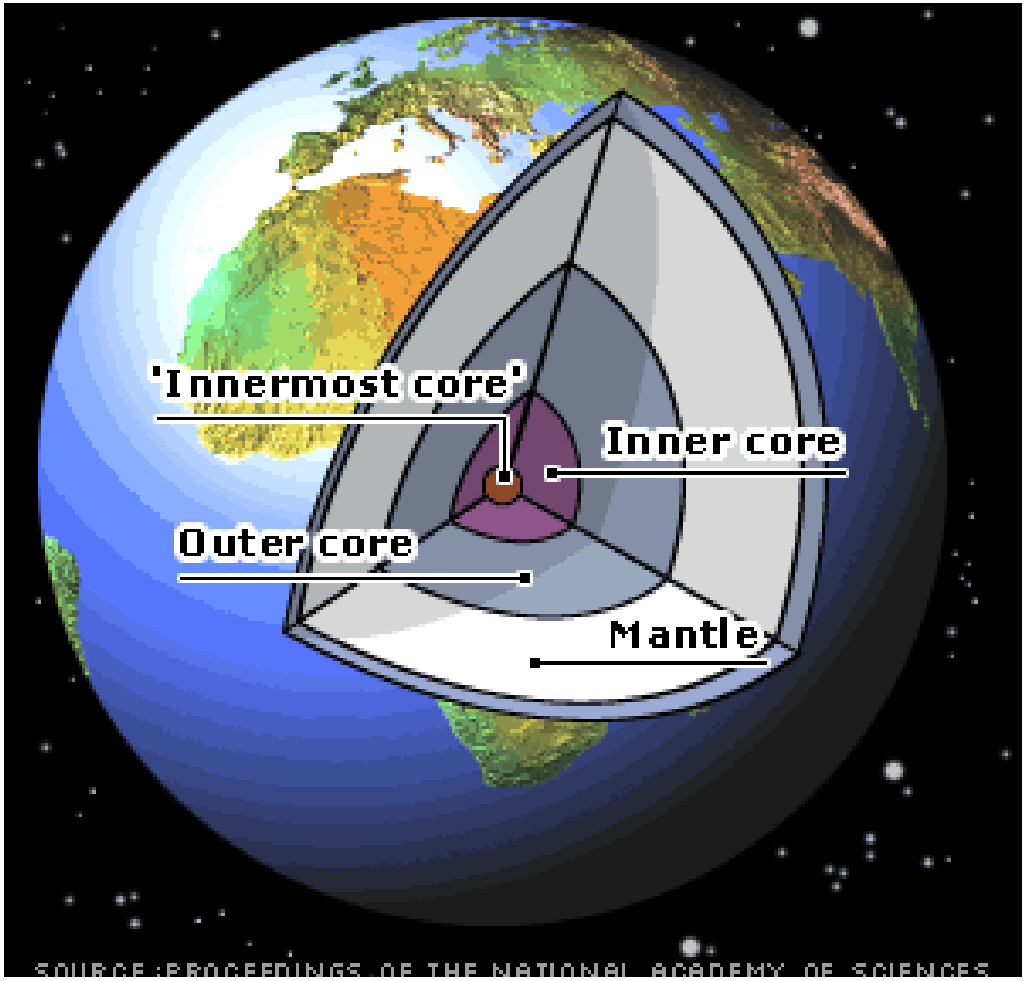
The Earth

Geology 1

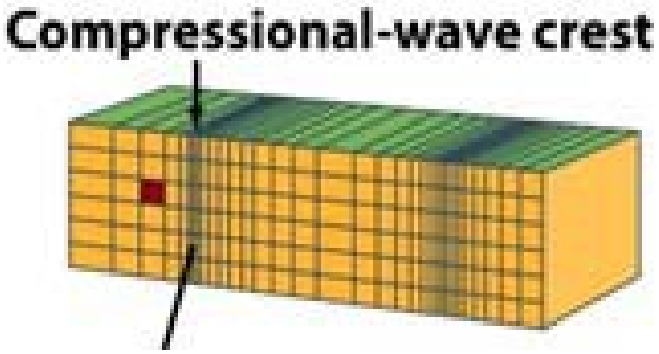
G. Bertotti

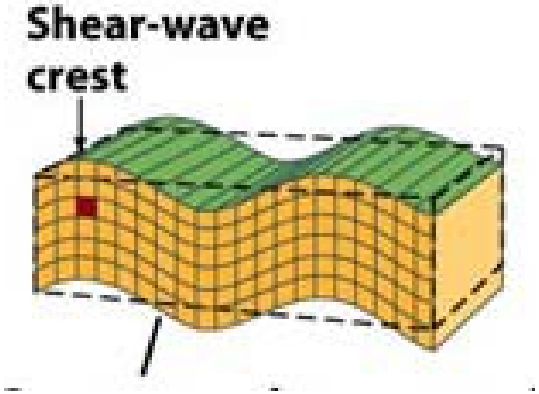
The architecture of the Earth

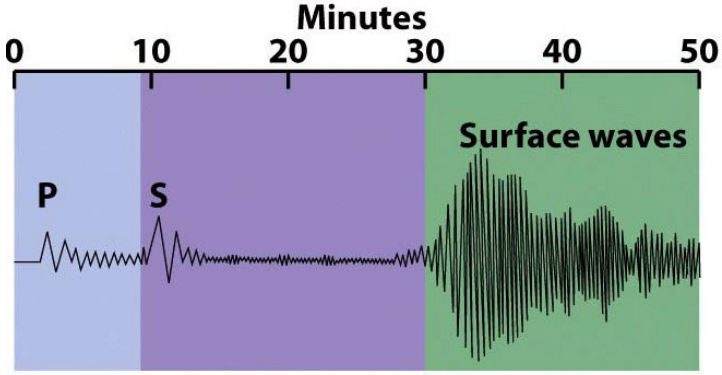


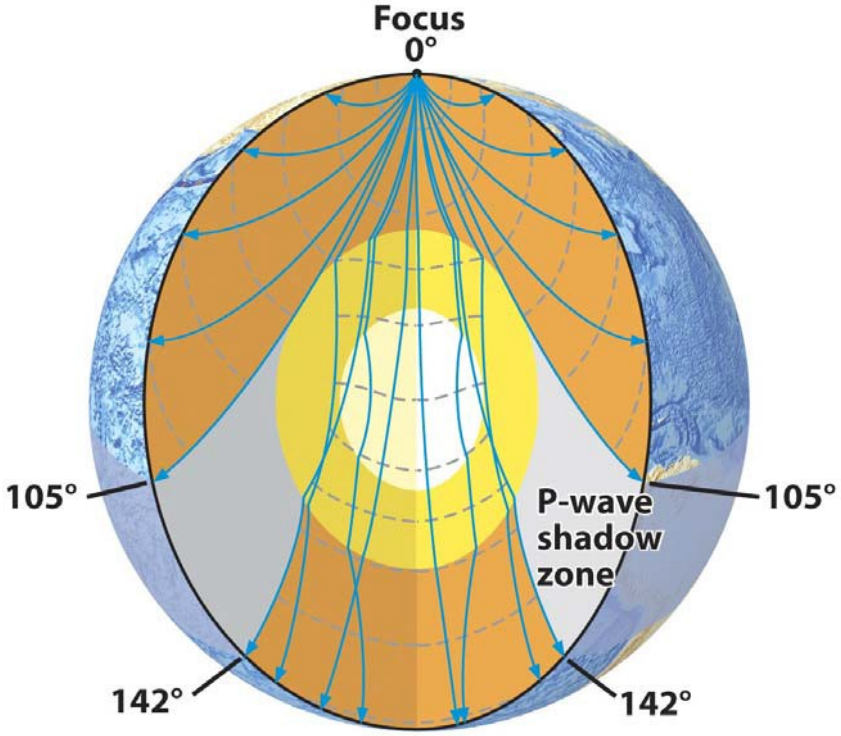
Tools to investigate the deep Earth

Seismic waves (P and S)

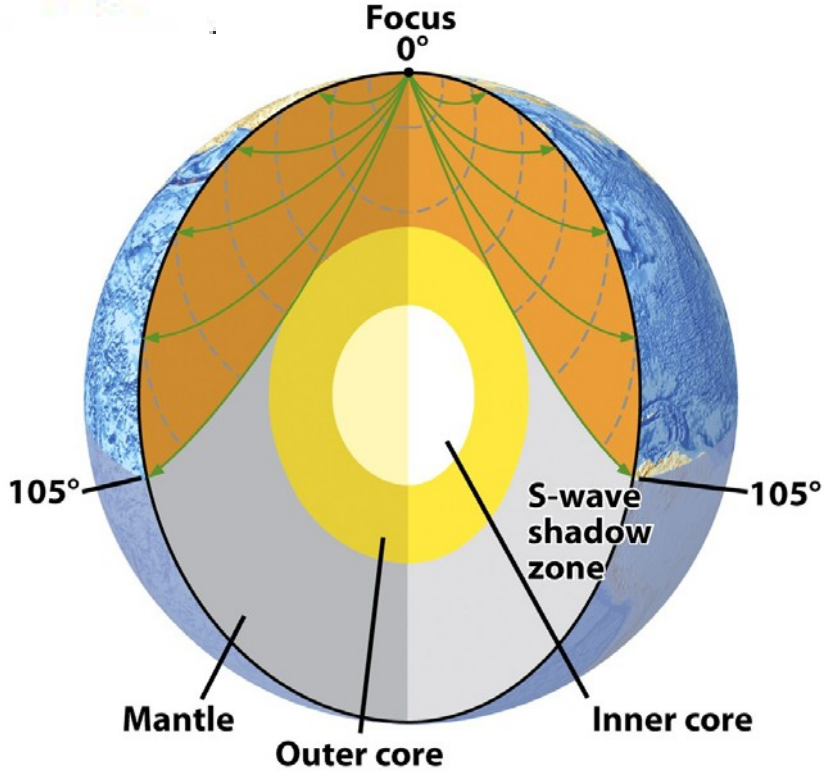






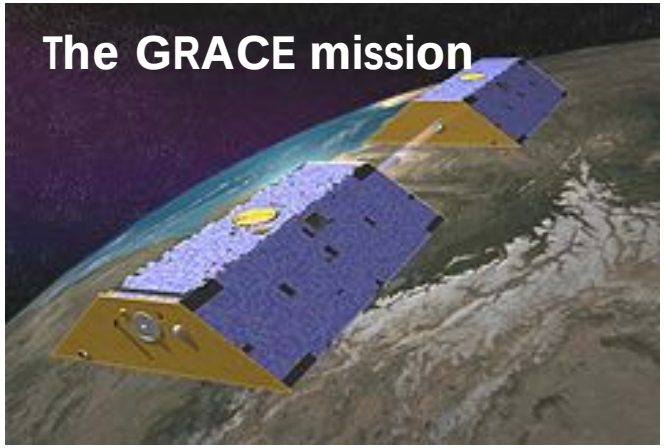


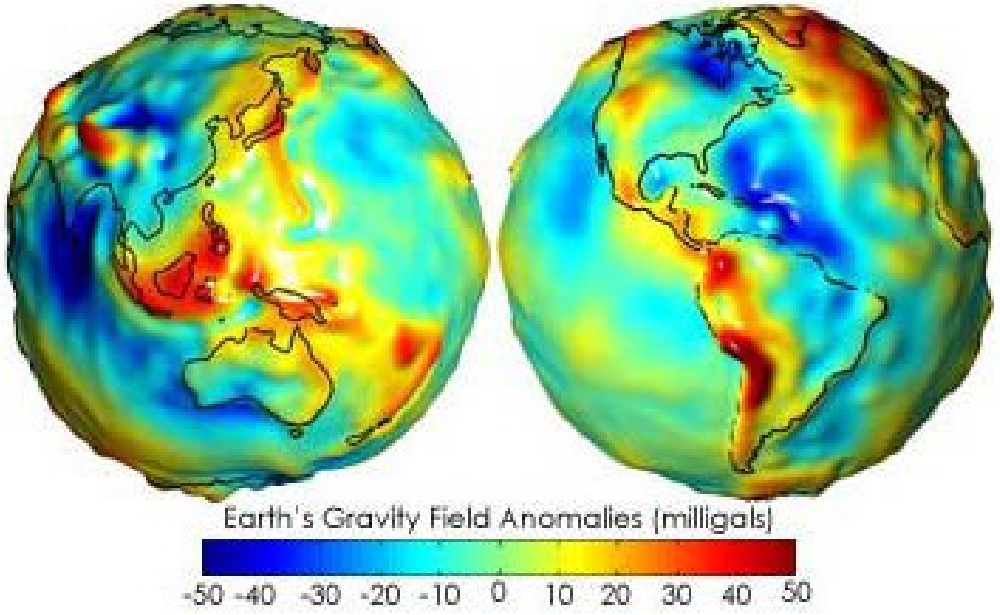
P waves



S waves

A lot of information from space





Gravity constrains distribution of masses in the Earth

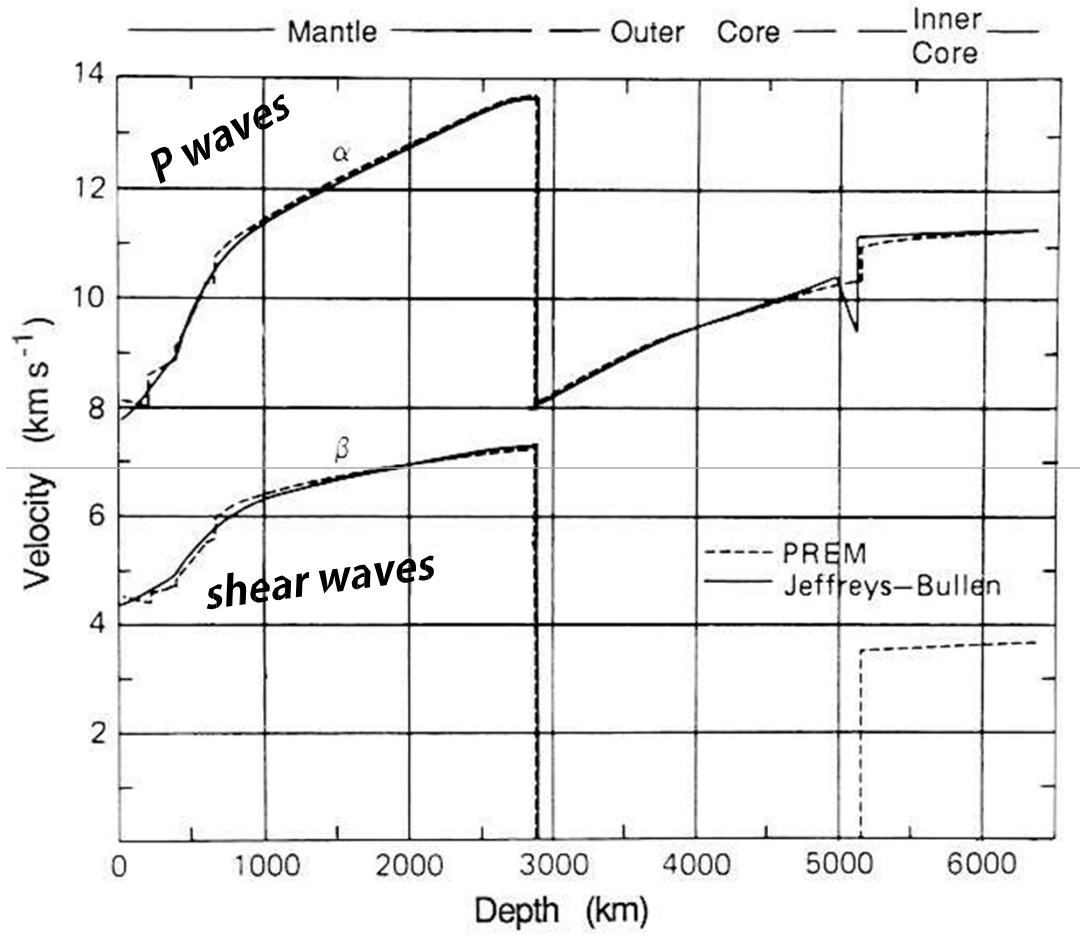
Meteorites

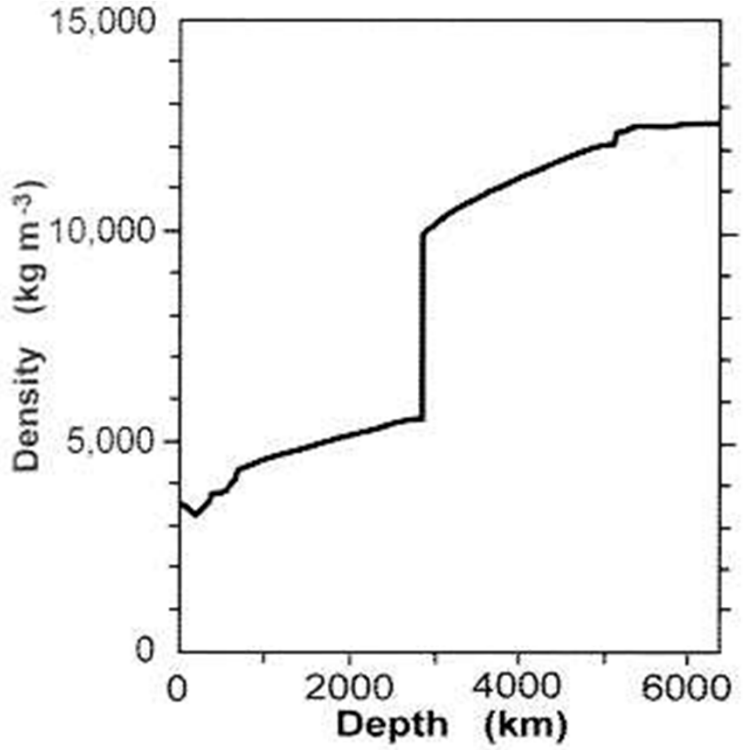
Mostly derived from particles which never aggregated to form a planet

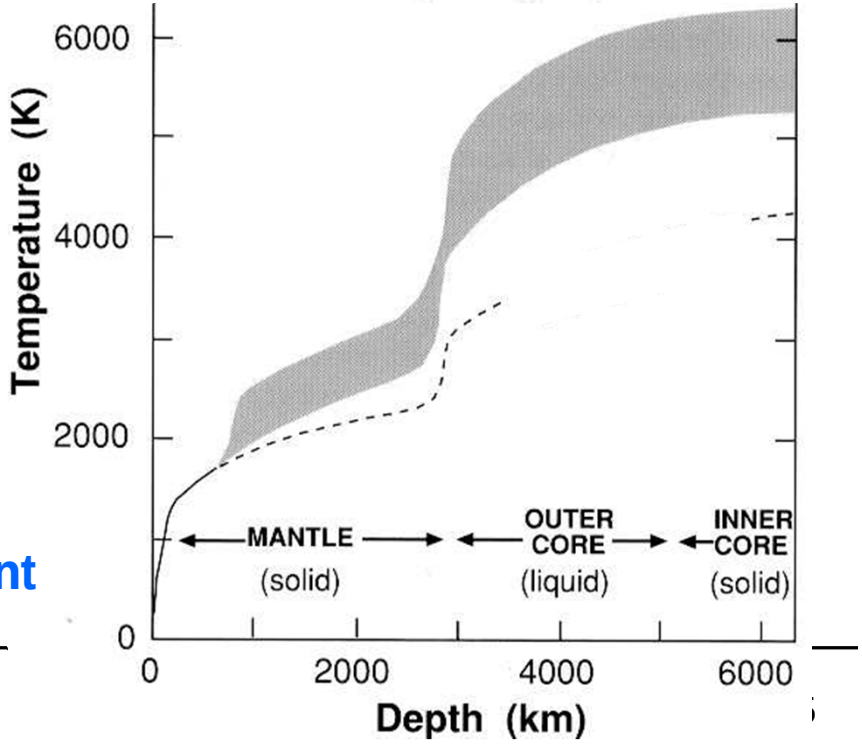
Considered to be similar to the Earth interior

We start a trip from the deepest Earth to the surface

Some data





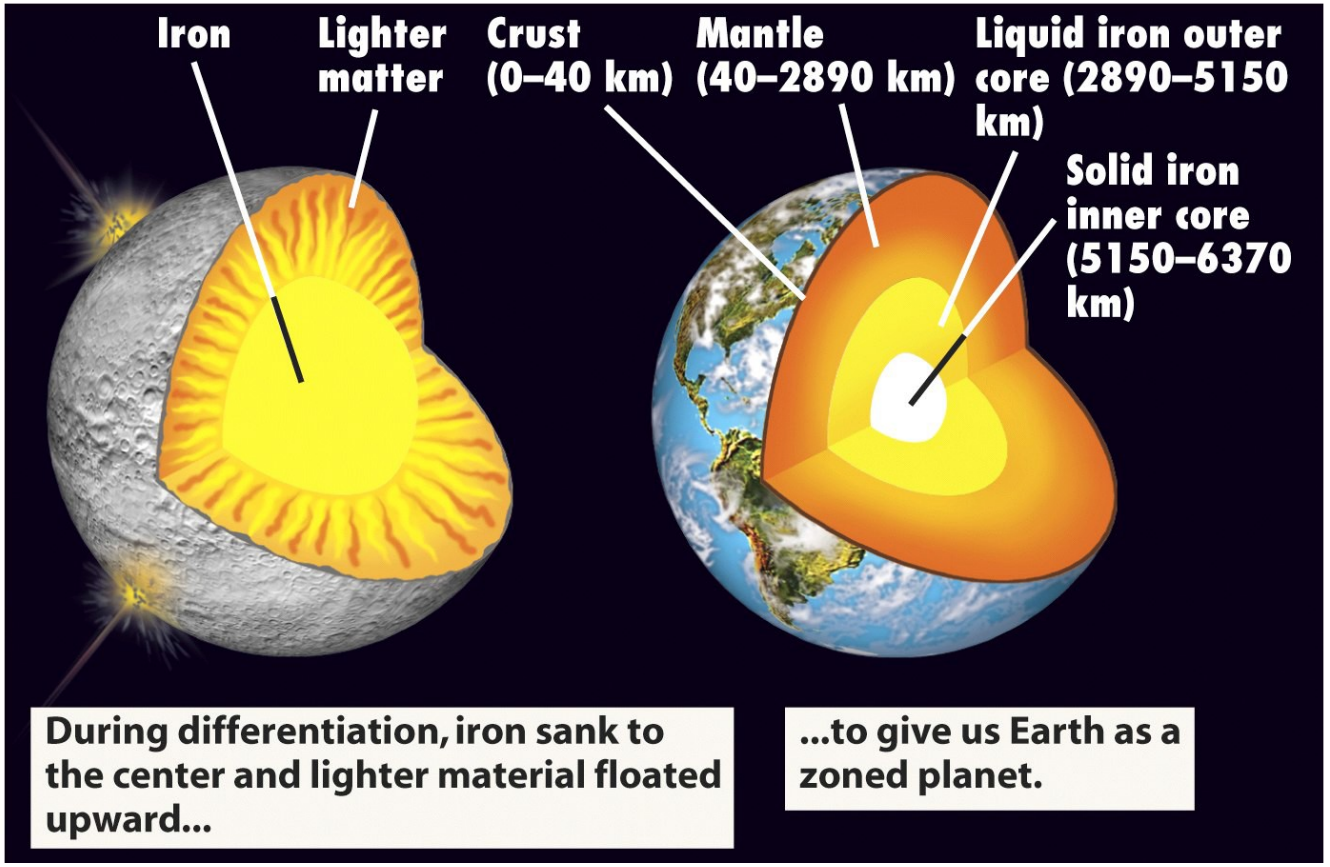


A major discontinuity at ~3000km (Gutenberg discontinuity) forming the Core-Mantle-Boundary

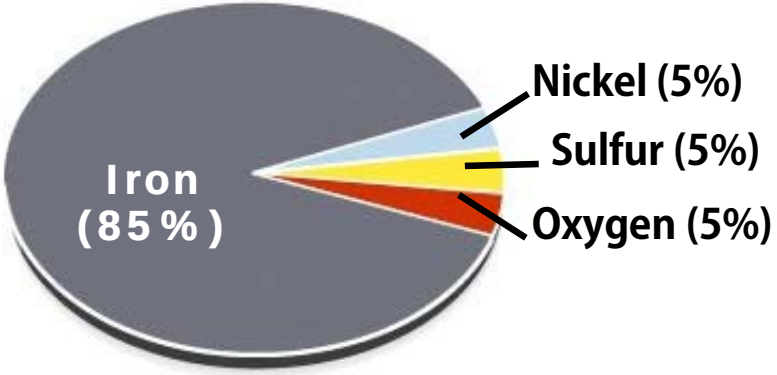
- **molten outer core/solid inner core**
- **solid mantle**
- **compositions of mantle and core are very different**

The core

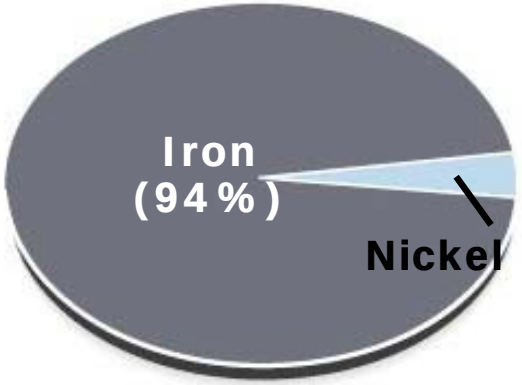
Composed of Fe(80%) + Ni resulting from the sinking of heavy elements towards the center of the Earth during the initial stages of the planet



OUTER CORE



INNER CORE

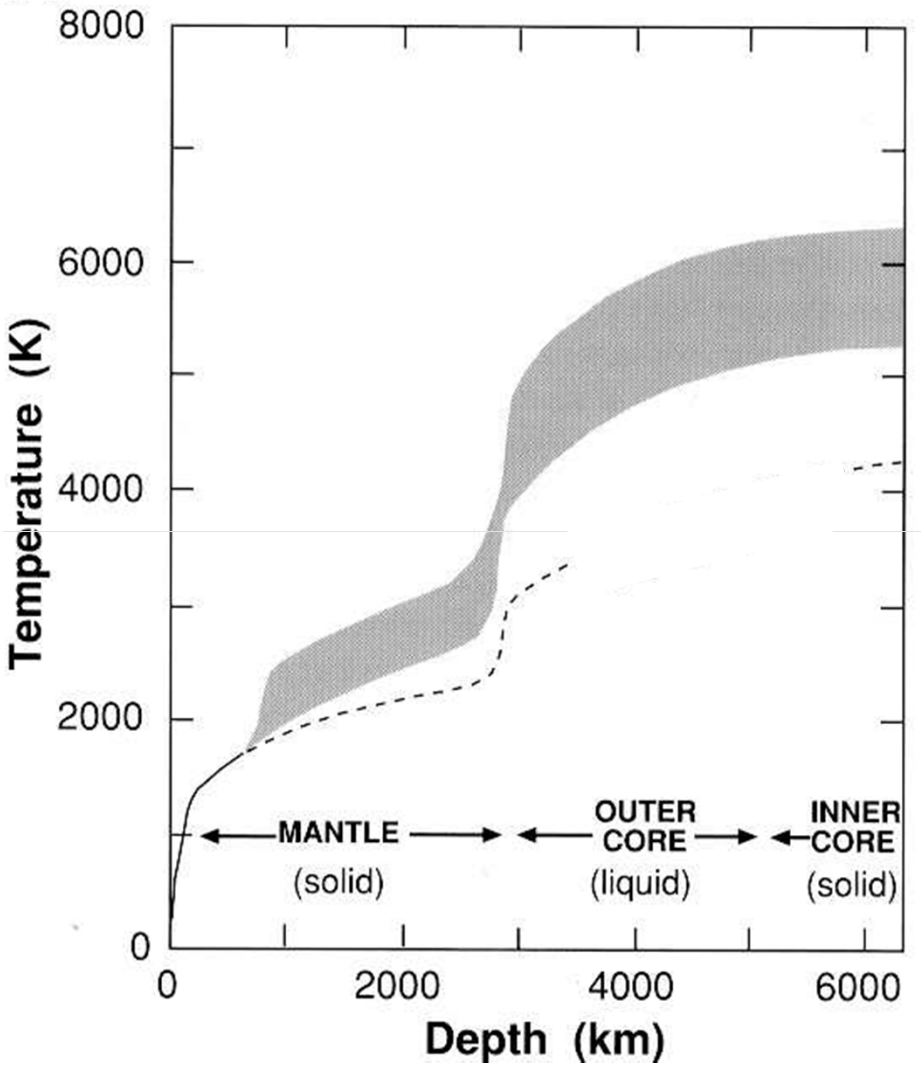


The core provides the heat and magnetic field

Heat

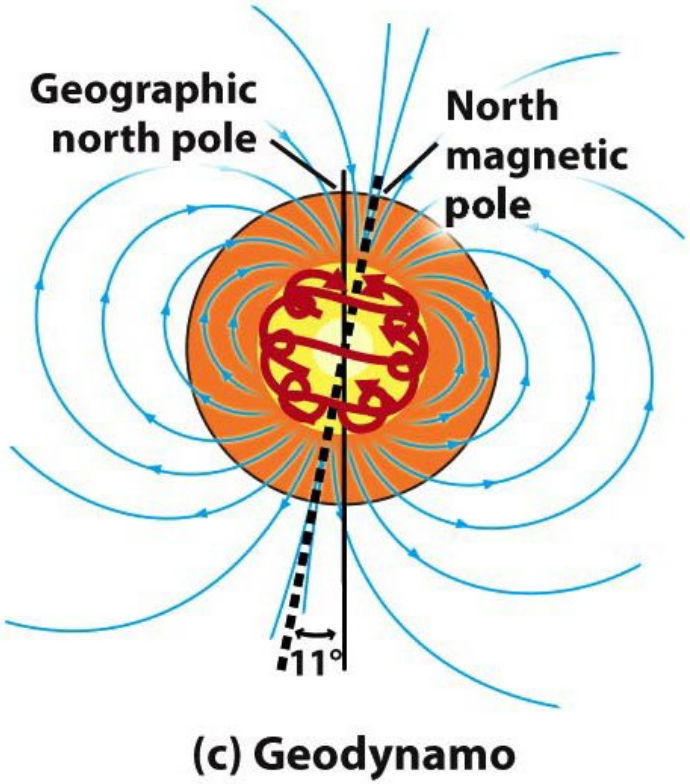
Very high T in the core; still the remnant of primary heat distributed by vigorous convective movements in the outer core

20% of the heat flow at the surface of the Earth comes from the CMB!
This is not renewable



Earth's magnetic field

Very intense movements take place in the outer core of the Earth. They are the source of the geomagnetic field

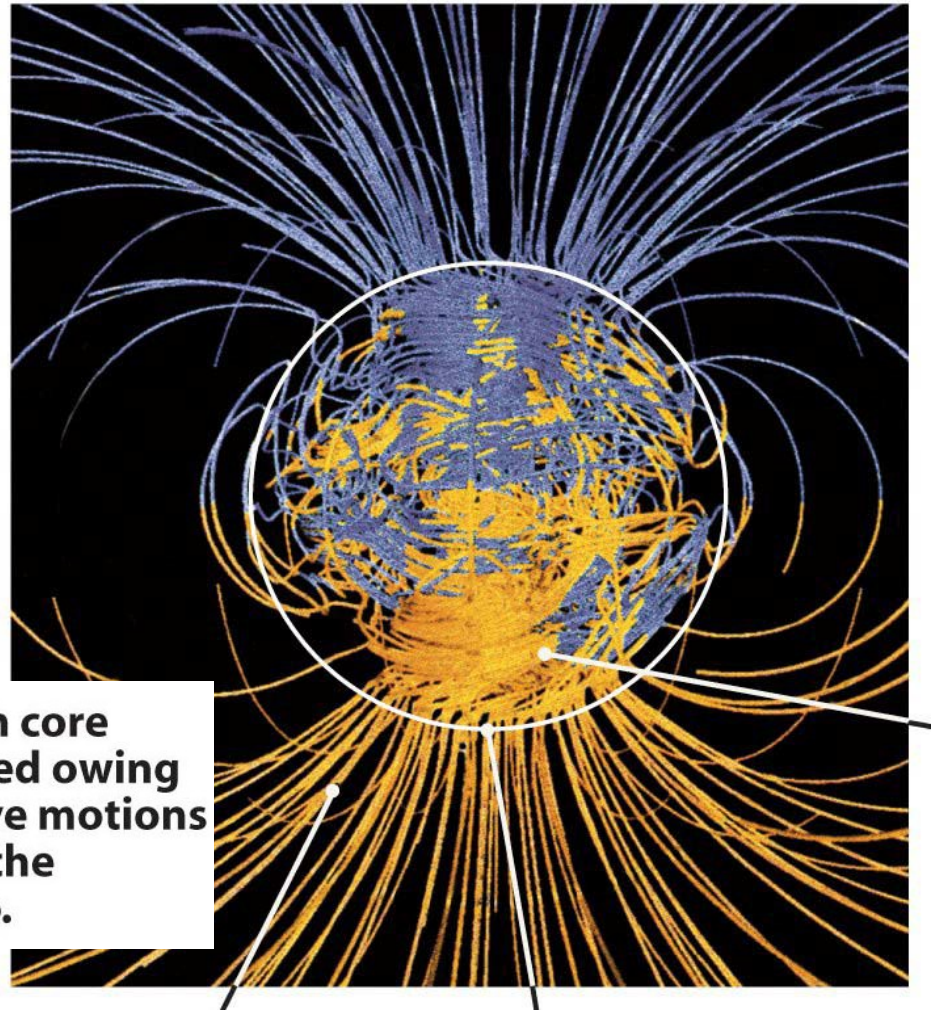


(c) Geodynamo

A simple dipole situation at and above the surface of the Earth

But inside…

Computer model of magnetic field lines



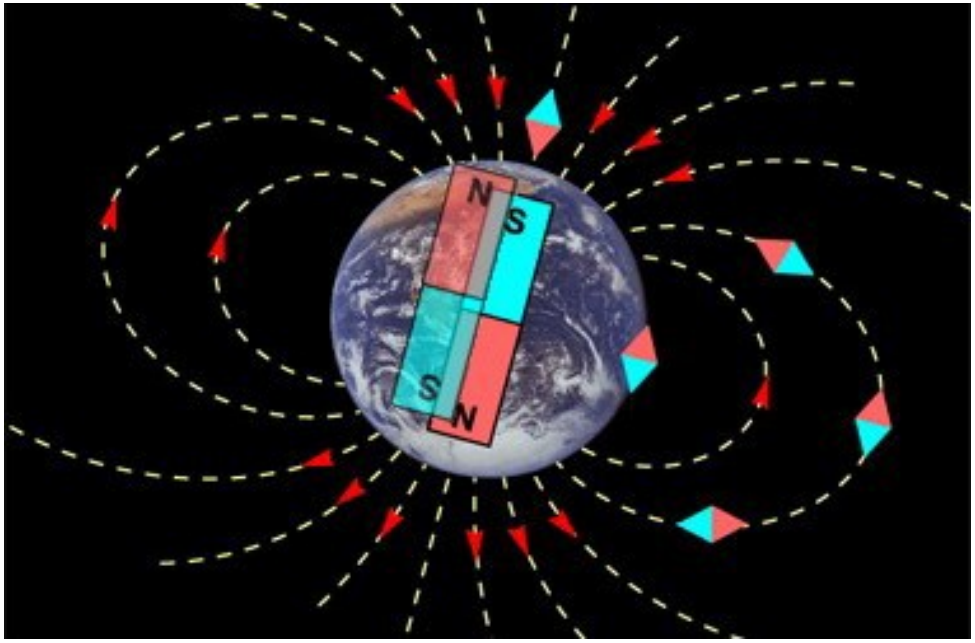
Field lines in core are entangled owing to convective motions that create the geodynamo.

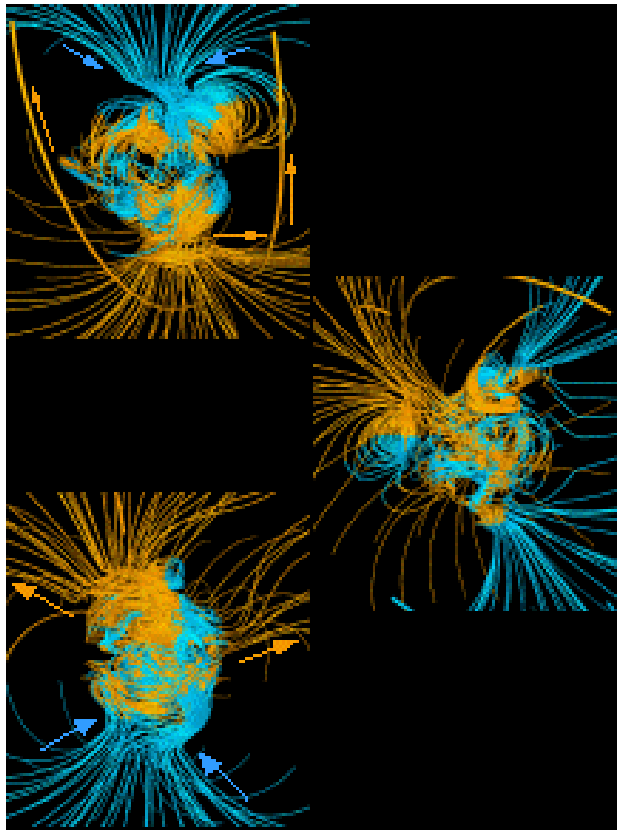
Magnetic field lines in mantle approximate those of a dipole.

Field mapped at core-mantle boundary reveals complexities in the core.

Strongly non-linear processes such as (outer core) convection cause periods of quiet separated by short abrupt changes

The geomagnetic field these are polarity reversals, when the magnetic N becomes S and vice versa.

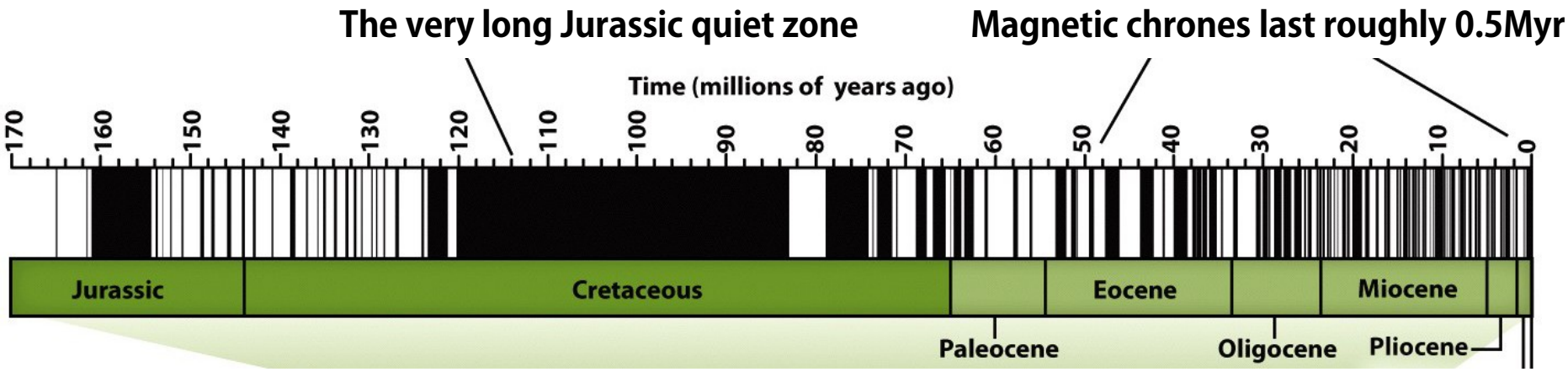




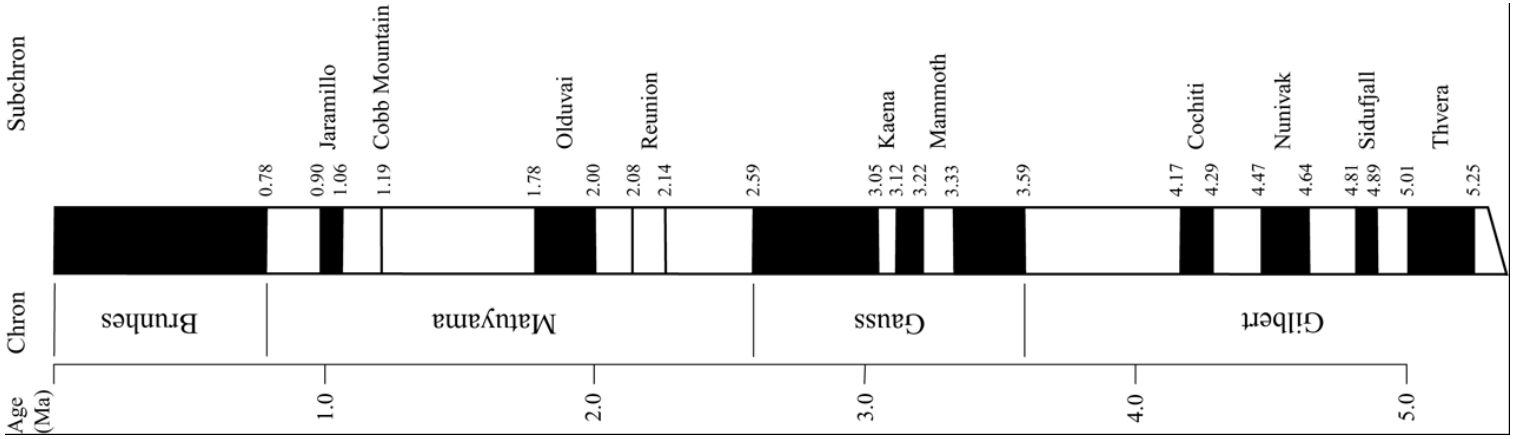
The reversals are random; therefore, also the duration of the *chrons* si random

A reversal lasts 1000-10000yr, but might be even faster

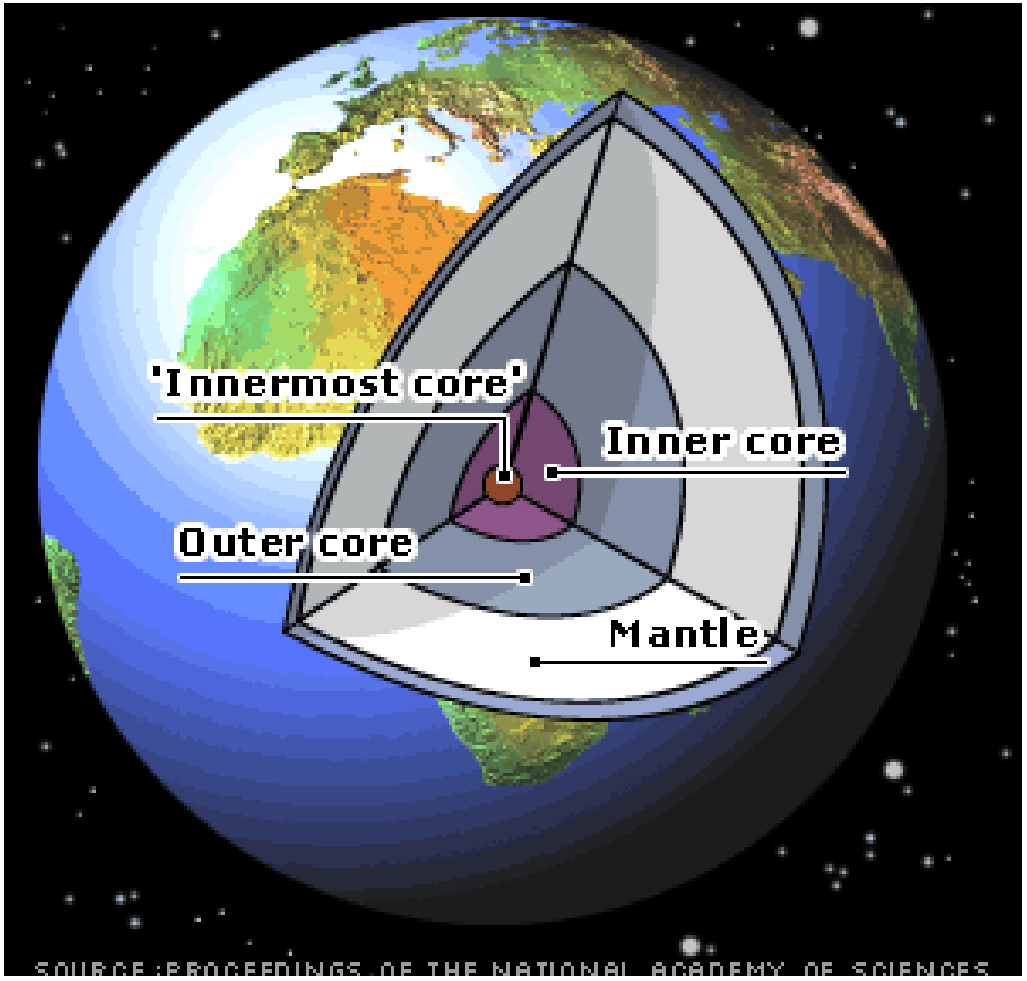
Reversals in geological history



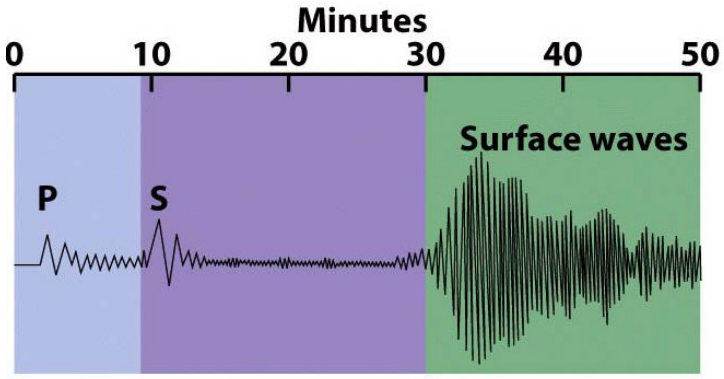
A very active situation during the last few Myr!



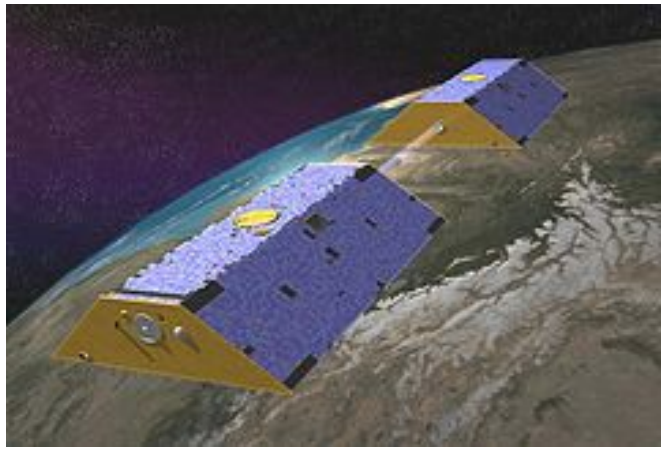
In the mantle!



Tools

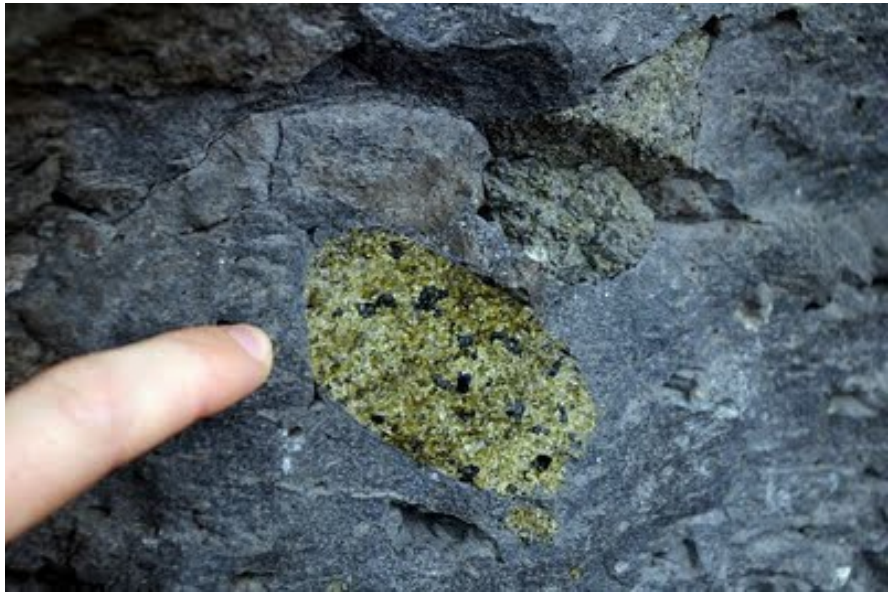


Seismics/seismology



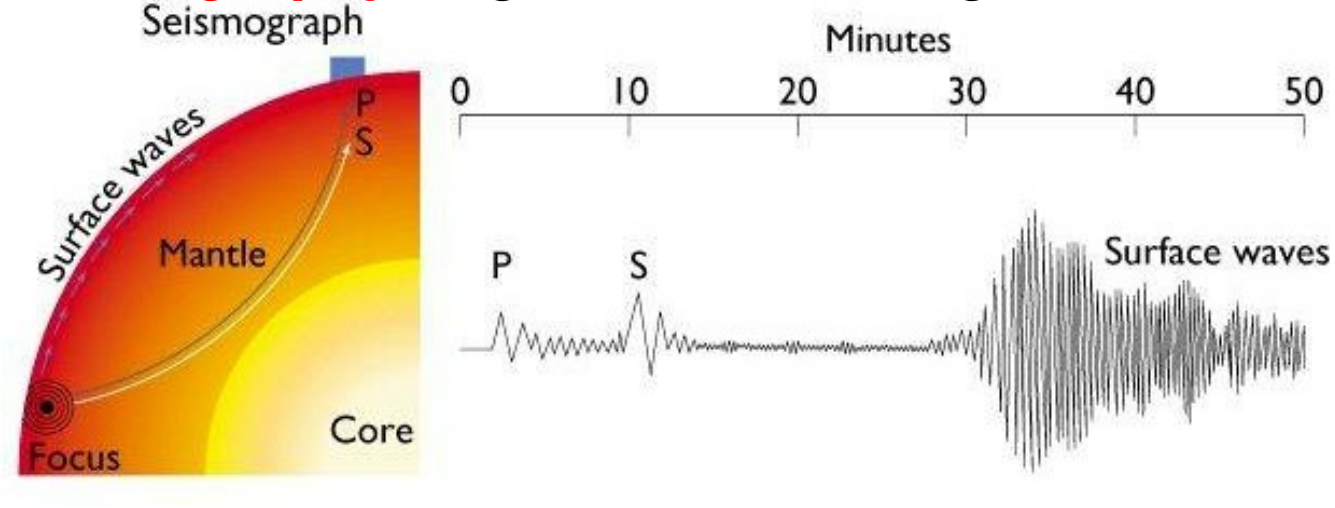
gravity

Xenoliths: fragments of very deep rocks brought to the surface by volcanoes

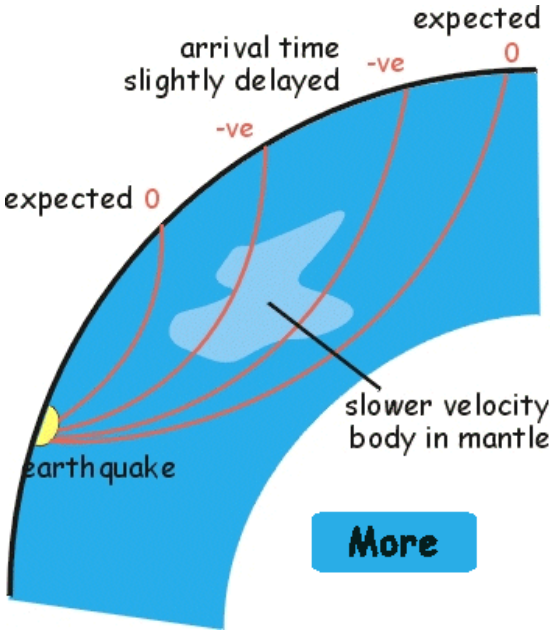


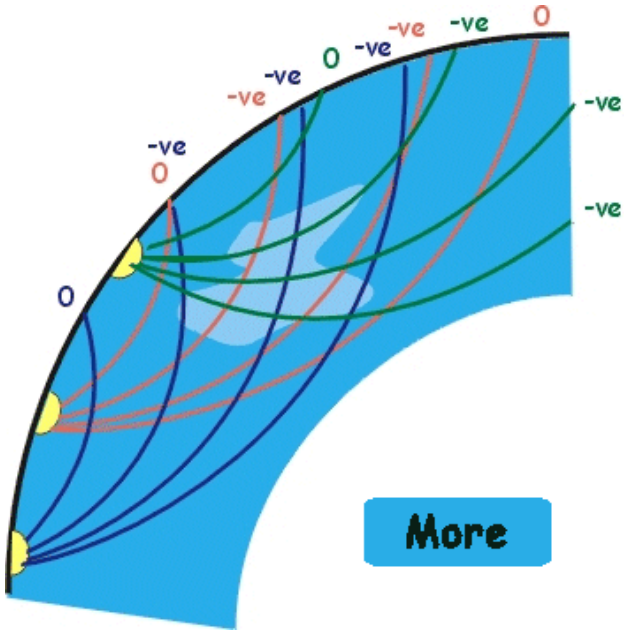
From seismic data to tomography, a great tool to image the Earth

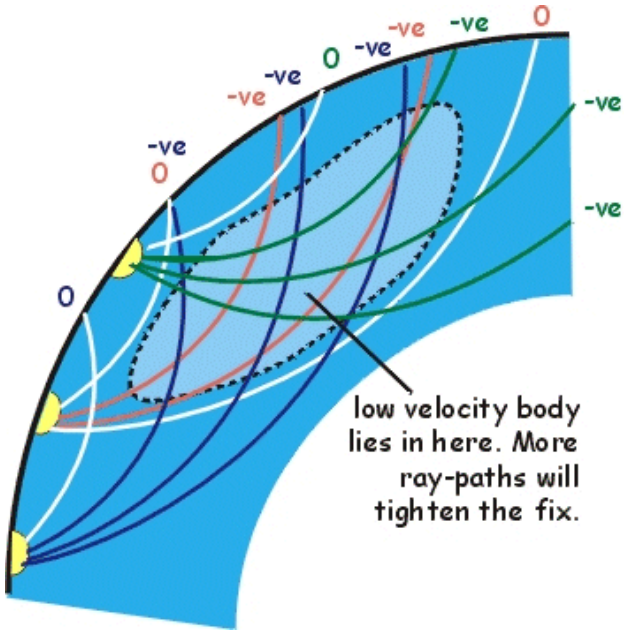
The basics of tomography (applicable at very different scales)



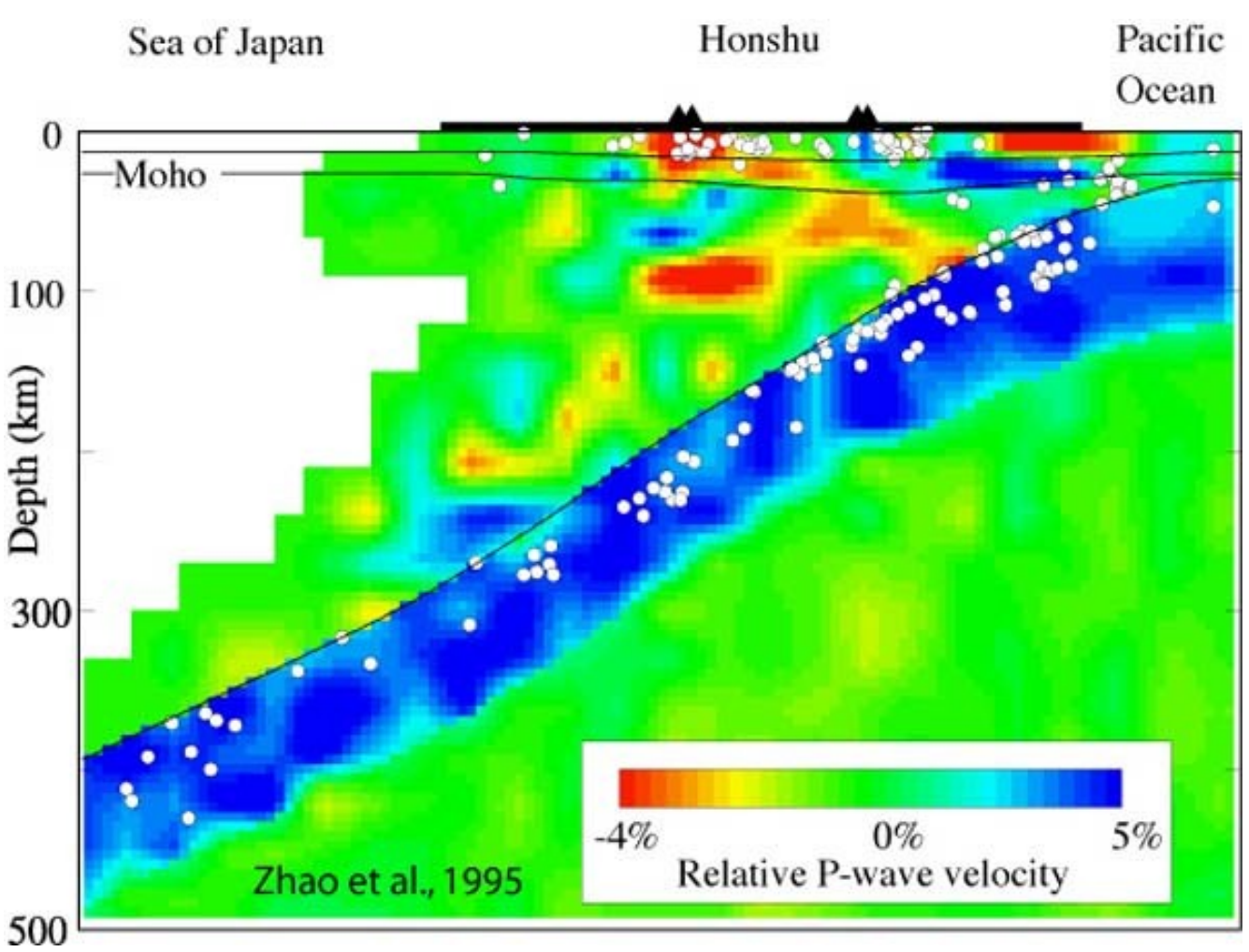
Using a large number of ray paths we determine the velocity deviations with respect to a given model





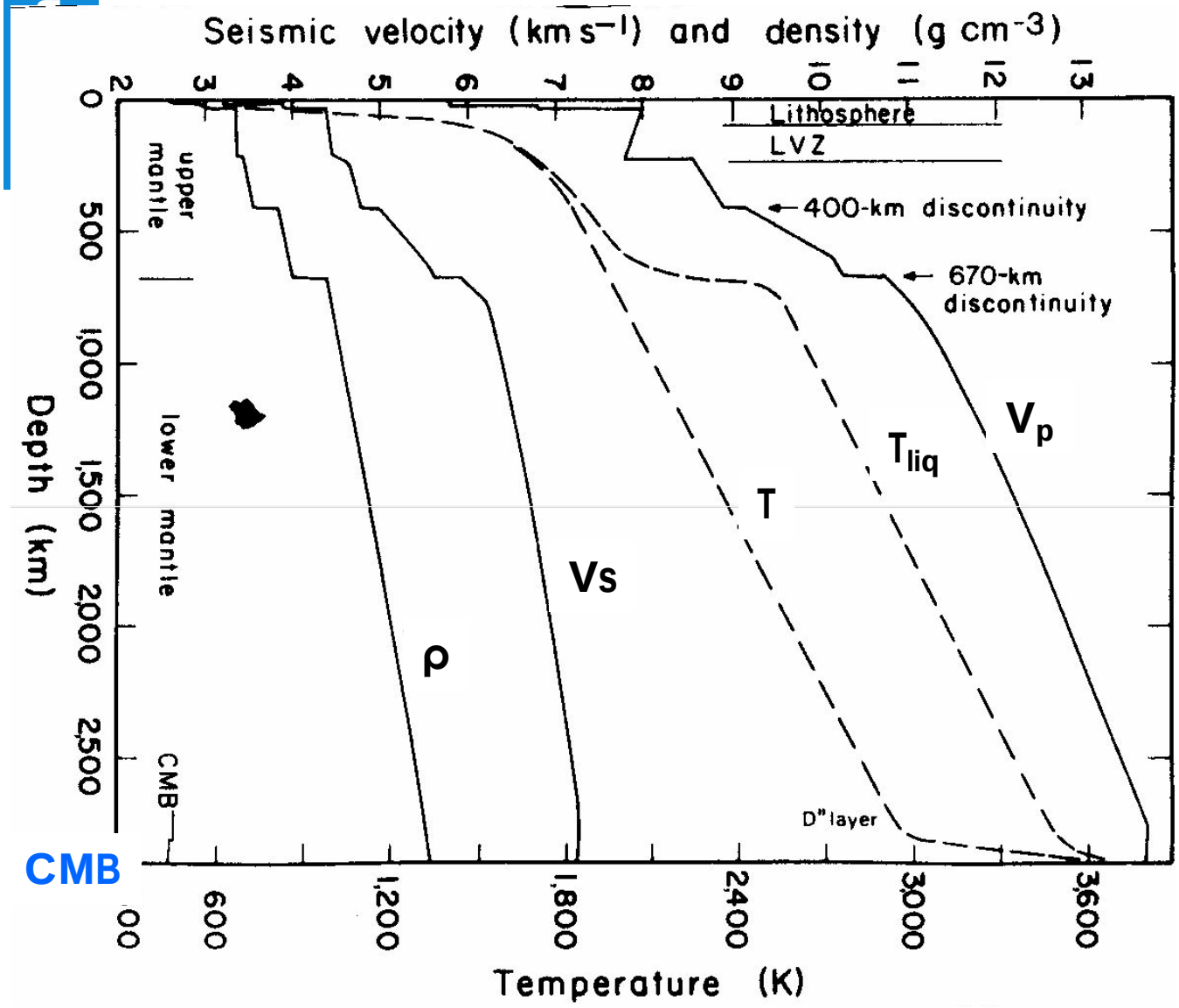


An example

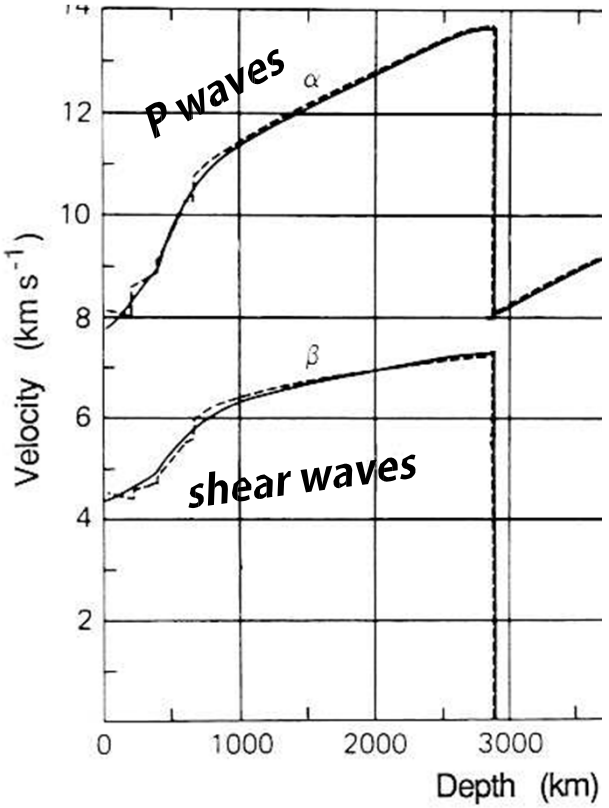


What controls the seismic velocity? What is the geological information we can extract from this data?
It is a question of temperature or composition?

The mantle: between the CMB and the base of the crust (Moho)



CMB

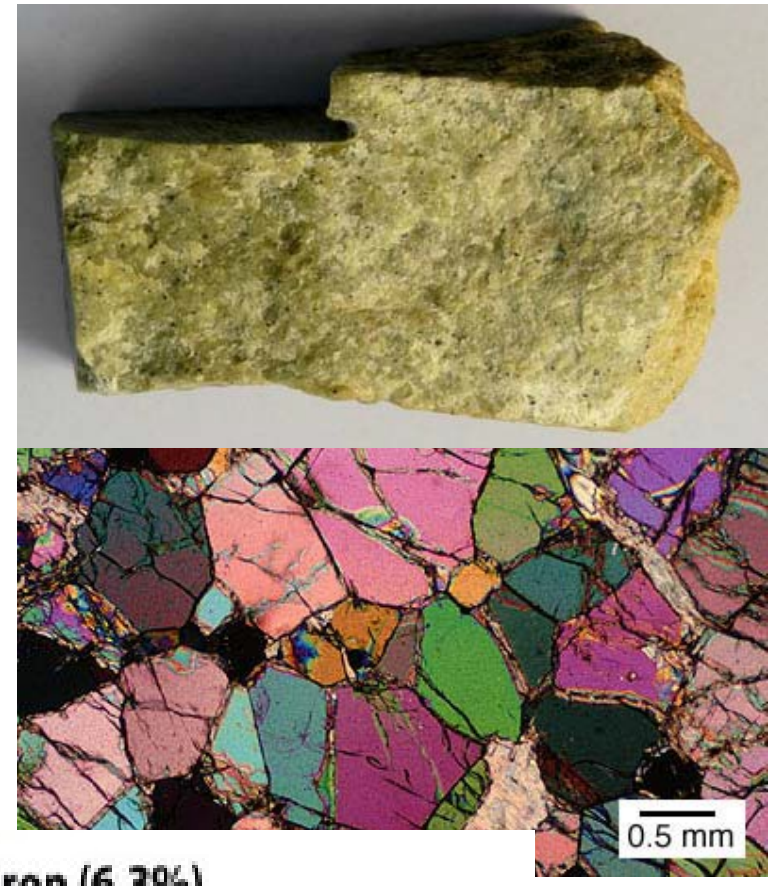


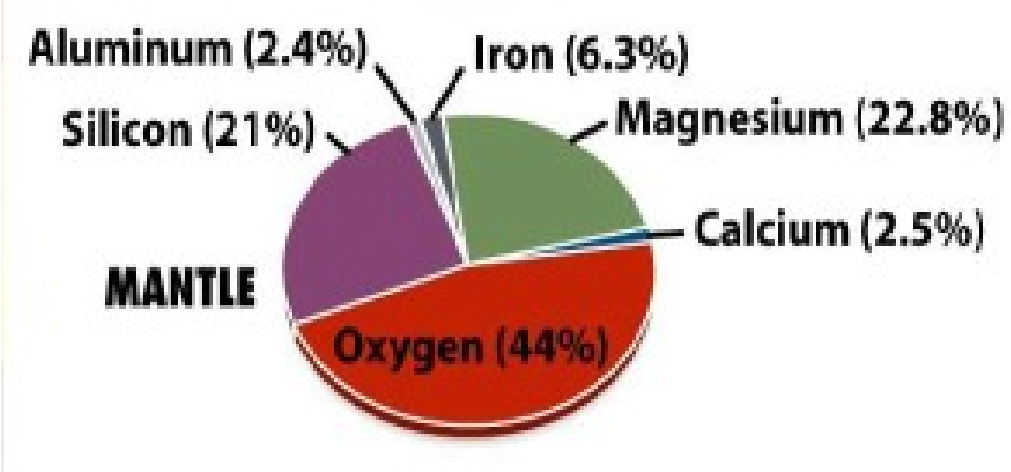
- fairly homogeneous until 670km
- weird things at 100-200km
- something very different in the uppermost few 10s of km. This is the crust

The mantle has a fairly homogeneous composition

Is composed of dunites and peridotites.

Dominant minerals are olivine and pyroxens (and their high P pahses)

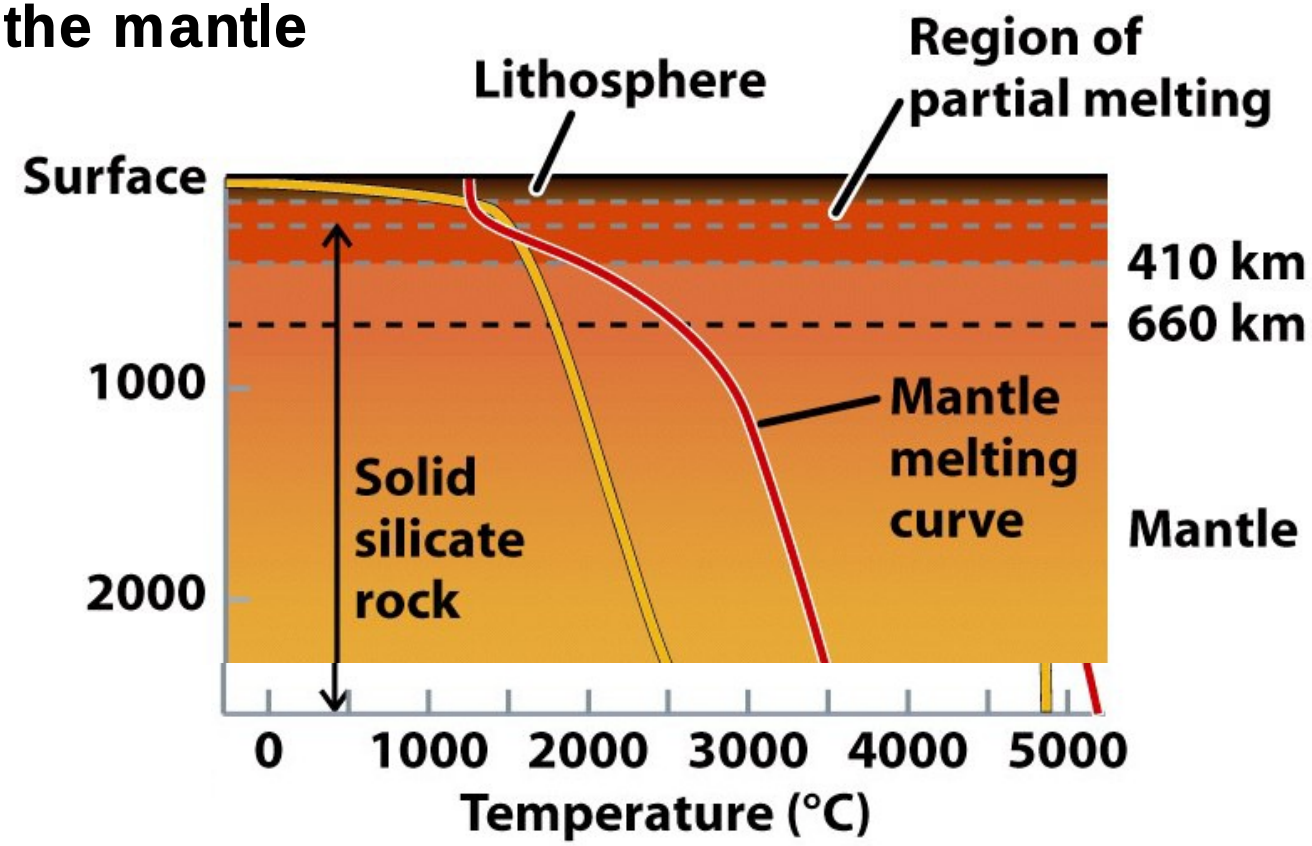




Overall chemical composition

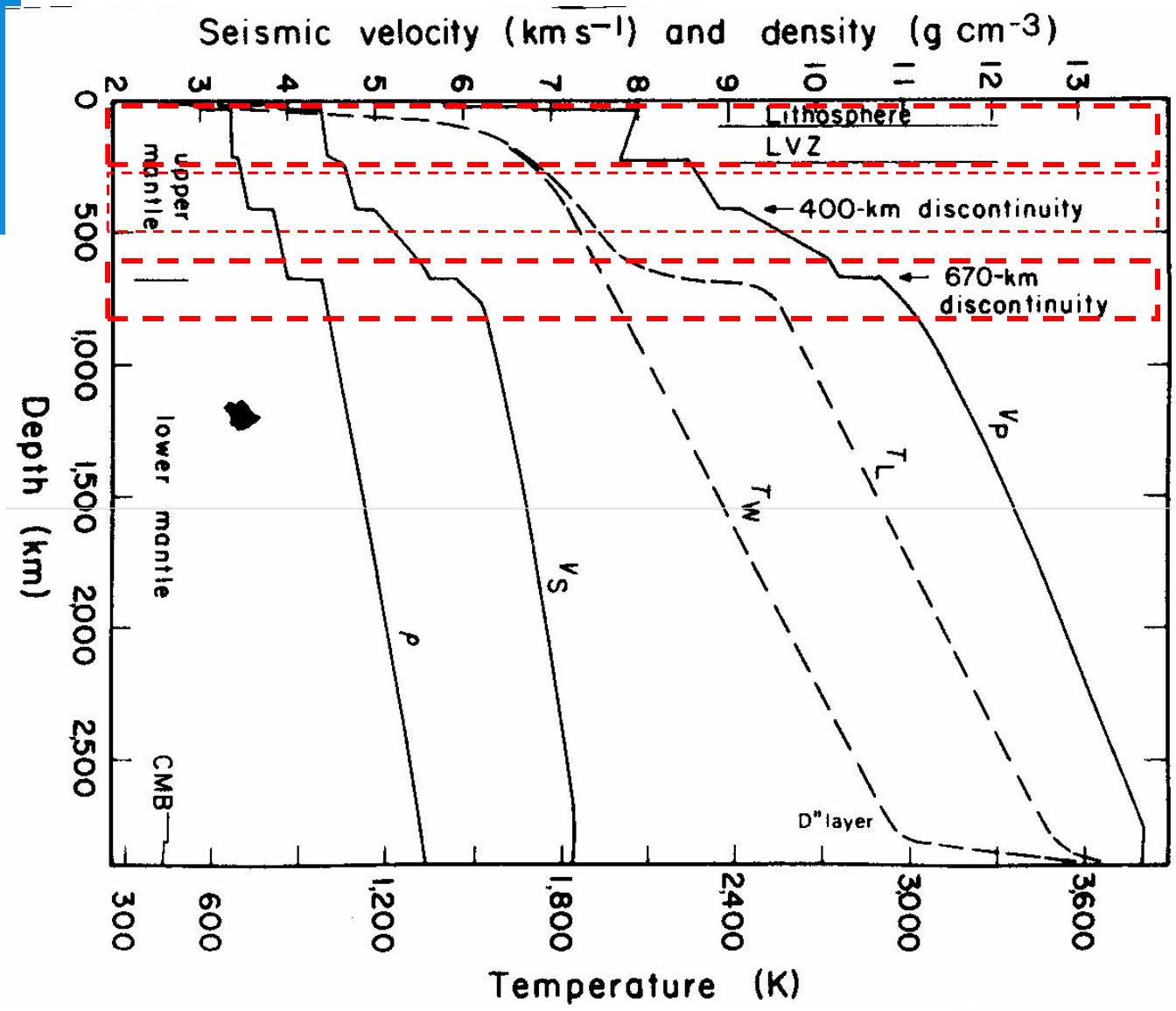
There are variations at the level of detailed geochemistry

The physical state of the mantle



With the exception of a thin interval at 100-200km depth (see later), the mantle is solid.

The mantle: fairly homogeneous but with discontinuities



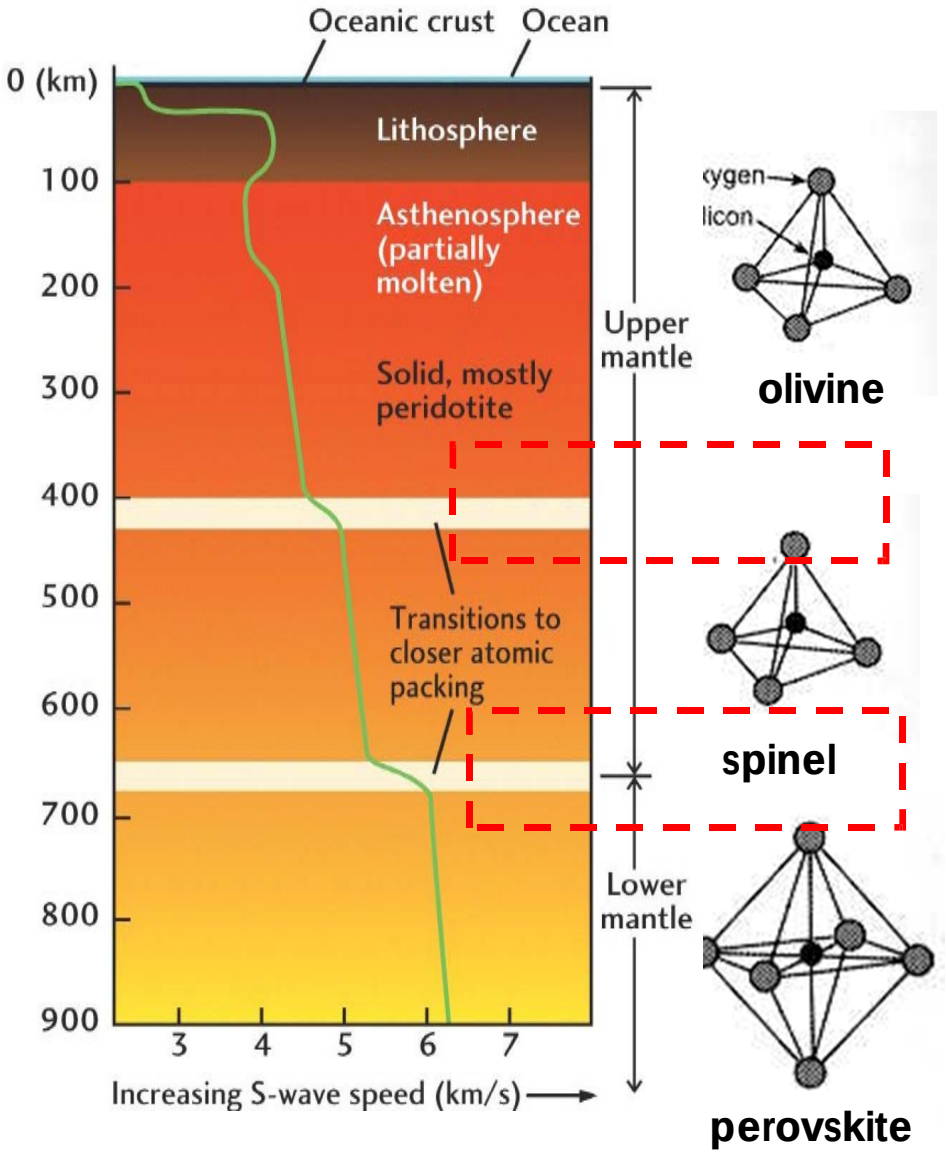
at 50-150km (very important)

at ~400km (less important)

at 670-700km

Discontinuities within the mantle

The deeper ones are crucially controlled by the state of olivine, the dominant mineral in the mantle

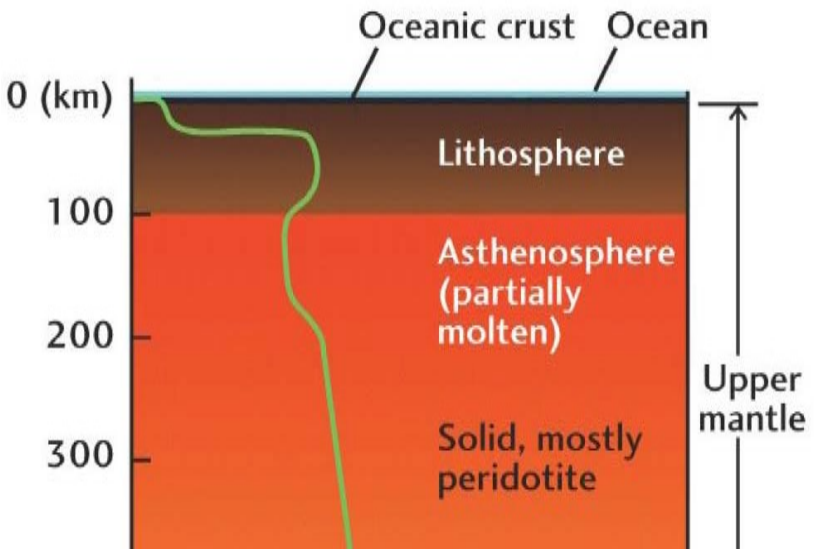


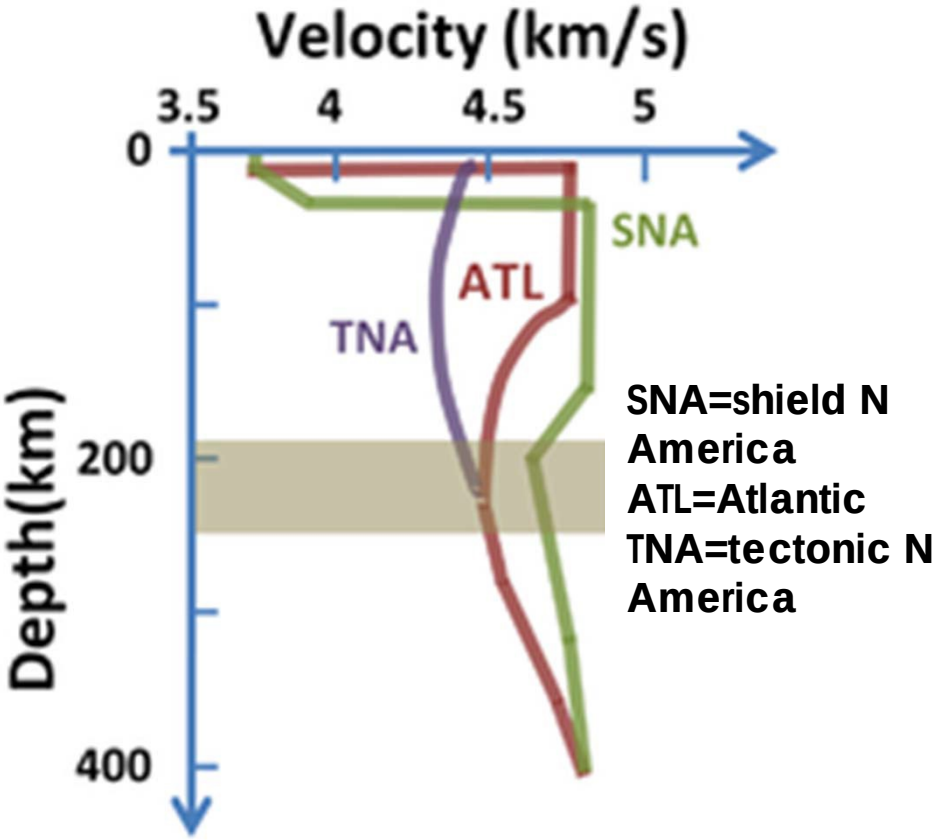
SiO_4 cells change their organization: olivine changes to β spinel with a 5-10% increase in density.

Spinel changes to perovskite, with a 10% increase in density and corresponding increase in seismic velocities

The low-velocity zone (LVZ)

In the upper part of the mantle an anomalous interval with low seismic velocities: the base of the lithosphere (LAB)





SNA=shield N America
ATL=Atlantic
TNA=tectonic N America

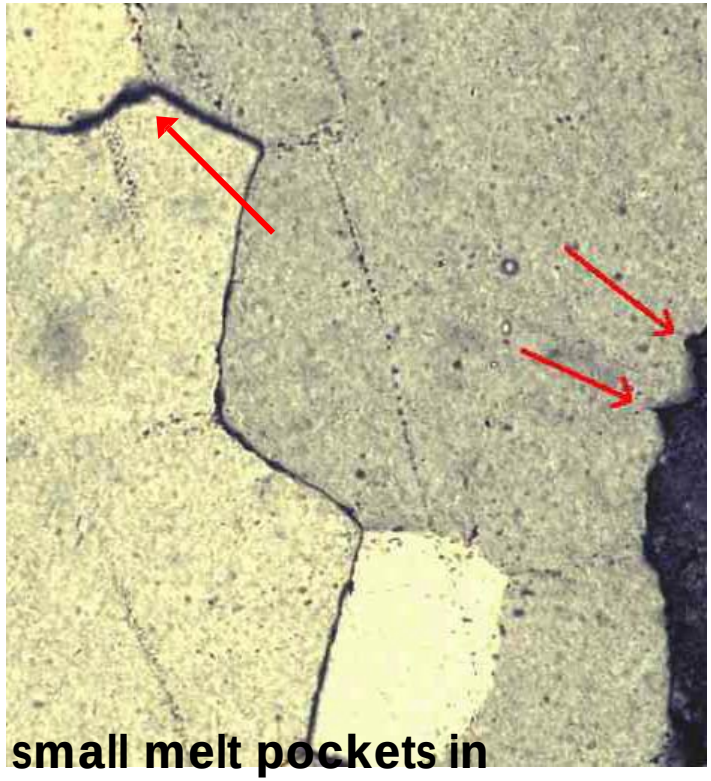
The analysis of seismic waves shows a low velocity zone at >80-100km.

The change is gradual and spread of few tens of kms

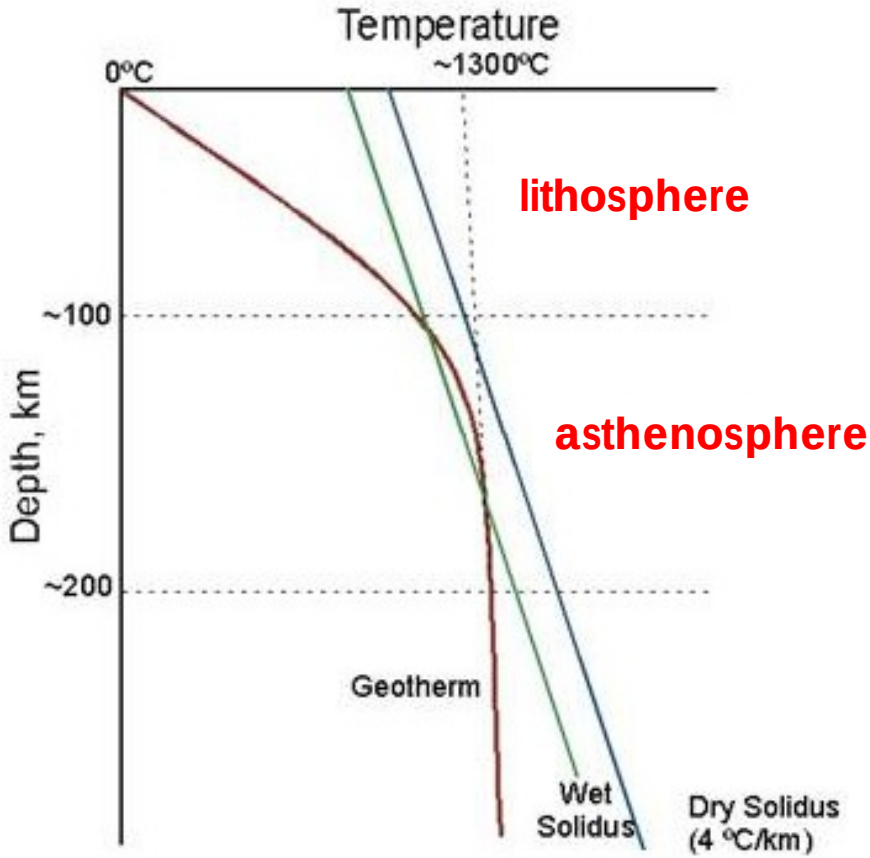
The depth and the amplitude of the transition are variable

Experimental petrology and inferred geothermal gradients indicate that this is a zone of partial melting

It is only a few % but enough to change mechanical properties of the mantle in a fundamental manner



small melt pockets in mantle rocks

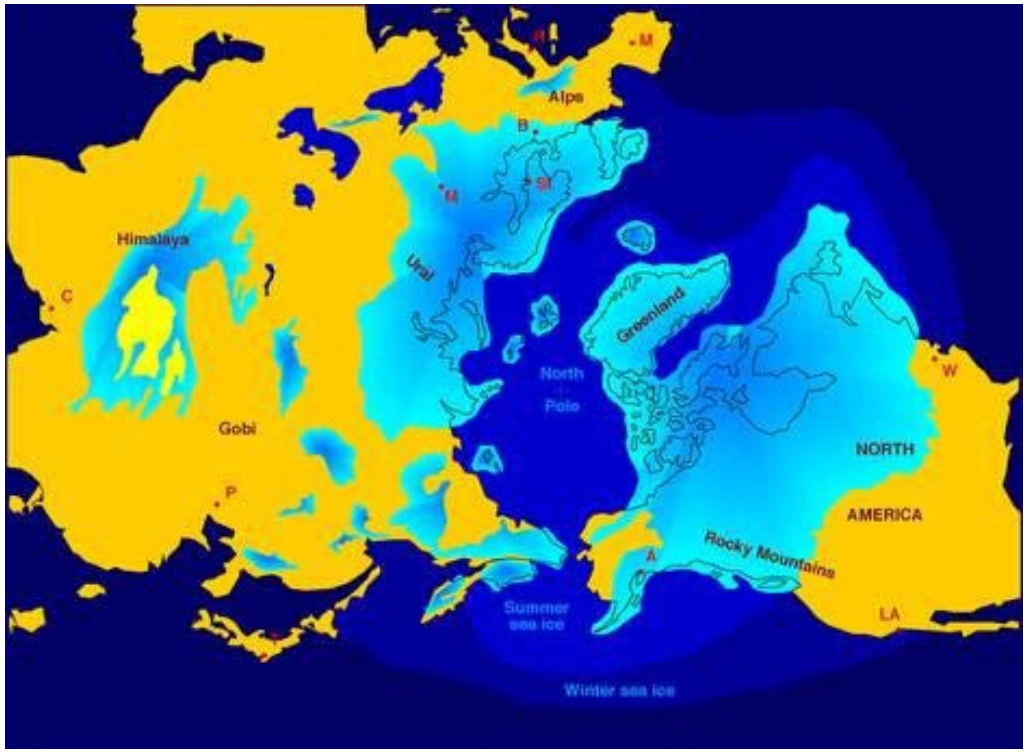


The LVZ is the asthenosphere!
What is above it is the lithosphere
(we neglect complications in the lithosphere, for the moment)

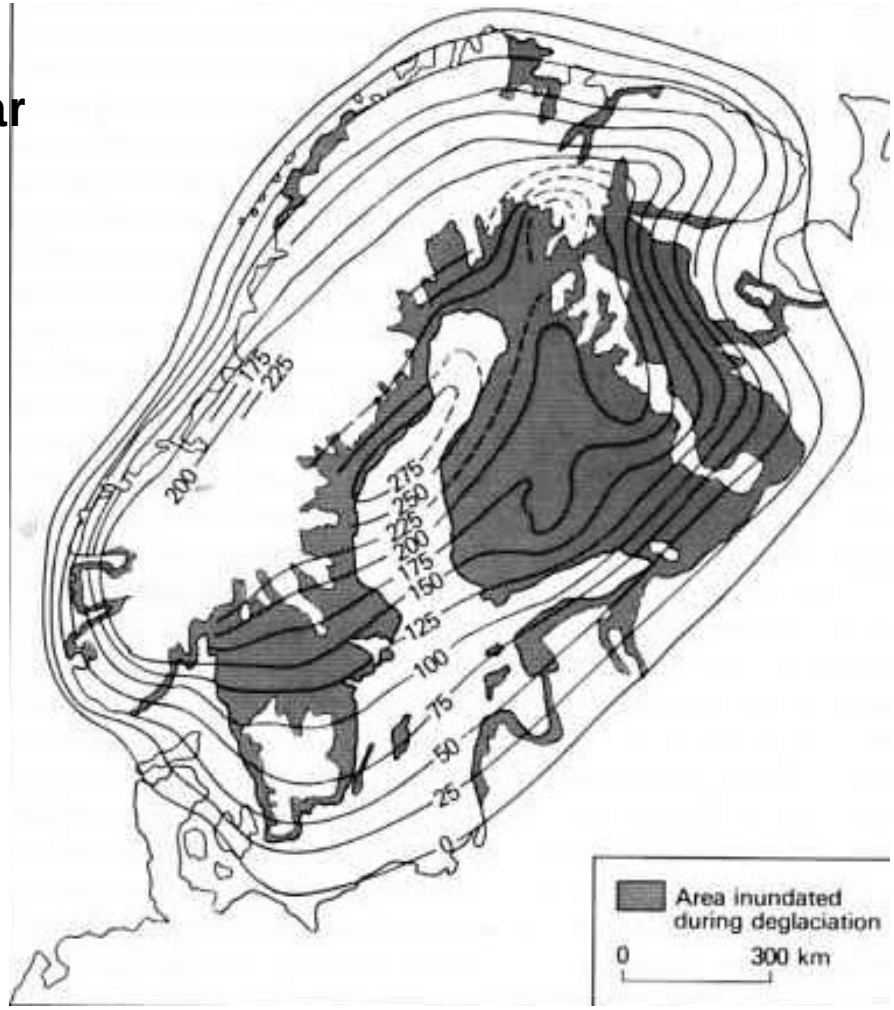
The lithosphere is a more rigid layer "floating" on rocks able to flow at higher rates

The consequences of having a rigid layer on top of a softer layer: glacial rebound

- Scandinavia is uplifting
- >200m in the last 6000yr.
- uplift rates are in the order of 1cm/year



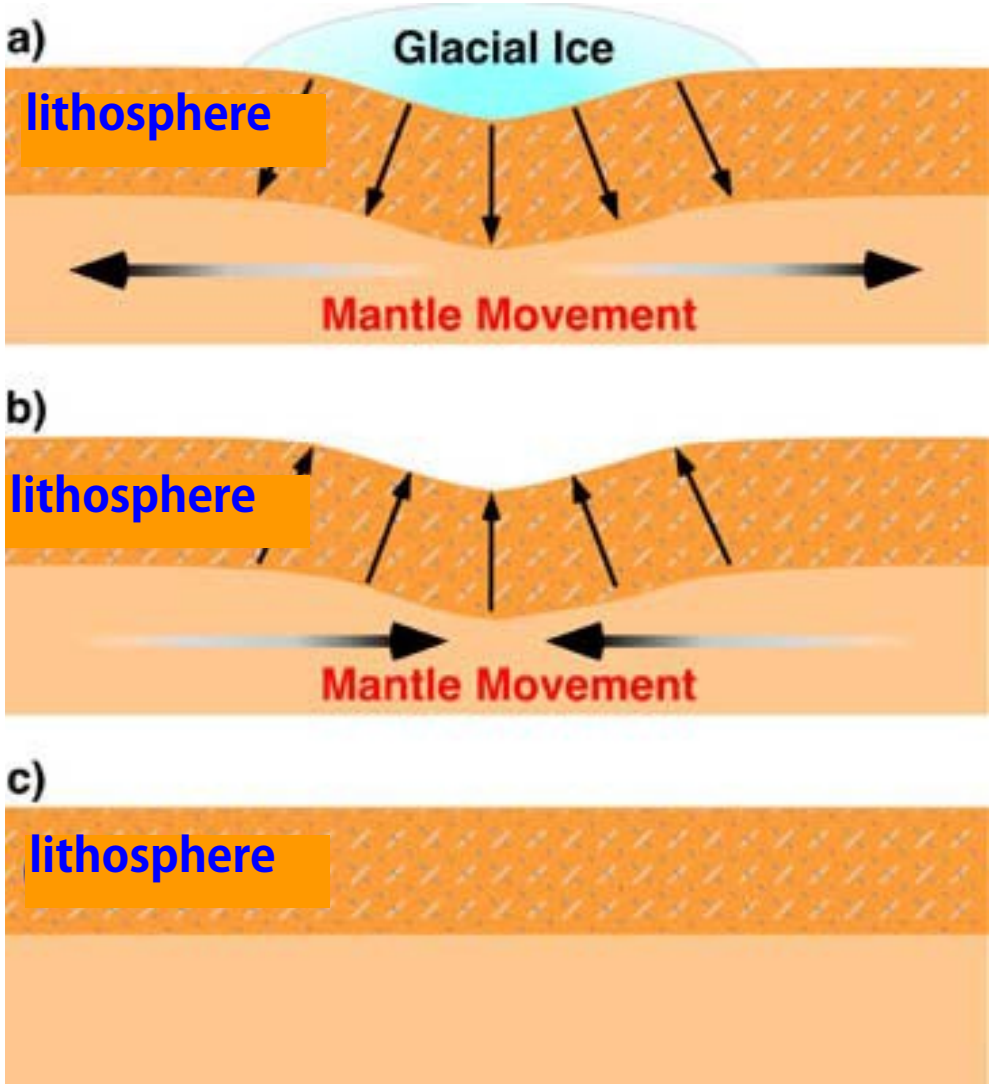
ice caps ~20.000 y ago



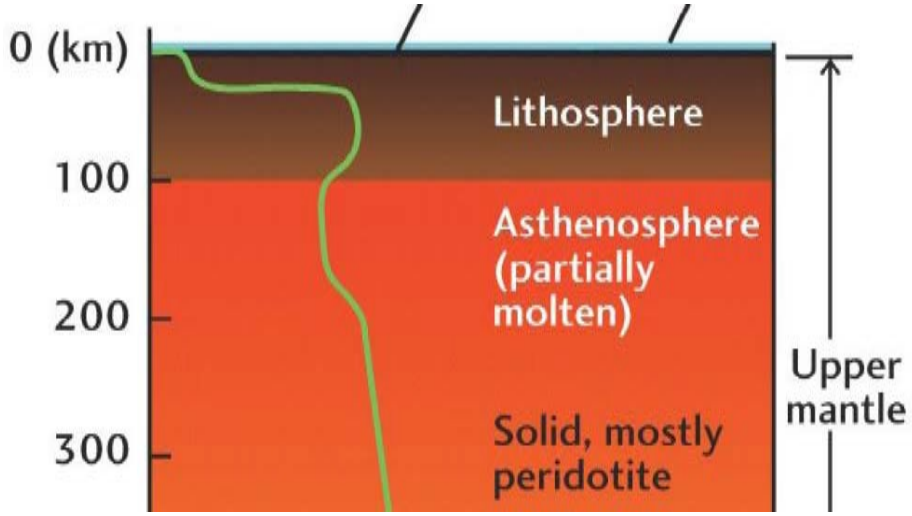
The uplift is caused by the rebound of the Erath after the end of the last glaciation (ca. 8000 years ago)

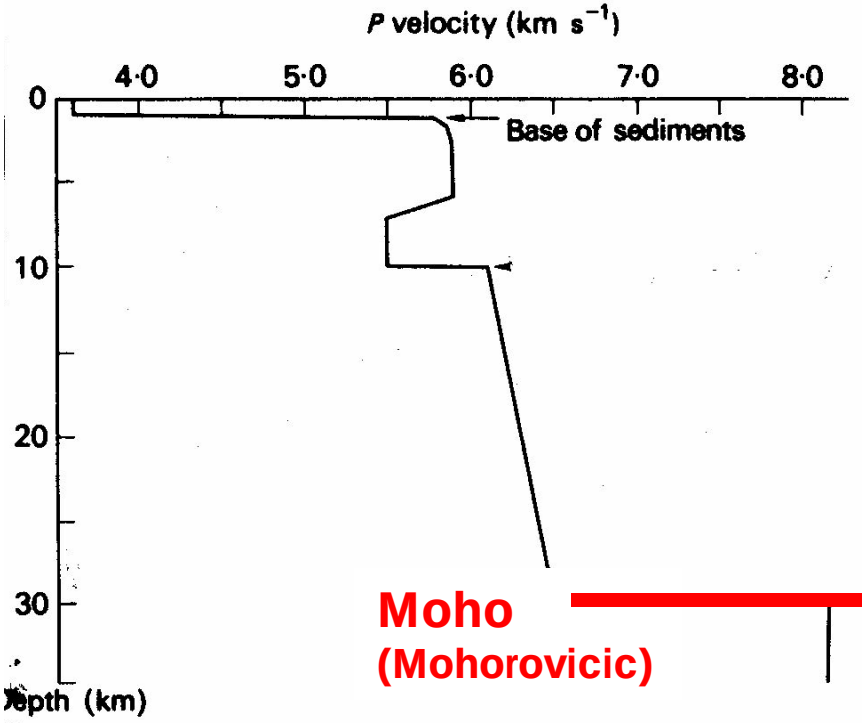
What do we need

- **a somewhat stronger layer overlying a softer layer**
- **downward movement reached a maximum**
- **upward movement continues at present even if the glaciers are not there any more**
- **In mechanical terms this corresponds to an upper "rigid" layer overlying a viscous lower layer**



Everything simple in the lithosphere?



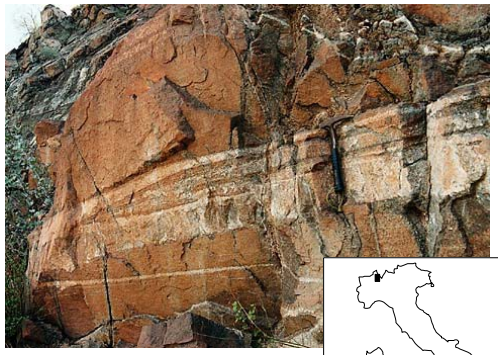


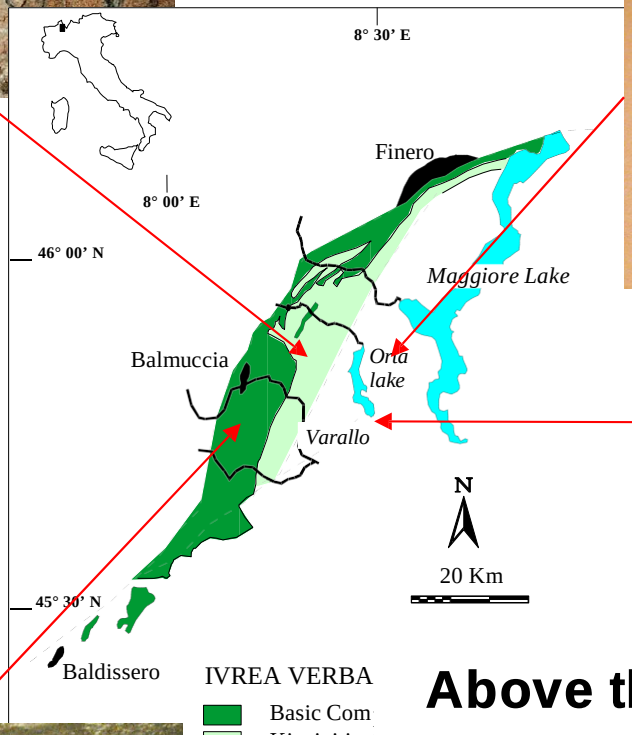
An upper part (30km in this case) with low seismic velocities

a sharp decrease of velocities (moving upward) (different from the LAB)

A lower part with high seismic velocities

In some localities the Moho is exposed!



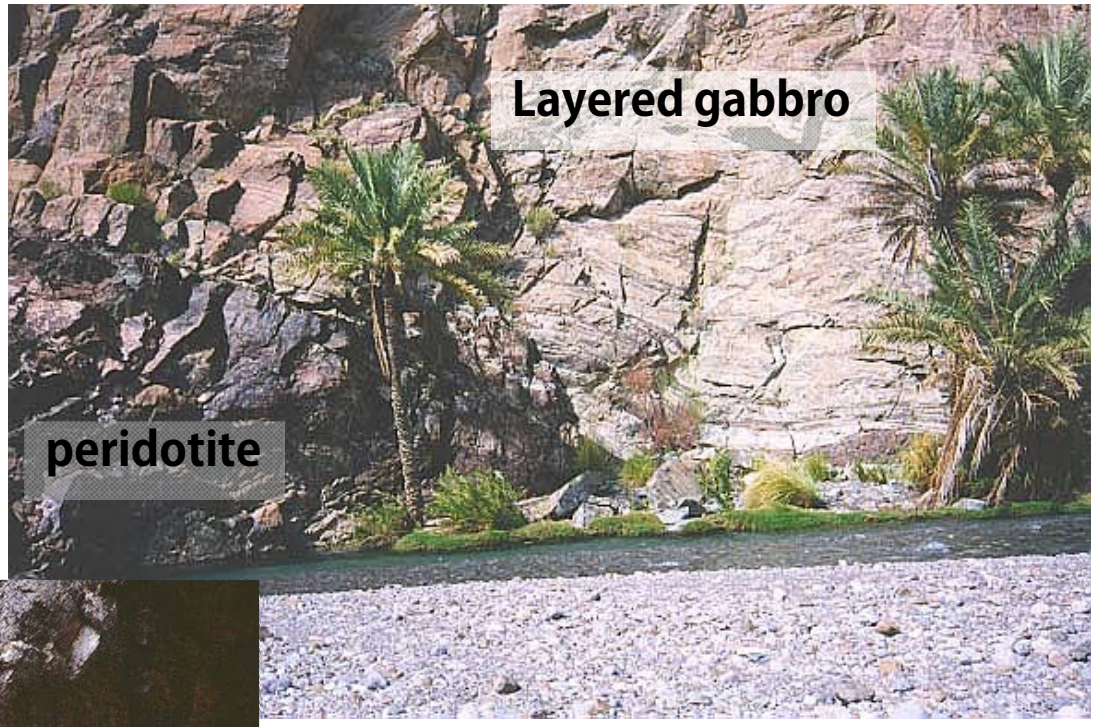


Above the Moho, gabbros and metamorphic rocks (light and slow)

Beneath the Moho homogeneous peridotie (heavy and fast)

The Moho is a material boundary, that is, a thin zone which separates different kinds of rocks!

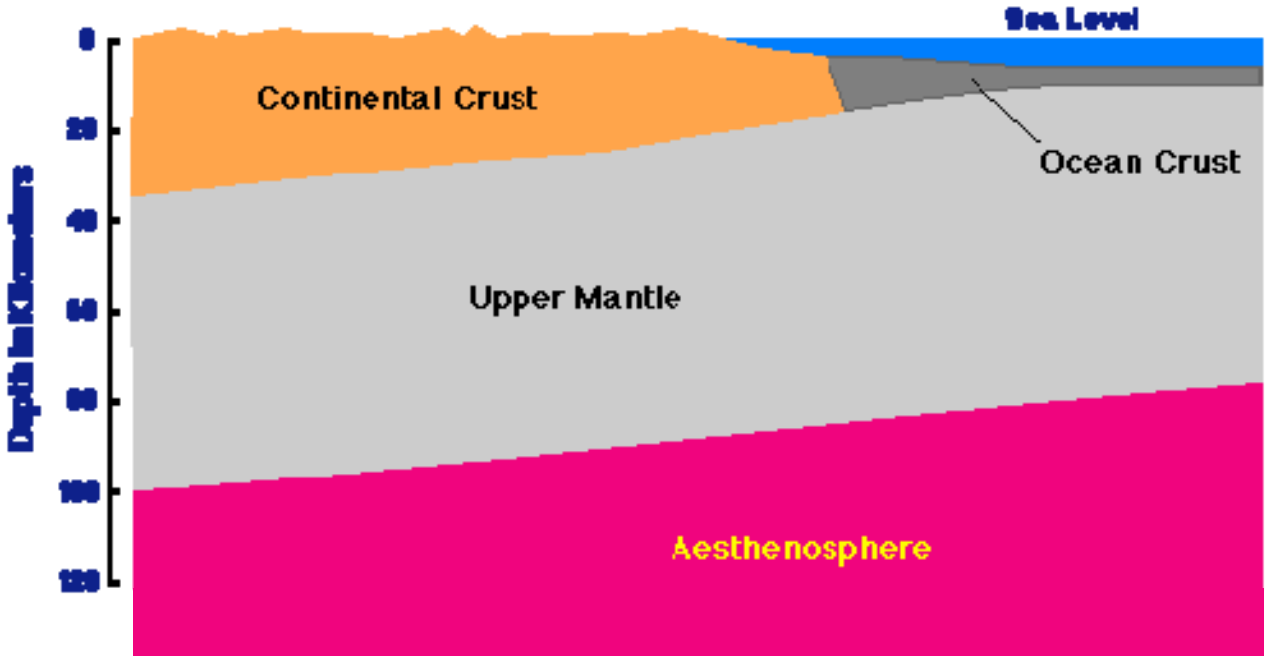
The Moho in Oman



The Moho:
harzburgite in contact with layered gabbro

Above the Moho, the crust

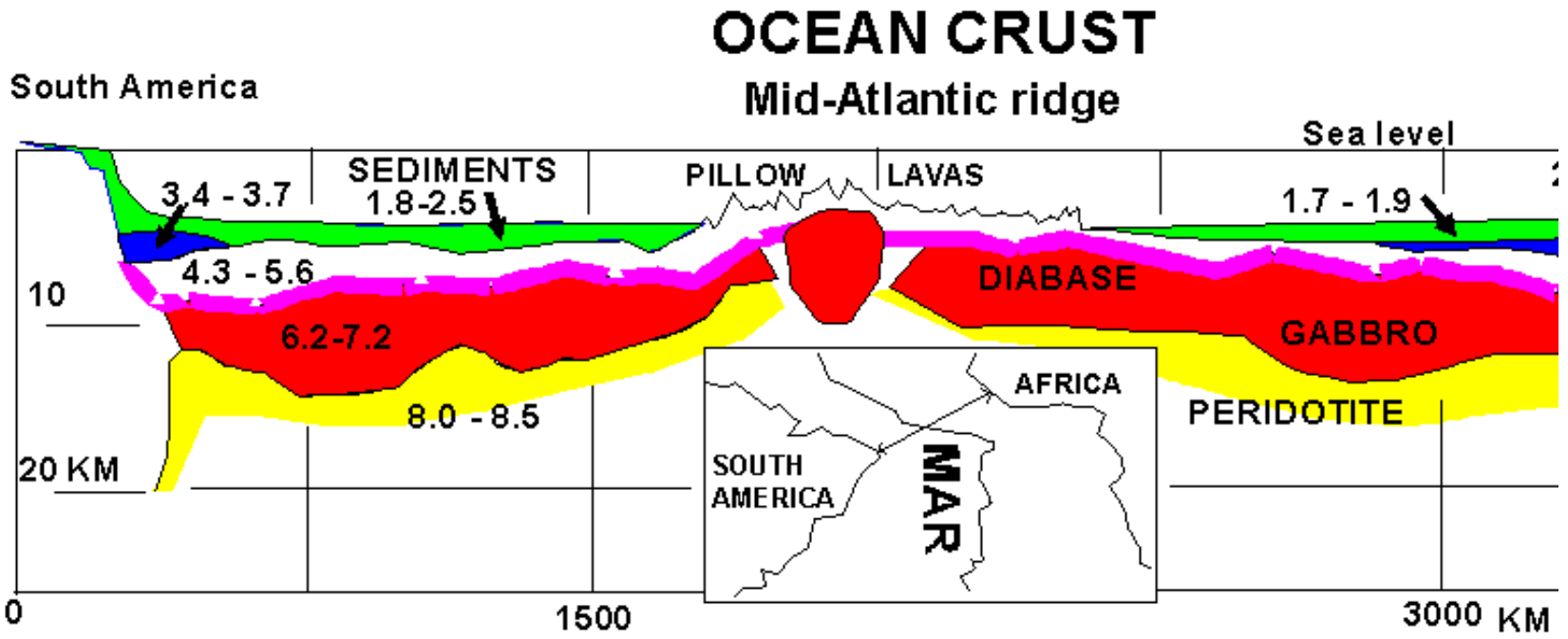
Two very different types of crust: the continental and oceanic crust



NB: Oceanic and continental crust can lie on the same lithospheric mantle.

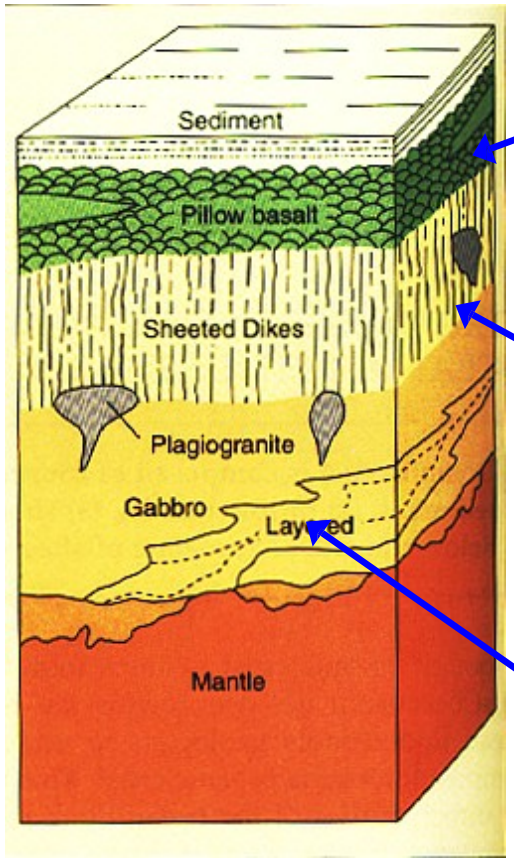
The oceanic crust

- Simple structure of three layers: sediments, basalts and intrusive rocks (gabbros)
- thickness is very homogeneous (beside near the ocean ridges)
- no oceanic crust older than 180Myr



Warning: the geologic definition does not coincide with the geographic one: you can have sea on continental plates (e.g. the NL) and, rarely, oceanic crust forming emerged lands

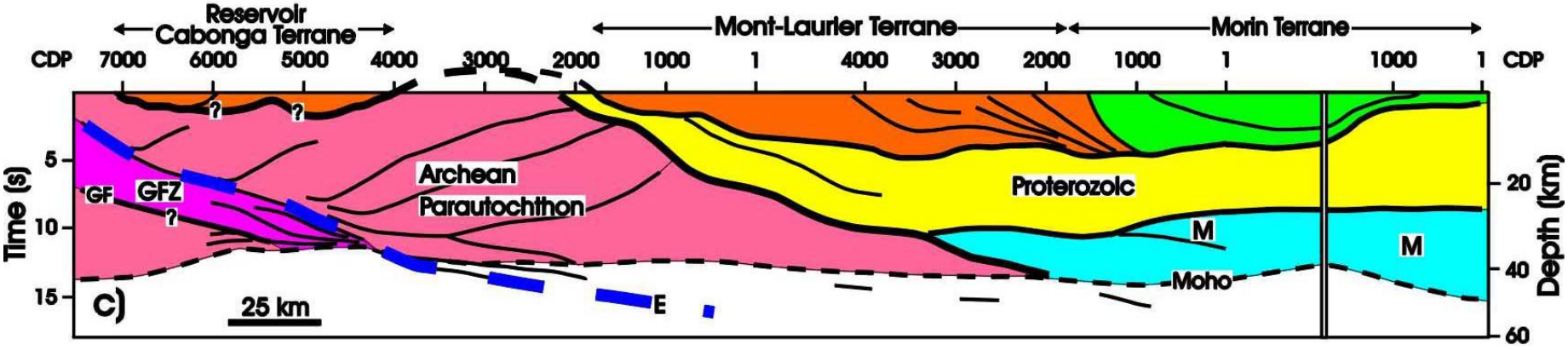
Some details



We will see later how this is formed

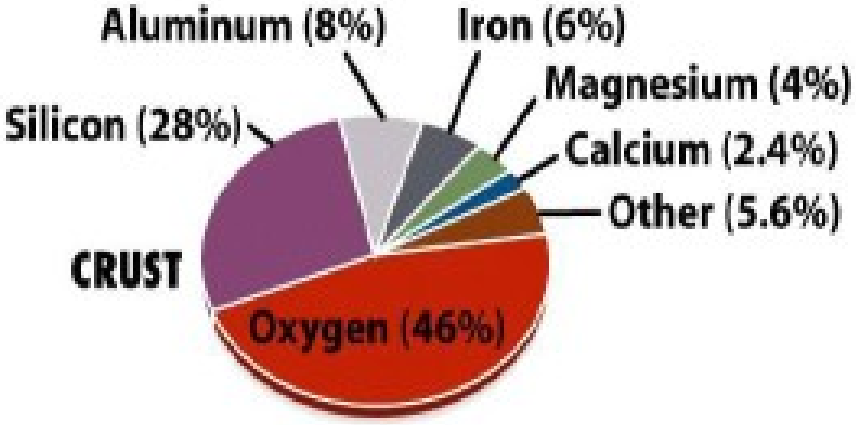
The continental crust

A very complex internal structure

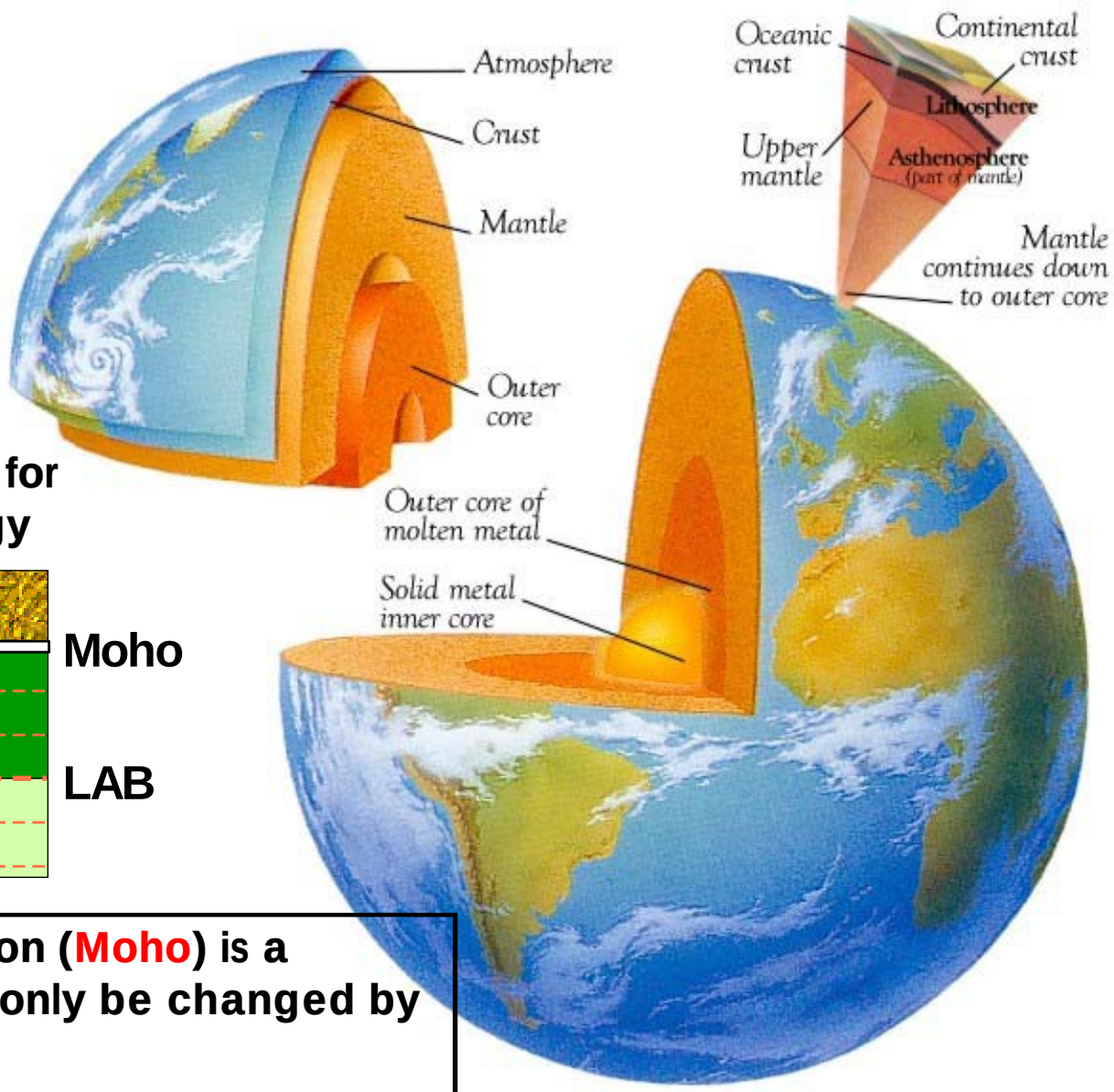


Variable:

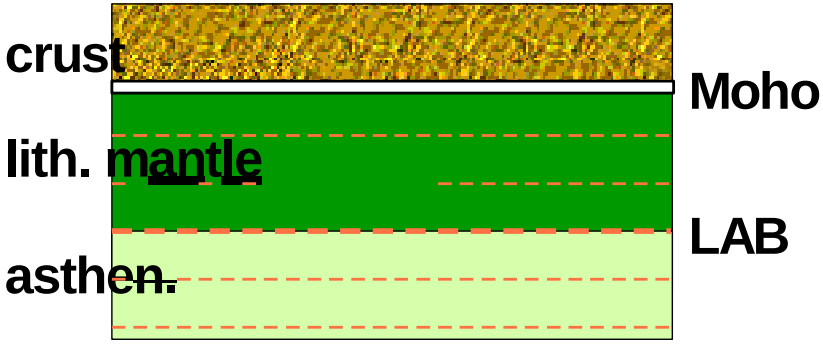
- **Thickness** (from ~10km to >60km)
- **Composition** variable but in general silica-rich
- **age** of rocks (up to >3.4Gyr)



A summary



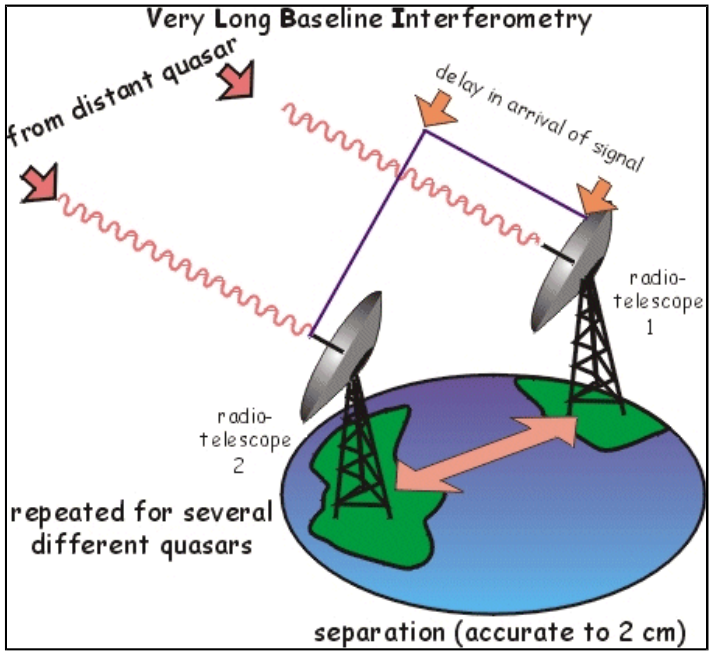
The lithosphere: a major element for fundamental and applied geology

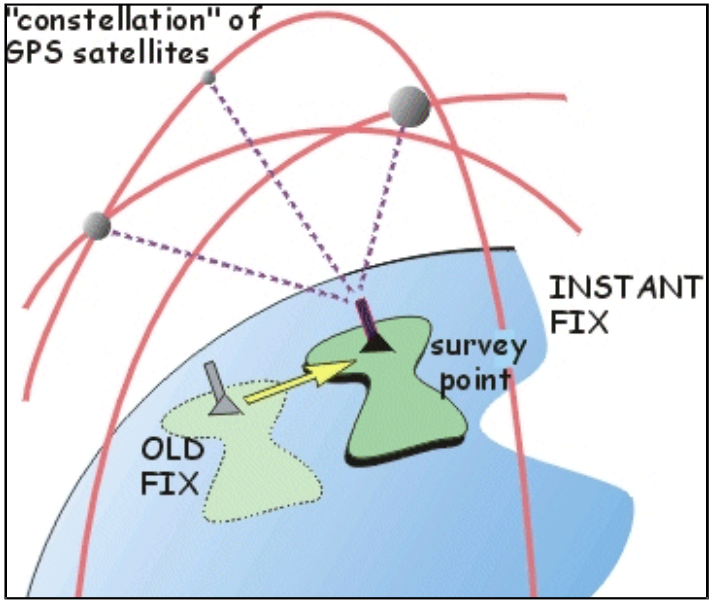


The crust-lithospheric mantle transition (Moho) is a material boundary. Its position can only be changed by thickening and thinning

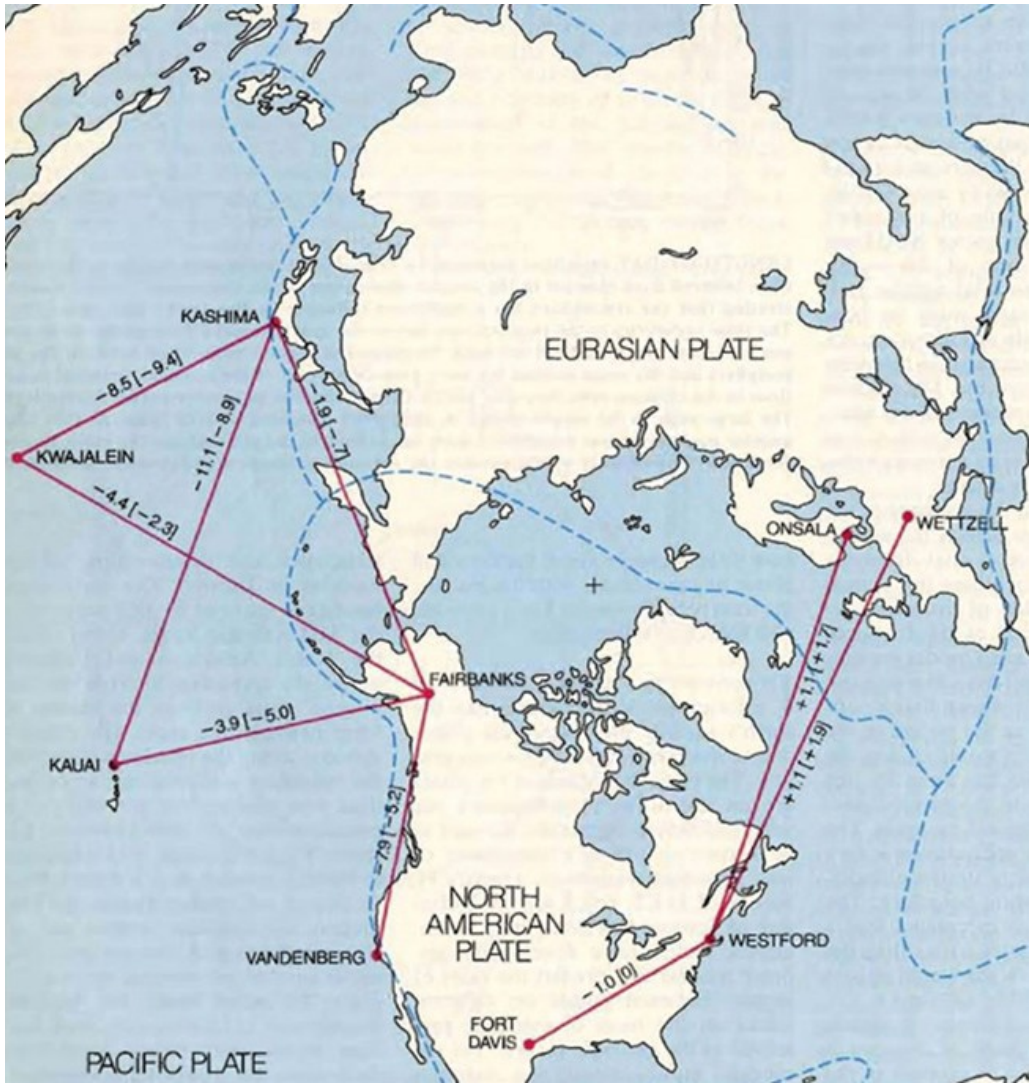
The lithosphere- asthenosphere transition (LAB) is a thermal boundary the position of which depends on the geothermal gradient.

There is movement in the system!

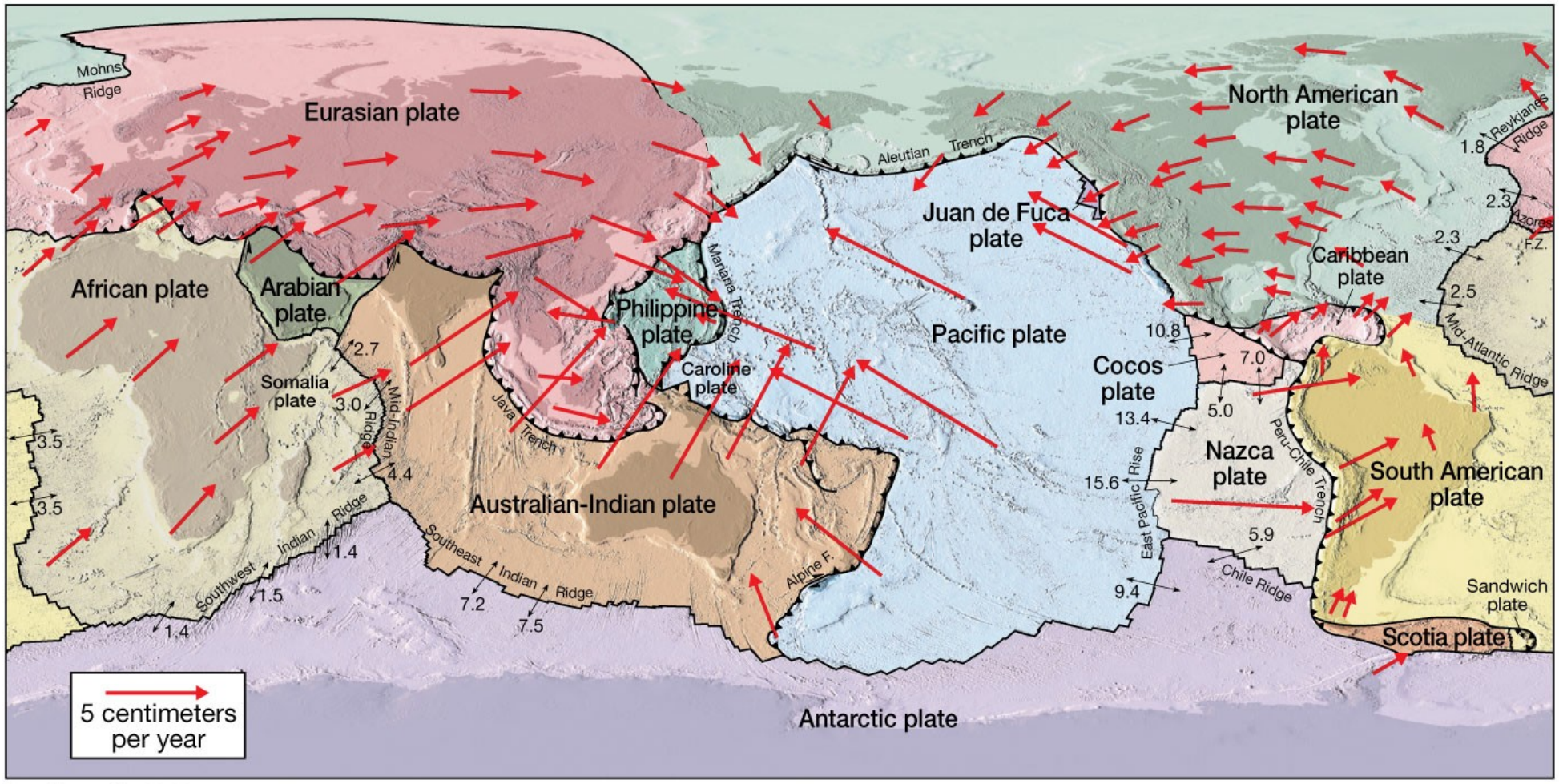




We know very well how plates are presently moving (=kinematics)
Very Long Baseline Interferometers and GPS measurements are used

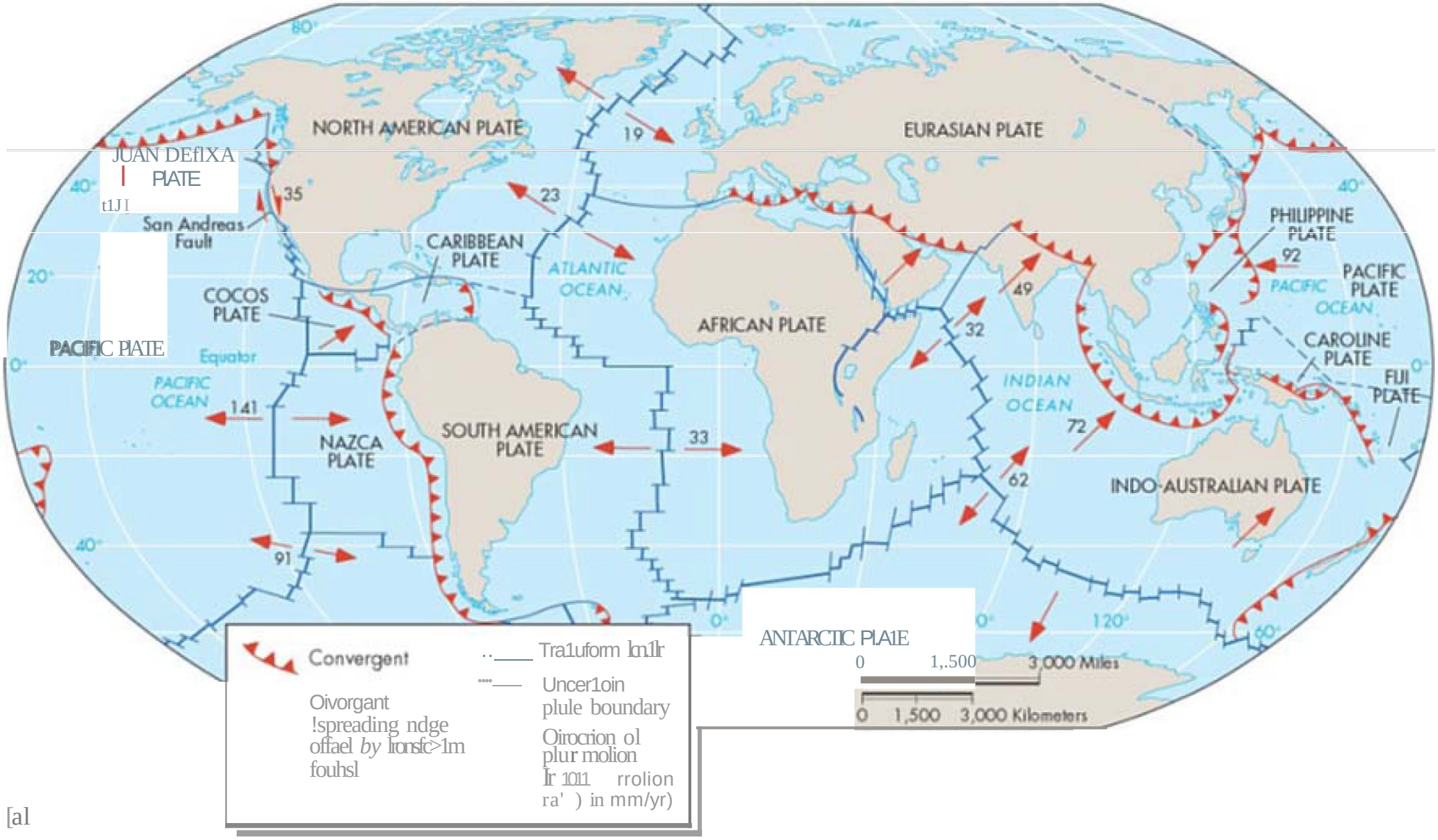


Displacement vectors of GPS stations world-wide



Large regions with coherent displacement vectors separated by sharp boundaries

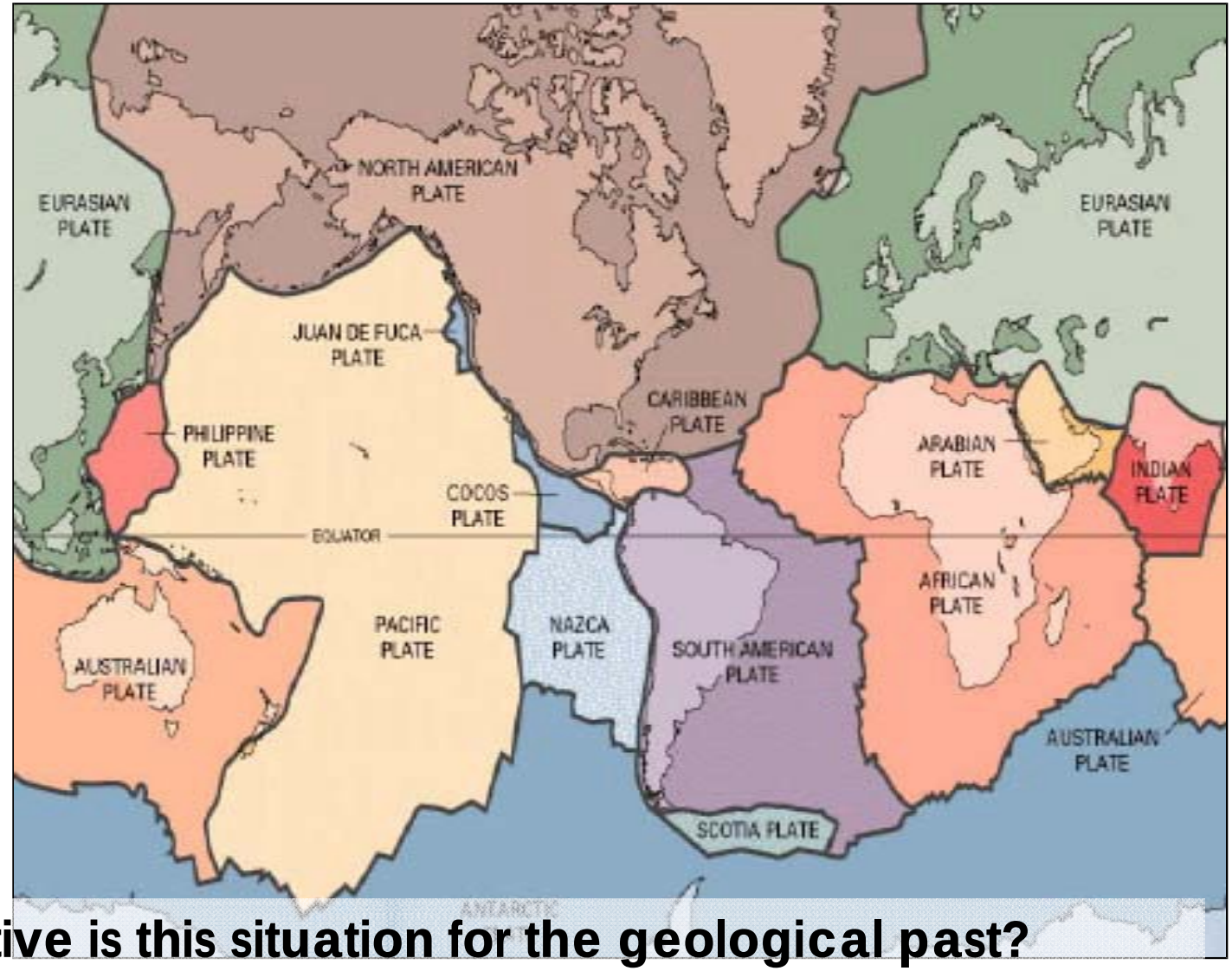
Looking at relative movements: 12 major blocks (plates) moving with respect to each other and with little internal movements



[al

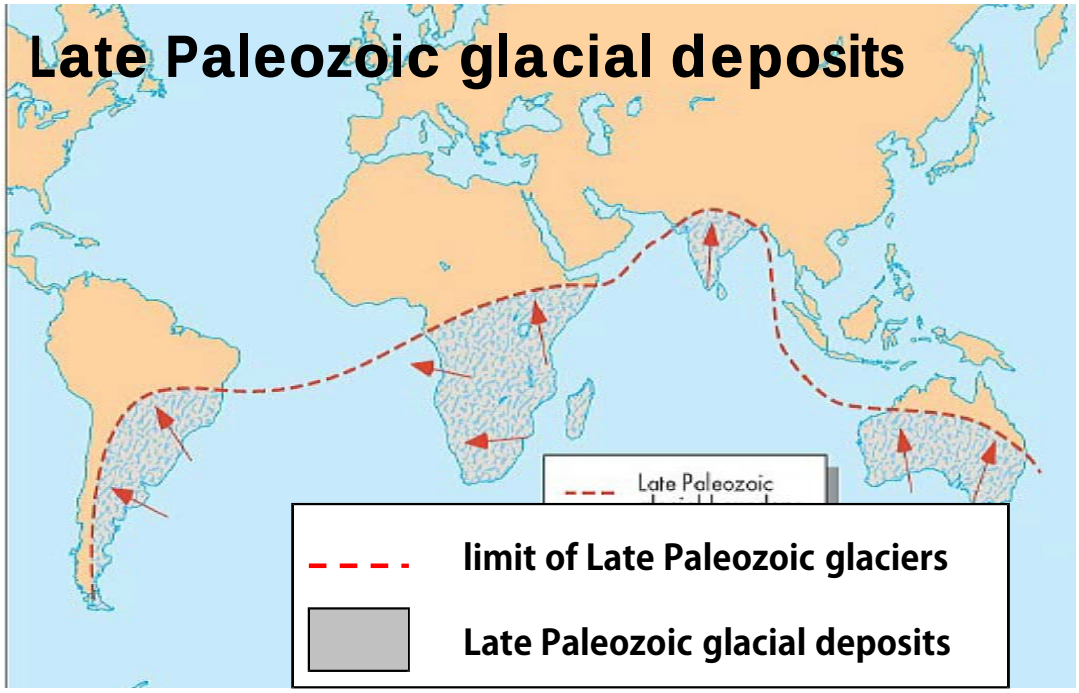
The lesson:

12 major plates can be defined in the outer part of the Earth which move with respect to each other and which display little internal deformation



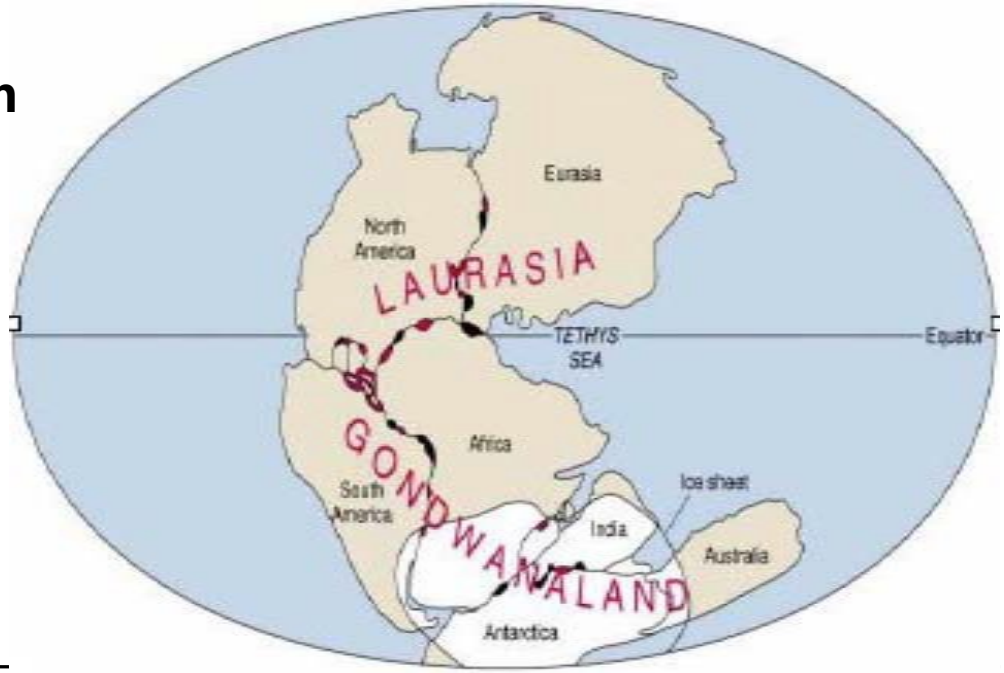
How representative is this situation for the geological past?

Late Paleozoic glacial deposits

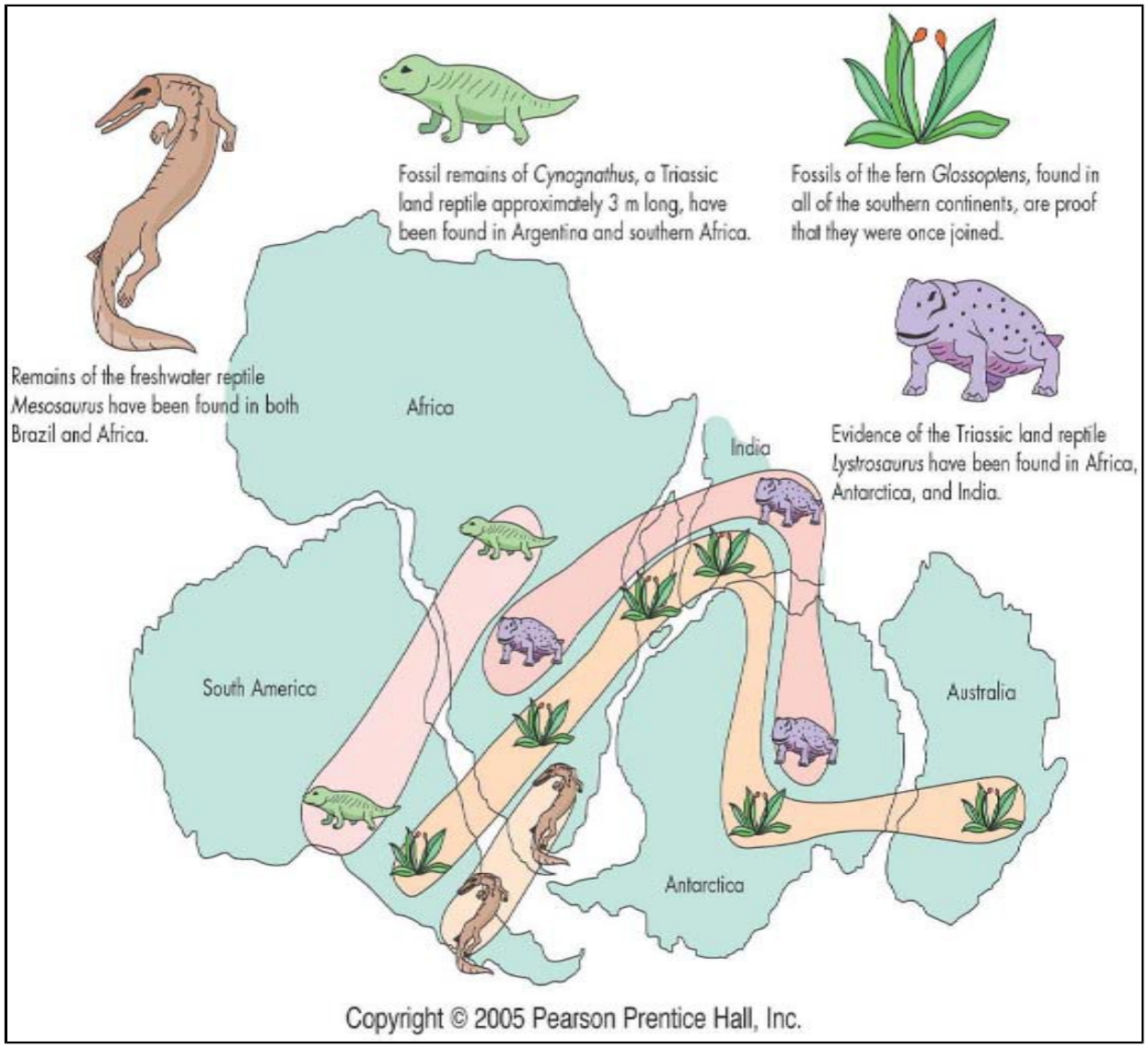


- Glacial deposits of the same age found in areas vey far away from each other
- Glacial deposits founds at “absurd” latitudes

The explanation: the absolute and relative position of the continents was different from the present day one and together they formed the mega-continent Pangea



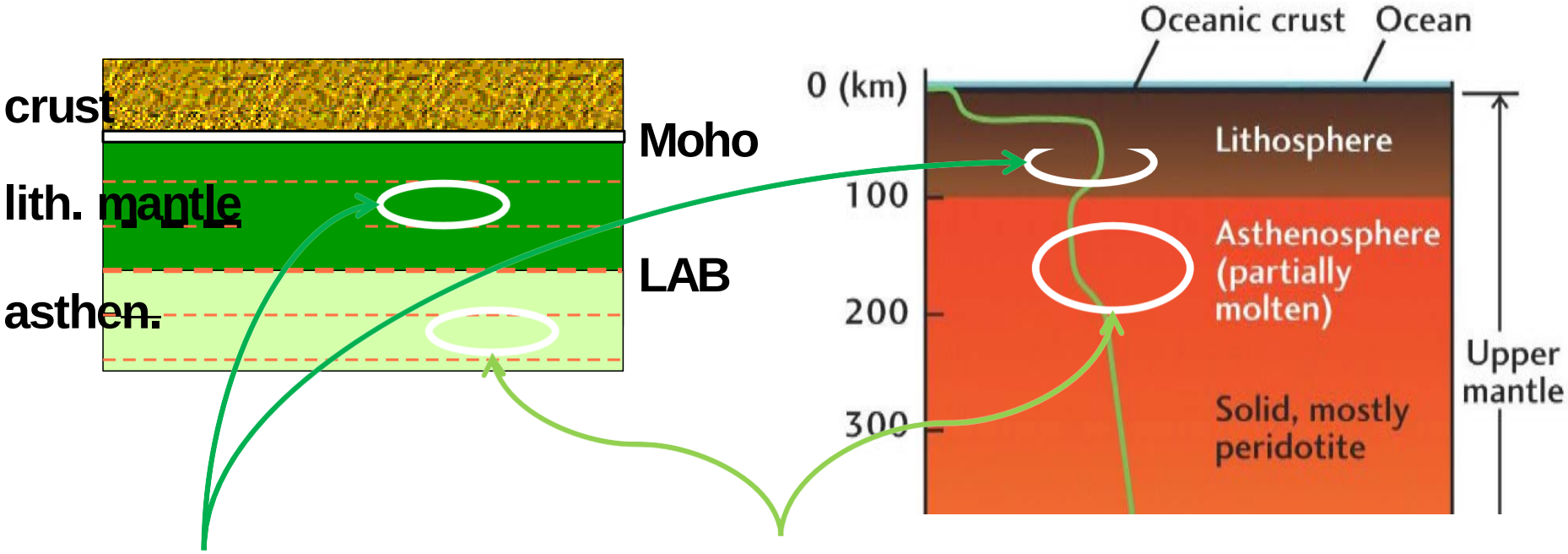
A similar conclusion is reached looking at Paleozoic (600-250Myr ago) plants and animals

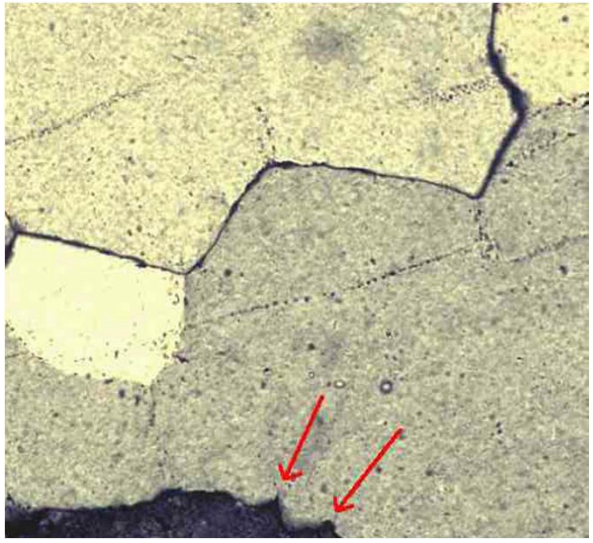


We think that plate movements have taken place since ~500-600Ma

We need a system which allows for large movements over a large amount of time

The tectonic plates correspond to the lithosphere!

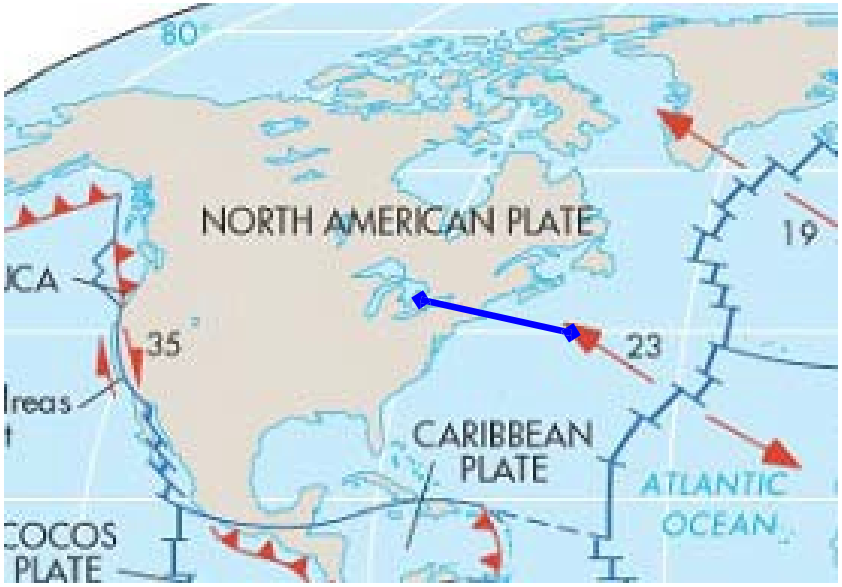


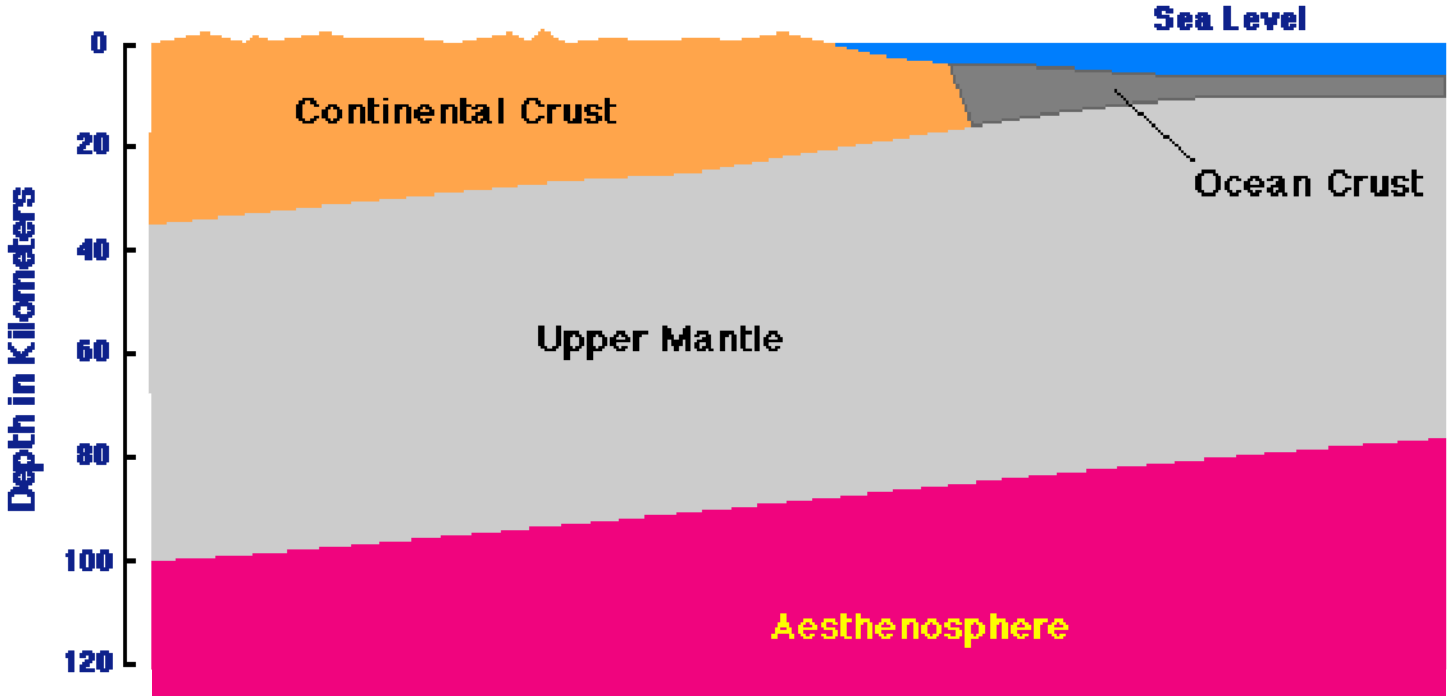


The lithosphere is lighter than the asthenosphere and can float on it

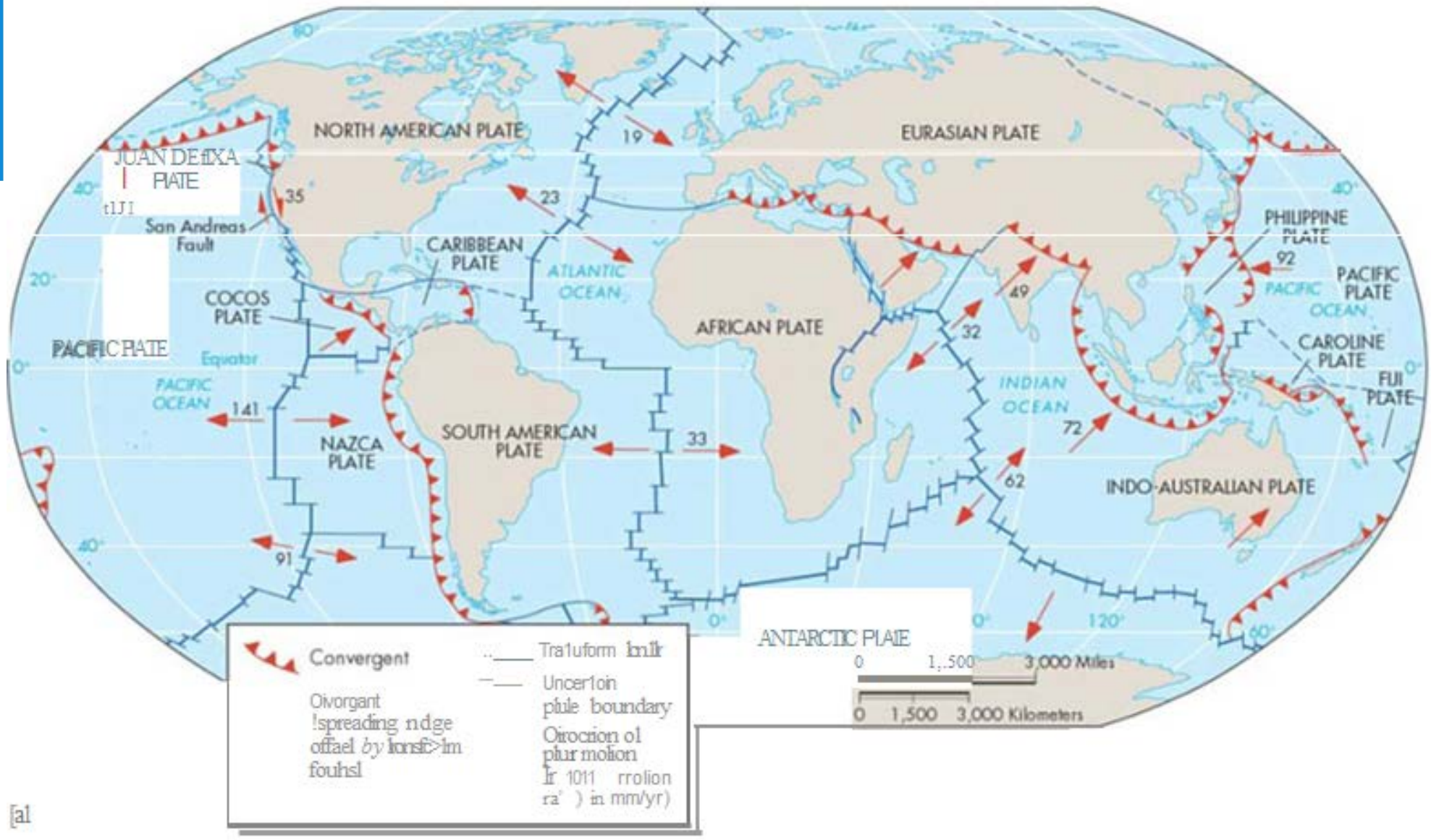
The (rigid) lithosphere lies on the softer and more deformable substratum of the asthenosphere

Remember: the lithospheric mantle is relatively homogeneous underneath continents and oceans; the crusts are, on the contrary very different.

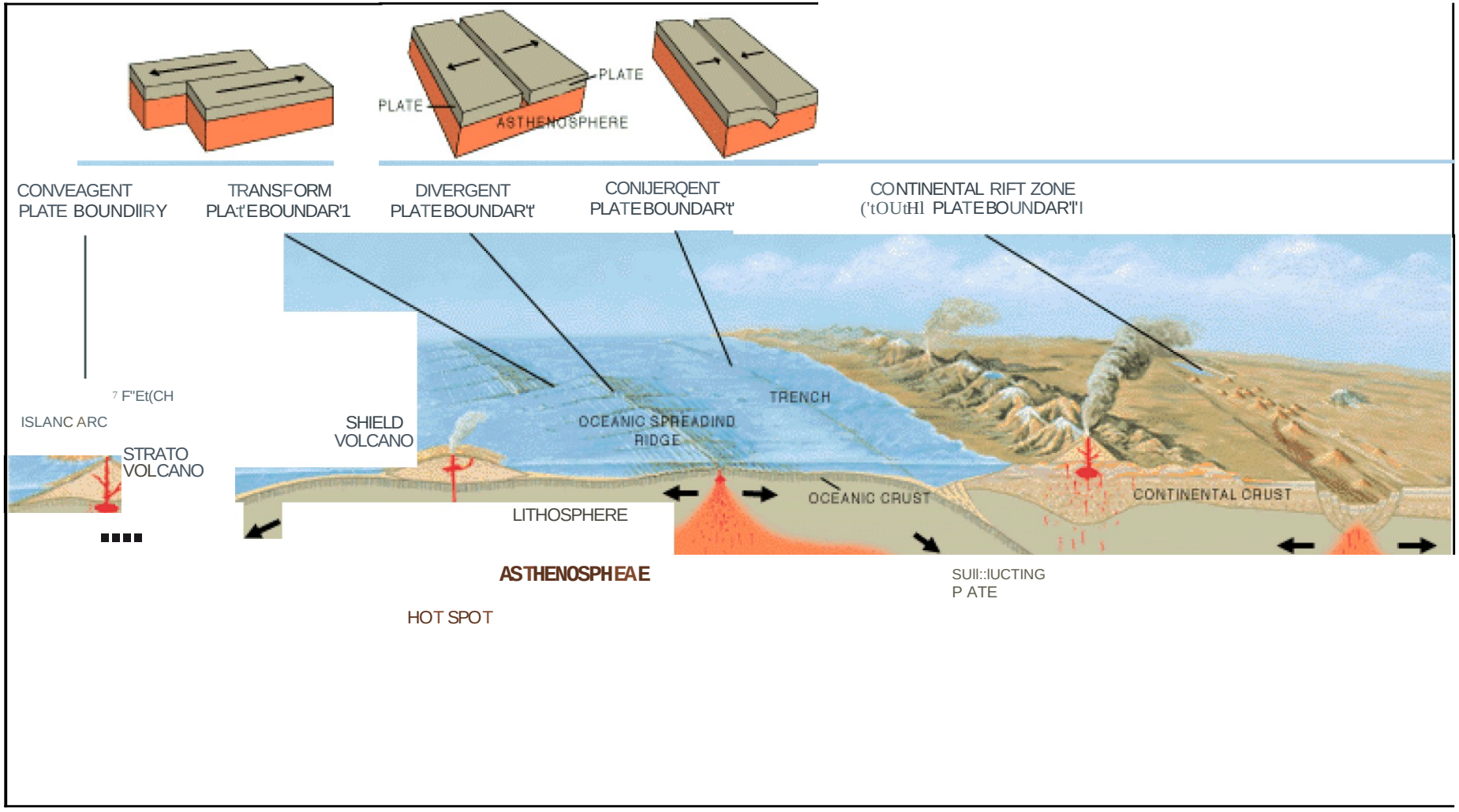




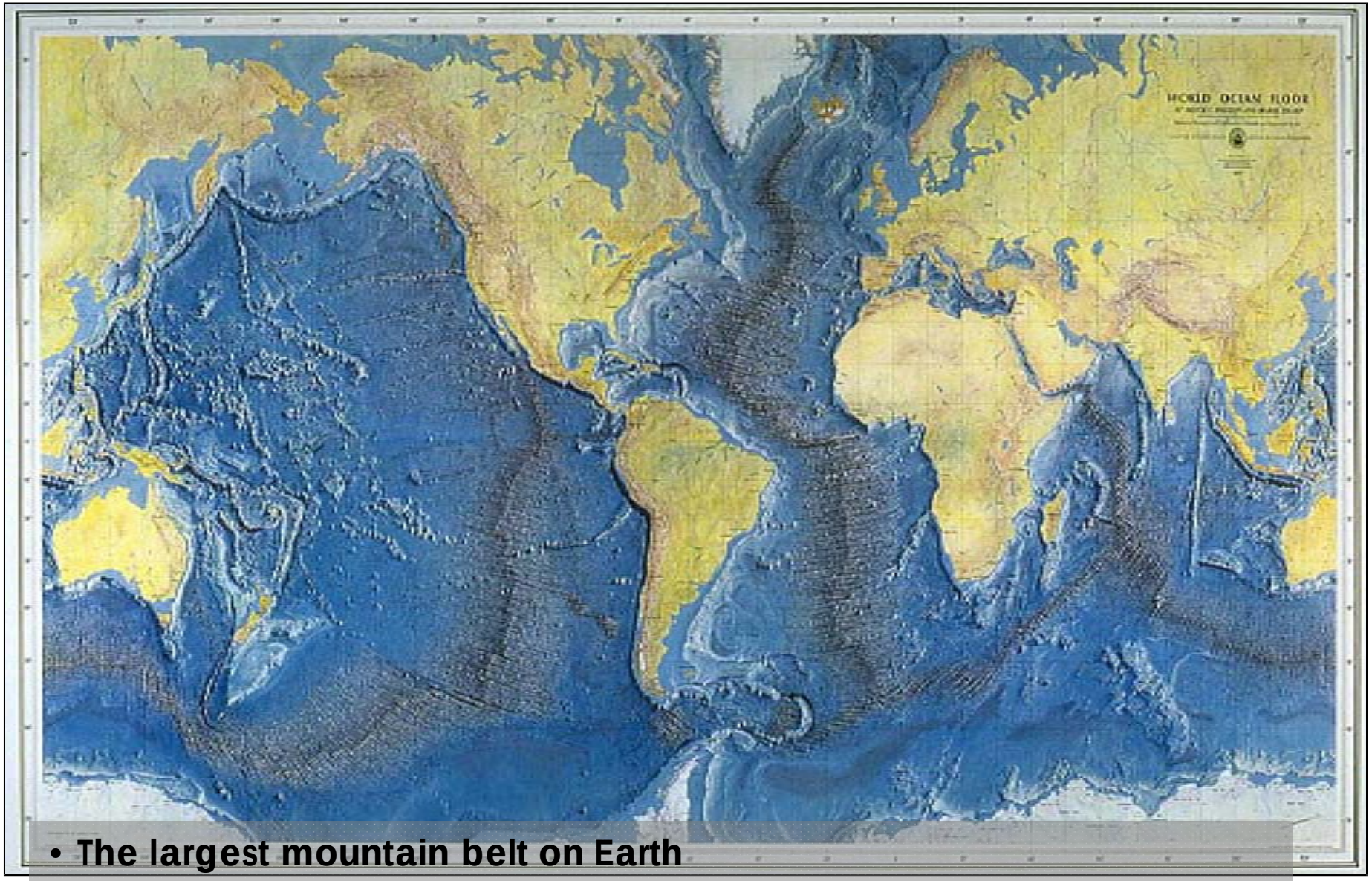
Different types of plate margins



Different processes at plate margins



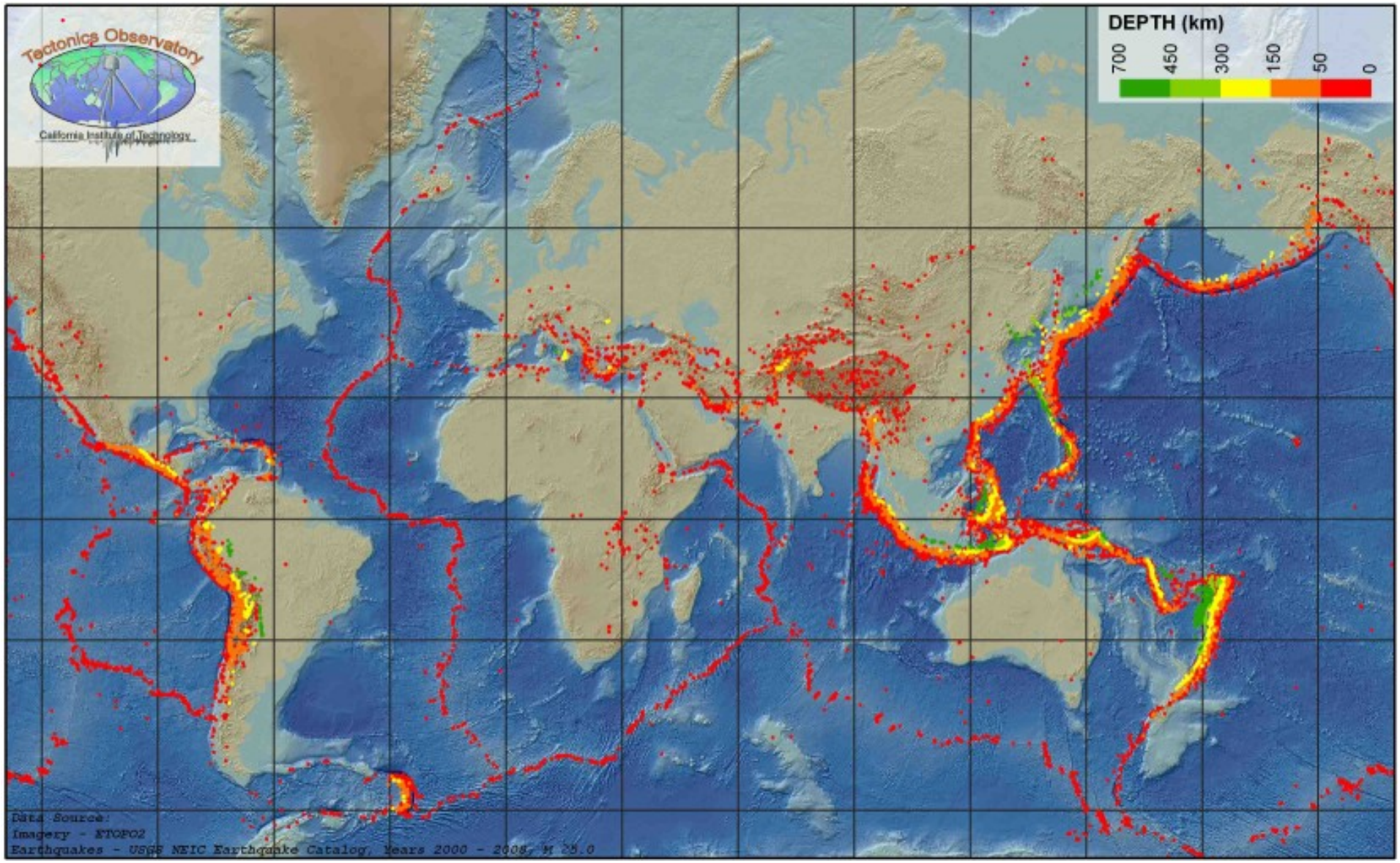
The areas where lithosphere is created: mid-oceanic ridges



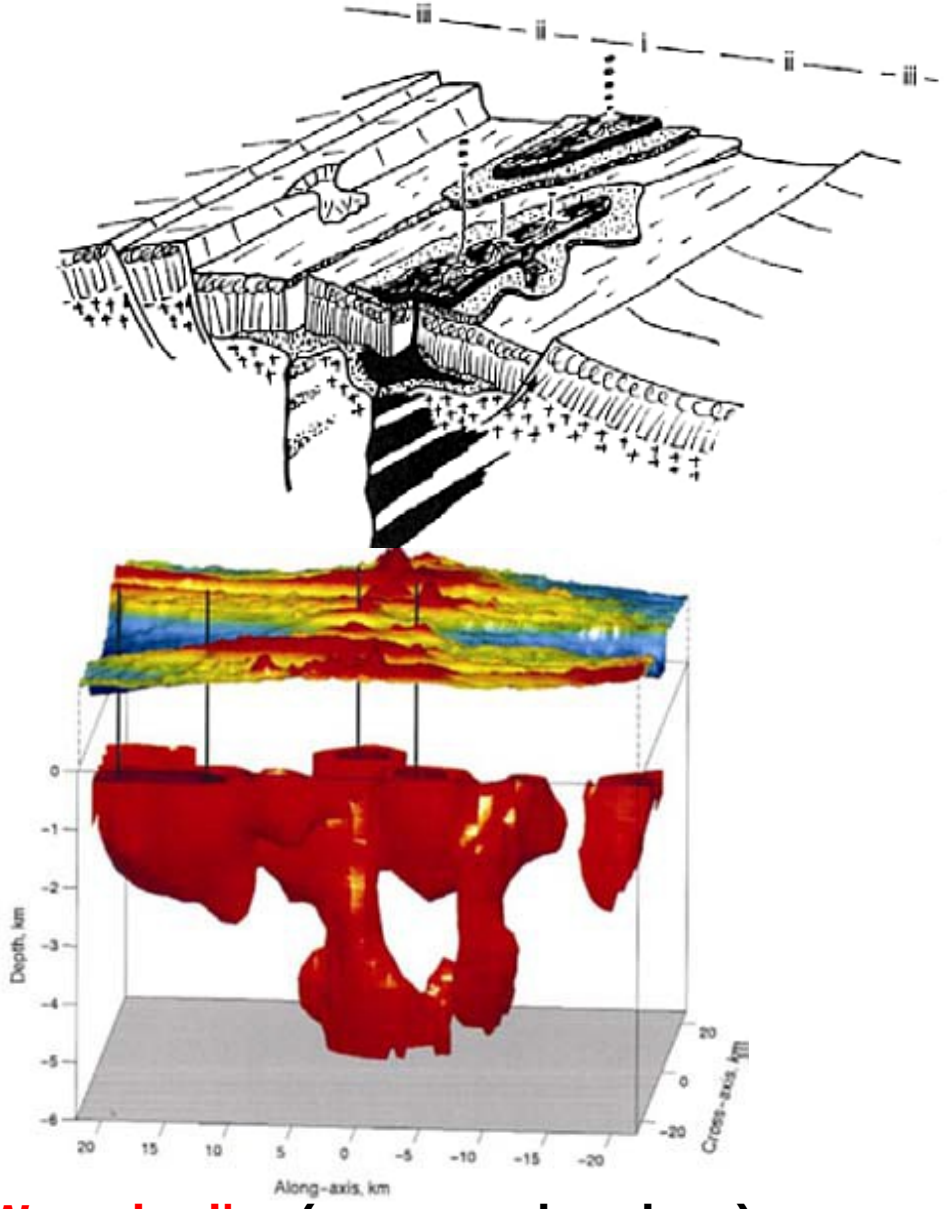
- The largest mountain belt on Earth
- elevation of 3-5km above sea floor
- very rugged topography, flattening moving away from the axis

The rift valleys: a very active places!

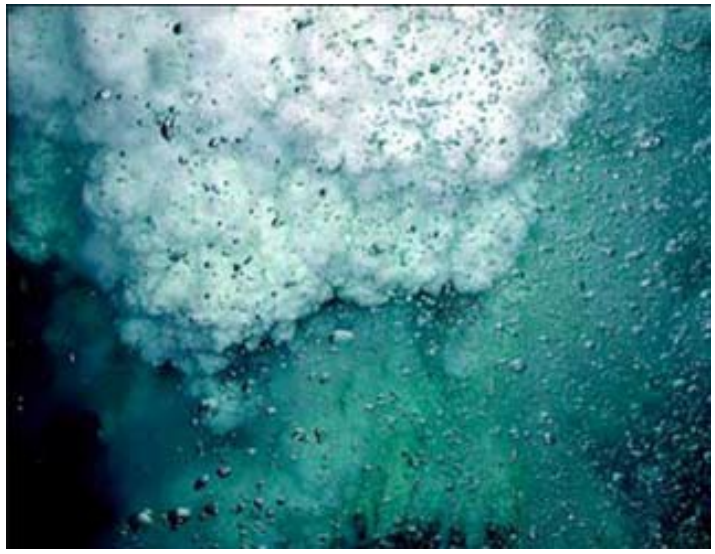
Distribution of earthquakes in the Earth

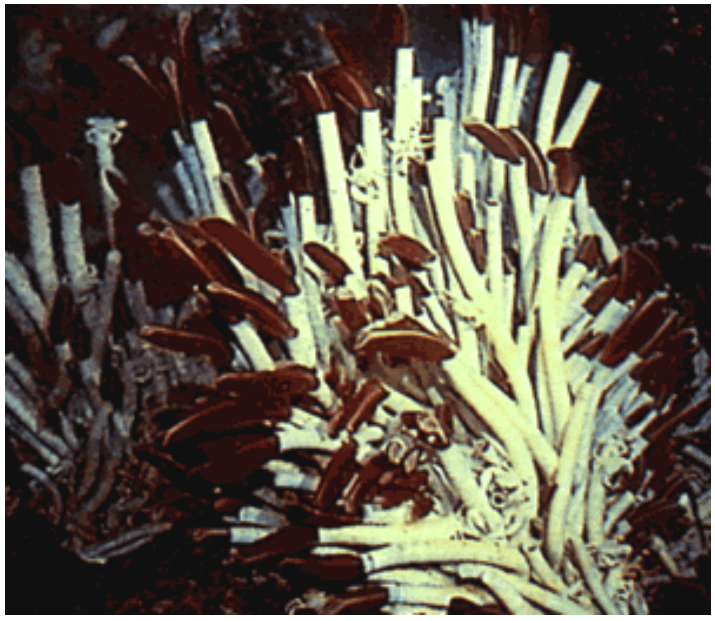


Oceanic ridges: Very intensive volcanism



Warm bodies (magma chambers) underneath oceanic ridges

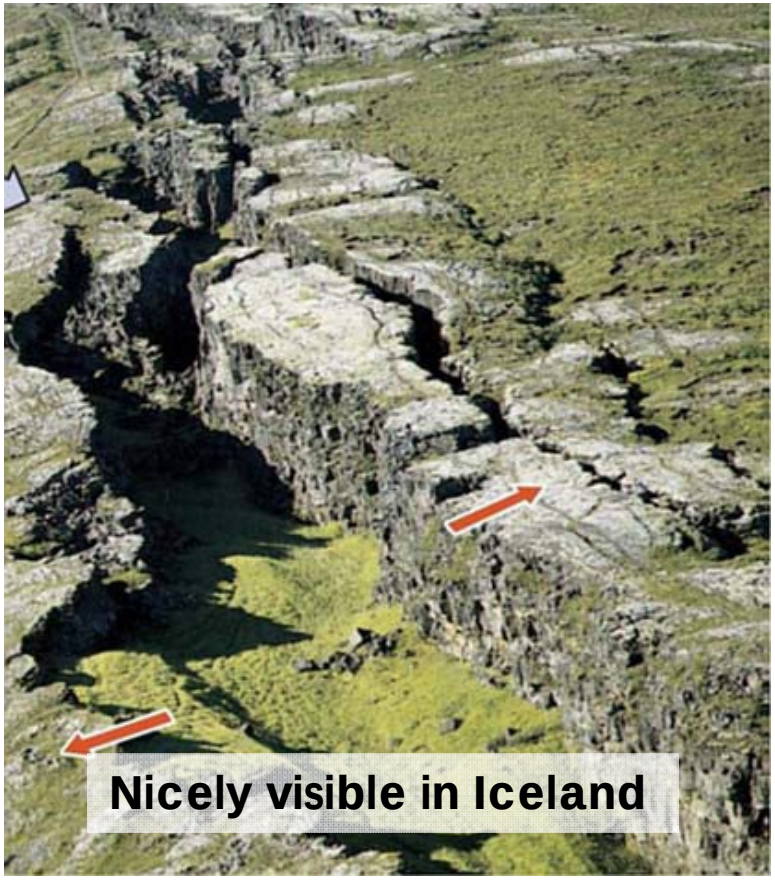


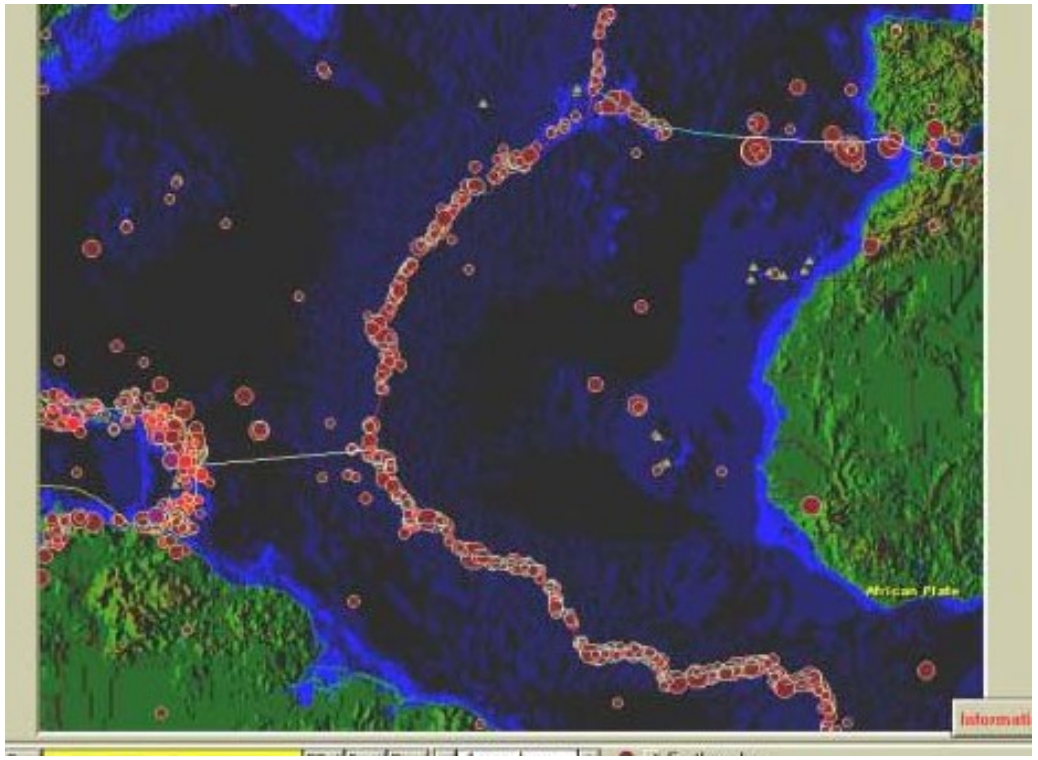


Not everybody finds it a bad place to live!

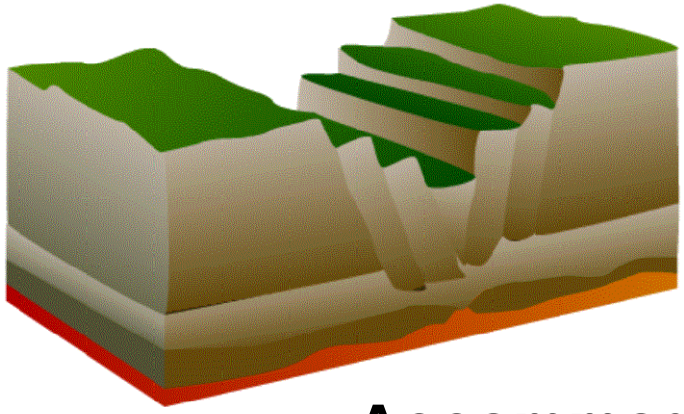
http://media.marine-geo.org/video/vigorous-hydothermal-flow-sully-2005

And very active extension





Earthquakes in the Central Atlantic

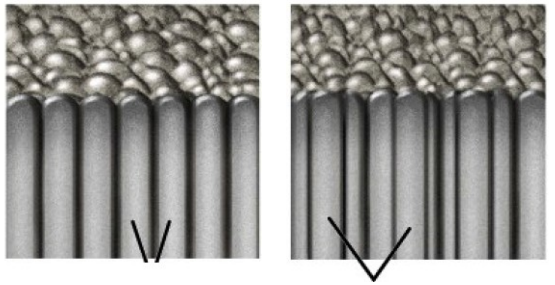


Accommodate extension

Summarizing the processes

2 A thin dike erupts, spilling lava on the ocean floor in characteristic "pillows:'

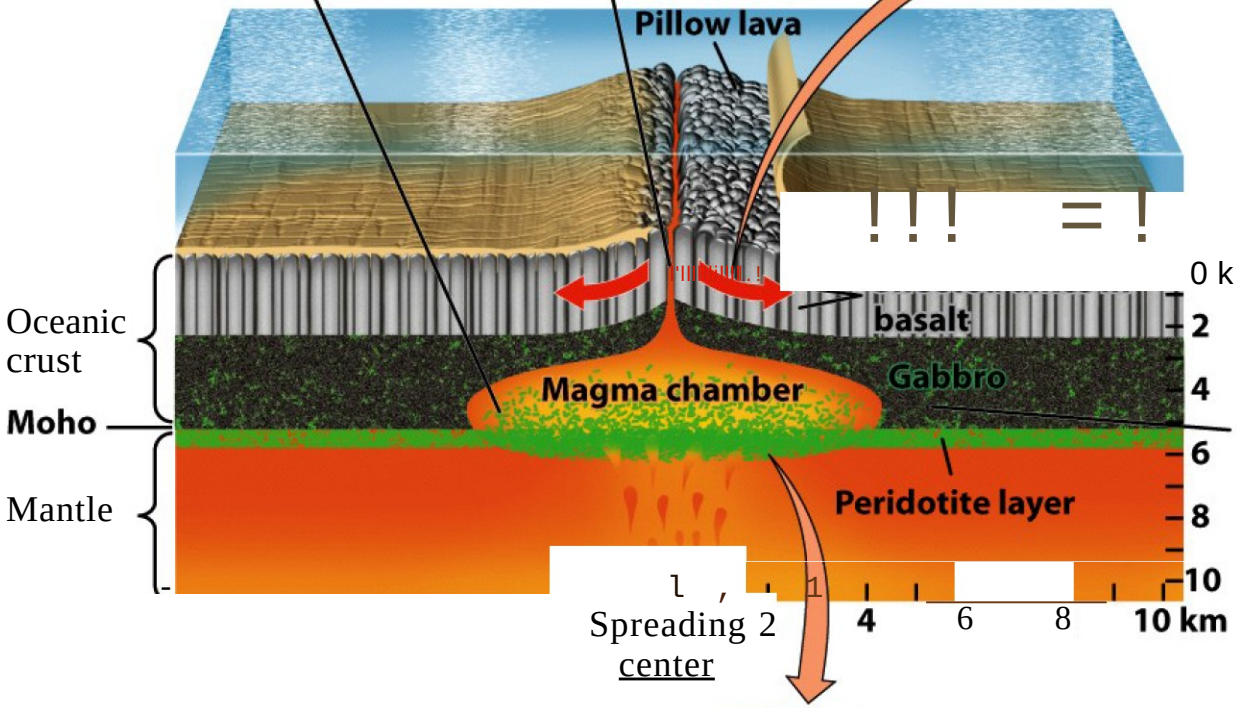
1 Hot mantle rock rises, decompresses, and melts to a mush of crystals and basaltic magma.



Dikes Dikes intruding dikes

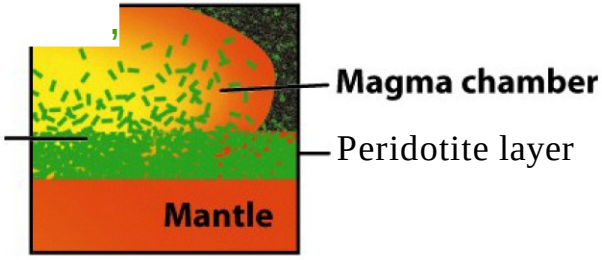
3 As the basalt mush cools, dikes intrude dikes to form sheeted dikes. Remnants of the spreading center move away laterally.

4 Sediments are deposited on the spreading seafloor.



5 A gabbro layer is formed adjacent to the magma chamber.

6 In the magma chamber, crystals settle out of the magma, forming the peridotite layer.



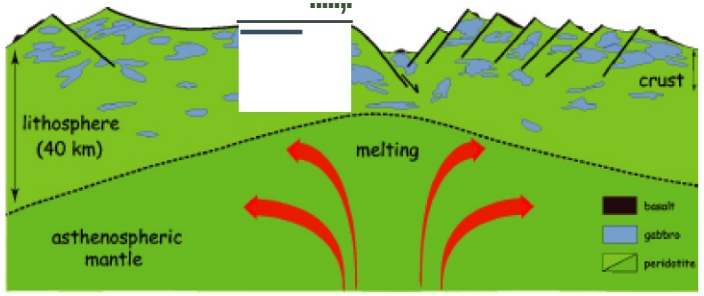


Figure4.15
Understanding Earth, Sixth Edition

With time, the newly formed oceanic rocks move away from the ridge

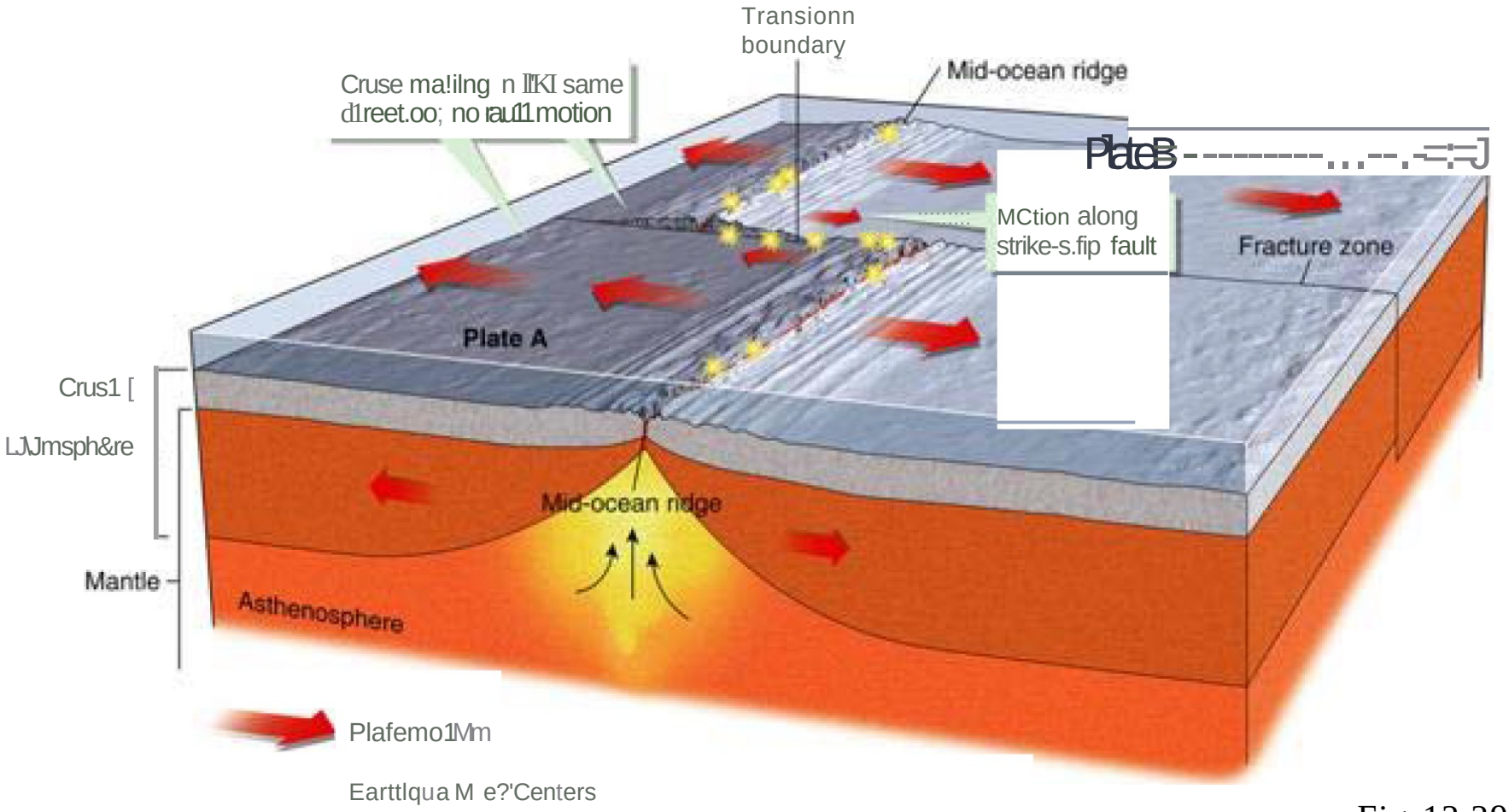
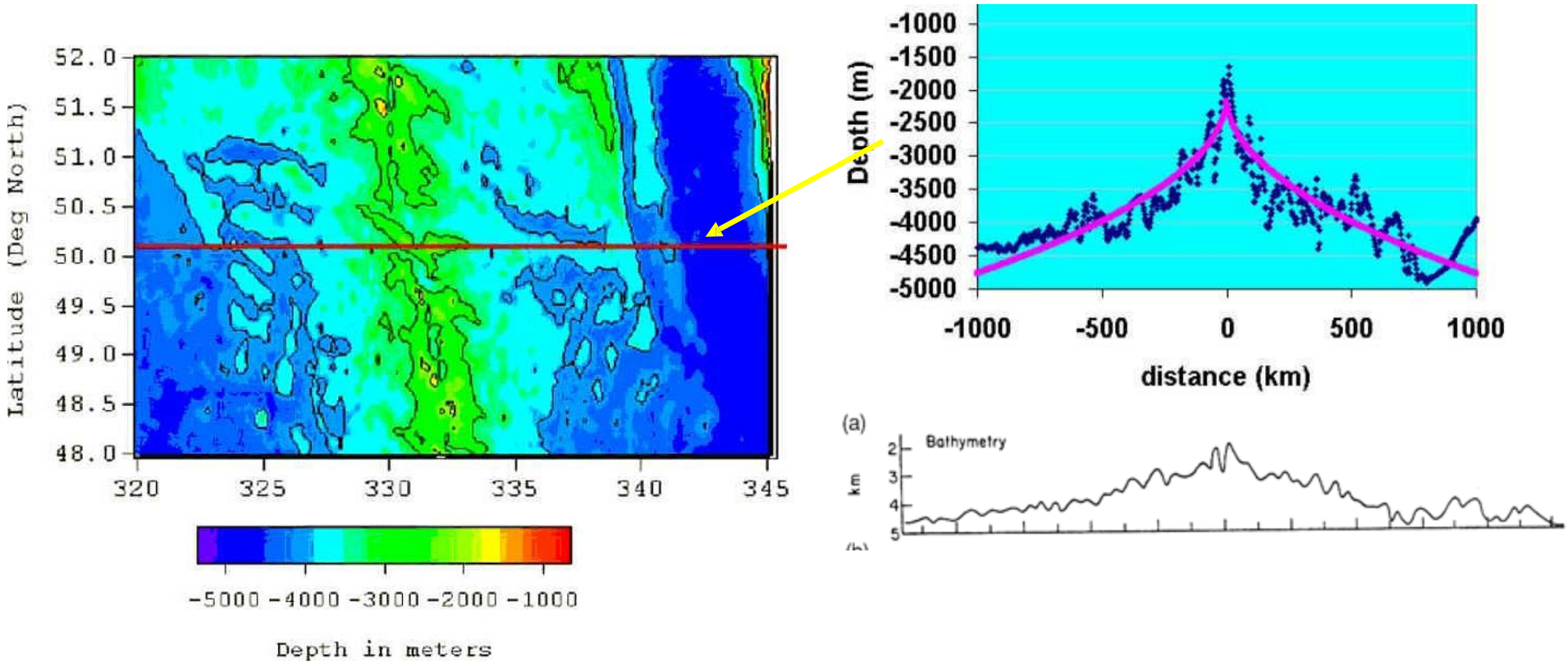


Fig 12.29

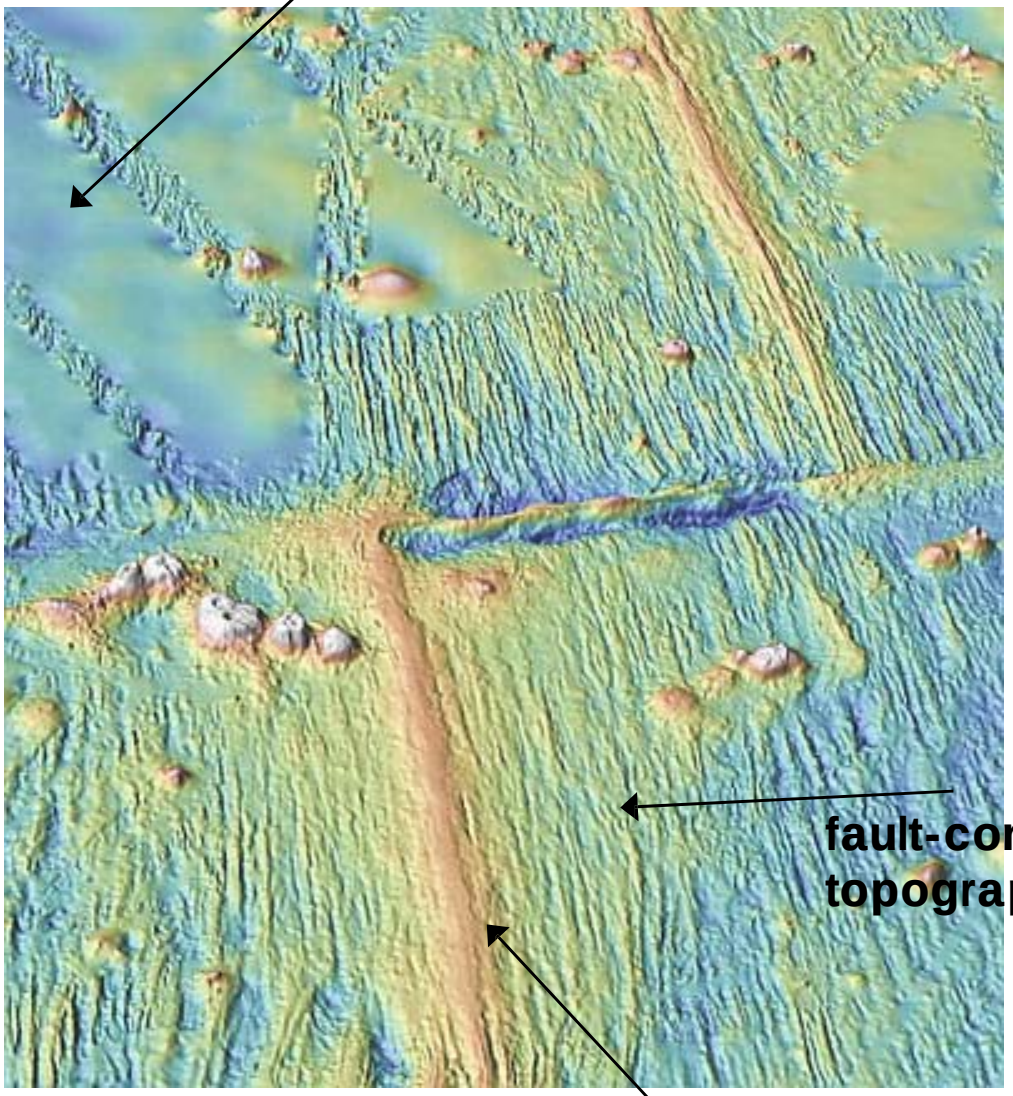
The depth of the ocean floor changes!



The further away, the deeper the ocean

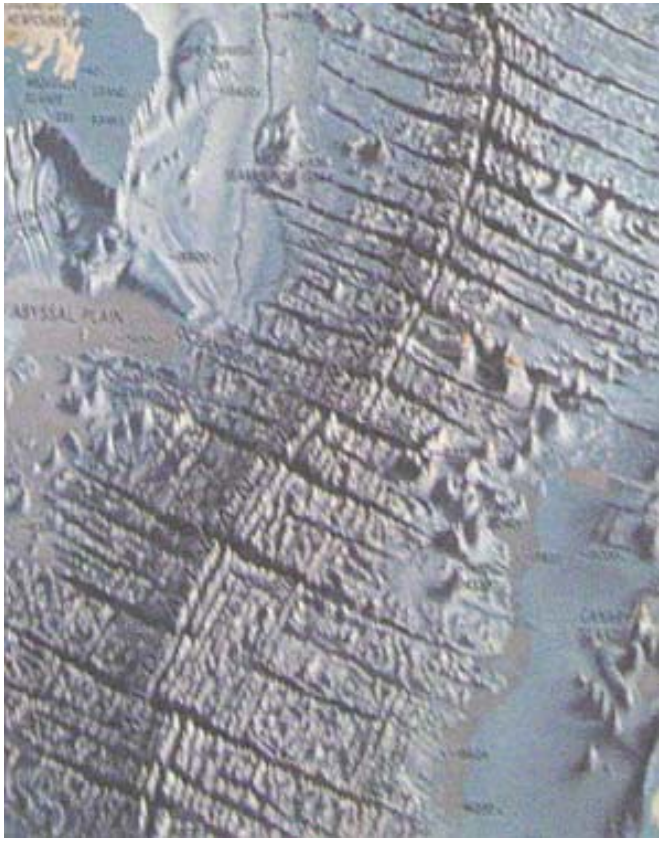
Ocean floor bathymetry

sea floor flattens away from ridge

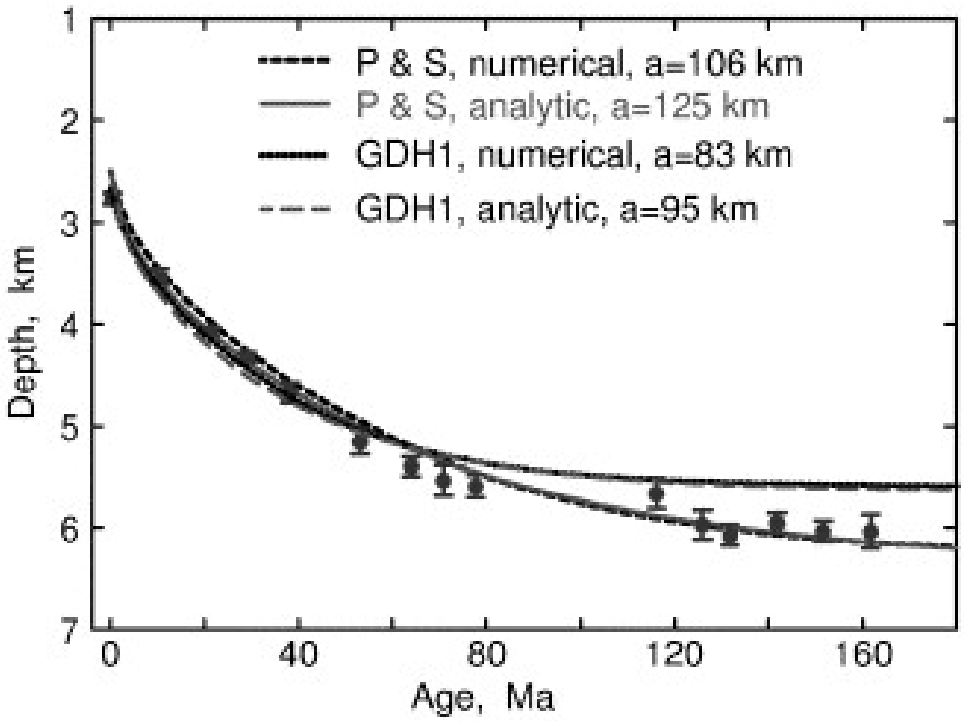


fault-controlled topography

high topography

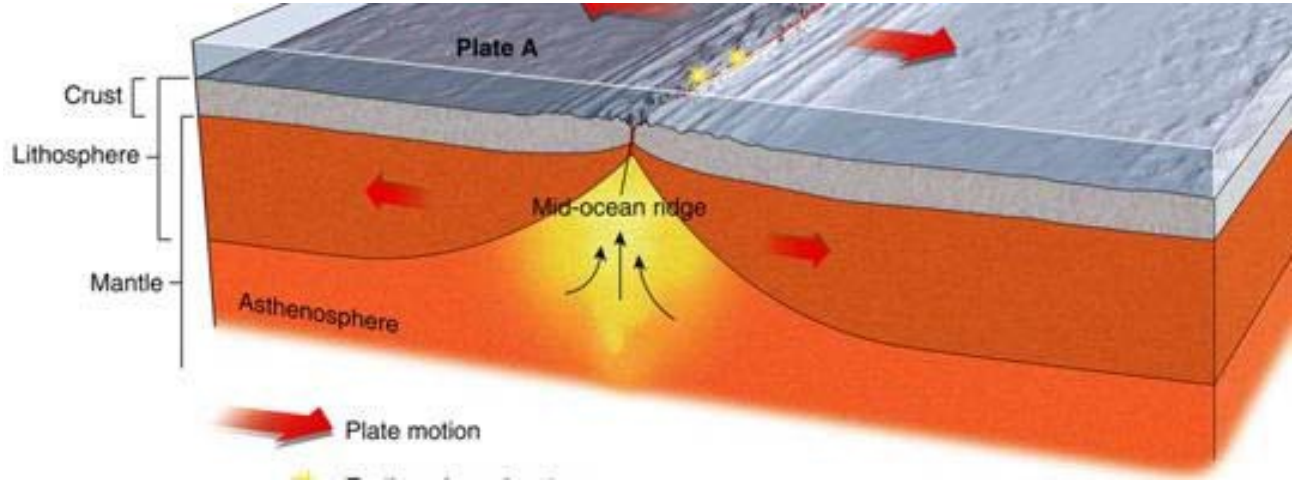


Searching for a motor for vertical movements (subsidence)



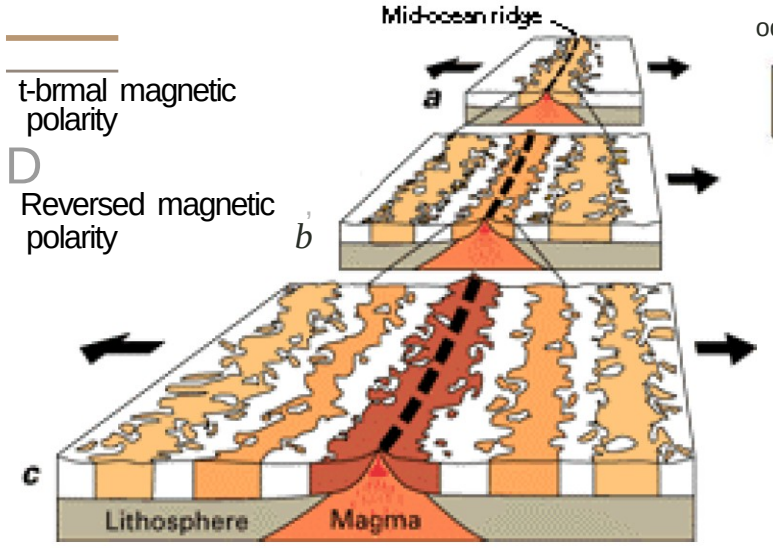
Variations of ocean floor depths nicely fit the *Parson-Sclater equation*: fast at the beginning and flattening then out
Rates depend on age!

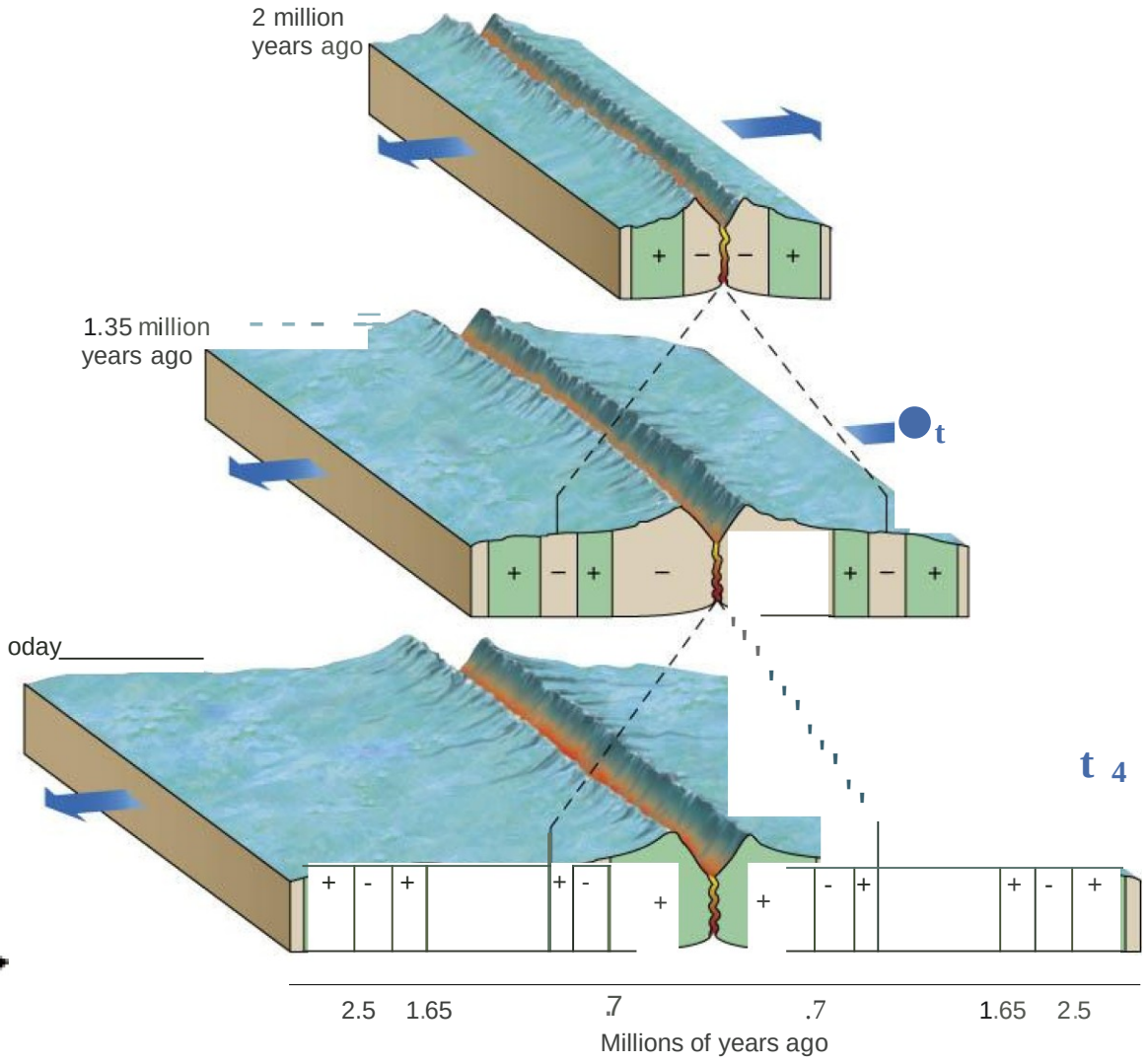
Typical pattern of cooling related processes



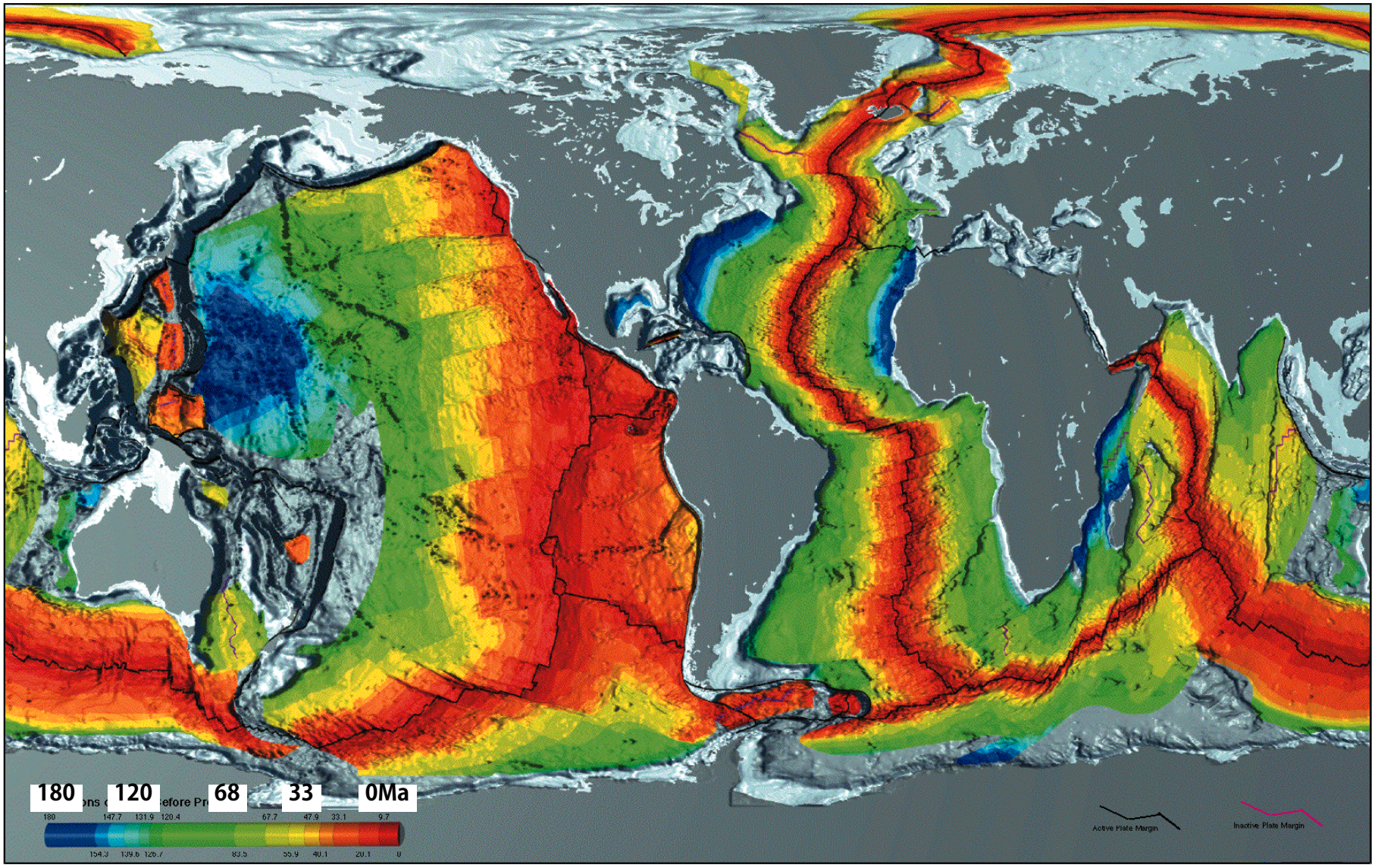
Rocks cool and the lithosphere becomes thicker

Moving away of plates and magma generation at ridges allows for dating of the oceanic crust



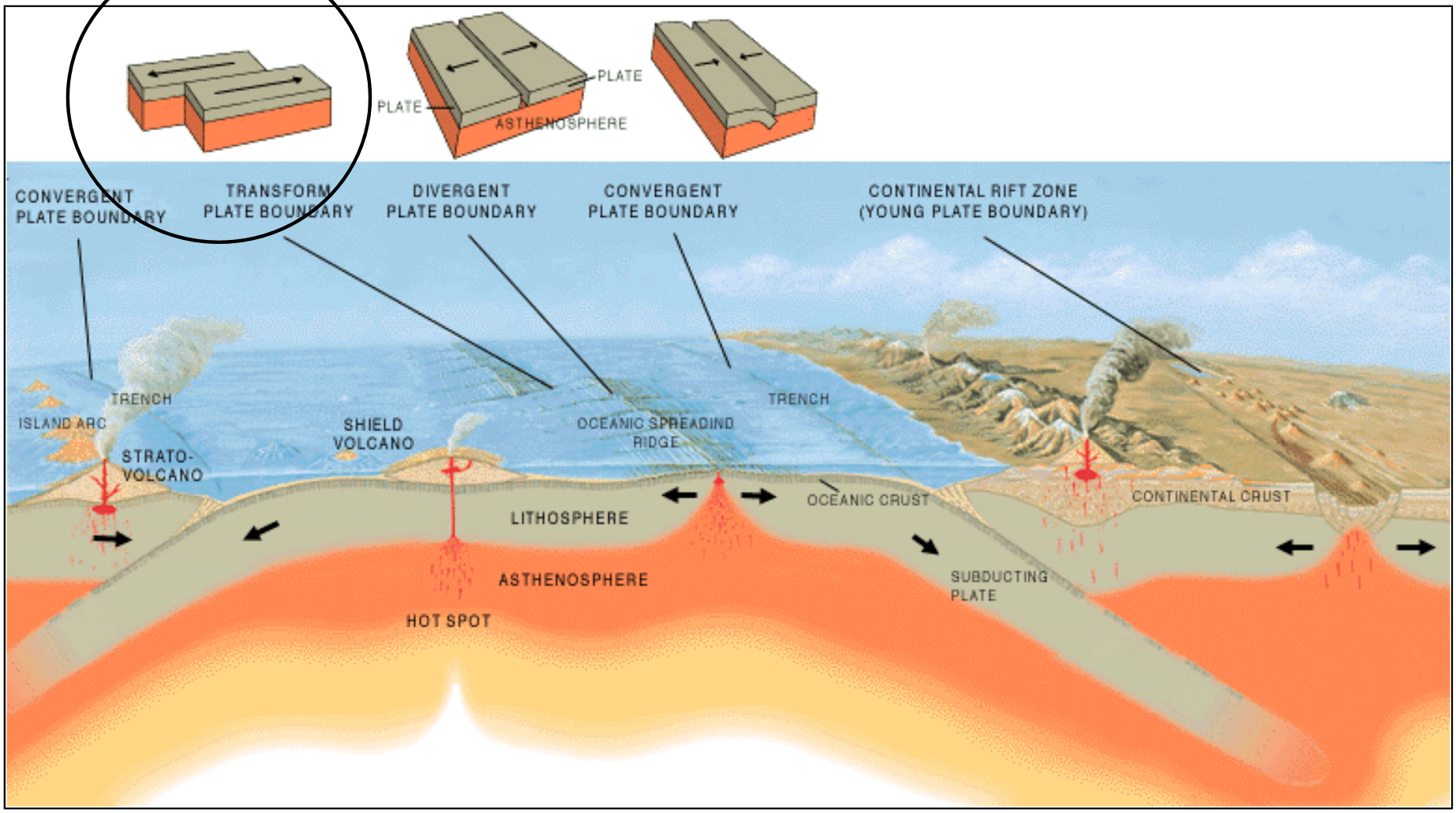


Ages of oceanic crust

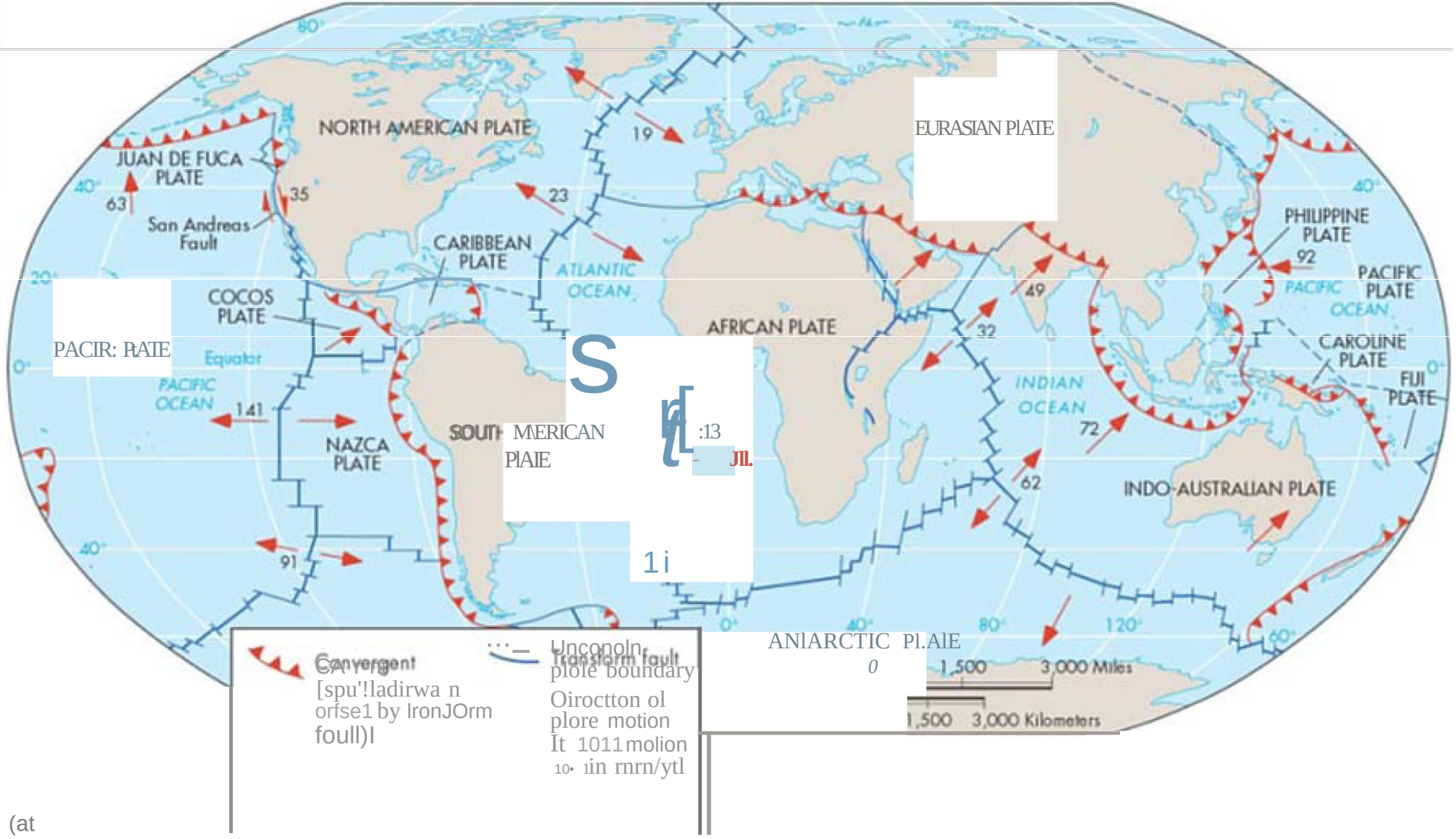


Keep for later: no oceanic crust older than 180Myr!
The accretion is not uniform through time

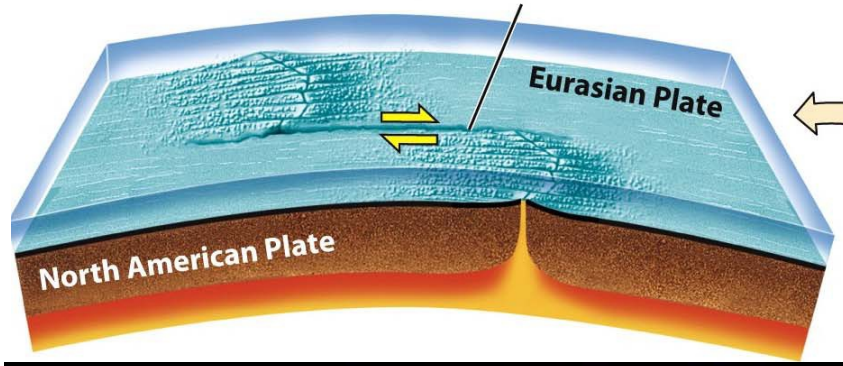
Conservative plate boundaries (strike-slip, transcurrent, transform)
=
Displacement is parallel to the boundary

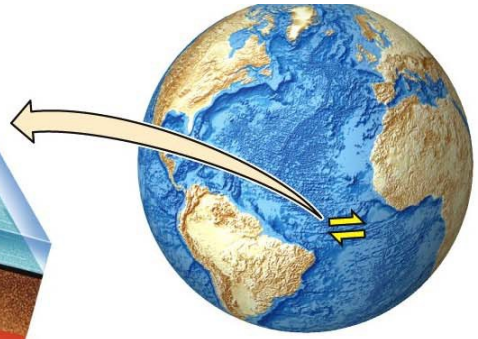


Where are they?

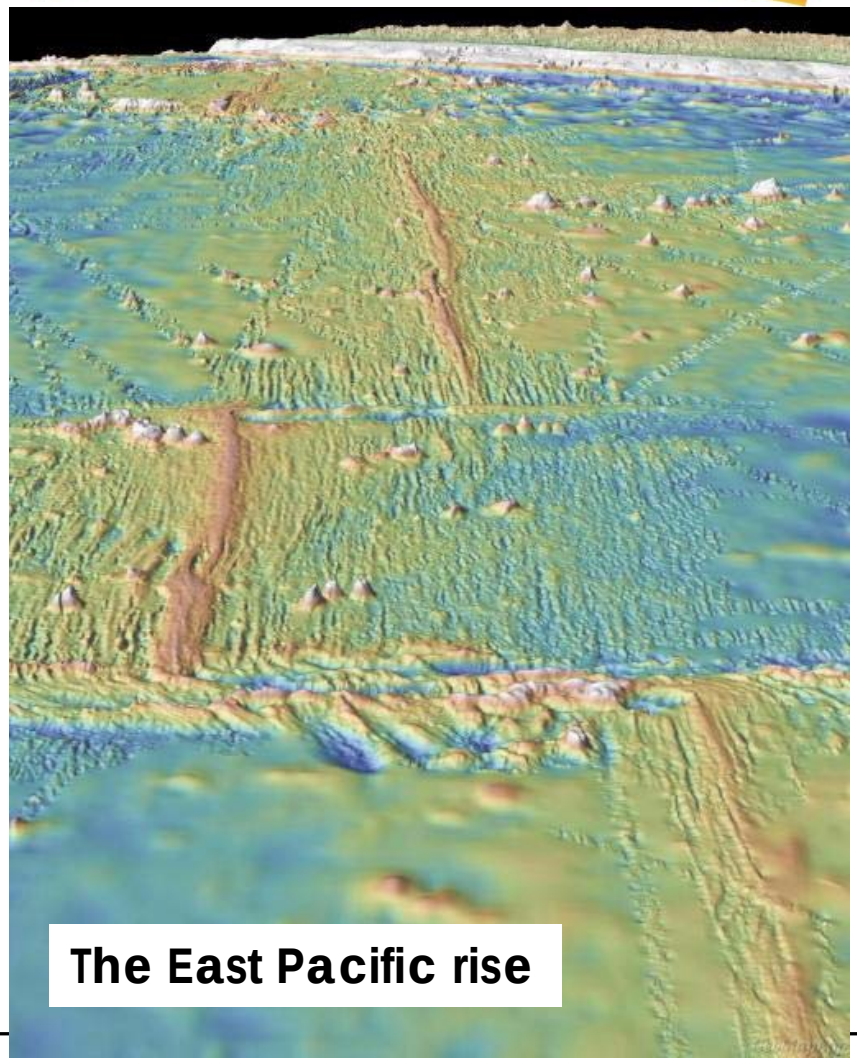


(at



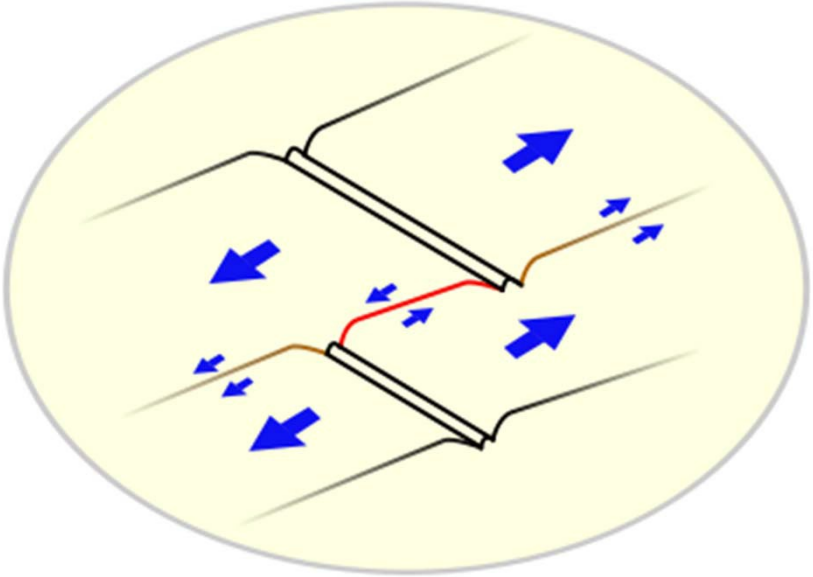


In the oceanic domain

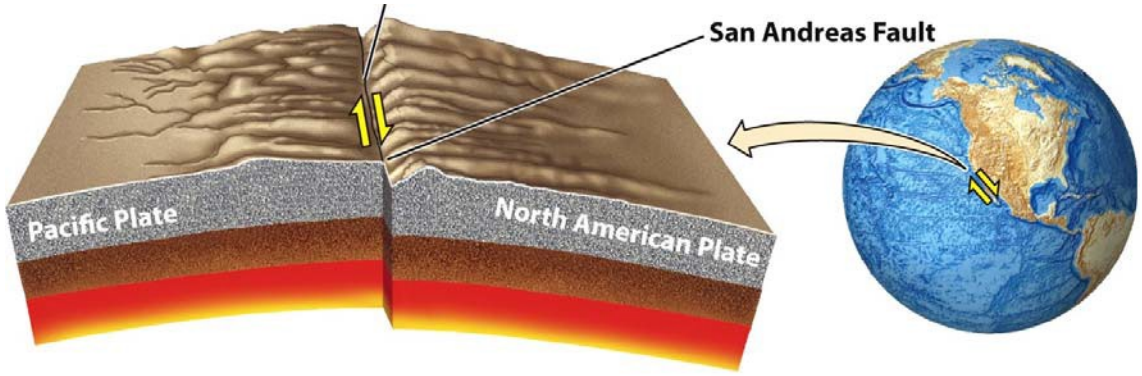


The East Pacific rise

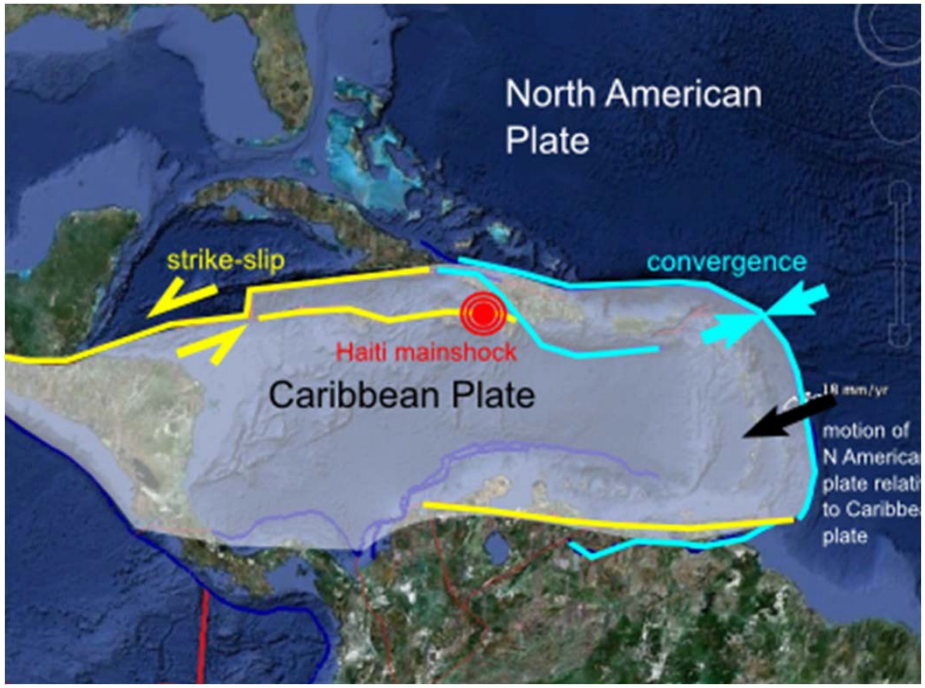
Link two segments of the oceanic ridges

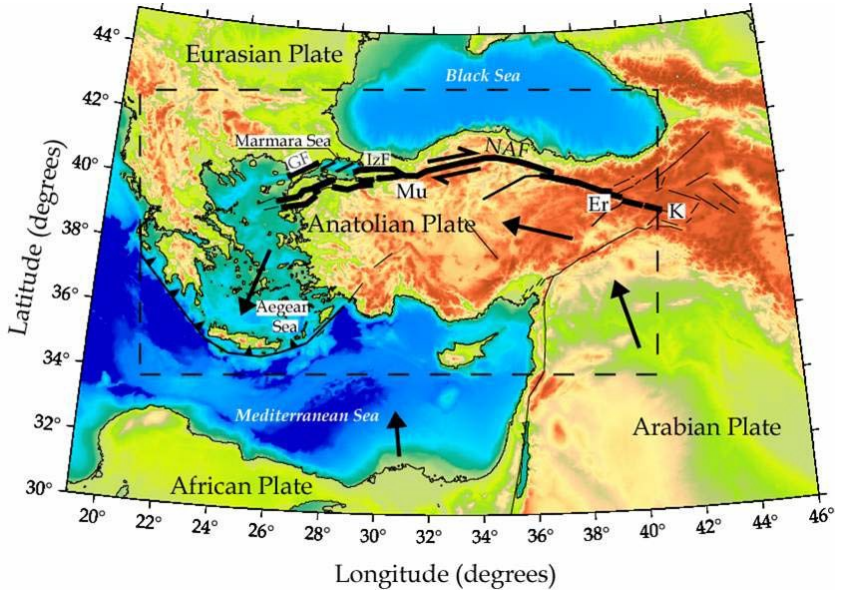


In the continental domain

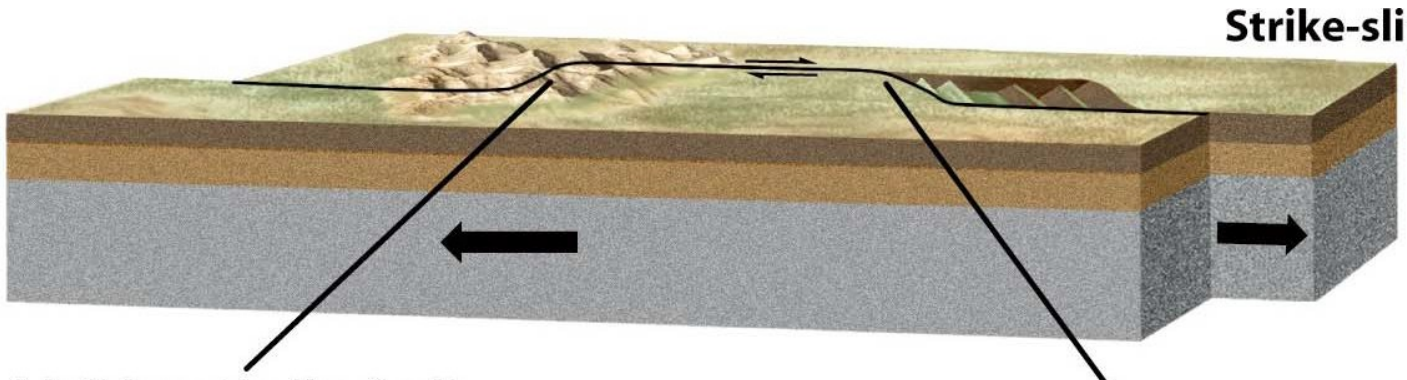


Major earthquakes are associated with transform faults in continents

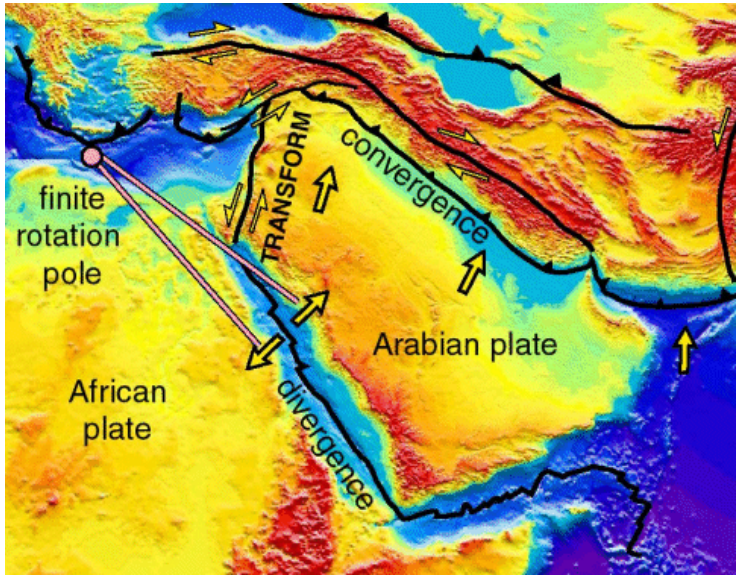


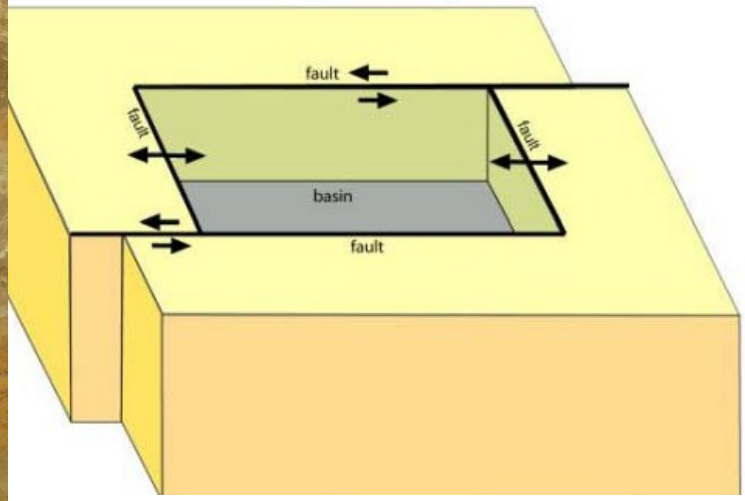


Secondary structures develop when the trace of the fault is not straight

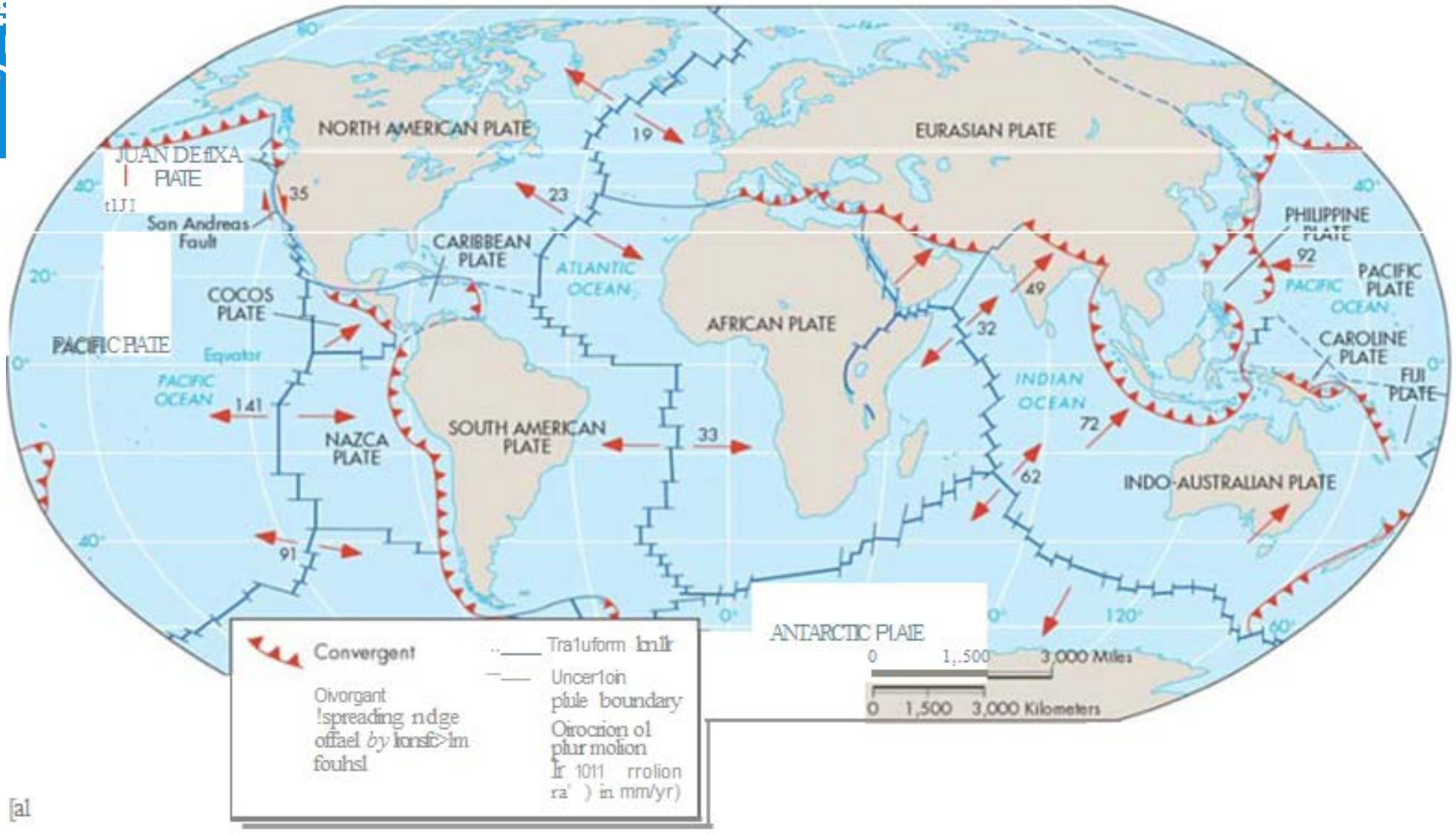


The Dead Sea pull-apart basin



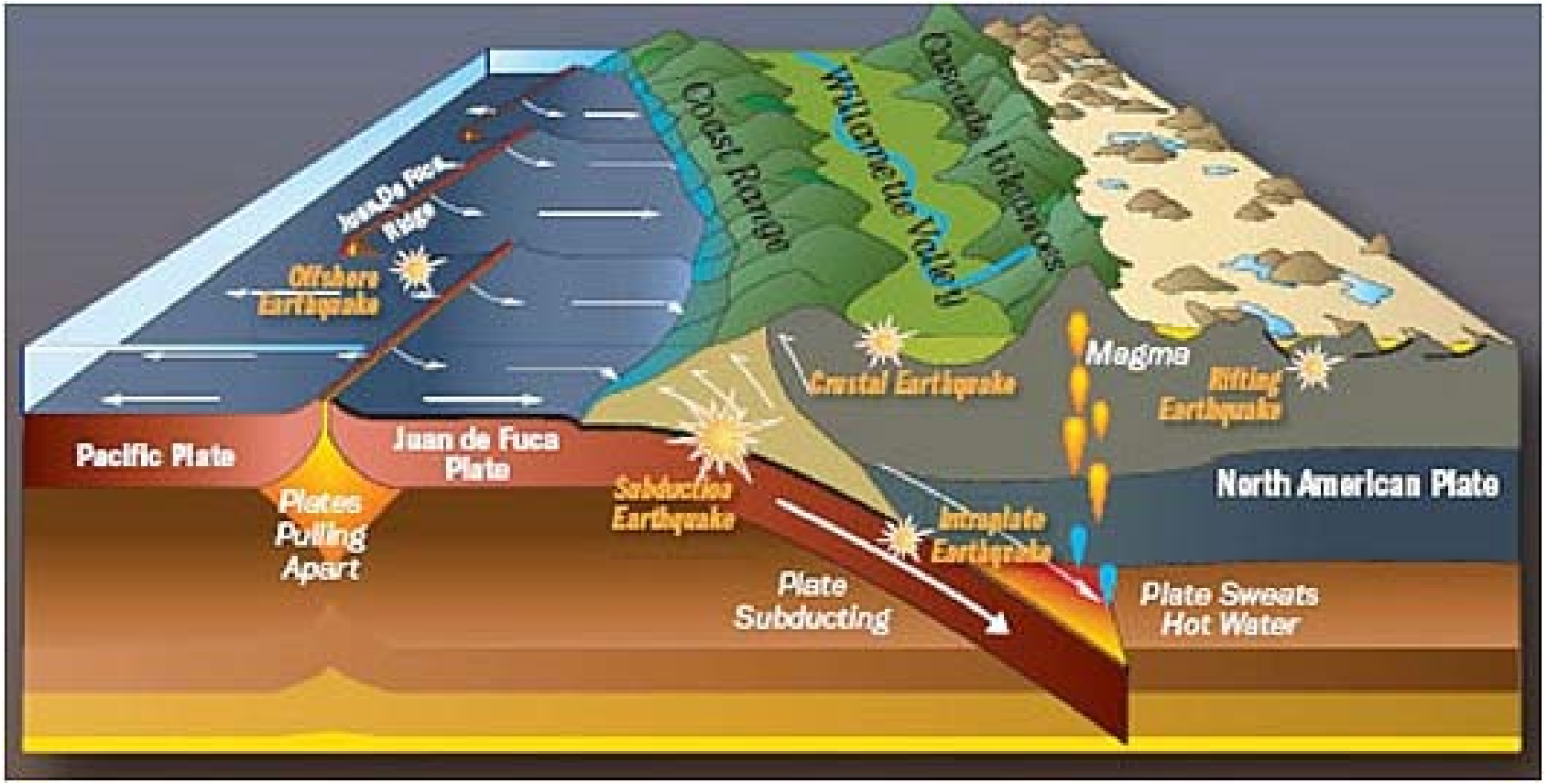


The areas where lithosphere is consumed



[a]

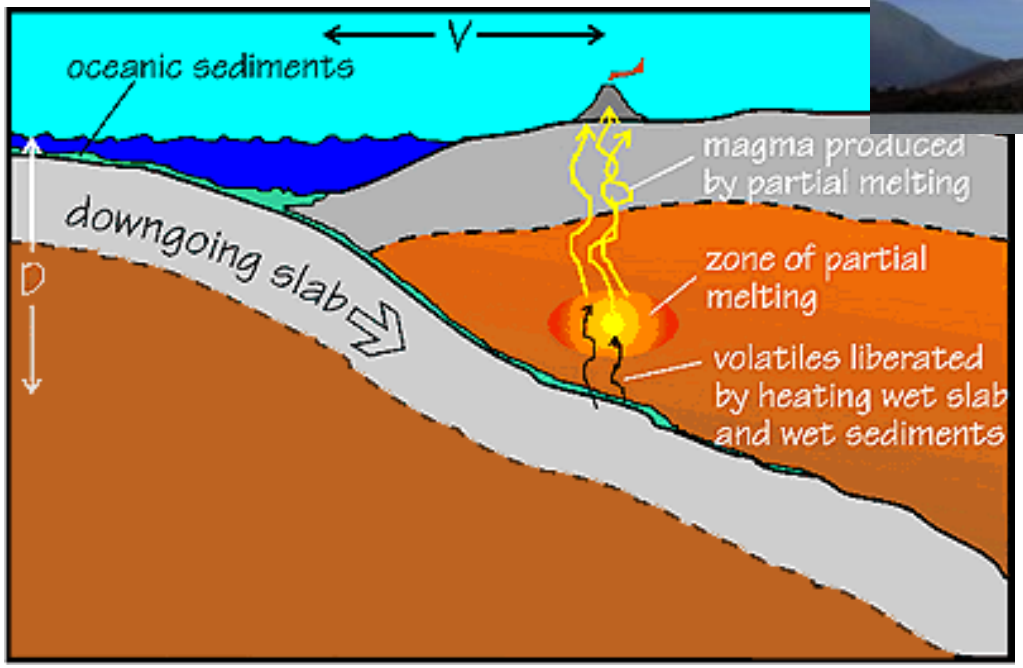
Convergence, protracted over long time, is accommodated by subduction



Three major processes occur

- **volcanism** fluid-driven melting
- **Earthquakes** (friction between plates)
- **accretion**

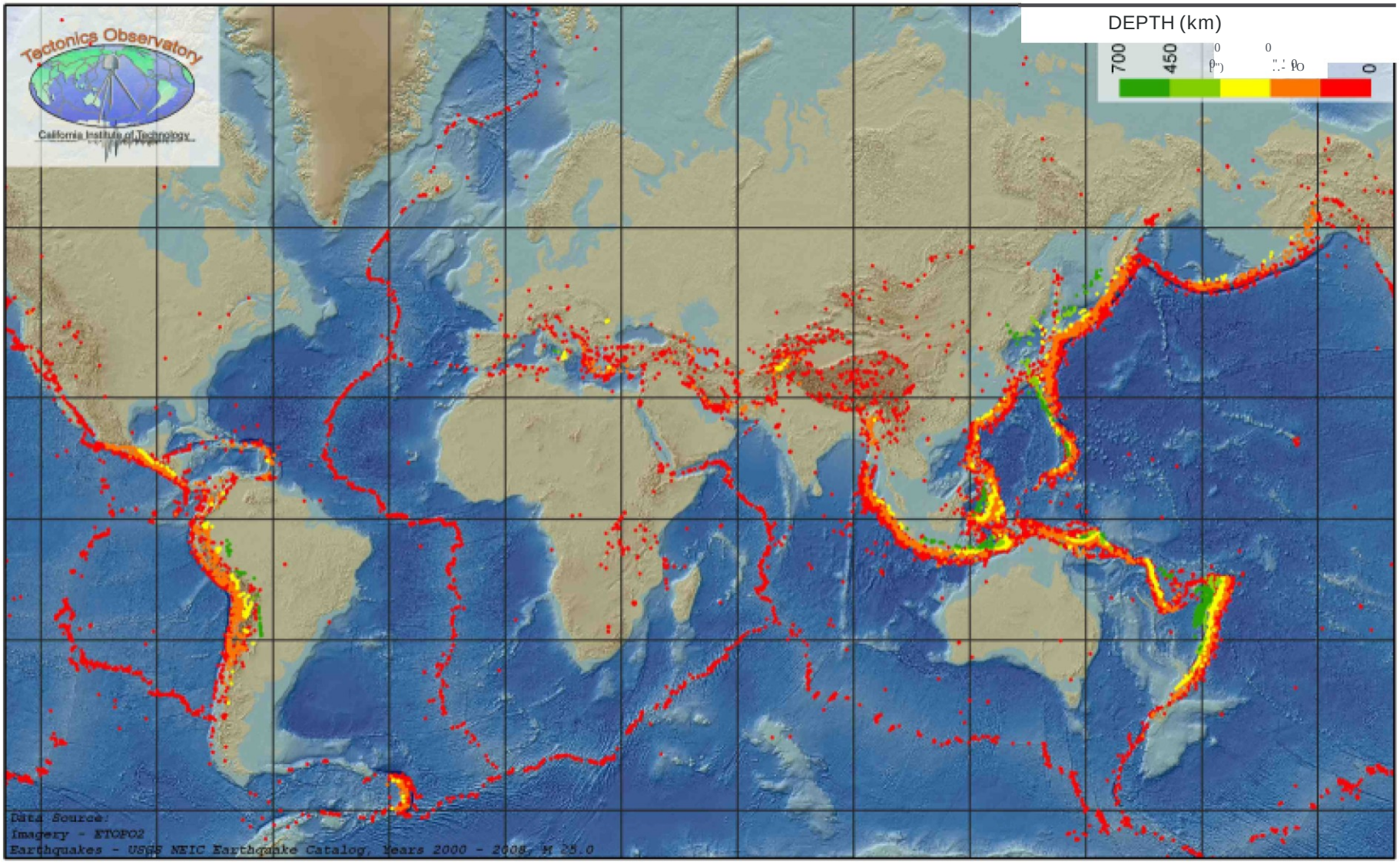
Volcanism in subduction zones: subduction is needed



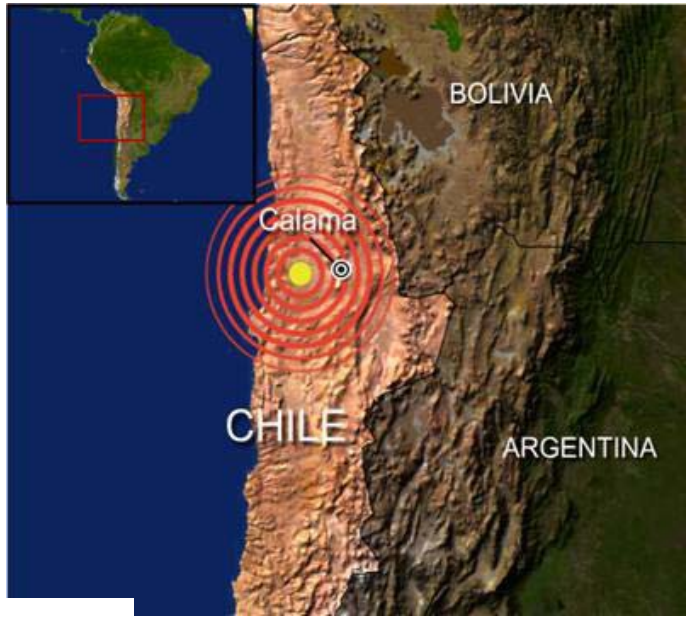
Fluids are carried at depth by the subducting slab

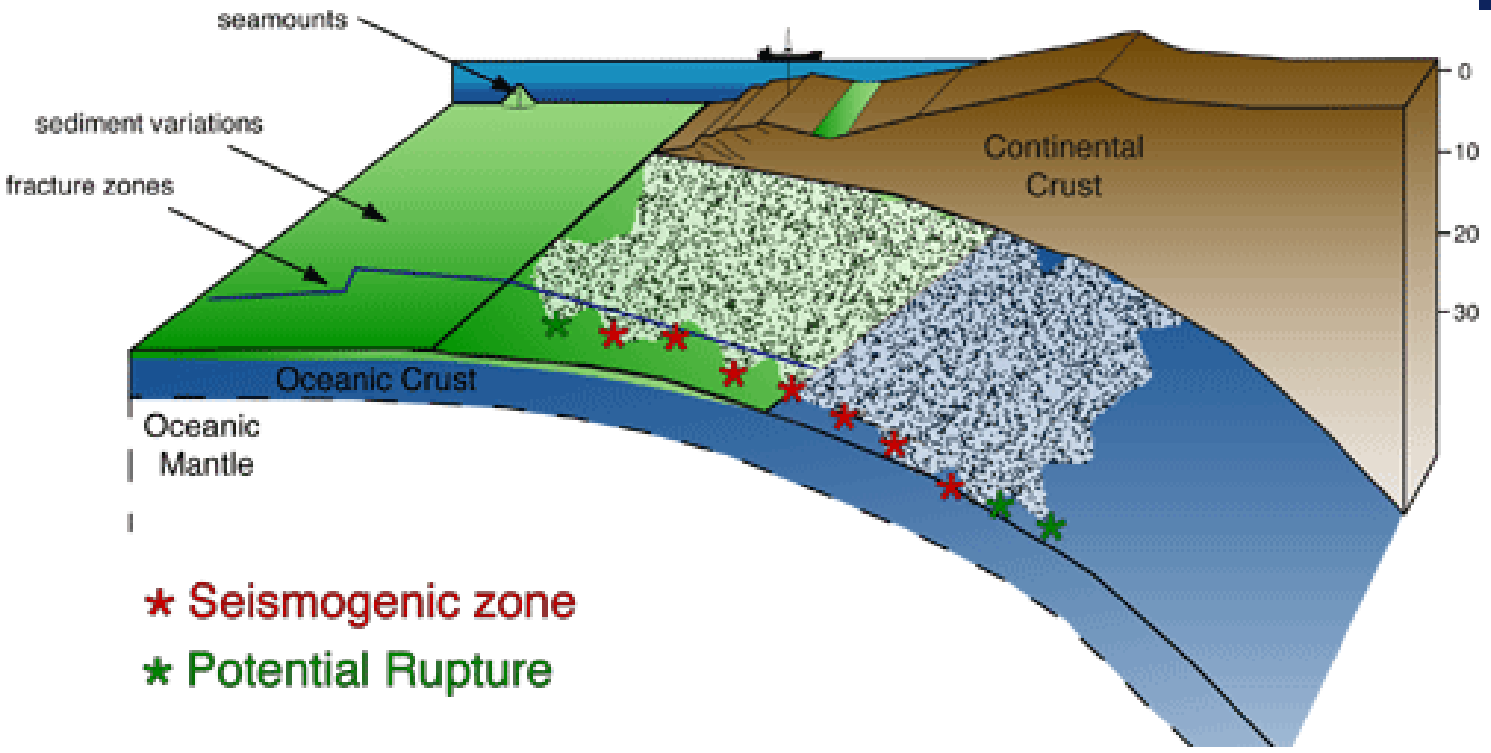
Once they reach a depth of ~100km they are expelled and move upward thereby melting overlying rocks

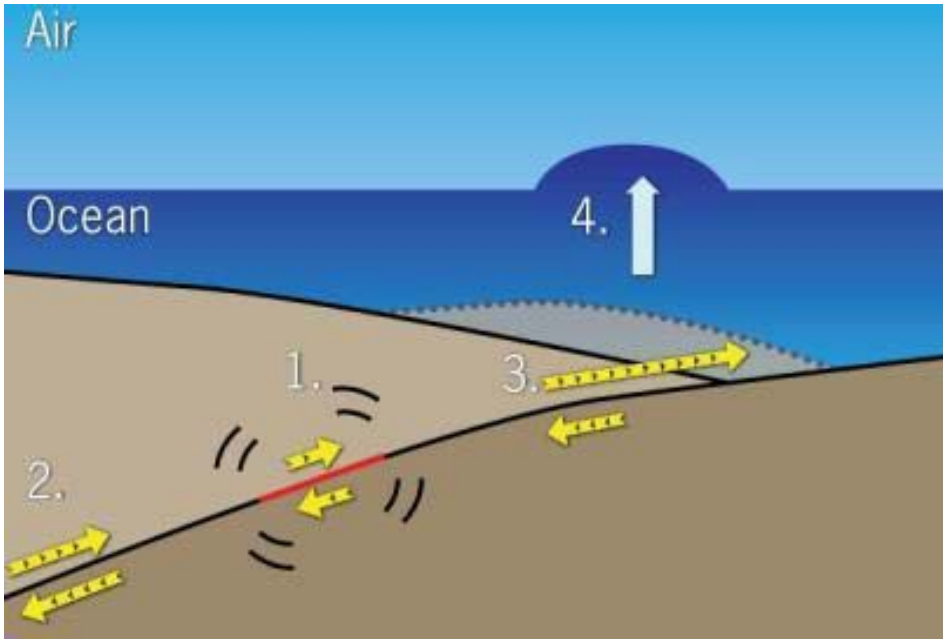
The earthquake map



Earthquake: huge friction is generated between the upper and the lower (subducting) plate



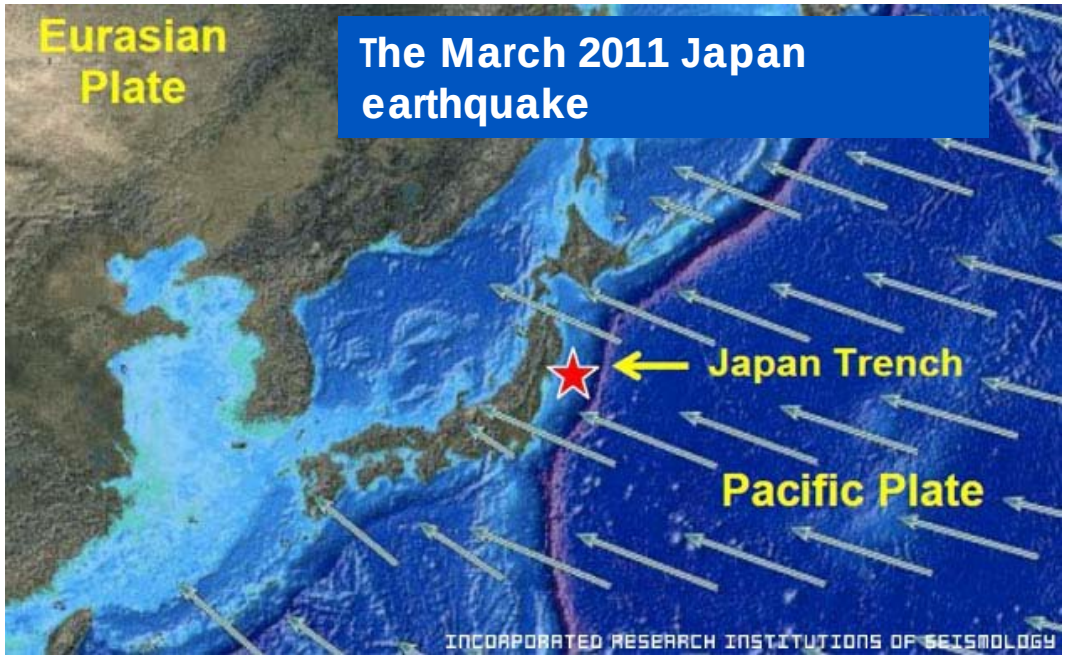


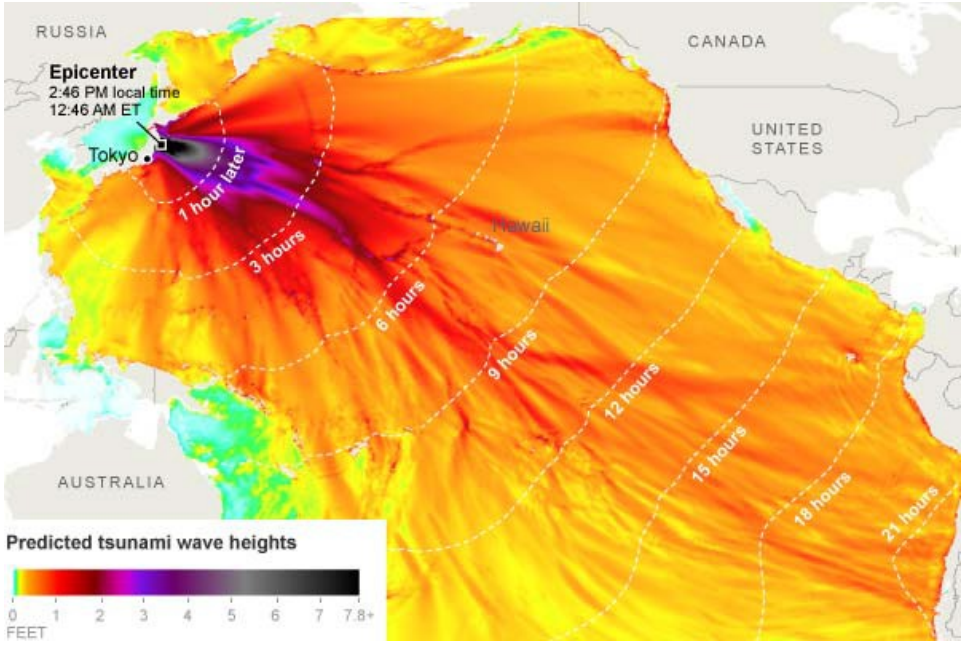


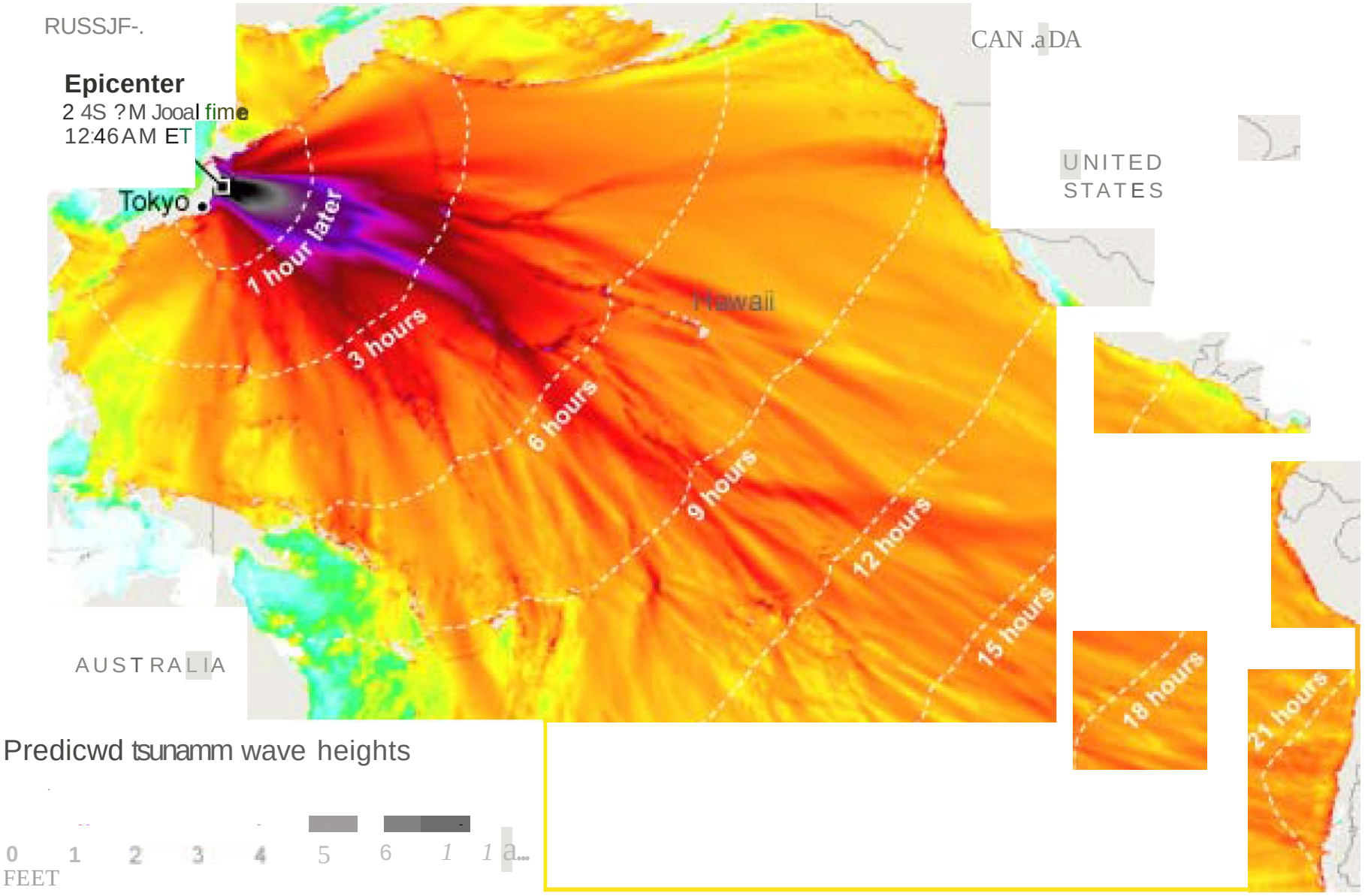
Convergence during the inter-seismic stage is accommodated by warping of the upper plate. Stress is accumulated.

During the earthquake, the upper plate suddenly rebounds to its previous position.

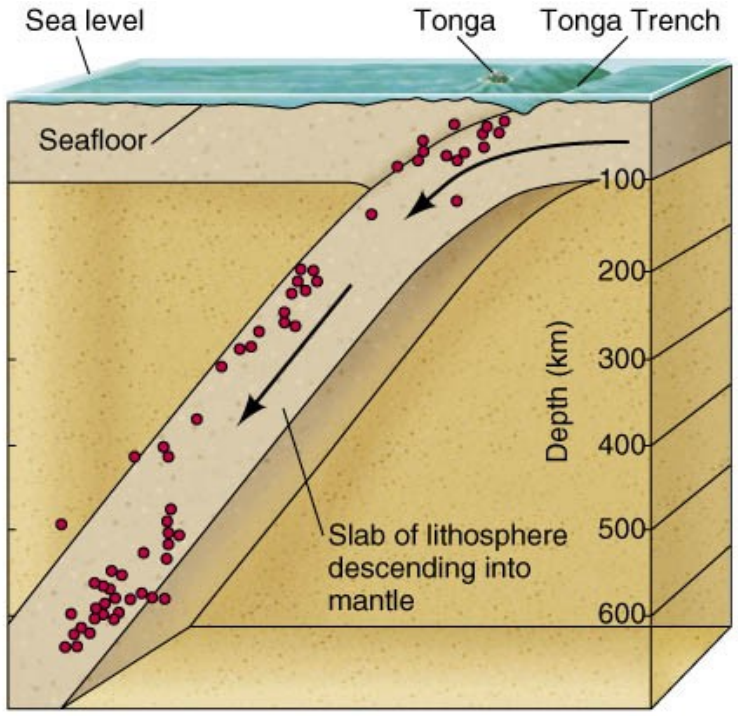
When submarine a tsunami is generated

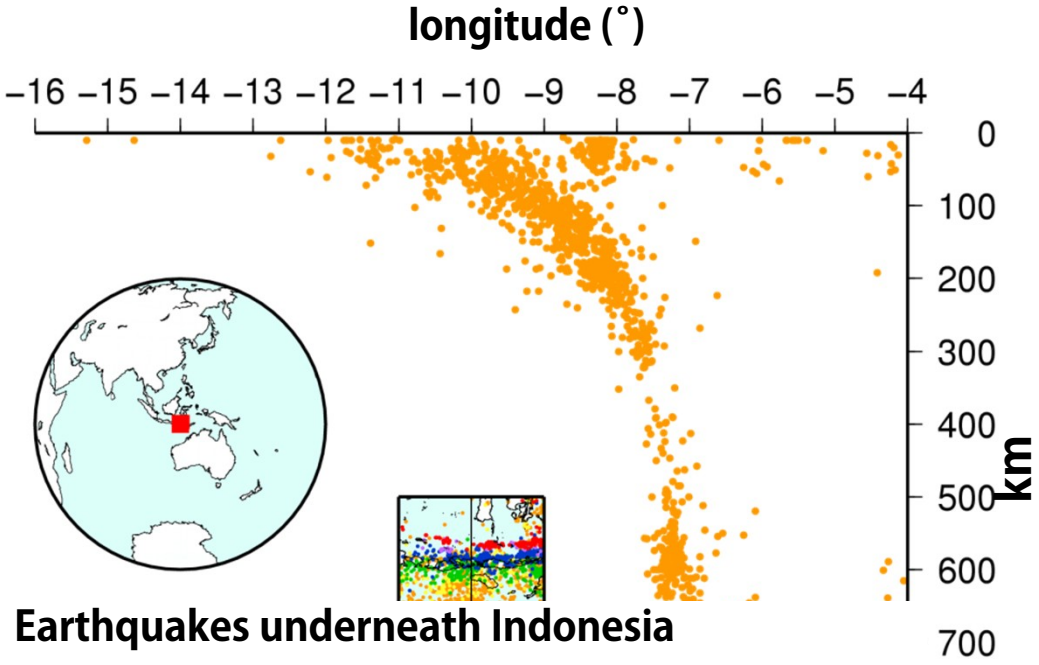





RUSSJF-.
CAN .aDA
Epicenter
2 4S ?M Jooal fime
12:46AM ET
Tokyo
UNITED
STATES
1 hour later
3 hours
6 hours
9 hours
12 hours
15 hours
Hawaii
18 hours
21 hours
AUSTRALIA
Predicwd tsunamm wave heights
0 1 2 3 4 5 6 1 1 a...
FEET

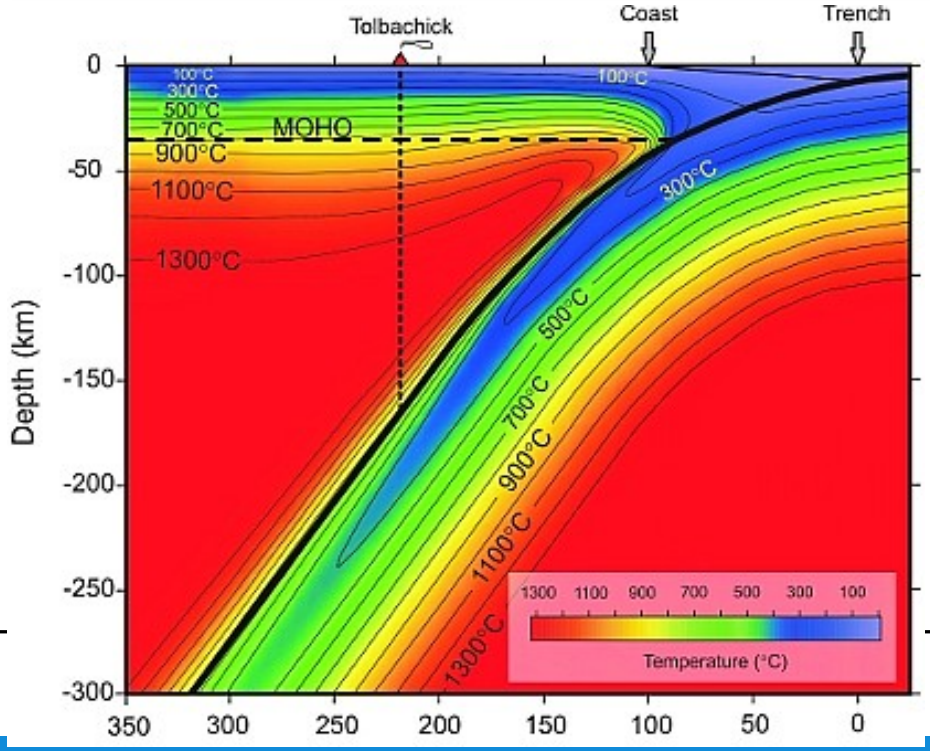
Earthquakes occur down to >500km depth (Wadati-Benioff zone)





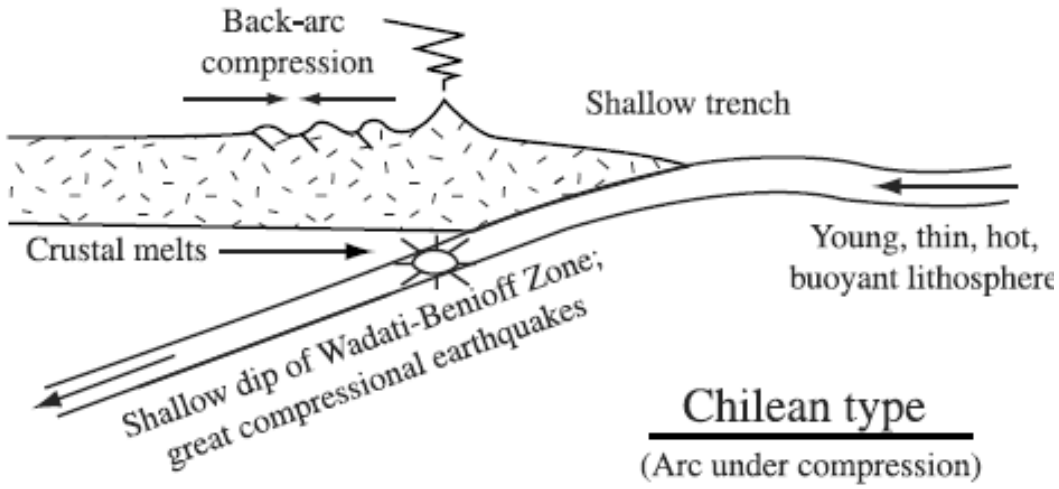
Earthquakes underneath Indonesia

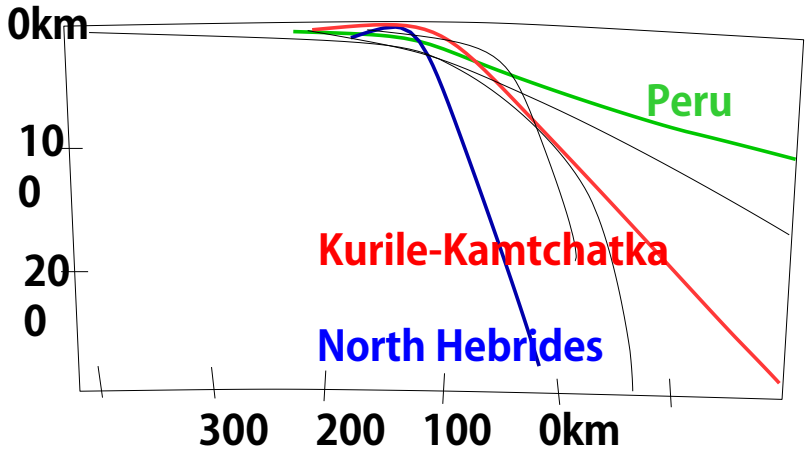
Implies friction down to large depths



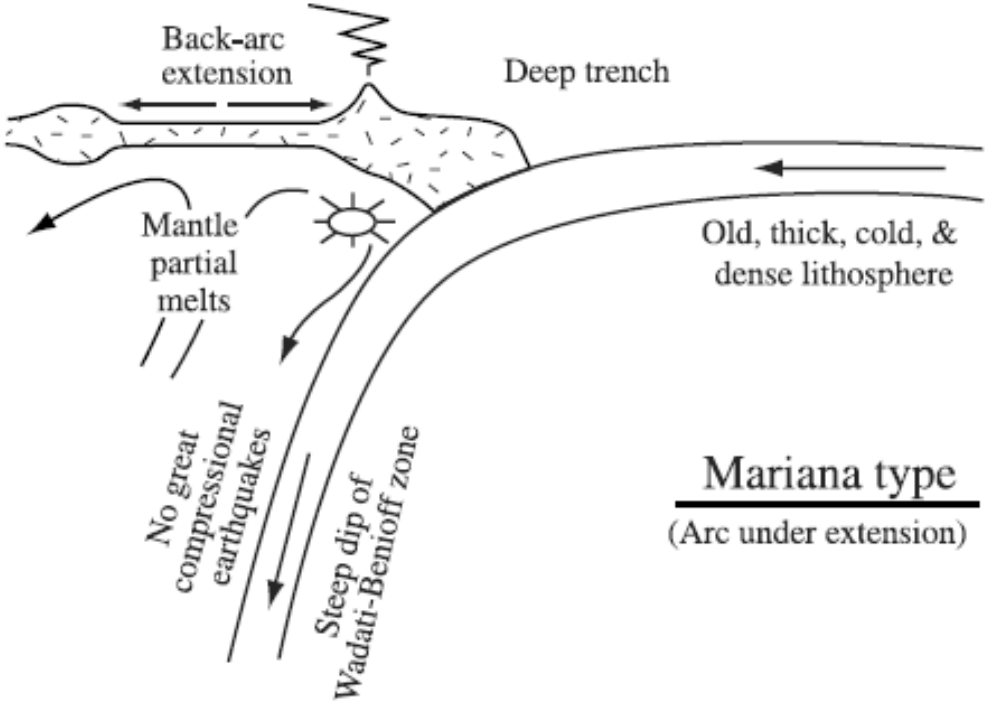
thermal structure of subduction zone

Two end-member settings of subduction zones: Andean- and Pacific-type



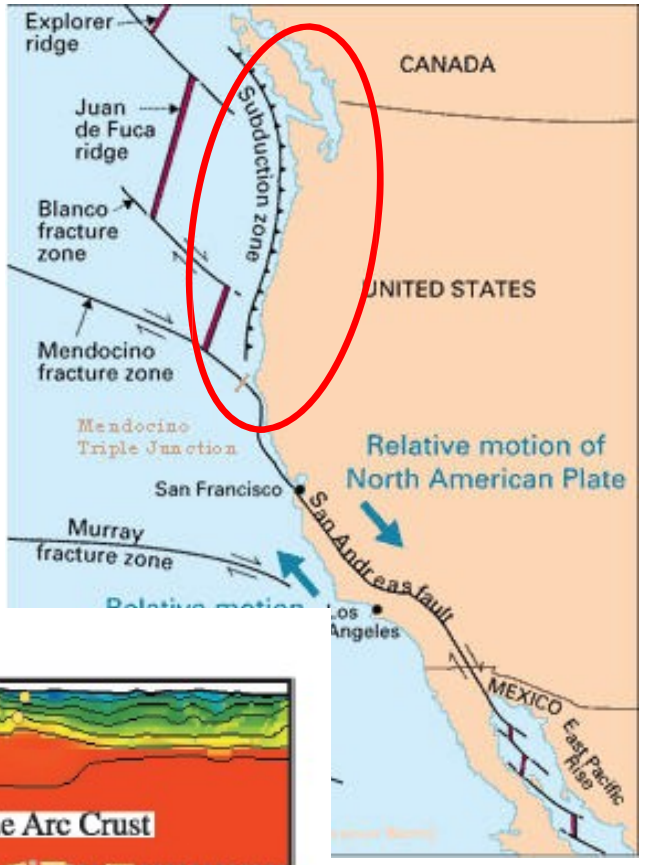


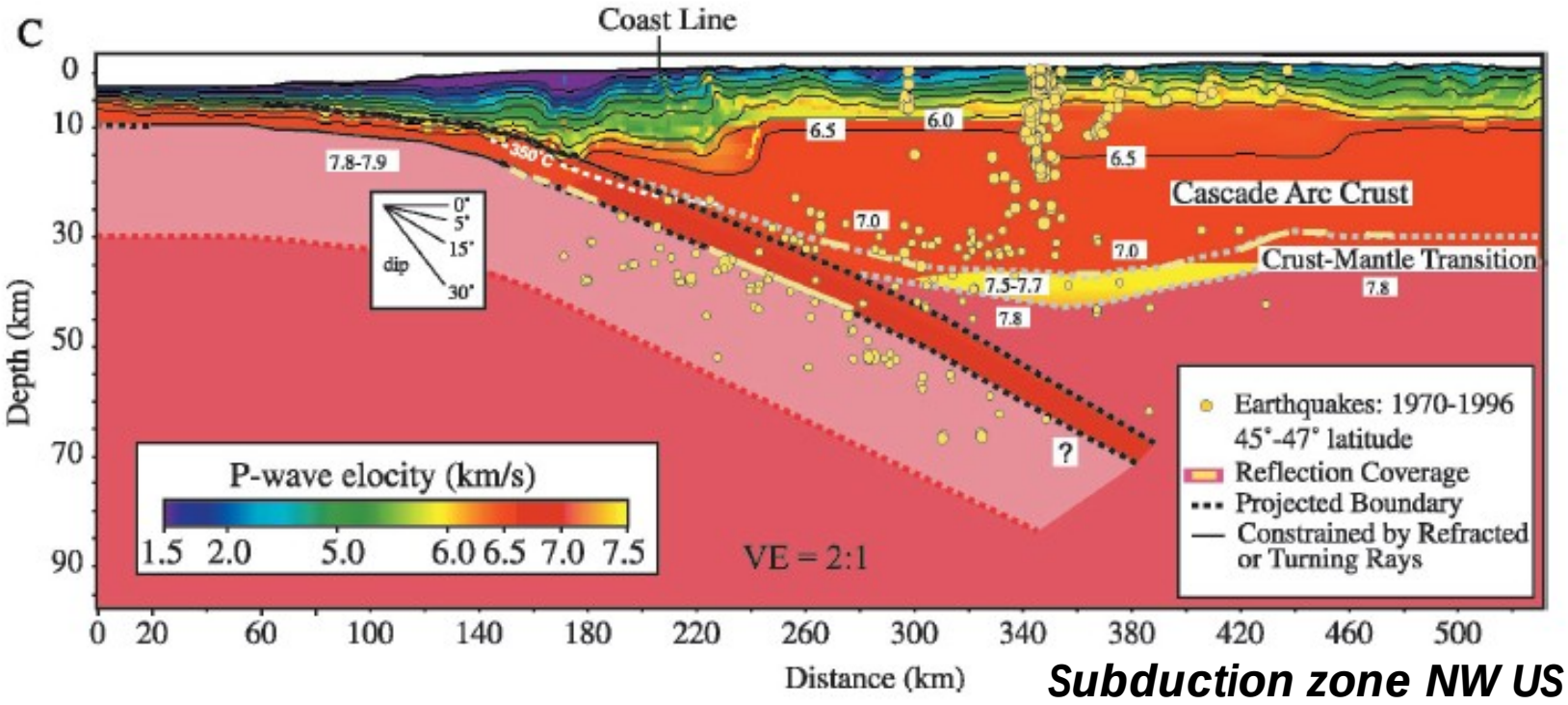
Dips of different subduction zones



Andean type

- shallow dipping slab
- high mountains
- little to no deformation in the upper plate
- major, not-too-shallow earthquakes

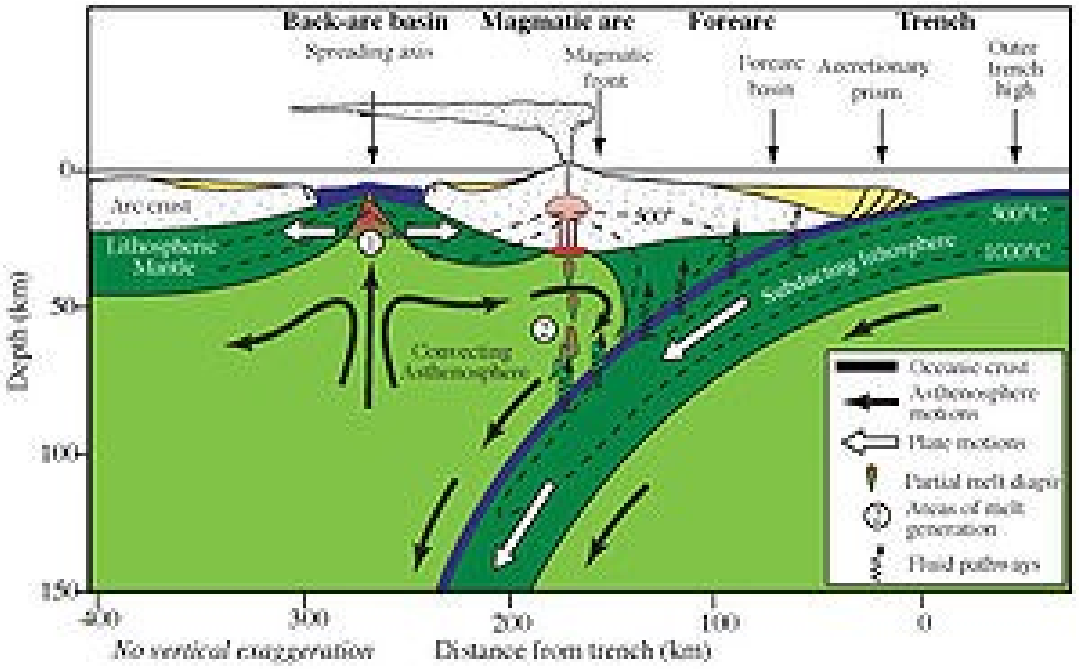




Subduction zone NW US - (Stern 2002)

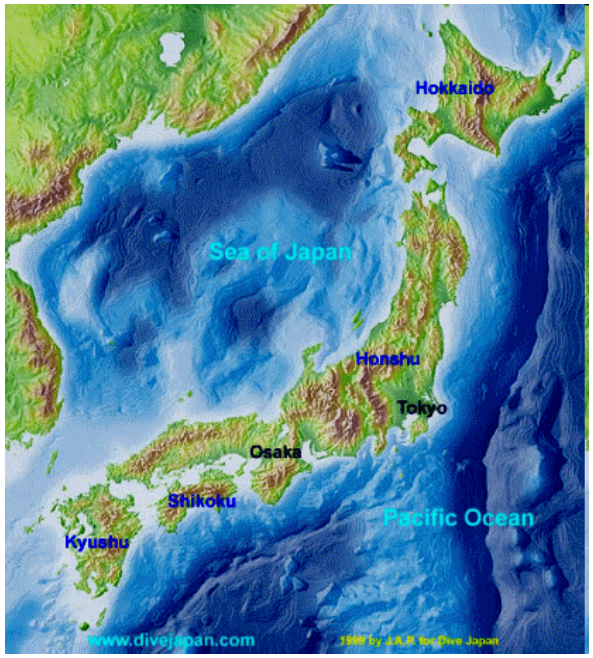
Pacific type

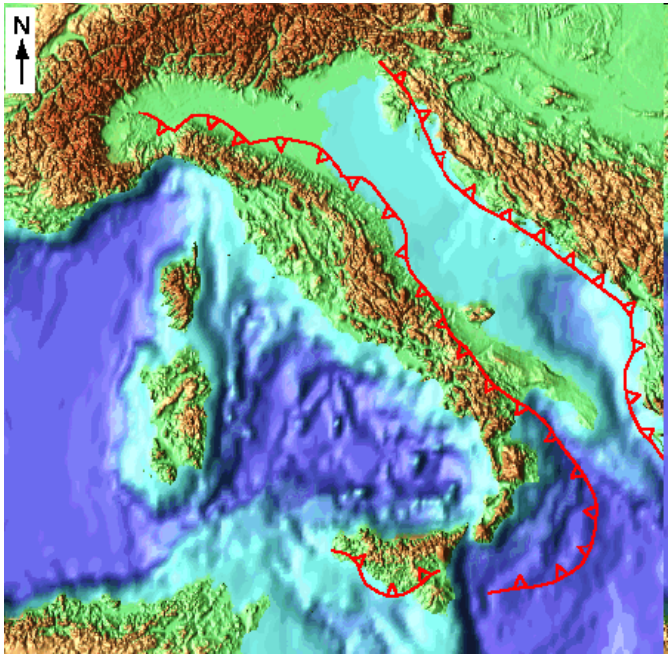
- steep slabs
- low relief-mountains
- major extension in the upper plate (back-arc basins). Can lead to the opening of an ocean



Two famous examples: Japan and the Tyrrhenian Sea

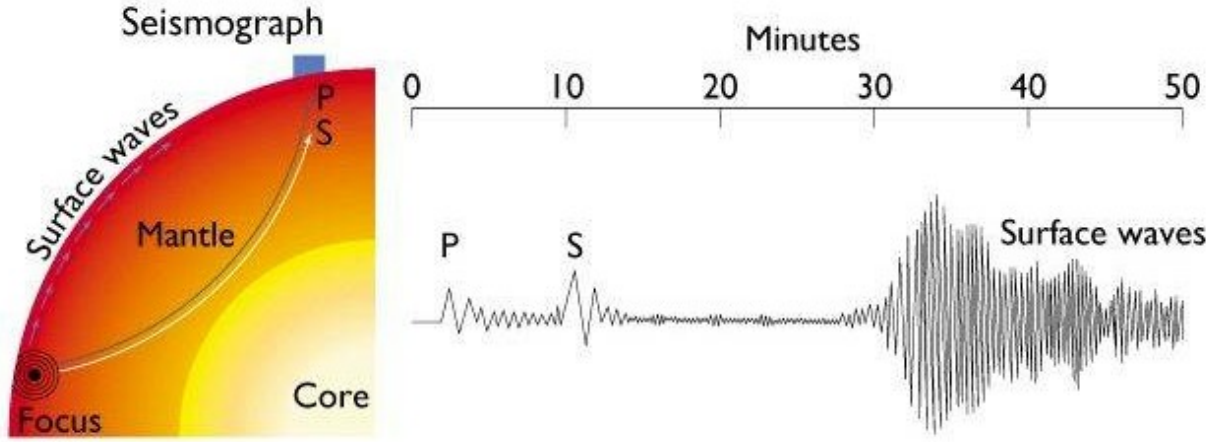
Steep subduction zones and associated belts are (very) curved

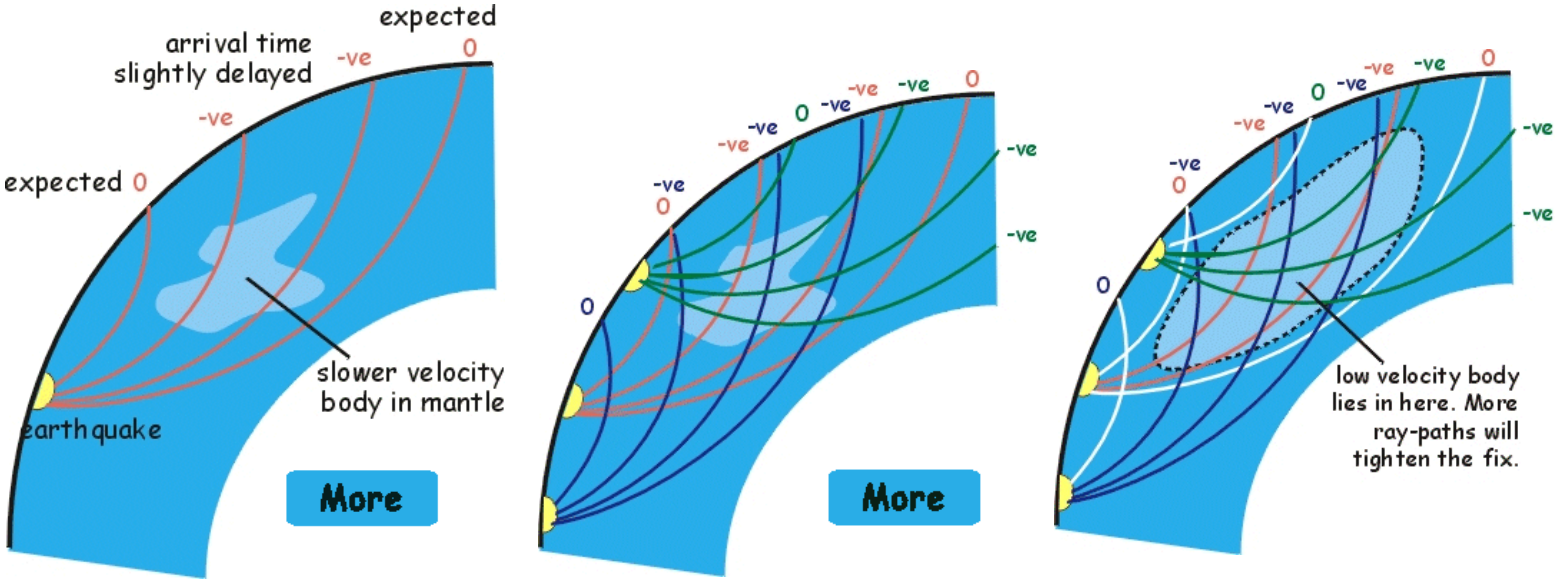




Remember tomography? a great tool to image the Earth

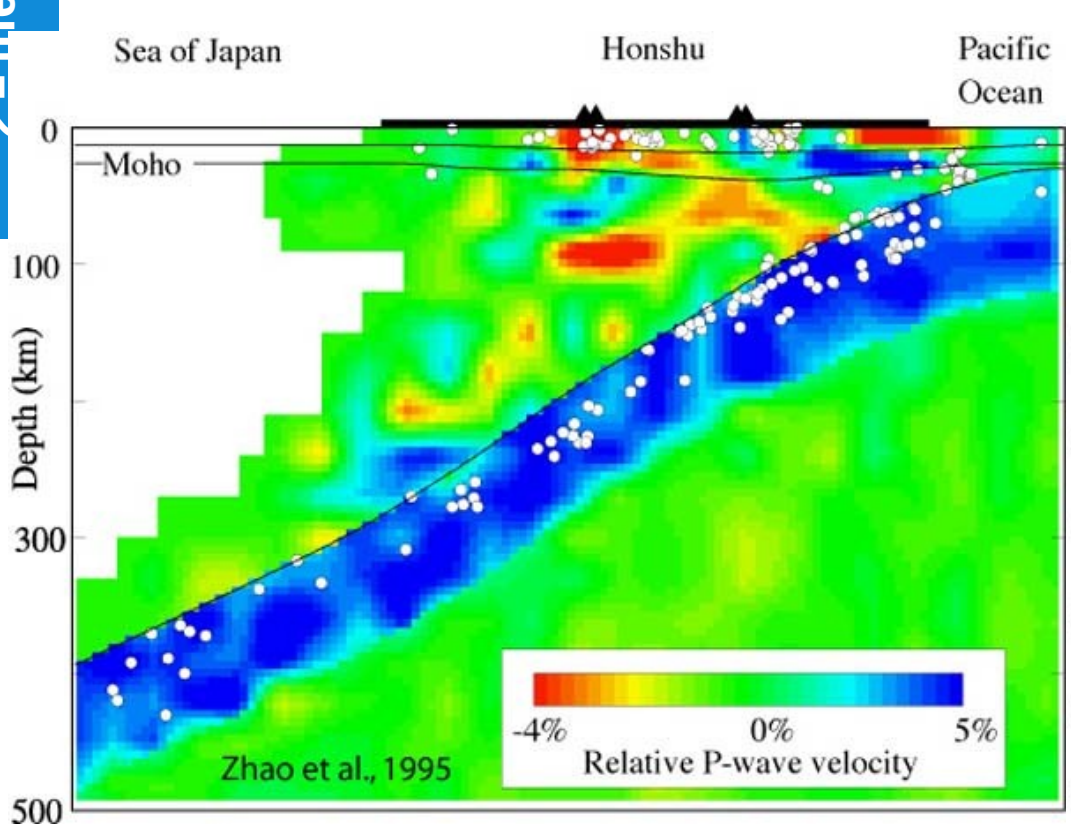
The basics of tomography (applicable at very different scales)

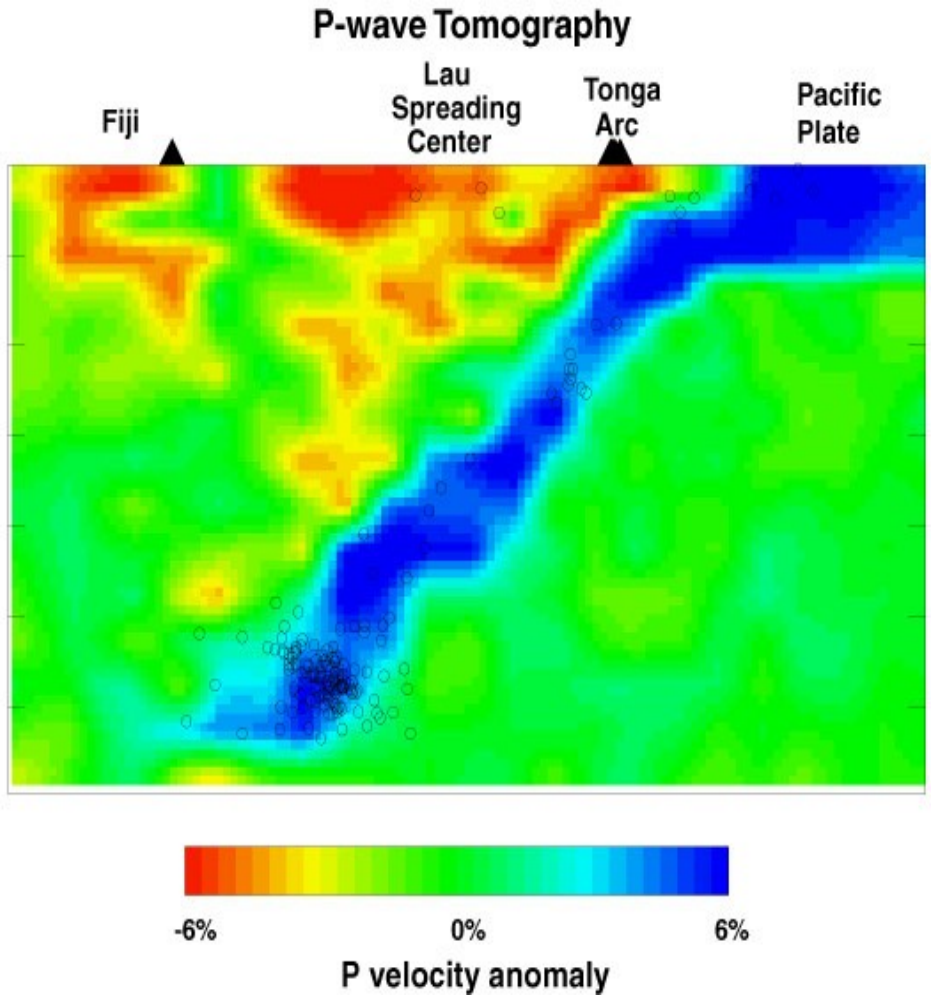




Using a large number of ray paths we determine the velocity deviations with respect to a given model

Examples

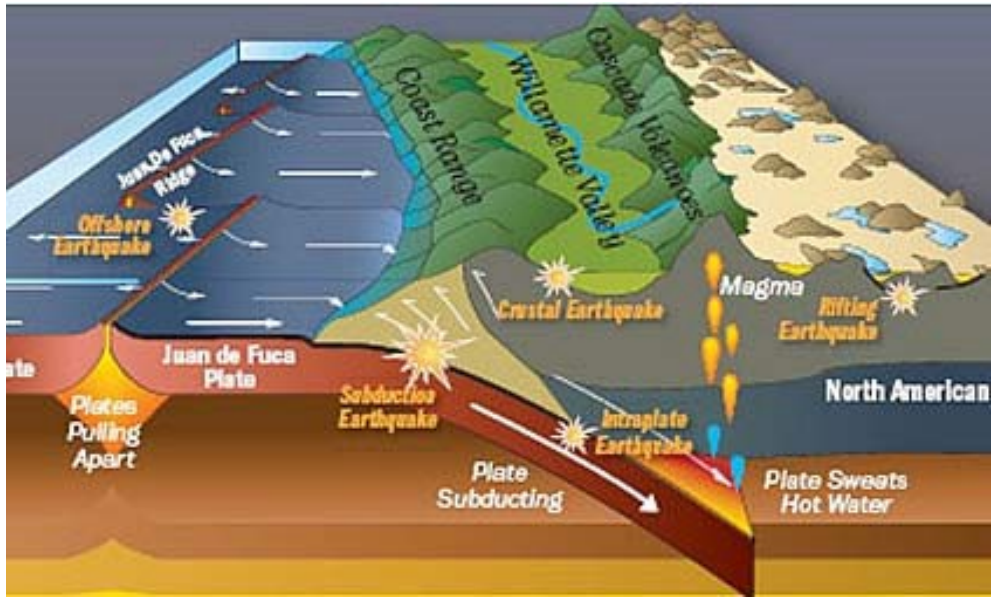


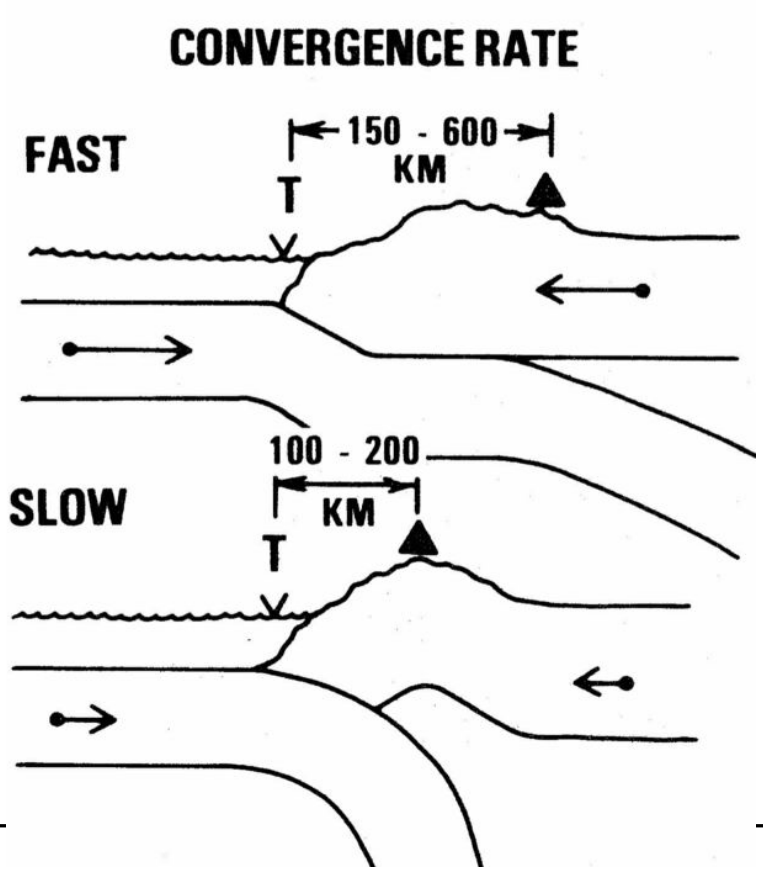


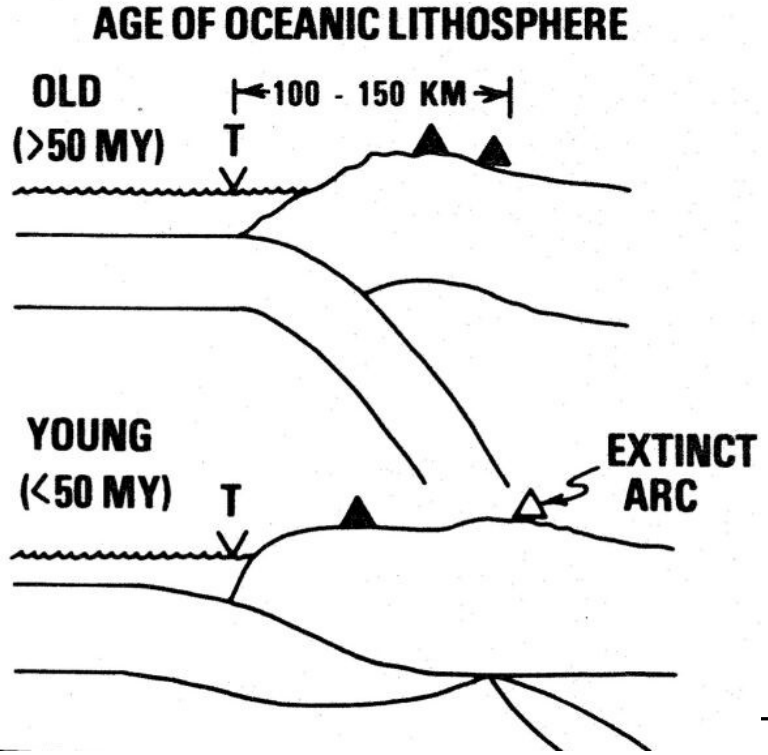
What controls the seismic velocity? What is the geological information we can extract from this data?

Andean or Pacific type?

Which of the two mode develops depends on the competition between horizontal velocity and gravity (=weight of the subducting plate)

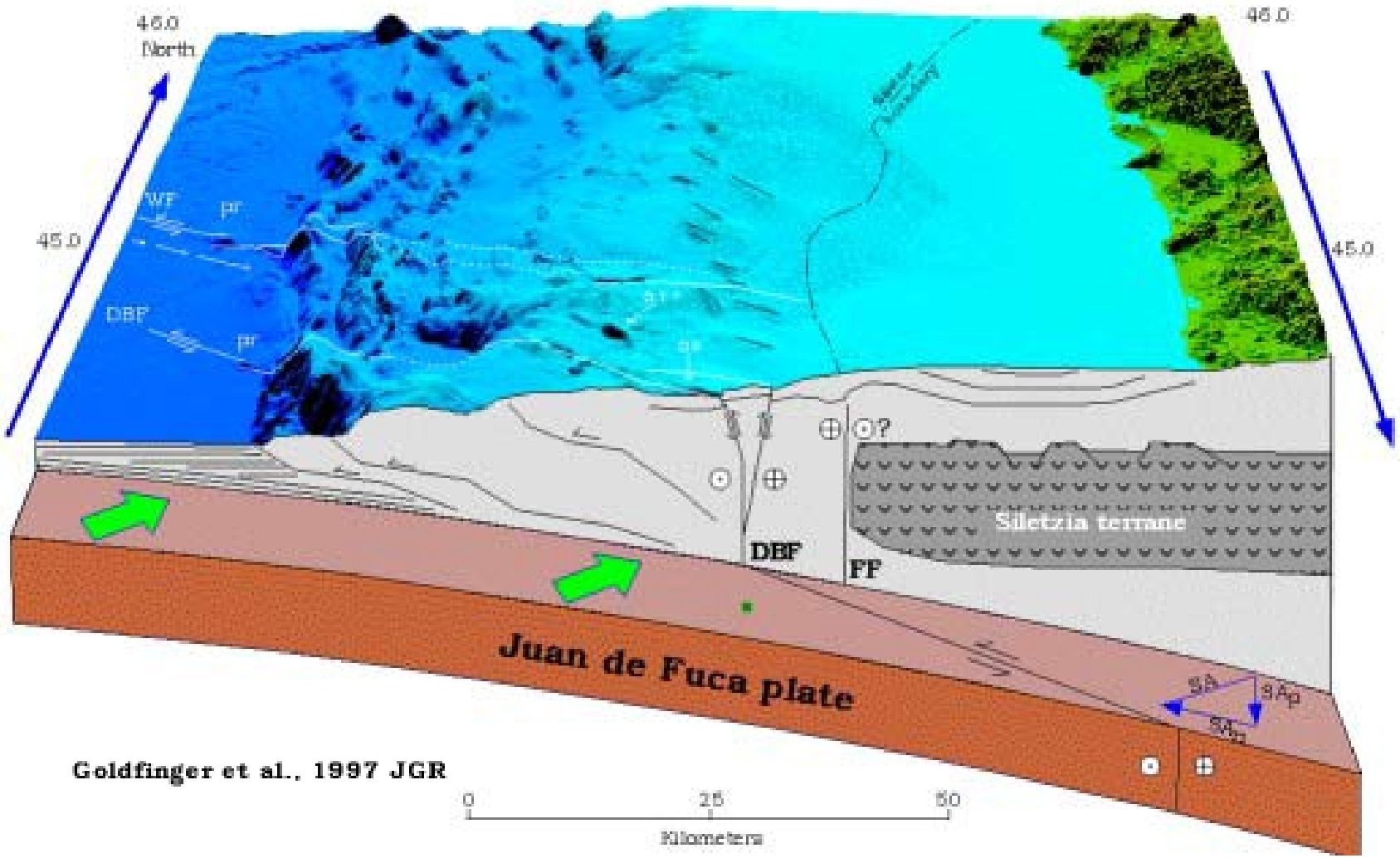




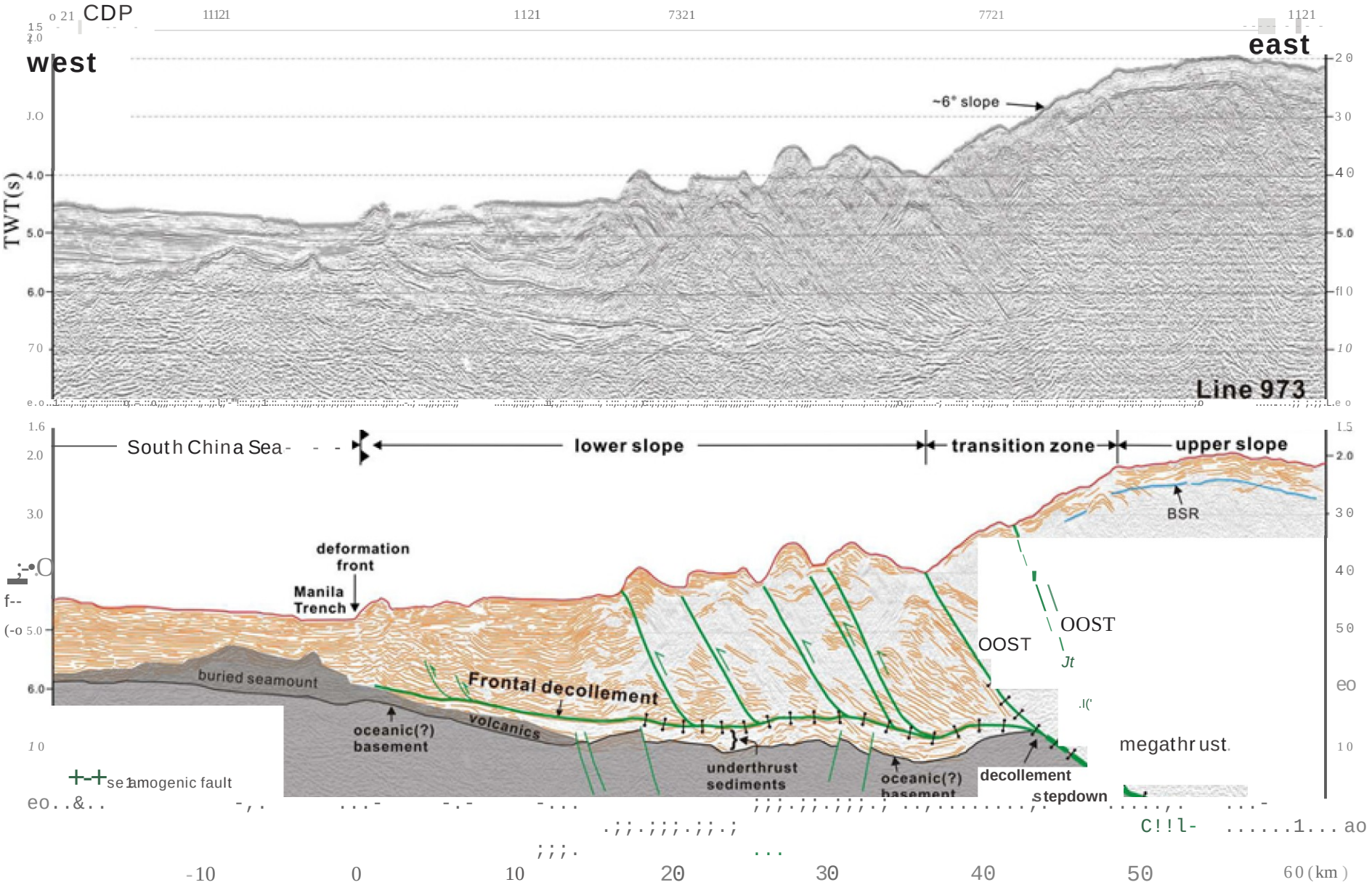


Accretionary wedge

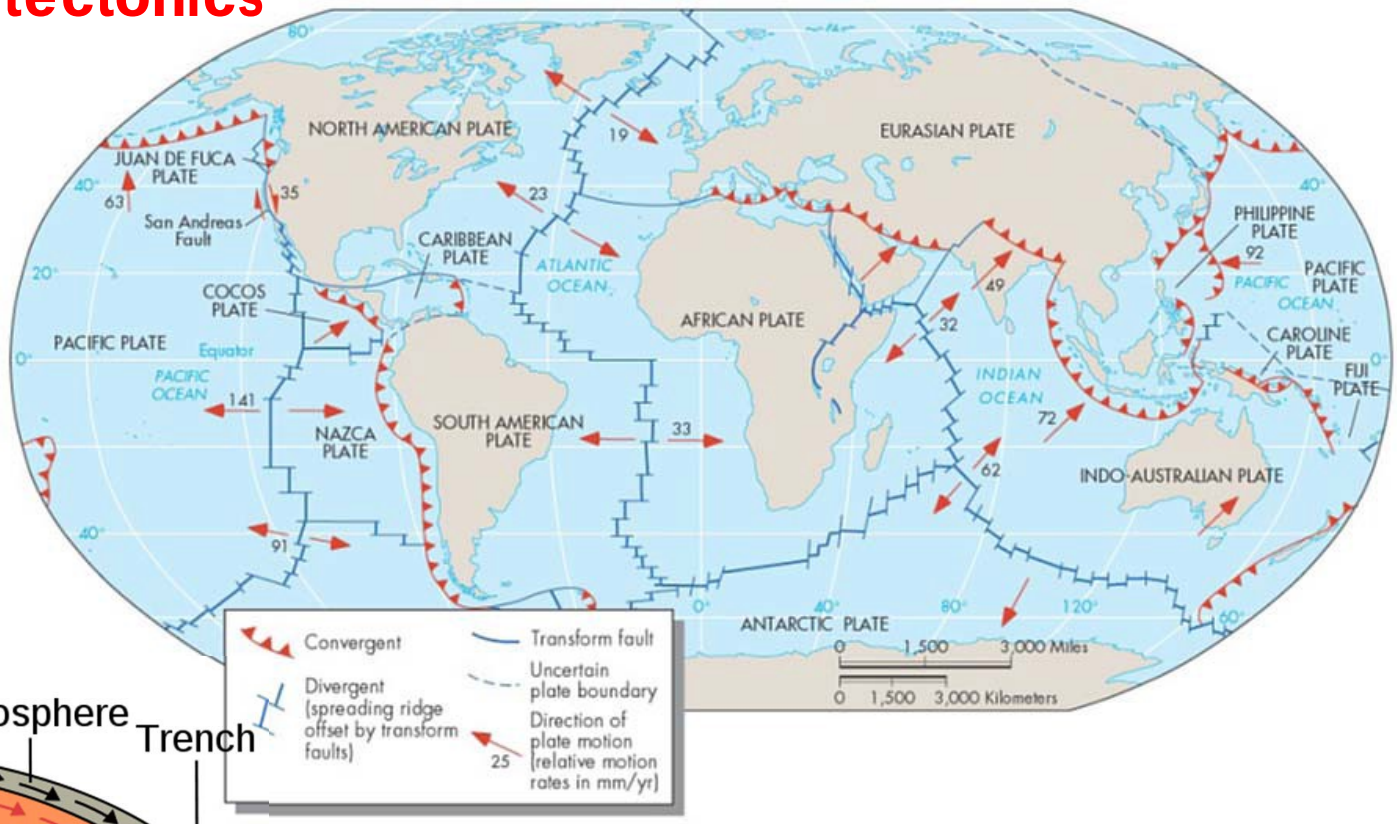
During subsidence, rocks from the lower plate are moved taken away form the lower plate and incorporated in the upper plate.

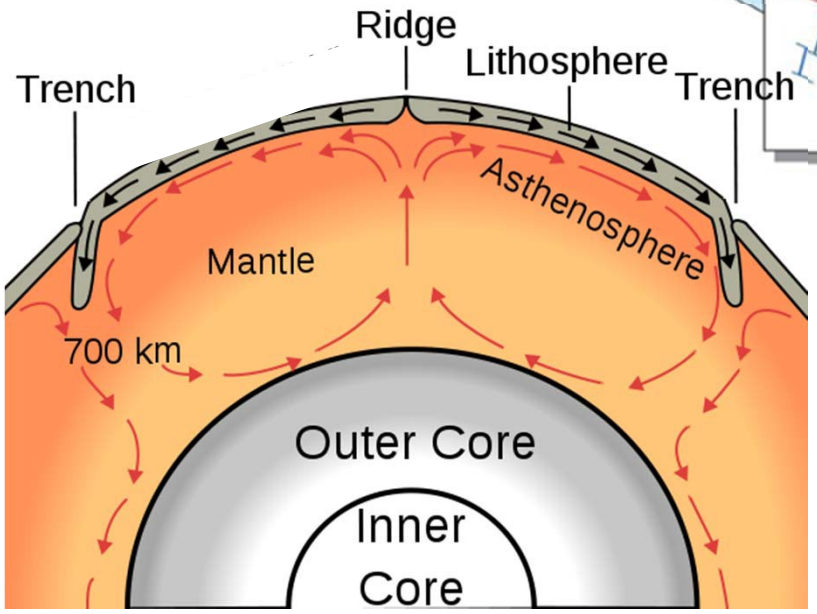


The Nankai orogenic wedge (Taiwan)



Summary of plate tectonics

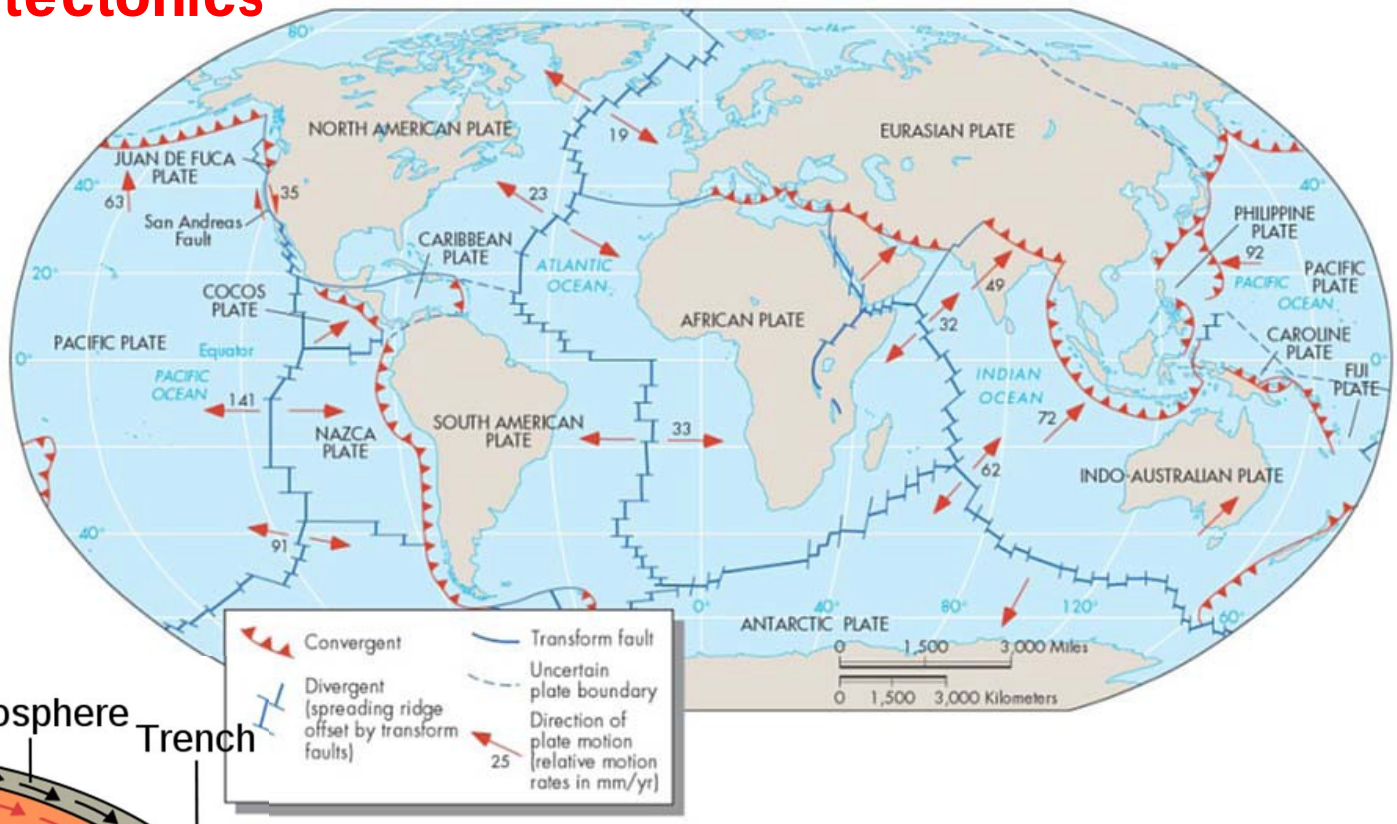


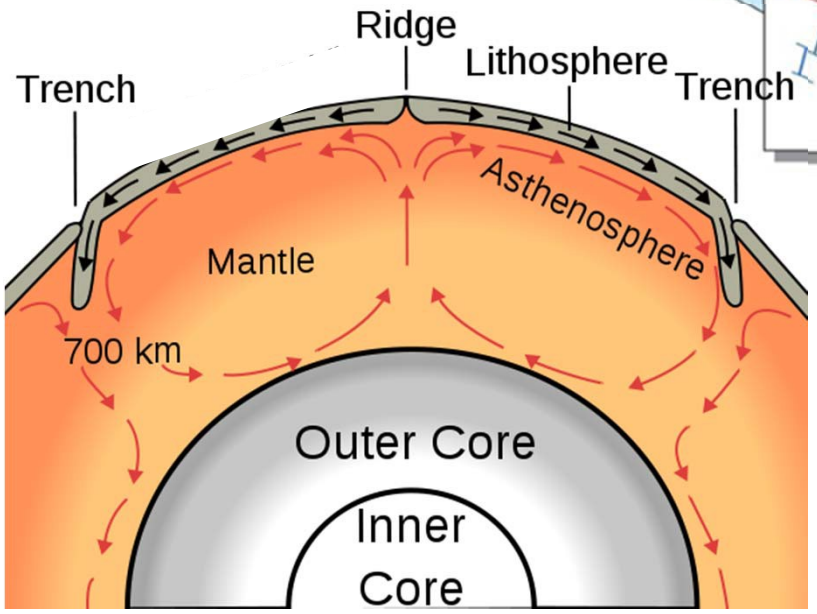


Everything working well?

Real world plate tectonics

Summary of plate tectonics



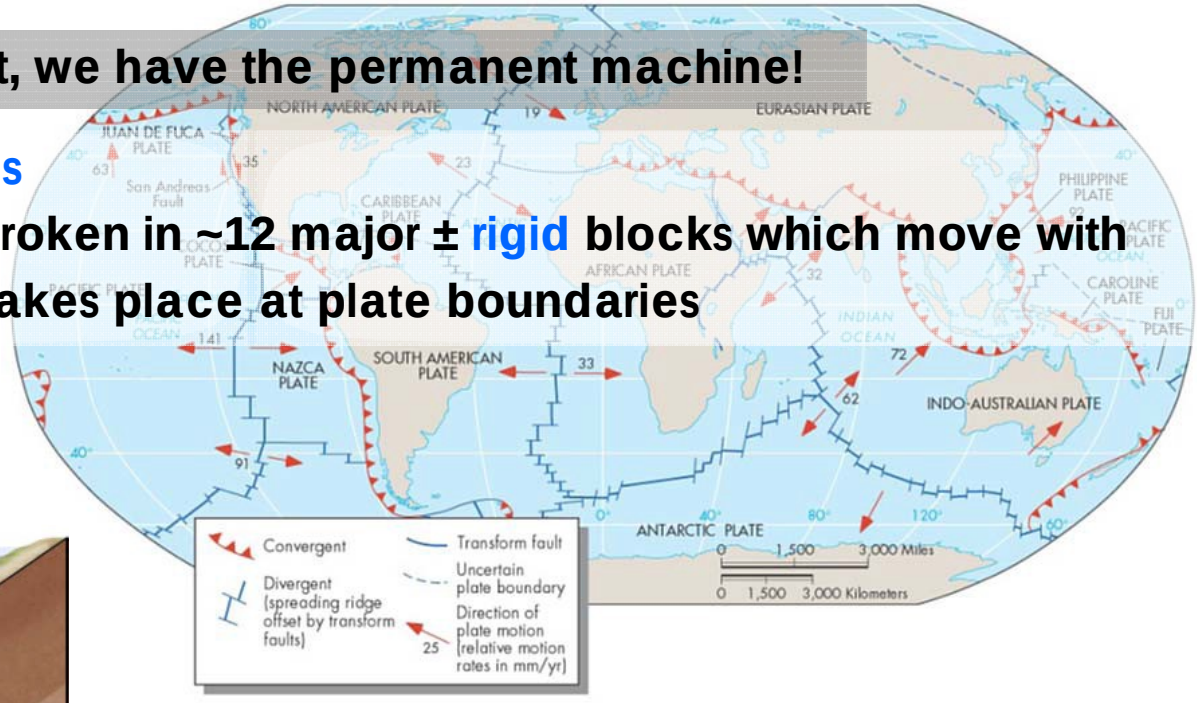


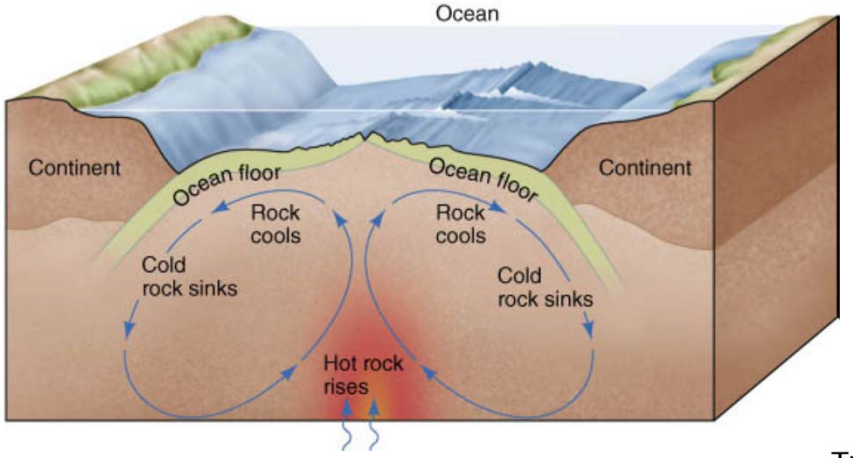
Everything working well?

Everything seems to be perfect, we have the permanent machine!

(Mickey Mouse) plate tectonics

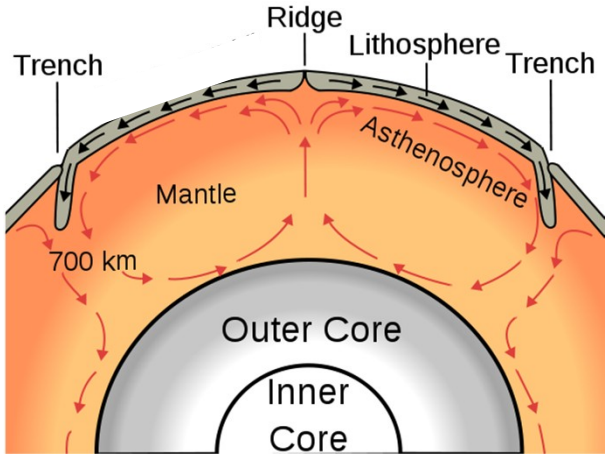
The lithosphere of the Earth is broken in ~12 major ± rigid blocks which move with respect to each other; action takes place at plate boundaries





The machine goes on forever without modifications (no history).

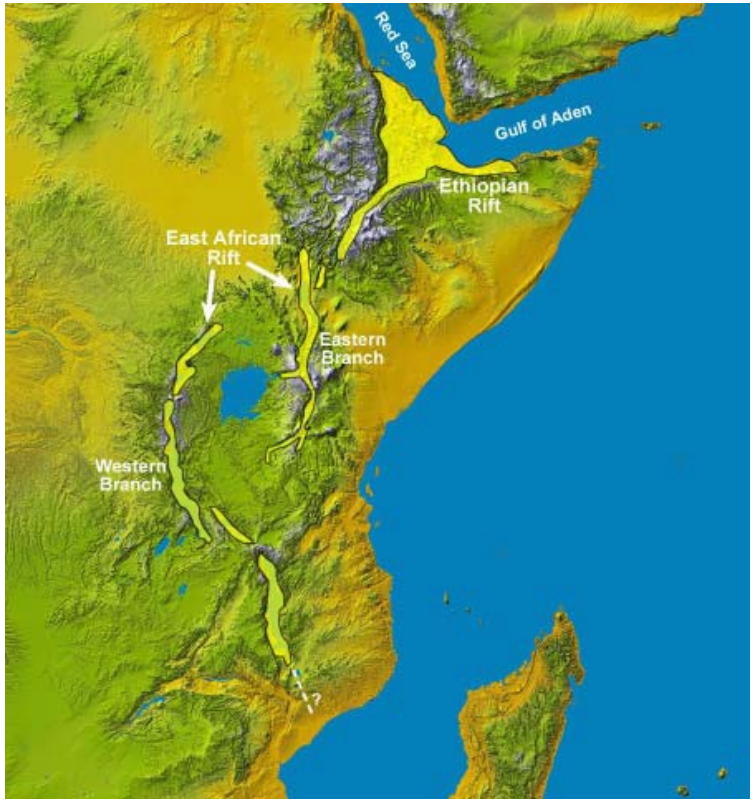
Implies very simple convection patterns

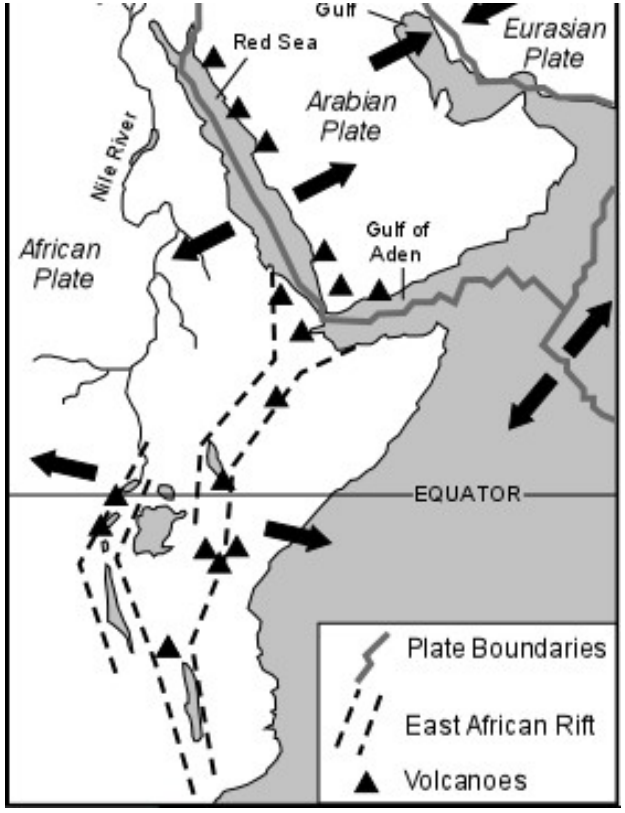


Looking carefully…. serious problems

Divergent boundaries are born

The East African rift



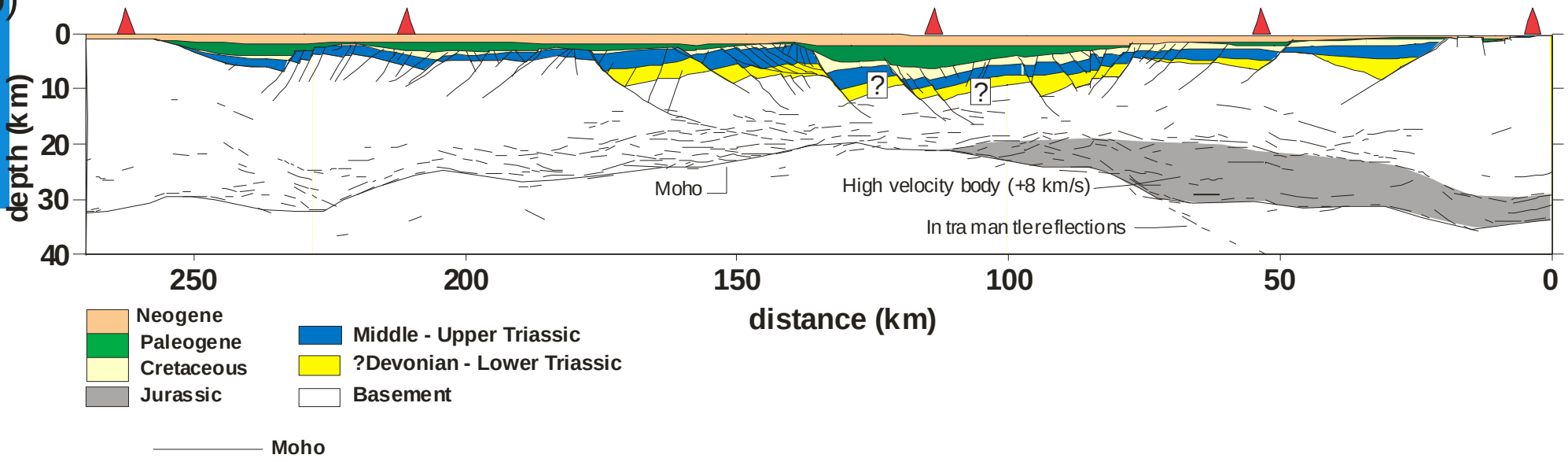


This is continental rifting

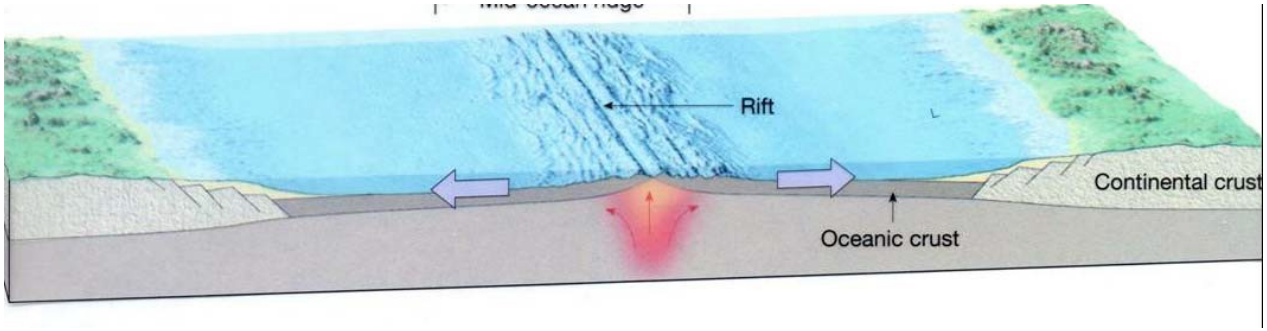
Continental rifting produces crustal thinning and creates accommodation space

the North Sea

b)



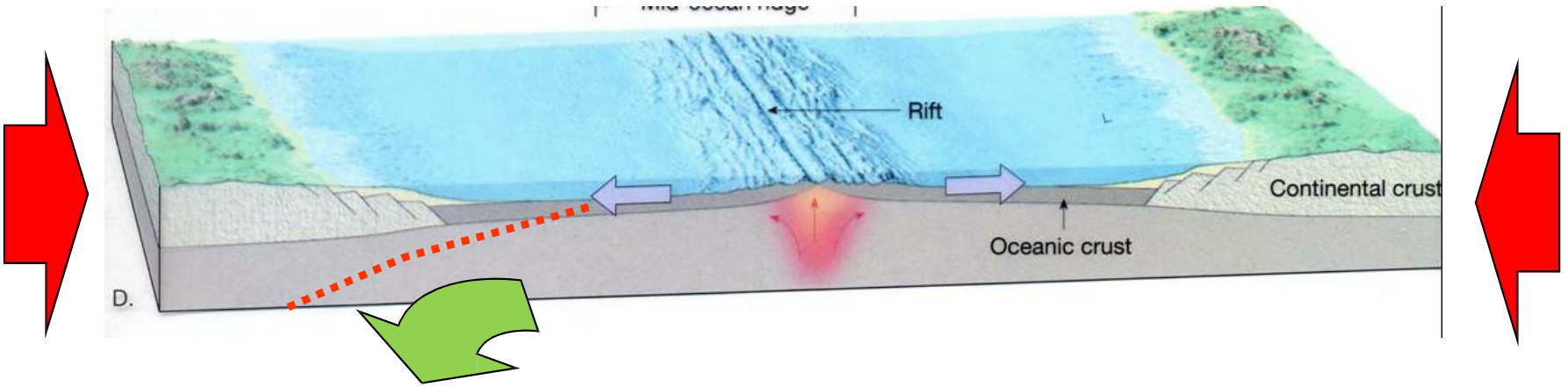
Note: at present there is no extension across the North Sea. Rifting died



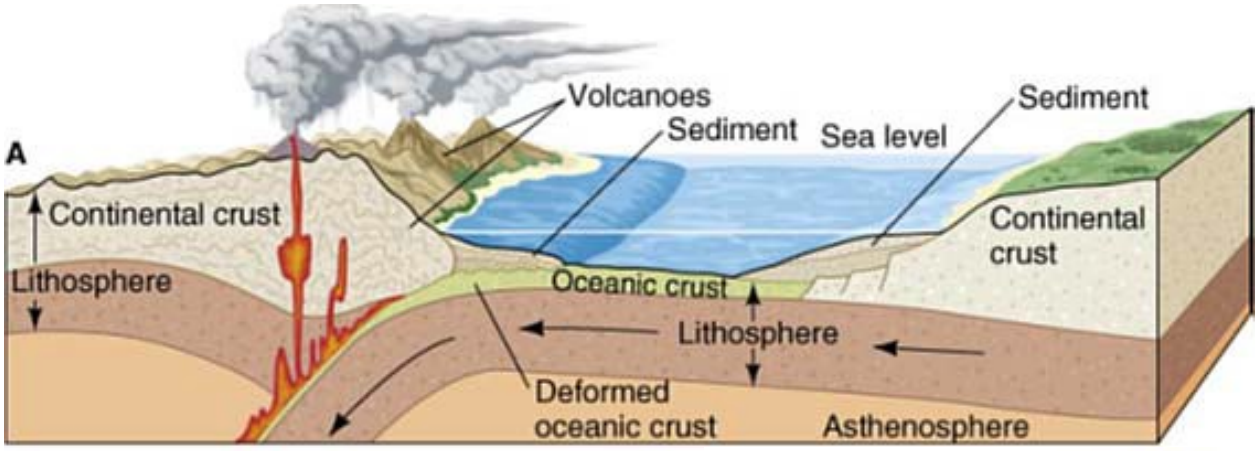
Had extension continued we would have had

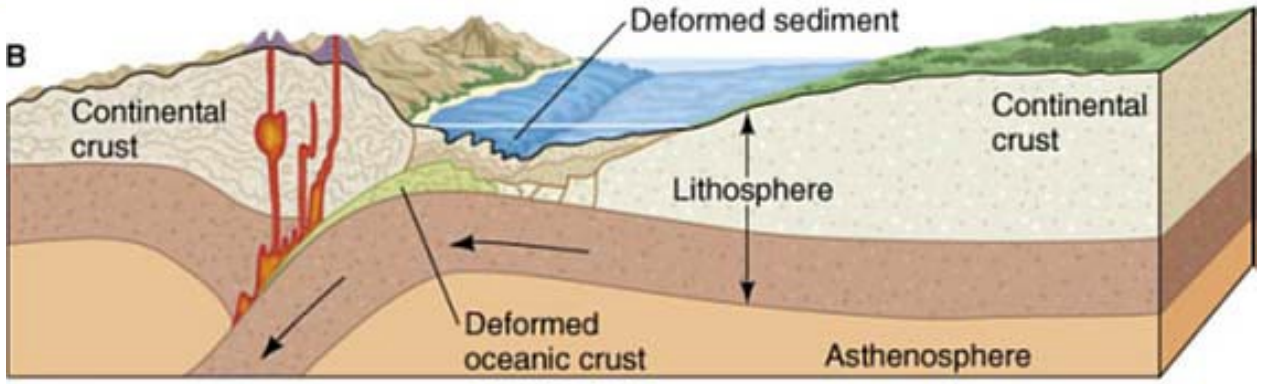
- **two plates**
- **two plate margins**

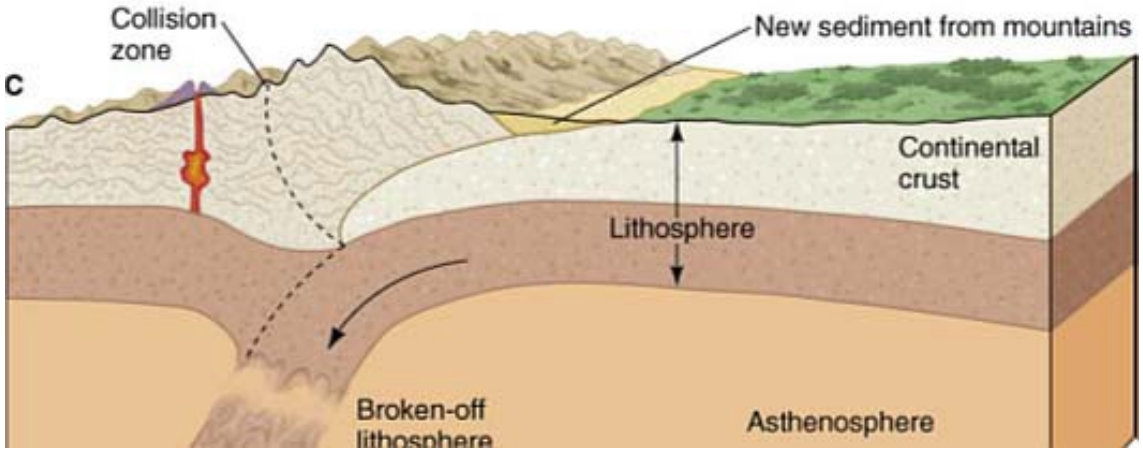
Not only, rifts can begin and die. In some situations the forces can change and the system is set under compression



The oceanic ridge and the passive continental margin will progressively enter the subduction zone







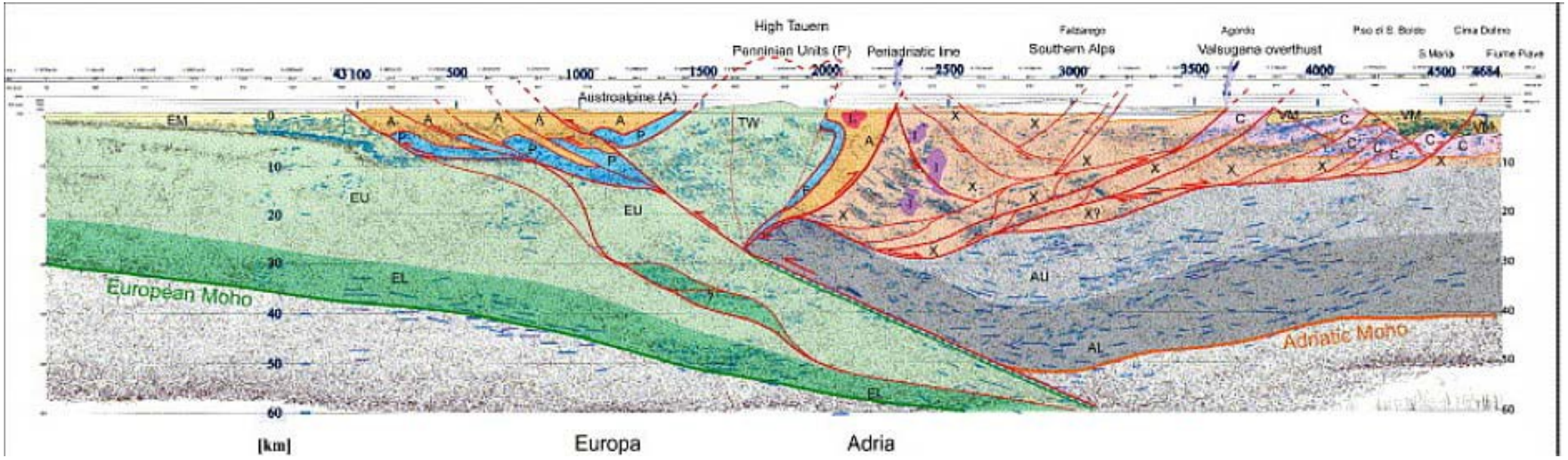
The continental collision marks a slow-down of the convergence between the two plates and, often, the end of subduction.

Any idea why?

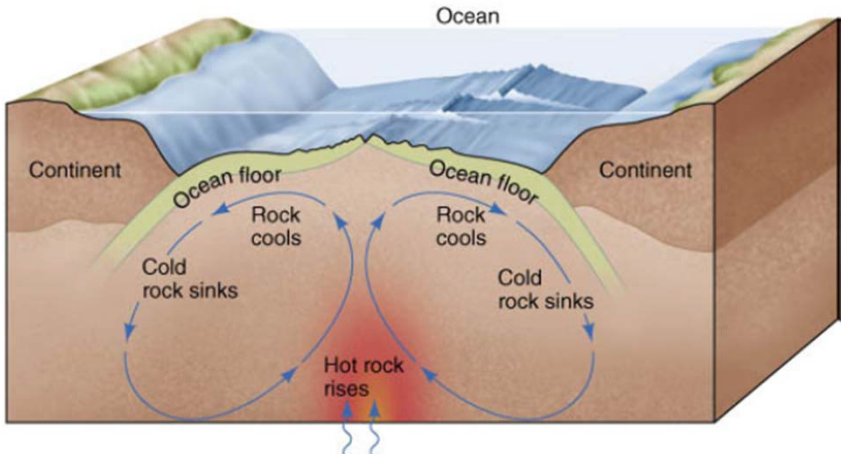
The Alps

A great example of collisional belt (between Africa and Europe).

•The convergent boundary is nearly dead,
• the two plates are becoming one.



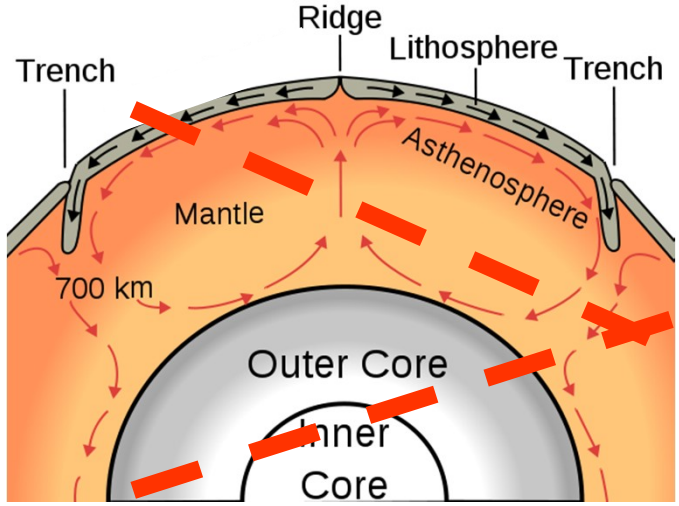
The simple-minded convection models does not seem to work very well

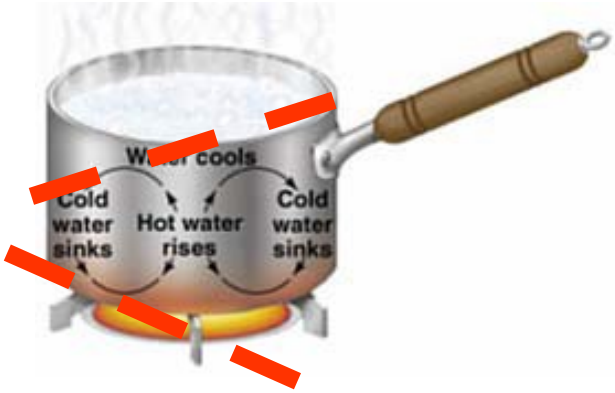


~~Subducting plates should all be of oceanic nature~~

~~Subducting plates should be infinitely long~~

If the Mickey Mouse plate tectonic does not work well, we conclude that also the underlying simple convection model is inadequate





How does convection work?

Sources of figures

http://www.studyblue.com/notes/note/n/chapter-8-earths-interior/deck/1294532

http://bc.outcrop.org/images/earthquakes/press4e/

http://www.somebits.com/weblog/2010/01/

http://foter.com/photo/murnpeowie-meteorite/

http://www.nasa.gov/mission_pages/Grace/multimedia/pia04235.html

http://professoralexeinowatzki.webnode.com.br/geologia/estruturas-da-terra/

http://beforeitsnews.com/earthquakes/2013/04/spring-disappears-from-northern-hemisphere-the-winter-that-wont-end-2457450.html

http://thewatchers.adorraeli.com/2011/03/15/about-geomagnetic-reversal-and-poleshift/

http://www.es.ucsc.edu/~glatz/geodynamo.html\

http://www.pinterest.com/nancyshogren/geology/

http://plate-tectonic.narod.ru/plum1photoalbum.html

http://www.teara.govt.nz/en/photograph/9075/dunite

Sources of figures

http://serc.carleton.edu/NAGTWorkshops/mineralogy/optical_mineralogy_petrography.html

http://bc.outcrop.org/GEOL_B10/lecture19.html

http://www.physicalgeography.net/fundamentals/10h.html

http://www.kennislink.nl/publicaties/klimaatverandering

http://gore.ocean.washington.edu/classpages/oman/geology_auto.html

http://instruct.uwo.ca/earth-sci/200a-001/12occrst.htm

http://scitechdaily.com/scientists-probe-earths-core-to-gain-a-better-understanding-of-planet-formation/

http://celebrating200years.noaa.gov/magazine/vlbi/Figure2.html

http://www.astronautforhire.com/2009/09/theres-space-on-kauai.html

http://www.hwsw.hu/hirek/34748/Navigacio_Galileo_GPS_muhold_finanszirozas.html

http://users.indigo.net.au/don/ee/about.html

http://www.dailygalaxy.com/my_weblog/images/2008/07/13/morenoglacier.jpg

Sources of figures

http://wetenschap.infonu.nl/wetenschappers/90252-beroemde-wetenschappers-harry-hammond-hess.html

http://svtmarcq.over-blog.com/article-naissance-d-une-theorie-la-derive-des-continents-1ere-s-91041389.html

http://georneys.blogspot.nl/2010/12/famous-ocean-floor-map.html

http://www.keesfloor.nl/artikelen/zenit/berlusconi/index.htm

http://geoscience.wisc.edu/~chuck/Classes/Mtn_and_Plates/volcano.html

http://quizlet.com/25506653/world-geography-chapter-4-section-1-flash-cards/

http://www.getdomainvids.com/keyword/atlantic%20ocean%20depths/

http://www.pacificislandtravel.com/nature_gallery/platetectonics.html

http://www.turkish-media.com/forum/topic/107167-yerbilimleri-insan-din/

http://serc.carleton.edu/nnn/mathstatmodels/examples/SFSxl2.html

http://www.geomapapp.org/gallery/Midoceanridgesgallery.html

http://gomyclass.com/geology10/files/lecture12/html/web_data/file63.htm

Sources of figures

http://esc135.wix.com/platentectoniek#!theorie

http://www.kennislink.nl/publicaties/plaattektoniek

http://all-geo.org/highlyallochthonous/2010/01/tectonics-of-the-haitian-earthquake/

http://sciencythoughts.blogspot.nl/2012/12/earthquake-beneath-eastern-black-sea.html

http://heavenawaits.wordpress.com/the-garden-of-eden-and-the-%E2%80%9Cpit%E2%80%9D-%E2%80%93-tioran-land-drift-theory/

http://www.onweer-online.nl/forum/topic/28856/wat-is-de-zwaarste-aardbeving-die-de-vs-kan-treffe/

http://volcano.oregonstate.edu/vwdocs/vwlessons/volcano_types/subd1.htm

http://wikitravel.org/nl/Krakatau

https://umdrive.memphis.edu/hdeshon/www/courses.html

http://safety.worldnomads.com/Chile/55134/Chile-earthquakes-advice-for-travelers#axzz2nOGv7xN9

http://www.nytimes.com/interactive/2011/03/11/world/asia/maps-of-earthquake-and-tsunami-damage-in-japan.html?_r=0

Sources of figures

http://www.geography.learnontheinternet.co.uk/topics/japan_earthquake.html

http://domaine-geologique.com/documents.php?id=17

http://www.platetectonics.com/book/page_5.asp

http://esimo.oceanography.ru/esp2/index/index/esp_id/4/section_id/2/menu_id/319

http://www.geodynamics.no/buiter/apennines.html

http://www.explorevolcanoes.com/Volcano%20Glossary%20Back%20Arc%20basin.html

http://svtmarcq.e-monsite.com/pages/comment-disparait-le-plancher-oceanique.html

http://cascadiaseismic.blogspot.nl/2012/07/coast-science-why-are-we-out-here.html

http://www.iftechnology.nl/wm.cgi?id=183;ws=1

http://www.earth-of-fire.com/article-tectonique-de-la-branche-ouest-du-rift-africain-64415627.html

http://www.educa.madrid.org/web/ies.alonsoquijano.alcala/carpeta5/carpetas/quienes/departamentos/ccnn/CCNN-1-2-ESO/2eso/2ESO-12-13/Bloque-II/Tema-1-Energia-interna-Tierra-I/Tema-1-E-I-Tierra-I.html

http://www.vmapas.com/Europe/Italy/Italy_Satellite_Image.jpg/maps-en.html