudes the Earth's magnetic field is horizontal.
- If the ridge extends east-west, then the remnant magnetization is across the ridge is in the same direction as the Earth's field.
- At this location the ridge crest is a **negative** magnetic anomaly.

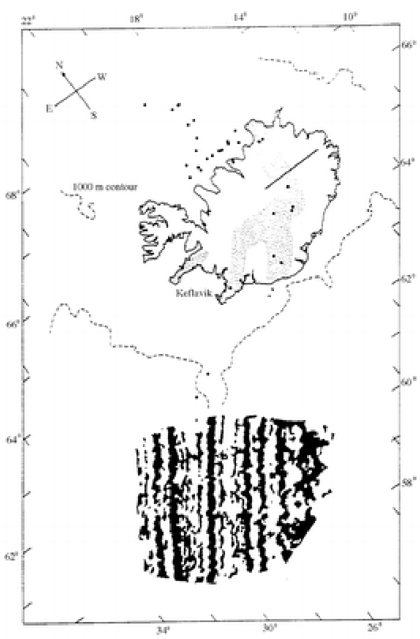
- Drilling of the mid-Atlantic ridge revealed a much more complicated pattern of seafloor magnetism (Hall and Robinson, 1979). Still some debate about exactly which part of the crust is magnetized and contributes to the magnetic stripes.

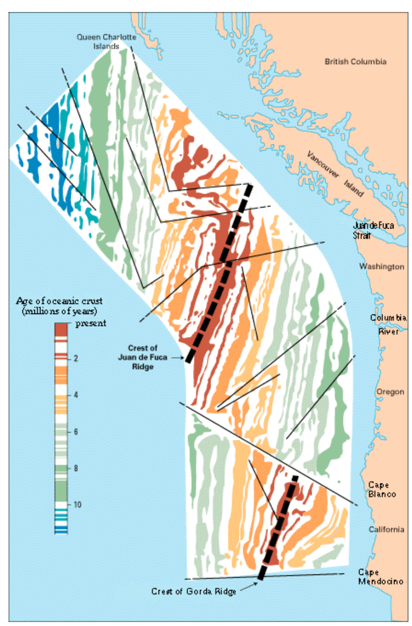


- Fit of the continents by Bullard et al., (1965) derived using a computer algorithm to optimize the location of continents on a sphere.
- Bullard aligned the edges of the continental shelves rather than the present coastline.
- Large deltas that have form since rifting began cause overlaps.



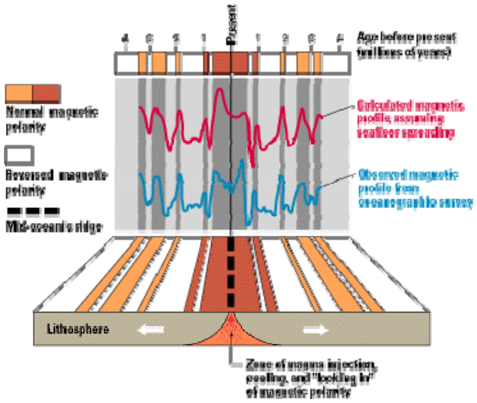
Heirtzler et al., (1968) presented a detailed study of the Reykjanes Ridge showed symmetric stripes in map form. Similar patterns observed on each side of the Juan de Fuca ridge on the west coast of North America (Vine, 1966).

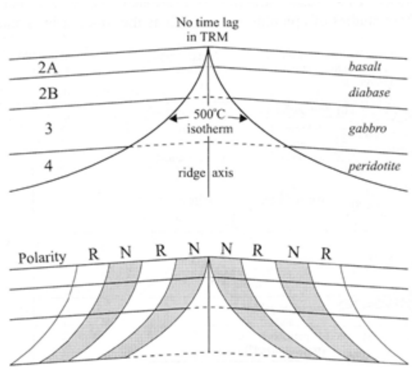




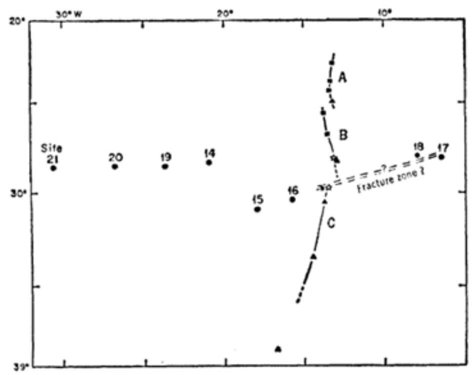
Heirtzler et al., (1968)

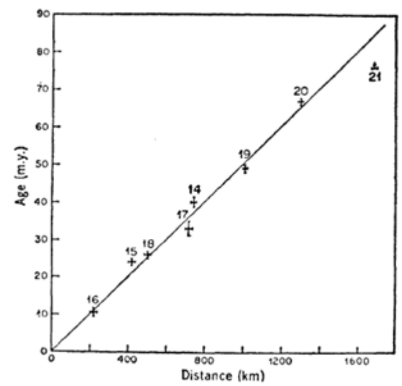
Based on Vine (1966)



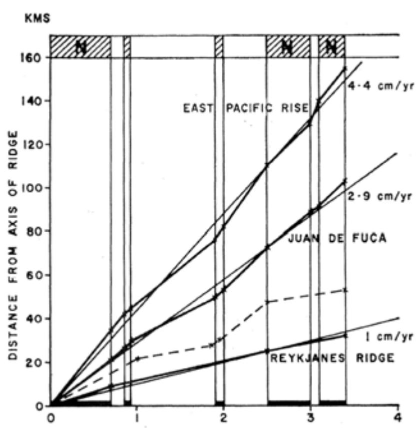


- Confirmation of seafloor spreading rates and seafloor ages inferred from anomalies by ocean drilling and dating of basalt. Figure below from Maxwell et al., 1970 and also Fowler Figure 3.13.





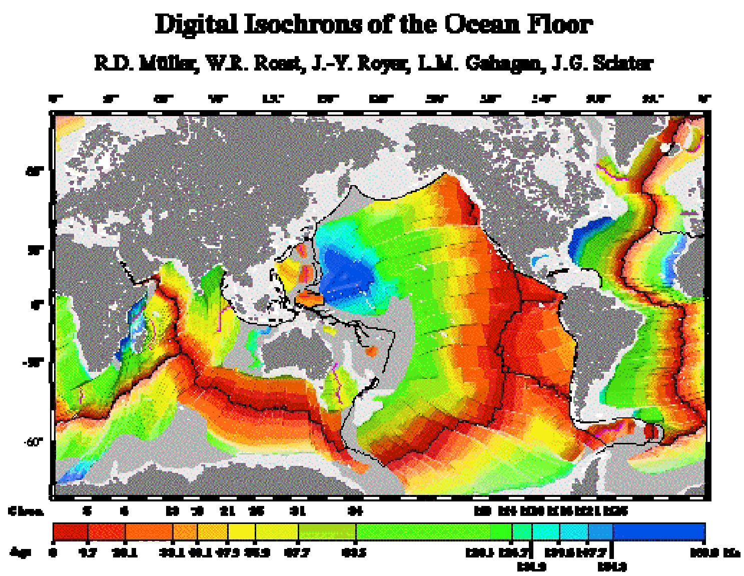
- Rate of seafloor spreading varied from one ridge to another (Vine, 1966)



- Correlation between magnetic anomaly and age provides a method for **measuring the age** of the ocean floor by studying the magnetic anomalies. Figure below from (Muller et al., 1997).

- This information allows the **reconstructions** of past plate motions. Please read Fowler 3.3.

- The ocean floor is one of the **youngest** parts of the Earth's surface, with very little older than 200 million years.



D4.6 Modern reconstructions of plate motion

- Magnetic data was key evidence for acceptance of plate tectonics
- Animations of last 200 million years (TASA)
- Reconstruction of each ocean basin in Fowler Chapter 3

References

Brunhes, B., Recherches sur la direction d'aimentation des roches volcaniques (1), *J. Physique*, 4e ser., 5, 705-724, 1906.

Bullard, E., J.E. Everett and A.G. Smith, The fit of the continents around the Atlantic, *Phil. Trans. Royal Society of London, Series A*, 258, 41-51, 1965.

Dietz, R.S., Continent and ocean basin evolution by spreading of the sea floor, *Nature*, 190, 854-7, 1961.

Hall, J.M., and P.T. Robinson, Deep crustal drilling in the North Atlantic ocean, *Science*, 204, 573-586, 1979.

Heirtzler, J.R. et al., Marine Magnetic Anomalies, Geomagnetic Field Reversals and Motions of Ocean Floor and Continents, *J. Geophys. Res*. 73, 2119-36, 1968

Hospers, J., Remnant magnetism of rocks and the history of the geomagnetic field, *Nature*, 168,1111-1112, 1951.

Matuyama, M., On the Direction of Magnetisation of Basalt in Japan, Tyosen and Manchuria, *Japan Academy Proceedings* 5, 203-5, 1929.

Maxwell, A.E., et al., Deep sea drilling in the South Atlantic, Science, 168, 1047-1059, 1970

Menard, H.W., The world-wide oceanic rise-ridge system, *Phil. Trans. Royal Society of London, Series A*, 258, 109-122, 1965.

Muller, R.D., W.R. Roest, J. Royer, L.M. Gahagan, J.G. Sclater, Digital isochrons of the worlds ocean floor, *J. Geophys. Res*., 102, 3211-3214, 1997.

Rothe, J.P., La zone seismique mediane Indo-Atlantique, *Proceedings of the Royal Society of London, Series A*, 222, 387-397, 1954.

Vine, F.J., and D.H. Matthews, Magnetic anomalies over oceanic ridges, *Nature*, 199, 947-949, 1963.

Vine, F.J., Spreading of the Ocean Floor : New evidence, *Science*, 154, 1405-1415, 1966.

http://pubs.usgs.gov/gip/dynamic/exploring.html
http://en.wikipedia.org/wiki/Snider-Pellegrini
http://pangea.stanford.edu/courses/gp025/webbook/08_tectonics.html