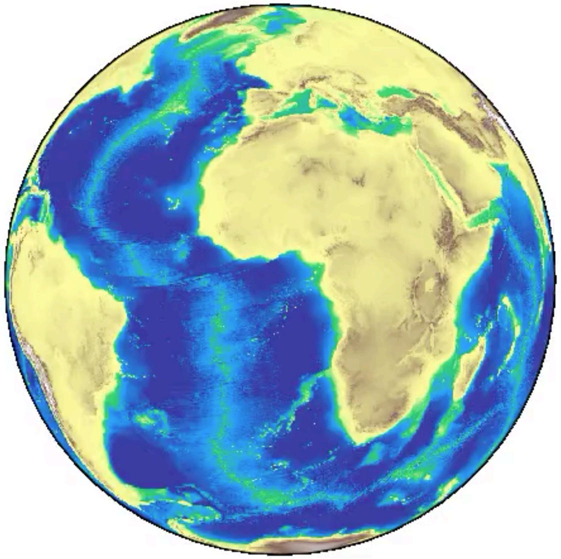
Australian National University

PHYS 3070 Section 2:

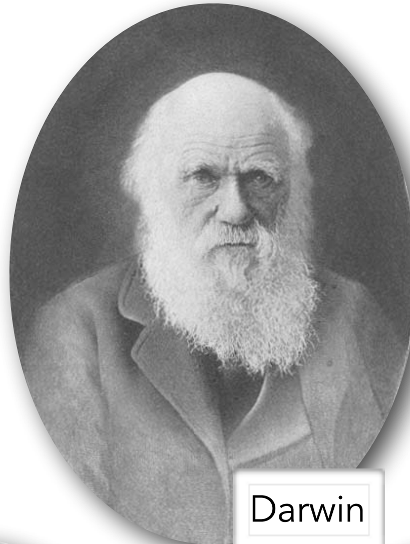
History of Plate Tectonics



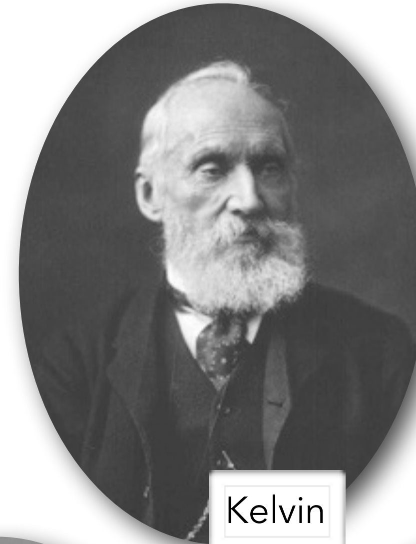
In which we consider observations of the Earth as a planet that were made before the advent of satellite remote sensing and globally network seismometers. How did these data lead to the notion of plate tectonics ?

Some Historical Perspectives on the Theory of Plate Tectonics

Tharp



Darwin



Kelvin

Curie

Wegener

Holmes

Wilson

With content from Peter Betts
Peter.Betts@monash.edu

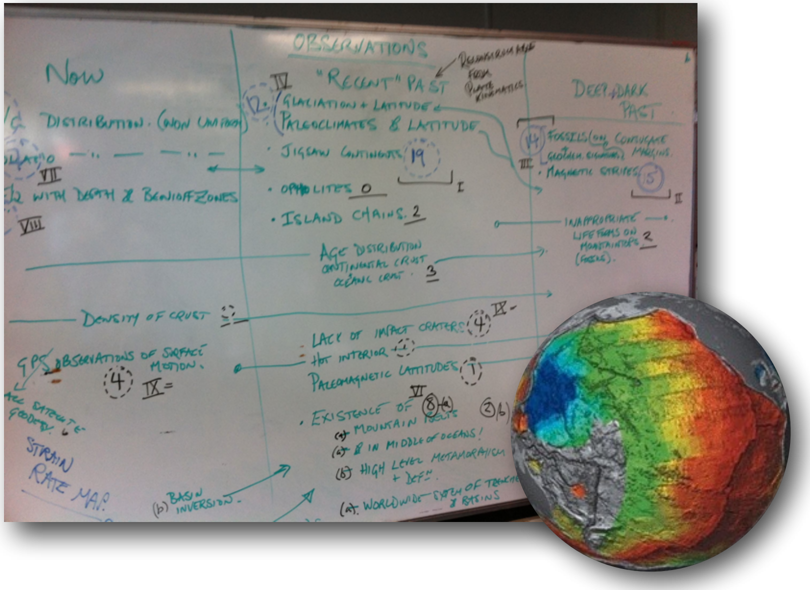
History of Plate Tectonics

Plate Tectonic theory is sometimes listed as one of the eight greatest scientific discoveries of all time.

- Of the eight it is also the most recently discovered (first presented in the late 1960's)
- The ***dynamics*** behind plate tectonics is also listed as one of the major unsolved scientific problems !

Today most geoscientists take plate tectonic theory for granted. To get there was in fact a 100 year scientific journey involving many different scientists and scientific disciplines.

In this lecture we will briefly go through this journey and look at some of the most influential observations and the people who made them.



What does Plate Tectonics mean?

The word "Tectonics" is derived from the Greek work "**Tekton**" — "**builder**".

There are many definition variations – here are a few.

- "Study of the deformation of the rocks that make up the Earth's crust and the forces that produce such deformation. It deals with the folding and faulting associated with mountain building; the large-scale, gradual, upward and downward movements of the crust; and sudden horizontal displacements along faults. Other phenomena studied include igneous processes and metamorphism".
- "Relating to, causing, or resulting from structural deformation of the Earth's crust".
- "Relating to the forces involved in plate tectonics or the structural features resulting from them".
- "Concerned generally with the structures within the crust of the Earth and particularly with the forces and movements that have operated in a region to create these structures"

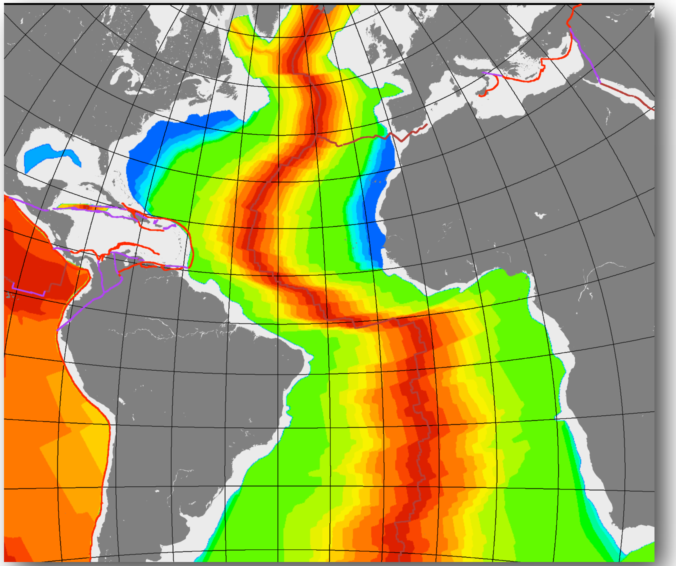


Plate Tectonic theory

- Represents the first theory that provides a unified explanation of the Earth's major surface features.

- Enables linking of many different aspects of geology that had been considered independent or unrelated.

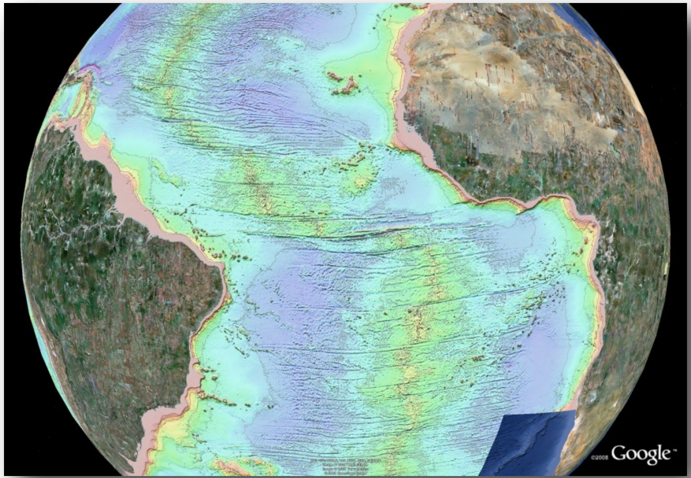
- Provides a framework in which to interpret geology.

  - (eg., past distribution of flora and fauna, the spatial relationship between volcanic rock suites at plate margins). Plate tectonic theory is the unifying THEORY of the Earth Sciences which describes

  - The large scale movements of the Earth's crust & mantle

  - The causes and consequences of these movements.

  - Secular changes in the behaviour of the Earth through geological time.

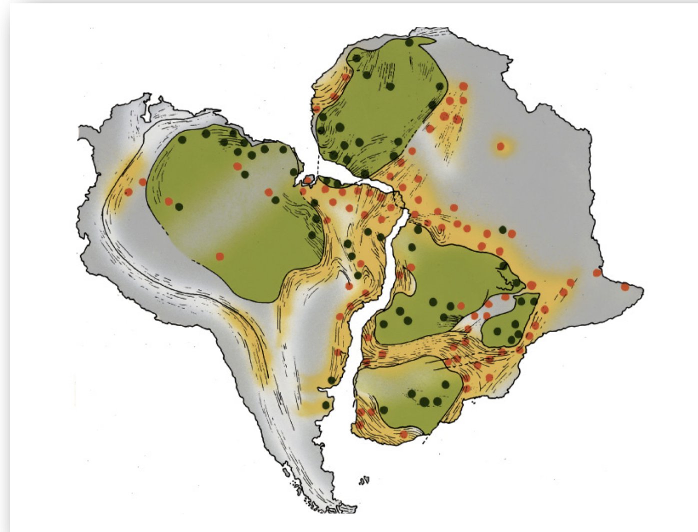


Pre-history of a theory

The theory of plate tectonics has largely been developed since 1967.

However, Early recognition of similarity in the geometry of coast lines of the western African continent & the east coast of the South American continent.

In 1858, American geographer Antonio Snider-Pellegrini made these two maps showing his version of how the American and African continents may once have fit together.



Uniformitarianism

In the 19th Century there was a gradual change to "uniformitarianism" or "actualism". Theory driven by British Geologists *James Hutton* & *Sir Charles Lyell*.

- "No powers are to be employed that are not natural to the globe, no action to be admitted of except those of which we know as principle, and no extraordinary events to be alleged in order to explain a common appearance".
- "The present is the key to the past"
- That is: the slow processes going on or beneath the Earth's surface have been going on through geological time and have shaped the surface record.

The question of the age of the Earth

We can date the formation of rocks accurately using the long timescale of radioactive decay to indicate the point at which parent and daughter isotopes became trapped into a crystalline form.

This technique was not available in the mid 19th century.

- Geologists and biologists favoured an old Earth to allow sufficient time for the slow processes of tectonics and evolution to play out [$\sim 10^9$ years]
- Biblical scholars favoured a younger Earth in keeping with the description of the creation in Genesis and the subsequent biblical tales leading up to the start of historical records.
- Lord Kelvin approached this from a quantitative, mathematical viewpoint: it should be possible to work out how old the Earth was by looking at how much it had cooled from its initial state.
  - This is the same idea as the "time of death" computation based on a dead body's temperature (measure the liver !)
  - Assuming that the Earth was initially molten, we would know the initial temperature quite well.
  - This gives a value of 40-100 million years

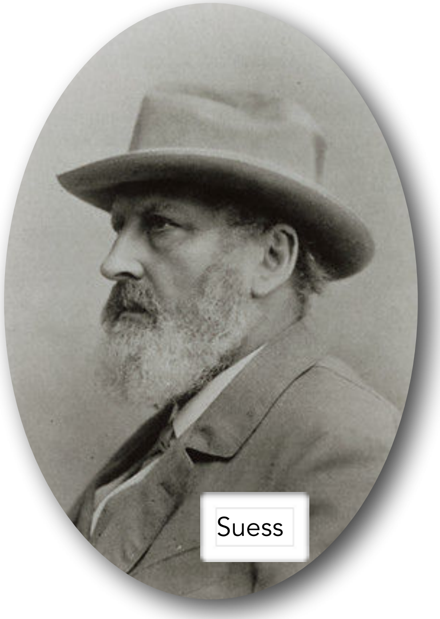
The contracting Earth

Attempts to develop global theories, and global structural patterns were particularly discussed in the early twentieth century.

The most famous of these studies was Eduard Suess's *Das Antlitz der Erde*.

A particular aspect of Suess's theory, based on mountain ranges and the patterns of coastlines was the idea of an Earth that had been contracting since its formation.

Suess rejected the idea that the present continents and oceans had existed from earliest times, believing that the Pacific Ocean was the oldest, possibly formed when the Moon separated from the Earth.

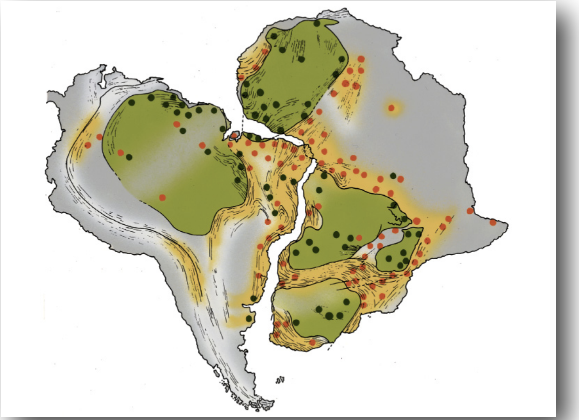


Portrait of Eduard Suess (1831- 1914), Austrian geologist whose theories about the changing face of the Earth foreshadowed the development of plate tectonics. Suess rose to prominence as the professor of geology at Vienna University. He mainly studied mountains, volcanic islands and deep-sea trenches. He proposed that there had once been a single supercontinent that had split up to form the present continents. **He named this supercontinent Gondwanaland after the Gonds, the supposed human inhabitants**. His most important book was Das Antlitz der Erde (The Face of the Earth) published during 1885-1909.

Continental Drift ?

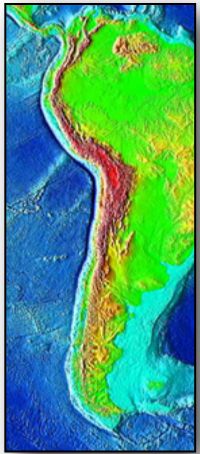
In 1910 the American physicist *F.B Taylor* considered that drift was taking place today and at least during the past 100-200 m.y.

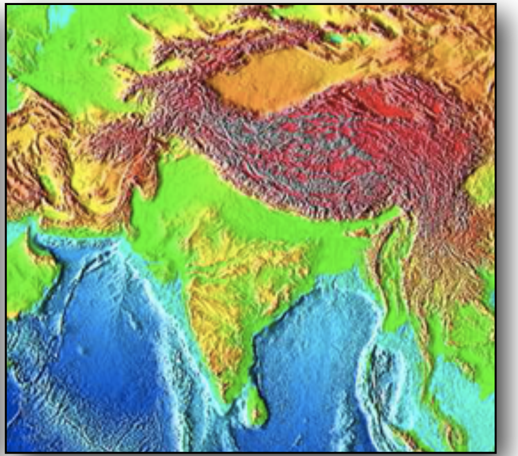
- UNIFORMITARIANISM



Drift could explain

- The geometrical and geological similarities of the edges of continents around the Atlantic & Indian Oceans.
- The formation of young fold Mountain belts at the leading edge of the continent.

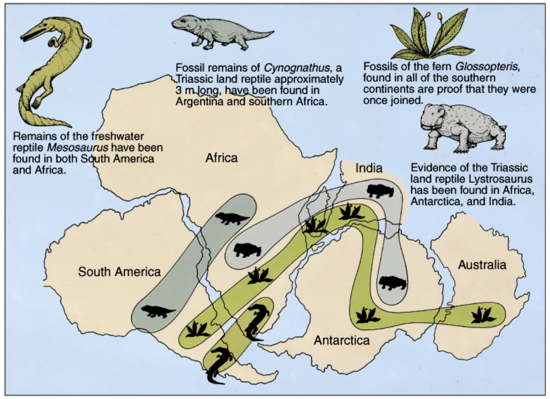


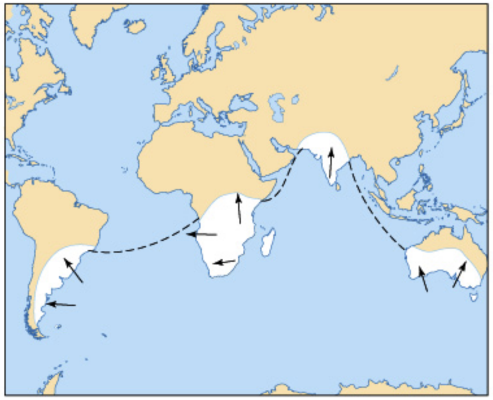


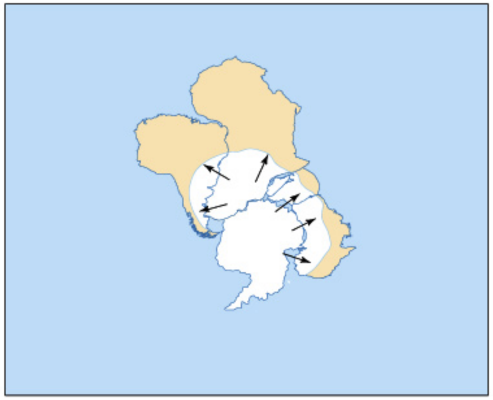
Continental Drift ?

In 1912 the German Astronomer and Meteorologist “Alfred Wegener” (1880-1930) noticed the jigsaw fit of many continents and proposed that the continents were once part of a single protocontinent which he called Pangaea (meaning "all lands").

- “The Origin of the Continents and the Oceans” 1915-1928.
  - Detailed much of the older, pre-drift, geological data and maintained that the continuity of older structures, formations & fossil fauna and flora was more readily understood on a pre-drift reconstruction.







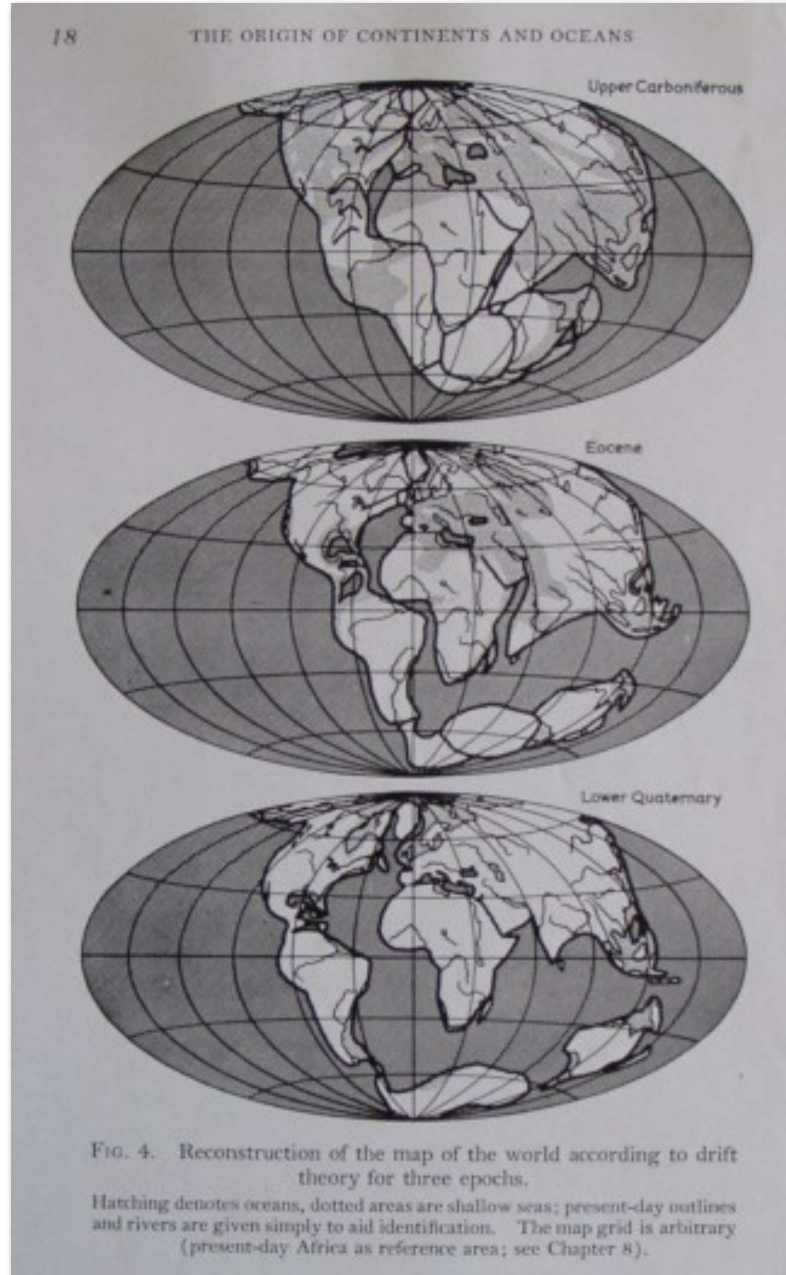
Palaeontological observation that the same fossilized plants and animals from the same time period were found in South America and Africa, in Europe and North America, and in Madagascar and India.

Recognised the presence of widespread glaciation during the Permo-Carboniferous which had affected large areas of the southern continents

North Europe and Greenland had experienced tropical climates.

Pangea to Present

Wegener



18 THE ORIGIN OF CONTINENTS AND OCEANS

FIG. 4. Reconstruction of the map of the world according to drift theory for three epochs.

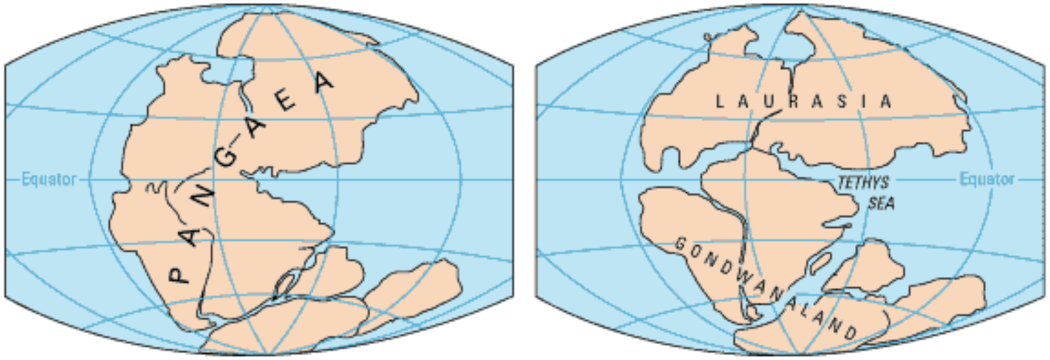
Hatching denotes oceans, dotted areas are shallow seas; present-day outlines and rivers are given simply to aid identification. The map grid is arbitrary (present-day Africa as reference area; see Chapter 8).

Pangaea

Wegener believed that Pangaea was intact until about 300 million years ago, when it began to break up and drift apart.

- The northern supercontinent is referred to as "Laurentia" and the southern supercontinent was called "Gondwana".
- Separating the continents were the Palaeo-Tethys ocean (Greek for Goddess of the sea) and the Palaeo-Pacific ocean called "Panthalassa" (all-ocean).

- "Preposterous"
- "Antiquated"
- "Serious Error"
- "Footloose"
- "Dangerous"
- "A fairy tale"
- "A very dangerous idea, and liable to lead to serious error."



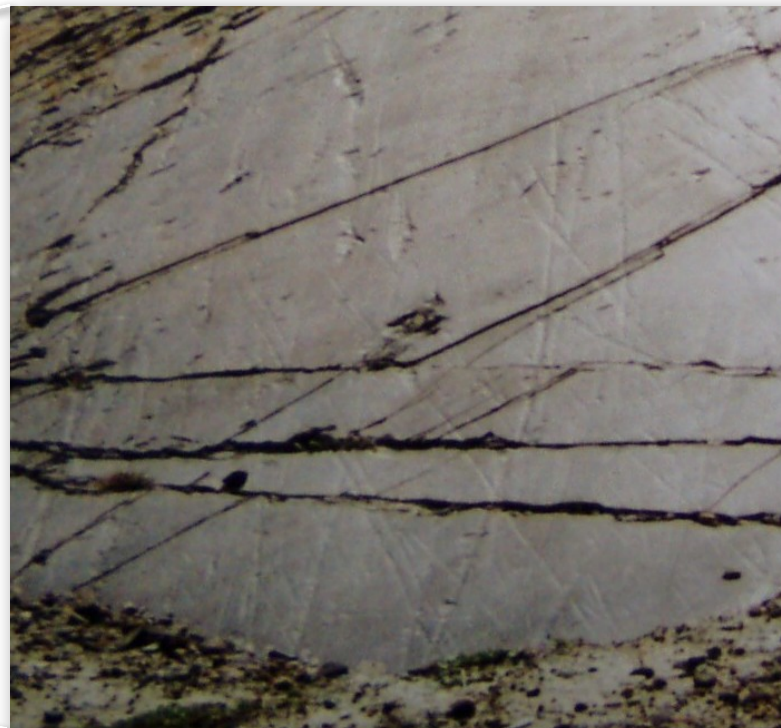
PERMIAN
225 million years ago

TRIASSIC
200 million years ago

Lacked a geological mechanism to explain how the continents could drift across the earths surface.

Served as the catalyst and framework for the development of the theory of *plate tectonics*.

Gondwana Glaciation



Permian striated glacial pavement, Marino Rocks, South Australia

Convection

Wegener was initially unaware that a solution for the Alpine deformations had been suggested by *Otto Ampferer* in 1906 — the action of massive convection undercurrents within the upper mantle causing what Ampferer called 'subduction'.

In 1925 Ampferer told Wegener that these currents must be contributing factors in the mechanism of continental drift.

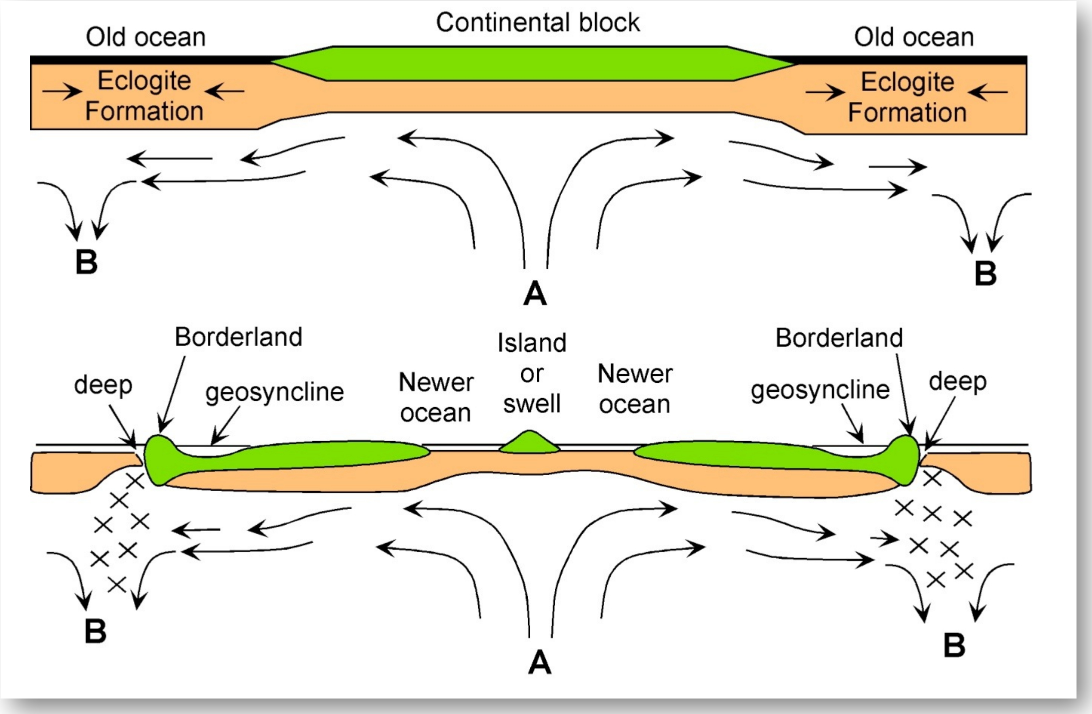
Arthur Holmes, in 1928, explained how massive slow-moving convection currents could operate within the upper mantle

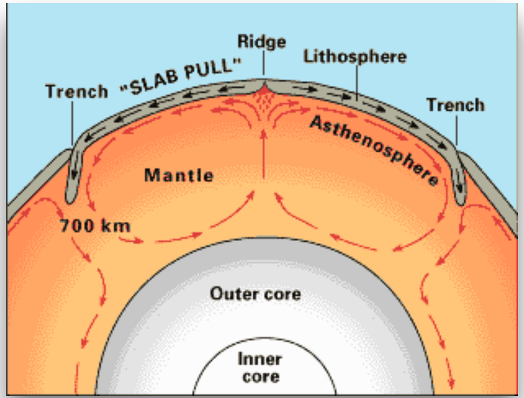
Ampferer

Holmes

Convection & Drift

Holmes suggested that continents were moved by convection currents powered by the heat of radioactive decay.





1931 - concept of thermal convection in the mantle

- Driving force for continents?
- Concept that continents are carried by larger pieces of crust.

Oceanic crust was considered to be a thick continuation of the continental basaltic layer.

Currents ascended at A & spread laterally causing the continent to go into tension & split it.

The formation of eclogite at B where currents meet & descend making space for the continents to advance

Drift down South

Some European geologists supported Wegener's idea
but they were rejected out-of-hand by the majority of
North American geologists.

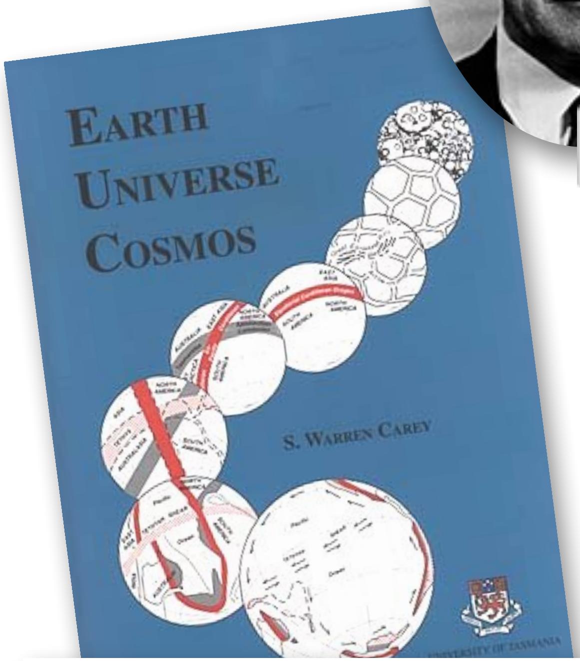
Southern-hemisphere geologists (e.g., Alexander du Toit)
accumulated evidence from Late Palaeozoic glaciations,
Permian coals, and Mesozoic continental successions
in the southern continents (and India) to substantiate
Wegener's views.

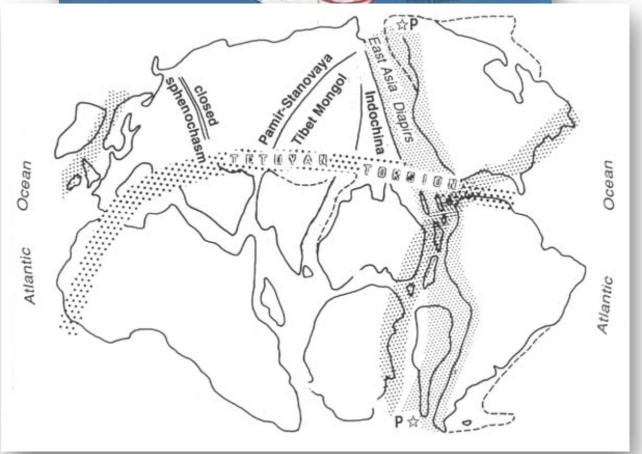
The idea of continental drift was kept alive into the 1950s
by the South African Lester King and the Australian
Sam Carey, who were not in the mainstream.

Carey's symposium on continental drift, held in
Tasmania in 1958, attracted considerable attention

Carey later advocated expanding Earth theory


Carey





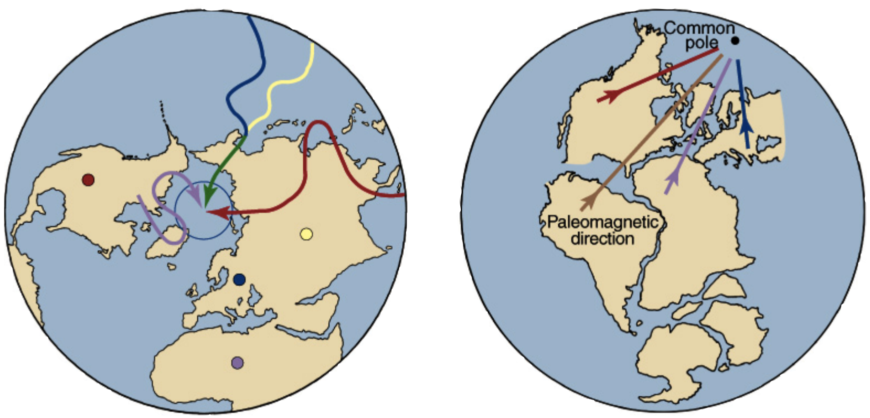
Paleomagnetism

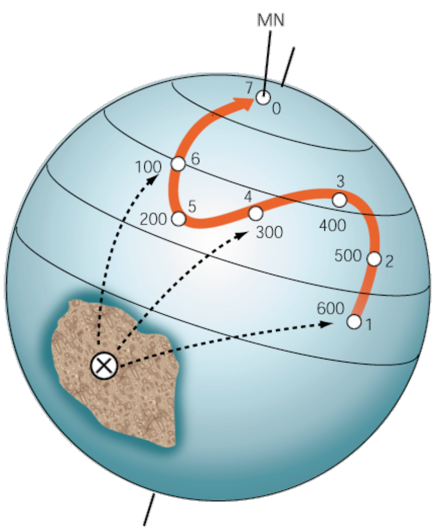

Brunhes

The discovery that some minerals can become magnetized parallel to the Earth's magneti
in the nineteenth century.

Early in the twentieth century, Bernard Brunhes made the startling discovery that some rocks are magnetized in the opposite orientation to the Earth's present-day magnetic field:

The Earth's magnetic field had reversed its polarity in the past.



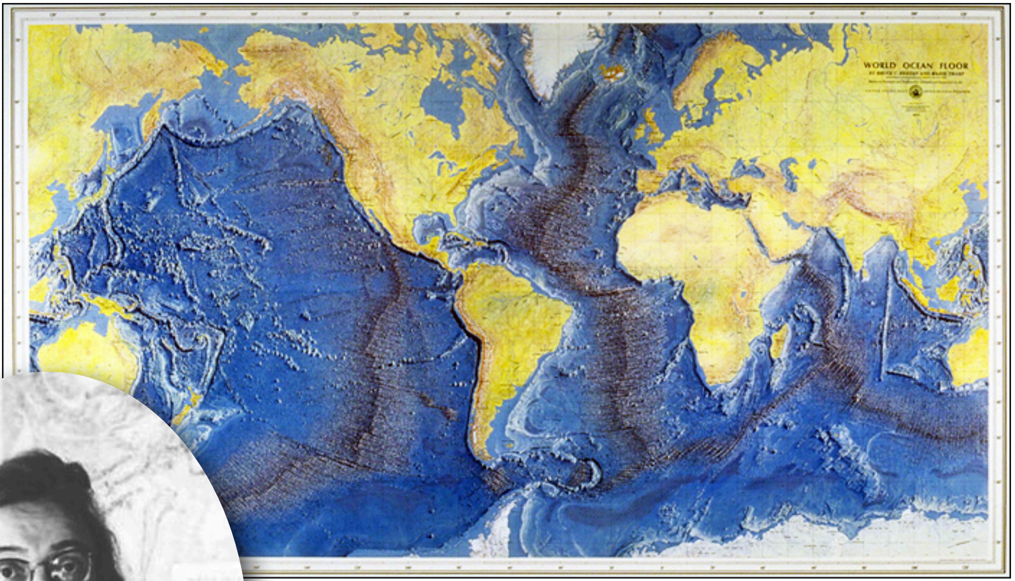


Focussed on the continents; little was known about the ocean floor.

The discovery of Palaeomagnetic methods in the 1950's coupled with newly developed radiometric dating techniques was a major step forward.

Showed that the continents had been moving around ***independently*** *since the Mesozoic.*

Clues from the Atlantic Ocean



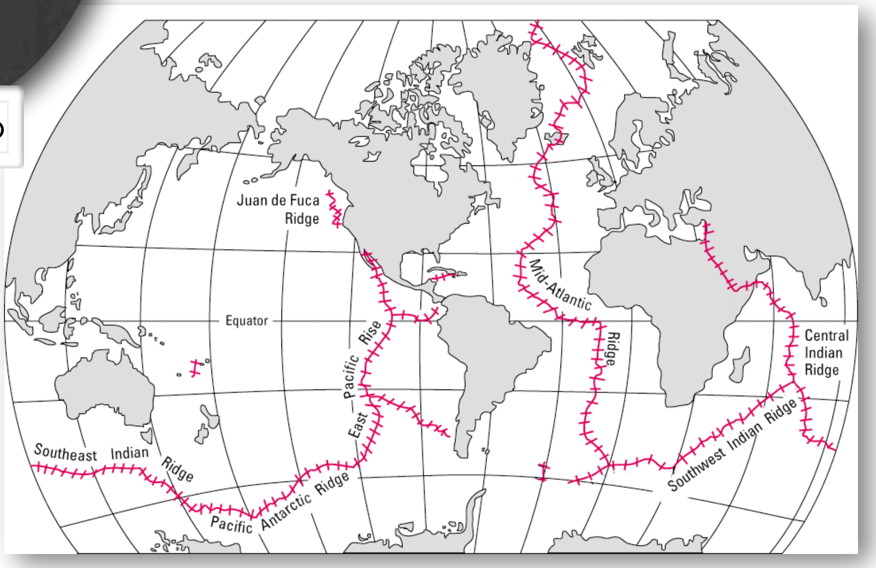
Lamont ships produced detailed topographic charts of the mid-Atlantic Ridge and its linkage to what would prove to be a Great Global Rift defined by a submarine mountain ranges nearly 60 000 km long, 1–3000 km wide at the base, and 2 km high, with peaks rising to 4 km above the ocean floor.

The rift was reported in 1956 by Maurice Ewing and Bruce Heezen.

Tharp

Heezen and Marie Tharp published ‘physiographic diagrams’ showing how the ocean floors would look with the waters drained away (1960’s).

Then in 1960 and 1961, Hess and Dietz independently but simultaneously, proposed hypotheses that addressed global dynamics in terms of moving seafloor driven by convection in the mantle.



Harry Hess - 1960 -1962 an essay in 'geopoetry'.


Hess

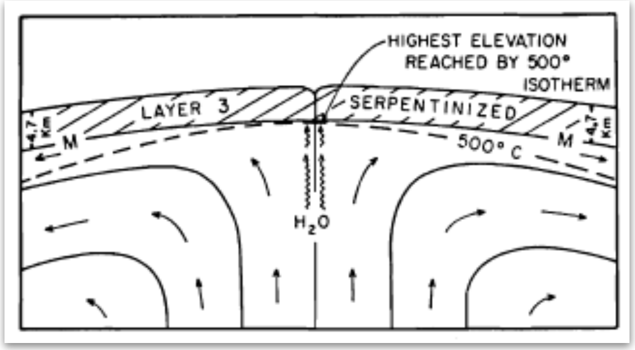

Dietz

Described the ocean floors as the exposed surface of the mantle.

Large-scale convection cells in the mantle create new ocean floor at the ridges, where the rising limbs diverge and move to either side until they cool and plunge down into the mantle at the trenches (& no expansion of the Earth !).

Hess suggested that granite is too buoyant to sink into the mantle, some fragments of continents have survived since the beginning of geologic time

Ocean floors are recycled and replaced by new mantle material every 300–400 my.



Almost simultaneously and independently the term "**sea floor spreading**" was coined by Dietz (1961).

Dietz proposed that mantle was moving at a rate of a few cm/yr and was capable of producing the overall structure of the oceans.

Ocean crust mantle derived.

Argued the importance of the relative strength of the Earth's outermost layer.

The terms lithosphere and asthenosphere were popularized.

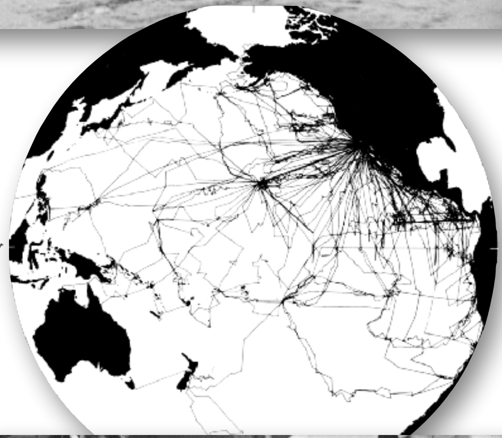
Clues from the Pacific ocean

The geology of the ocean basins, which occupy more than 60% of the Earth's surface, remained largely unknown until after World War II.

Significant US Naval funding led to a concerted effort of ocean floor scientific exploration.

Some early discoveries included:

- The oceanic crust contained three layers:
  - Sediment (260m).
  - Consolidated sediments or volcanics or both (1-2 km).
  - Bedrock with a relatively uniform thickness of 4.5 km.
- Unexpected topography (~30%).
- Elevated heat flow (~10% greater than granite and the continents).
- Corals that were less than 100 m.y.
- Faults on the ocean floor



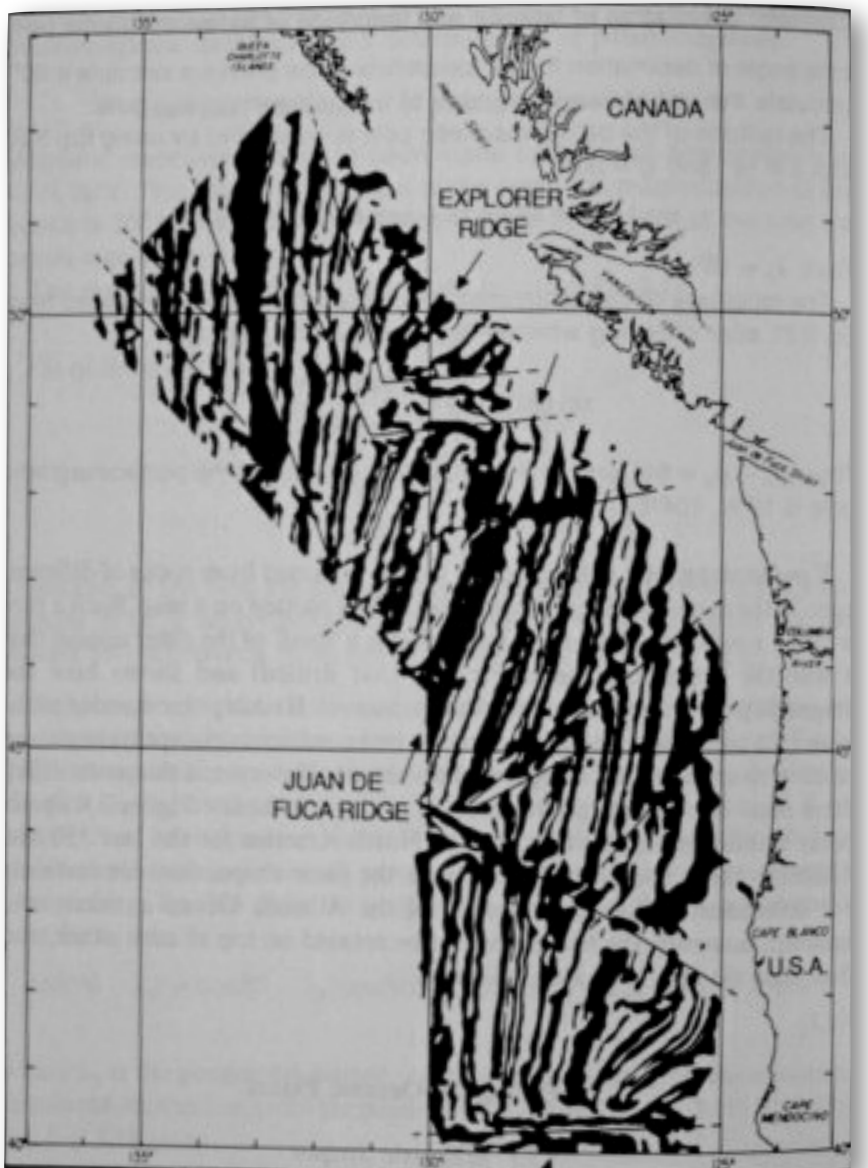
Convincing the skeptics — Helped by the Cold War

Bathymetry:

- seafloor mountain ranges
- rift valleys
- seamounts

Magnetics:

- stripes! (1% variations)
- symmetric about ridge



after Raff & Mason 1961

Magnetic stripes

In 1966 The symmetry of magnetic stripes was demonstrated across mid ocean ridges

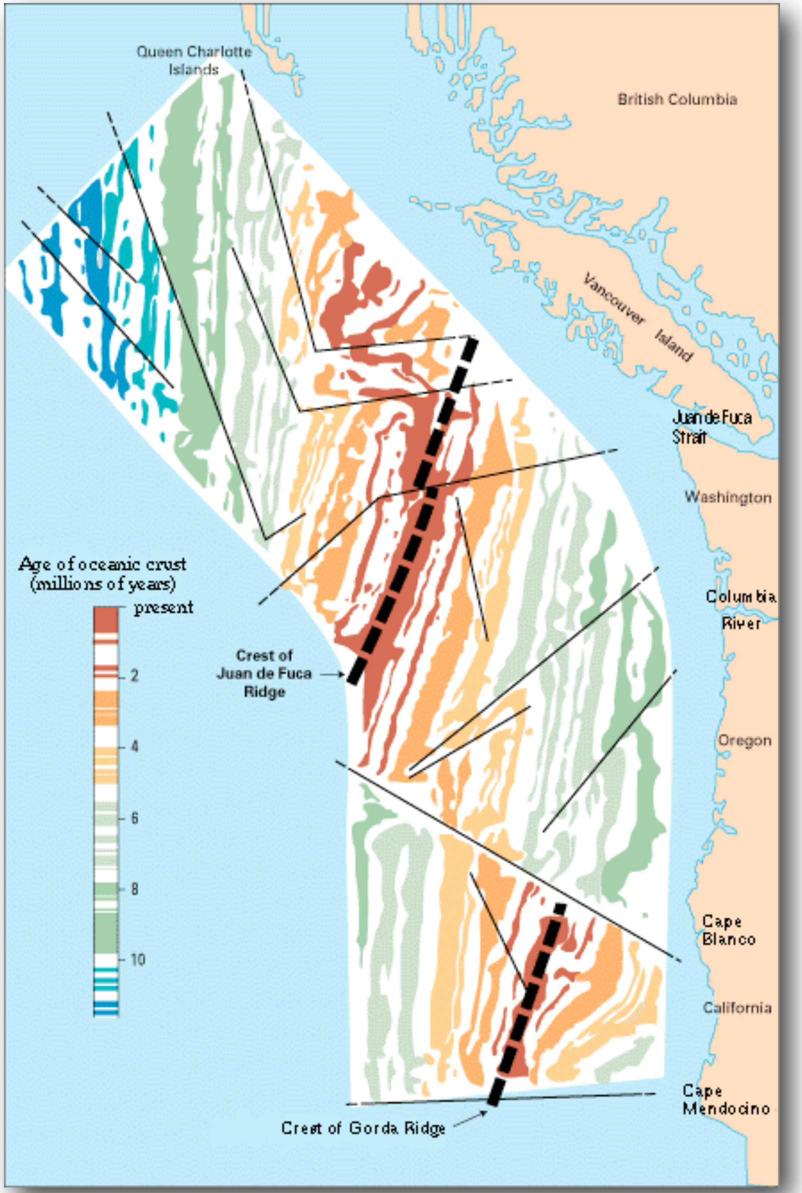
Aeromagnetic survey across Iceland (aeromagnetic survey)

Pacific-Antarctic ridge (ship based survey)

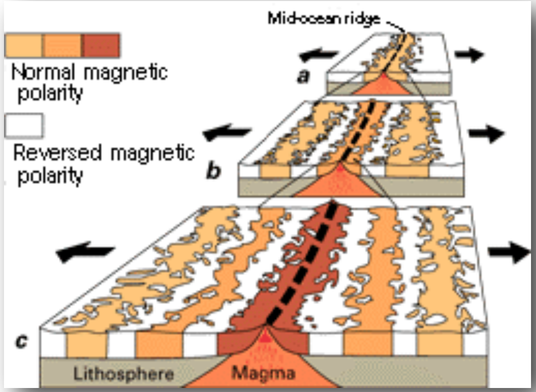
- Allowed for a calculation of the rate of spreading using dated magnetic epochs.
- Extended magnetic reversal back to 10Ma

1961: ocean floor magnetic stripes published (*Mason and Raff*)

- Contrasting intensities might reflect structural ridges and troughs or a system of sub-parallel dykes
- Subsequent topographical and gravity surveys failed to detect either one
- *Morley* made the link between the stripes and sea-floor spreading and proposed that the stripes record a N- and S-polarity.
- Manuscript rejected by Nature and the Journal of Geophysical research.
- “such speculation was more appropriate to cocktail party chatter”



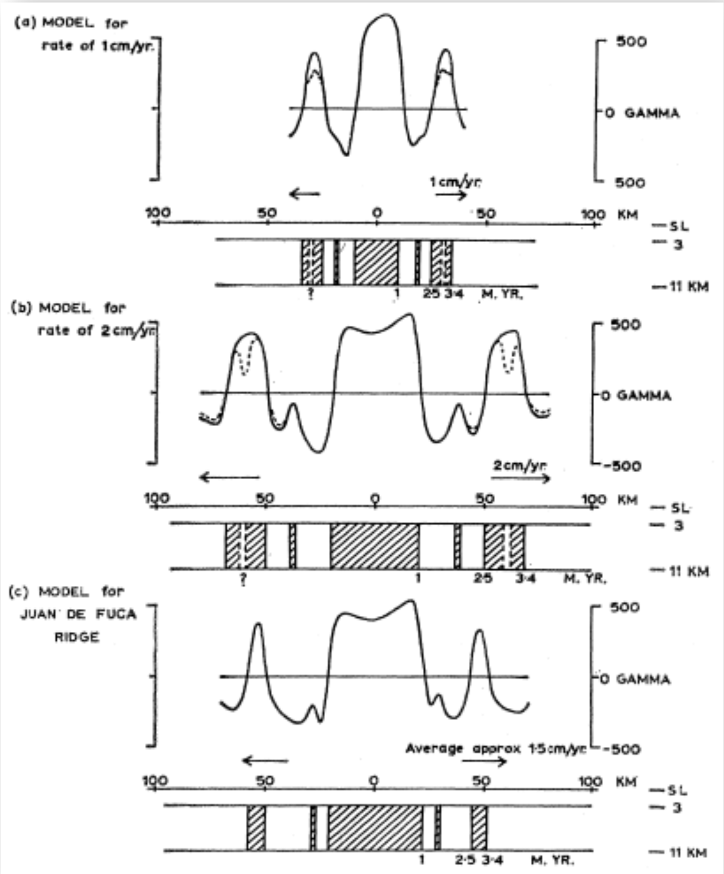
Magnetic stripes



In 1963 *Vine and Matthews* published "Magnetic anomalies over ocean ridges".

Assumed mantle convection, sea-floor spreading, and magnetic polarity changes.

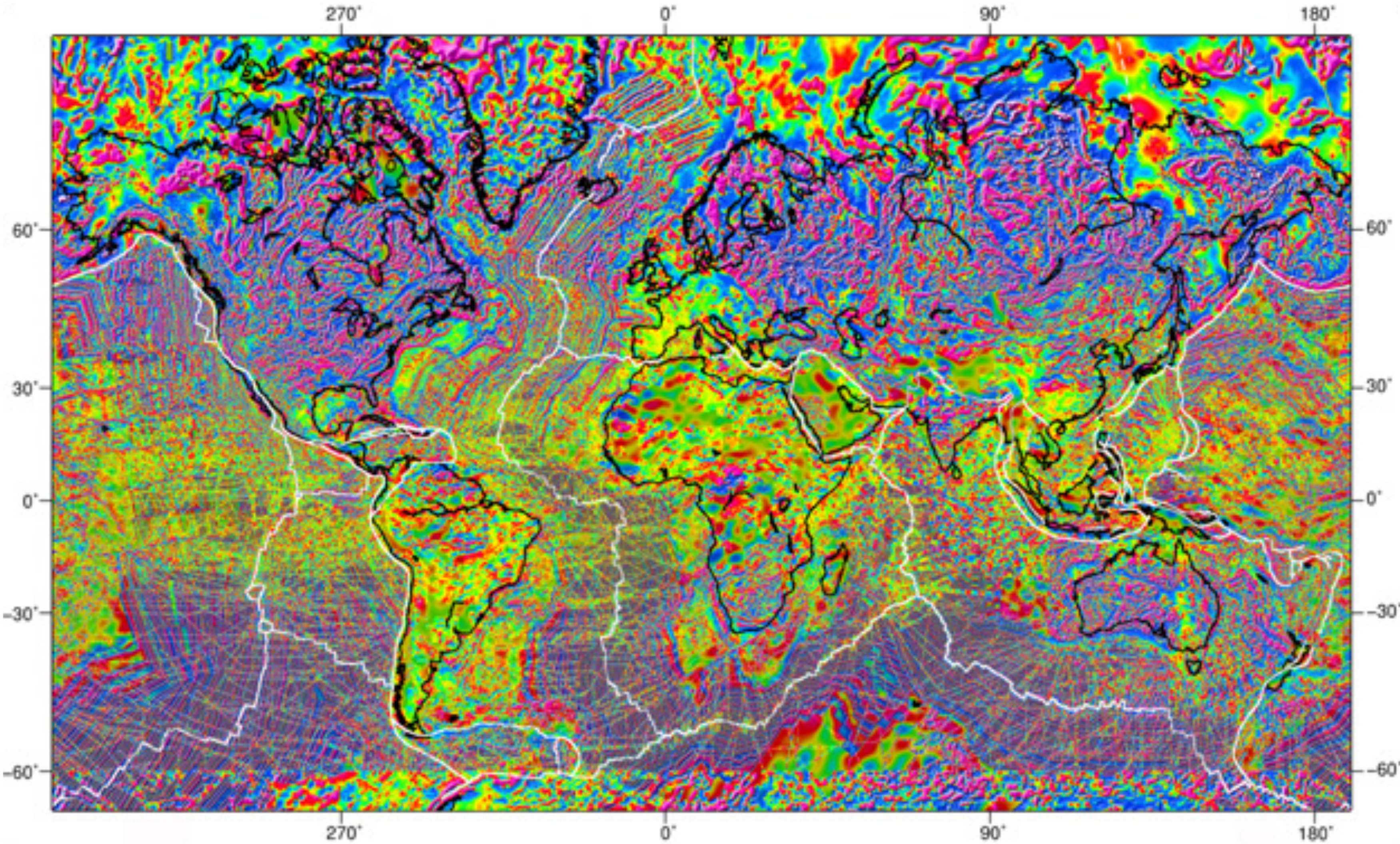
- FOUNDING PAPER OF PLATE TECTONICS
- Poorly received and largely ignored for 3 years.



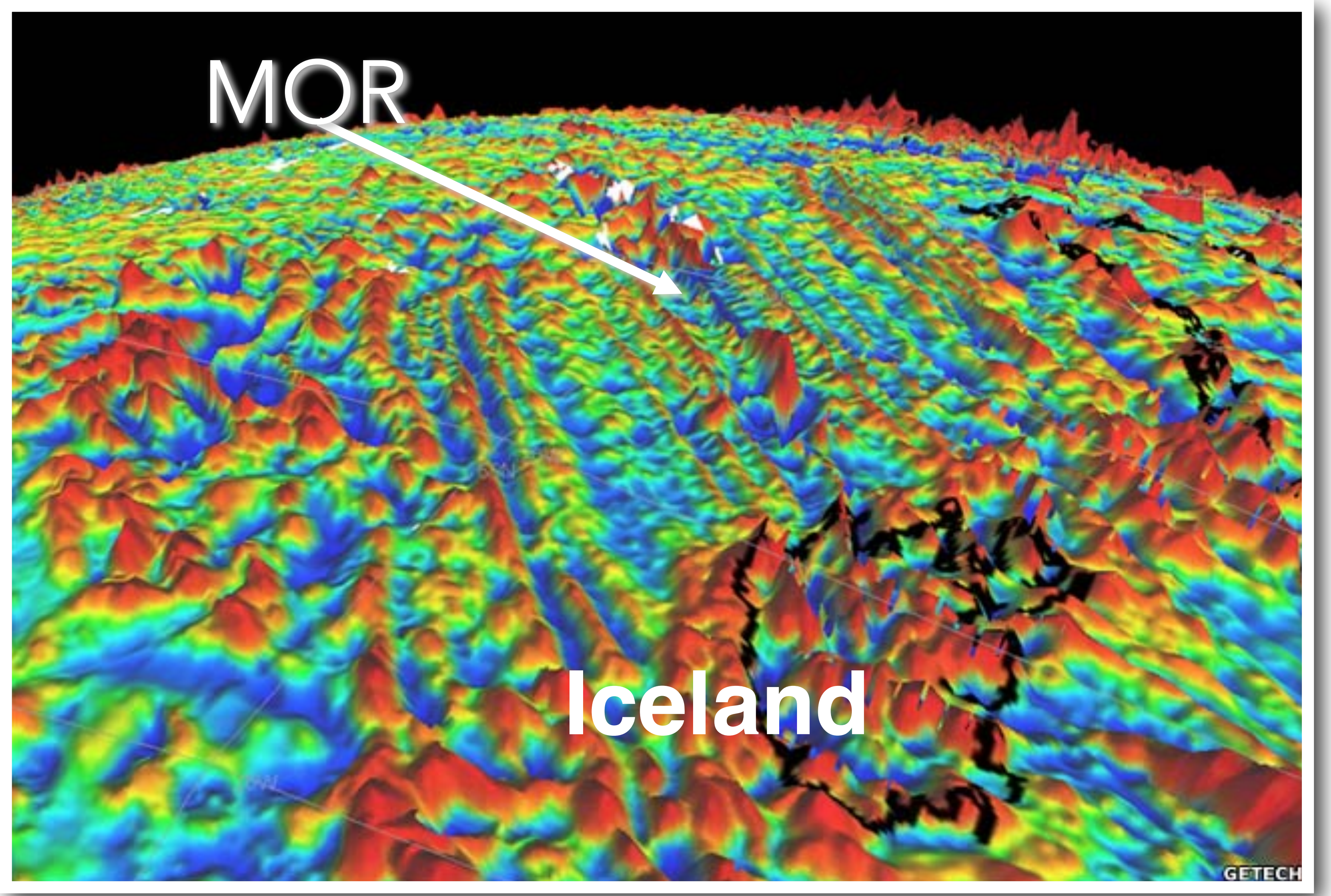
In 1964, K-Ar dating of basaltic rocks allowed for temporal constraints of the magnetic stripes – several reversals in the past 3.5 million years (Cox et al., USGS).

A few weeks later a paper titled "Dating Polarity Geomagnetic Reversals" by Ian McDougal and Donald Tarling was published in Nature (Australian National University)

Magnetism and the Oceans



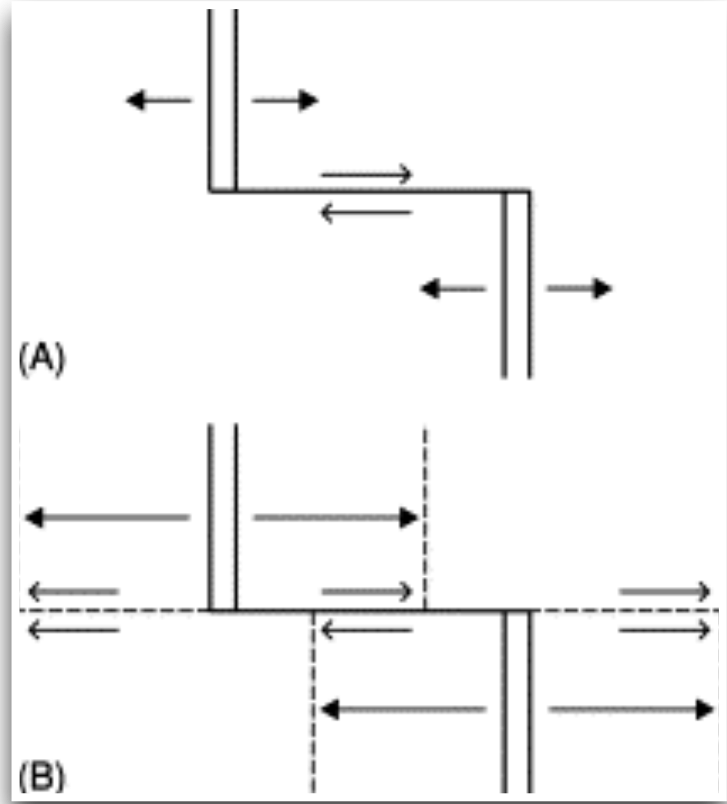
Magnetism and the Oceans



Transform Faults

In 1965 Tuzo Wilson published a paper defining "transform faults" as a test for sea-floor spreading.

- Linking with MOR's, island arcs, mountain chains, and trenches.
- Offset MOR and San Andreas Fault
- Relative motions defined.

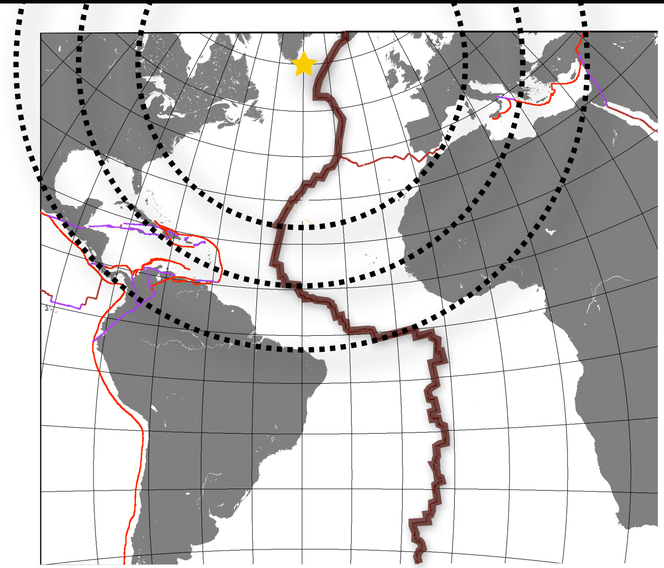


Alan Coode had much earlier sent a short note illustrated with a block diagram of ridge segments connected by a transform fault (he gave no new name to it) to the Canadian Journal of Earth Sciences.

Coode's article was published, to little notice, a week or two after Wilson's paper appeared in Nature.

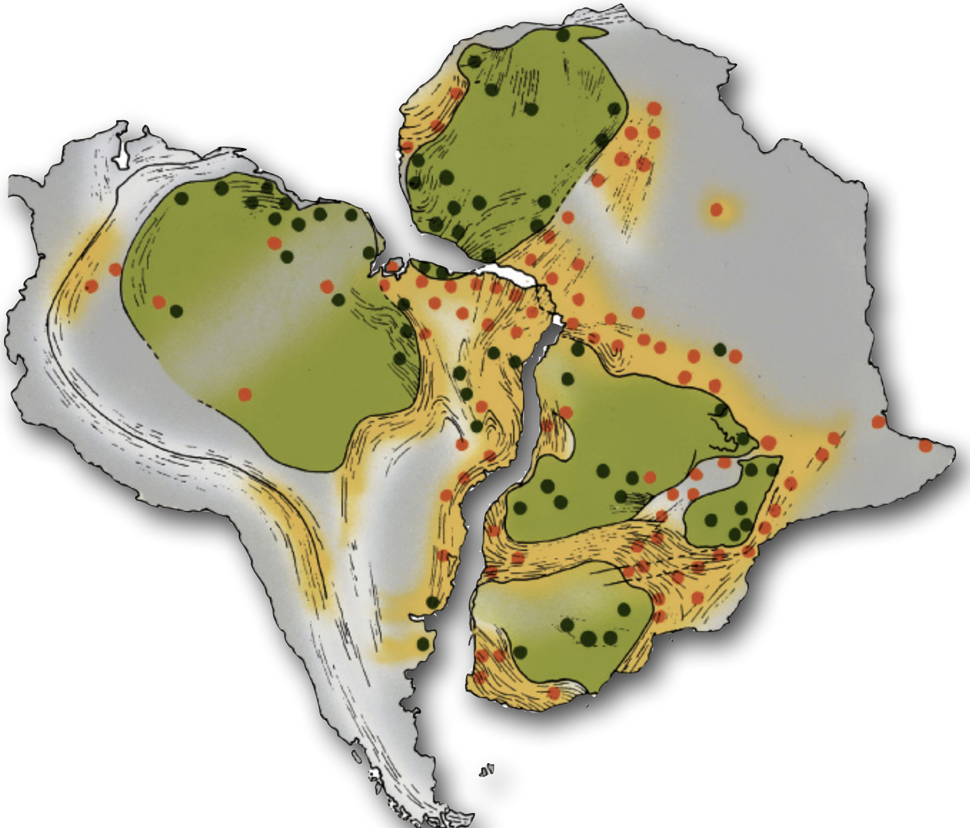
Continental drift

In 1964 Edward Bullard showed that Euler's theorem could be applied to find the best fit across the continents.

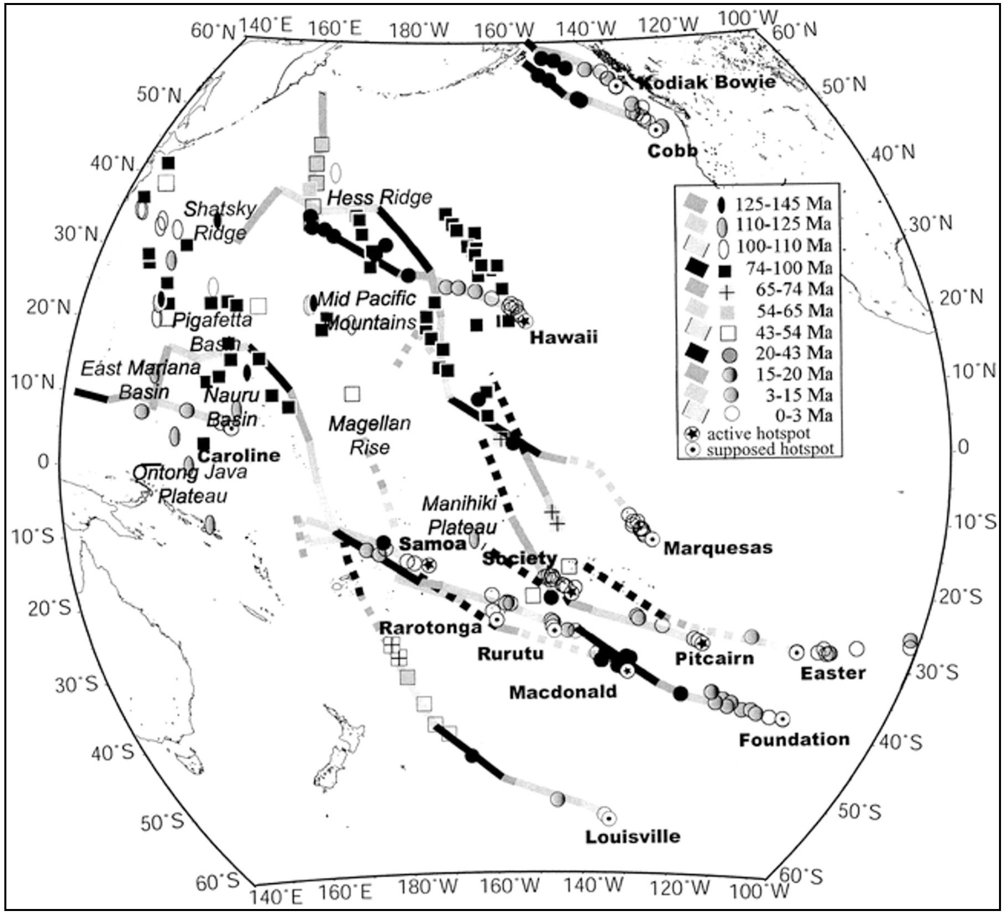


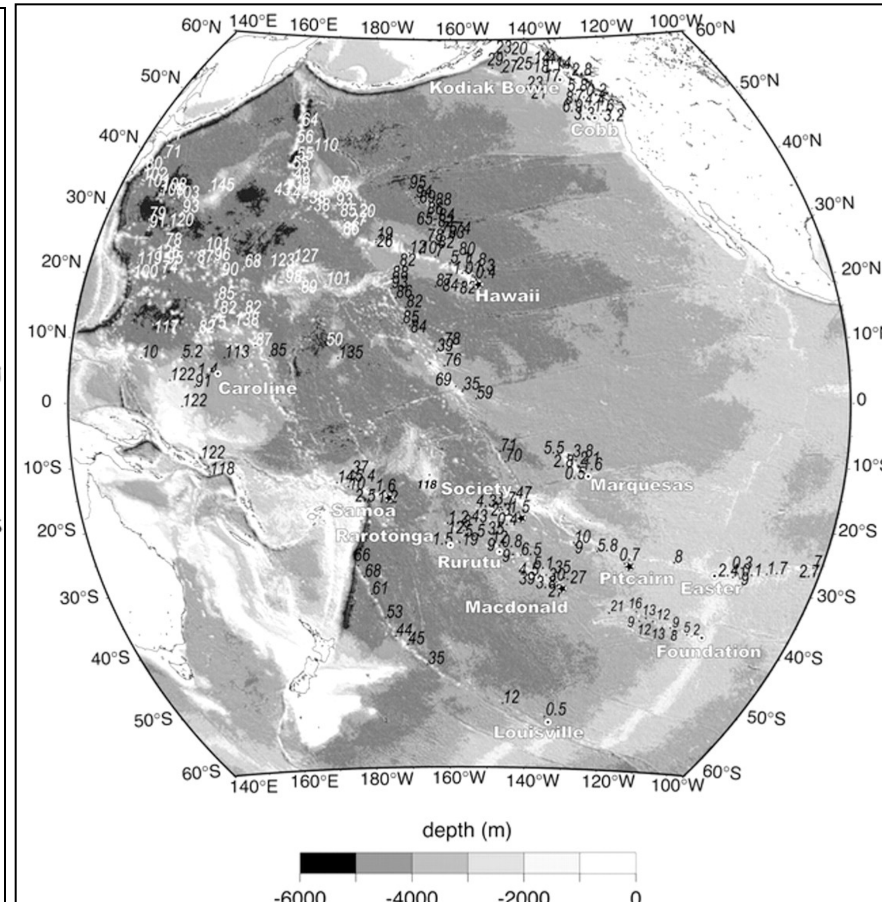
This observation inspired Patrick Hurley at MIT to sample rocks in both Brazil and Ghana and radiometrically date them.

- The results showed an excellent match.
- Enough to persuade American Geologists of continental drift.



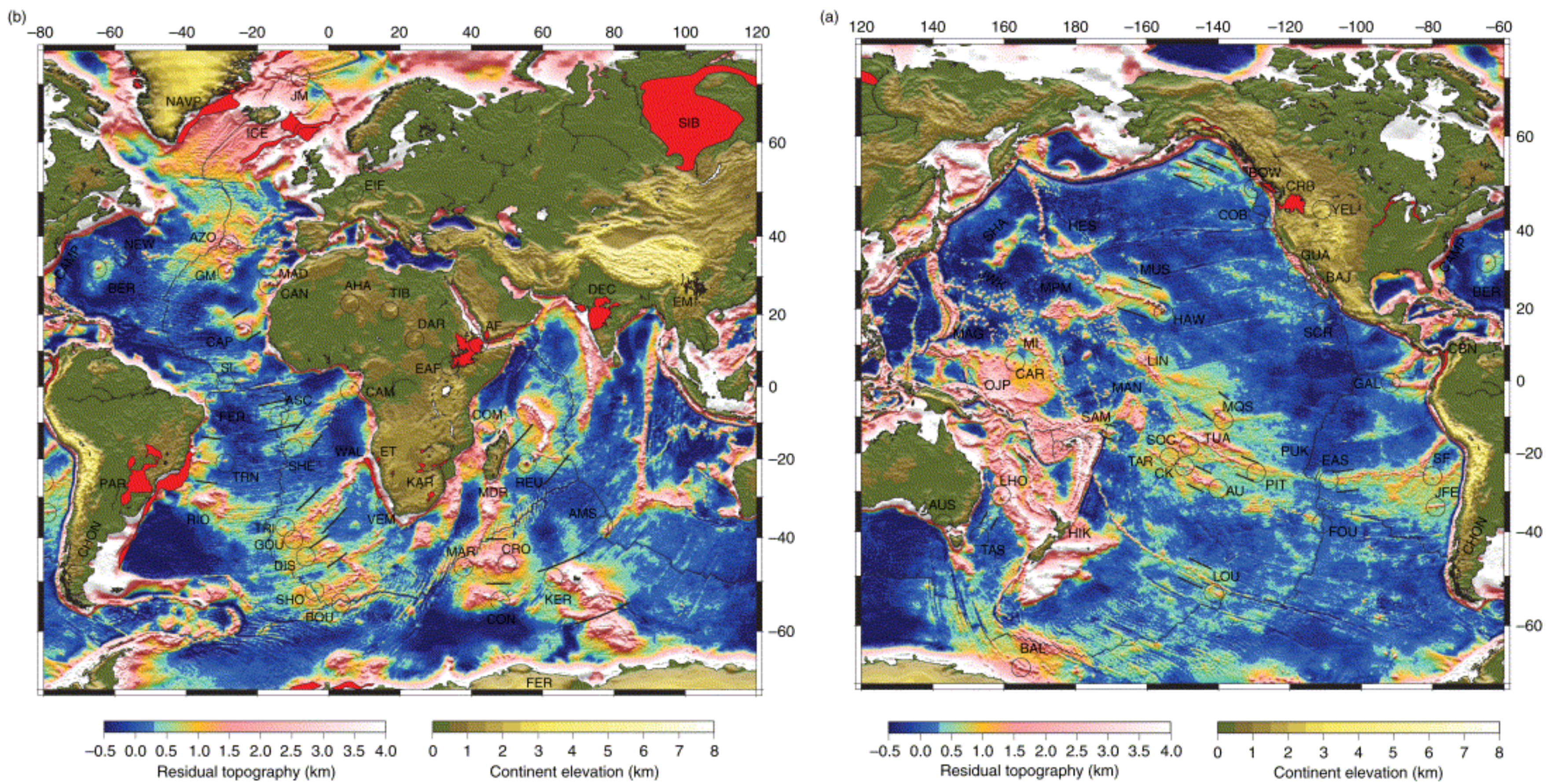
Continental Drift — Hotspots





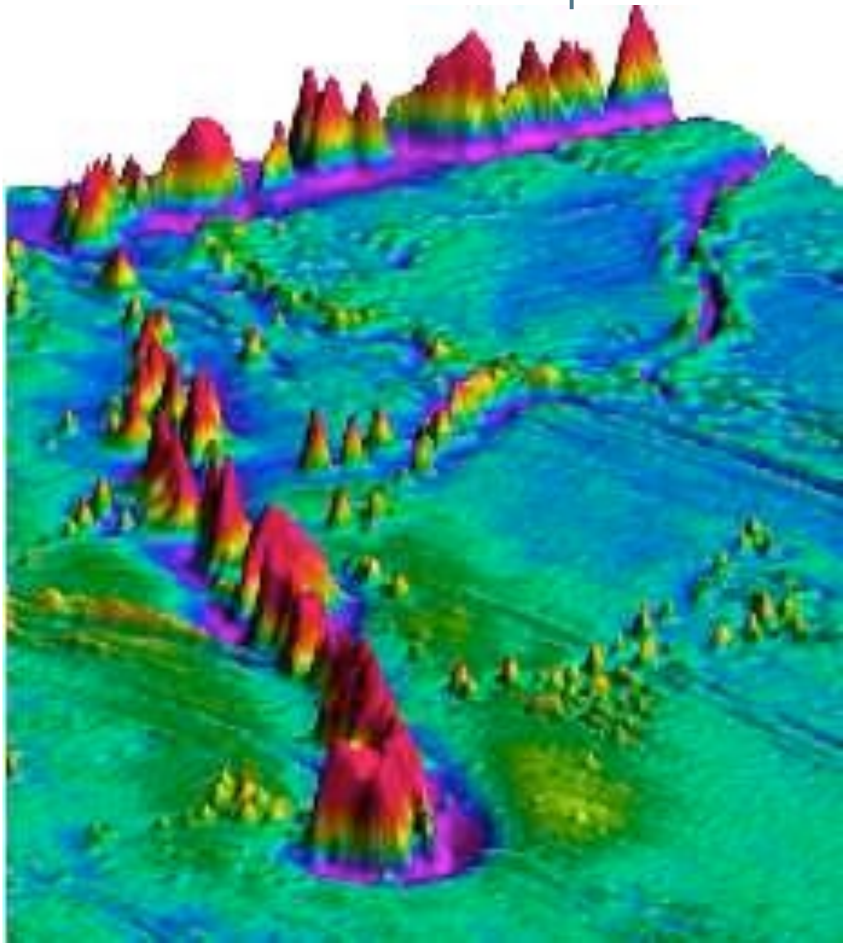
Clouard V, Bonneville A Geology 2001;29:695-698

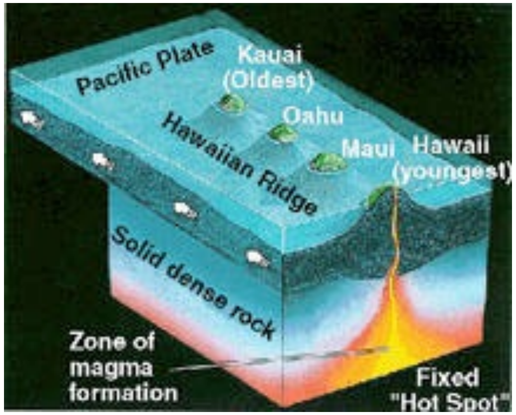
Continental Drift — Hotspots

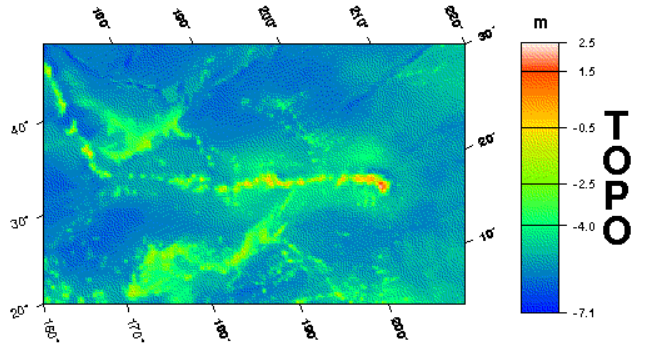


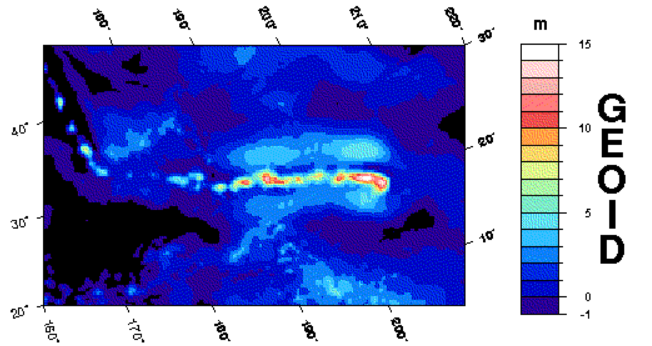
Treatise in Geophysics

Continental Drift — Hotspots









Hotspots — volcanic regions in the middle of plates which leave scars as the plate moves overhead

Plates

Wilson (1965) – division of earth into plates and importance of fracture zones for plate motion

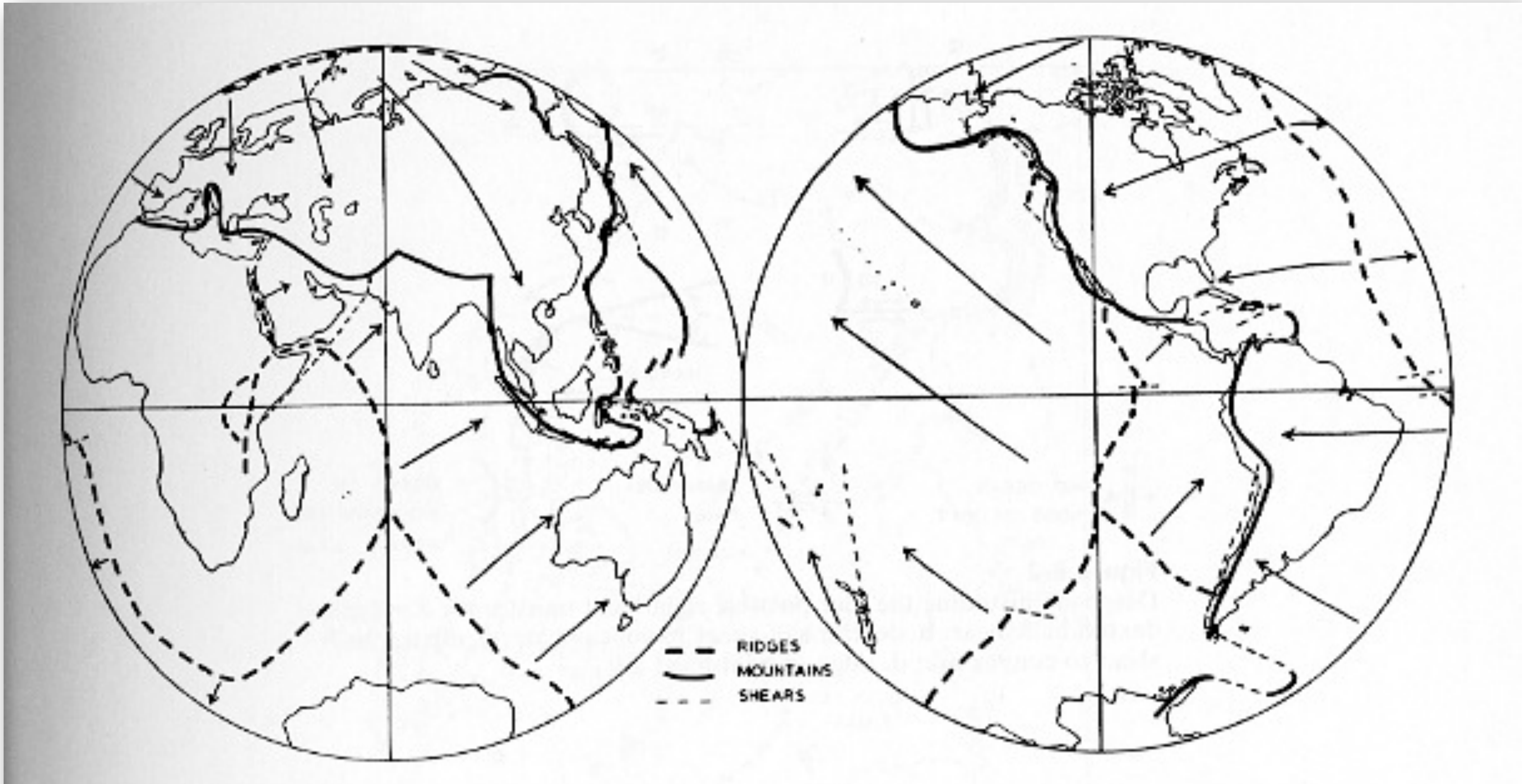


Figure 6-1

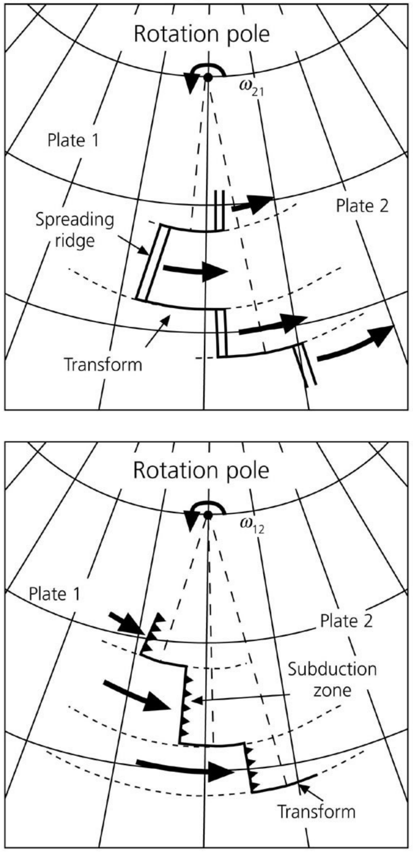
Plate Tectonics 1967-1968

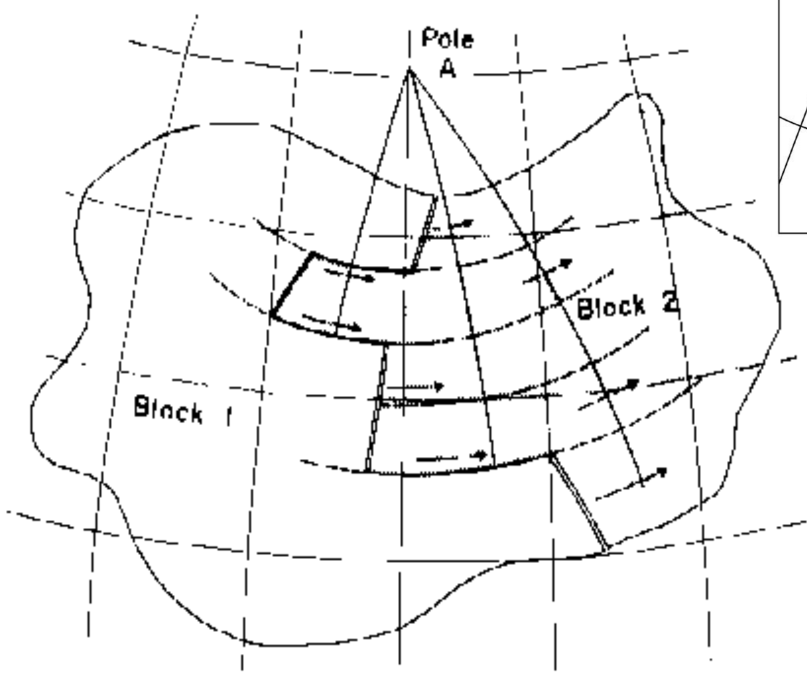
Four milestone papers reflect the emergence of Plate tectonic theory.

1) The North Pacific: An example of Tectonics on a Sphere by Dan MacKenzie and David Parker.

- This paper applied the concept of transform faults to motions on a sphere.
- Slip vectors must be applied to small circles around Euler poles.
- Used fault plane solutions to work out slip directions and the results conformed with prediction of sea-floor spreading.

Figure 5.2-2: Relationship between plate boundaries and the Eurer pole.





The remaining three papers appeared during early 1968.

2) Jason Morgan's paper entitled "Rises , Trenches, Great Faults and Crustal Blocks" JGR: divided the surface of the Earth into rigid blocks each with three types of boundaries:

- Trenches (where crust is created)
- Trenches and Mountain Ranges (where crust is destroyed)
- Great Faults.

Development of the idea of a rigid and strong tectosphere that slides above the asthenosphere.

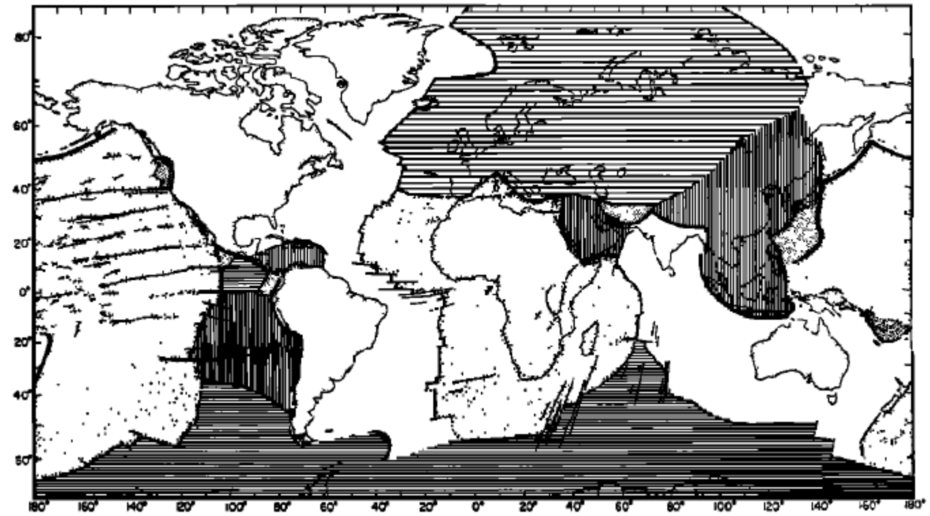
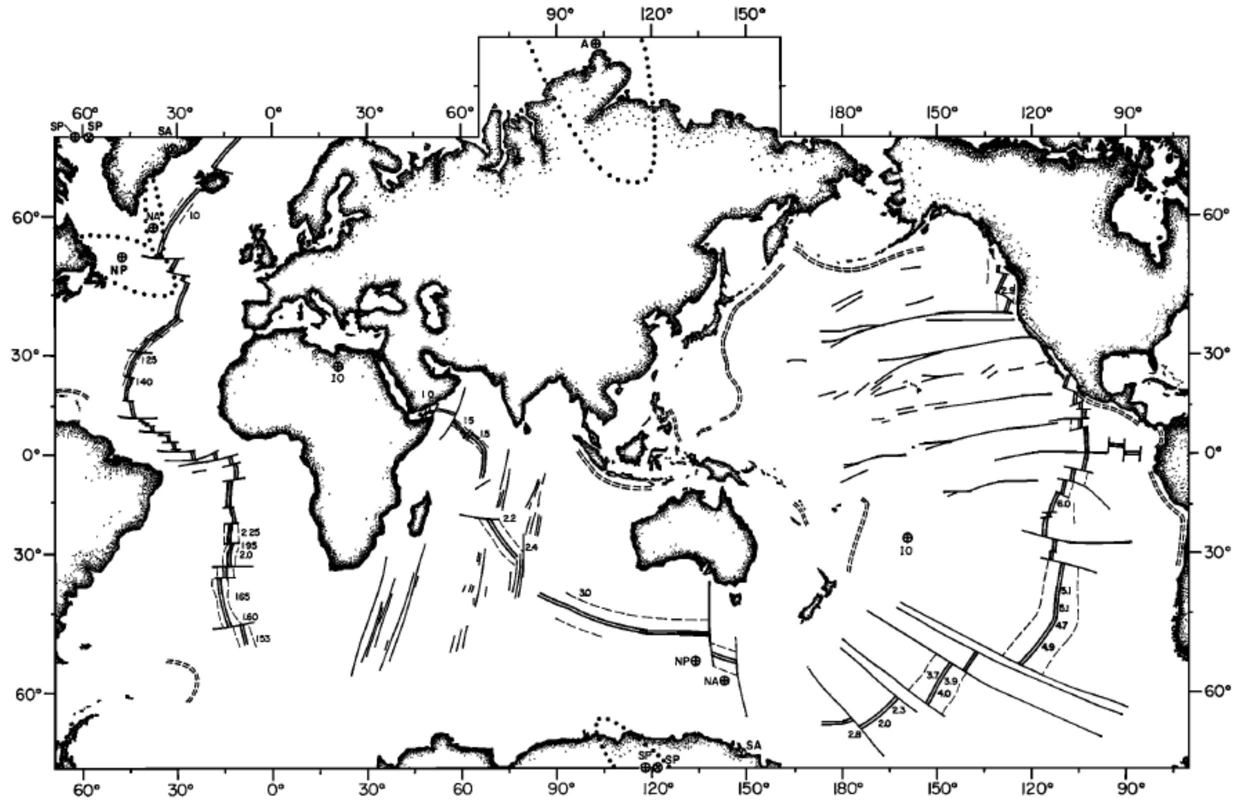


Fig. 1. The crust is divided into units that move as rigid blocks. The boundaries between blocks are rises, trenches (or young fold mountains), and faults. The boundaries drawn in Asia are tentative, and additional sub-blocks may be required. (Figure is based on *Sykes*'s [1968*b*] map of the ridge system with additional features from *Heezen and Tharp*'s [1965] tectonic map.)

Plate Tectonics 1967-1968

3) Xavier LePichon published an article entitled 'Sea floor spreading and Continental drift'.

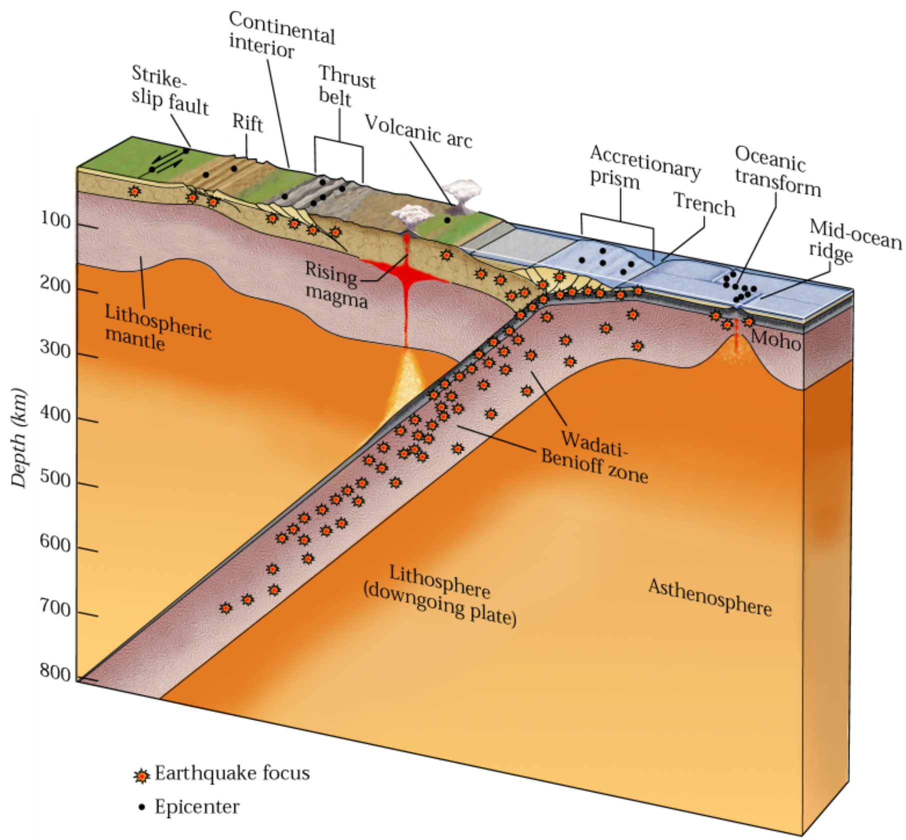
- Analysed slip vectors of 6 large blocks and recognised that the results had a reasonable match with the globes physiography, seismic and geological data.
- Extended to the past 65 m.y. looking for continental drift patterns.
- 3 cycles of spreading recognised



Benioff Zone

Bryan Isacks, and Lynn Sykes examined earthquake activity in a trench near Tonga - 1964

- They collected seismic data of earthquake activity and observed, as had Benioff and Wadati, that the earthquake foci outlined a plane tilting down from the ocean floor at about 45 degrees.
- Geoscientists at Lamont were the first to recognize that this plane was a slab of descending material cool and hard enough to sustain earthquakes
- The slab-containing the seafloor itself was being bent down into the trench, creating the earthquake zone.

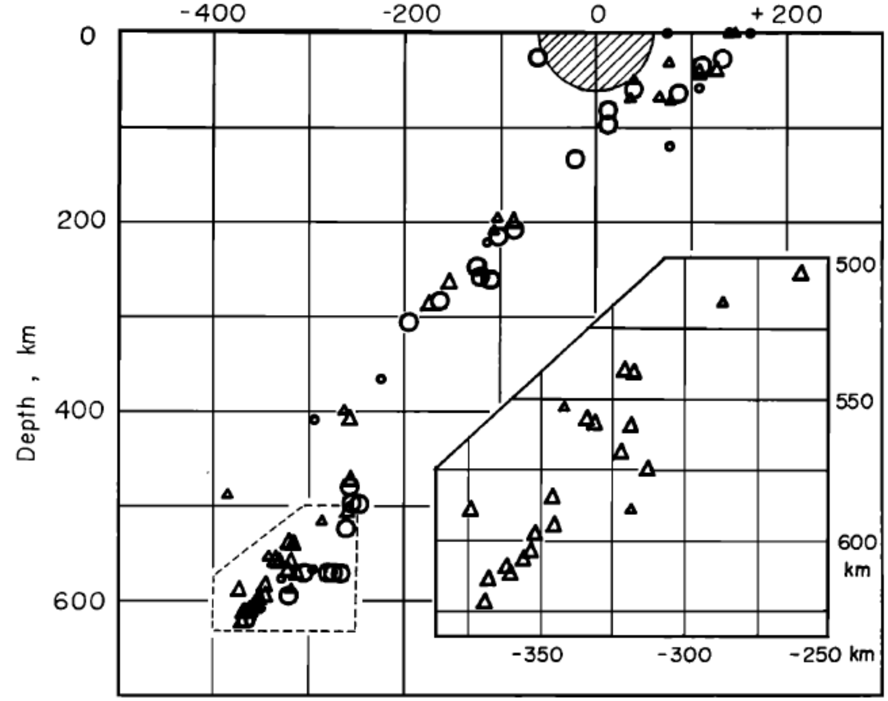


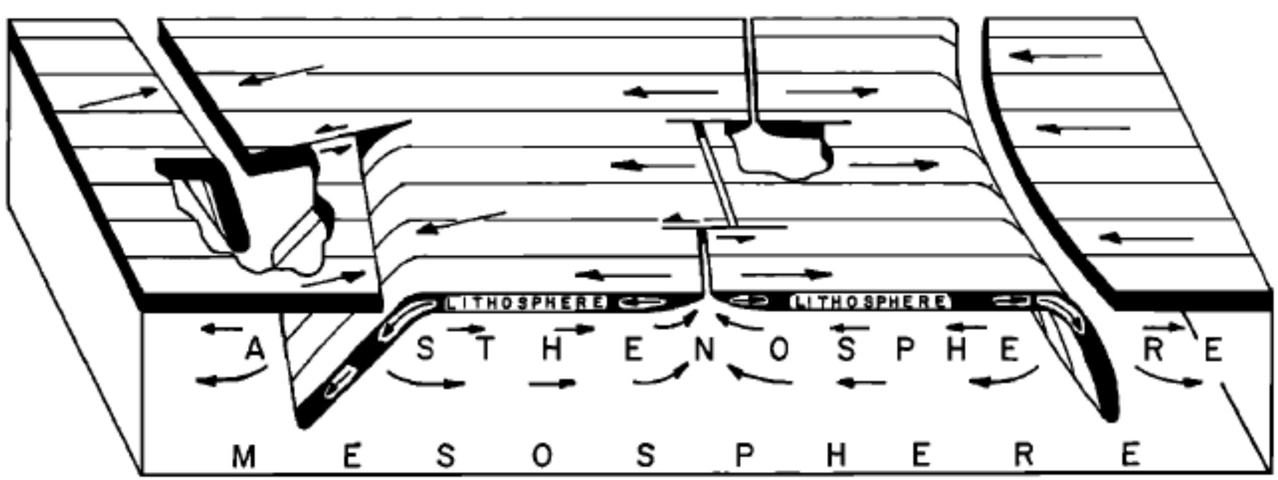
Subduction

4) Isacks, Oliver, and Sykes (seismologists from Lamont) published "seismology and the New Global Tectonics"

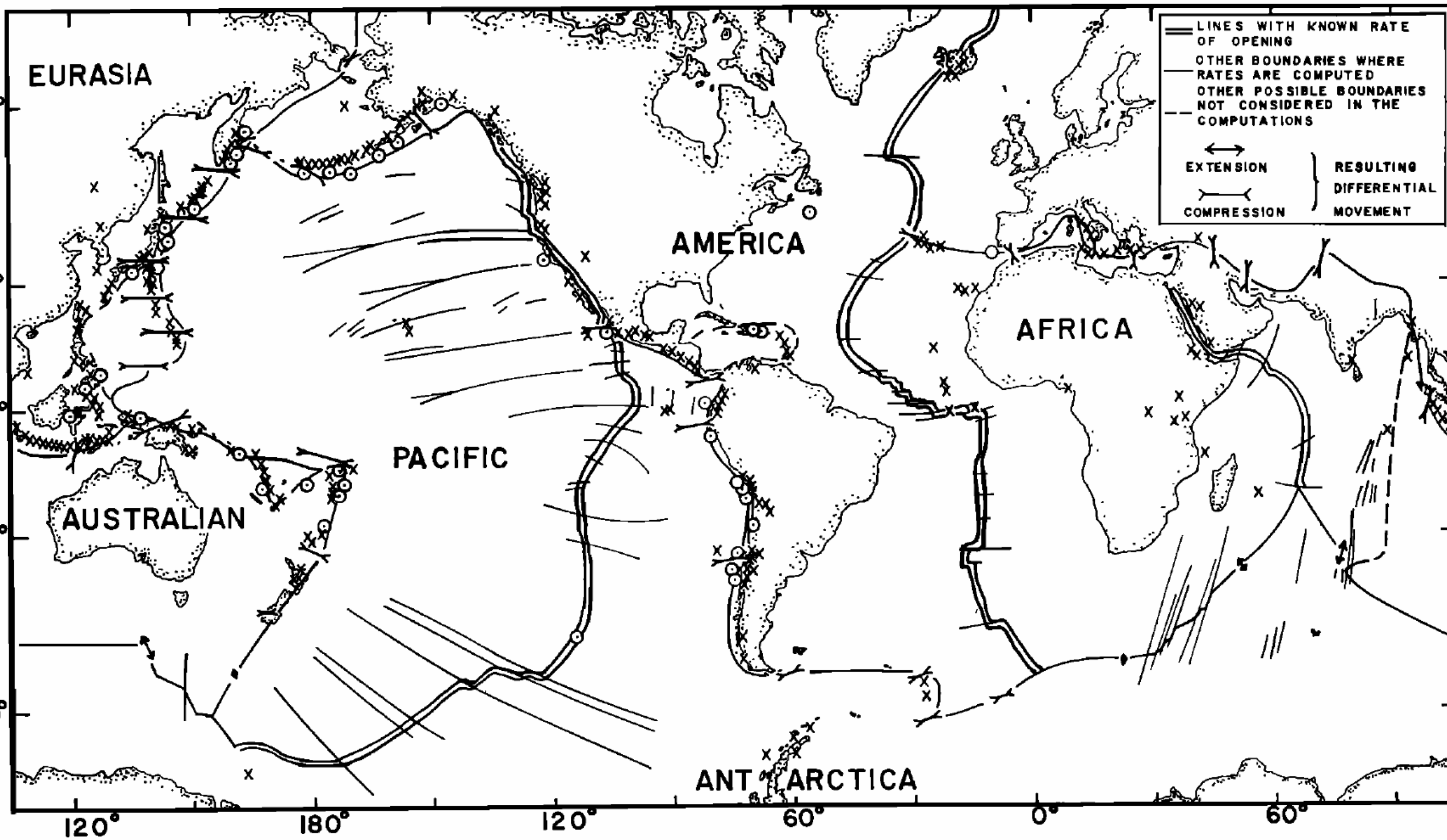
Recognised the global pattern of seismicity

- Deep earthquakes only occurred beneath continents and linking with trenches.
- Recognised that earthquakes only occurred along rigid plates.
- Cold sinking plates played a major role in generating plate motions.





The state of play in the Earth 1970s



Discoveries in Plate Tectonics and Seafloor Spreading

This chronology shows the chain of basic research that led to key insights about plate tectonics and related processes.

1890s
John Milne develops the seismograph, establishes a network of seismographic stations in the British empire.

Early 1900s
Scientists use seismographic research to probe Earth's inner structure, developing a model of concentric layers of core, mantle, and surface crust.

1915
German scientist Alfred Wegener publishes his then-radical theory of continental drift in *The Origin of Continents and Oceans*.

Mid-1950s
Patrick M. S. Blackett, S. Keith Runcorn, and Edward Irving produce paleomagnetic data from several continents showing apparent polar wandering consistent with Wegener's drift theory.

1959
Bruce Heezen, Marie Tharp, and Maurice Ewing of Columbia University publish the first detailed map diagrams of the globe-girdling midocean ridge system.

1962
In seeking to explain the midocean ridges, Harry Hess of Princeton University proposes that the seafloor is slowly spreading away from the ridges, driven by convection currents in the mantle.

1963
Fred Vine and Drummond Matthews at Cambridge University conceive of a connection between seafloor spreading and the "stripes" of magnetic reversal in the seafloor.

1965
Vine and J. Tuzo Wilson of the University of Toronto bolster the Vine-Matthews hypothesis with additional magnetic reversal evidence from the seafloor at the Juan de Fuca Ridge. Later that year deep-sea cores collected by Columbia's Neil Opdyke show a matching timescale. Seafloor spreading is confirmed.

1963—1966
Allan Cox, Richard Doell, and Brent Dalrymple of the U. S. Geological Survey and Ian McDougall of the Australian National University determine the timescale of reversals of Earth's magnetic field from measurements of lava flows on land.

Late 1960s
Wilson coins the term "plate" in developing the concept of seafloor spreading into a new scientific worldview—plate tectonics.

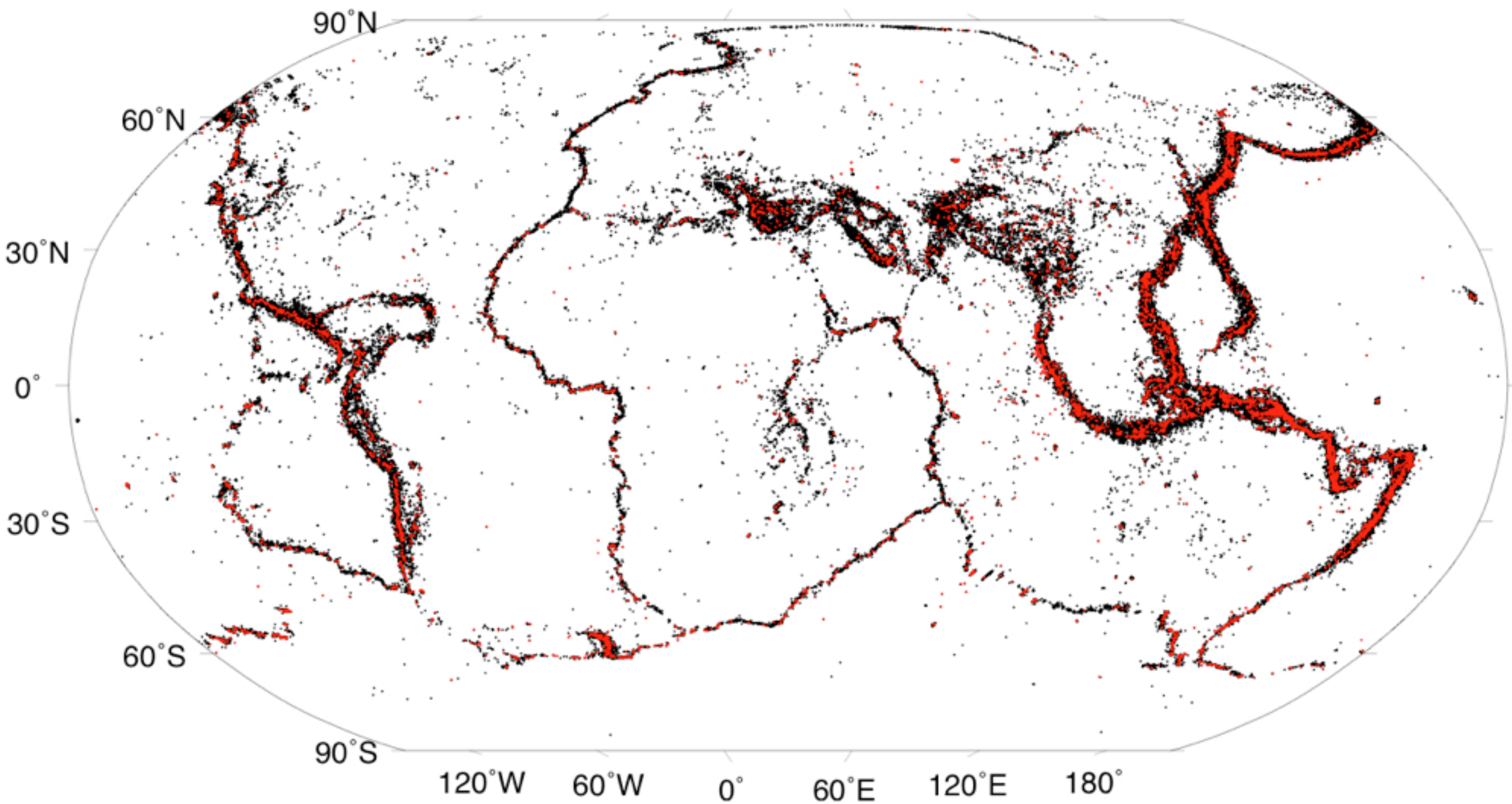
Late 1960s
Xavier Le Pichon, Dan McKenzie, and W. Jason Morgan define the shapes of the plates and how their movement and location on the globe could be described by elementary spherical geometry.

1968
Bryan Isacks, Jack Oliver, and Lynn Skyes recognize that slabs of material rigid enough to sustain earthquakes are descending into deep trenches, creating earthquake zones.

1977
The National Earthquake Reduction Program is established to reduce earthquake hazards throughout the United States.

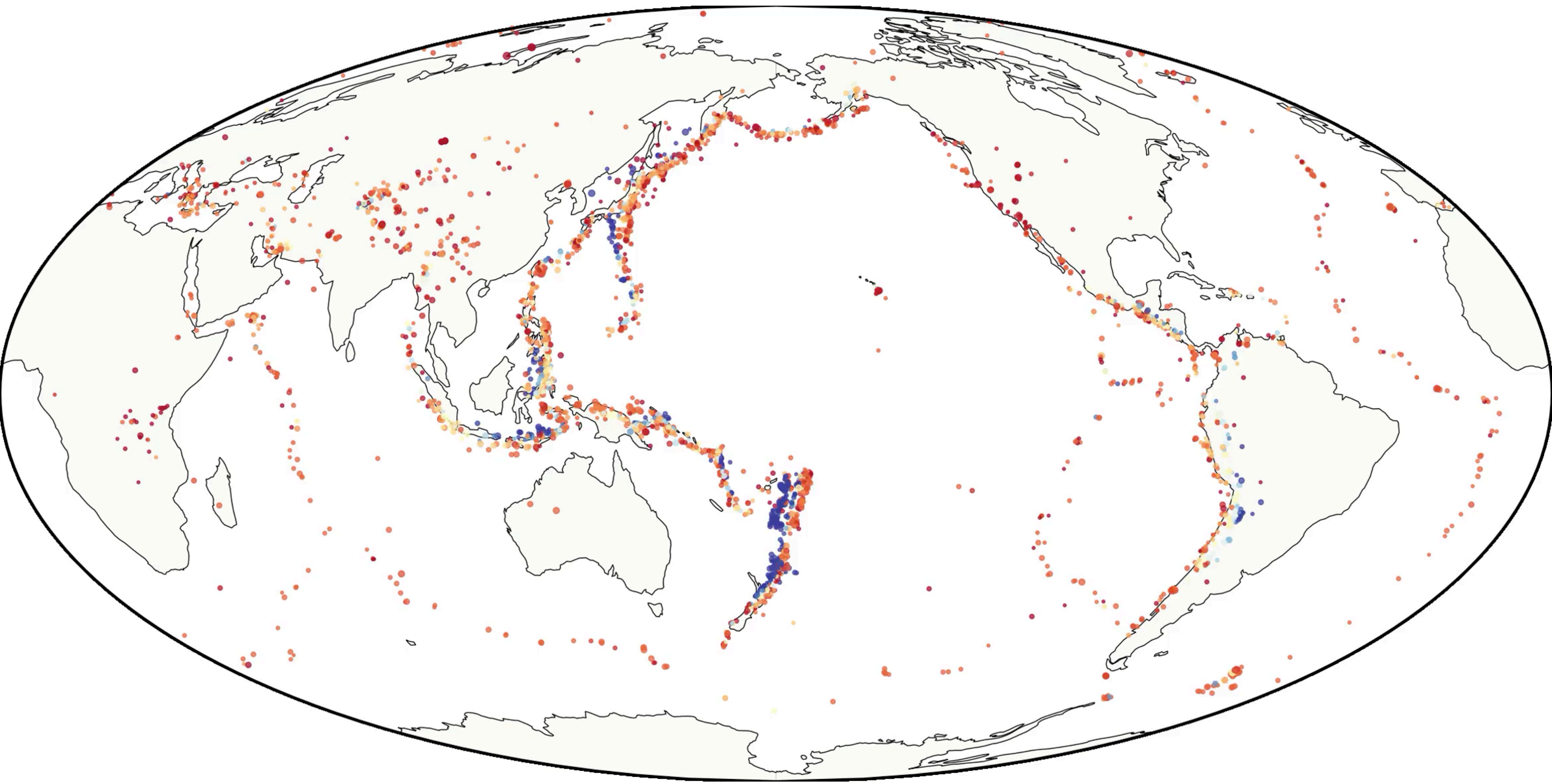
1977
The first seafloor hot springs are discovered at the Galápagos Rift in an expedition led by Jack Corliss of Oregon State University and Robert Ballard of Woods Hole Oceanographic Institution. The scientists observe unique and unexpected animal communities living in the seafloor vents.

Earthquake distribution



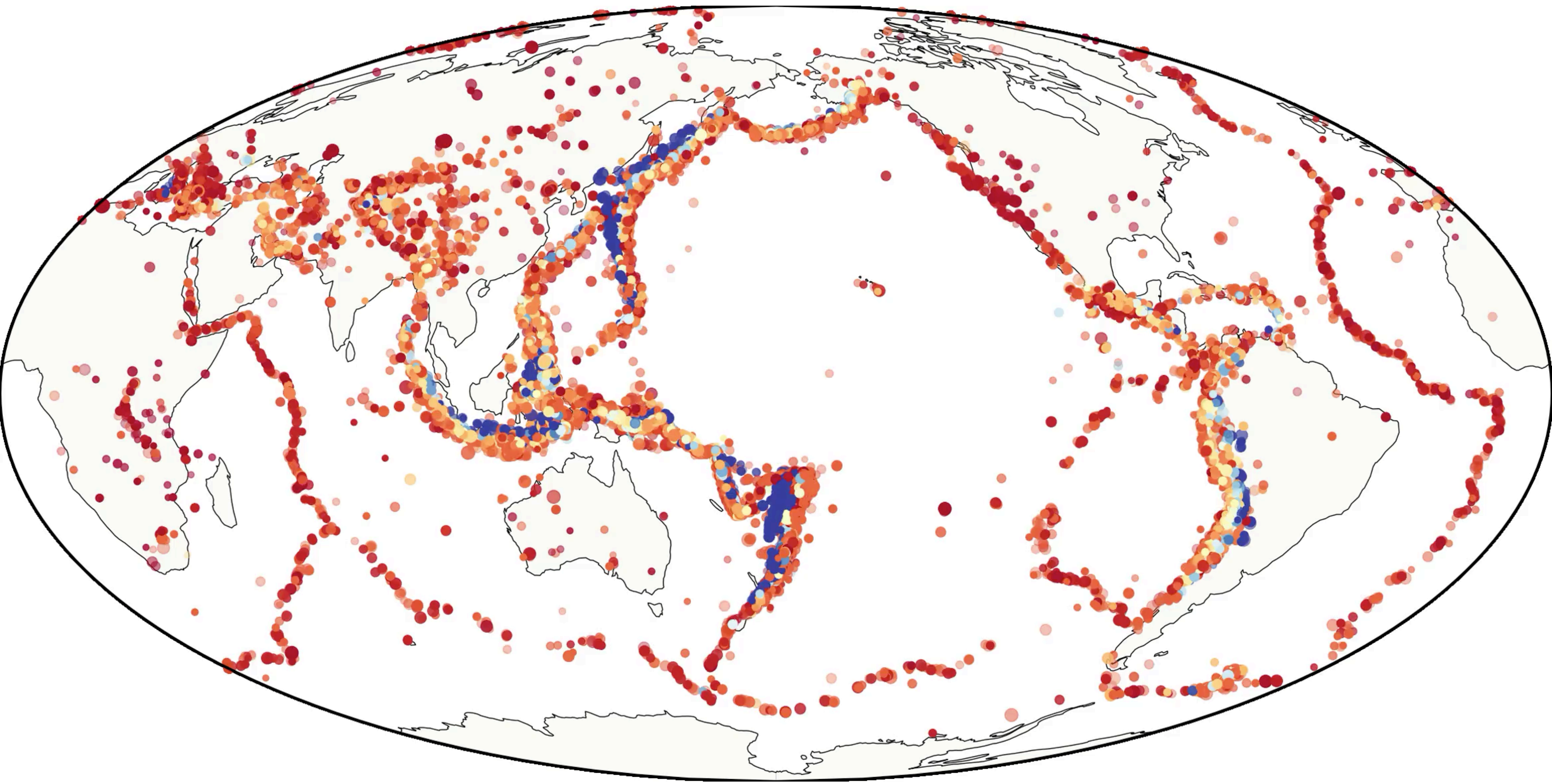
This is a typical "present day" map of earthquakes — The plate boundaries are just obvious here !

Earthquake distribution



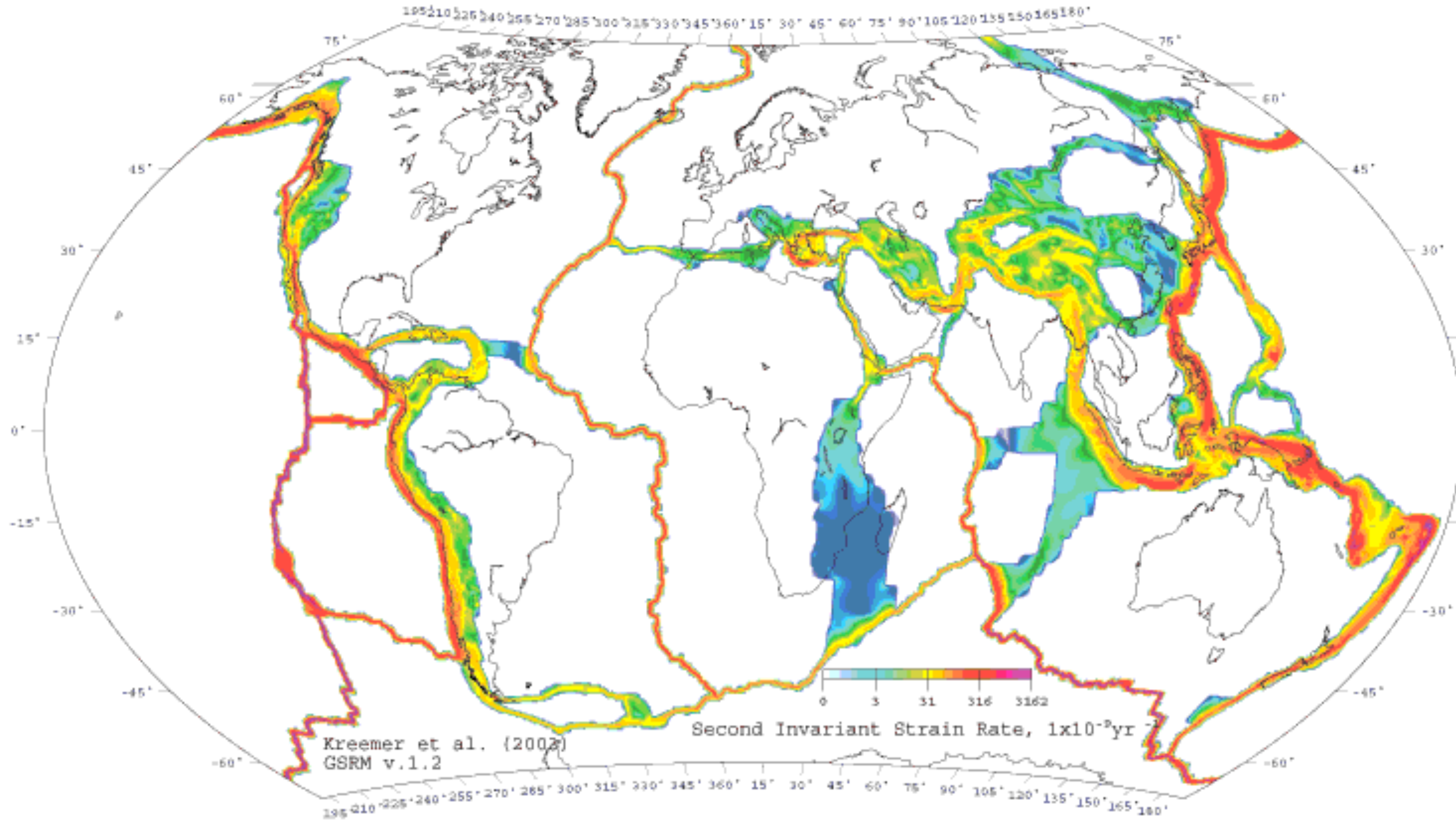
Cumulative data 1975 - 2019

Earthquake distribution

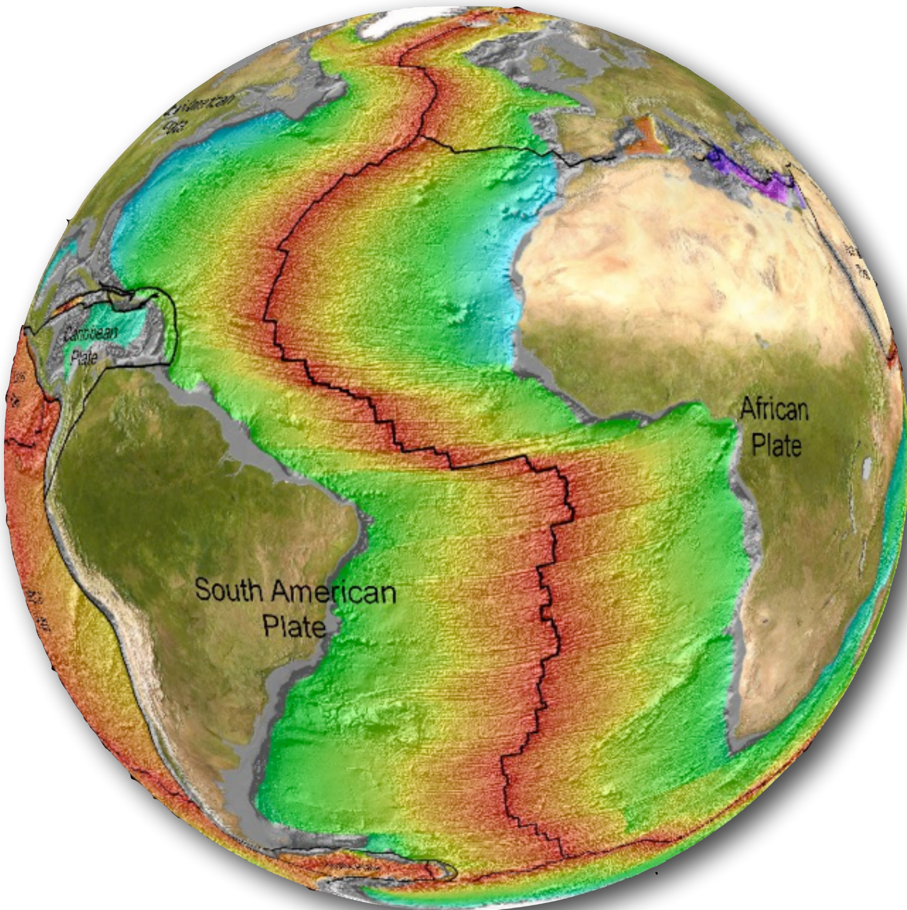


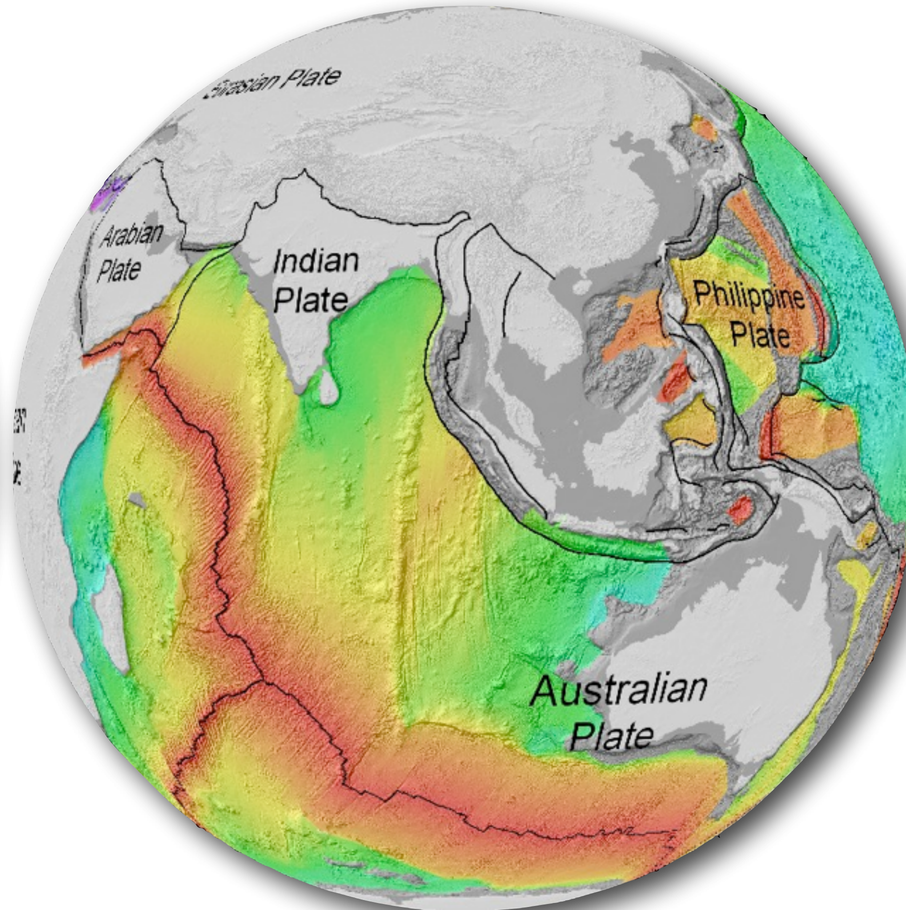
5 year rolling EQ distribution (1975 - 2019)

Global strain rate (geodesy)

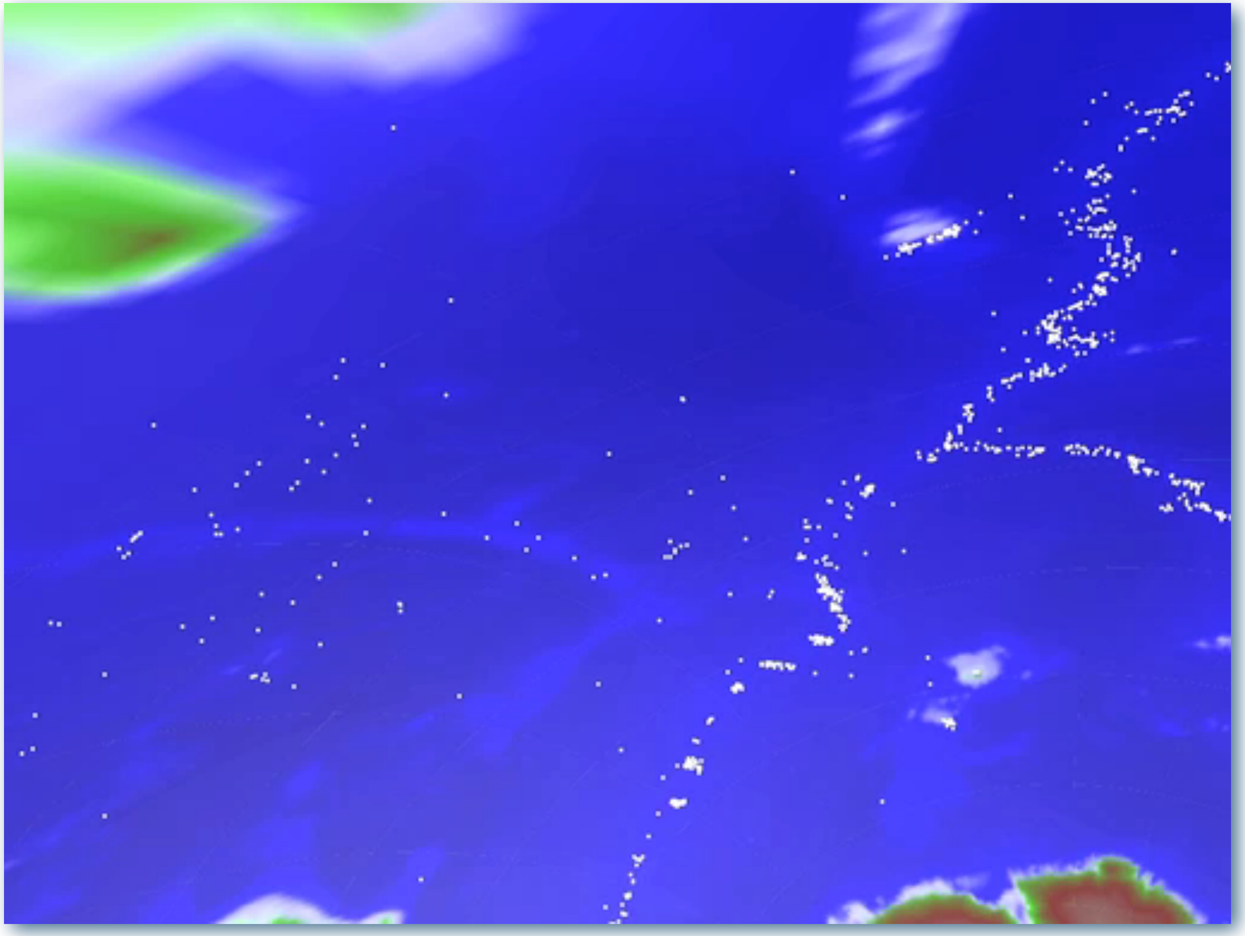


Global sea-floor age map



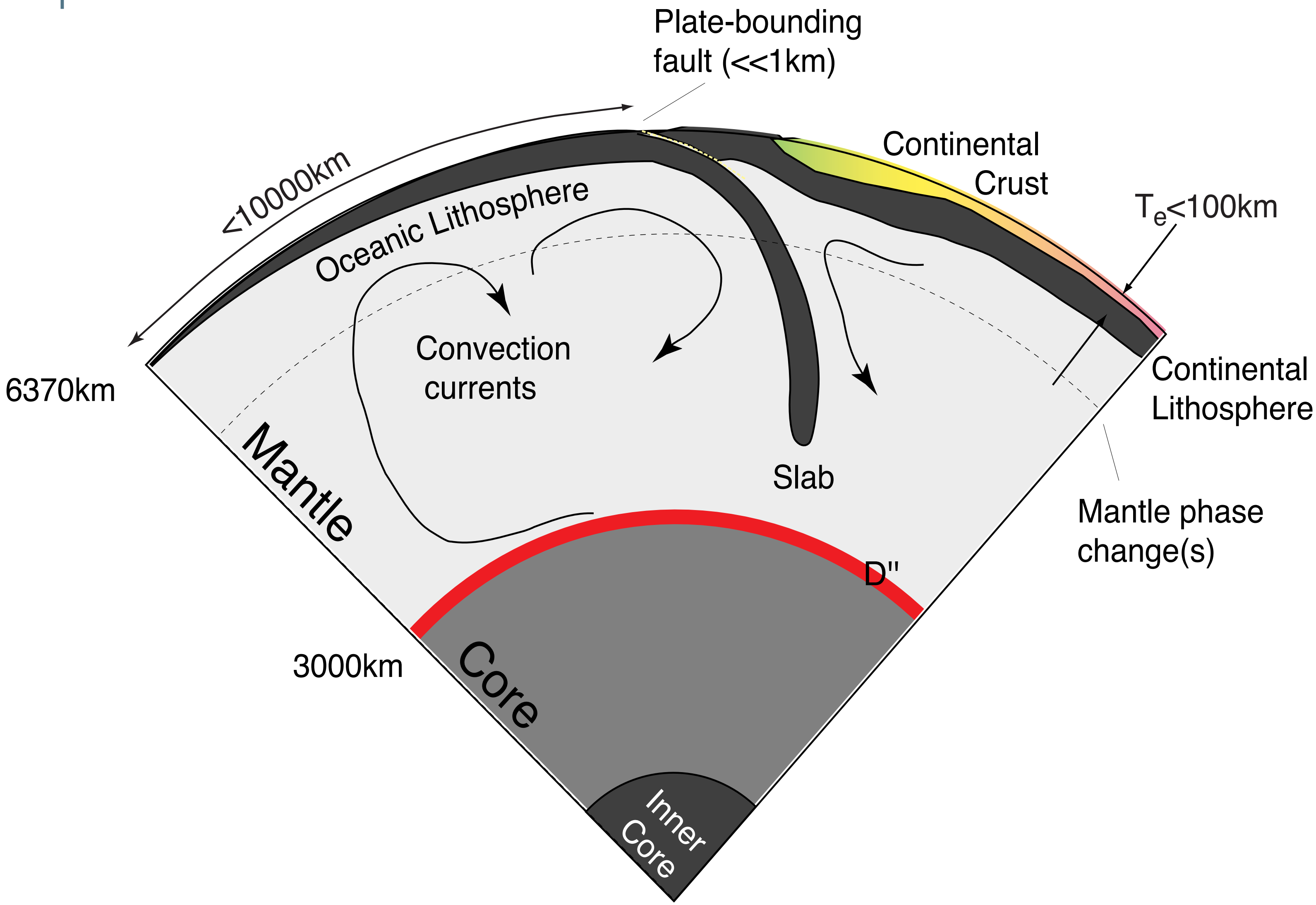


What lies beneath ?



From a surface perspective, Australia is very quiet but from a mantle perspective it is much less so.

Dynamics of planets



We have a reasonable 3D picture of the Earth from the many methods of remote sensing and theoretical (mathematical and computational) models.

Earth Interior

Major layering

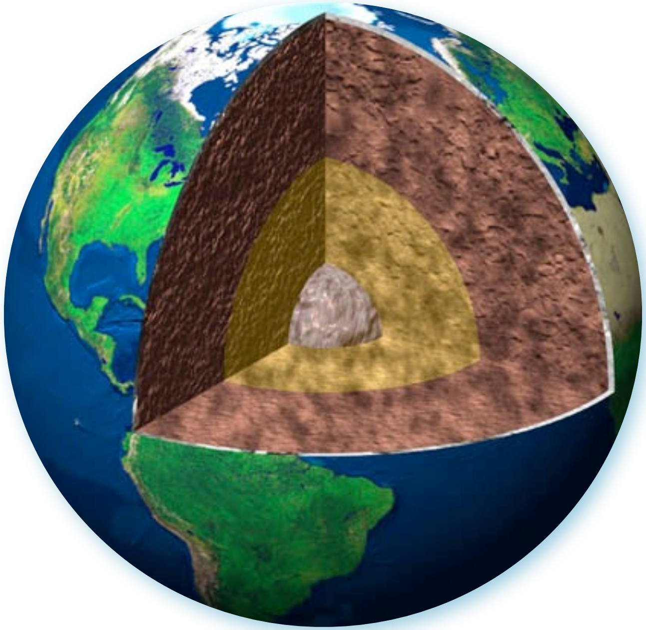
- Solid inner core
- Liquid outer core
- Solid silicate lower mantle
- Solid silicate upper mantle
- Crust (oceanic & continental)
- Hydrosphere/atmosphere/biosphere

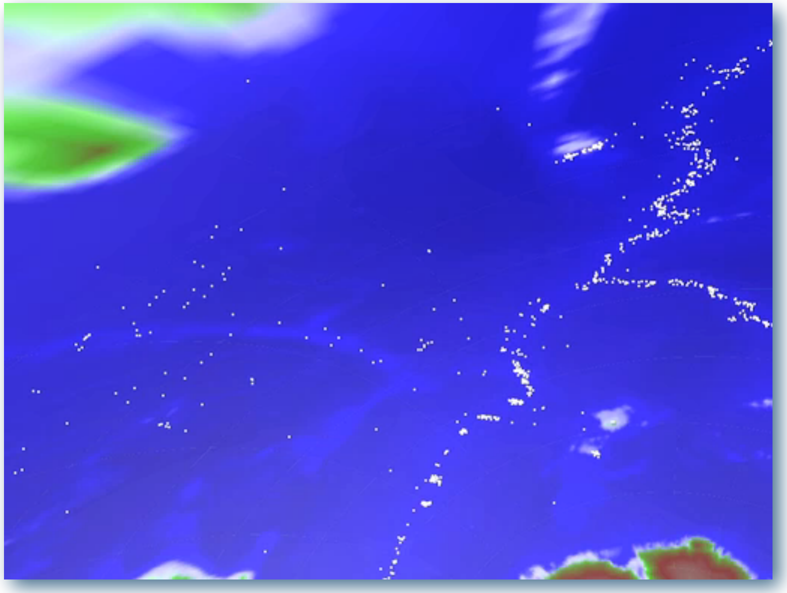
Rheological domains

- Lithosphere
- Asthenosphere
- Transition zone
- D″ layer

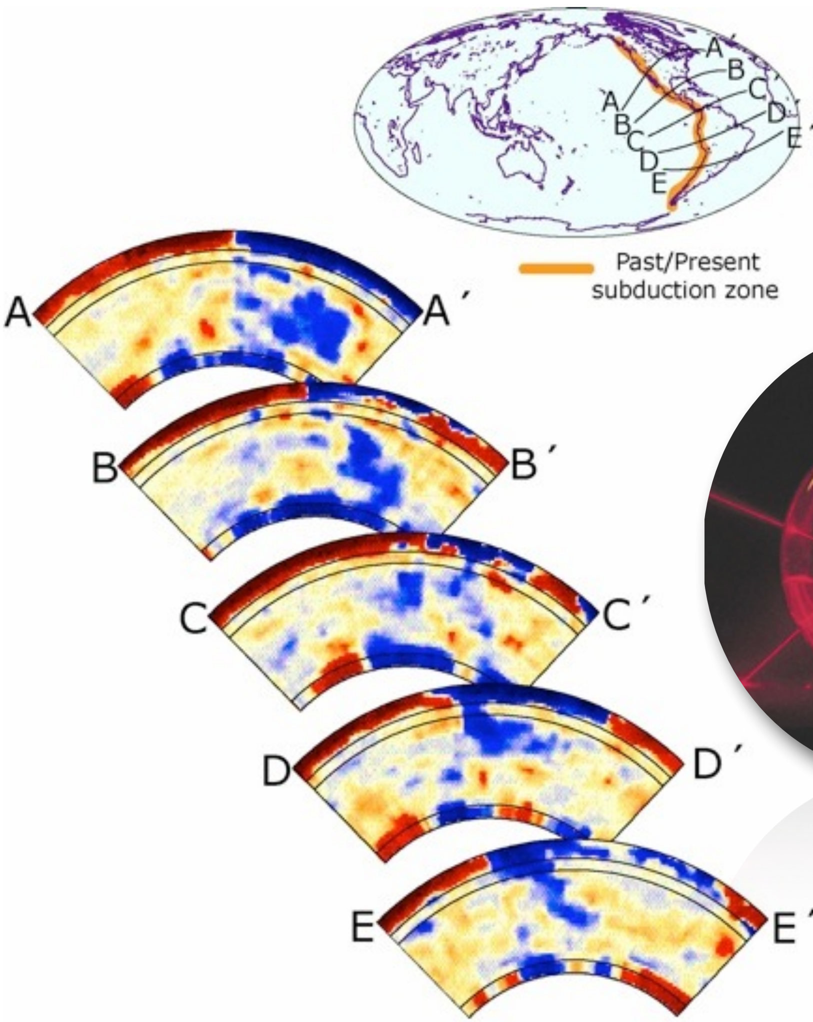
Surface Features

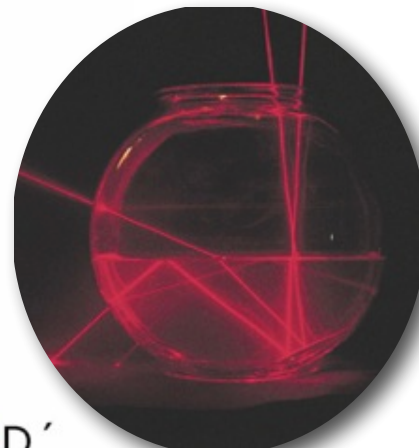
- Young ocean basins
- Continents of all ages
- Erosion, weather Active tectonics, volcanism, hotspots
- Isostasy
- Strong surface magnetic field

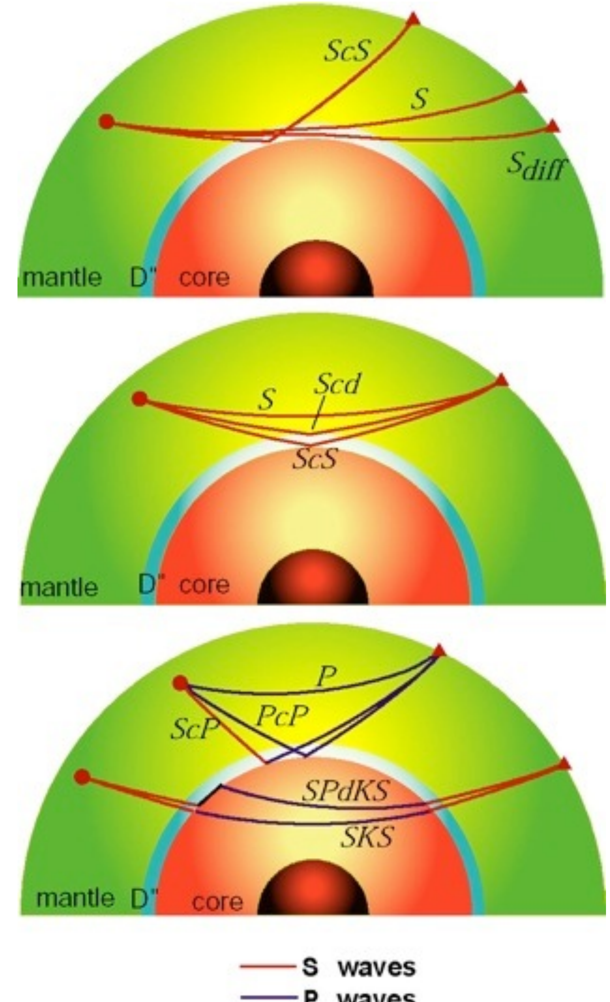




Earth - interior

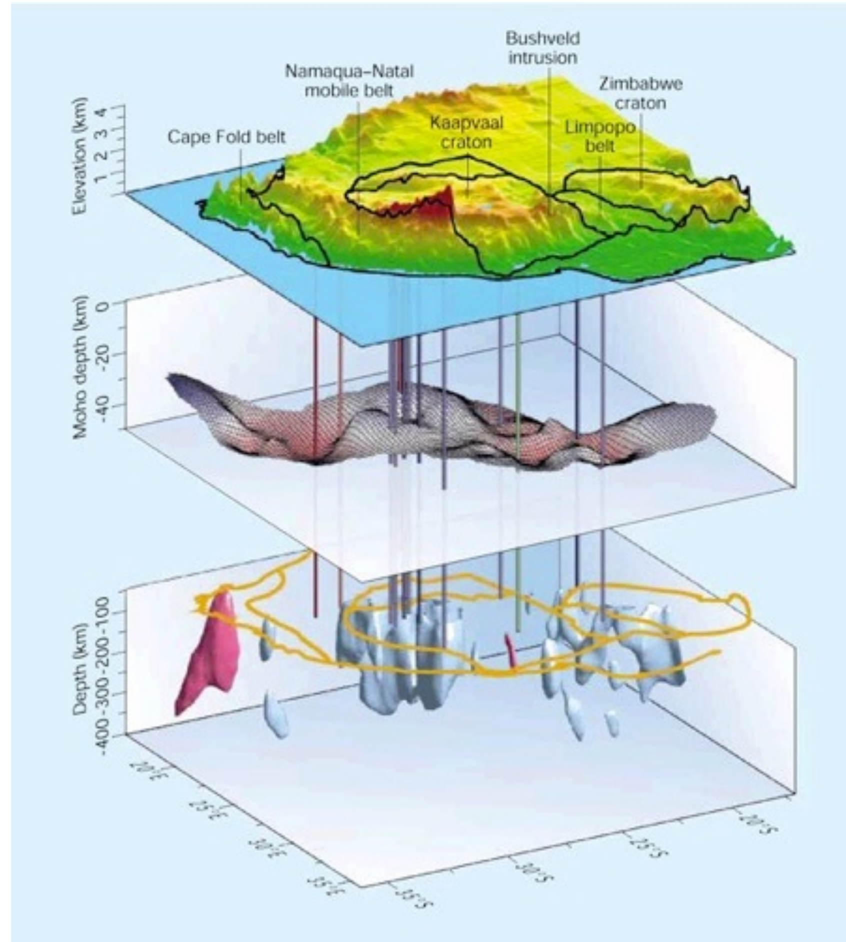






Seismology — elastic waves triggered by earthquakes propagating through the Earth allow us to image the interior in considerable detail

Earth - interior



Xenoliths — rocks dredged up from the "deep" interior during volcanic eruptions etc.