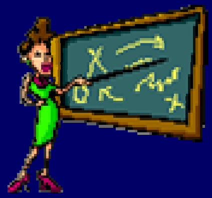
Ivana Vasiljević

Department of Geophysics, Faculty of Mining and Geology, University of Belgrade, Serbia

Geophysical Investigations of Global Phenomena



This part of the course will be mostly dedicated to geophysical investigations of global phenomena. We will discuss the place of geophysics in understanding the dynamics of the Earth’s crust, especially plate tectonics.

Major topics:

1. **Seismology** - distribution and characteristics of earthquakes connected to different types of plate boundaries, structure and nature of the interior of the Earth as defined by seismic methods;

2. **Geomagnetism** - paleomagnetic evidences of sea floor spreading, apparent polar wander paths and tectonic applications of paleomagnetics;

3. **Gravity** - isostasy, gravity maps of former Yugoslavia and Serbia.

Developing the plate tectonics theory

Alfred Wegener (1880-1930) first published his theory of continental drift in 1915 in a book called “The Origin of Continents and Oceans”. Wegener’s ideas were not accepted by geological community, continental drift was debated for decades, before it was largely dismissed. In the 1950s, new evidences emerged to revive the debate about Wegener's ideas.

Four major scientific developments were significant for the formulation of the plate-tectonics theory:

(1) demonstration of the ruggedness and youth of the ocean floor;

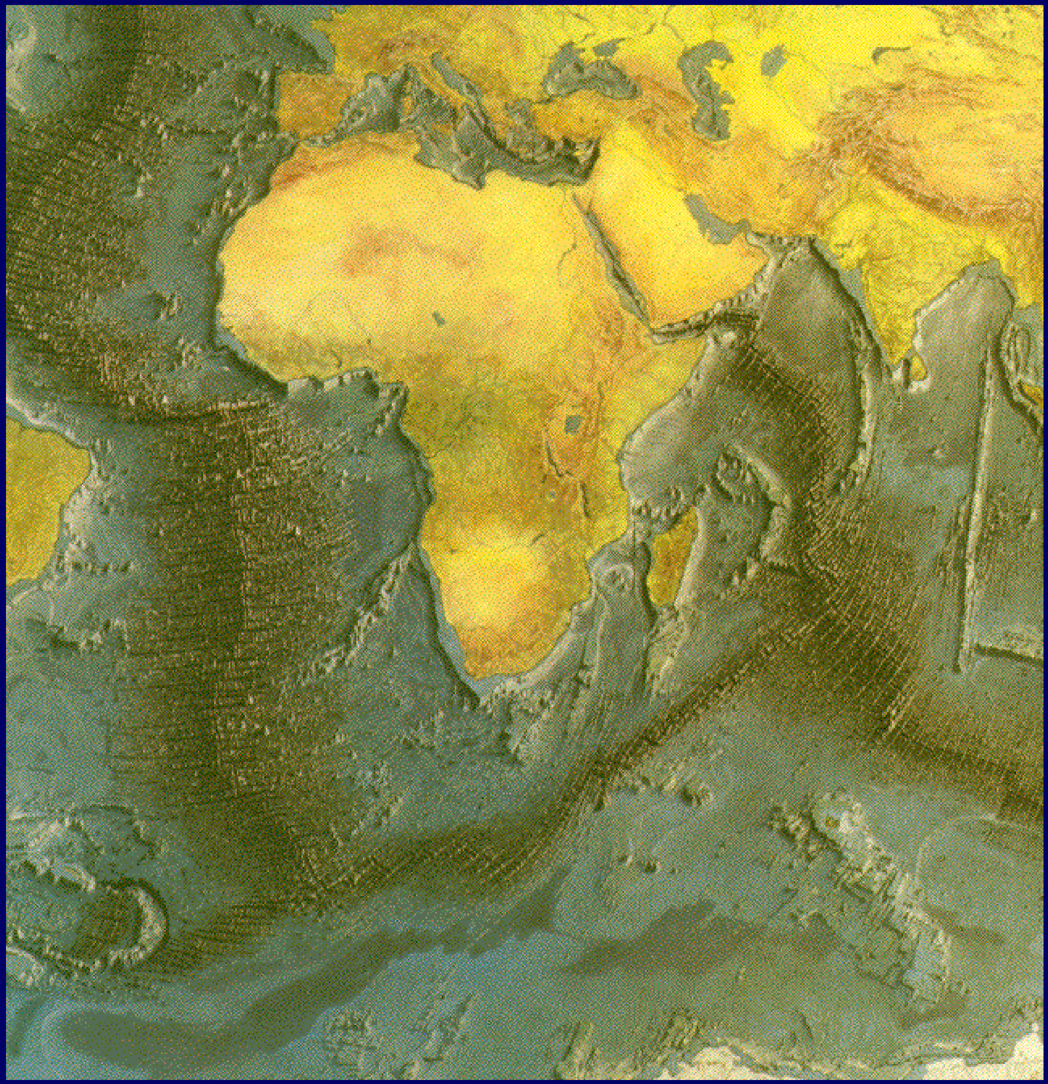
(2) precise documentation that the world's earthquakes and volcanic activity are concentrated along oceanic trenches and submarine mountain ranges;

(3) confirmation of repeated reversals of the Earth magnetic field in the geologic past;

(4) emergence of the seafloor-spreading hypothesis and associated recycling of oceanic crust.

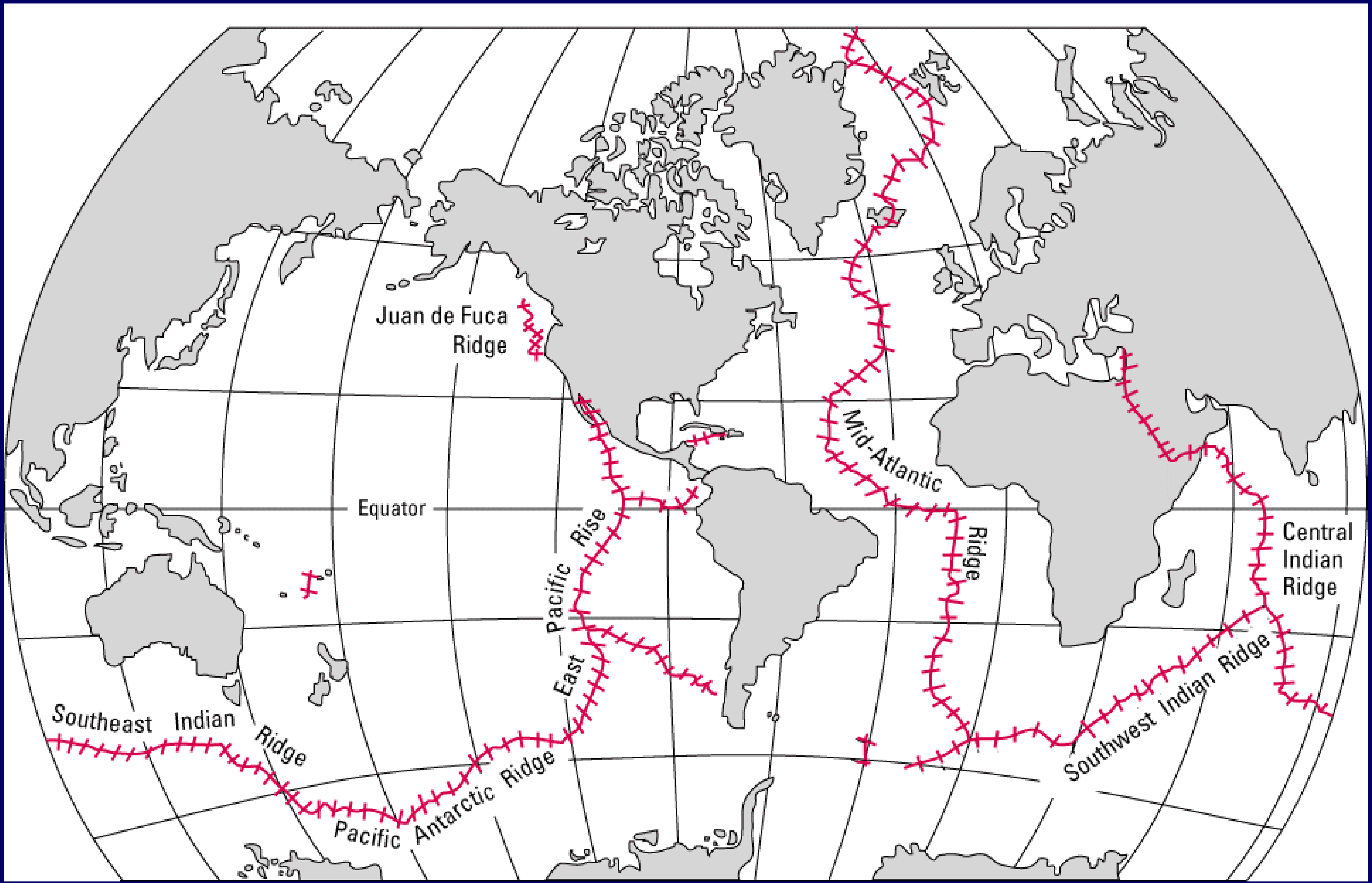
Ocean floor mapping

About two thirds of the Earth's surface lies beneath the oceans. Before the 19th century, the depths of the open ocean were largely a matter of speculation, and most people thought that the ocean floor was relatively flat and featureless.



Oceanic exploration improved our knowledge of the ocean floor. We now know that most of the geologic processes occurring on land are linked, directly or indirectly, to the dynamics of the ocean floor.

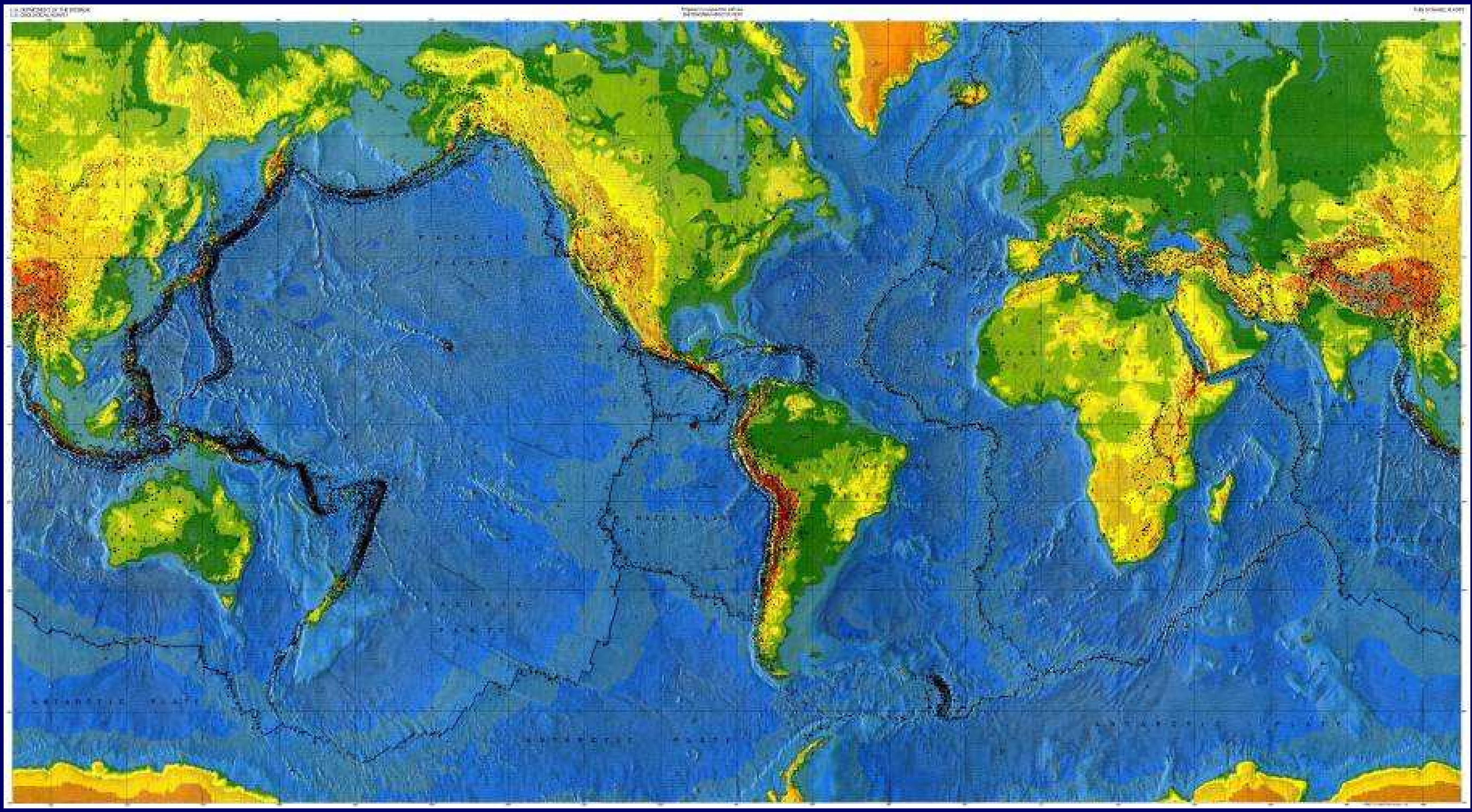
The Mid-Ocean Ridge



Seismology

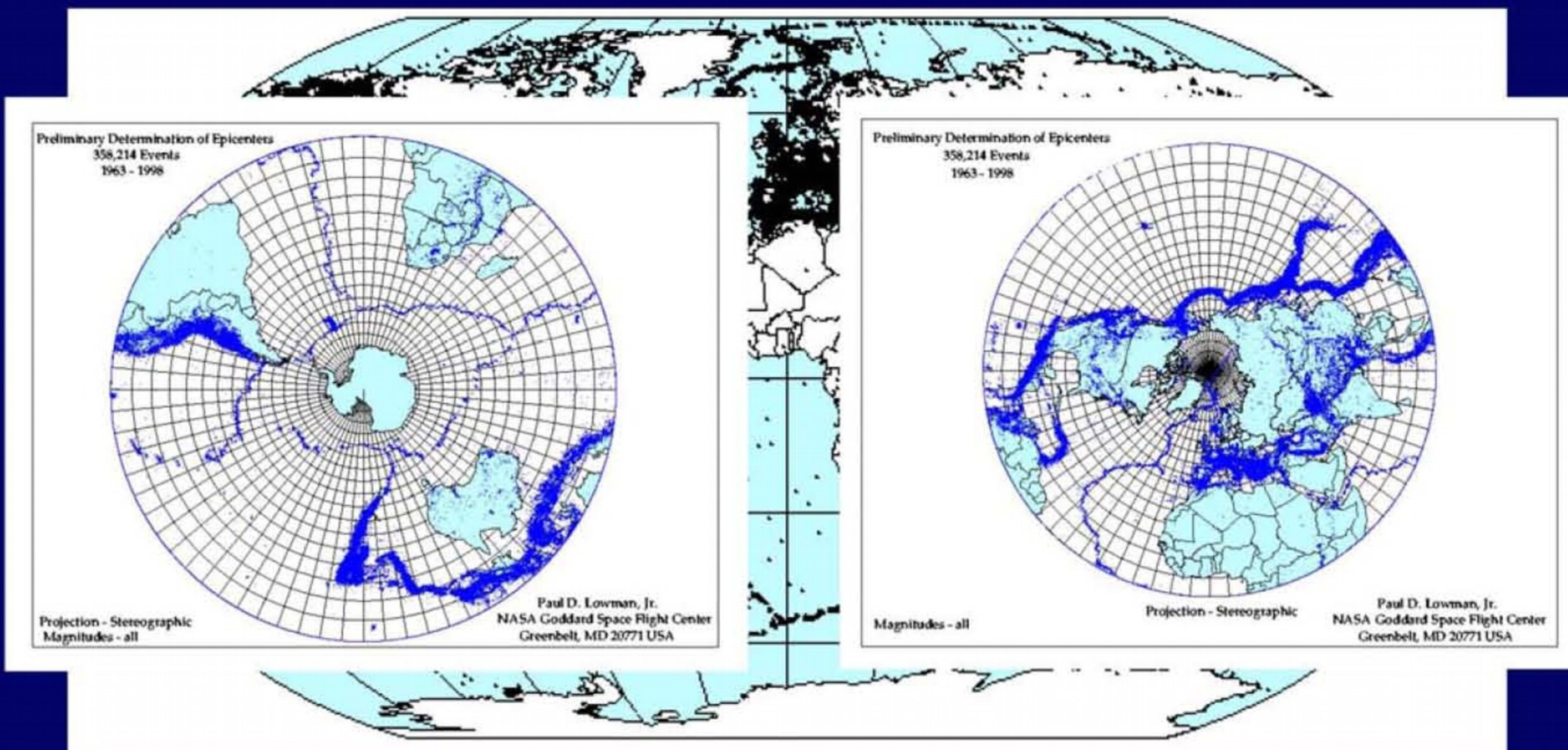
Distribution of the earthquakes
Structure of the interior of the Earth
as defined by seismic methods

World Map of Volcanoes, Earthquakes, Impact Craters and Plate Tectonics

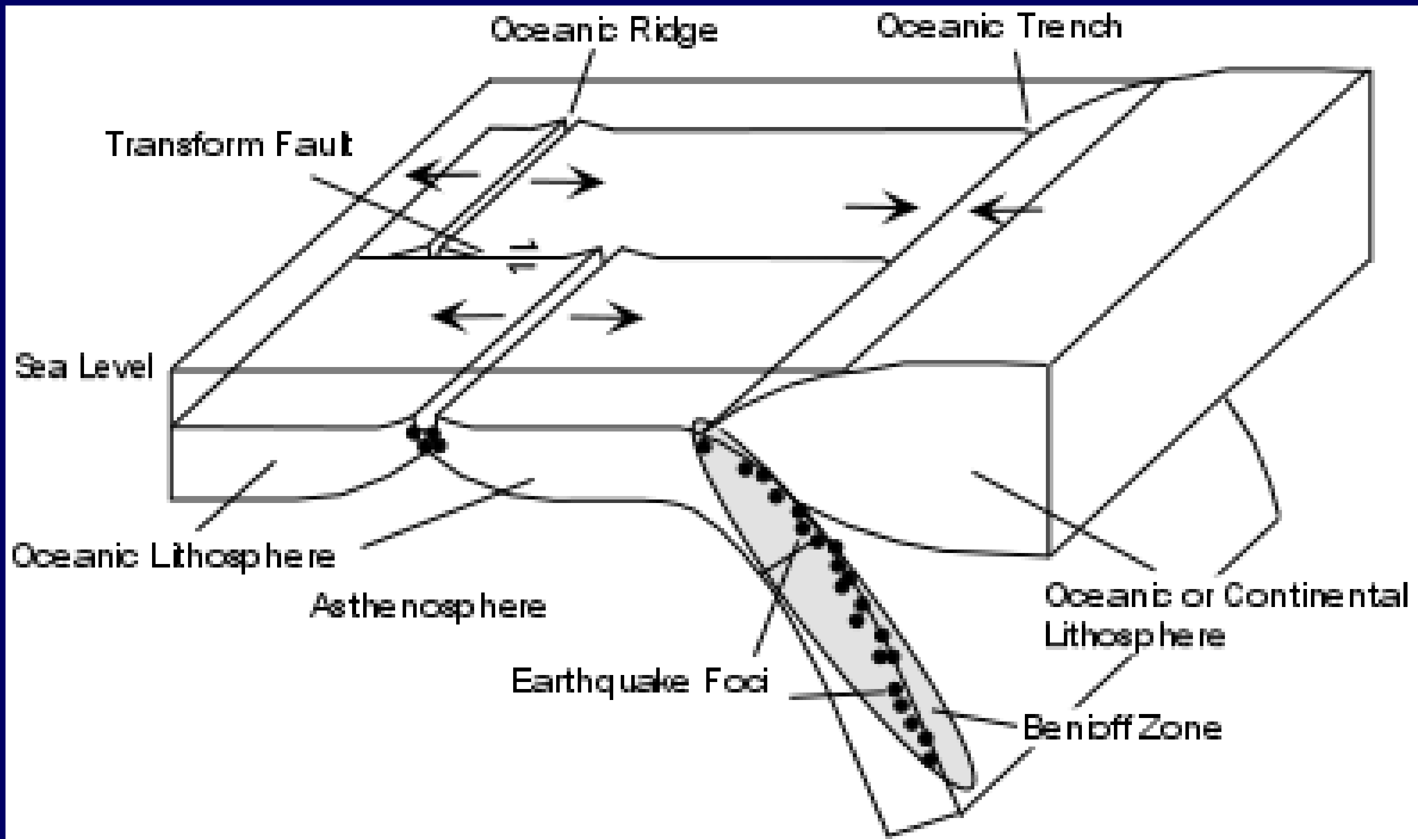


Concentration of earthquakes

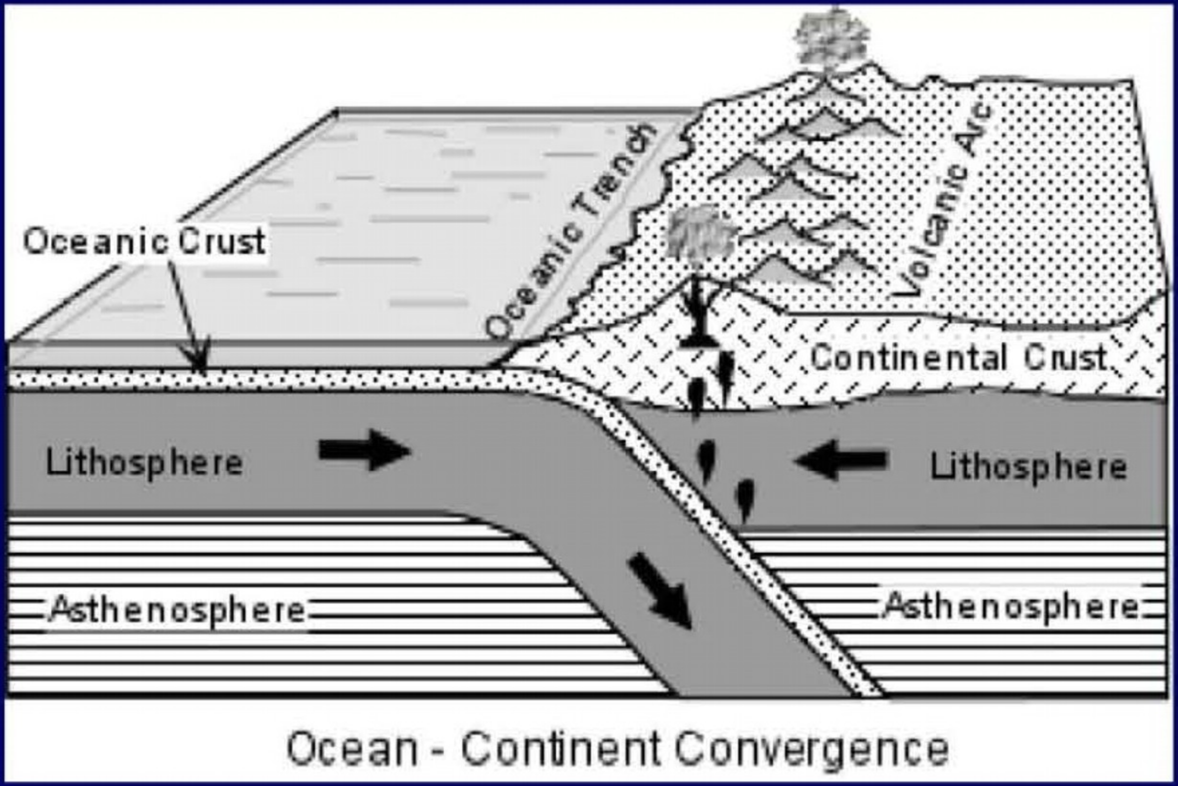
During the 20th century, improvements in seismic instrumentation and greater use of earthquake-recording instruments (seismographs) worldwide enabled scientists to learn that earthquakes tend to be concentrated in certain areas, most notably along the oceanic trenches and spreading ridges. This makes sense, since plate boundaries are zones along which lithospheric plates mover relative to one another. Earthquakes along these zones can be divided into shallow focus earthquakes that have focal depths less than about 70 km and deep focus earthquakes that have focal depths between 75 and 700 km.



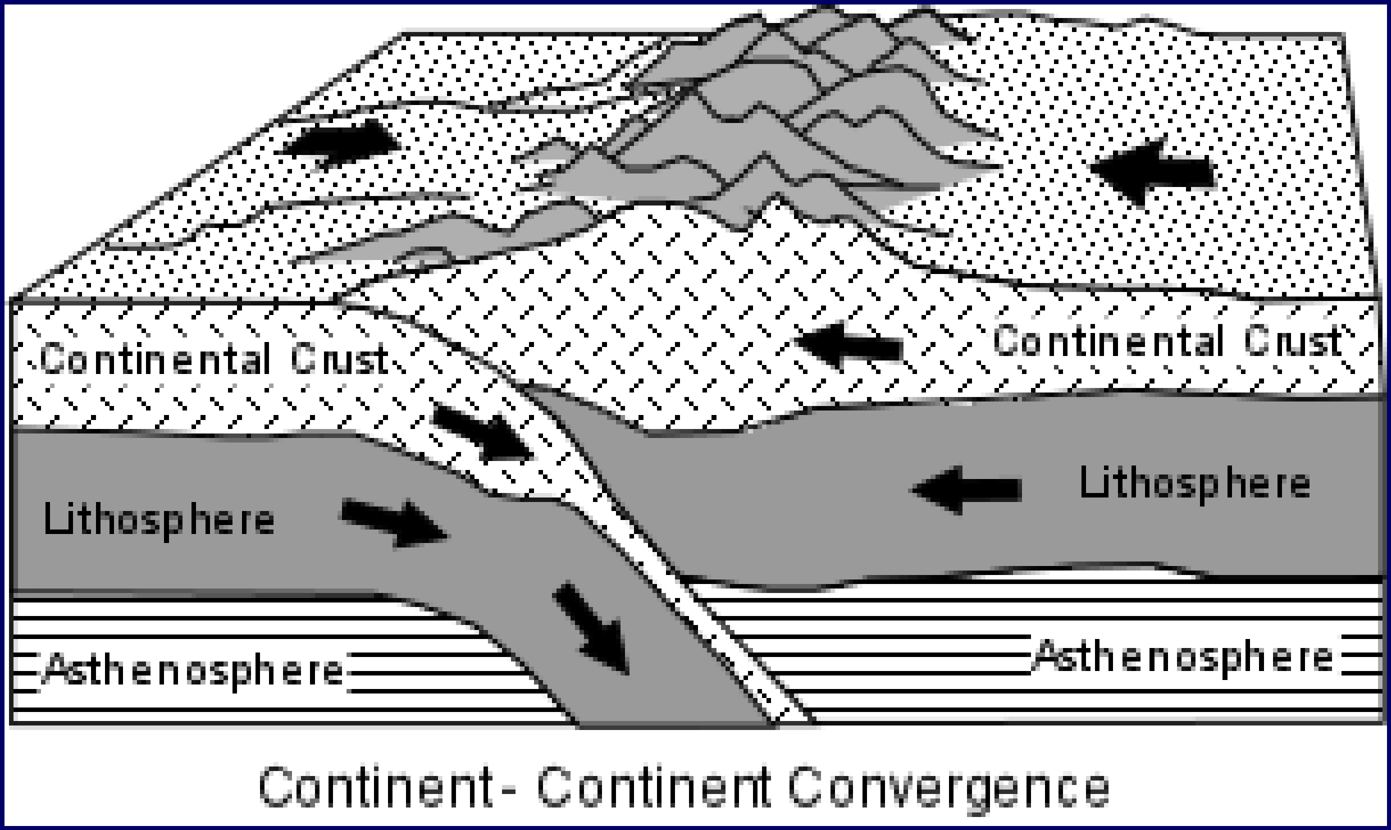
By the late 1920s, seismologists were beginning to identify several prominent earthquake zones parallel to the trenches that typically were inclined 40-60° from the horizontal and extended several hundred kilometers into the Earth. These zones later became known as *Wadati-Benioff zones,* or simply *Benioff zones,* in honor of the seismologists who first recognized them, Kiyoo Wadati of Japan and Hugo Benioff of the United States.



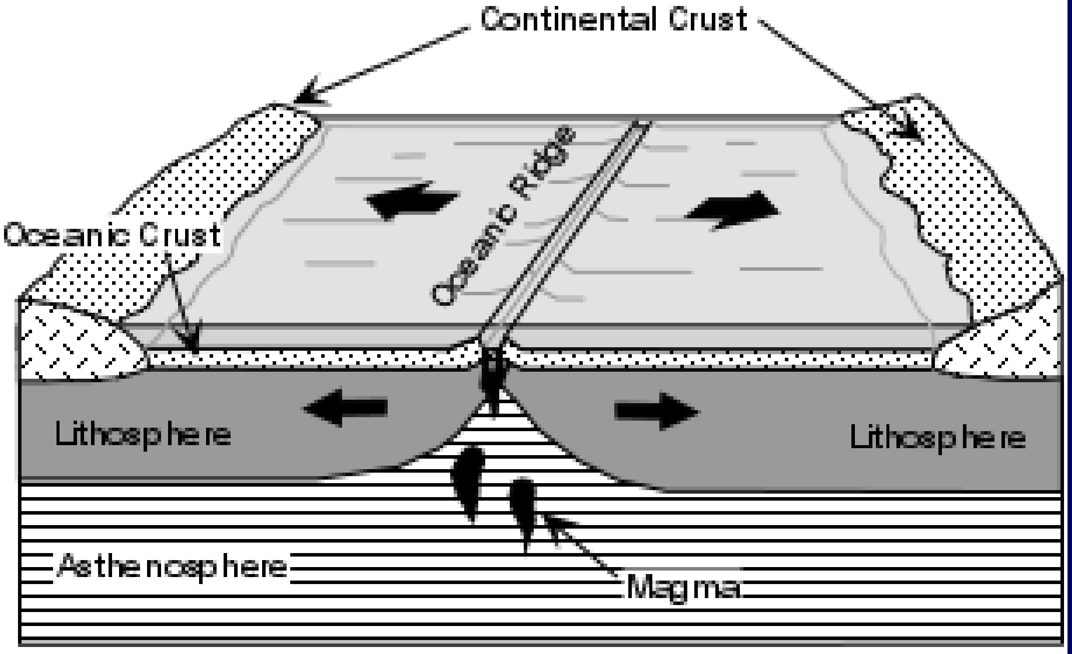
Earthquakes at Converging Plate Boundaries - Convergent plate boundaries are boundaries where two plates run into each other. Thus, they tend to be zones where compressional stresses are active and thus reverse faults or thrust faults are common. Subduction boundaries -At subduction boundaries cold oceanic lithosphere is pushed back down into the mantle where two plates converge at anoceanic trench. Because the subducted lithosphere is cold it remains brittle as it descends and thus can fracture under the compressional stress. When it fractures, it generates earthquakes that define a zone of earthquakes with increasing focal depths beneath the overriding plate-BenioffZone. Focal depths of earthquakes in the BenioffZone can reach down to 700 km.



Collision boundaries - At collisional boundaries two plates of continental lithosphere collide resulting in fold-thrust mountain belts. Earthquakes occur due to the thrust faulting and range in depth from shallow to about 200 km.



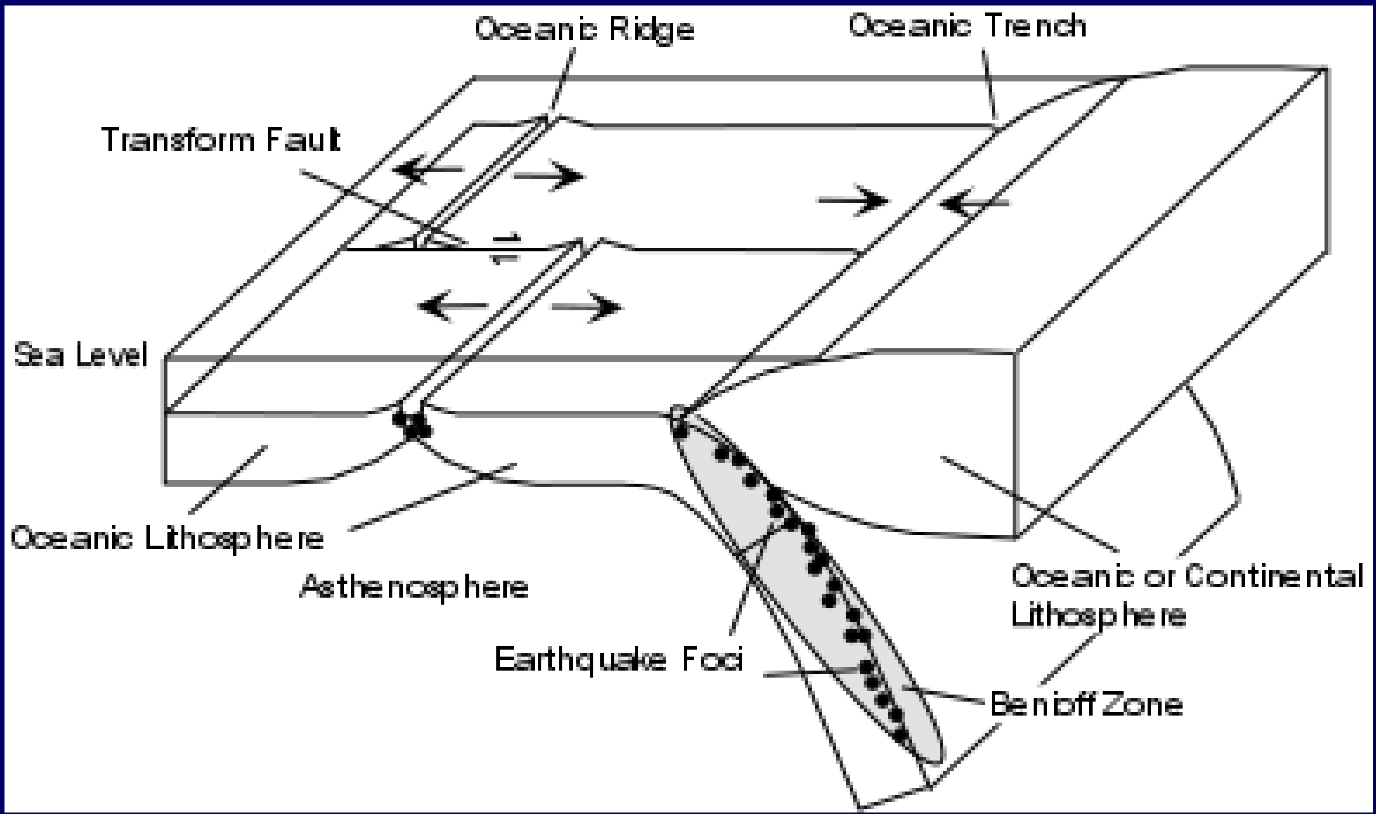
Earthquakes at Diverging Plate Boundaries. Diverging plate boundaries are zones where two plates move away from each other, such as at oceanic ridges. In such areas the lithosphere is in a state of tensional stress and thus normal faults and rift valleys occur. Earthquakes that occur along such boundaries show normal fault motion and tend to be shallow focus earthquakes, with focal depths less than about 20 km. Such shallow focal depths indicate that the brittle lithosphere must be relatively thin along these diverging plate boundaries.



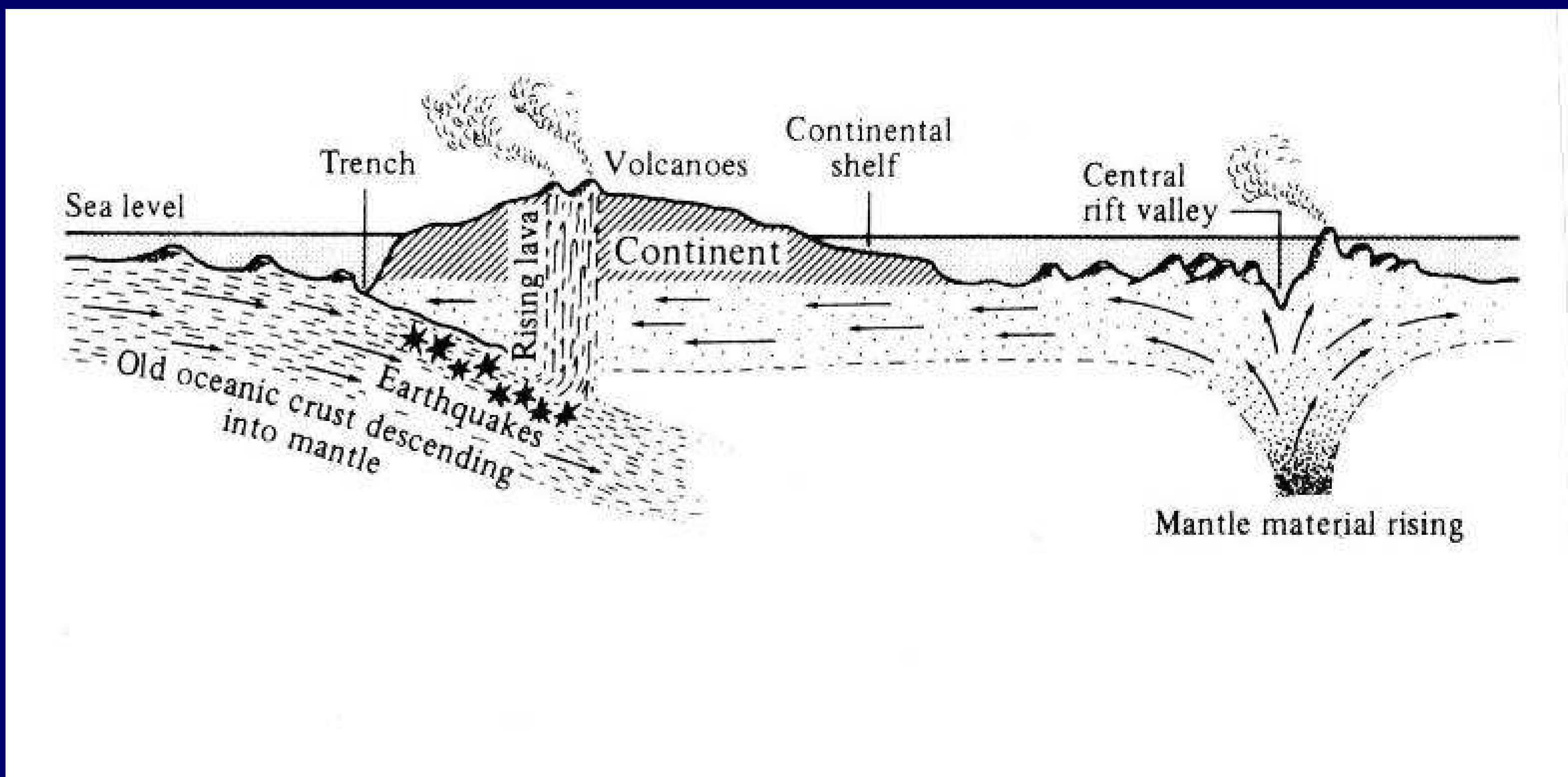
Diverging Plate Boundary

Oceanic Ridge - Spreading Center

Earthquakes at Transform Fault Boundaries. Transform fault boundaries are plate boundaries where lithospheric plates slide past one another in a horizontal fashion. Earthquakes along these boundaries show strike-slip motion on the faults and tend to be shallow focus earthquakes with depths usually less than about 50 km.

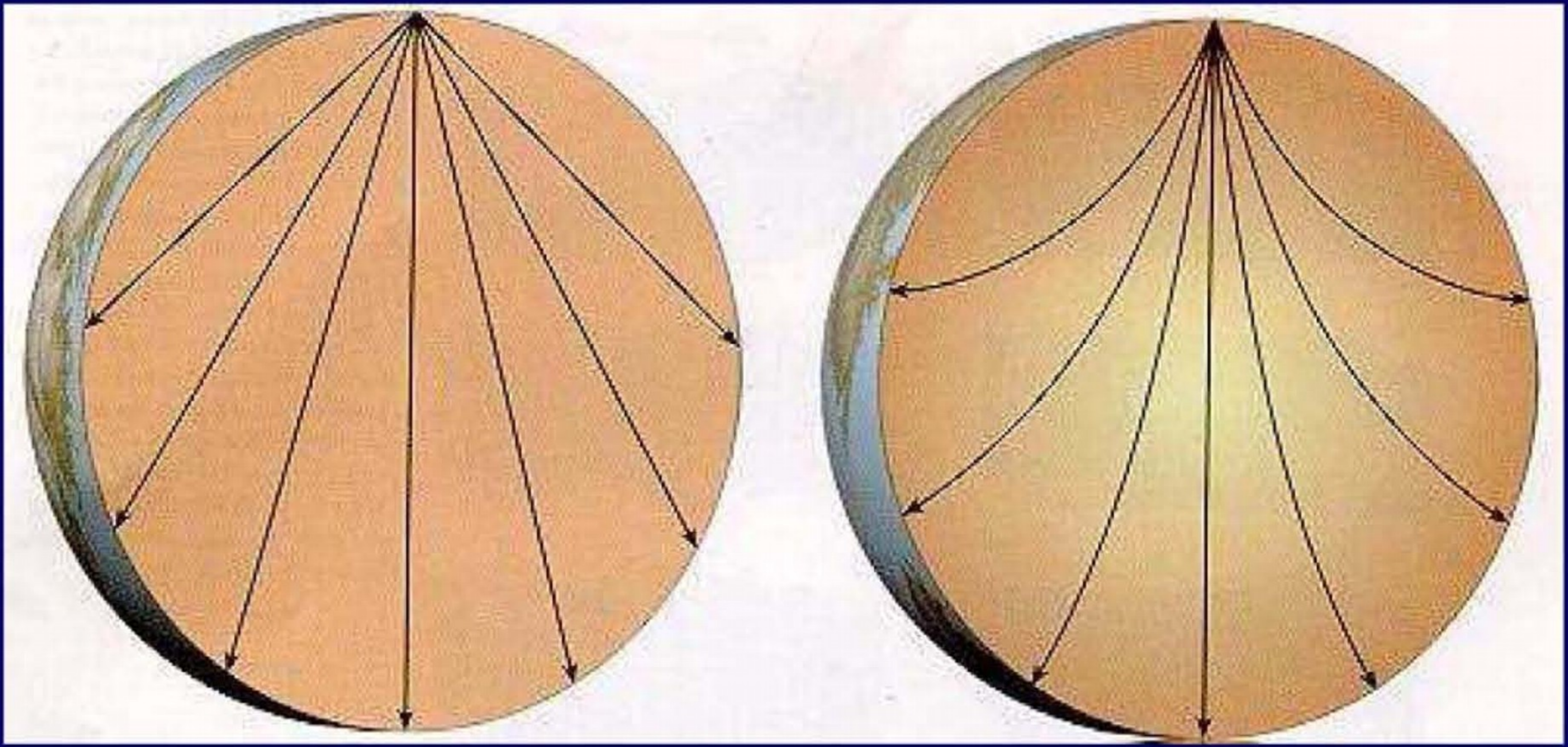


But what was the significance of the connection between earthquakes and oceanic trenches and ridges? The recognition of such a connection helped confirm the seafloor-spreading hypothesis by pin-pointing the zones where Hess had predicted oceanic crust is being generated (along the ridges) and the zones where oceanic lithosphere sinks back into the mantle (beneath the trenches).



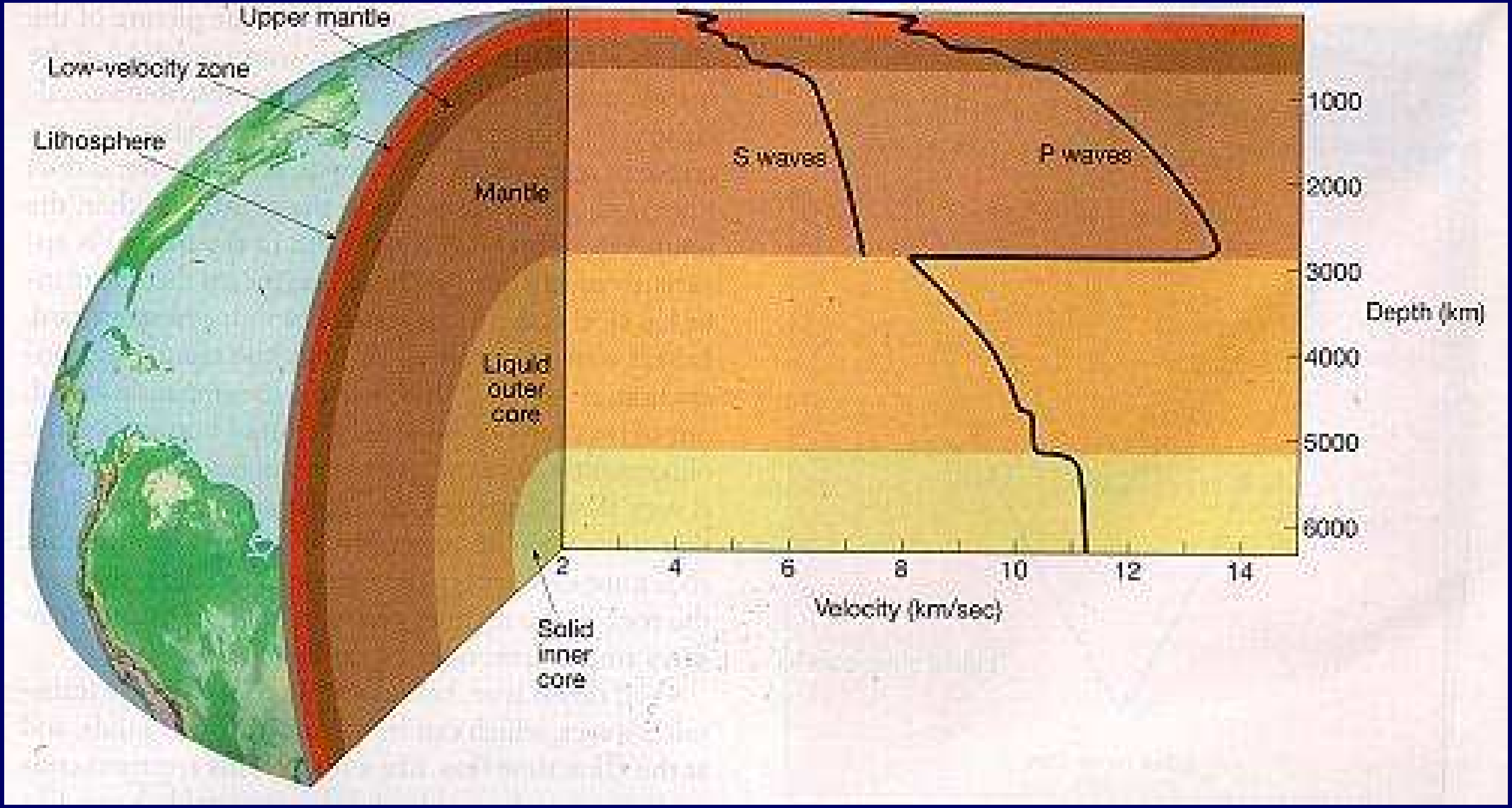
Homogeneous vs nonhomogeneous interior Earth concepts

The paths of body waves moving through the Earth's interior will be straight if the interior is homogeneous or broken or curved if not homogeneous. The body waves are not straight therefore the Earth is not homogeneous. Structure of the interior of the Earth as defined by seismic methods. Structure and composition of the interior of the earth has been determined from information obtained from studies of body waves and meteorite composition.

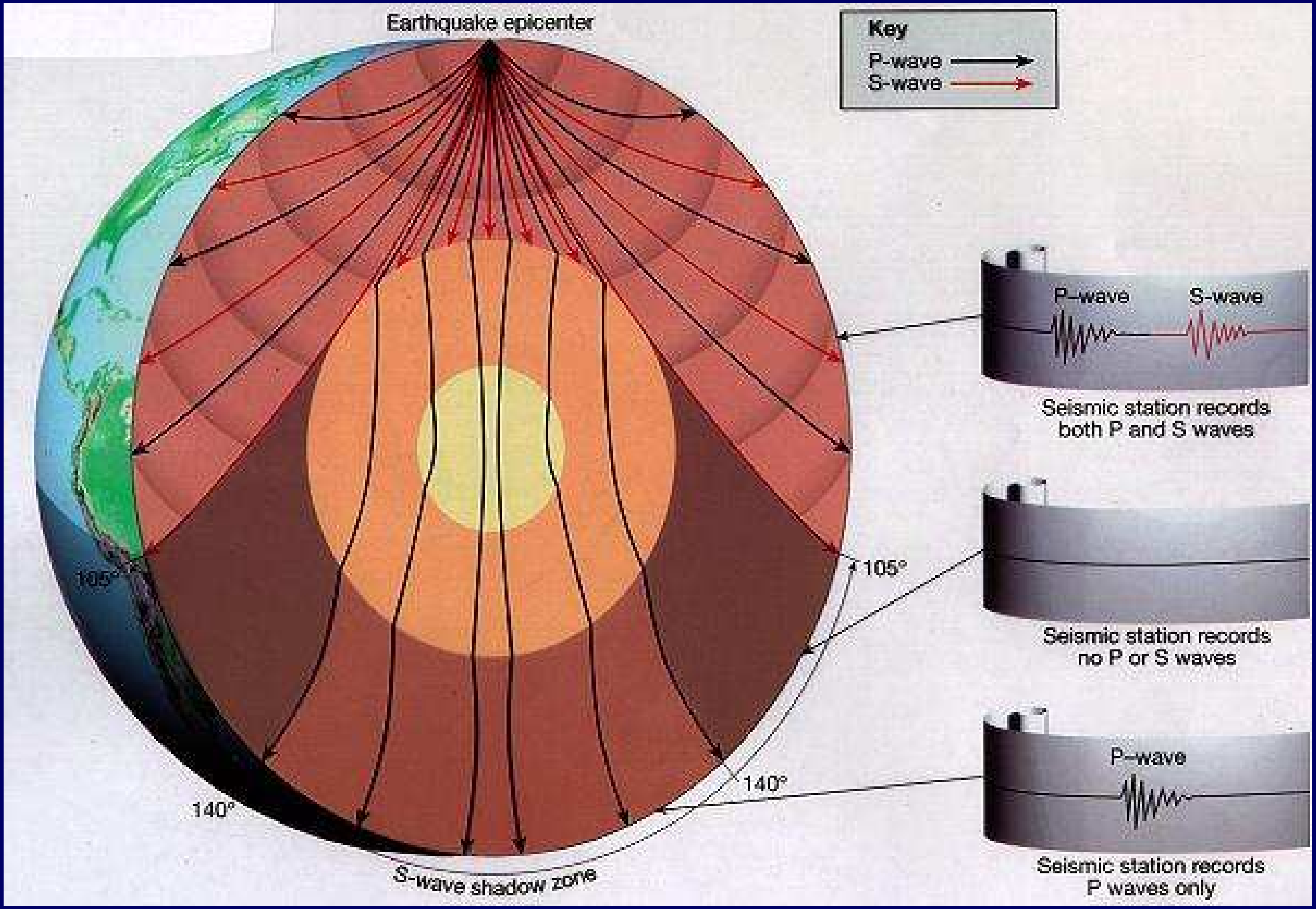


Specific velocities and paths of body waves

The velocities of P and S waves increase with a function of depth changing velocities at the boundary of each minor and major interior Earth section. At the lower mantle and outer core boundary the P wave velocity decreases significantly and the S wave ceases to exist which indicates the presence of a liquid core.

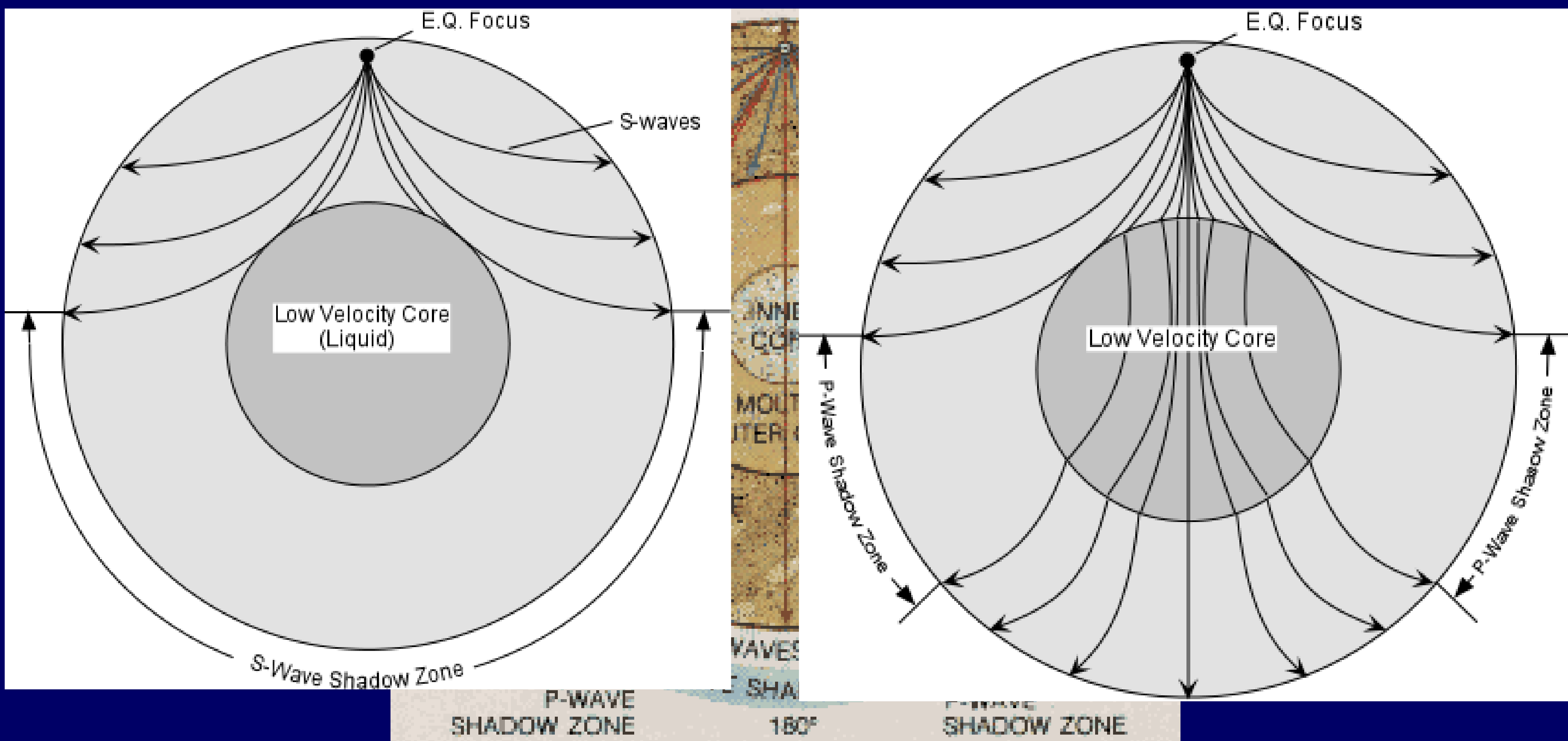


Seismic wave propagation



Shadow zones of P and S waves

Shadow zones of P and S waves are areas on the Earth's surface which do not receive P and/or S waves from earthquakes and can be explained by the Earth's interior structure. The S wave includes an area between 105 degrees on both sides from the epicenter. The P wave shadow zone lies between 105-140 degrees from the epicenter on both sides of the Earth.

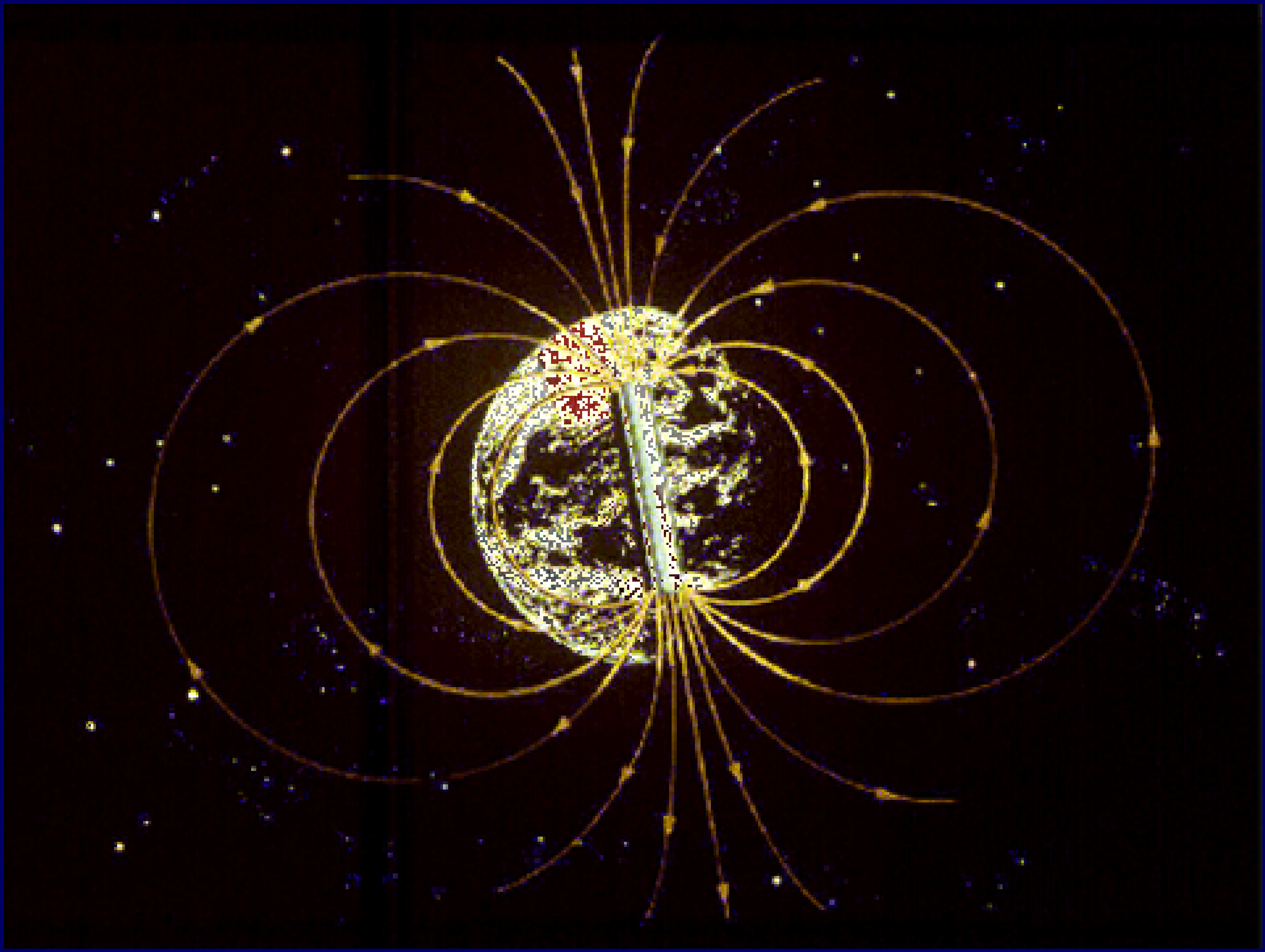


Geomagnetism

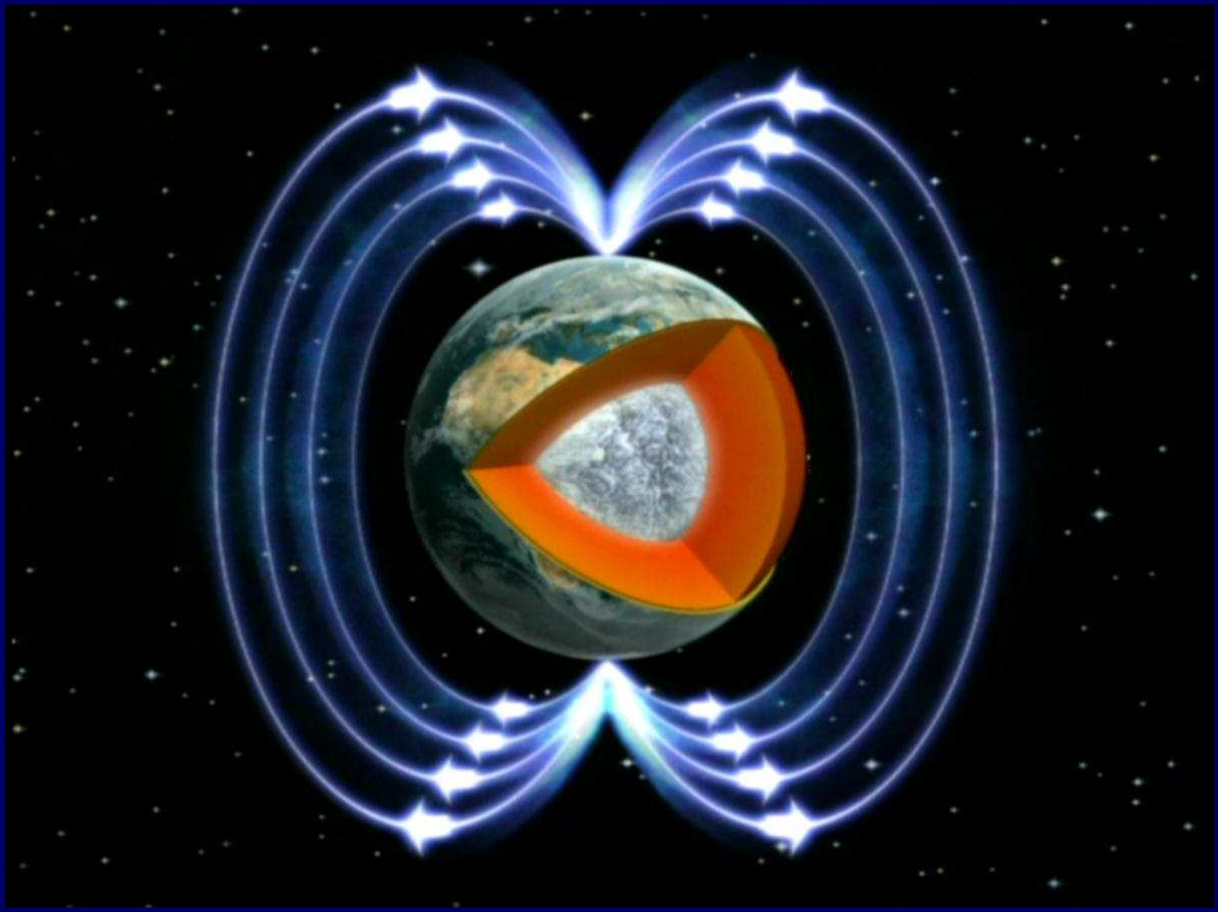
Paleomagnetic evidences of sea floor spreading!!!!

Apparent polar wander paths and tectonic applications

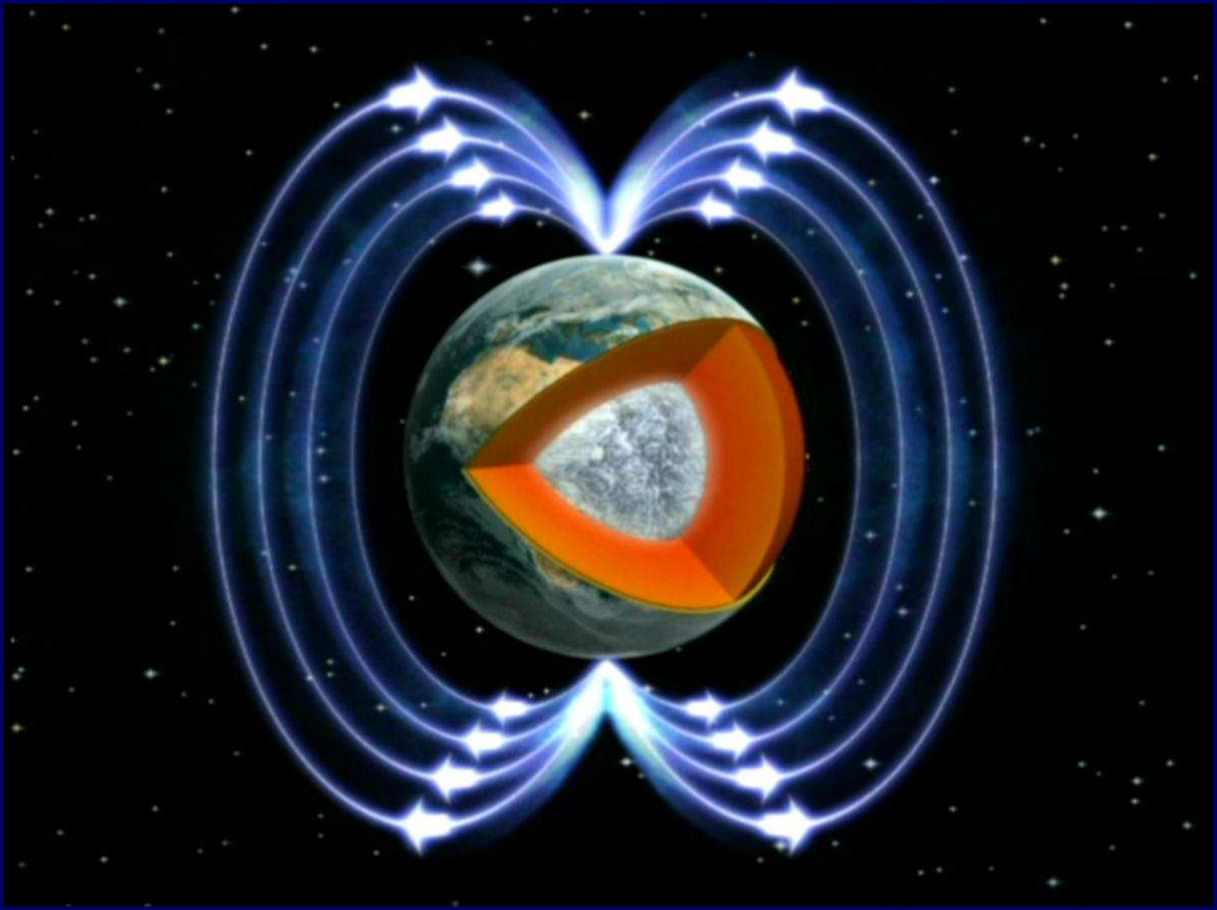
Earth Magnetic Field – magnetic field of a bar magnet



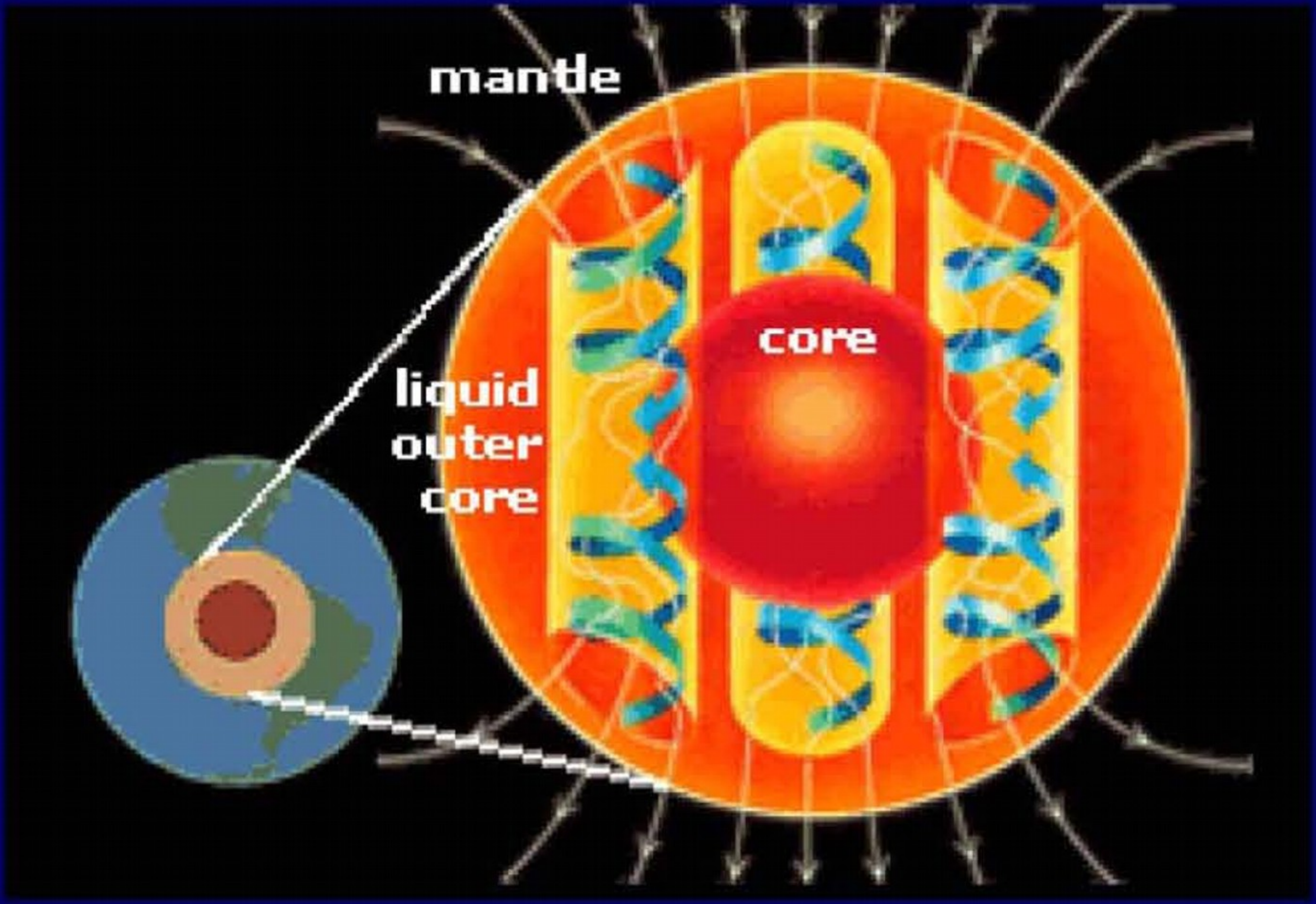
Earth Magnetic Field - animation



Earth Magnetic Field - animation



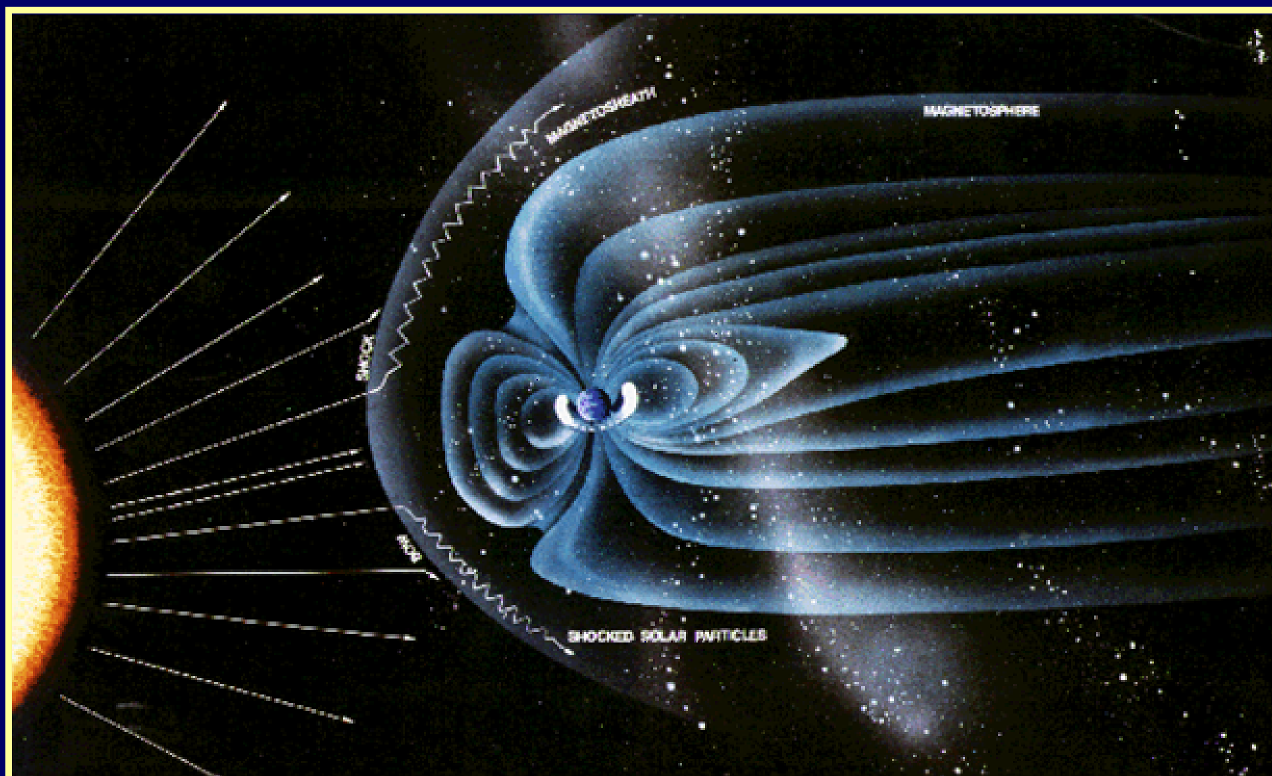
How Earth Magnetic Field is created? We don't know, but here is an idea… Lines show a possible configuration of fluid flow and magnetic field in the liquid outer core. The inner core is a hot solid ball full of iron, that spins at its own rate, as much as 0.2° of longitude per year faster than the Earth above it. It is surrounded by the outer core - a very deep layer also filled with liquid iron. The outer core is the source of the geomagnetic field, as an electrically conducting fluid in constant motion. These complex motions generate our planet's magnetism through a process called the dynamo effect.



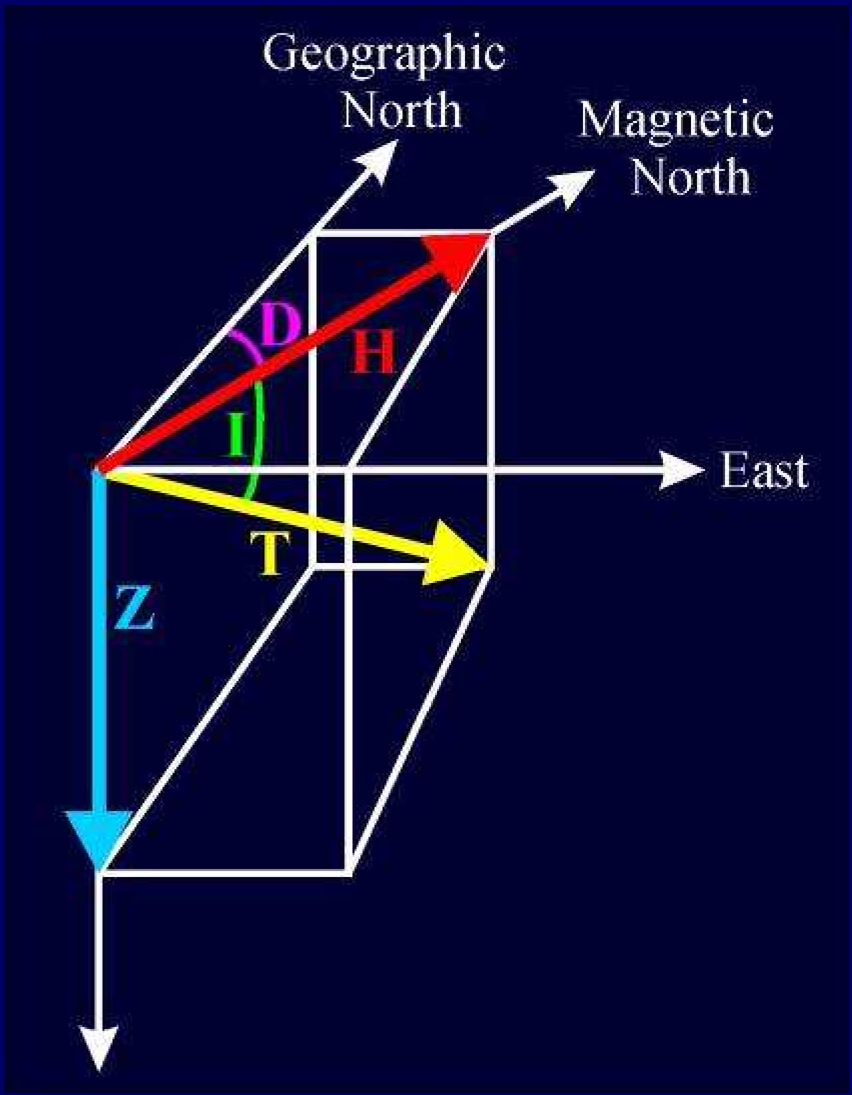
Shape of Earth’s magnetosphere is under the influence of the Sun…

Solar wind envelopes the Earth’s magnetic field…

High energy pulses of solar wind (from sunspot activity) distort the Earth’s magnetic field and produce geomagnetic storms that disrupt the Earth’s environment.



Elements of the Earth's magnetic field



T - total magnetic field

Z - vertical component of magnetic field

H - horizontal component of magnetic field

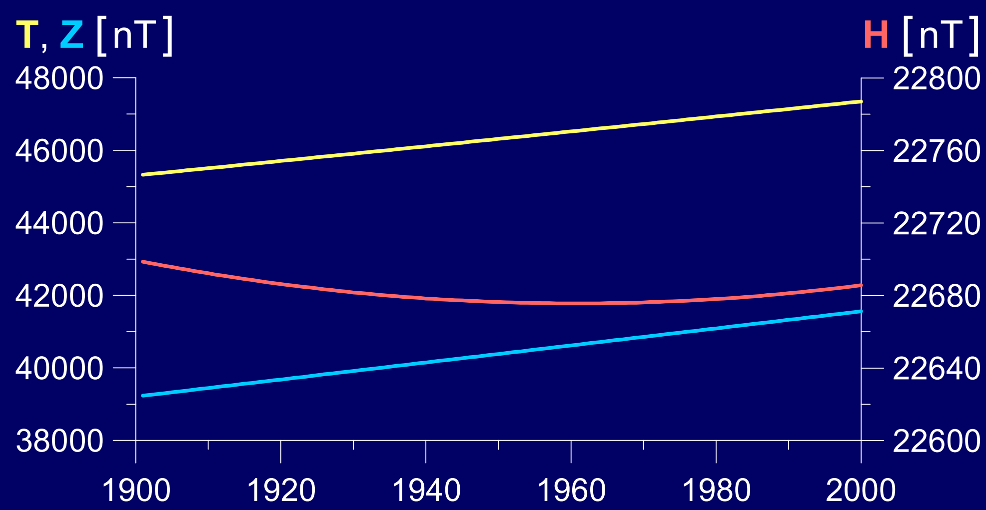
D - declination

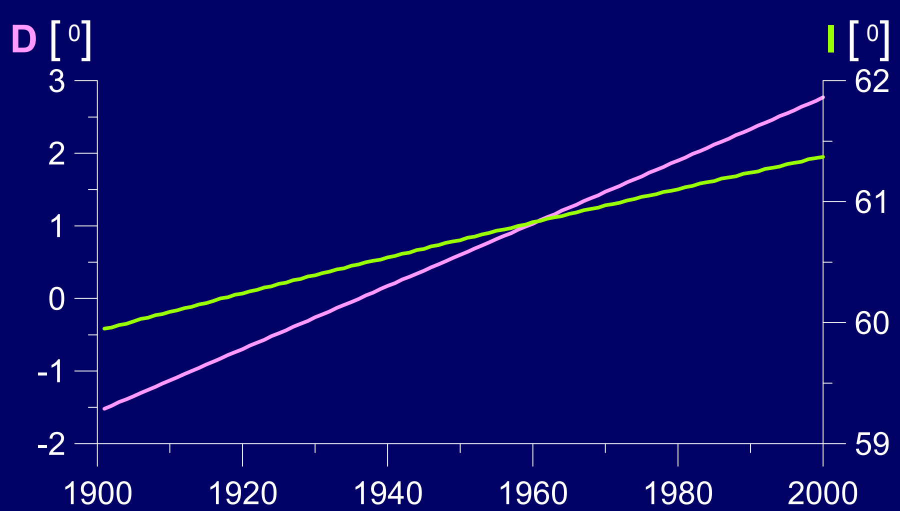
I - inclination

So, the question is…

"Professor, why doesn't the compass just make up its mind and point one direction."

ELEMENTS OF EARTH'S MAGNETIC FIELD
for Belgrade over a period from year 1901- 2000





Earth's magnetic field is changeable both in space and in time. Variations of the elements of normal Earth's magnetic field at station in Belgrade over a period from year 1901-2000 are presented.

T - total magnetic field

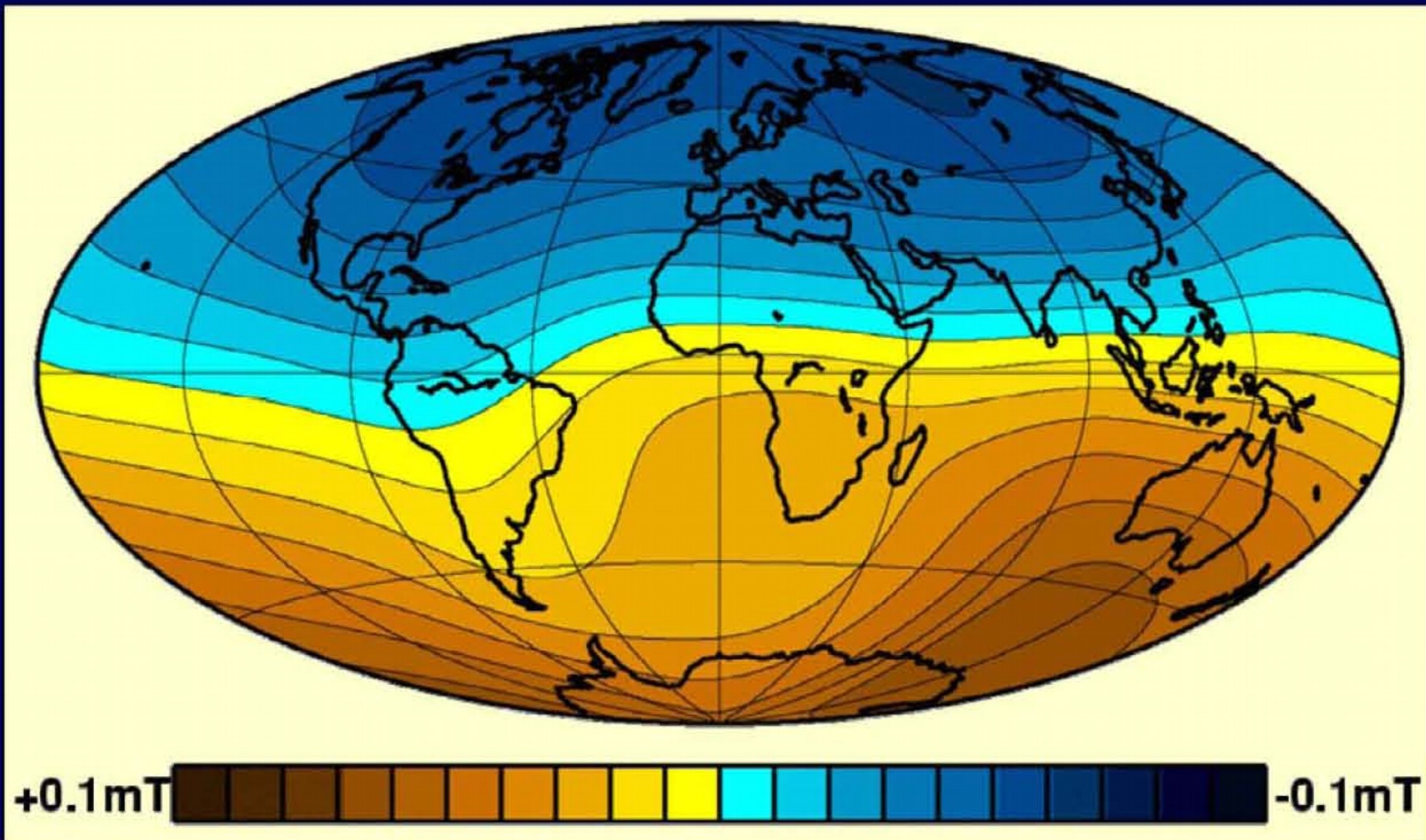
Z - vertical component of magnetic field

H - horizontal component of magnetic field

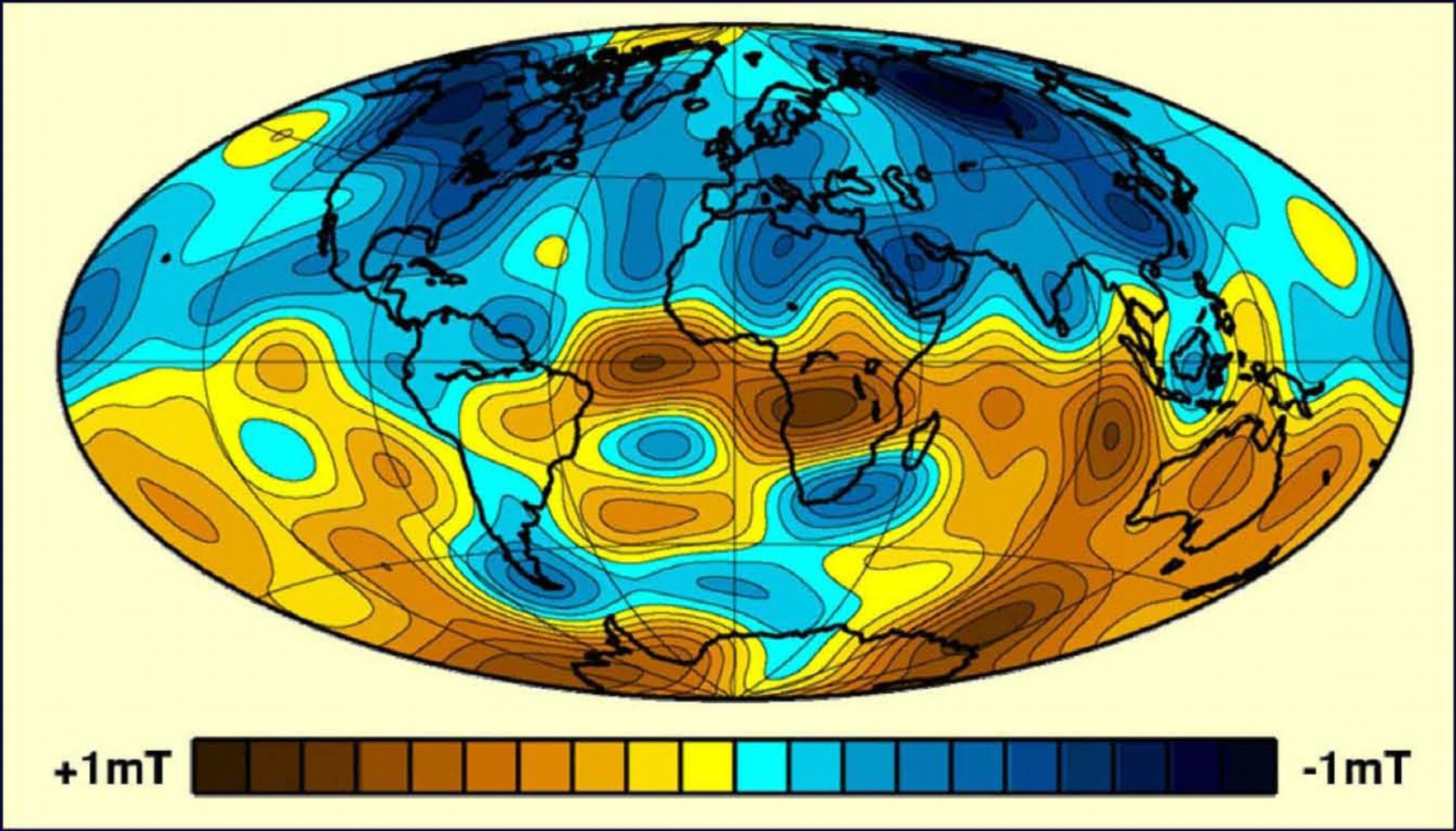
D - declination

I - inclination

Magnetic field at Earth's surface - model calculated using data from the satellites. The majority of the magnetic field we measure at the Earth's surface comes from sources internal to the Earth. We can use the measurements of the magnetic field (especially from satellites) to construct a map of the large scale surface magnetic field (wavelengths greater than order 1000 km).



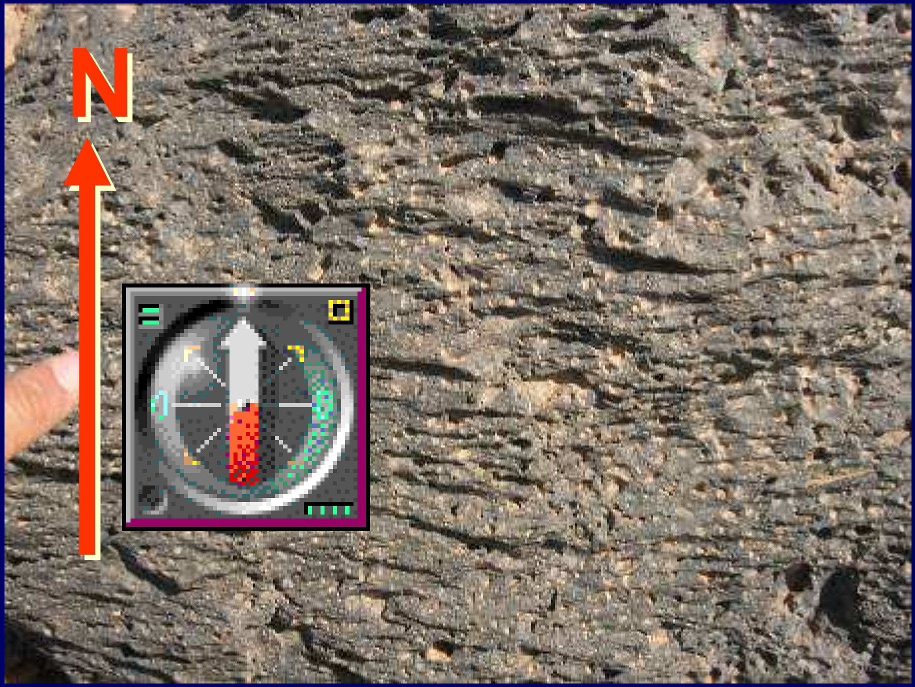
We use the geomagnetic field to probe the structure and dynamics of the Earth. Map shows the long-wavelength field in 2001, on the assumption that the surface field with wavelength longer than 3000 km is dominated by this source (wavelengths shorter than 3000 km arise from the lithospheric field).



A bit of history…

Strongly magnetized rocks had been noticed in 18th century, because of their effect on compass needles.

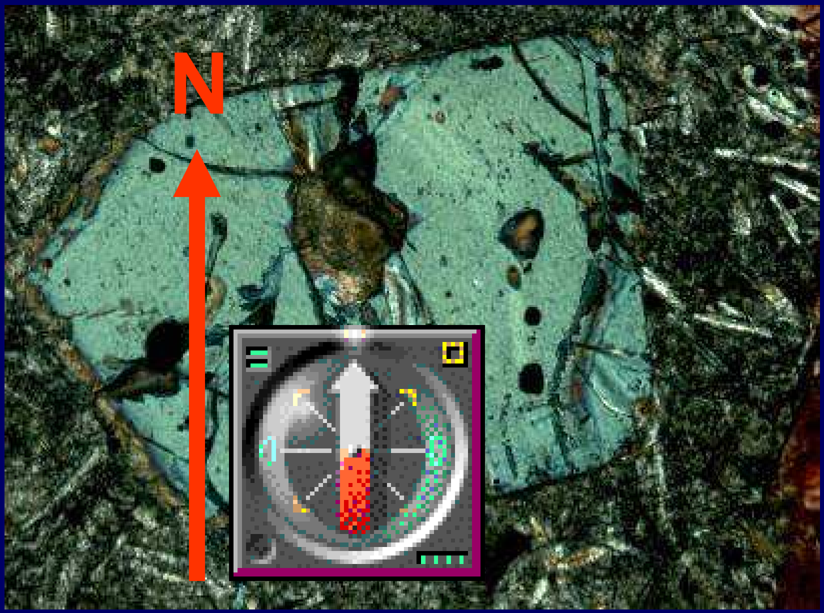
The fact that certain rocks were magnetized in the direction of Earth's field was discovered by Delesse (1849) and Melloni (1853).



Early in the 20th century, B. Brunhes in France (in 1906) and M. Matuyama in Japan (in the 1920s), recognized that rocks generally belong to two groups according to their magnetic properties.

One group has normal polarity, characterized by the magnetic minerals in the rock having the same polarity as that of the Earth's present magnetic field.

The other group has reversed polarity, indicated by a polarity alignment opposite to that of the Earth's present magnetic field.

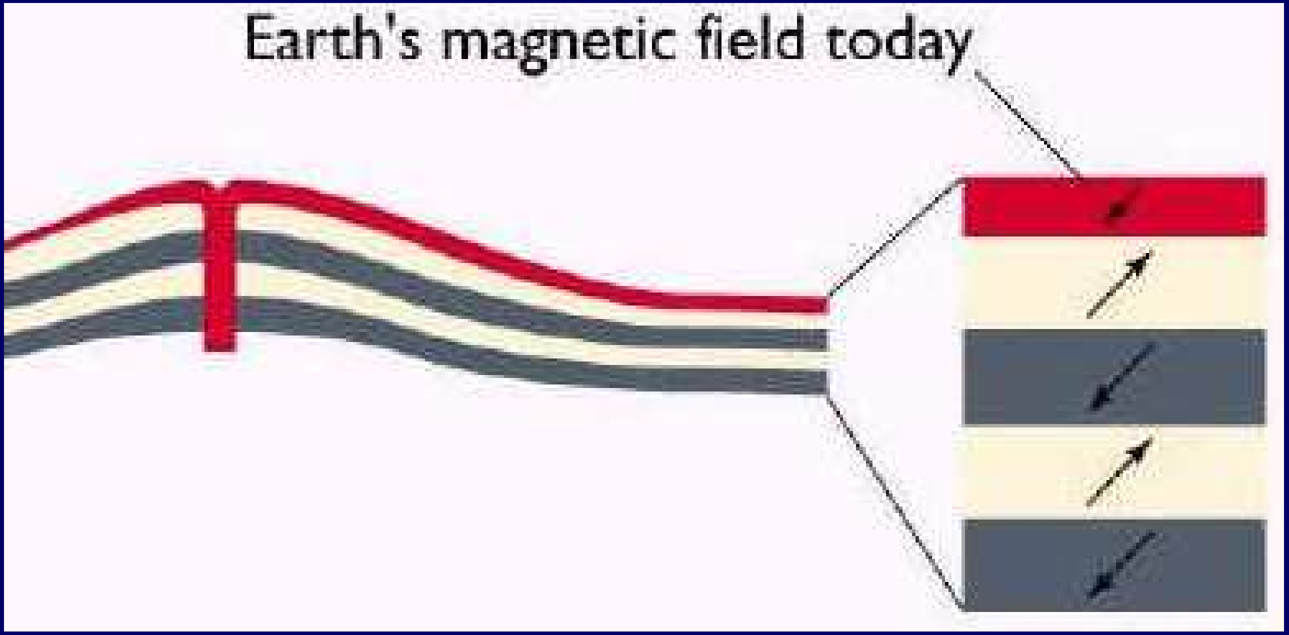


Paleomagnetism was born!

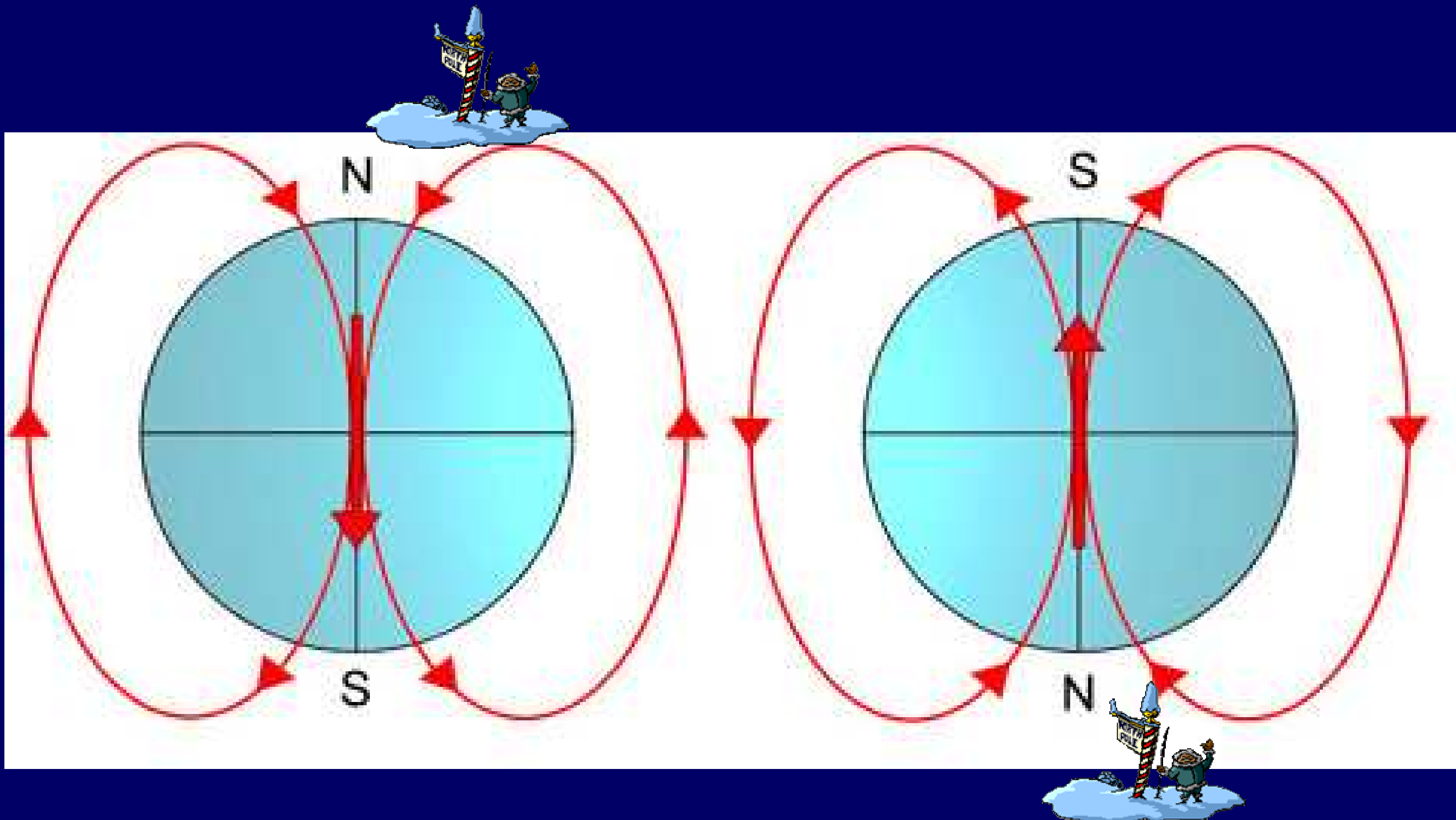
Paleomagnetism - part of geomagnetism that studies the Earth's ancient magnetic field

Mercanton (1926) argued that the magnetic field had reversed – reversely magnetized rocks were found all around the world.

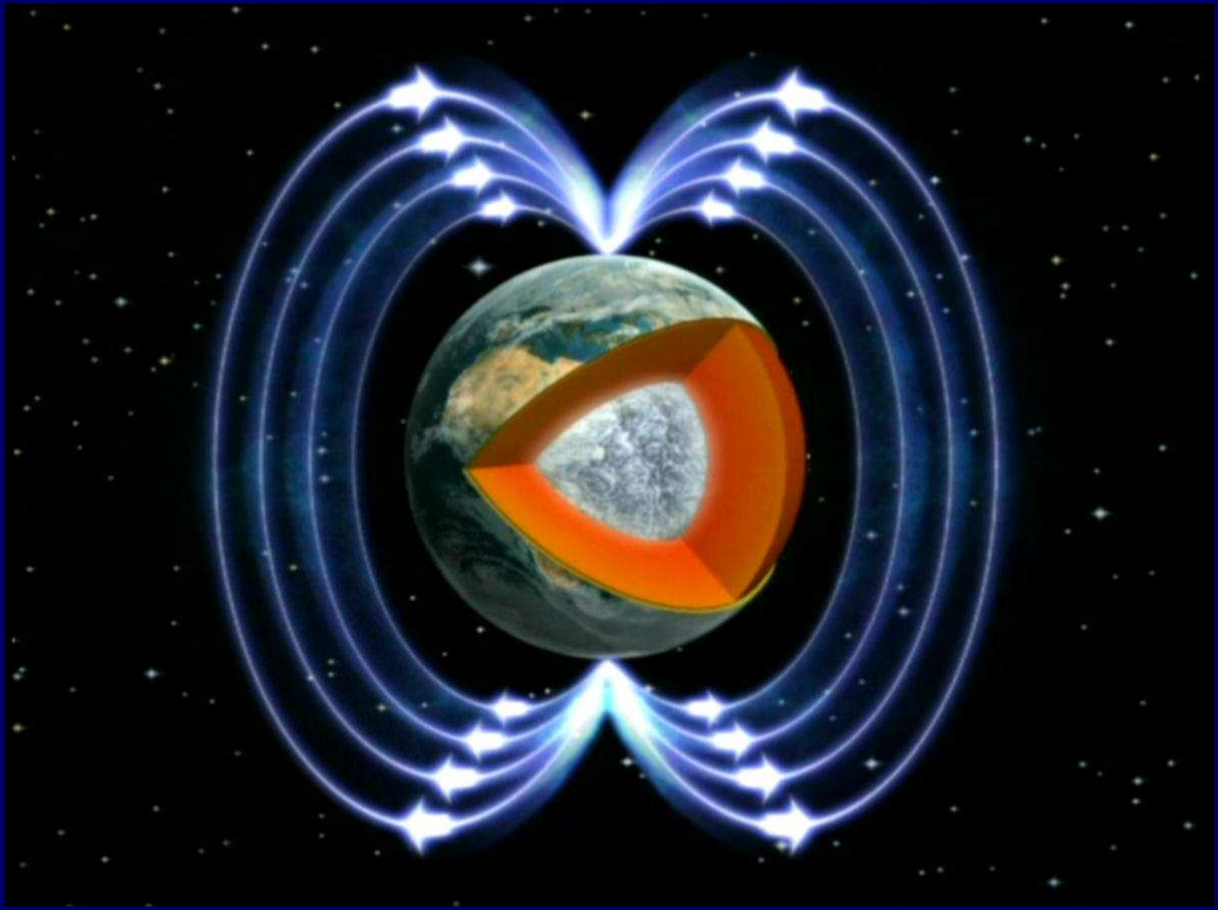
Matuyama (1929) showed that all reversely magnetized rocks in Japan are older than overlaying normally magnetized rocks.



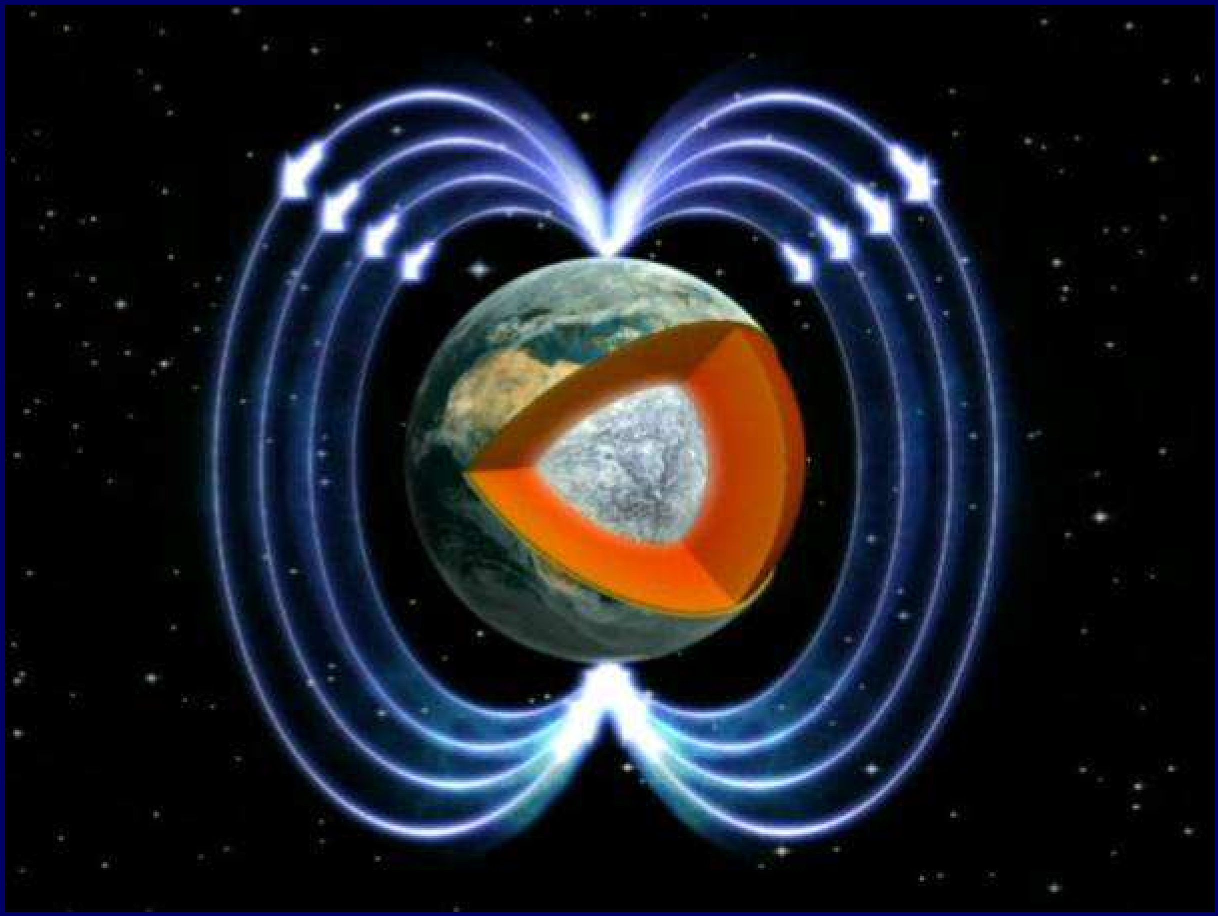
Combined use of paleomagnetism and K-Ar dating (1963) showed the global synchrony of polarity intervals - **a prove of polarity reversals**.



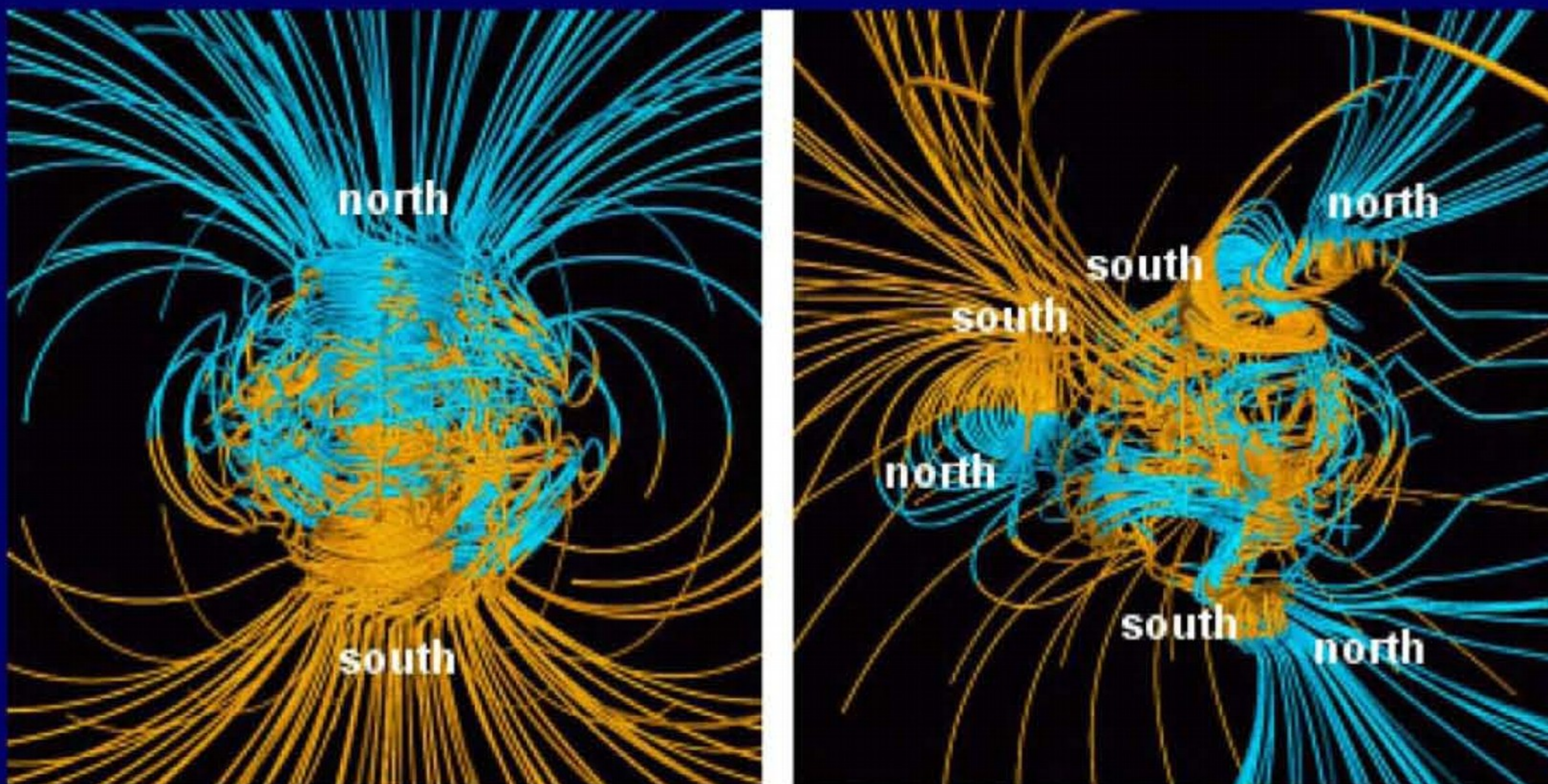
Polar reversals - animation



Polar reversals -animation



We are not quite sure, but it seems to be a traffic jam of poles. Supercomputer models of Earth's magnetic field (Glatzmaier and Roberts) show a normal dipolar field between polarity reversals and the sort of complicated magnetic field during the upheaval of a reversal. What is happening during the polar reversals? Polar reversals, recorded in the magnetism of ancient rocks, are unpredictable. During the course of the last 5 million years reversals have happened around 25 times. They come at irregular intervals averaging about 300 000 years, the last one was approximately 780 000 years ago. The phenomenon will certainly repeat itself, we just don't know when. The dynamo in the Earth's interior is unstable such that on occasion the field weakens (but it does not vanish, it is still protecting us from space radiation and solar storms), loses its bipolar character, gets more complicated and regenerates with reversed polarity. It is believed that the reversal process takes several thousand years, but some modern opinions suggest a shorter time.



between reversals | during a reversal

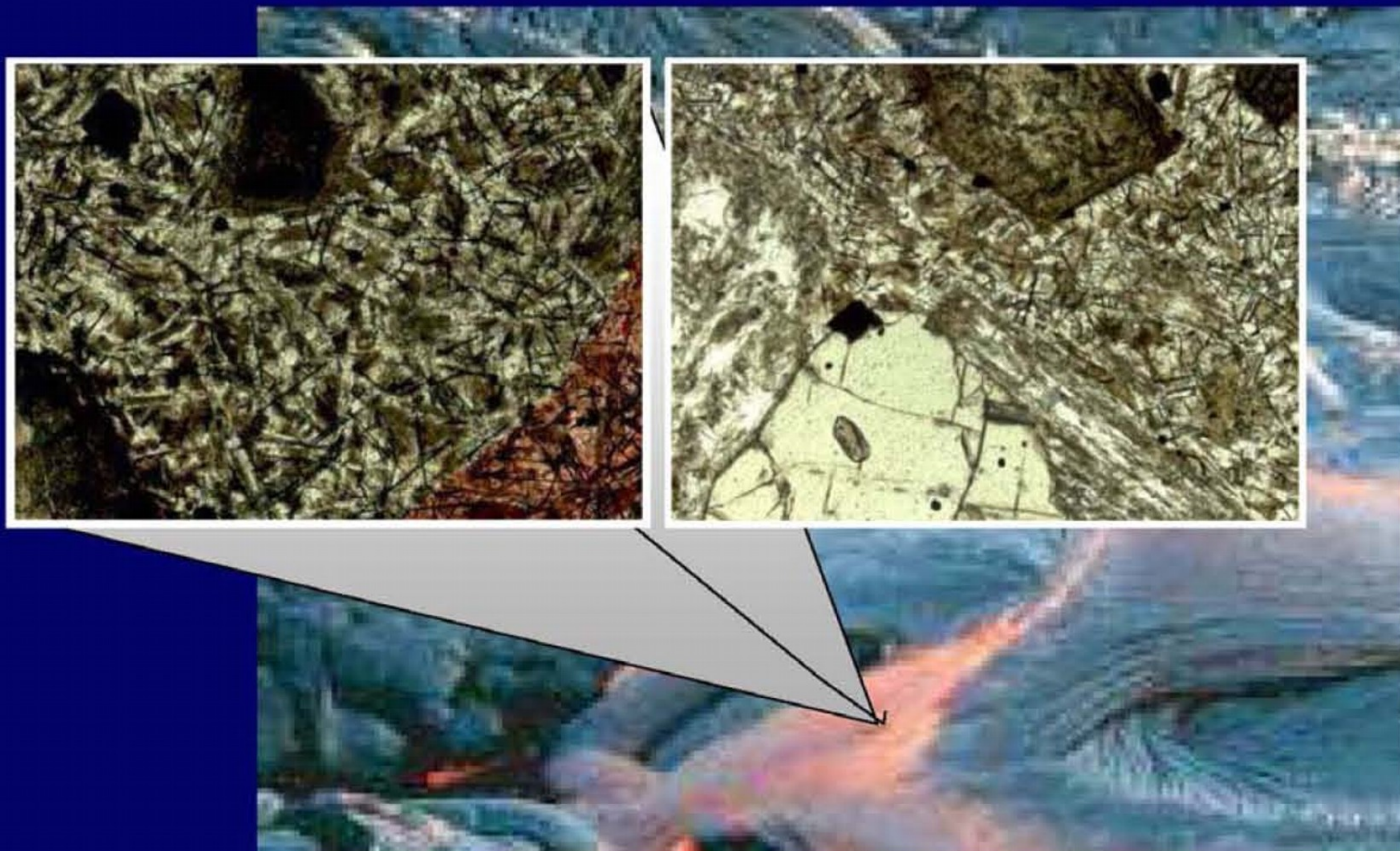
Globally the magnetic field has weakened 10% since the 19th century.

Is Earth's magnetic field collapsing?

Probably not. These changes are mild compared to what Earth's magnetic field has done in the past. The ongoing decline doesn't mean that a reversal is imminent. From studies of the paleomagnetic records we know that the field is increasing or decreasing all the time. Earth's present-day magnetic field is, in fact, much stronger than normal. The dipole moment is now twice larger than the million-year average.

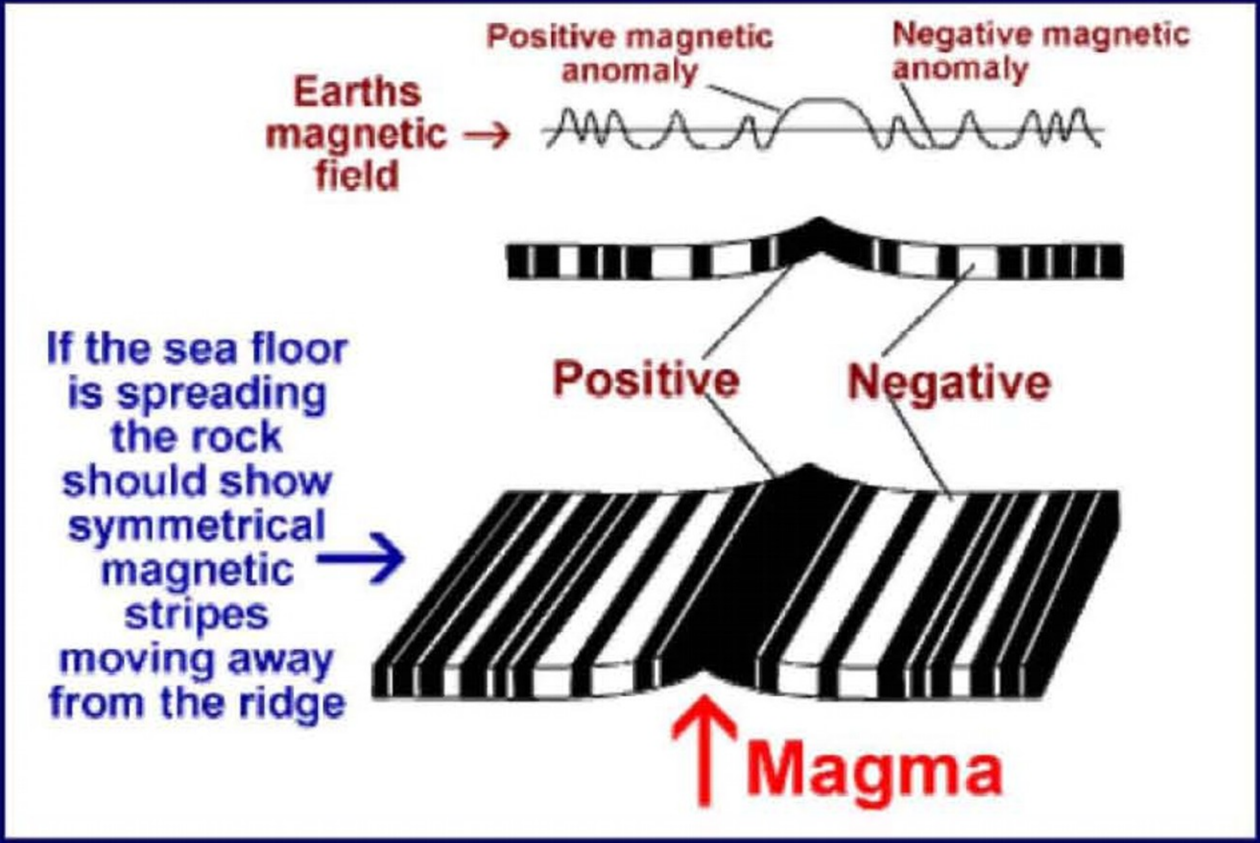
This answer lies in the magnetite in volcanic rock. How can rock remember magnetic past? Grains of magnetite, behaving like little magnets, can align themselves with the orientation of the Earth's magnetic field. When magma cools to form solid volcanic rock, the alignment of the magnetite grains is "locked in", recording the Earth's magnetic orientation or polarity (normal or reversed) at the time of cooling.

First there is a lava flow, but rock is to young to remember. While the lava is still well above the Curie temperature, crystals start to form, but are non-magnetic. Below the Curie temperature, but above the blocking temperature, certain minerals become magnetic. Their moments continually flip among the easy axes with a statistical preference for the applied magnetic field. As the lava cools down, the moments become fixed, preserving a thermal remanence.



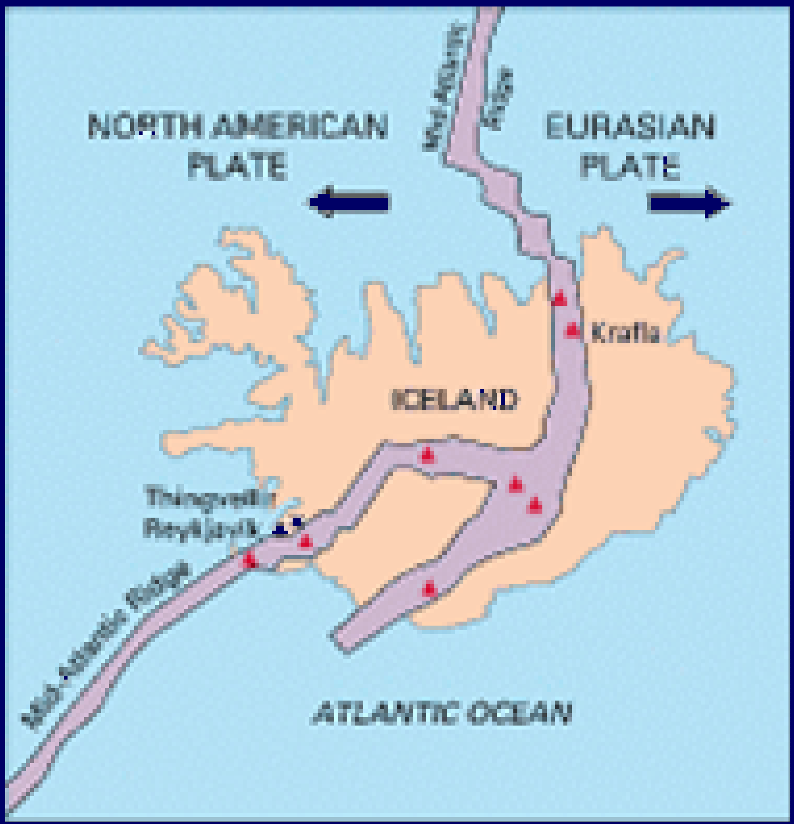
Magnetic striping and polar reversals

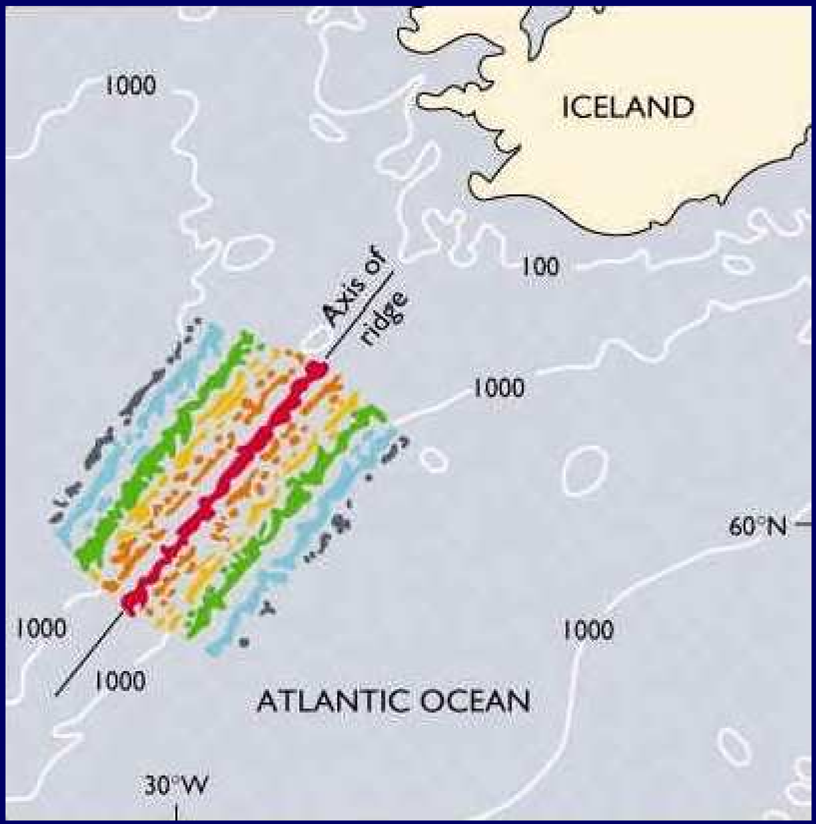
Beginning in the 1950s, scientists began recognizing odd magnetic variations across the ocean floor, obtained by geomagnetic measurements. This finding, though unexpected, was not entirely surprising because it was known that basalt (the iron-rich volcanic rock making up the ocean floor) contains a strongly magnetic mineral and can locally distort compass readings.



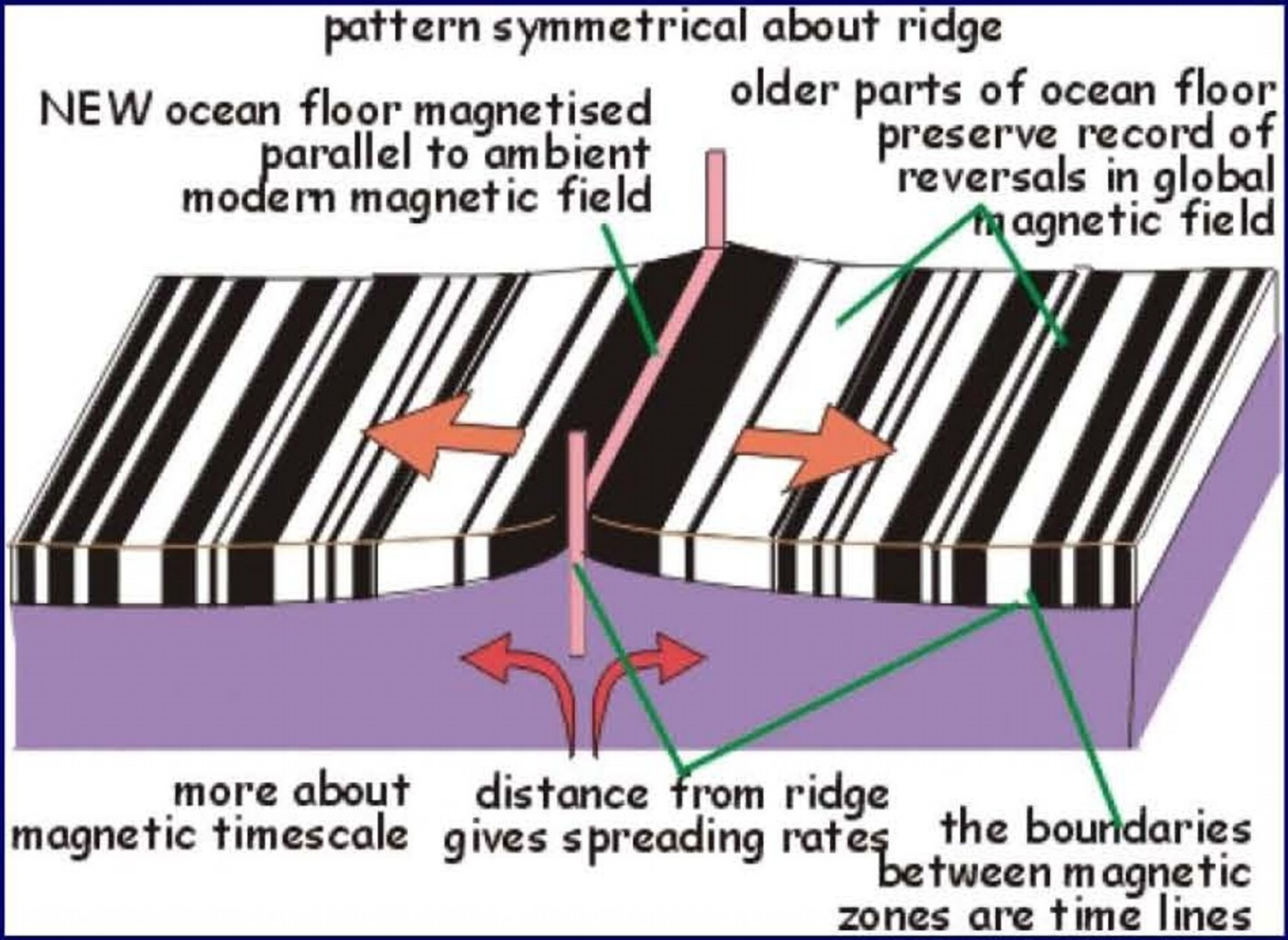
This distortion was recognized by Icelandic mariners as early as the late 18th century.

Newly discovered magnetic variations provided another means to study the deep ocean floor.

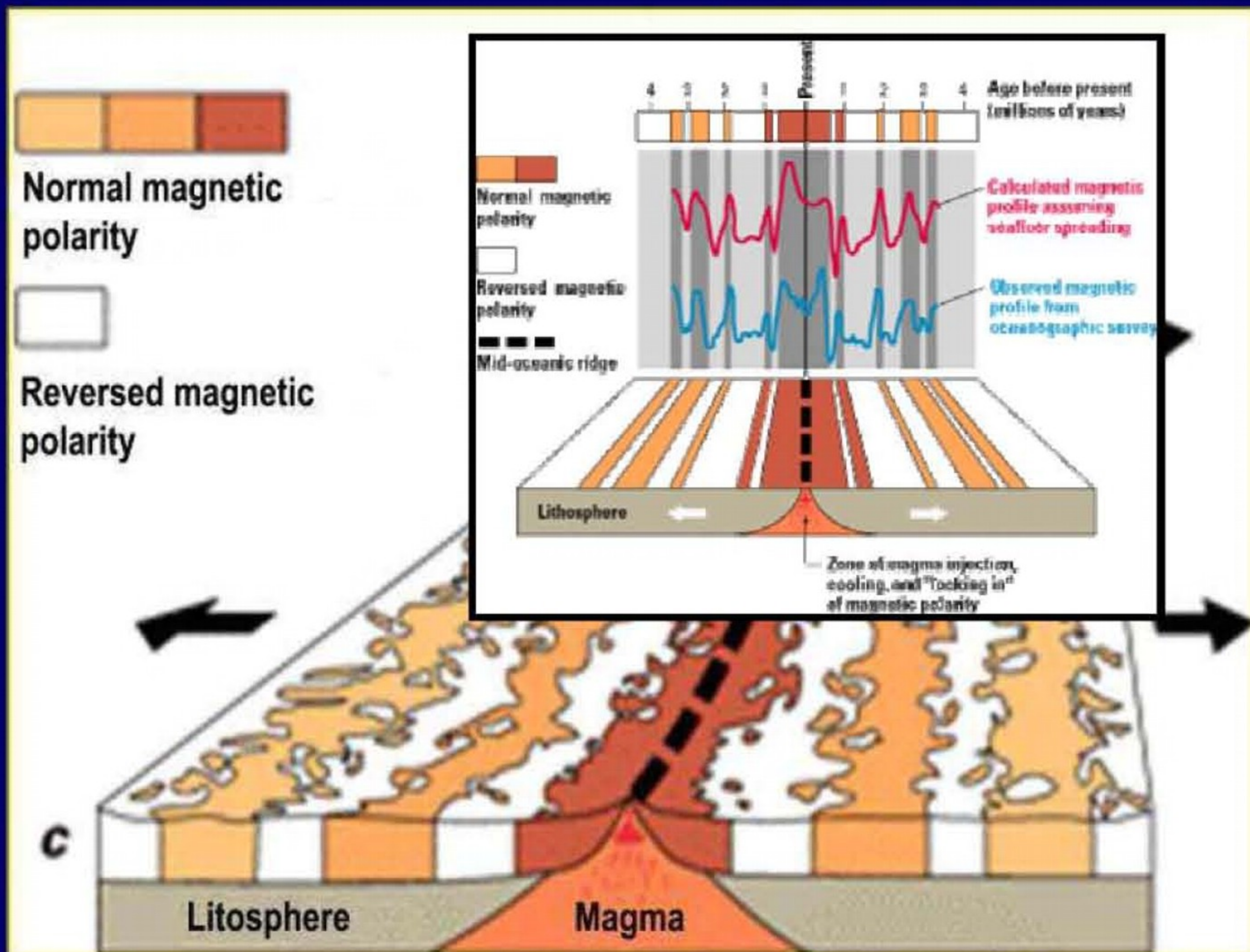




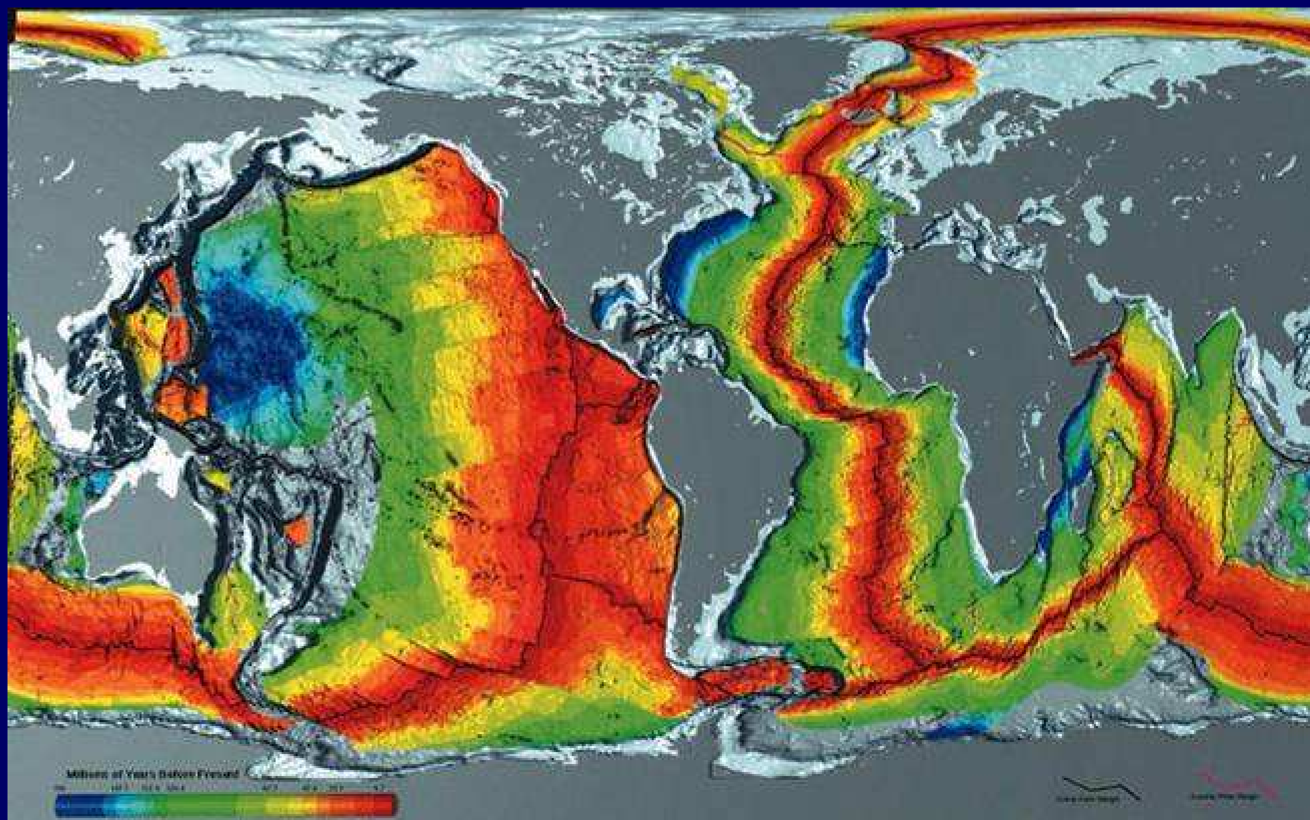
The overall pattern, defined by these alternating bands of normally and reversely polarized rock, became known as magnetic striping. When magnetic patterns were mapped over a wide region, the ocean floor showed a zebra-like pattern. Alternating stripes of magnetically different rock were laid out in rows on either side of the mid-ocean ridge.

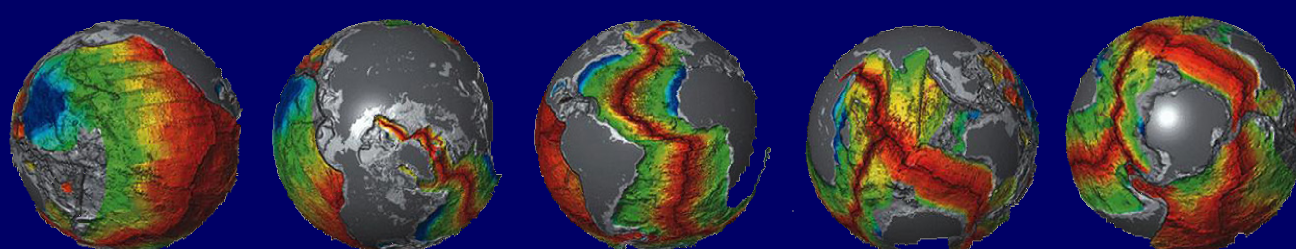


A theoretical model of the formation of magnetic striping. New oceanic crust forming continuously at the crest of the mid-ocean ridge cools and becomes increasingly older as it moves away from the ridge crest with seafloor spreading. a. the spreading ridge about 5 million years ago; b. about 2 to 3 million years ago; c. present-day.

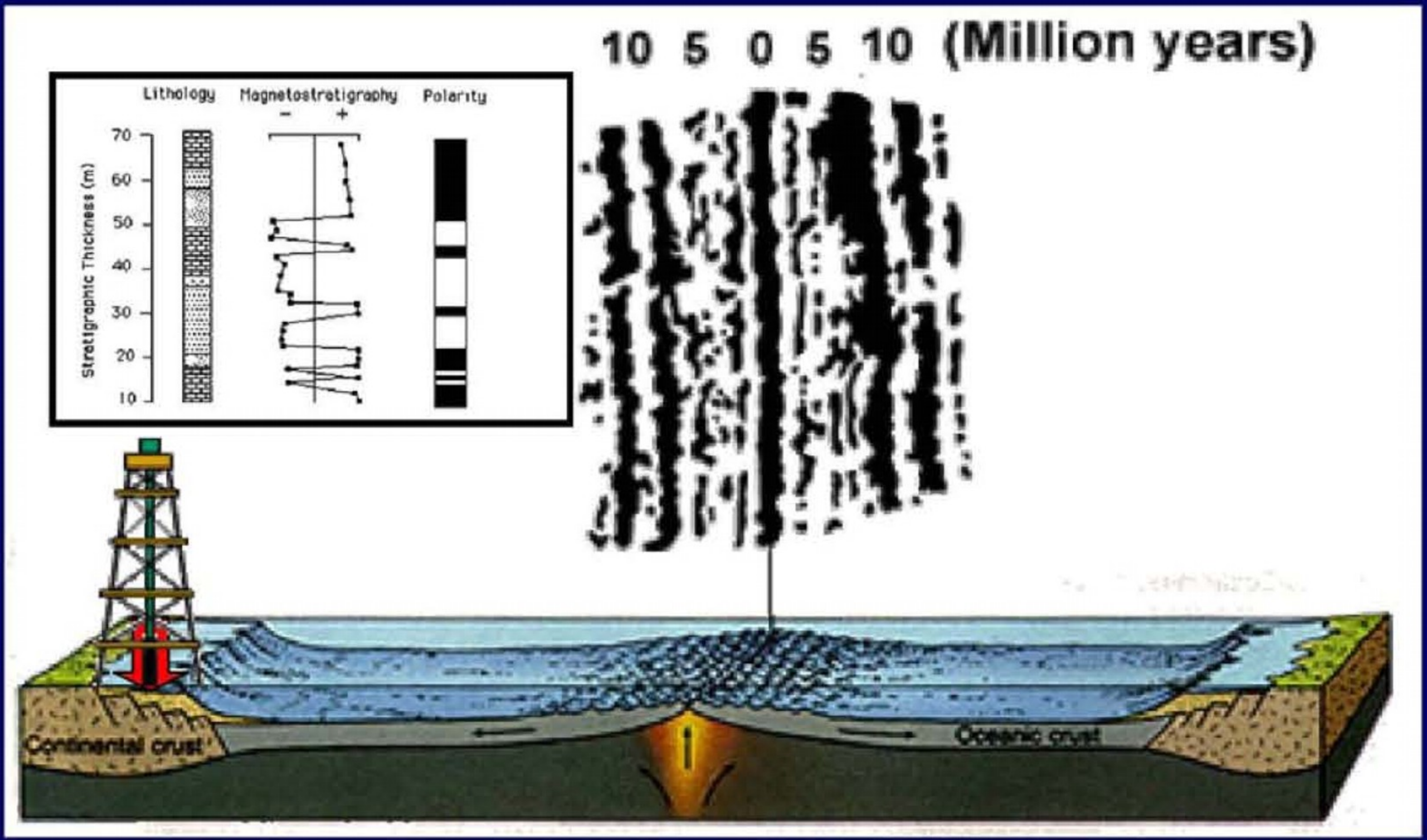


Magnetic variations turned out not to be random or isolated occurrences, but instead revealed recognizable patterns.

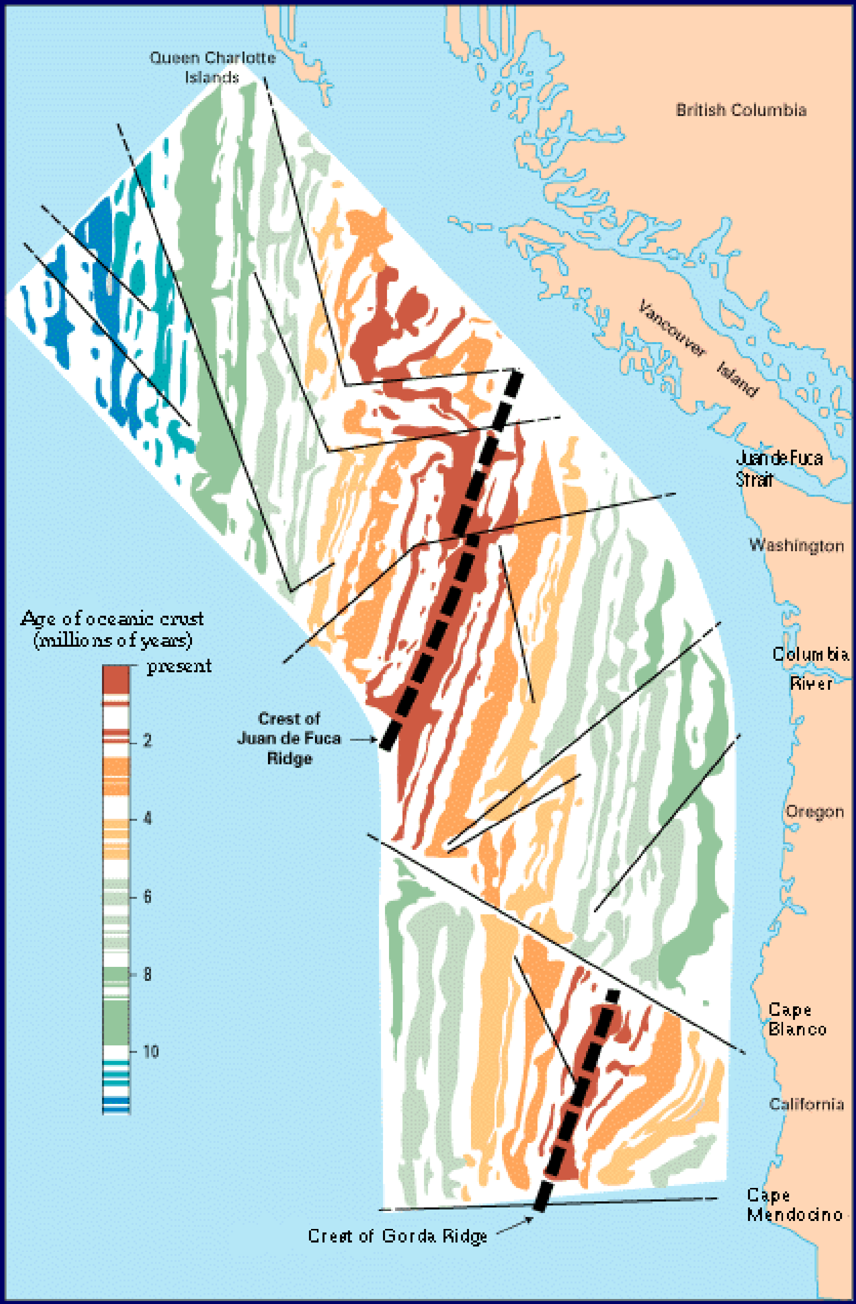




Field reversals had already been demonstrated for magnetic rockson the continents, and a logical next step was to see if these continental magnetic reversals might be correlated in geologic time with the oceanic magnetic striping. In 1963, hypothesis that the magnetic striping was produced by repeated reversals of the Earth's magnetic field was born.



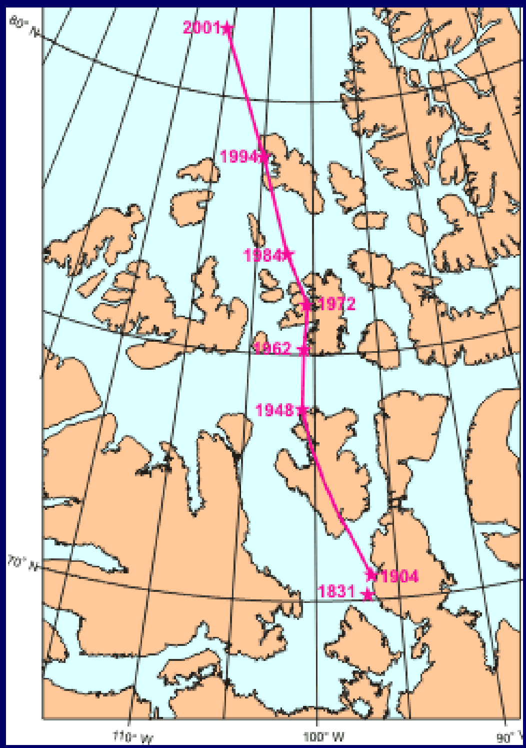
Age of oceanic crust was determined using the results of the magnetic measurements and isotopic K/Ar dating.



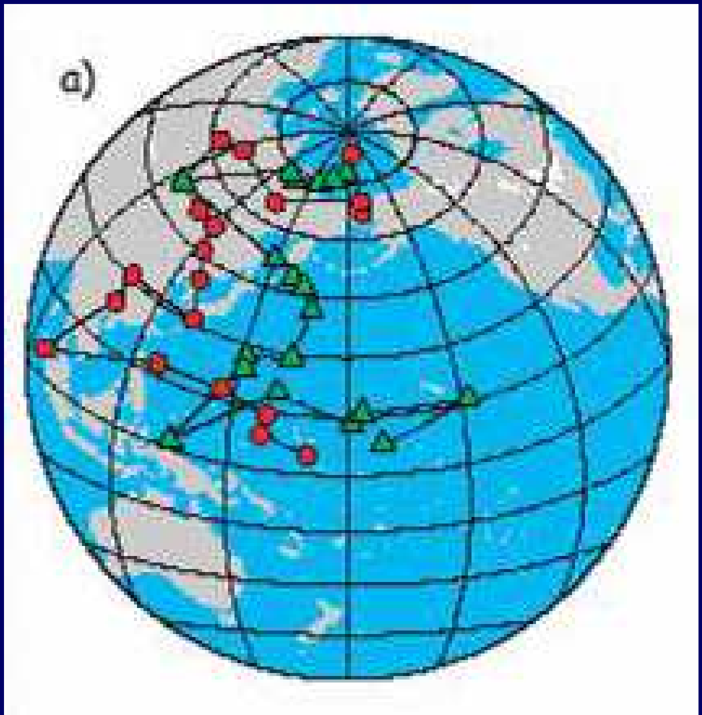
Apparent polar wander paths and tectonic applications of paleomagnetism

There are two types of magnetic polar wander:

a) **true polar wonder**
wandering of the magnetic pole

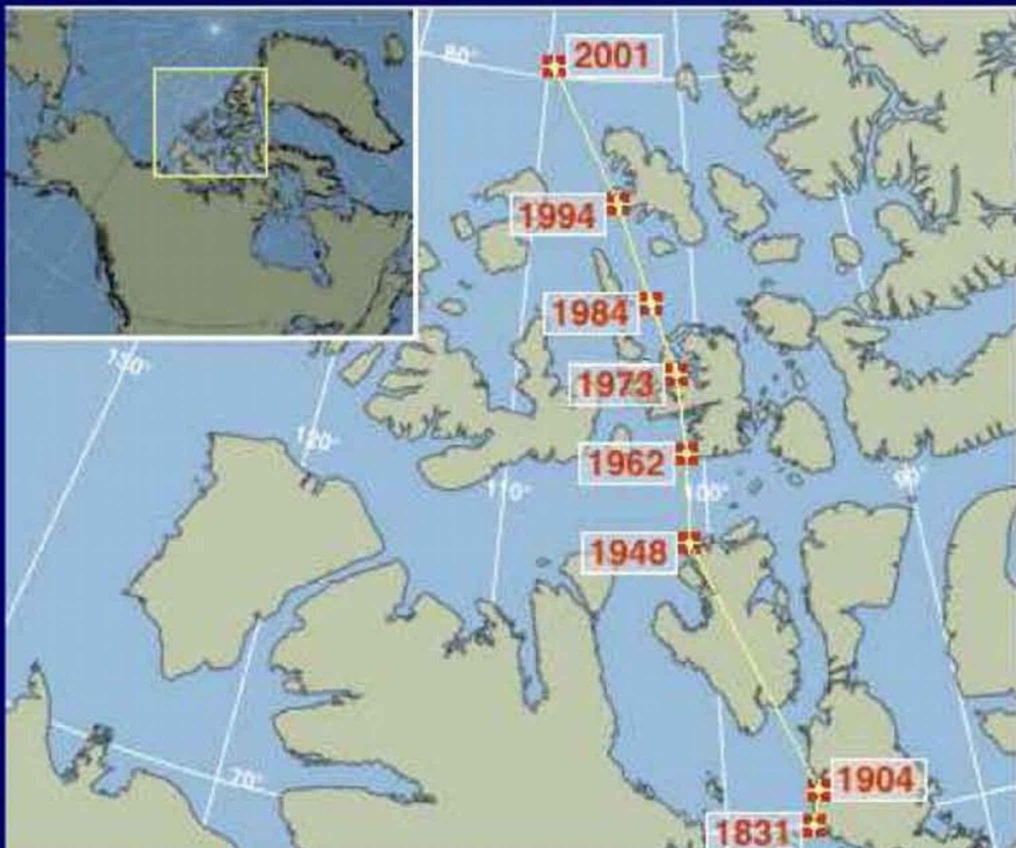


b) **apparent polar wander**
wandering of the continents



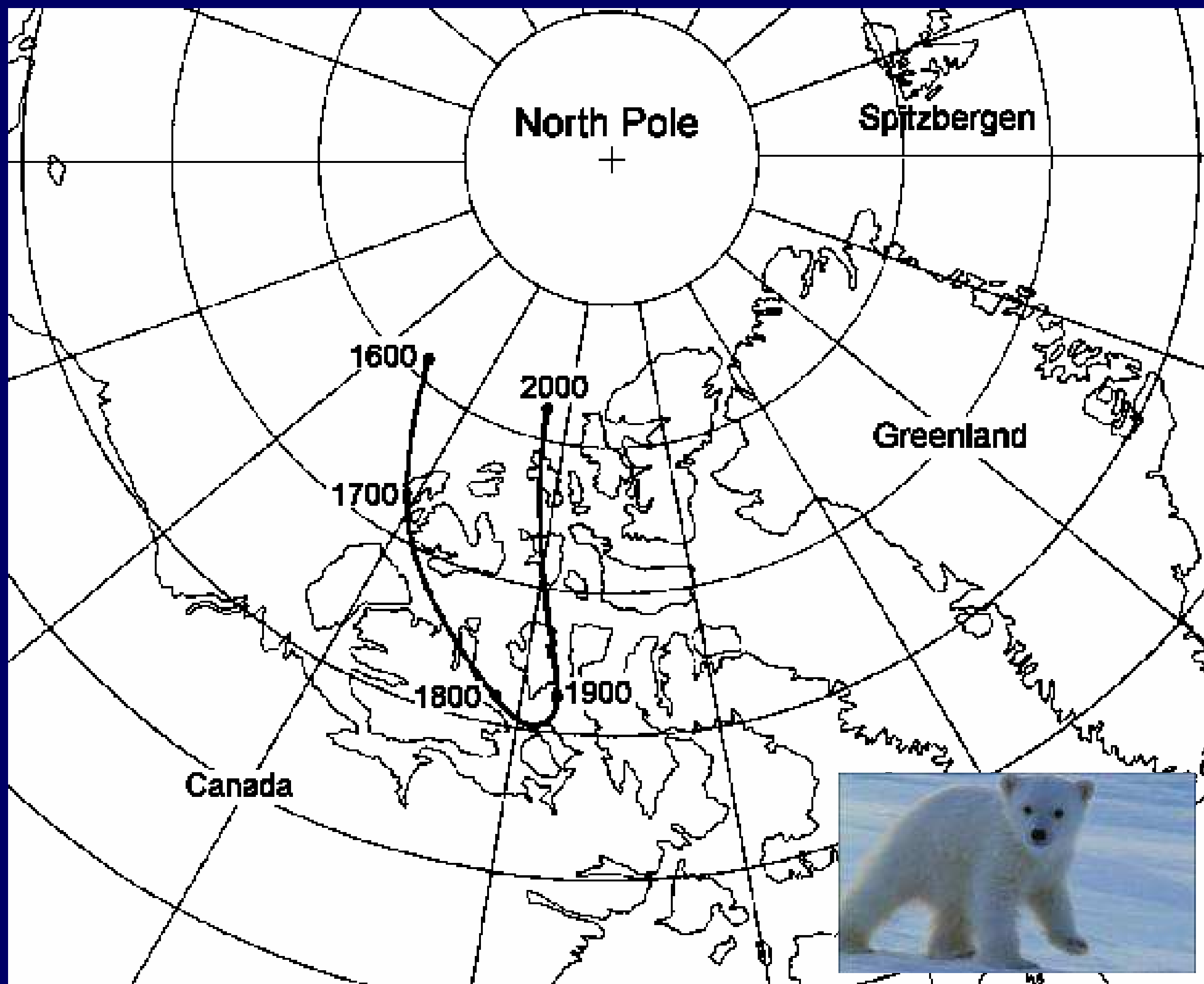
True polar wonder - wandering of the magnetic pole

The "North" magnetic pole moves day by day an oval loop. The pole shifts to the north/northwest, at an average speed of 10 km per year, lately accelerating to 40 km per year. At this rate it will exit North America and reach Siberia in a few decades. Such predictions could prove wrong. The direction and speed of polar movement could easily change a few years from now.



The points on the map of the Canadian Arctic depict where explorers have plotted the migrated pole for almost two centuries. The "North" magnetic pole is currently about 1000 kilometers from the terrestrial pole. Scientists have long known that the magnetic pole moves. James Ross located the pole in 1831 after an exhausting journey during which his ship got stuck in the ice for 4 years. In 1904, Roald Amundsen found the pole again and discovered that it had moved at least 50 km since the days of Ross.

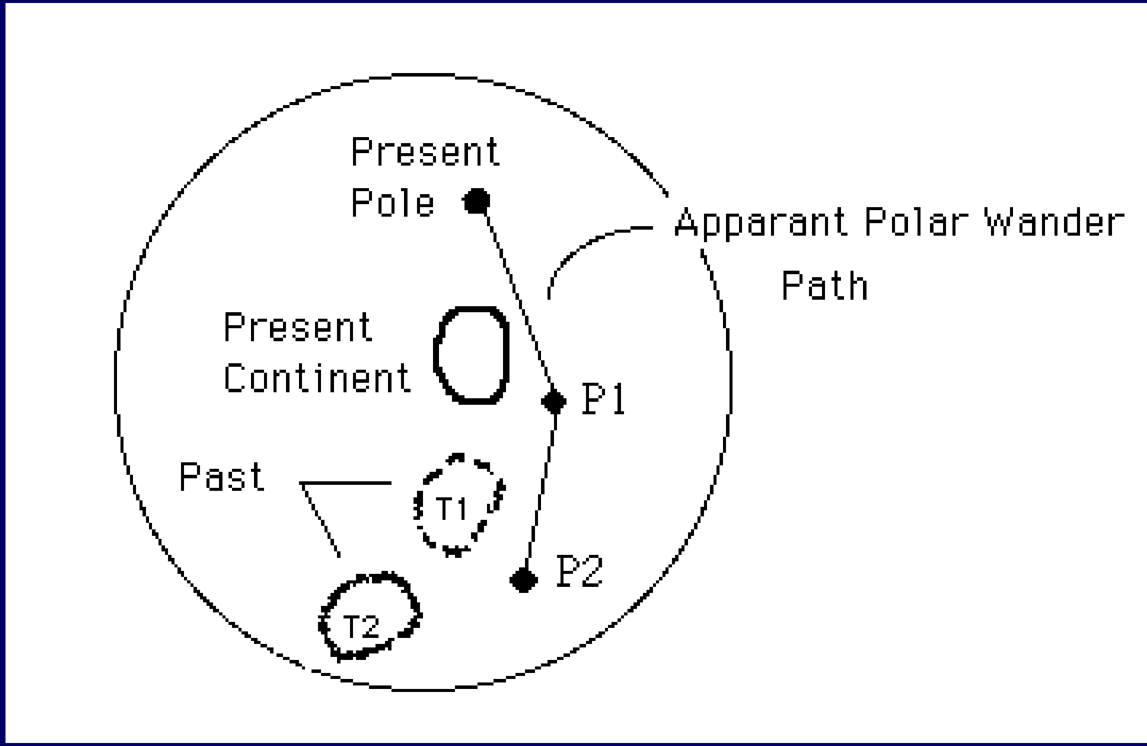
If we use all the observations from the 1500s until today and employ Gauss' model, we obtain the map that shows movement of the magnetic north pole from 1600 to 2000.



Apparent polar wonder - wandering of the continents

Paleomagnetic data hold the secret of the movements of the continents.

To reveal that secret we have to reverse the process of forming the rock. We have to demagnetize the rock by the process of step by step heating, up to the Curie temperature (thermal demagnetization). This way we can remove all the magnetization rock "picked up" after forming and reveal the original magnetization of the rock.

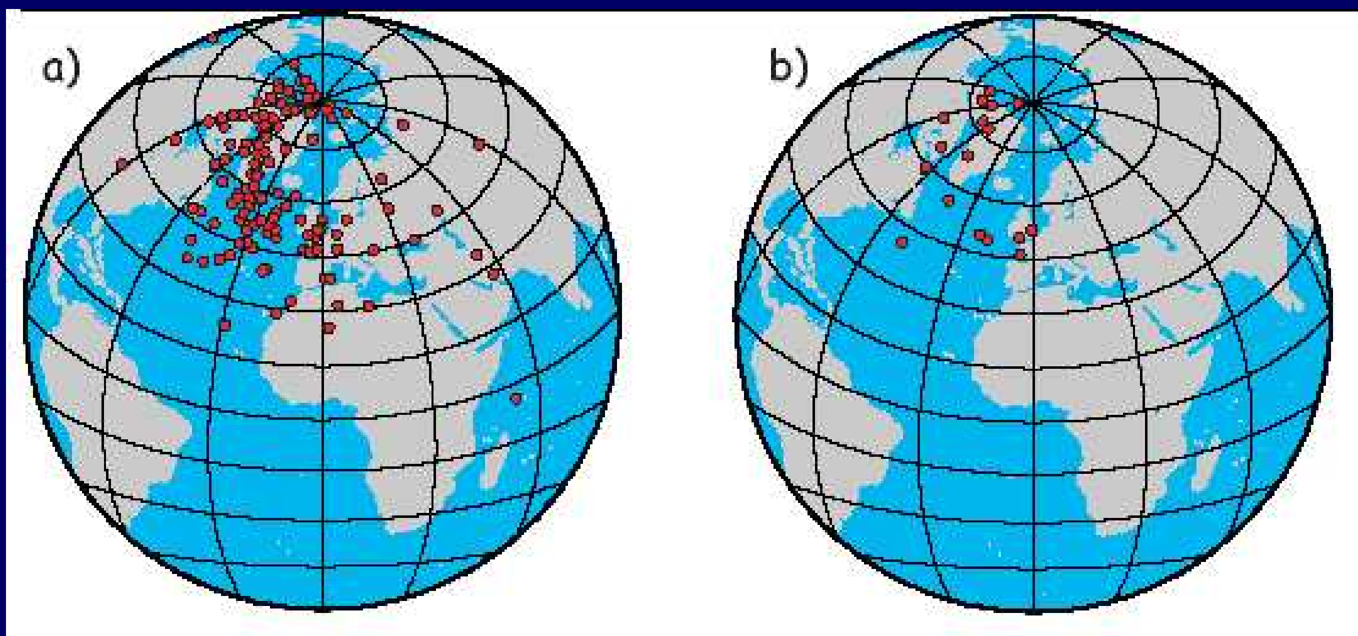


Since the rock can change its original position inside of the continent through geological history, we have do peleomagnetic measurements on large number of rock samples from different investigation sites.

Example from Australia shows the positions of paleomagnetic poles for the last 200 million years. Picking out the meaningful poles from large number of data is the art of paleomagnetism:

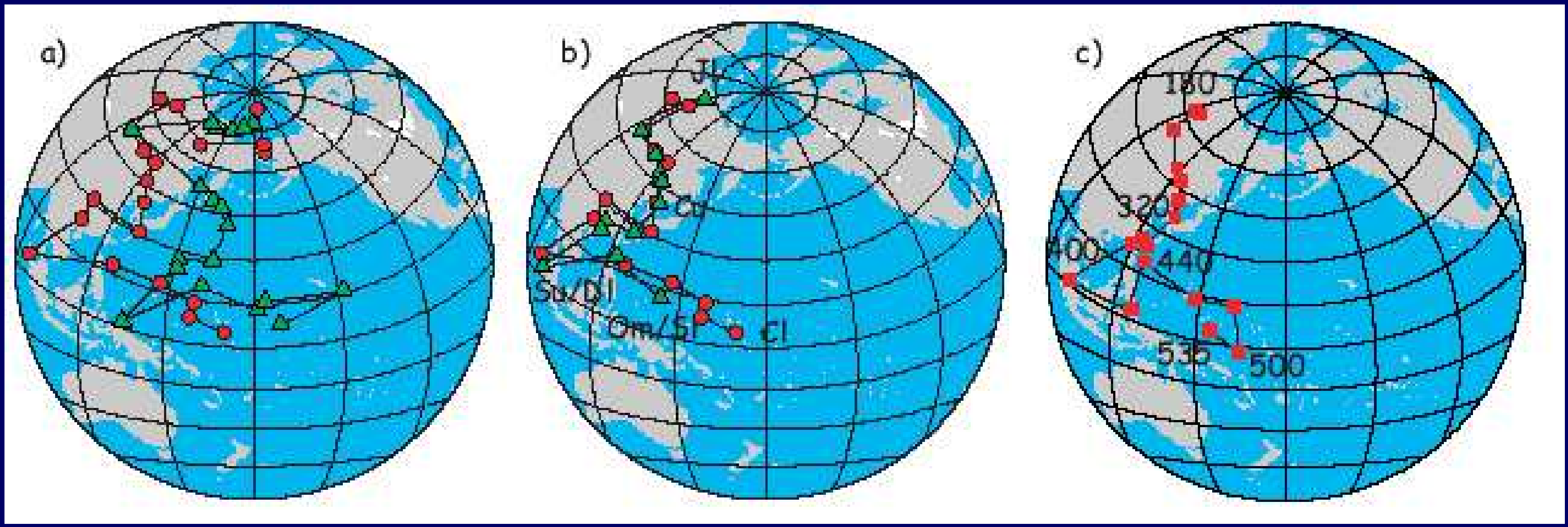
a) no selection criteria

b) using BC02 selection criteria.

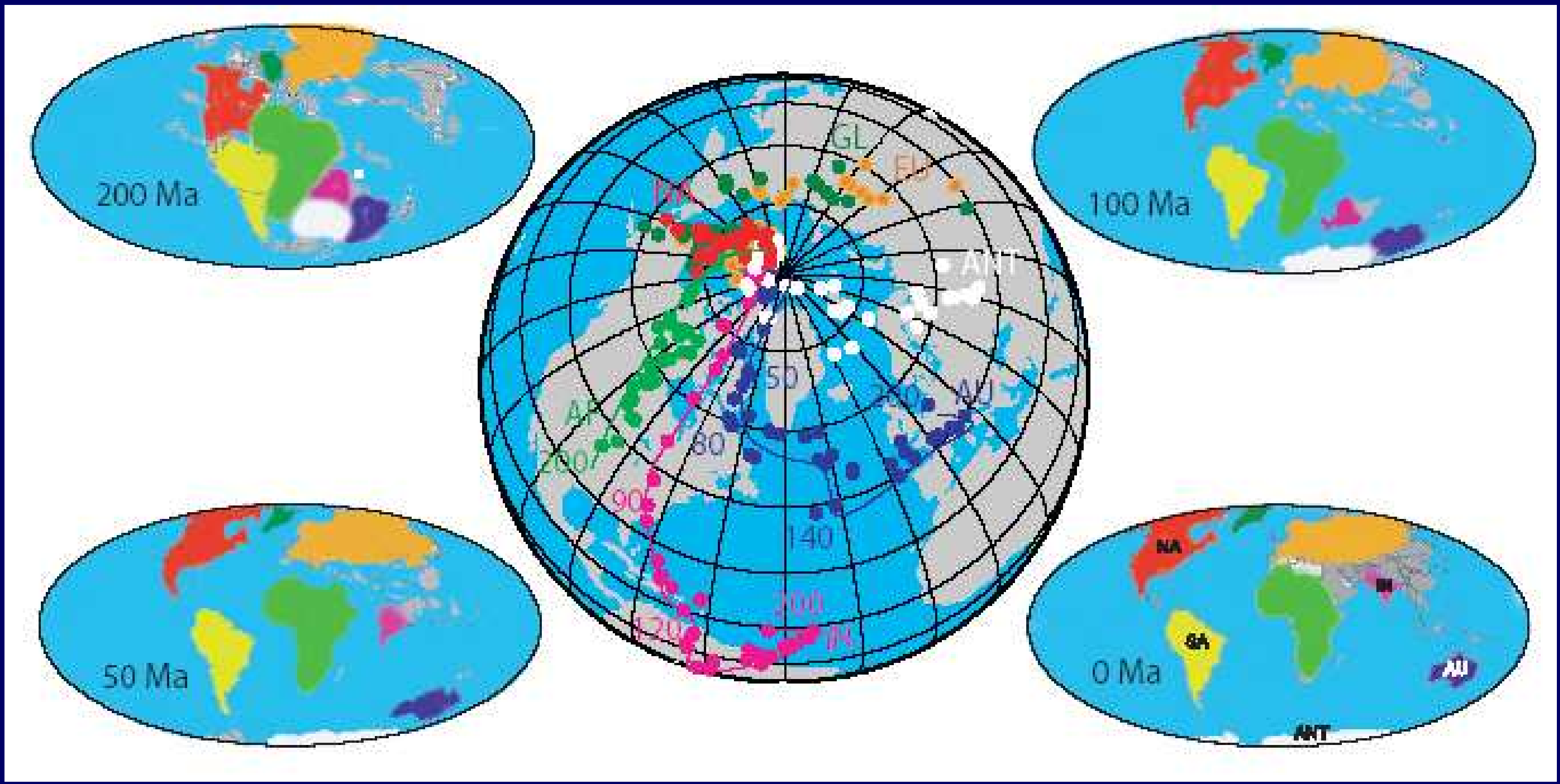


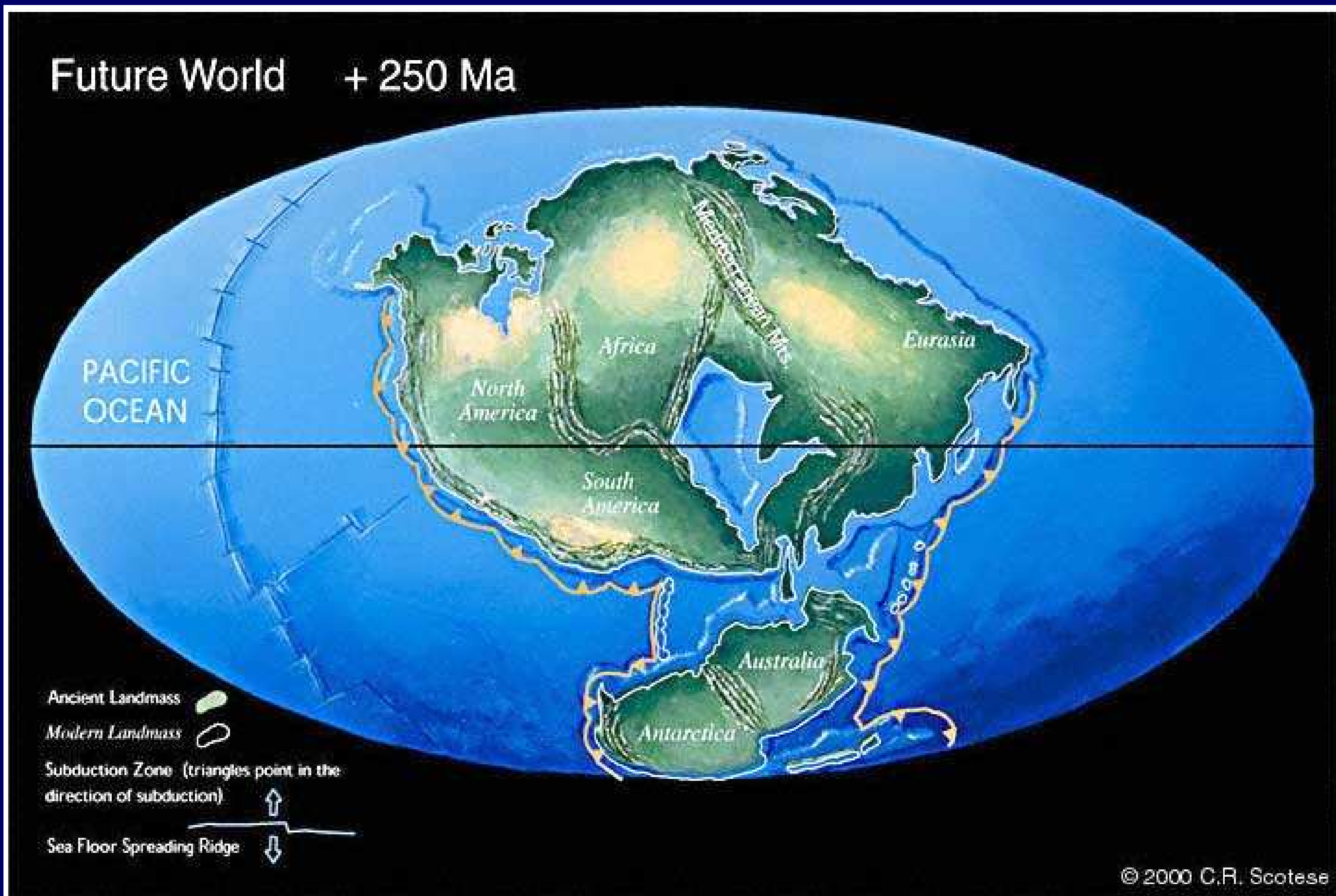
To find out how continents were moving, we need to have data from at least two continents.

Poles from North America (red circles) and Europe (green triangles):
a) in present day coordinates,
b, c) after rotation of Europe to close the Atlantic Ocean .



Maps of continental reconstructions for 200, 100, 50 and 0 million years ago. The central map shows the apparent wonder polar pats for the various continents (continental tectonic plates) for the last 200 million years.



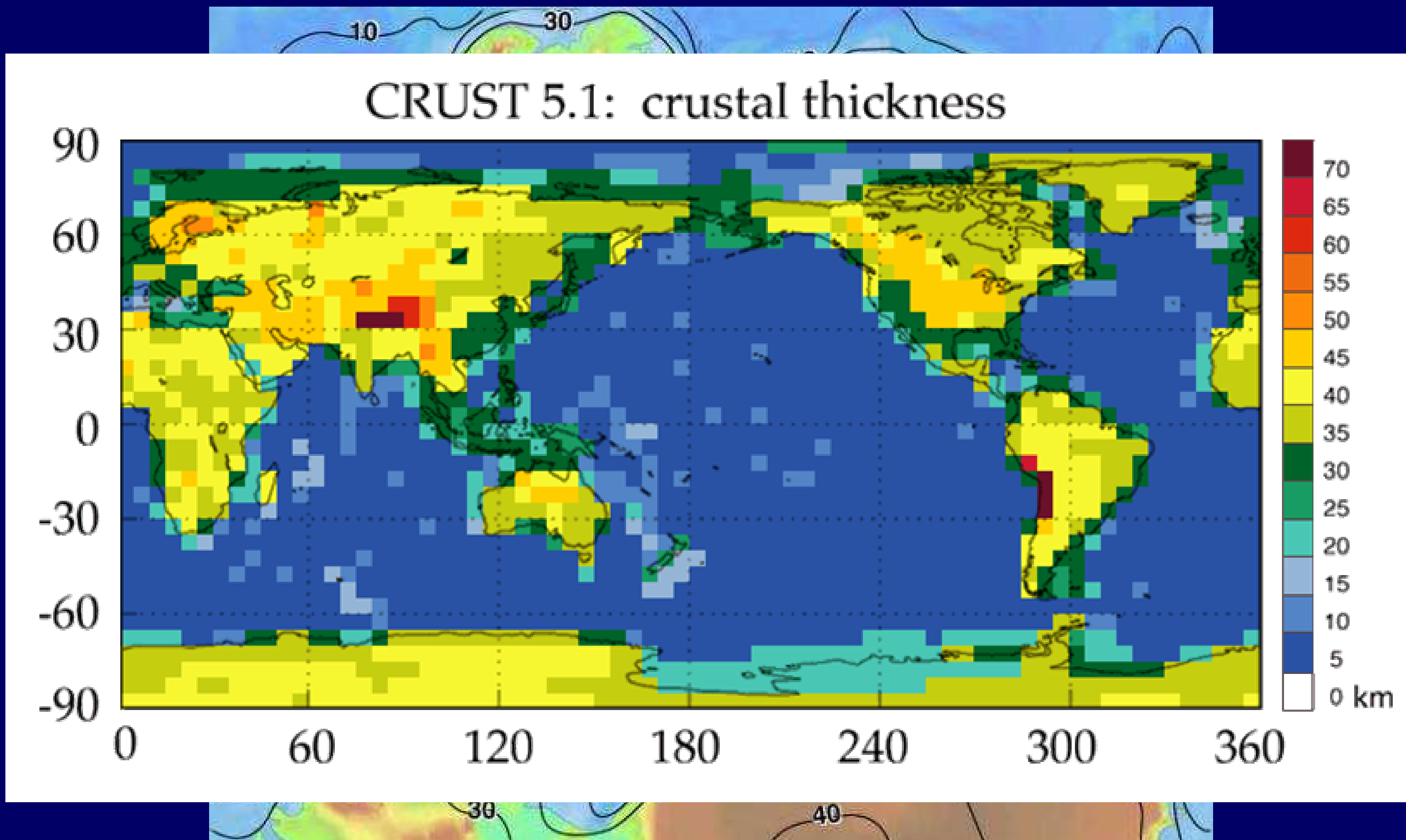

Future World + 250 Ma
PACIFIC OCEAN
North America
Africa
Eurasia
South America
Australia
Antarctica
Ancient Landmass
Modern Landmass
Subduction Zone (triangles point in the direction of subduction)
Sea Floor Spreading Ridge
© 2000 C.R. Scotese

Gravity

Gravity maps of former Yugoslavia and Serbial sostasy

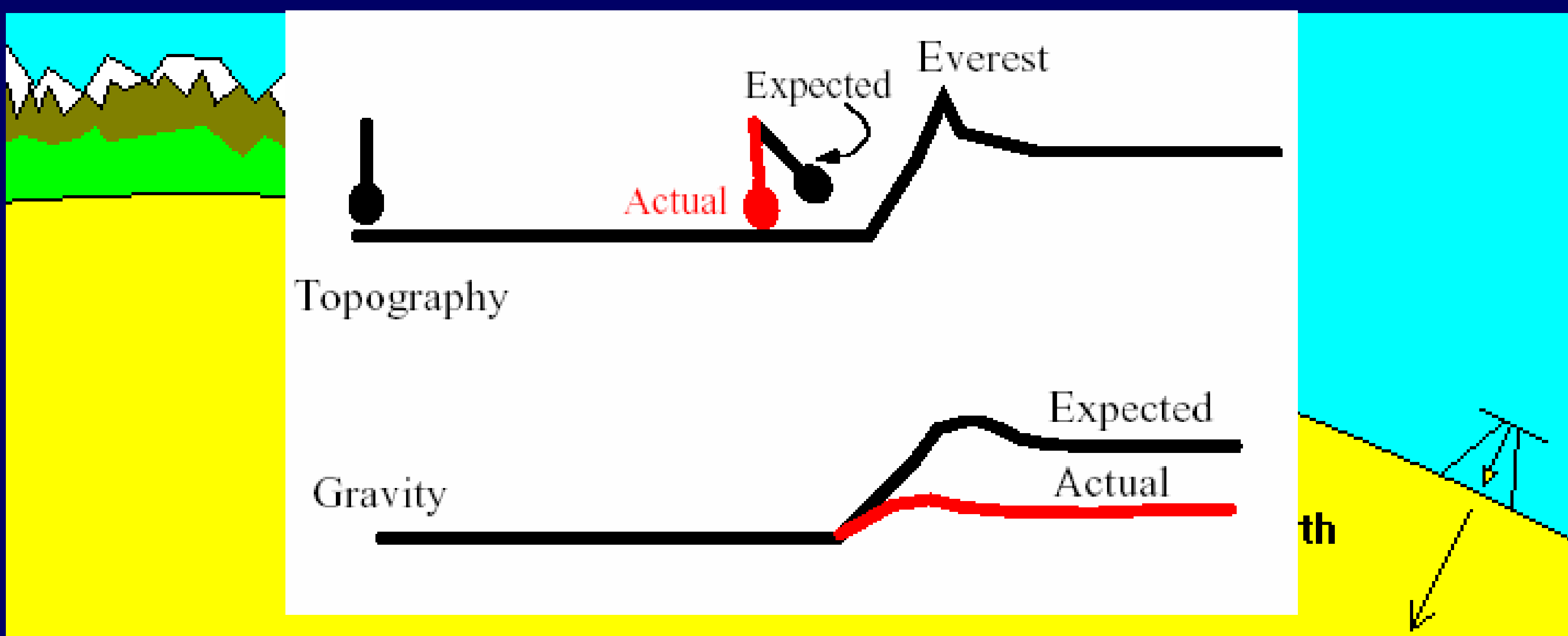
The Earth's surface is not flat. Thickness of the Earth crust is not constant all over the planet, it varies a lot.

How can we explain this? The key concept is **isostasy**.

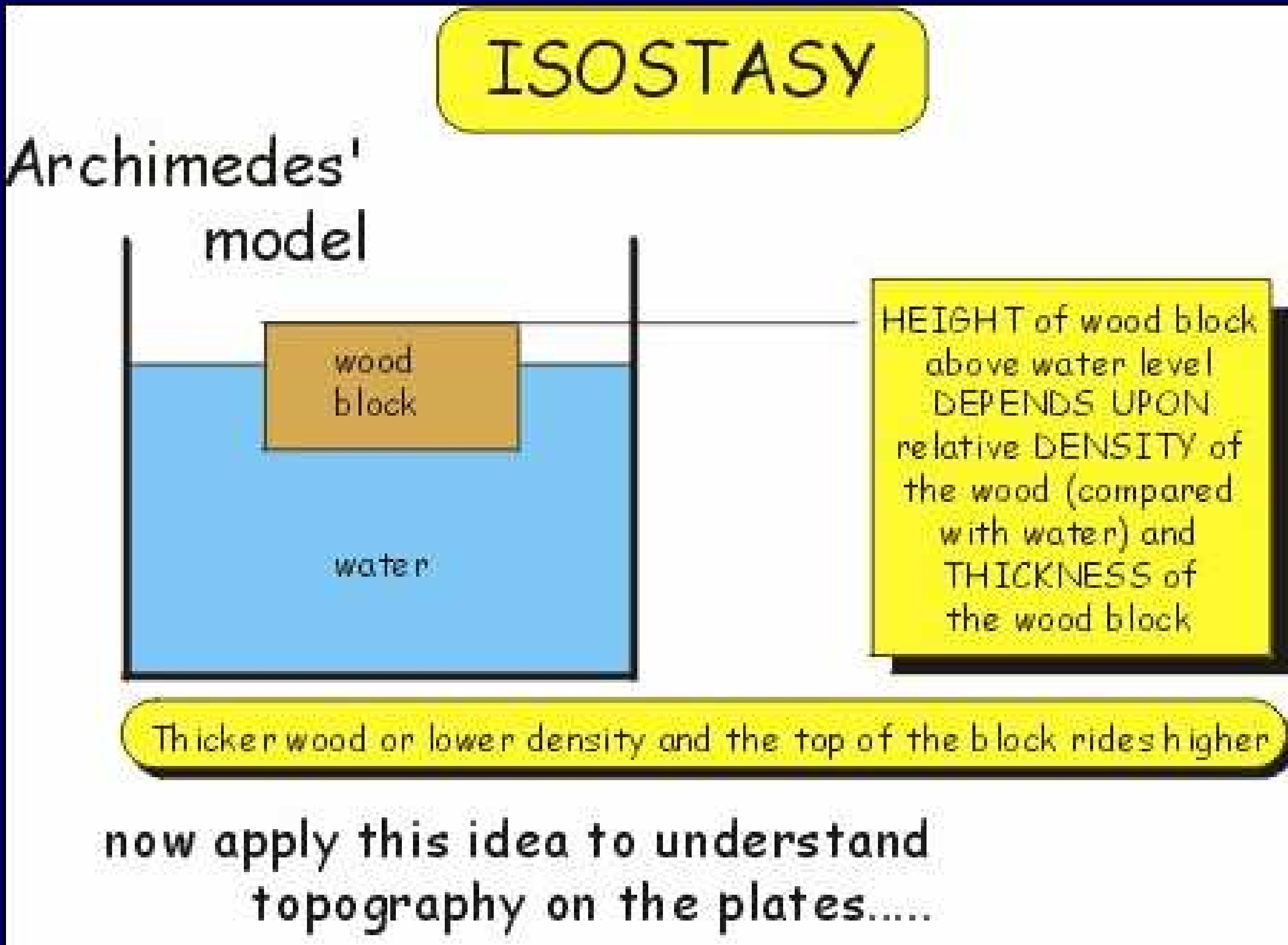


In 1735, expeditions over the Andes led by Pierre Bouguer (pendulum gravity measurements), noted that the Andes could not represent a protuberance of rock sitting on a solid platform. If it did, then a plumb-line should be deflected from the true vertical by an amount proportional to the gravitational attraction of the mountain range. The deflection was less than that which was anticipated.

About a century later, similar discrepancies were observed by Sir George Everest in surveys south of the Himalayas, indicating a lack of compensating mass beneath the visible mountain ranges.

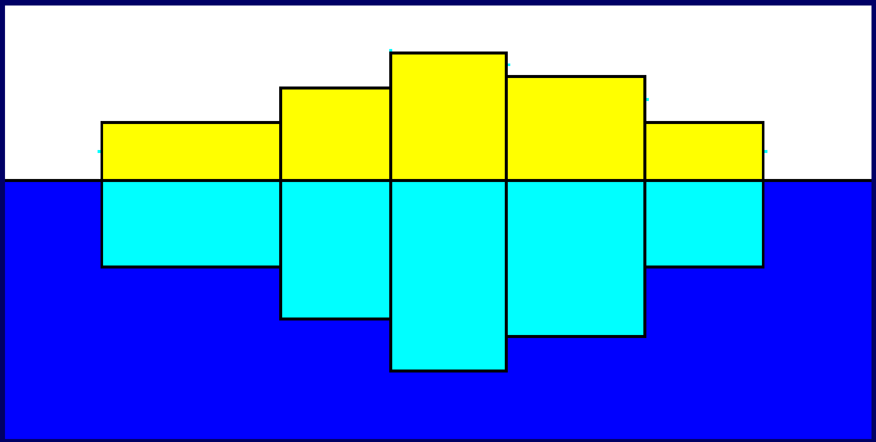


Basic concept of isostasy



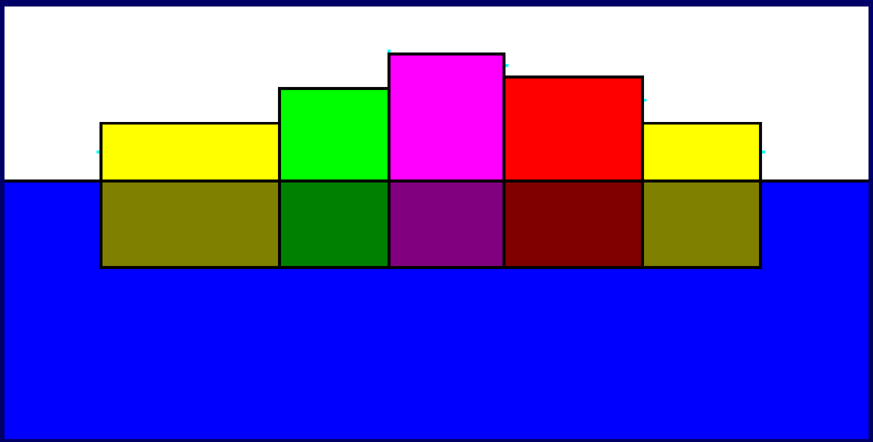
Two models, first suggested in the 19th century, have been used to explain the variations in topography.

The Airy Model

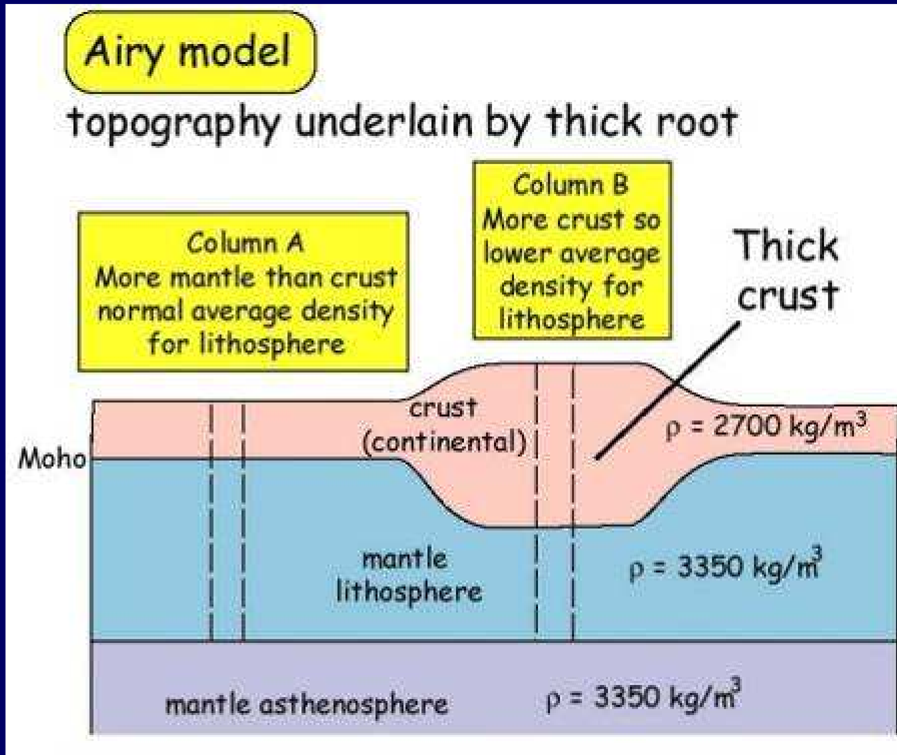


Airy assumed that the crust has a uniform density throughout. Earth's crust is a more rigid shell floating on a more liquid substratum of greater density. The thicker parts of the crust sink deeper into the substratum. Mountains have roots below the surface that are much larger than their surface expression.

The Pratt Model

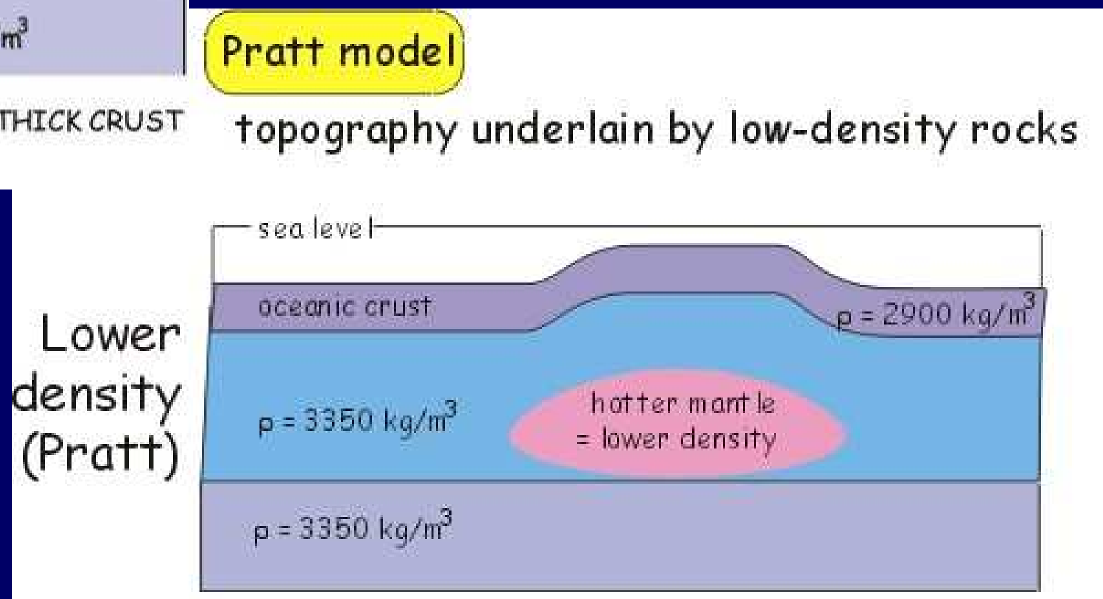


Pratt assumed that Earth's crust has a uniform thickness below sea level with base at a depth of compensation. Areas of lesser density (mountain ranges) project higher above sea level than those of greater density. Mountains resulted from upward expansion of locally heated crustal material, which had a larger volume but a lower density after it had cooled.



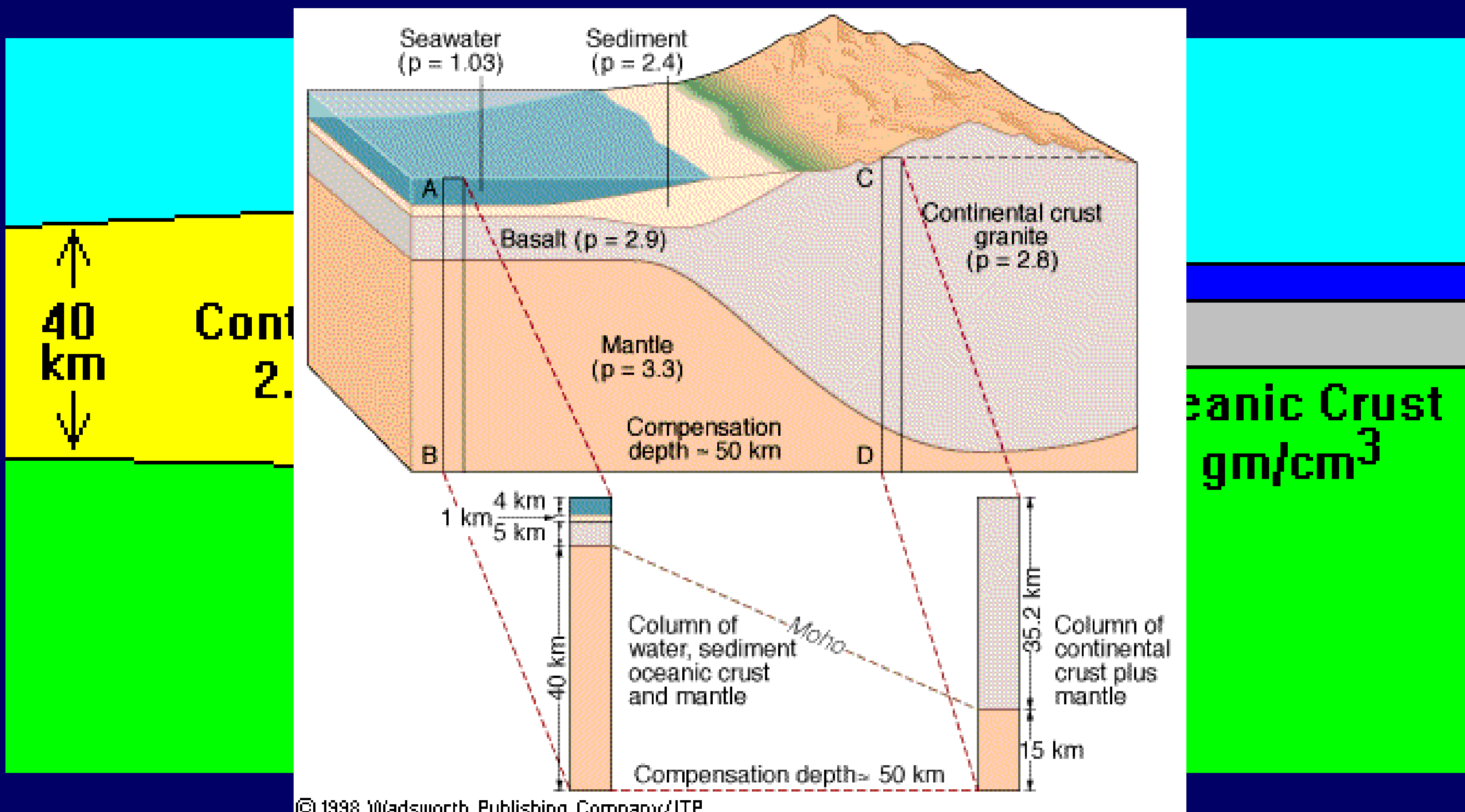
High topography (relative to surroundings) due to THICK CRUST
Example - Himalayas/Tibet

Both ideas are correct at times

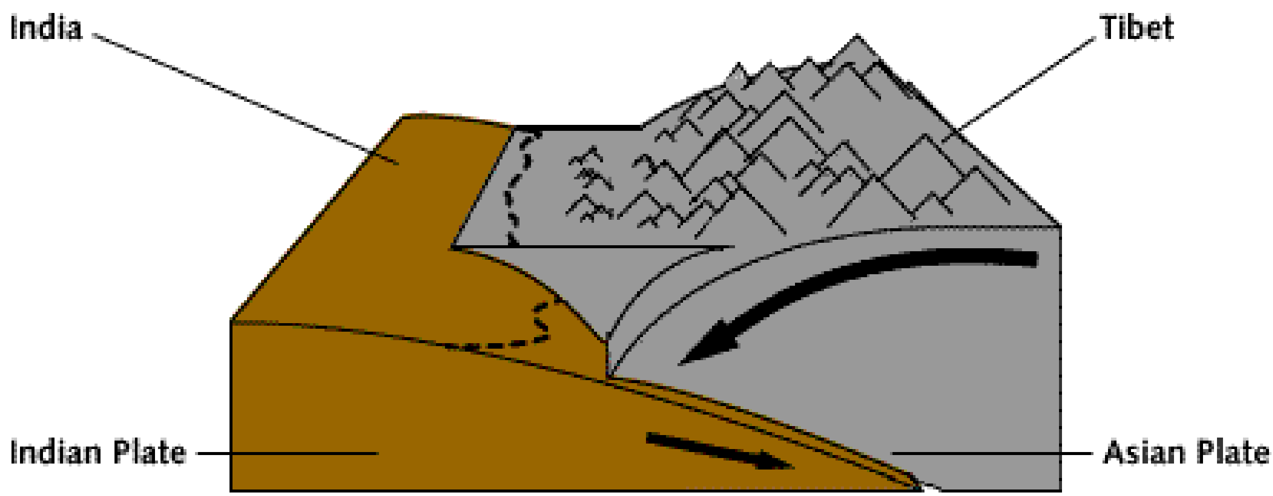


High topography (relative to surroundings) due to LOWER DENSITY
Example - Mid atlantic ridge (submarine "mountains")

The Heiskanen hypothesis is an intermediate, or compromise, hypothesis between Airy's and Pratt's. This hypothesis says that approximately two-thirds of the topography is compensated by the root formation (the Airy model) and one-third by Earth's crust above the boundary between the crust and the substratum (the Pratt model).



Lets see how Himalayas were born…

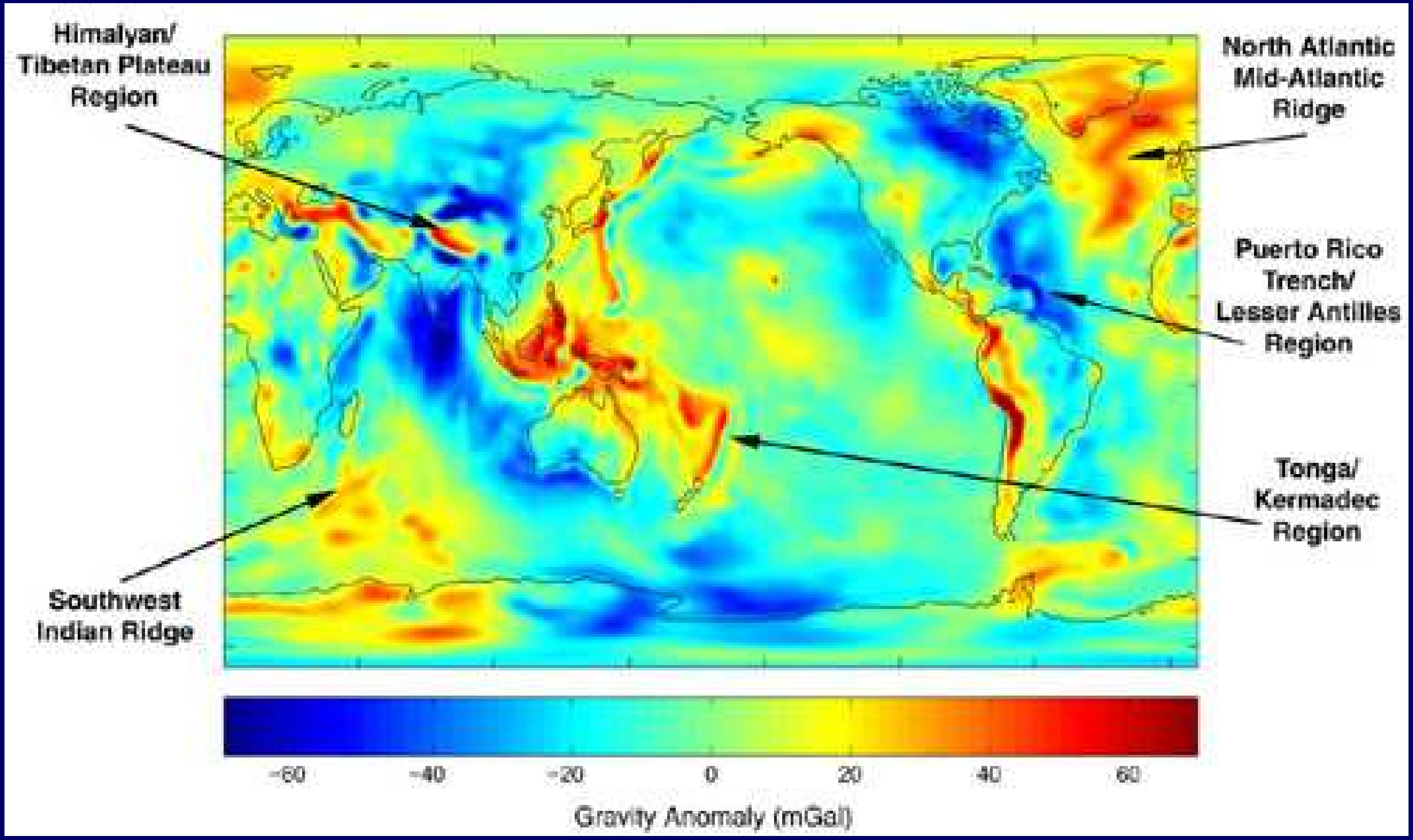


Ten Million Years from Now

As the boundaries of Nepal approach each other, Nepal ceases to exist. The Himalaya, however, still exist, as foothills and mountains continue to form over the advancing edge of India.

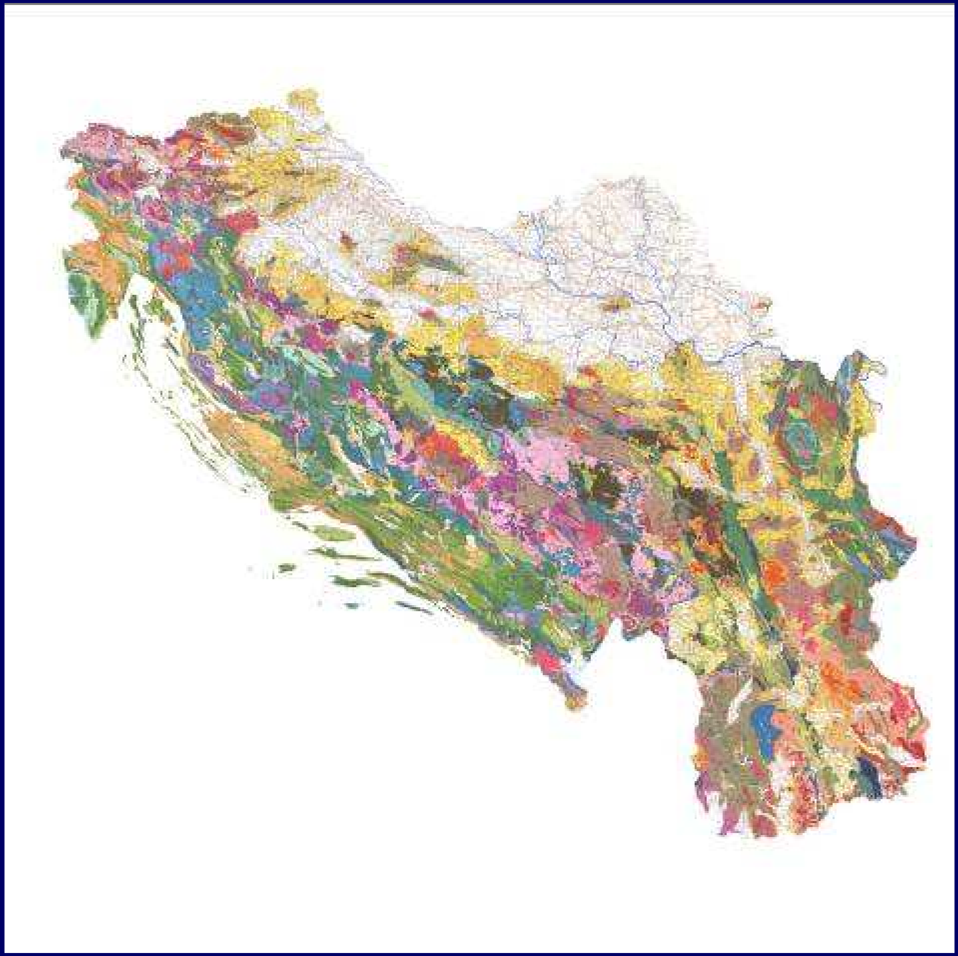
Gravity Map of the Earth

These detailed geophysical features are being detected by GRACE with no surface gravity measurements (July 21, 2003)

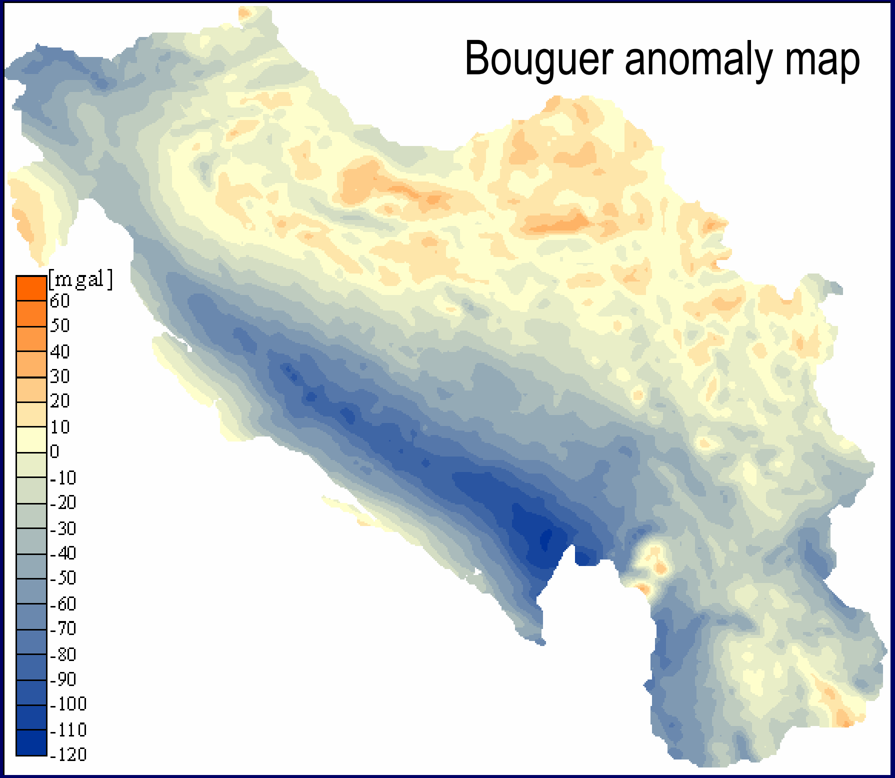


Geological and Gravity Maps

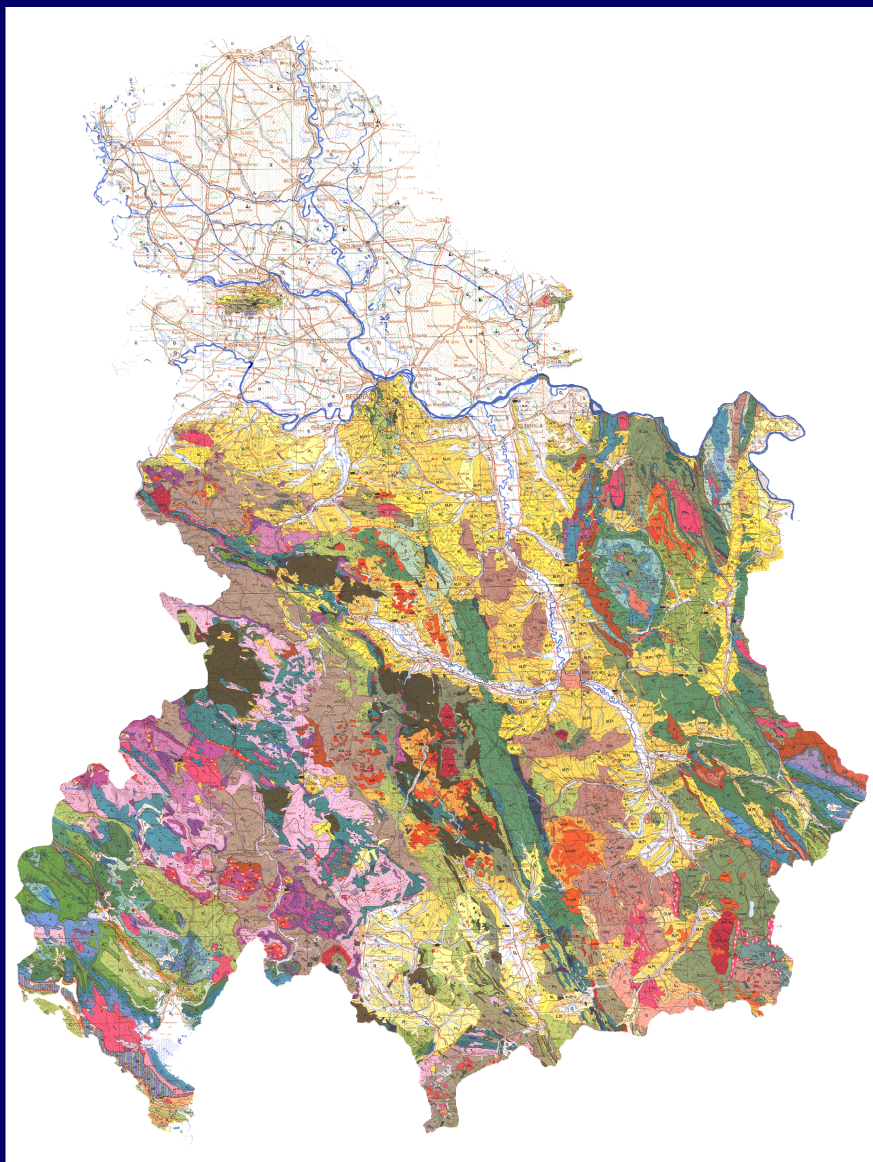
Geological map of former Yugoslavia



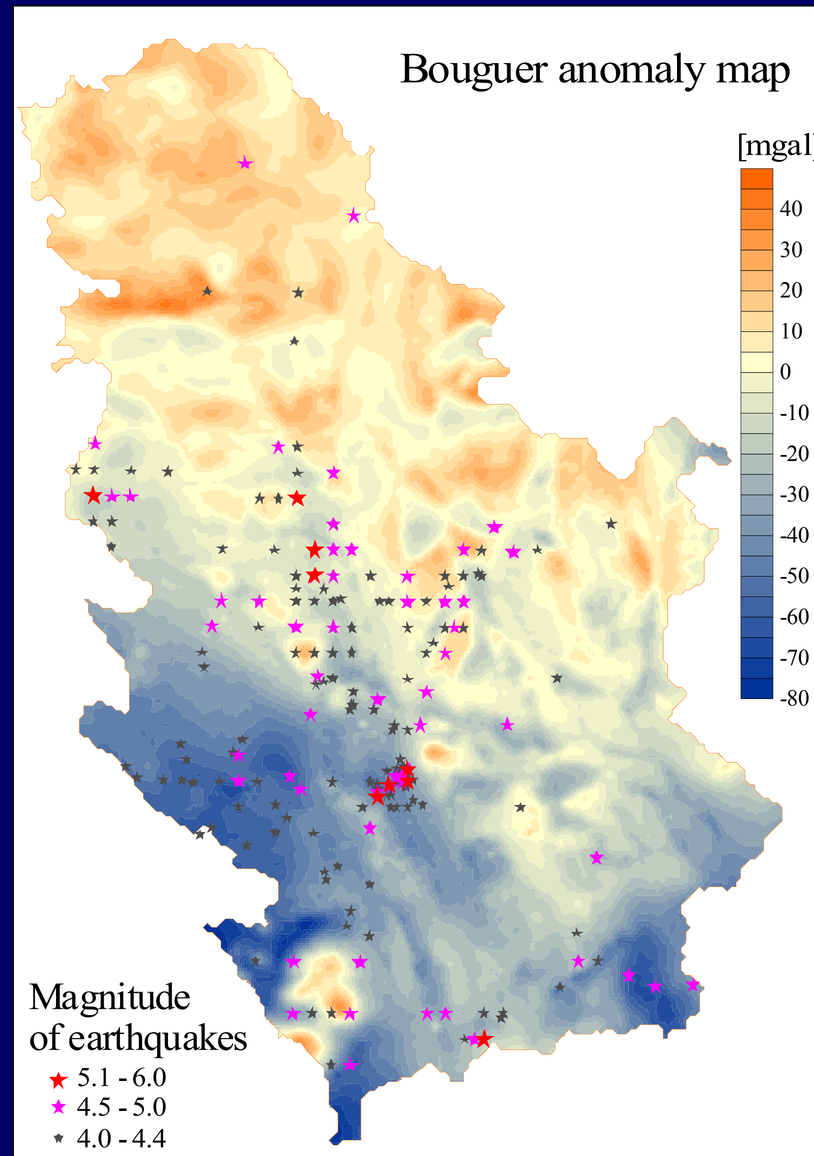
Gravity map of former Yugoslavia



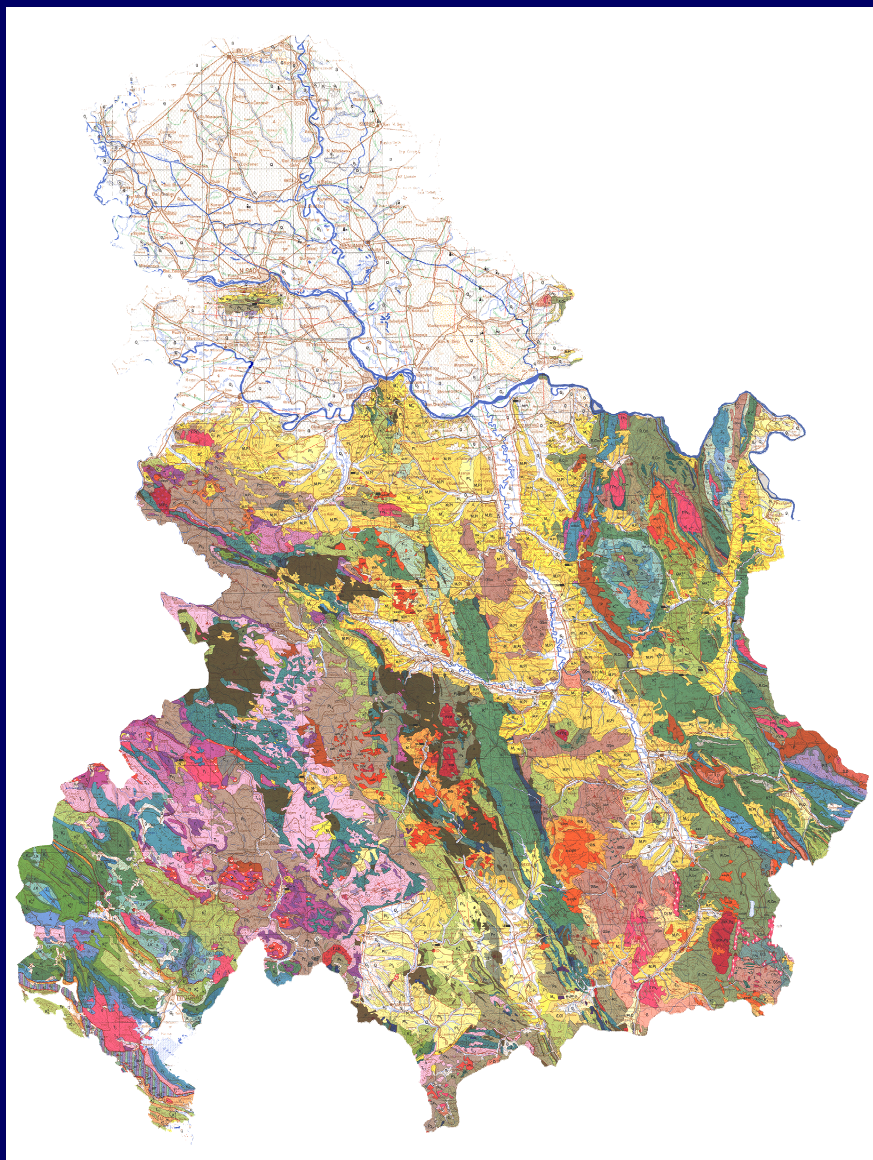
Geological map of Serbia



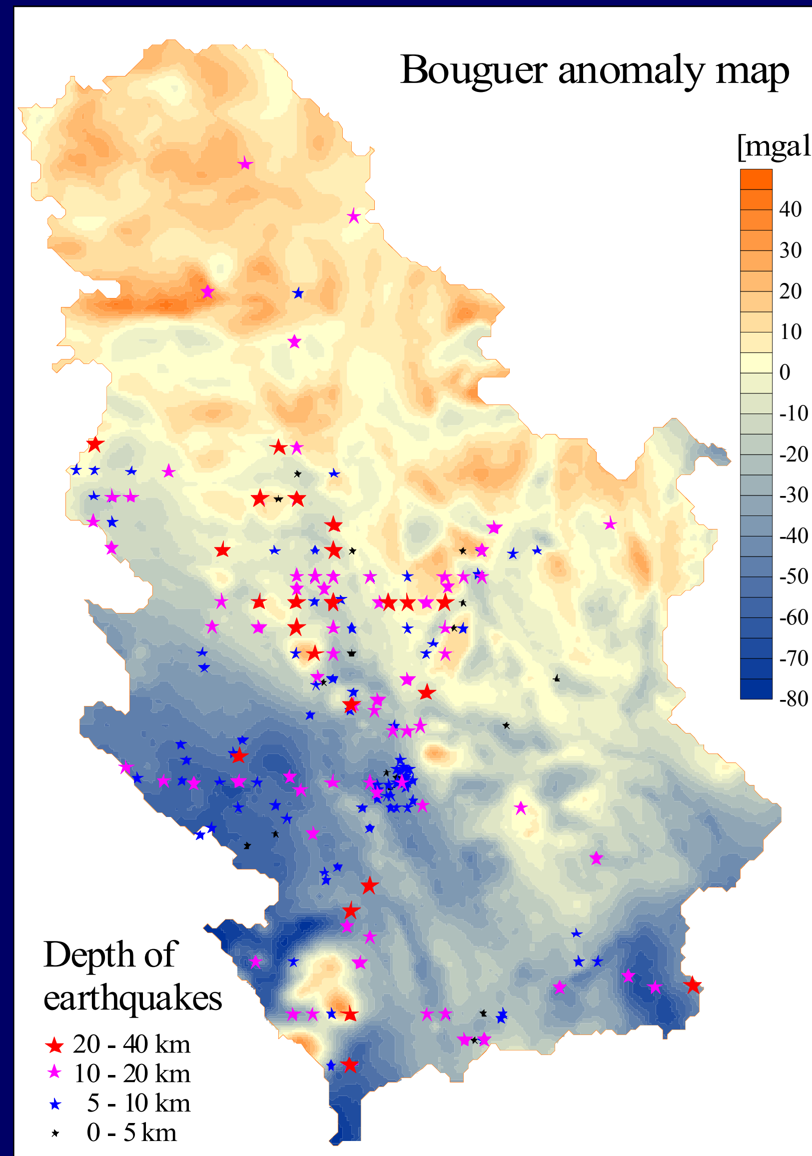
Gravity map of Serbia



Geological map of Serbia



Gravity map of Serbia



Thank you for your attention!

THE END

(or maybe just the beginning)

References:

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Lindeberg, P., "This Dynamic Earth: the Story of Plate Tectonics", USGS online edition (URL: http://pubs.usgs.gov/publications/text/dynamic.html).

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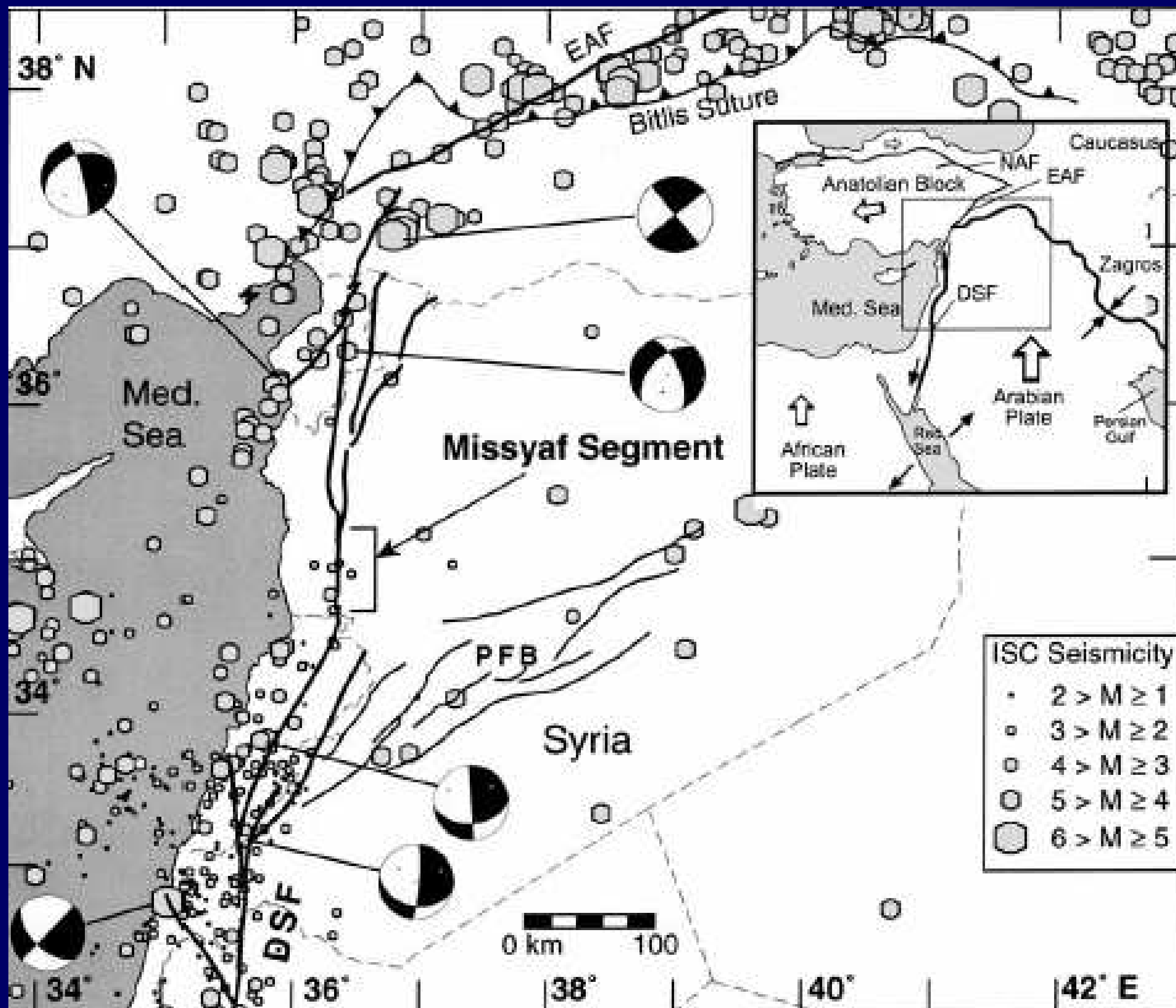
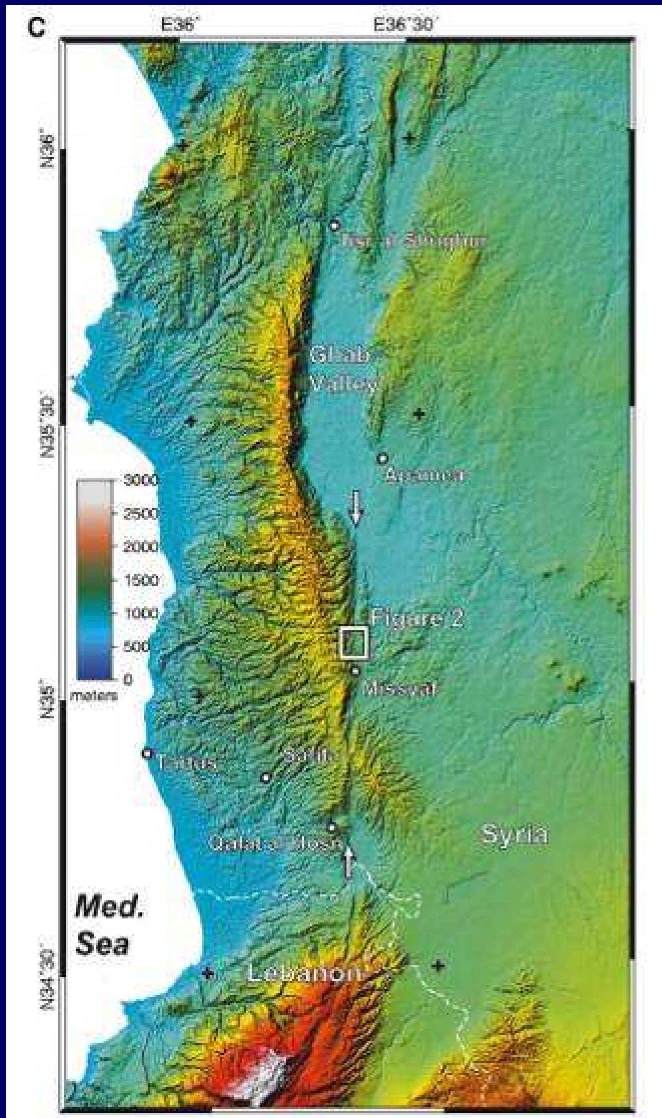
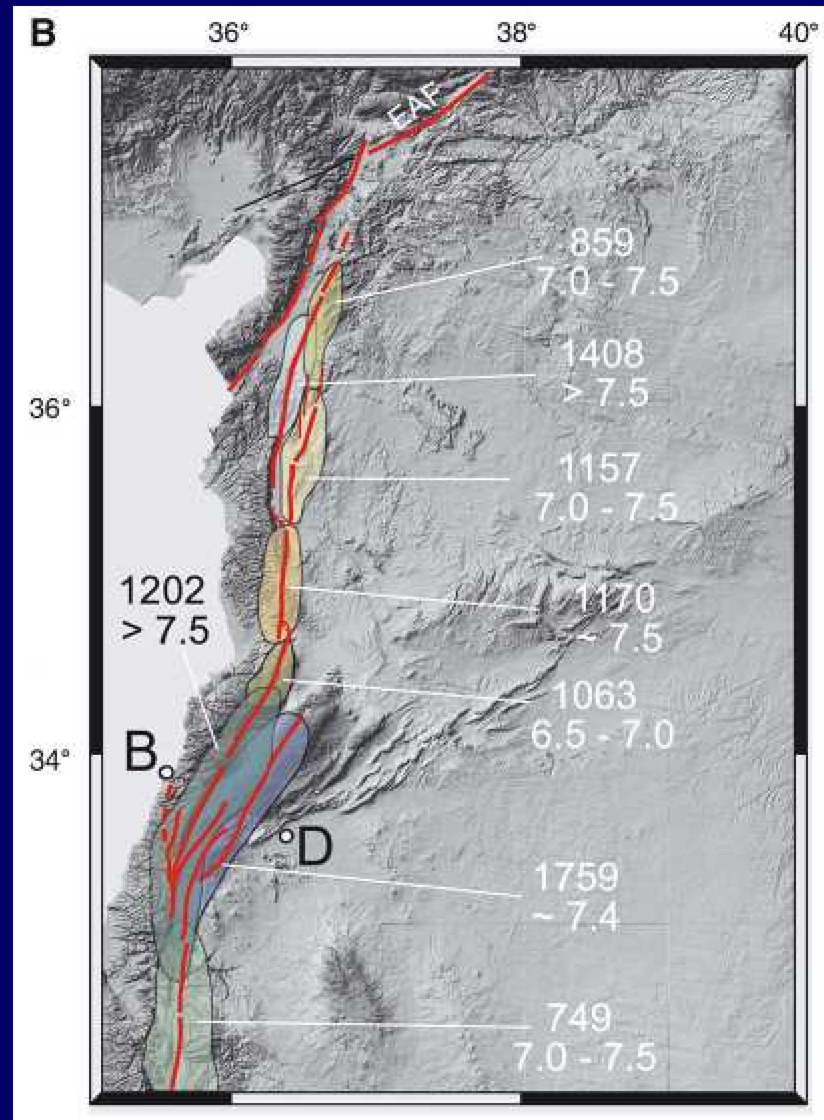
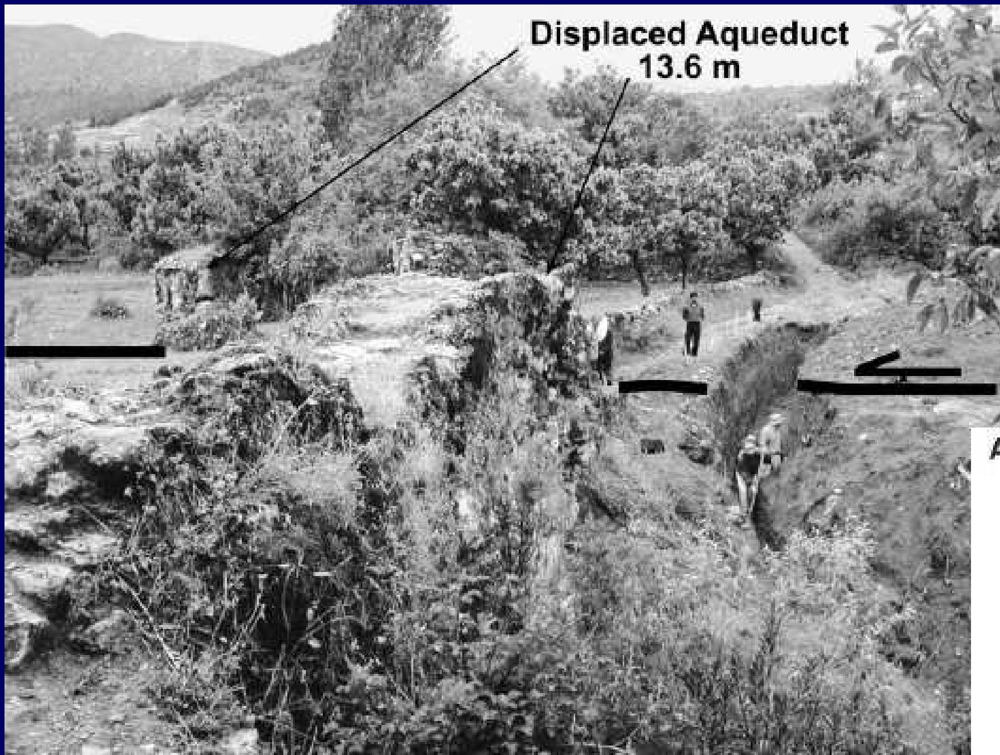
http://www.see.leeds.ac.uk/structure/dynamicearth/index.htm

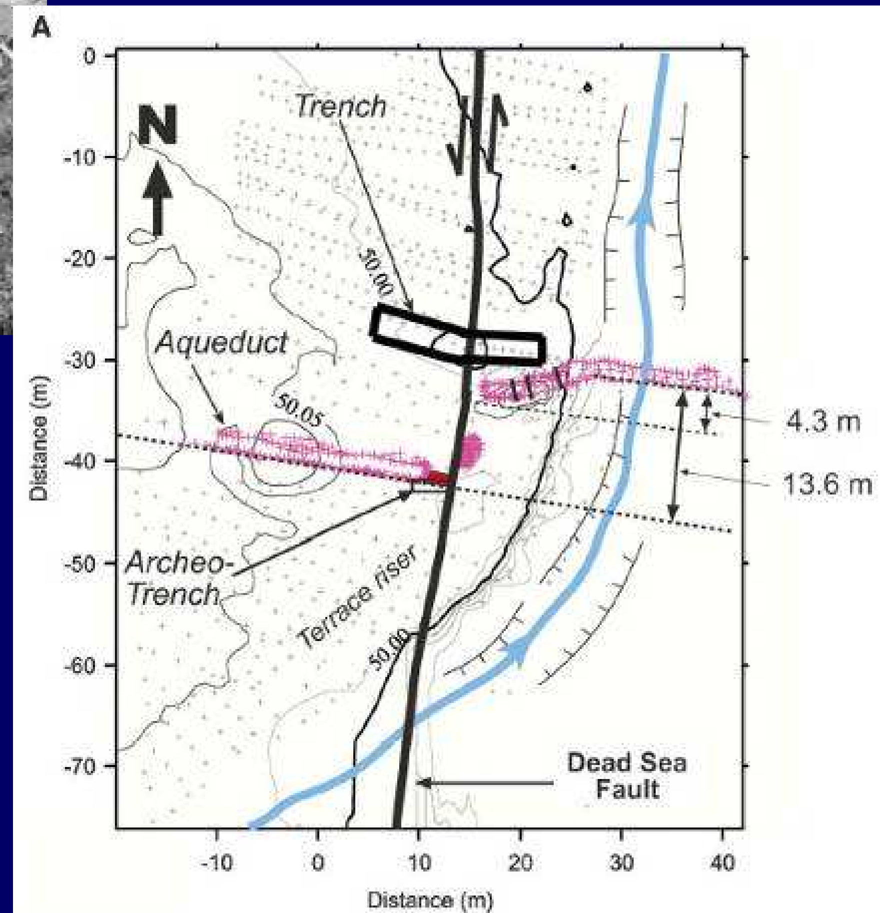
Paleoseismology




C
E36°
E36°30'
N36°
Ghab
Valley
N35°30'
3000
2500
2000
1500
1000
500
0
meters
Figure 2
N35°
Syria
Med.
Sea
Lebanon
N34°30'


B
36°
38°
40°
EAF
859
7.0 - 7.5
1408
> 7.5
36°
1157
7.0 - 7.5
1202
> 7.5
1170
~ 7.5
1063
6.5 - 7.0
34°
B
D
1759
~ 7.4
749
7.0 - 7.5


Displaced Aqueduct
13.6 m


A
N
Trench
Aqueduct
Archeo-
Trench
Terrace riser
50.00
50.05
4.3 m
13.6 m
Dead Sea
Fault
Distance (m)
Distance (m)