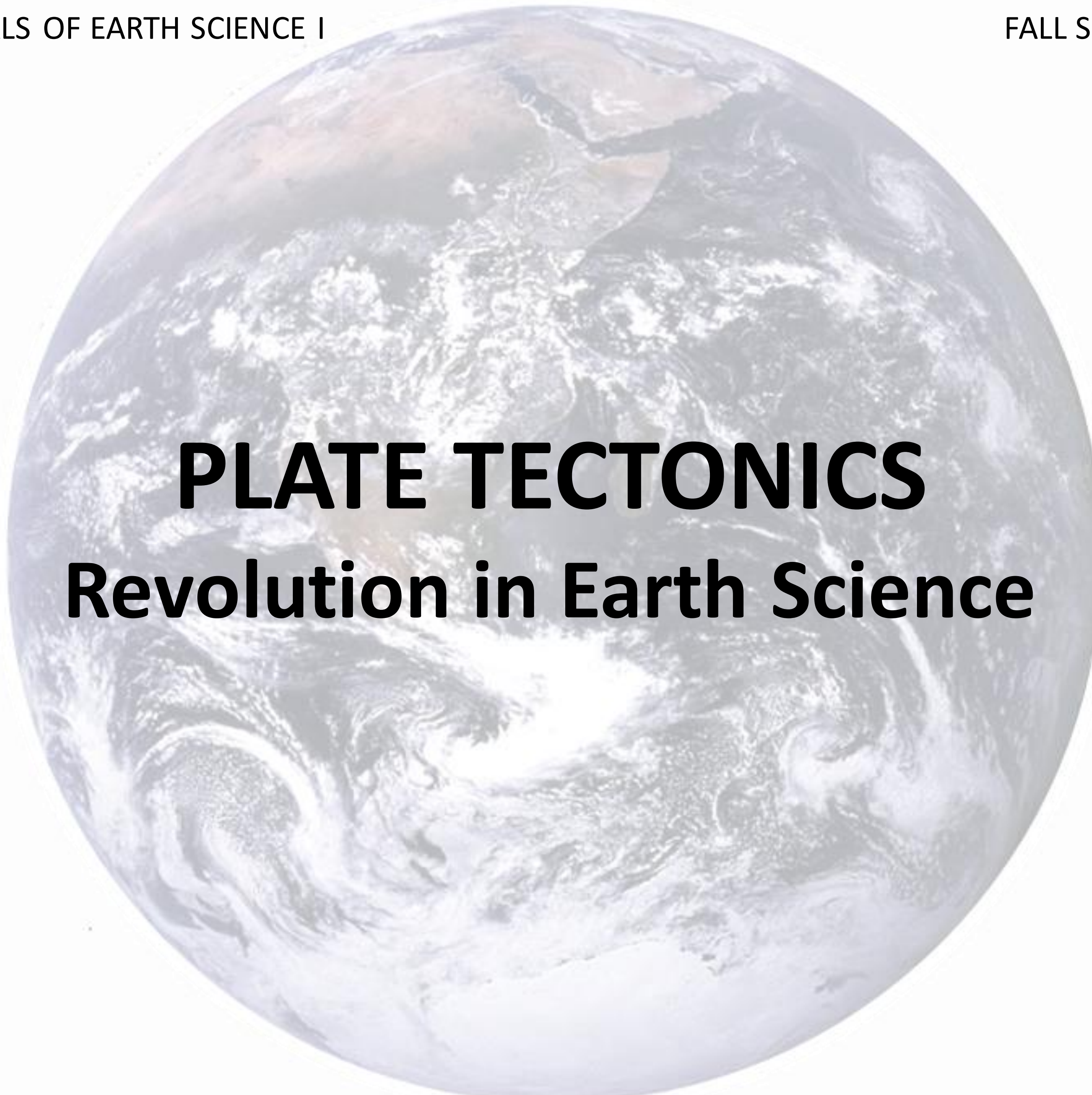
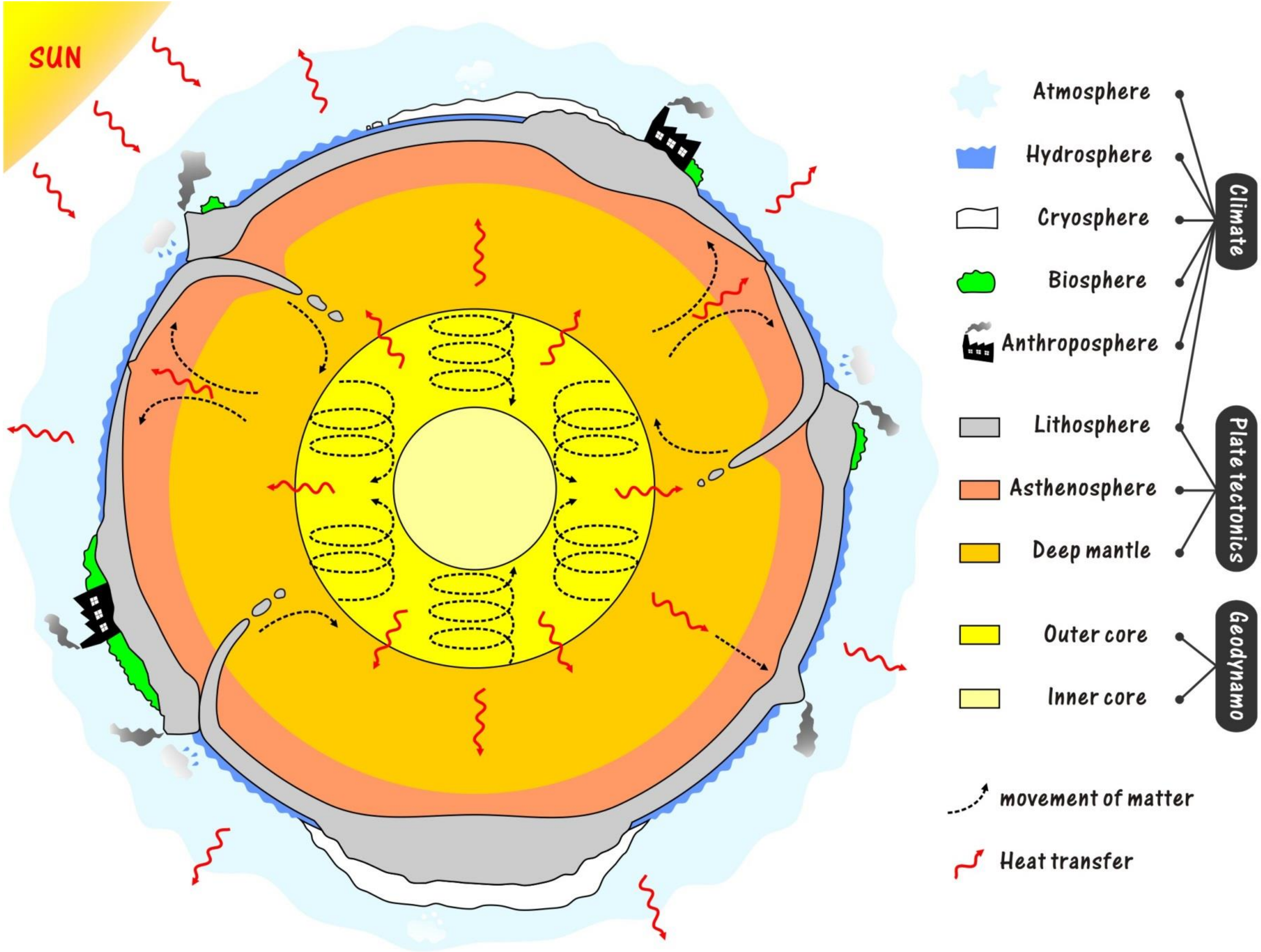


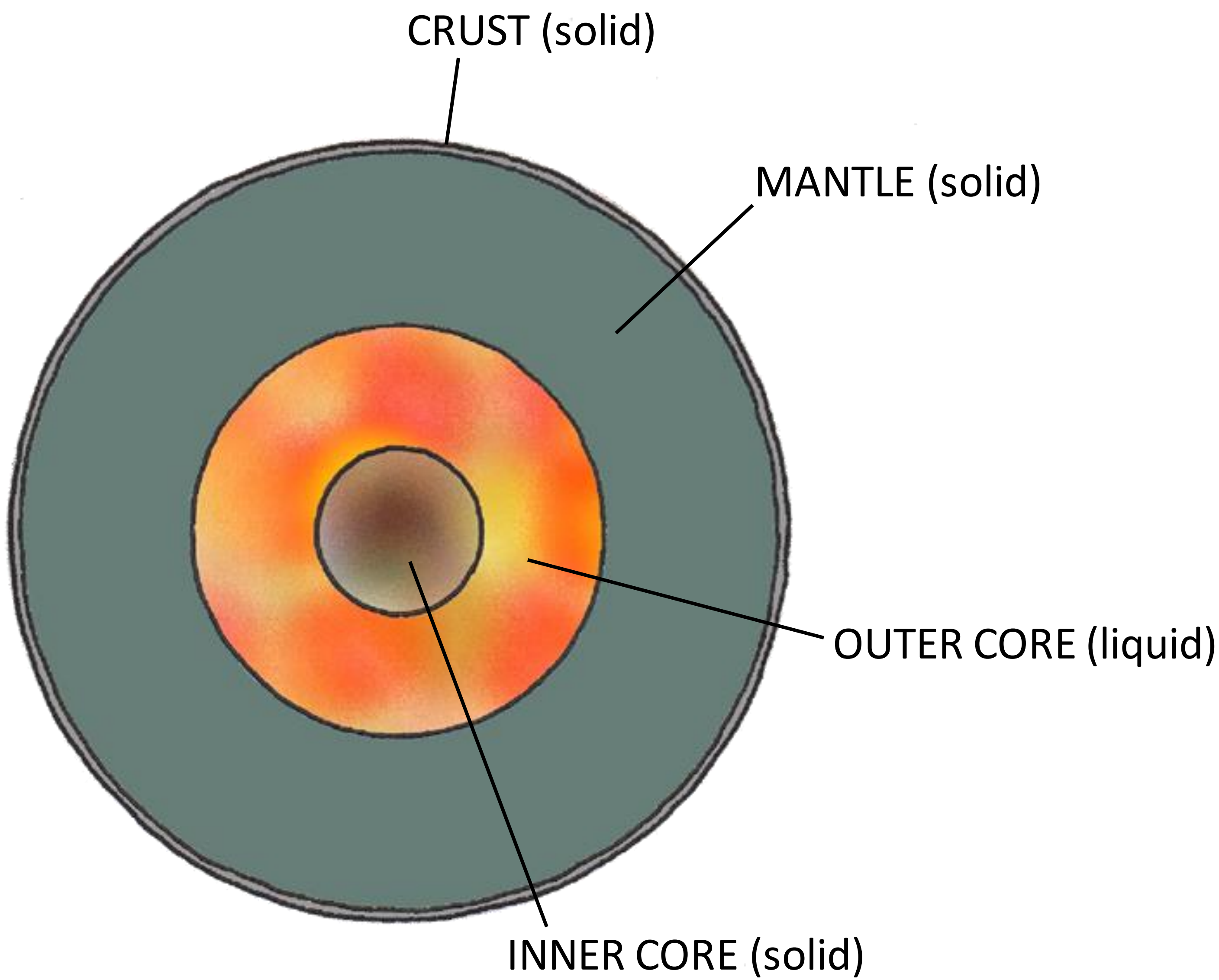
PLATE TECTONICS
Revolution in Earth Science

The Earth System



Understanding Earth 6th edition

Earth's layers



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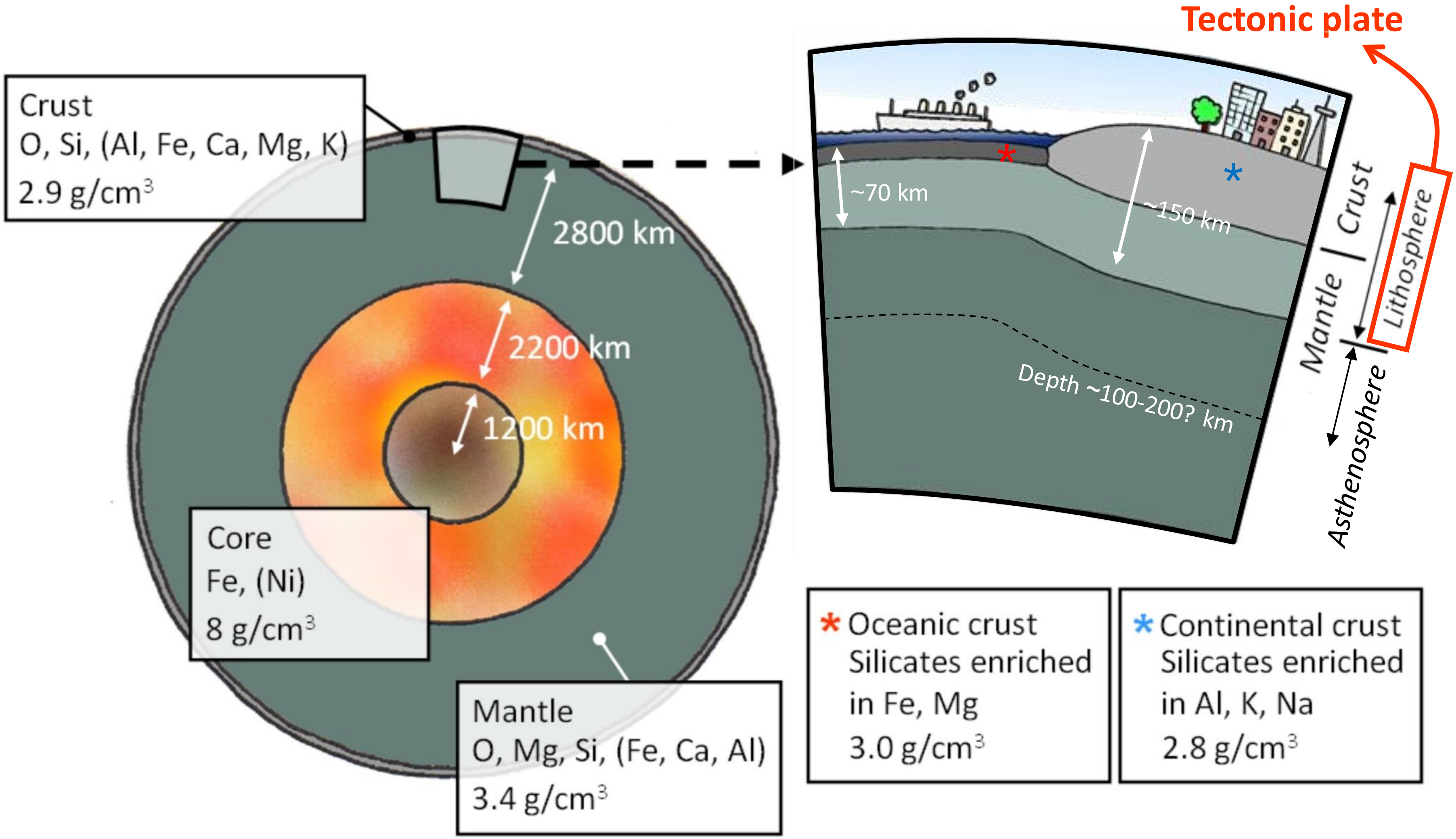

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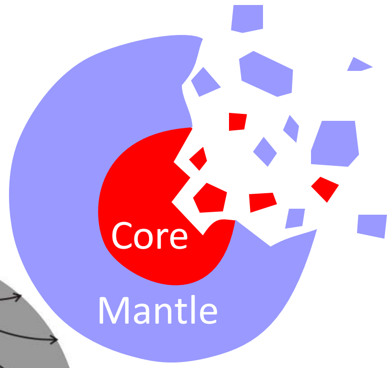
Oceanic crust: av. 7 km

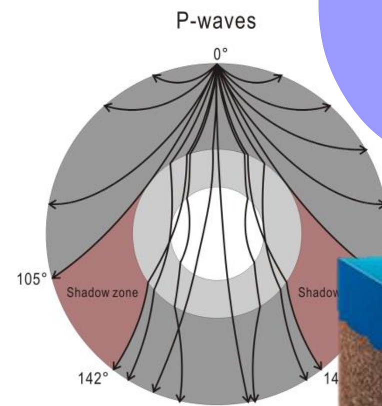
Continental crust: av. 40 km

Boundary between crust and mantle = Mohorovicic Discontinuity (or **Moho**)

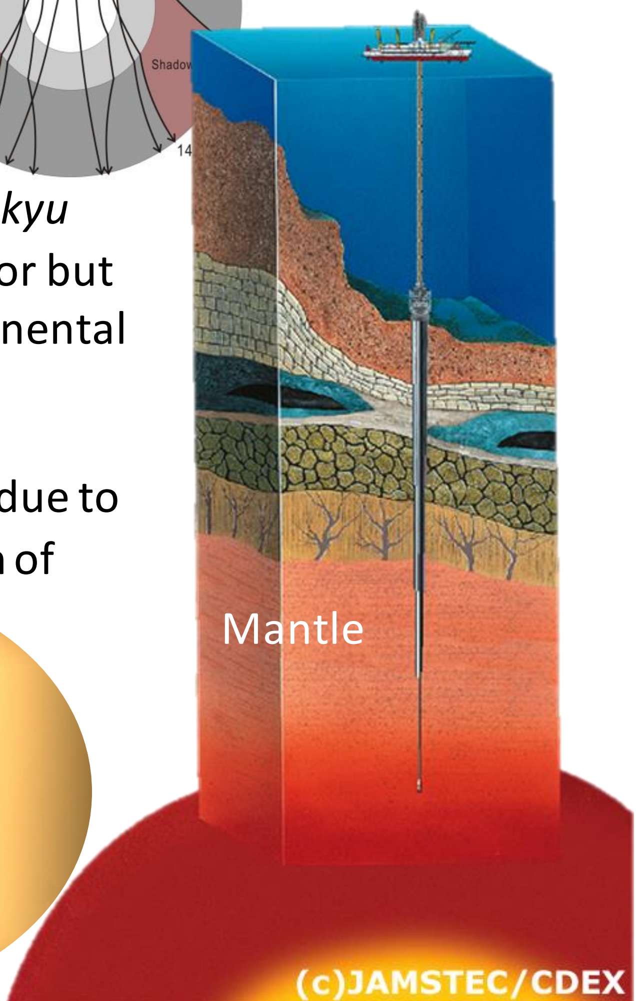
SUPPORTING EVIDENCE



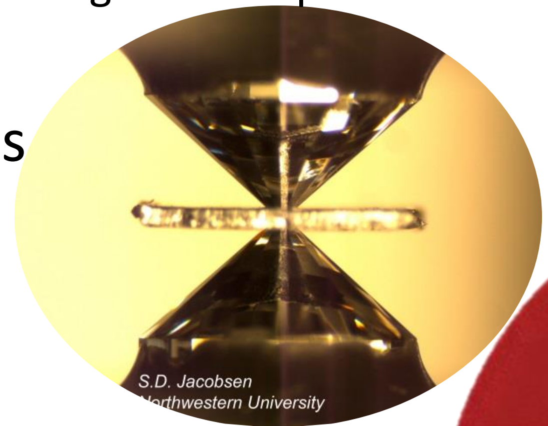
- Differentiated meteorites
- Seismic waves



- Field observations (ophiolites, xenoliths of mantle rocks)
- Deep drilling (in 2012, the Japanese drilling vessel *Chikyu* retrieved rock samples from around 2200 m below seafloor but has not yet reached the mantle; longest borehole in continental crust was drilled in Russia and is about 12 km long)



- Gravimetry (examines variations in gravitational field due to density differences resulting from changes in composition of crust and mantle)
- High-pressure experiments (diamond anvil cell)

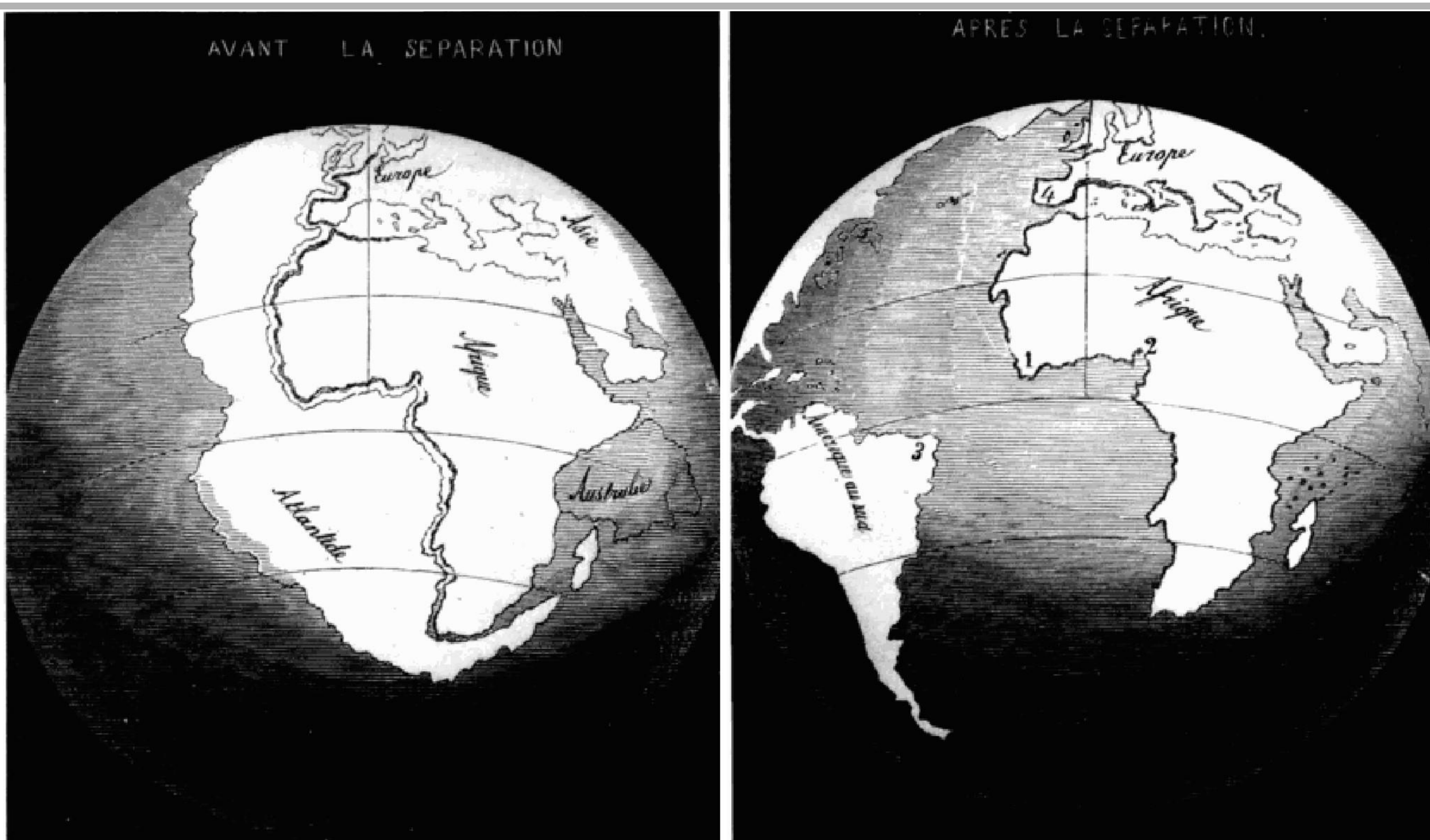


- Computer models

Ship Classification (or Class)	Class NK: Mobile Offshore Drilling Unit	
Navigation Area	All Oceans (Worldwide)	
Length	210 m	Approx. 8 Bullet-Train Cars
Breadth	38.0 m	Approx. the Length of a Futsal Court
Height (from ship bottom)	130 m	A 30-Floor Building

http://www.jamstec.go.jp/chikyu/e/about/data/

✶ Continental drift (Alfred Wegener, 1880-1930)



Continent are moving and they once formed one single supercontinent called Pangaea.

A. Snider-Pellegrini (1802-1885), source: USGS

SUPPORTING EVIDENCE

1. Jigsaw-puzzle fit of continents around the Atlantic Ocean

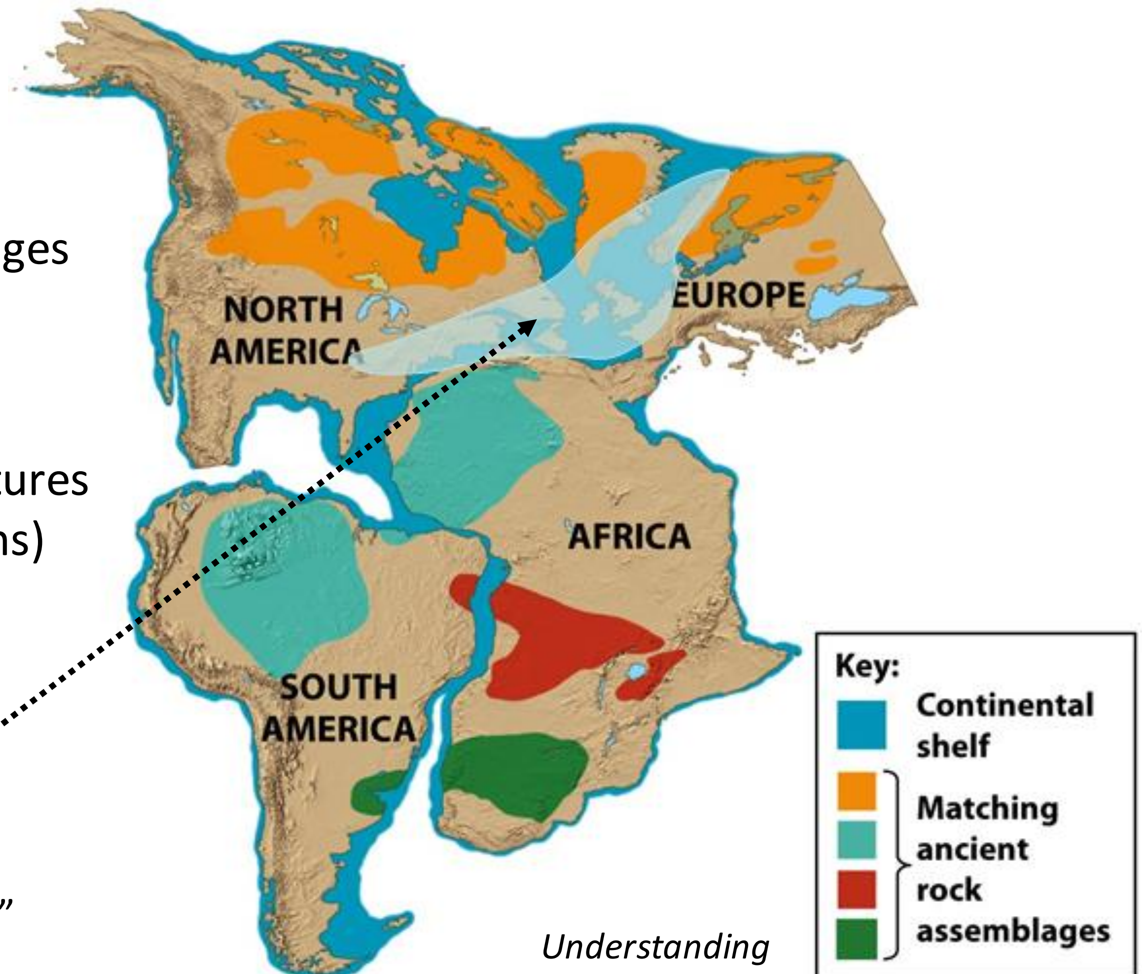
2. Similarities in rock types and ages on both sides of the Atlantic

3. Similarities in geological structures (orientation of mountain chains)

Appalachian mountain belt (eastern USA)
Caledonian mountain belt (NW Europe)

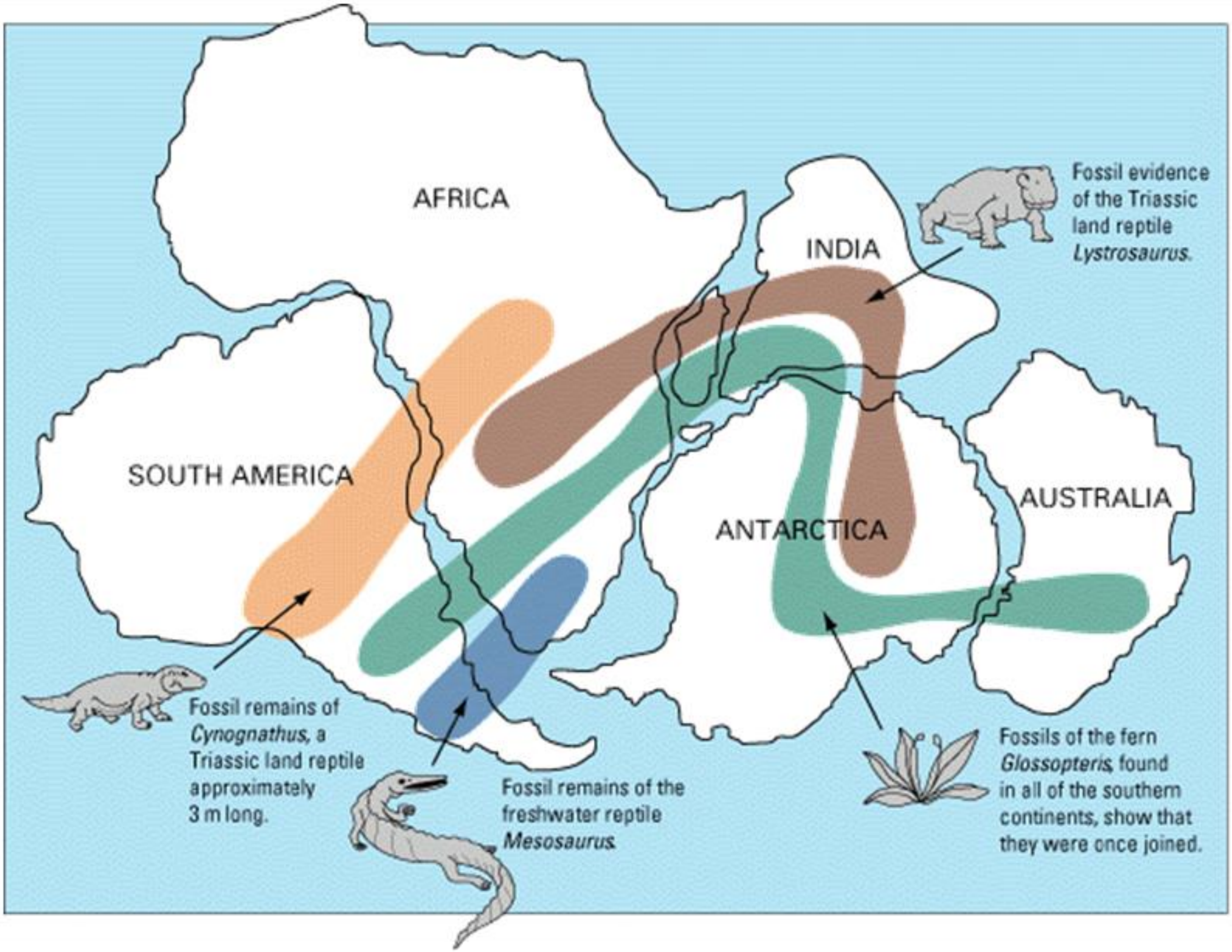
"Appalachian-Caledonian orogeny" (~500-400 Ma)

Orogeny = episode of mountain formation



Understanding Earth (modified)

4. Geographic distribution of fossils of plants and animals



Distribution of some fossils (Gondwana, 300 10^6 yr ago)

USGS

5. Paleoclimate data

Glacial deposits (~300-250 Ma, Permian) found in South America, Africa, India, Antartica, and Australia

→ **Suggests high-lat. location**

Tillite = rock composed of unsorted material deposited directly by glacial ice and showing no stratification

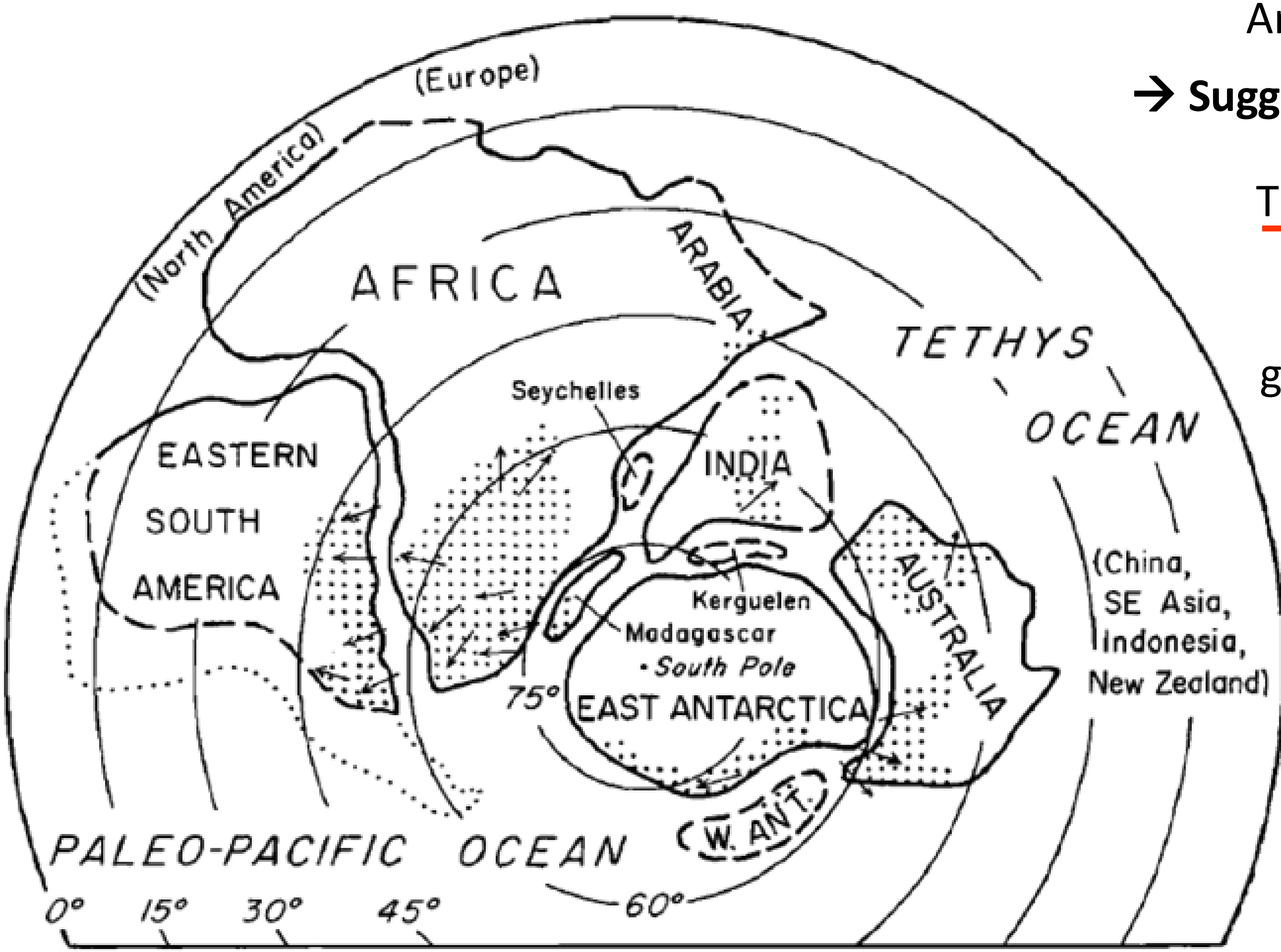


Figure 1. Reconstruction of Gondwanaland at beginning of Permian time, showing paleolatitudes. Stipple marks regions of known tillite, and arrows show directions of ice flow determined from glacial pavements.

Hamilton and Krinsley (1967)

Glacial erratic

Robert Siegel (Stanford Uni.)

Glacial striation

Wikipedia

Glacial till (moraine) – *coarse unsorted sediment in fine-grained (clay) matrix*

USGS

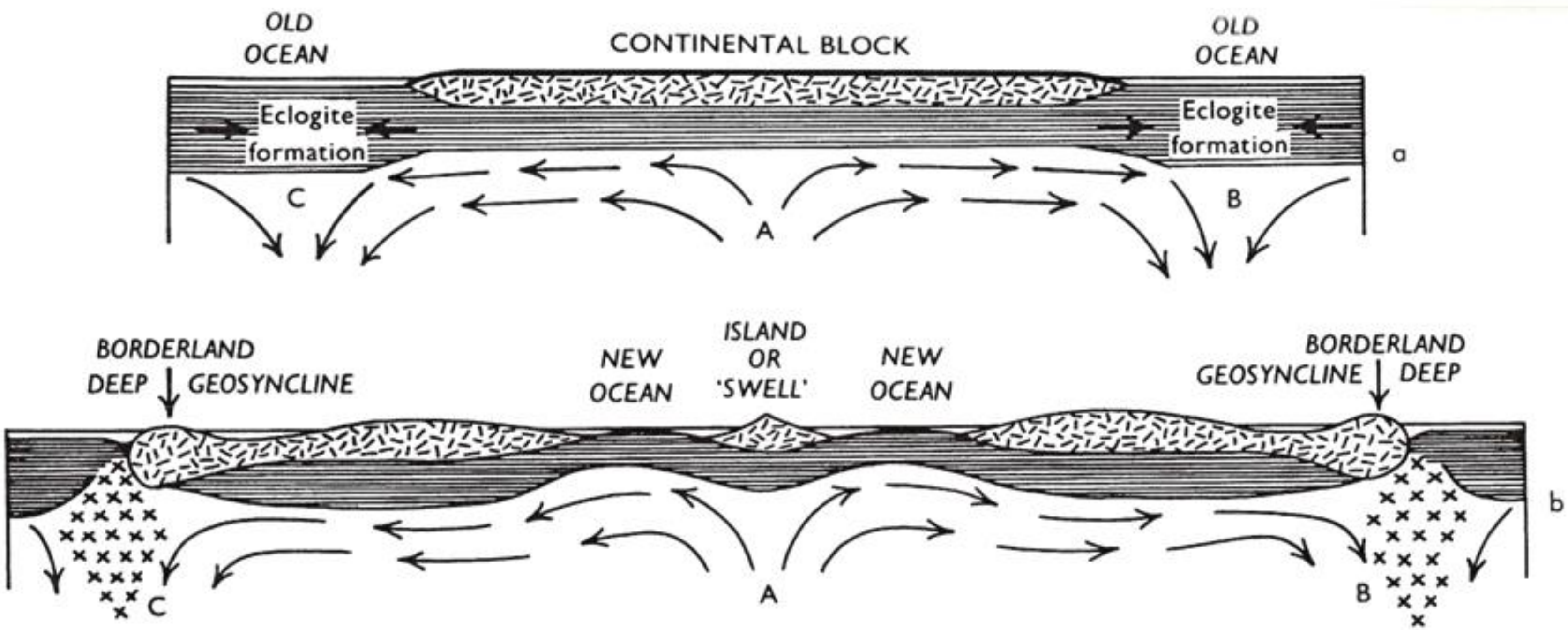
Glacial valley

Wikipedia (Mick Knapton)

Glacial tillite (Smalfjord Fm, 600 10^6 yr) and pavement, northern Norway

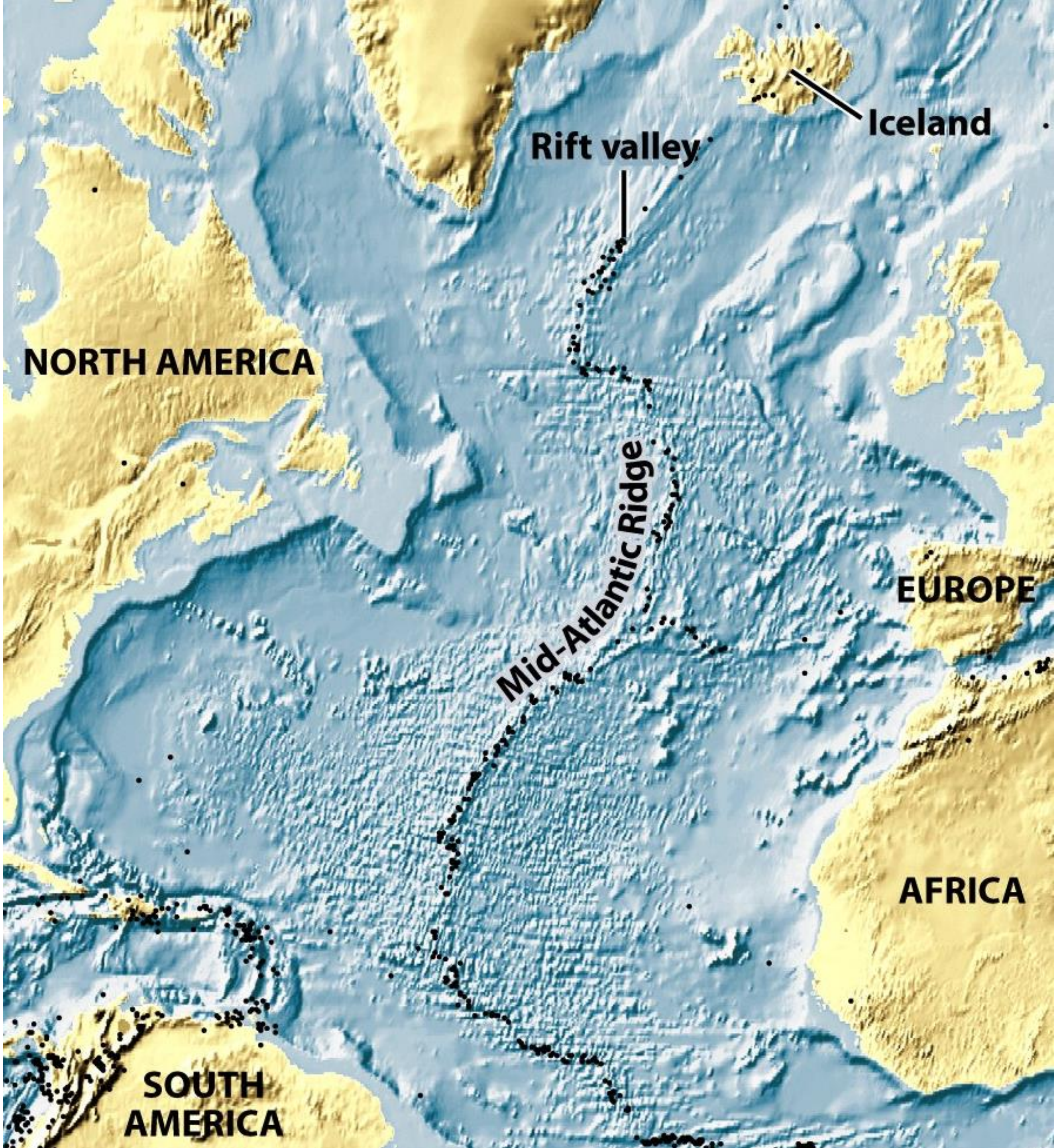
✶ What is the driving force of continental drift?

Arthur Holmes (1890-1965) suggested in 1928 that convection currents resulting from the heat generated by radioactivity within the Earth's interior could push and pull continents apart (note: radioactivity discovered in 1896 by Henri Becquerel)



BUT LACK OF EVIDENCE… UNTIL…

Figure from Holmes' article published in 1928, source: Gohau (1990)



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✶ Seafloor spreading hypothesis: a mechanism explaining continental drift

Harry Hess (1906-1969) **and Robert Dietz** (1914-1995) suggested in the early 1960s that continents move apart through the creation of new lithosphere at Mid-Ocean Ridges (MORs).

SUPPORTING EVIDENCE

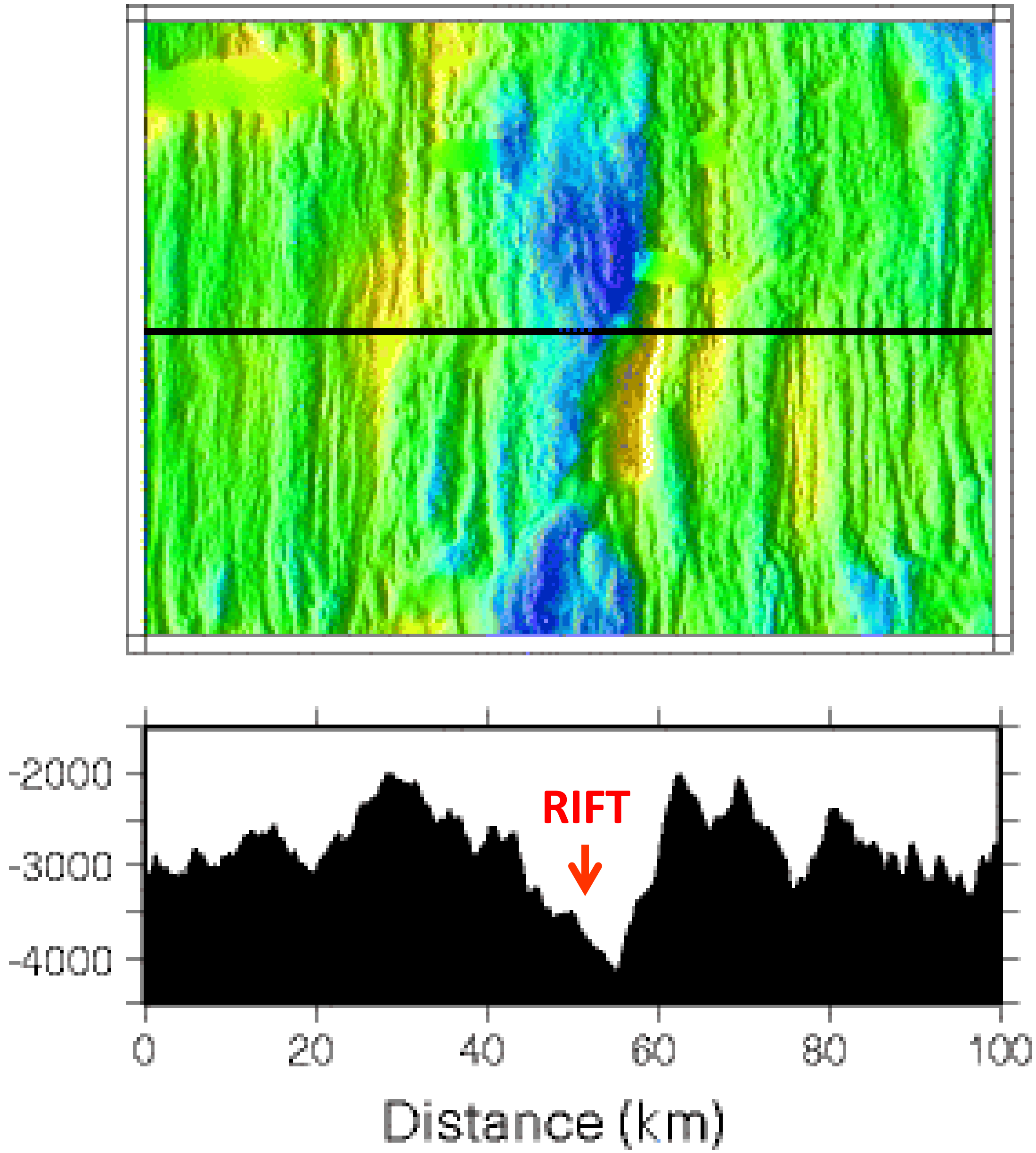
1. Mapping of the Mid-Atlantic Ridge* (MAR) revealed a rift along its axis

   Note that oceanographic surveys conducted after WWII benefitted from new technologies developed during the war, particularly the **SONAR** (**S**ound **NA**vigation and **R**anging) which is used to map the seafloor with great accuracy.

2. The seafloor is made of young basaltic rock (getting older away from the ridge)

* MAR is ~1000-km wide, ~2-km high, discovered in 1872 during the installation of the transatlantic telegraphic cable

Mid-Atlantic Ridge 22.6°N,44.9°W



Buck and Poliakov (1998)

3. Seismic data: almost all earthquakes in the Atlantic occur along the ridge

Black dots = Locations of earthquakes

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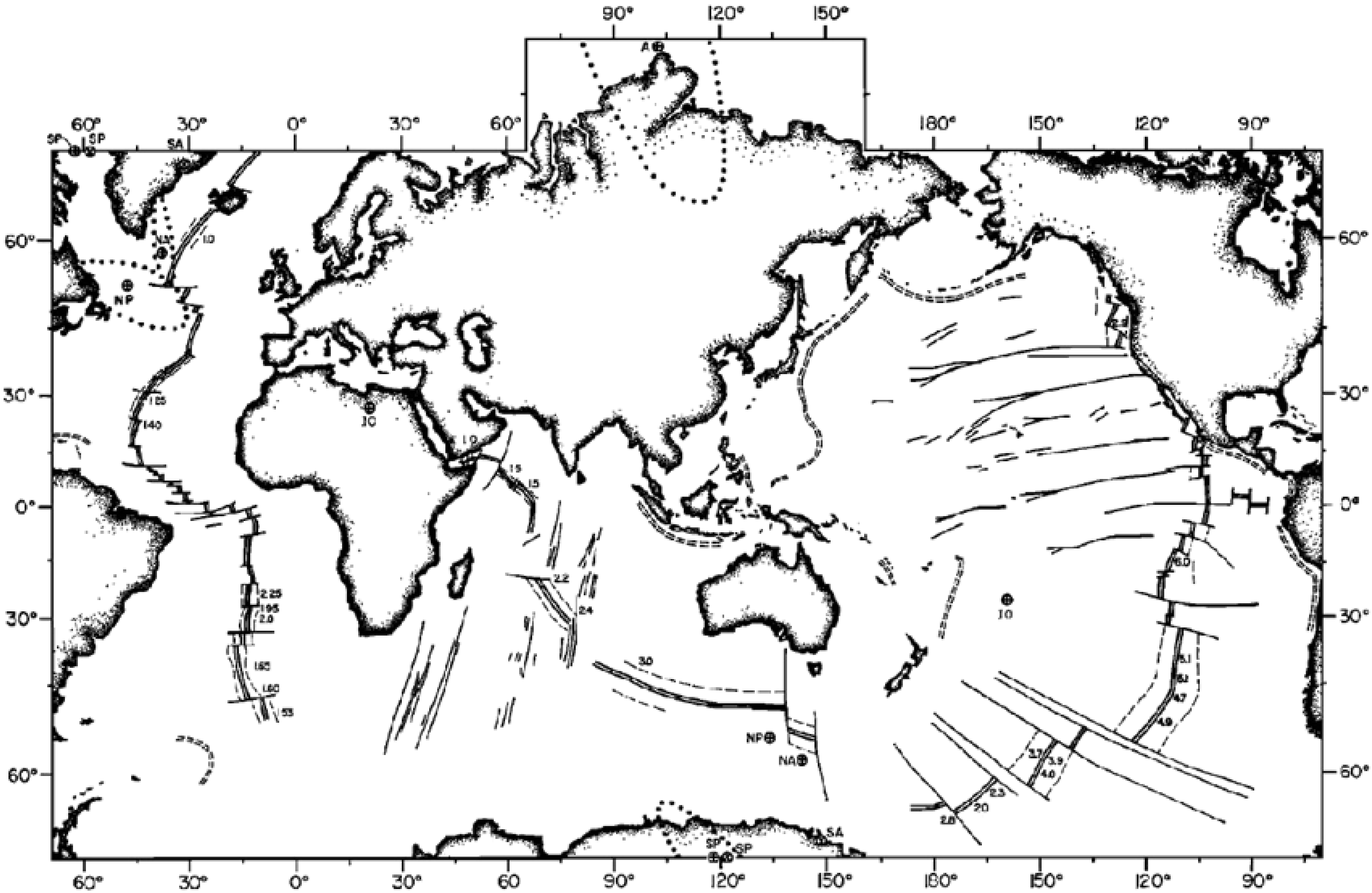
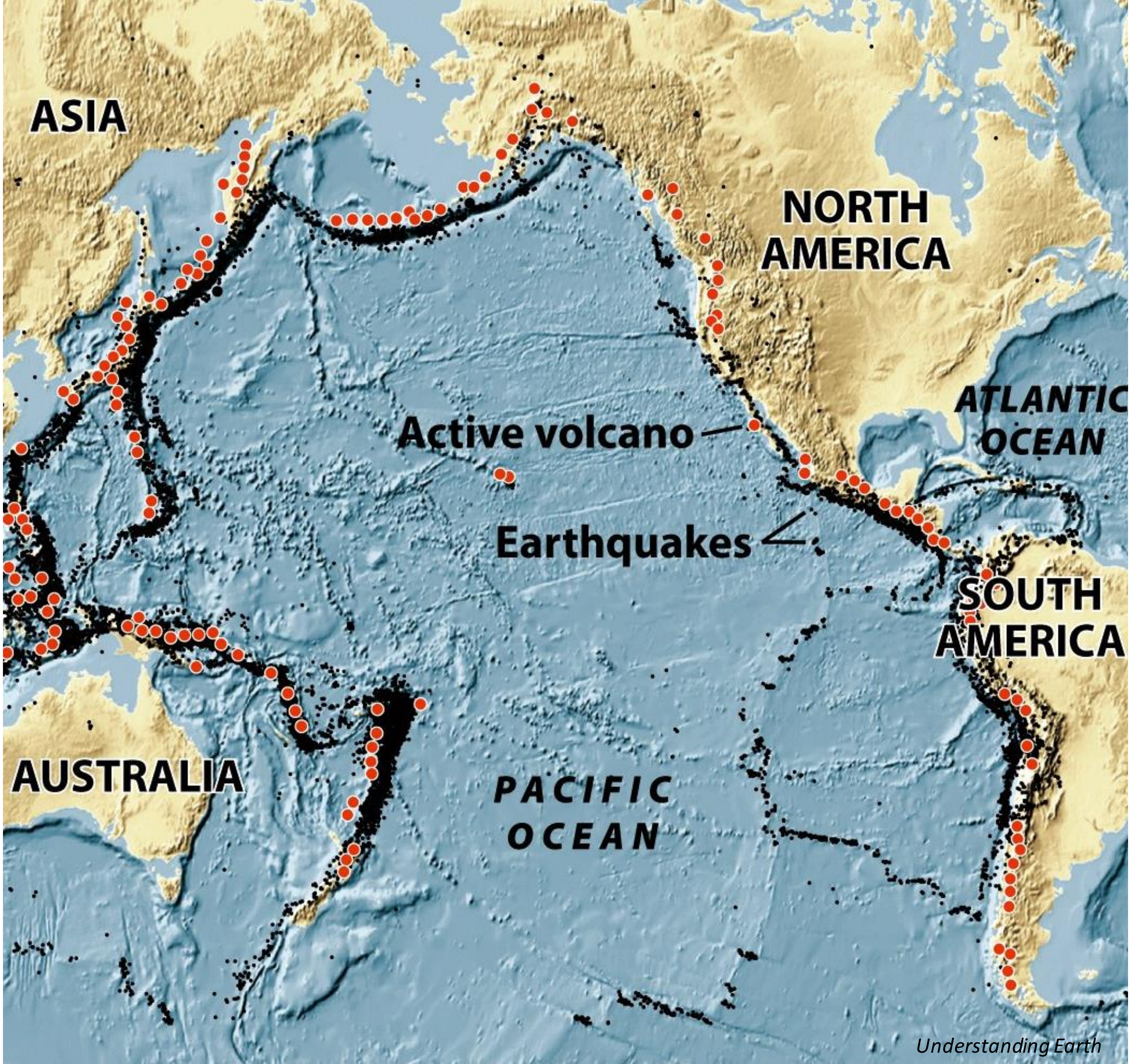
4. Other Mid-Ocean Ridges discovered in the Pacific and Indian Oceans



Le Pichon (1968)



Understanding Earth

✶ Plate tectonics: the unifying theory

The Earth’s surface is divided into rigid plates that are moving relative to one another.

Three types of plate boundaries can be distinguished:

1. **Divergent boundaries** where plates move apart and new oceanic lithosphere is produced (include Mid-Ocean Ridges)

2. **Convergent boundaries** where plates come together and form a mountain chain (include Subduction Zones)

3. **Transform faults** where plates slide horizontally past each other.

J. T. Wilson (1908-1993) was the first to describe this model in 1965

No. 4995 July 24, 1965 NATURE 343

A NEW CLASS OF FAULTS AND THEIR BEARING ON CONTINENTAL DRIFT

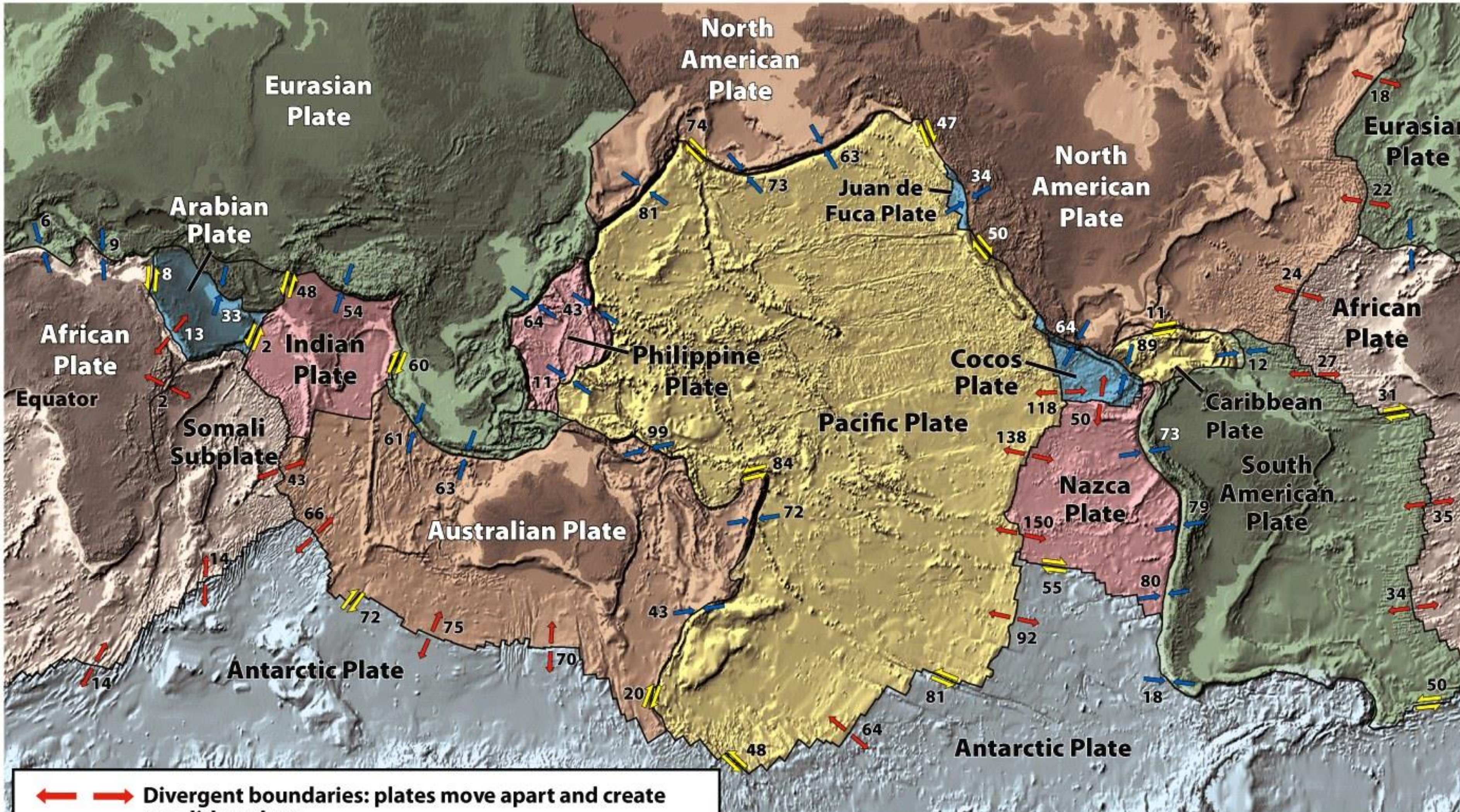
By Prof. J. TUZO WILSON, O.B.E.
Institute of Earth Sciences, University of Toronto

Transforms and half-shears. Many geologists[1] have maintained that movements of the Earth's crust are concentrated in mobile belts, which may take the form of mountains, mid-ocean ridges or major faults with large horizontal movements. These features and the seismic activity along them often appear to end abruptly, which is puzzling. The problem has been difficult to investigate because most terminations lie in ocean basins.

This article suggests that these features are not isolated, that few come to dead ends, but that they are connected into a continuous network of mobile belts about the Earth which divide the surface into several large rigid plates (Fig. 1). Any feature at its apparent termination may be transformed into another feature of one of the other two types. For example, a fault may be transformed into a mid-ocean ridge as illustrated in Fig. 2*a*. At the point of transformation the horizontal shear motion along the fault ends abruptly by being changed into an expanding tensional motion across the ridge or rift with a change in

In this article the term 'ridge' will be used to mean mid-ocean ridge and also rise (where that term has been used meaning mid-ocean ridge, as by Menard[3] in the Pacific basin). The terms mountains and mountain system may include island arcs. An arc is described as being convex or concave depending on which face is first reached when proceeding in the direction indicated by an arrow depicting relative motion (Figs. 2 and 3). The word fault may mean a system of several closely related faults.

Transform faults. Faults in which the displacement suddenly stops or changes form and direction are not true transcurrent faults. It is proposed that a separate class of horizontal shear faults exists which terminate abruptly at both ends, but which nevertheless may show great displacements. Each may be thought of as a pair of half-shears joined end to end. Any combination of pairs of the three dextral half-shears may be joined giving rise to the six types illustrated in Fig. 3. Another six sinistral forms can also exist. The name transform fault is pro-



Divergent boundaries: plates move apart and create new lithosphere.

Convergent boundaries: plates move together, oceanic lithosphere is recycled back into the mantle, continental plates are deformed.

Transform-fault boundaries: plates slide horizontally past each other.

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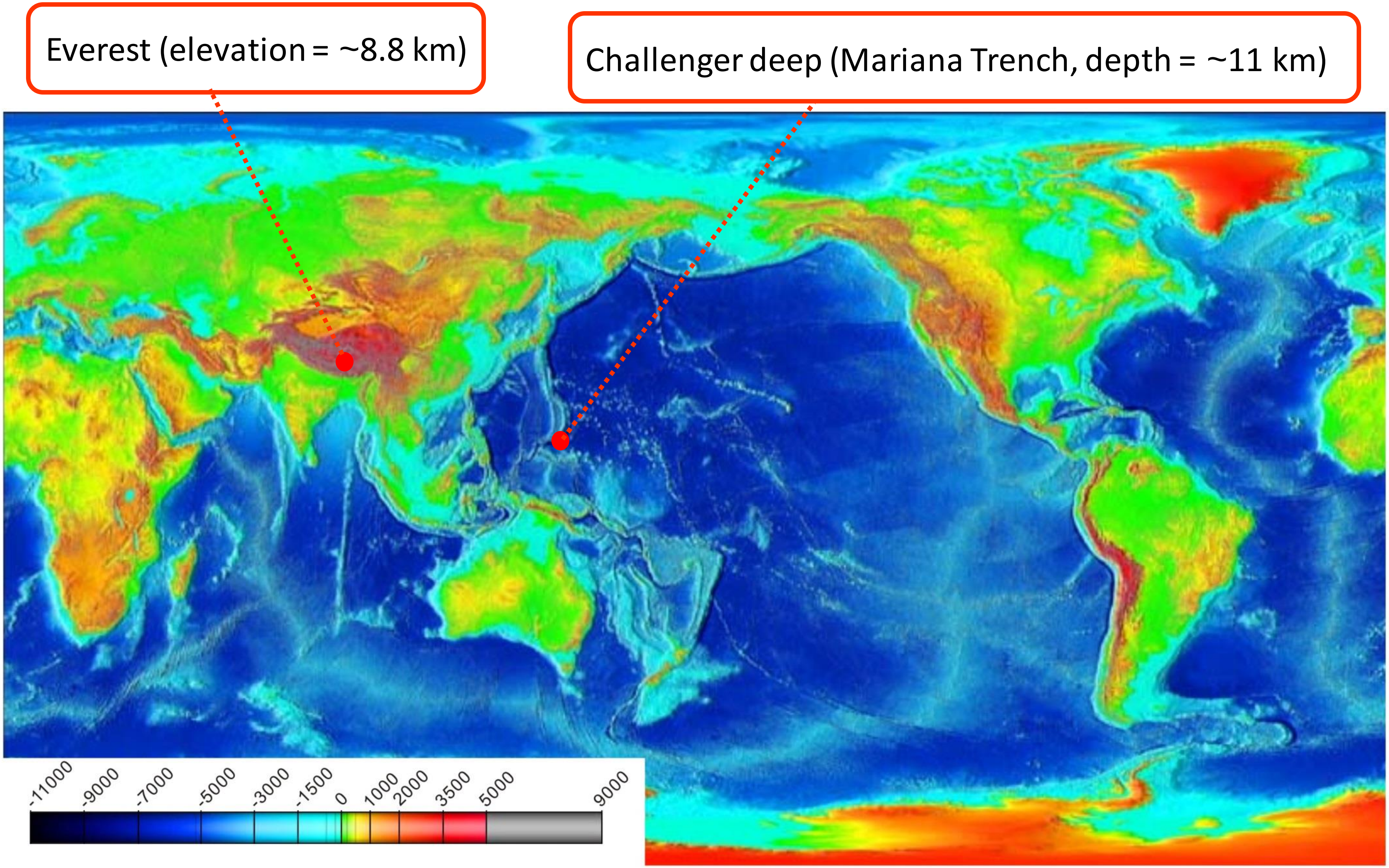
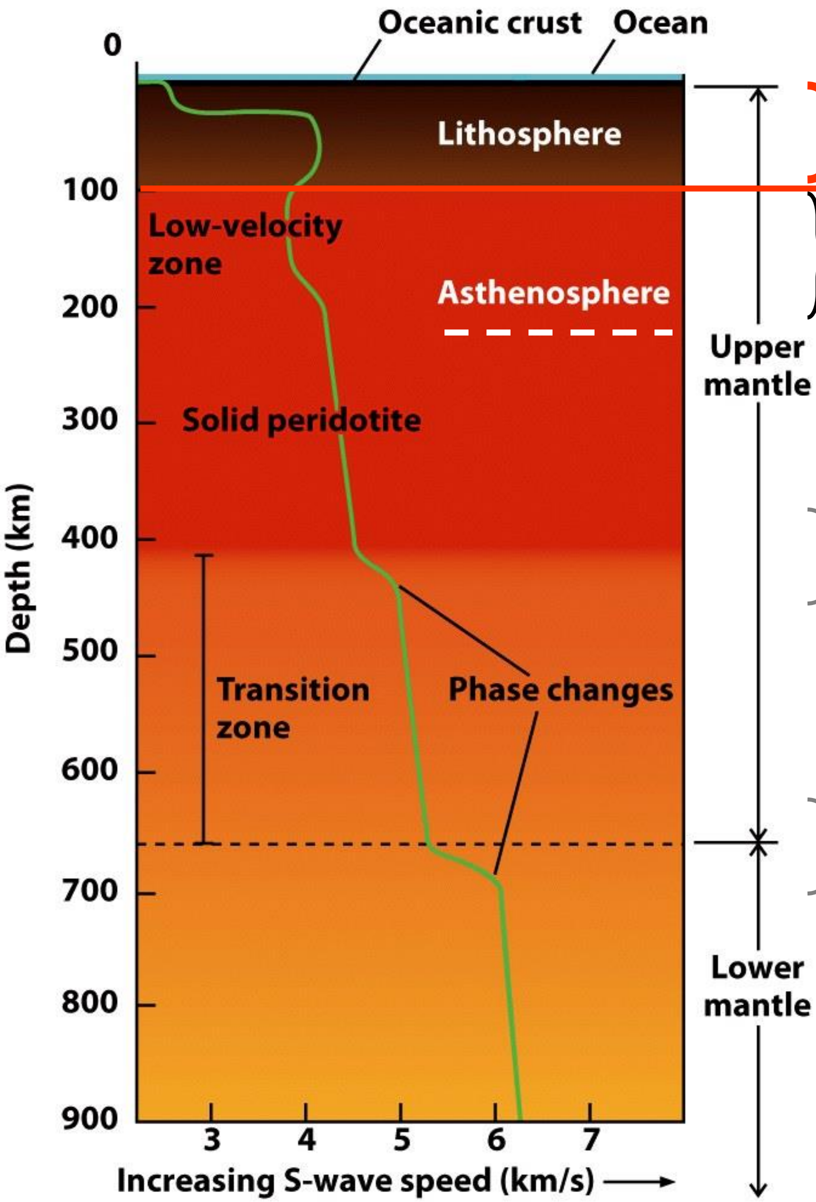

Everest (elevation = ~8.8 km)
Challenger deep (Mariana Trench, depth = ~11 km)
-11000
-9000
-7000
-5000
-3000
-1500
0
1000
2000
3500
5000
9000

NOAA



Rigid, **brittle** **lithosphere** (**crust** + uppermost part of **mantle**) **= tectonic plates**

Weak, **ductile** **asthenosphere** (layer of the upper **mantle** on which tectonic plates slide)

Phase change: olivine → spinel (~400 km)

Phase change: spinel → perovskite (~650 km)

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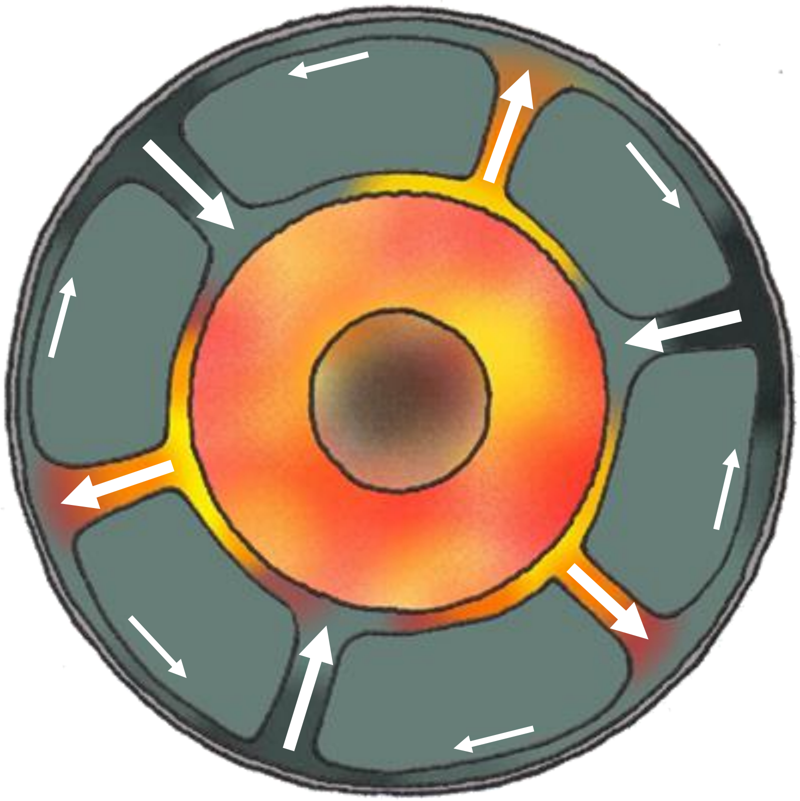
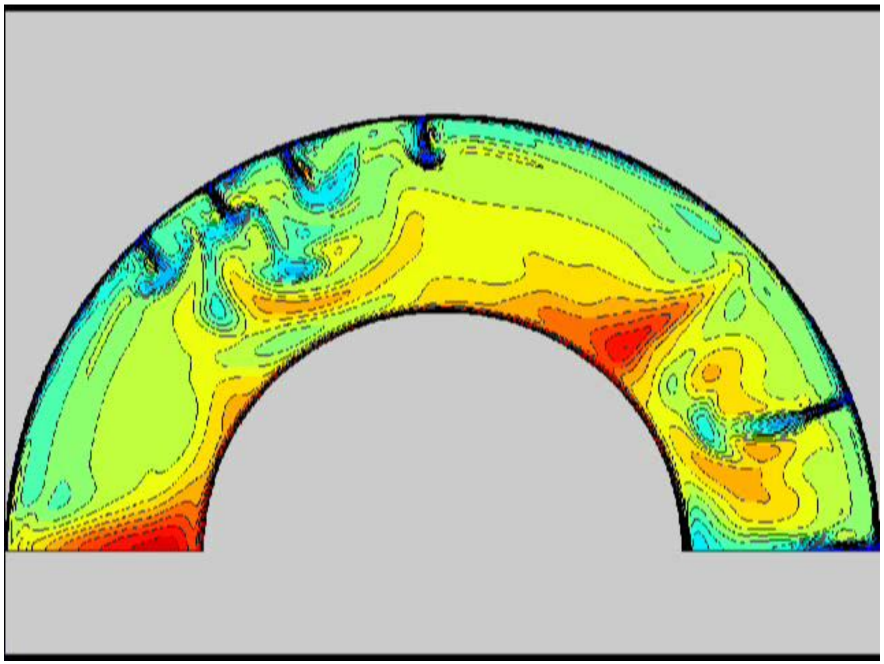
Earth's internal heat engine

In the **mantle** below tectonic plates:
hotter material rises, colder material sinks (**CONVECTION**)





S.L. Butler simulation (University of Saskatchewan, Canada)

Think about the "miso soup effect"

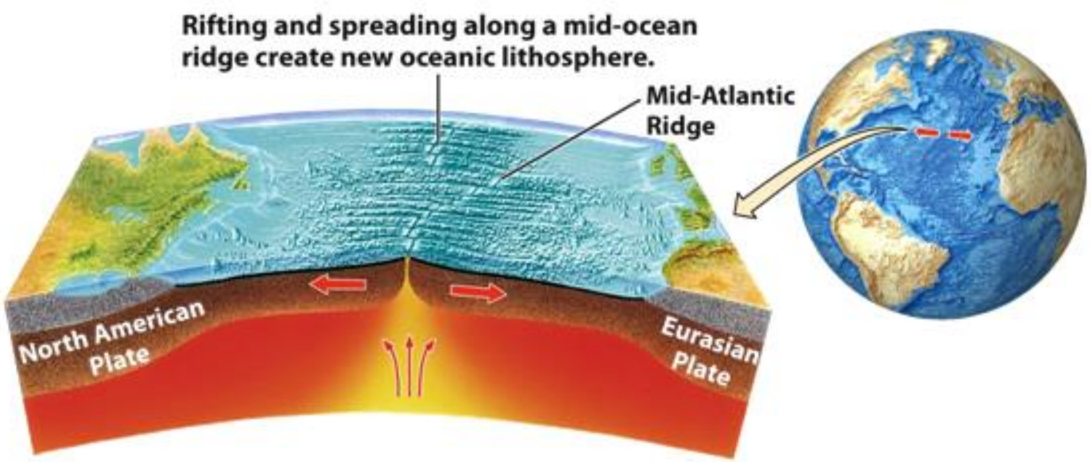
2 main sources of heat: 1. Original heat (**meteorite impacts + contraction**)

2. **Decay of radioactive elements**

✶ Plate boundaries

1. DIVERGENT BOUNDARIES

MID-OCEAN RIDGES (MOR)



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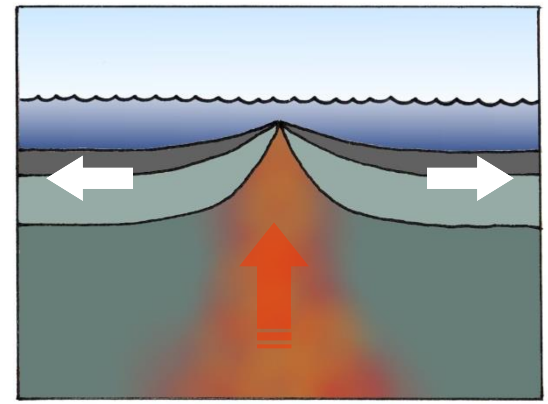
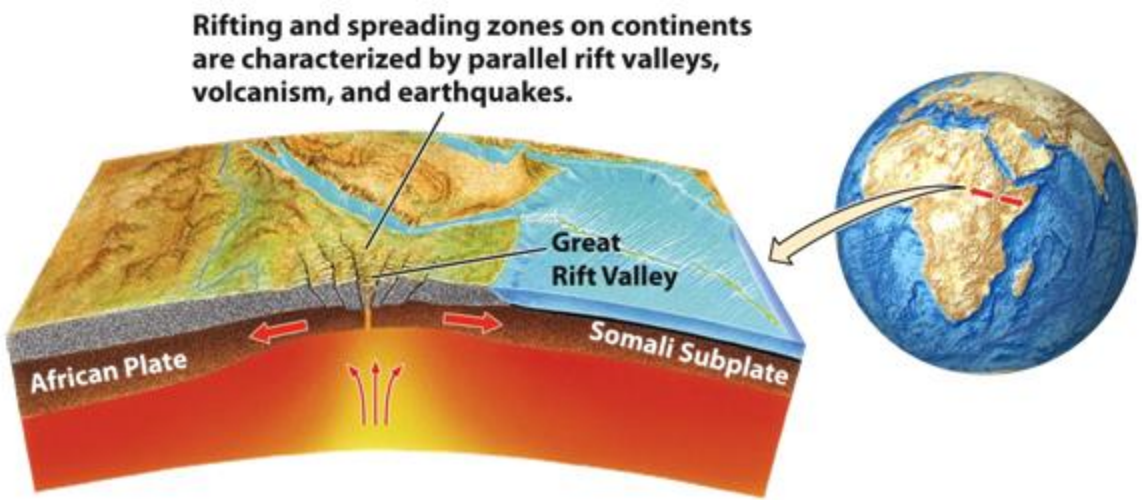
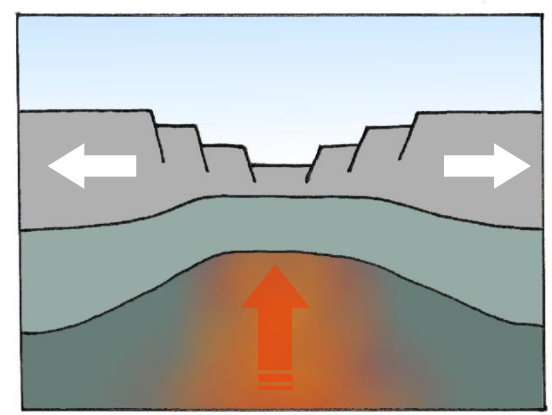


CONTINENTAL RIFTS





Hydrothermal vents

Juan de Fuca Ridge

Mid-Ocean Ridge characteristic features

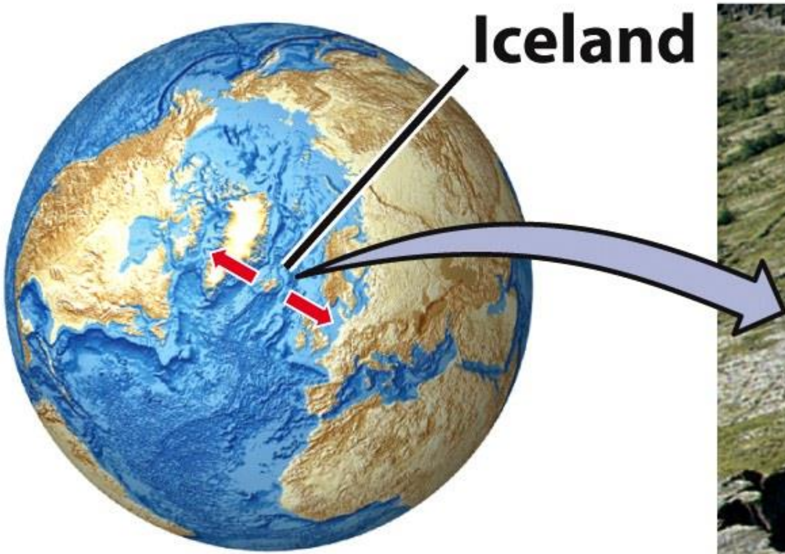
Faults   Pillow lavas

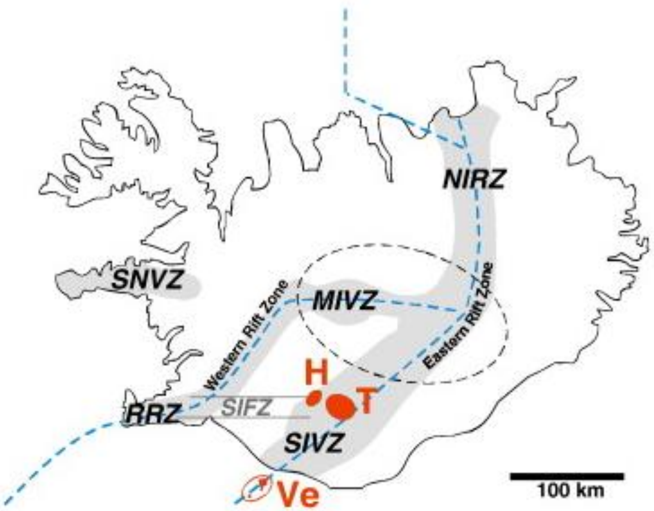
R/V Atlantis, WHOI

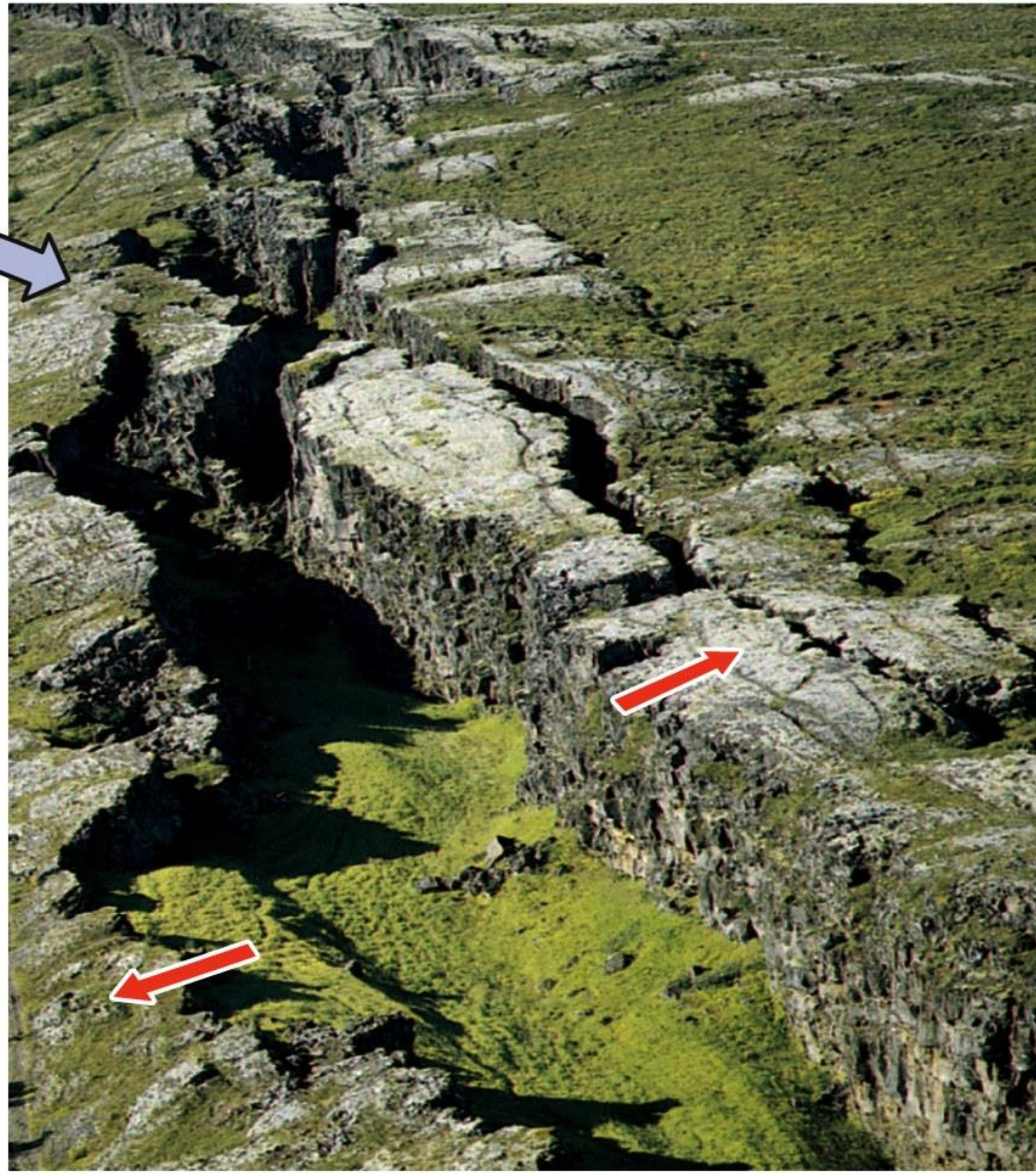
DEEP-SEA VOLCANIC ERUPTION ALONG THE AXIS OF JUAN DE FUCA RIDGE

Video capture by ROV Jason in 2011 (NOAA) – depth: ~1600 m

The eruption occurred a few months earlier before the video was taken







The Mid-Atlantic Ridge is cutting Iceland in two.

Schuessler et al. (2009)

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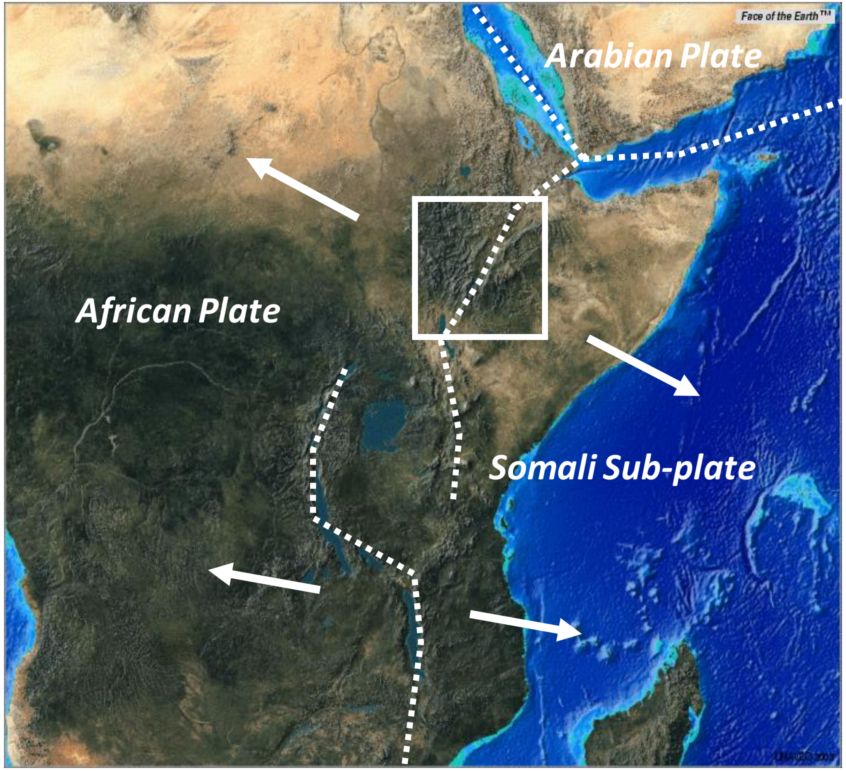
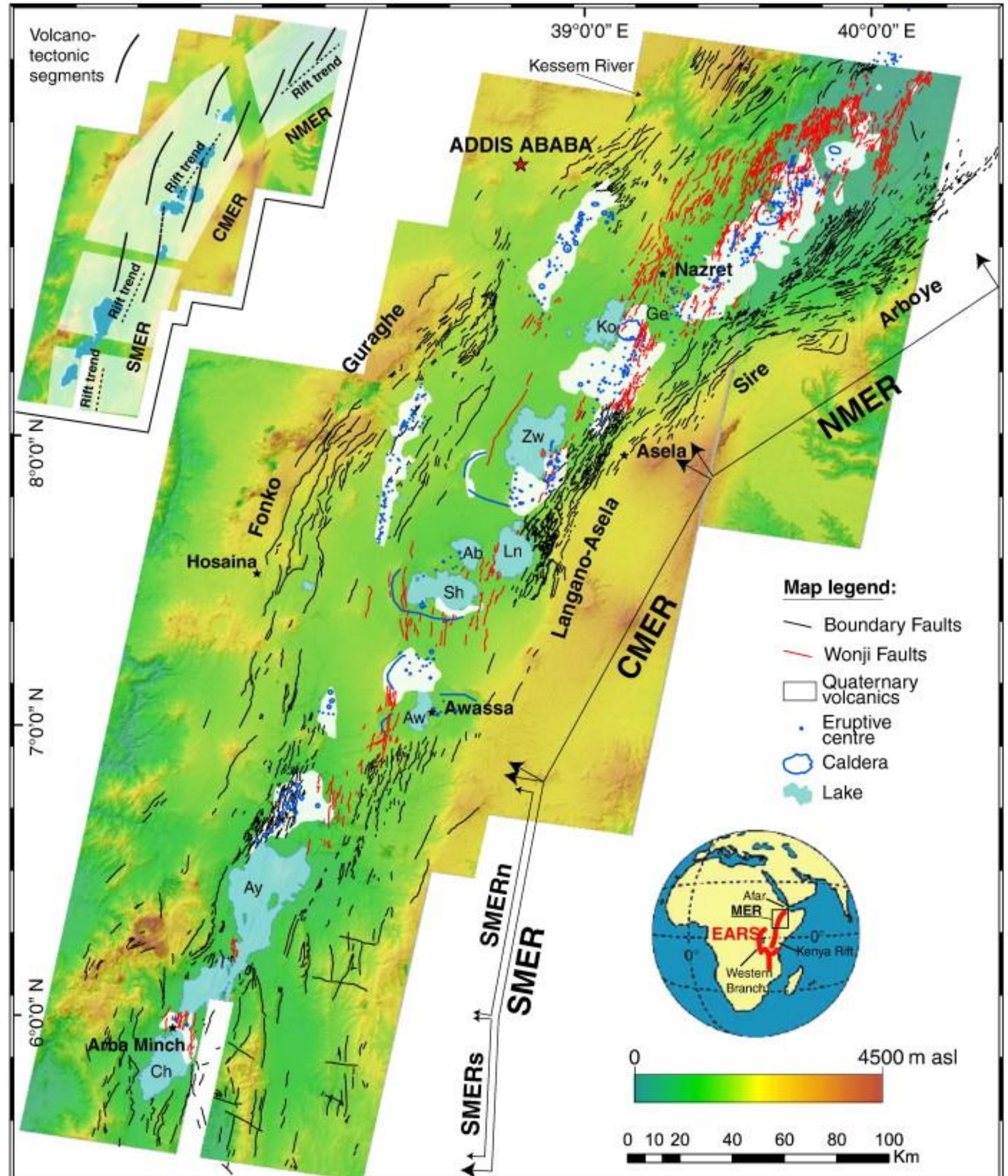


The East African Rift

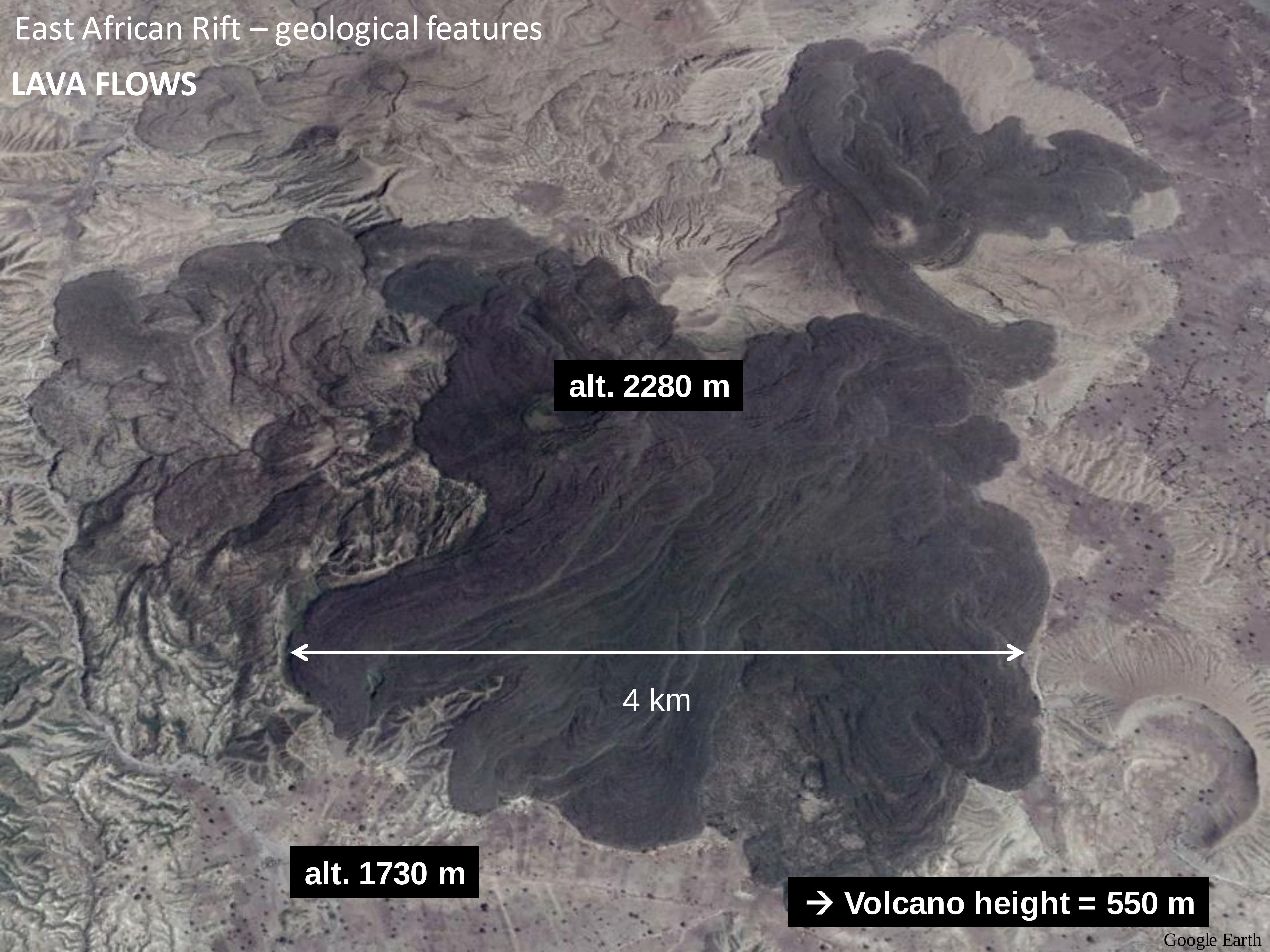
Lakes and volcanoes occupy the depression of the rift.



http://jules.unavco.org *Agostini et al. (2011)*

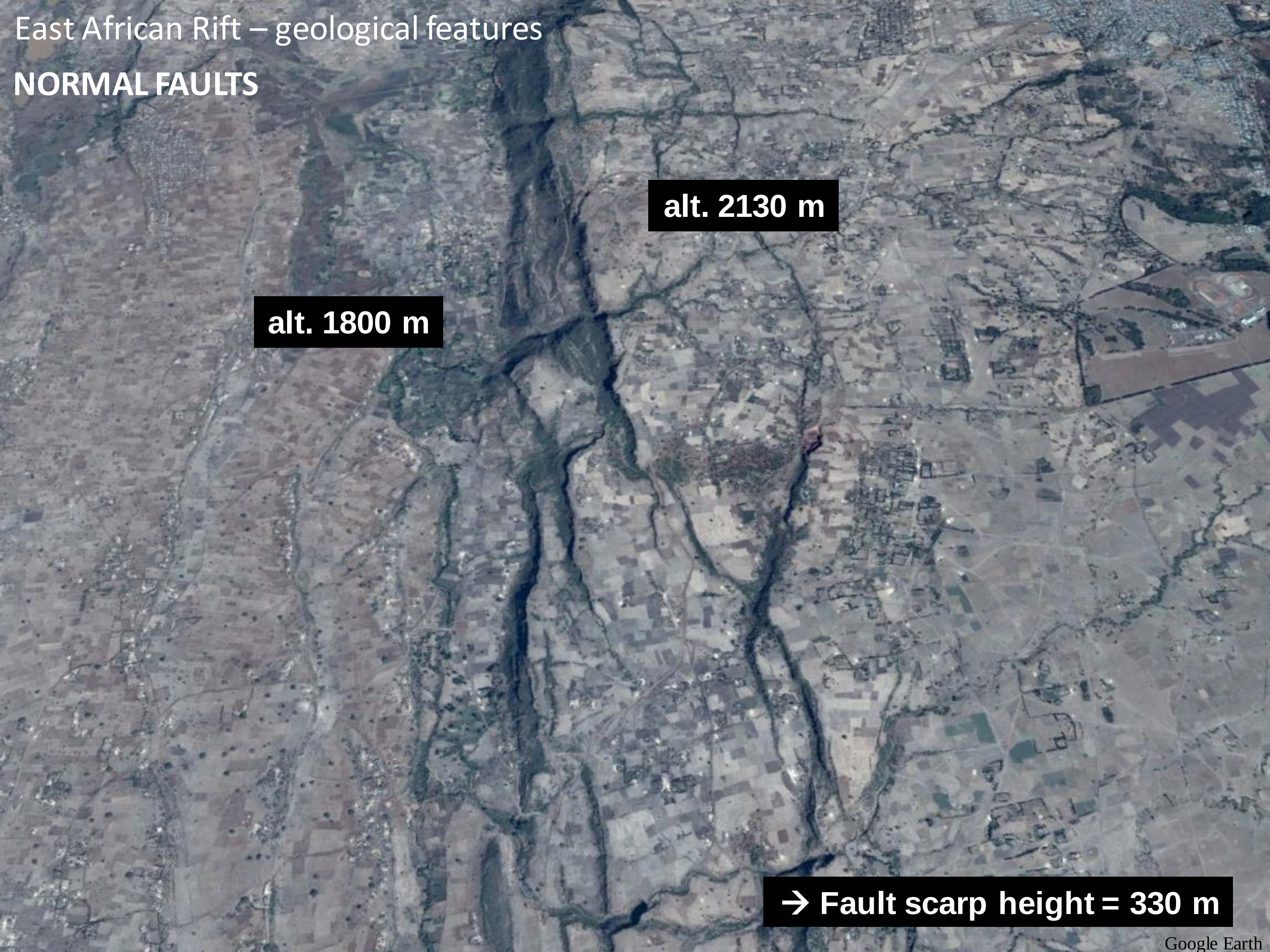
East African Rift – geological features

LAVA FLOWS



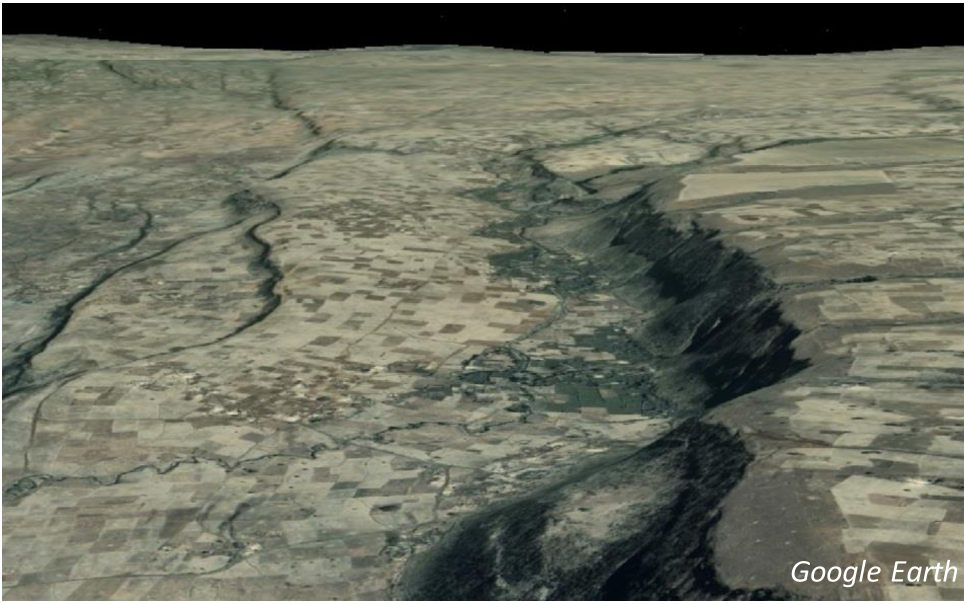
East African Rift – geological features

NORMAL FAULTS

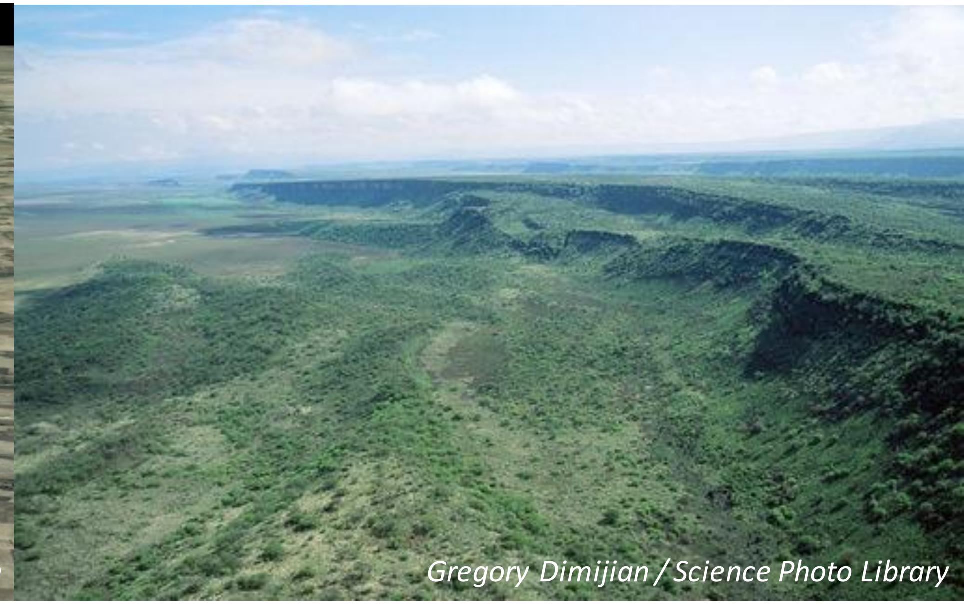



http://www.geology.com

Eastern wall of African Rift (Ethiopia)



Eastern wall of African Rift (Kenya)

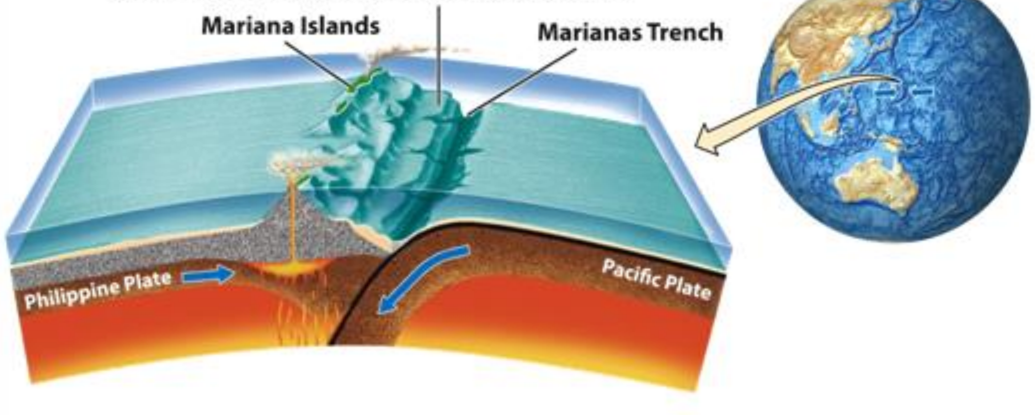


Ol Doinyo Lengai (Tanzania)

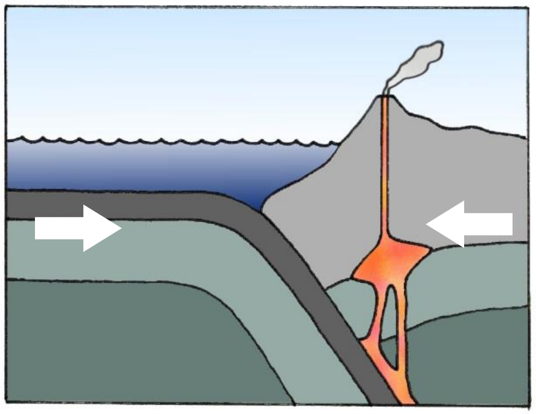
Ethiopian Rift Valley

OCEAN-OCEAN CONVERGENCE

Where oceanic lithosphere meets oceanic lithosphere, one plate is subducted under the other, and a deep-sea trench and a volcanic island arc are formed.

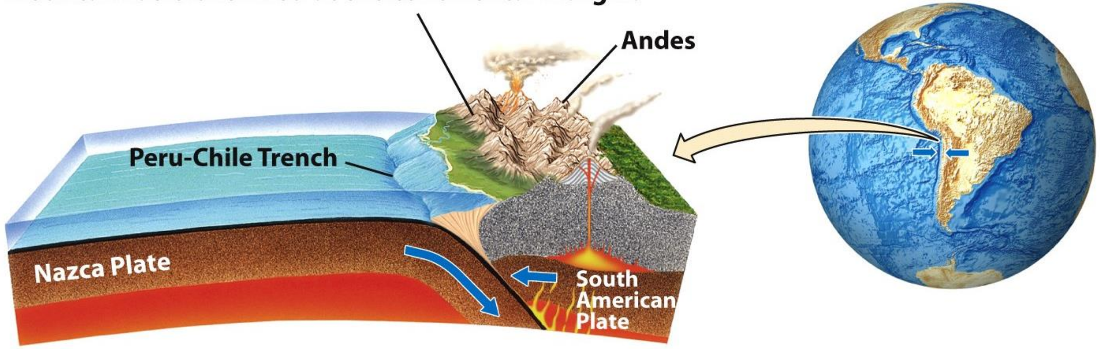


Subduction zones



OCEAN-CONTINENT CONVERGENCE

When oceanic lithosphere meets continental lithosphere, the oceanic lithosphere is subducted, and a volcanic mountain belt is formed at the continental margin.



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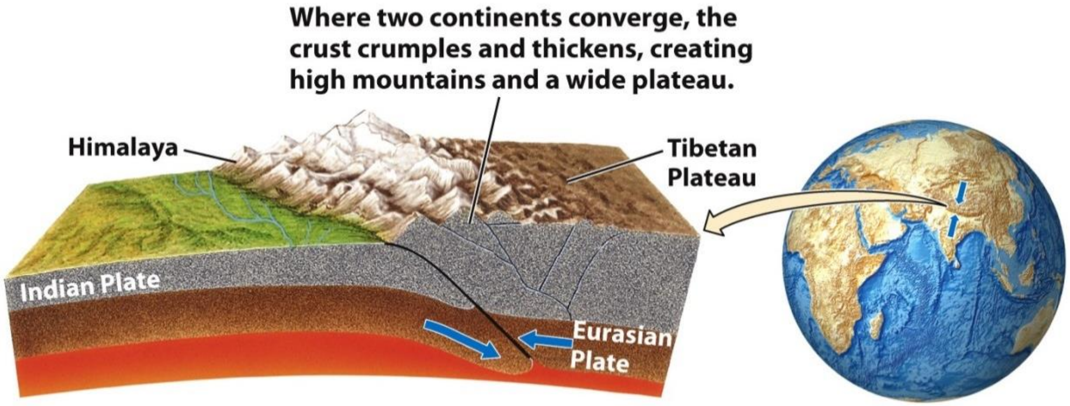
CONTINENT-CONTINENT CONVERGENCE



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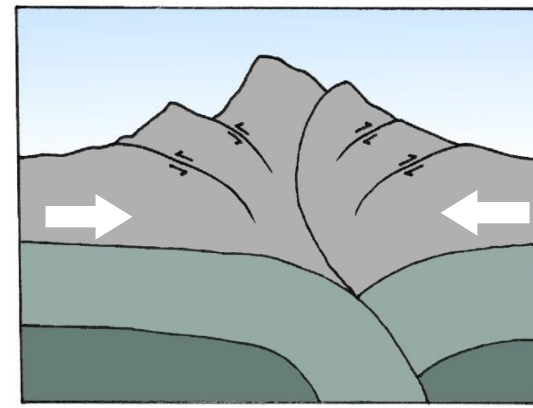
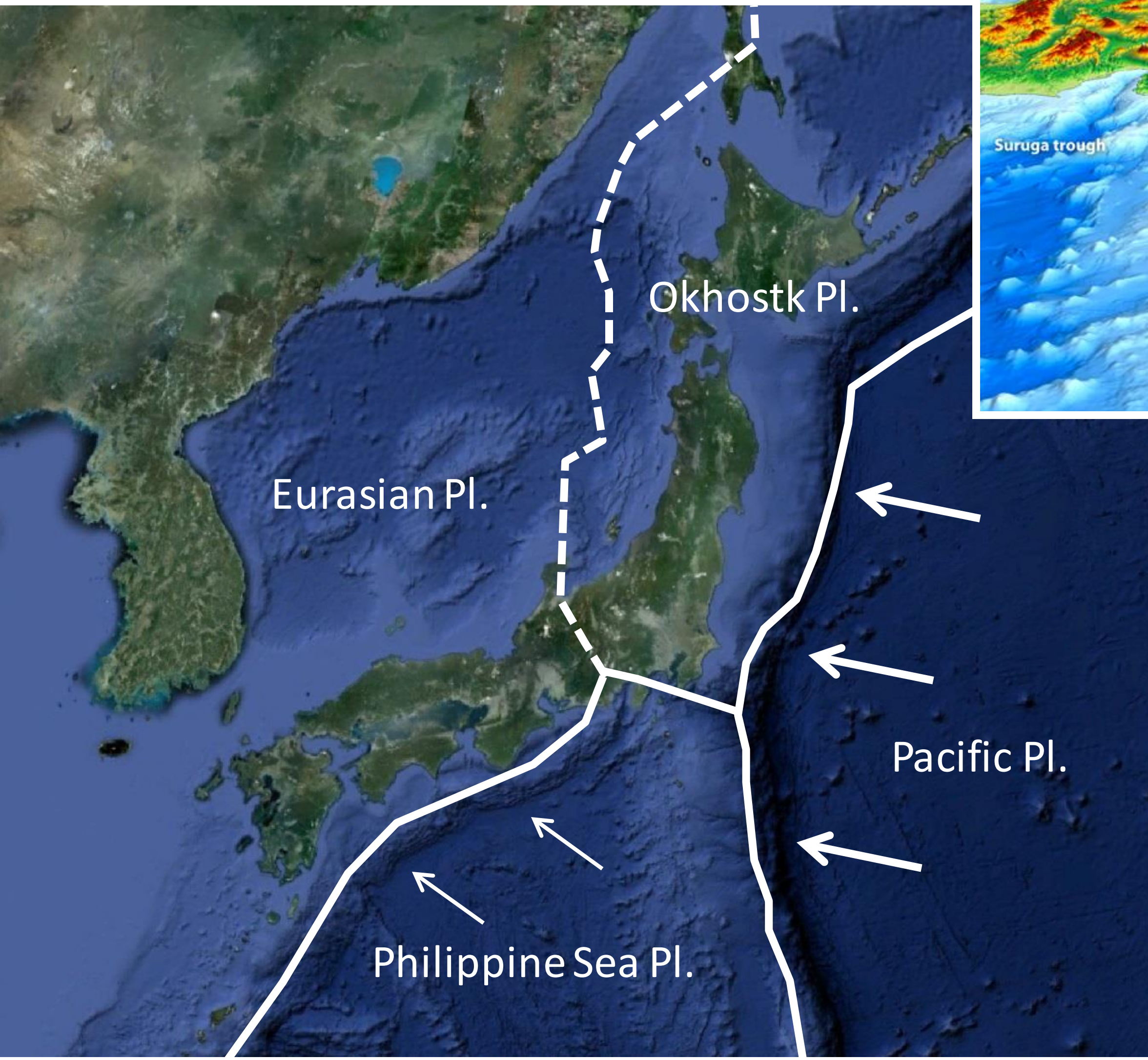
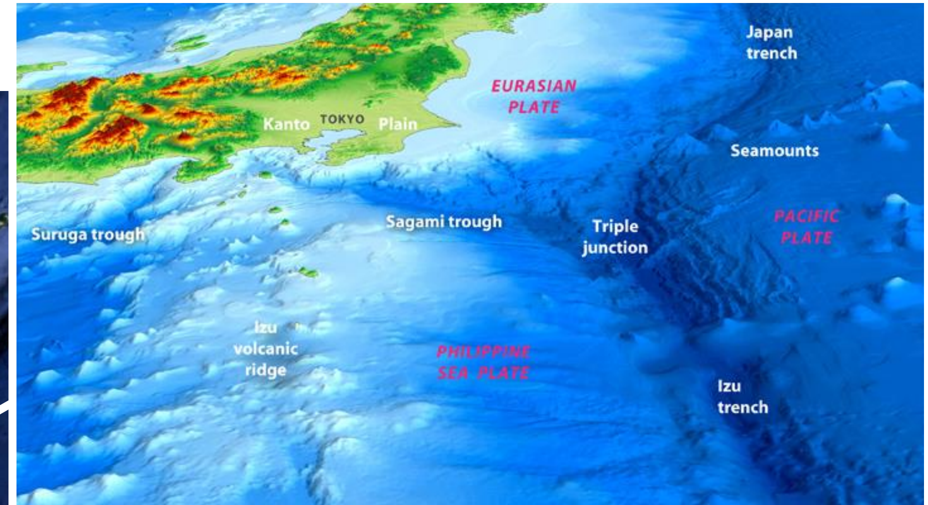


Subduction zone: Japan





http://usgsprojects.org/fragment/

Google Earth

Plate boundaries from http://www.earthquakes.bgs.ac.uk/

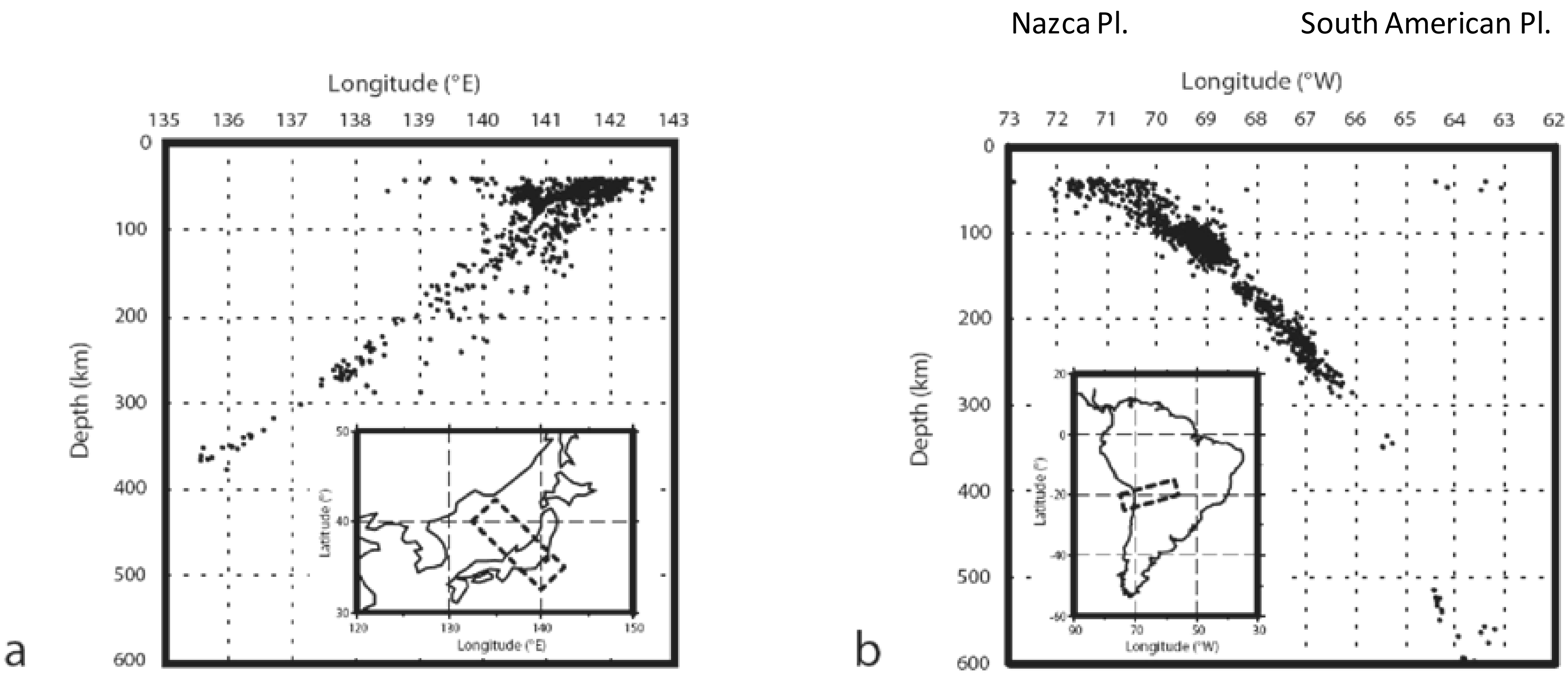


Fig. 13. Two examples of classical two-dimensional representation of Wadati-Benioff zones, with hypocentral depth greater or equal to 40 km. a) A section-box under the Japanese arc. b) A section under the central part of the South American Cordillera.

Deepest earthquakes at subduction zones (no deeper than 700 km)

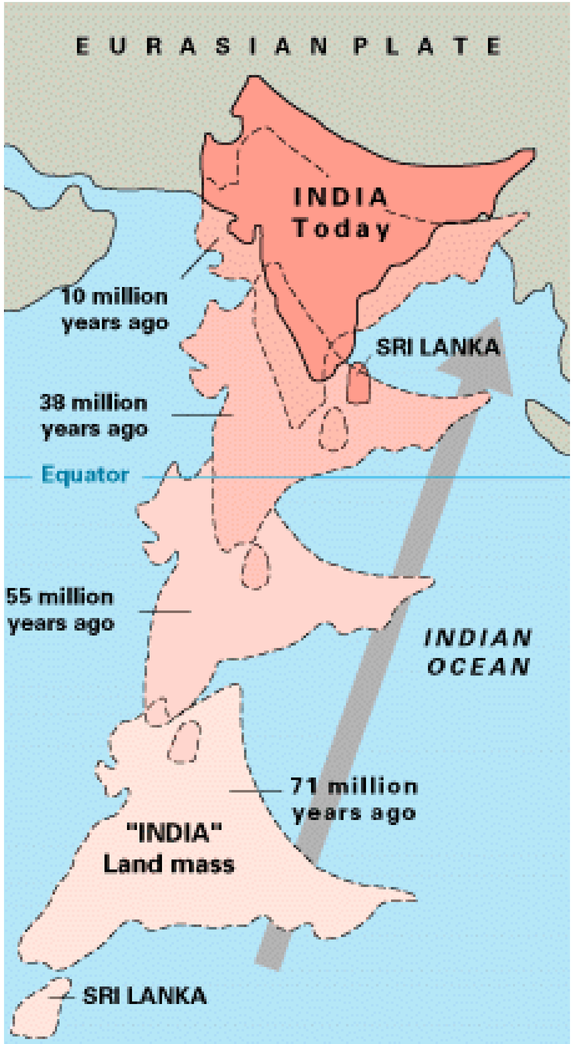
Scalera (2007)

DEEP-SEA VOLCANIC ERUPTION NEAR A SUBDUCTION ZONE (TONGA TRENCH)

Video capture by ROV Jason in 2009 (NOAA) – depth: 1200 m

TED-Ed video 2012 "Deep ocean mysteries and wonders" (David Gallo, Woods Hole Oceanographic Institution)

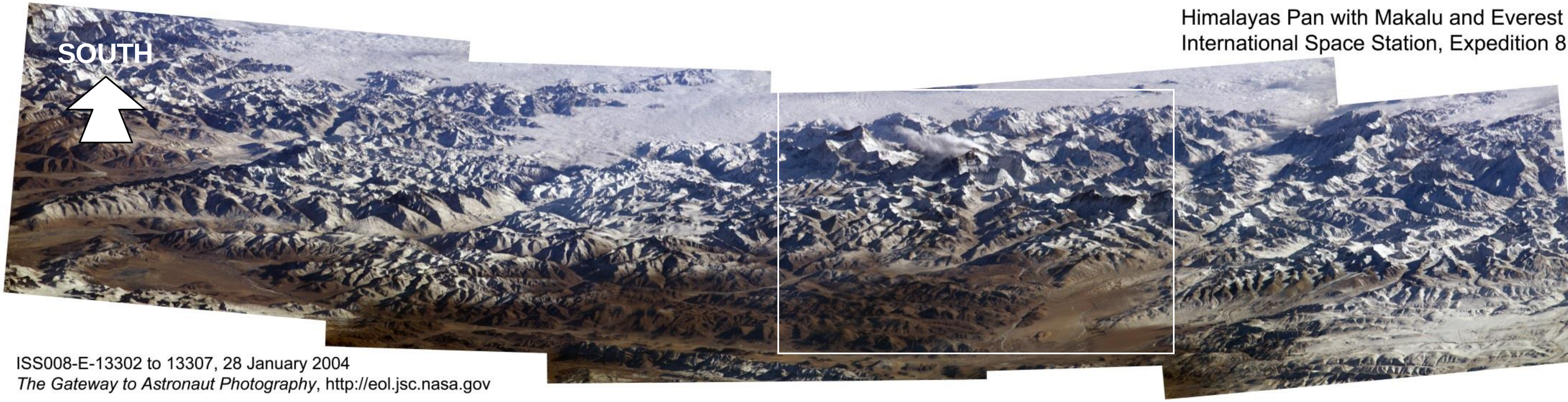
Continental collision: Himalaya



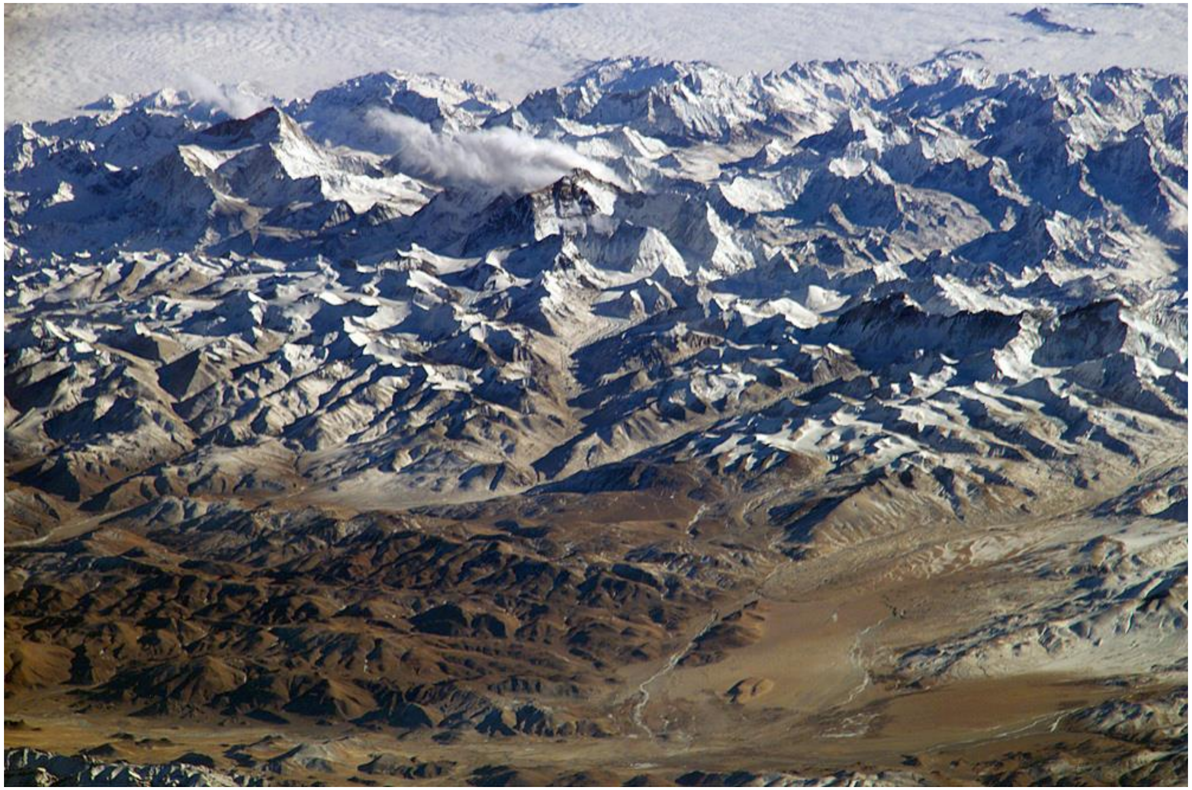
USGS

Google Earth

Himalayas Pan with Makalu and Everest
International Space Station, Expedition 8



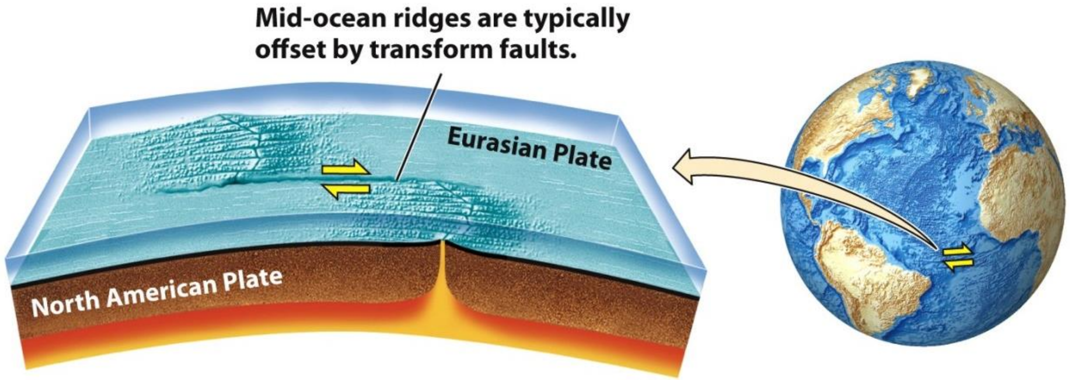
ISS008-E-13302 to 13307, 28 January 2004
The Gateway to Astronaut Photography, http://eol.jsc.nasa.gov

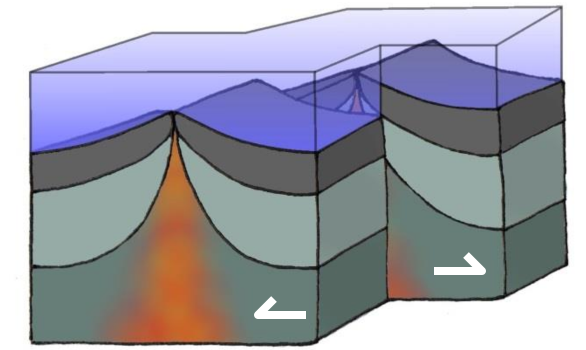


NASA

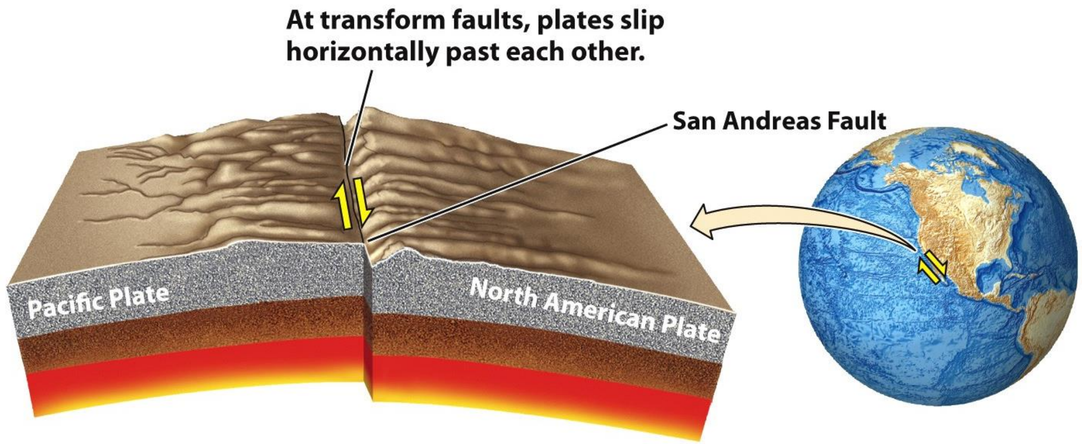
3. TRANSFORM FAULTS

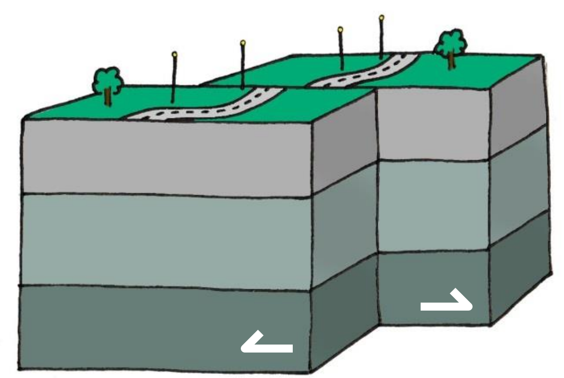
OCEANIC TRANSFORM FAULTS





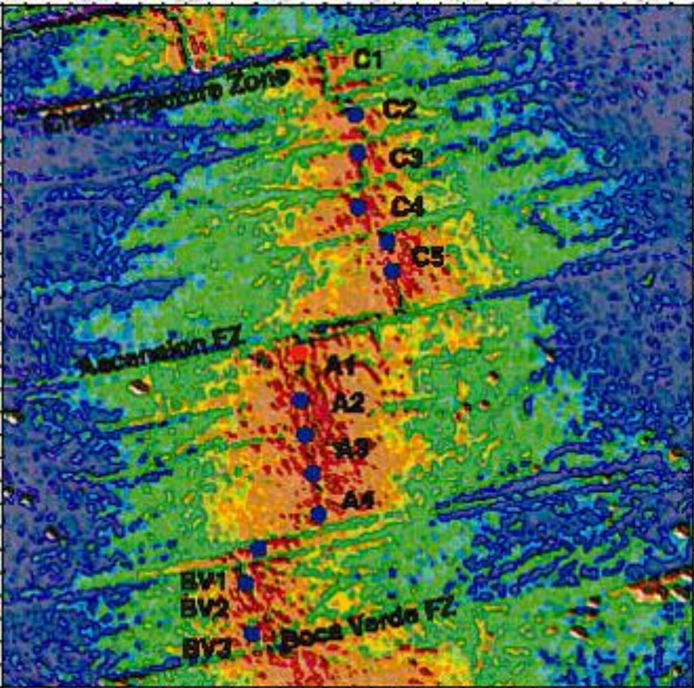
CONTINENTAL TRANSFORM FAULTS



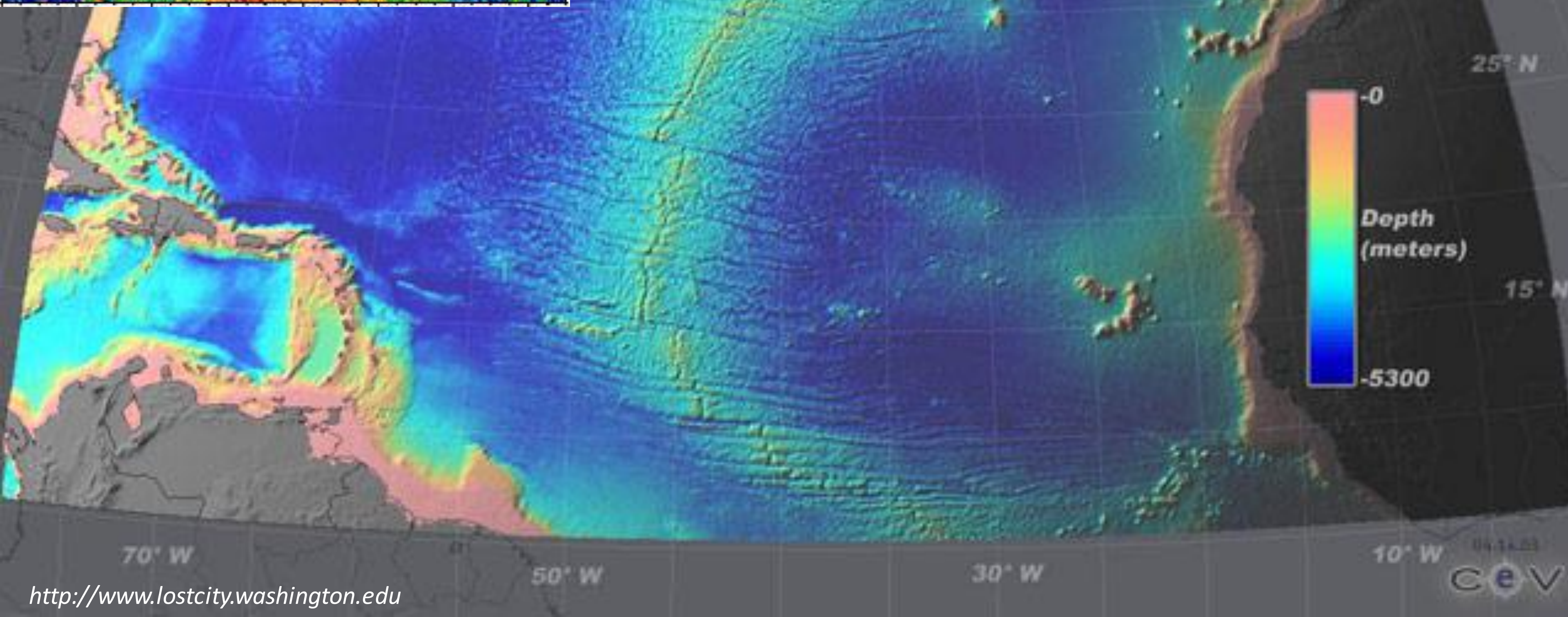


Understanding Earth

Oceanic transform faults

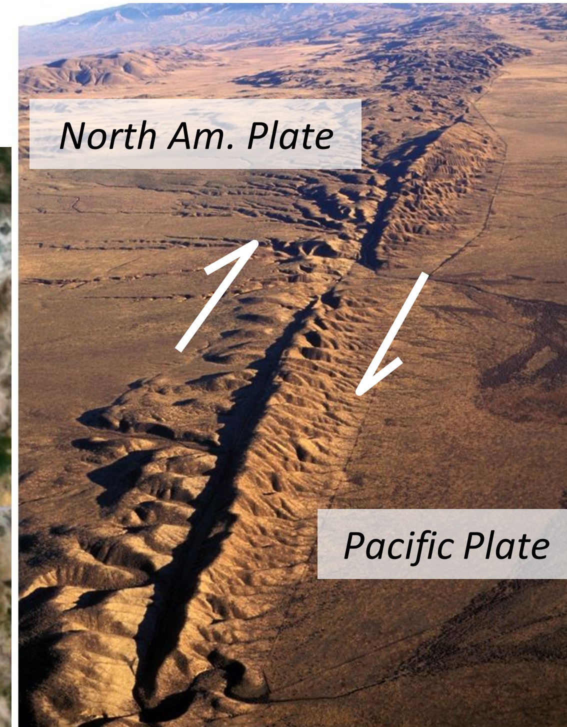


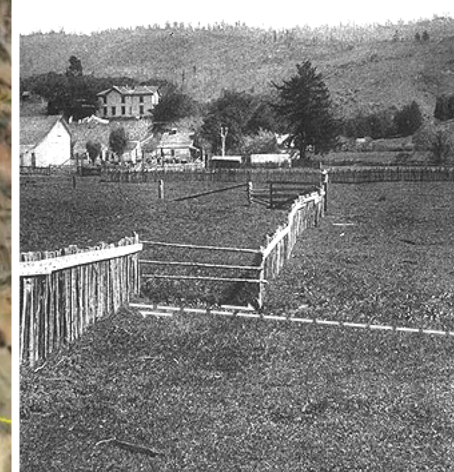
WHOI (Tim Shank)



http://www.lostcity.washington.edu

Cont. transform fault: San Andreas Fault

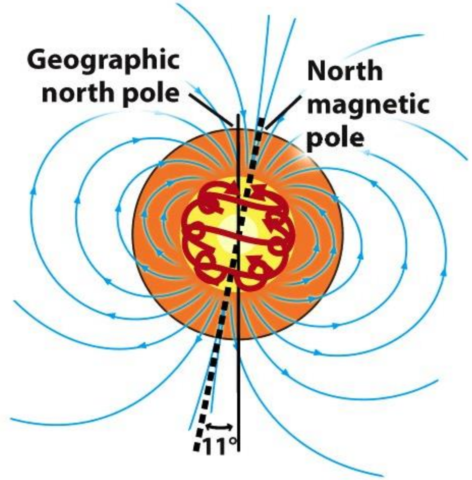


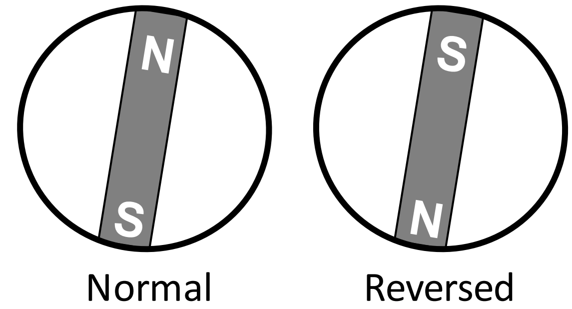


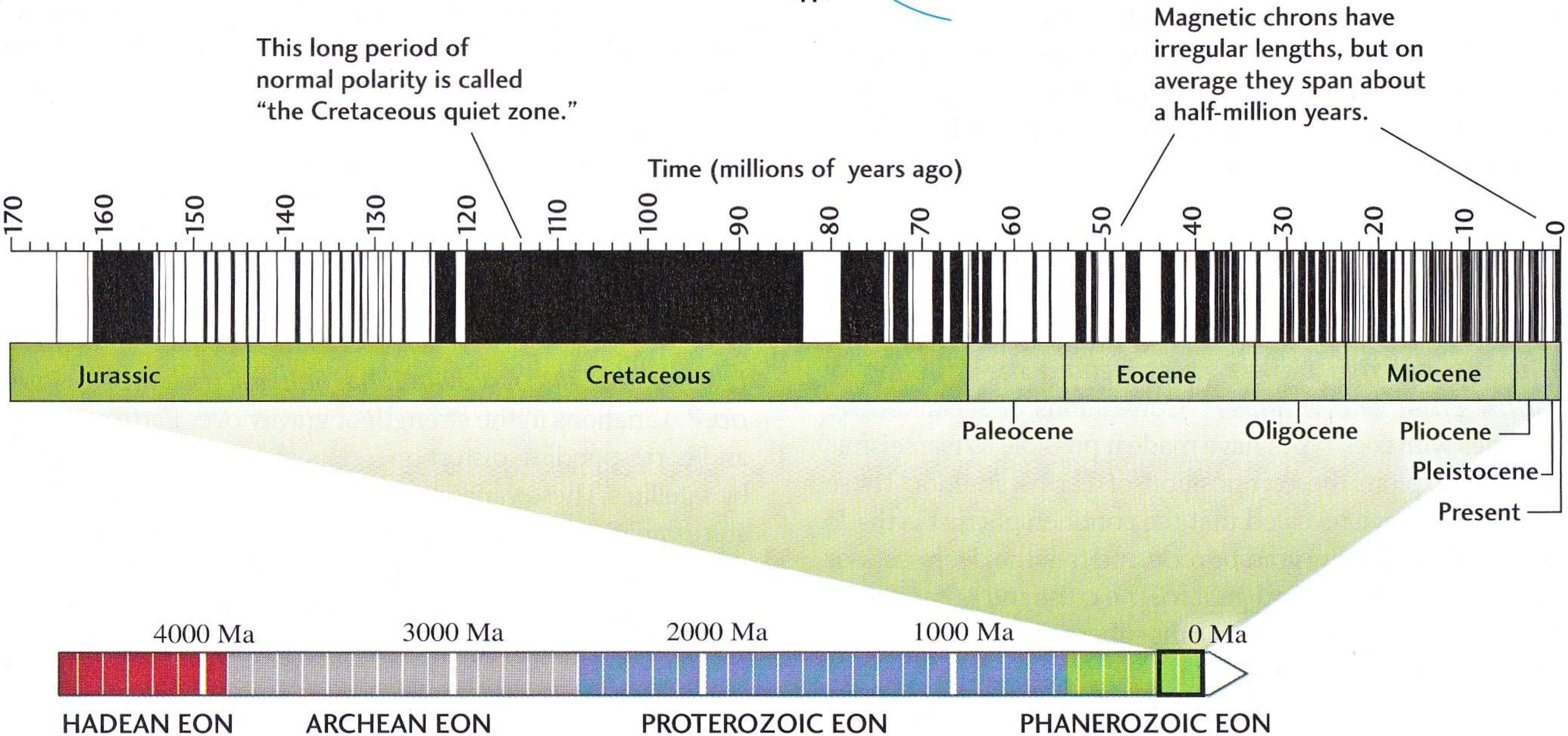
USGS

Rates of plate motion

The magnetic polarity time scale







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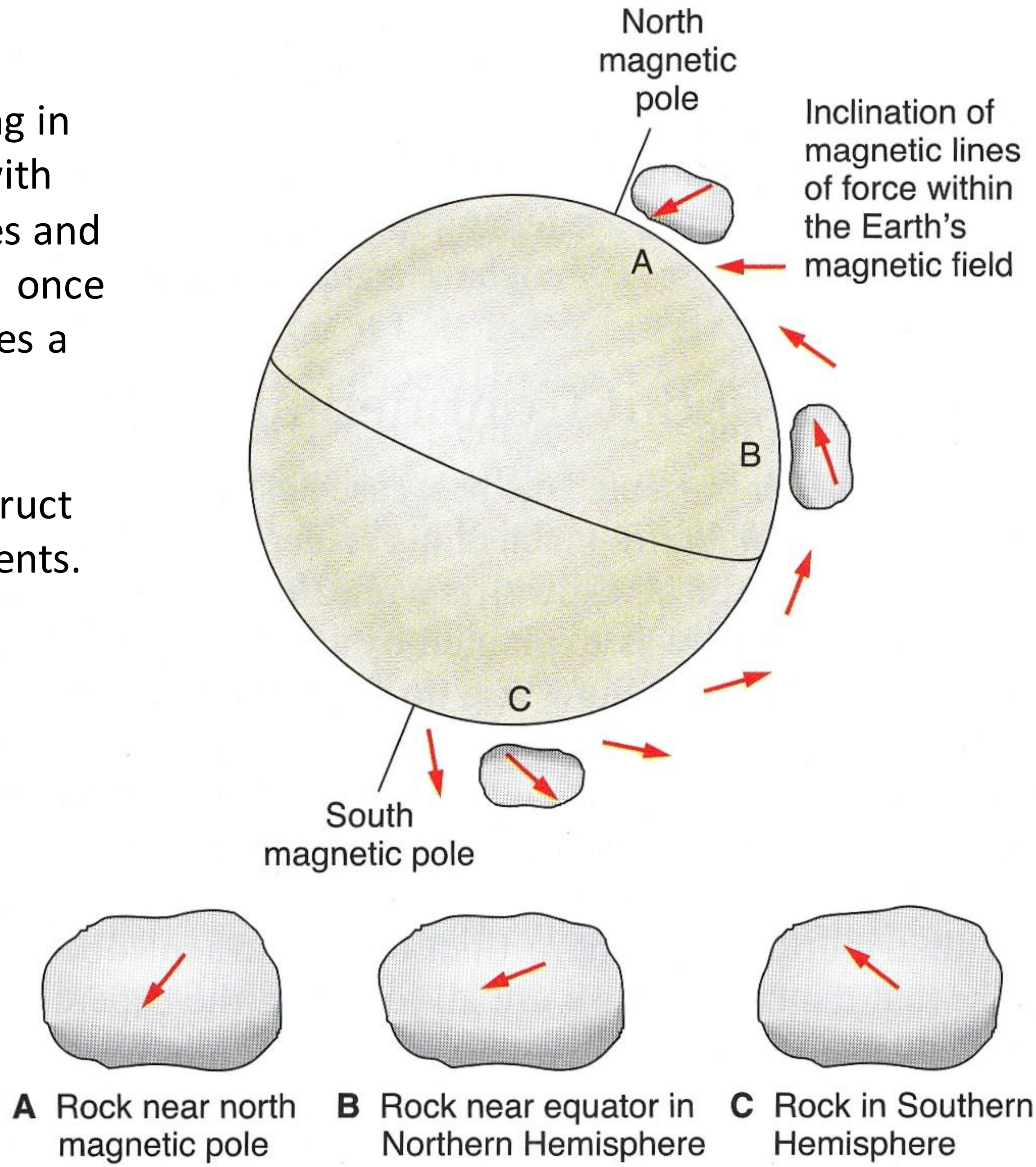
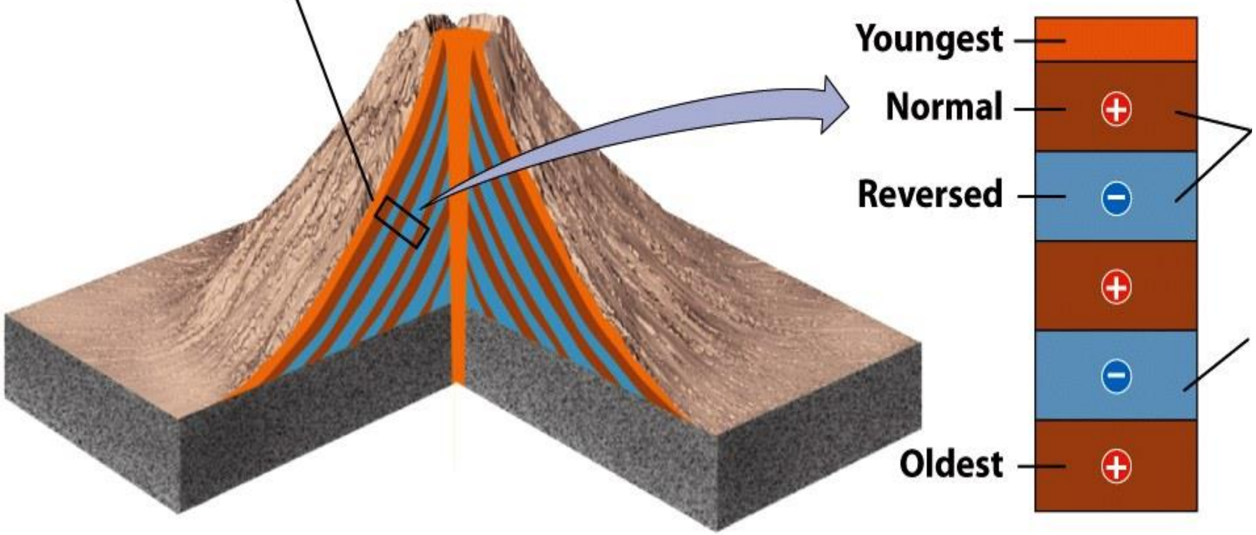
Magnetic minerals forming in lava (molten rock) align with Earth's magnetic field lines and preserve their orientation once the lava cools and becomes a solid rock.

NB: also useful to reconstruct the position of old continents.



Physical Geology

Volcanic lavas also revealed magnetic anomalies. When iron-rich lava cools, it becomes magnetized in the direction of Earth's magnetic field.



Lavas "remember" the magnetic field (thermoremanent magnetization).

Older, deeper layers preserve the direction of the magnetic field at earlier times.

By determining the ages of magnetic reversals at many volcanoes, scientists constructed a magnetic time scale.

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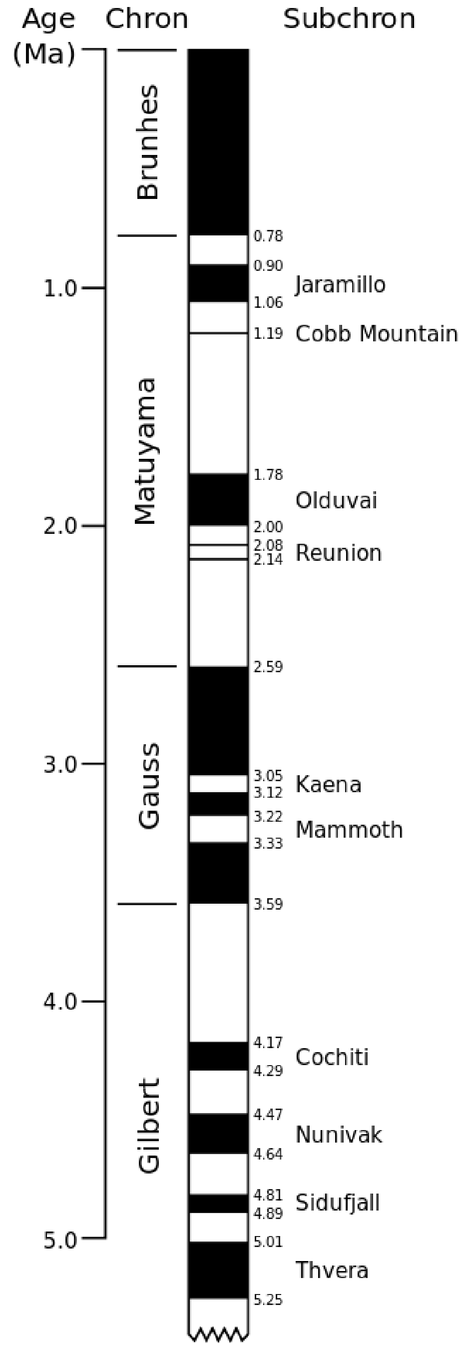


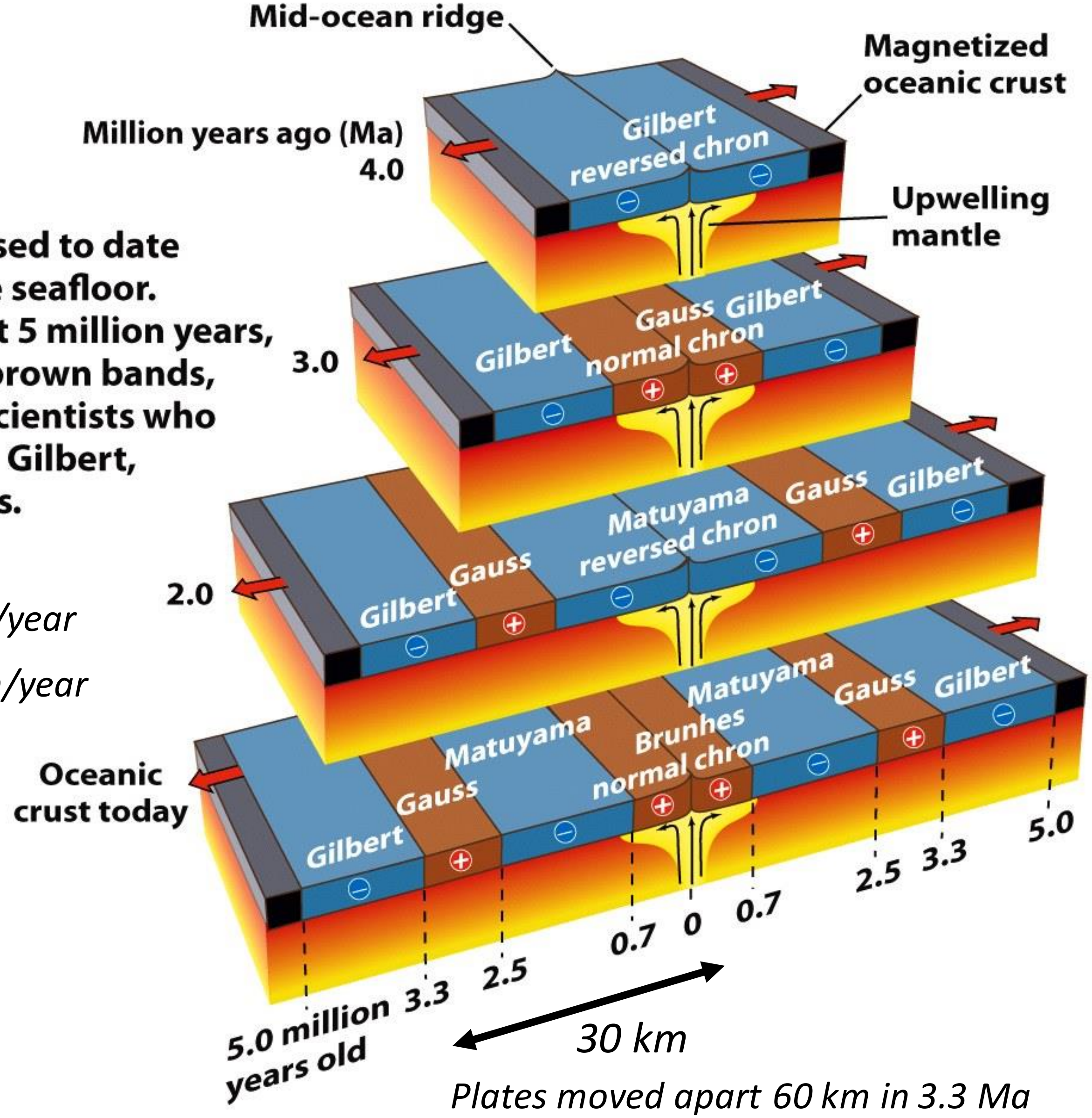
Age (Ma)
Chron
Subchron
1.0
2.0
3.0
4.0
5.0
Brunhes
Matuyama
Gauss
Gilbert
0.78
0.90
Jaramillo
1.06
1.19
Cobb Mountain
1.78
Olduvai
2.00
2.08
Reunion
2.14
2.59
3.05
Kaena
3.12
3.22
Mammoth
3.33
3.59
4.17
Cochiti
4.29
4.47
Nunivak
4.64
4.81
Sidufjall
4.89
5.01
Thvera
5.25

Wikipedia

The magnetic time scale was used to date the magnetic anomalies on the seafloor. The magnetic chrons of the last 5 million years, represented here as blue and brown bands, were named after prominent scientists who studied Earth's magnetic field: Gilbert, Gauss, Matuyama, and Brunhes.

Average spreading rate ~50 mm/year

Highest spreading rate ~150 mm/year



Plates moved apart 60 km in 3.3 Ma

= 18 mm/year

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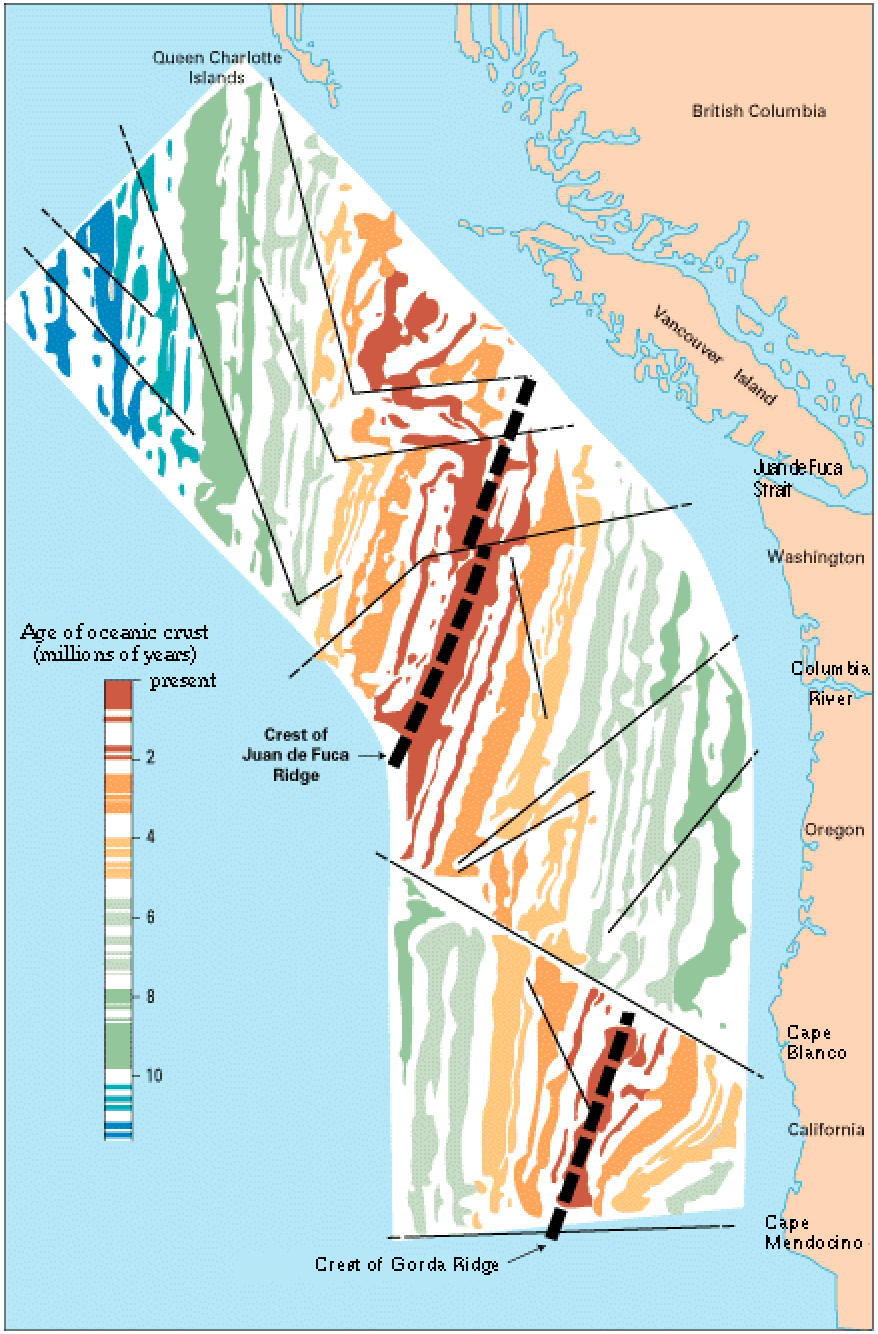
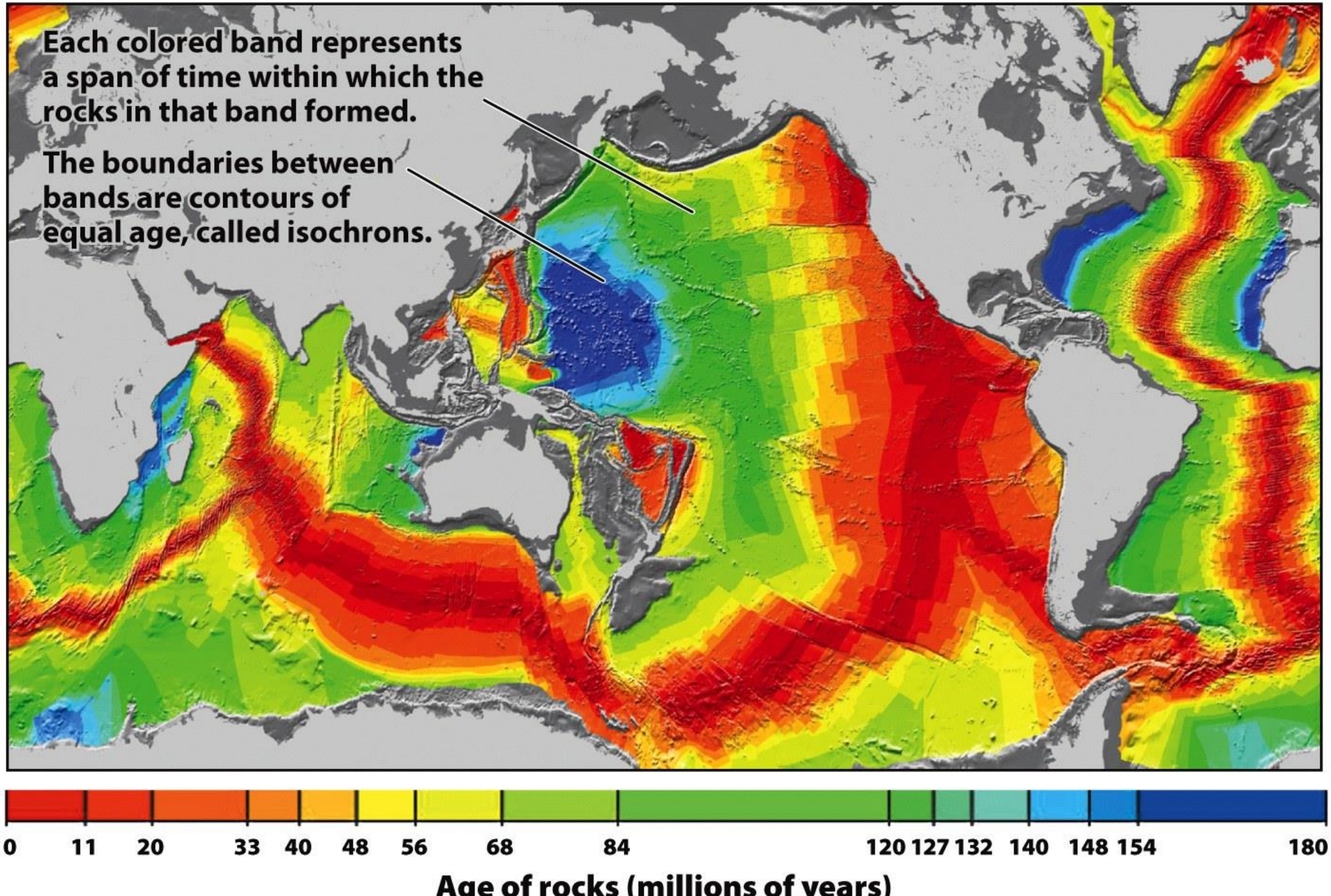
This is yet another piece of evidence that has lead to the hypothesis of seafloor spreading and the theory of plate tectonics.



Magnetic striping mapped by oceanographic surveys offshore of the Pacific Northwest.

Figure and caption from http://pubs.usgs.gov/gip/dynamic/magnetic.html



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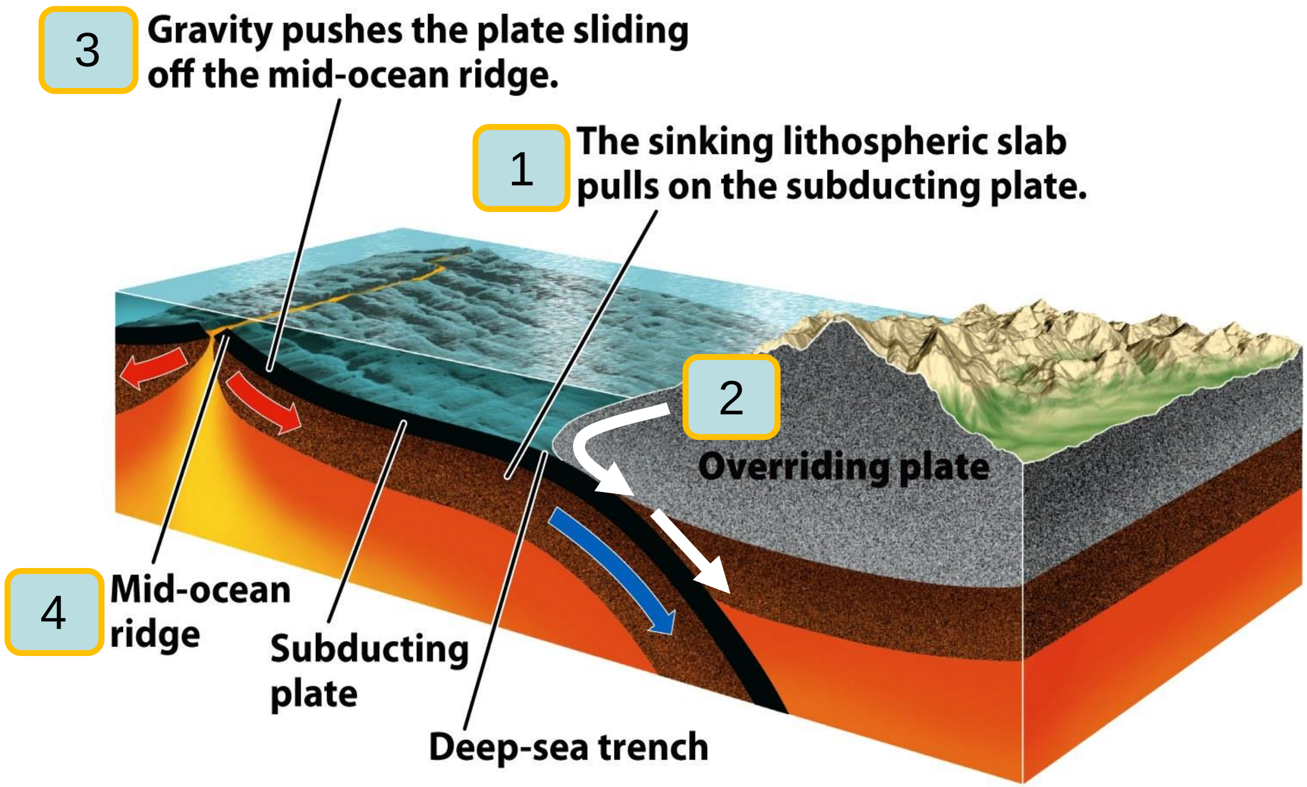
Driving forces of plate tectonics

1. Gravitational pull of plates sinking into the mantle (plates with a large portion of their margin subducting are moving faster)
2. Sucking effect of the subducting plates (force acting on overriding plate)
3. Gravitational force related to elevated Mid-Ocean Ridges
4. Heat rising from the Earth's interior (may initiate break-up of plates)



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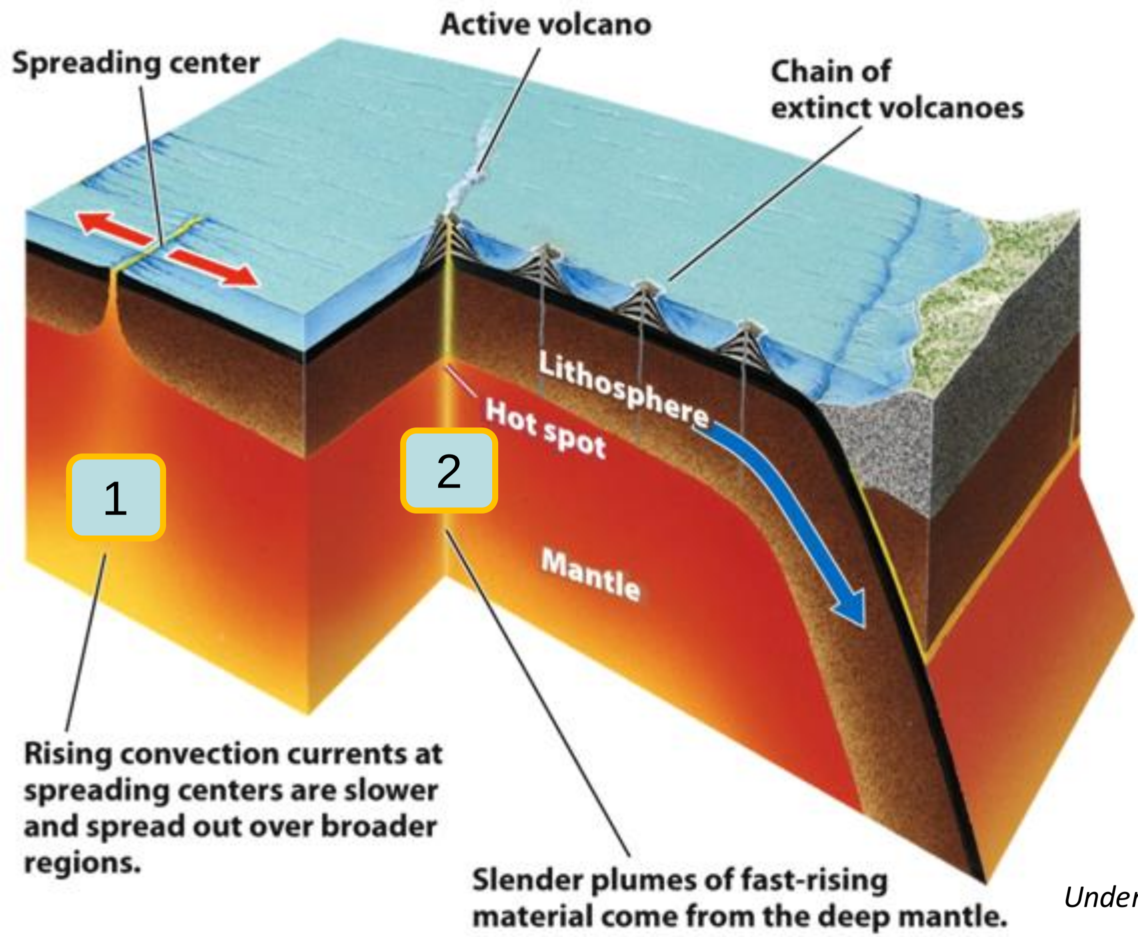
*Rates of plate movement probably control primarily by **1** and **3***

Two types of rising magma

1. Slow, diffuse rise of magma beneath spreading centers

2. Fast, narrow plumes of magma known as **hot spots** (e.g. Hawaii)



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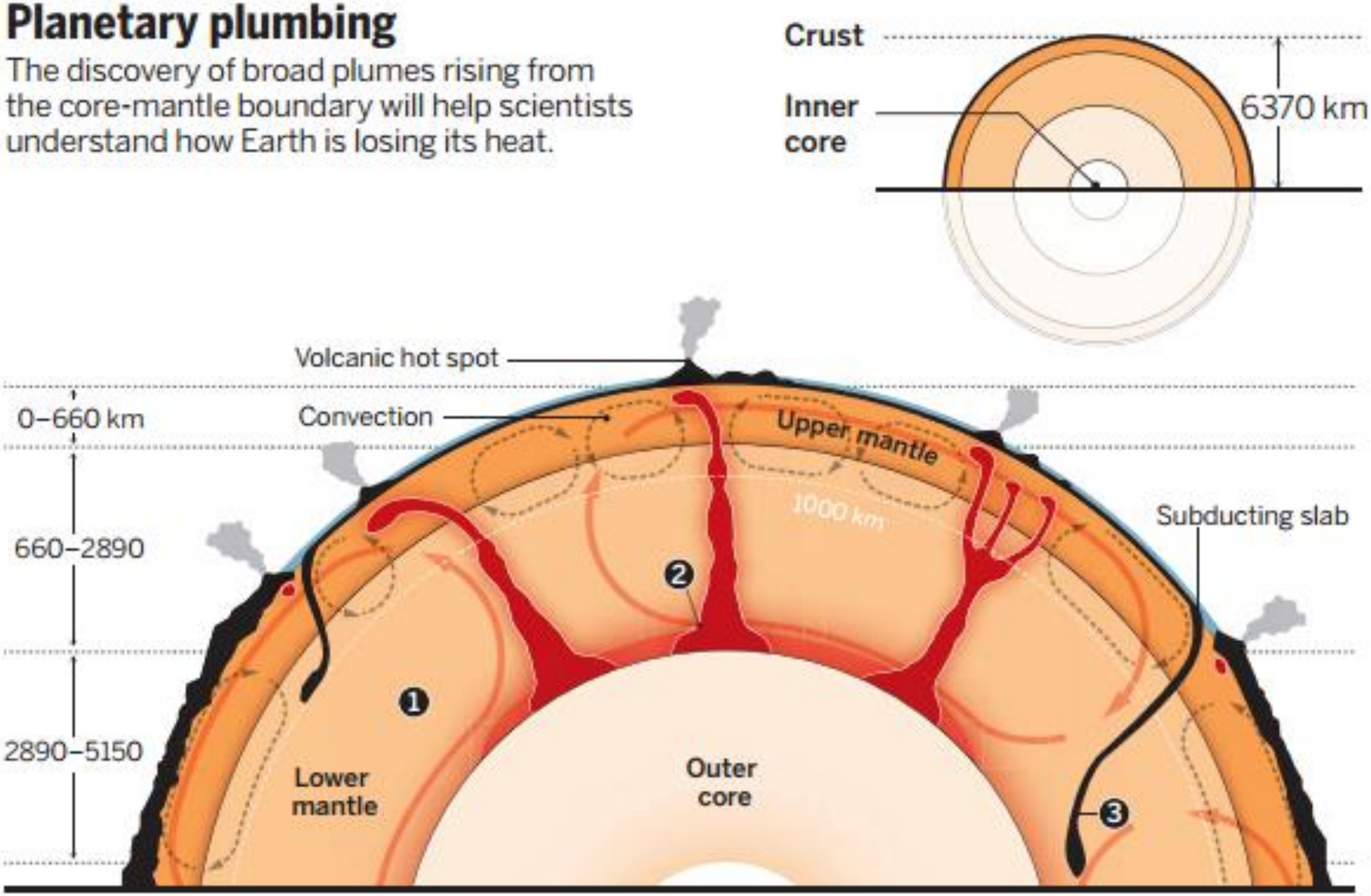
Planetary plumbing

The discovery of broad plumes rising from the core-mantle boundary will help scientists understand how Earth is losing its heat.



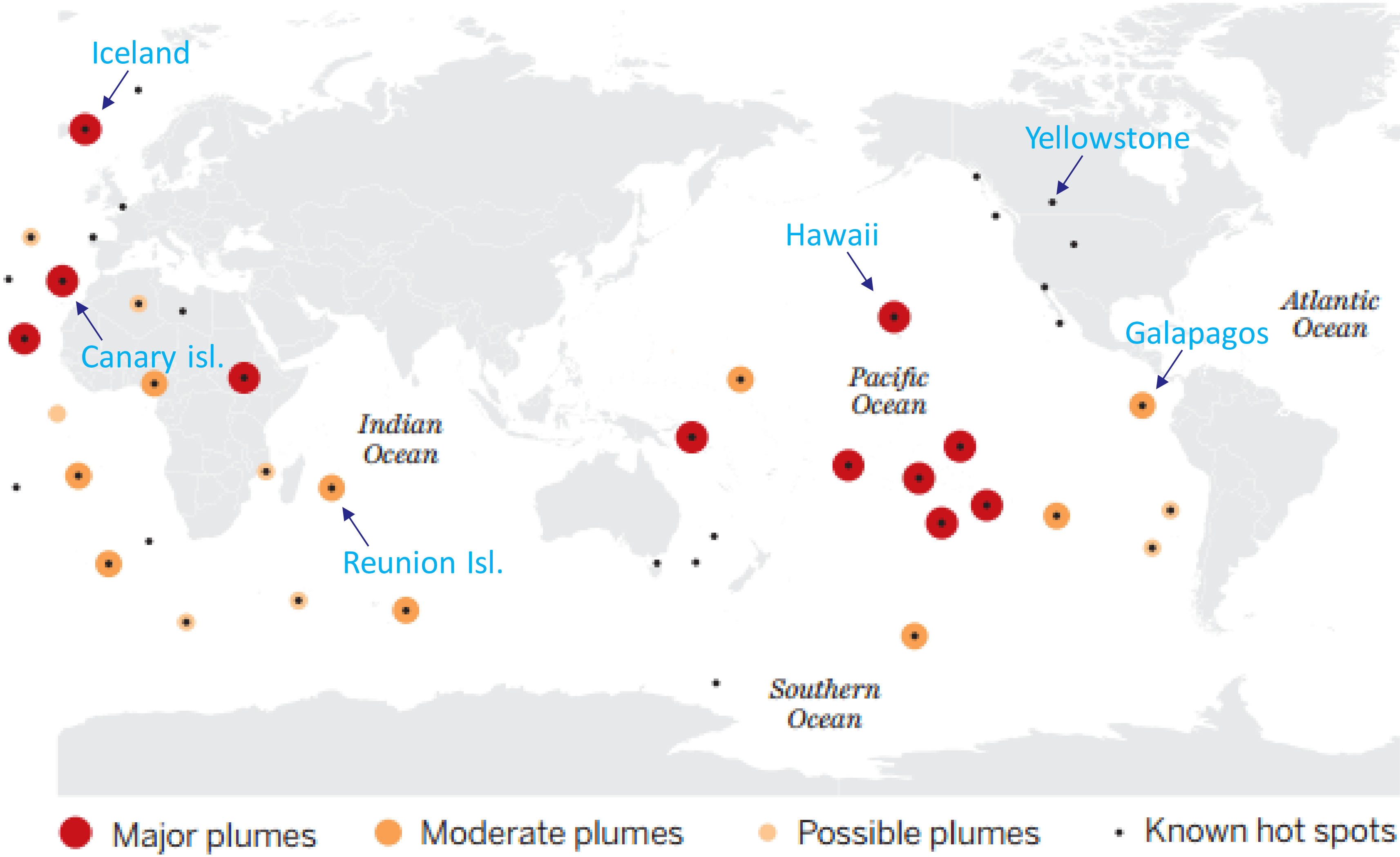
1. CORE COOLING
The plumes are fat and unbent by lower mantle convection—a sign that they are more important than background convection for releasing heat from the core.

2. LOW-VELOCITY ZONES
Many plumes originate in "ultra-low velocity zones," pools of material that could be partially melted or enriched in iron.

3. DEEP SLABS
Subducting slabs of oceanic crust may pond at depths of 660 kilometers, 1000 kilometers, or even lower.

Hand, E. (Science, 2015)

HOT SPOTS Researchers have identified 28 plumes in the mantle—and nearly all of them correspond with volcanic regions called hot spots.



Hand, E. (Science, 2015)