

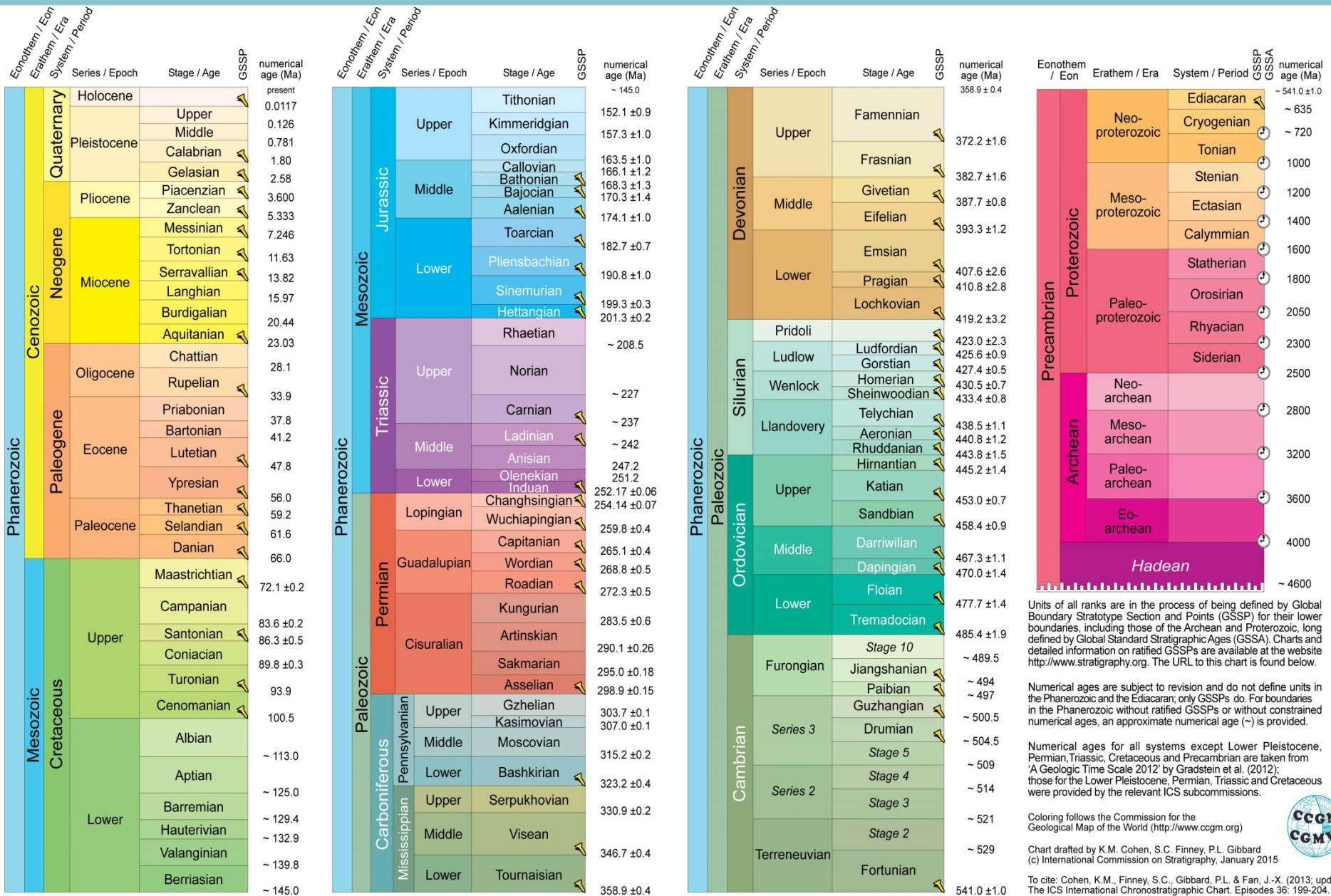
CONTINENTS STRUCTURE AND HISTORY

065 Ma K-T boundary

Equatorial Tethys view

Oblique West-hemi view

★ Review: Geologic time scale



Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Charts and detailed information on ratified GSSPs are available at the website <http://www.stratigraphy.org>. The URL to this chart is found below.

Numerical ages are subject to revision and do not define units in the Phanerozoic and the Ediacaran; only GSSPs do. For boundaries in the Phanerozoic without ratified GSSPs or without constrained numerical ages, an approximate numerical age (~) is provided.

Numerical ages for all systems except Lower Pleistocene, Permian, Triassic, Cretaceous and Precambrian are taken from 'A Geologic Time Scale 2012' by Gradstein et al. (2012); those for the Lower Pleistocene, Permian, Triassic and Cretaceous were provided by the relevant ICS subcommissions.

Coloring follows the Commission for the Geological Map of the World (<http://www.ccgmg.org>)

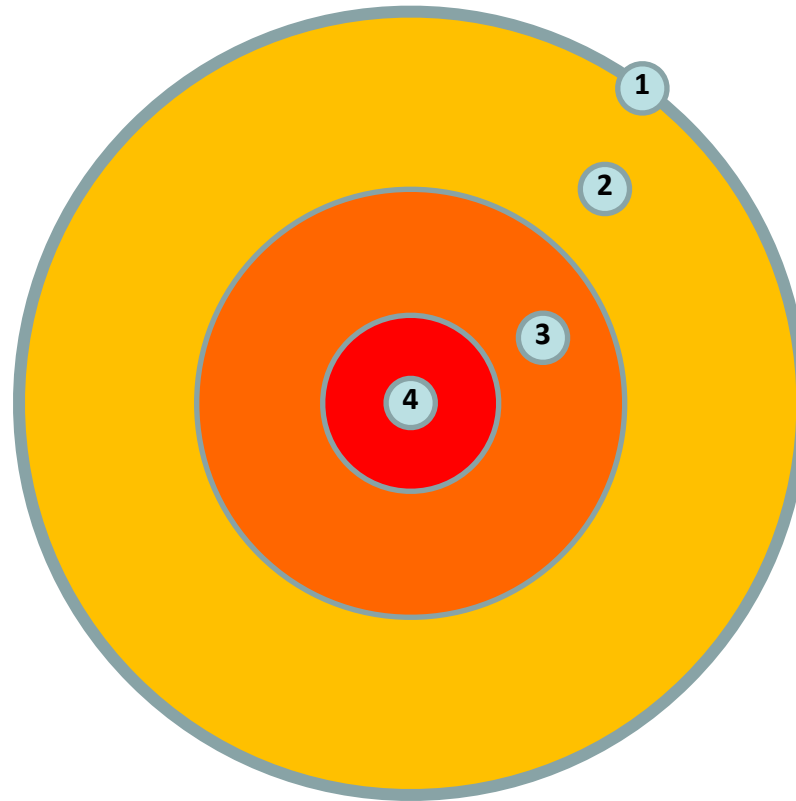
Chart drafted by K.M. Cohen, S.C. Finney, P.L. Gibbard (c) International Commission on Stratigraphy, January 2015

To cite: Cohen, K.M., Finney, S.C., Gibbard, P.L. & Fan, J.-X. (2013), updated. The ICS International Chronostratigraphic Chart. Episodes 36: 199-204.

URL: <http://www.stratigraphy.org/ICSchart/ChronostratChart2015-01.pdf>



★ Review: Earth's layered structure



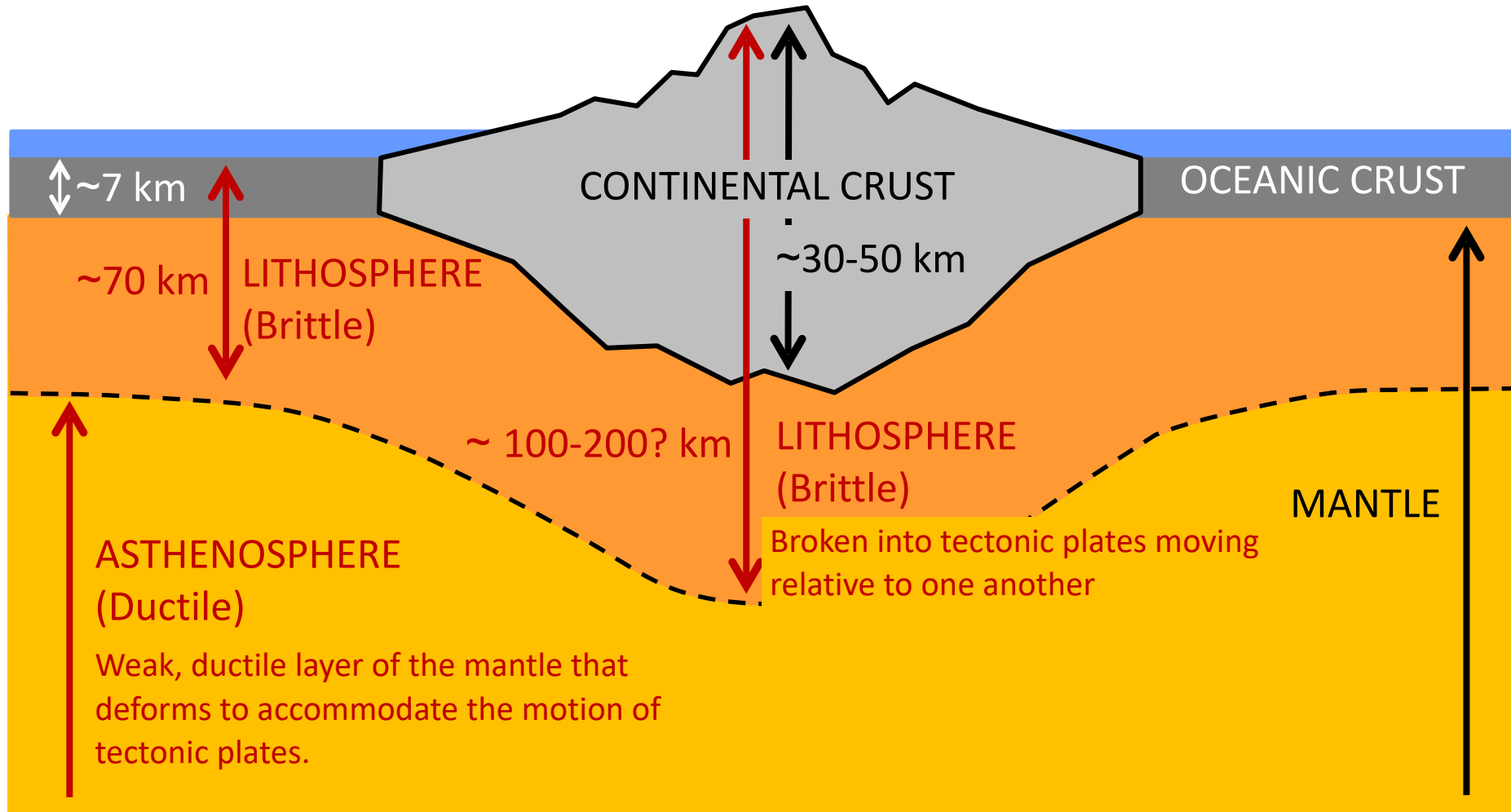
① CRUST (0-~75 km)

② MANTLE

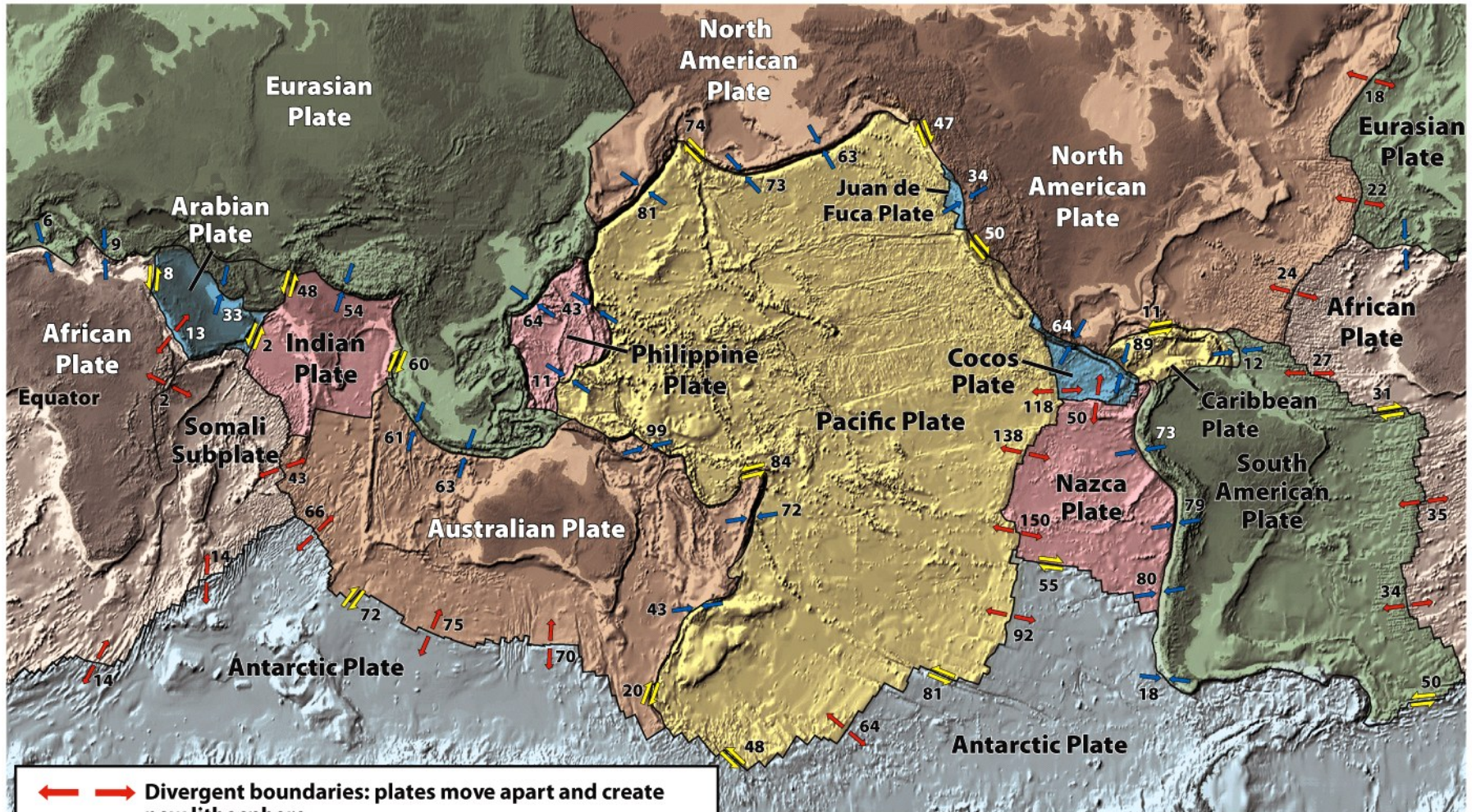
③ OUTER CORE (~3000-5000 km)

④ INNER CORE (~5000-6000 km)

★ Review: Crust, Mantle, Lithosphere and asthenosphere



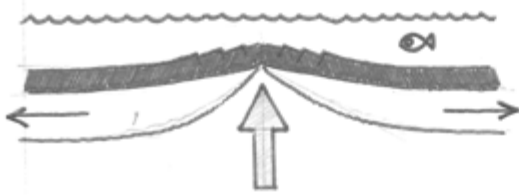
★ Review: Plate boundaries



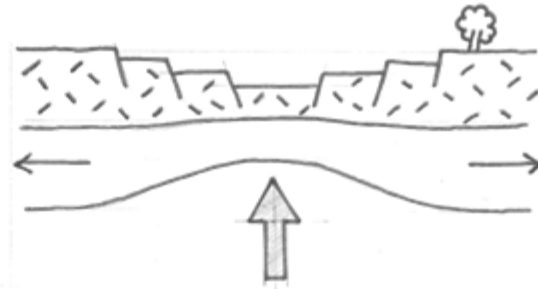
- Divergent boundaries: plates move apart and create new lithosphere.**
- Convergent boundaries: plates move together, oceanic lithosphere is recycled back into the mantle, continental plates are deformed.**
- Transform-fault boundaries: plates slide horizontally past each other.**

DIVERGENT BOUNDARIES

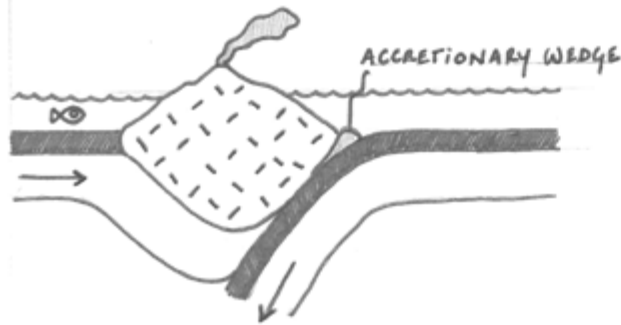
Mid-Ocean Ridge



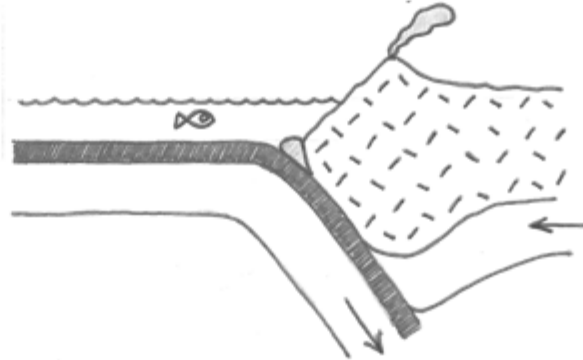
Continental Rift



Ocean-Ocean Subduction



Ocean-Continent Subduction

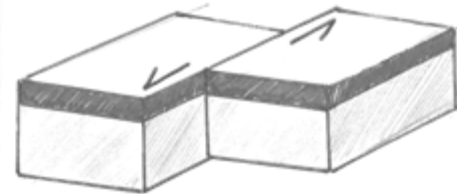


Continent-Continent Collision

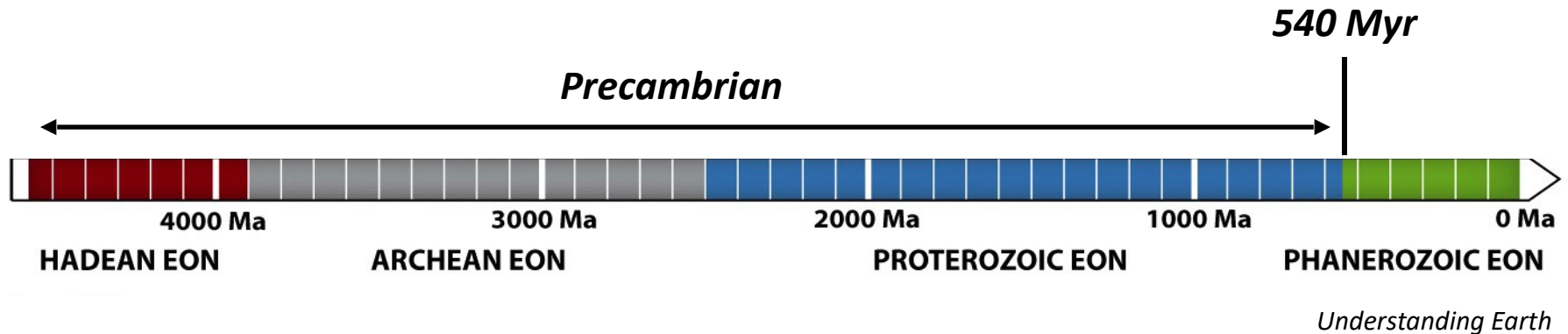


CONVERGENT BOUNDARIES

TRANSFORM FAULTS



★ How to reconstruct the history of the Earth's crust?

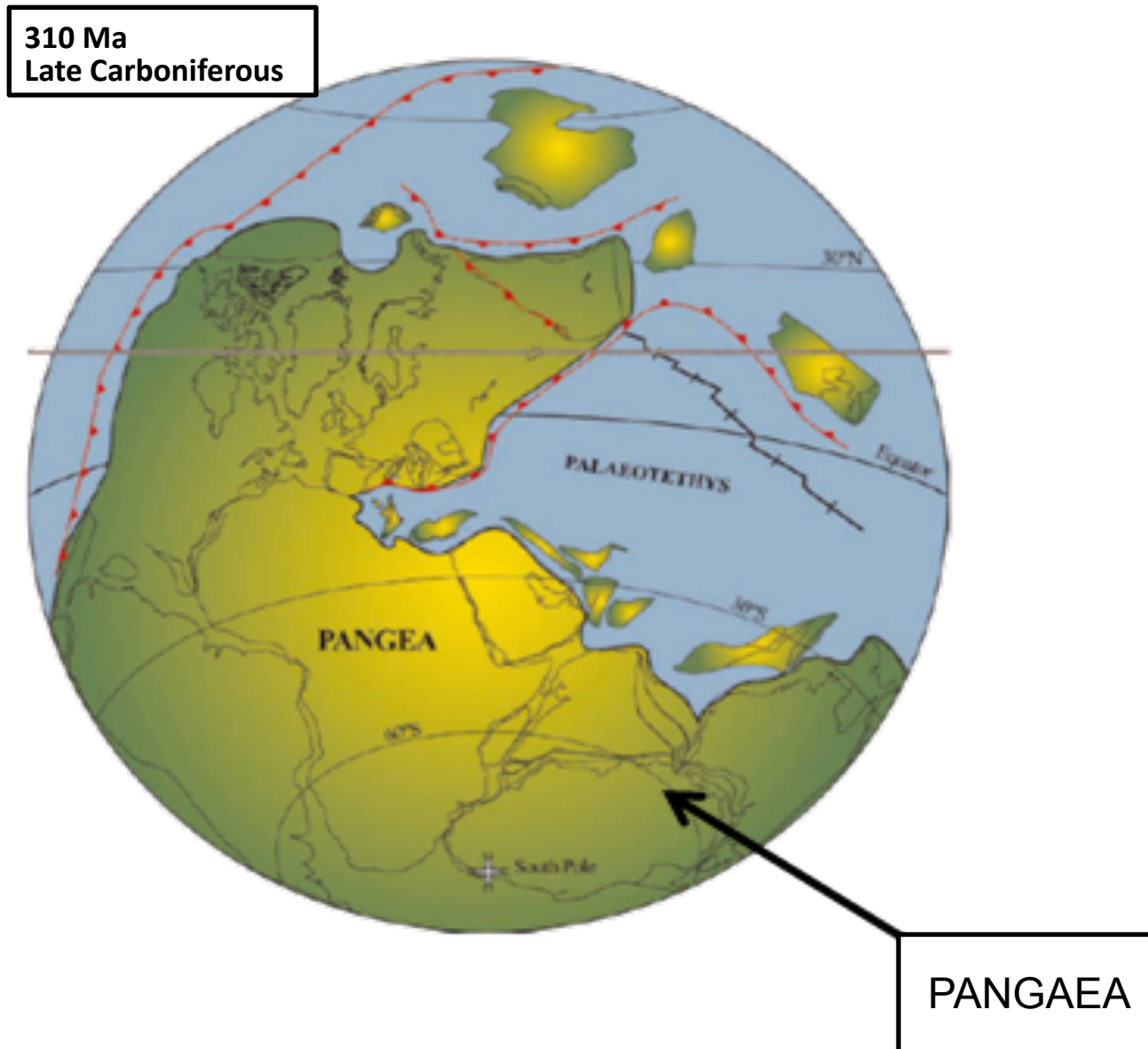


- The Earth is 4.6 billion years old.
- The oldest oceanic crust is “only” 200 million years old.
- The oldest uncontroversial age of a rock from the continental crust is 4 billion years (the Acasta Gneiss from northwestern Canada).



Information on the distant past of our planet is locked in rocks composing the continents

★ Review: Supercontinents



ASSEMBLY OF PANGAEA

RODINIA

(a) Late Proterozoic, 750 Ma



(b) Late Proterozoic, 650 Ma



1 The supercontinent of Rodinia formed about 1.1 billion years ago and began to break up about 750 million years ago.

(c) Middle Ordovician, 458 Ma



2 The supercontinent Pangaea was mostly assembled by 237 Ma, surrounded by a superocean called Panthalassa (Greek for "all seas"), the ancestral Pacific Ocean. The Tethys Ocean, between Africa and Eurasia, was the ancestor of the Mediterranean Sea.

(d) Early Devonian, 390 Ma



PANGAEA

(e) Early Triassic, 237 Ma



BREAKUP OF PANGAEA

(f) Early Jurassic, 195 Ma



4 By about 150 million years ago, Pangaea was in the early stages of breakup. The Atlantic Ocean had partially opened, the Tethys Ocean had contracted, and the northern continents (Laurasia) had all but split away from the southern continents (Gondwana). India, Antarctica, and Australia began to split away from Africa.

(g) Late Jurassic, 152 Ma



5 By 66 million years ago, the South Atlantic had opened and widened. India was well on its way northward toward Asia, and the Tethys Ocean was closing to form the Mediterranean.

(h) Late Cretaceous, Early Tertiary, 66 Ma



THE PRESENT-DAY AND FUTURE WORLD

6 The modern world has been produced over the past 65 million years. India collided with Asia, ending its trip across the ocean, and is still pushing northward into Asia. Australia has separated from Antarctica.

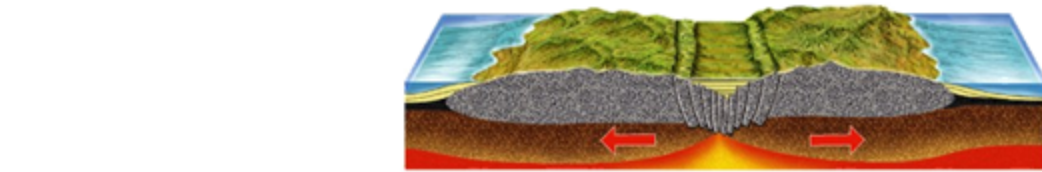


(i) PRESENT-DAY WORLD

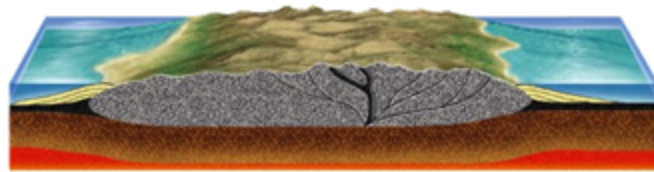


(j) 50 million years in the future

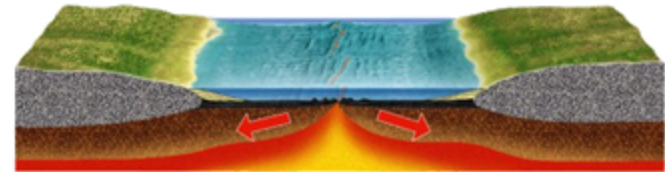
★ The Wilson Cycle



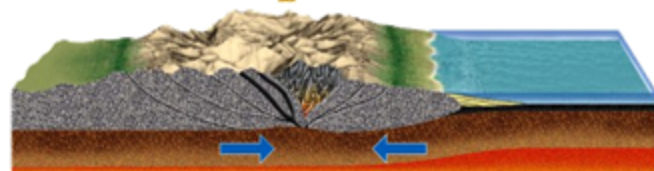
1 Rifting within a continent splits the continent,...



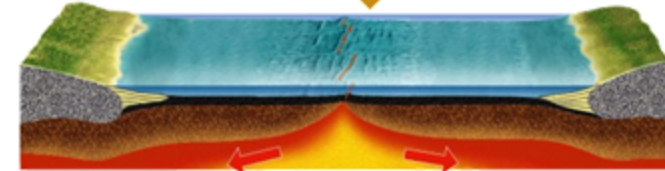
7 The continent erodes, thinning the crust. Eventually the process may begin again.



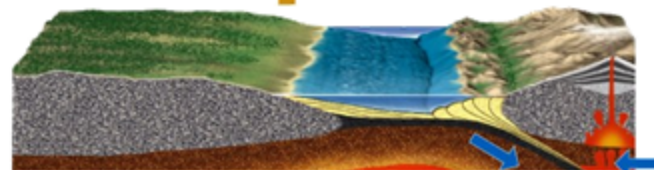
2 ...leading to the opening of a new ocean basin and creation of new oceanic crust, starting the cycle.



6 As continents collide, orogeny thickens the crust and builds mountains, forming a new supercontinent.



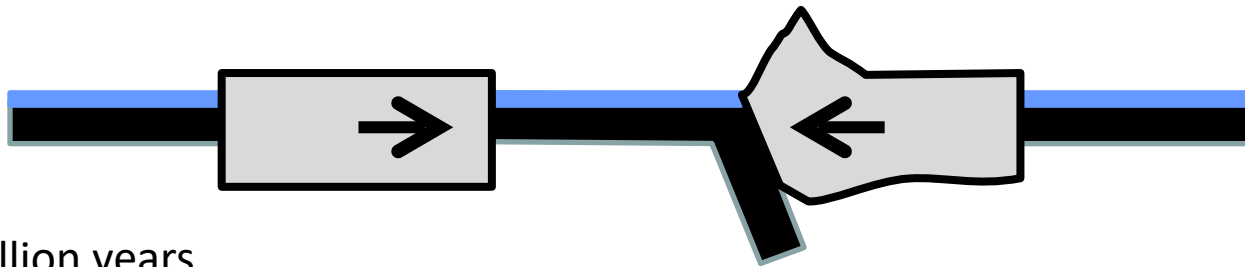
3 As seafloor spreading continues and an ocean opens, passive margin cooling occurs and sediment accumulates.



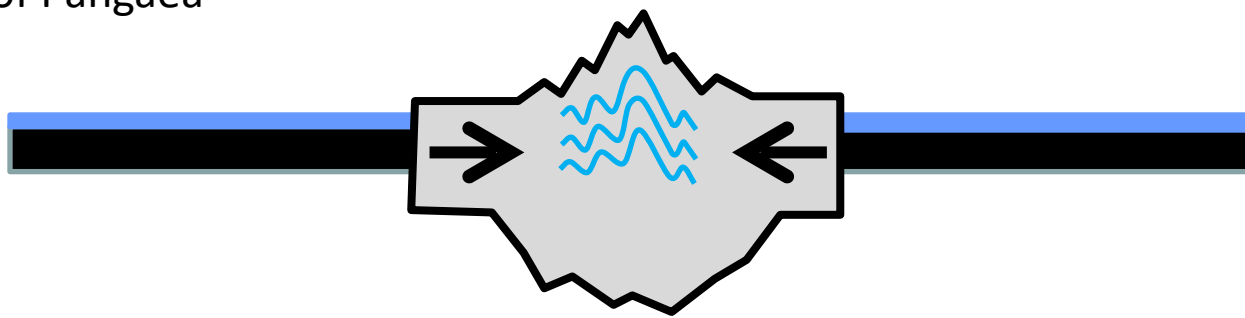
5 Terrane accretion—from the sedimentary accretionary wedge or fragments carried by the subducting plate—welds material to the continent.



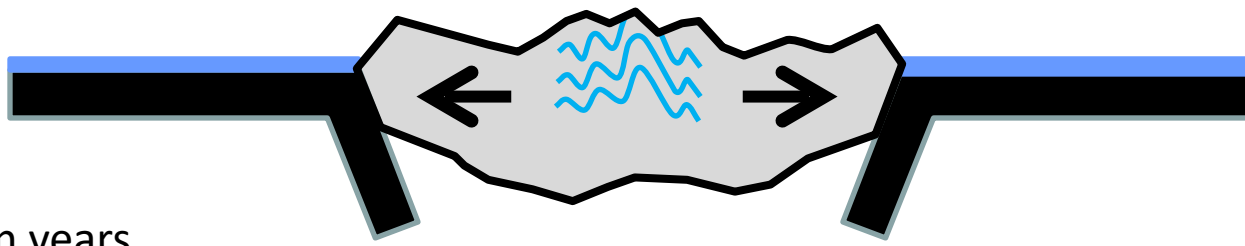
4 Convergence begins; oceanic crust is subducted beneath a continent, creating a volcanic mountain belt at the active margin.



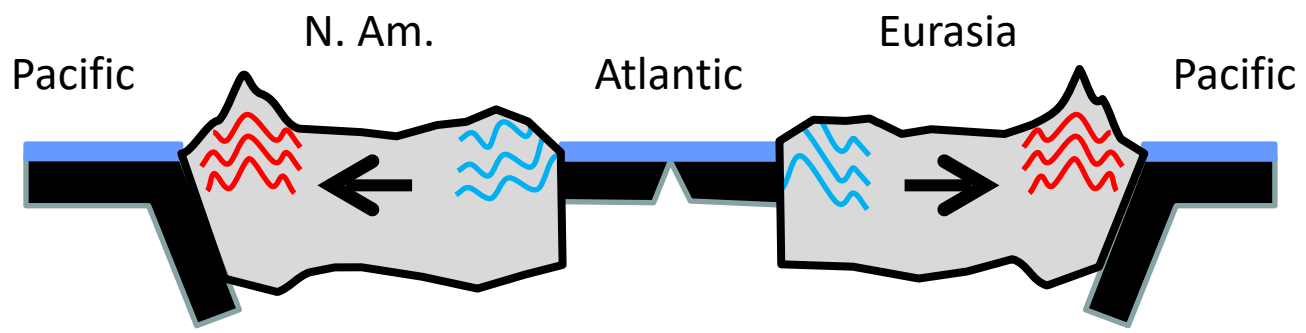
470-270 million years
Formation of Pangaea



Pangaea



<180 million years
Opening of the Atlantic



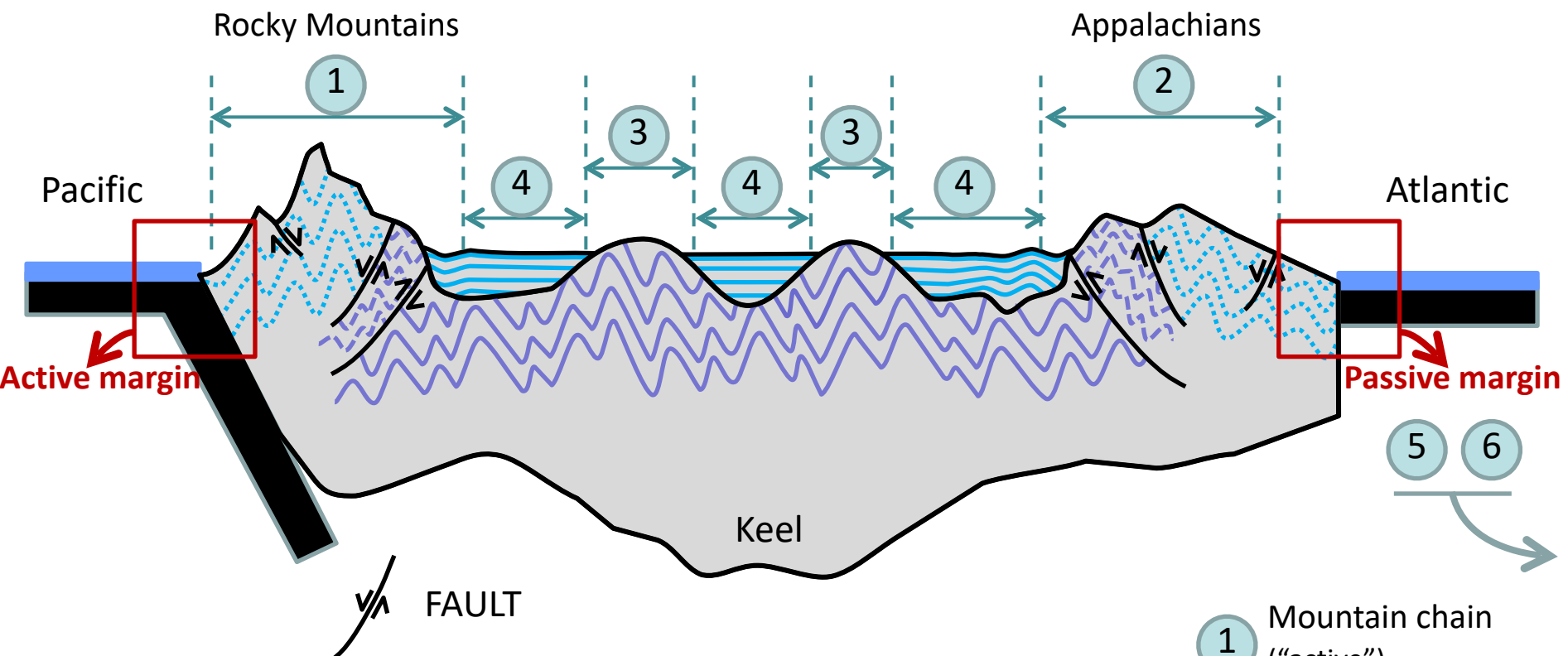
Pacific

N. Am.

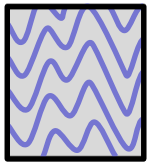
Atlantic

Eurasia

Pacific



Precambrian rocks (>540x10⁶ years)



Undeformed during the Phanerozoic

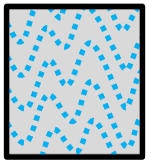


Deformed during Phanerozoic orogenies

Phanerozoic rocks (<540x10⁶ years)



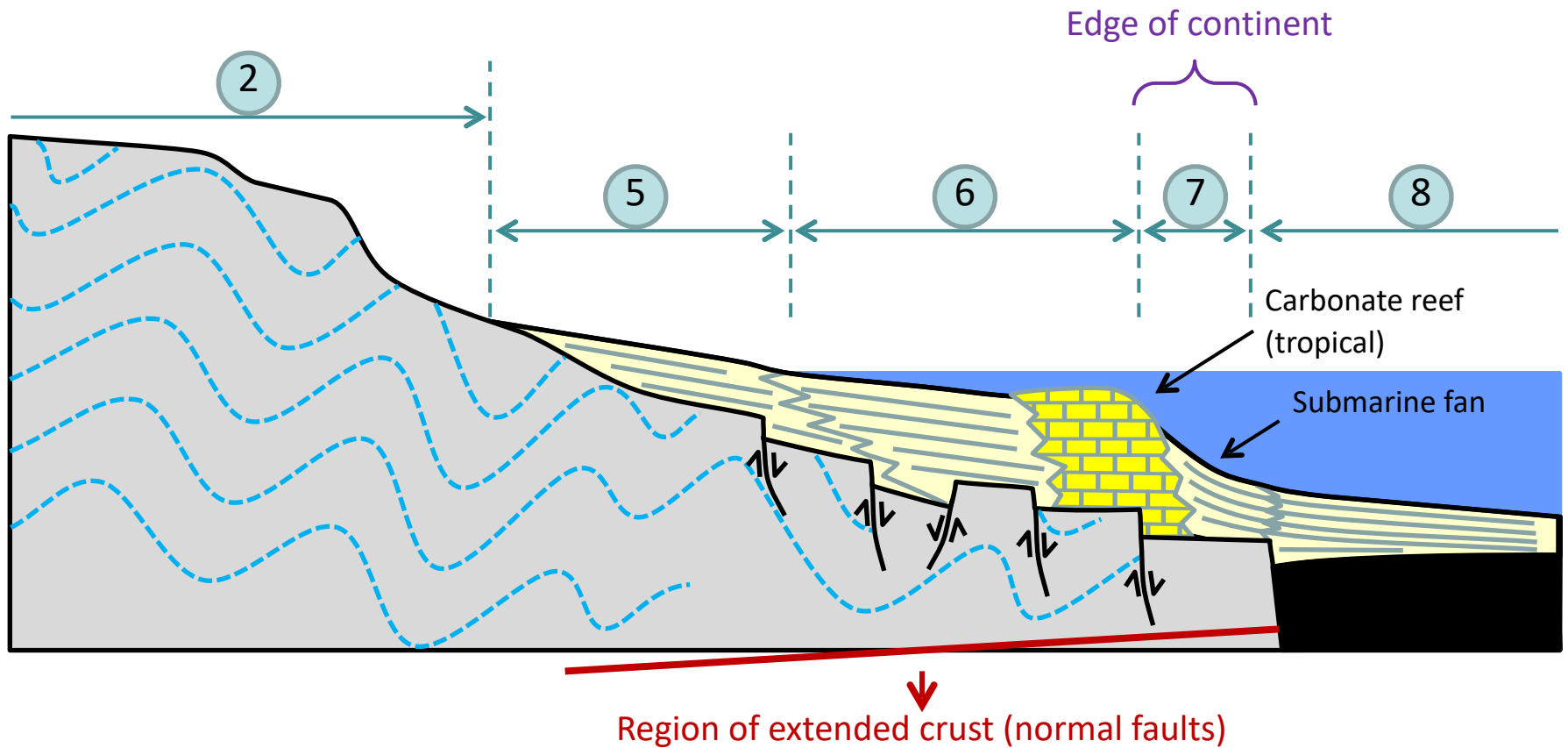
Undeformed



Deformed

- 1 Mountain chain ("active")
- 2 Mountain chain ("inactive")
- 3 Precambrian Shield
- 4 Platform
Sediments deposited in inland seas, lakes, wetlands... (2-5 km thick)
- 3 + 4 = craton

Passive margin

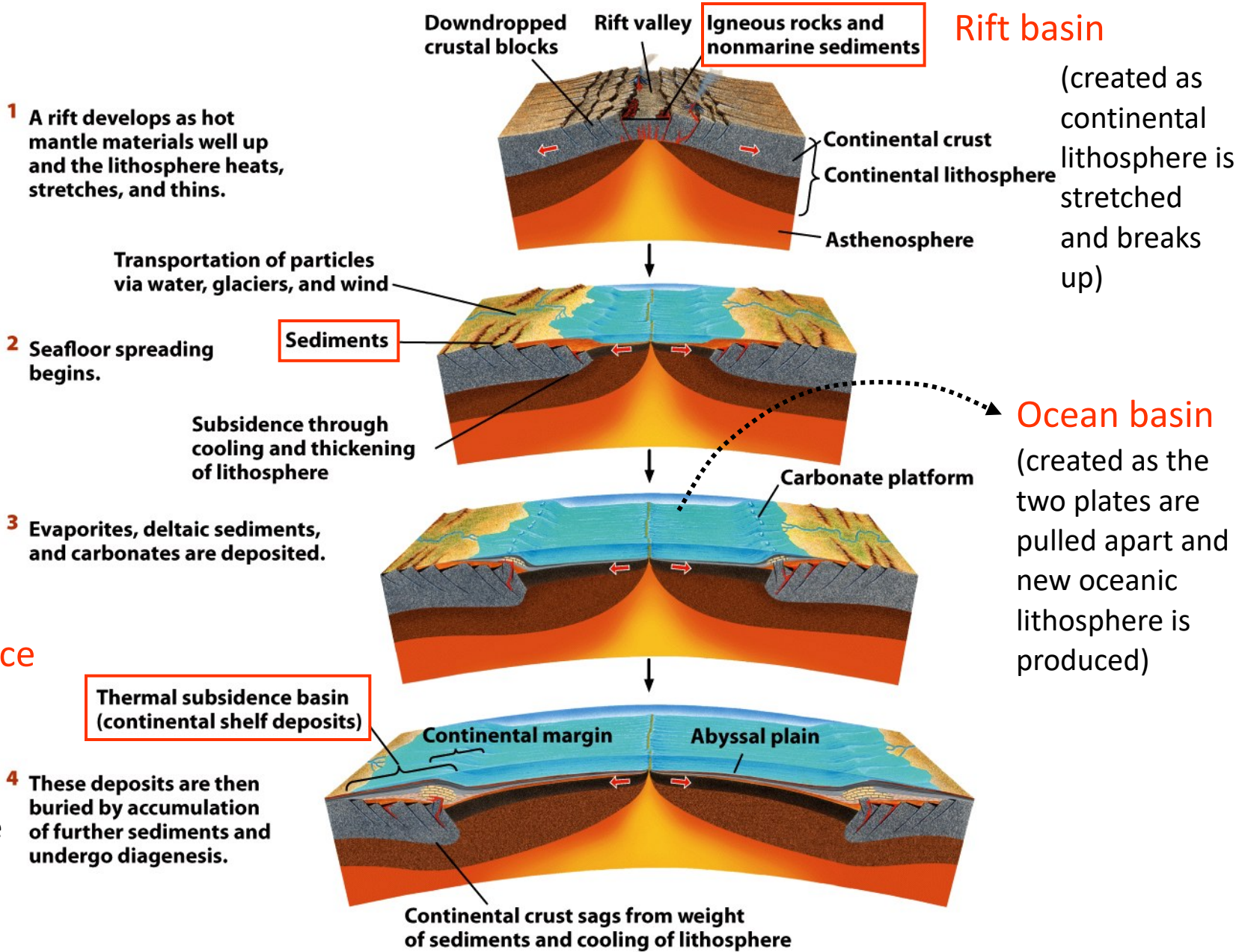


5 Coastal Plain
Sediments transported by rivers and deposited in the coastal area.

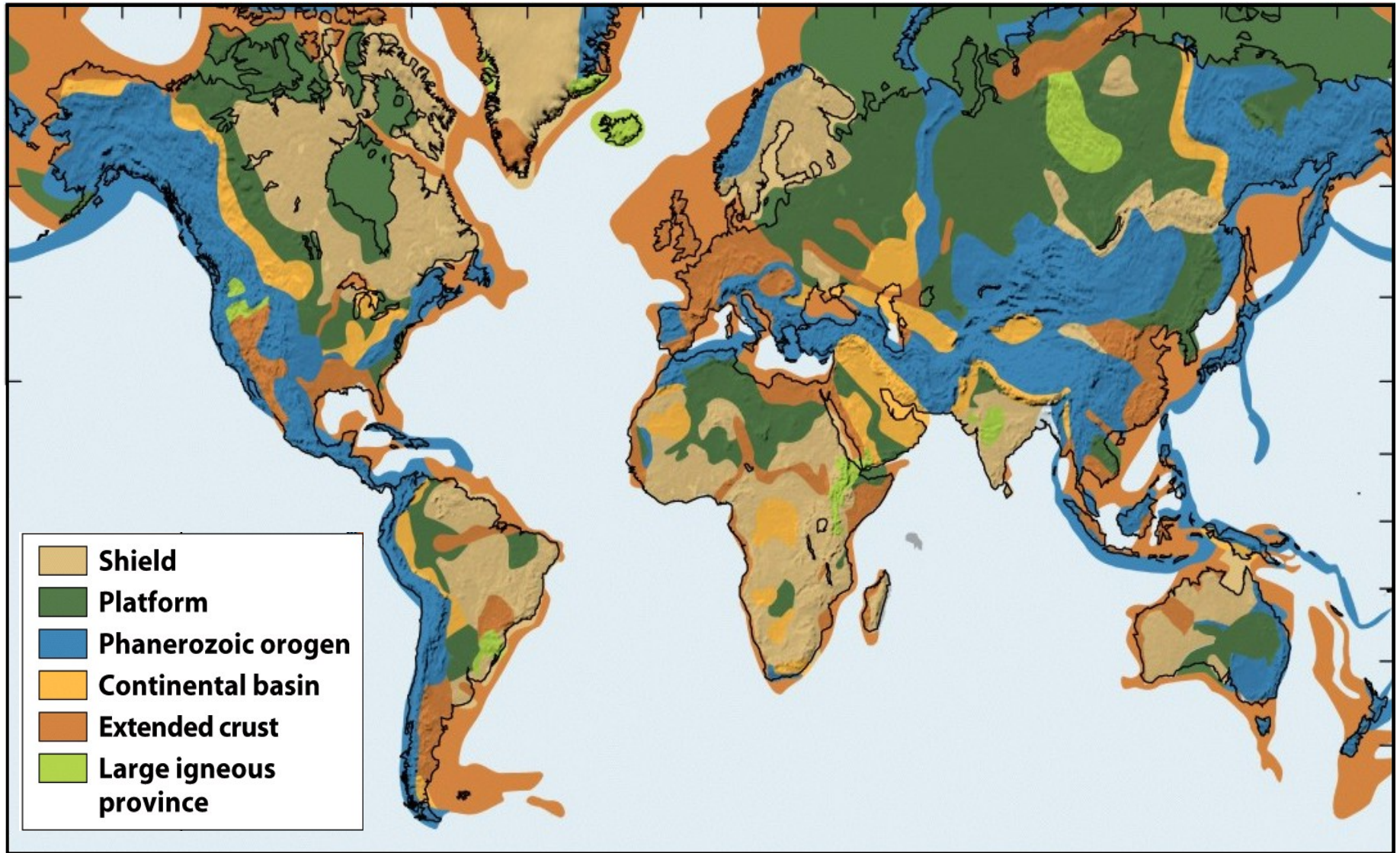
6 Continental Shelf
Region near the edge of continents below sea level that is subsiding and where thick piles of sediments can accumulate.

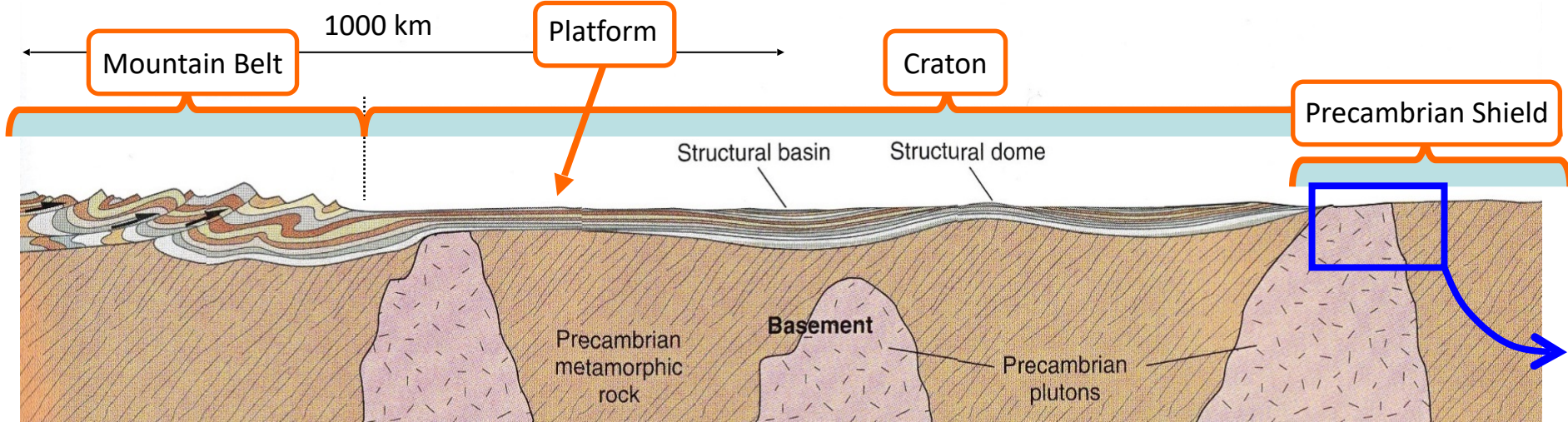
7 Continental slope

8 Abyssal Plain



★ Tectonic provinces of the continents





Physical Geology (9th ed.)



Stable Craton:

- Precambrian shield
- Platform cover and basins

★ Shield

- Uplifted Precambrian rocks exposed to the surface.
- Undeformed during the Phanerozoic.

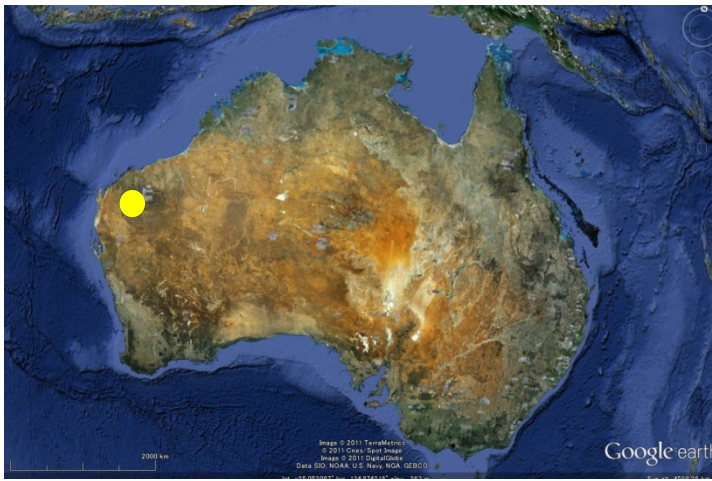
★ Platform

- Flat-lying sediments covering the Precambrian basement rocks.
- Undeformed

Shield + Platform = **Craton**

A craton is the oldest and most stable part of continents
 (→ relatively unaffected by Phanerozoic orogenies)

Metamorphosed igneous intrusion (granite) (Archean)



Metamorphosed sedimentary and extrusive igneous (basaltic) rocks (Archean)

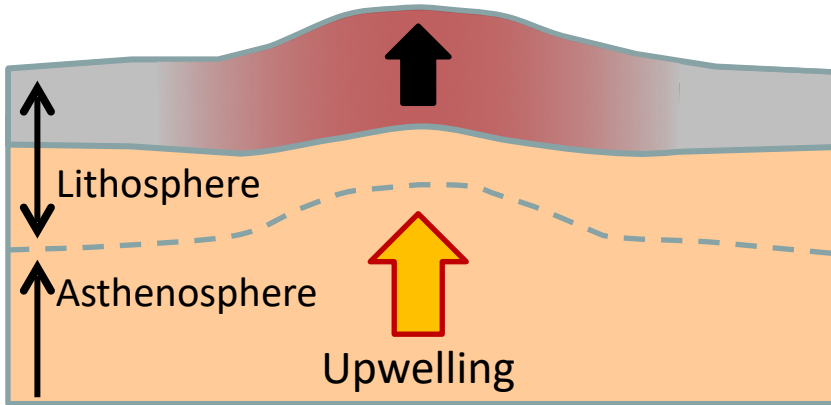
~ 10 km



★ Intracratonic BASINS and DOMES

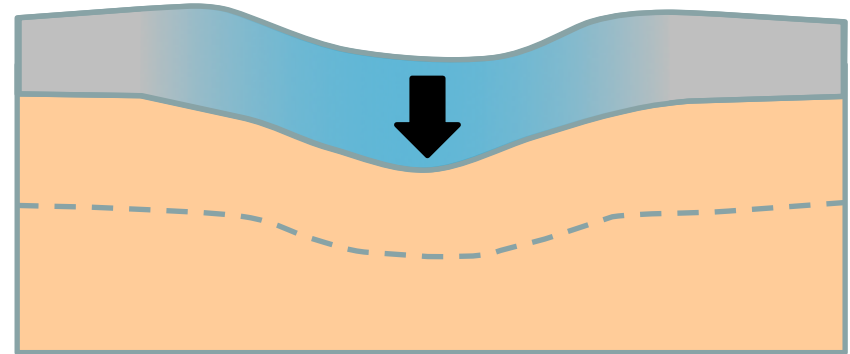
DOME

Heating → uplift



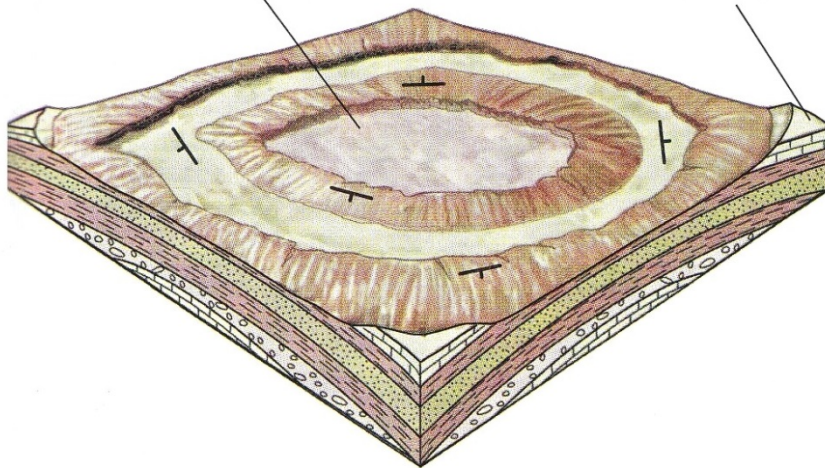
THERMAL SUBSIDENCE BASIN

Cooling → subsidence



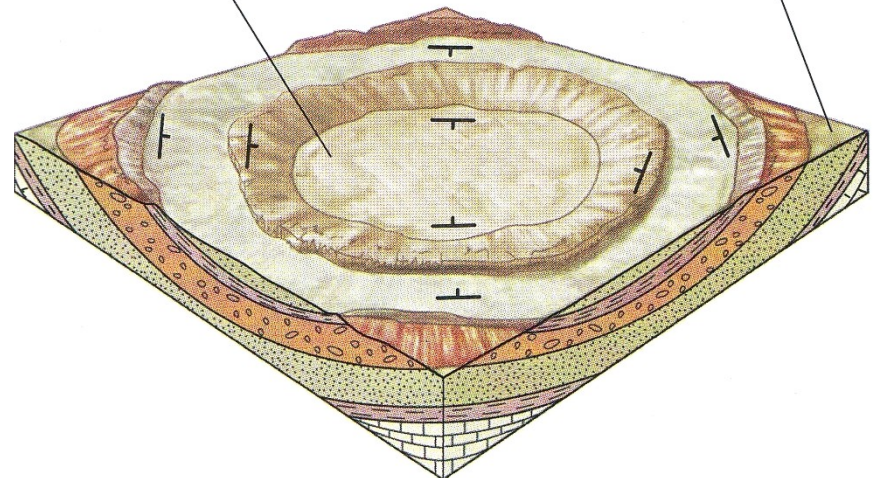
Oldest layer exposed at the surface

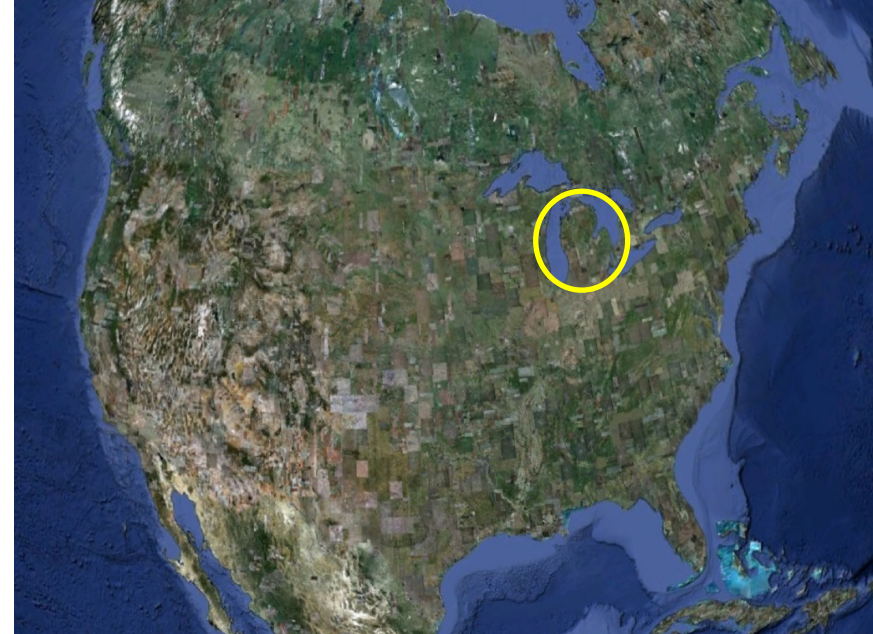
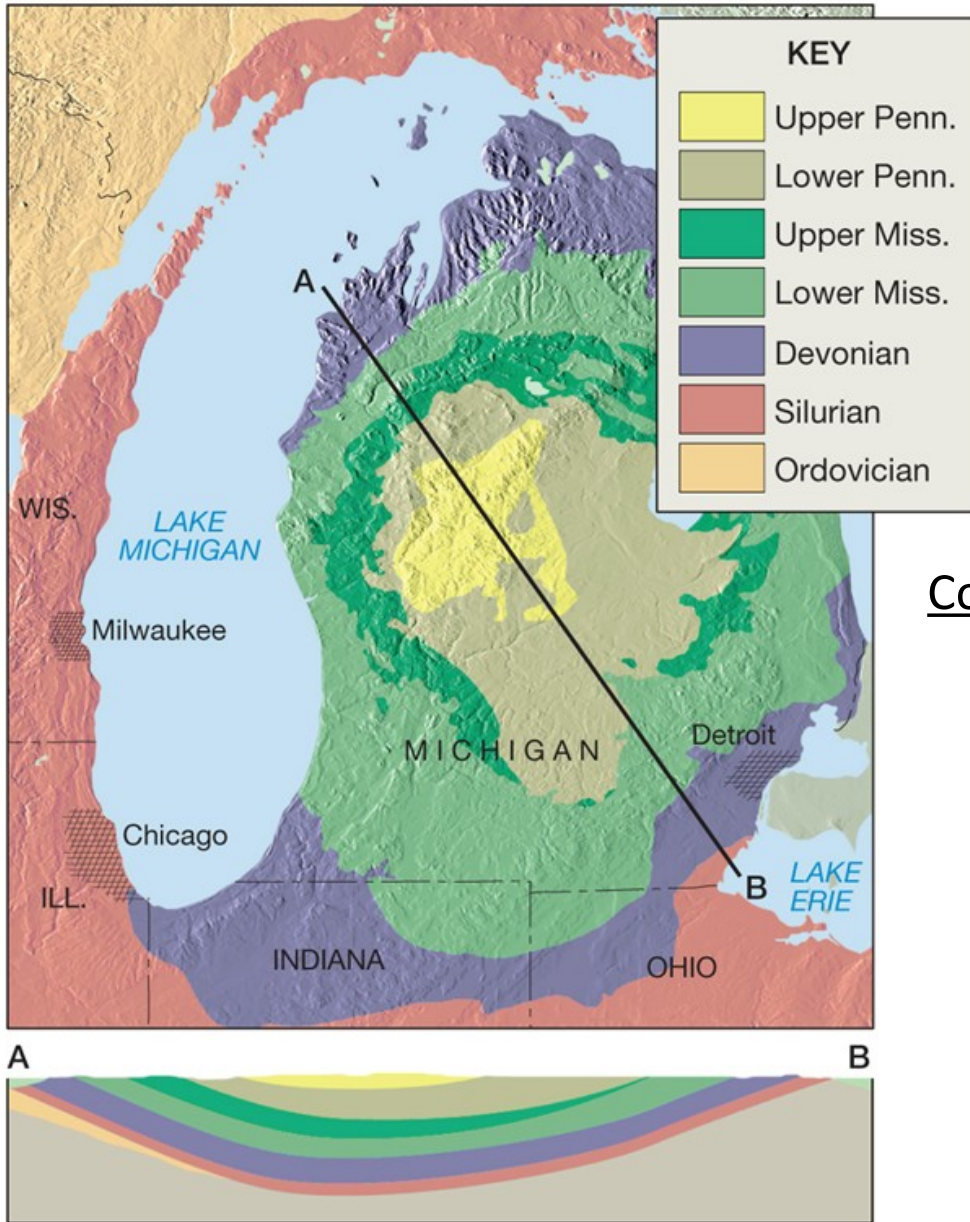
Youngest layer



Youngest layer

Oldest layer exposed at the surface





Continental Basin

- Region of the continental crust that has subsided and formed a depression where sediments can accumulate.
- Sedimentary layers dip toward the center of the basin.

Example: Michigan Basin (USA)

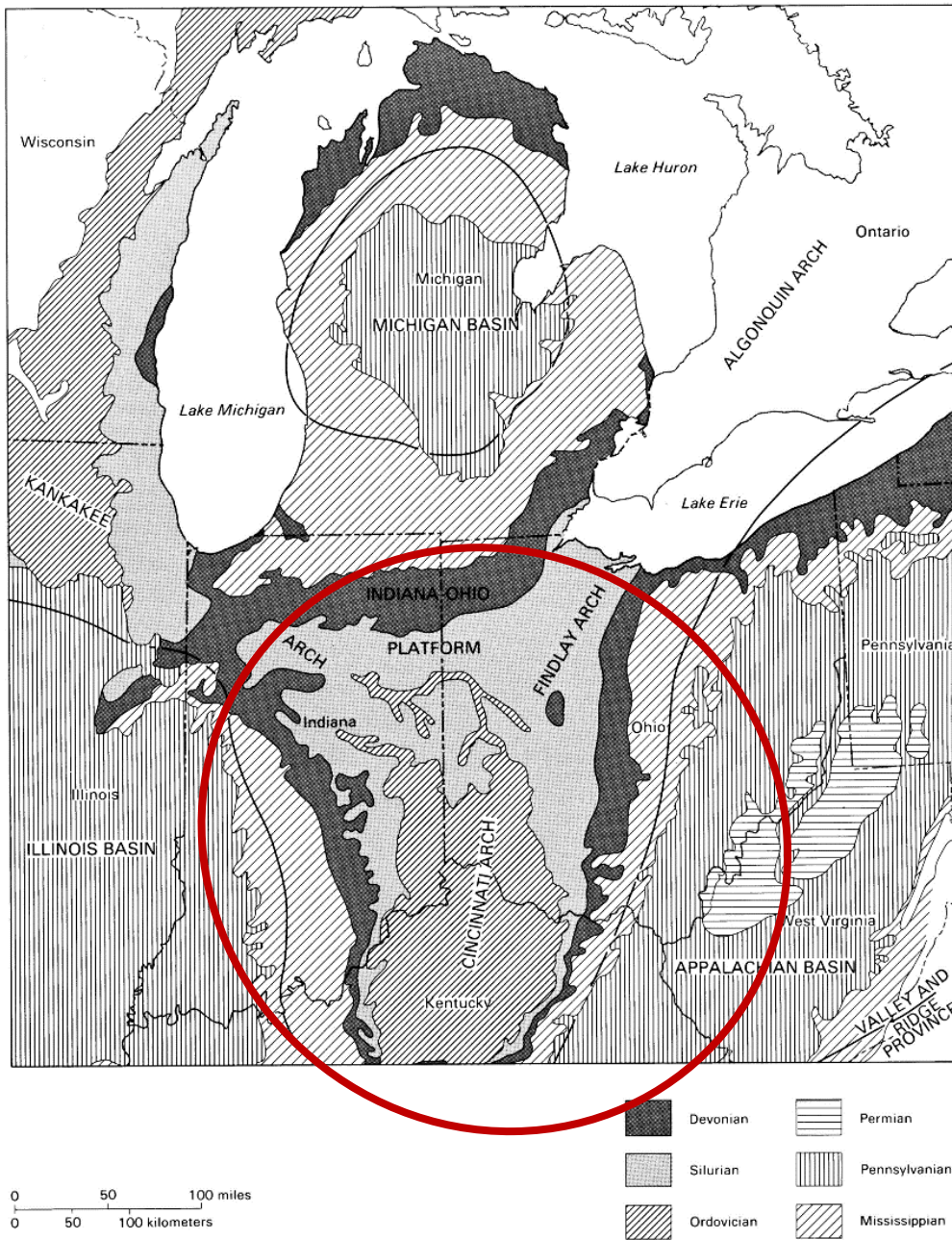
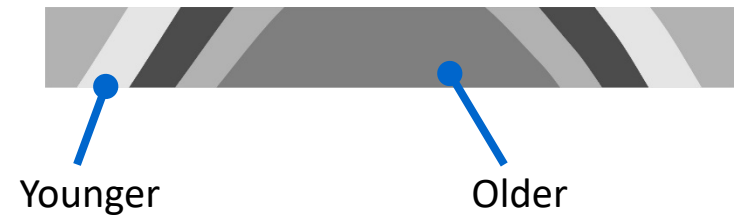


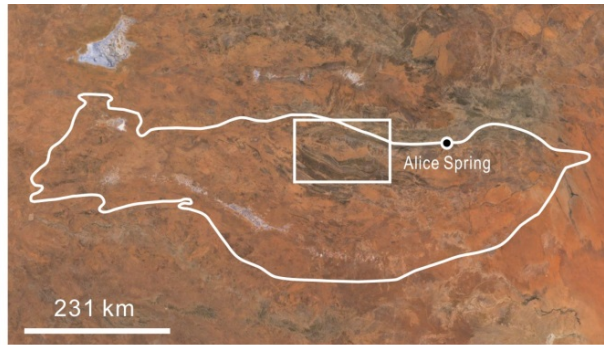
FIGURE 3-4.—Regional geologic structures of Ohio and adjacent states (from Carlson, 1991, fig. 4).

Continental Dome

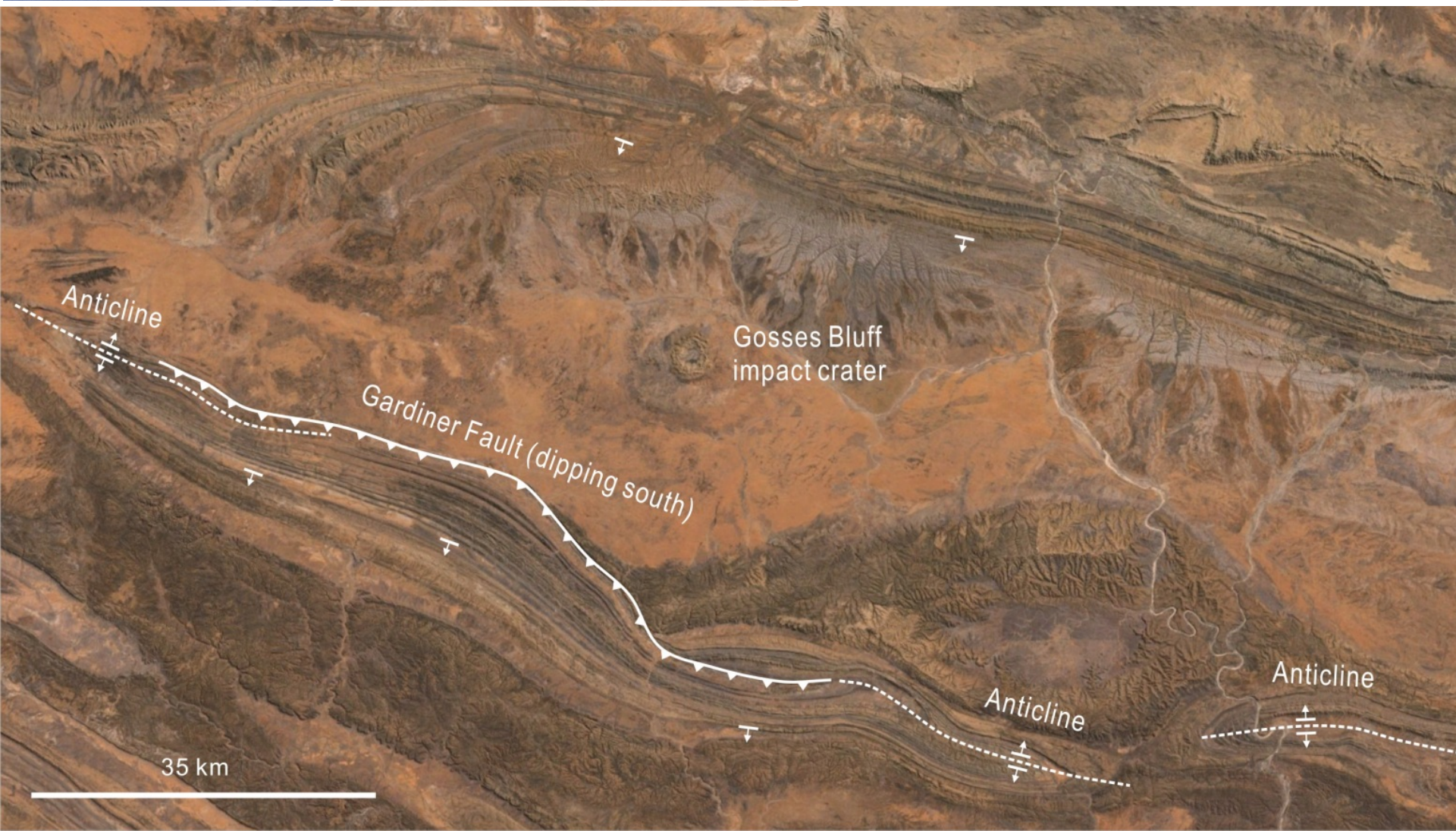
- Region of the continental crust that has been uplifted, forming a structural dome.
- Sedimentary layers dip away from the center of the basin.

Example: Cincinnati Arch (USA)





Intracratonic basin with a more complex history:
Example: Amadeus Basin (Australia)



Intracratonic basins: important reservoirs of coal, oil, and natural gas

Shale exploration

June 15, 2010:
Mitsubishi/New
Standard Energy
\$150m

Apr 14, 2012:
Hess undisclosed

Perth Basin
AWE

Sept 30, 2011:
ConocoPhillips/
Buru Energy
\$119.5m

Oct 2, 2012:
Santos/Central
Petroleum \$150m

Nov 15, 2012:
Fortescue
\$14.2m

Nov 6, 2012:
Total/Central
Petroleum \$190m

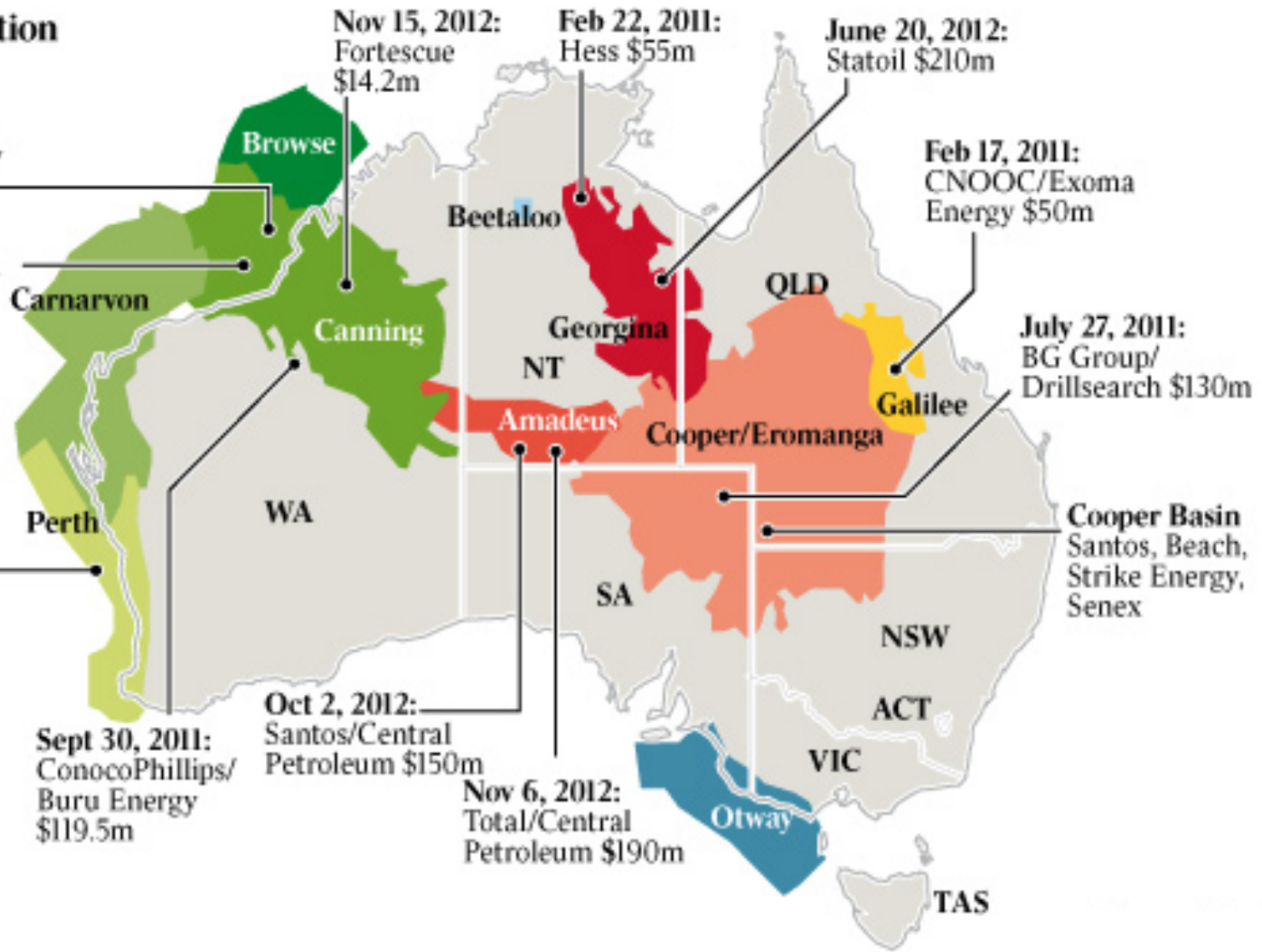
Feb 22, 2011:
Hess \$55m

June 20, 2012:
Statoil \$210m

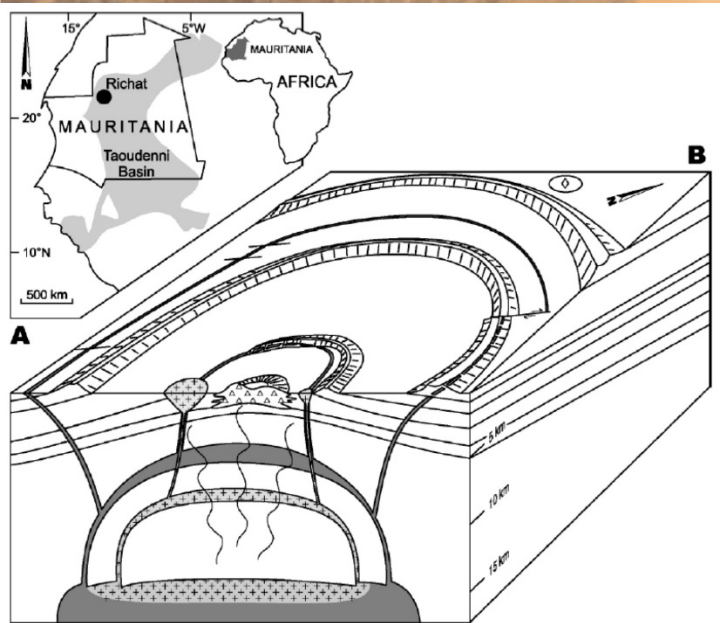
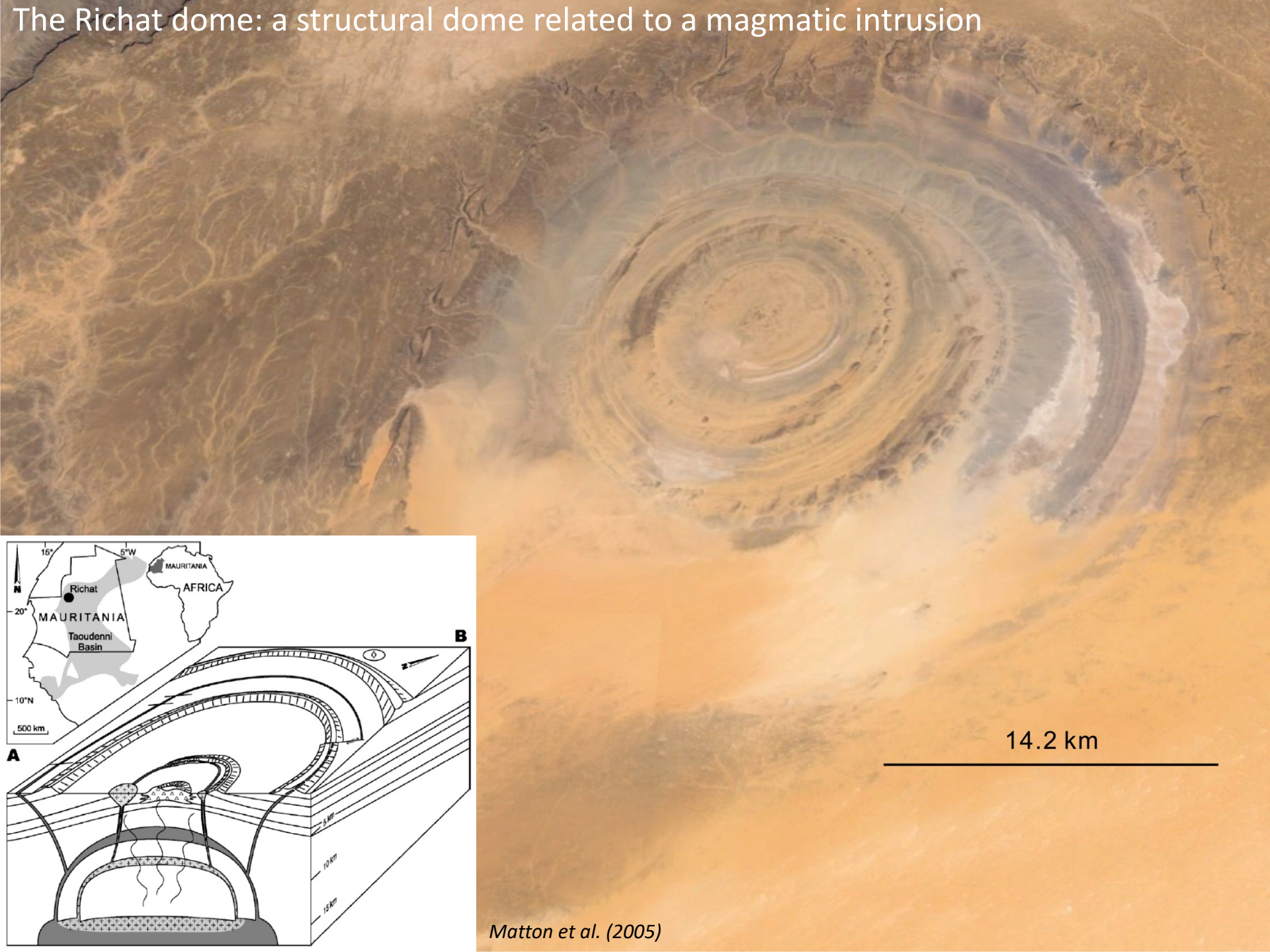
Feb 17, 2011:
CNOOC/Exoma
Energy \$50m

July 27, 2011:
BG Group/
Drillsearch \$130m

Cooper Basin
Santos, Beach,
Strike Energy,
Senex



The Richat dome: a structural dome related to a magmatic intrusion



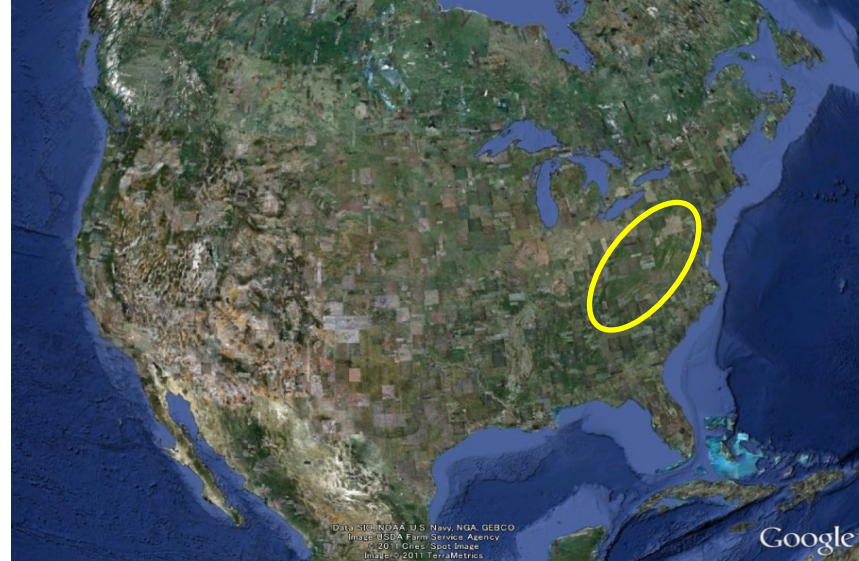
14.2 km

Matton et al. (2005)

★ Phanerozoic orogens (= mountain belts)

- Mountain belts are formed by episodes of compressive deformation where two tectonic plates converge.
- Orogeny refers to the process of mountain building.

Examples: Appalachian Mountains (USA)
Alpine-Himalayan orogenic belt (Eurasia)



The **Appalachian mountains** are marked by two distinct successive episodes of compressive deformation (orogenies):

- **Caledonian orogeny** resulting from the collision of the continents **Laurentia** (part of N America, Greenland), **Baltica** (N-E Europe), and **Avalonia** (part of N-E America, part of W Europe) **450-400 Ma** ago.

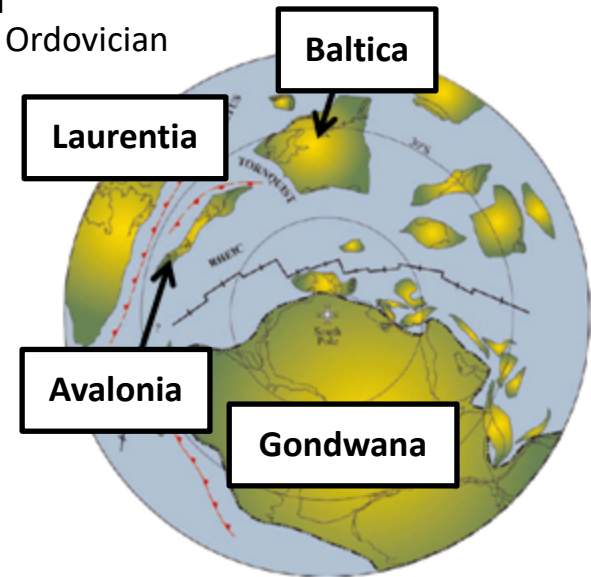
The collision between Laurentia, Baltica, and Avalonia resulted in the formation of the continent **Laurussia**.

- **Variscan* orogeny** resulting from the collision of the continents **Laurussia** and **Gondwana** (S America, Africa, Madagascar, India, Antarctica, and Australasia) **400-300 Ma** ago.

The collision between Laurussia and Gondwana resulted in the formation of the supercontinent **Pangaea**.

*also referred to as the Hercynian orogeny

460 Ma
Middle Ordovician



400 Ma
Early Devonian



Appalachians-USA



Eifel-Germany



Ardennes-Belgium



460 Ma
Middle Ordovician

Baltica

Laurentia

Avalonia

Gondwana

440 Ma
Late Ordovician

420 Ma
Late Silurian

400 Ma
Early Devonian

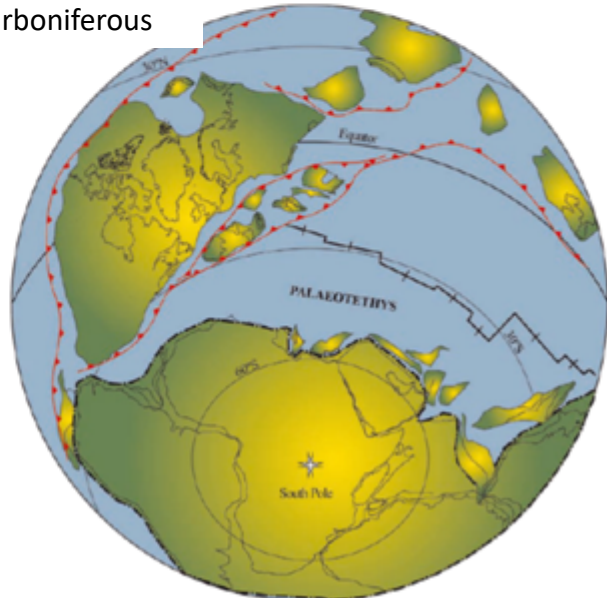
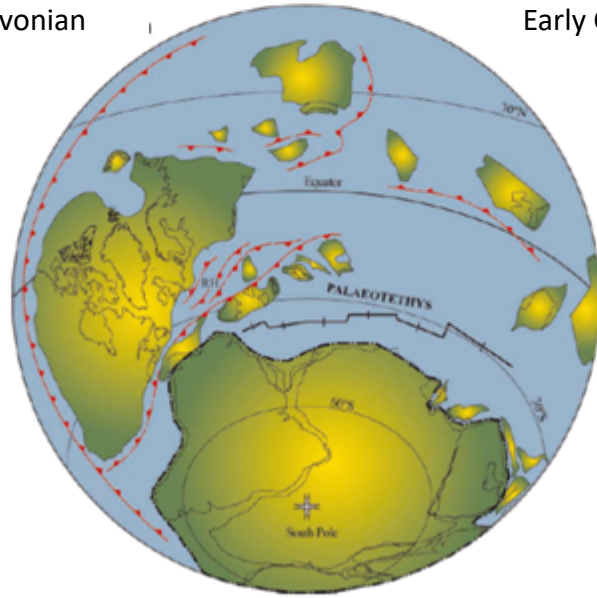
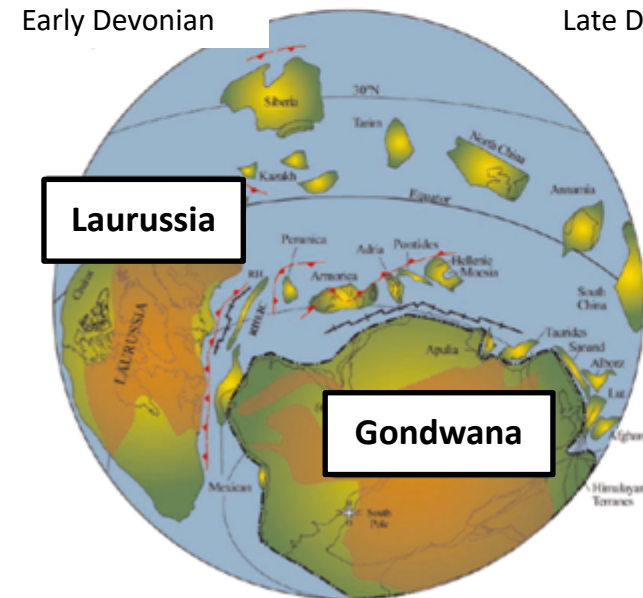
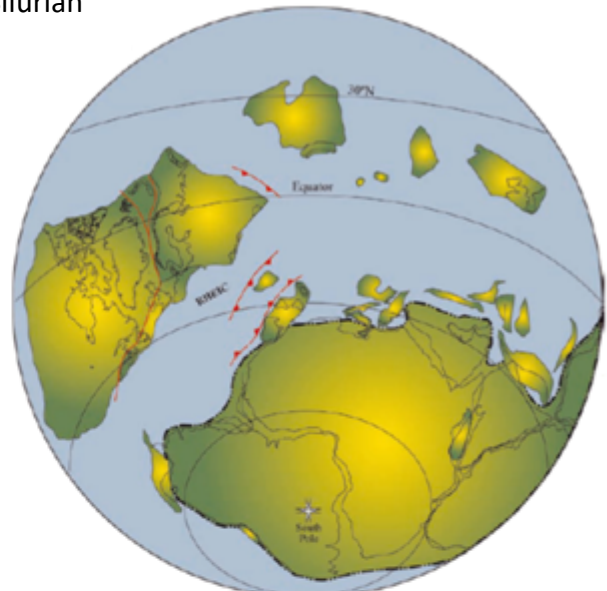
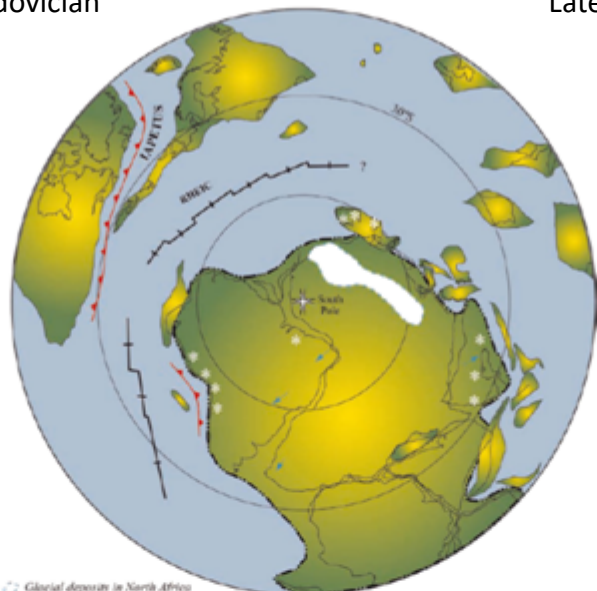
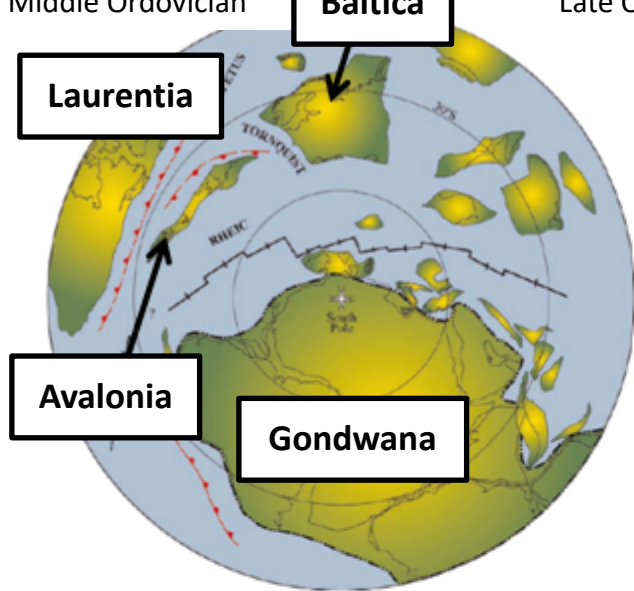
370 Ma
Late Devonian

340 Ma
Early Carboniferous

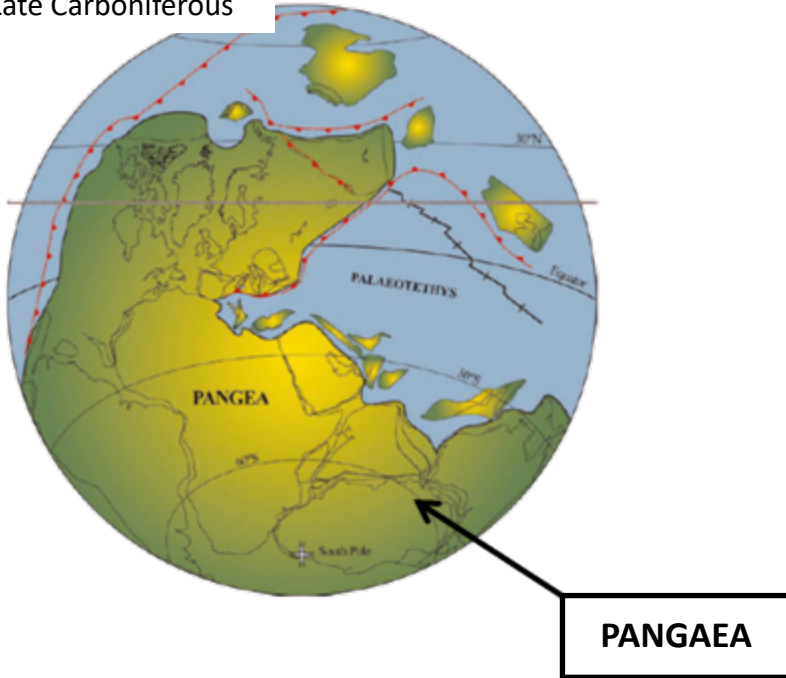
Laurussia

Gondwana

○ Glacial deposits in North Africa
■ Glacial depostones, rills etc.
↖ Glacial deposits with ice direction



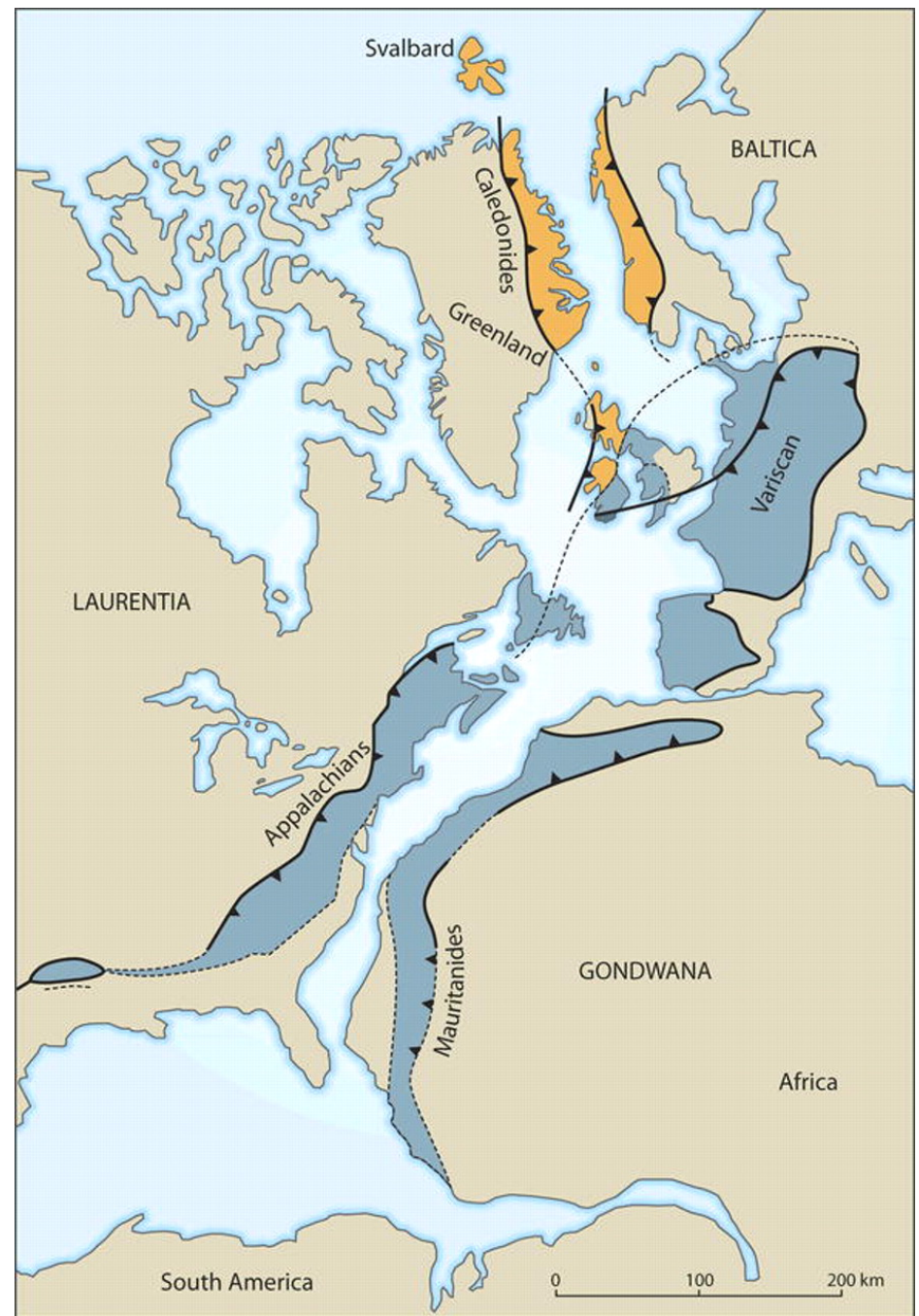
310 Ma
Late Carboniferous



Paleogeographic reconstructions based on:

- Mapping rock types and geologic structures
- Fossil distribution
- Rock paleomagnetism

When lava cools, iron-rich minerals become magnetized in the direction of Earth's magnetic field. By measuring rock magnetization, it is possible to determine the paleolatitude at which the rock formed.



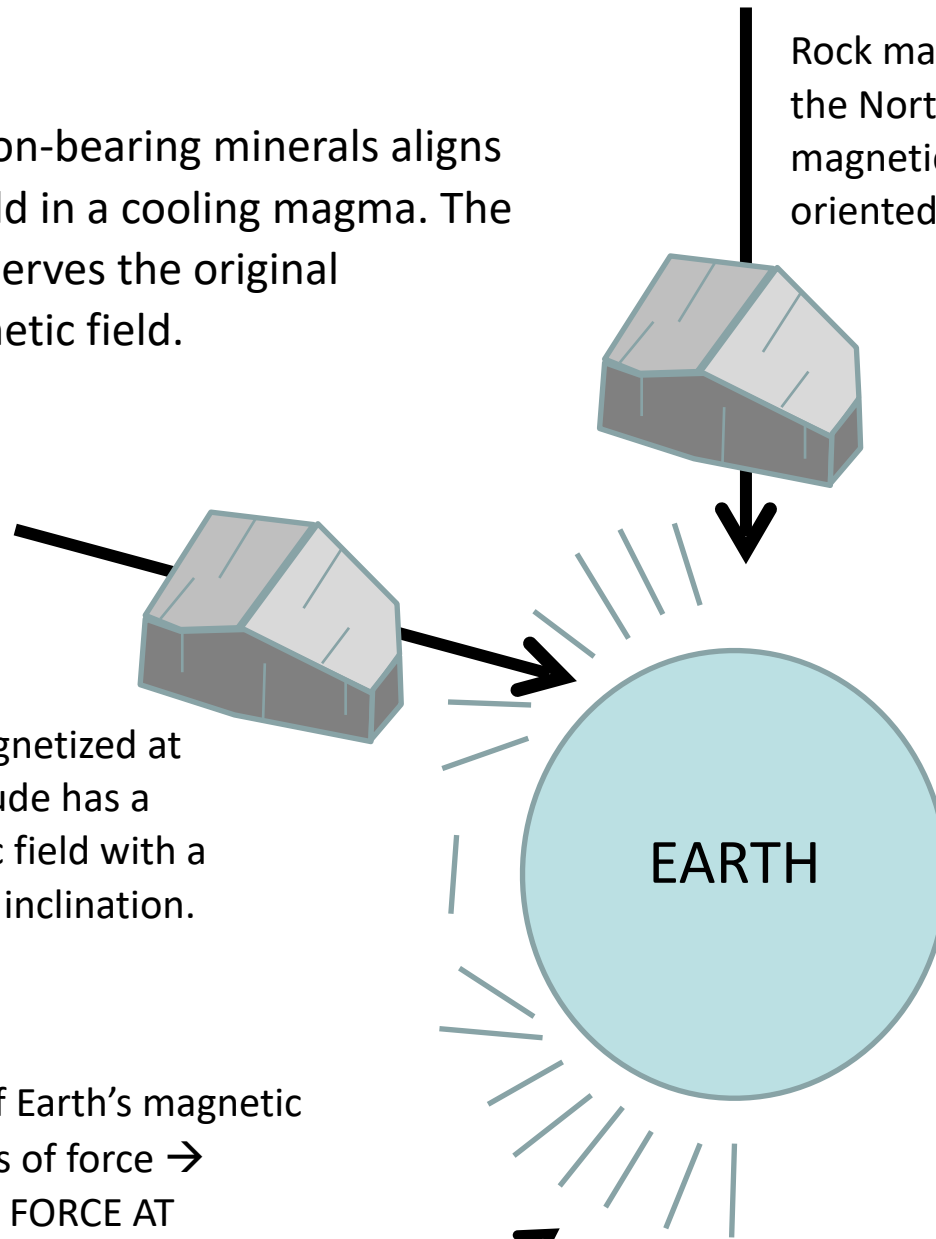
Cocks and Torsvisk (2006) Henriksen et al. (2008)

The magnetic field of iron-bearing minerals aligns with Earth magnetic field in a cooling magma. The resulting solid rock preserves the original orientation of the magnetic field.

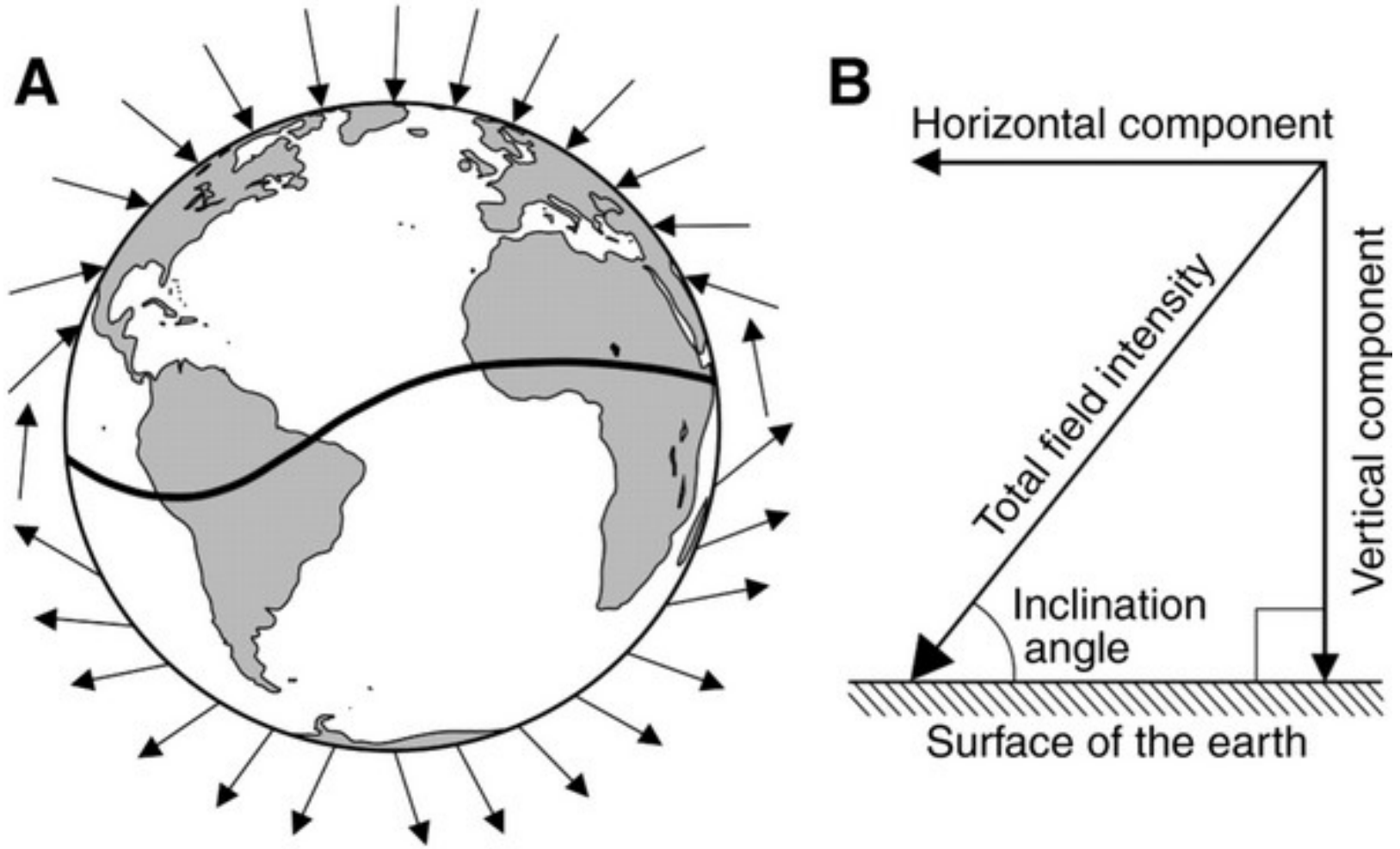
Rock magnetized at the North Pole bears a magnetic field oriented vertically.

Rock magnetized at this latitude has a magnetic field with a different inclination.

Trends of Earth's magnetic field lines of force →
LINES OF FORCE AT DIFFERENT LATITUDES HAVE DIFFERENT INCLINATIONS!

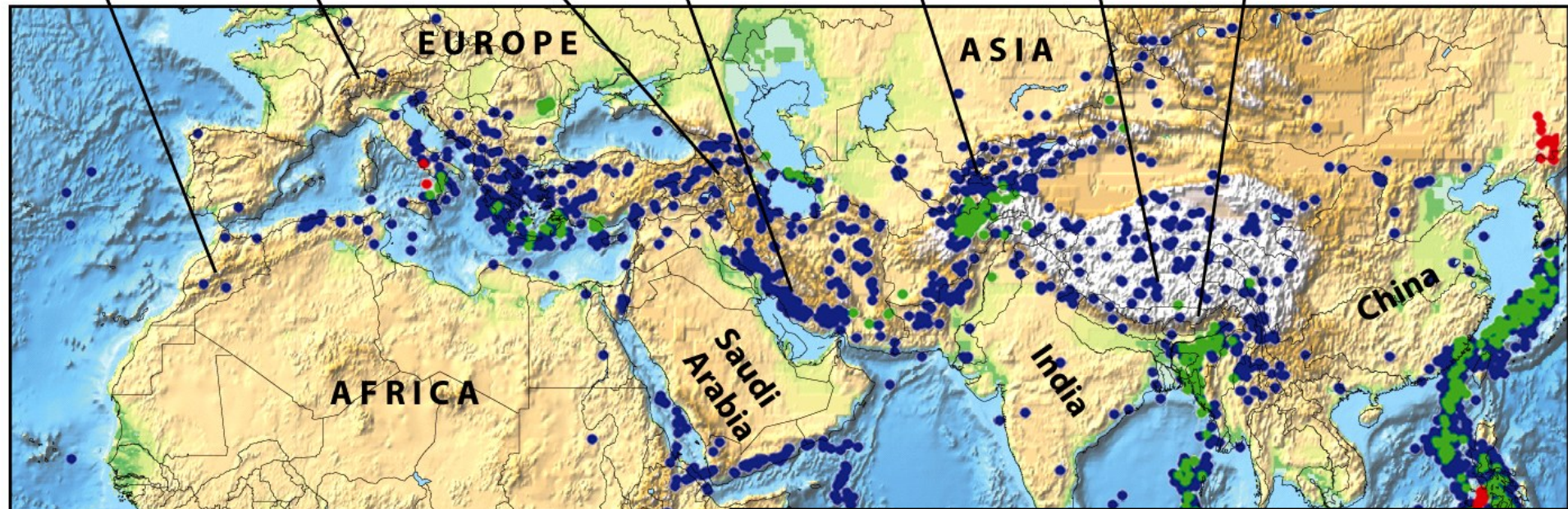


Rock paleomagnetism constrains the paleo-latitude of a rock formation but not its paleo-longitude.



Alpine-Himalayan orogenic belt (still active)

Atlas Mountains Alps Caucasus Zagros Mountains Tien Shan Tibetan Plateau Himalaya



Earthquake depth

- ≤ 50 km deep (shallow focus)
- 50–300 km deep
- > 300 km deep (deep focus)

Chains of mountains resulting from the collision between the African, Arabian, and Indian plates with the Eurasian plates.

6 The modern world has been produced over the past 65 million years. India collided with Asia, ending its trip across the ocean, and is still pushing northward into Asia. Australia has separated from Antarctica.



(i) PRESENT-DAY WORLD

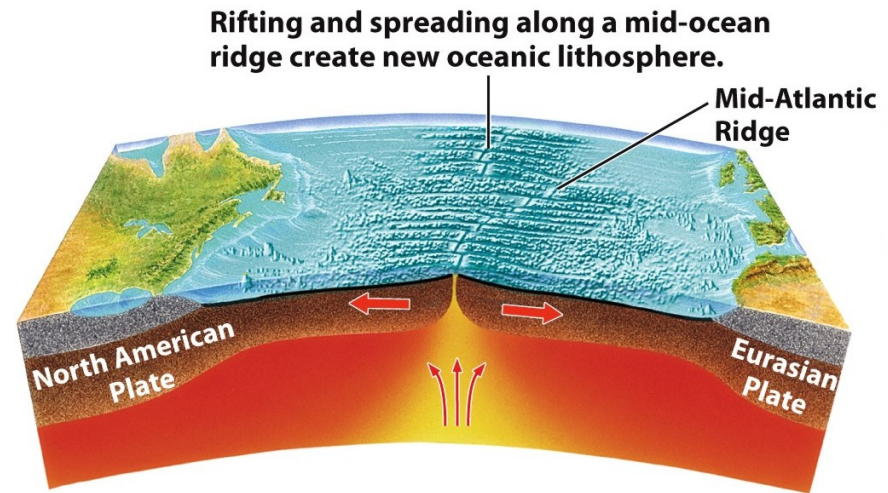


(j) 50 million years in the future

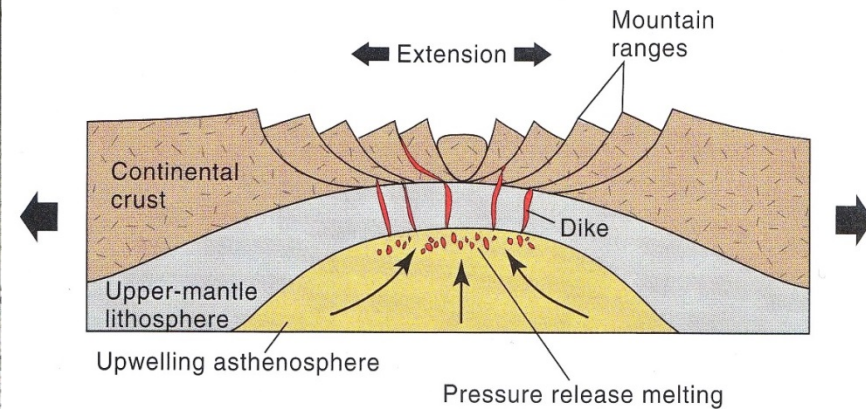
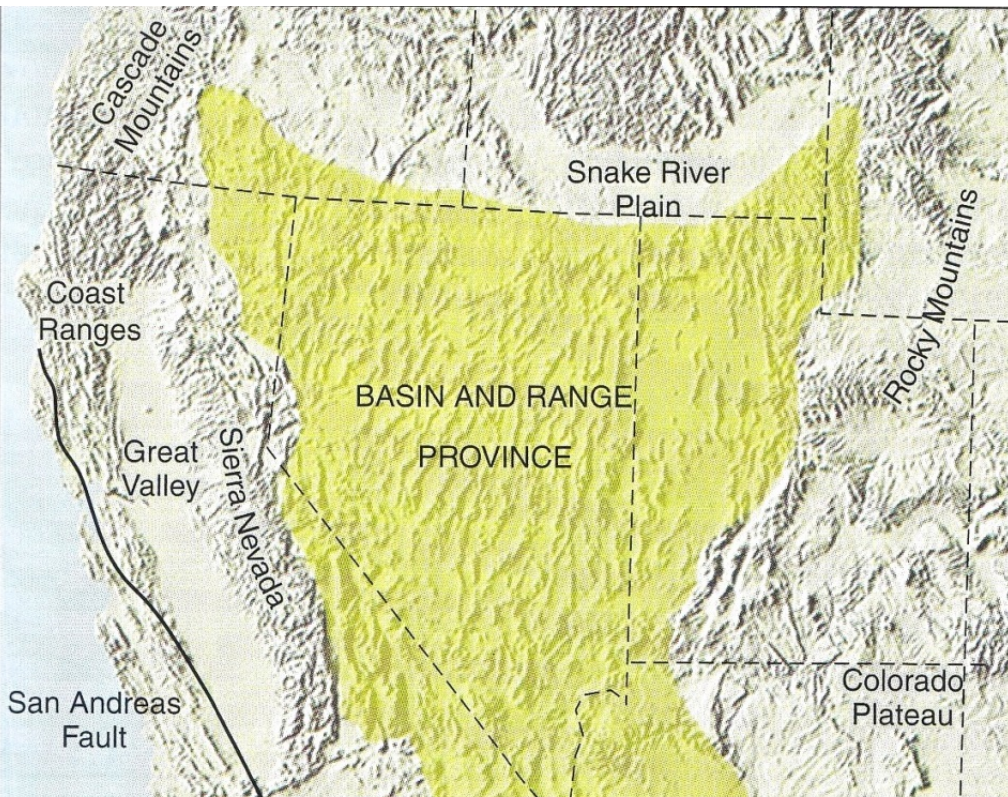
★ Extended crust

- Region of the crust where the most recent deformation has involved large-scale crustal extension.

e.g. Atlantic coastal plain
Basin and Range Province (USA)

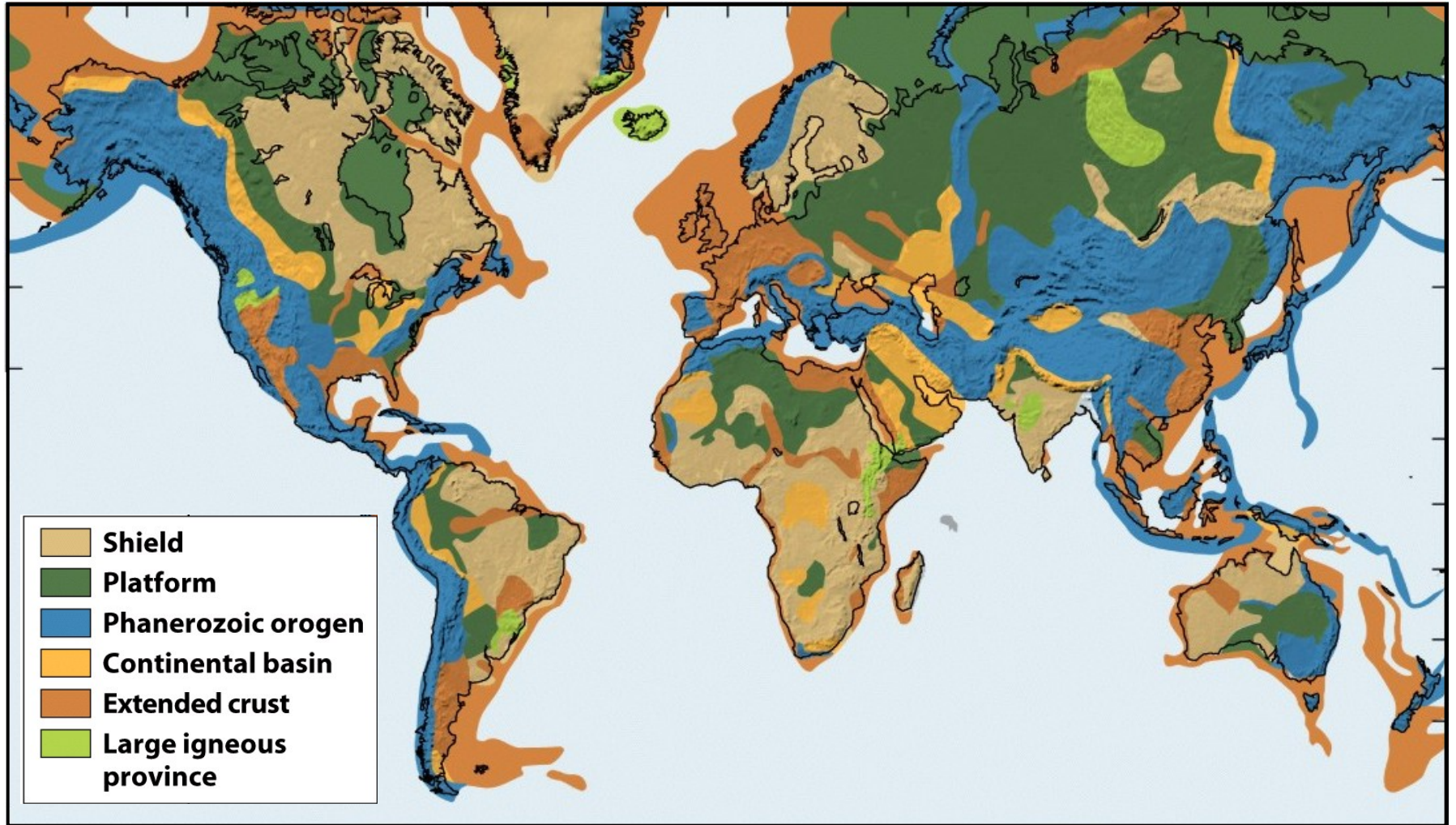


Extension resulting from the opening of the Atlantic Ocean beginning 180 million years ago.

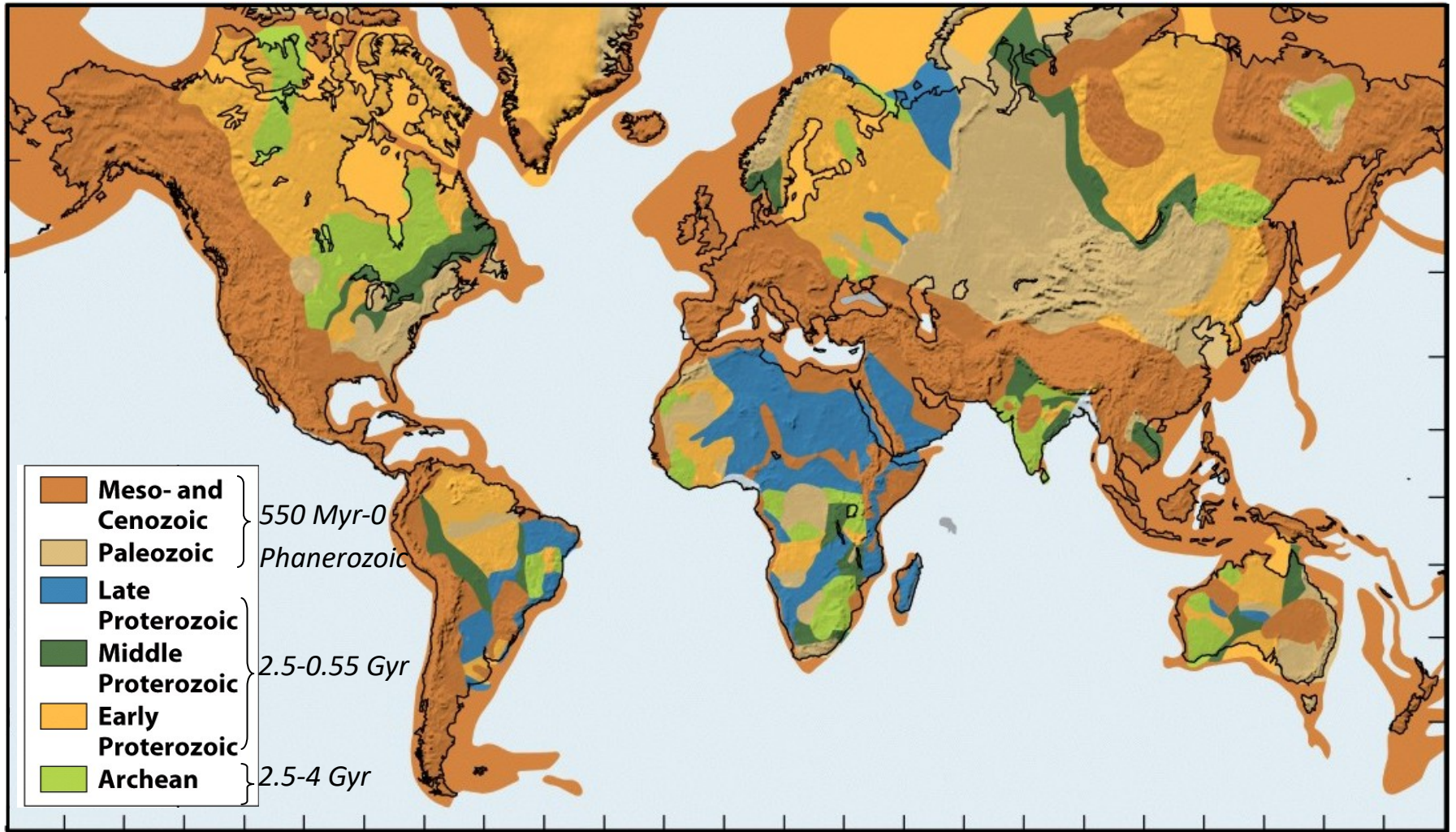


Extension resulting from upwelling convection currents in the mantle.

★ Tectonic provinces vs. tectonic ages



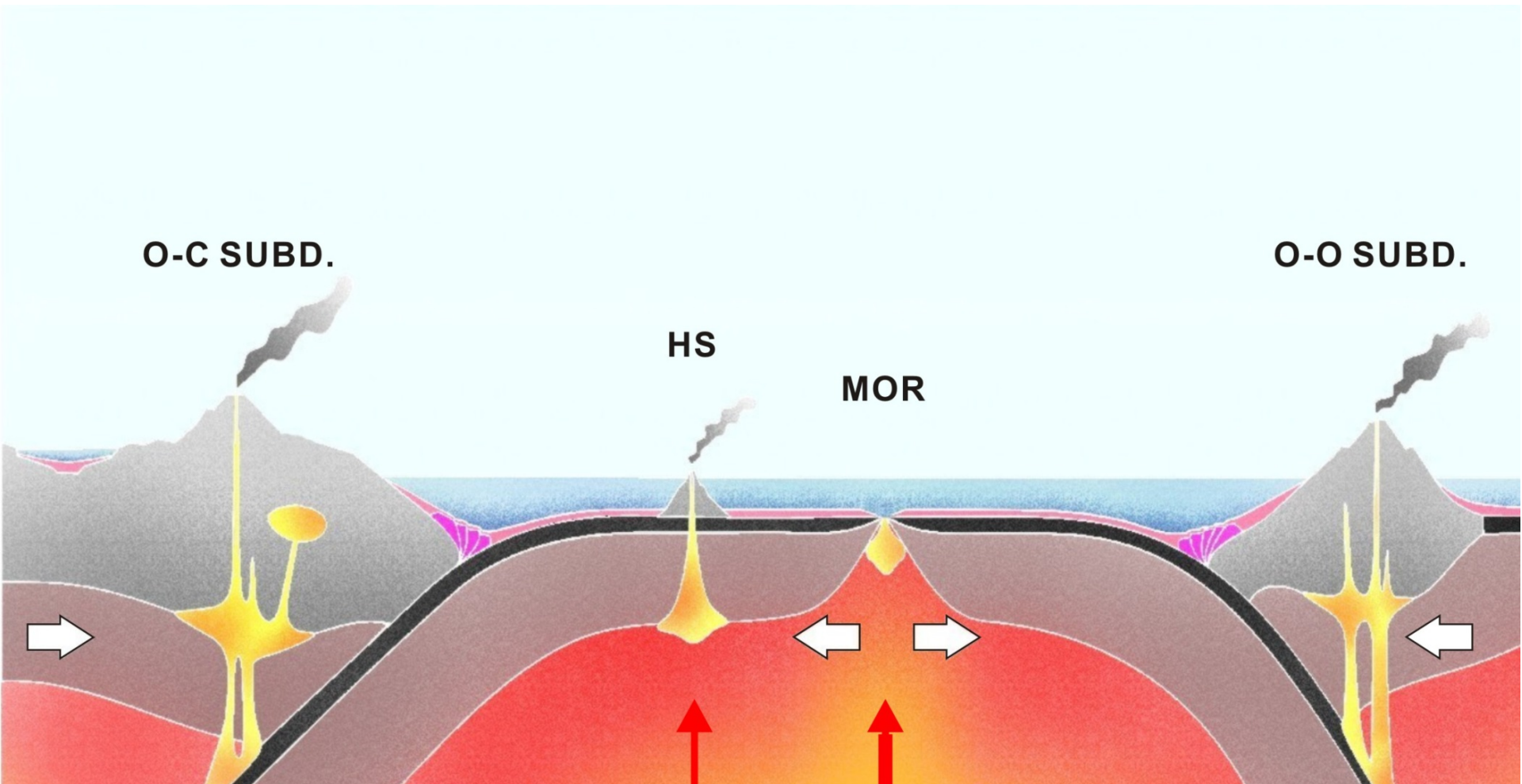
Tectonic age = time of the last major episode of crustal deformation

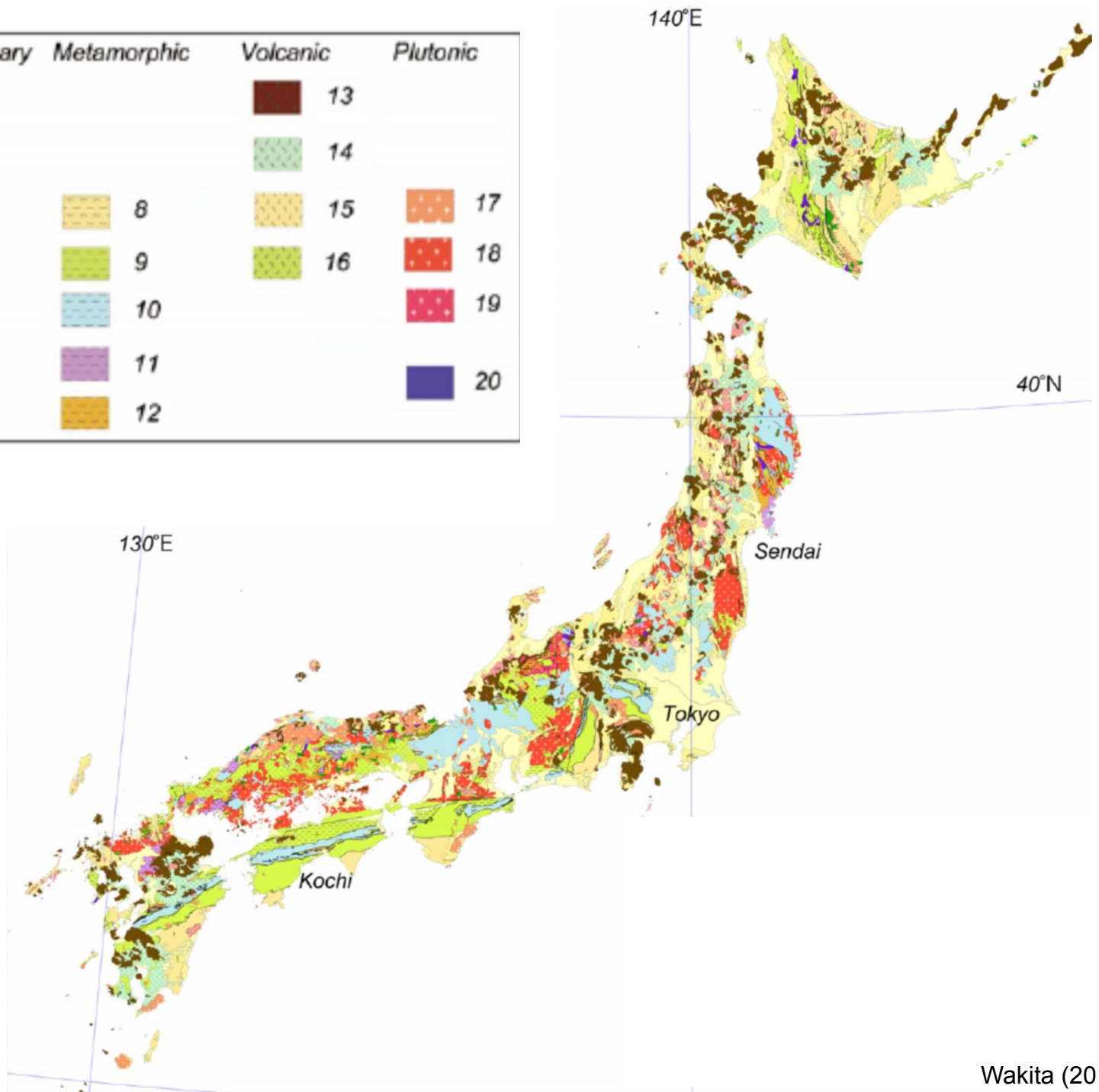
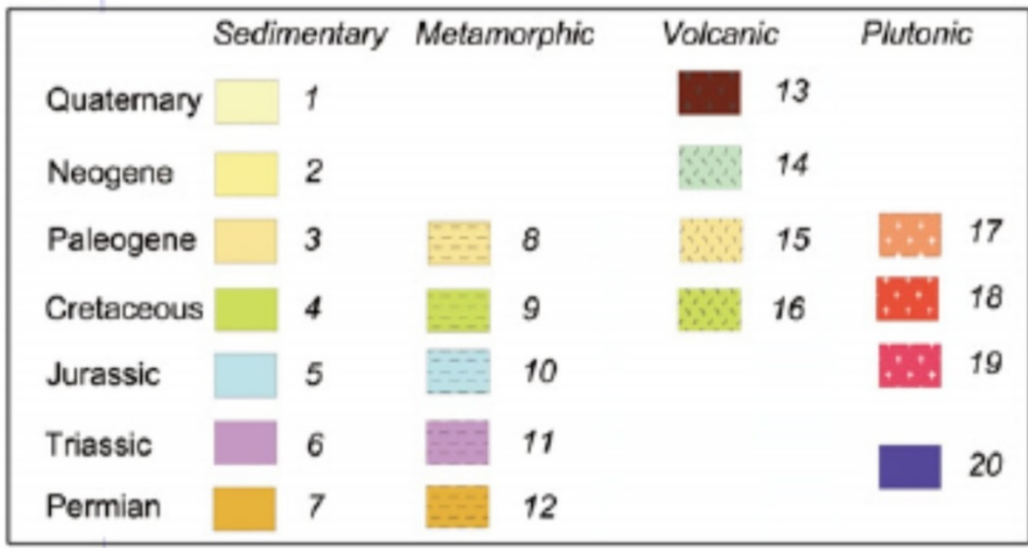


★ The growth of continents

★ Magmatic addition

- Direct addition of magma in subduction zones (water-induced melting, various igneous rocks produced)

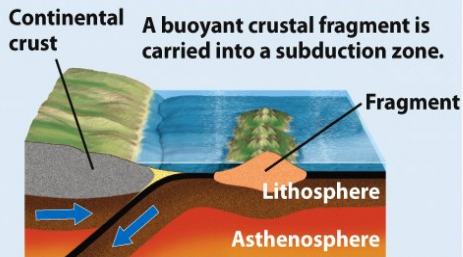




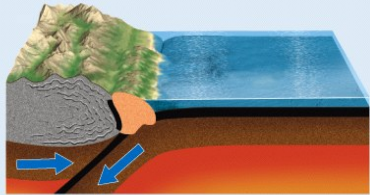
★ Accretion

- Tectonic plates carry crustal material that can be incorporated to existing continental masses.

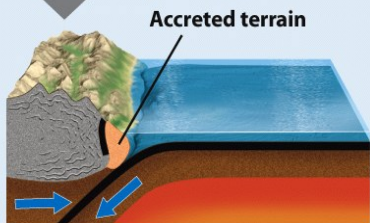
ACCRETION OF A BUOYANT FRAGMENT TO A CONTINENT



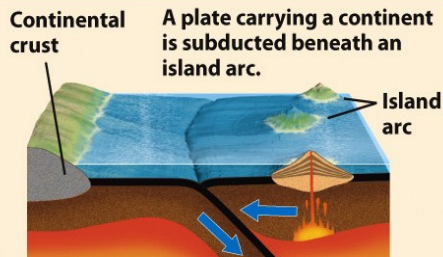
The fragment is more buoyant than the subducting lithosphere, so it is not subducted.



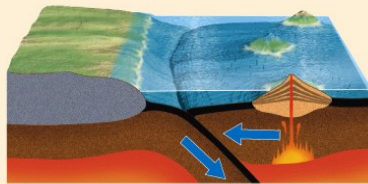
The fragment becomes welded to a continent on the overriding plate.



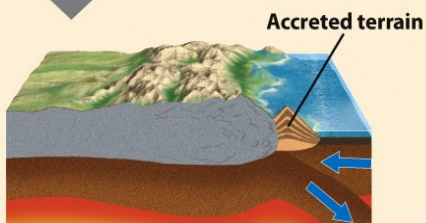
ACCRETION OF AN ISLAND ARC TO A CONTINENT



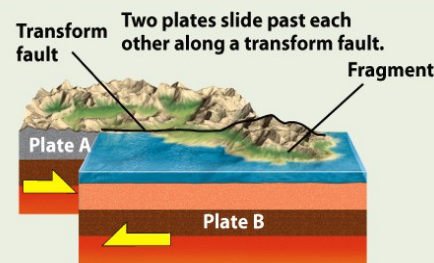
The continental crust is more buoyant than the subducting lithosphere,



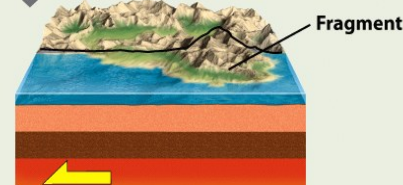
The sea closes, and the island arc becomes welded to the continent.



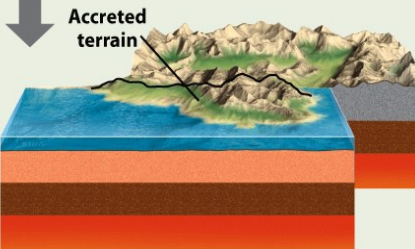
ACCRETION ALONG A TRANSFORM FAULT



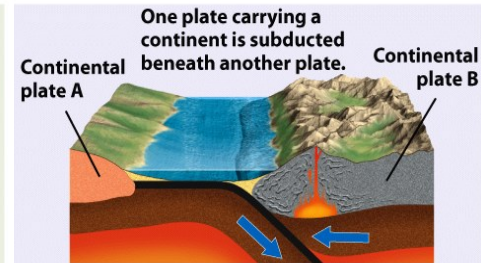
A crustal fragment on plate B is carried along the margin of plate A.



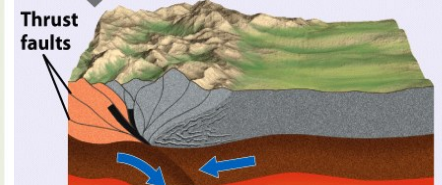
When the fault becomes inactive, the fragment becomes welded to plate A in a position distant from its original position.



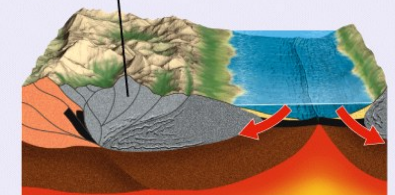
ACCRETION BY CONTINENTAL COLLISION AND RIFTING










The continent is not subducted, so the two continents are sutured together along a set of thrust faults.

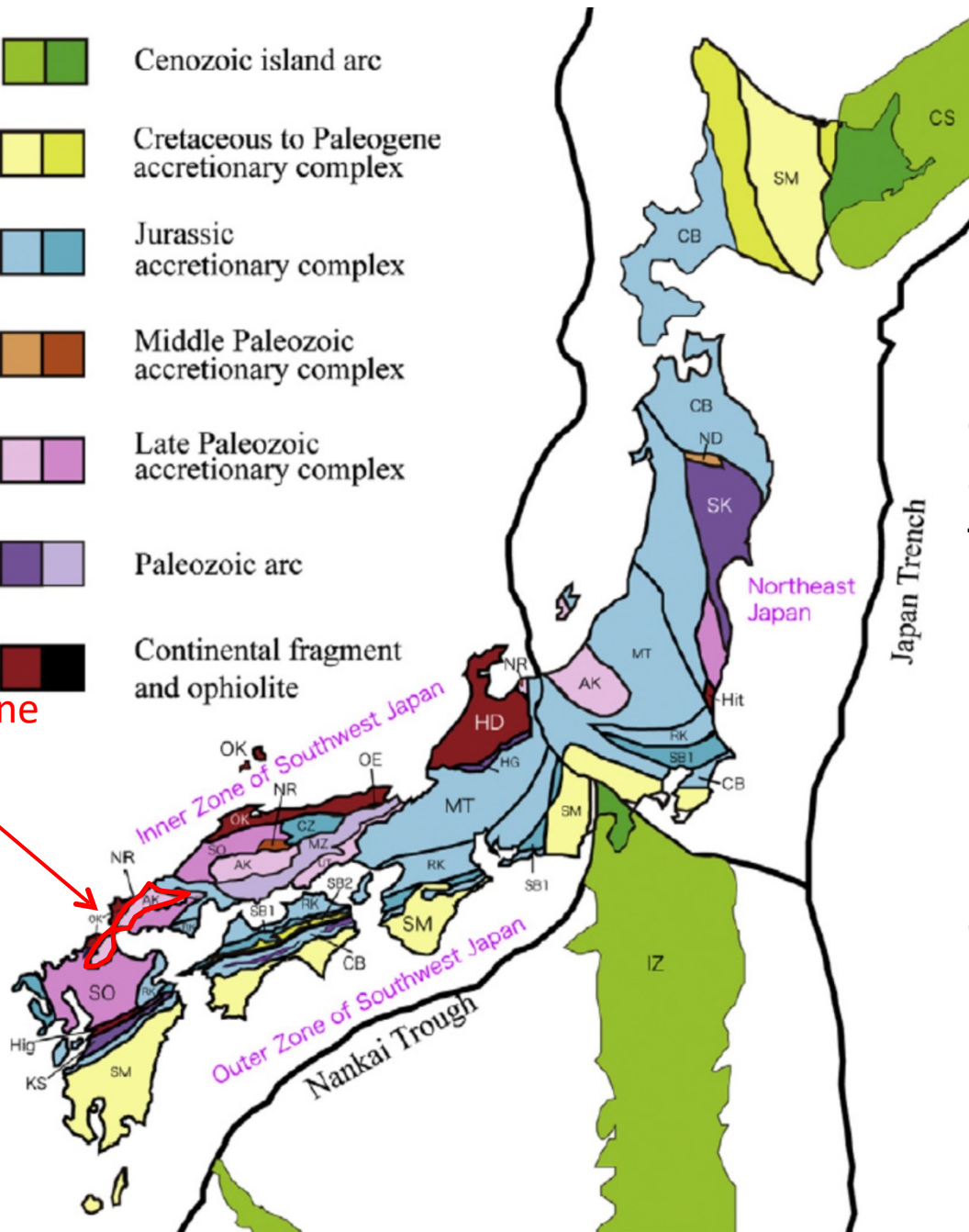
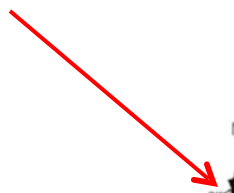


Later, rifting and seafloor spreading carry the plates apart, leaving a fragment of one continent welded to the other.



-  Cenozoic island arc
-  Cretaceous to Paleogene accretionary complex
-  Jurassic accretionary complex
-  Middle Paleozoic accretionary complex
-  Late Paleozoic accretionary complex
-  Paleozoic arc
-  Continental fragment and ophiolite

Akiyoshi terrane

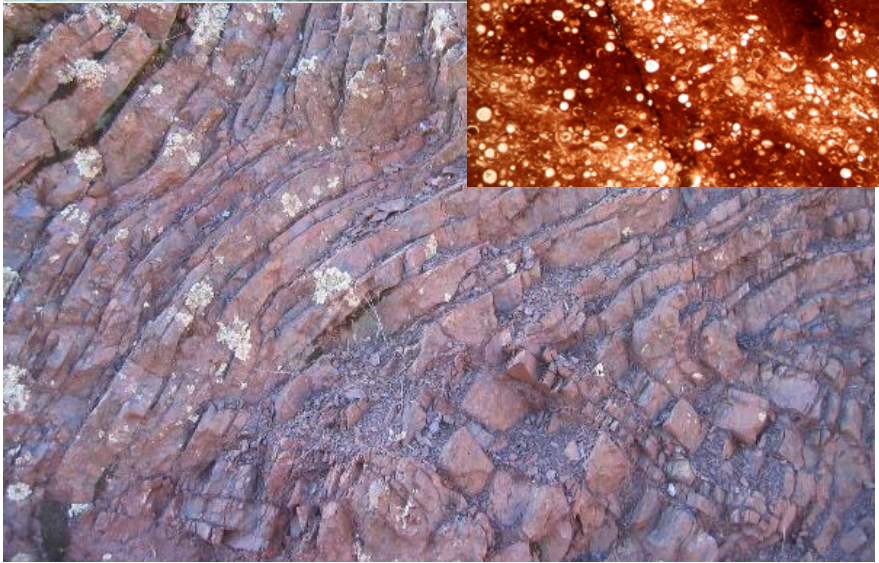
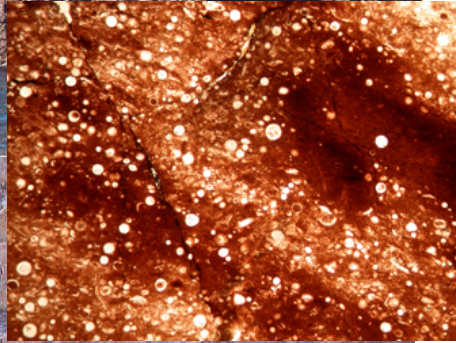


Pieces of buoyant, light material plastered onto other continental masses are called **accreted terranes** (10s to 100s of km in width).

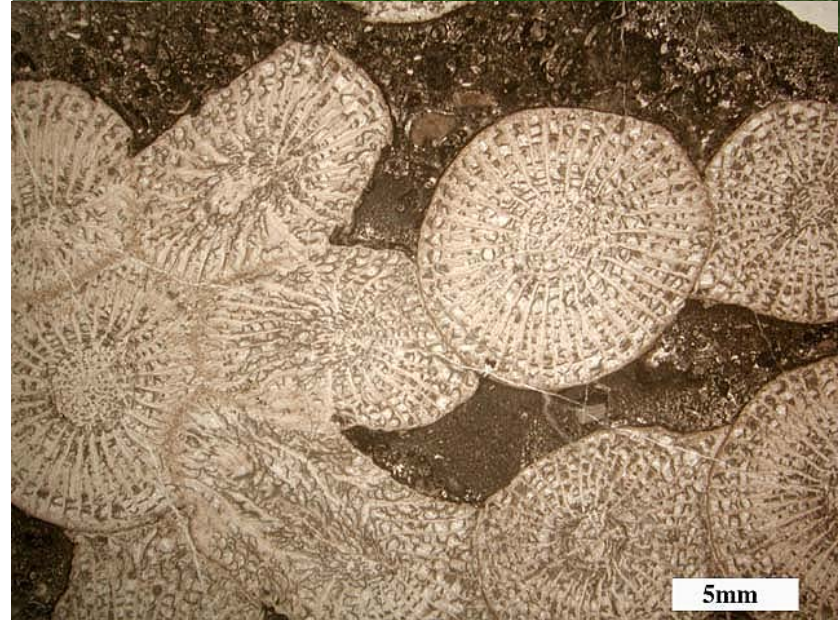
Examples of accreted material: islands, underwater volcanoes, ocean floor sediments.

Examples of accreted material from the subducting plate in Japan

Radiolarian chert



Fossil atoll reefs (Akiyoshidai, Carboniferous-Permian)



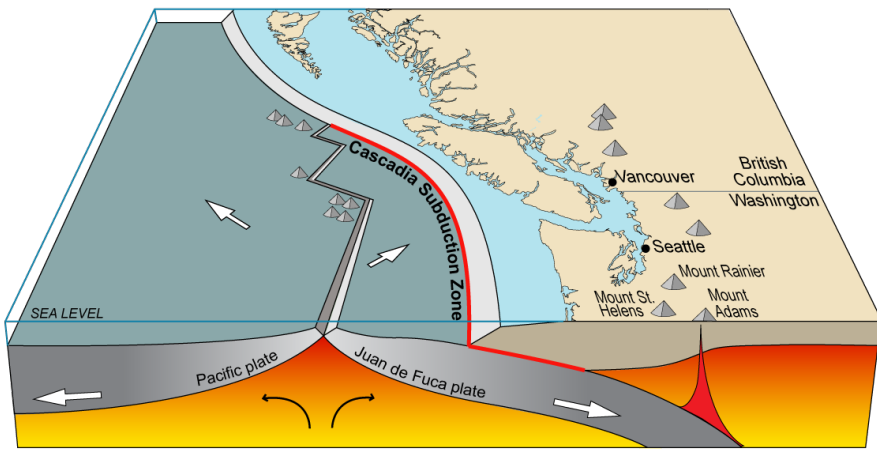
[http://www.geological-survey-of-japan](http://www.geological-survey-of-japan.go.jp/)

<http://www.geocaching.com>

University of Edinburgh

<http://www.pref.yamaguchi.lg.jp>

<http://www.geol.sci.hiroshima-u.ac.jp>





*figure modified from USGS Cascadia earthquake graphics at <http://geomaps.wr.usgs.gov/pacnw/pacnweq/index.html>

The west coast of North America is mainly composed of “small” crustal blocks incorporated to the continental mass over the past 200 million years.



Wrangellia terrane moved 5000 km north before reaching its present position.

 Spreading center (divergent boundary)

 Subduction margin (convergent boundary)

 Transform fault

 Island arc

 Submarine deposits

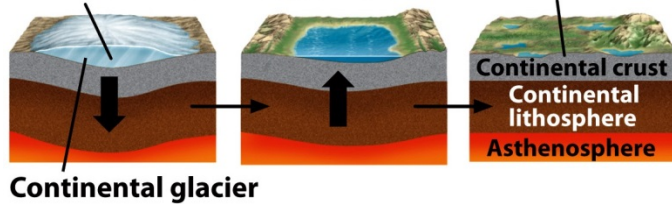
 Ancient ocean floor

 Displaced continental fragments

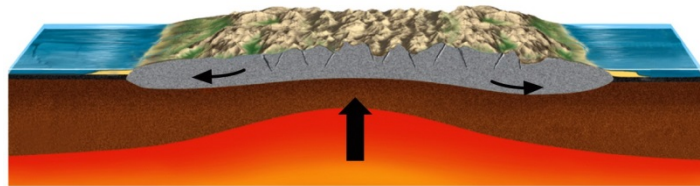
★ Epeirogeny

GLACIAL REBOUND

The weight of glacial ice downwarps the continental lithosphere, ... which rebounds once the ice is removed.



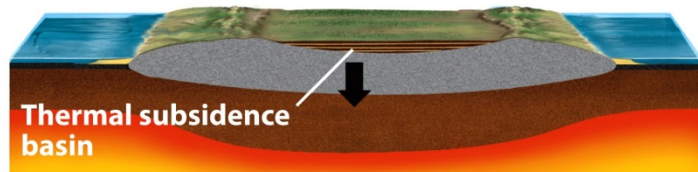
HEATING OF LITHOSPHERE *(expansion of litho.)*



Upwelling of mantle material causes uplift and thinning of the continental lithosphere.

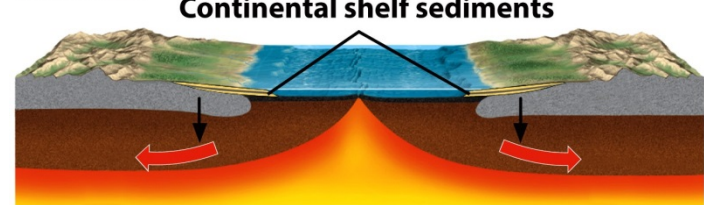
Heating → lower density → lithosphere “floats”
Expansion higher on asthenosphere

COOLING OF LITHOSPHERE IN CONTINENTAL INTERIOR



As the lithosphere cools and contracts, it subsides to form a basin within the continent.

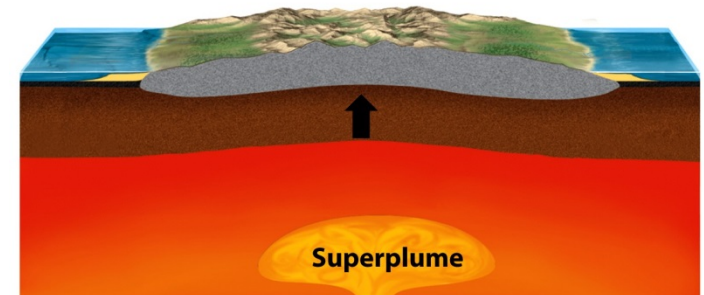
COOLING OF LITHOSPHERE ON CONTINENTAL MARGIN



When seafloor spreading splits a continent apart, the edges subside as they cool, accumulating thick sediments.

(Mantle material

HEATING OF DEEP MANTLE *pushes the lithosphere)*



A superplume rising from the deep mantle heats the lithosphere and raises the base of the continent, upwarping the surface over a broad area.

Example of glacial rebound: raised beaches resulting from the melting of the ice cap after the last glacial maximum 20,000 years ago. The land that was once covered with ice is progressively raised after the ice melted (ice unloading)

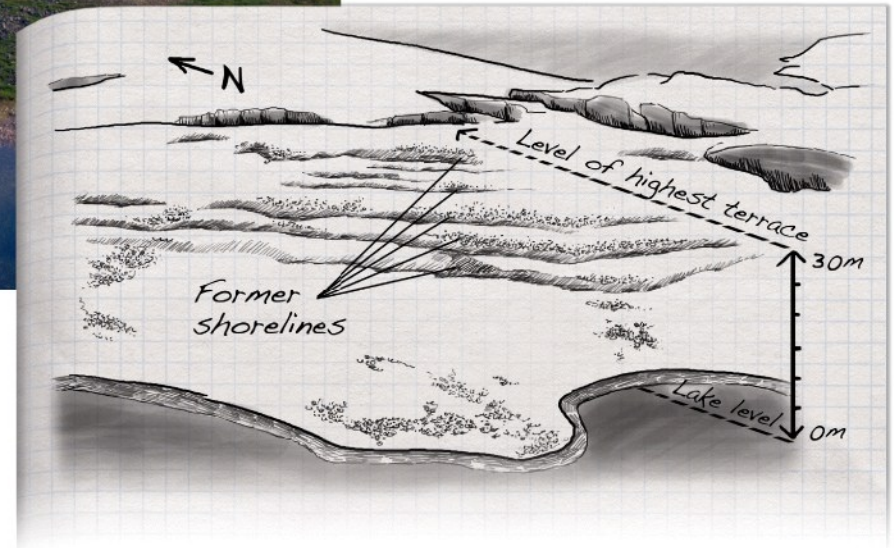


Shores of Point Lake (Canada)

Land raised



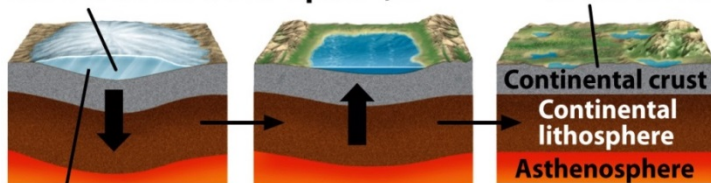
Relative drop
of water level!



GLACIAL REBOUND

The weight of glacial ice downwarps the continental lithosphere,...

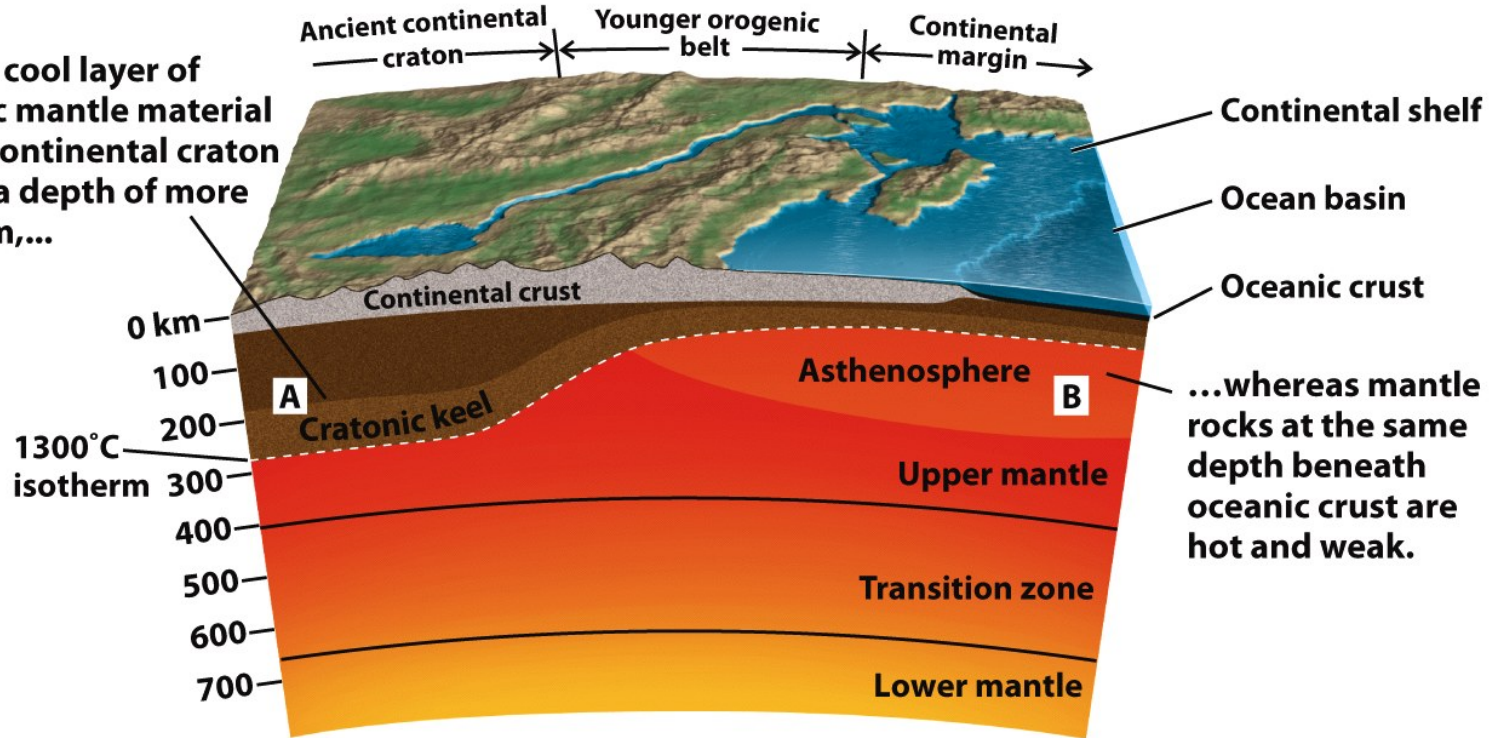
...which rebounds once the ice is removed.



Continental glacier

★ What explains the long-term stability of cratons?

The strong, cool layer of lithospheric mantle material beneath a continental craton extends to a depth of more than 200 km,...

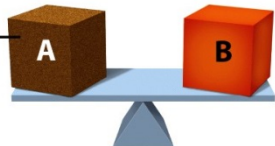


The peridotites of cratonic keels are depleted of their heavier constituents, so they are less dense under standard conditions than normal mantle peridotites.



Density at standard (surface) conditions

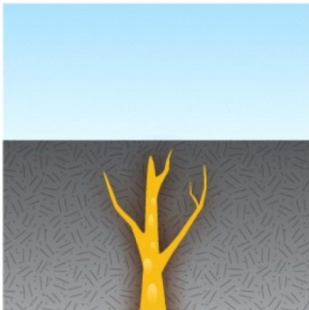
However, at 150 km deep in the mantle, they are cooler than normal mantle peridotites, so the densities of the two rock types are approximately equal.



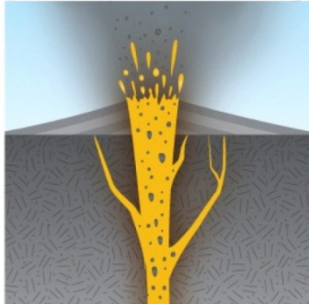
Density at mantle conditions

Diatreme

1.



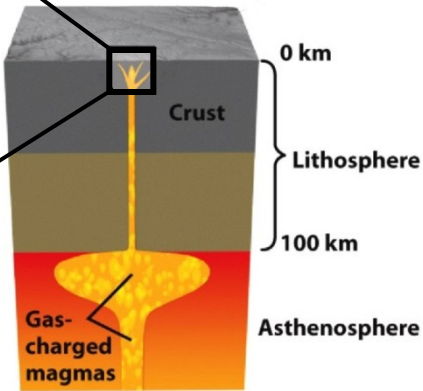
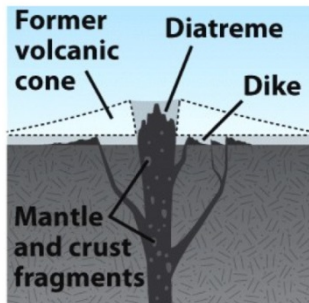
2.



3.



4.

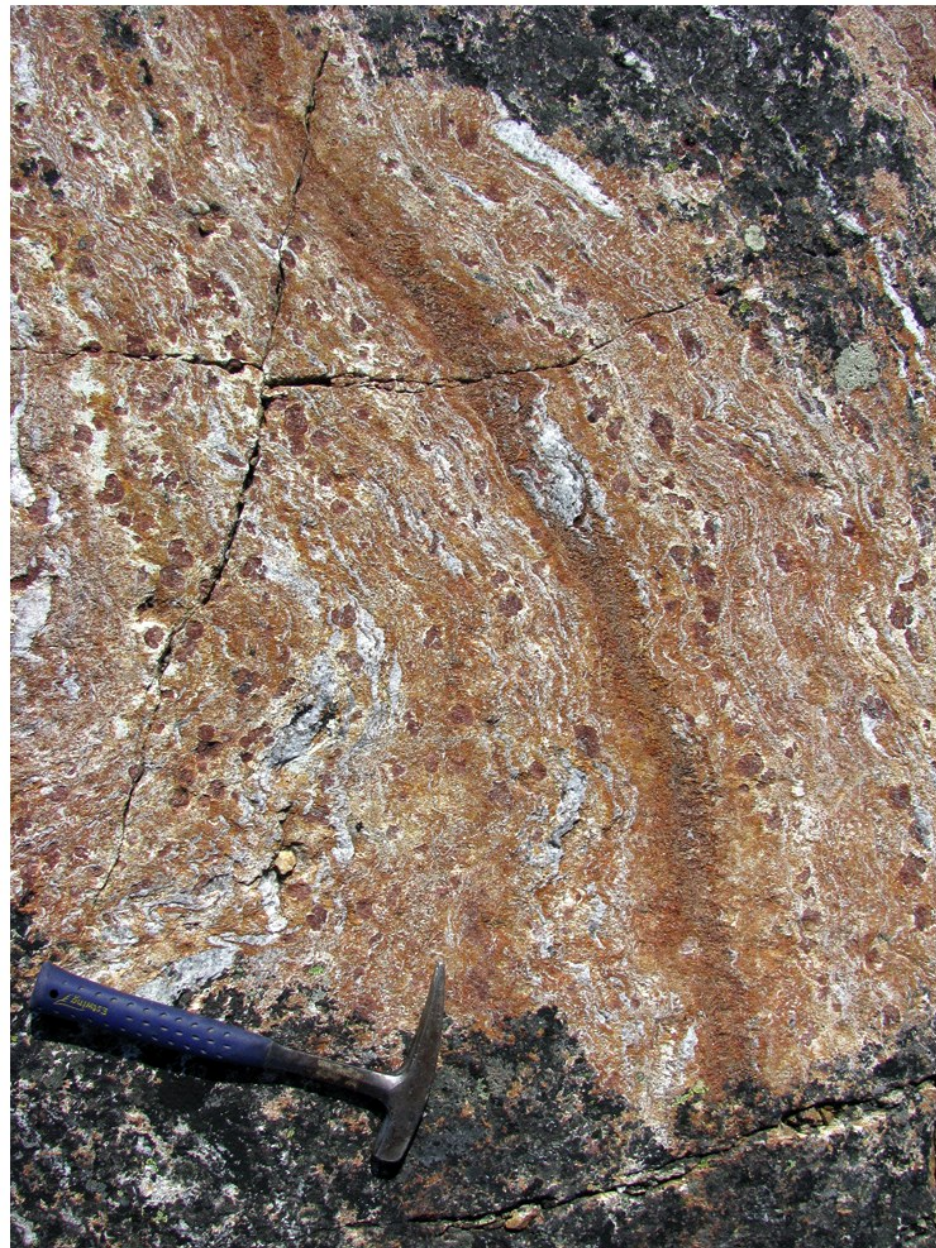


Kimberlite





Acasta Gneiss
(Canadian Shield, 4.0 Ga)



Amphibole-bearing rock
(Canadian Shield, 4.28 Ga)

John Grotzinger & Thomas H. Jordan (2010) *Understanding earth* 6th edition W H Freeman & Co