From Wegener until now

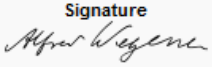
Trond H. Torsvik

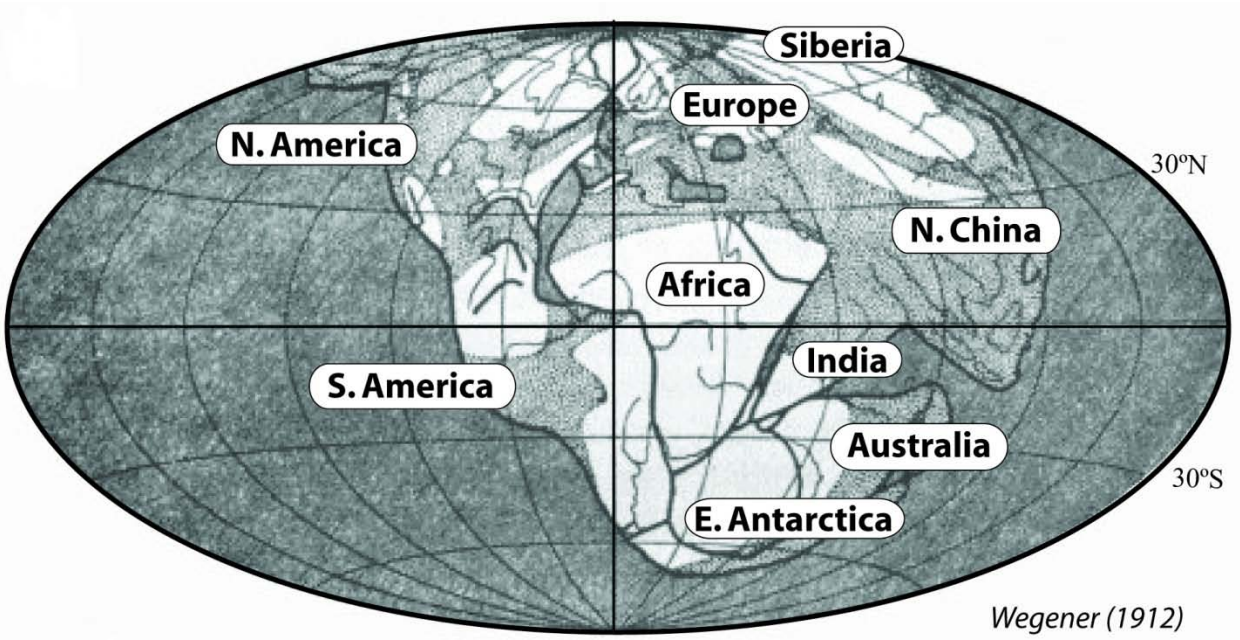
Alfred Wegener

Alfred Wegener, around 1925

Born	November 1, 1880 Berlin, German Empire
Died	November 1930 (aged 50) Clarinetania, Greenland
Residence	Germany
Citizenship	German
Nationality	German
Fields	Meteorology, Geology, Astronomy
Alma mater	University of Berlin
Doctoral advisor	Julius Bauschinger
Known for	Continental drift theory
Influenced	Johannes Letzmann

Signature



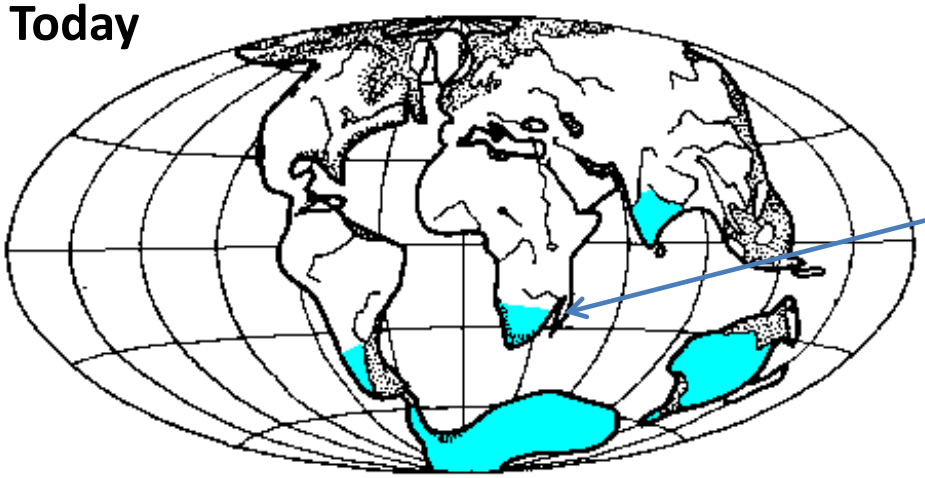


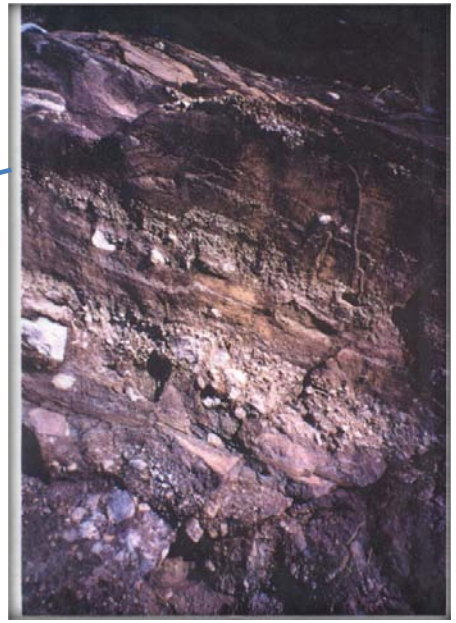
Wegener (1912)

- One hundred years ago, Alfred Wegener proposed that all the continents once formed a single supercontinent (Urkontinent).
- A short summary of Wegener's ideas on continental drift was published in 1912, but it was not until 1915 that the first edition (in German) of his monumental book emerged.

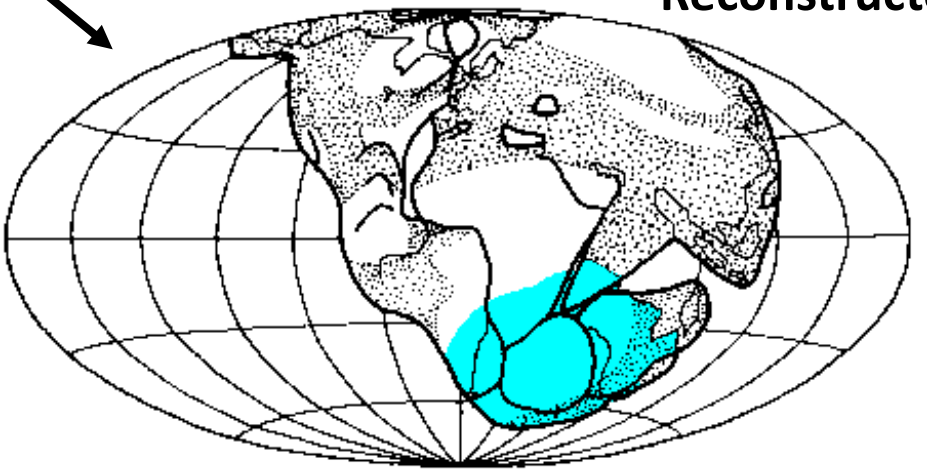
Glacial deposits of the same age (c. 300 Myr) on continents now separated

Today



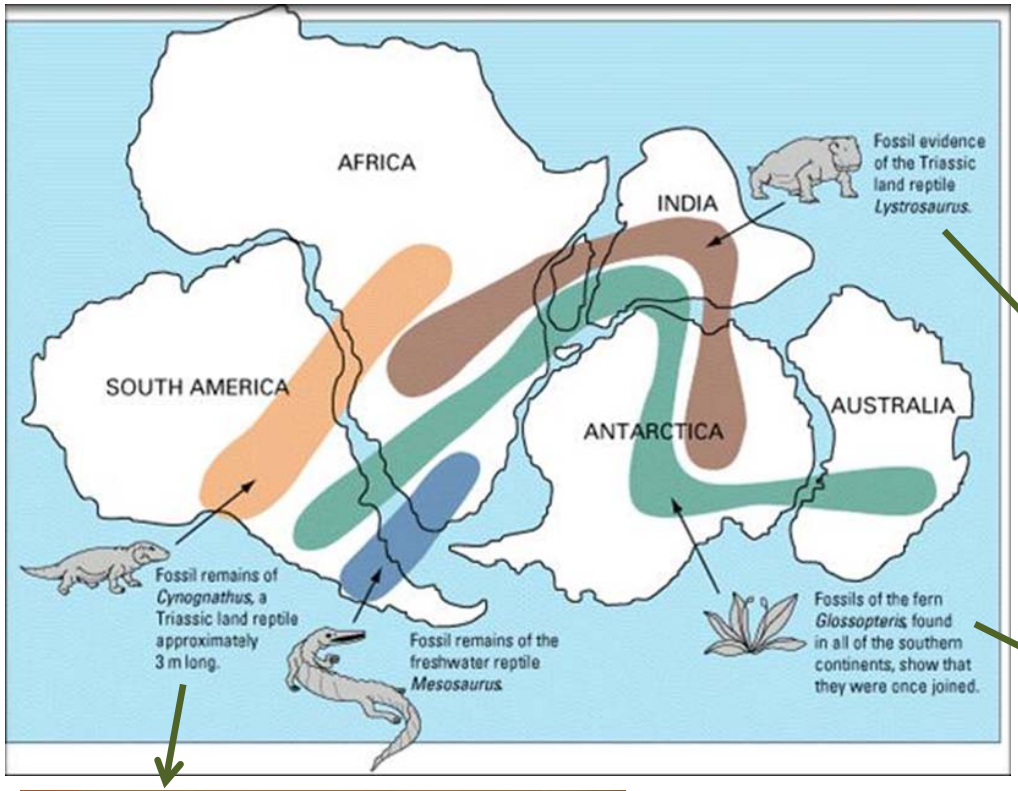


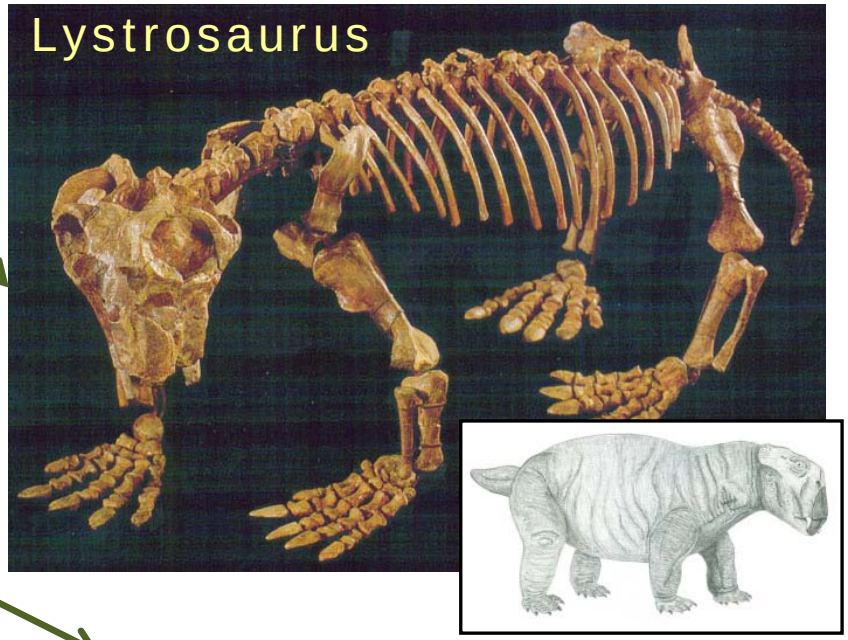
Reconstructed



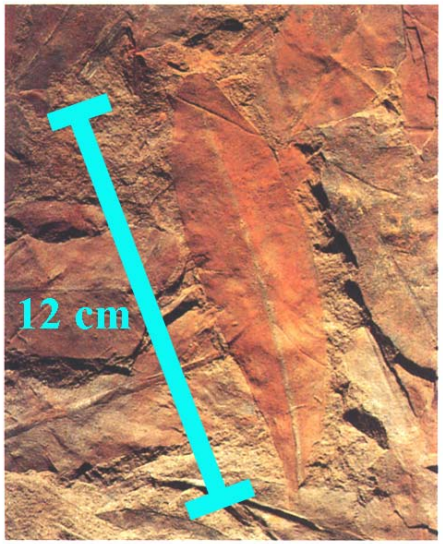
Wegener used glacial relicts (blue) to group the continents around a reconstructed icecap at the south pole

Similar plants and animals separated by great oceans.



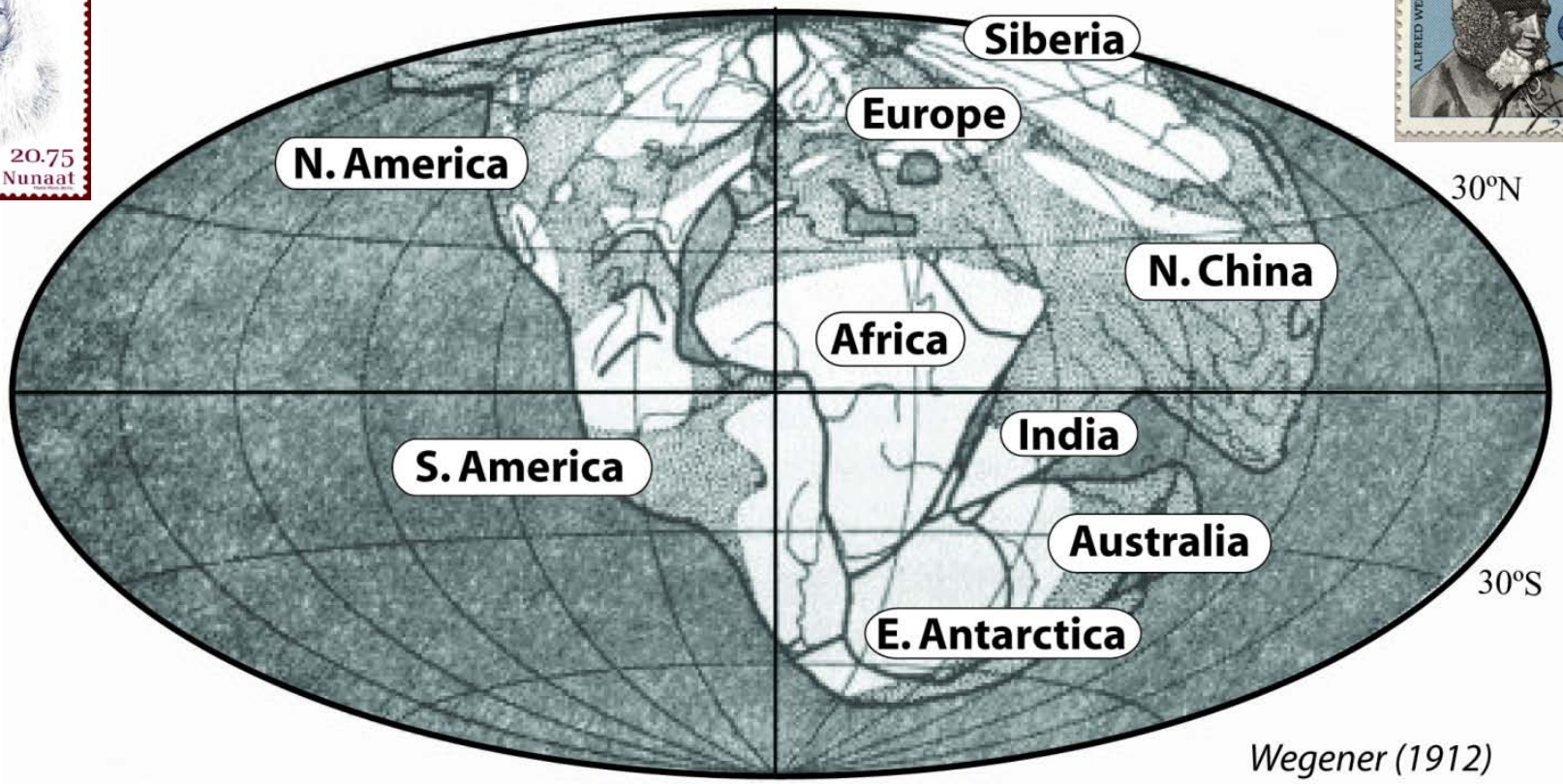


"[mammal-like reptiles](#)"



Glossopteris leaves

The 1st revolution: Continental Drift (1912)



✓The Shapes Match
✓The Rocks Match

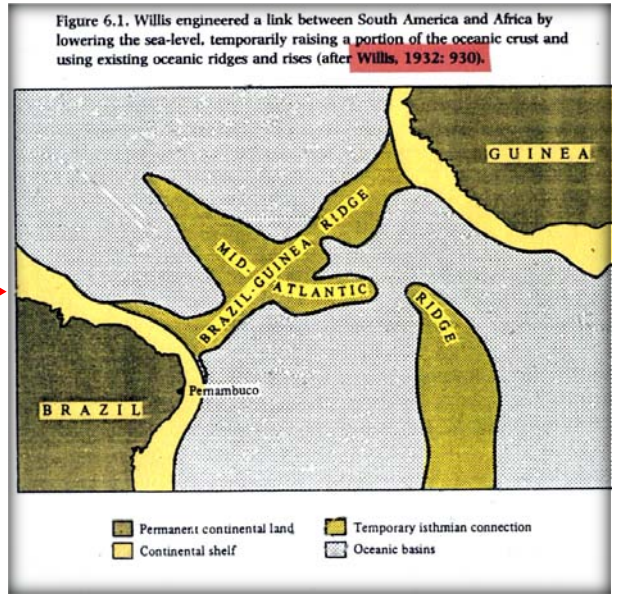
✓The Plants & Animals Match
✓The Ice Matches

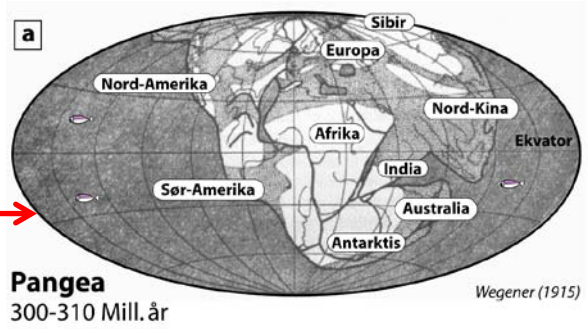
"Doesn't the east coast of South America fit exactly against the west coast of Africa, as if they had once been joined?" wrote Alfred Wegener to his future wife in December 1910. "This is an idea I'll have to pursue."

Some reactions, objections and alternatives to Wegener's theory

"Utter, damned rot!" said the president of the prestigious American Philosophical Society.

- There is no mechanism for continents to 'raft' through oceanic crust
- Landbridges can take animals across oceans
- Changing climatic conditions can be caused by a toppling of the whole Earth (True Polar Wander)
- If present oceans formed by continental drift, why did this happen only once and so late in Earth's history?





Anything before Pangea?

Anyone who "valued his reputation for scientific sanity" would never dare support such a theory

- If present oceans formed by continental drift, why did this **happen only once** and **so late in Earth's history?**

This comment or objection is very unfair — It is not clear exactly what figure Wegener imagined to be correct for the Earth's age in 1912 when he proposed his continental drift theory, but at that time nobody really knew the age of the Earth!

Arthur Holmes

Arthur Holmes around age 22

Born	14 January 1890
Died	20 September 1965
Nationality	British
Institutions	Durham University (1924-1942), Edinburgh University (1943-1956)
Alma mater	Imperial College

Arthur Holmes was the first geologist to date a rock (from Norway) with the U-Pb method while an undergraduate at the Royal College of Science (now Imperial College) in **1911**. He created the first radiometric time scale, and concluded in 1913 in his famous booklet "The Age of the Earth", that the Earth was more than 1600 million years old, and many times older than almost all previous estimates.

Age of the Earth

c. 1700: 6000 year
c. 1800: 300 Myr+
1863: 25 Myr
1911: 370 Myr
1913: 1.6 Ga
2000: 4.55 Ga

Evolution of A Theory

Arthur Holmes **1931**

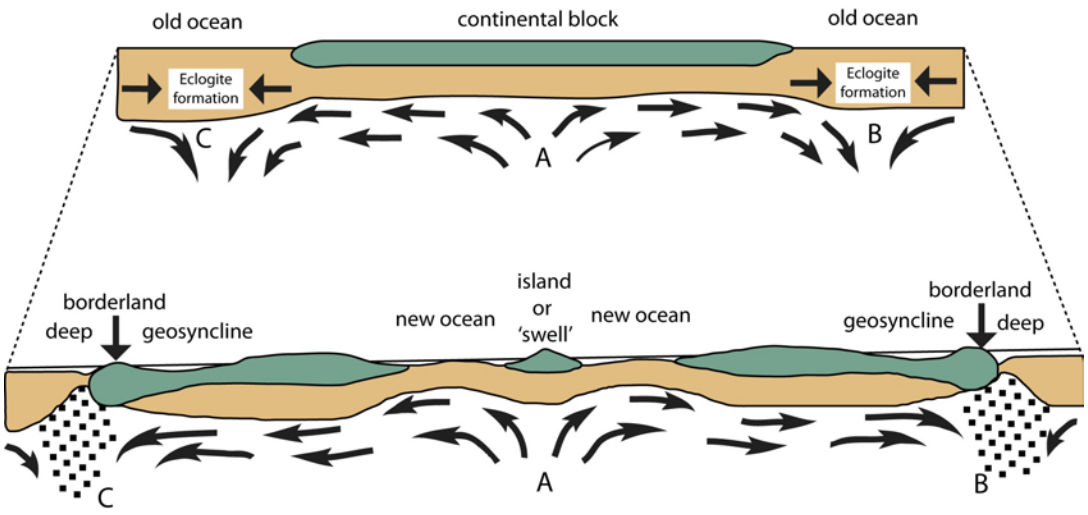


Figure 2: Arthur Holmes' concept of convection zones in the mantle which flow from upwelling under the mid-ocean (Zone A) and then laterally to downwelling at Zones B and C (redrawn from Holmes, 1931).

Arthur Holmes suggested thermal convection in the mantle as a mechanism to move continents.

'Lateral flowage' in the crust could be caused by convection currents which would be necessary to dissipate the radiogenic heat generated in the Earth's mantle. Holmes schematically depicted the convection currents as being the driving force behind the breakup of a theoretical continent into two pieces, with 'new ocean' between the two, and the new ocean itself divided by a central island or 'swell'.

Evolution of A Theory

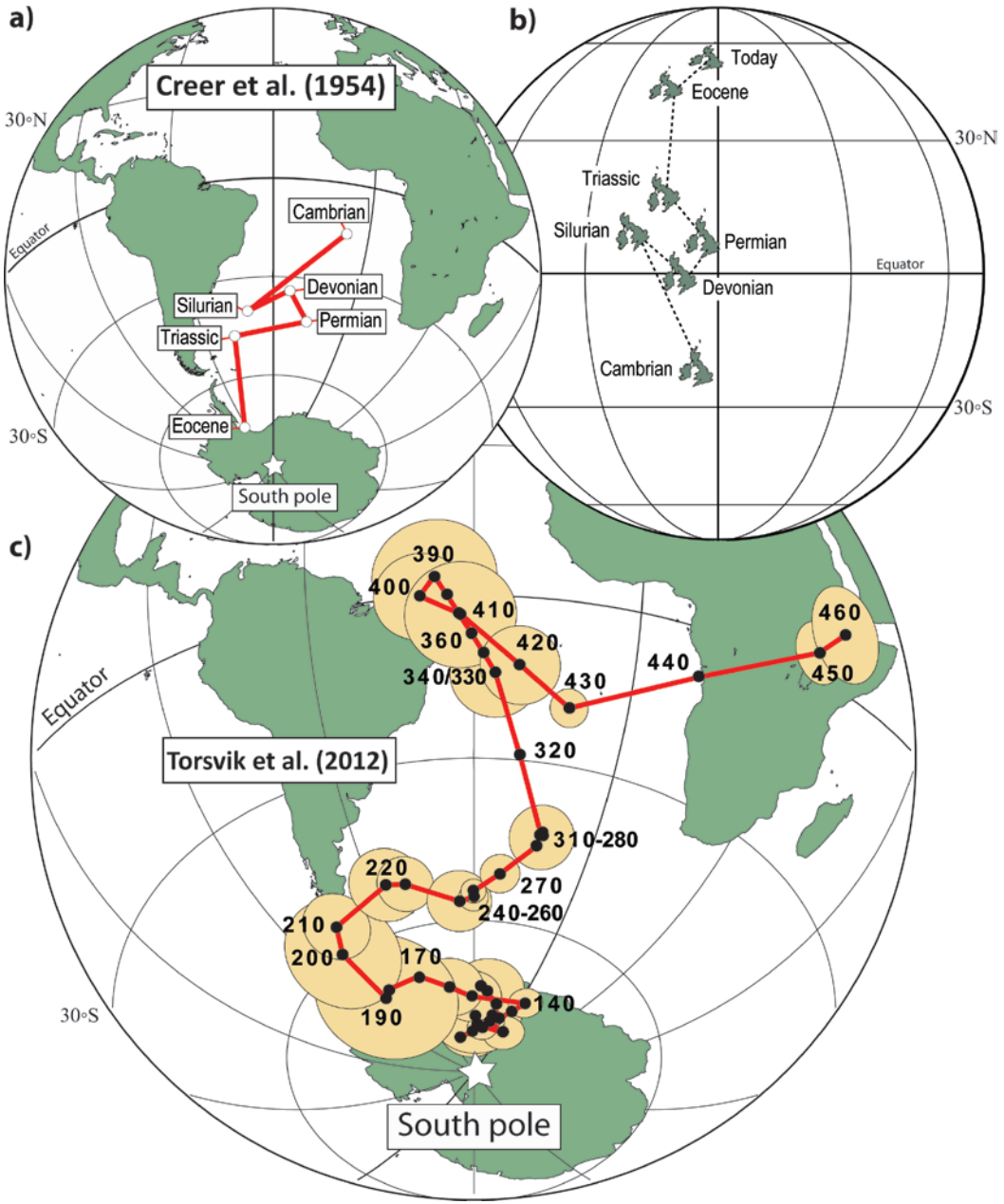
Creer et al **1954**

All at Cambridge

The first ever apparent polar wander path: Creer, Irving & Runcorn (1954)

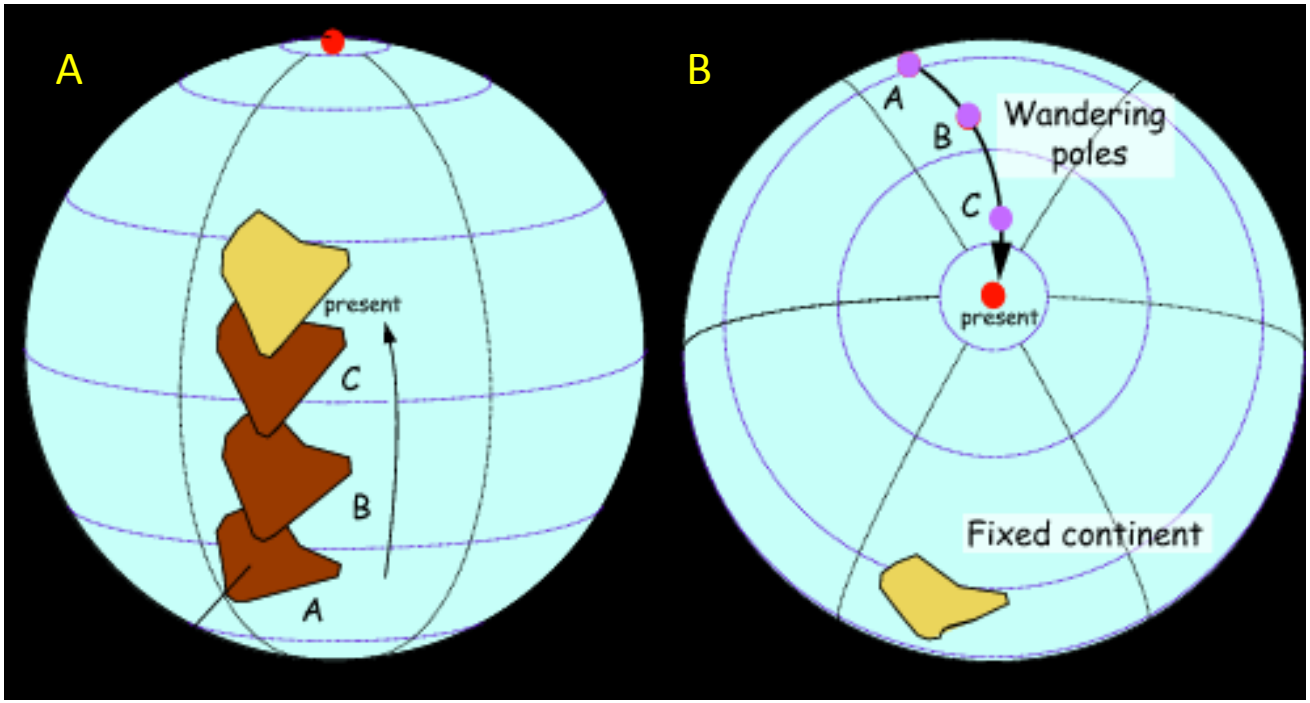
"In Pre-Tertiary times the axis of this dipole field diverges considerably from the present geographical axis and this is tentatively interpreted as a slow change in the axis of rotation of the earth with respect to its surface"

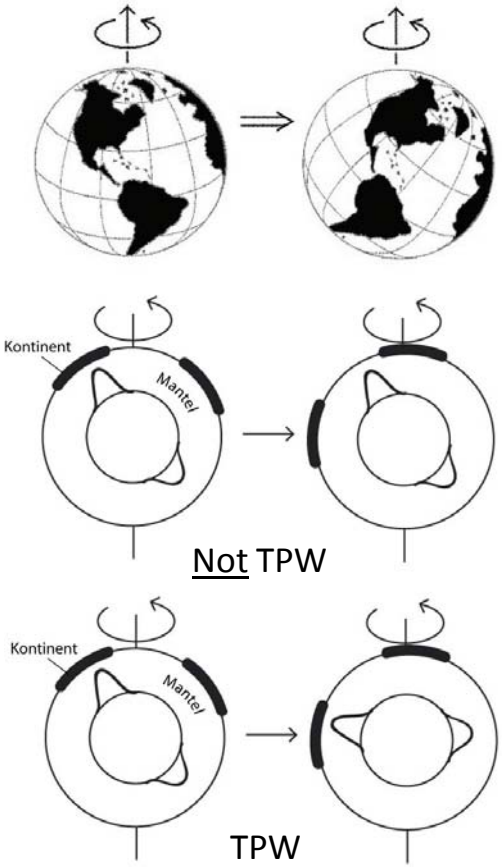
Of all their poles, only the Permian pole resembles more modern 'European' compilations. BUT their observations, even though now known to be partly faulty, that the 'axis of the dipole field diverges considerably from the present geographical axis' have had a fundamental and long-lasting impact.



Two possible explanations for this 1954 stunning observation:

A. The continent moves (apparent polar wander, 'continental drift')
B. The pole moves (true polar wander)

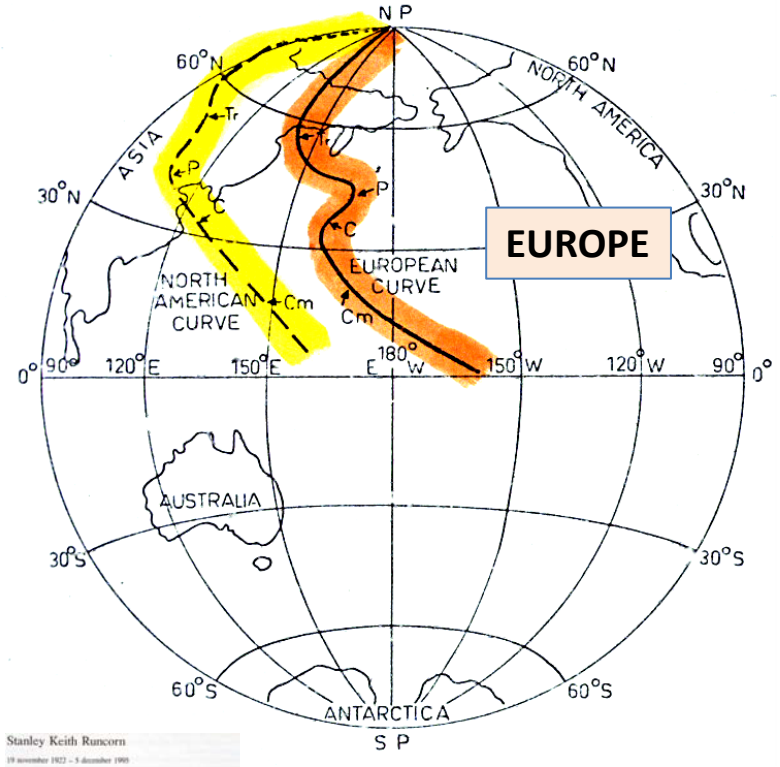




Evolution of A Theory

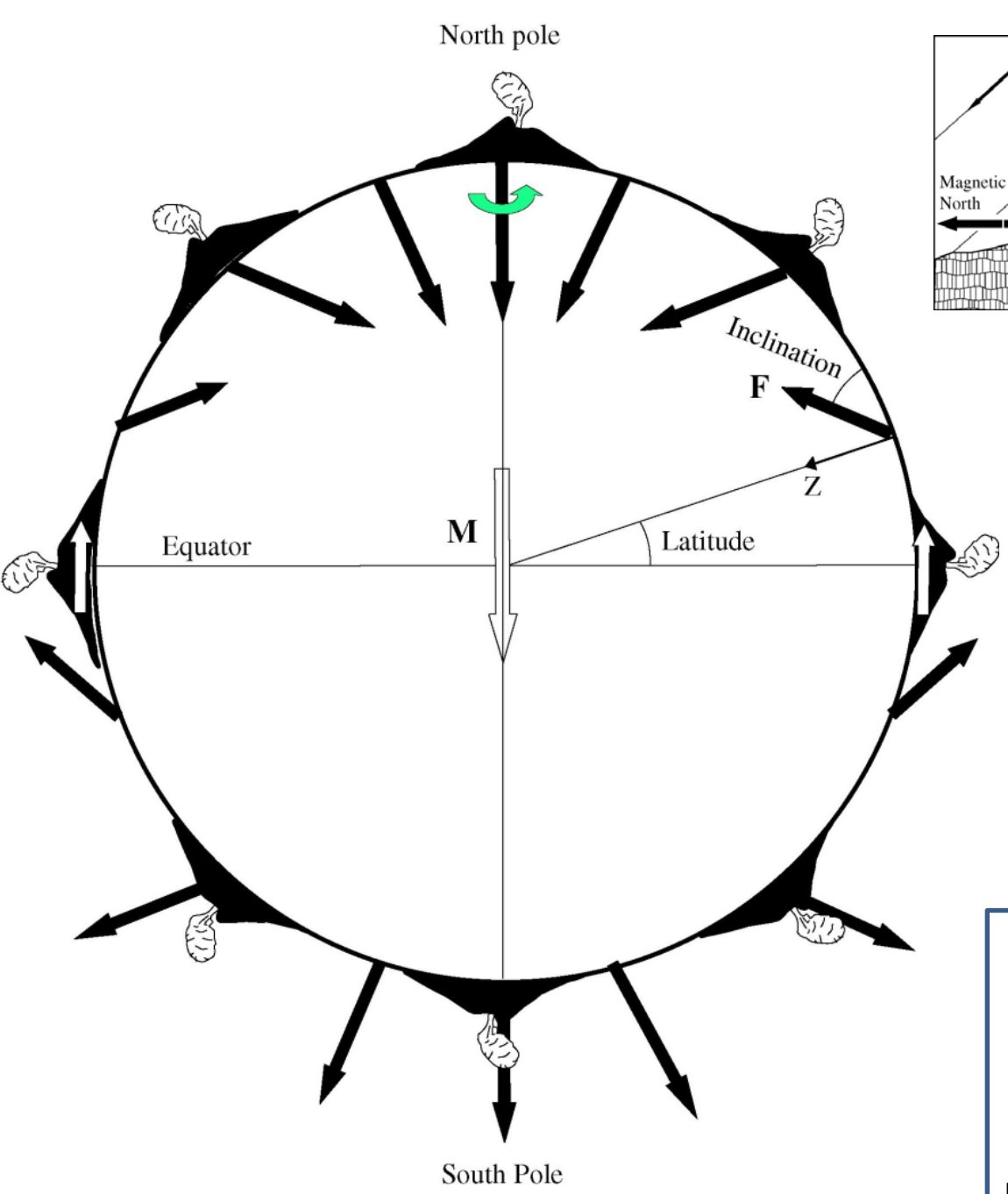
Runcorn 1956

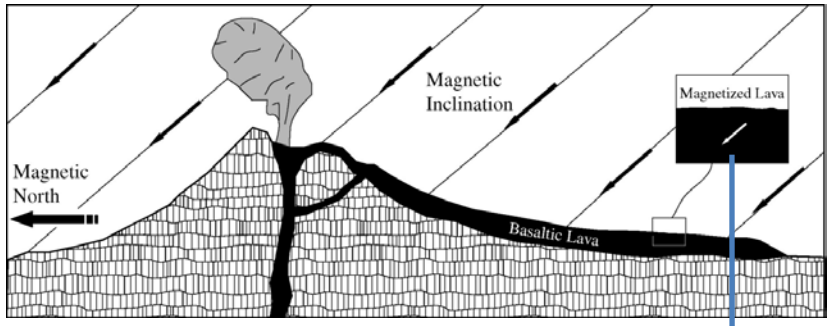
Runcorn shows that apparent polar wander paths from Europe (orange) and North America (yellow) differ – First 'solid' evidence for continental drift.

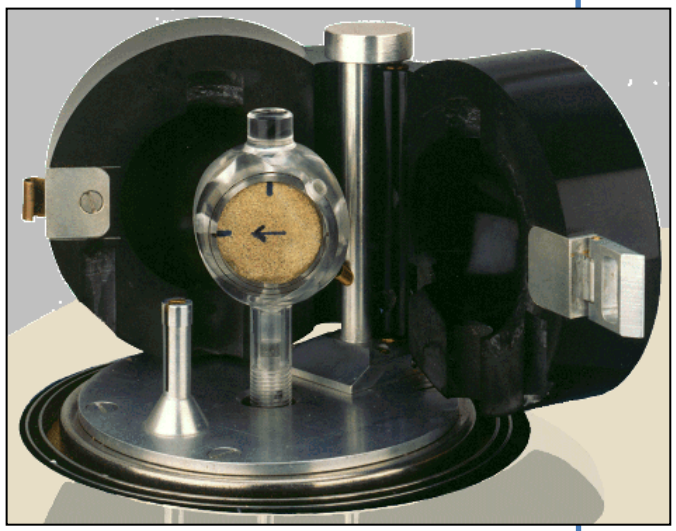


Creer et al. (1954) initially interpreted their results as 'a slow change in the axis of rotation of the earth with respect to its surface' (i.e. True Polar Wander).

Two years later, however, Runcorn (1956) published an APWP for North America and that allowed him to compare the European and North American paths for the first time. He noted that they were broadly similar in shape, but some 30° apart in longitude, which he **interpreted to be due to the opening of the modern Atlantic**; thereby establishing the first independent geophysical evidence that the continents had indeed drifted away from each other.







tan(Inclination)=2 tan (Latitude)

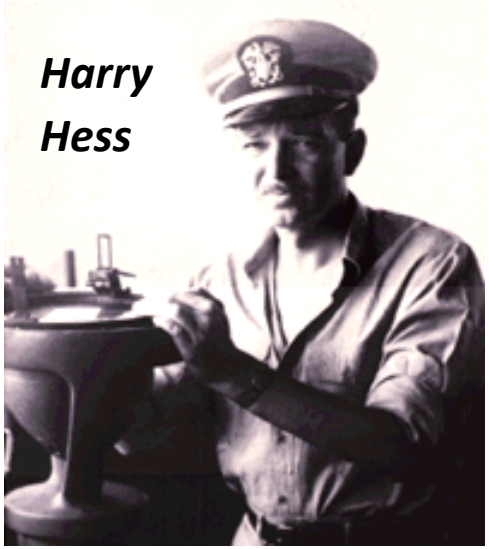
Measured in the laboratory

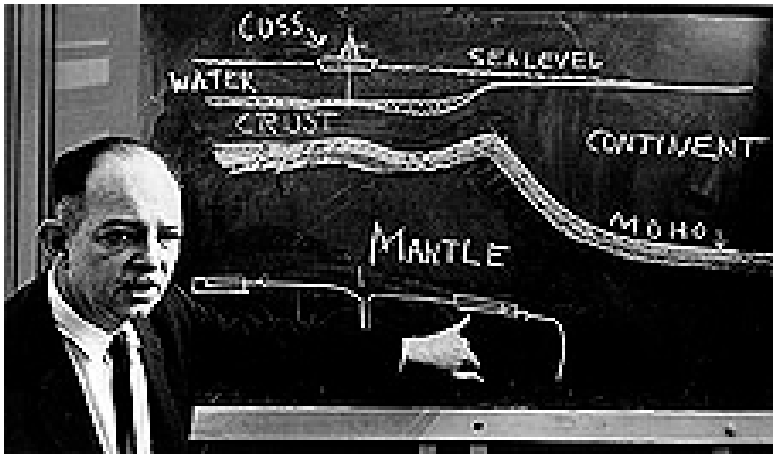
Latitude = atn [tan(Inclination)/2]

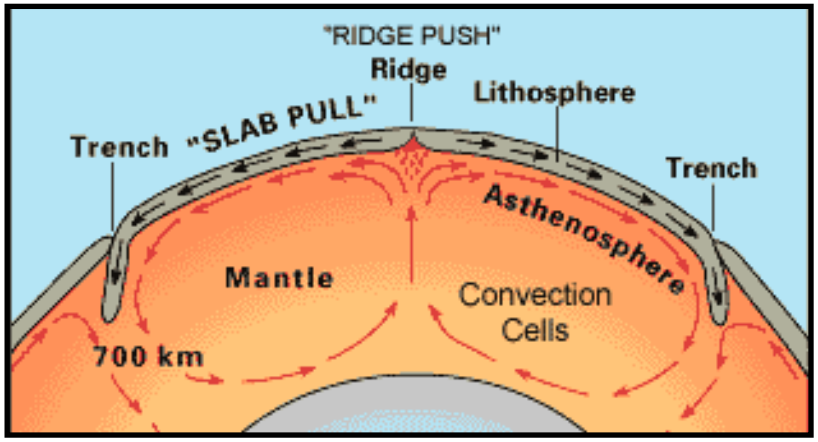
The 2nd revolution: Seafloor Spreading (1962)

Hess's historic article "**History of the Ocean Basins**" was published, suggesting that the continents do not plow through oceanic crust, but that upwelling of mantle material along the mid-ocean ridge system created new sea floor. The convective motion of mantle material carries the sea floor in a conveyor belt fashion to the deep-ocean trenches, where the sea floor descends into the mantle.

(for many years the single most referenced work in solid-earth geophysics).



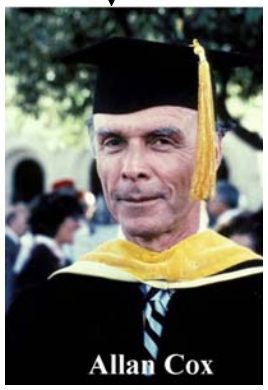




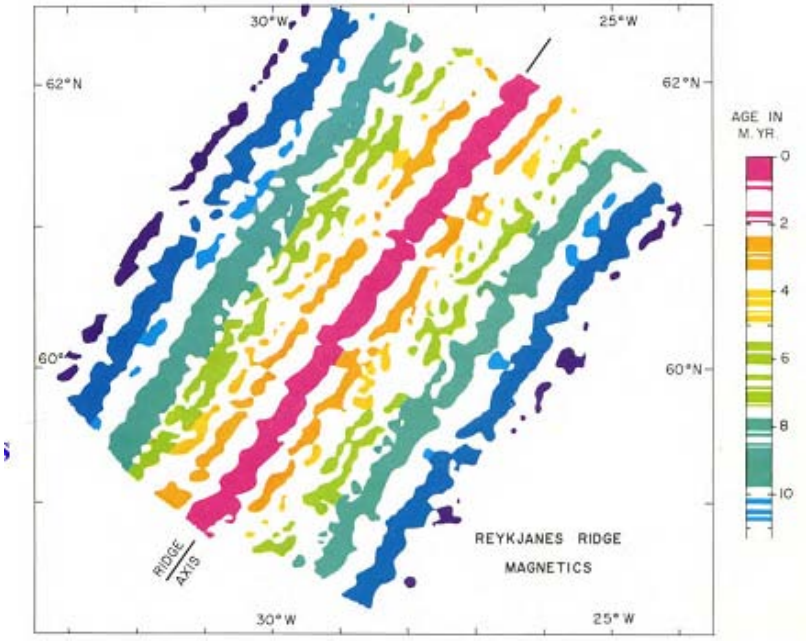
Evolution of A Theory

Vine & Matthews **1963**

Fred Vine and **Drummond Matthews** of Cambridge explained the linear magnetic anomalies parallel to active ridges by **correlating earlier theory on seafloor spreading** with research then being done on the time scale for geomagnetic reversals.



The revelation of the model of Vine & Matthews is that it allowed anomalies in color, matching Cox's time scale.



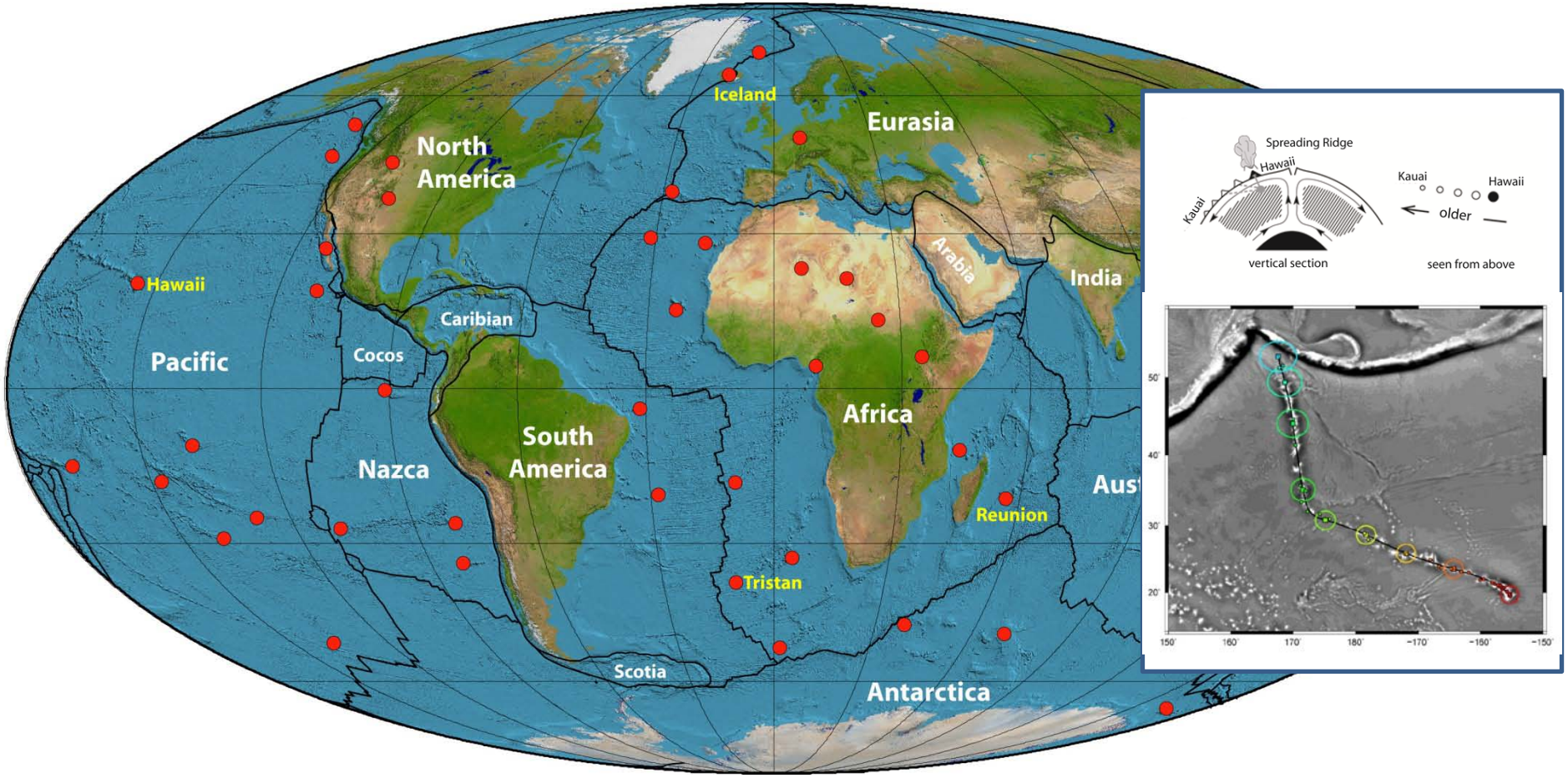
Fred Vine (left) and Drummond Matthews

Positive anomalies are colored, negative ones are white.

Evolution of A Theory

Wilson **1964**

Tuzo Wilson, University of Toronto, postulated that oceanic islands such as the Hawaiian Islands were formed by the movement of a plate over a hot spot deep in the mantle.



Evolution of A Theory

Wilson **1965**

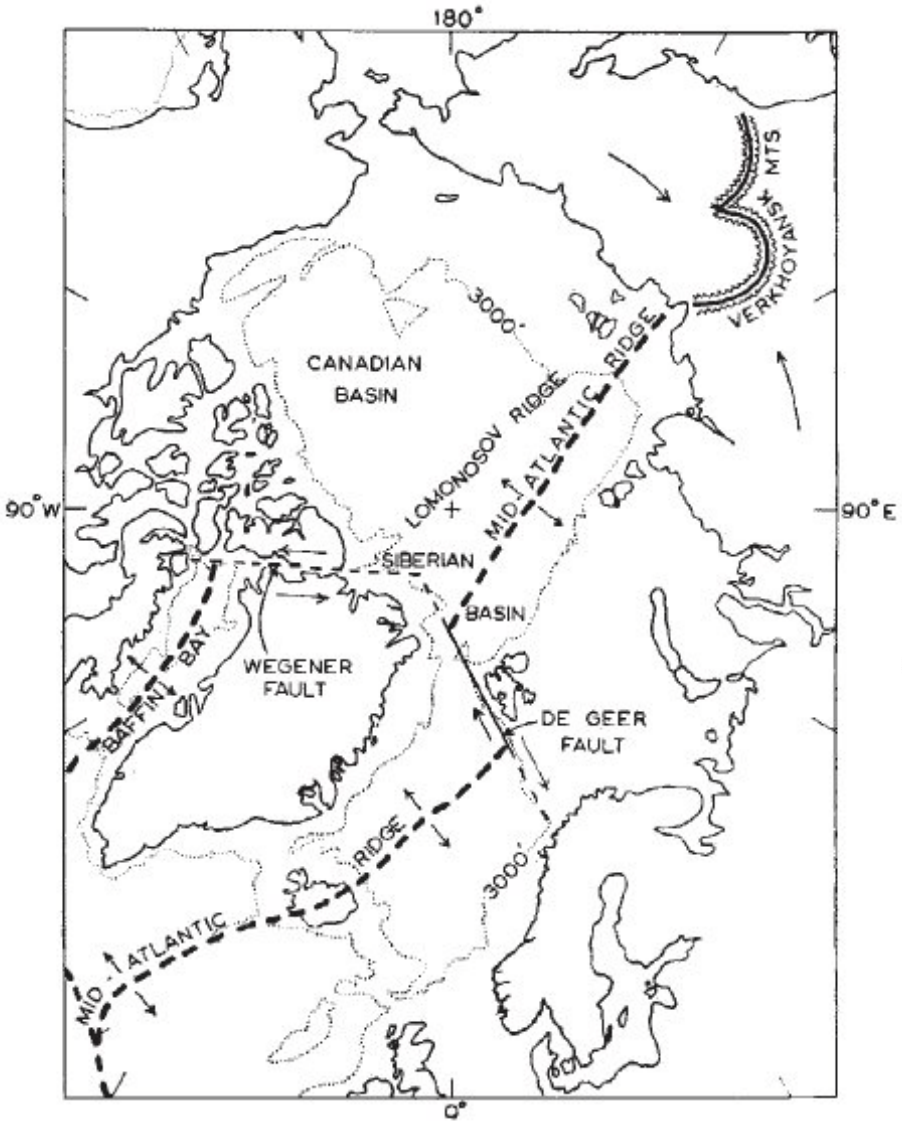


Fig. 5. Sketch map of the termination of the Mid-Atlantic ridge by two large transform faults (Wegener and De Geer faults) and by transformation into the Verkhoyansk Mountains

Tuzo Wilson recognized a new class of faults and wrote the definitive paper on **transform faults** and their bearing on continental drift.

No. 4995 July 24, 1965 NATURE 343

A NEW CLASS OF FAULTS AND THEIR BEARING ON CONTINENTAL DRIFT

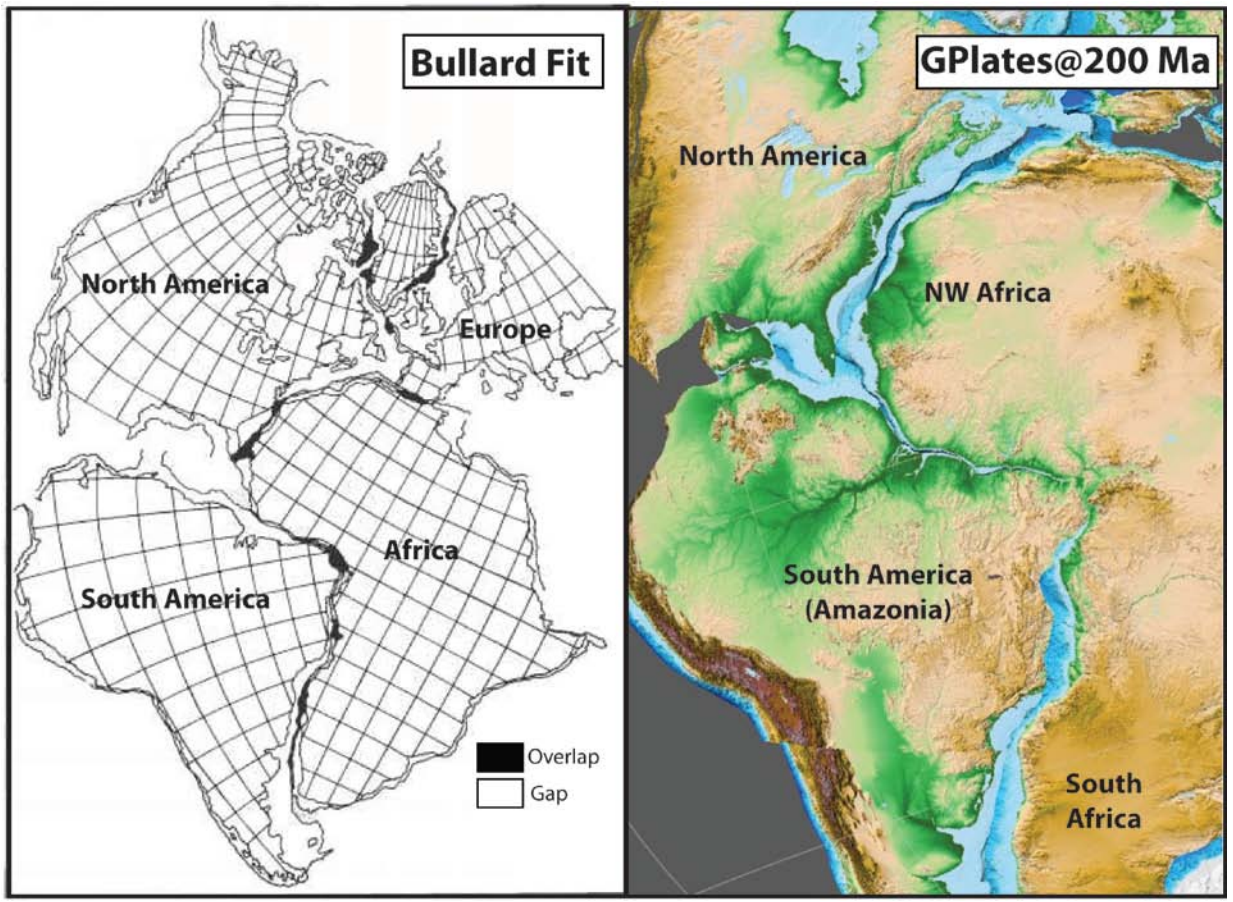
By Prof. J. TUZO WILSON, O.B.E.
Institute of Earth Sciences, University of Toronto

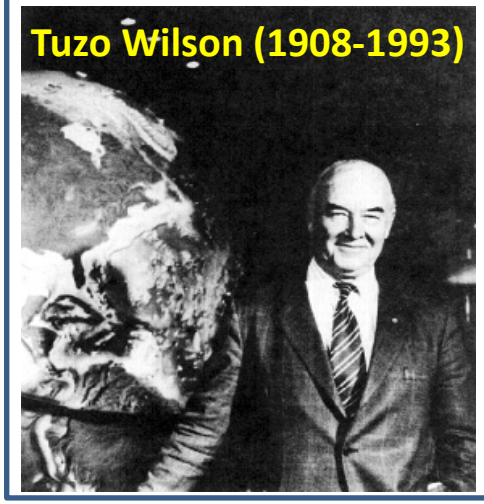
Evolution of A Theory

Bullard et al. **1965**

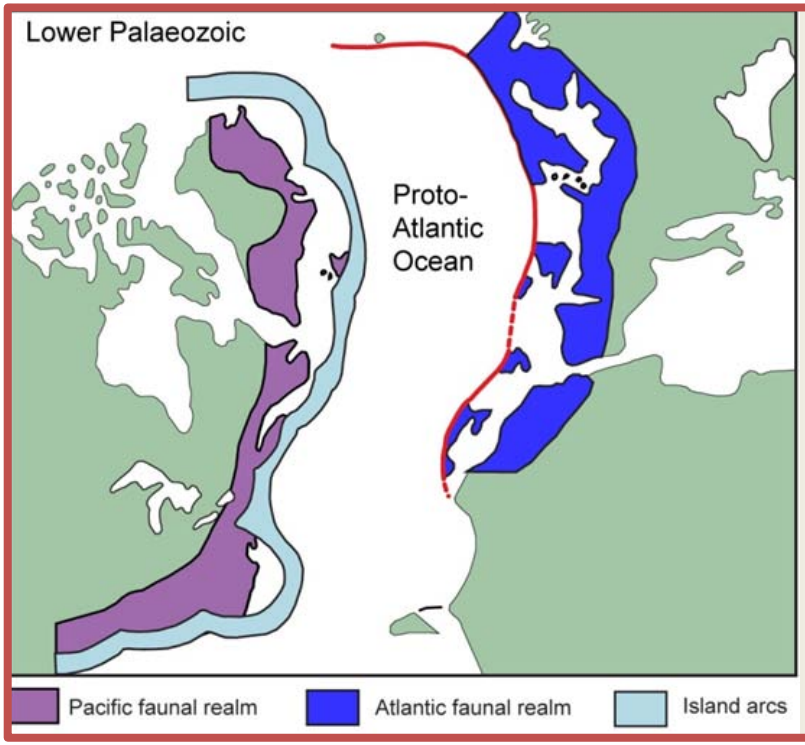
Bullard, Everett and **Smith** of Cambridge introduced axis of rotation to describe displacement on a sphere (Euler theory), a geometric technique that became an important tool for later plate tectonic studies

They produces the ever first computer-based reconstruction by matching the c. 900 meter bathymetry contours



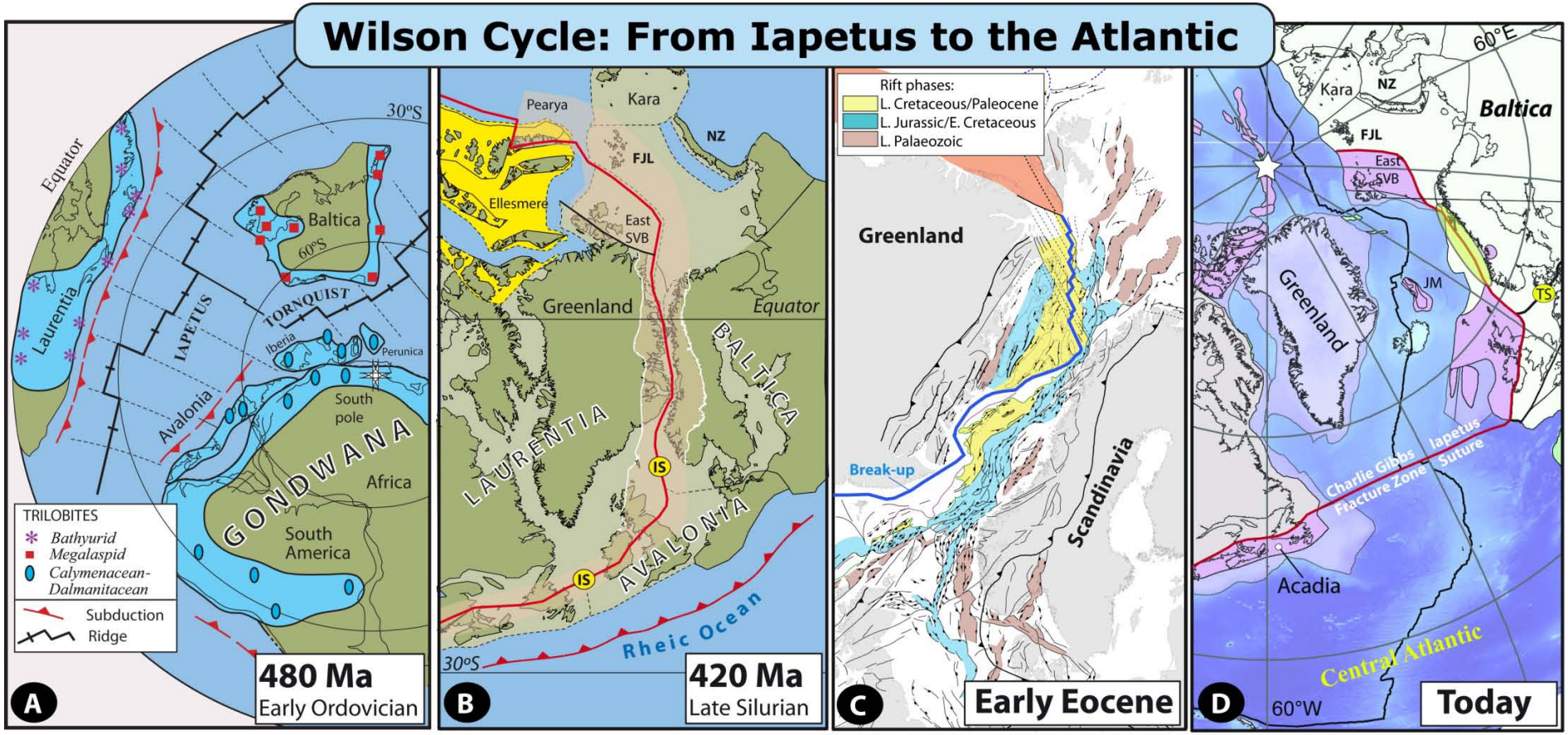


Wilson was 55 to 60 years old (peak of his scientific career) when he made his most important contributions to plate tectonic theory



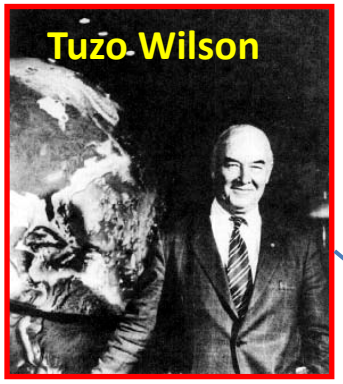
Wilson (1966) deduced that a proto-Atlantic Ocean must have formed a barrier between two faunal realms in the Lower Palaeozoic, and that this ocean must have closed and later re-opened to form the present-day Atlantic Ocean — Such movements were dubbed **'Wilson Cycle Tectonics'** Kevin Burke, and for the first time, plate tectonic processes were understood to have been operating before the time of Pangea.

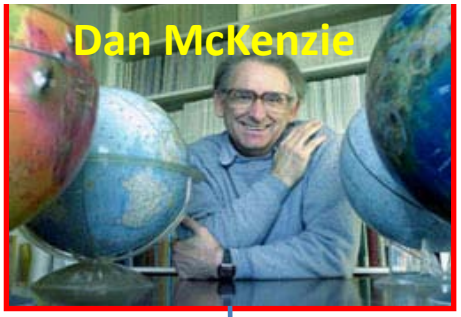
WILSON CYCLE TECTONICS



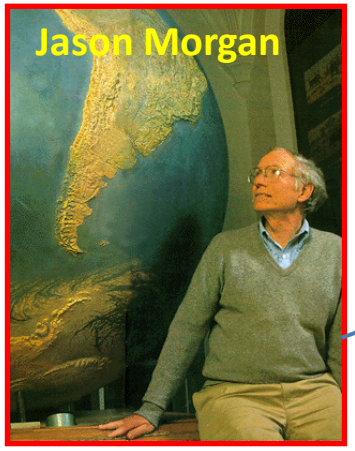
Cocks & Fortey (1982), Torsvik & Trench (1991), Cocks & Torsvik (2011), Faleide et al. (2011)

The 3rd revolution: Plate Tectonics (1967)

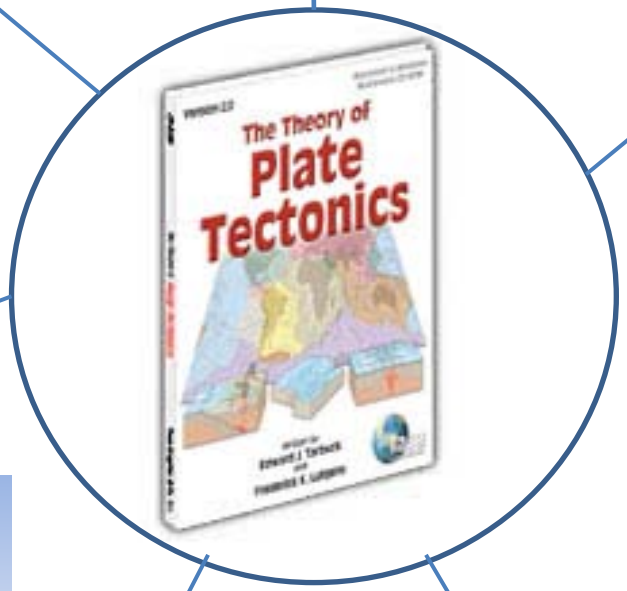




With Robert Parker published in **1967** the quantative principles for plate tectonics.

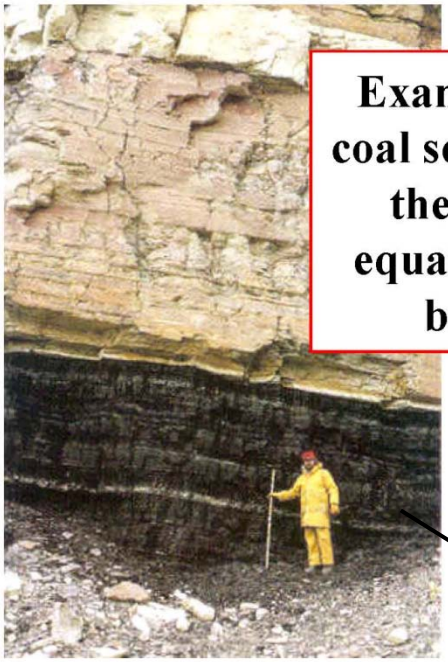


In **1965** (Wilson) and **1968** (Morgan) published primal papers that, taken together, constituted the plate-tectonics revolution.

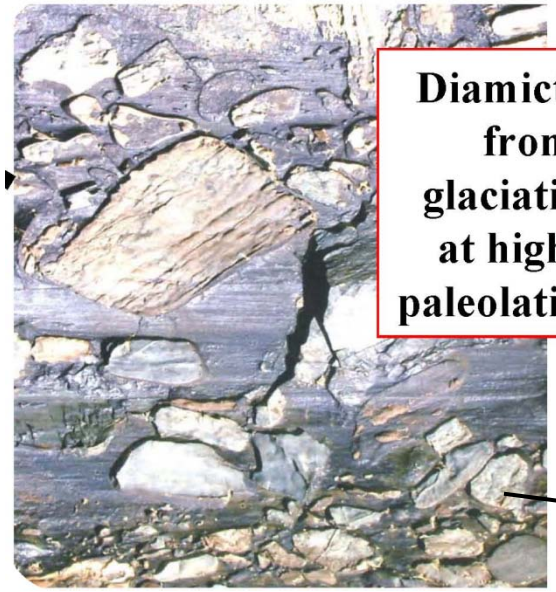


Ground-breaking proposal in **1968** of how plate tectonics could explain orogeny

…and many others

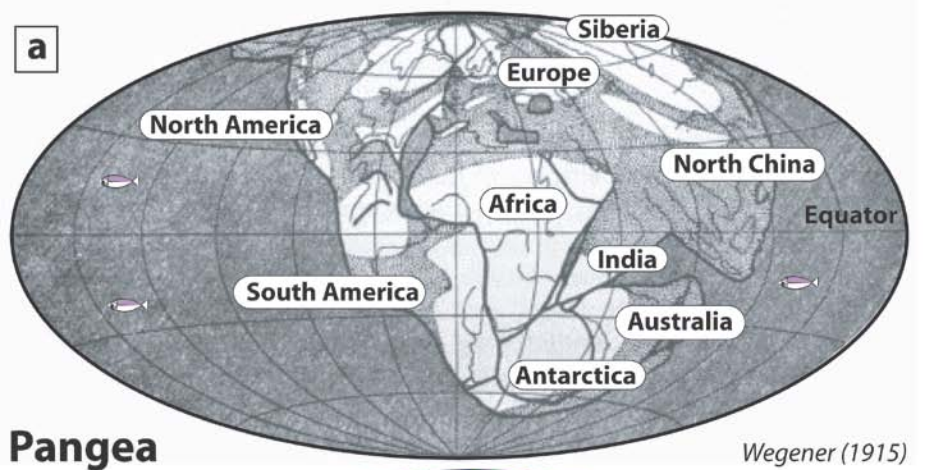


Examples: coal seams in the wet equatorial belt



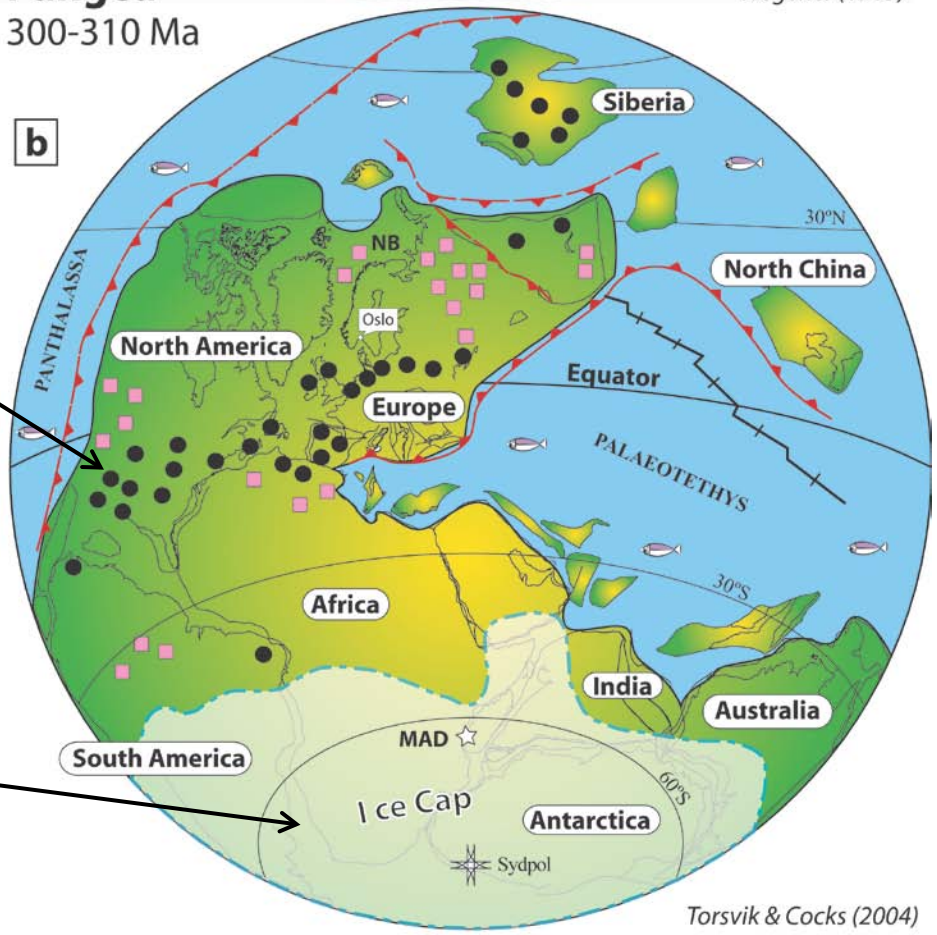
Diamictites from glaciations at higher paleolatitudes

Depositional facies match expectations in terms of zonal climate



Pangea
300-310 Ma

Wegener (1915)



Torsvik & Cocks (2004)

What have we learned in ca. 100 years?

And we can make movies — **even before Pangea** (thanks to Tuzo) — and quantify plate movements.

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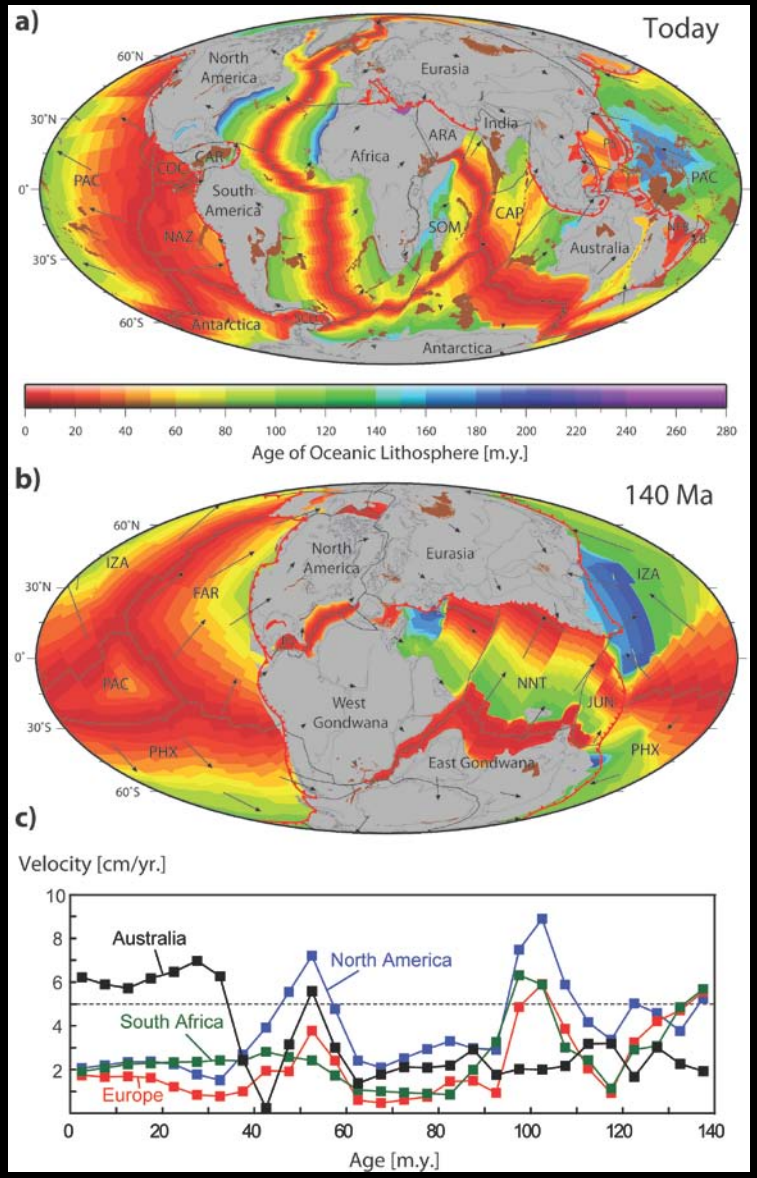
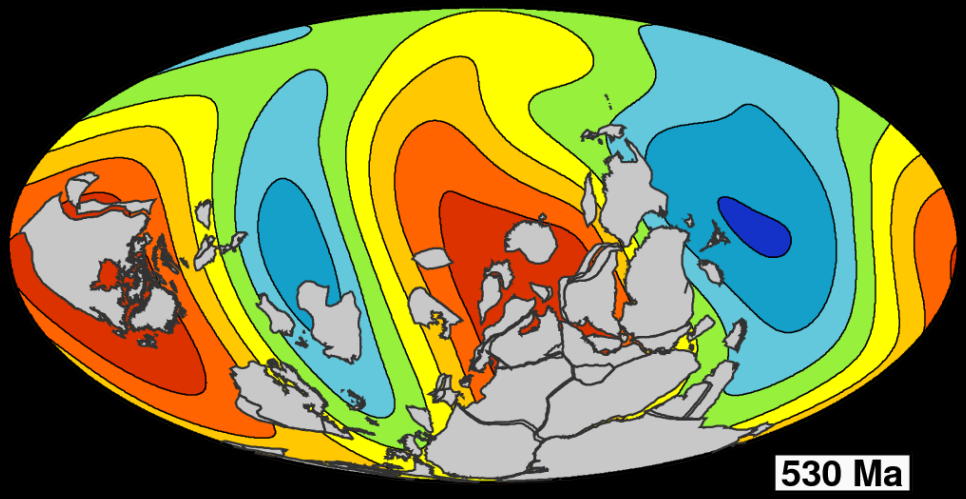
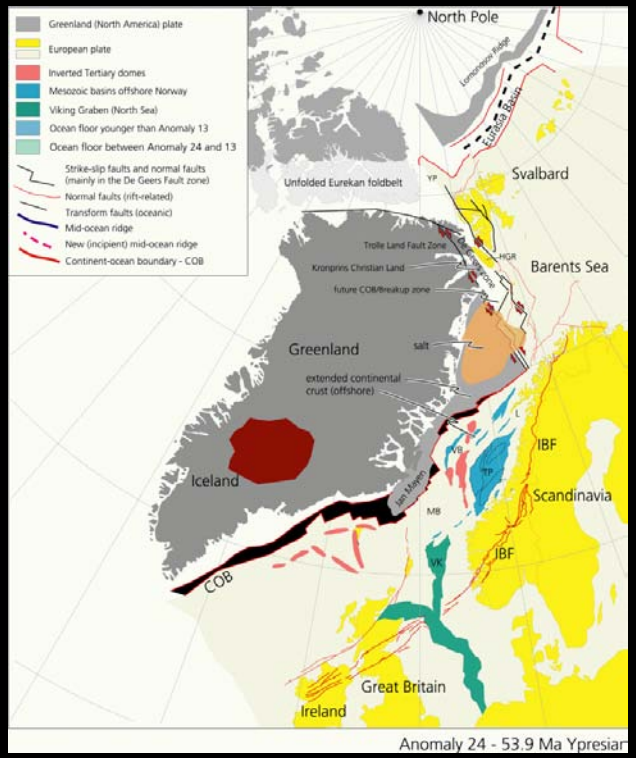
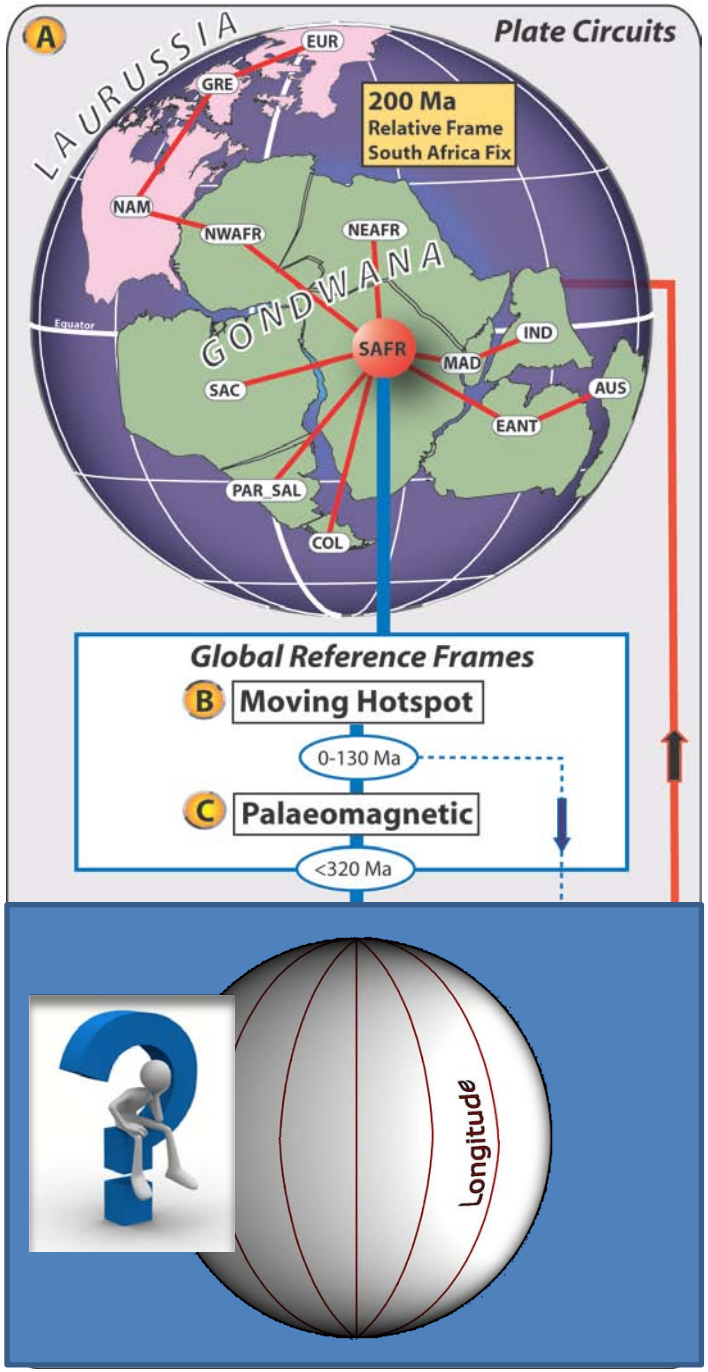
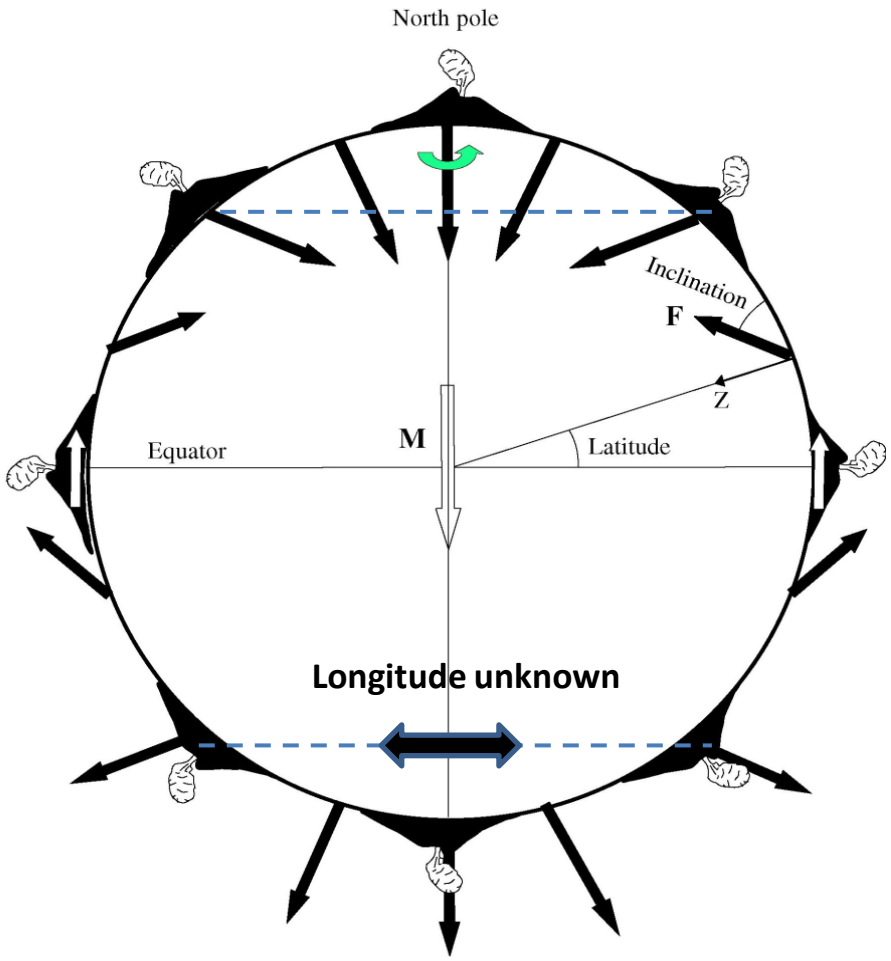






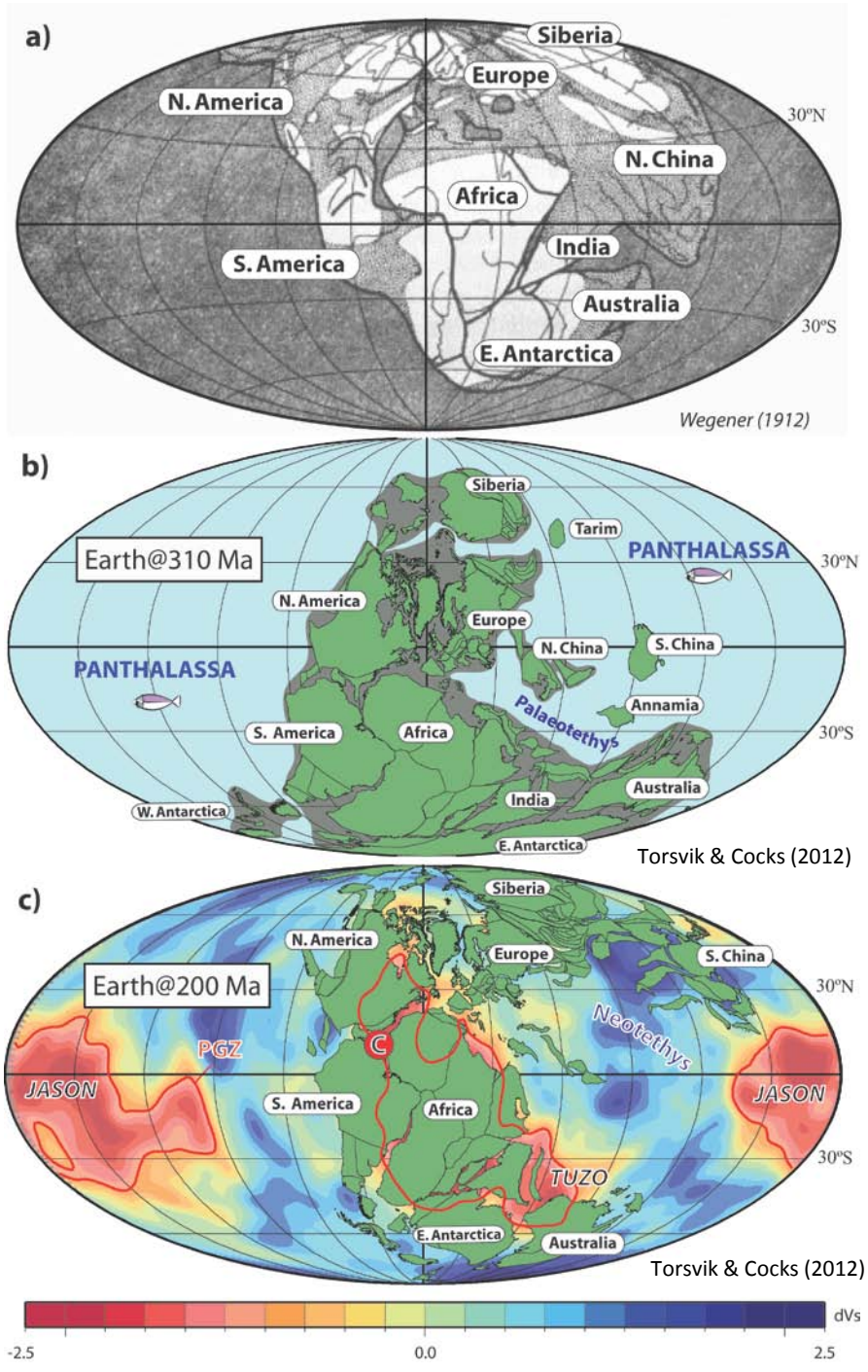


Palaeomagnetic data provide **latitude** and **rotation**



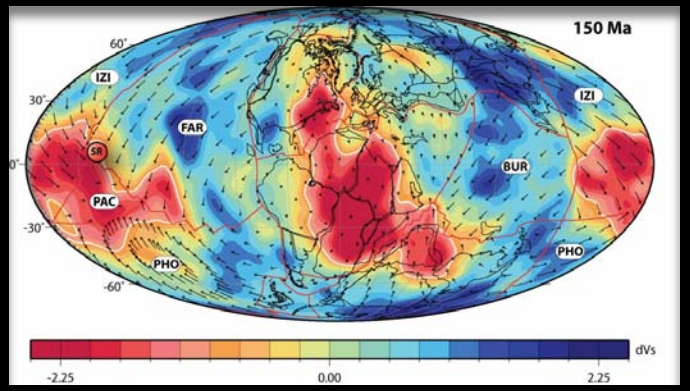
The **trick** (Burke & Torsvik 2004) is to choose a plate as an initial reference that has undergone the smallest amount of longitudinal movement. **Africa is the ideal candidate** because it has remained extremely stable for **since Pangea formation** **[do not work before Pangea]**

- Since Wegener and continental drift (1912) our description of the movement and deformation of the Earth's outer layer have evolved into seafloor spreading (1962) and then to plate tectonics by the mid-late 1960s.
- If we compare Wegener's Pangea with modern reconstructions there are many similarities, but **the most striking difference is that we are now able to position Pangea and other continents at their original <u>latitude</u> and <u>longitude</u>**.
- Many scientists did not accept continental drift for the lack of a mechanism. Ironically, there is **still no generally accepted mechanism that explains plate tectonics in the framework of mantle convection.**
- Conversely, the relationship between plates and plumes has become clearer (at least for some of us) over the past decade.



BEYOND PLATE TECTONICS

GOAL: Integrate Plate Tectonics into a new unifying theory of Mantle Dynamics (4th revolution in Earth Sciences)



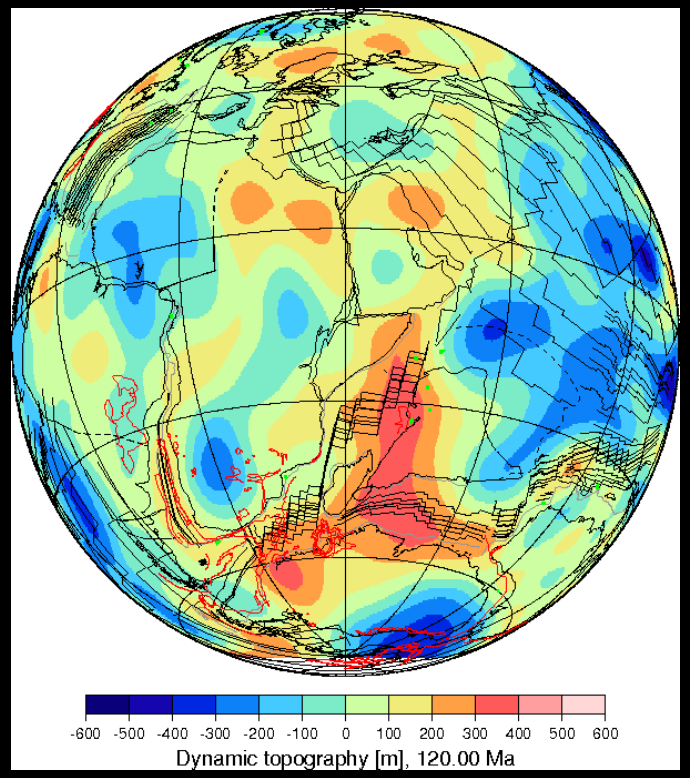
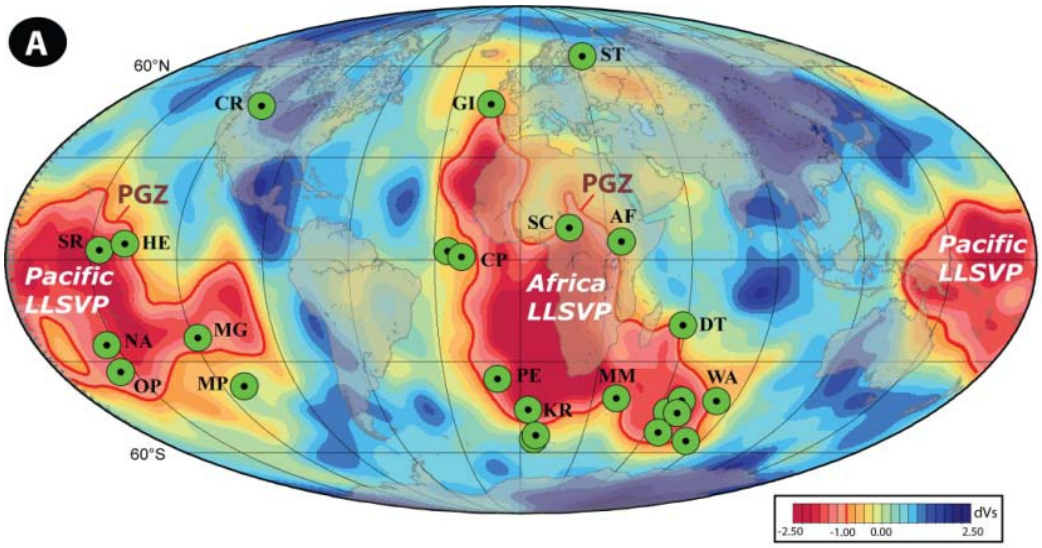
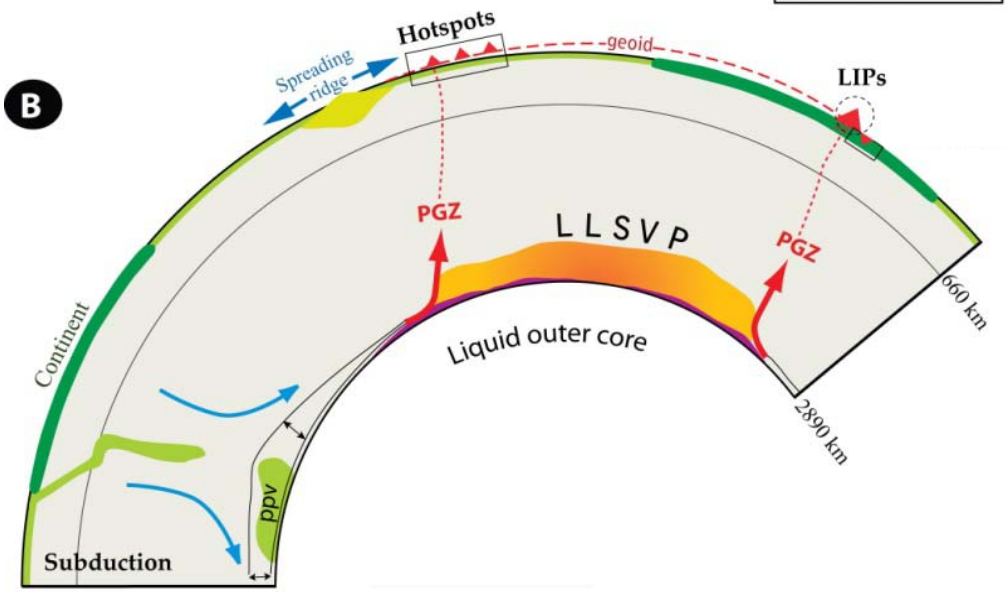


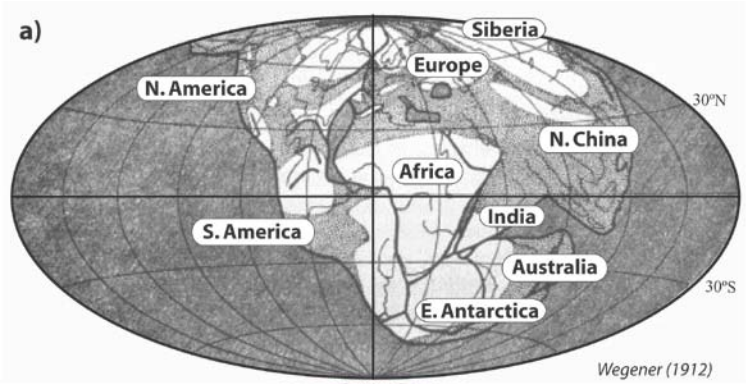
Plate tectonics, as fundamentally unifying to the Earth Sciences as Darwin's Evolution Theory is to Life Sciences, characterises the complex and dynamic evolution of the outer shell of the Earth <u>but</u> there is no accepted mechanism that explains Plate Tectonics in the framework of mantle convection and plumes from the deepest Earth.

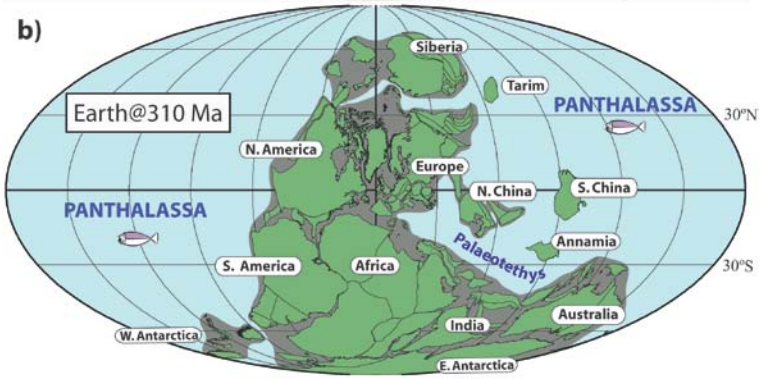
Linking Surface and Deep processes

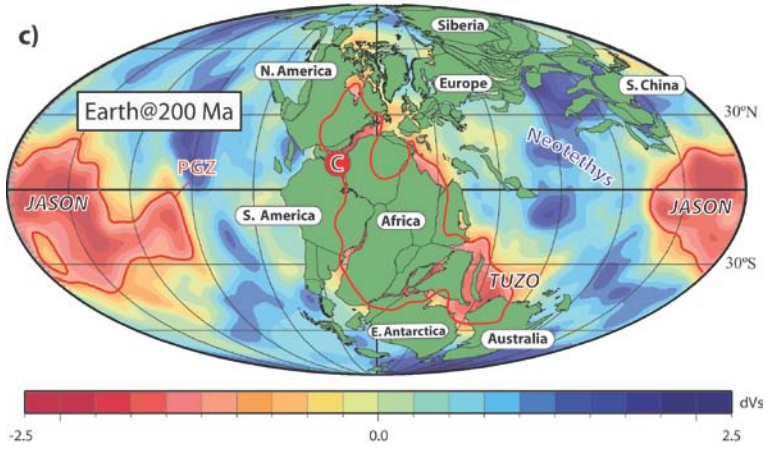
PLUMES: Generated near the CMB at the edges of stable LLSVPs (plume generation zones) and the main heat source for hotspots and LIPs





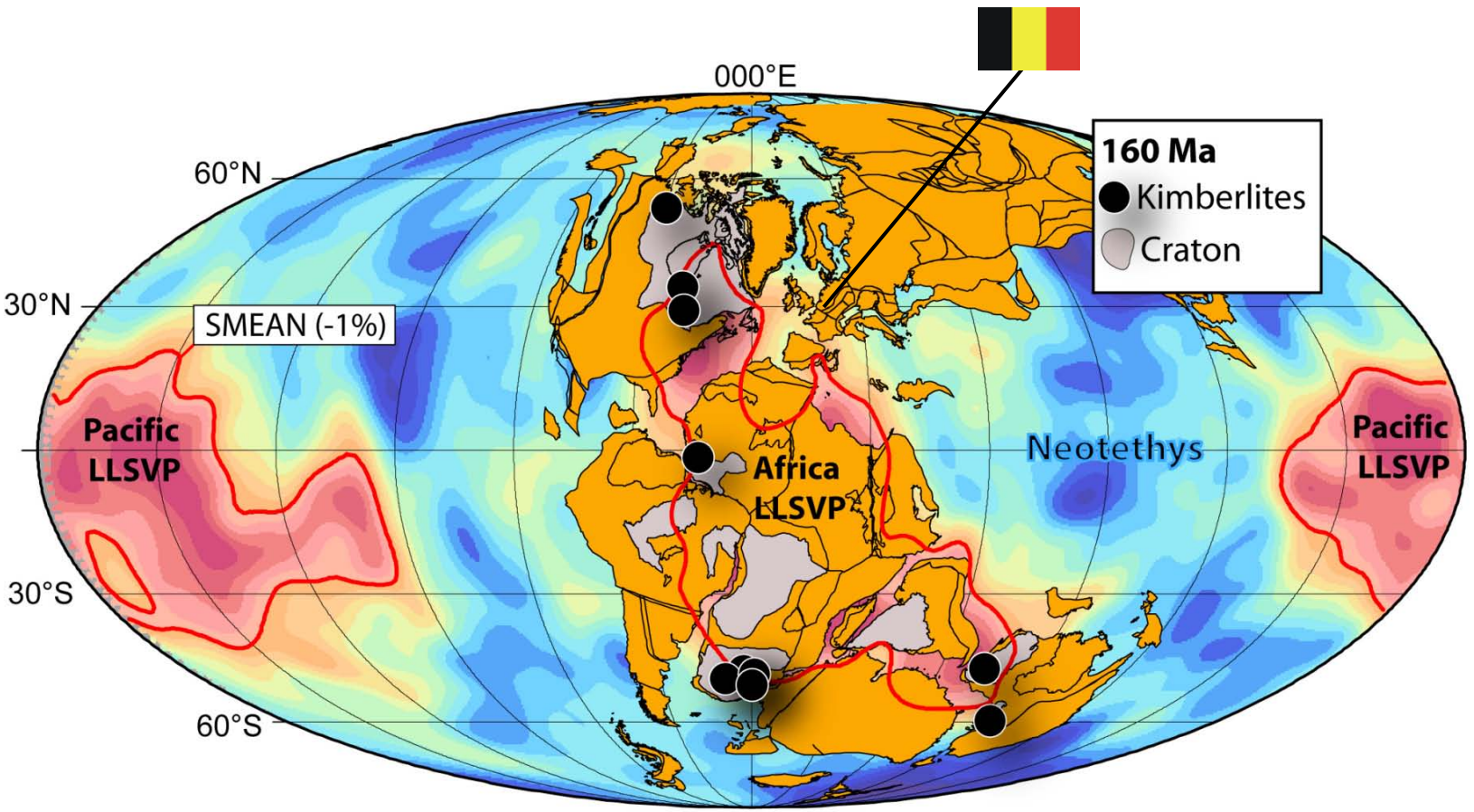






Torsvik et al. (2010); Torsvik & Cocks (2012)

Plumes from the CMB (margins of the LLSVPs) also the main heat source for **KIMBERLITES** (the diamond elevators)



Torsvik et al.(2010)

DE BEERS
A DIAMOND IS FOREVER

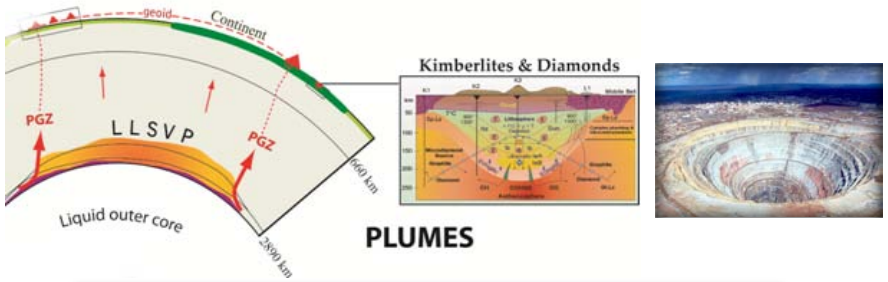
LLSVPs FOREVER: Primordial mantle reservoirs LIPs and Kimberlites:
HOW CAN WE TAKE ADVANTAGE OF THIS IN PALAEOGEOGRAPHY?

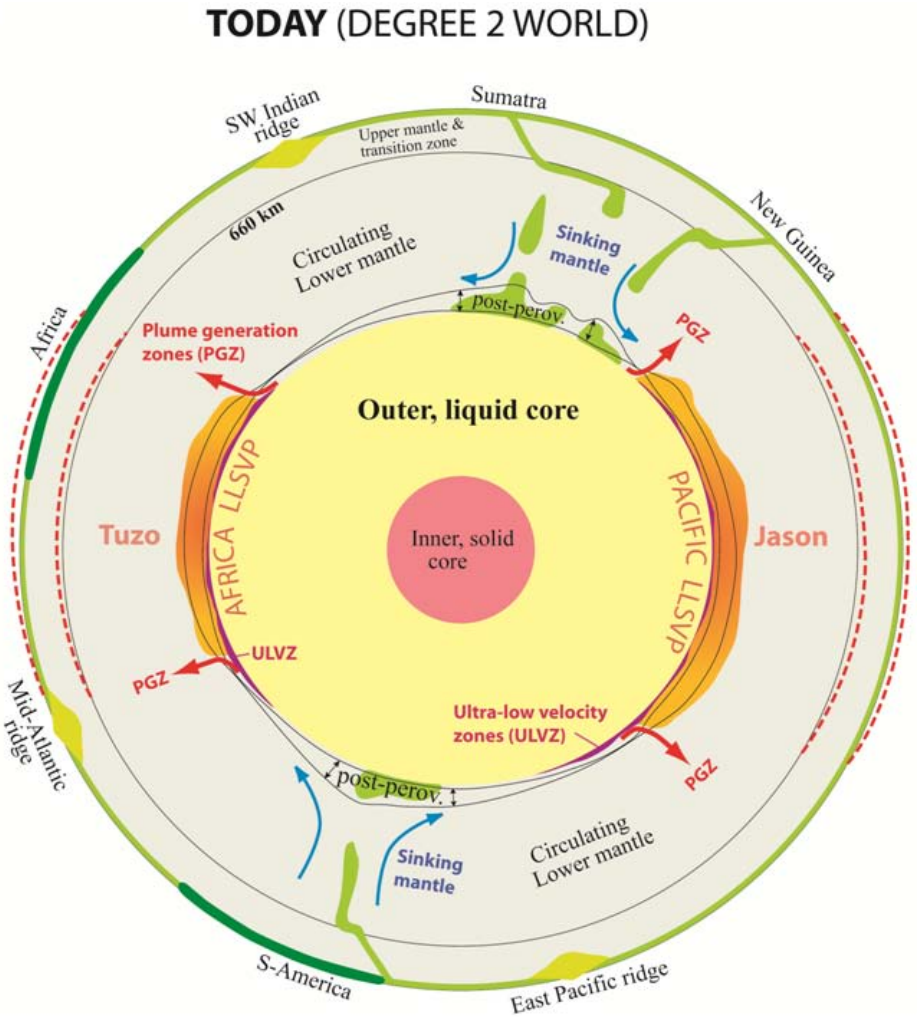
nature Vol 466|15 July 2010|doi:10.1038/nature09216

LETTERS

Diamonds sampled by plumes from the core–mantle boundary

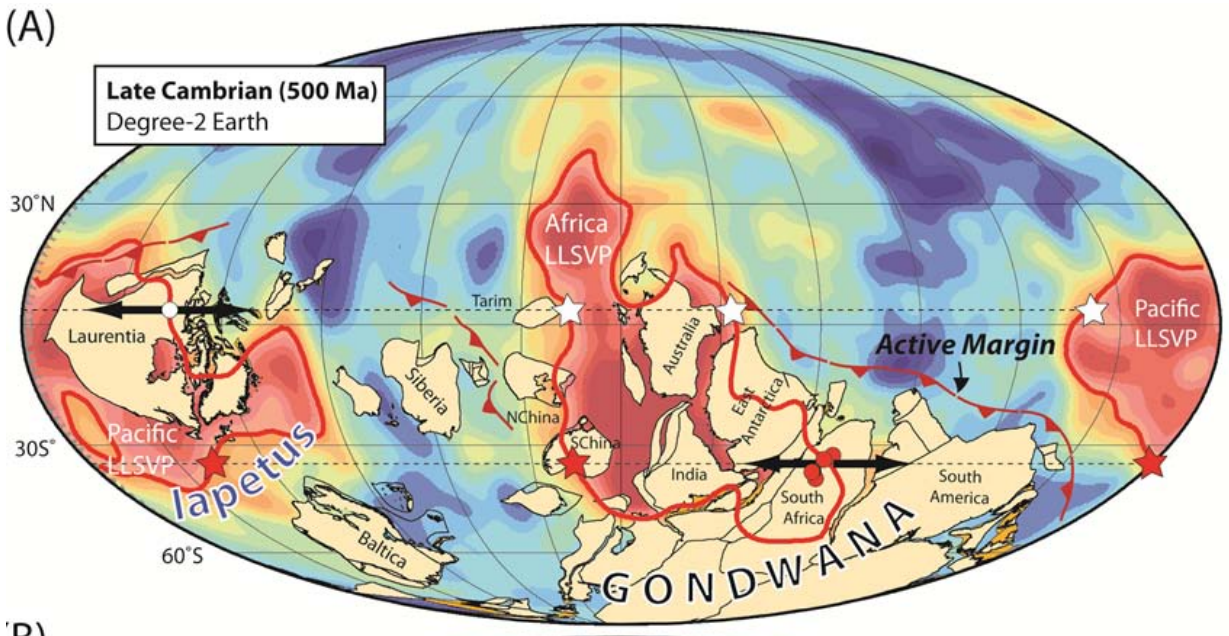
Trond H. Torsvik[1,2,3], Kevin Burke[3,4], Bernhard Steinberger[1,2,5], Susan J. Webb[3] & Lewis D. Ashwal[3]

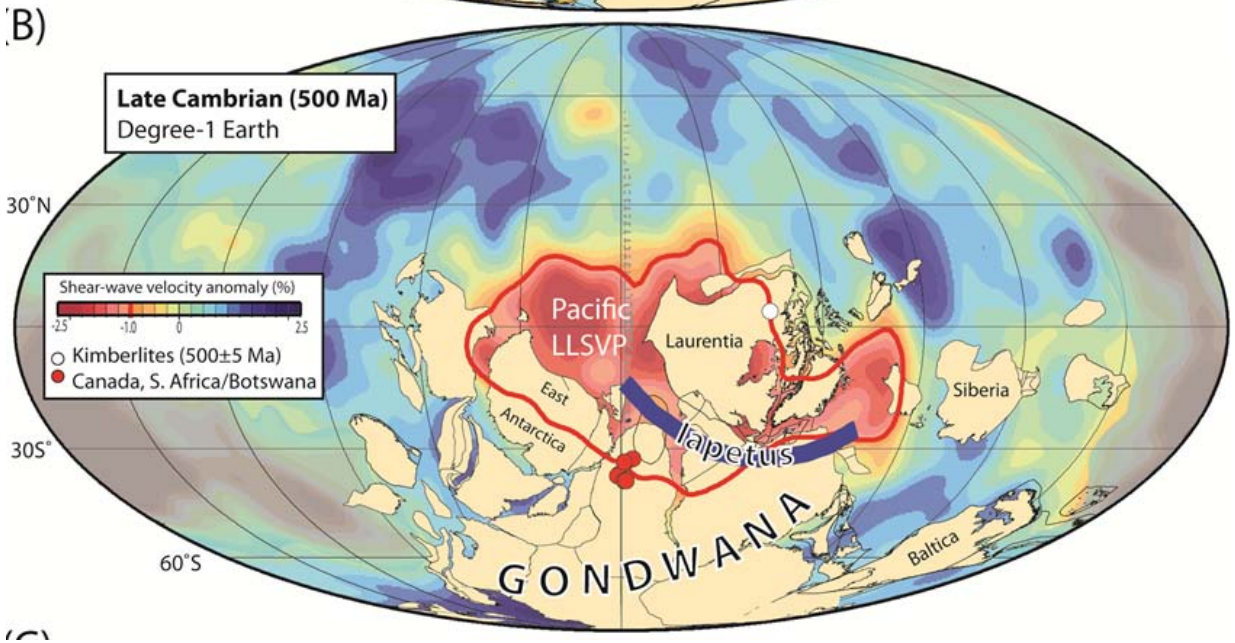


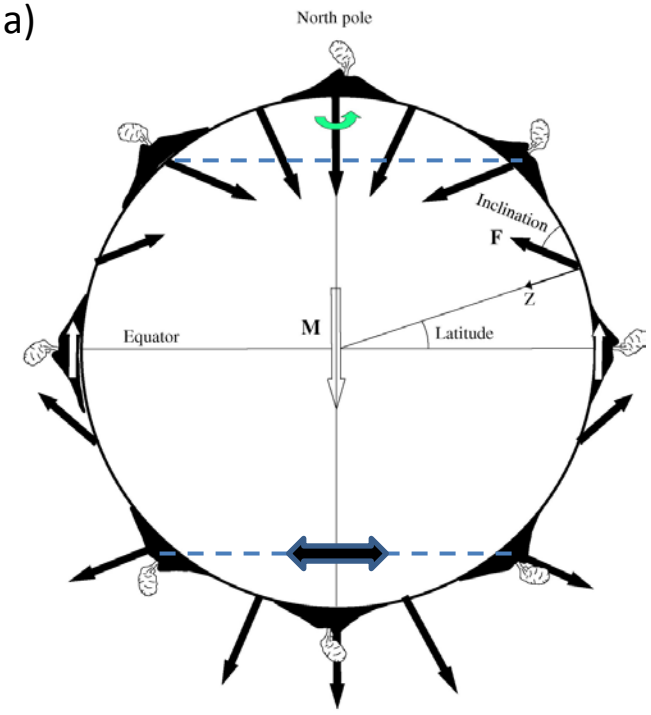


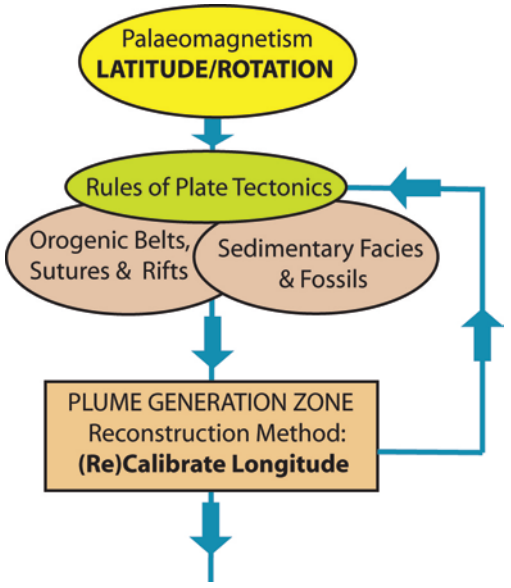
WE CAN USE THIS TO LOCATE CONTINENTS IN LONGITUDE IN THE PALAEOZOIC

Example: Kimberlites in Canada (Laurentia) and South Africa (Gondwana)



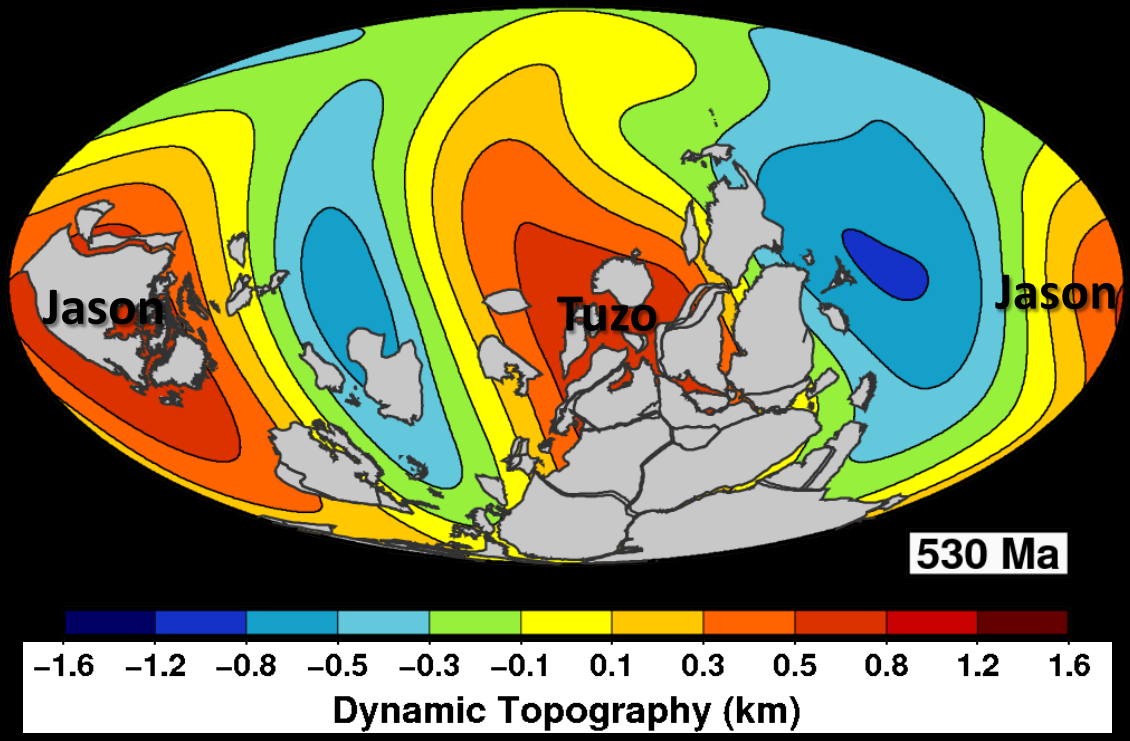




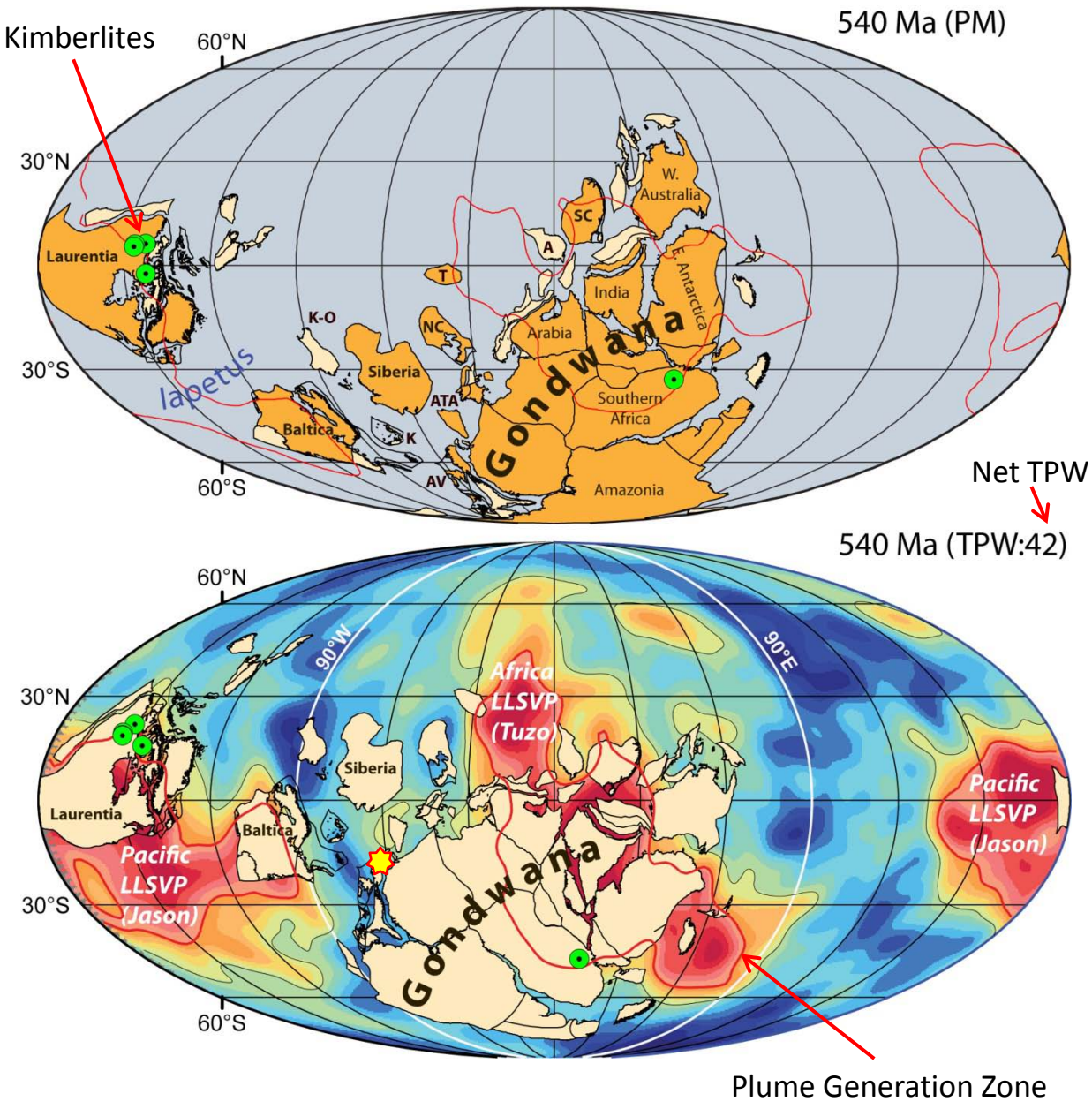


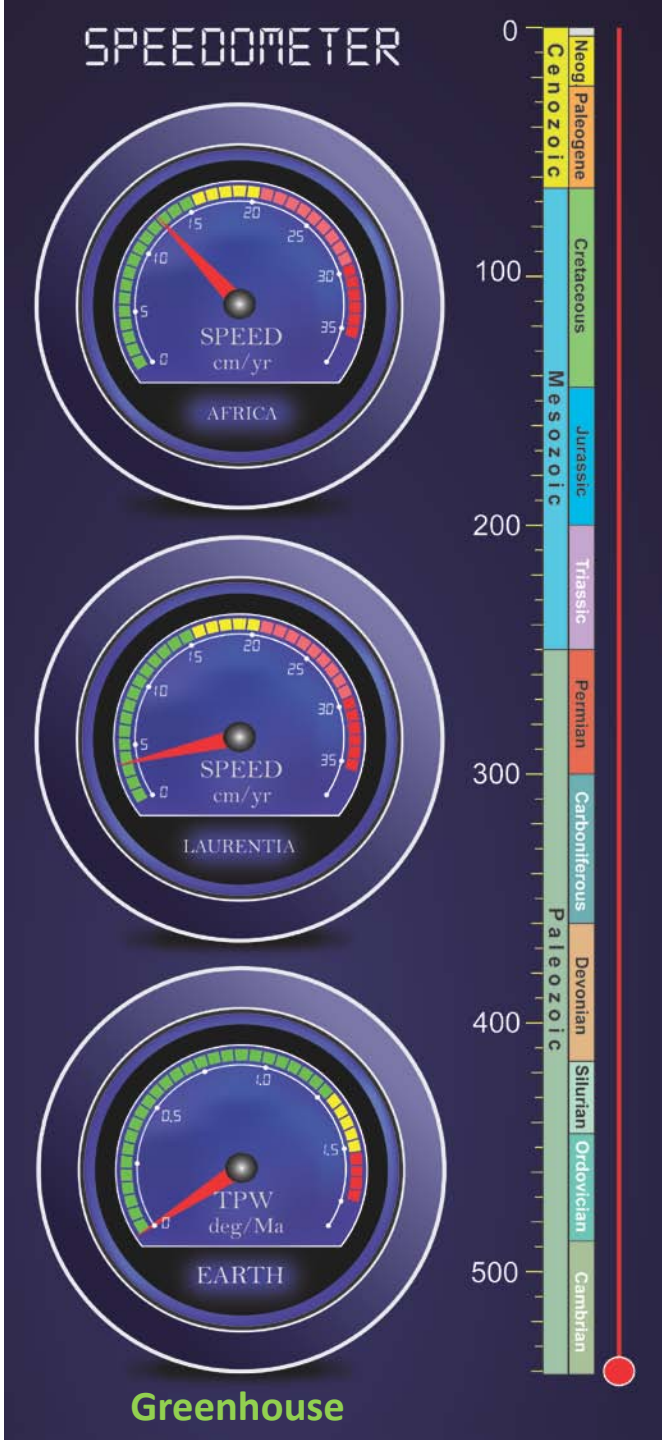
Palaeozoic Geodynamics

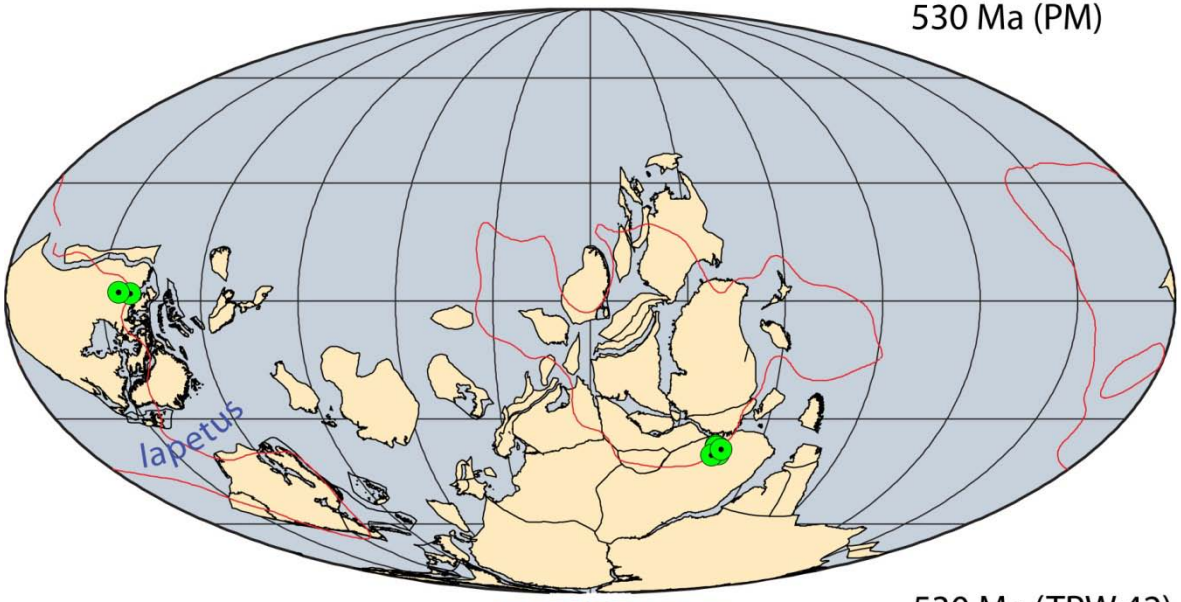
ABSOLUTE PLATE TECTONICS AND DRIFT OF BRUSSELS ON A DEGREE-2 PLANET WITH STABLE LLSVPS

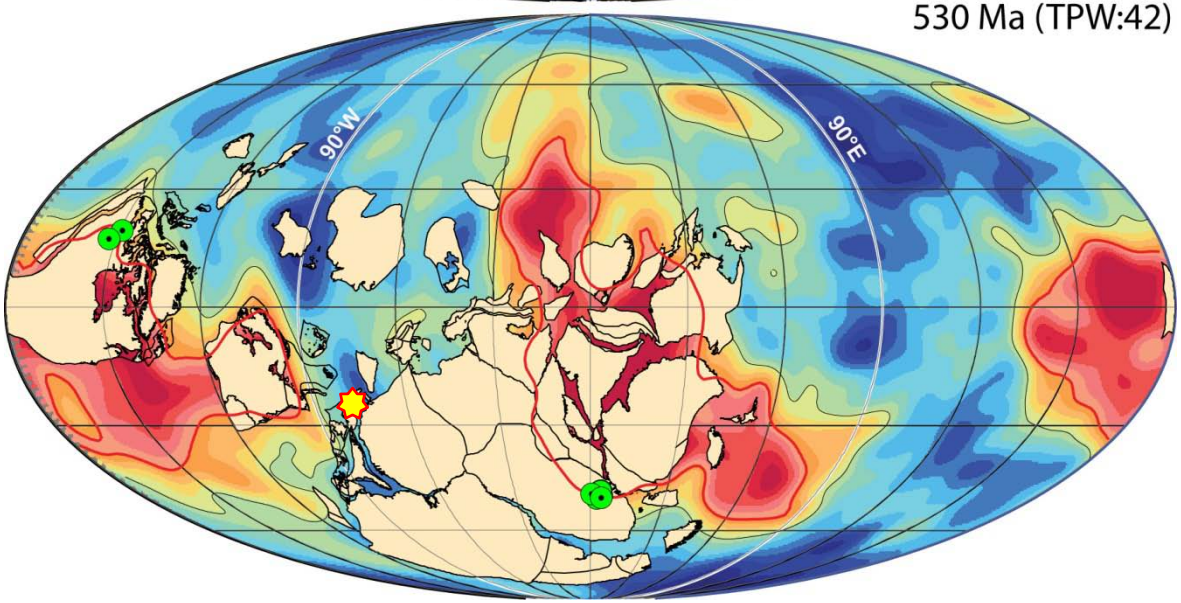


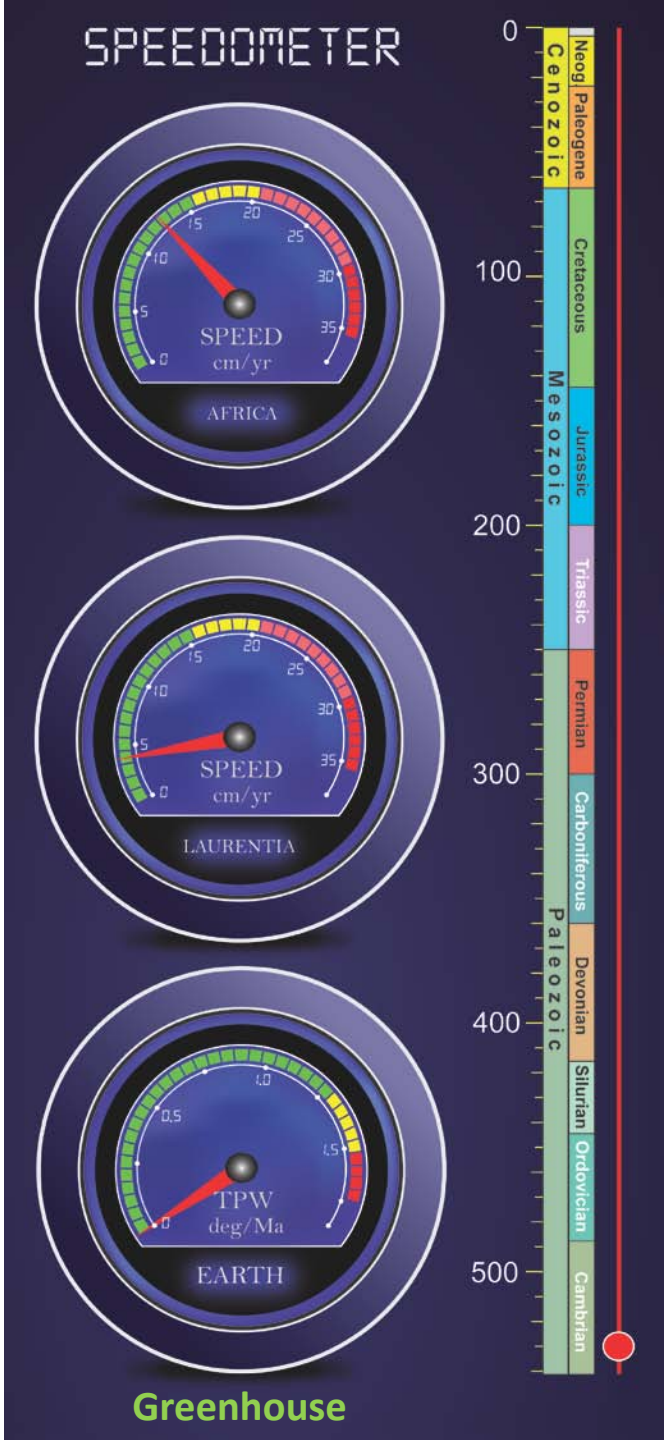
The dawn of the Palaeozoic

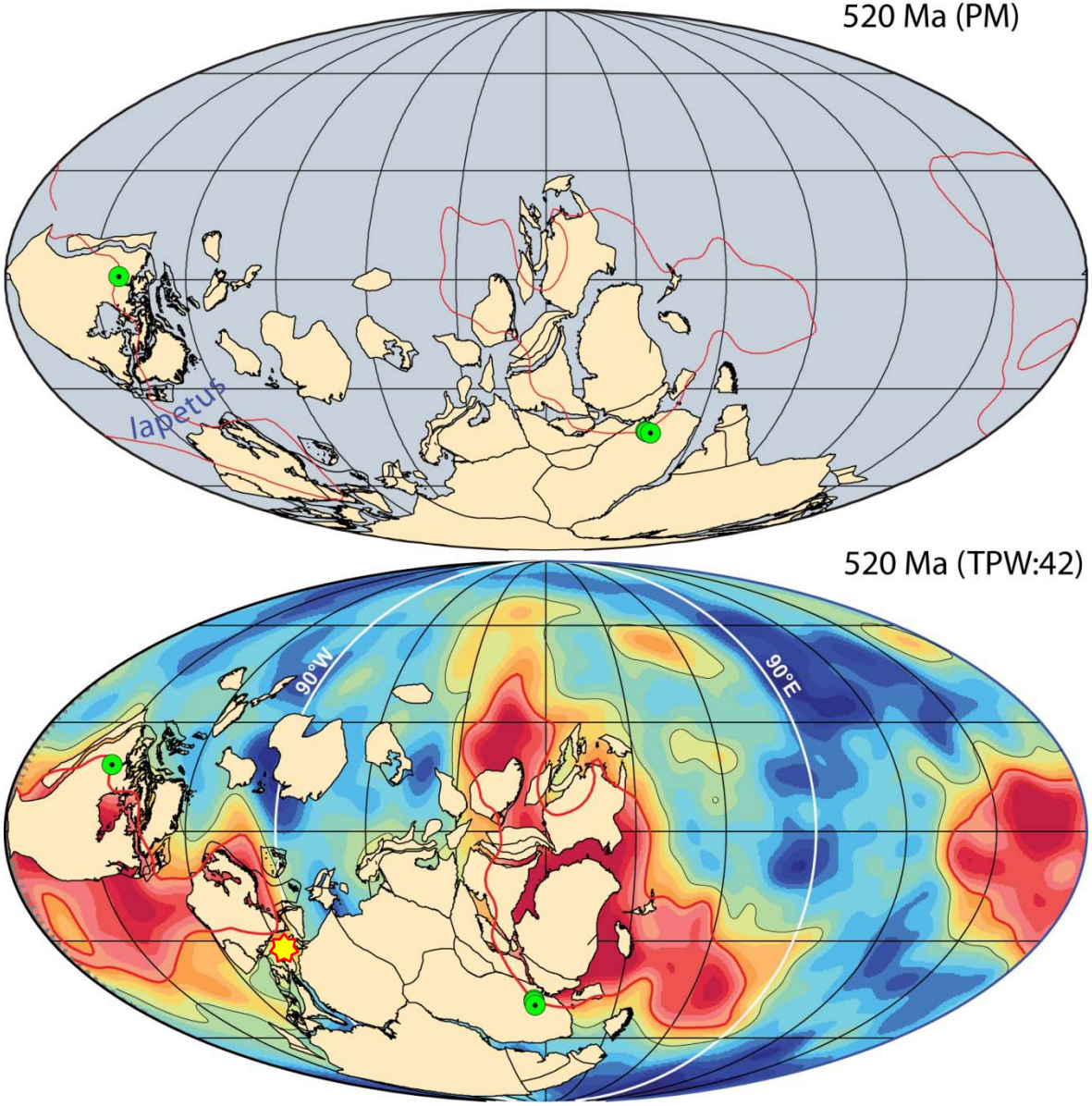


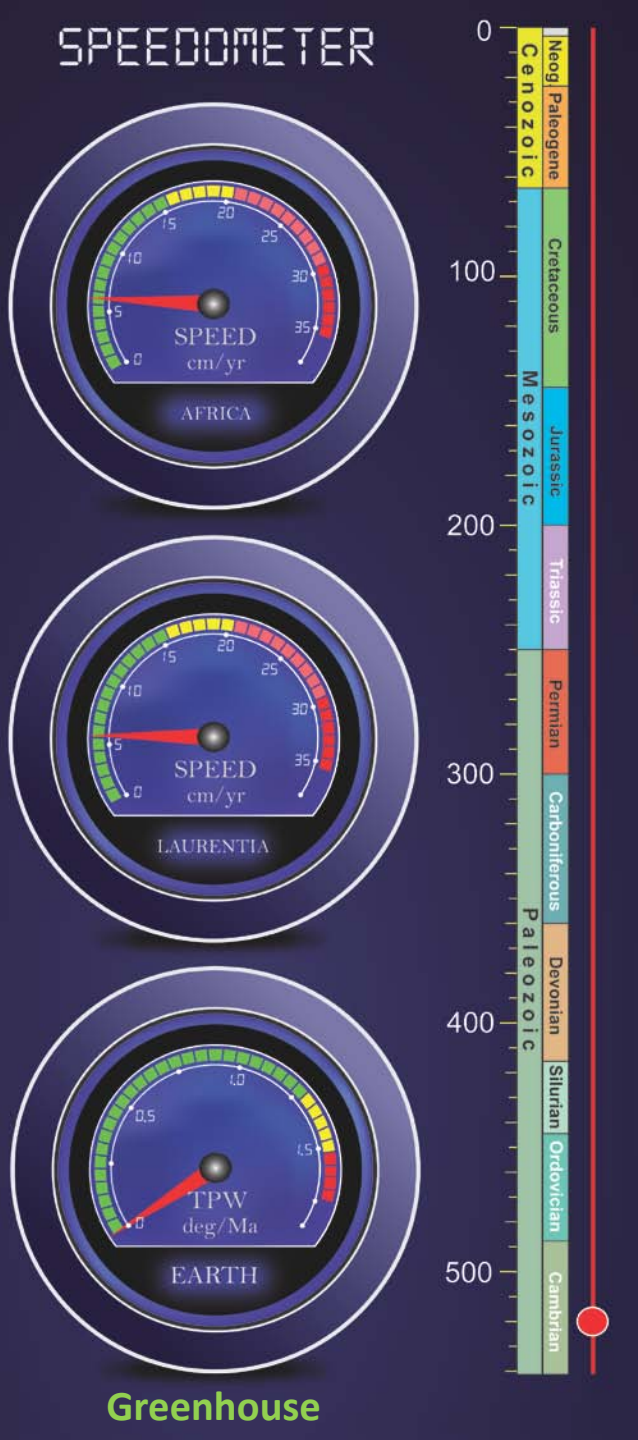



530 Ma (PM)
Iapetus

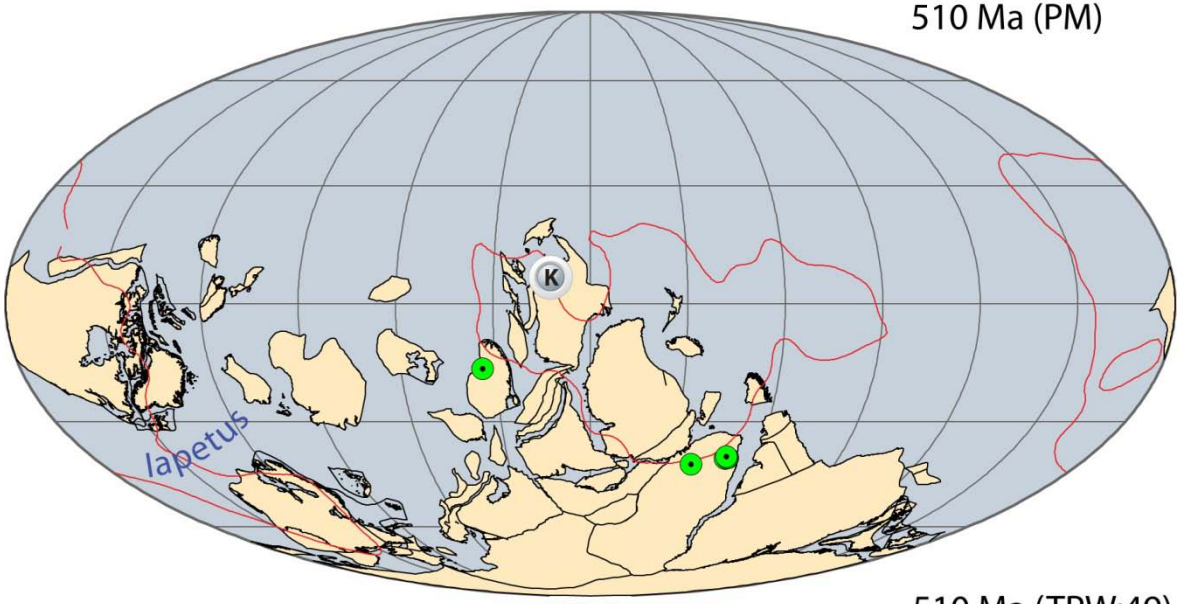

530 Ma (TPW:42)
90°W
90°E

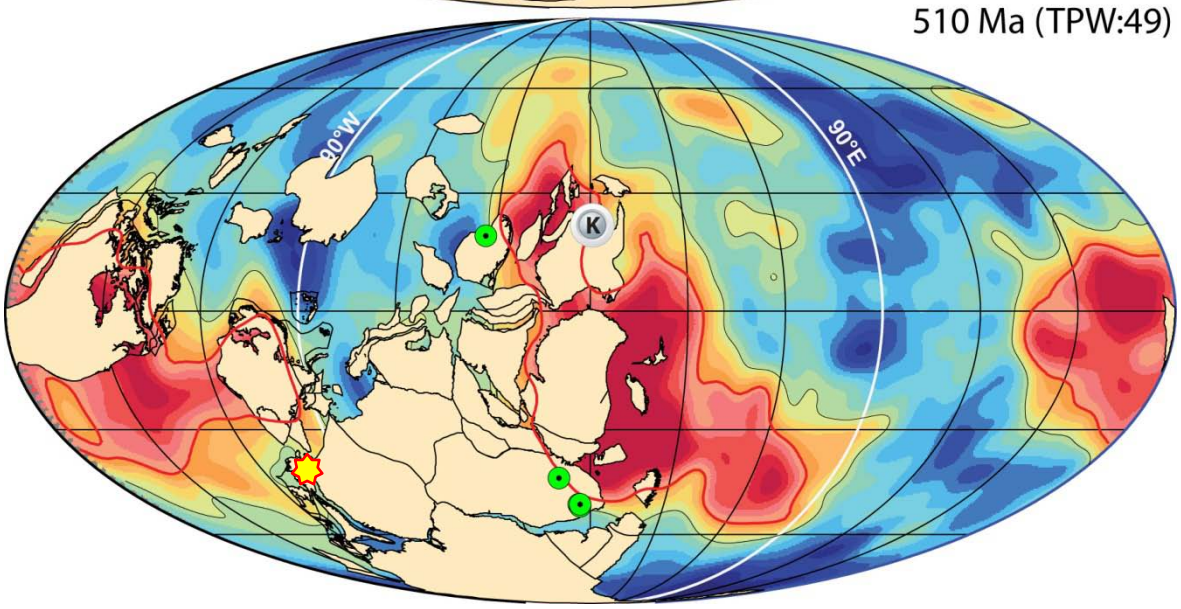

SPEEDOMETER
SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
0
100
200
300
400
500
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

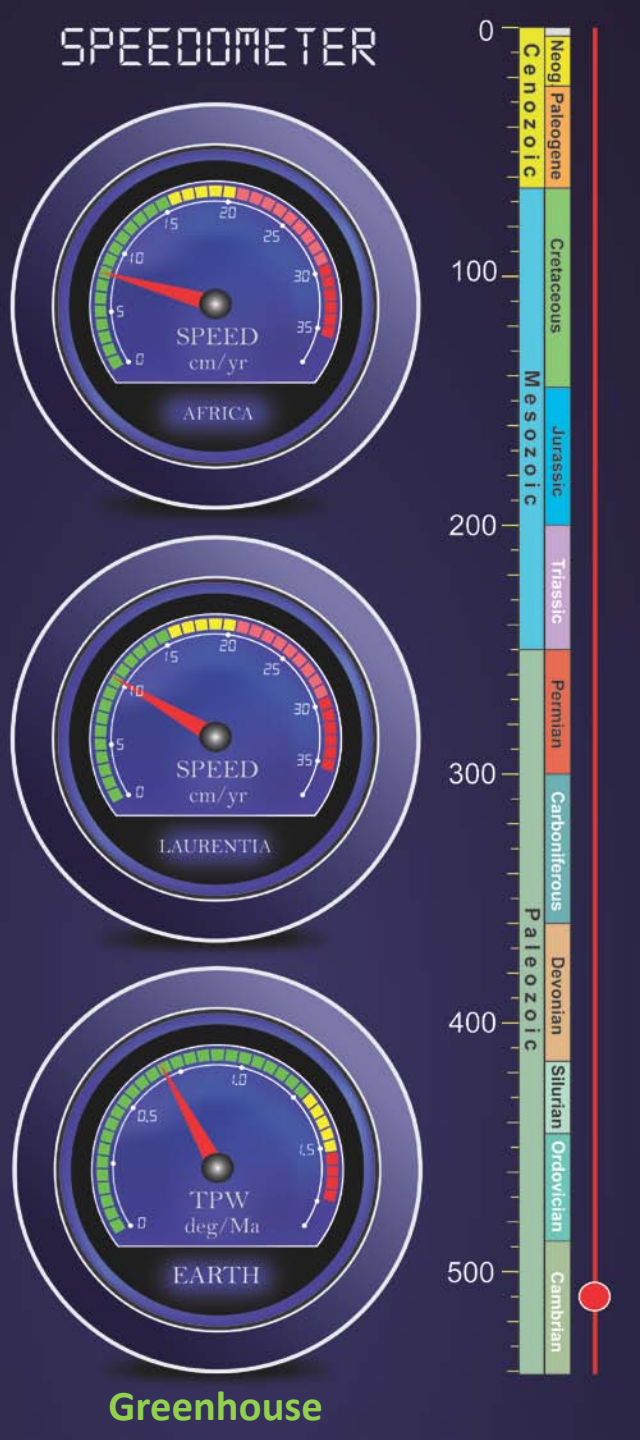

520 Ma (PM)
Iapetus
520 Ma (TPW:42)
90°W
90°E

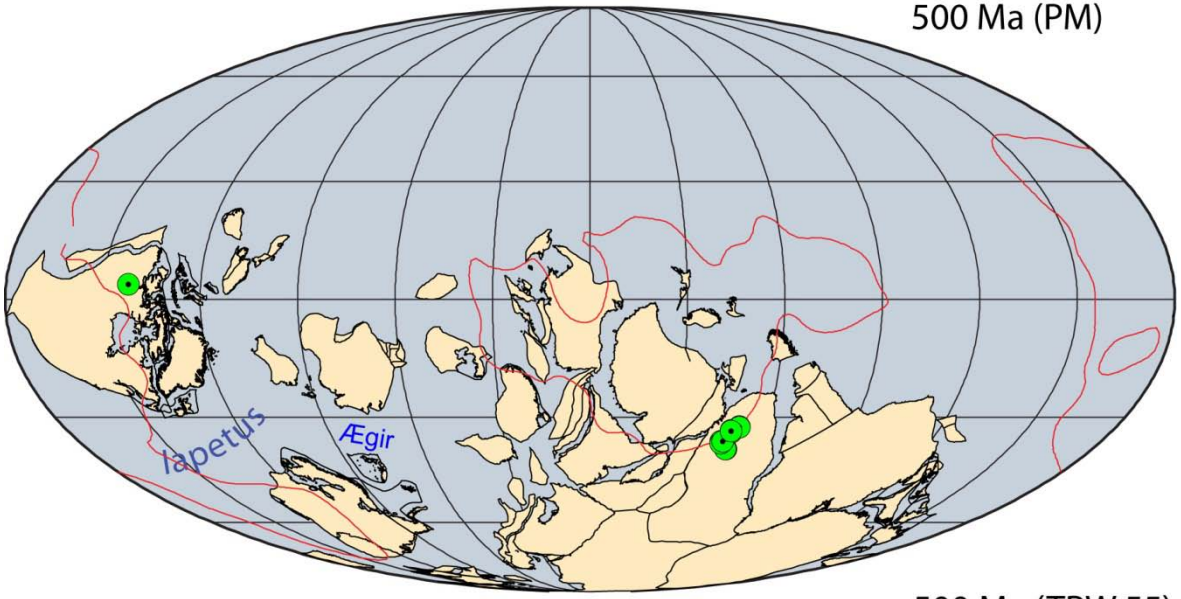

SPEEDOMETER
SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
0
100
200
300
400
500
Greenhouse

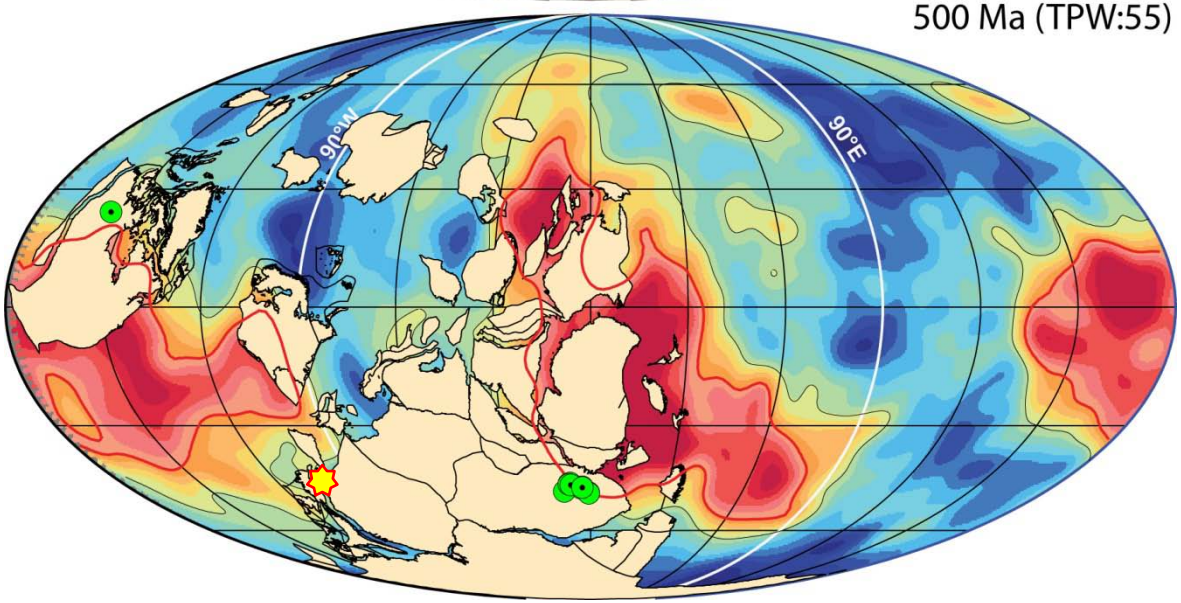
LIP: Kalkarindjii (West Australia)

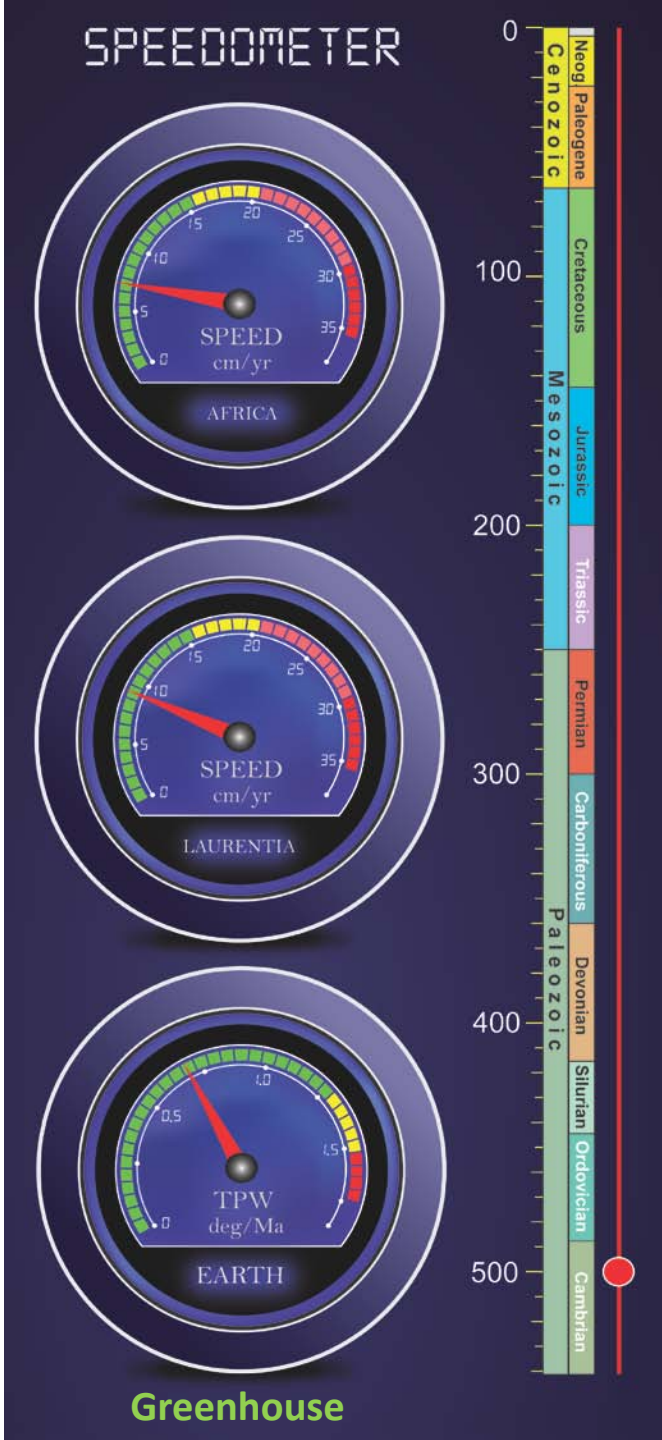







500 Ma (PM)
Iapetus
Ægir


500 Ma (TPW:55)
90°E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SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
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400
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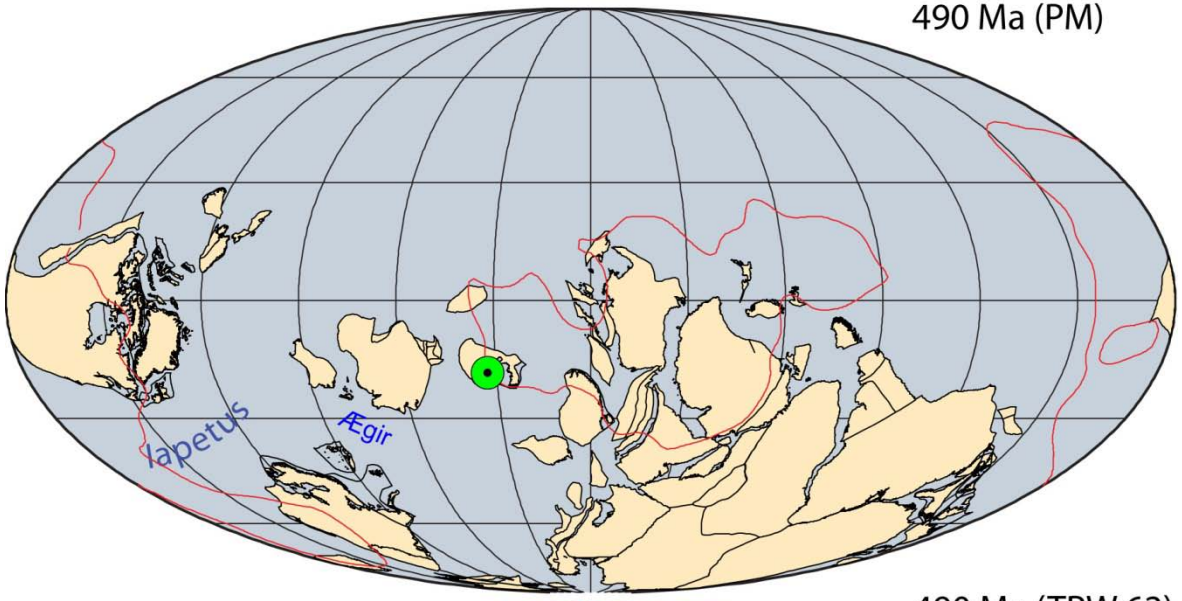
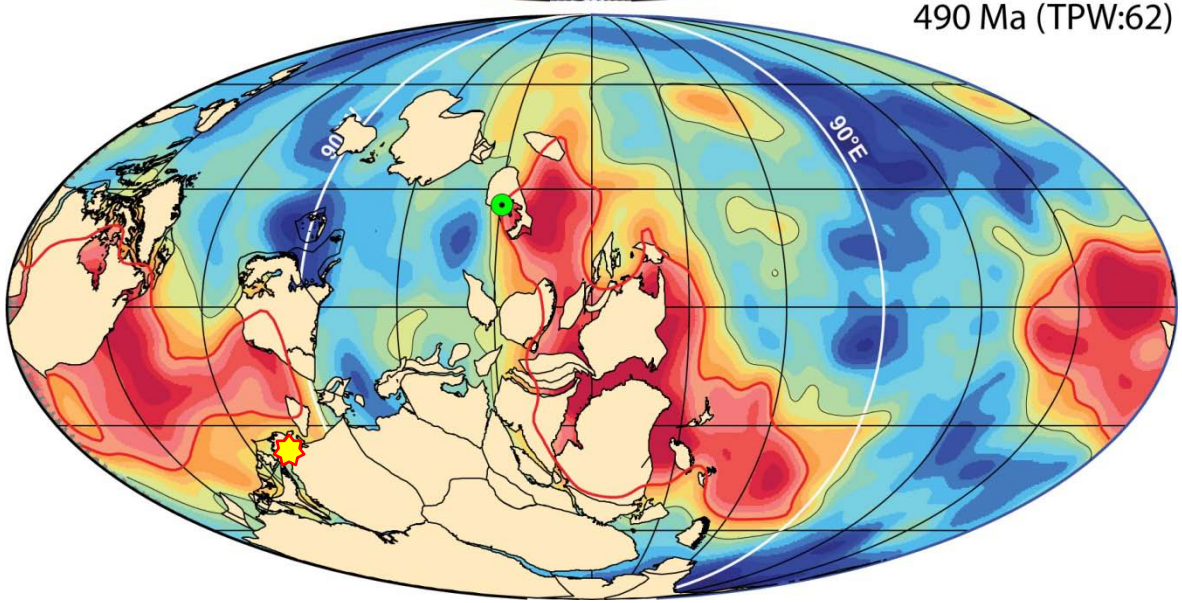
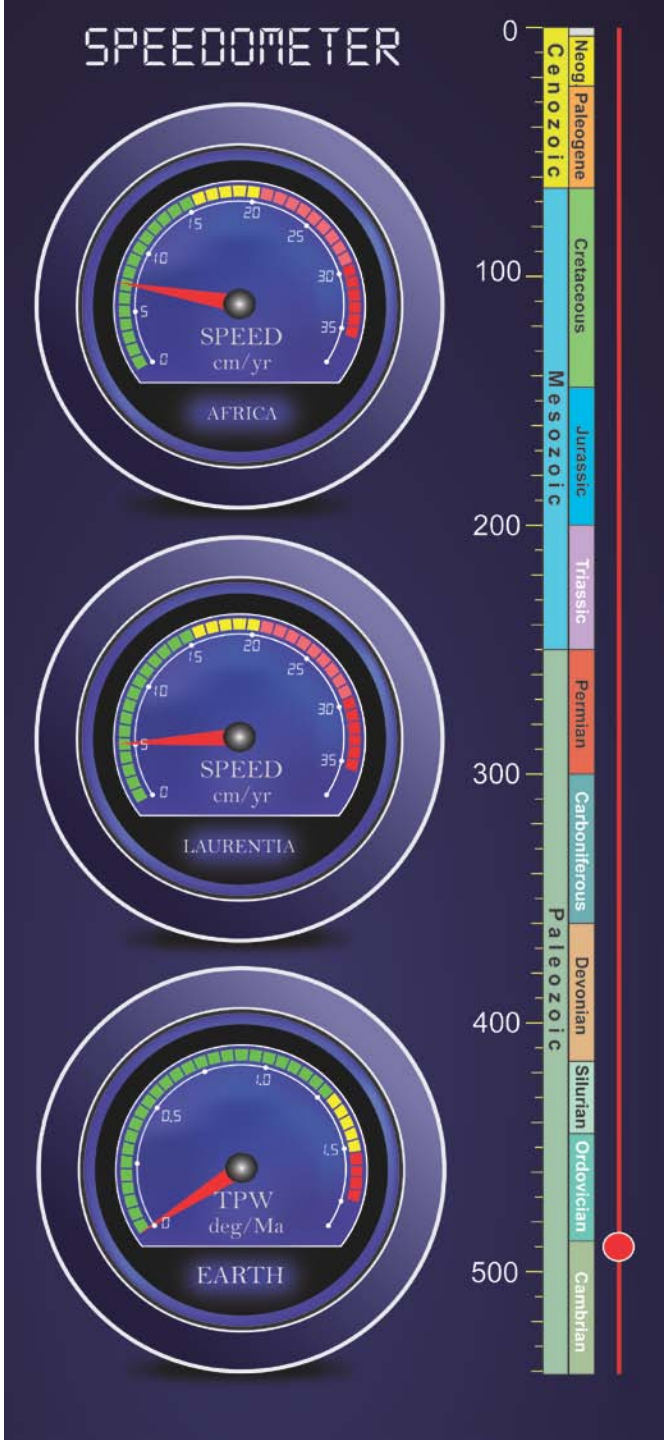
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

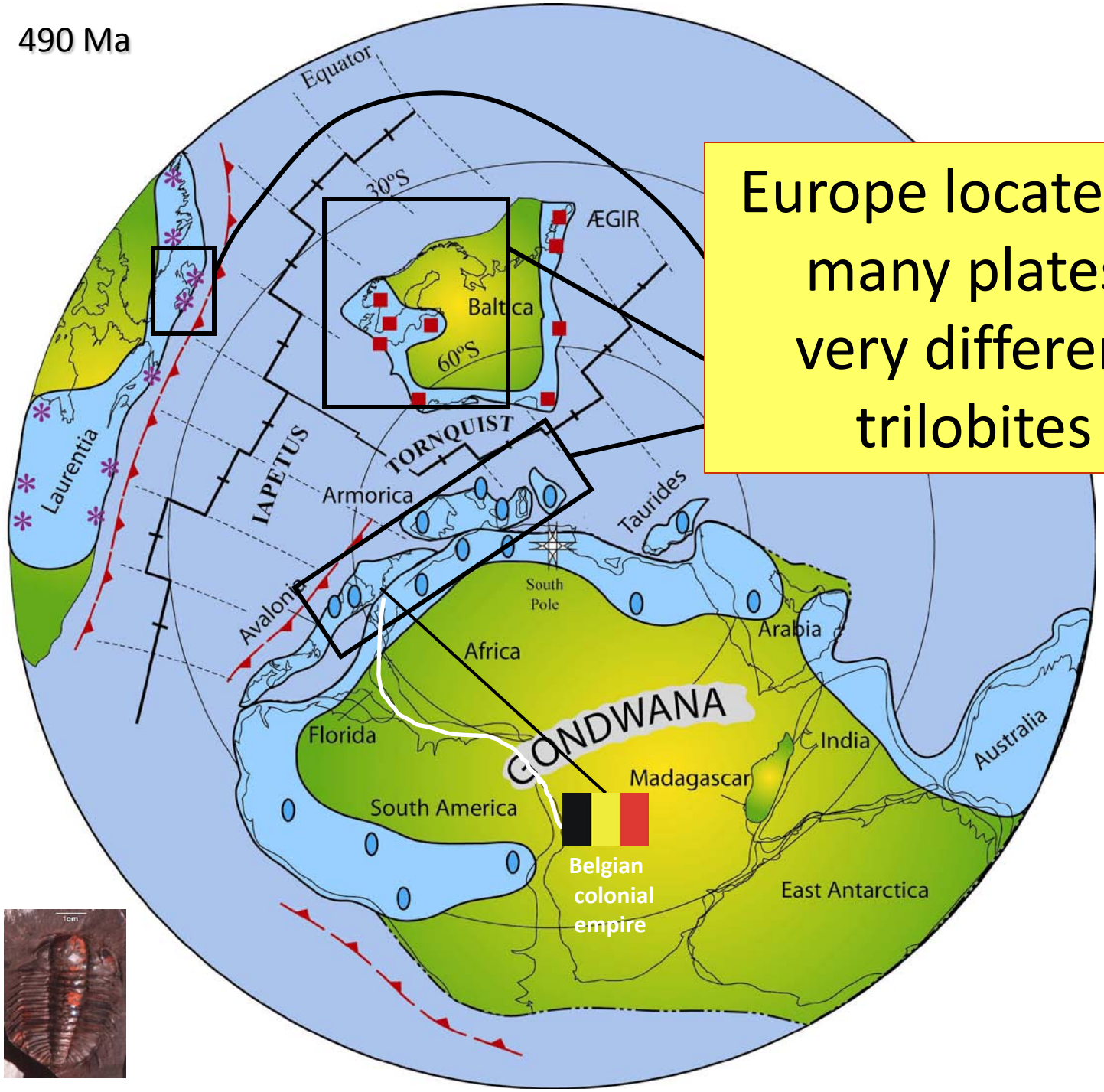
Wide Iapetus Ocean







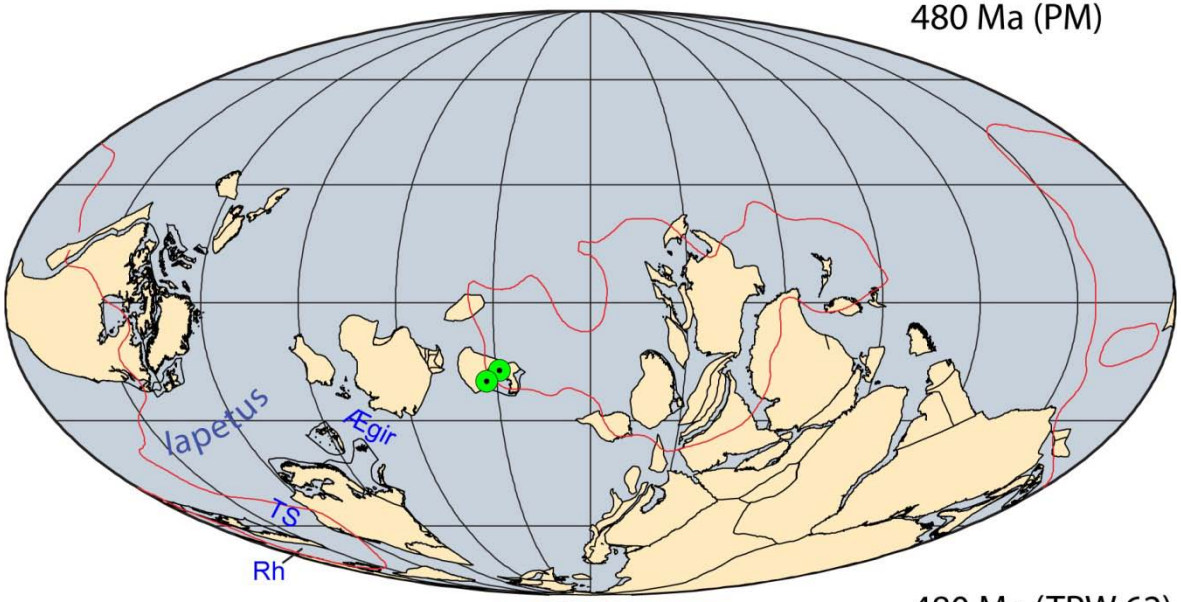
490 Ma

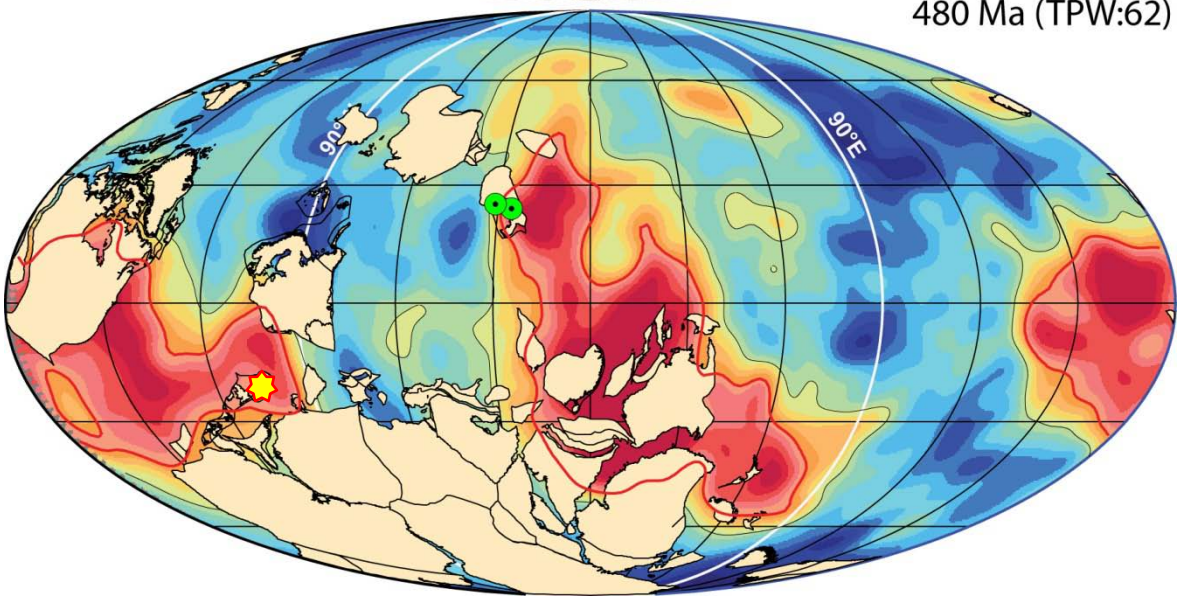


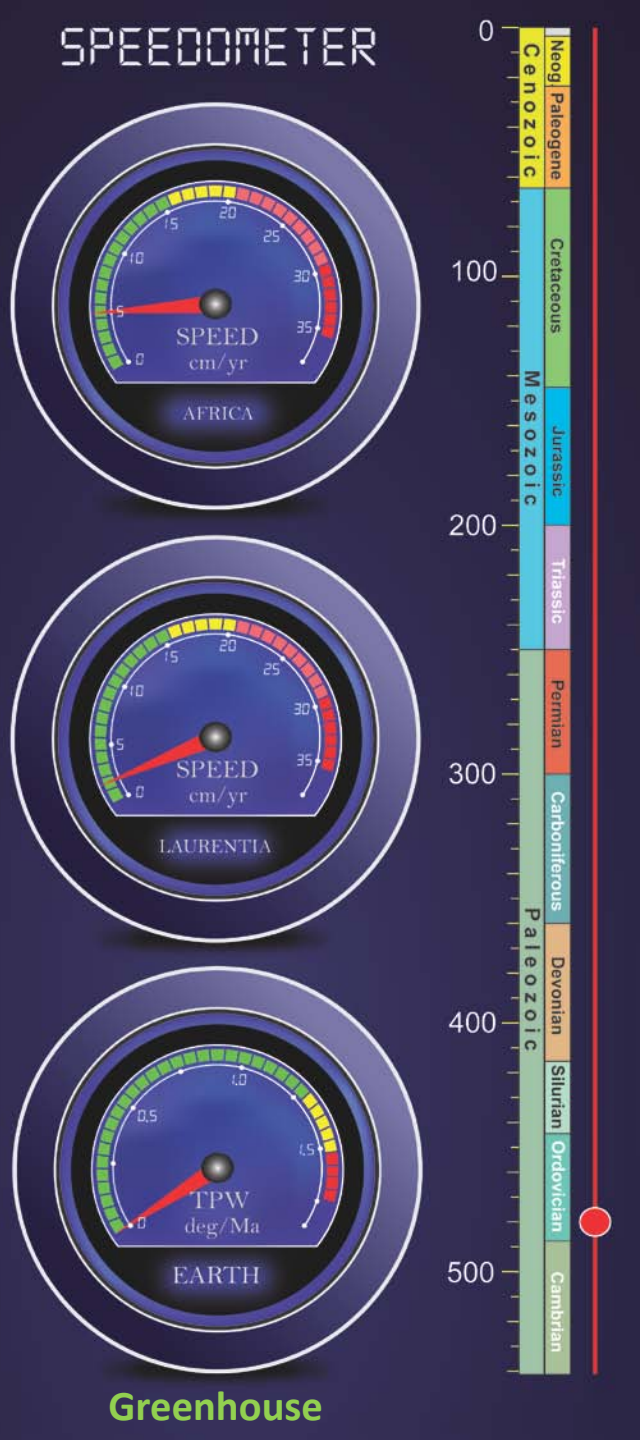
Europe located to many plates: very different trilobites

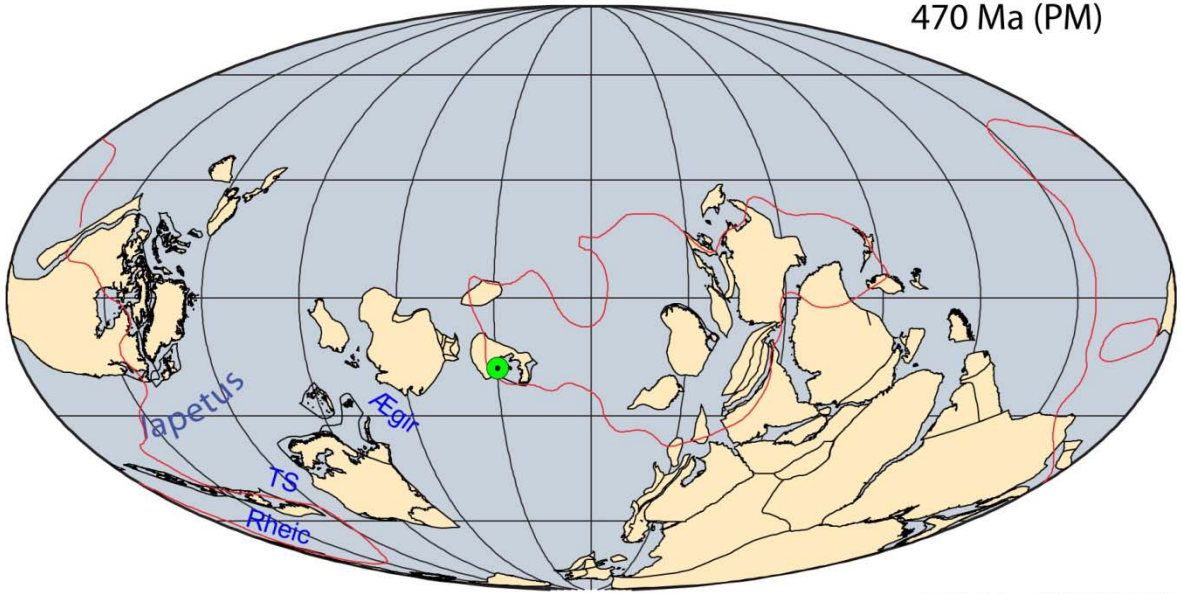
Torsvik (2005)

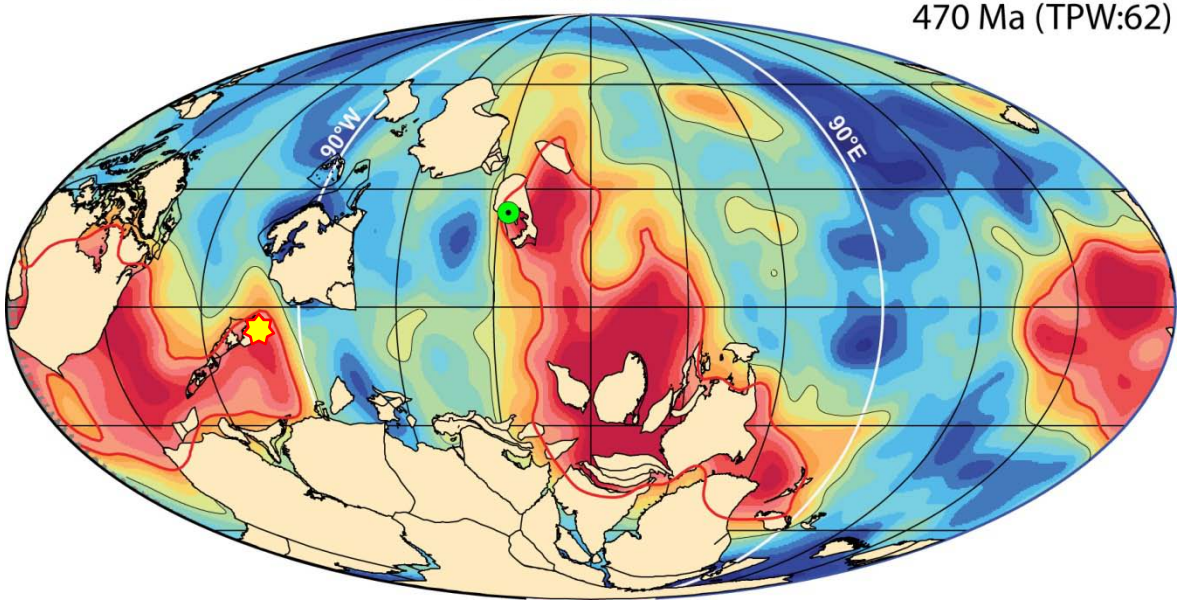
Rheic Ocean Opening

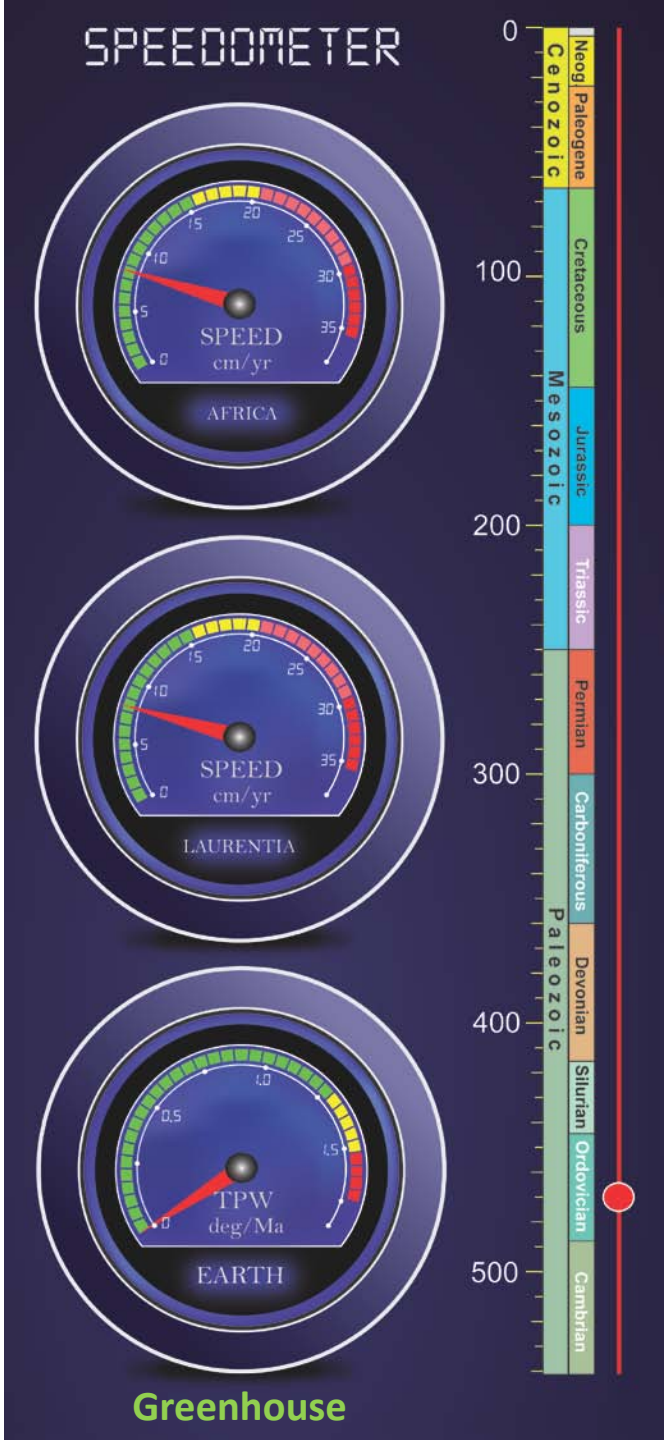







470 Ma (PM)
Iapetus
Aegir
TS
Rheic


470 Ma (TPW:62)
90°W
90°E


SPEEDOMETER
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cm/yr
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LAURENTIA
TPW
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Cenozoic
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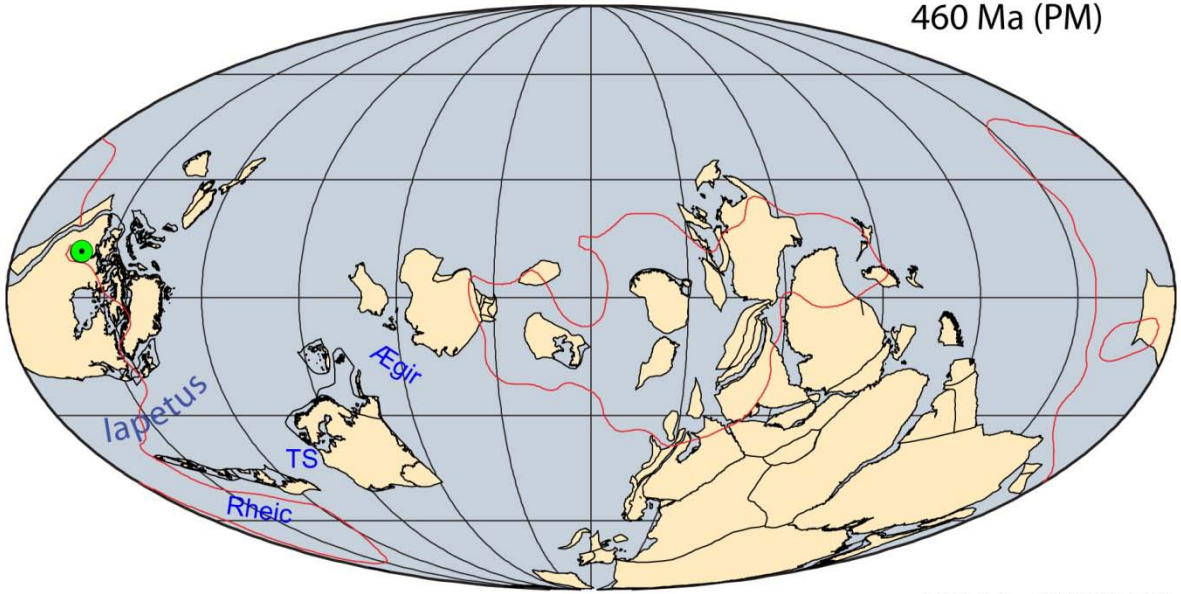
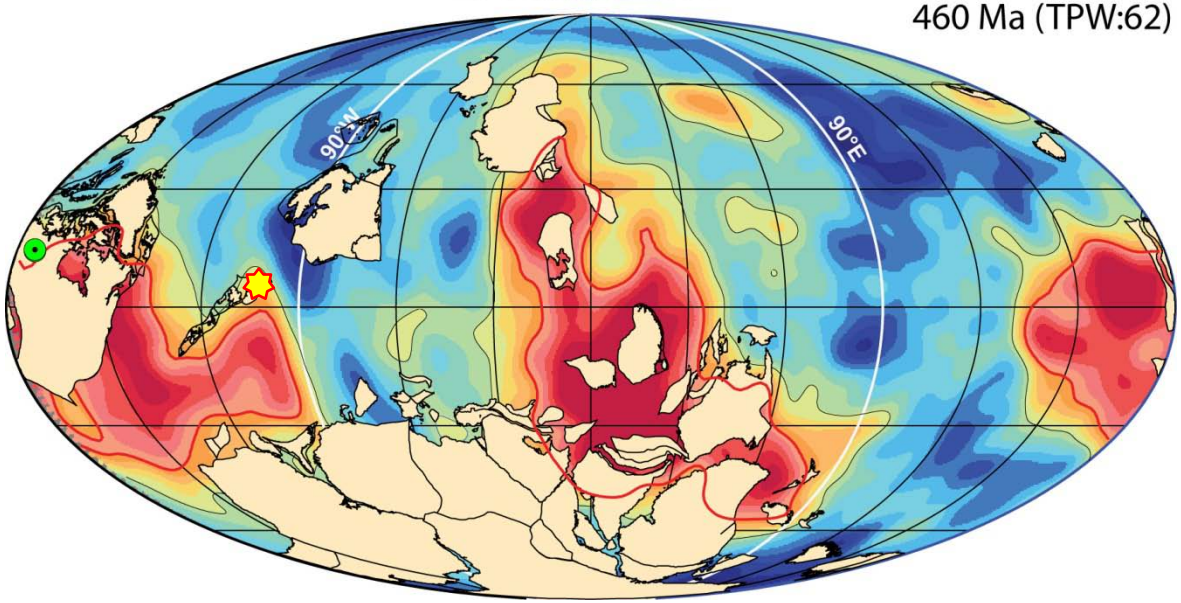
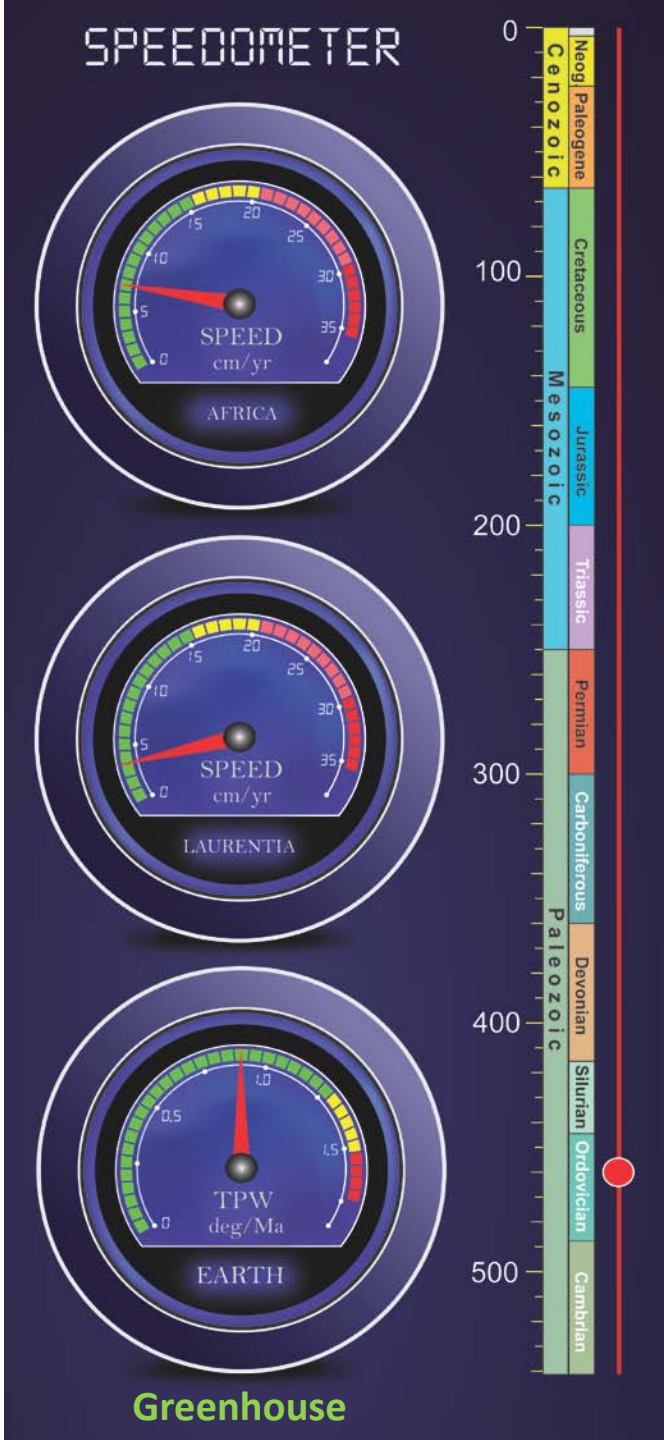
Devonian
Silurian
Ordovician
Cambrian

Greenhouse


460 Ma (PM)
Iapetus
Ægir
TS
Rheic


460 Ma (TPW:62)
90°W
90°E


SPEEDOMETER
SPEED
cm/yr
AFRICA
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cm/yr
LAURENTIA
TPW
deg/Ma
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Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
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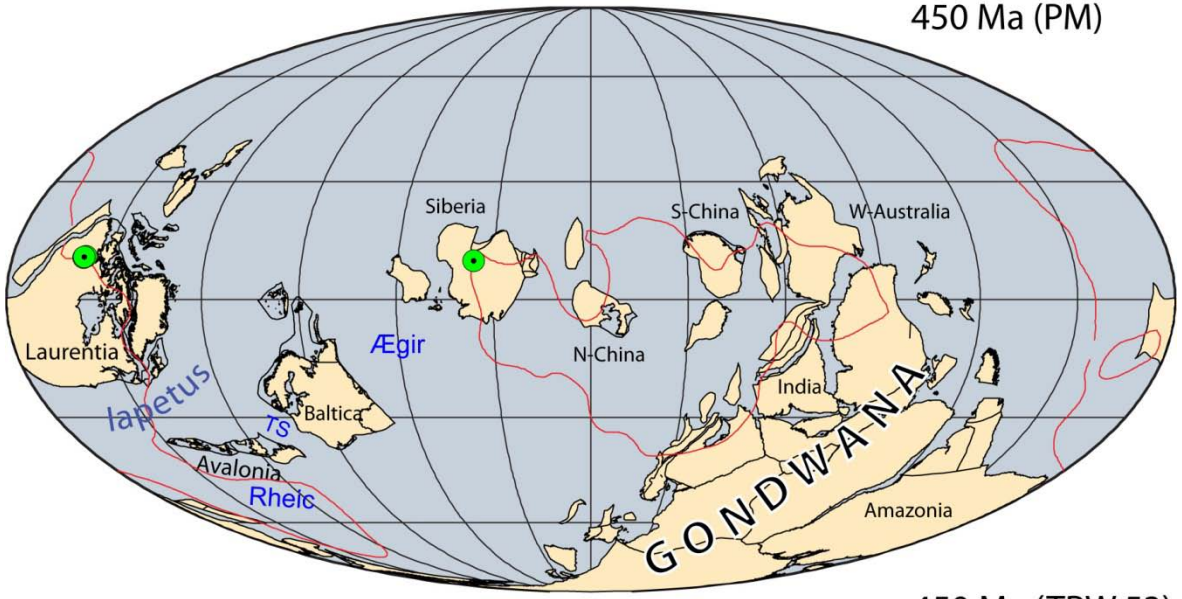
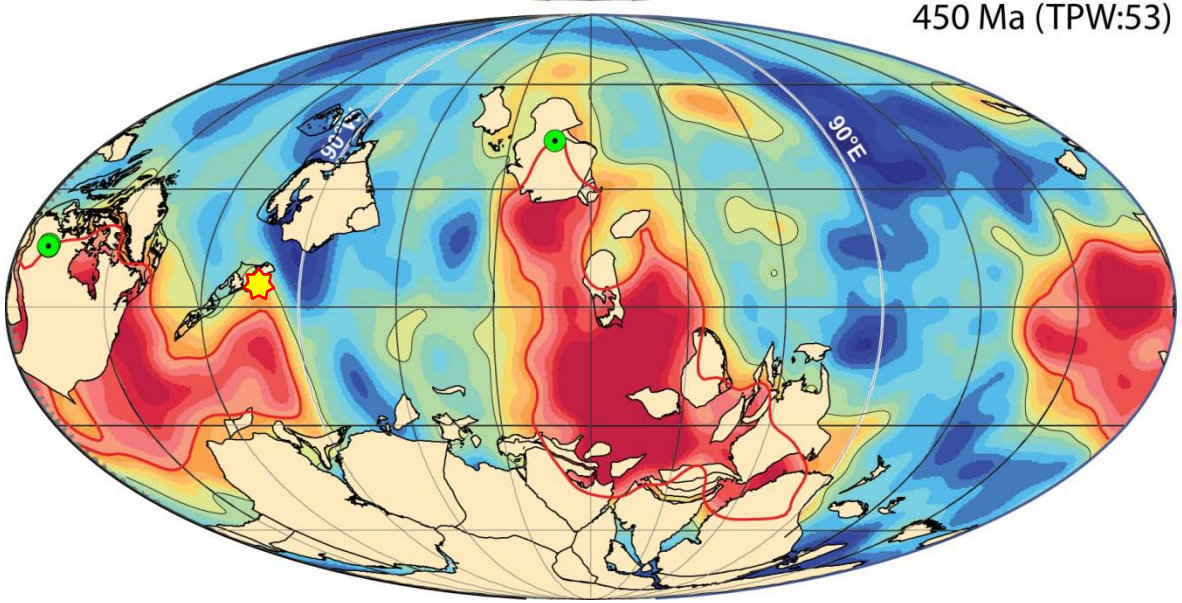
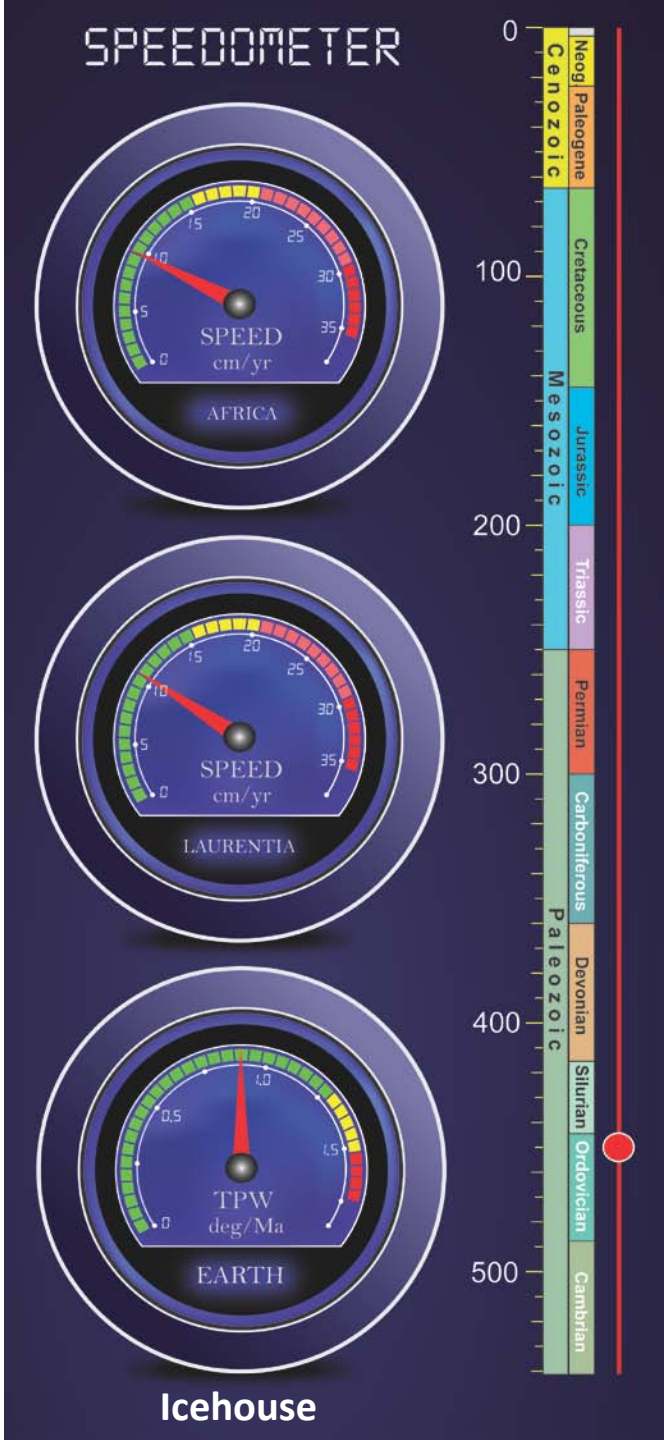
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

Tornquist Sea Closure



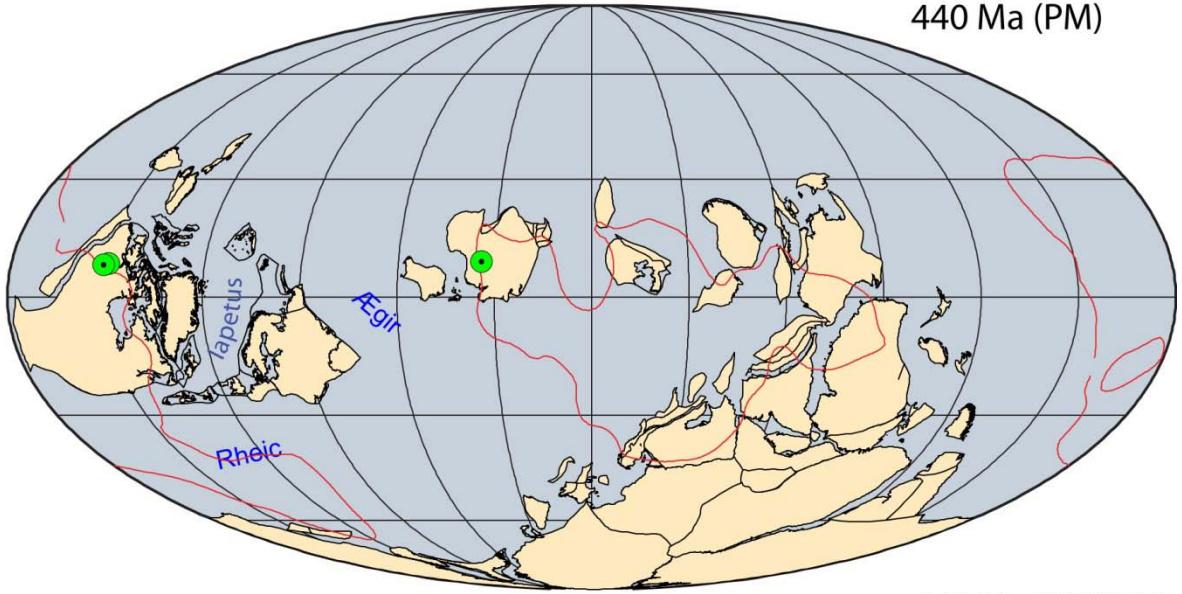


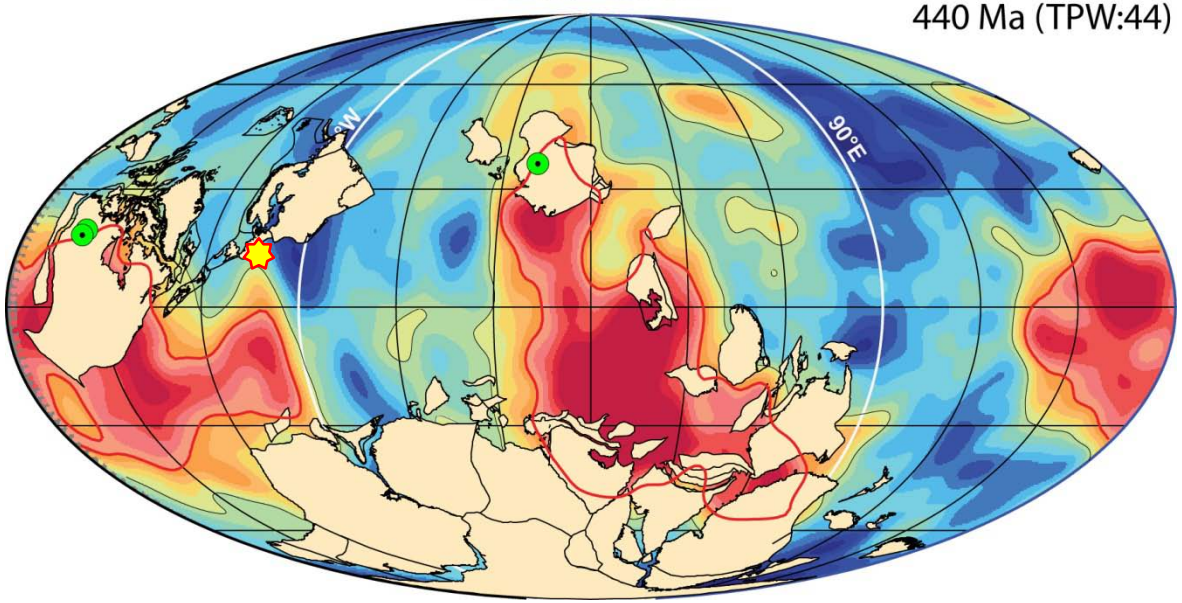


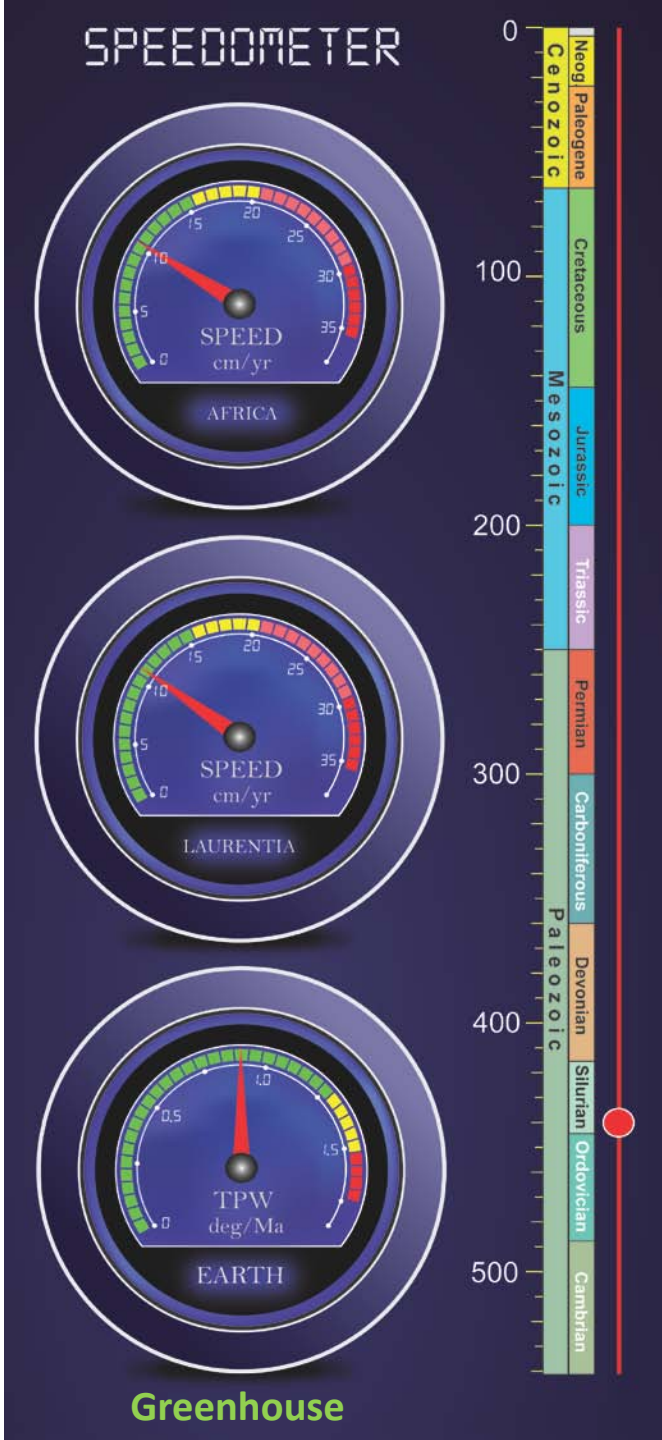
Icehouse

Creation of EUROPE:
Phase 1:
Baltica collides with Avalonia that had drifted off Gondwana at around 480 Ma

Baltica-Avalonia Docked



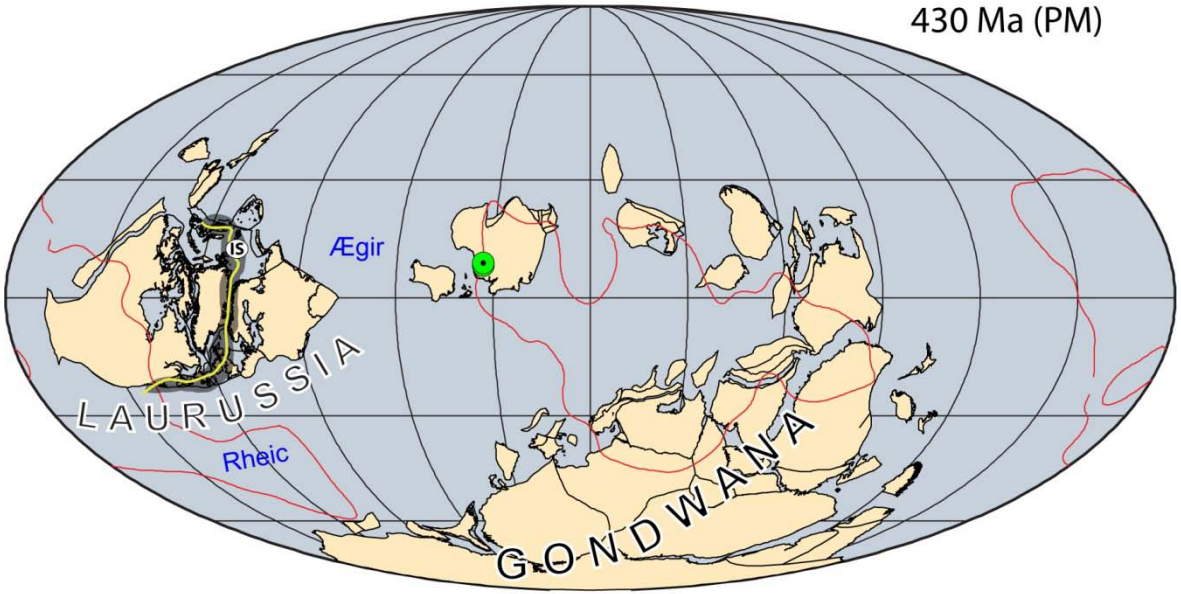


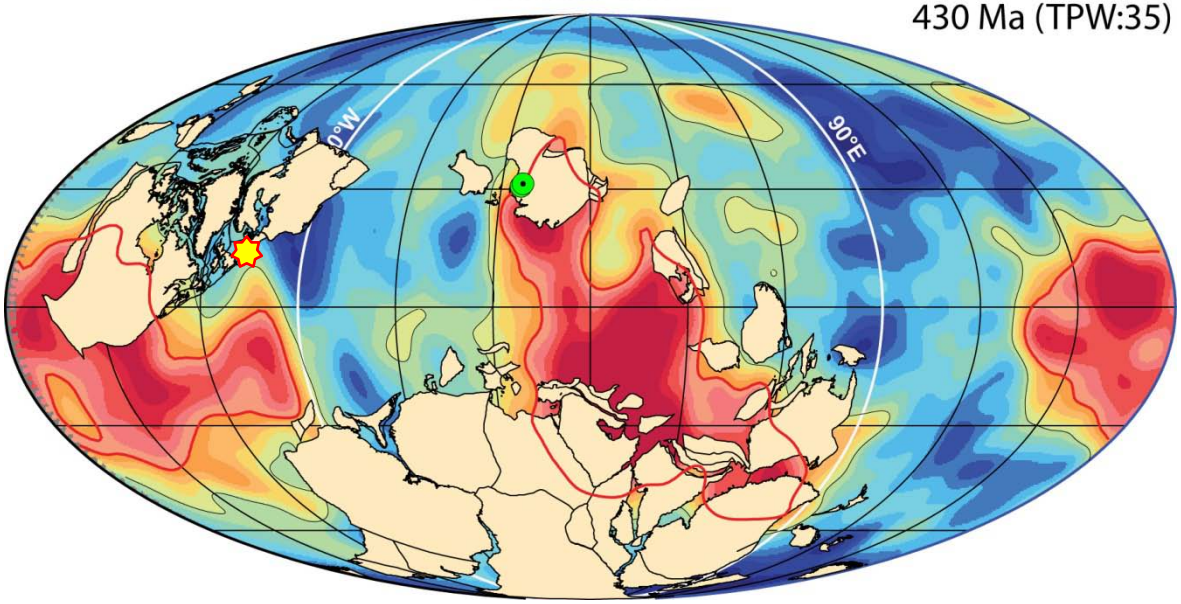


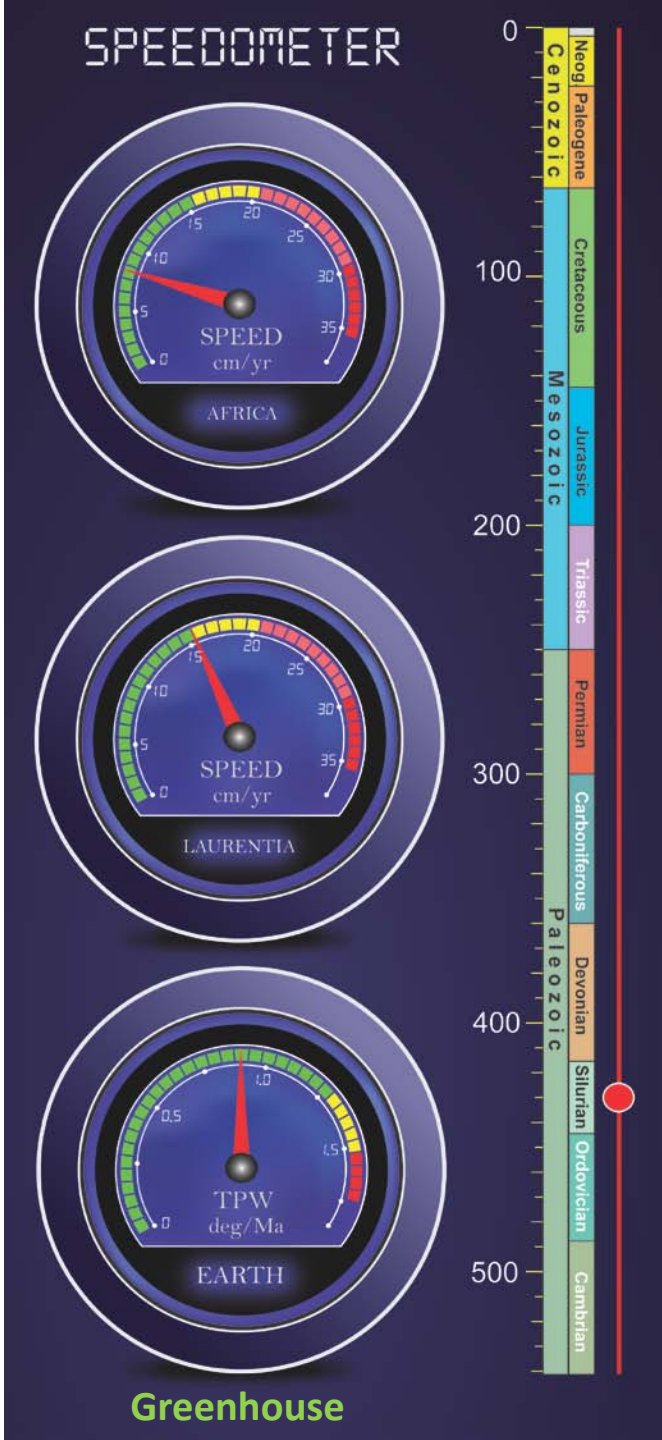
Creation of EUROPE:

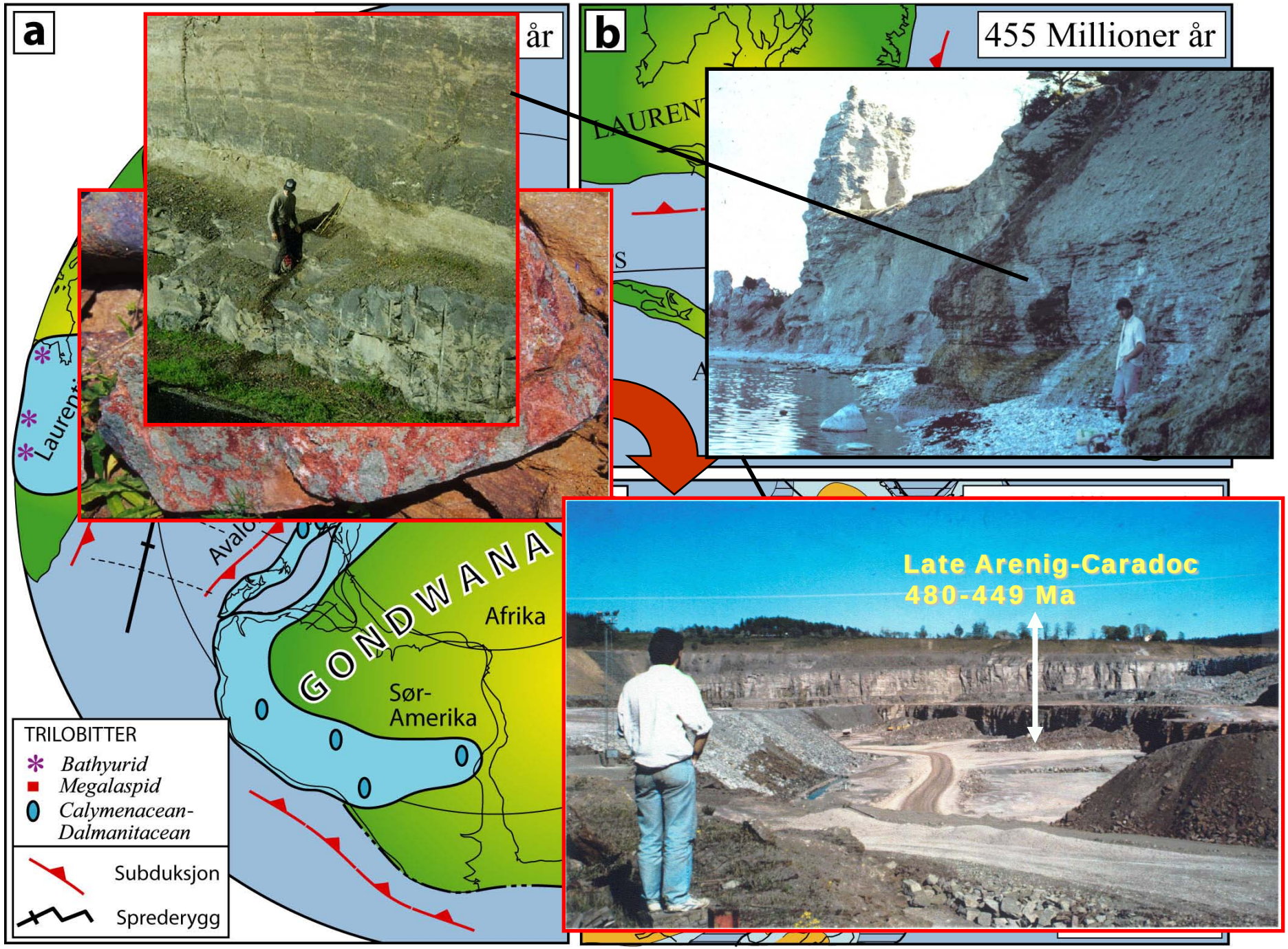
Phase 2: Baltica-Avalonia collides with Laurentia

Formation of Laurussia (Caledonian Orogeny)

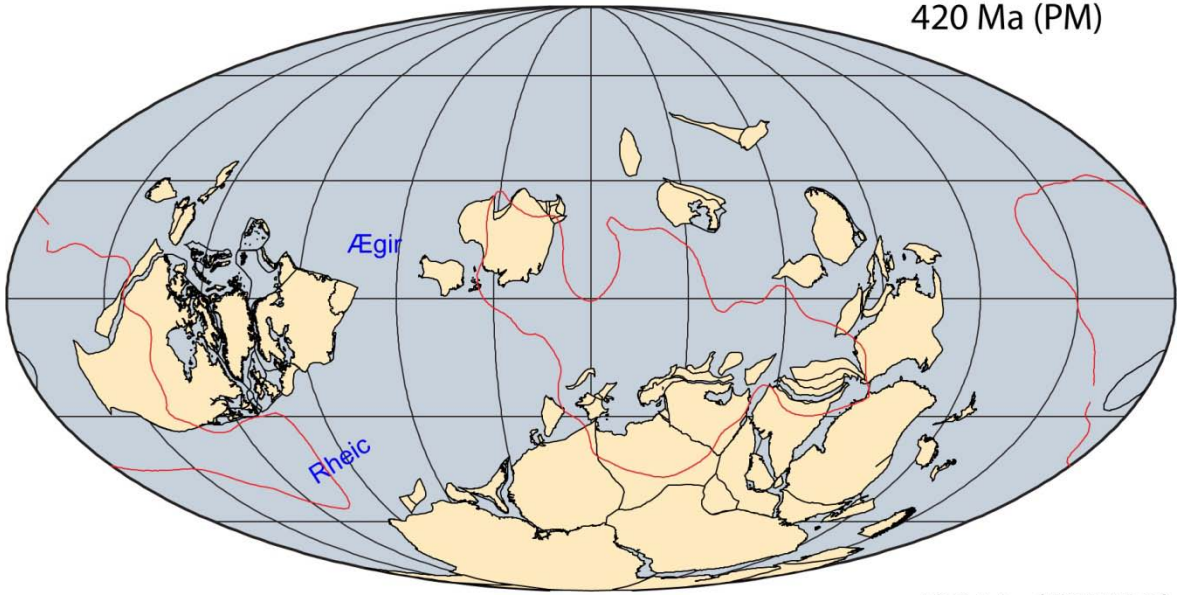


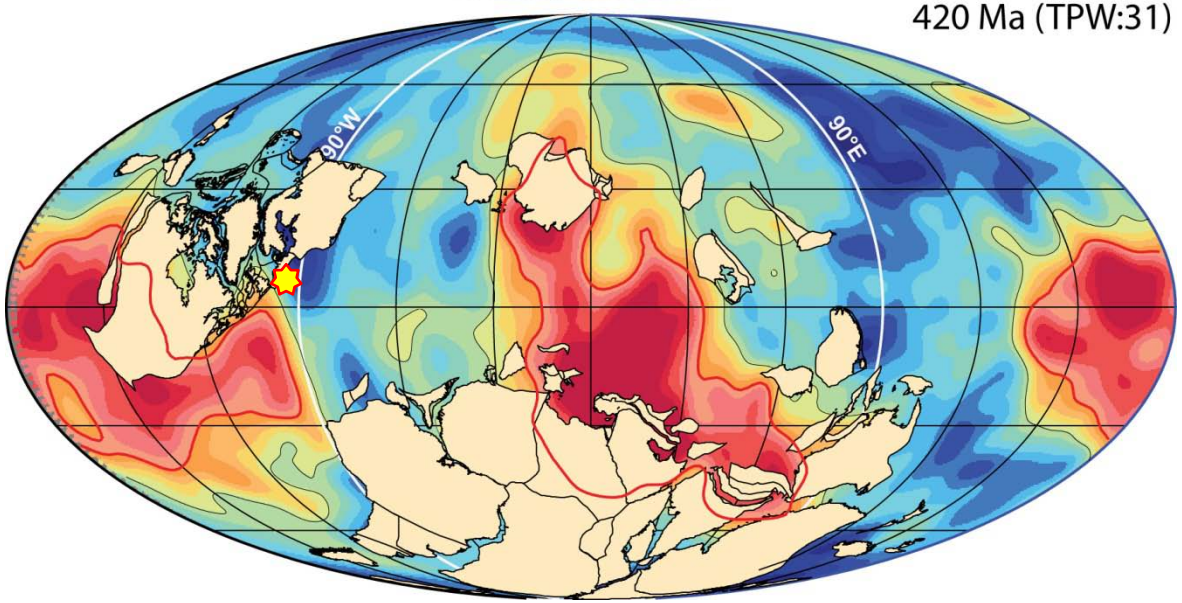


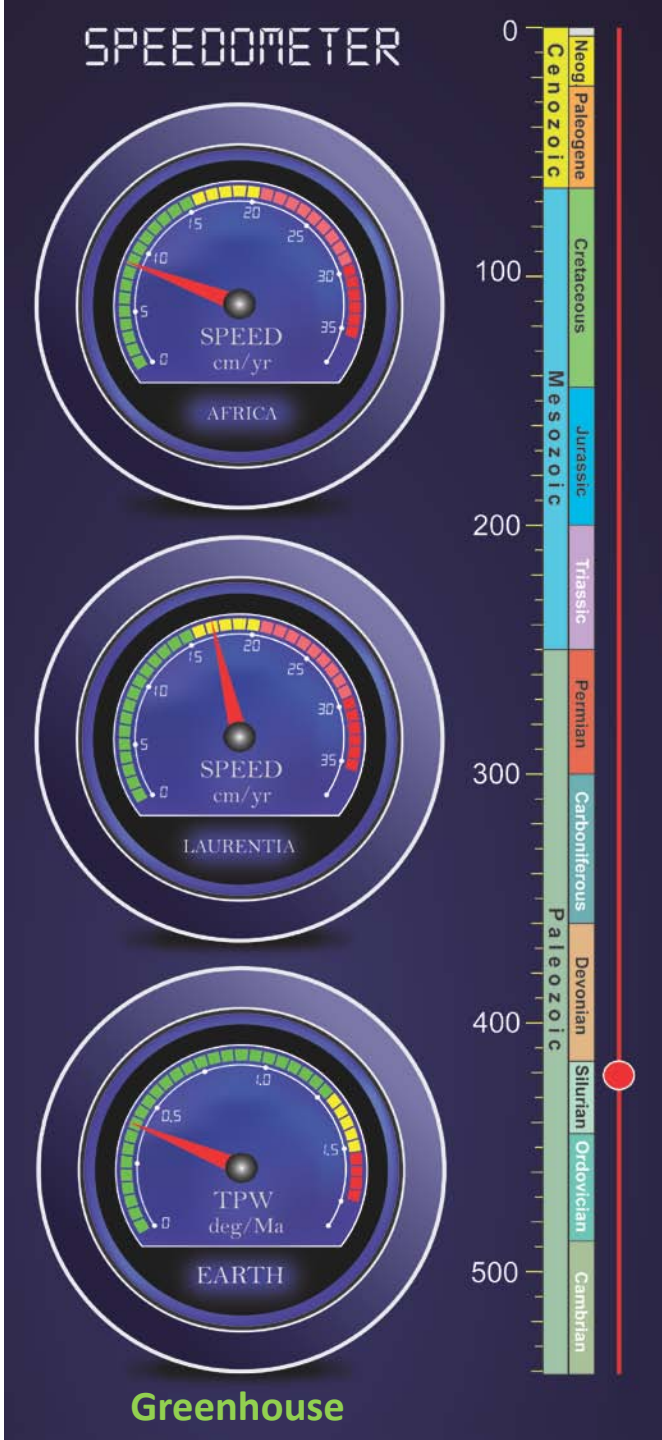


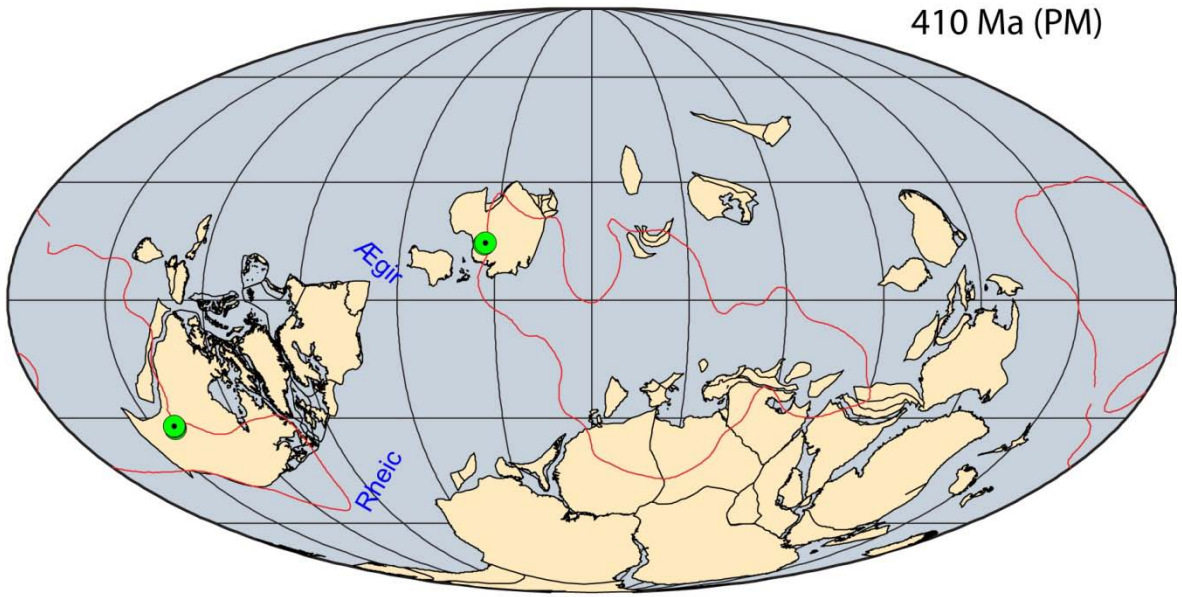

a
år
b
455 Millioner år
LAUREN
S
A
Laurent
Avalo
GONDWANA
Afrika
Sør-
Amerika
Late Arenig-Caradoc
480-449 Ma
TRILOBITTER
Bathyurid
Megalaspid
Calymenacean-
Dalmanitacean
Subduksjon
Spredерygg

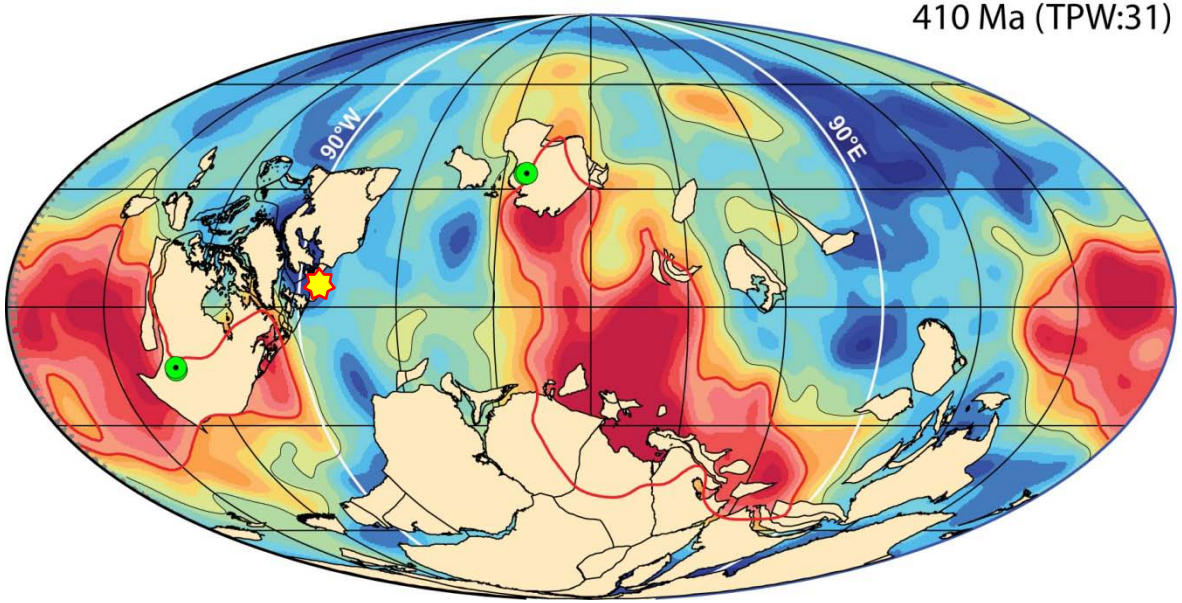
Wide Rheic Ocean

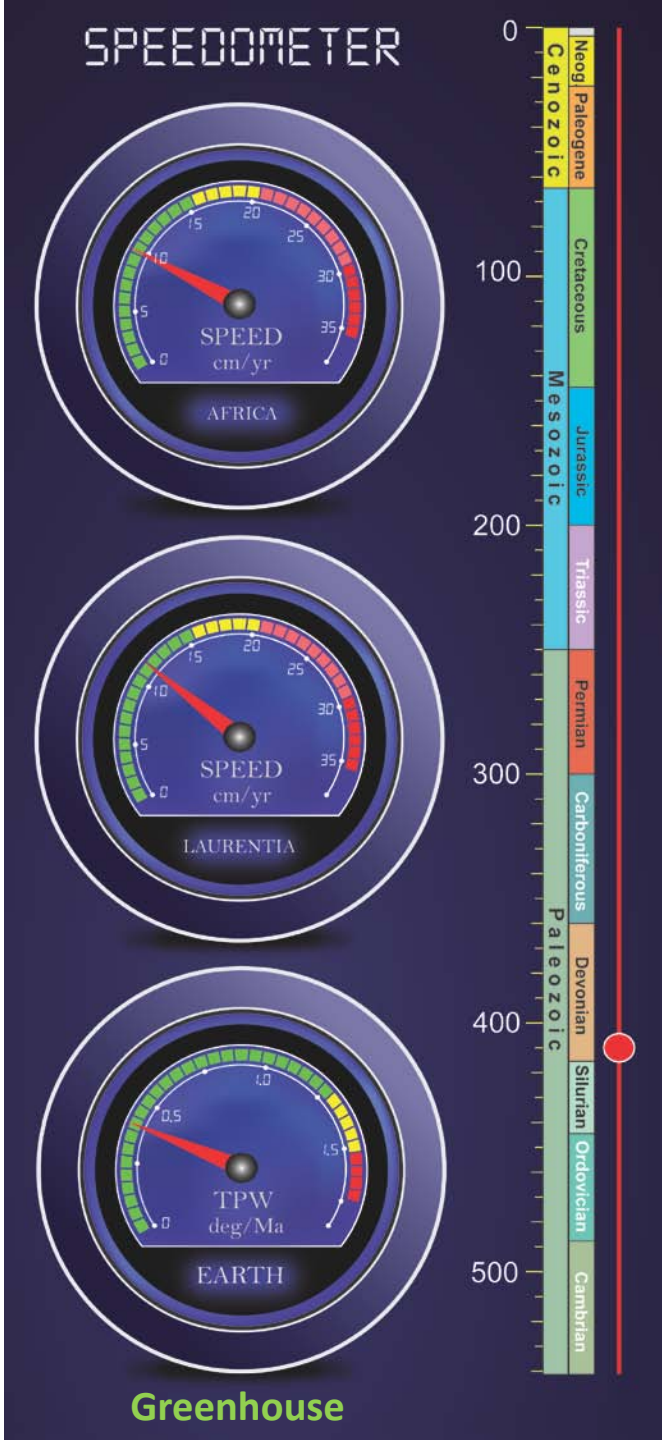




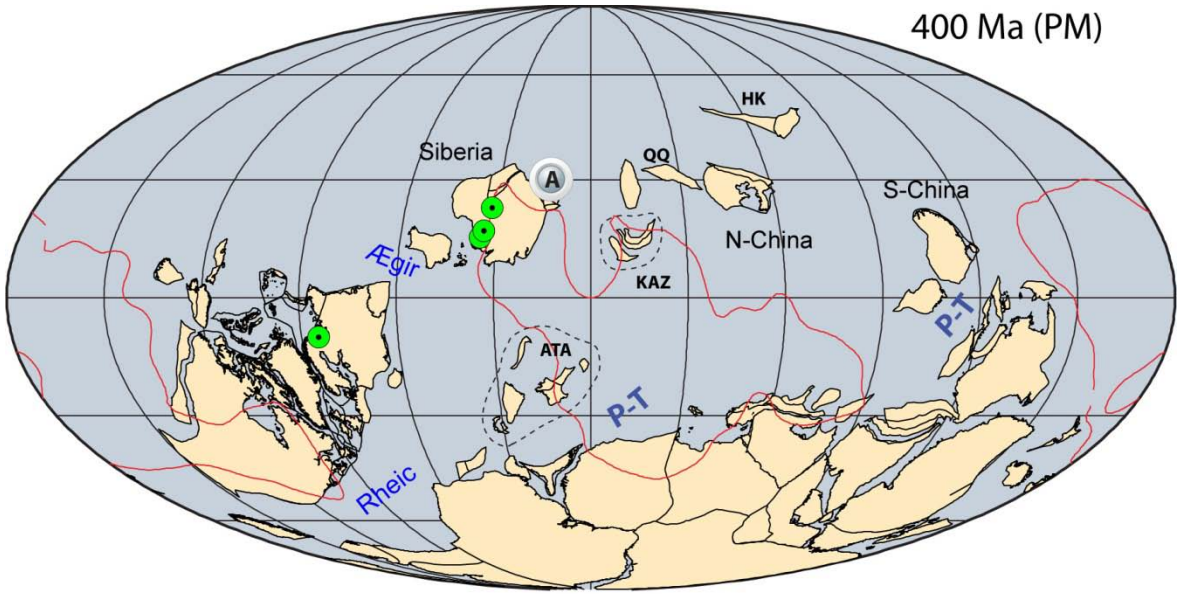


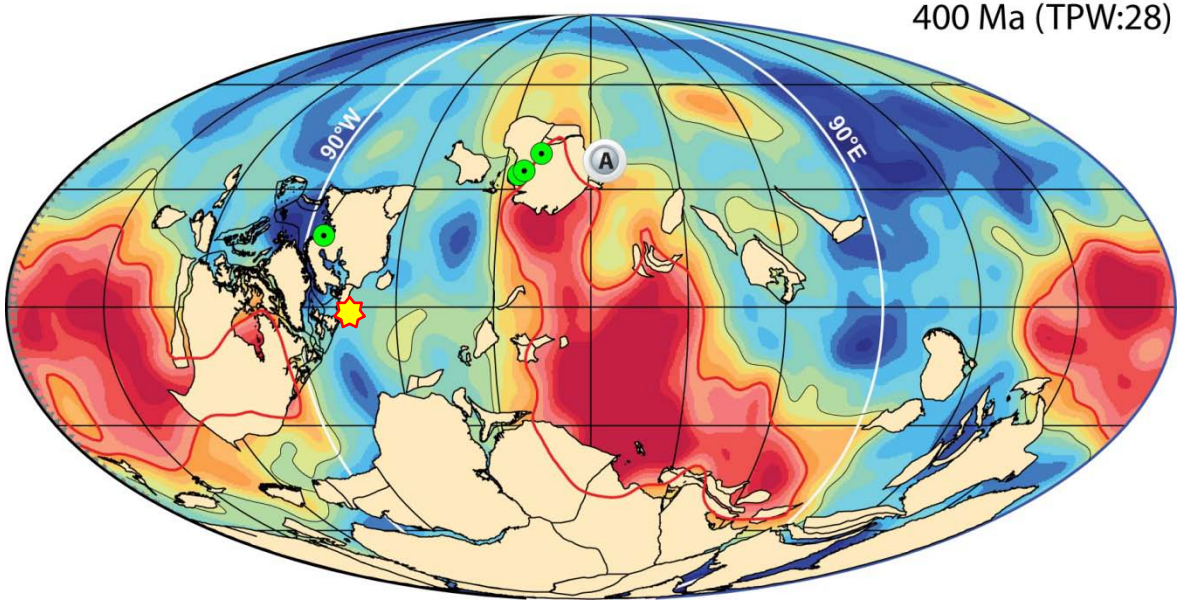

410 Ma (PM)
Ægir
Rheic

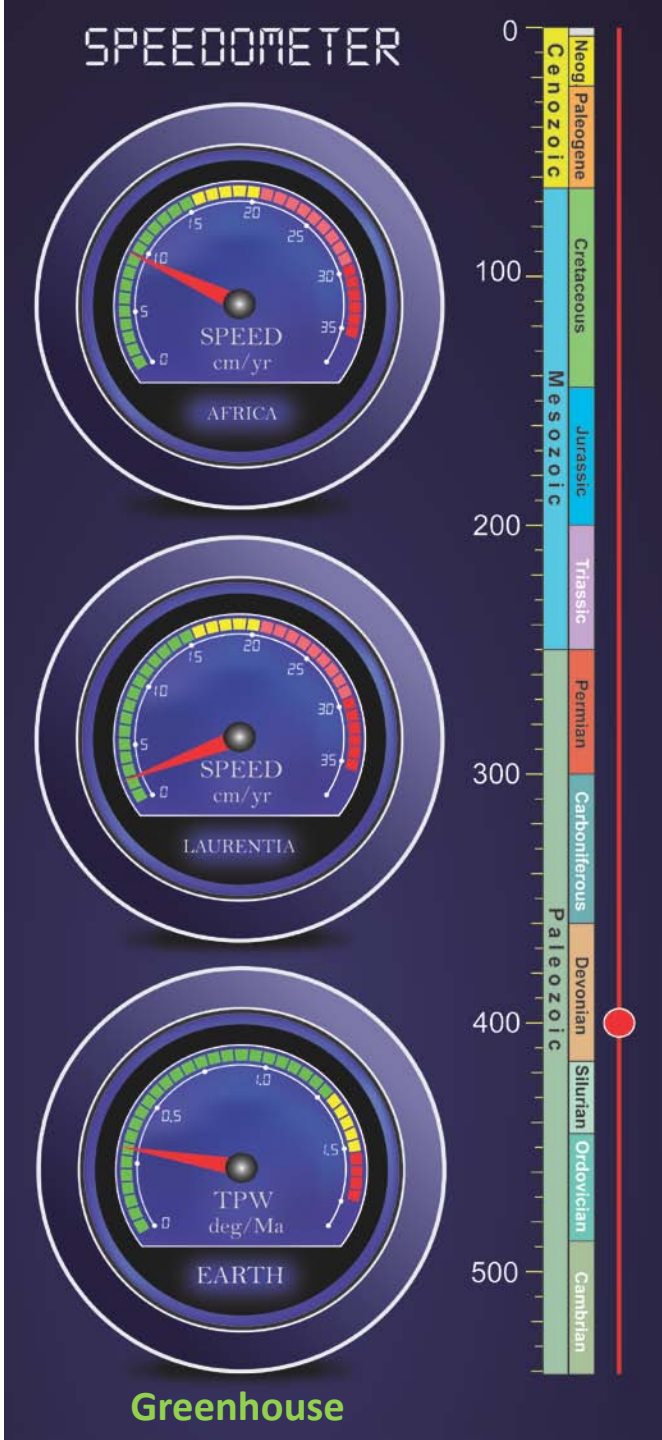

410 Ma (TPW:31)
90°W
90°E


SPEEDOMETER
SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
0
100
200
300
400
500
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

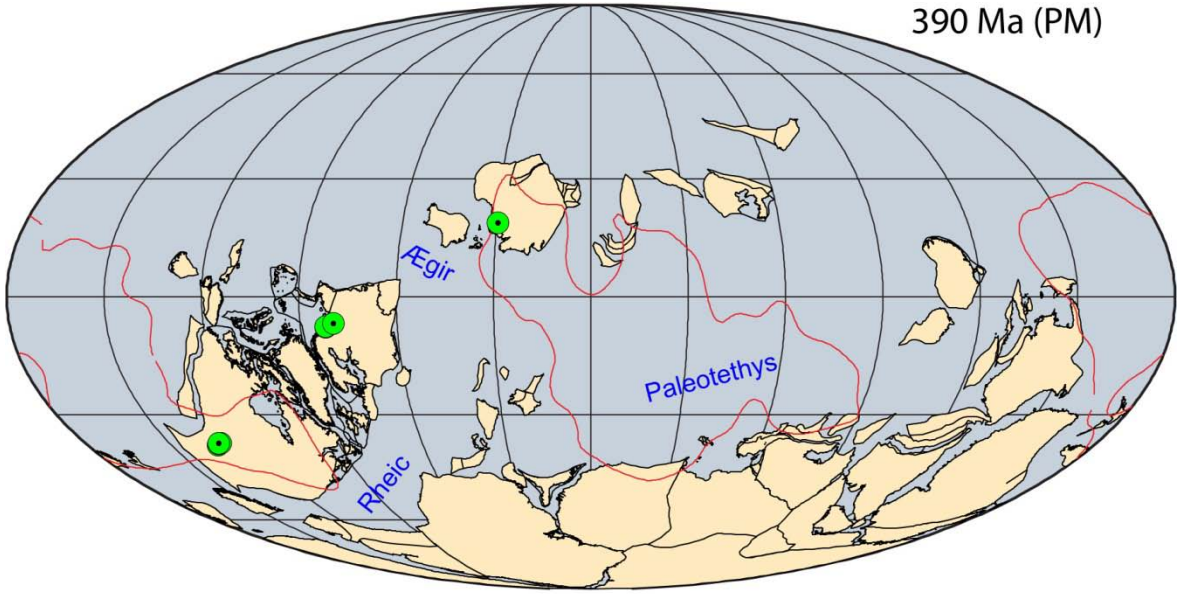
LIP: Altay-Sayan (Siberia)

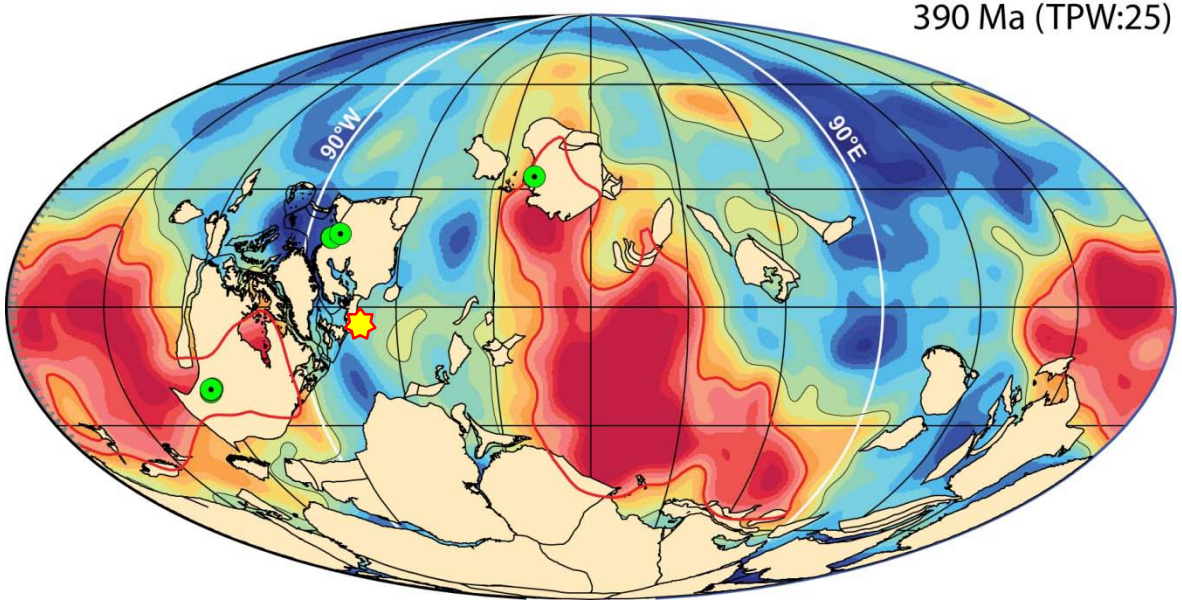


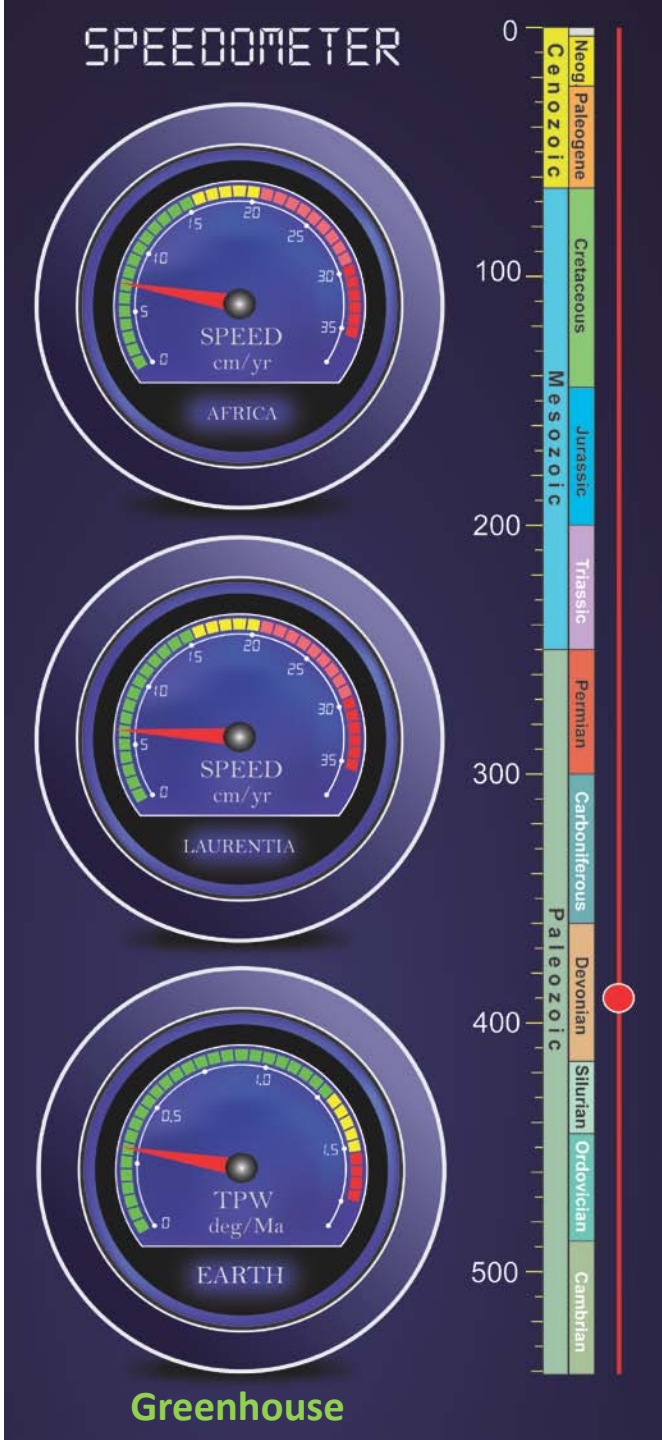




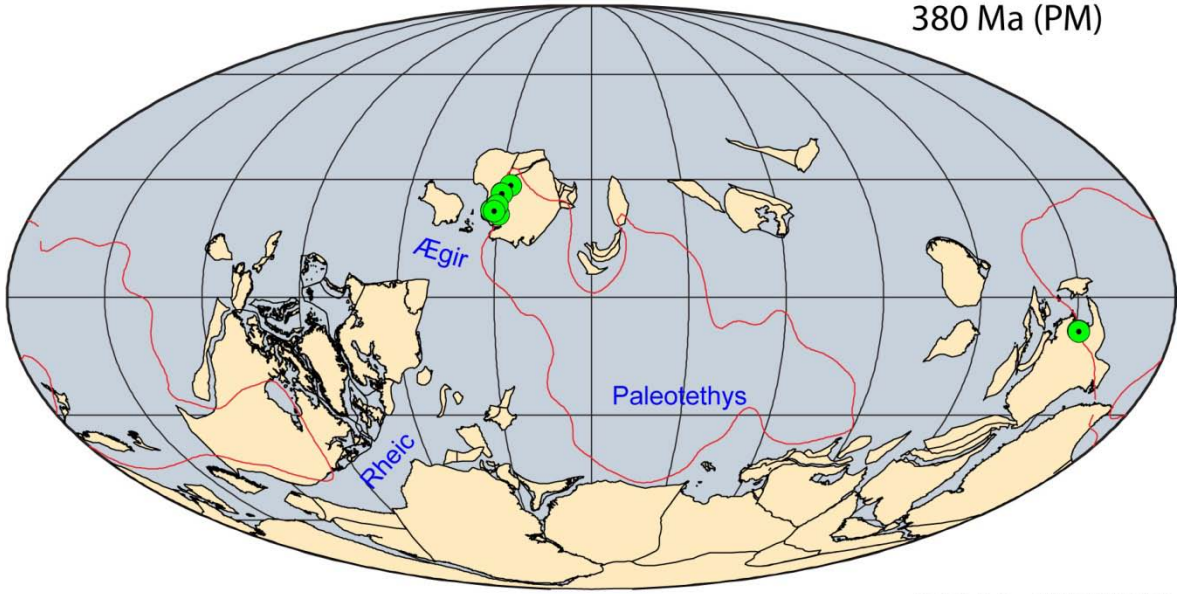
Narrowing Rheic Ocean

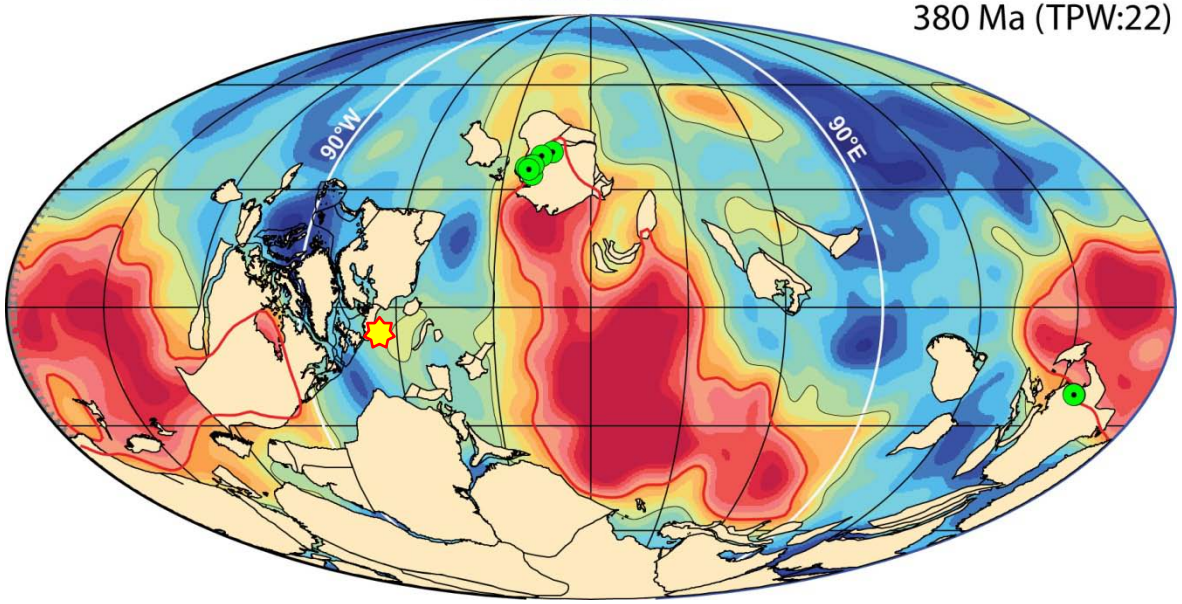


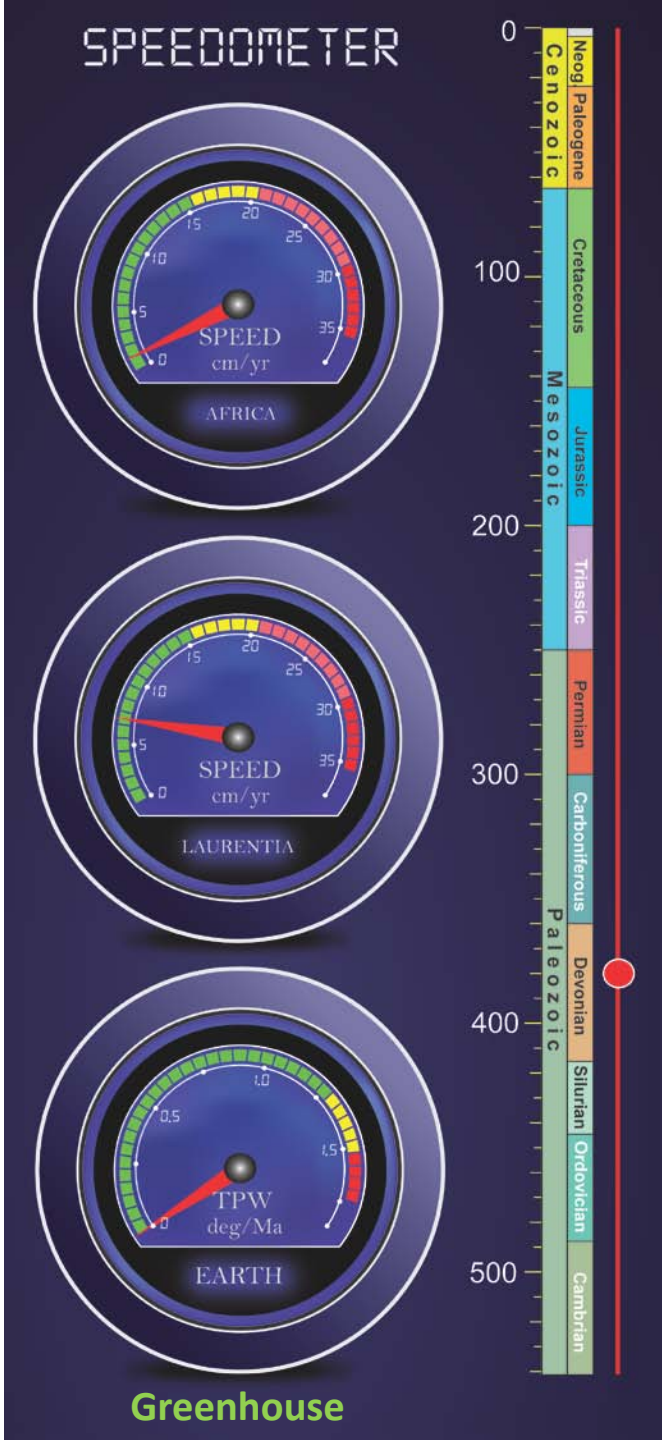




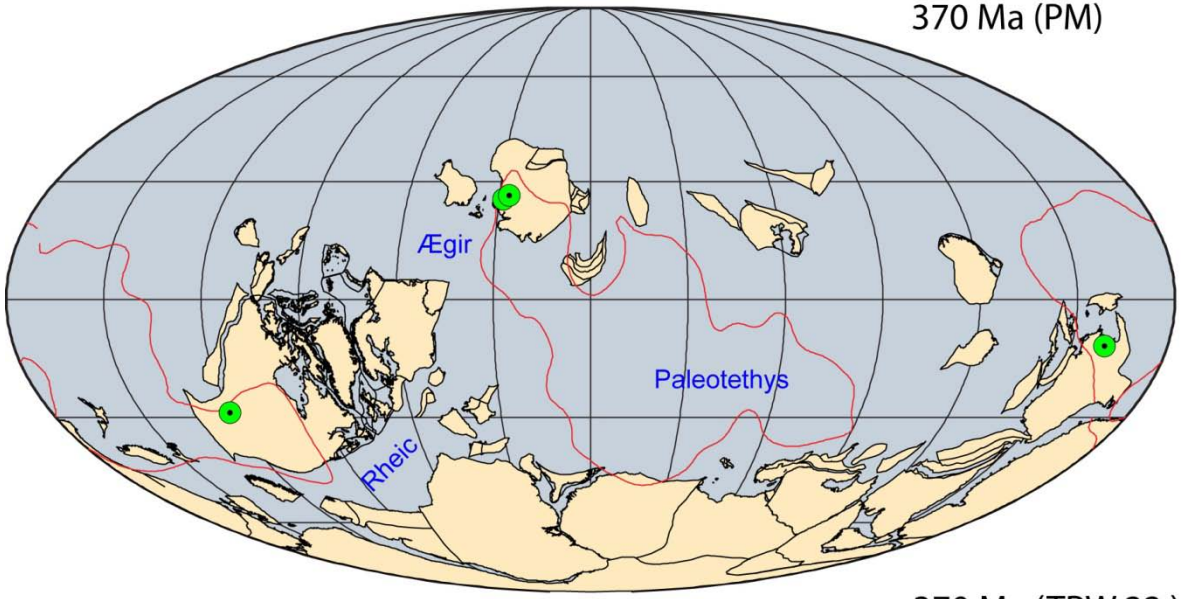
Narrowing Rheic Ocean

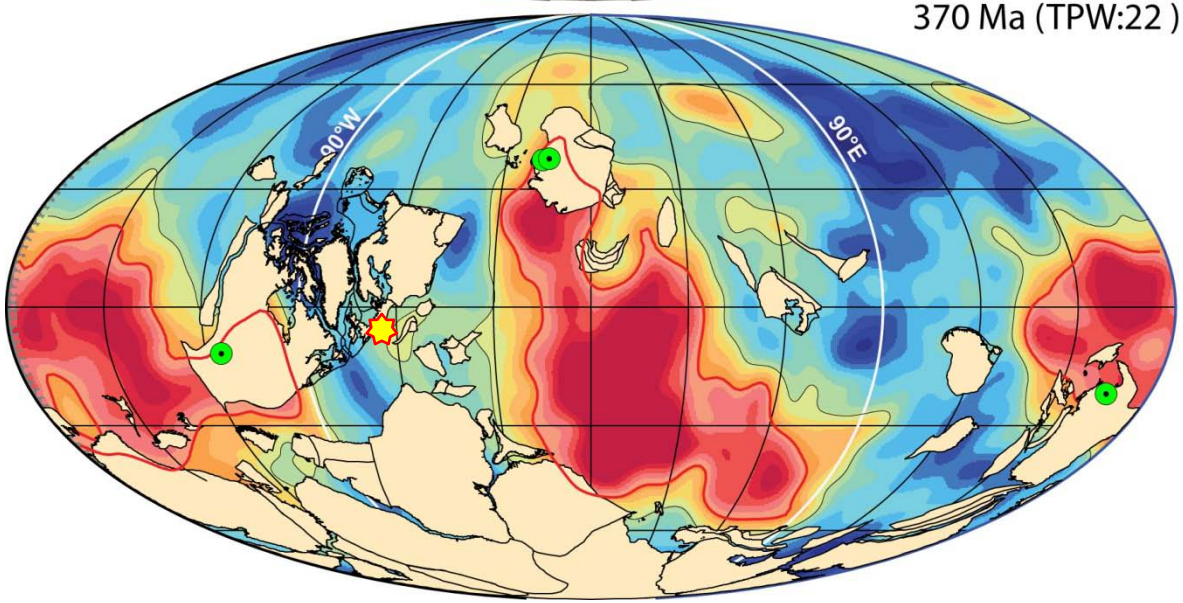


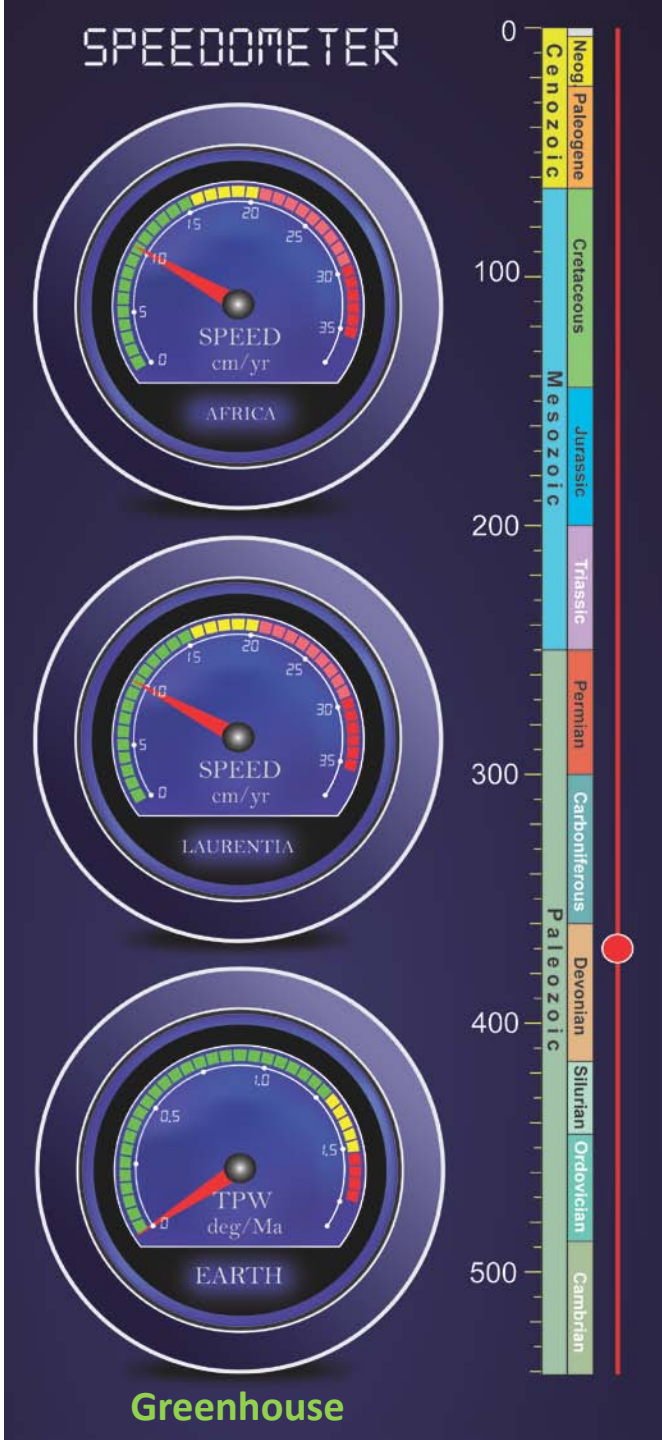




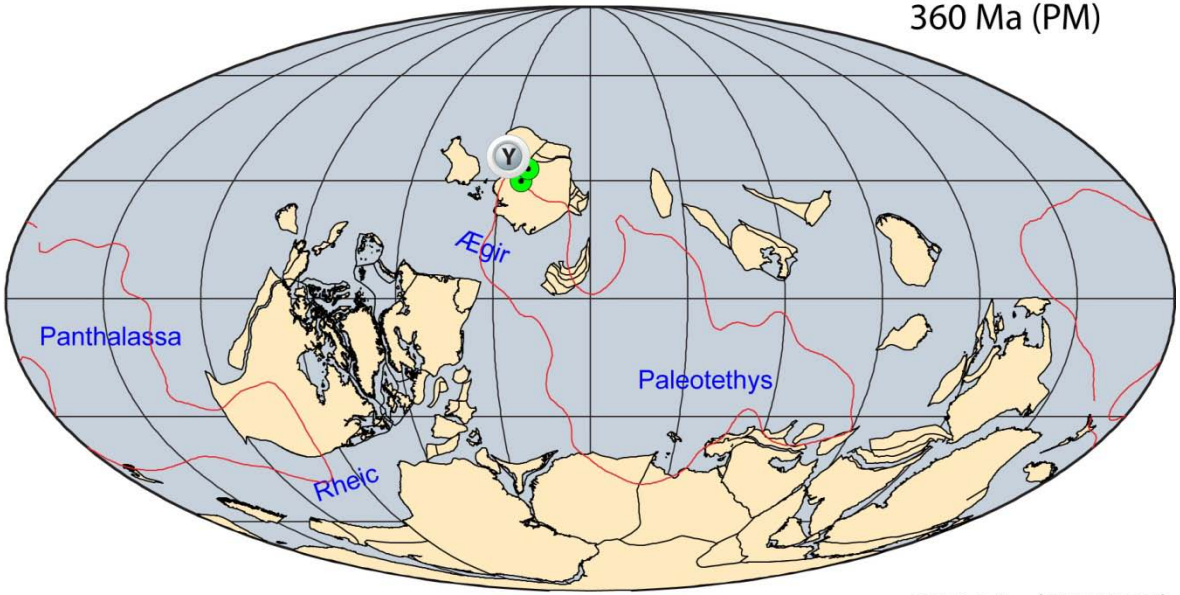
Greenhouse

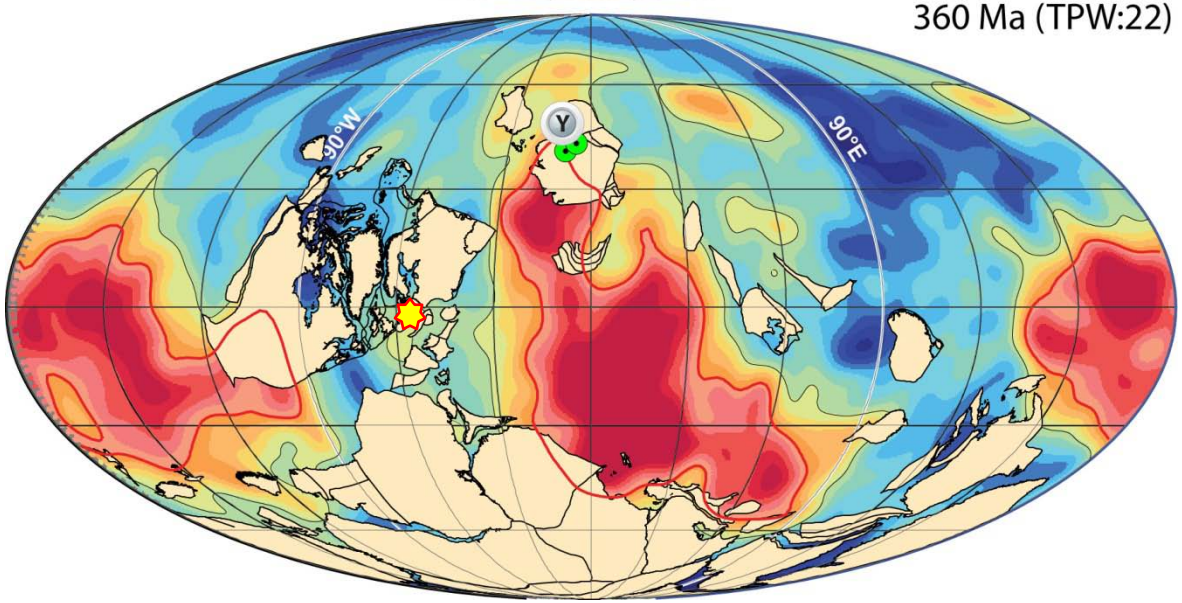

370 Ma (PM)
Ægir
Paleotethys
Rheic

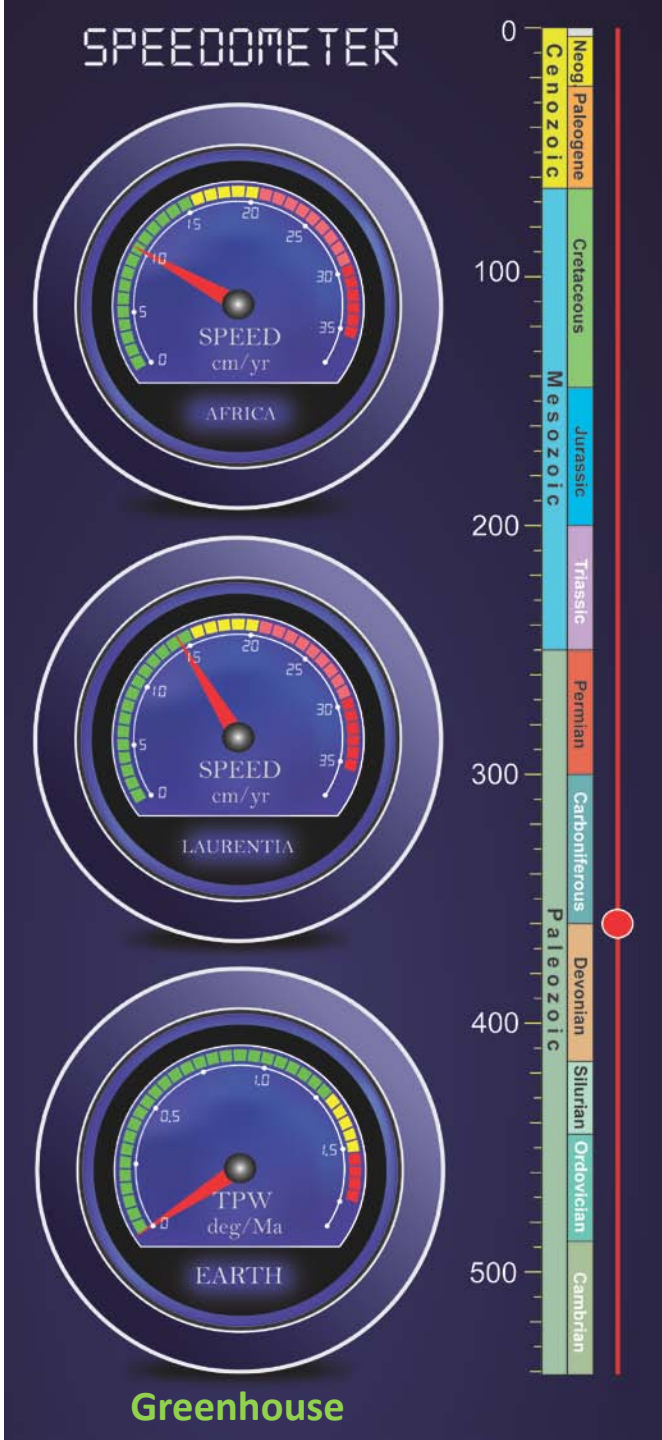

370 Ma (TPW:22)
90°W
90°E


SPEEDOMETER
SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
0
100
200
300
400
500
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

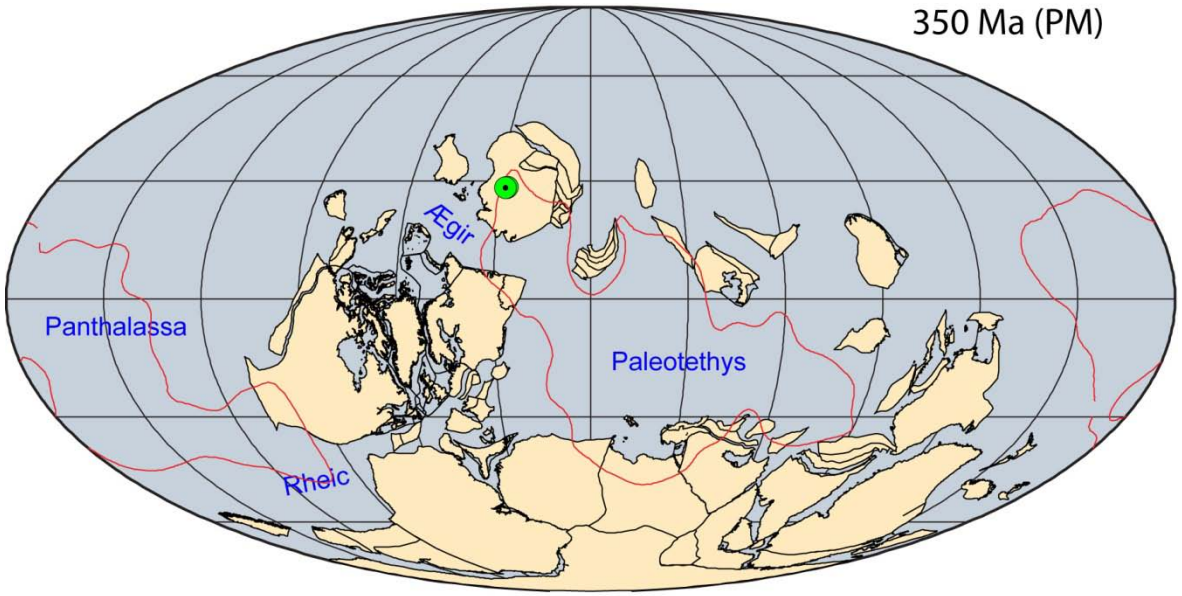
LIP: Yakutsk (Siberia)

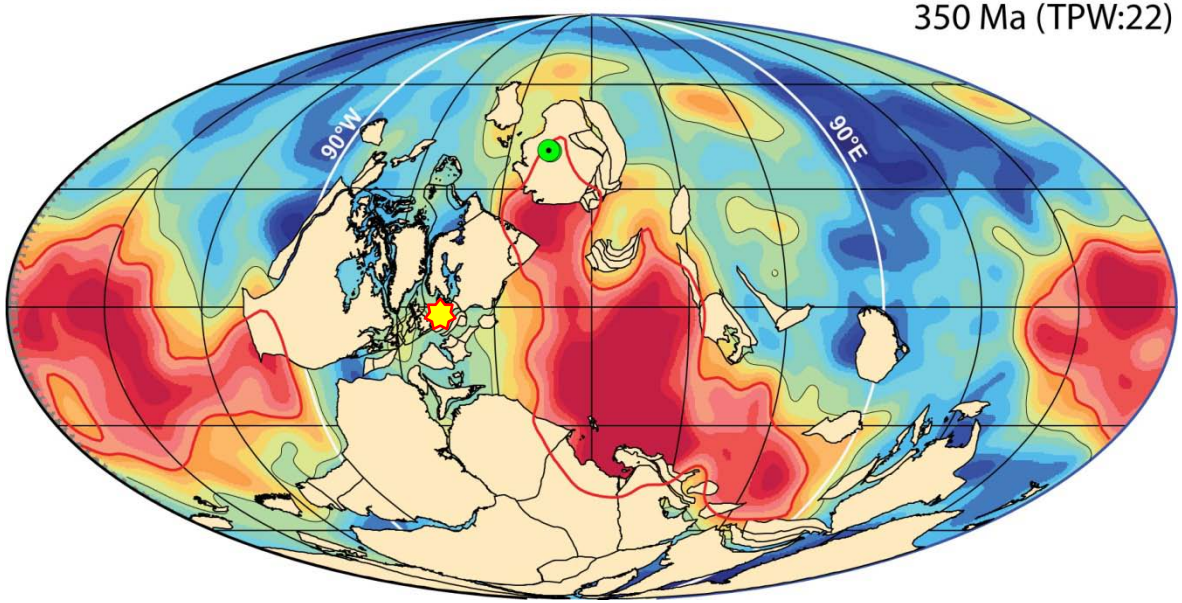


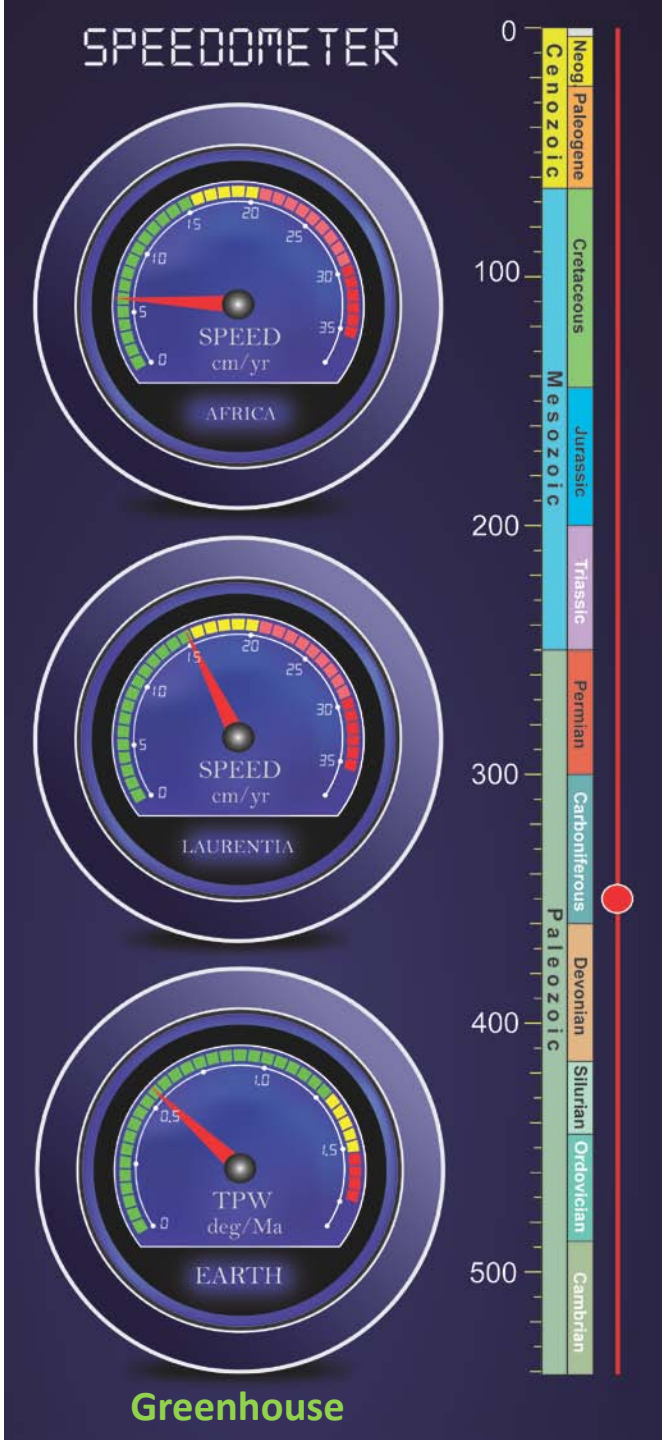




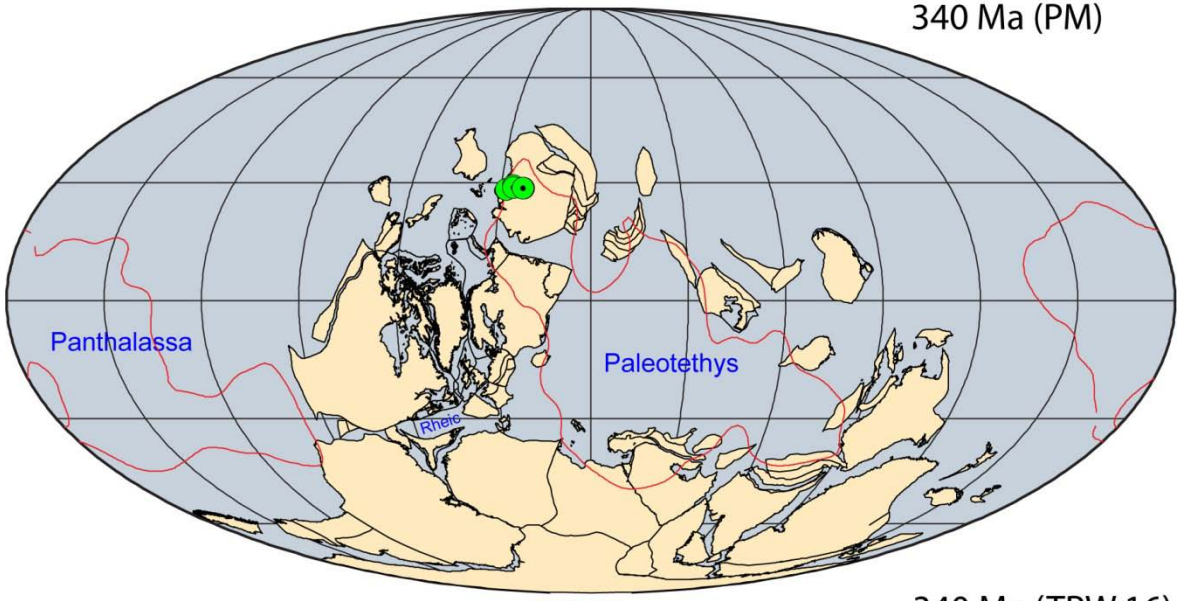
‘European’ Rheic almost vanished

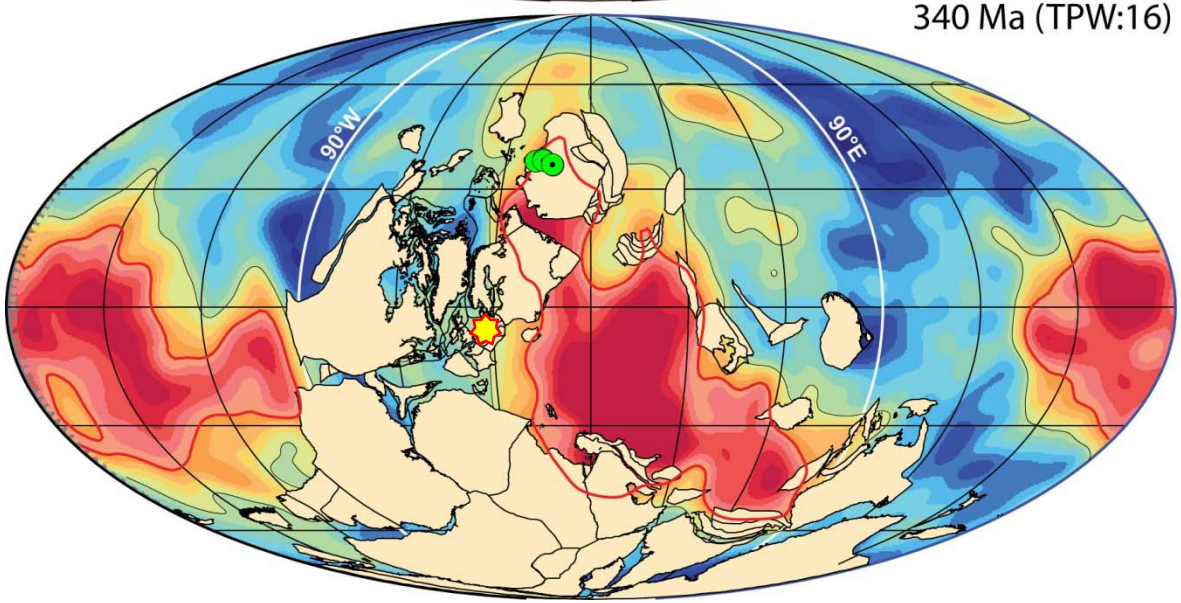


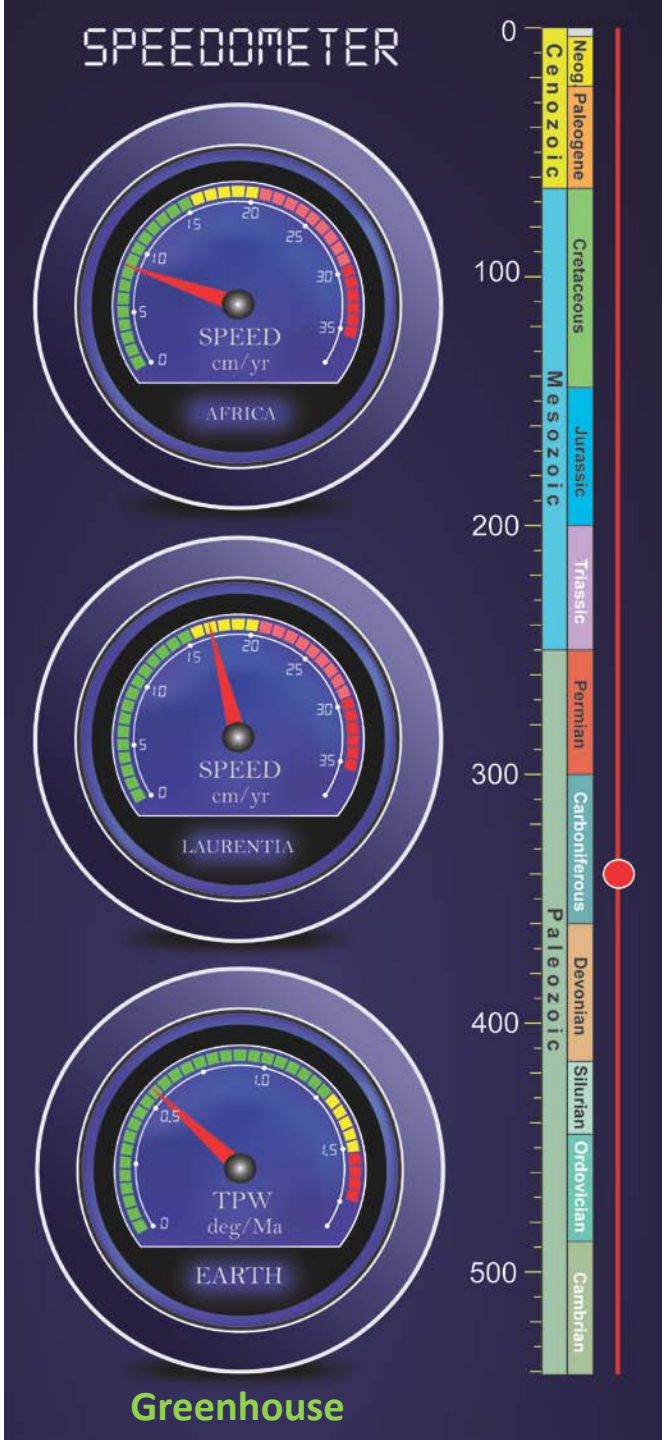




Greenhouse

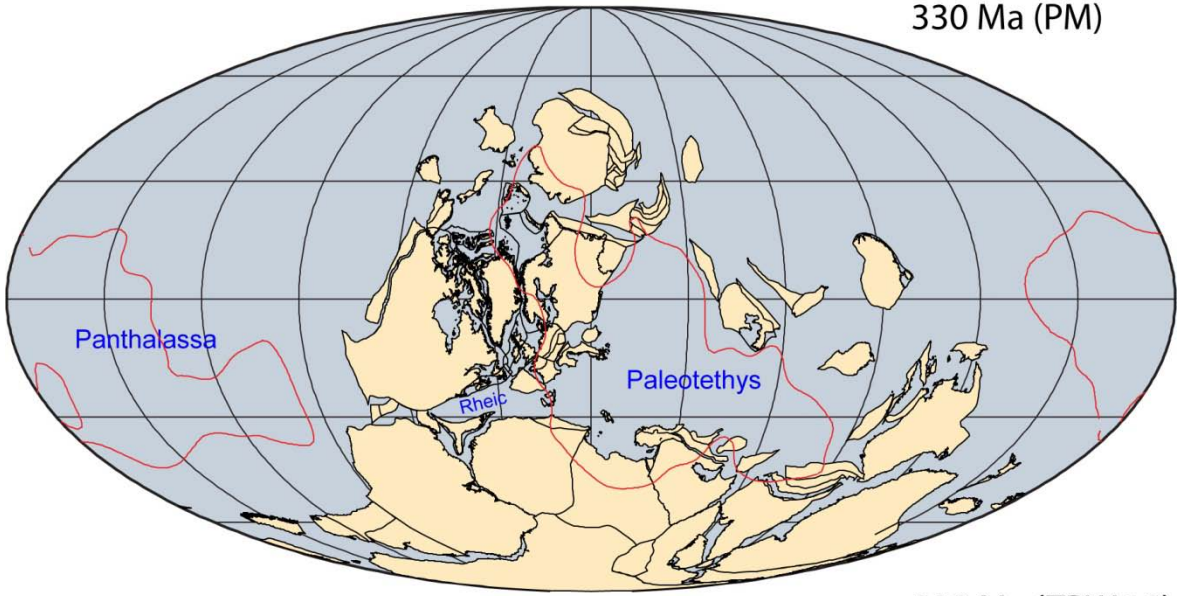

340 Ma (PM)
Panthalassa
Paleotethys
Rheic


340 Ma (TPW:16)
90°W
90°E

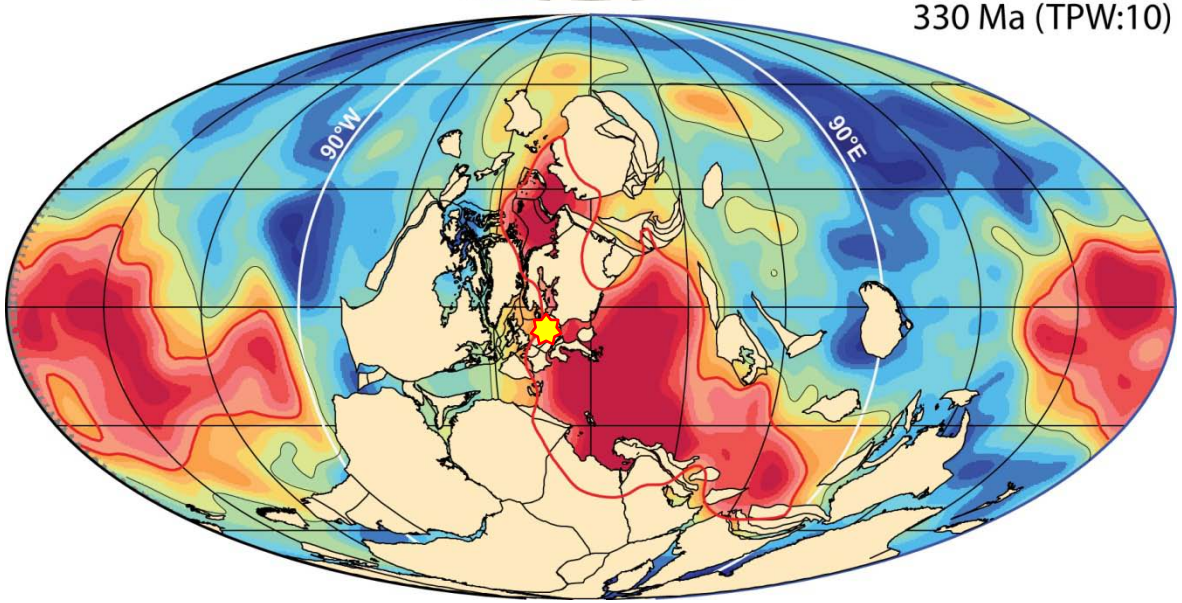

SPEEDOMETER
SPEED
cm/yr
AFRICA
SPEED
cm/yr
LAURENTIA
TPW
deg/Ma
EARTH
0
100
200
300
400
500
Cenozoic
Neog
Paleogene
Mesozoic
Cretaceous
Jurassic
Triassic
Paleozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Greenhouse

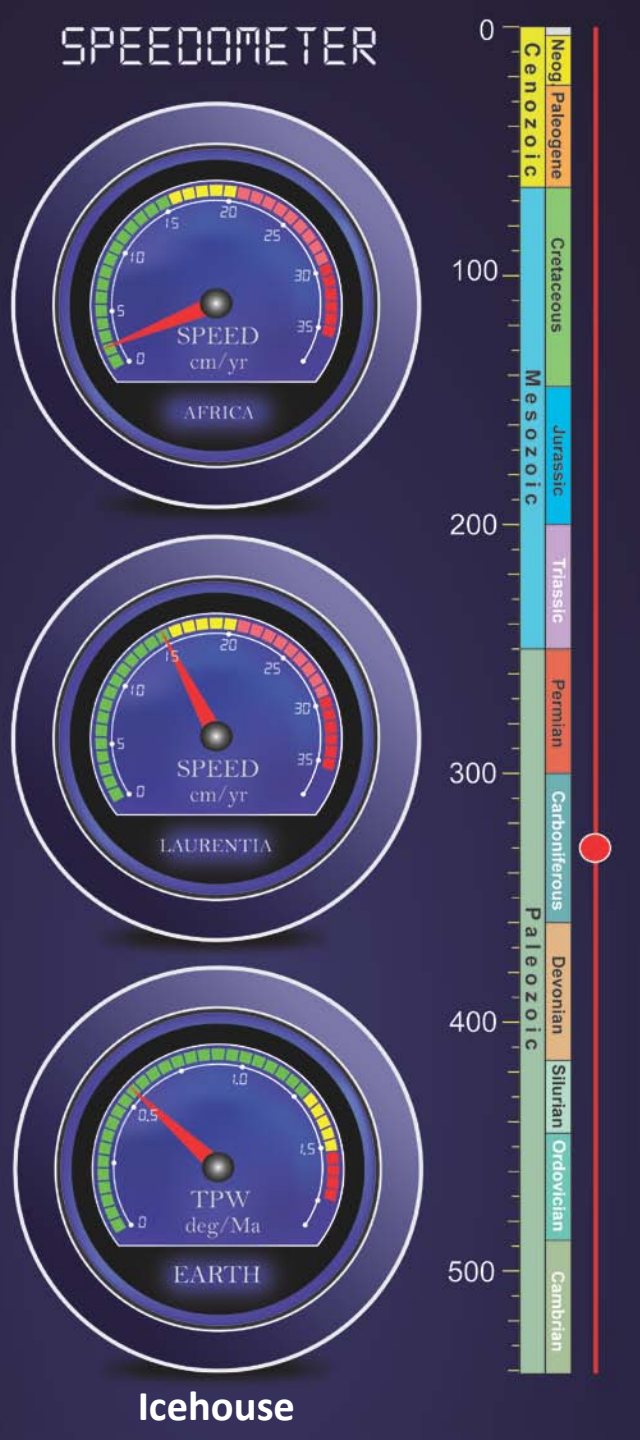
Start of Icehouse Conditions (Pangea nearly formed)

330 Ma (PM)



330 Ma (TPW:10)

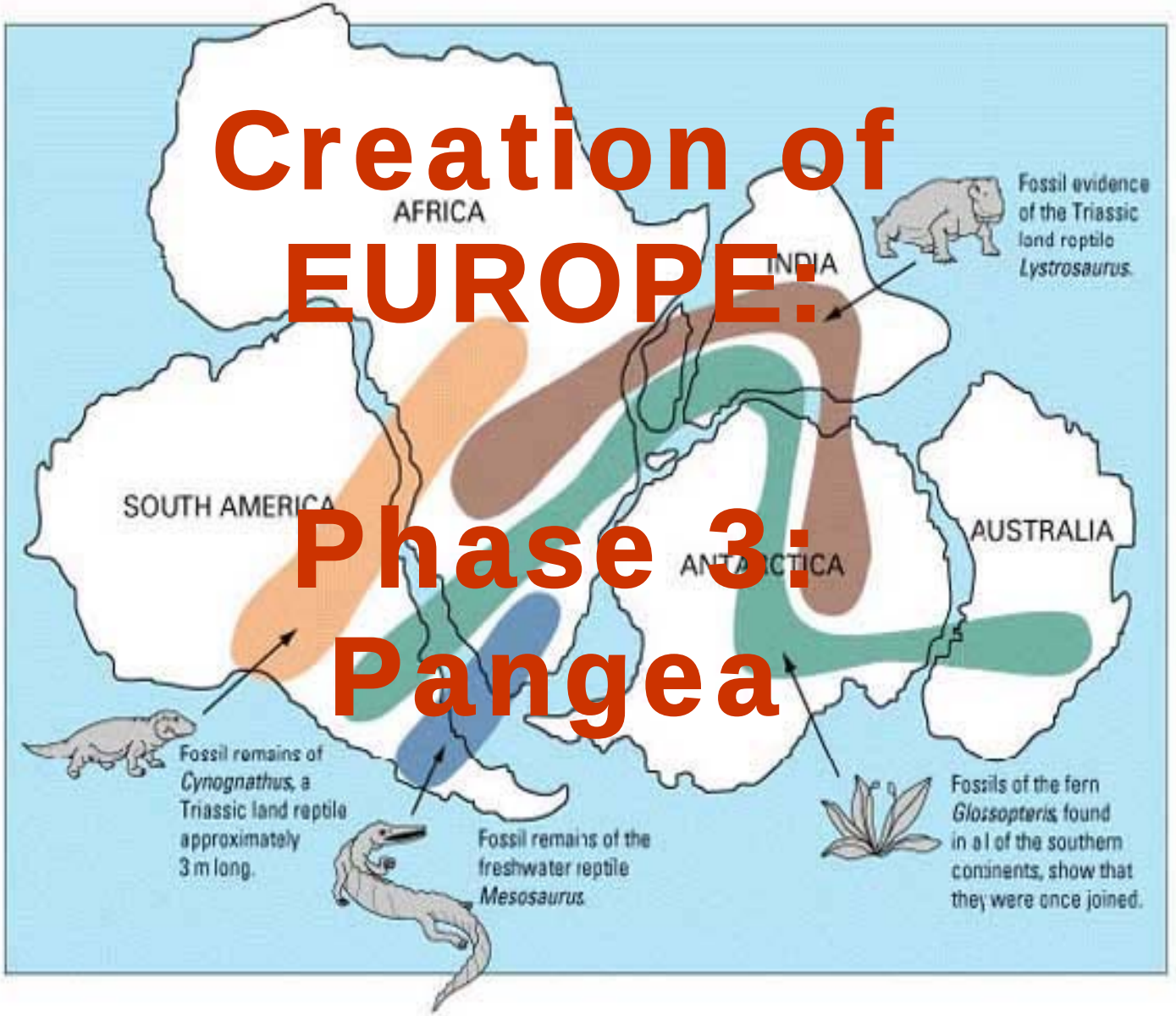




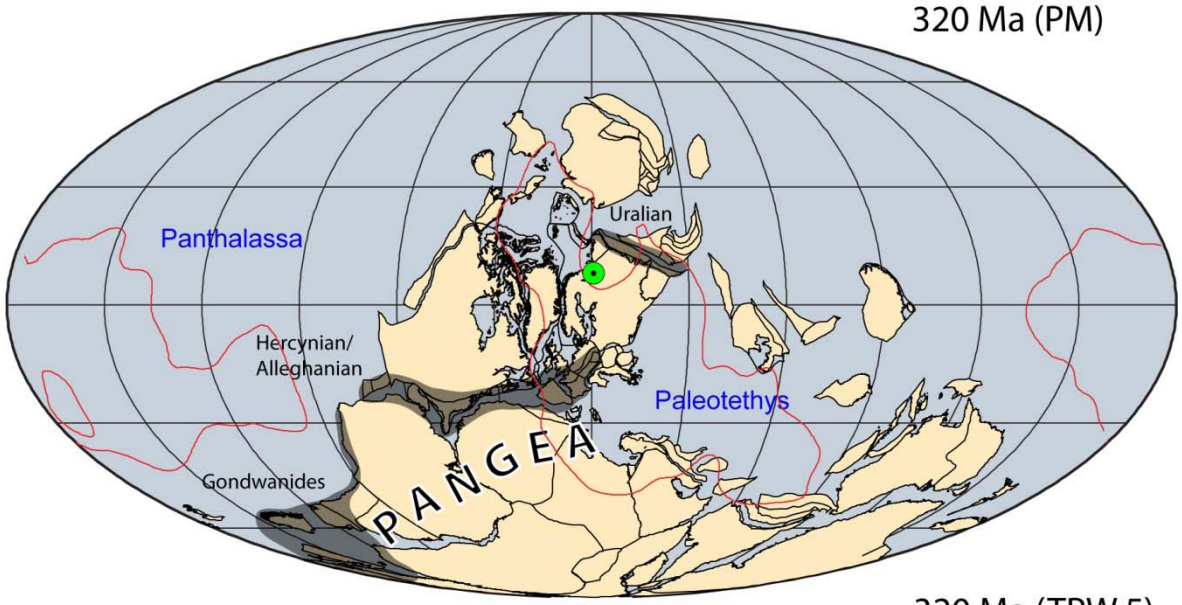
Icehouse

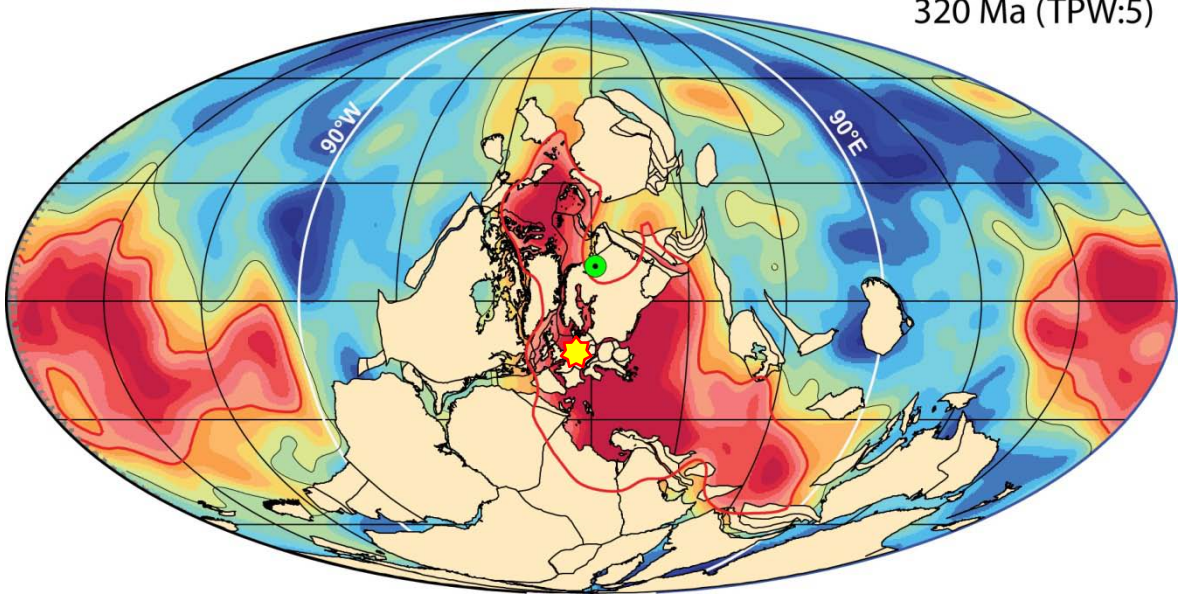
Creation of EUROPE:

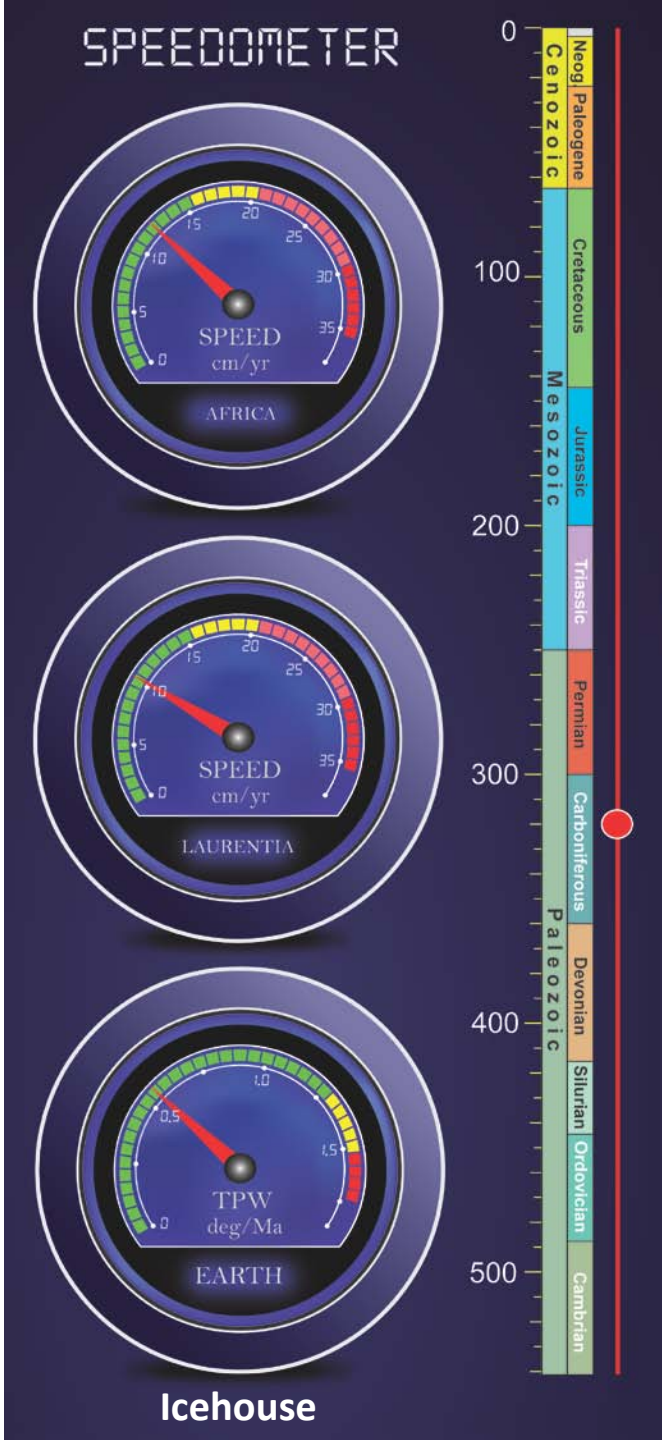
Phase 3: Pangea



Pangea Assembly

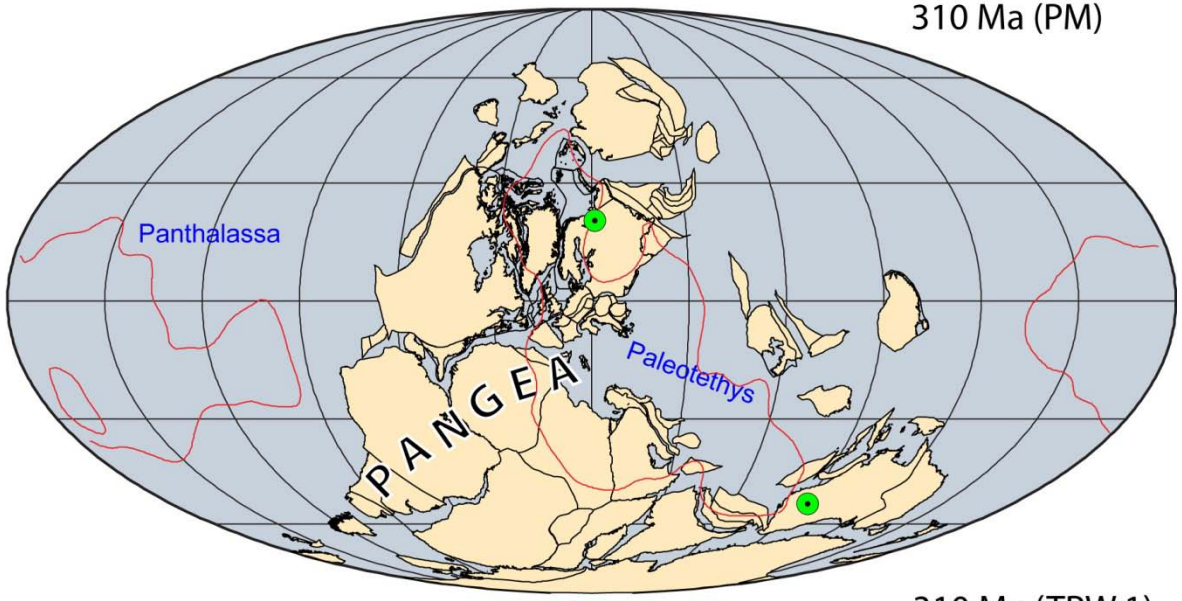


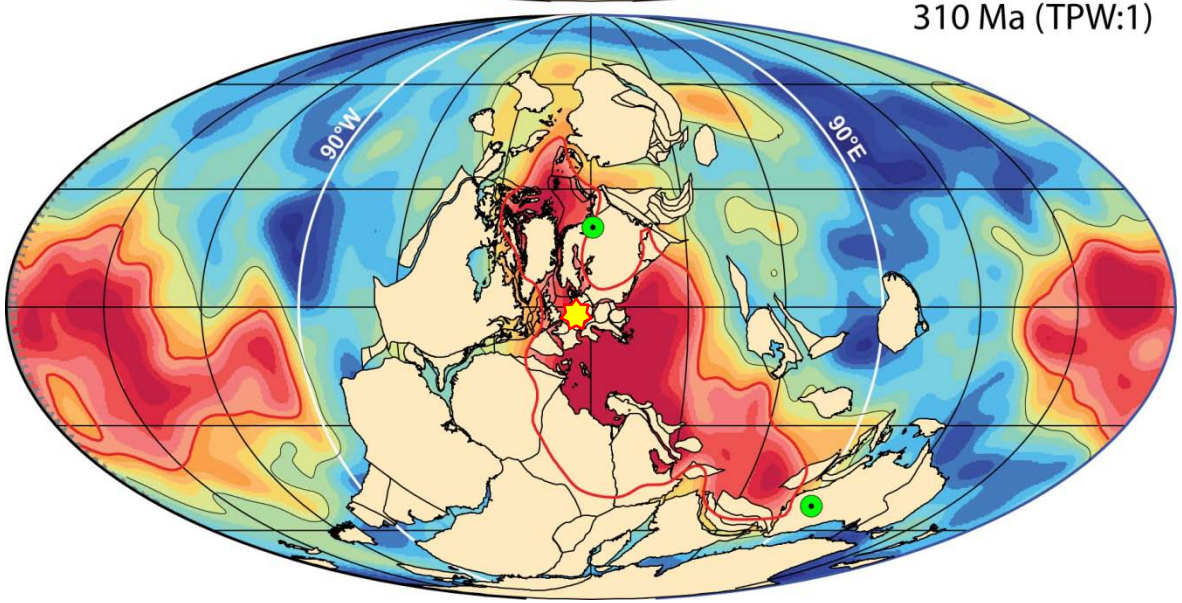


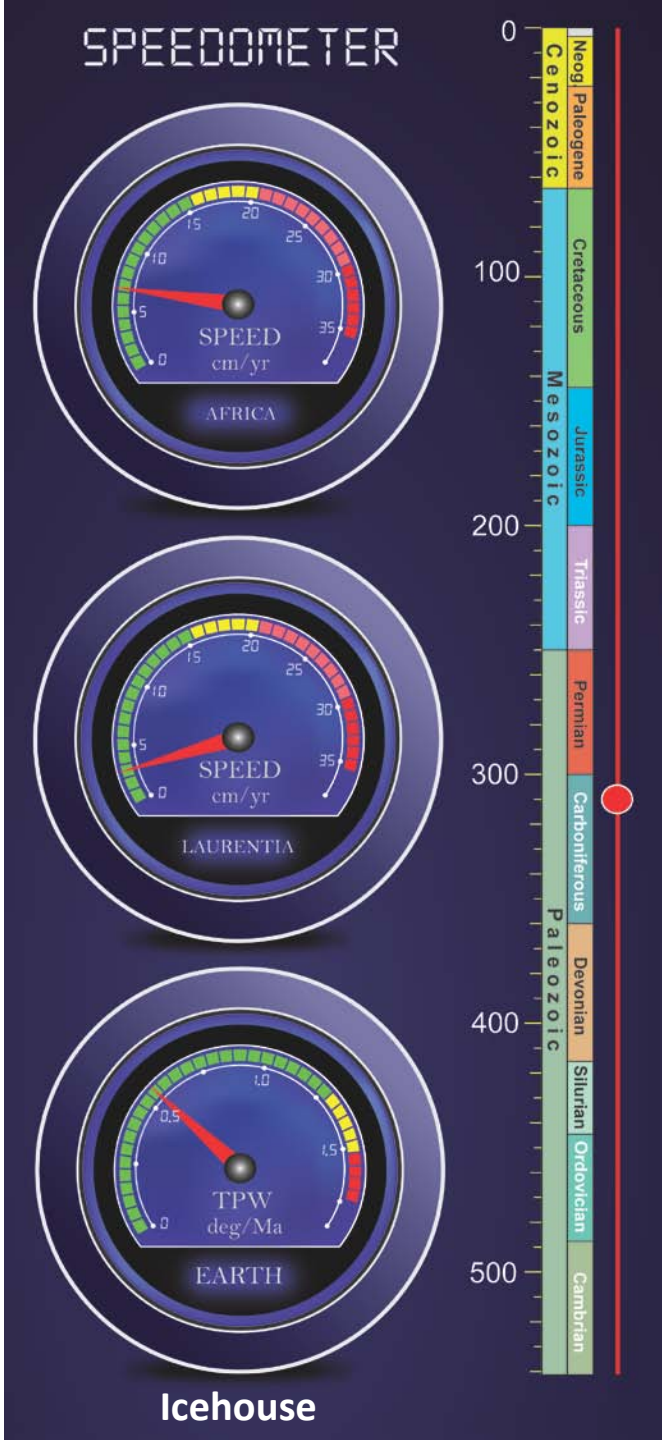


Icehouse

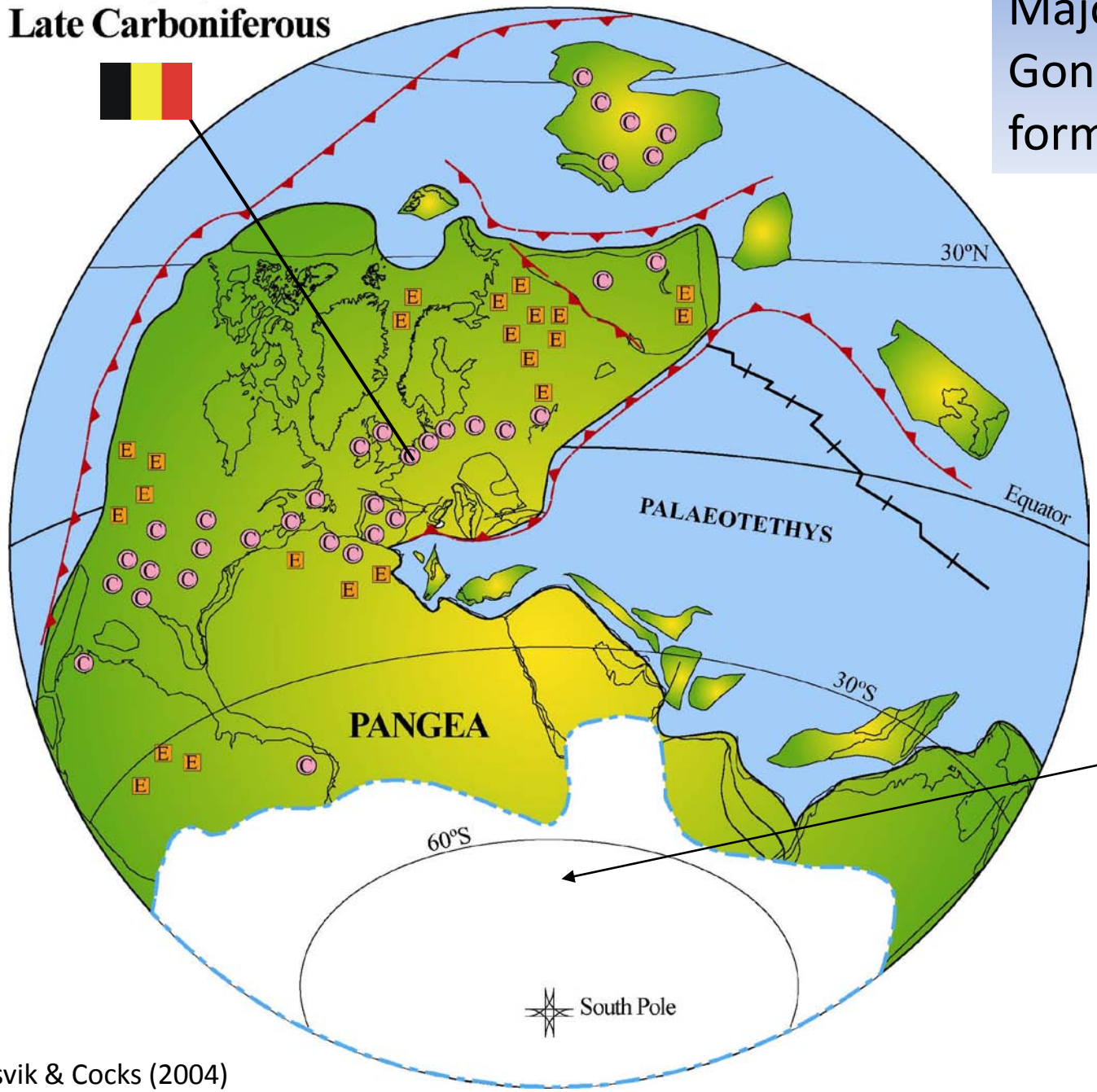
Icehouse Conditions





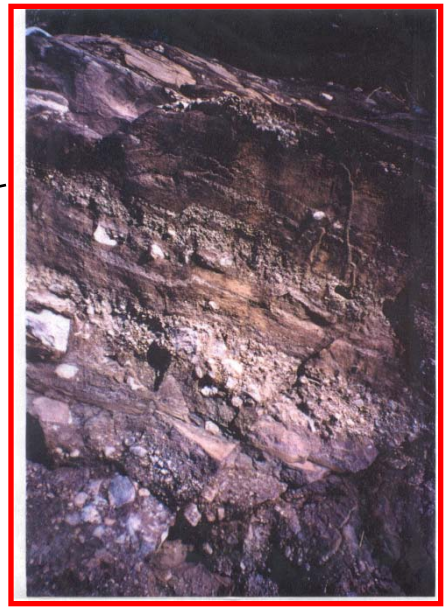


Icehouse



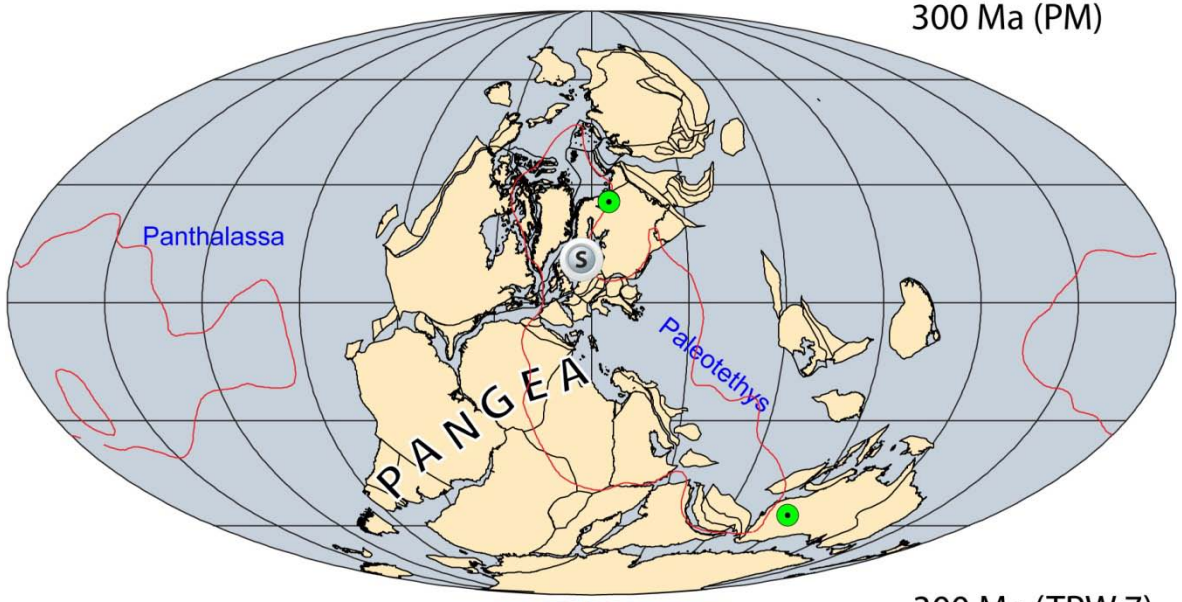
Major glaciation in Gondwana – Pangea formed at 320 Ma

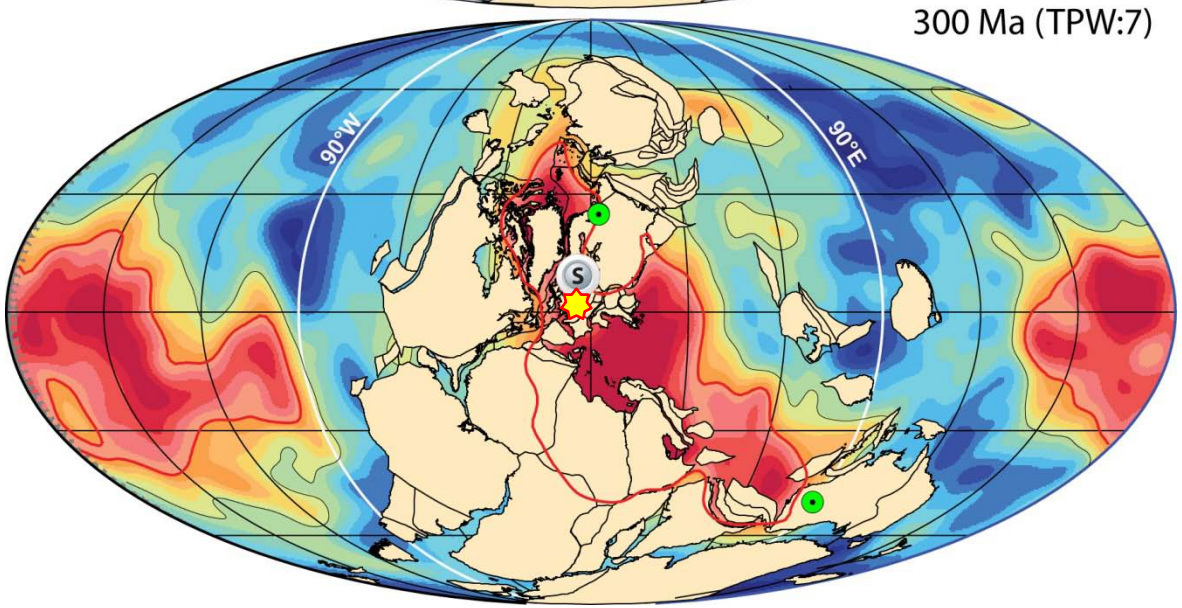
Madagascar

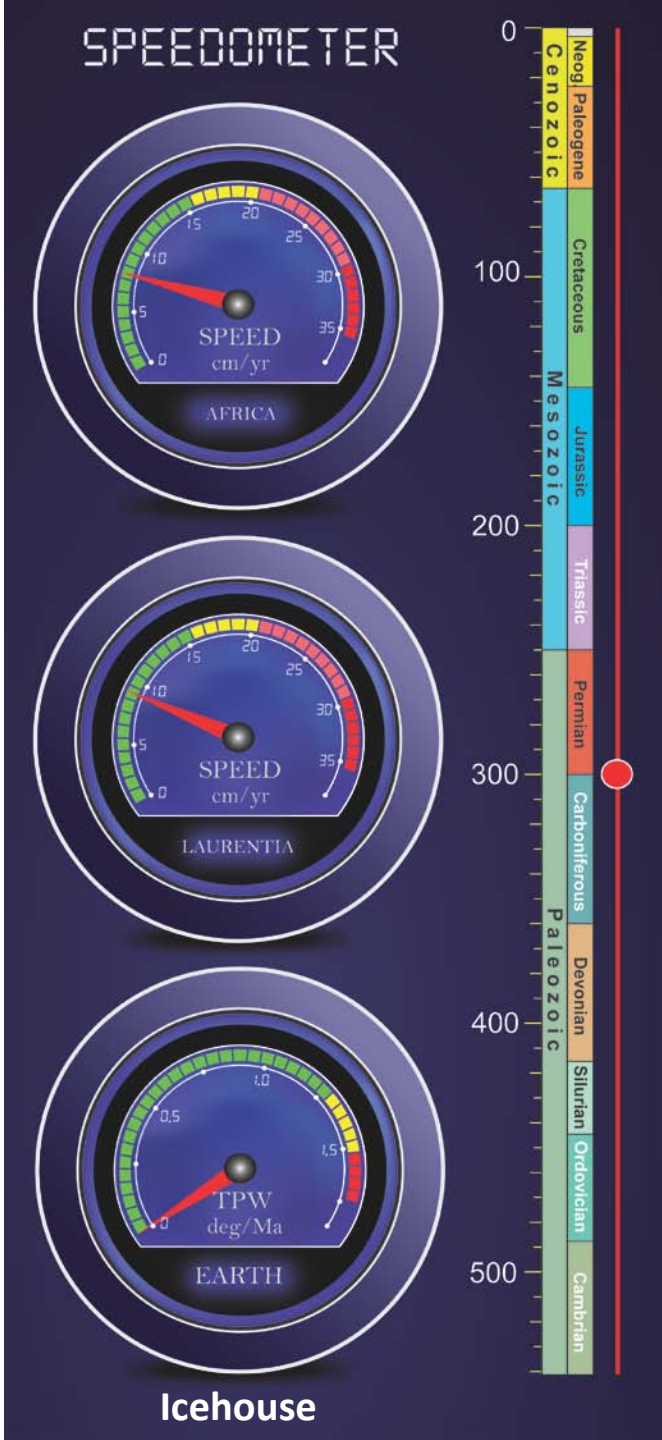


Torsvik & Cocks (2004)

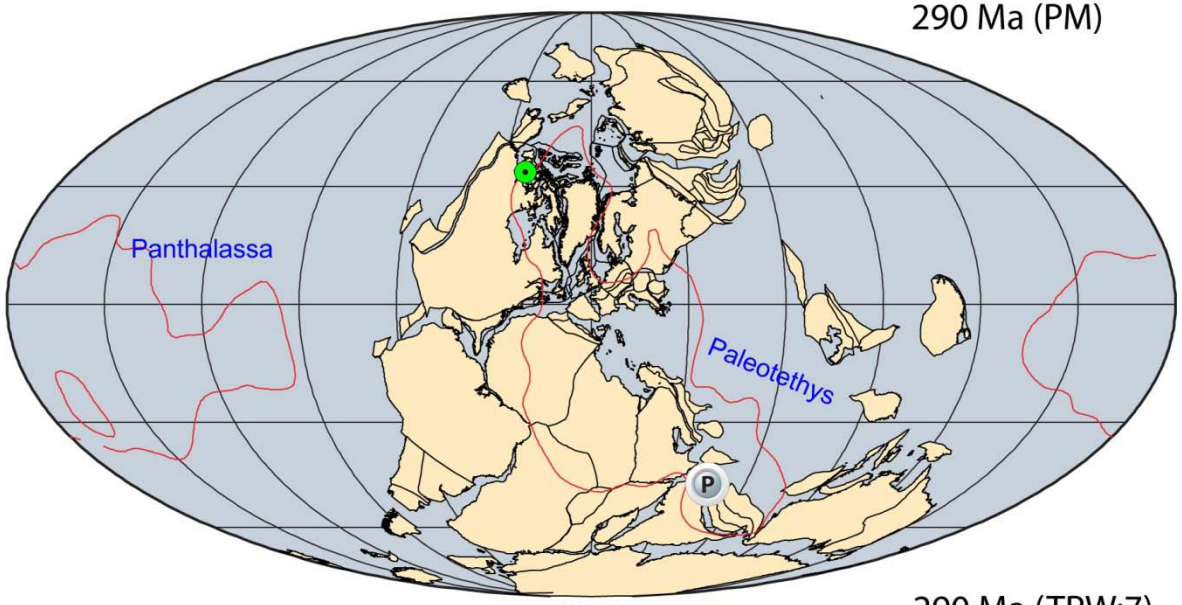
LIP: Skagerrak Centred LIP (SCLIP)

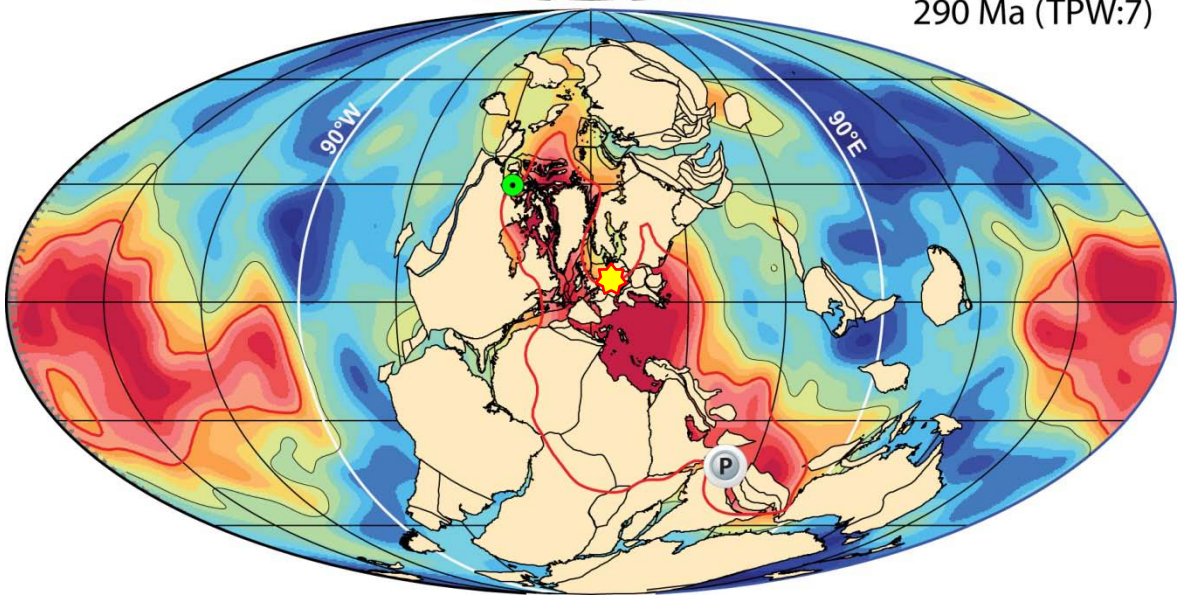


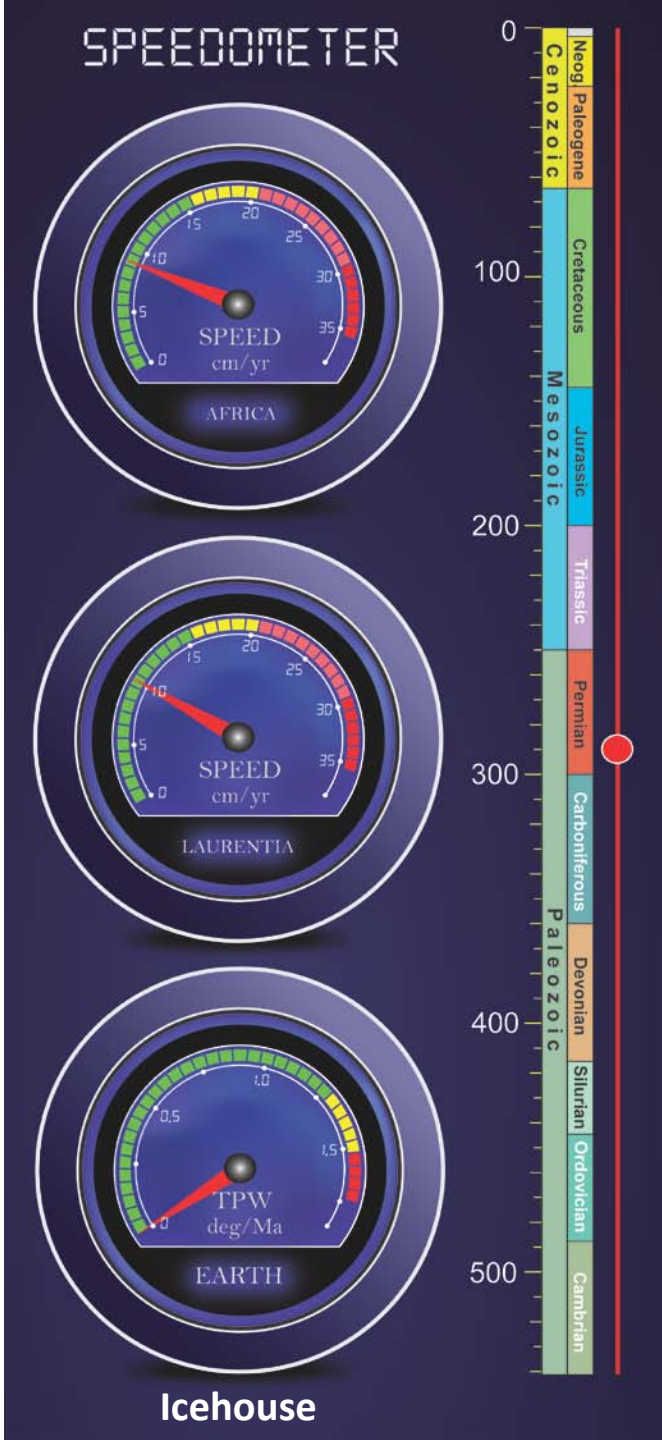




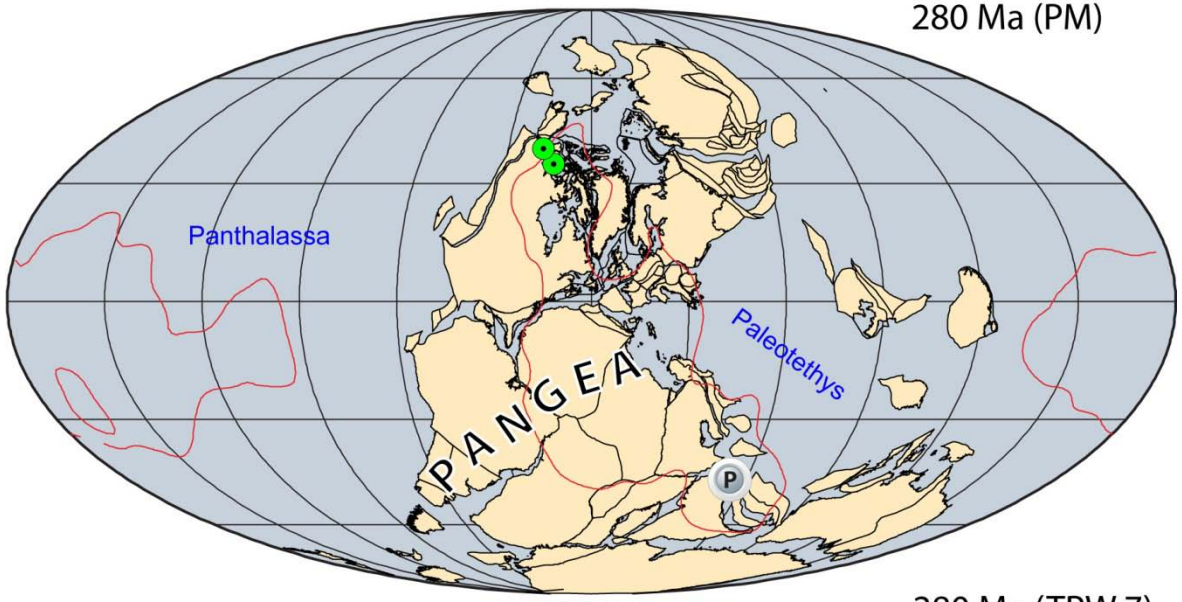
LIP: Panjal Traps (India/Himalaya)

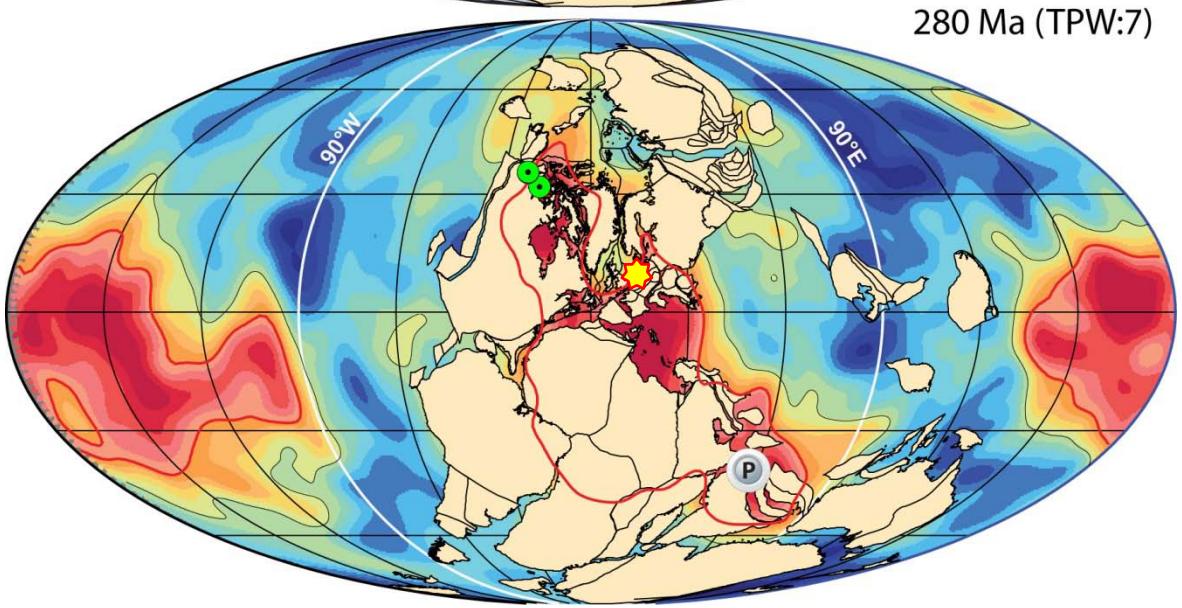


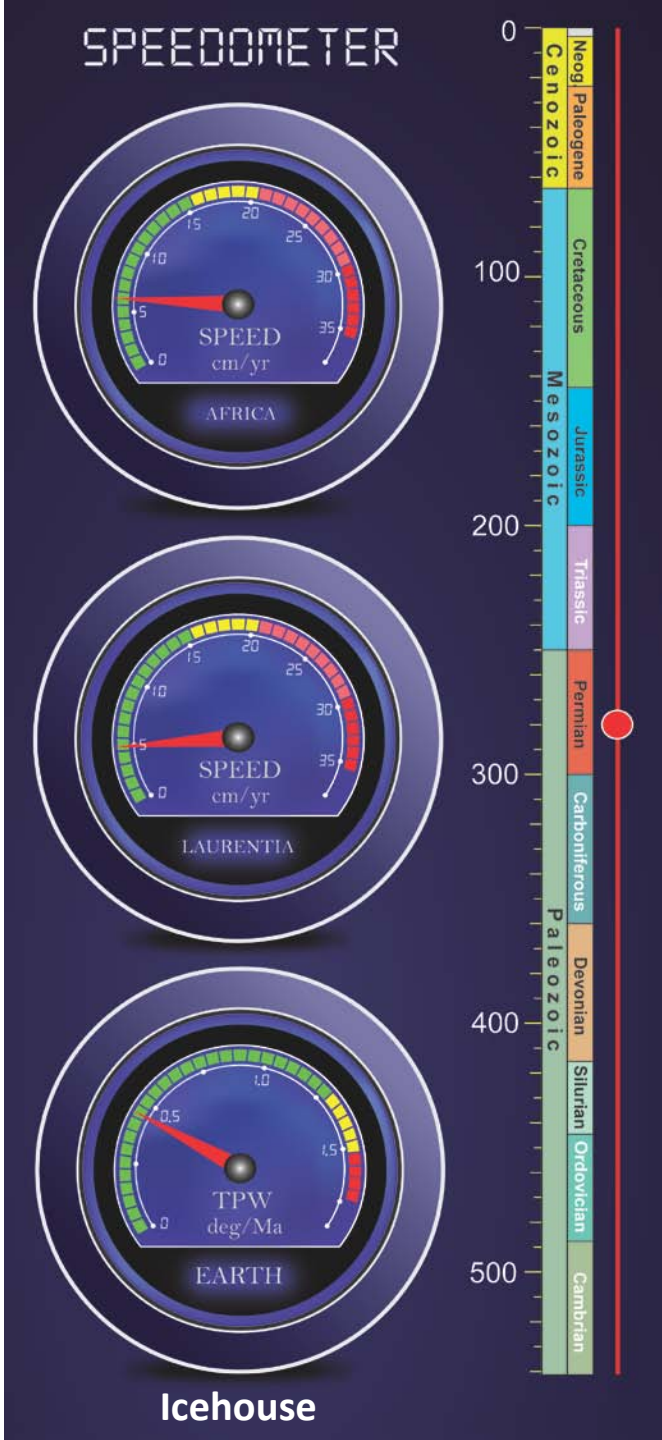




LIP: Panjal Traps (India/Himalaya)

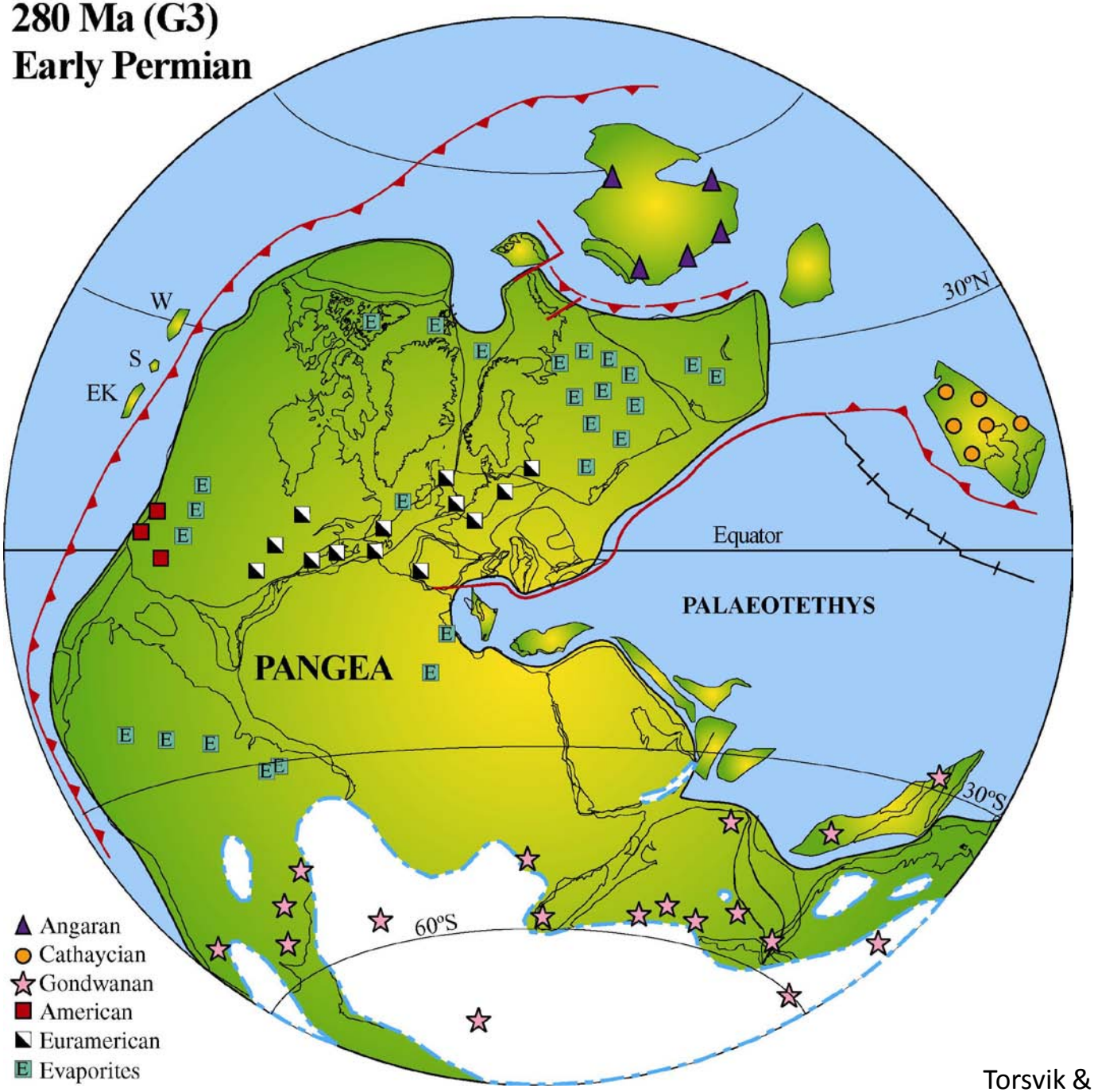






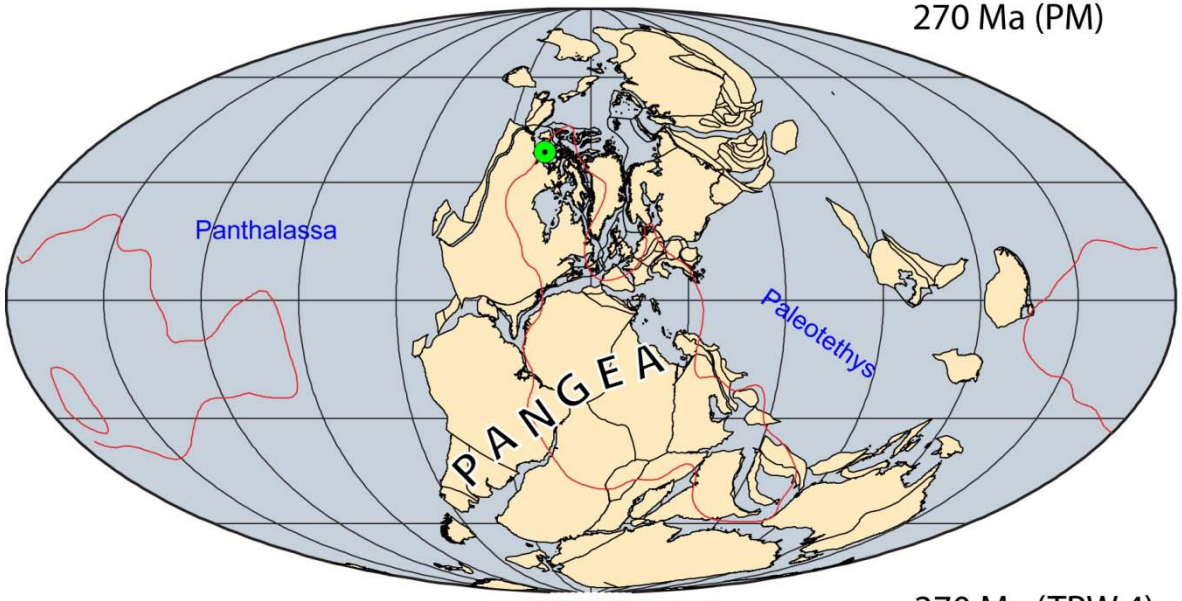
Icehouse

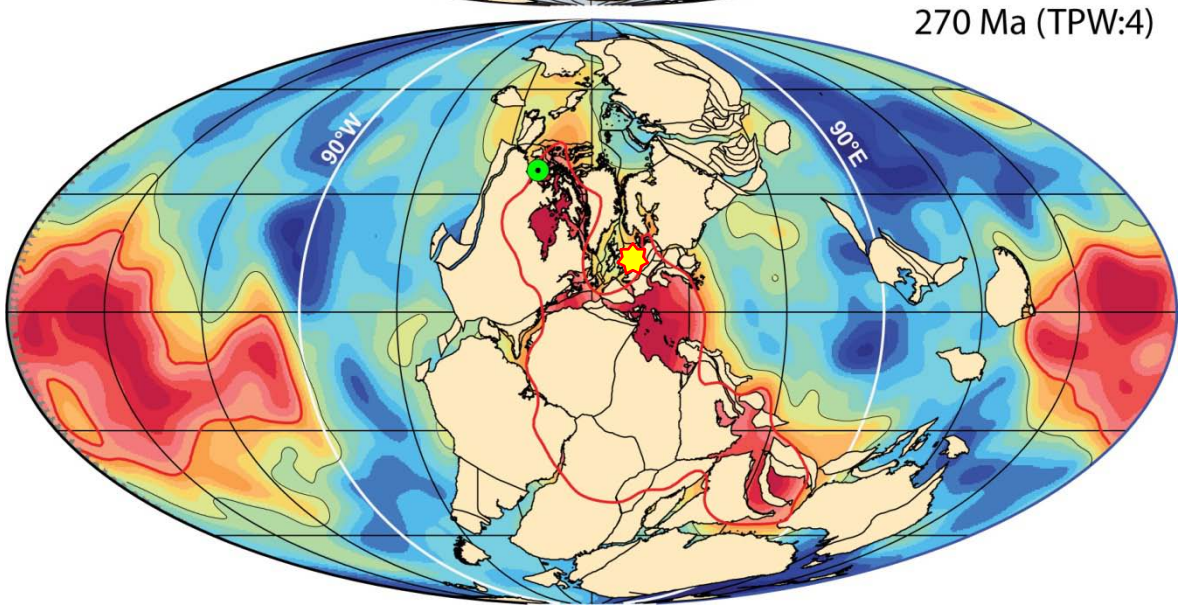
280 Ma (G3)
Early Permian

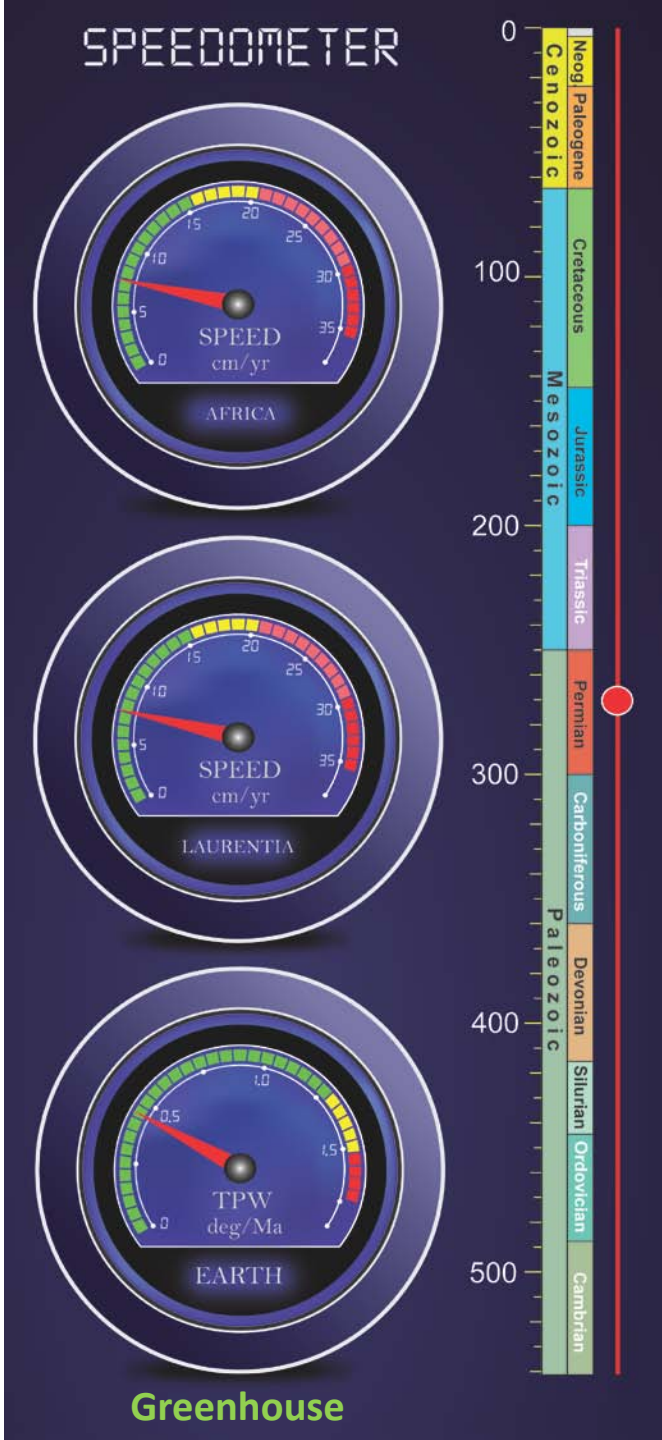


Torsvik & Cocks (2004)

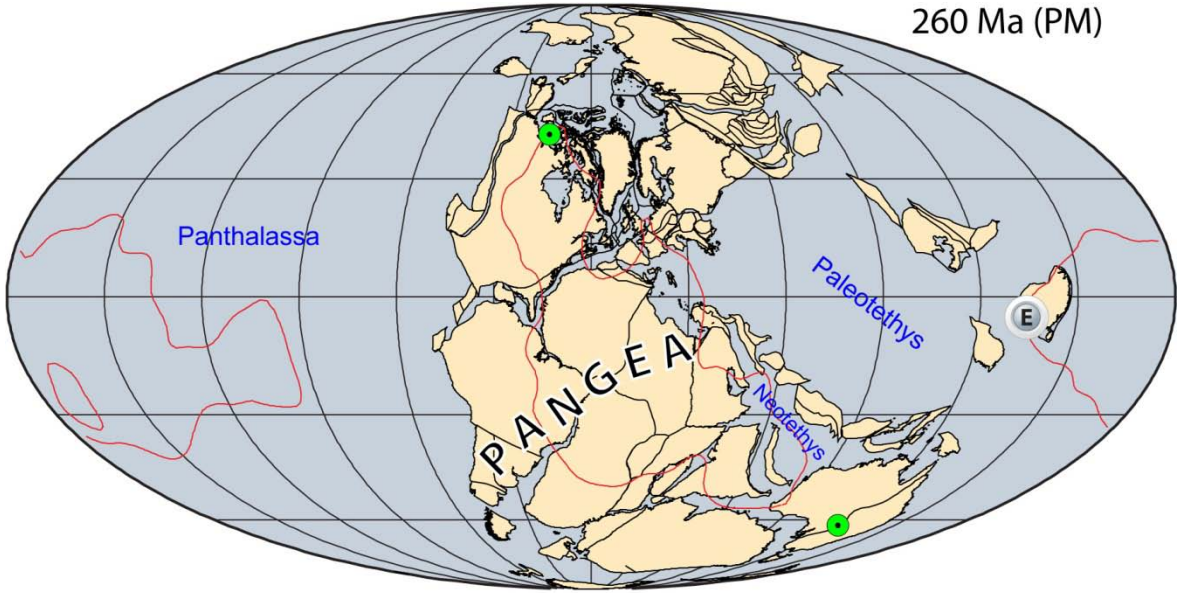
Start of Greenhouse Condition

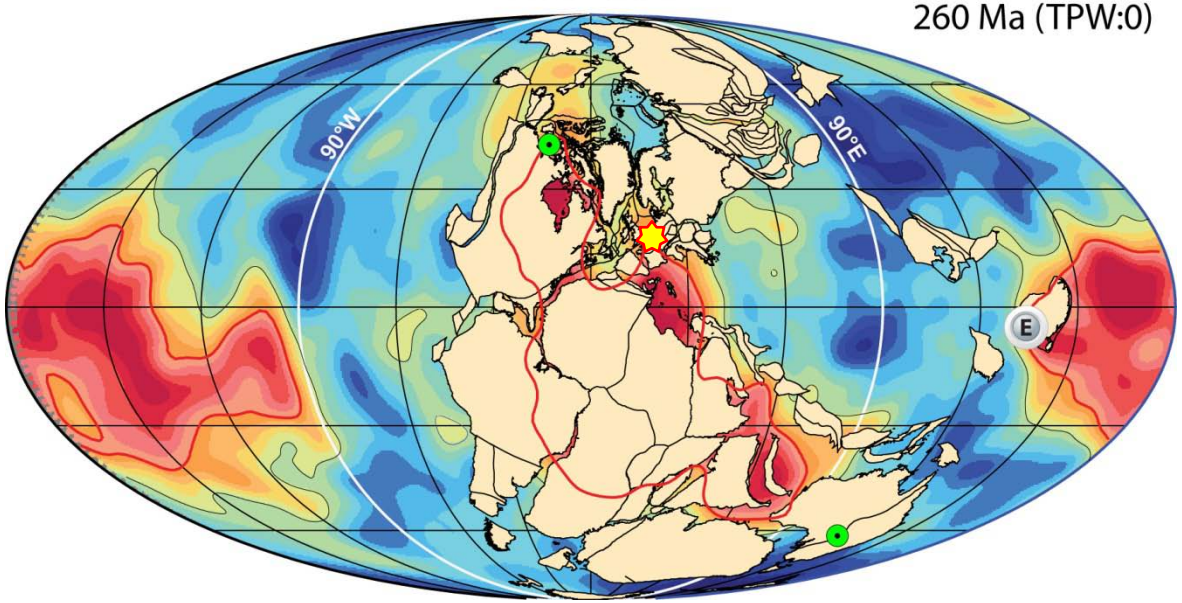


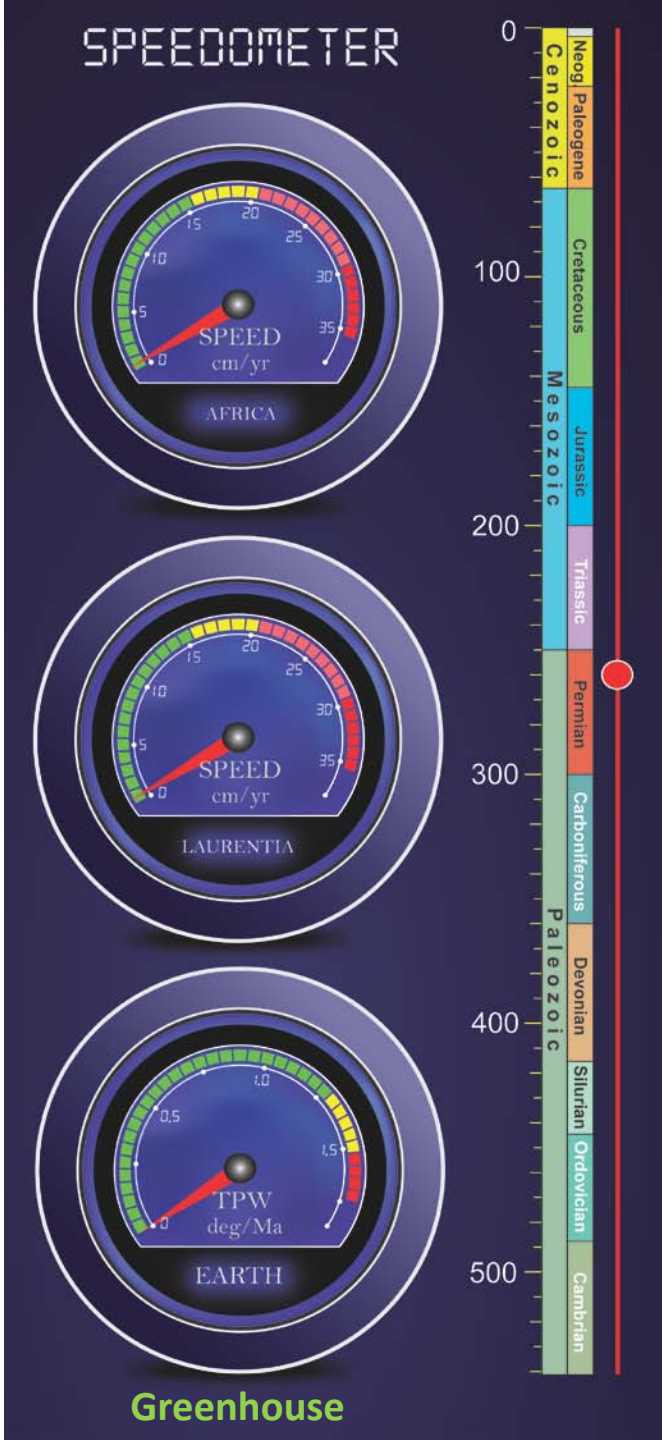




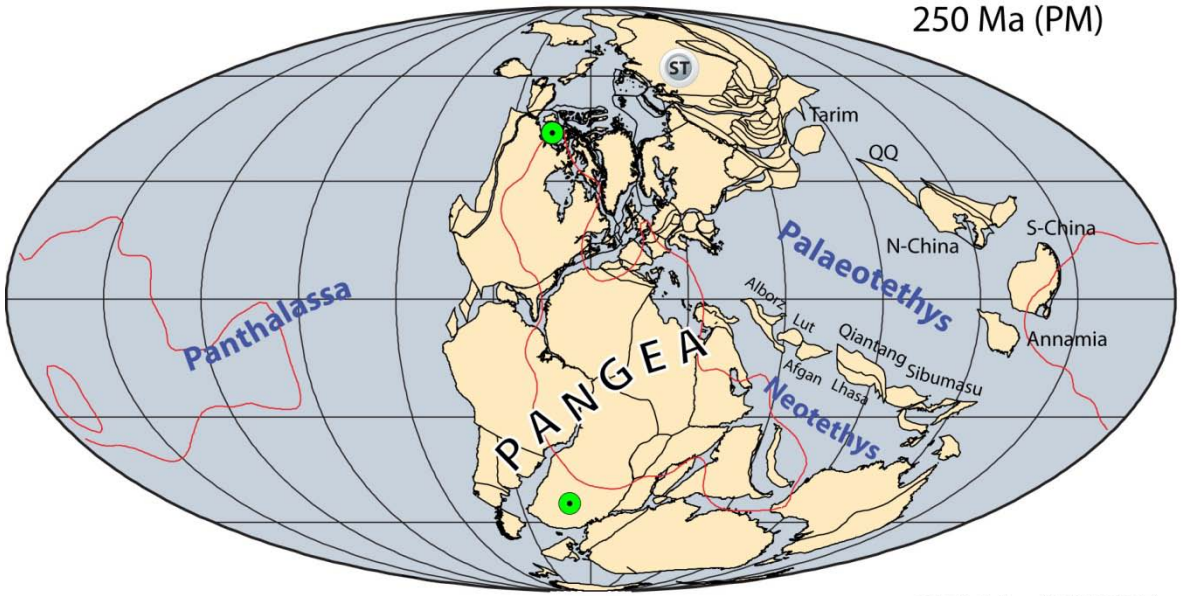
LIPS: Emeishan (Opening Neotethys)

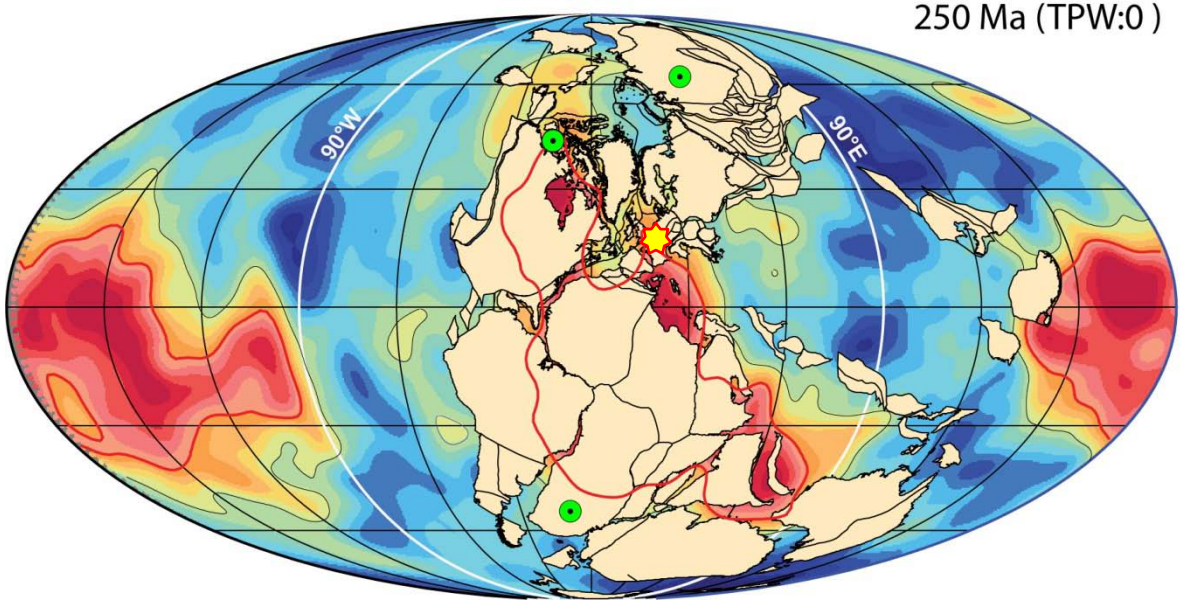






LIPS: Siberian Traps





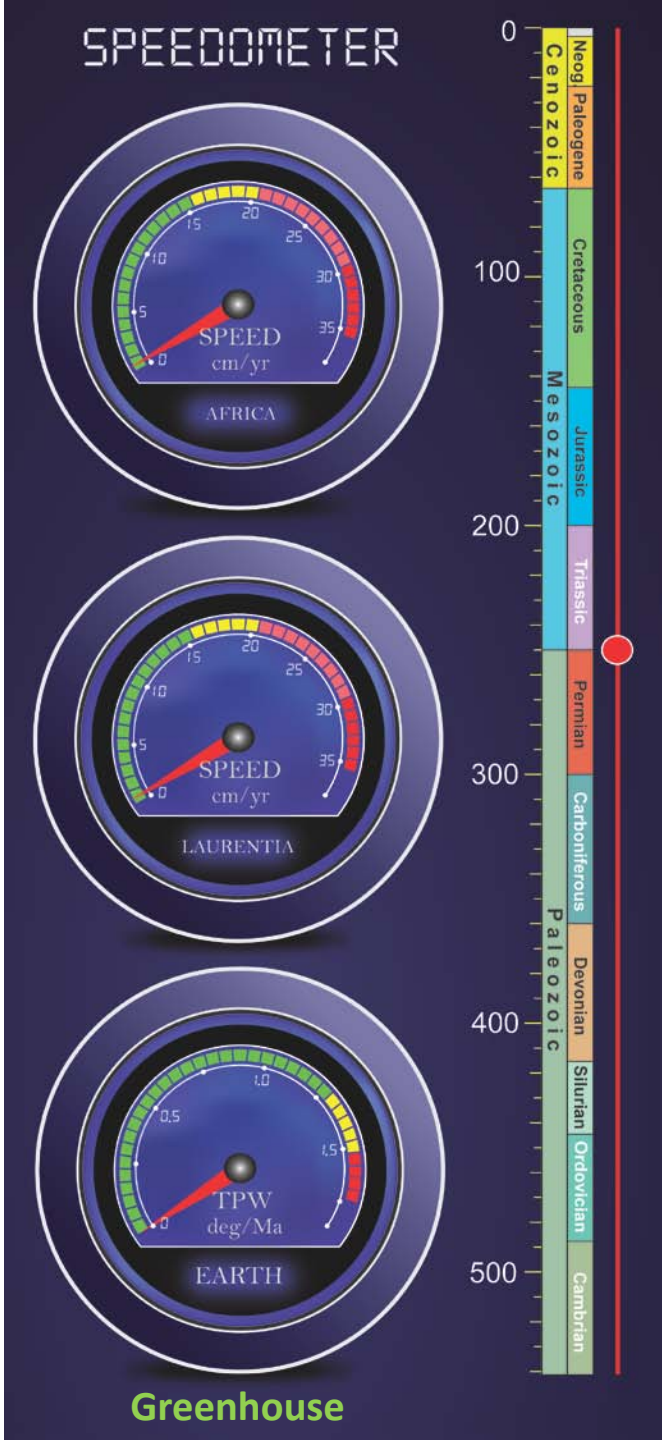
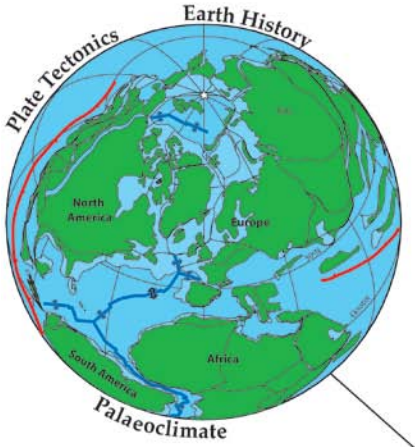
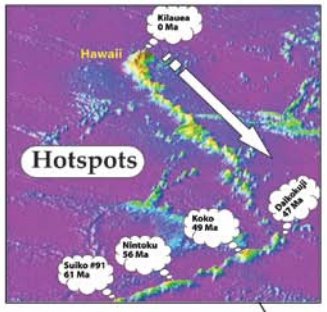
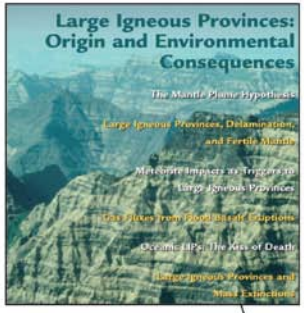


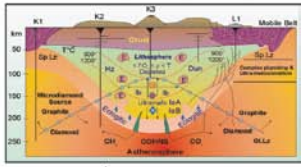
PLATE TECTONICS, LLSVPs and PLUMES

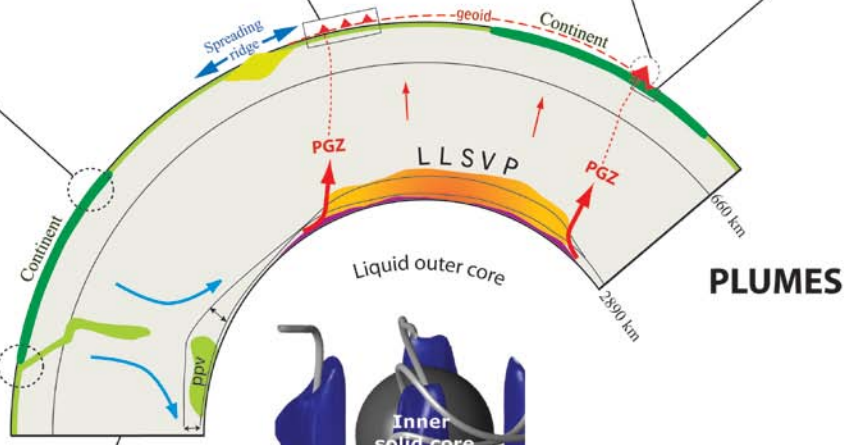






Kimberlites & Diamonds





Subduction

Seismic Tomography

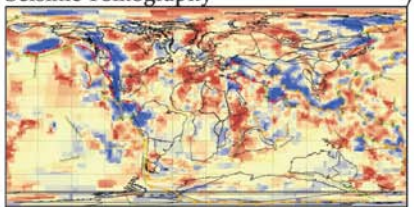


Plate Tectonics and Plumes are linked

- *Slabs restore mass to the deep Earth and could provide the **triggering mechanism for plumes** that rise from the margins of the stable LLSVPs (TOP-DOWN)*
- *The arrival of a LIP plume head can contribute to continental break-up and thus **punctuates plate tectonics** by creating and modifying **plate** boundaries (BOTTOM UP).*

THANKS!