European Geosciences Union

GIFT – Geosciences Information For Teachers

PLATE TECTONICS: THE SCIENTIFIC REVOLUTION THAT REVEALED HOW OUR PLANET WORKS

Massimo Mattei

Roma TRE University

Vienna, 9 April, 2018

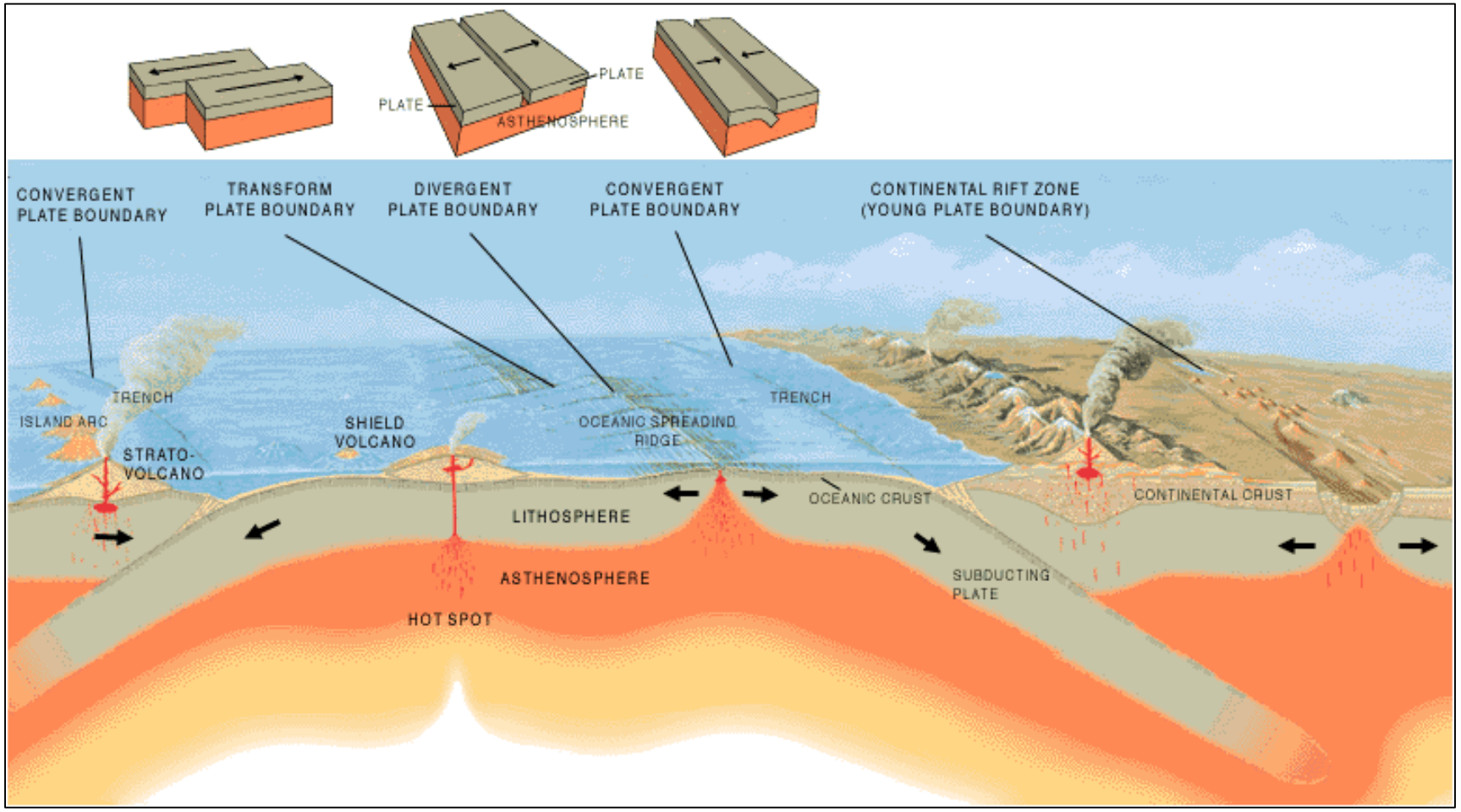
TALK ORGANIZATION

- In the first part we will talk about our present-day knowledge of Plate Tectonics and of subduction margins and how we acquired this knowledge;

- In the second part we will discuss the history of Plate Tectonics on the Earth and how scientists investigated this main issue of Earth Science

https://www.nasa.gov/multimedia/imagegallery/image_feature_1249.html

WHAT IS MODERN PLATE TECTONICS?

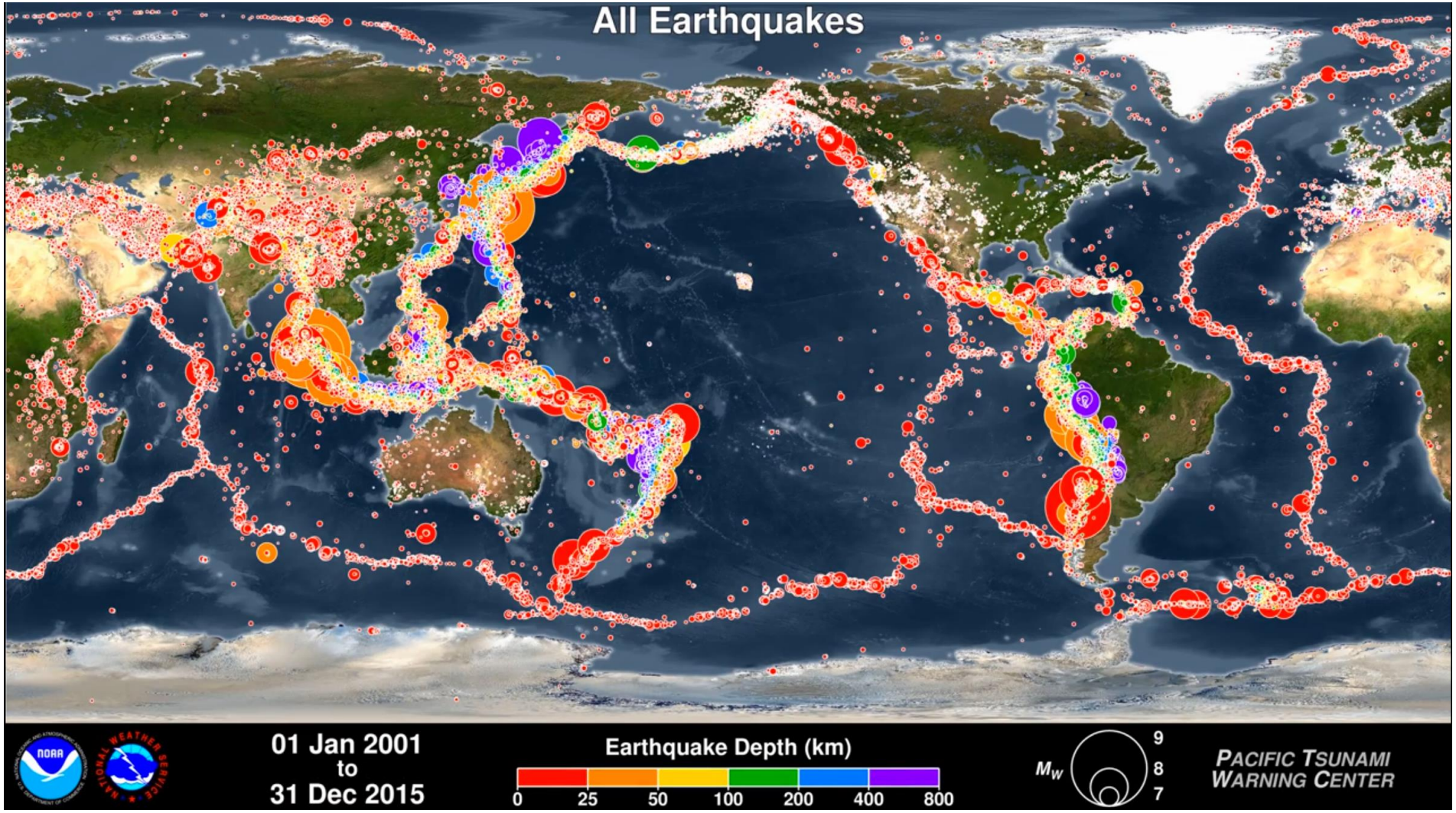


- New oceanic crust is produced along linear oceanic ridges;
- Oceanic lithosphere is consumed along convergent margins, subducting into the deep mantle;

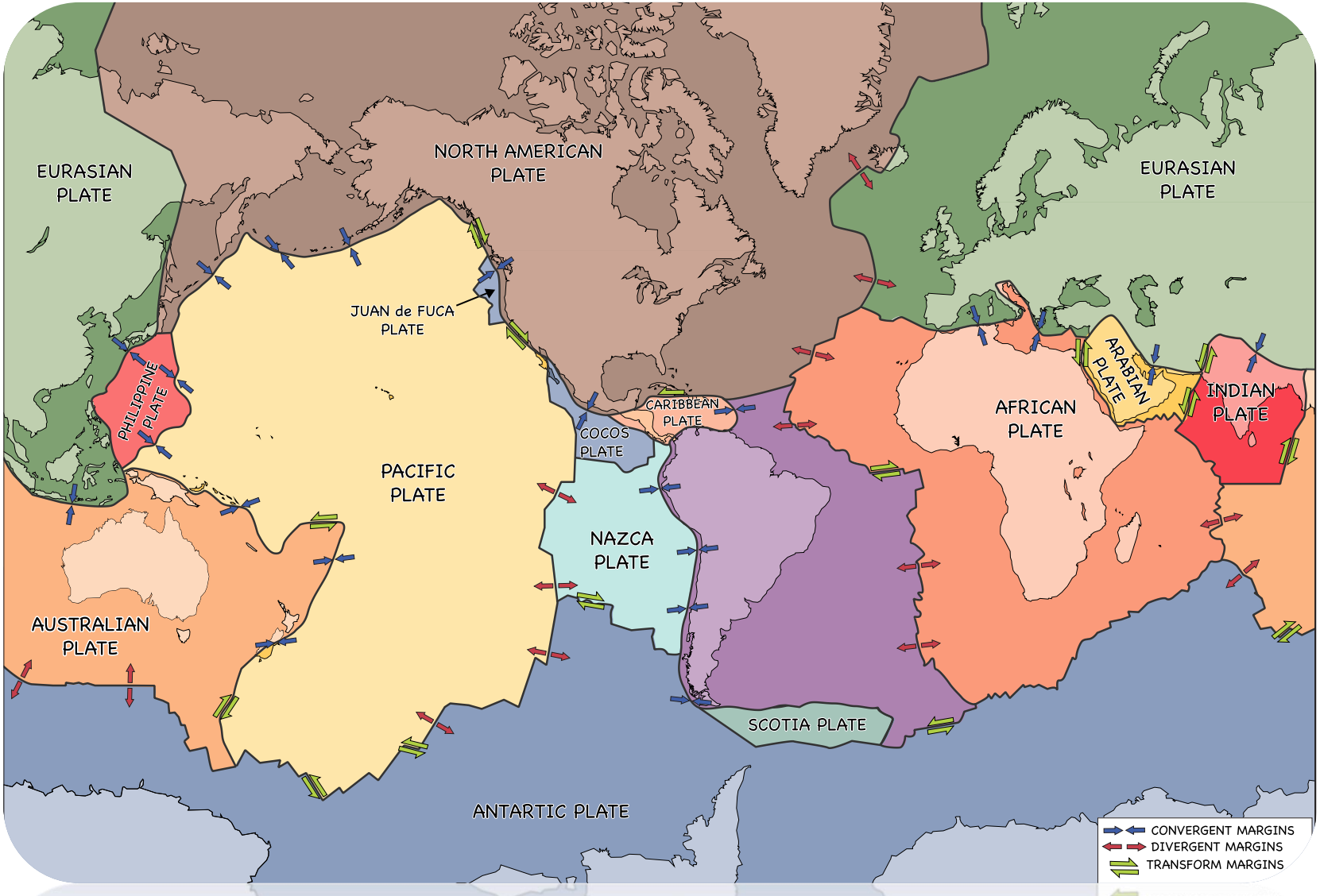
EARTHQUAKES

https://www.youtube.com/watch?v=ph7Eczs-nTI

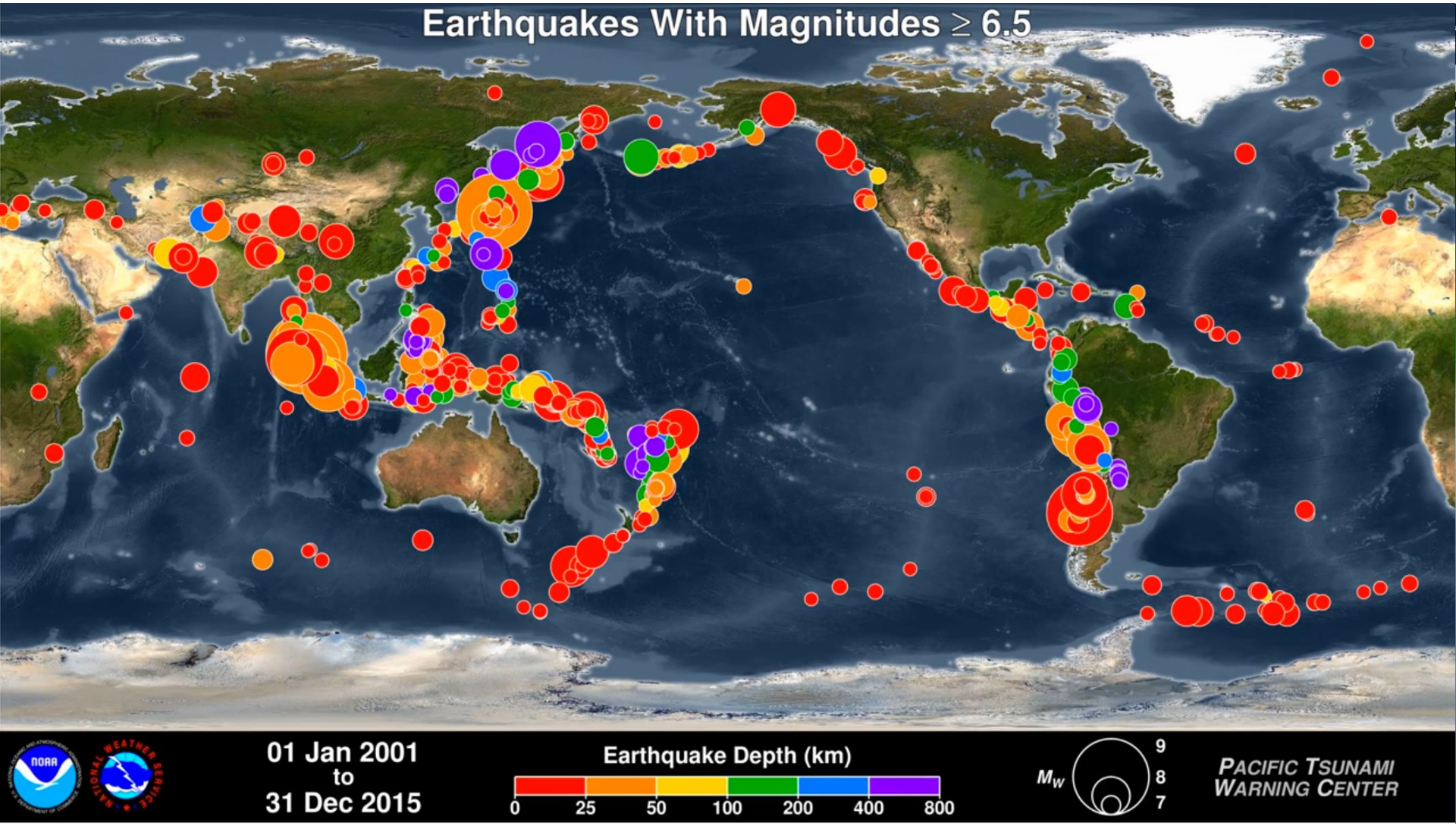
EARTHQUAKE DISTRIBUTION



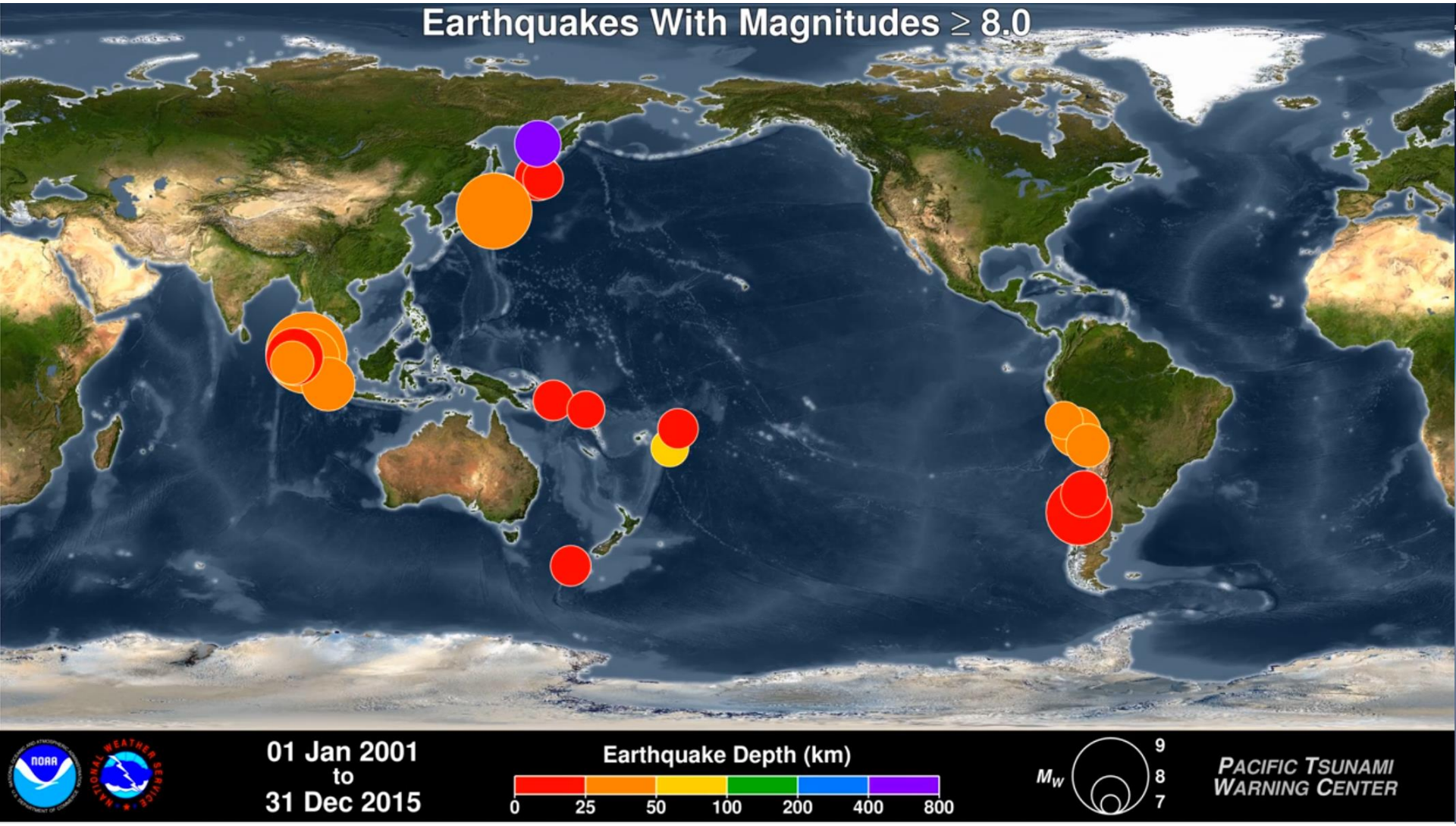
PLATES


EURASIAN PLATE
NORTH AMERICAN PLATE
EURASIAN PLATE
JUAN de FUCA PLATE
PHILIPPINE PLATE
CARIBBEAN PLATE
COCOS PLATE
ARABIAN PLATE
INDIAN PLATE
AFRICAN PLATE
PACIFIC PLATE
NAZCA PLATE
AUSTRALIAN PLATE
SCOTIA PLATE
ANTARTIC PLATE
CONVERGENT MARGINS
DIVERGENT MARGINS
TRANSFORM MARGINS

EARTHQUAKES WITH MAGNITUDES ≥ 6.5



EARTHQUAKES WITH MAGNITUDES ≥ 8.0



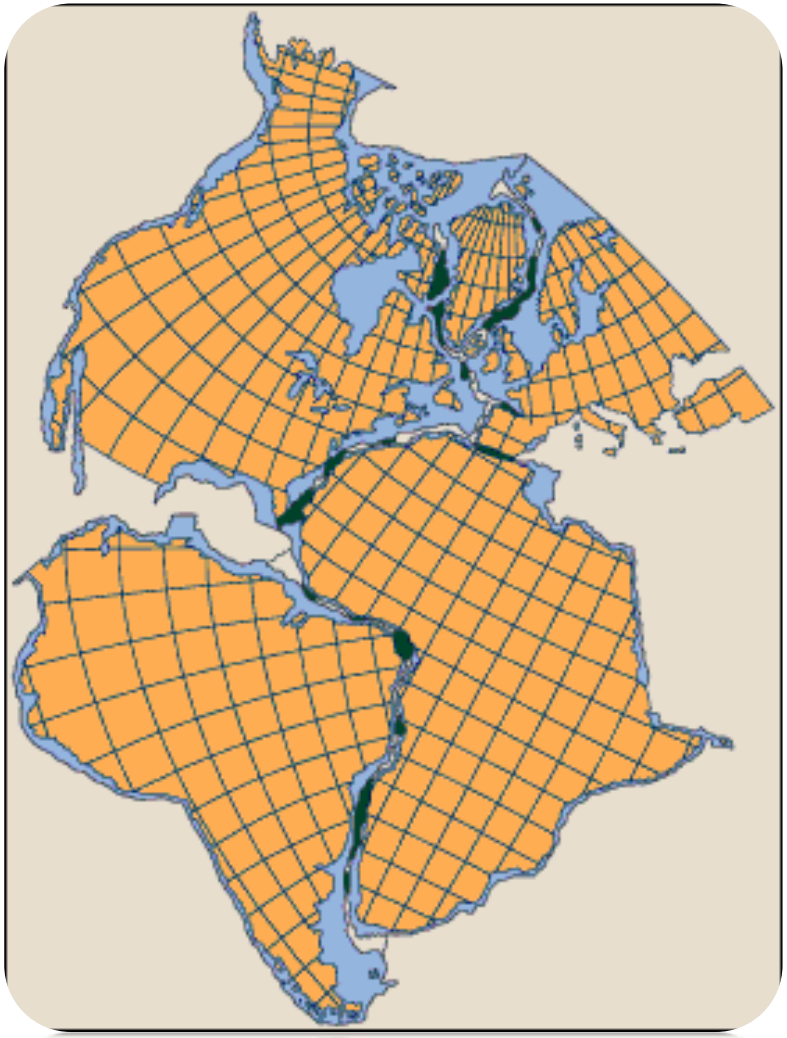
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)

https://en.wikipedia.org/wiki/File:Wegener_Expedition-1930_026.jpg#file

WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)

200 Ma emerged lands formed a unic supercontinent called **Pangea**

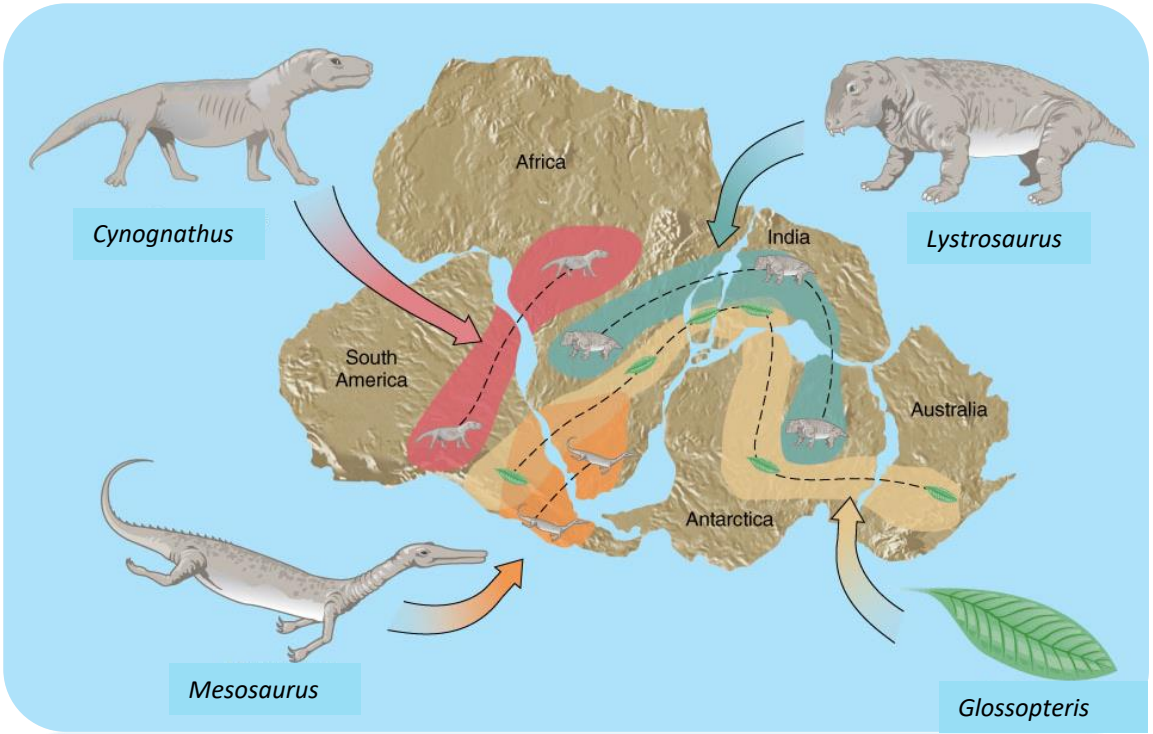
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)



Evidences of continental drift: the shape of coastal lines

https://www.e-education.psu.edu/earth520/content/l2_p20.html

WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)

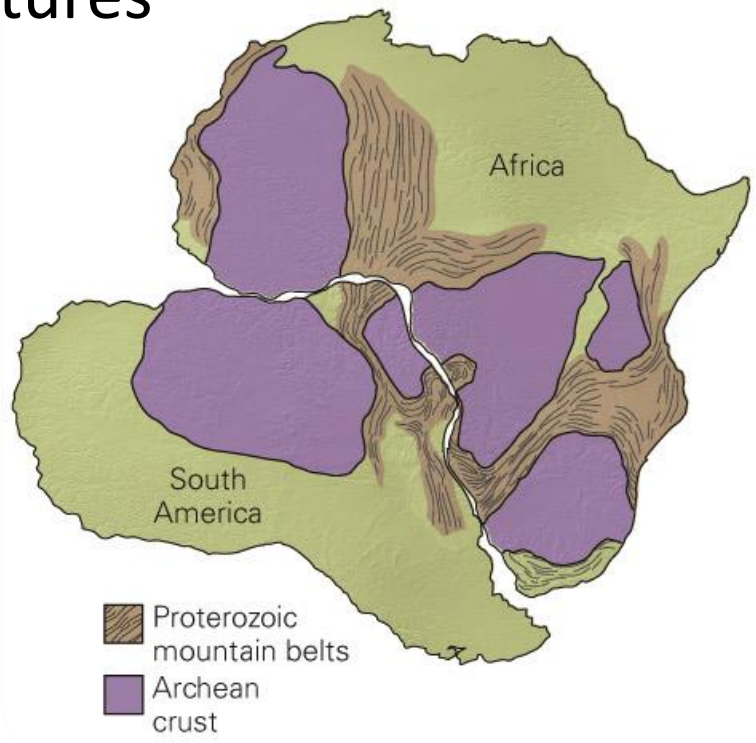


Evidences of continental drift: fossil distribution

http://www2.sunysuffolk.edu/vorwalb/Plate%20Tectonics%20&%20Cont%20Drift%20revised.ppt

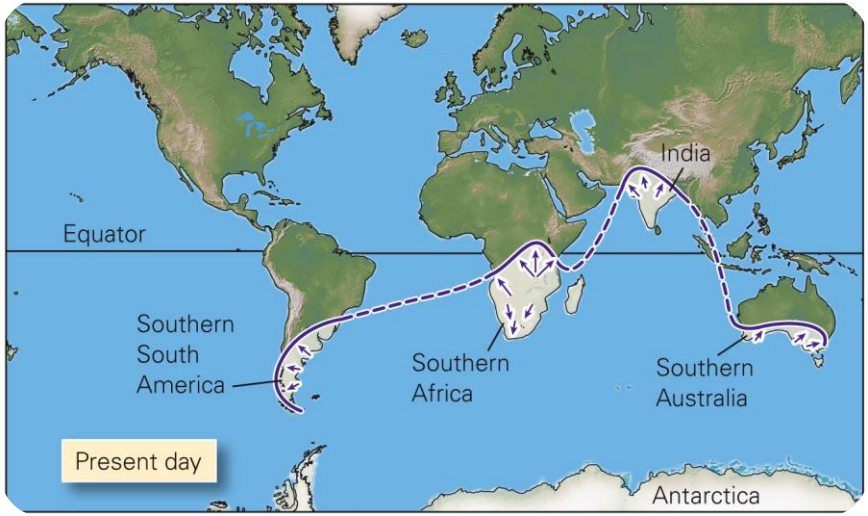
WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)

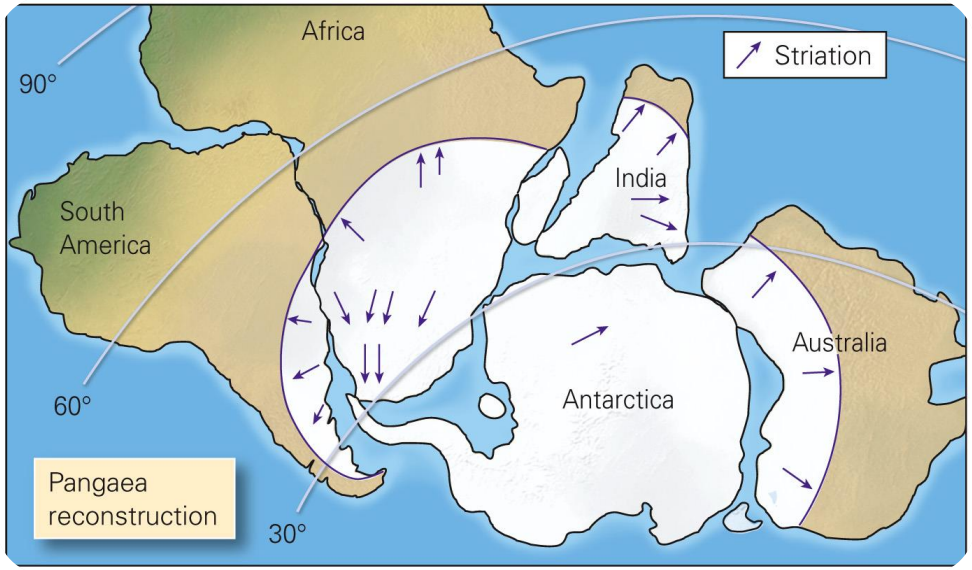
Evidences of continental drift: continuity of geological structures



Earth: Portait of a Planet 5/e, @2015 W.W Norton & Company Inc.

WEGENER AND THE CONTINENTAL DRIFT HYPOTHESYS (1912-1920)



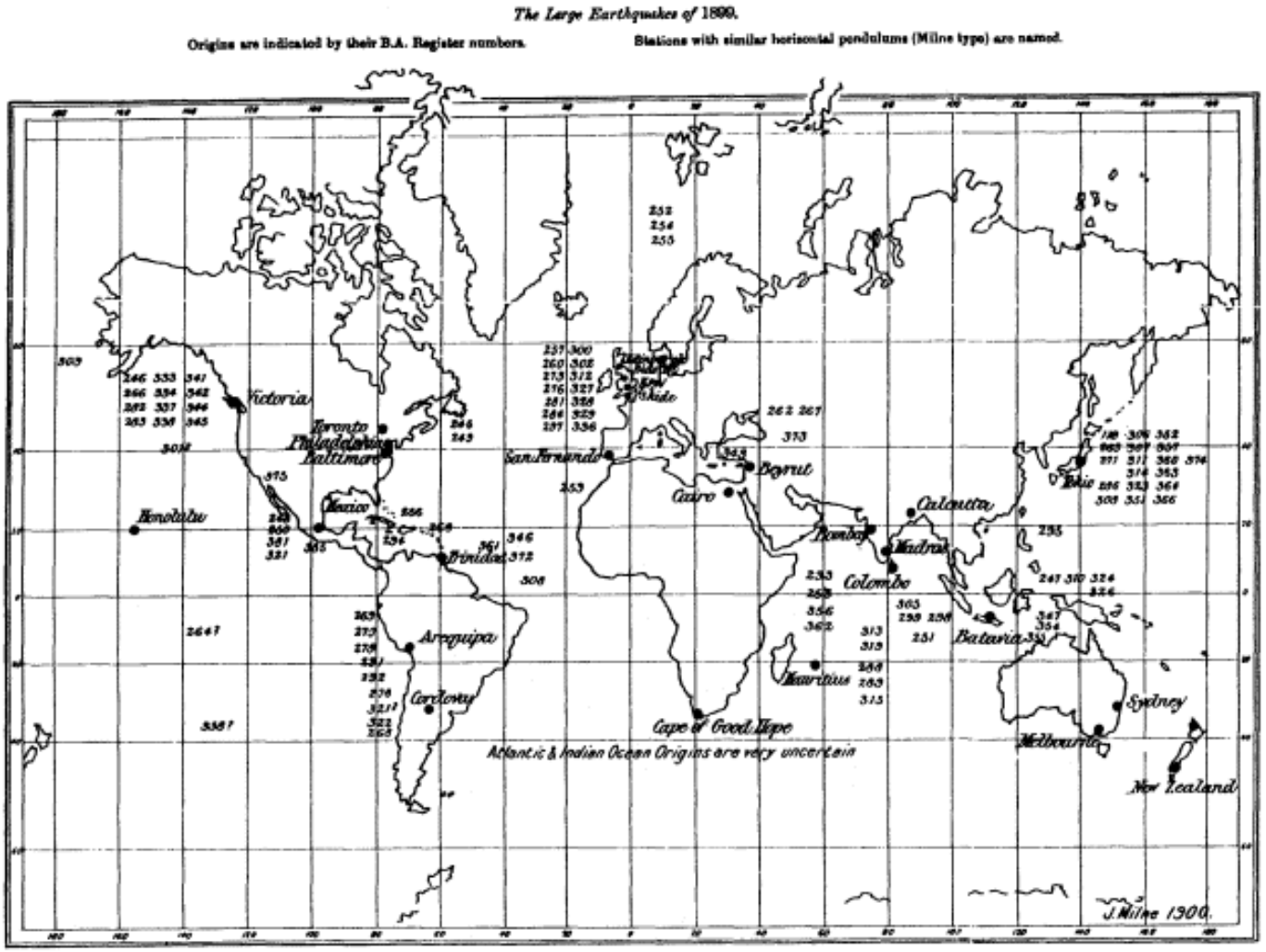


Evidences of continental drift: glacial deposits

Earth: Portait of a Planet 5/e, @2015 W.W Norton & Company Inc.

SEISMOLOGY IN THE WEGENER'S TIME

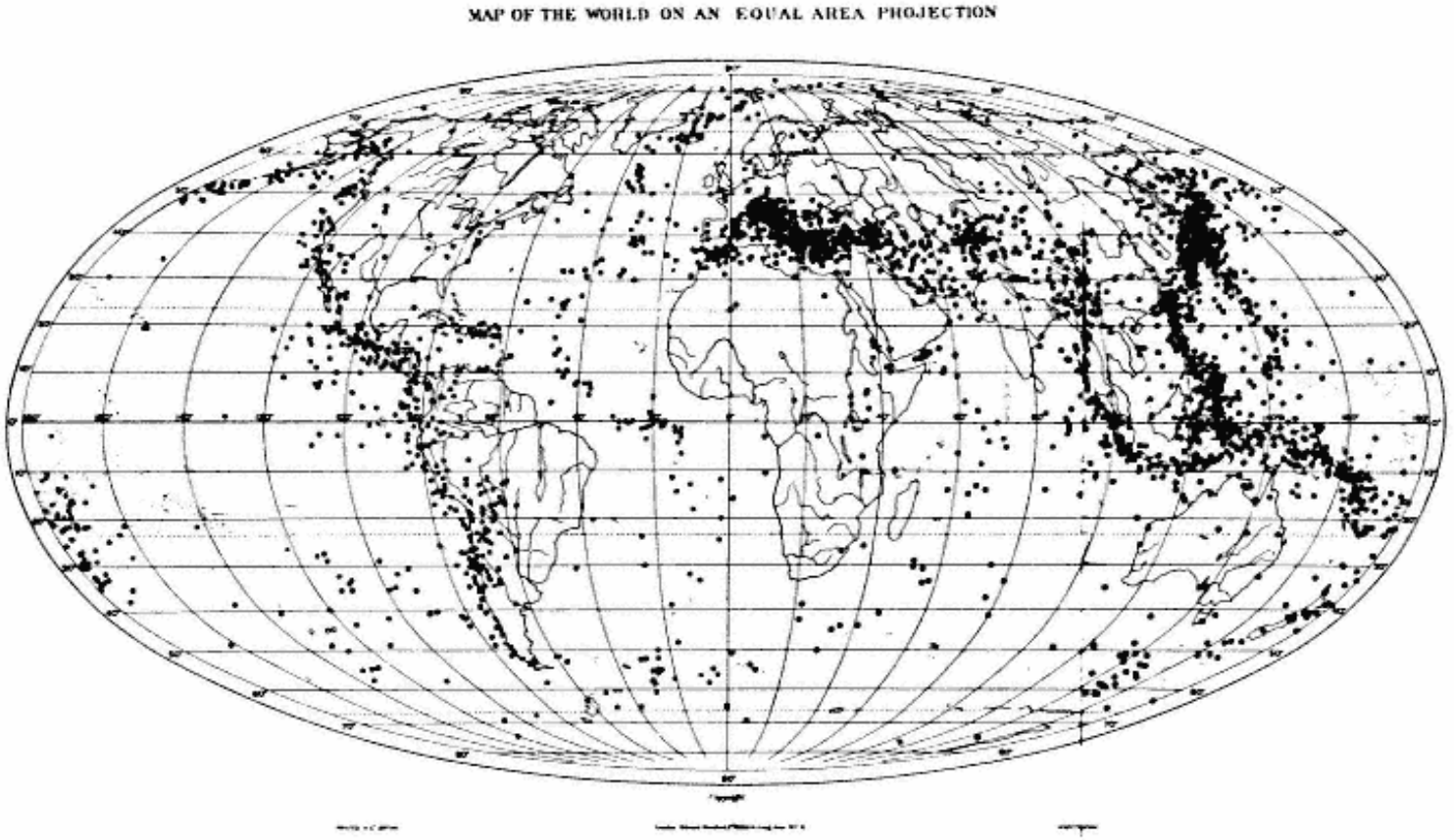
Earthquake distribution map (1900)



http://publishing.cdlib.org/ucpressebooks/view?docId=ft7m3nb4pj;chunk.id=0;doc.view=print

SEISMOLOGY BETWEEN THE TWO WORLD WARS

Earthquake distribution map (1913-1930)



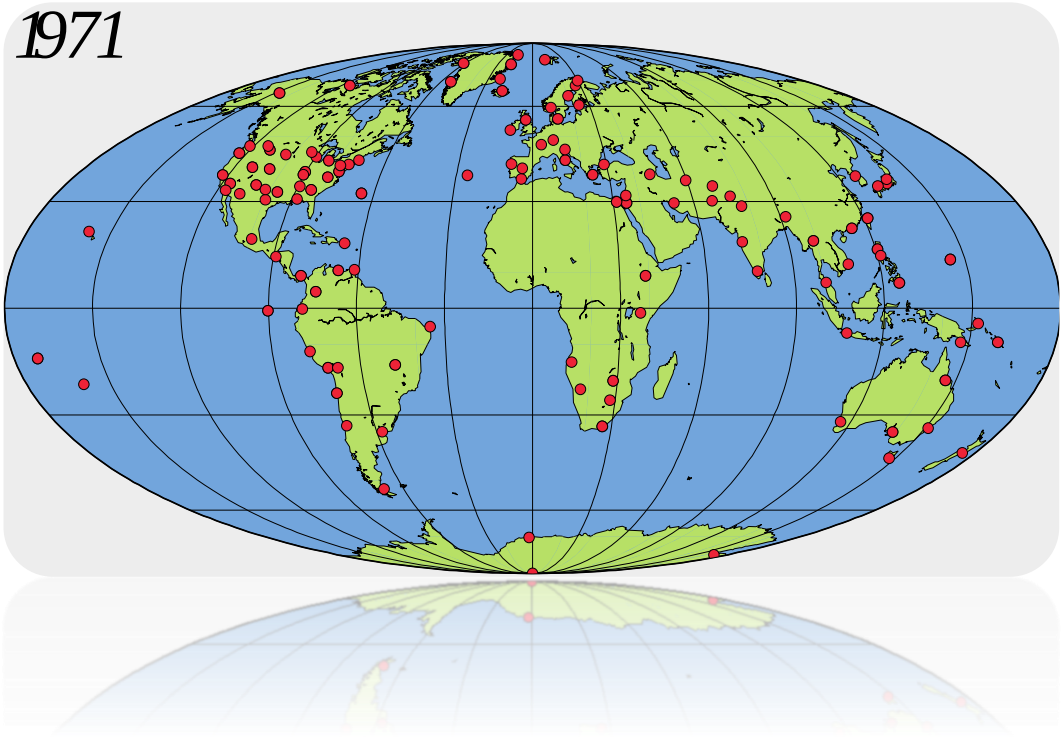
ORIGINS OF EARTHQUAKES FROM 1913—1930 INCLUSIVE.

http://publishing.cdlib.org/ucpressebooks/view?docId=ft7m3nb4pj;chunk.id=0;doc.view=print

MODERN SEISMOLOGY AND PLATE TECTONICS

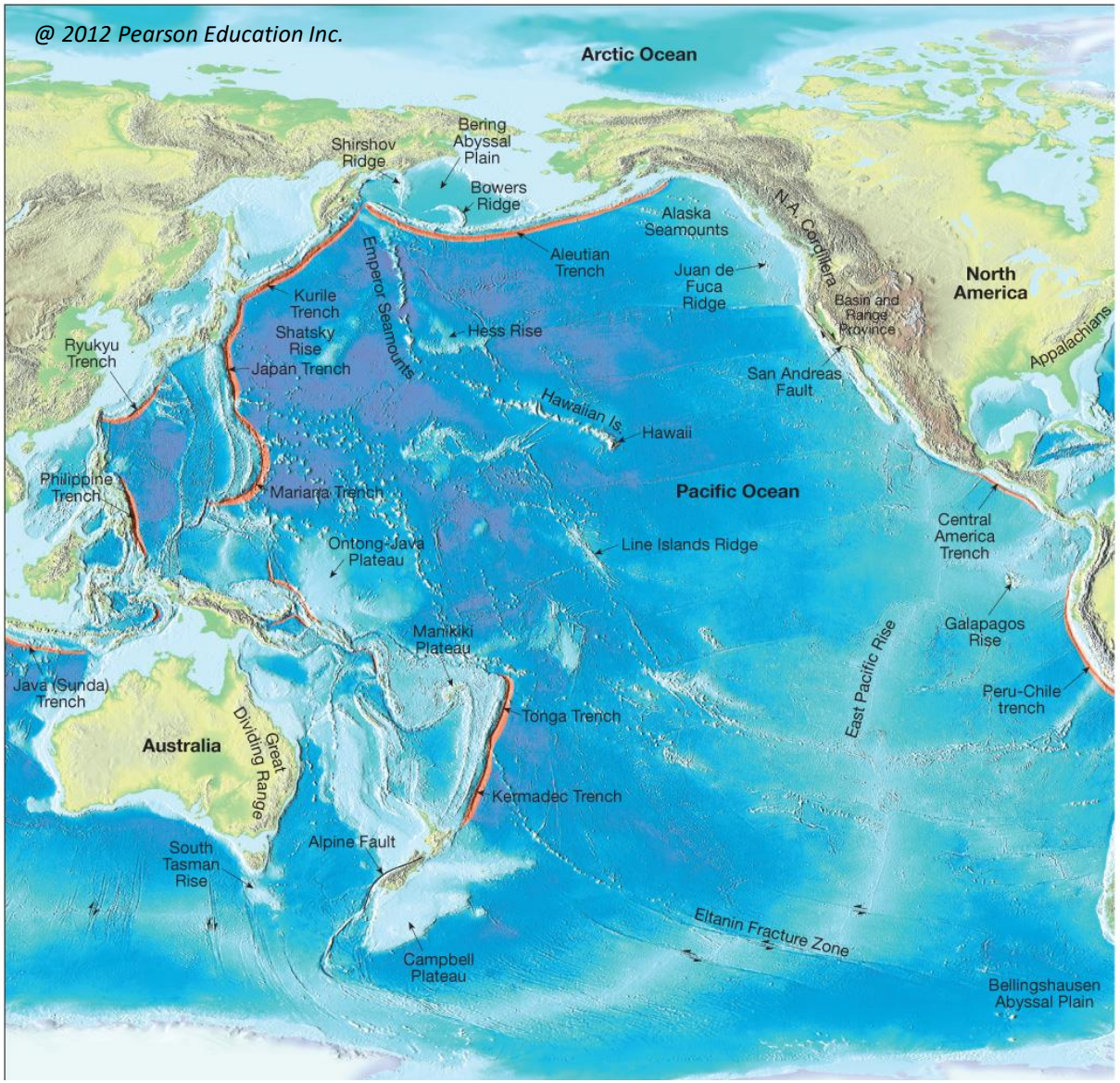
THE WORLDWIDE STANDARDIZED SEISMOGRAPH NETWORK (WWSSN)

123 STANDARD SEISMOGRAPH INSTALLED (1962–1971)



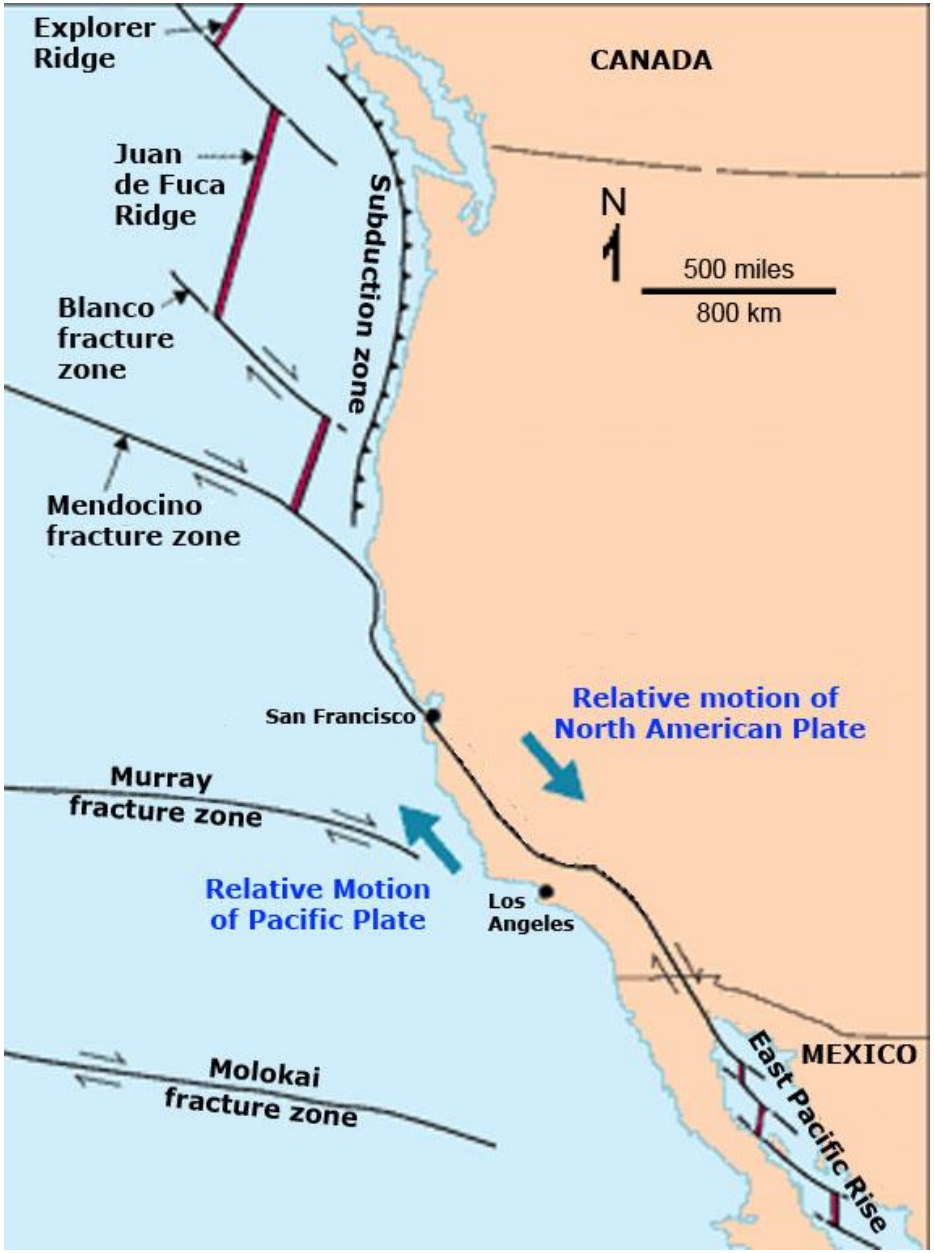
- Well established earthquakes location
- Focal mechanisms
- Earthquakes magnitude

CONVERGENT PLATE BOUNDARIES



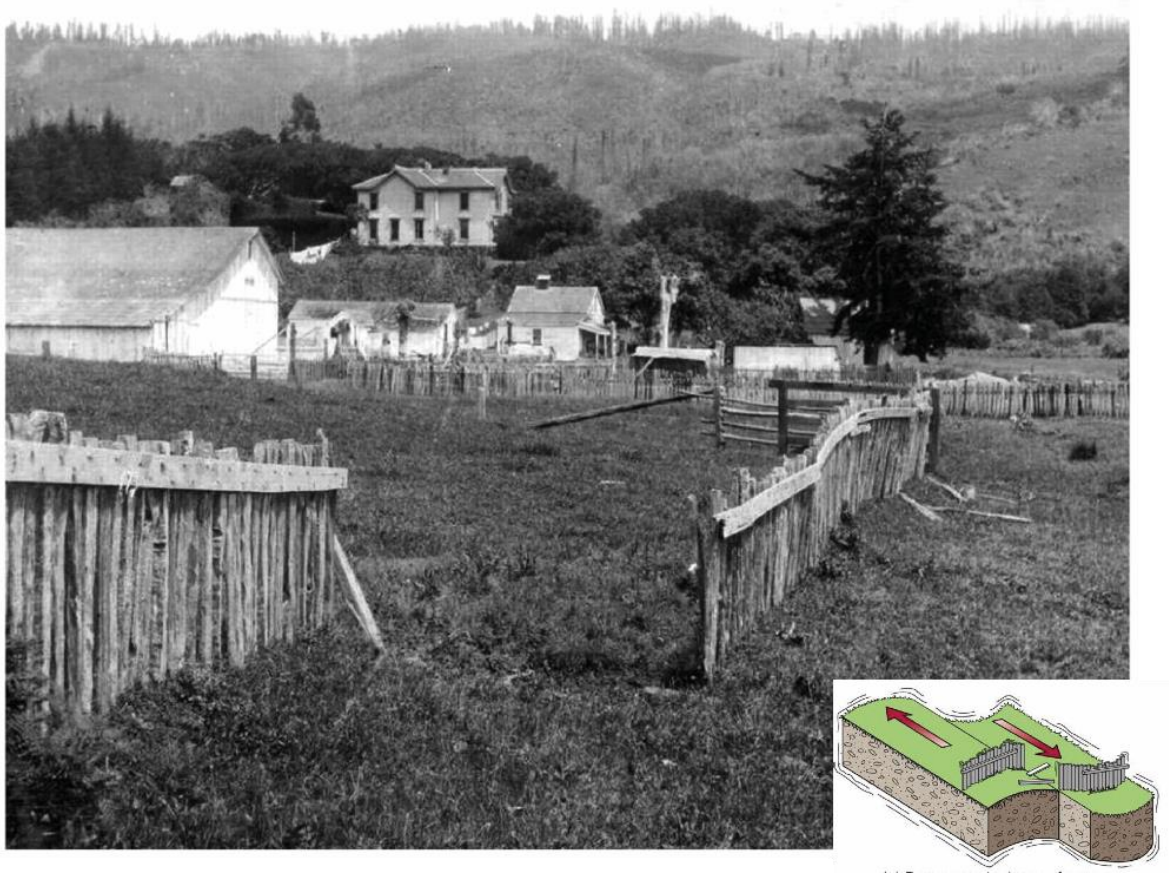
The real nature of the active margins between continental and oceanic lithosphere represented one of the main issues in Plate Tectonics

THE SAN ANDREAS FAULT



THE HERITAGE OF THE 1906 SAN FRANCISCO EARTHQUAKE

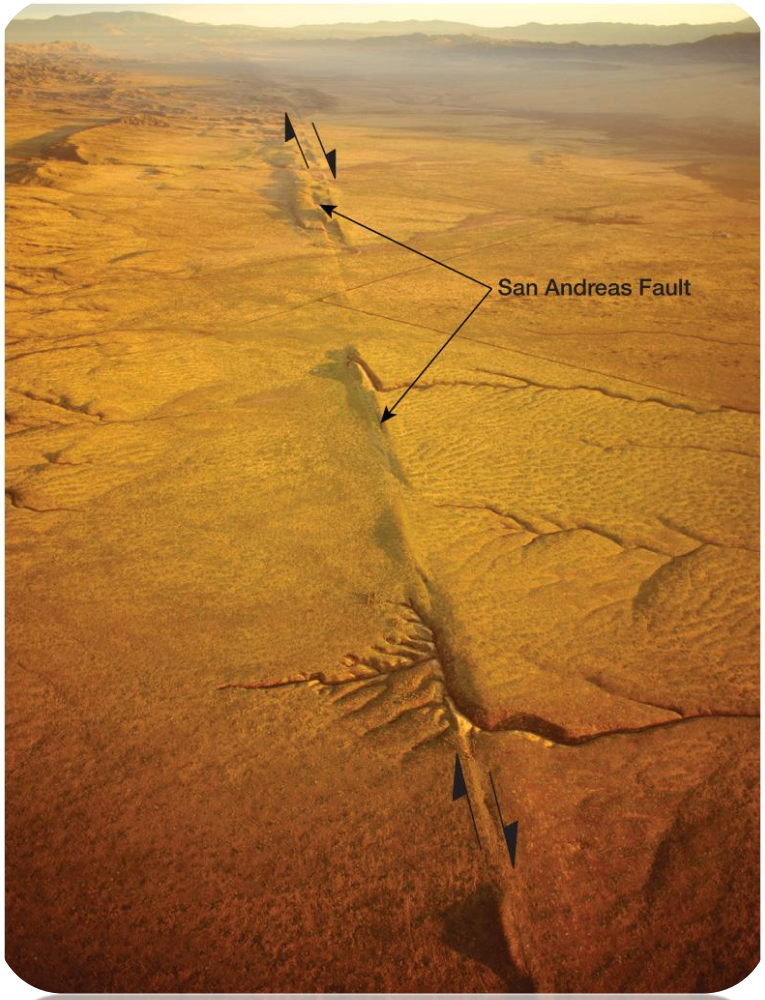
Horizontal displacement



https://en.wikisource.org/w/index.php?title=Popular_Science_Monthly/Volume_69/August_1906/The_Investigation_of_the_San_Francisco_Earthquake&printable=yes

THE HERITAGE OF THE 1906 SAN FRANCISCO EARTHQUAKE

Faults are sub-vertical



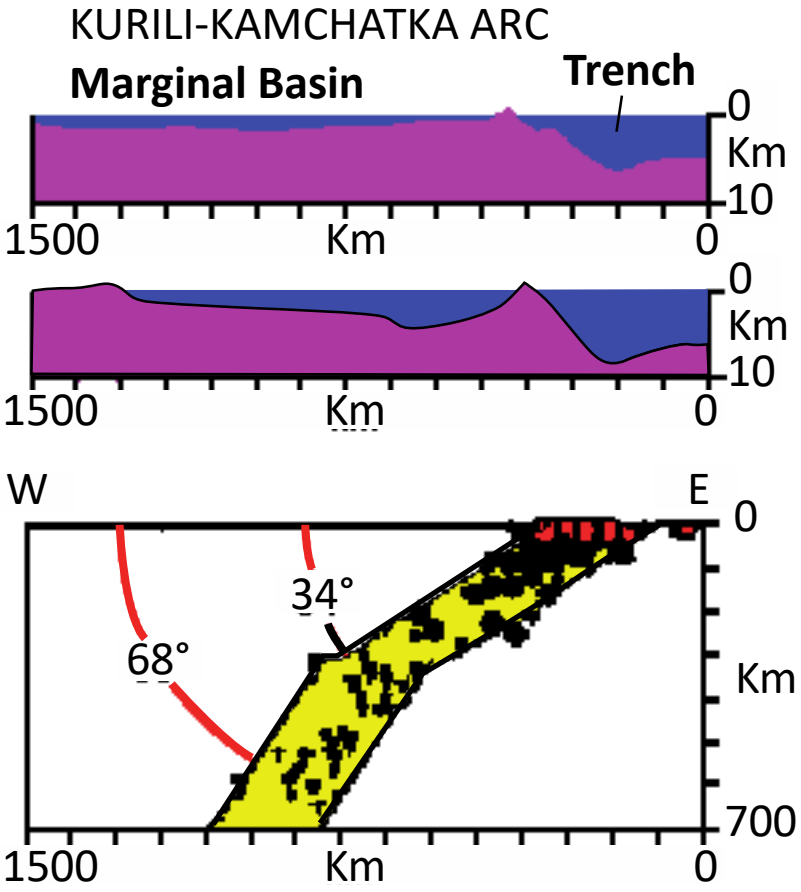
CONVERGENT PLATE BOUNDARIES

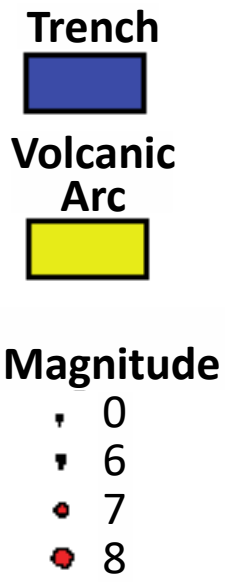
HUGO BENIOFF (1899-1968)

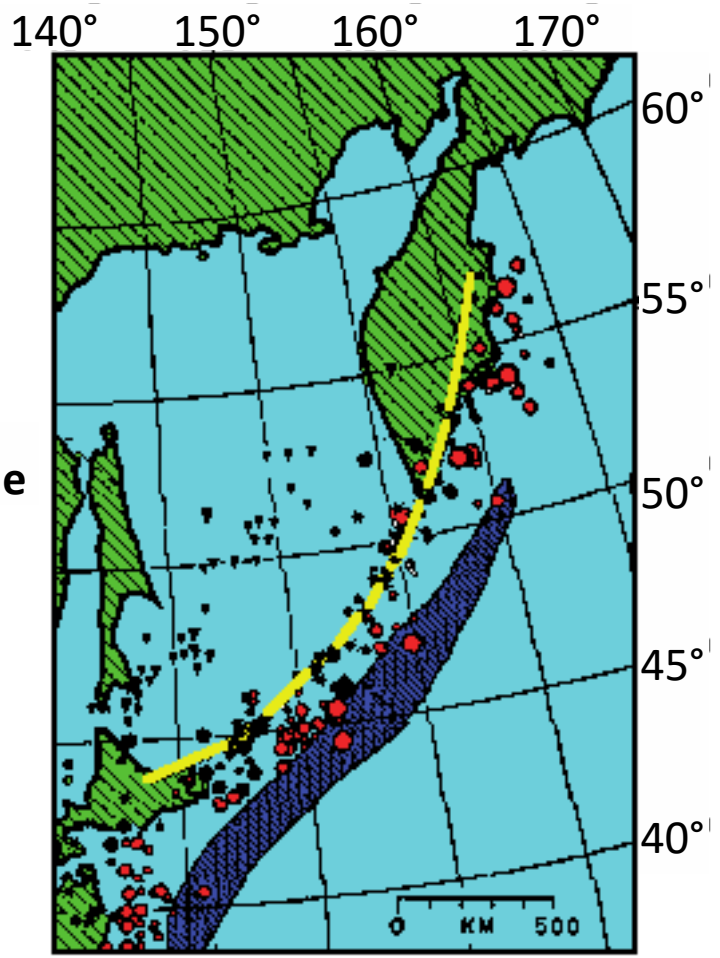
https://www.e-education.psu.edu/earth520/content/l2_p13.html

CONVERGENT PLATE BOUNDARIES

BENIOFF (1954)





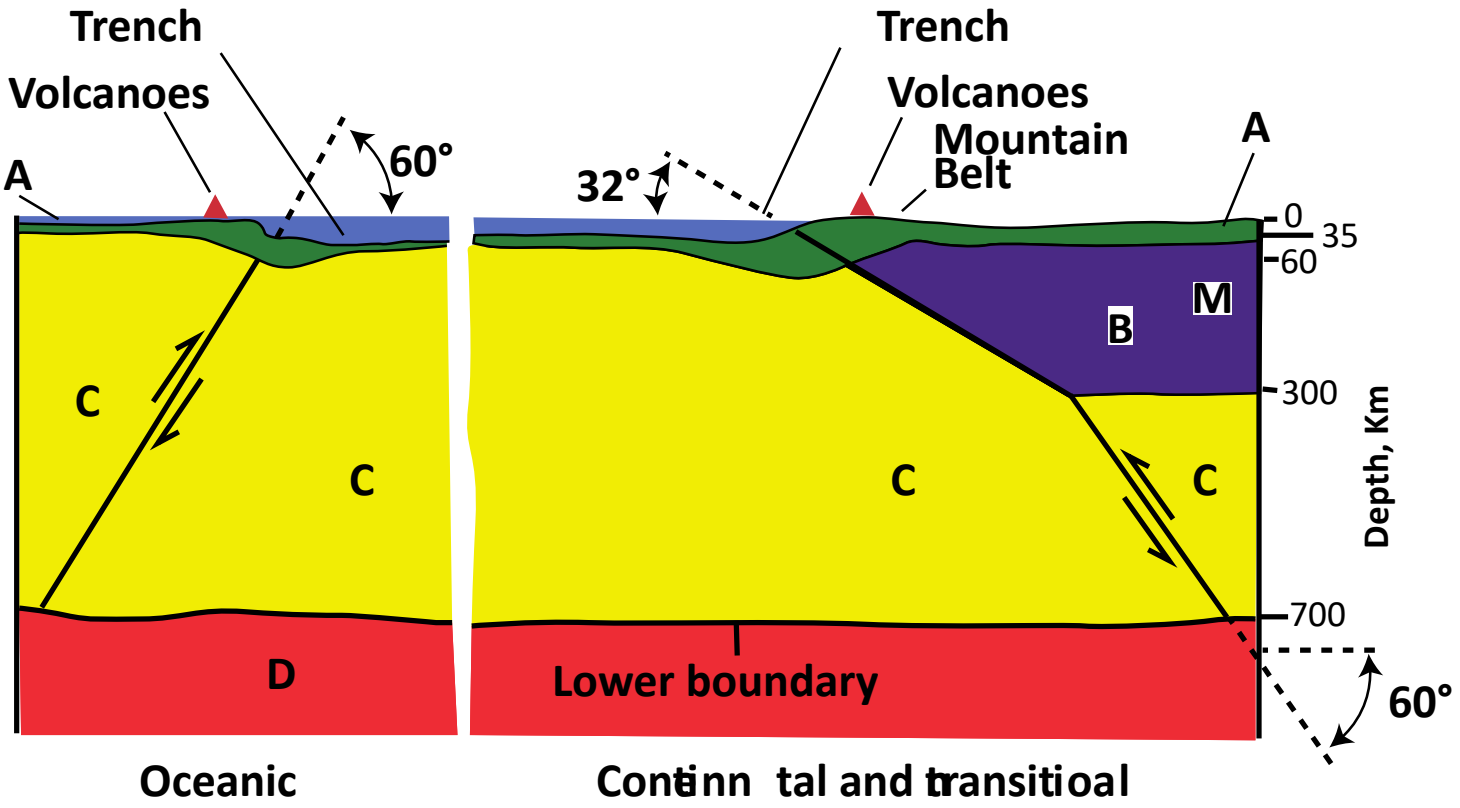


Modified from Benioff, 1954

CONVERGENT PLATE BOUNDARIES

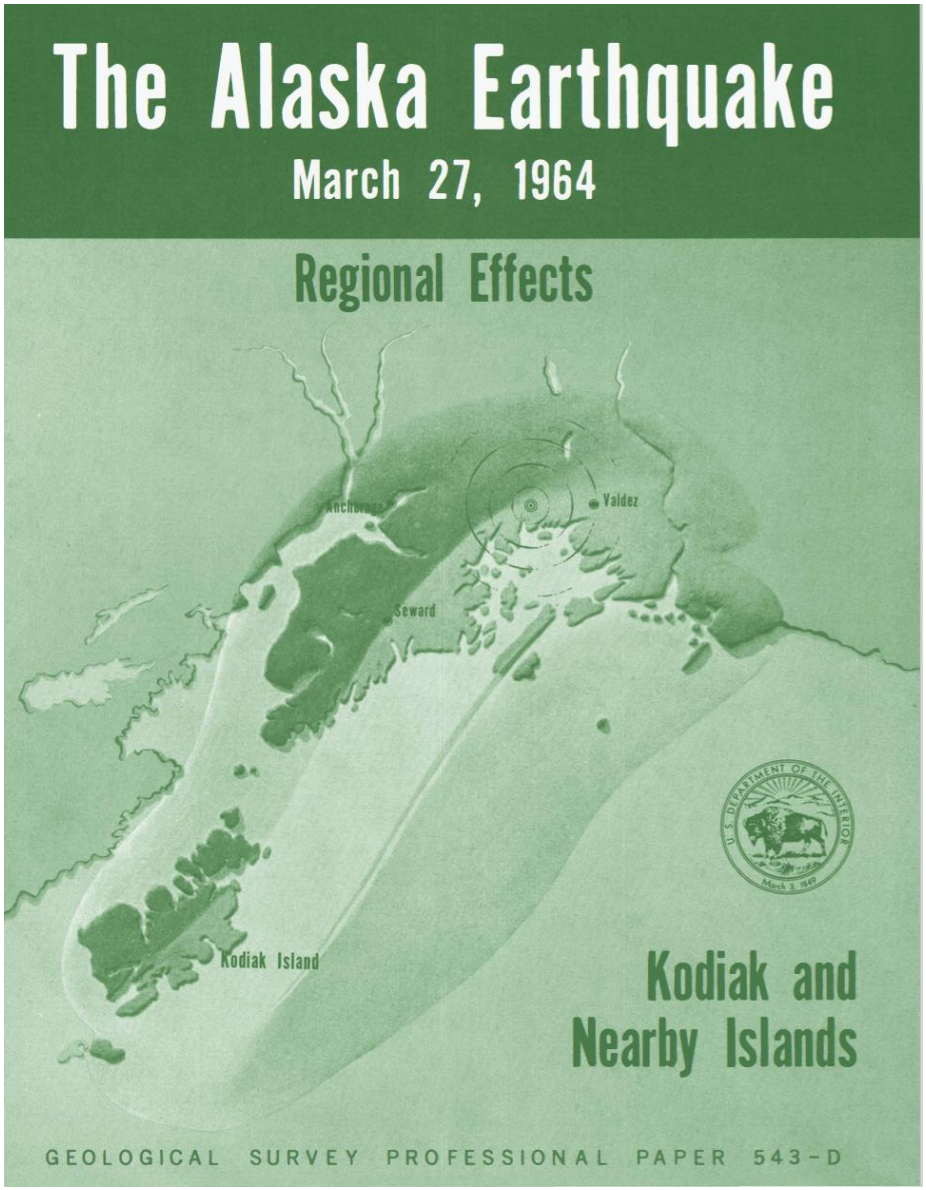
BENIOFF (1954)

Definition of the geometry and mechanism of subduction processes



Modified from Benioff, 1954

THE BIG 1964 ALASKA EARTHQUAKE



- *Mw=9.2*
- *Depth= 23 km*
- *139 human losses*
- *Run-up= 67 m at Shoup Bay (Alaska)*

THE FIRST INTERPRETATION

Science

Alaskan Earthquake, 27 March 1964: Vertical Extent of Faulting and Elastic Strain Energy Release

Frank Press and David Jackson

Science **147** (3660), 867-868.
DOI: 10.1126/science.147.3660.867

"…The length of the primary fault is approximately 800 km as estimated from the extent of the belt of aftershocks.
The distribution of polarity of first motion is consistent with a nearly vertical fault plane…."
"….We conclude that the primary fault came to within 15 to 20 km of the surface and extend to depths of 100 to 200 km….."

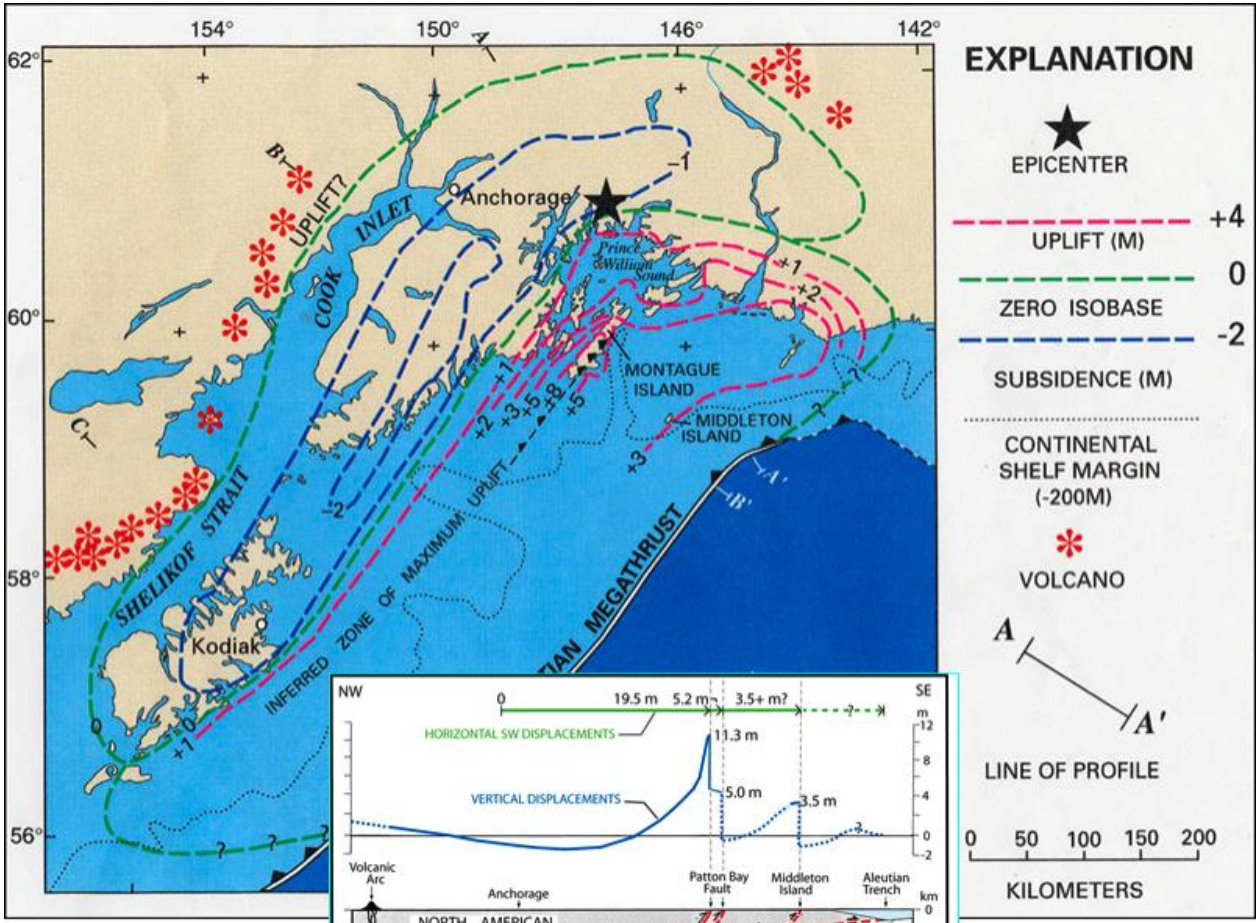
THE INTERPRETATION OF GEORGE PLAFKER

COSEISMIC DEFORMATION
(PLAFKER,1965)

Modified from USGS 2014

COSEISMIC VERTICAL DEFORMATION MAP

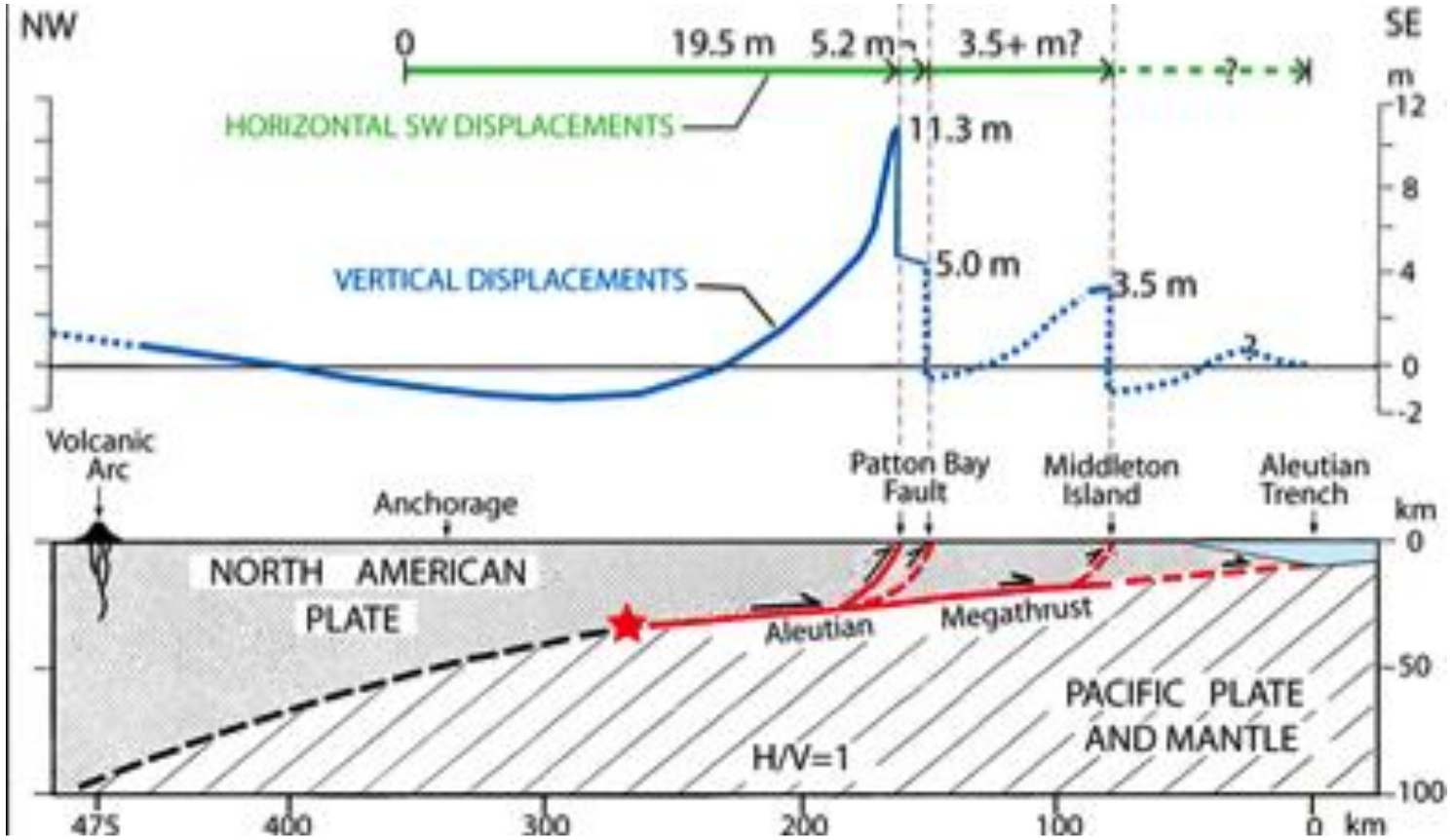
The deformation field with uplifted area up to 11 m and subsiding area down to 2 m was interpreted as related to a low angle thrust fault, as suggested by Benioff



Modified from USGS 2014

COSEISMIC VERTICAL DEFORMATION MAP

For the first time a big earthquake was explained using the new Plate Tectonics theory. The convergent margin are related to subducting plates into the mantle.



Modified from USGS 2014

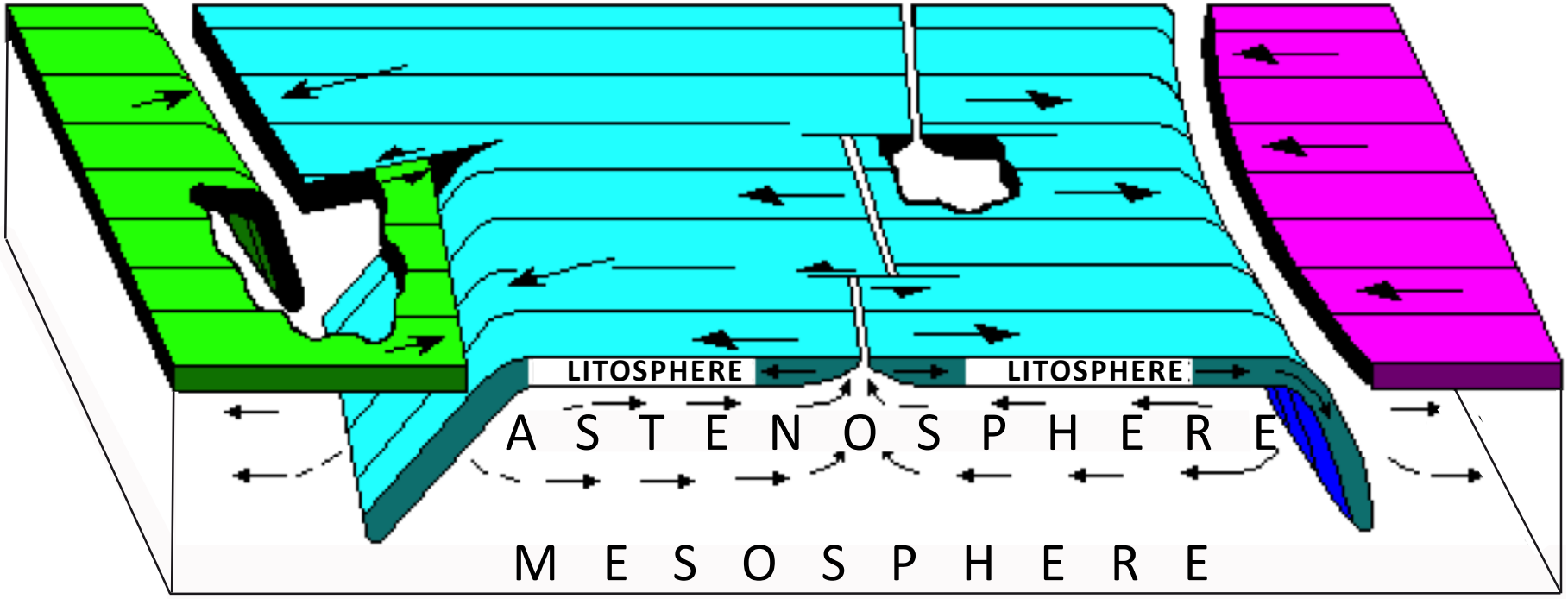
SUBDUCTION AT THE CONVERGENT PLATE BOUNDARY

The 1964 Great Alaska Earthquake demontrated that the dense Pacific Plate is moving north, pushed into and under the more buoyant North American Plate

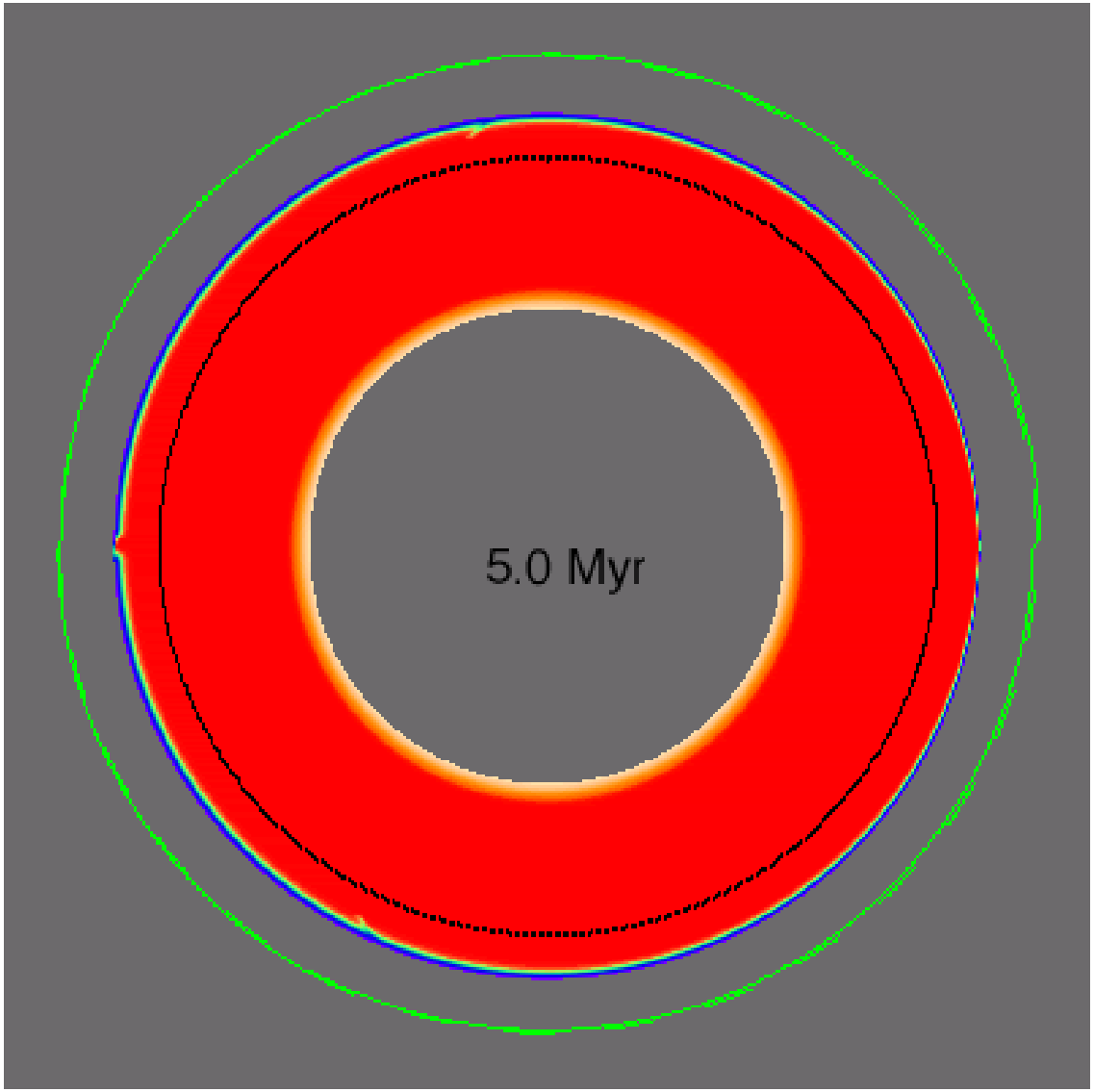
Modified from USGS 2014

THE GLOBAL TECTONIC MODEL BASED ON SEISMOLOGICAL DATA

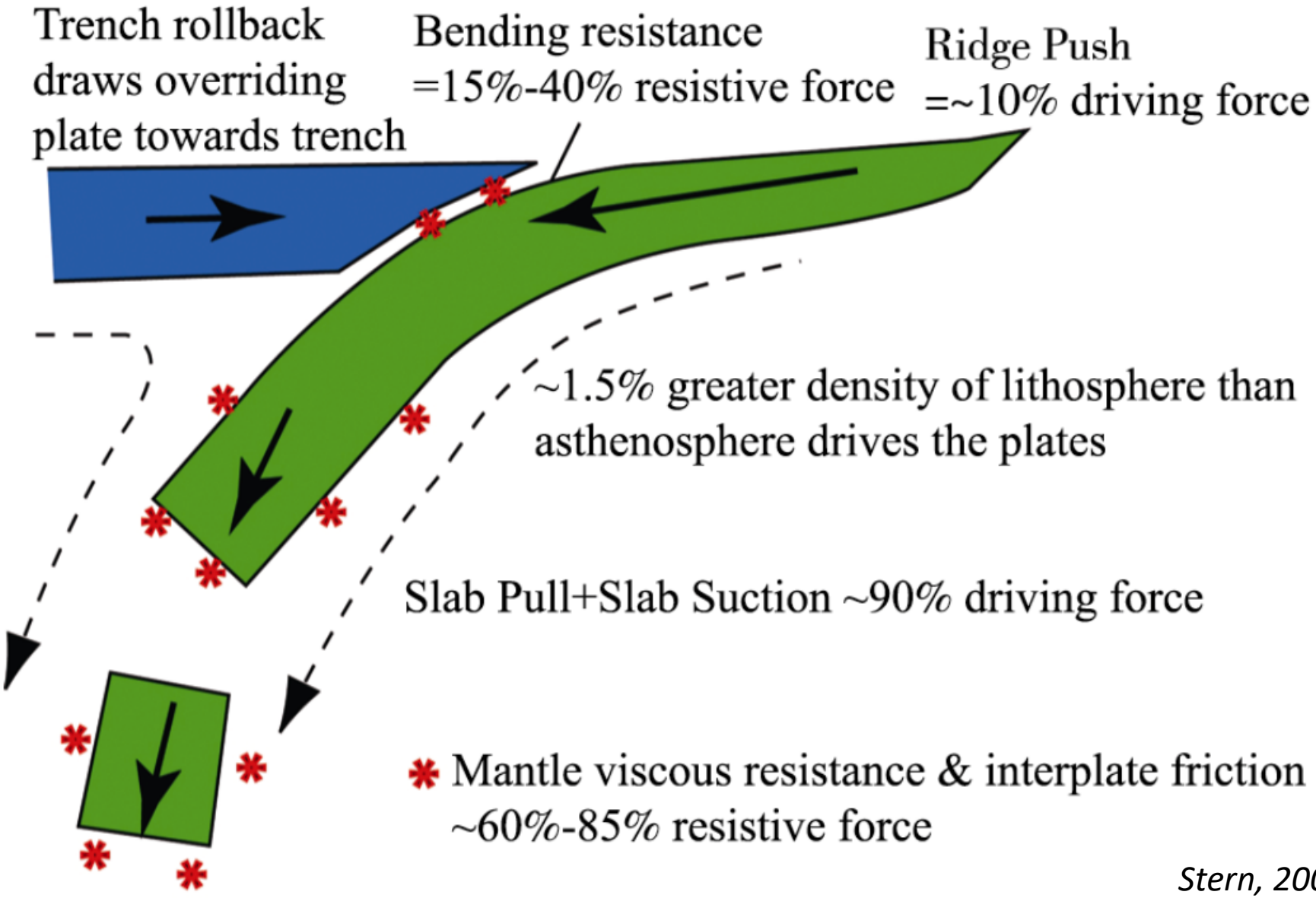
Isacks, Oliver & Sykes (1968)



MODERN-STYLE PLATE TECTONICS: WHOLE MANTLE CONVECTION

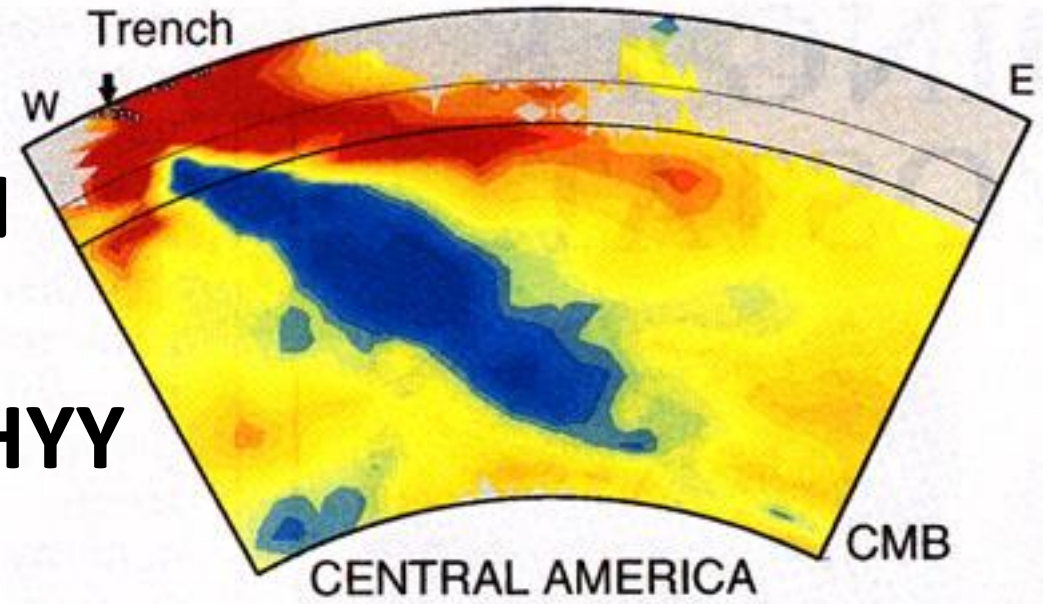


MODERN-STYLE PLATE TECTONICS: THE ROLE OF SUBDUCTING SLABS

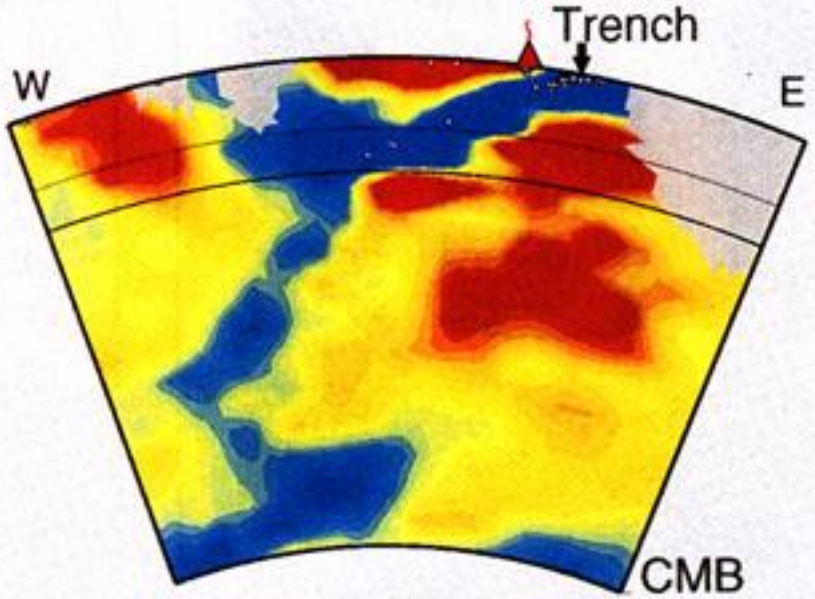


Stern, 2007

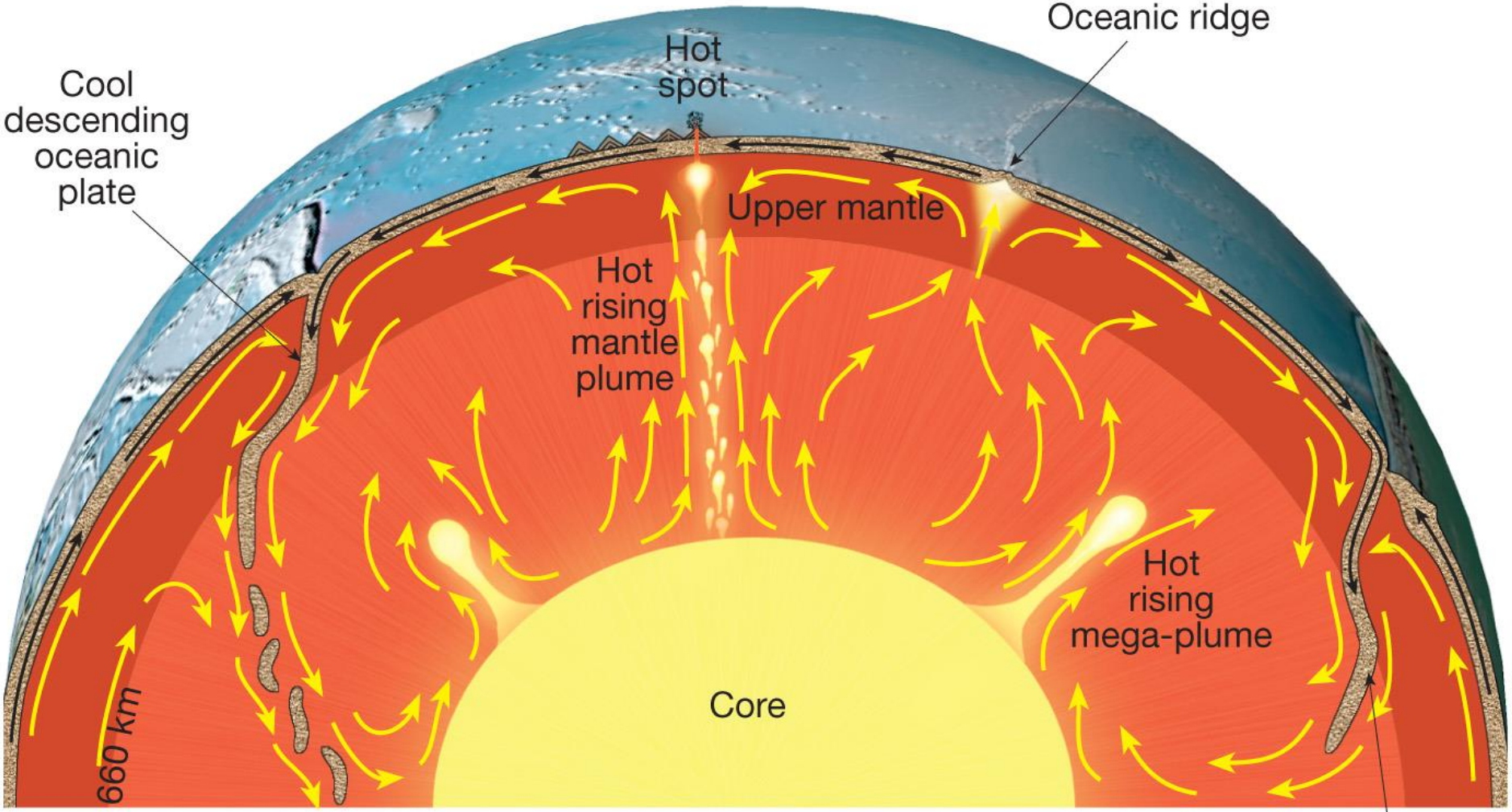
DEEP SUBDUCTION EVIDENCES FROM SEISMIC TOMOGRAPHYY



Lithospheric slabs on Earth reach great depths, typically 1100–1300 km, and possibly down to the core-mantle boundary (CMB).



MODERN-STYLE PLATE TECTONICS



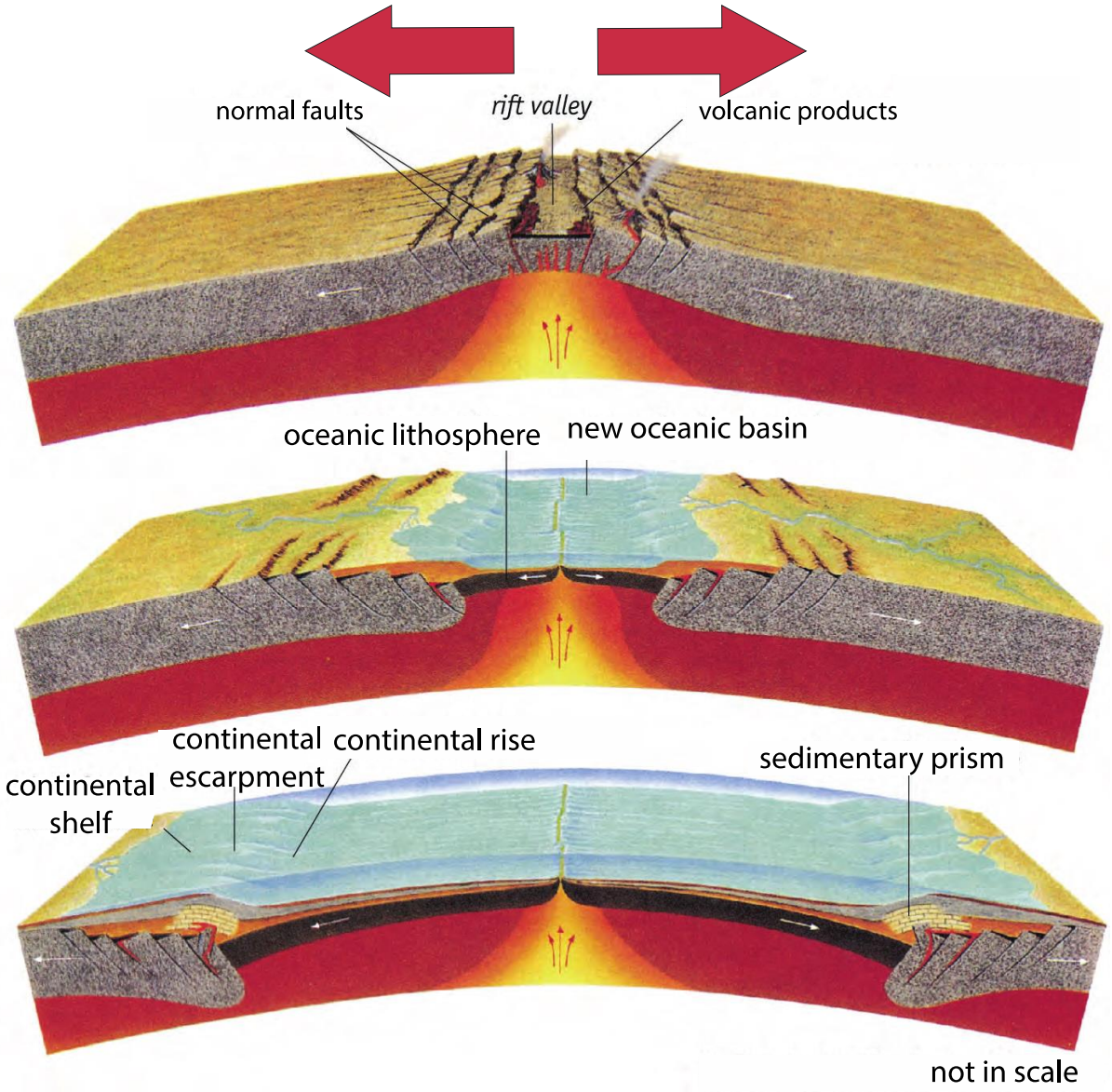
B. Whole mantle convection

MODERN-STYLE PLATE TECTONICS HAVE PETROTECTONIC ASSEMBLAGES THAT ORIGINATE IN SPECIFIC TECTONIC SETTINGS AND THAT ARE CHARACTERISTIC OF THOSE SETTINGS

1) ***Ophiolites:*** *indicate the formation and consumption of oceanic lithosphere*

2) ***High Pressure/Low Temperature (HP/LT) and Ultra High Pressure (UHP) metamorphic units****: indicate deep subduction along convergent margins*

SPREADING CENTERS TO CREATE NEW OCEANIC LITHOSPHERE



DEPOSITIONAL SYSTEMS GENERATING "OCEAN-PLATE STRATIGRAPHY"

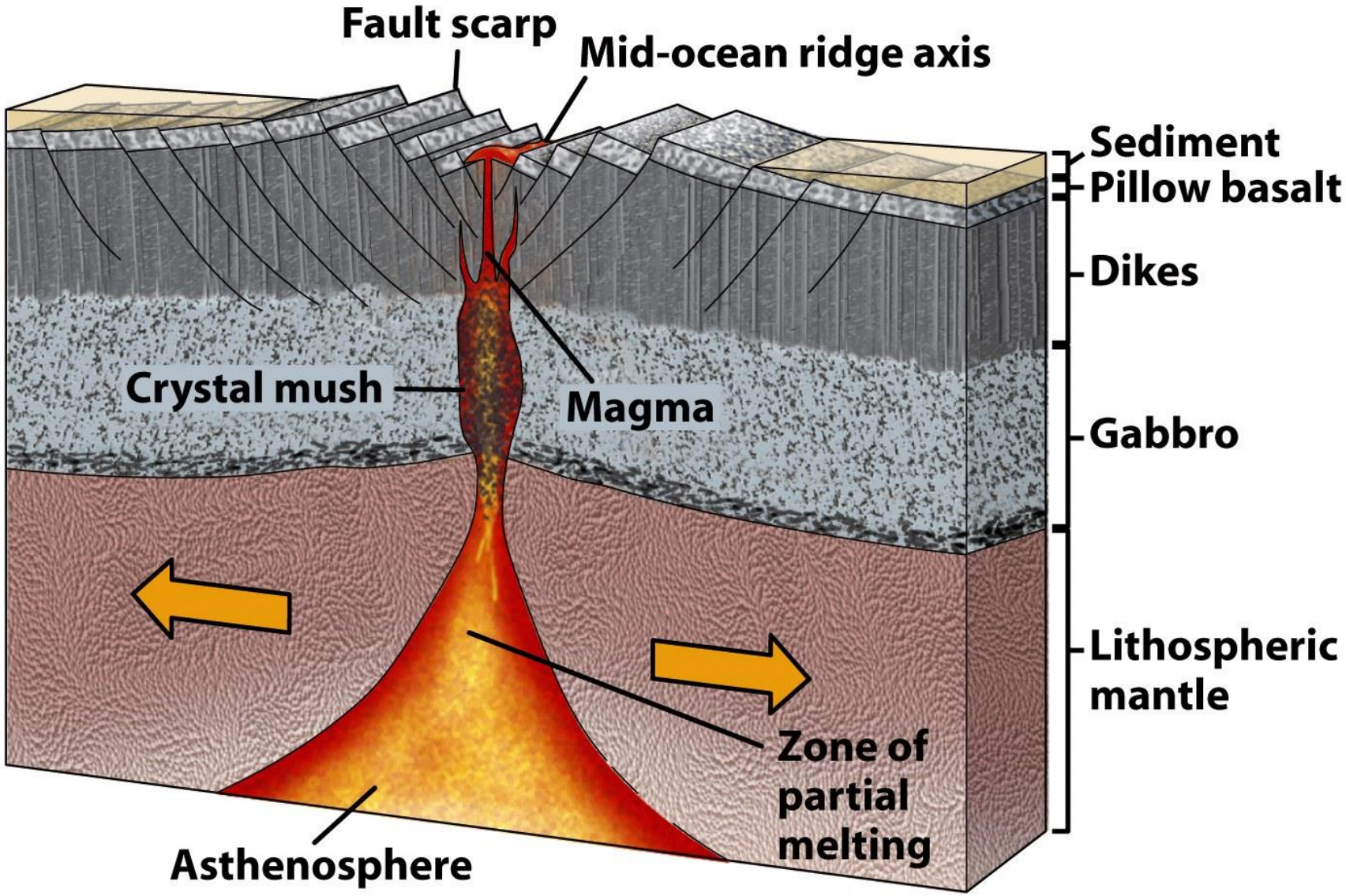
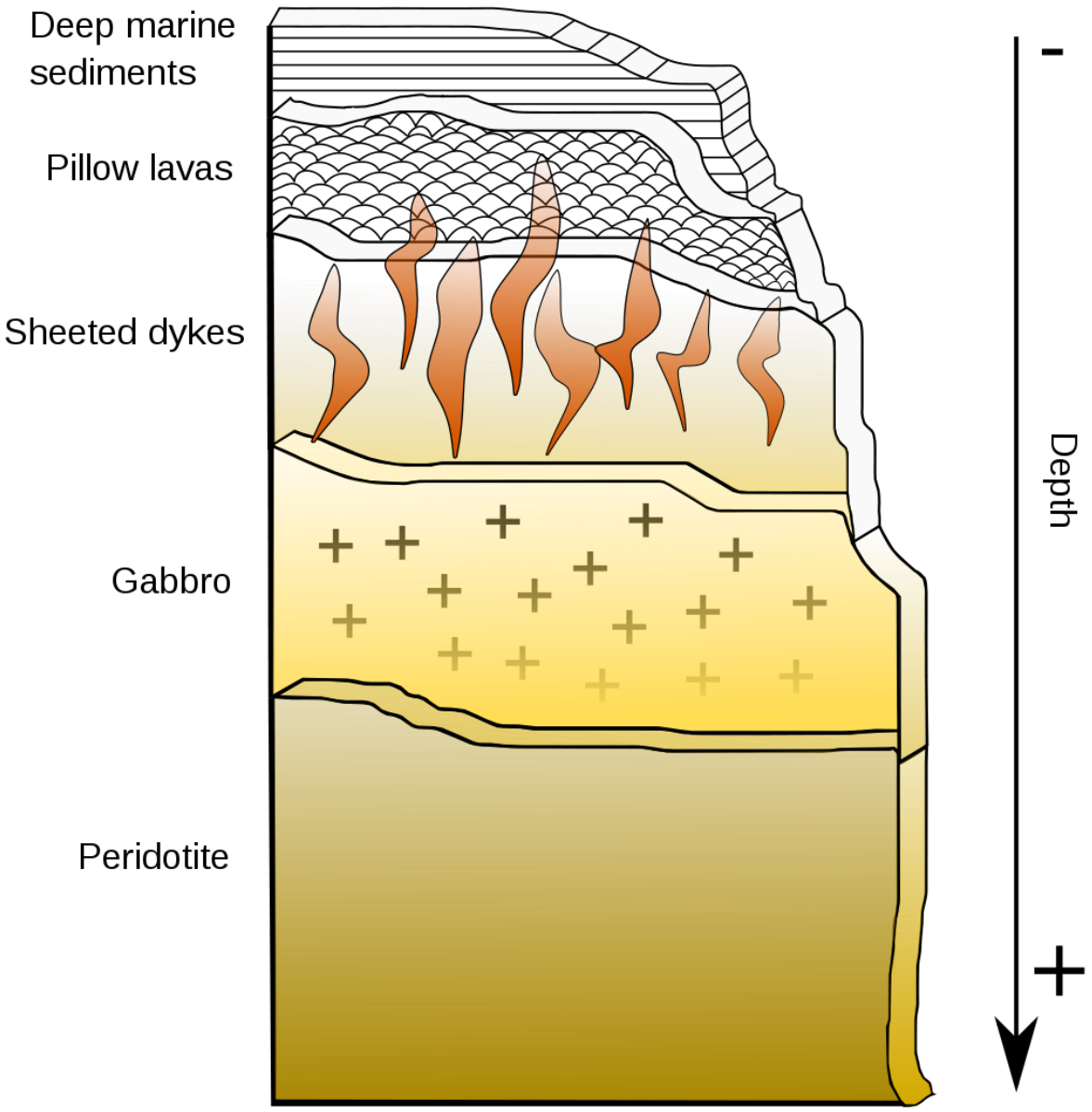


Figure 4-8 Earth: Portrait of a Planet 3/e

OPHIOLITES



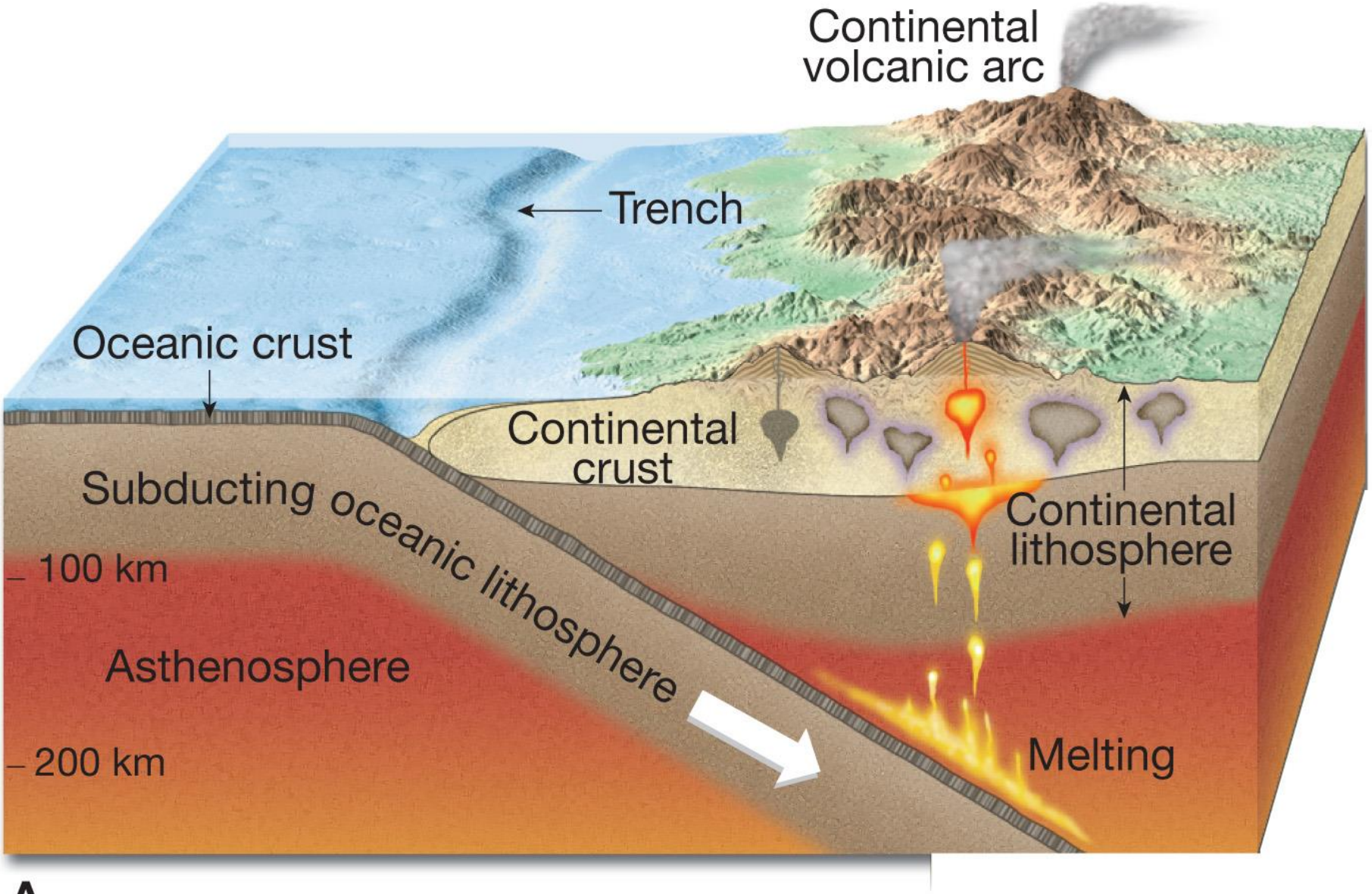
Represent vestiges of oceanic basins now closed and entrapped in mountain belts

OPHIOLITES

Present-day pillow lavas

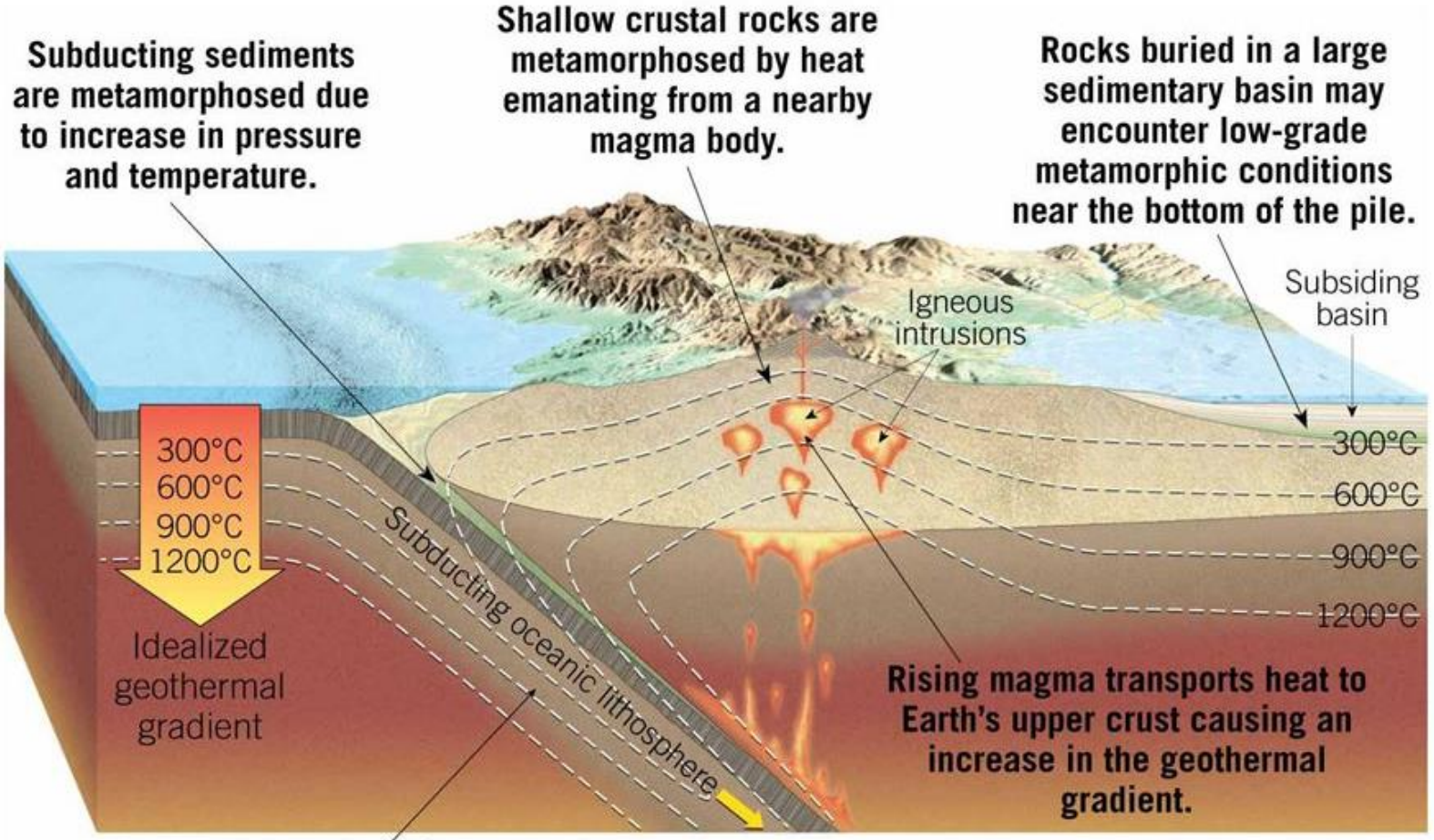
Mesozoic pillow lavas

SUBDUCTION ZONES WHERE OCEANIC LITHOSPHERE IS RETURNED TO THE MANTLE

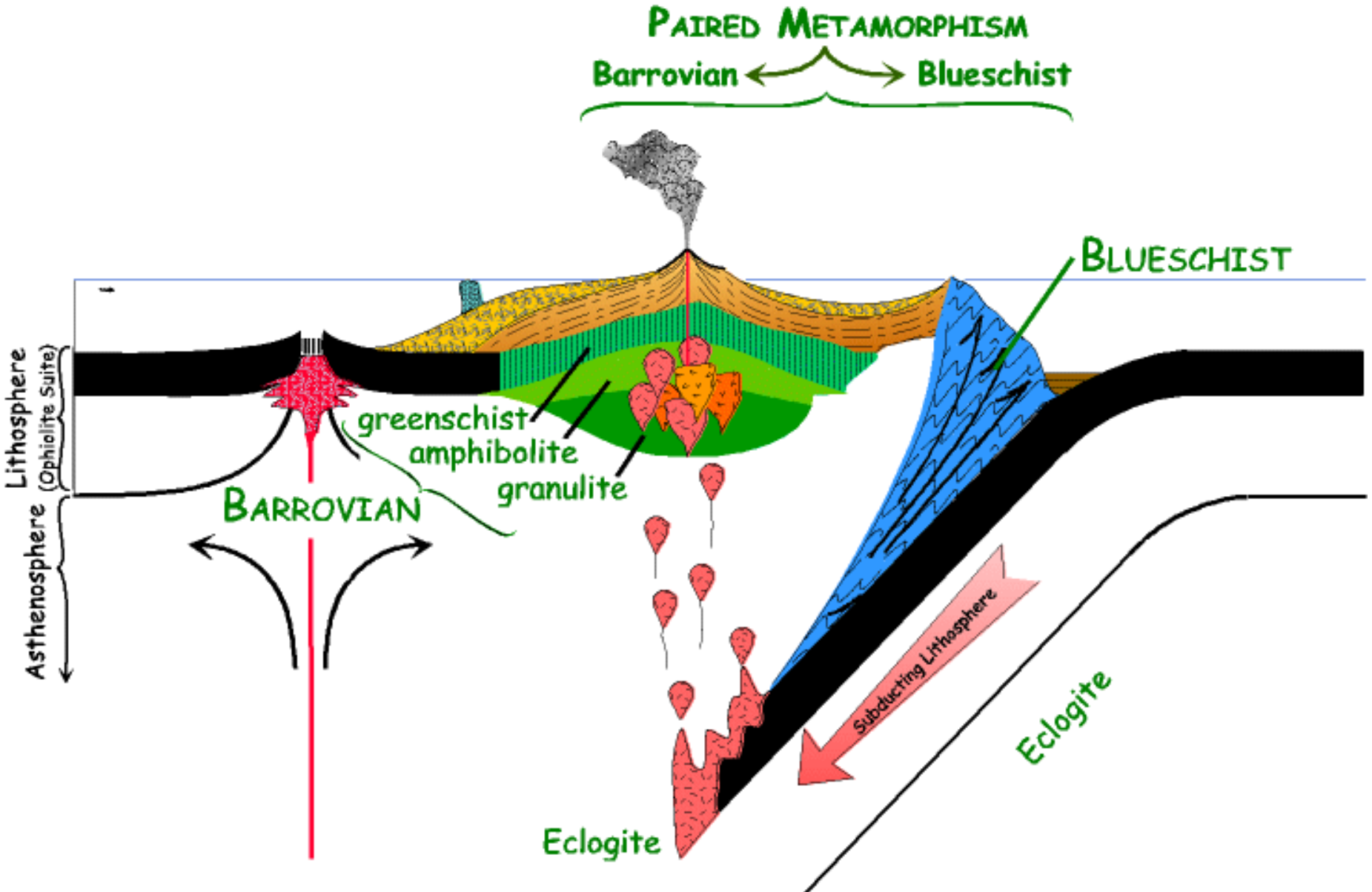


A.

DISTINCT GEOTHERMAL GRADIENTS SUBDUCTION ZONES

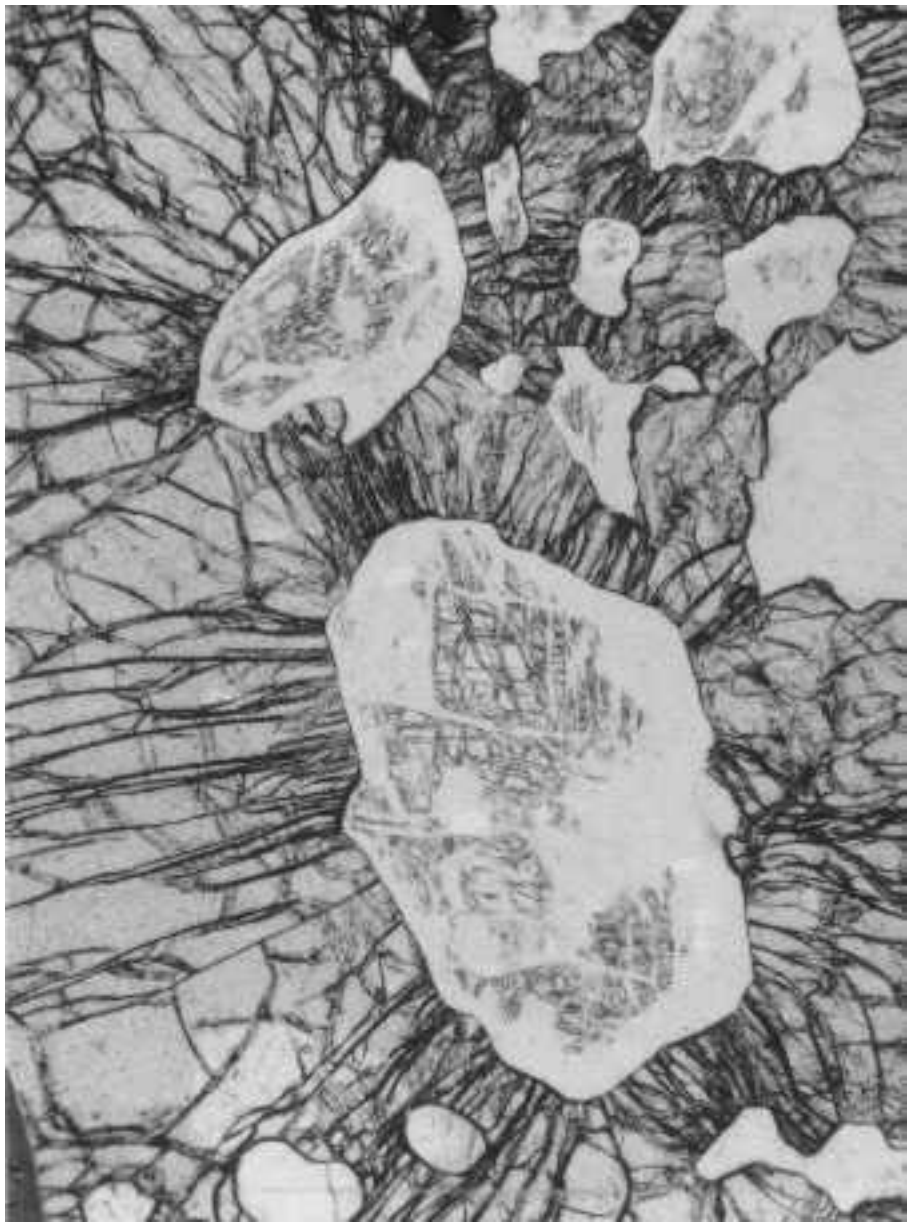


PAIRED METAMORPHIC BELTS
SUBDUCTION ZONES



UHP TERRAINS: ECLOGITES

SUBDUCTION OF CONTINENTAL CRUST: UHP TERRAINS



Coesite

SUBDUCTION OF CONTINENTAL CRUST: UHP TERRAINS

Diamonds

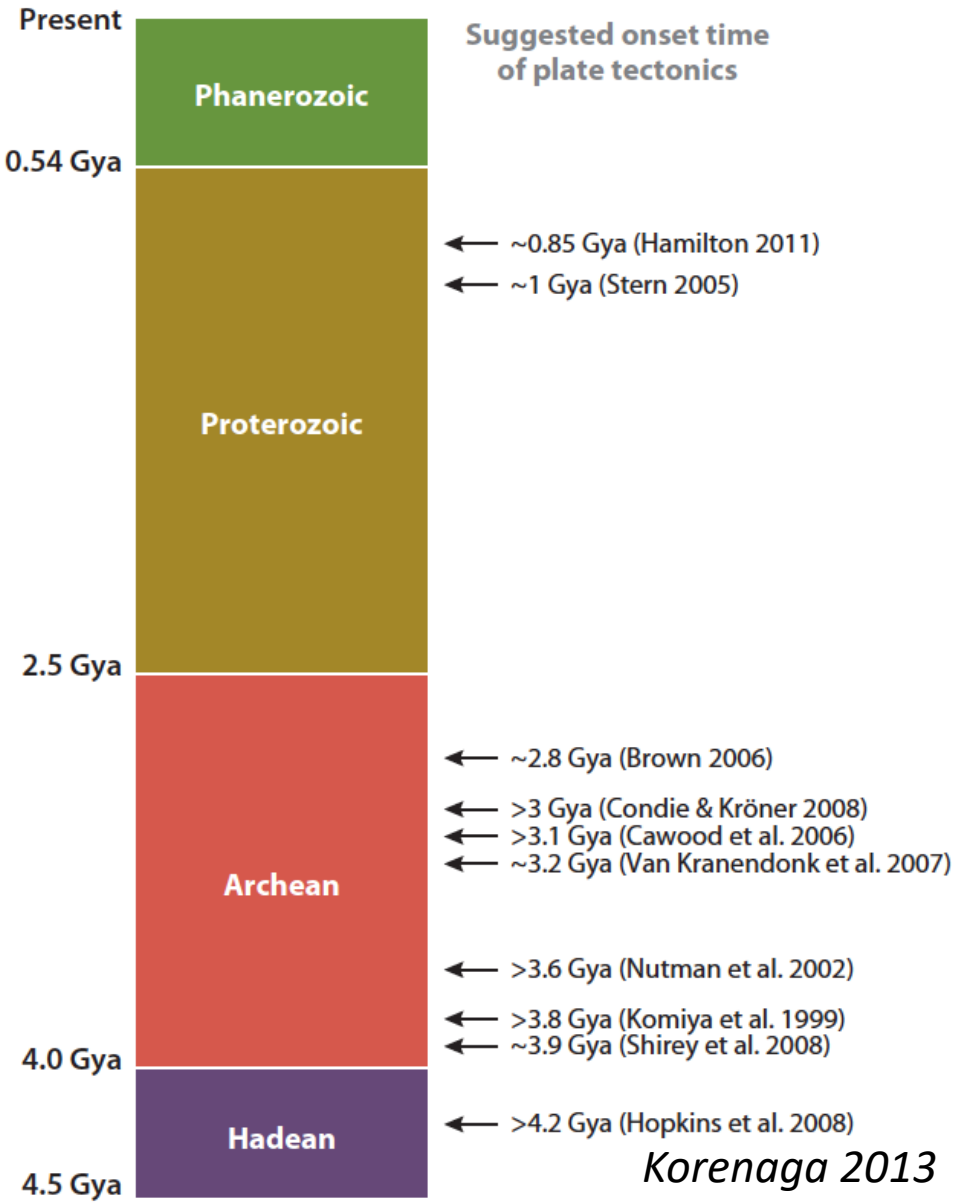
WHEN DID PLATE TECTONICS START?

There are several hypotheses about the starting of plate tectonics.

The main issues are:

1) *What do we consider as Plate Tectonics?*

1) *What do we consider as beginning of Plate Tectonics (episodic vs. steady state and local vs. global)?*



Korenaga 2013

CONDITIONS REQUIRED FOR PLATE TECTONICS TO OCCUR

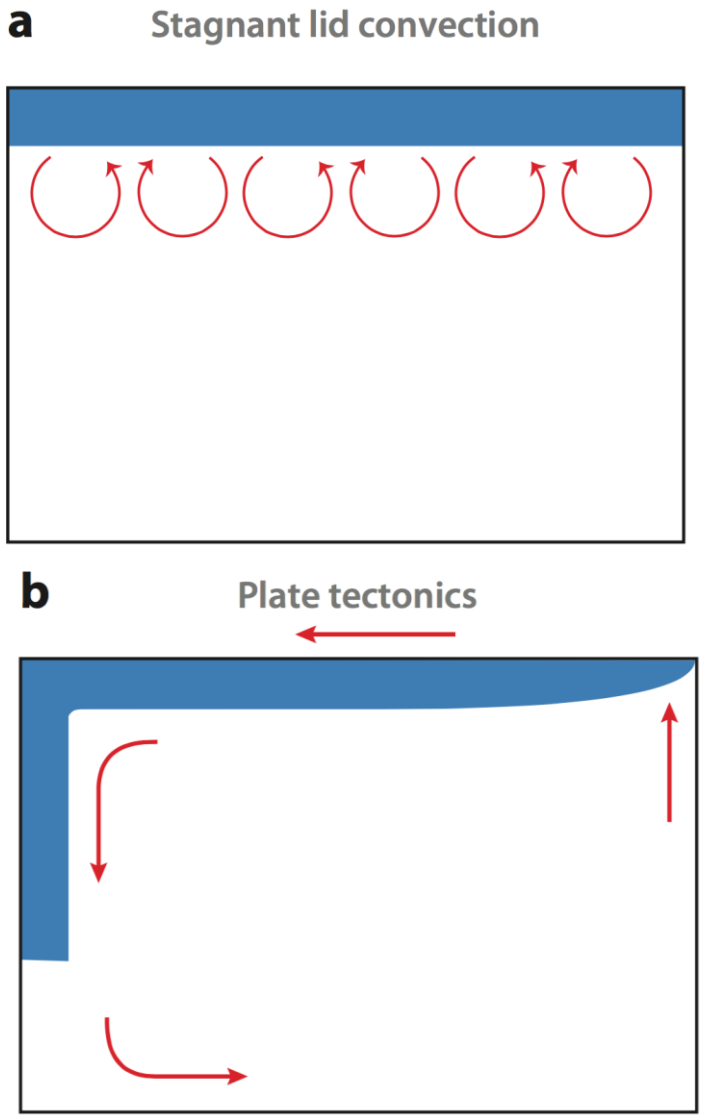
1) Plate tectonics could not have started until a significant fraction of the lithosphere became gravitationally unstable;

1) The lithosphere must be strong enough to remain coherent during subduction and plate motion, but weak enough to be broken into multiple plates.

PLATE TECTONICS CAN ONLY OCCUR WHEN APPROPRIATE MANTLE THERMAL CONDITIONS EXIST

- If the mantle is too cold, it is not possible to break the lithosphere and to form oceanic crust;

- If the mantle is too hot the oceanic crust is too thick and light to allow the oceanic lithosphere to subduct;

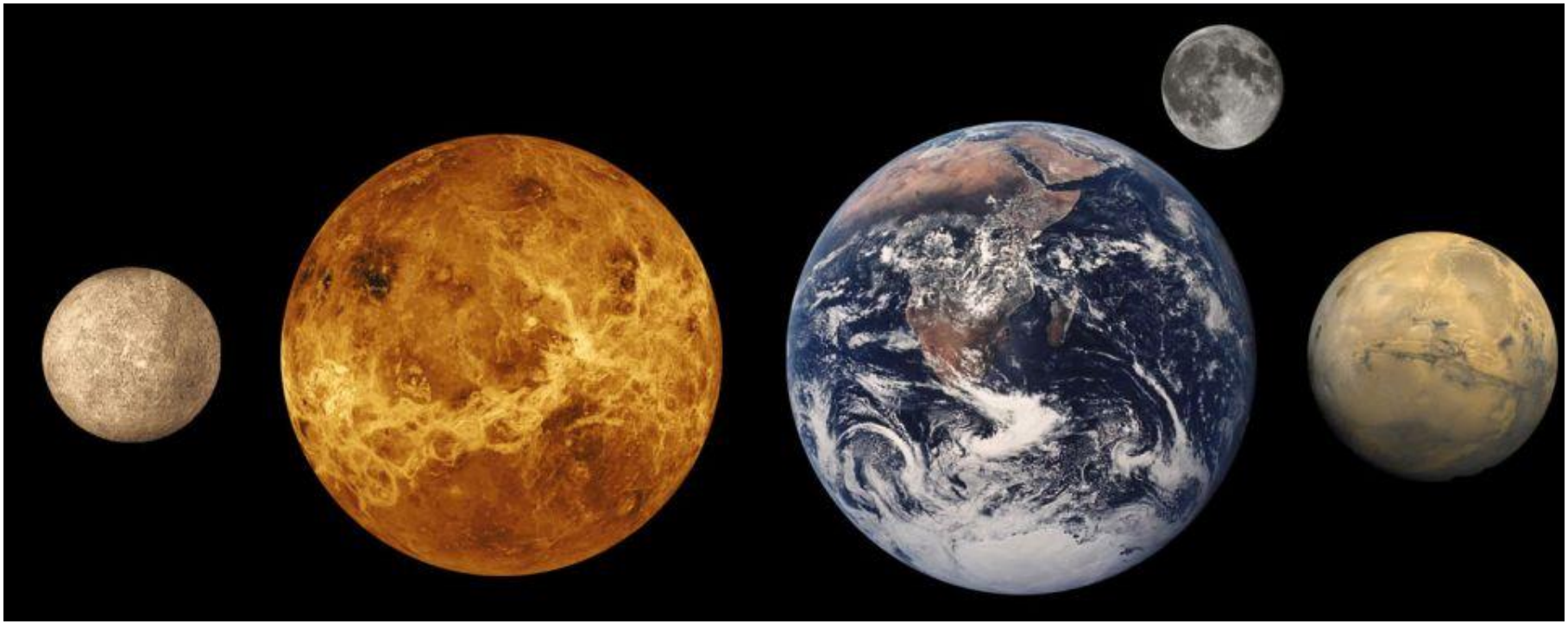


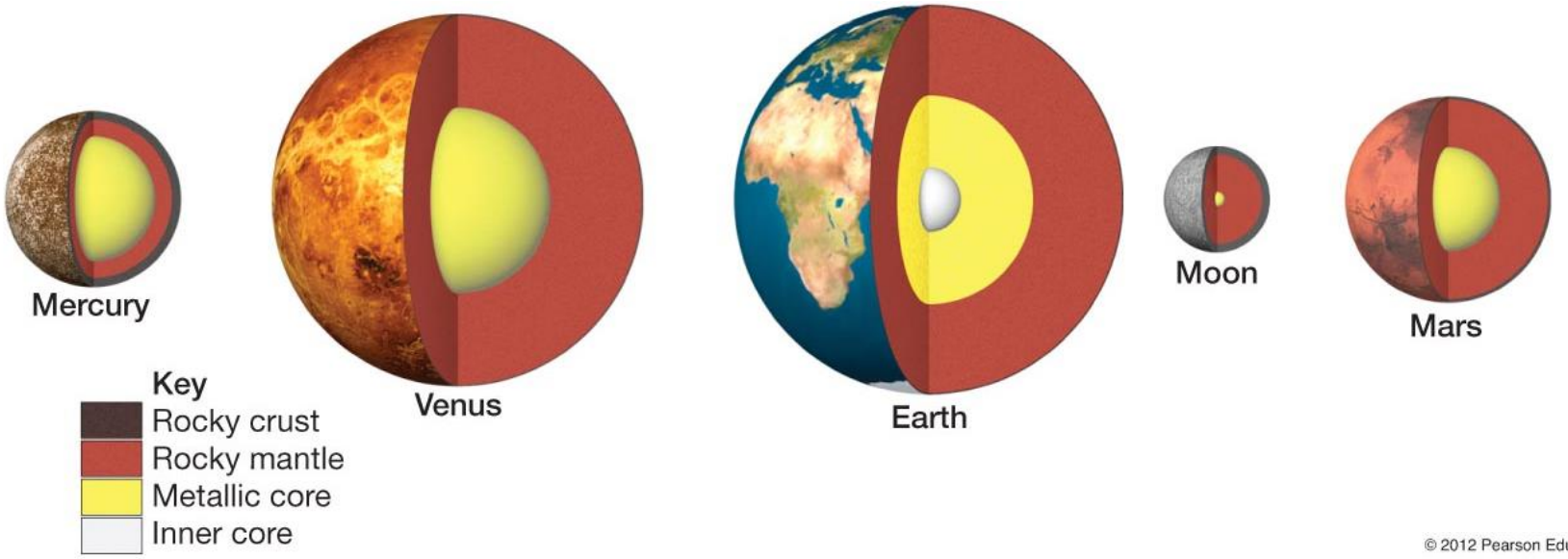
Korenaga 2013

PLATE TECTONICS IS AN UNUSUAL WAY FOR A SILICATE PLANET TO COOL

Of the 5 largest silicate bodies of the Solar System (Mercury, Venus, Earth, Moon, and Mars), only Earth has subduction zones and plate tectonics

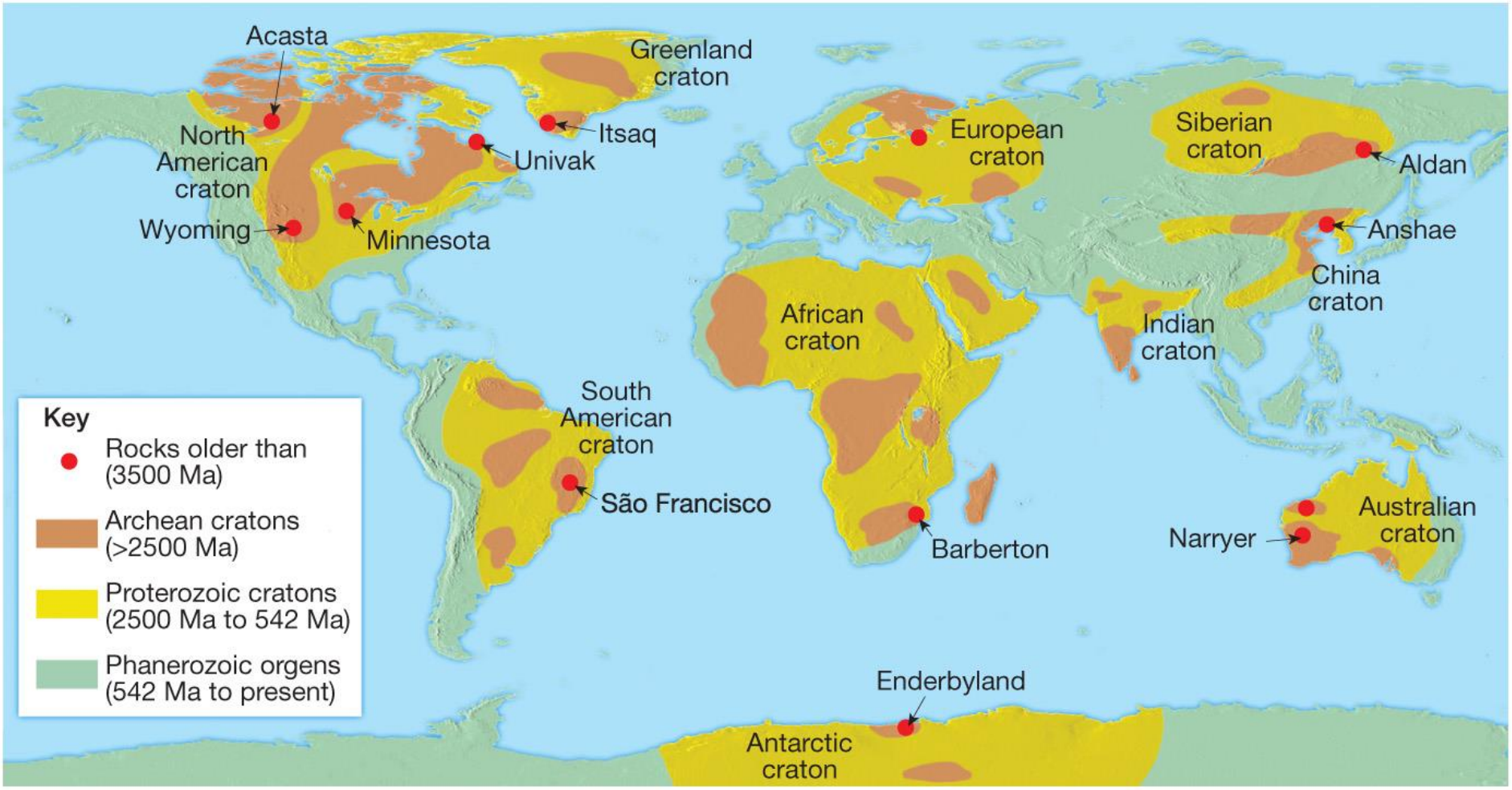
SILICATE PLANETS





CONTINENTAL CRUST

Continents contain the oldest rocks and minerals in our planet, and give information on the thermal and tectonic regimes in the past



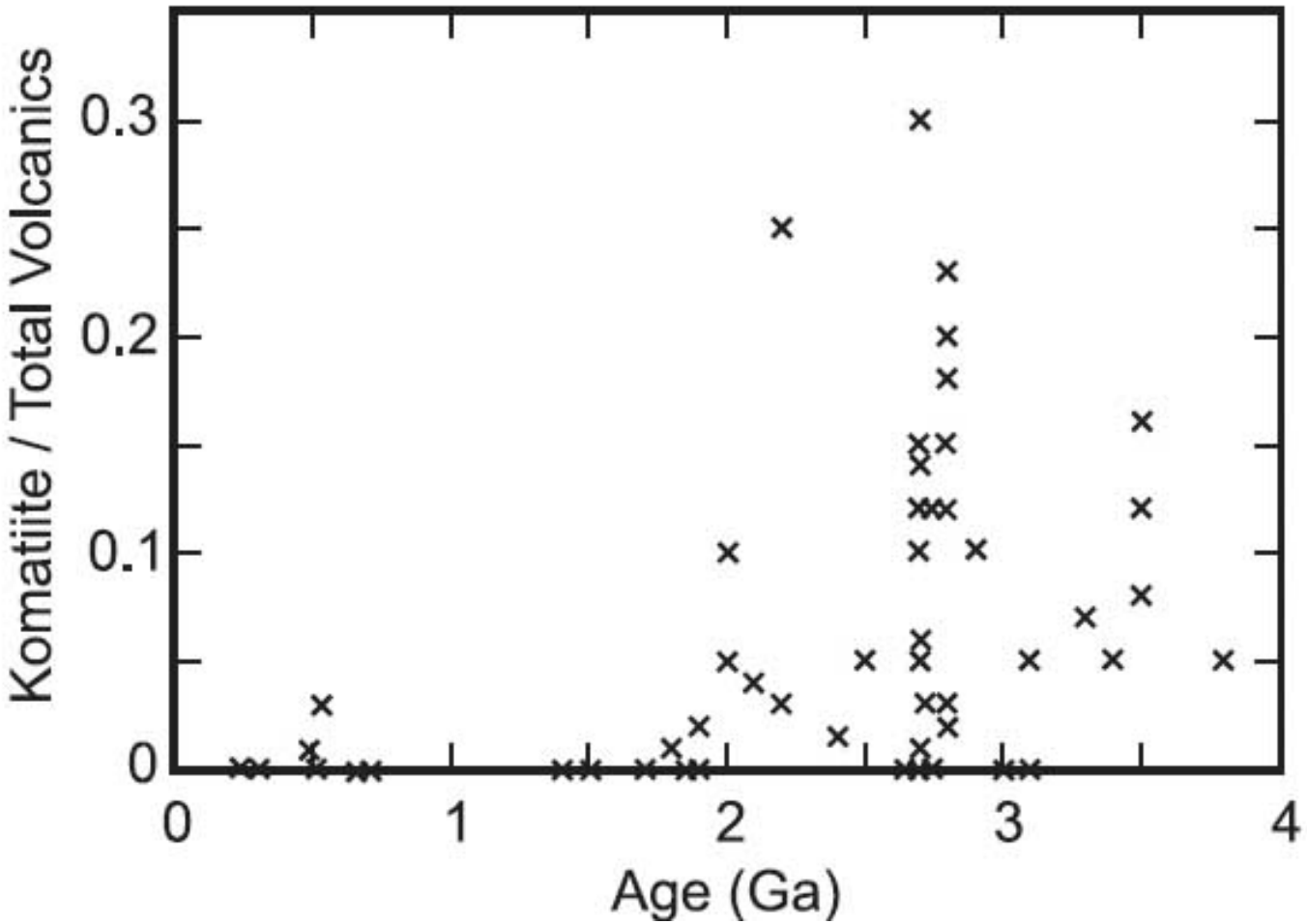
KOMATIITES

Komatiites are ultramafic extrusive volcanic rocks.

During the Archean and Paleoproterozoic, komatiite melting temperatures ranged from 1600–1900° C probably at depth of 150 to 200 km.
Their massive presence suggests a very hot mantle during Archean and Paleoproterozoic.

http://www.alexstrekeisen.it/english/vulc/komatiite.php

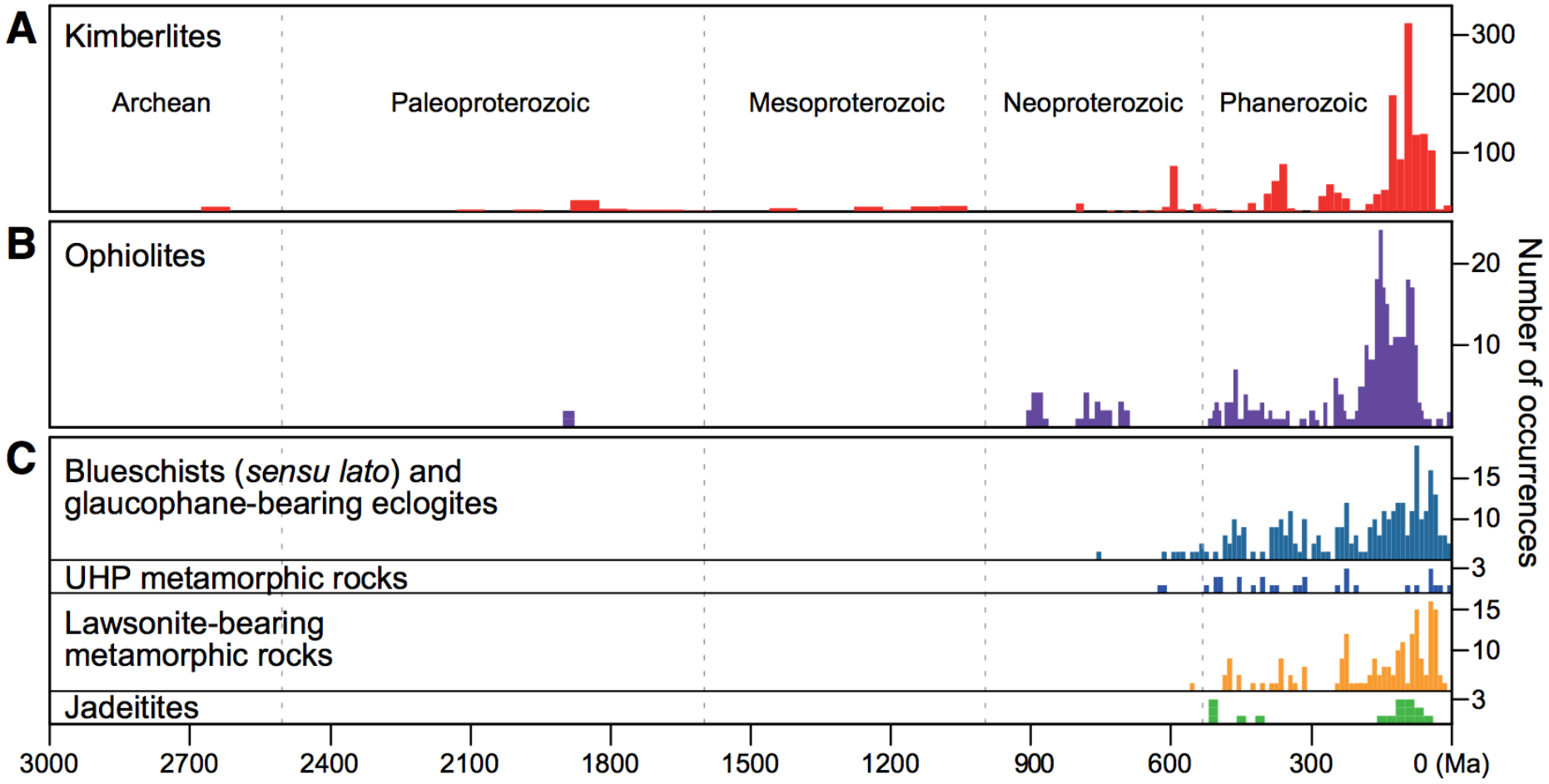
AGE DISTRIBUTION OF KOMATIITES



The predominance of komatiites in the Archean, their decreasing occurrence in the Proterozoic, and extreme rarity in the Phanerozoic have been interpreted to reflect secular cooling of the mantle

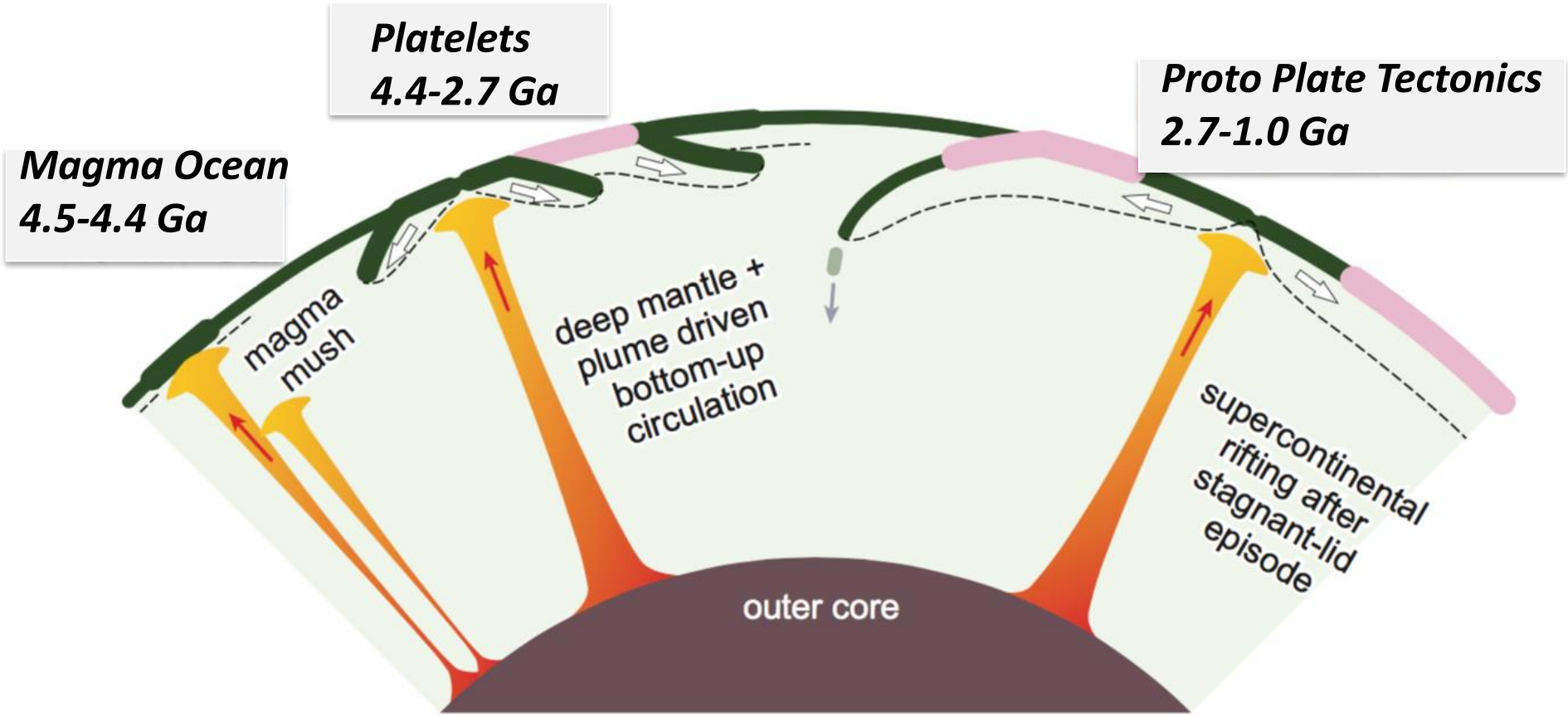
http://www.alexstrekeisen.it/english/vulc/komatiite.php

AGE HISTOGRAMS FOR DISTINCTIVE PLATE TECTONIC AND SUBDUCTION INDICATORS FOR THE PAST 3 GA OF EARTH HISTORY



Stern et al., 2018

BEFORE MODERN-STYLE PLATE TECTONICS

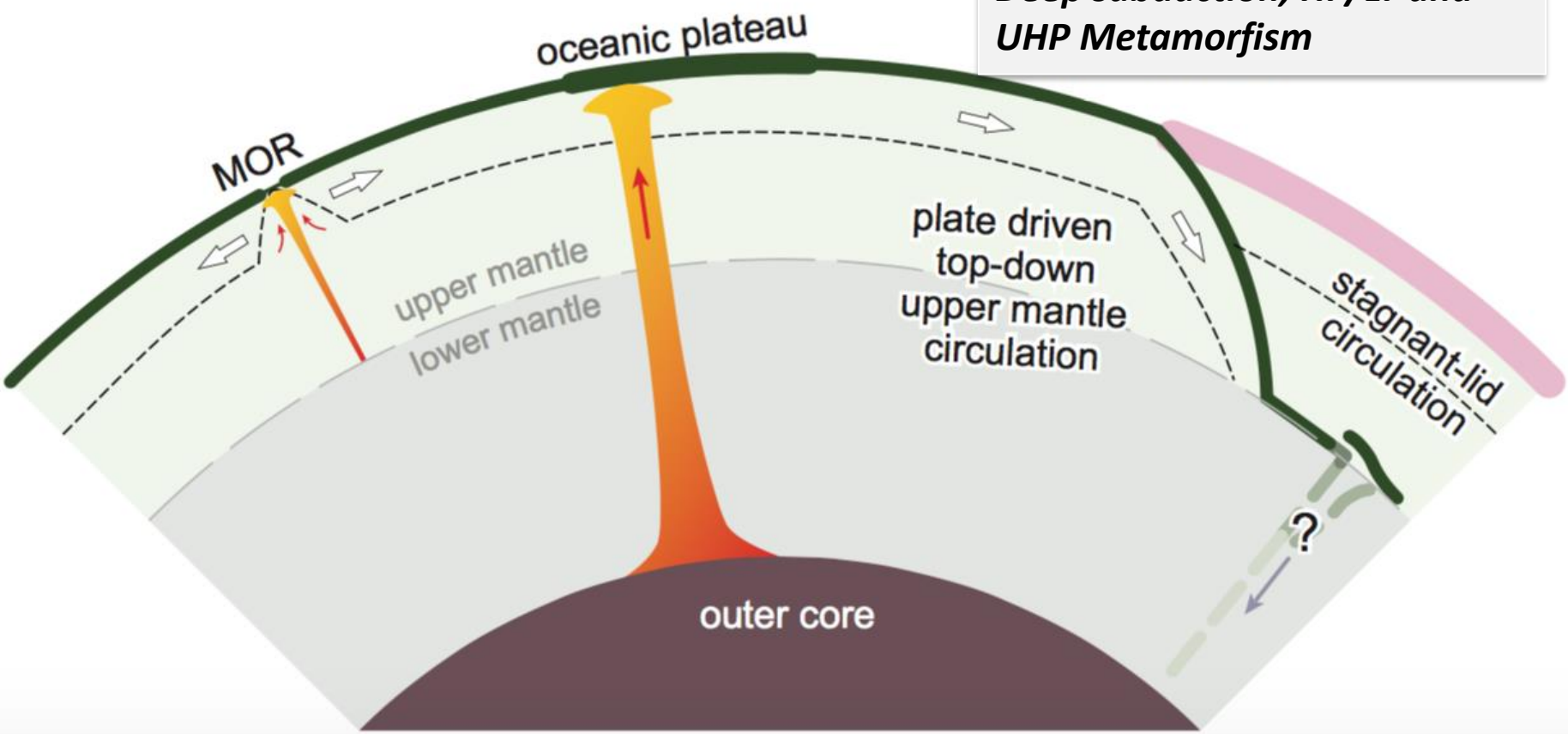


Ernst, 2017

MODERN-STYLE PLATE TECTONICS

1.0-0.0 Ga

Deep subduction, HP/LT and UHP Metamorfism



Ernst, 2017

PLATE TECTONICS IN THE EARTH

- *Small-scale convection and differentiation of continental crust started soon after the end of the Magma Ocean stage;*

- *Proto Plate Tectonics and paired metamorphic belts started ≈ 2.7 Ga;*

- *Modern-style Plate Tectonics started ≈ 1.0 Ga;*

- *Subduction is the main driving mechanism of modern-style Plate Tectonics;*

European Geosciences Union

GIFT – Geosciences Information For Teachers

James Hutton (1726-1796)

...no vestige of a beginning…

…no prospect of an end…

THANKS FOR YOUR ATTENTION!