Building a dynamic model for the Earth's mantle for the last 500 million years

Shijie Zhong

Department of Physics

University of Colorado at Boulder

U.S.A.

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Former students: Nan Zhang (now at Brown Univ.) and Wei Leng (now at Caltech)

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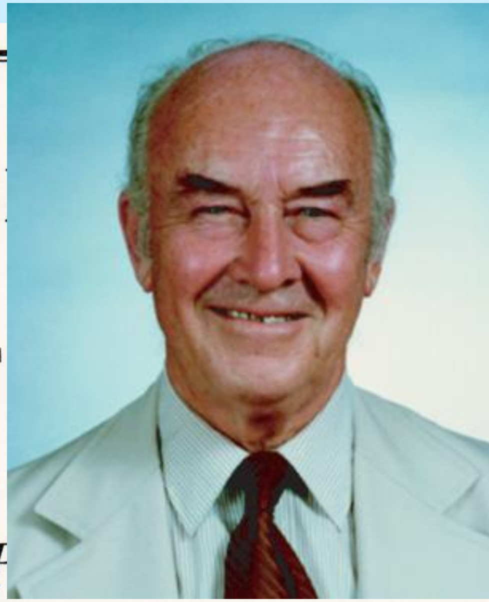
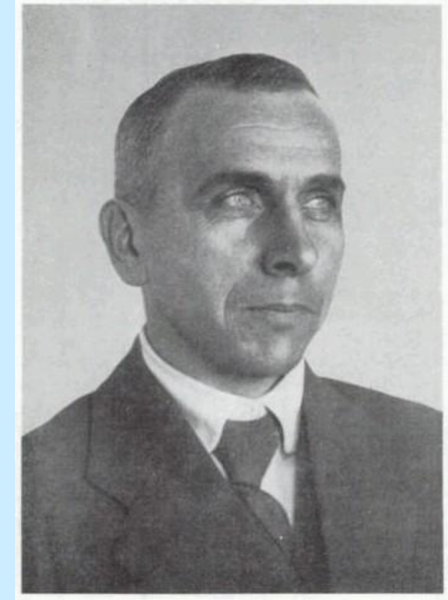


J. Tuzo Wilson

Wilson [1963] led to a paradigm shift in our understanding of the Earth system -- plate tectonics theory including Wilson cycle.

1941, 1947, 1959, and 1963

George Gamow



Alfred Wegener

Continental drift

Pangea

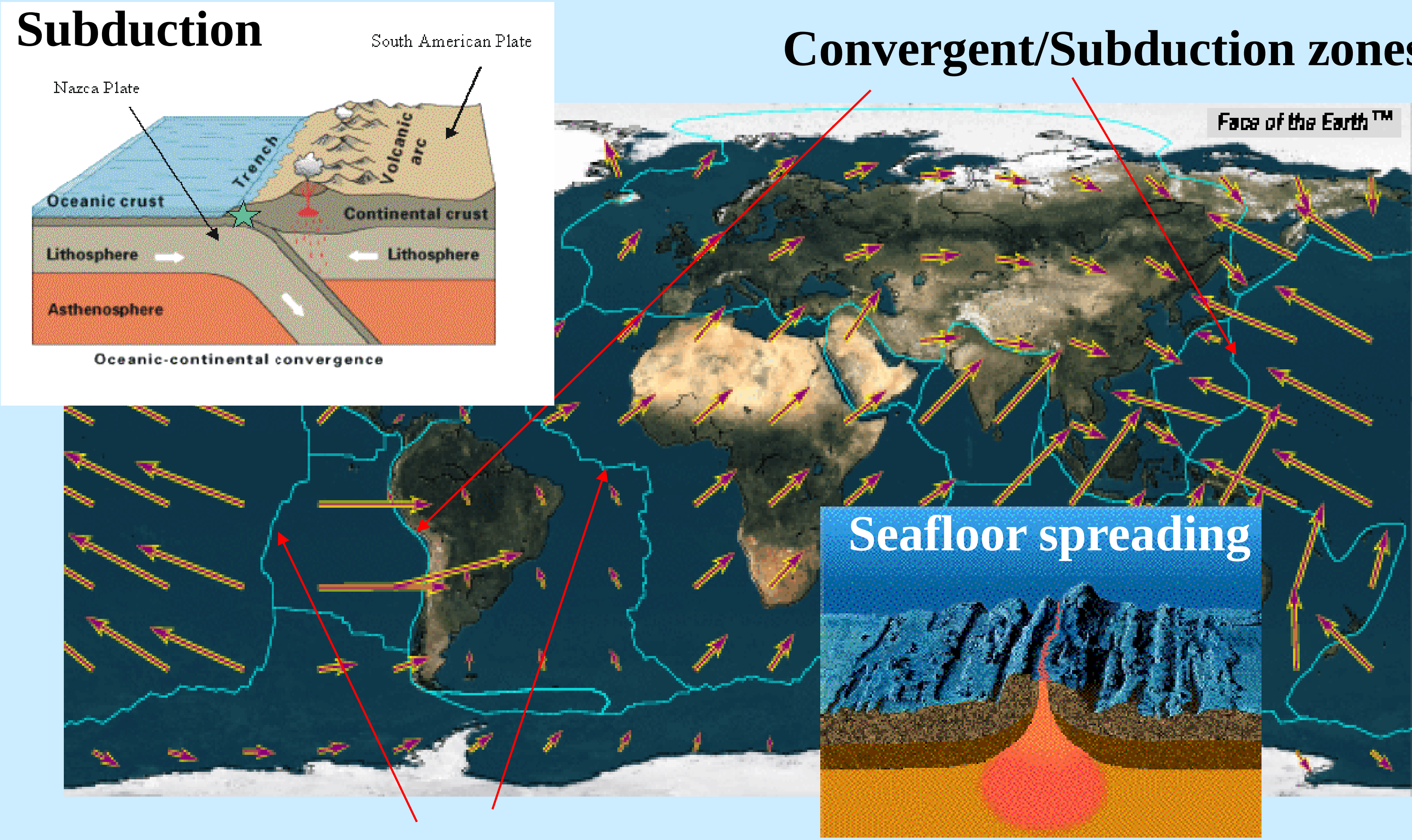
FIGURE 31

Relative position of the fragments of the original crust immediately after the separation of the Moon. (Not to be used as proof of the possibility of invasion of the United States.)

Outline

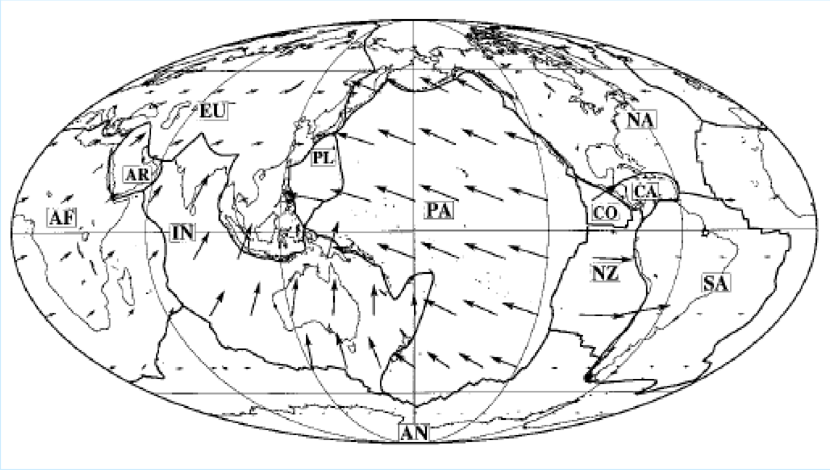
- ***Introduction – global-scale observations.***
- ***Generation of globally asymmetric flow structure (degree-1) – the cause for supercontinent formation?***
- ***1-2-1 model for mantle structure evolution.***
- ***A model for mantle structure and its implications.***
- ***Conclusions.***

The Present-day Earth's Surface Motion – Plate Tectonics (1960's)

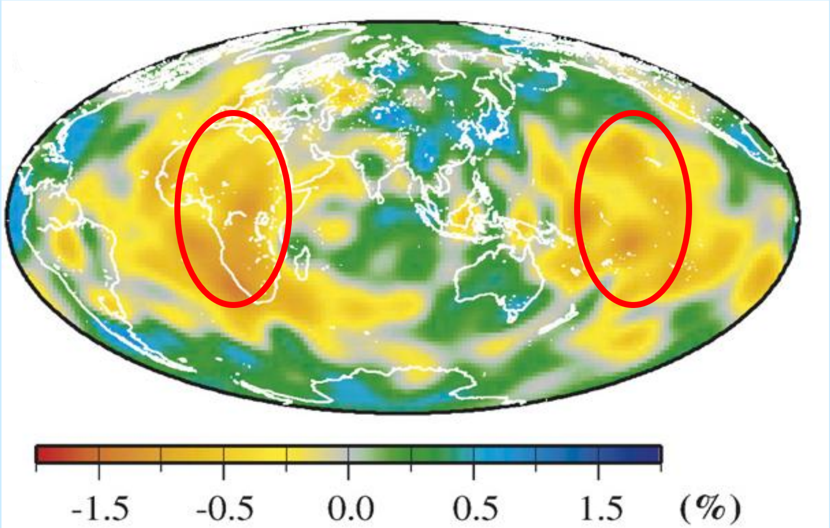


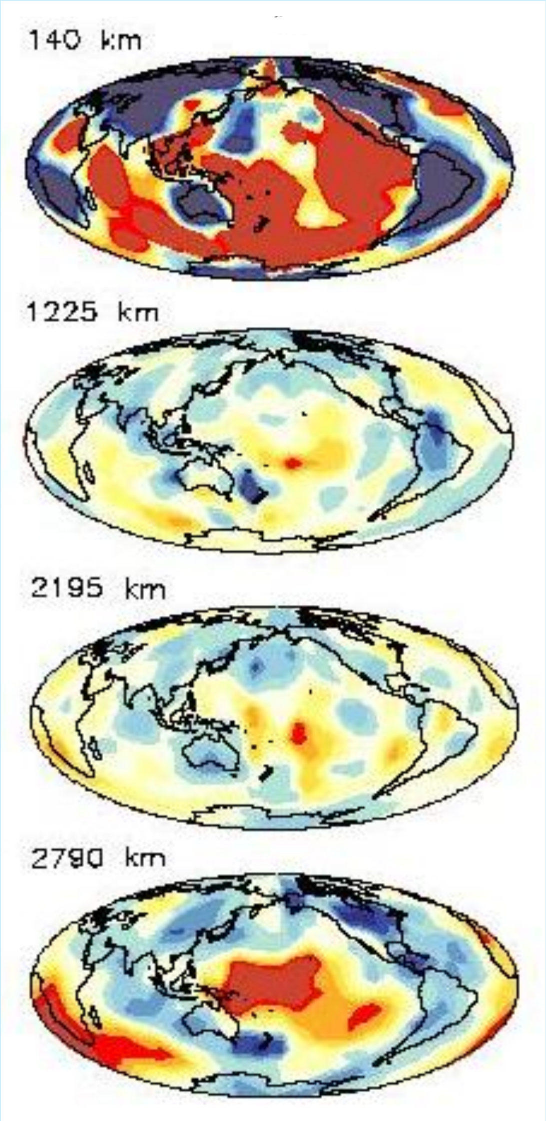
Divergent boundary/Spreading centers

The dynamic Earth – plate tectonics and the mantle structure



Vs at 2300 km depth from S20RTS [Ritsema et al., 1999]

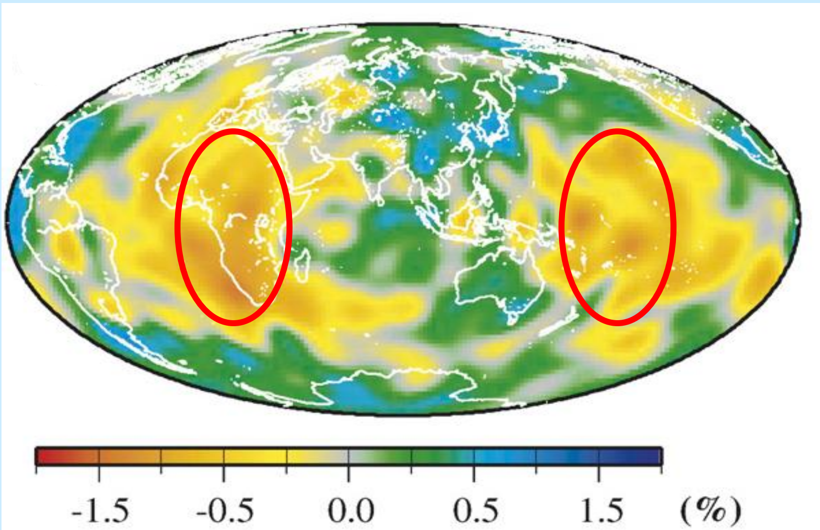




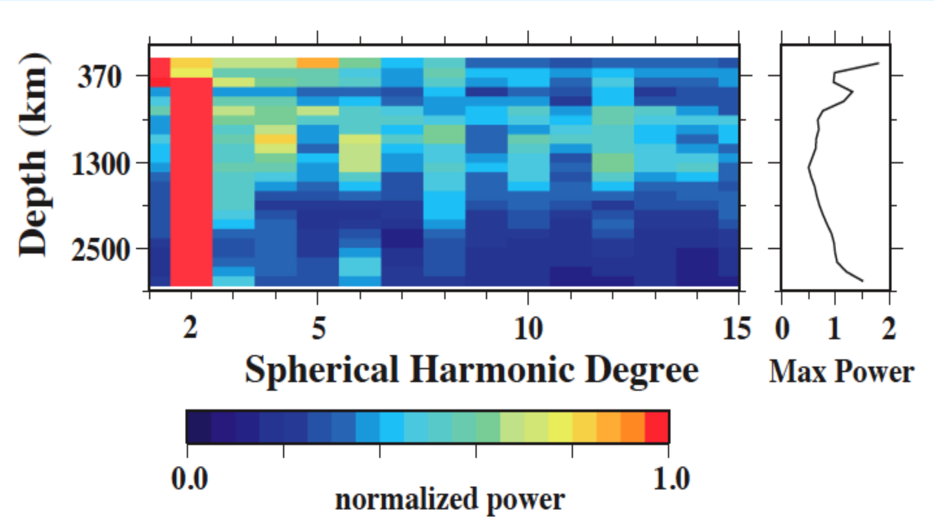
SB10L18 by Masters et al. [2000]

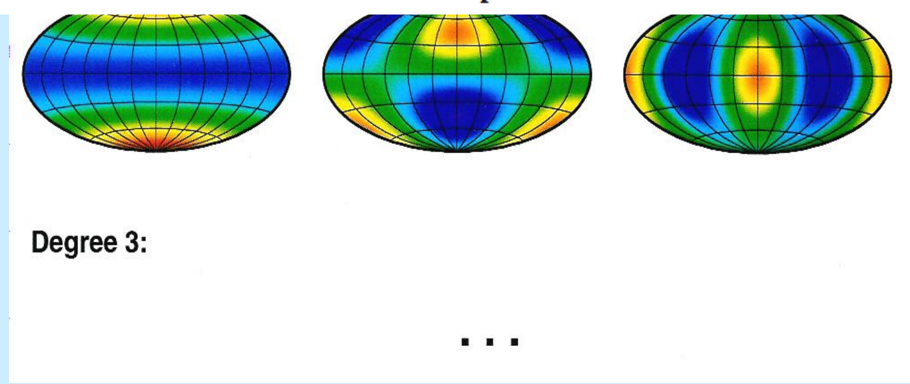
African and Pacific Superplumes
-- Spherical harmonic degree-2 Structure

Shear-wave anomalies at 2300 km depth from S20RTS [Ritsema et al., 1999]



Spherical harmonic functions $Y_{lm}(\theta,\phi)$





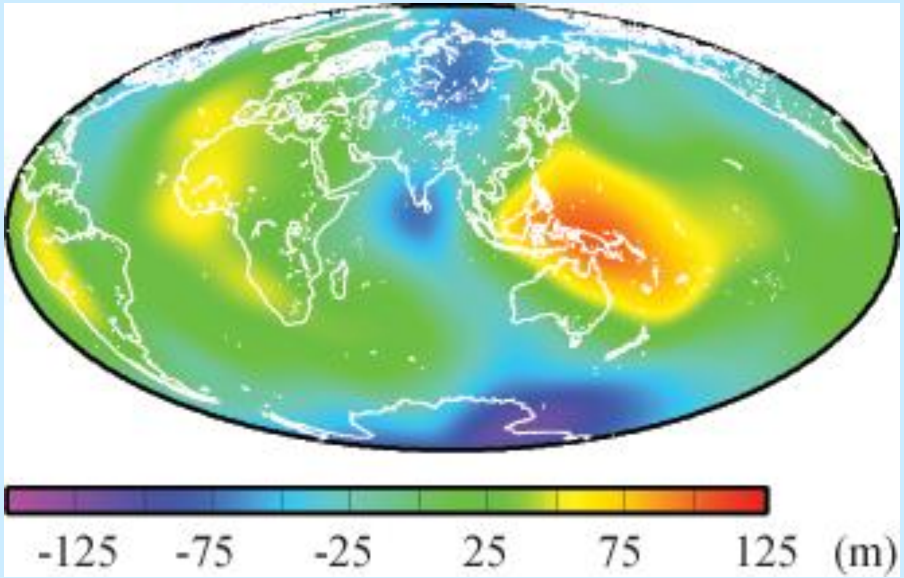
<u>Degree-2 structure:</u>
Dziewonski et al. [1984], van der Hilst et al. [1997], Masters et al. [1996, 2000], Romanowicz and Gung [2002], and Grand [2002].

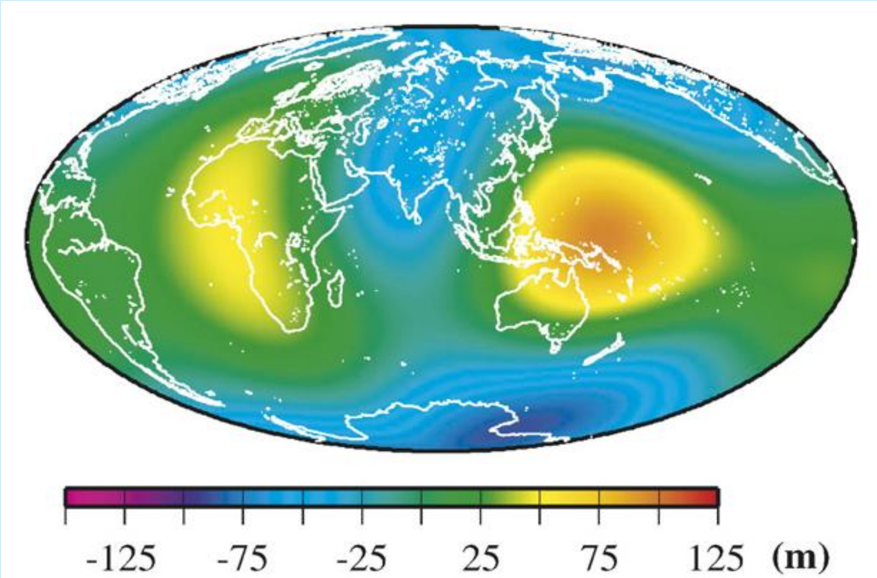
The Earth's gravity (geoid) anomalies

Geoid anomalies: a measure of gravitational potential anomalies at the Earth's surface.

$$N(\theta,\phi)=\frac{GM}{Rg}\{\sum_{l=2}^{L}\sum_{m=0}^{l}[C_{lm}\cos(m\phi)+S_{lm}\sin(m\phi)]P_{lm}(\cos\theta)\}$$

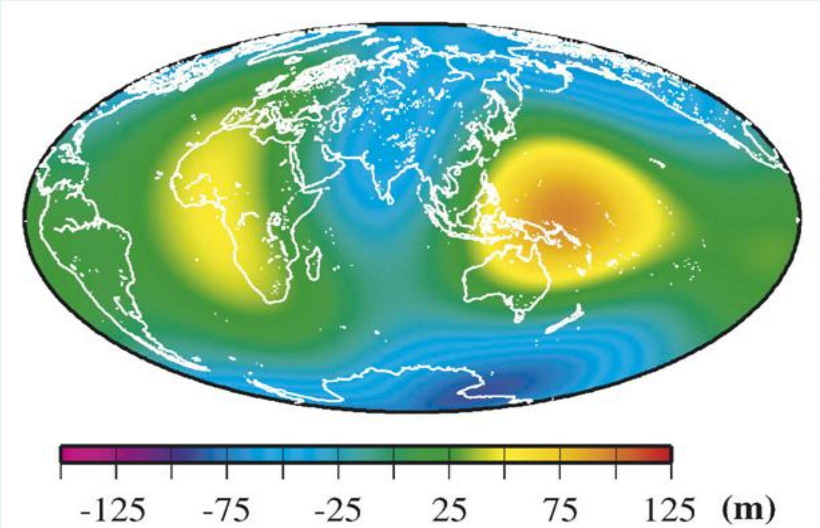
Long-wavelength geoid (degrees *l*=2 and 3)



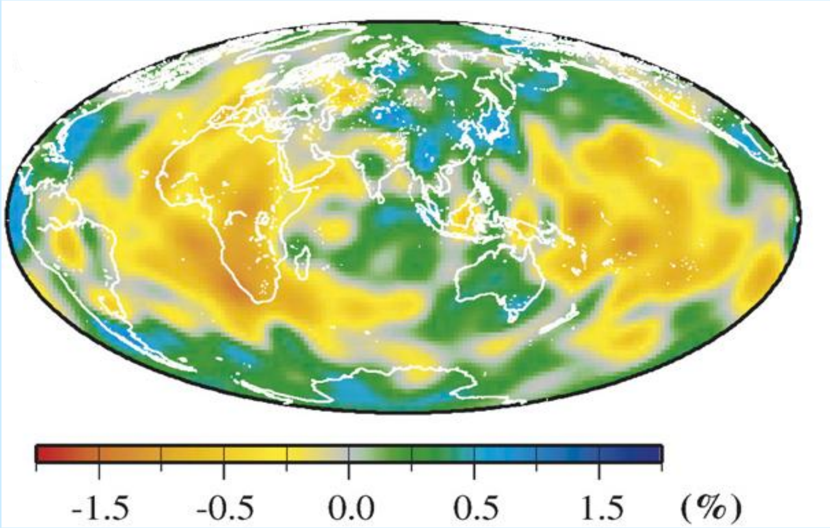


What controls the long-wavelength geoid anomalies? -- (density/thermal) structure in the lower mantle

Long-wavelength geoid (degrees 2-3)

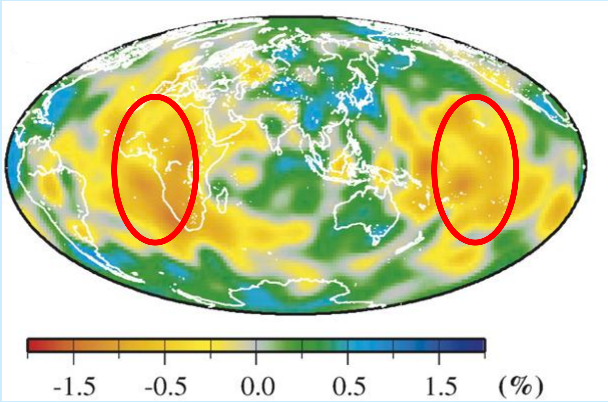


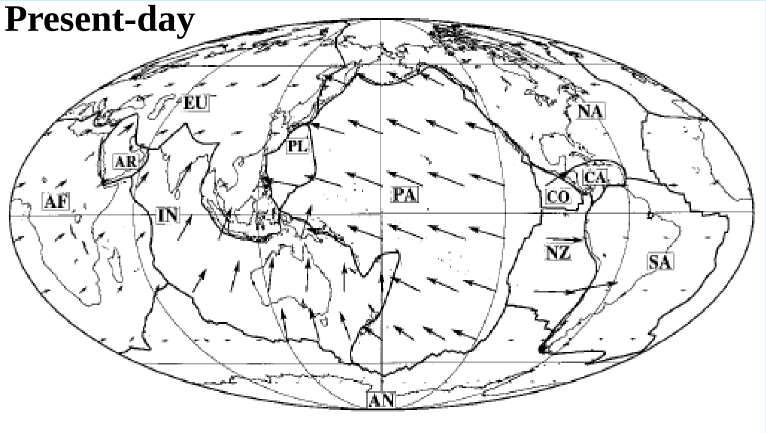
Vs at 2300 km depth from S20RTS [Ritsema et al., 1999]

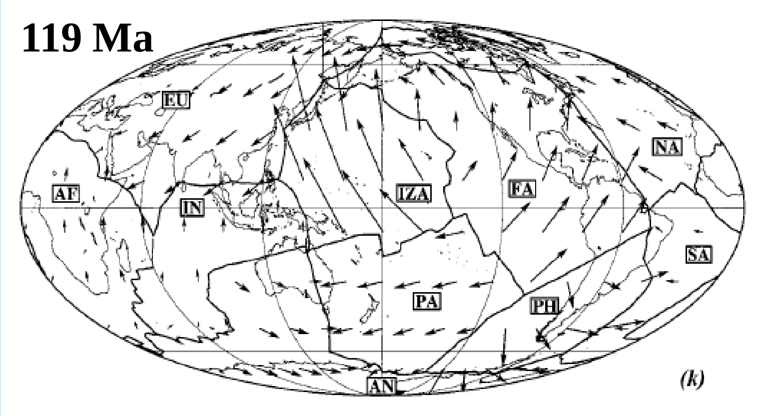


Hager et al. [1985] pointed out that the geoid at degrees 2 and 3 is controlled by the lower mantle seismic structure (i.e., seismically slow anomalies below Africa and Pacific are responsible for the broad geoid highs in these two regions) (Also Forte & Peltier, 1987).

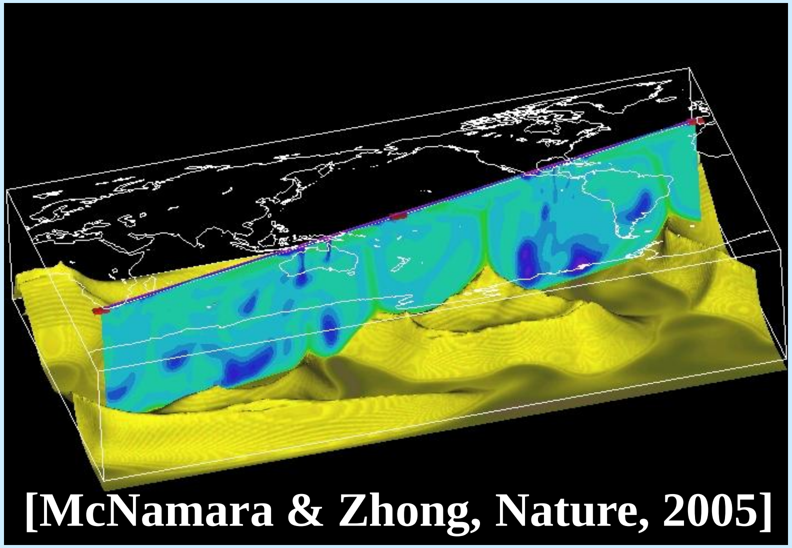
Degree-2 Structure in the Lower Mantle – A Dynamic/Convective Origin





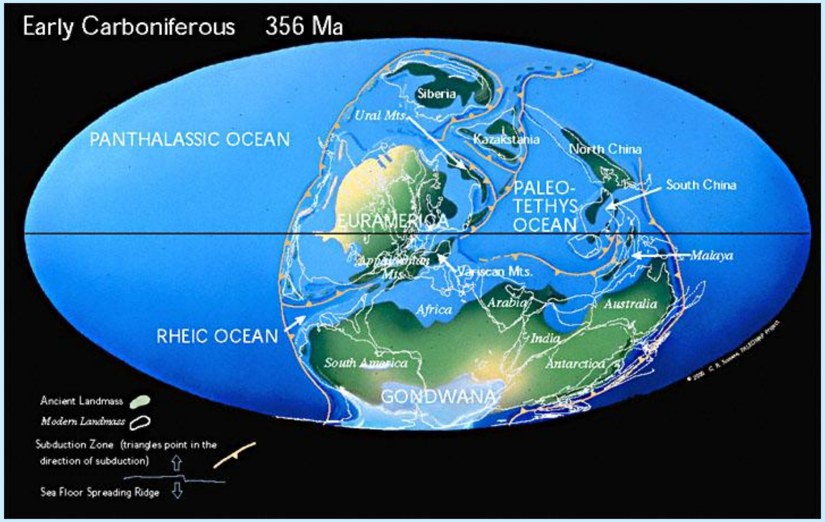


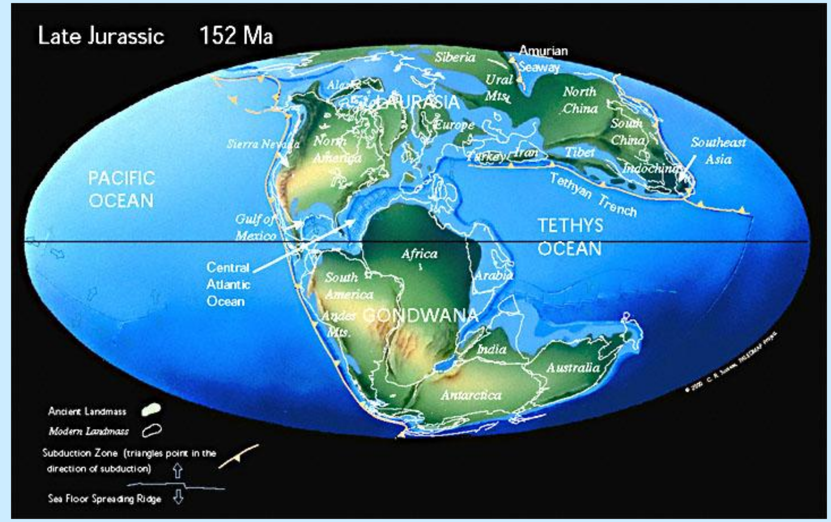
<u>Origin:</u> Controlled by plate motion and its history [Hager & O'Connell, JGR, 1981; Bunge et al., Science, 1998].

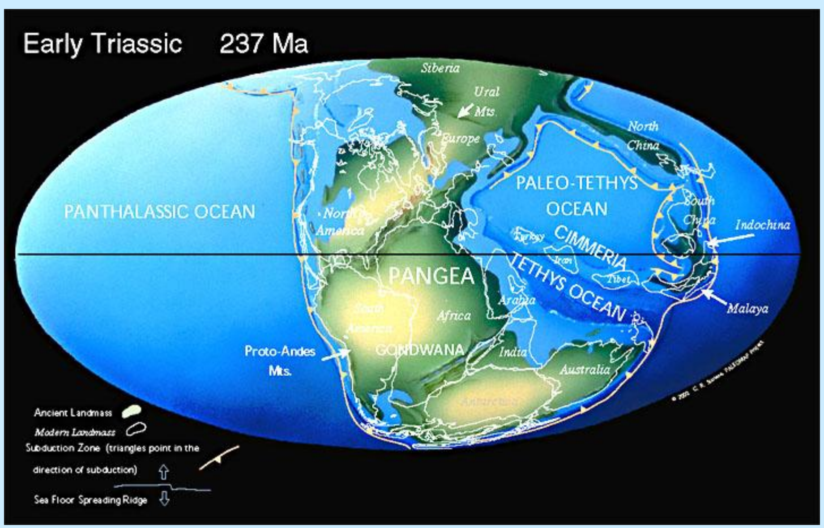


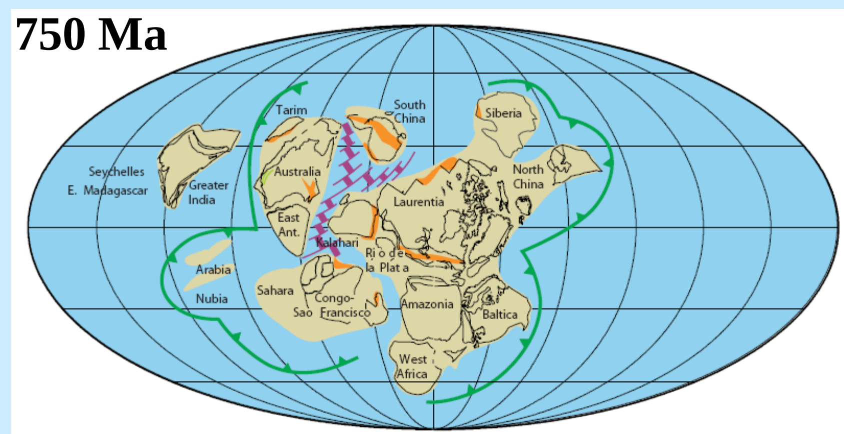
Engebretson et al. [1992]; Lithgow-Bertelloni & Richards [1998].

Supercontinent Pangea (330 -- 180 Ma) and Supercontinent Rodinia (900 -- 750 Ma)







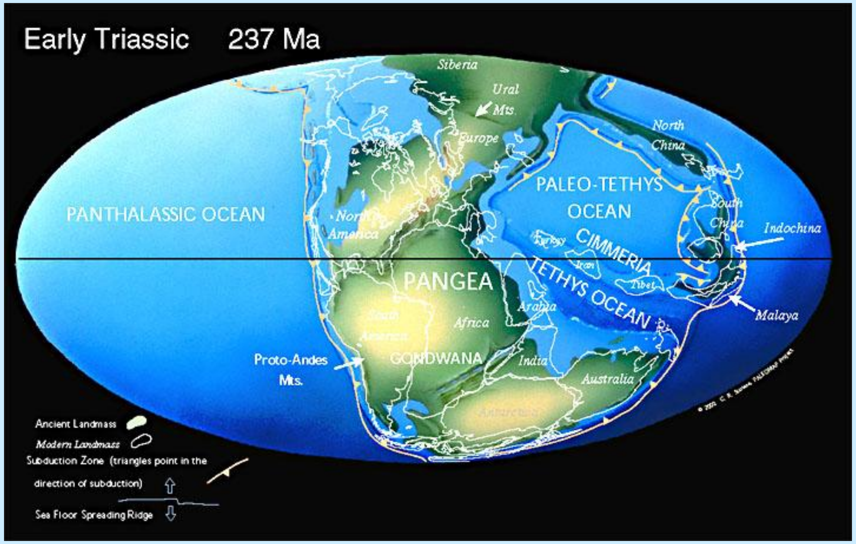


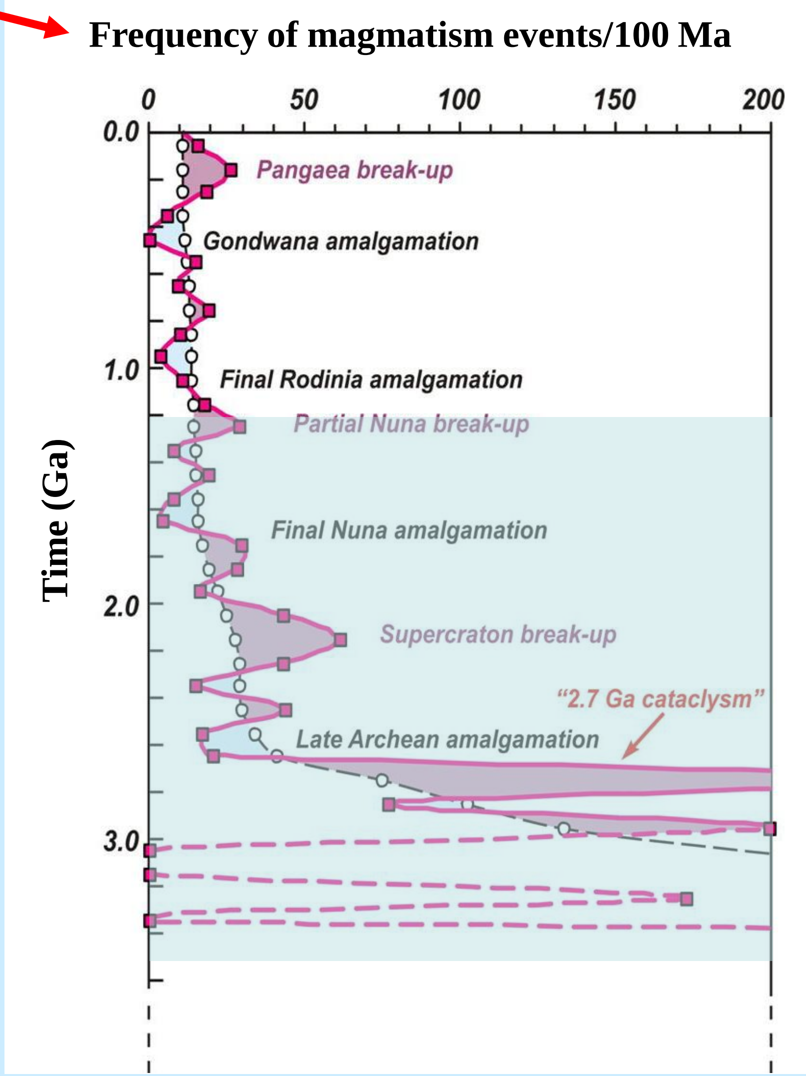
[Smith et al., 1982, and Scotese, 1997]

[Li et al., 2008; Hoffman, 1991; Dalziel, 1991; Torsvik, 2003].

Supercontinent events dominate tectonics and magmatism

Intraplate volcanism (i.e., hot-spot and large igneous provinces or super-volcanoes)

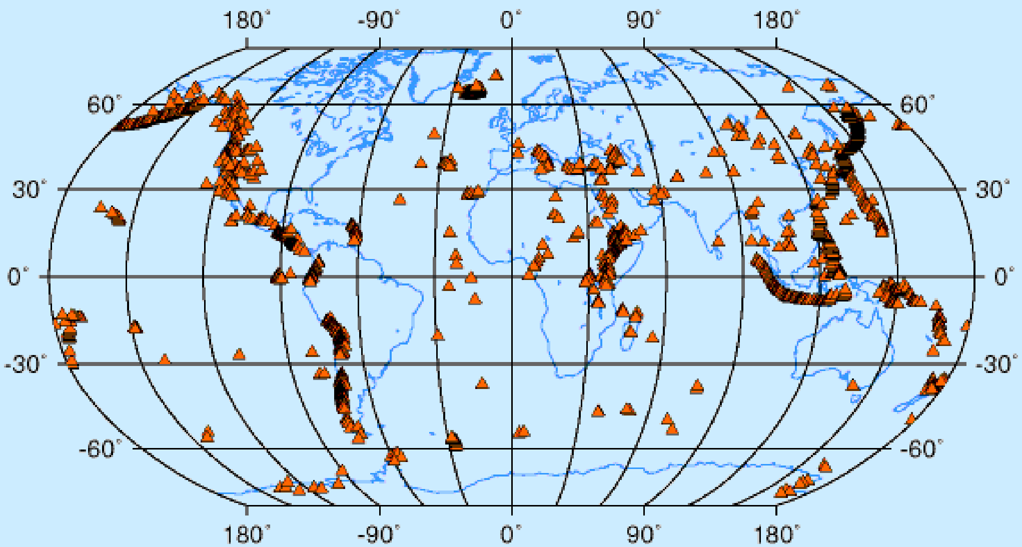


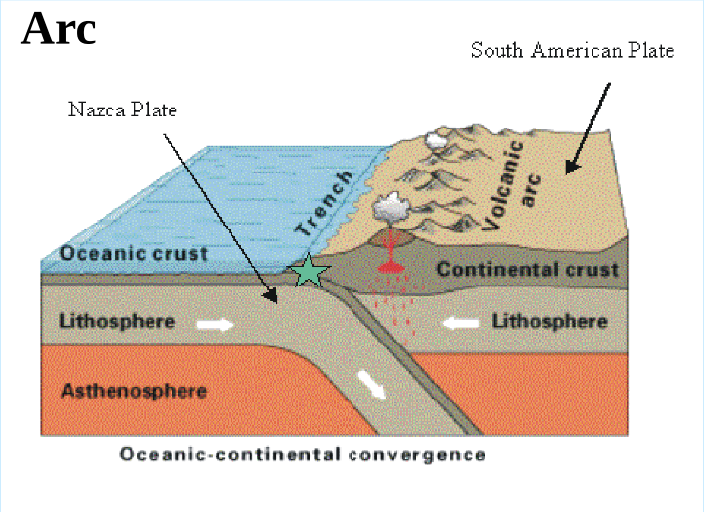


Major mountain belts (e.g., Urals in Russia and Appalachians in North America)

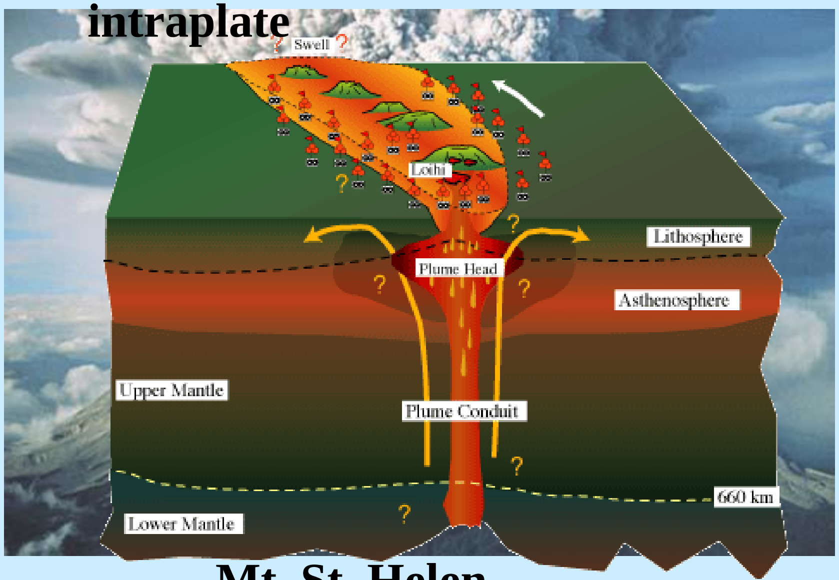
Bleeker & Ernst [2007]

Two types of volcanism: arc and intraplate





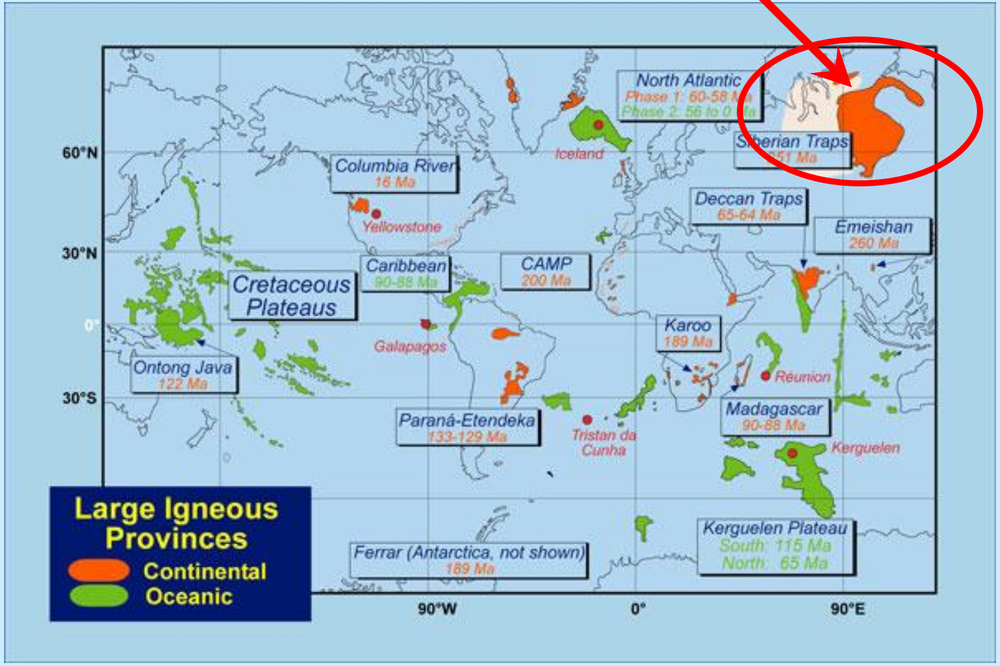
Hawaii volcanoes



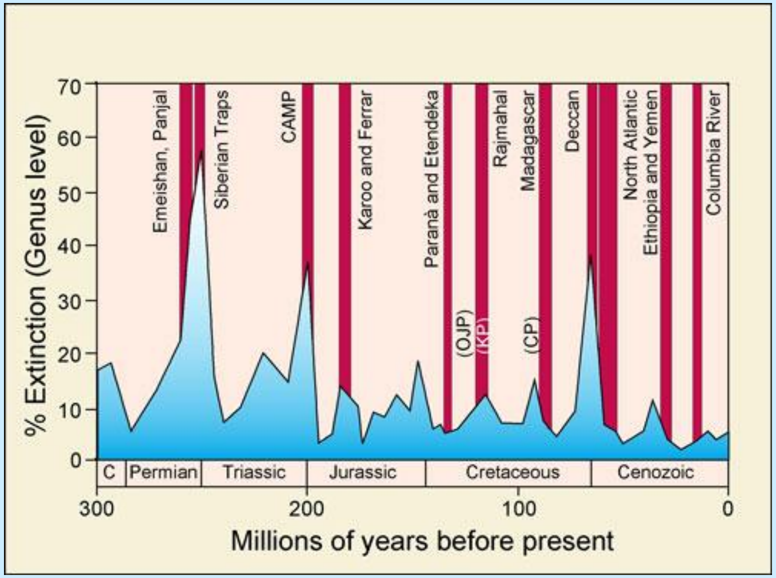
Mt. St. Helen

Large igneous provinces (LIPs) or super-volcanoes – A special type of intraplate volcanism

Covering ~4x10^6 km^2 (or 400 times of the big island of Hawaii) and formed within 1-2 Ma at ~250 Ma ago.

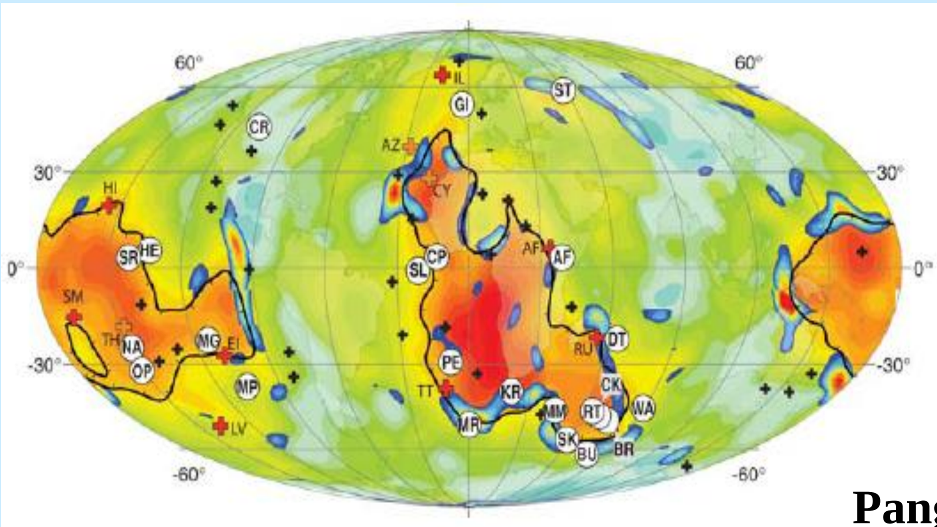


Coffin & Eldholm [1994]



White & Saunders [2005]

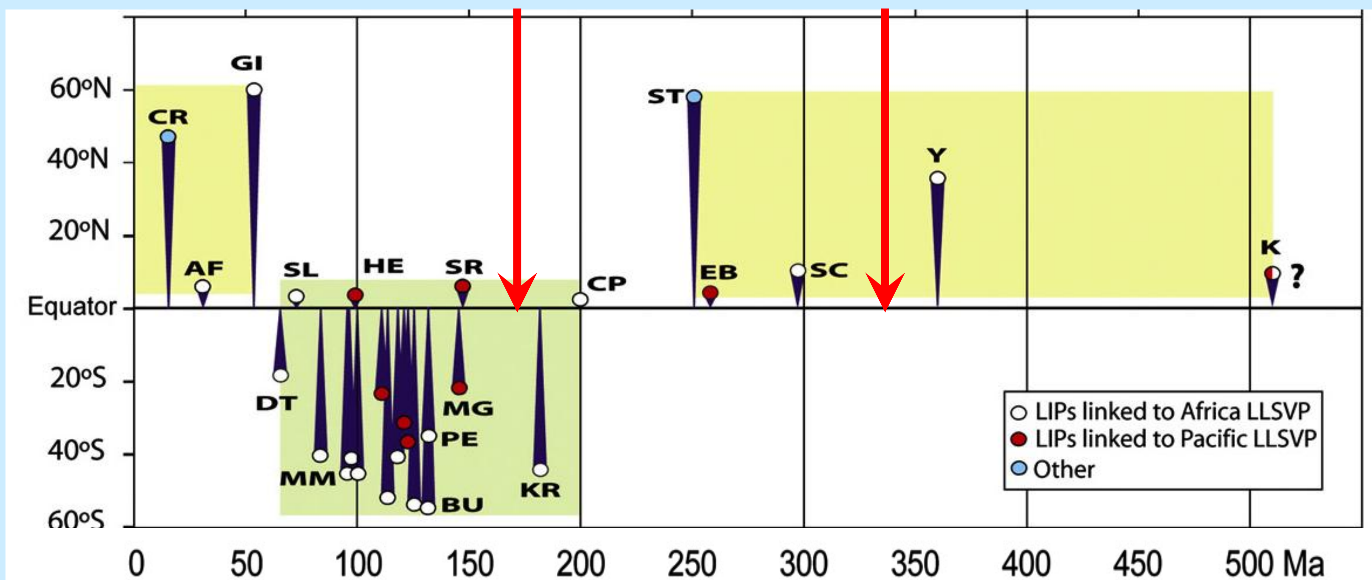
Distributions of LIPs and their relations to African and Pacific superplumes and supercontinent Pangea



Original eruption sites of LIPs and hotspots for the last 250 Ma

Torsvik et al. [2006]

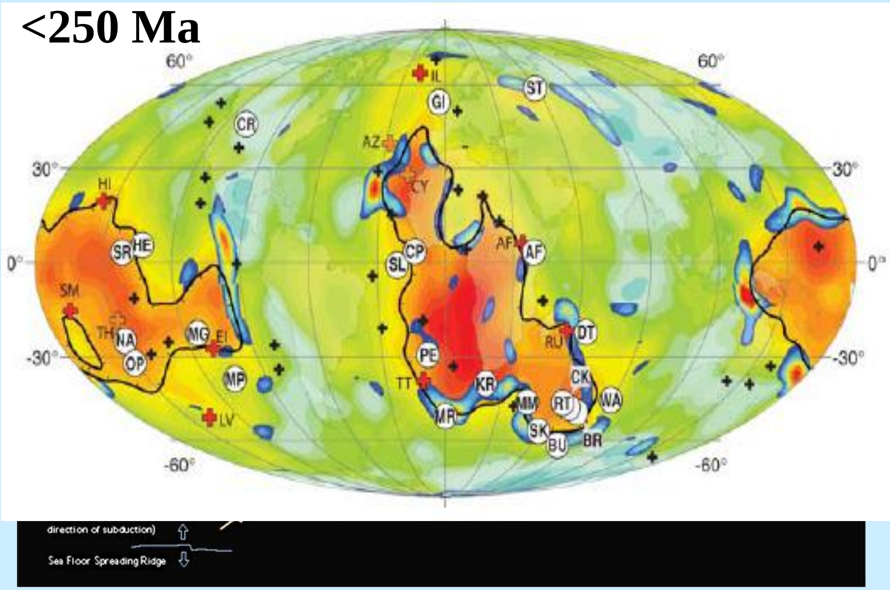
Pangea segregated **Pangea assembled**

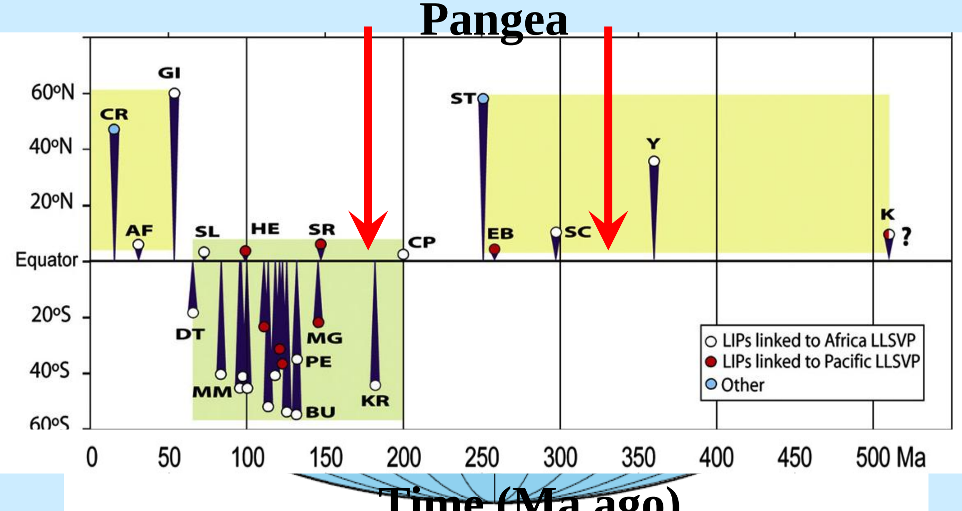


Time (Ma ago)

Torsvik et al. [2008]

Summary of the basic observations





- ***Seismic structure (African and Pacific two antipodal slow anomalies surrounded by subducted slabs).***
- ***The African and Pacific anomalies correlate well with the gravity anomalies at degrees 2-3.***
- ***Supercontinent cycles (Pangea and Rodinia)*. Surrounded by subduction zones (i.e., convergence zones). Only existed for 150 Ma before the breakup.**
- ***Spatial and temporal distributions of LIPs.***

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Some first-order questions

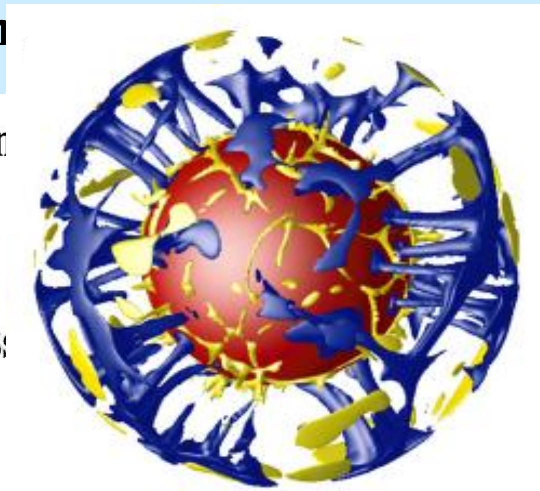
1. ***Why should a supercontinent form? Why are supercontinent events cyclic?***
2. ***How do we understand the present-day seismic structure (e.g., two antipodal African and Pacific slow anomalies) and supercontinent events in a general framework?***
3. ***Are those mantle structures stationary with time?***
4. ***How are mantle structure evolutions related to other geophysical and geological observations?***

Thermal convection in the mantle is the key to all these questions.

Thermal convection in the mantle

Earth's heat sources: radiogenic heating (U, Th ... ating.

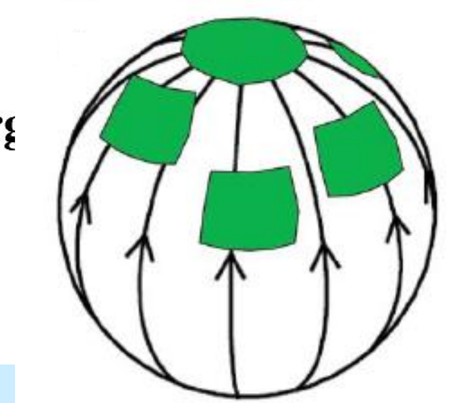
But…



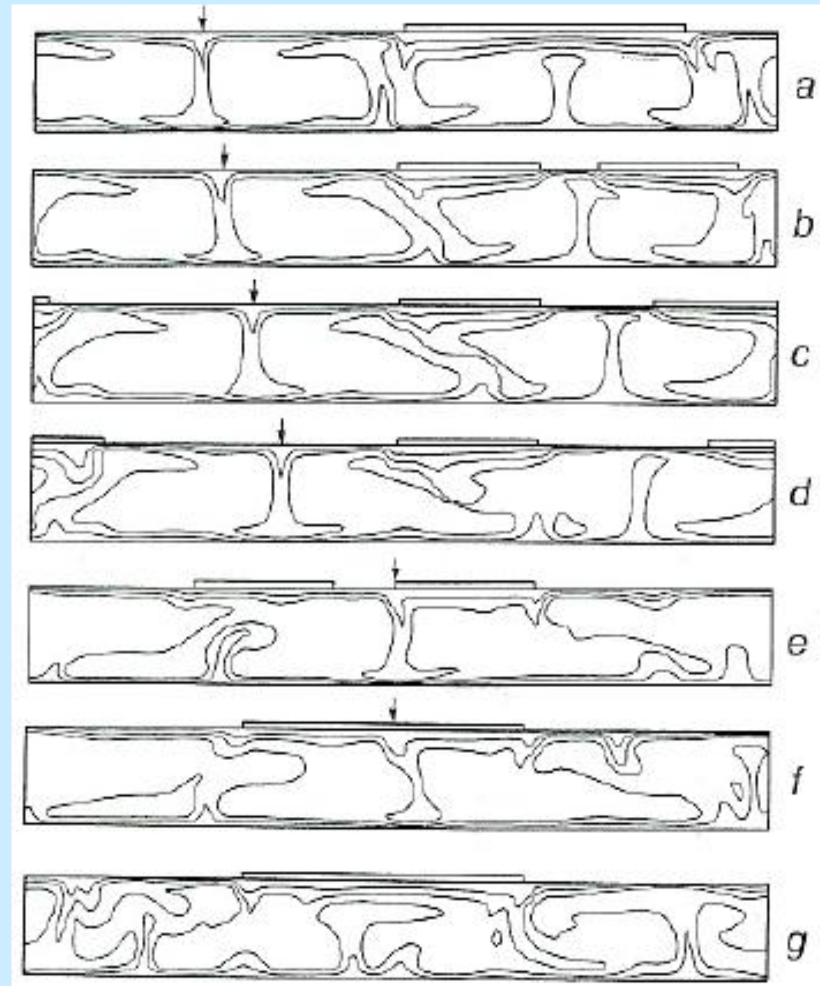
Co... Thermal
...tle

- **Mas...**
- **Momentum:**

Degree-1 flow?

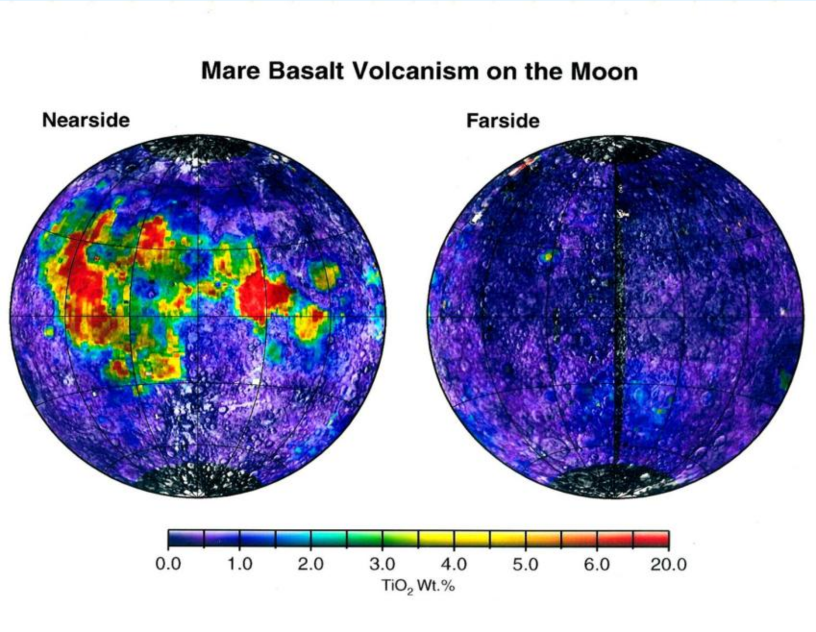


- **Energ...**

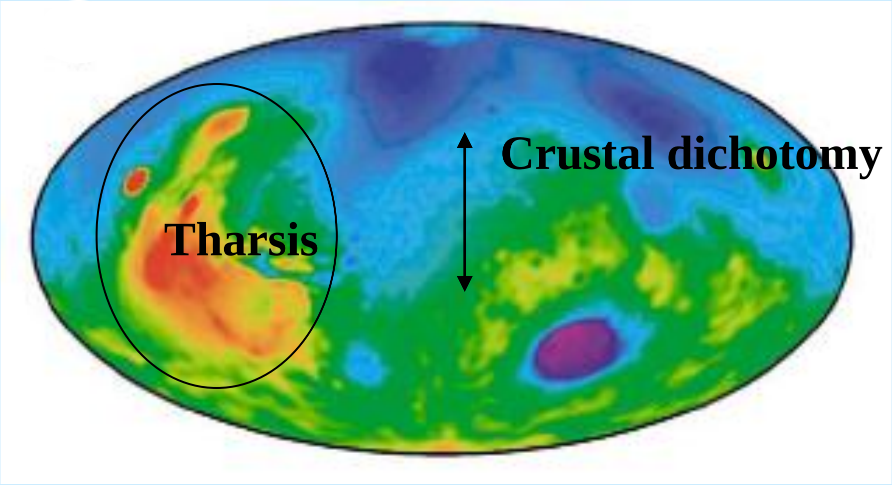


Gurnis [1988]; Lowman & Jarvis [1996]; Gait & Lowman [2007]

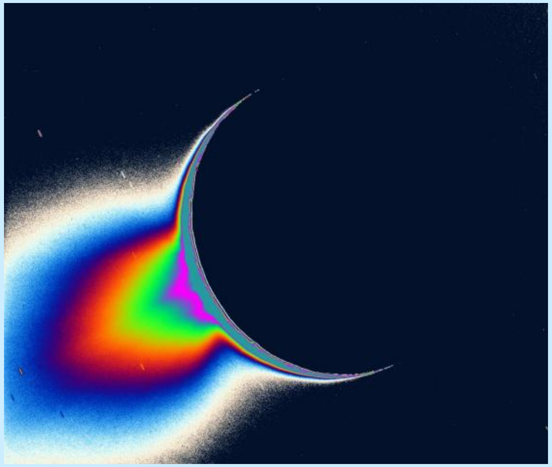
Degree-1 or hemispherically asymmetric structures for the other planetary bodies?



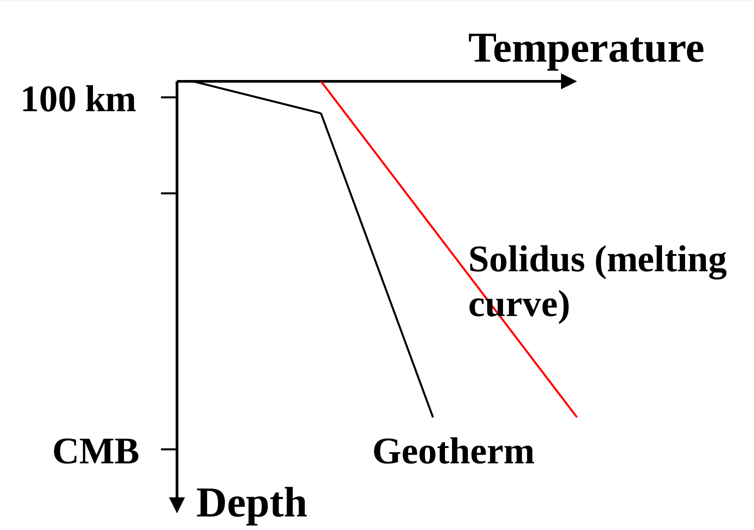
Surface topography on Mars

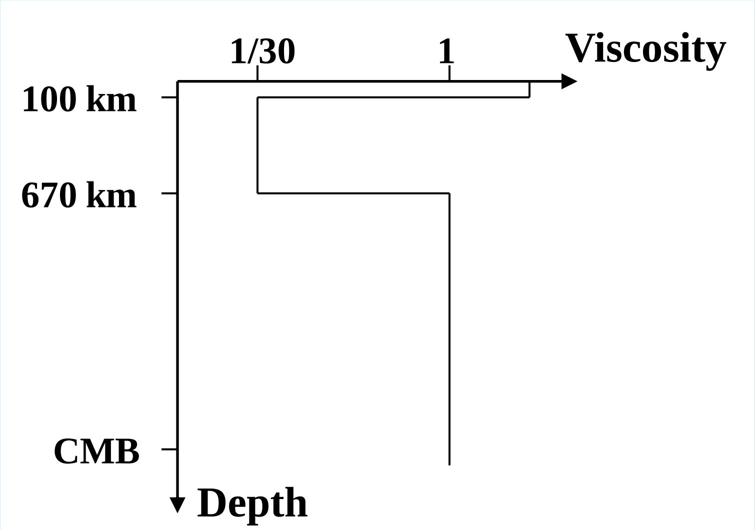


Icy satellite Enceladus



How to generate degree-1 mantle convection?
-- the effect of a weak upper mantle



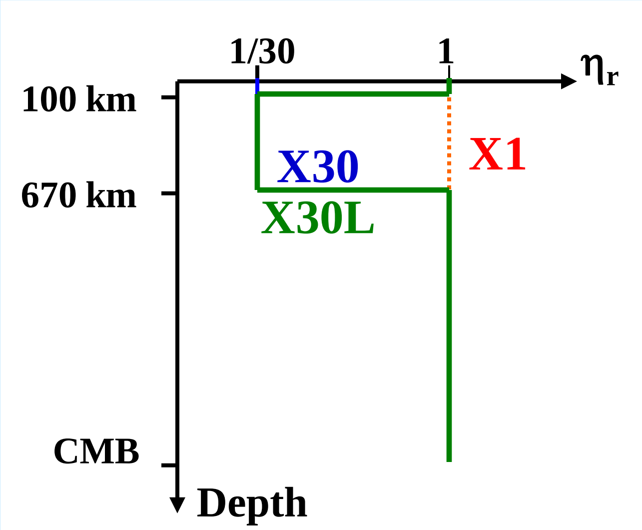


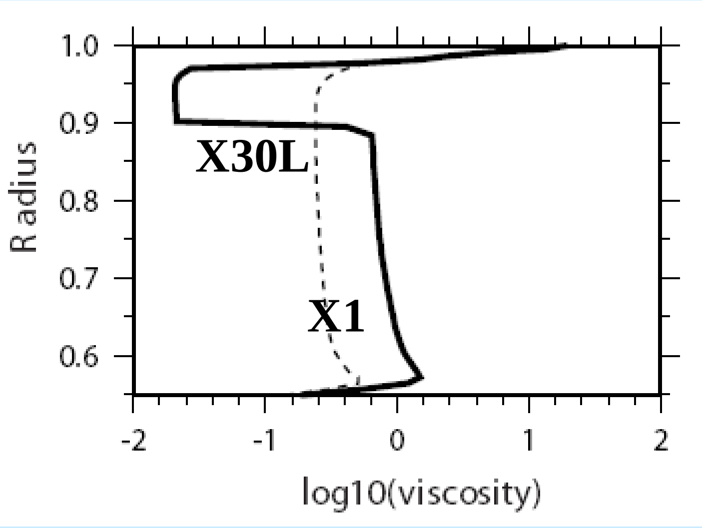
Constrained by postglacial rebound and gravity observations [Hager, 1991; Mitrovica et al., 2007]

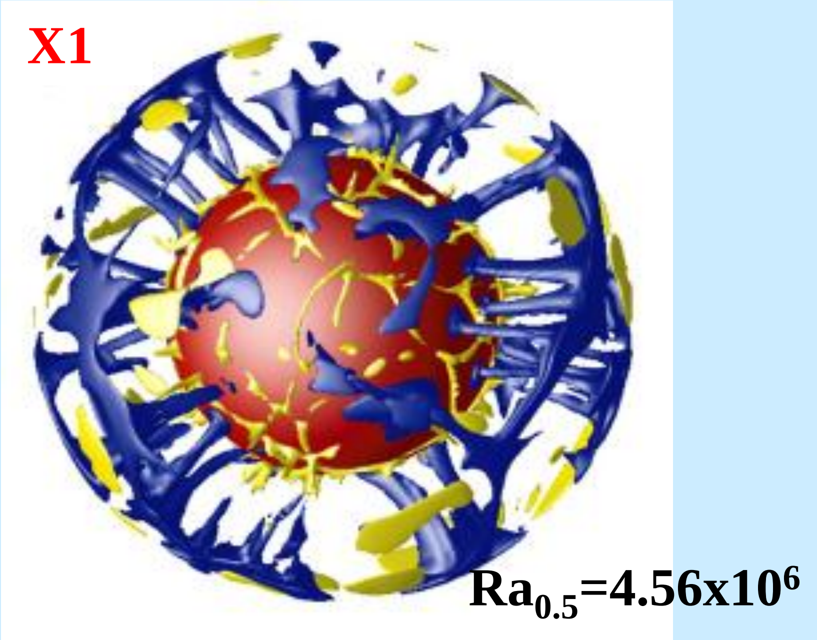
A weak upper mantle may increase convective wavelengths up to degree 6 [Jaupart & Parsons, 1985; Zhang & Yuen, 1995; Bunge et al., 1996].

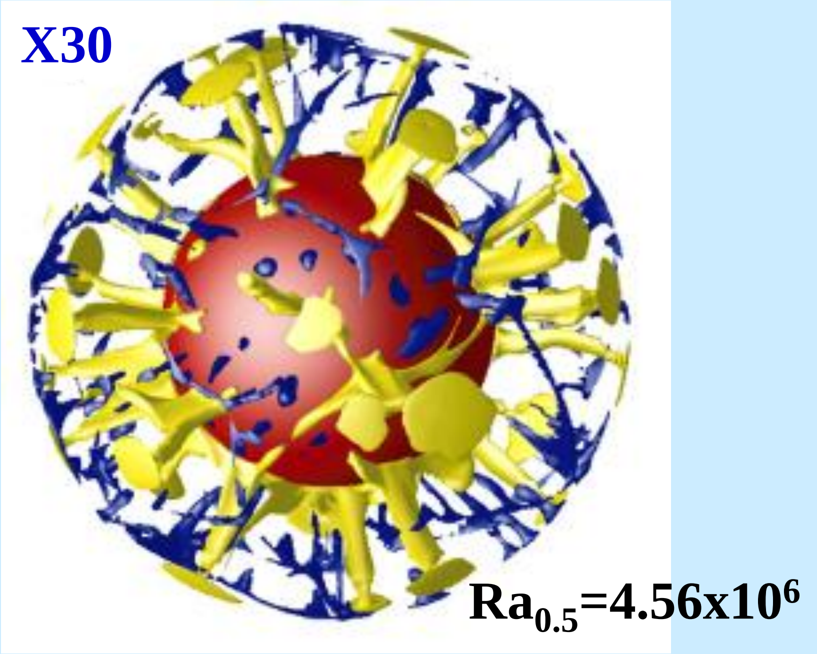
Degree-1 mobile-lid convection with realistic mantle viscosity

$\eta=\eta_r \exp[E(0.5-T)]$





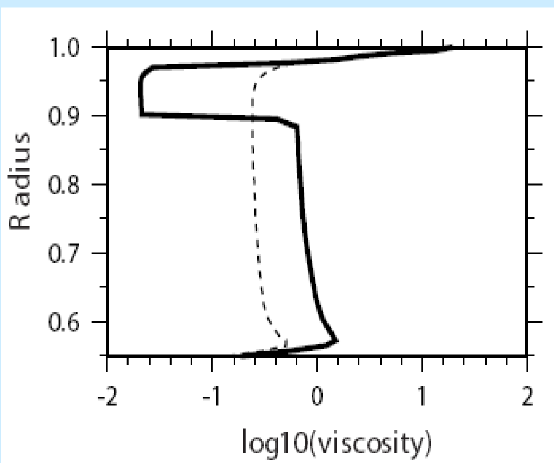


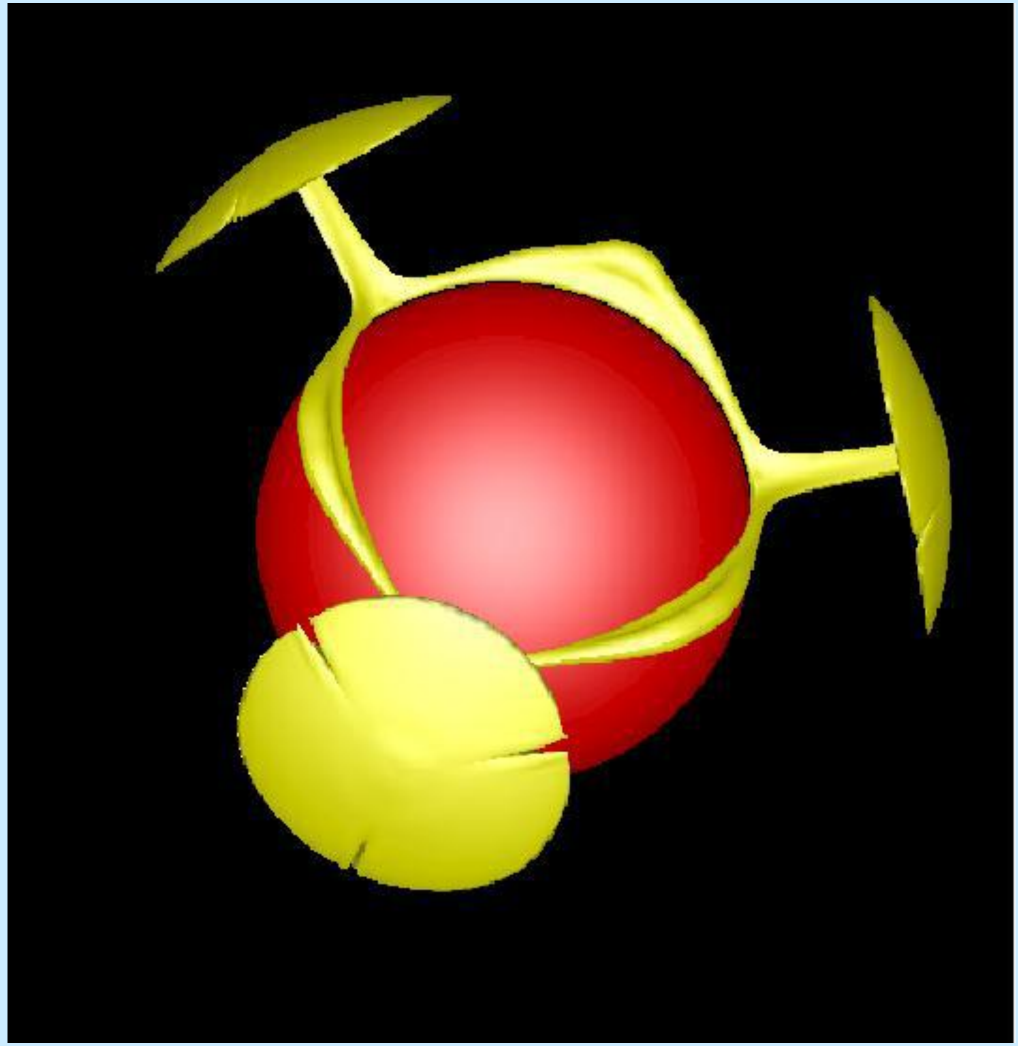


Movie 1: Evolving to degree-1 convective structure

Viscosity: η(T, depth).

$\eta_{lith} \sim 300\eta_{um}$
$\& \ \eta_{lm} \sim 30\eta_{um}$





Independent of convective vigor, heating mode, & initial conditions.

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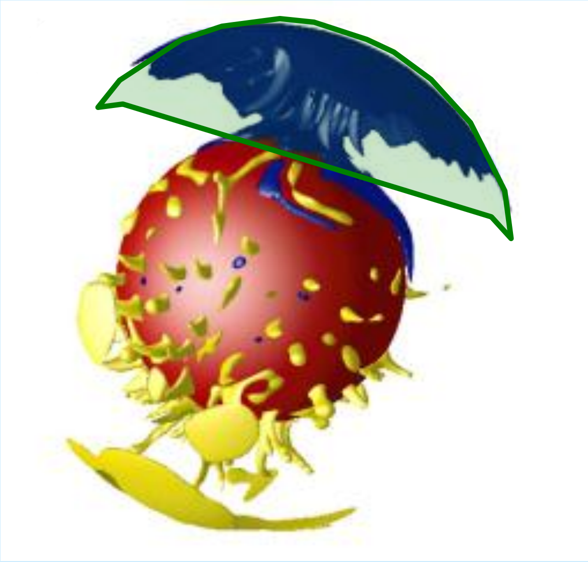
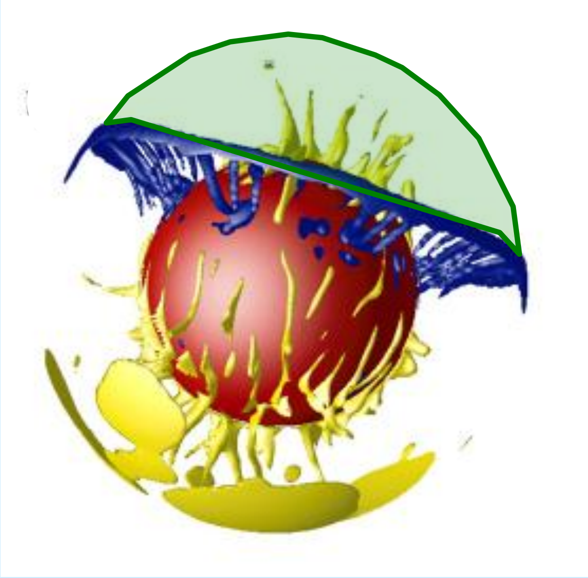
Movie 2: A supercontinent turns initially degree-1 to degree-2 structures

An 1-2-1 model for the evolution of mantle structure modulated by continents [Zhong et al., 2007]





Degree-1 convection with one major upwelling system.

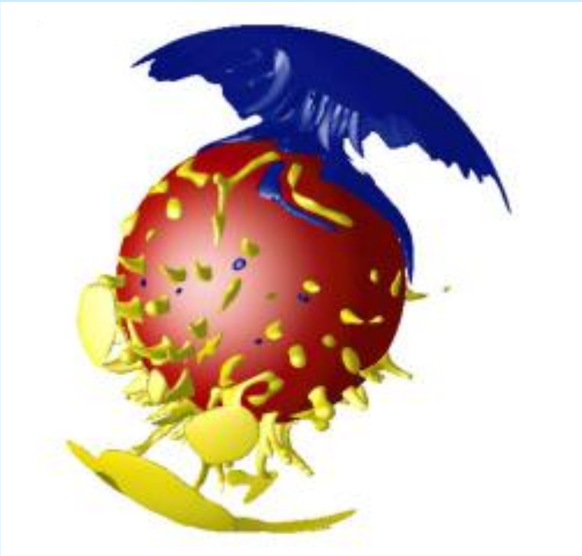
forming a supercontinent

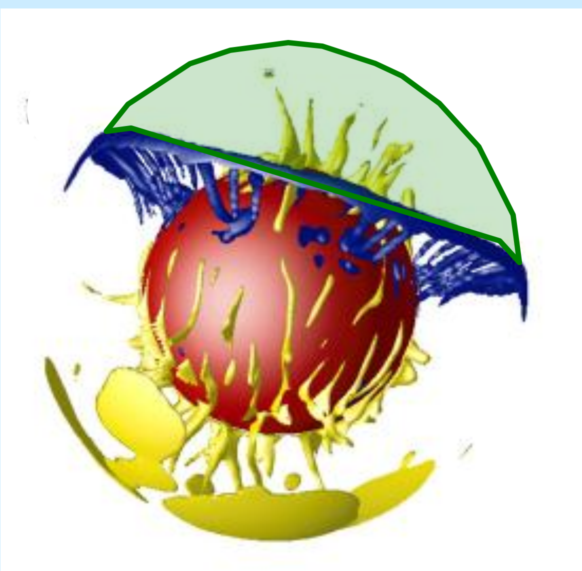
Degree-2 convection with two antipodal major upwelling systems, including one under the supercontinent.

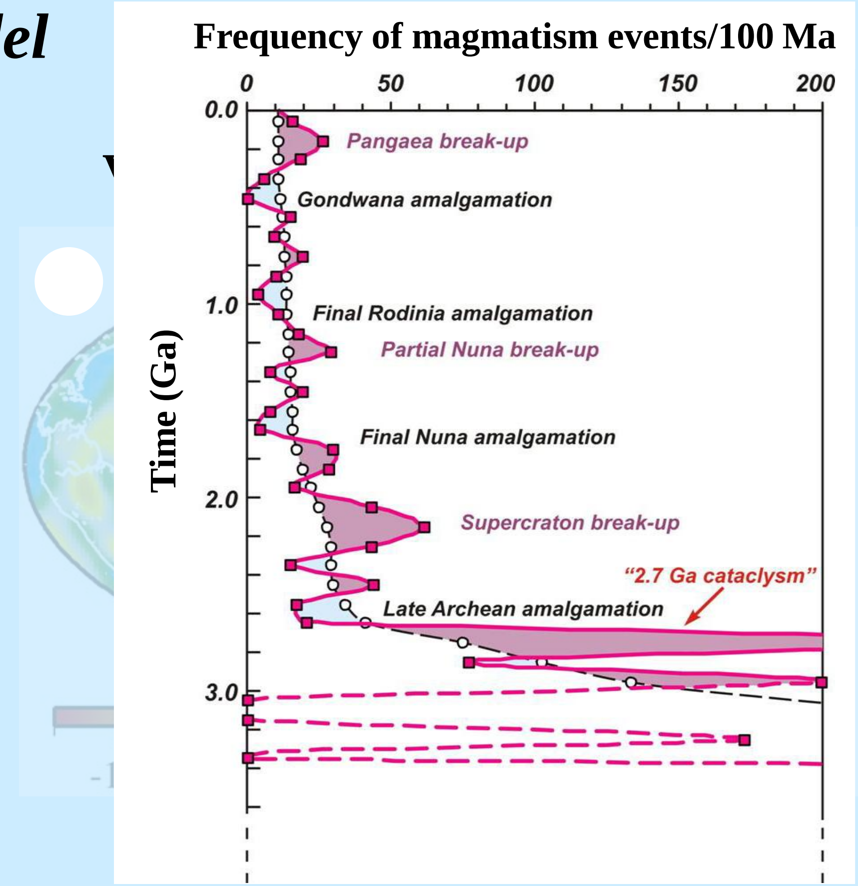
breaking up the supercontinent

Mantle structure: 1→2→1 cycle.
At the surface: supercontinent cycle.

Implications of the 1-2-1 model







- Large igneous provinces: reduced level during the supercontinent assembly, but enhanced after.
- The African and Pacific superplumes are antipodal to each other (i.e., degree-2).
- The African anomalies are younger than Pangea (330 Ma), but the Pacific anomalies are older.

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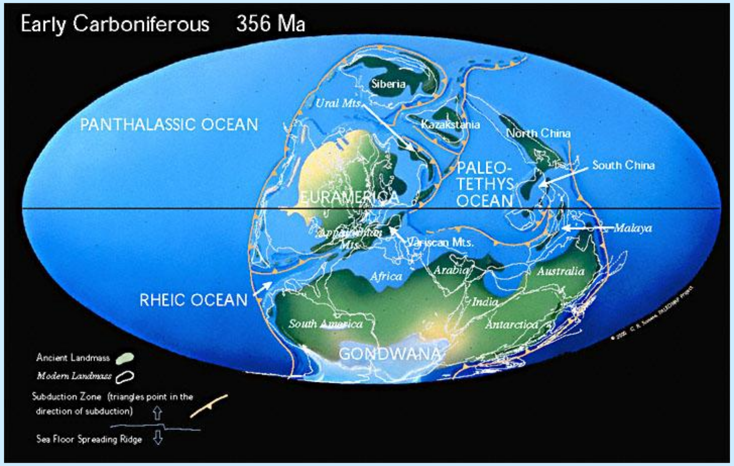
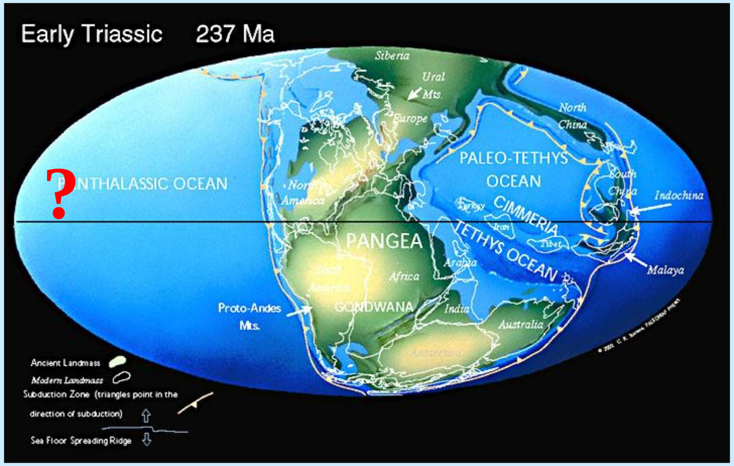
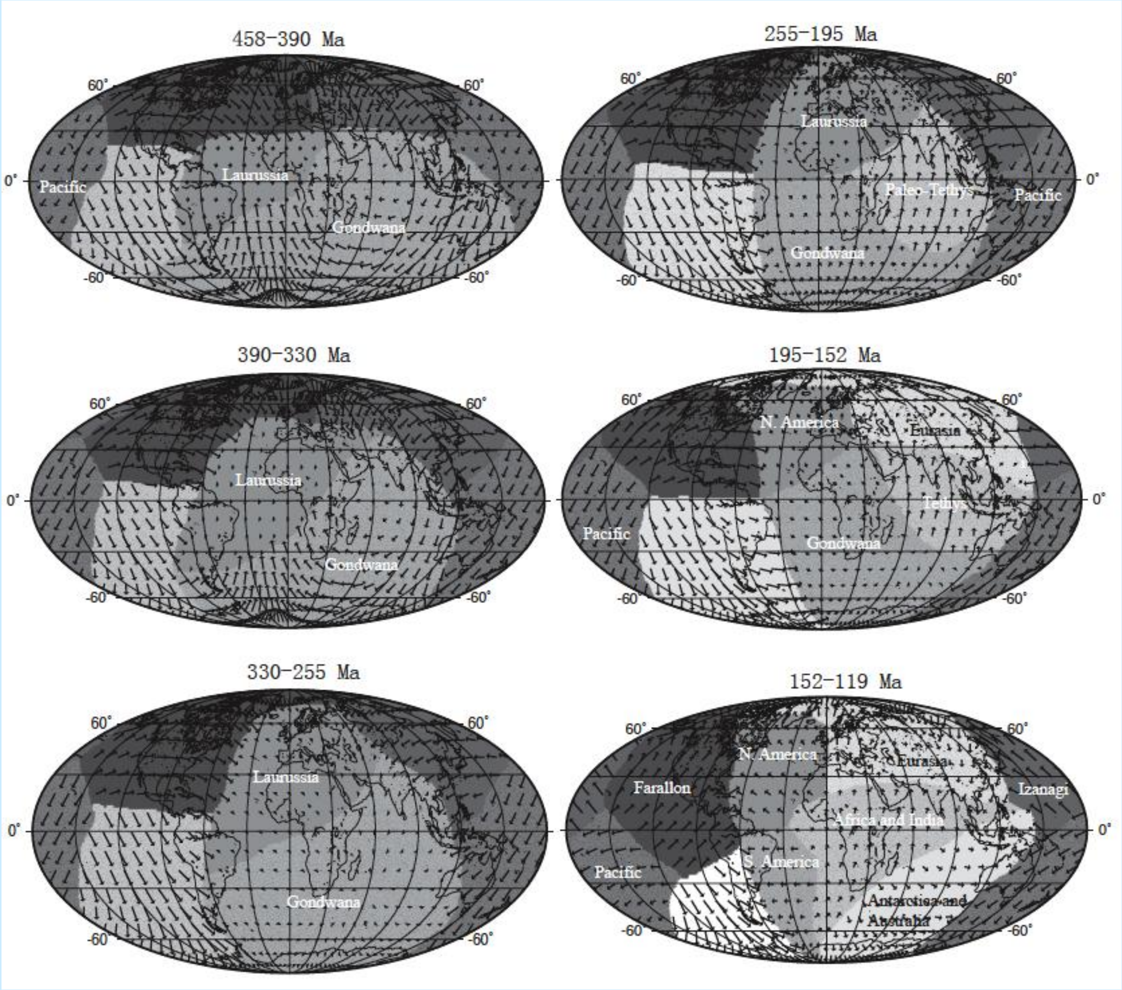
Testing the 1-2-1 model

How? Using present-day seismic structure, and geological observations of continental motion for the past 500 Ma.





[Scotese, 1997]



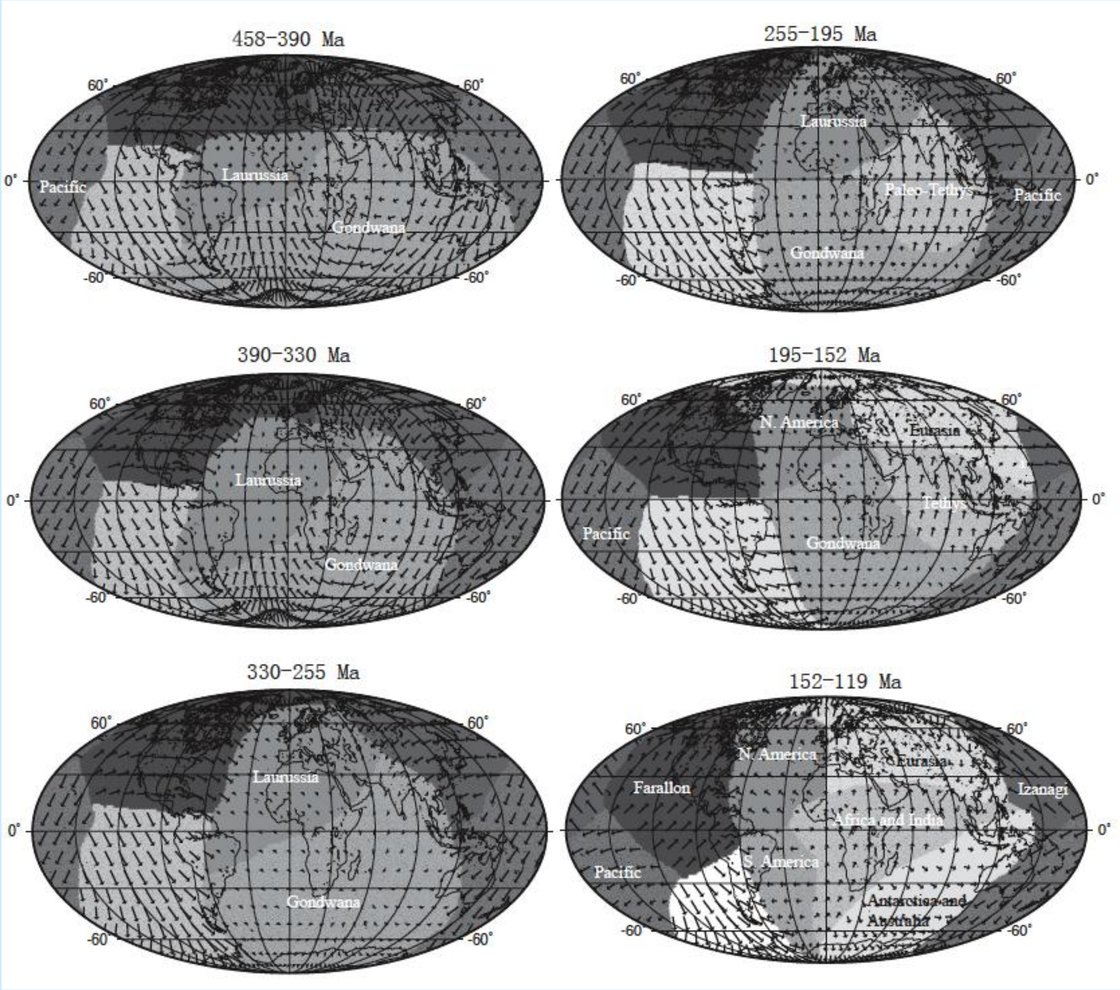
For the last 119 Ma, Lithgow-Bertelloni & Richards [1998]

Testing the 1-2-1 model

How? Using present-day seismic structure, and geological observations of continental motion for the past 500 Ma.

Use the plate motion history as time-dependent velocity boundary condition in mantle convection models to predict the mantle structure evolution.

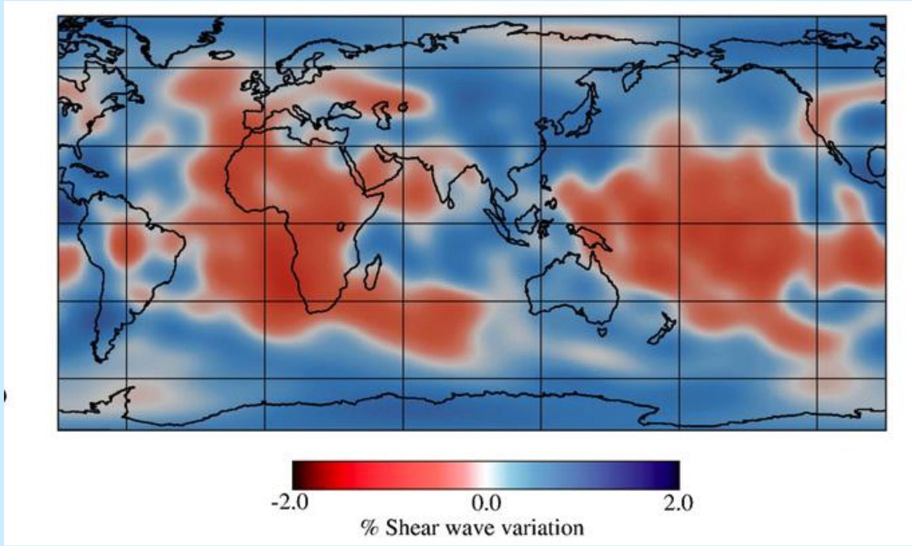
Our model is NOT a fully dynamic model with plate tectonics, which is a great challenge in mantle dynamics [Lowman, 2011].

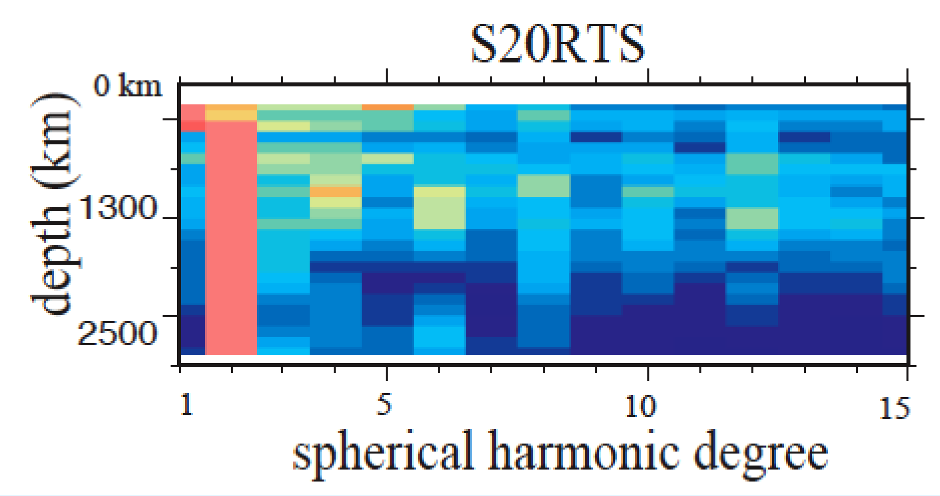


For the last 119 Ma, Lithgow-Bertelloni & Richards [1998]

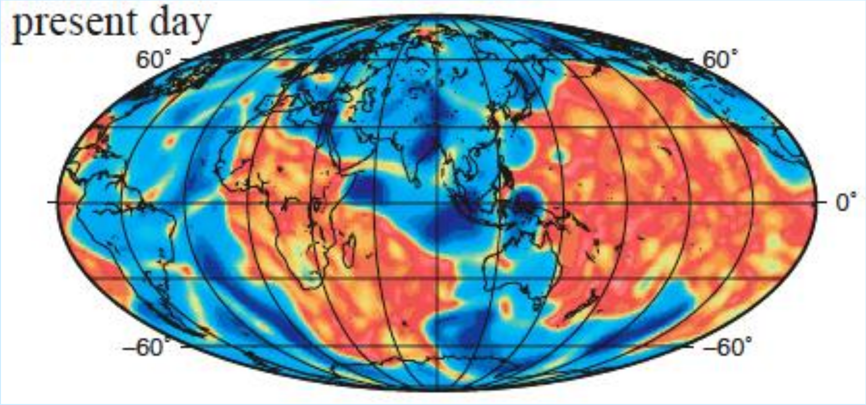
Comparison with present-day seismic structure

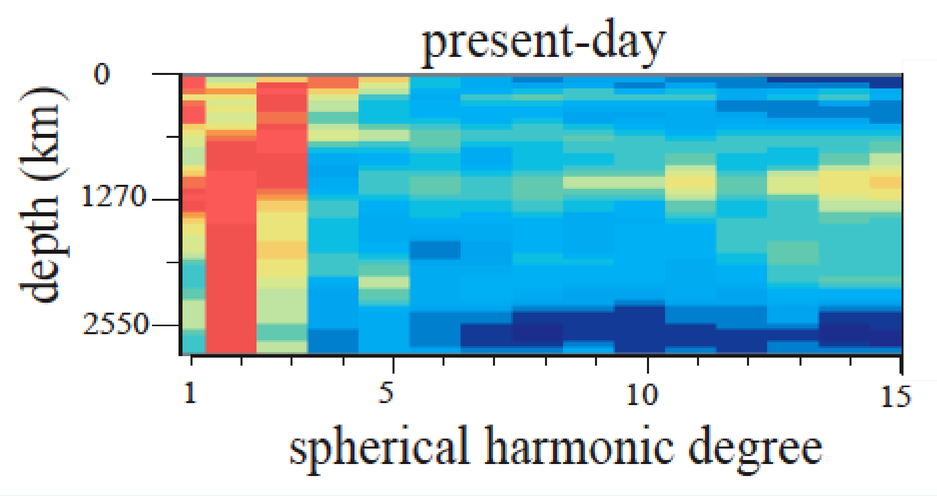
S20RTS @2750 km depth





@2700 km depth

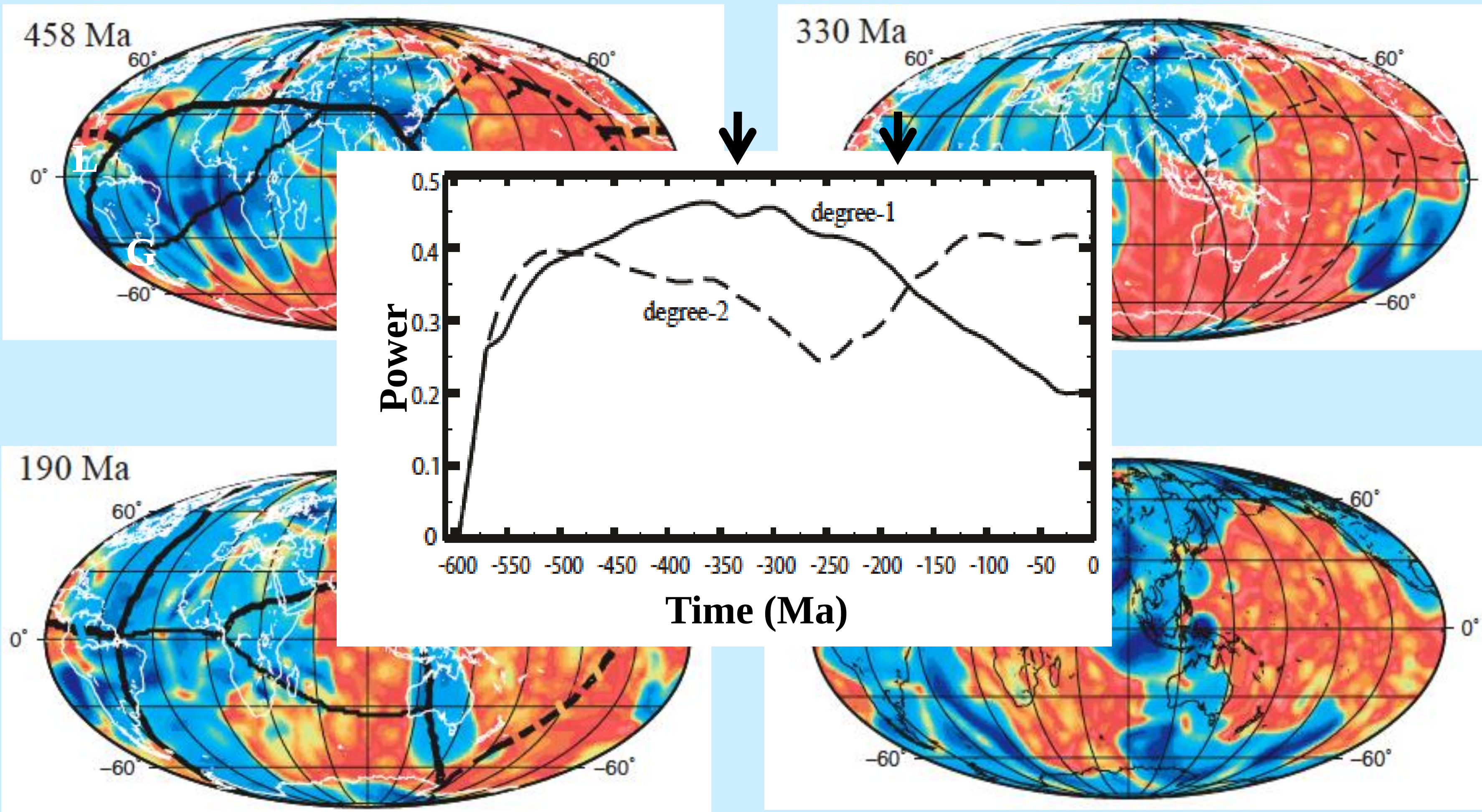




Zhang et al [2010]

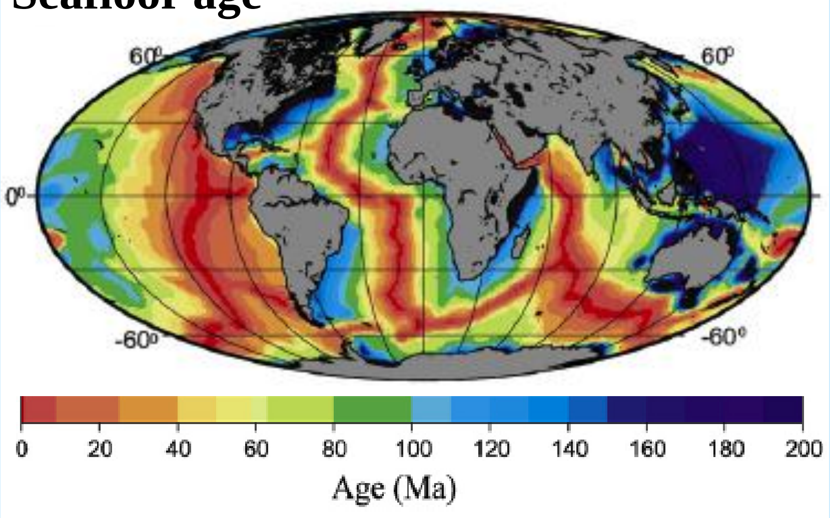
Time evolution of mantle structure with prescribed surface plate motions since the Paleozoic

2700 km depth

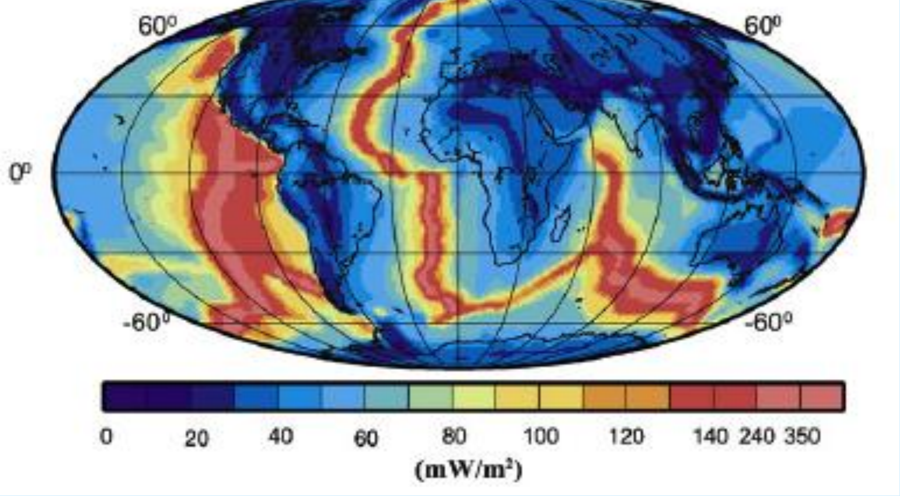


Predicted present-day seafloor age, surface heat flux, bathymetry and dynamic topography

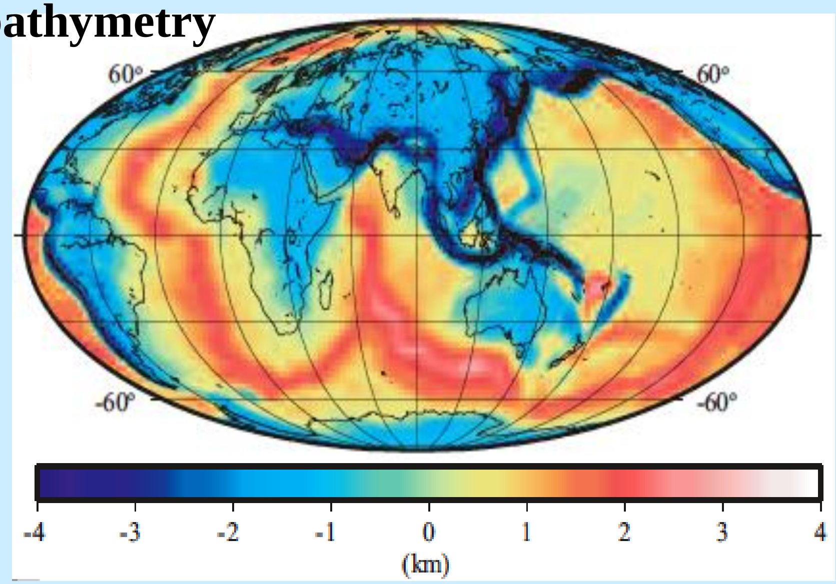
Seafloor age



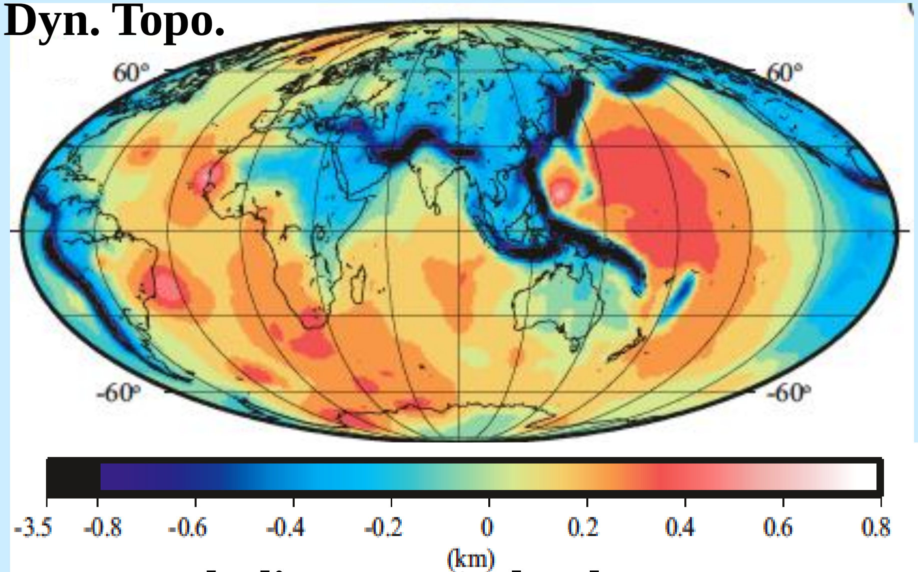
Heat flux



bathymetry



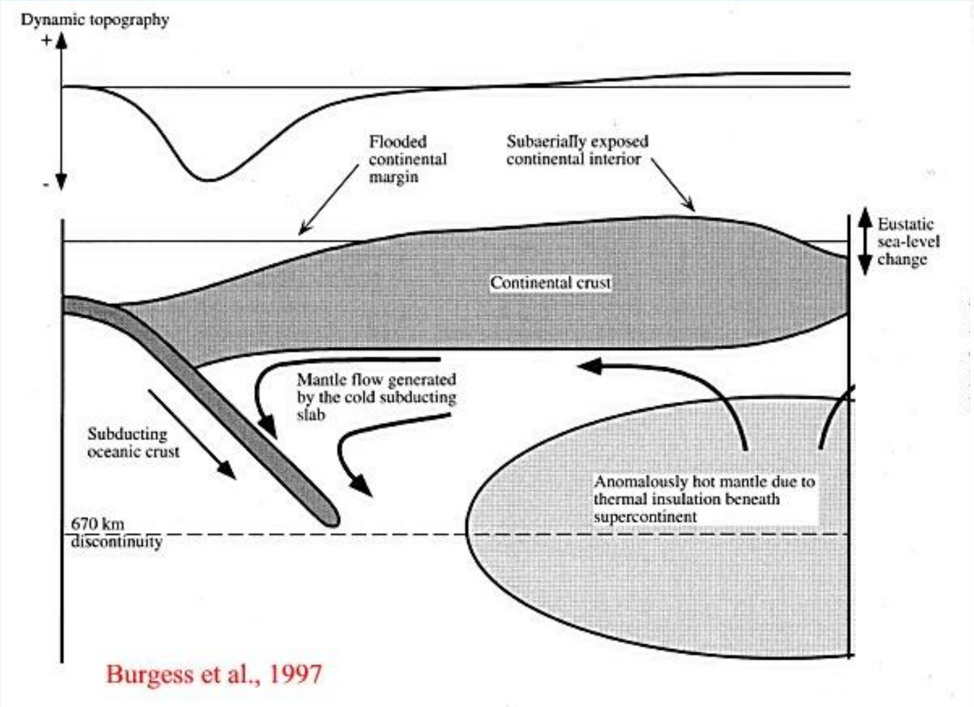
Dyn. Topo.



excluding top 200 km buoyancy

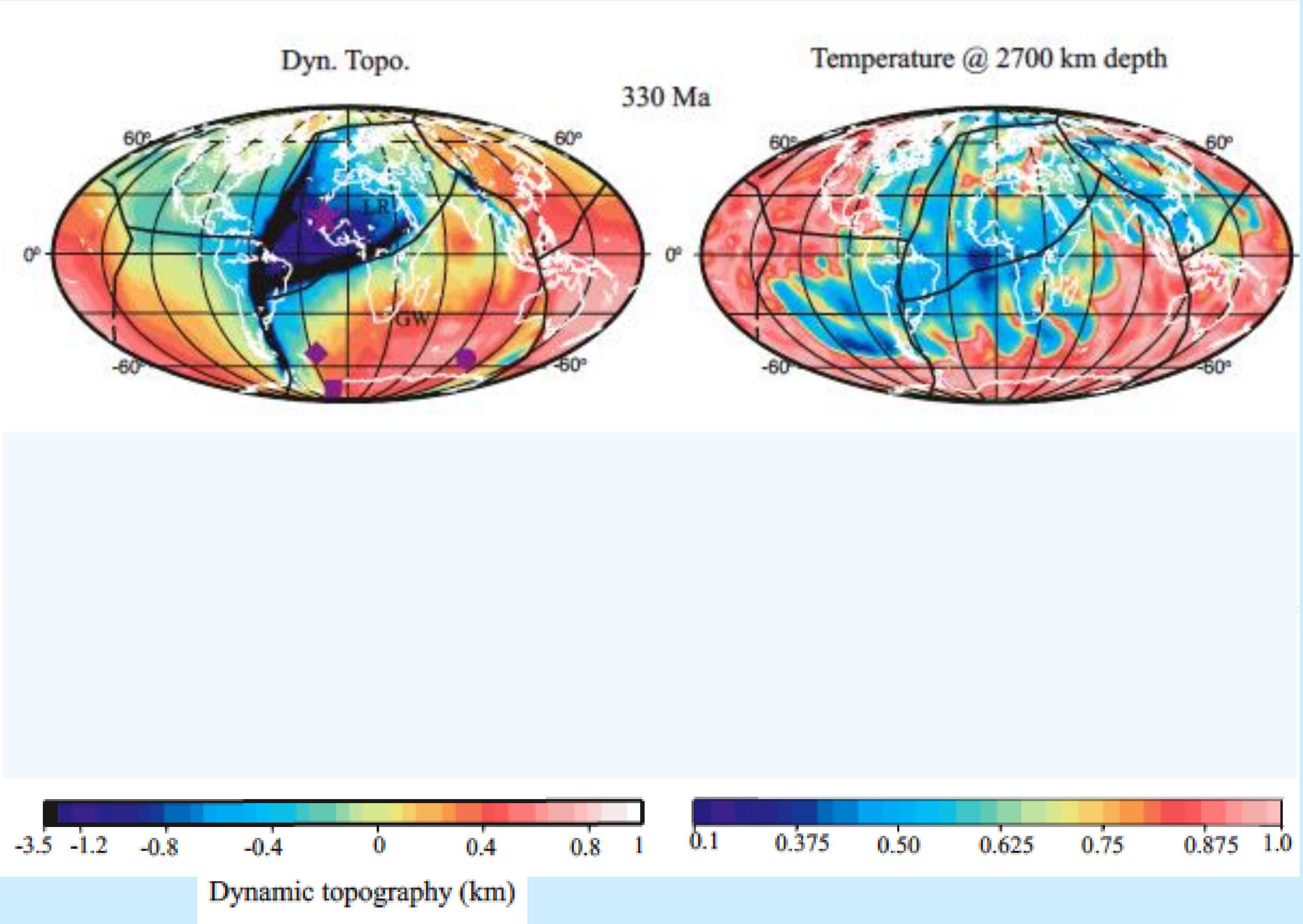
Dynamic topography

- ***Topography generated by the dynamics of mantle flow.***



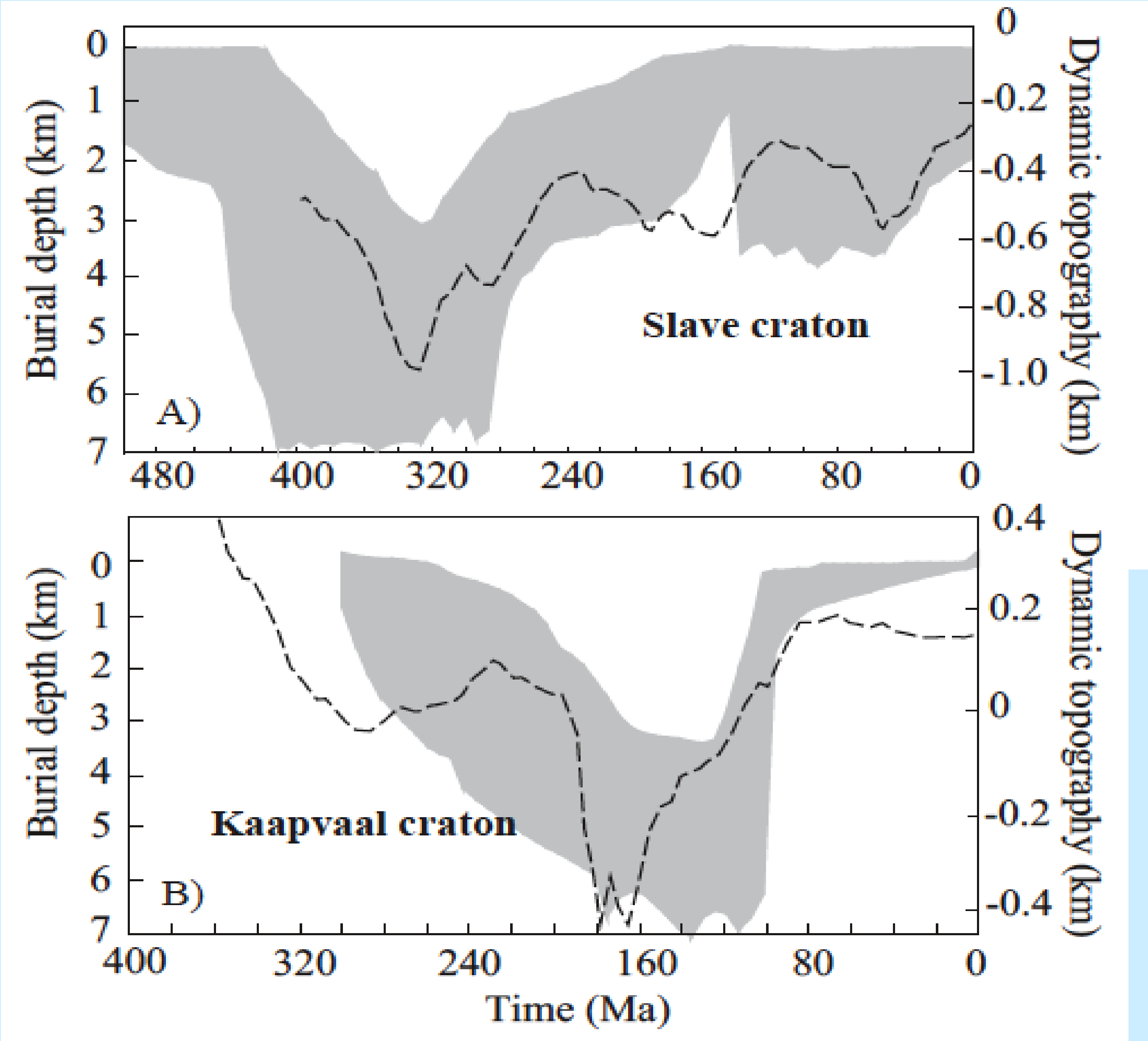
Mitrovica, Beaumont & Jarvis [1989] and Liu et al., [2008]

Predicting history of continental vertical motions (Zhang et al., 2011a)



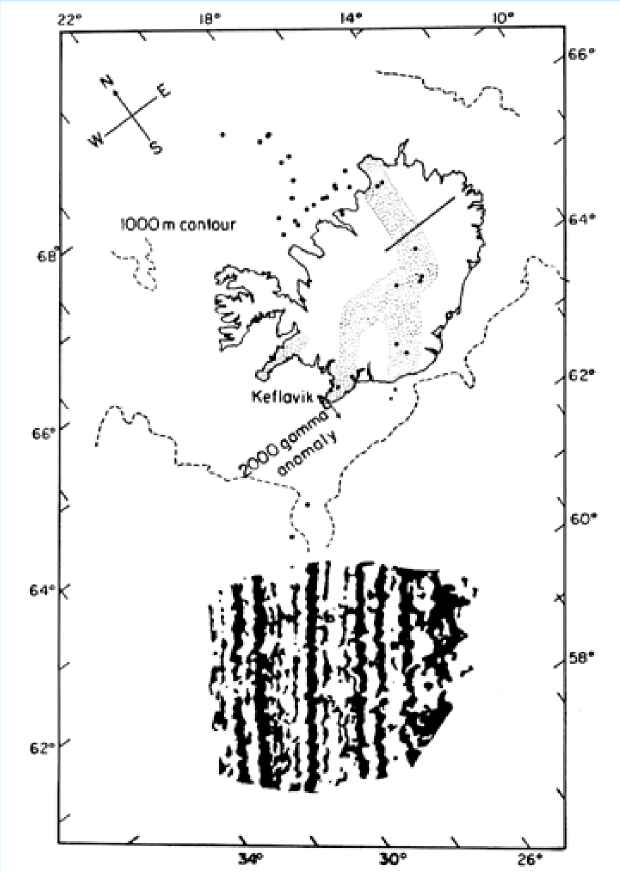
Comparing predicted continental vertical motions with burial/unroofing history from geochronology

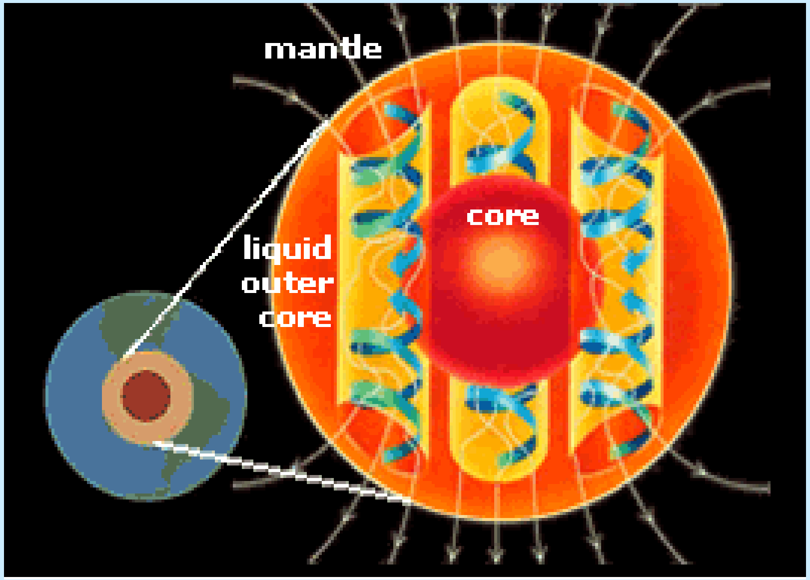
Flowers and Schoene, 2010

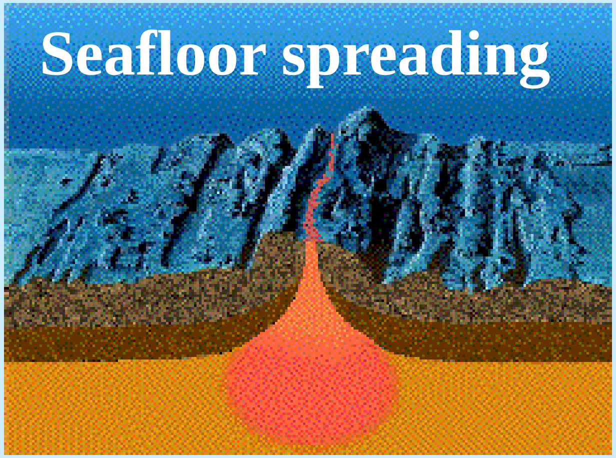


Flowers et al., 2011; Ault et al., 2009

Magnetic stripes on seafloor and magnetic polarity reversals

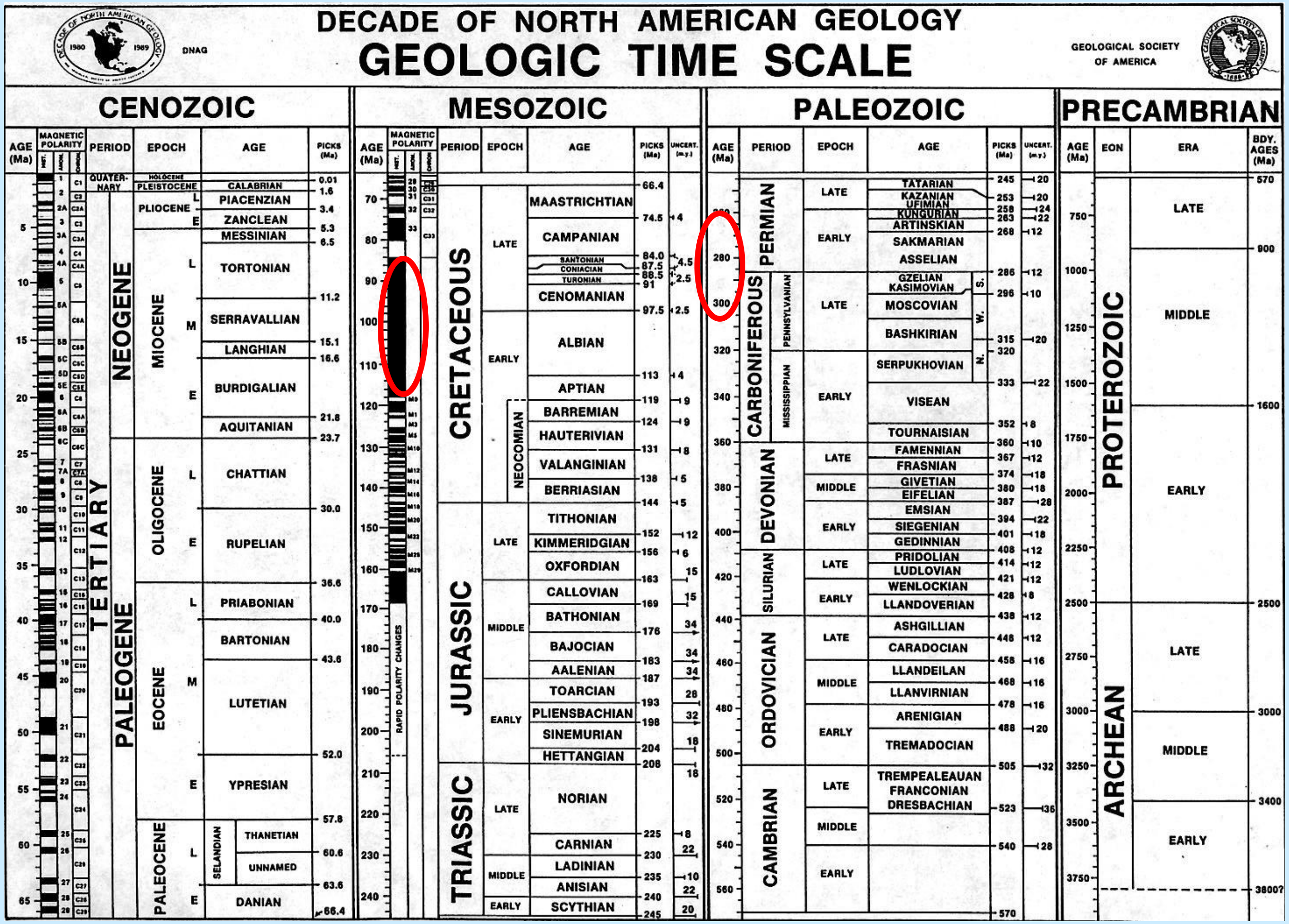






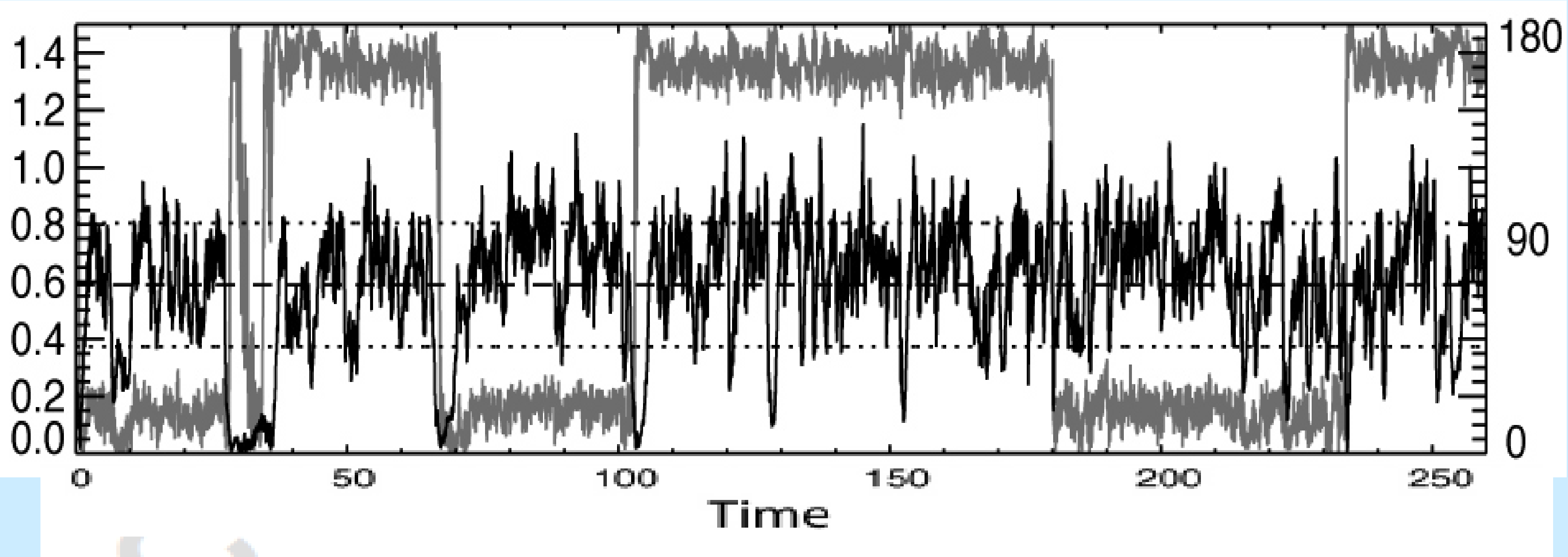
A key evidence for plate tectonics

Magnetic polarity reversals and superchrons



Cretaceous Superchron (120-83 Ma), and Kaiman Superchron (310-260 Ma)

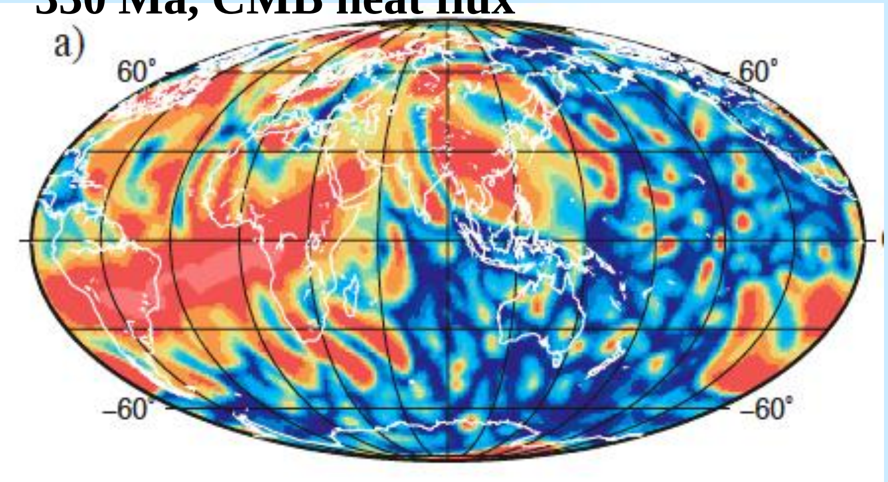
Controls of core-mantle boundary (CMB) heat flux on magnetic reversal frequency



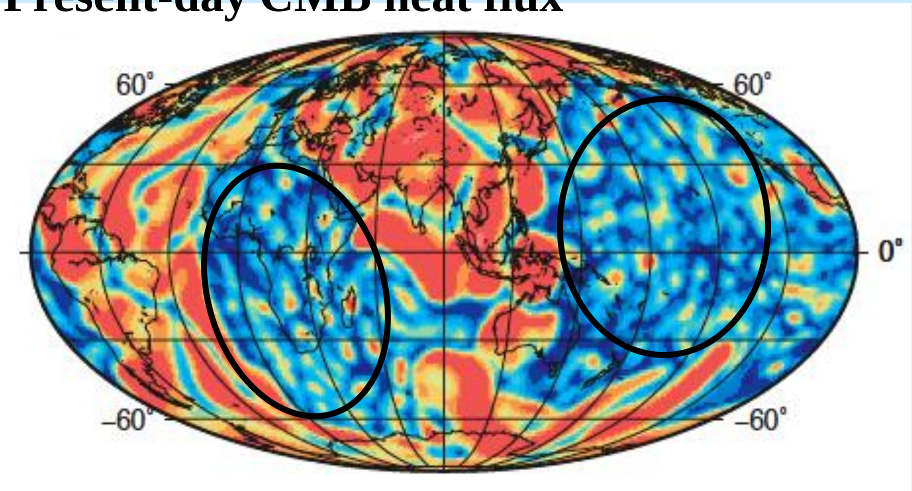
Olson et al. (2010) reported from dynamo simulation (magnetohydrodynamics or MHD) that stable magnetic polarity is associated with relatively small CMB heat flux in equatorial regions.

Predicted time evolution of CMB heat flux [Zhang & Zhong, 2011b]

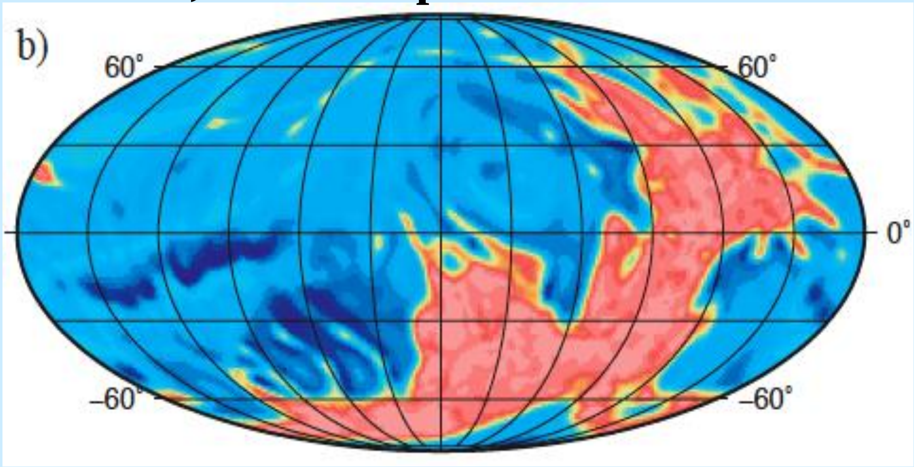
330 Ma, CMB heat flux



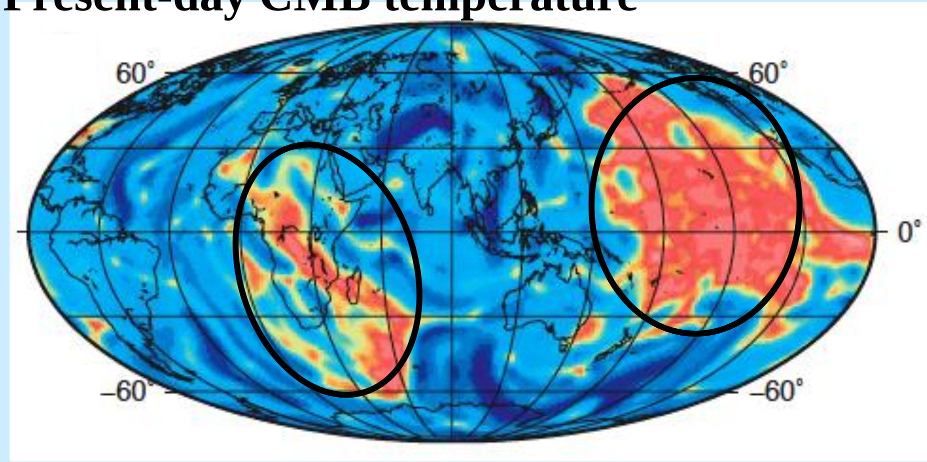
Present-day CMB heat flux



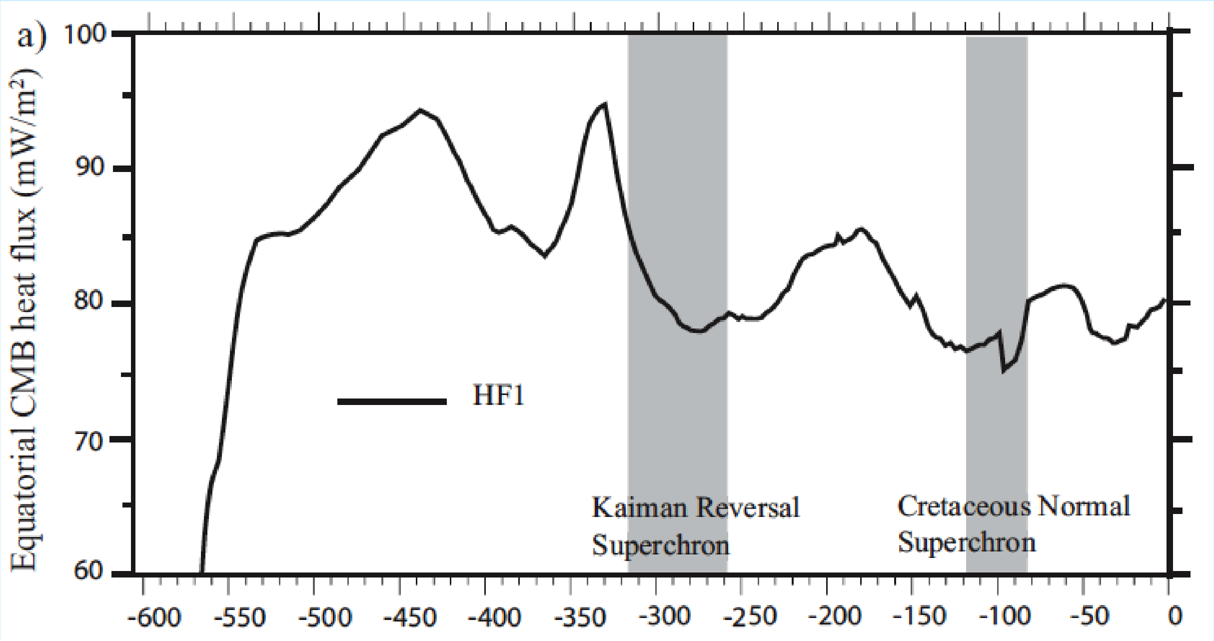
330 Ma, CMB temperature



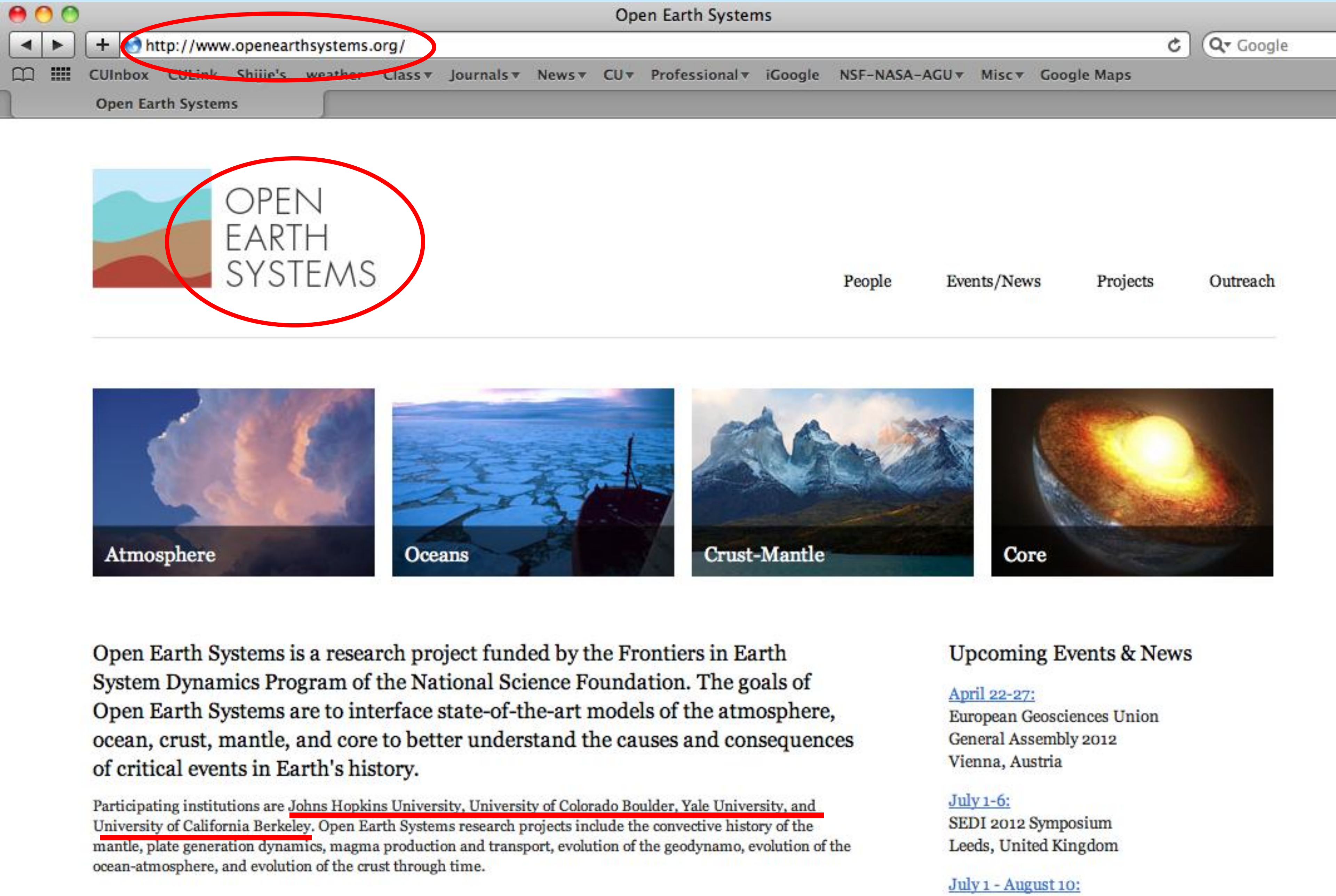
Present-day CMB temperature



Time evolution of equatorial CMB heat flux



The CMB heat flux maps are used by Olson's group for dynamo modeling in a major NSF-funded collaborative project – Open Earth Systems.



Open Earth Systems

http://www.openearthsystems.org/

CUInbox CULink Shijie's weather Class Journals News CU Professional iGoogle NSF-NASA-AGU Misc Google Maps

Open Earth Systems

OPEN
EARTH
SYSTEMS

People Events/News Projects Outreach

Atmosphere

Oceans

Crust-Mantle

Core

Open Earth Systems is a research project funded by the Frontiers in Earth System Dynamics Program of the National Science Foundation. The goals of Open Earth Systems are to interface state-of-the-art models of the atmosphere, ocean, crust, mantle, and core to better understand the causes and consequences of critical events in Earth's history.

Participating institutions are Johns Hopkins University, University of Colorado Boulder, Yale University, and University of California Berkeley. Open Earth Systems research projects include the convective history of the mantle, plate generation dynamics, magma production and transport, evolution of the geodynamo, evolution of the ocean-atmosphere, and evolution of the crust through time.

Upcoming Events & News

April 22-27:
European Geosciences Union
General Assembly 2012
Vienna, Austria

July 1-6:
SEDI 2012 Symposium
Leeds, United Kingdom

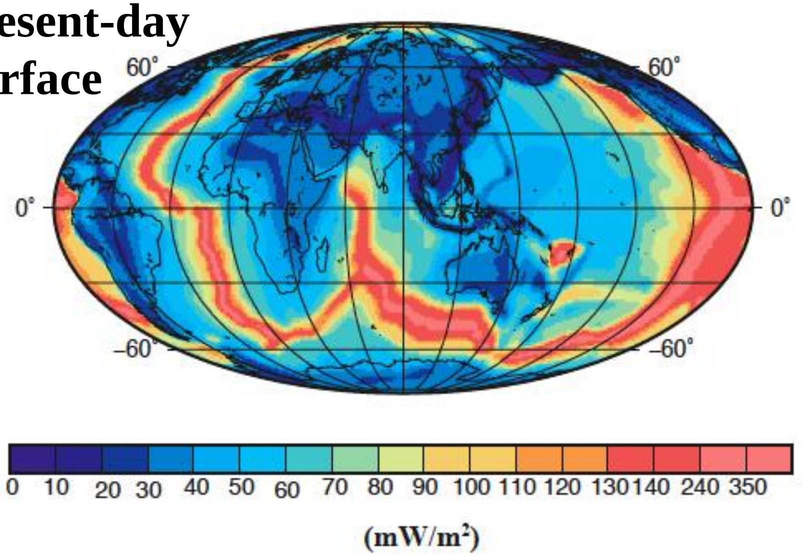
July 1 - August 10:

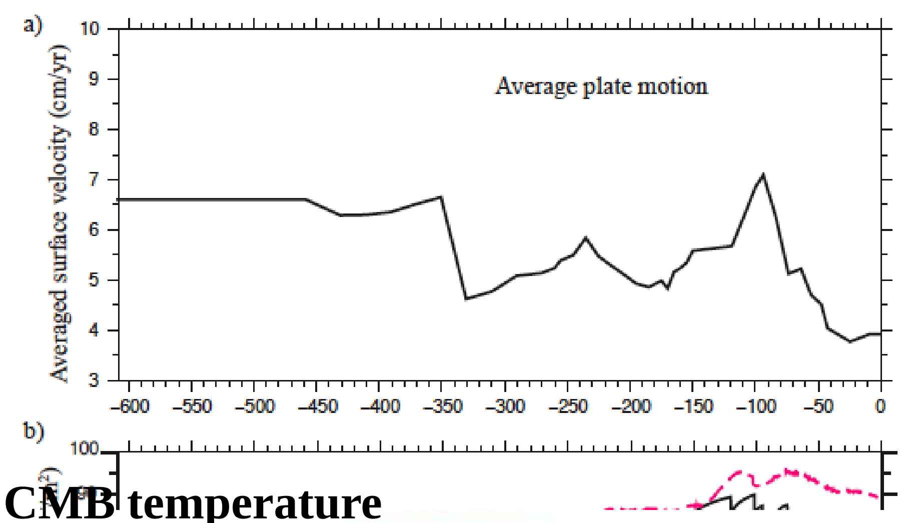
Summary

- **Proposed an 1→2→1 cyclic model for the evolution of mantle structure modulated by supercontinent cycle.**
- **Built a mantle evolution model for the last 500 Ma that is constrained by plate motion history, present-day seismic structures, and continental craton vertical motions.**
- **Implications for seismic structures (**_the African and Pacific superplumes – the African superplume is younger!_**), plume-related volcanism, magnetic polarity reversals (superchrons), and Earth system dynamics.**

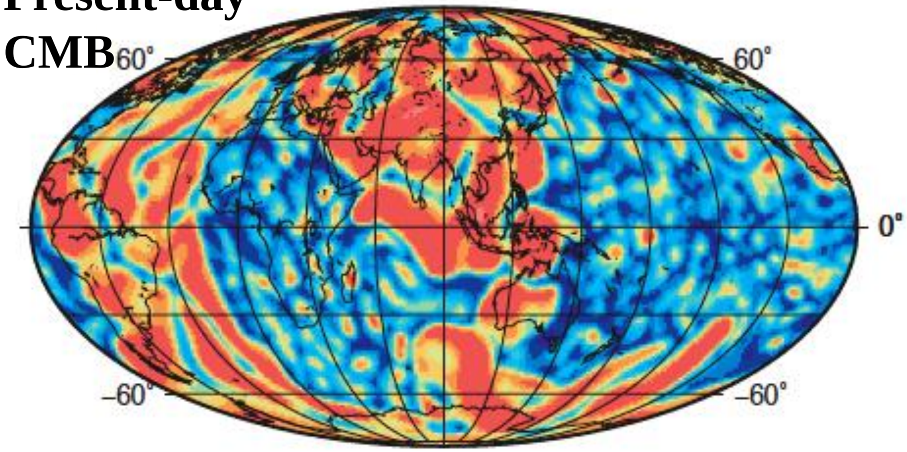
Time evolution of global surface and CMB heat flux [Zhang & Zhong, 2011b]

Present-day Surface

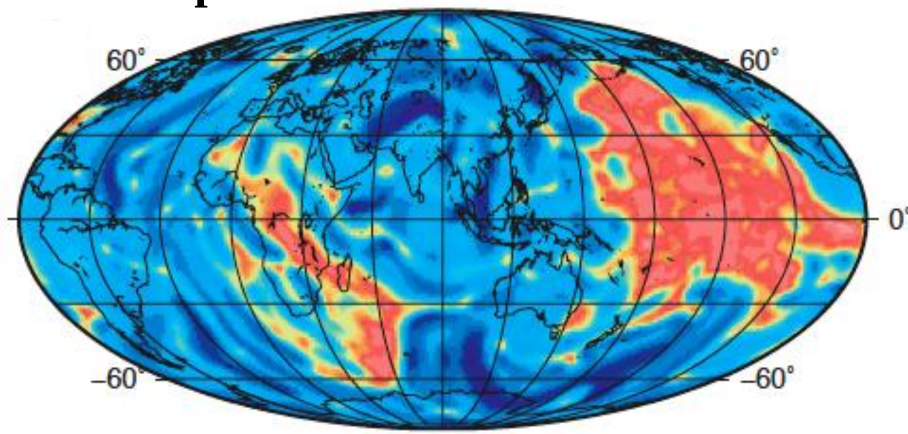




Present-day CMB

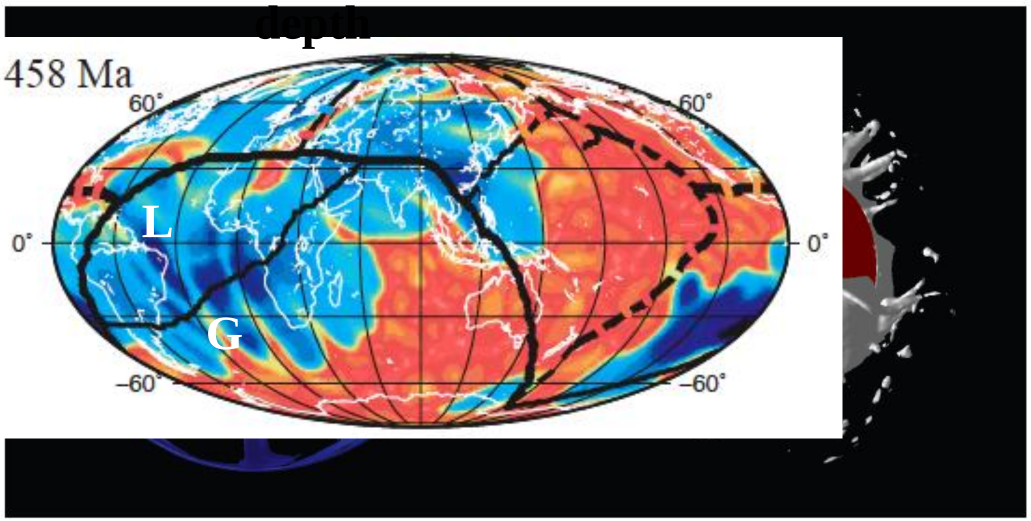


CMB temperature

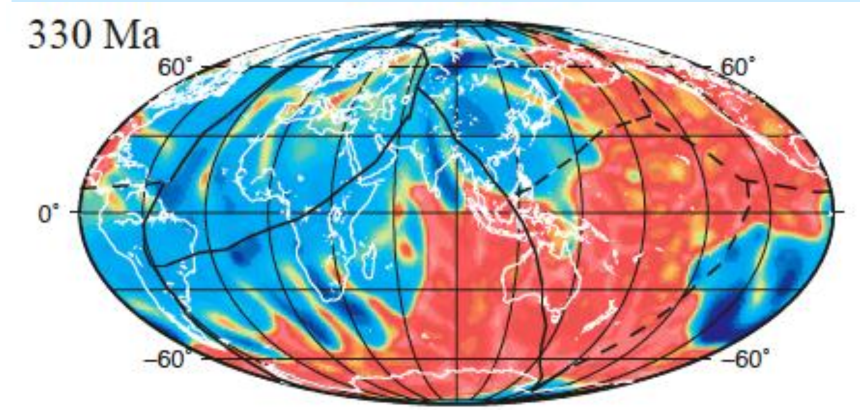


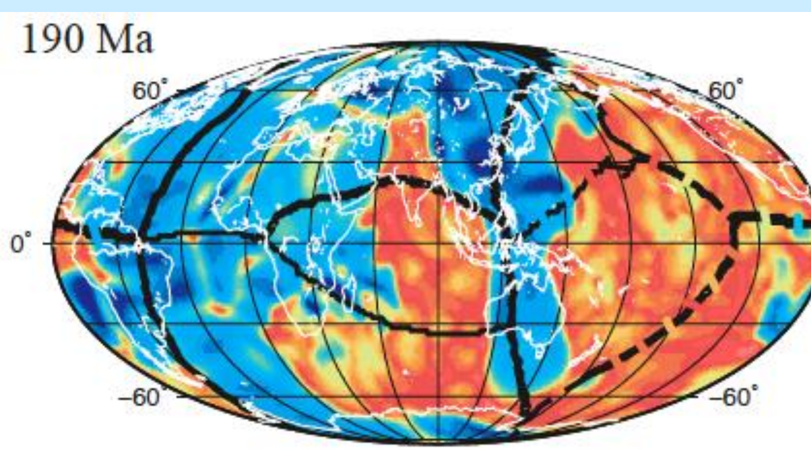
Results: Thermo-chemical structures at different times

330 Ma (i.e., when Pangea was formed)
depth

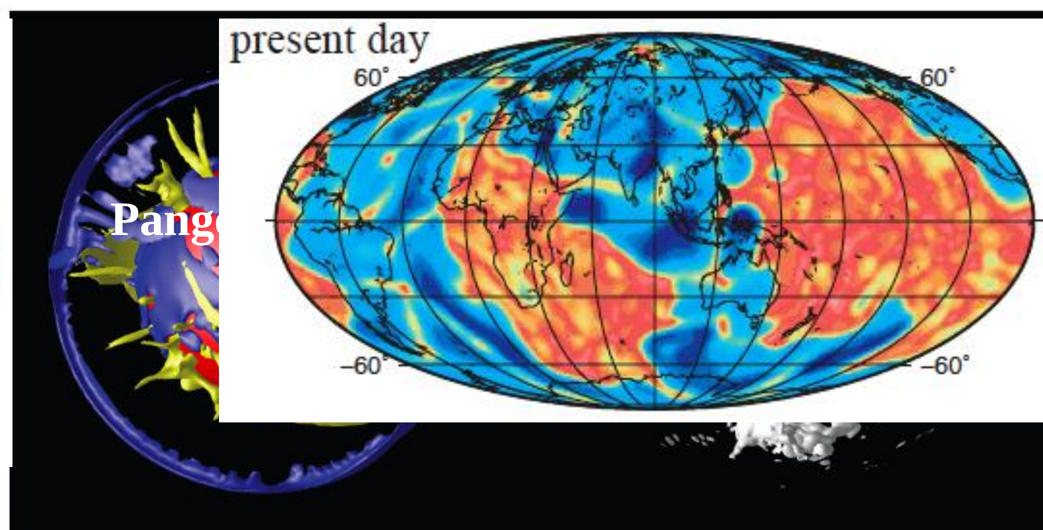


2700 km depth



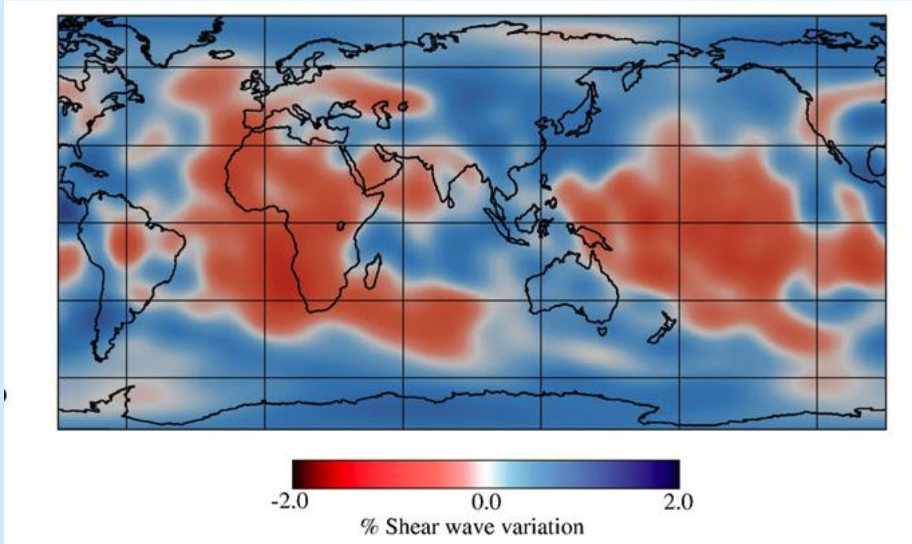


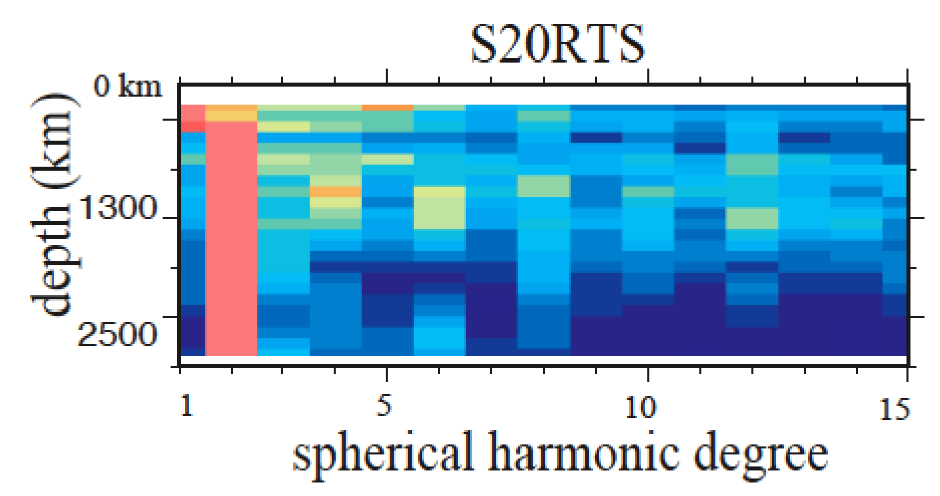
190 Ma



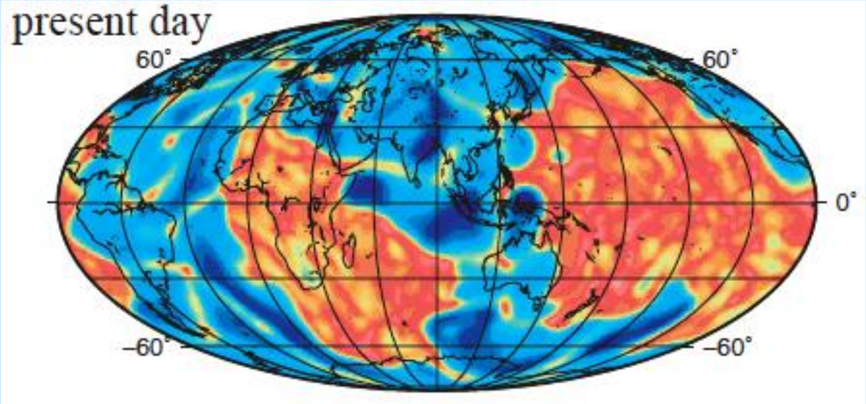
Comparison with present-day seismic structure

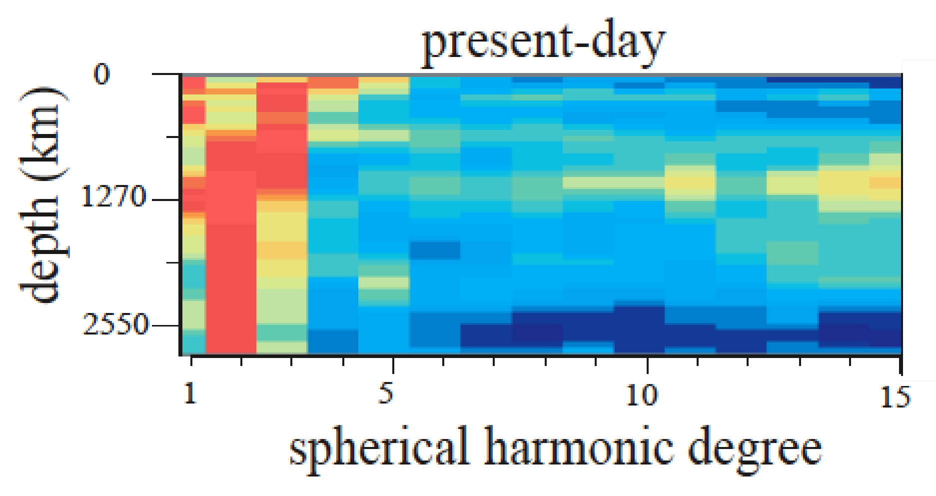
S20RTS @2750 km depth



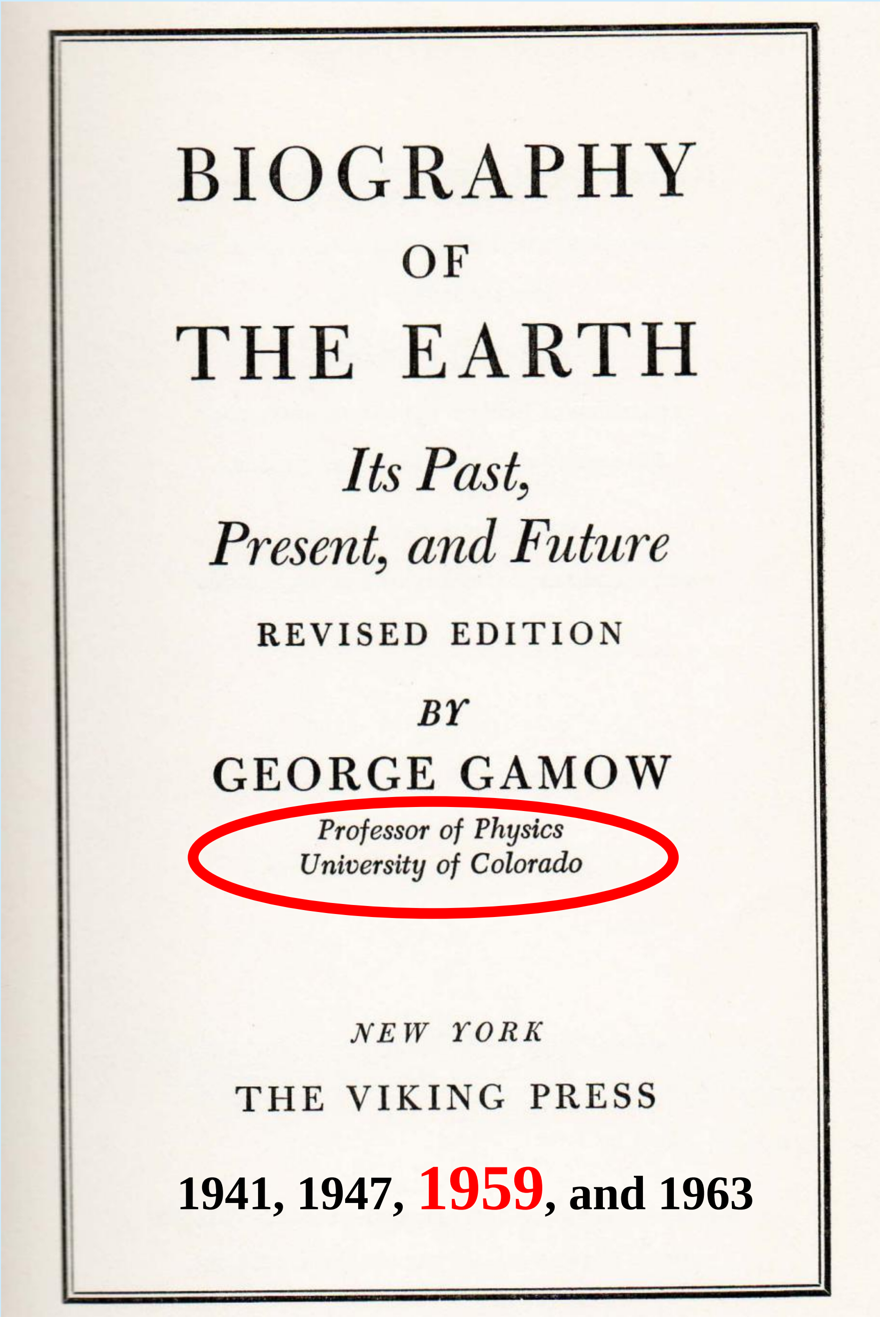


@2700 km depth





Zhang et al [2010]



BIOGRAPHY
OF
THE EARTH

Its Past,
Present, and Future

REVISED EDITION

BY

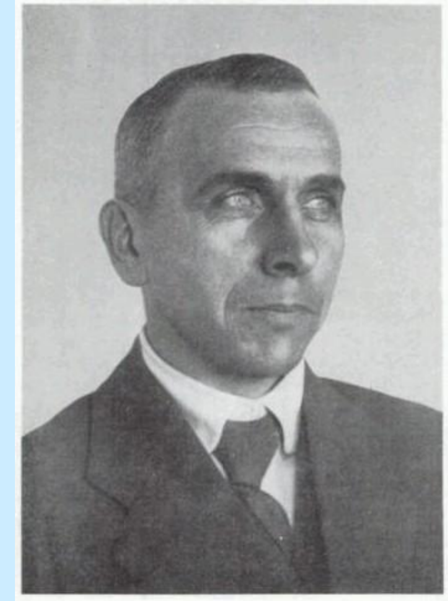
GEORGE GAMOW

Professor of Physics
University of Colorado

NEW YORK

THE VIKING PRESS

1941, 1947, 1959, and 1963



Alfred Wegener

Continental drift

Pangea

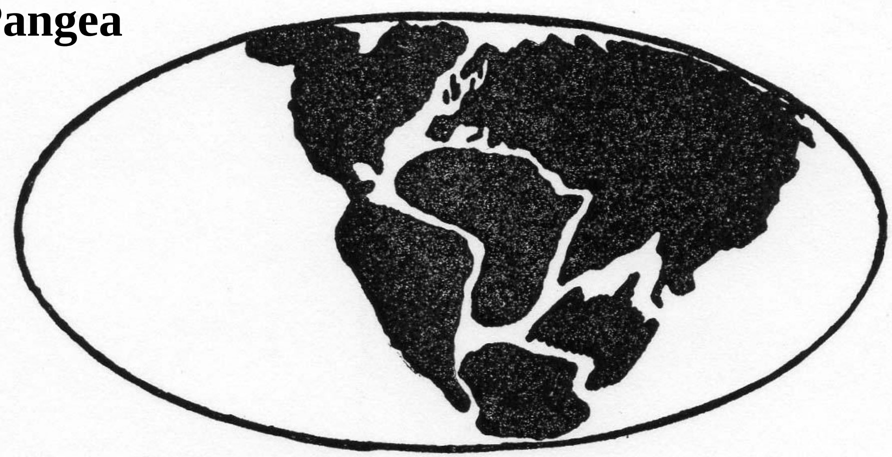
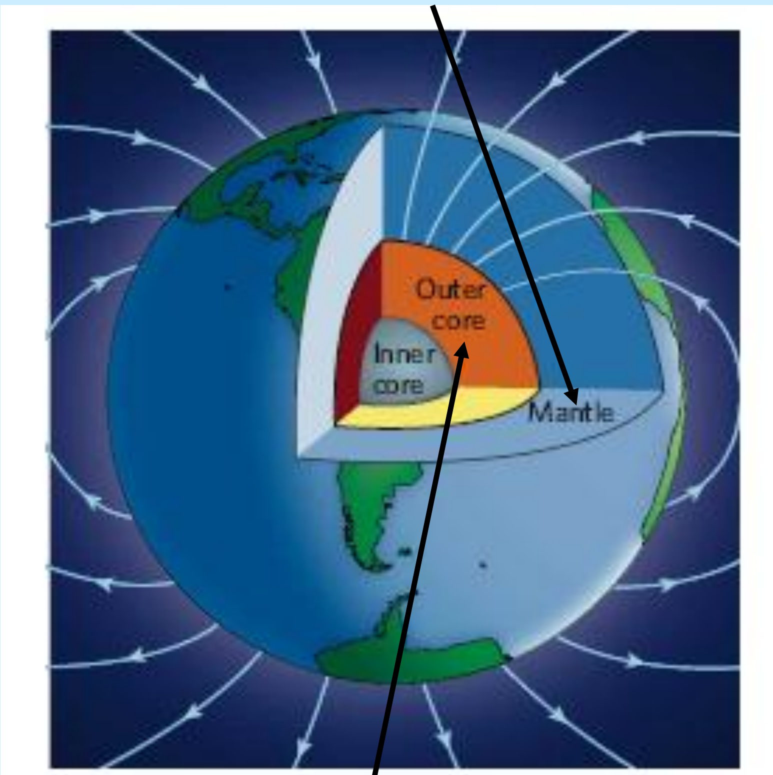


FIGURE 31
Relative position of the fragments of the original crust immediately after the separation of the Moon. (Not to be used as proof of the possibility of invasion of the United States.)

Confirmation of Continental Drift from Paleo-magnetism and Other Studies (1950's-1960's)

Rocky (Silicate)



Metallic (Fe, Ni). Liquid outer core.

Dynamo action caused by Earth's rotation and convective motion in the outer core.

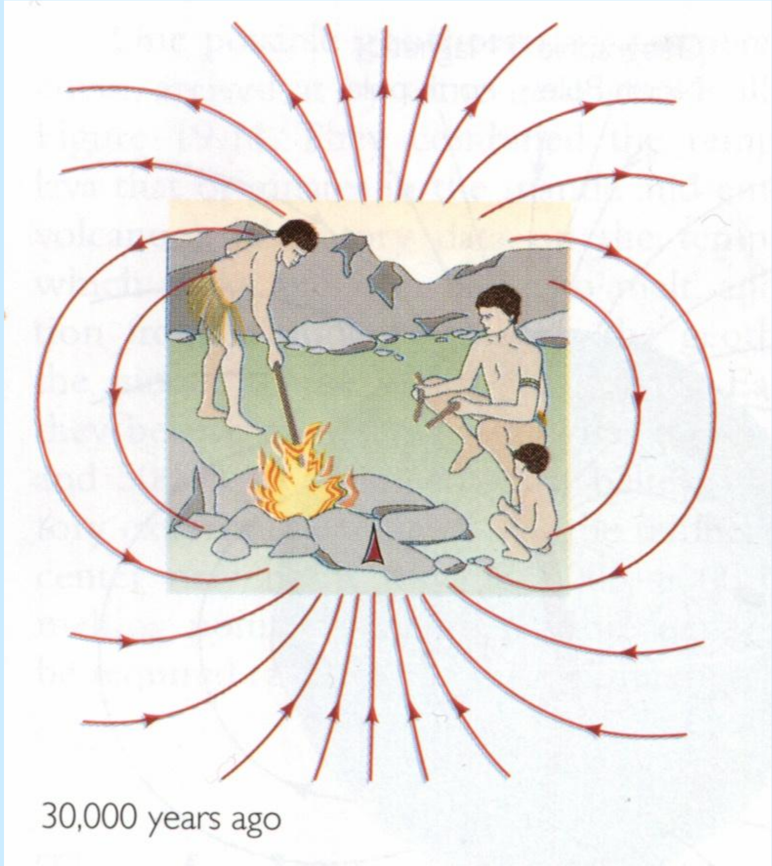
Keith Runcorn

Patrick Blackett

Earth's paleomagnetic field recorded in (magnetized) rocks.

Magnetization of rocks

(actually minerals such as magnetite Fe_3O_4)

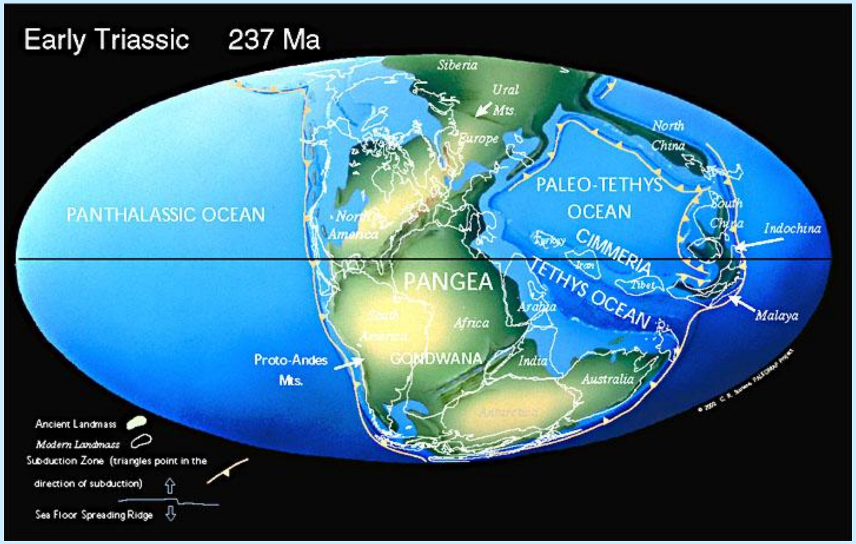


Determine B field direction to get paleo-latitude of the rock at the time of magnetization.

Magnetization of rocks while being cooled below Curie temperatures (500-900 ^{o}C).

Basic features of Supercontinents Pangea and Rodinia

Pangea [Scotese, 1997]

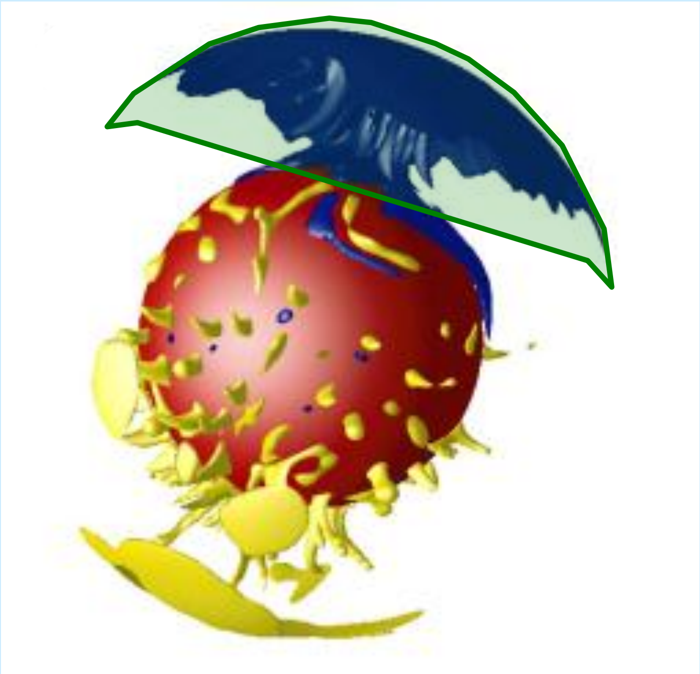


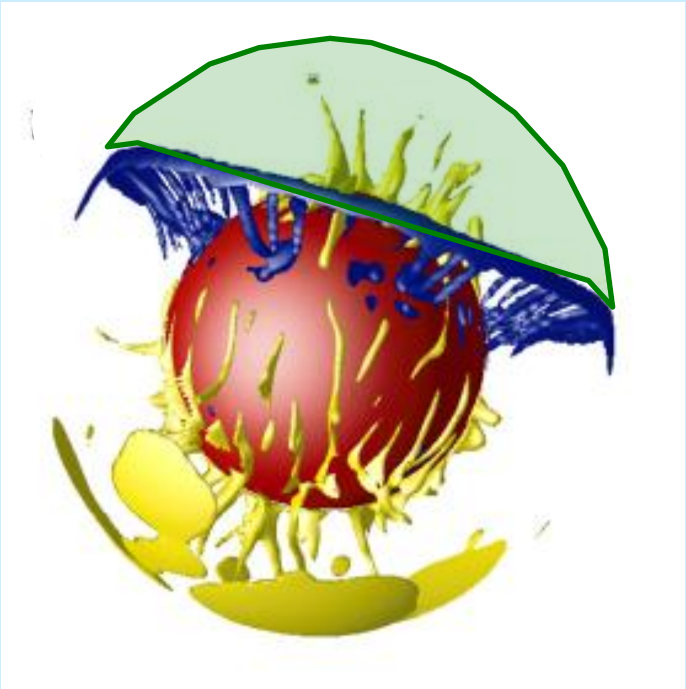
Rodinia [Li et al., 2008]

- **Cyclic process.**
- **Surrounded by subduction zones (i.e., convergence zones).**
- **Centered at the equator before the breakup.**
- **Only existed for 150 Ma before the breakup.**
- **Tectonics (mountain building at the formation and continental rifting and magmatism at the breakup).**
- **…**

Effects of a supercontinent after its formation

Add a supercontinent



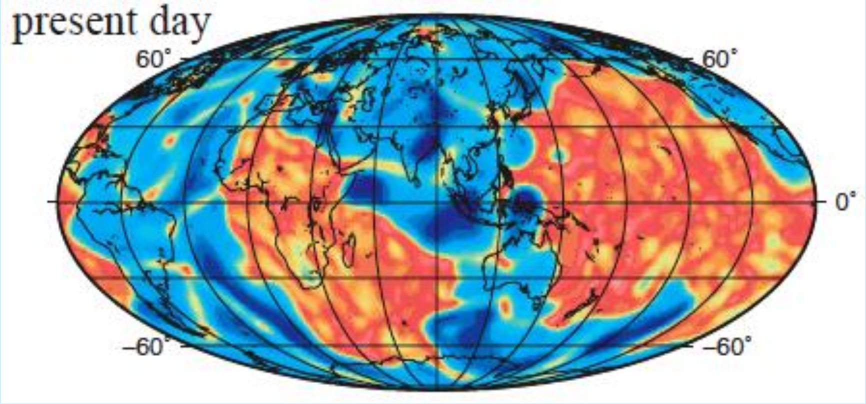


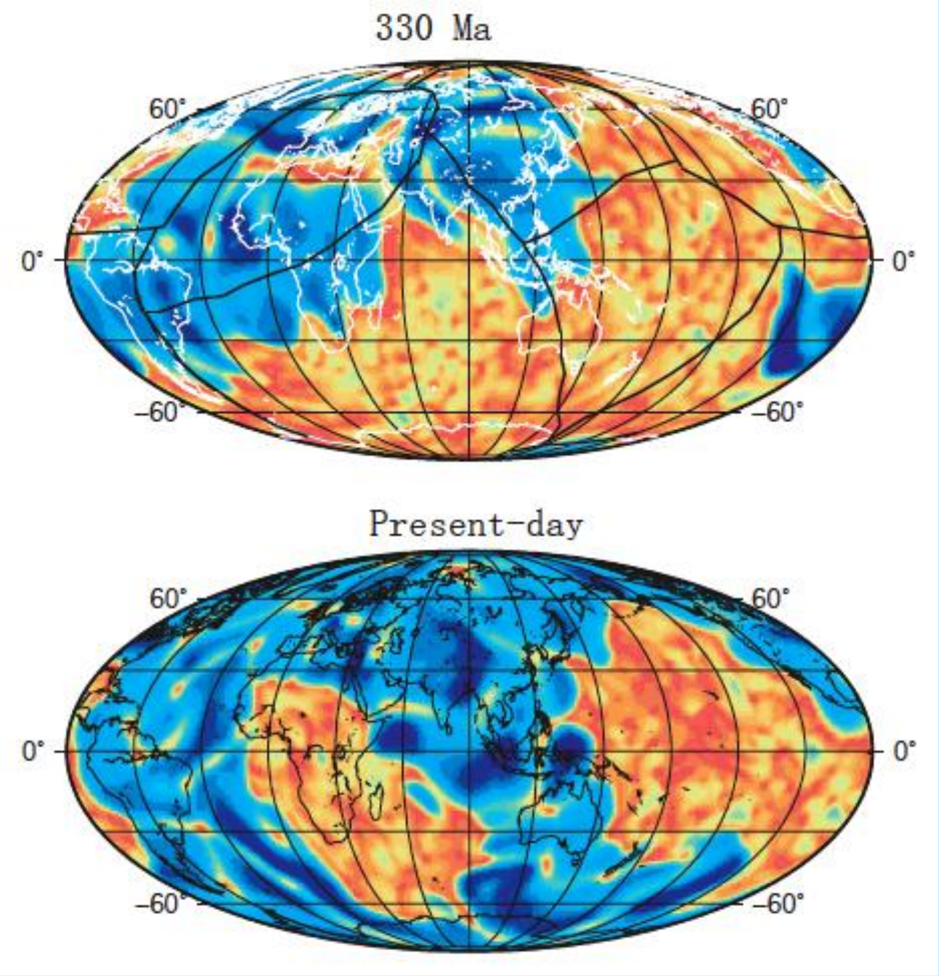
Consequences of a supercontinent:

- **Formation of another upwelling system below the supercontinent, largely in response to the circum-continent subduction.**
- **Transformation from degree-1 to degree-2 structures.**
- **Eventually breakup of the supercontinent.**

Test 1: Always Degree-2? (Burke et al., 2008)

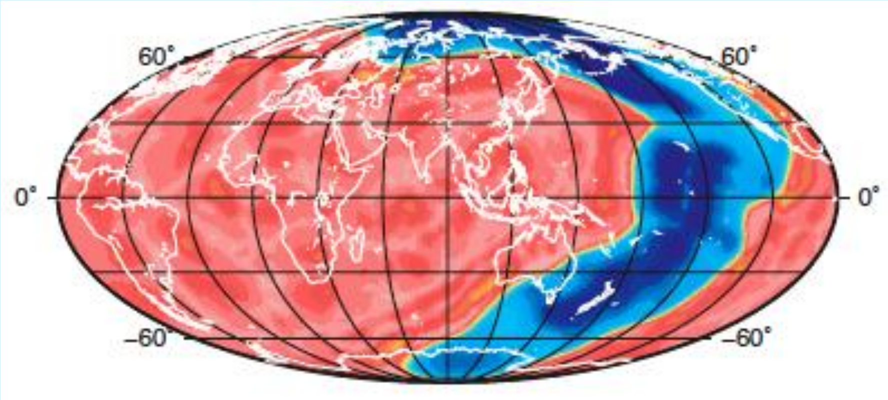
Using present-day modeled thermochemical structure (degree-2) as initial condition.



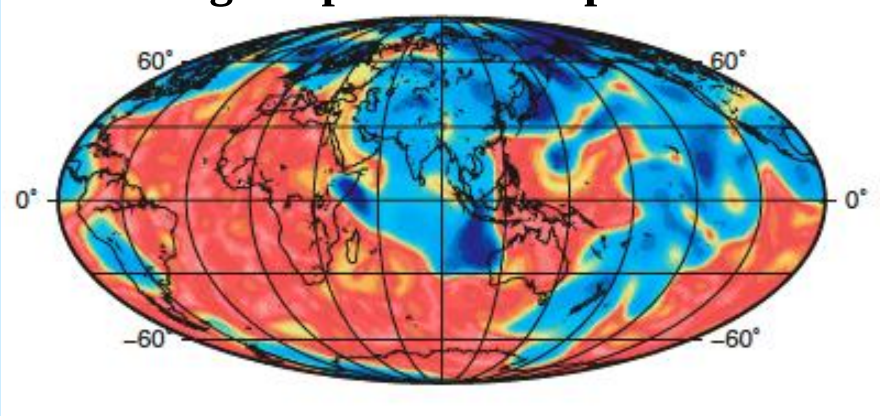


Test 2: Downwellings in the Pacific hemisphere?

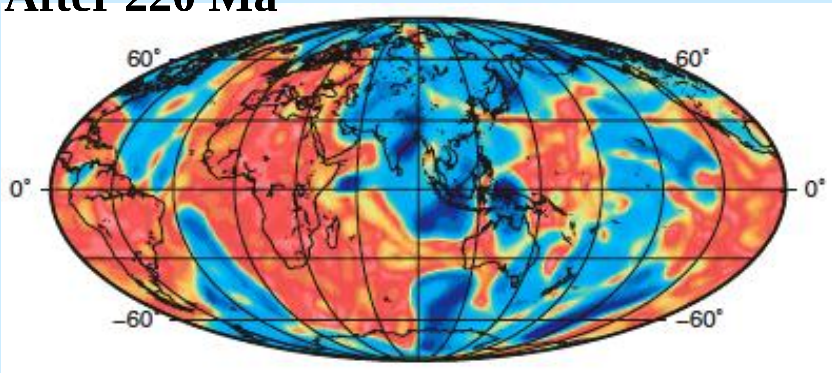
Initial condition includes a downwelling In the Pacific hemisphere.



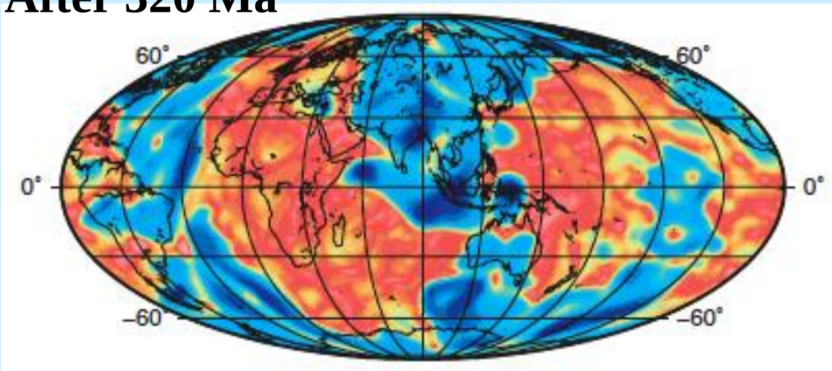
After using the past 120 Ma plate motion.



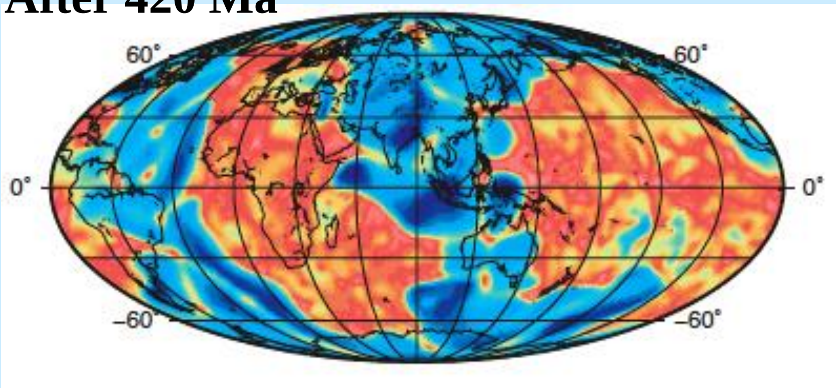
After 220 Ma

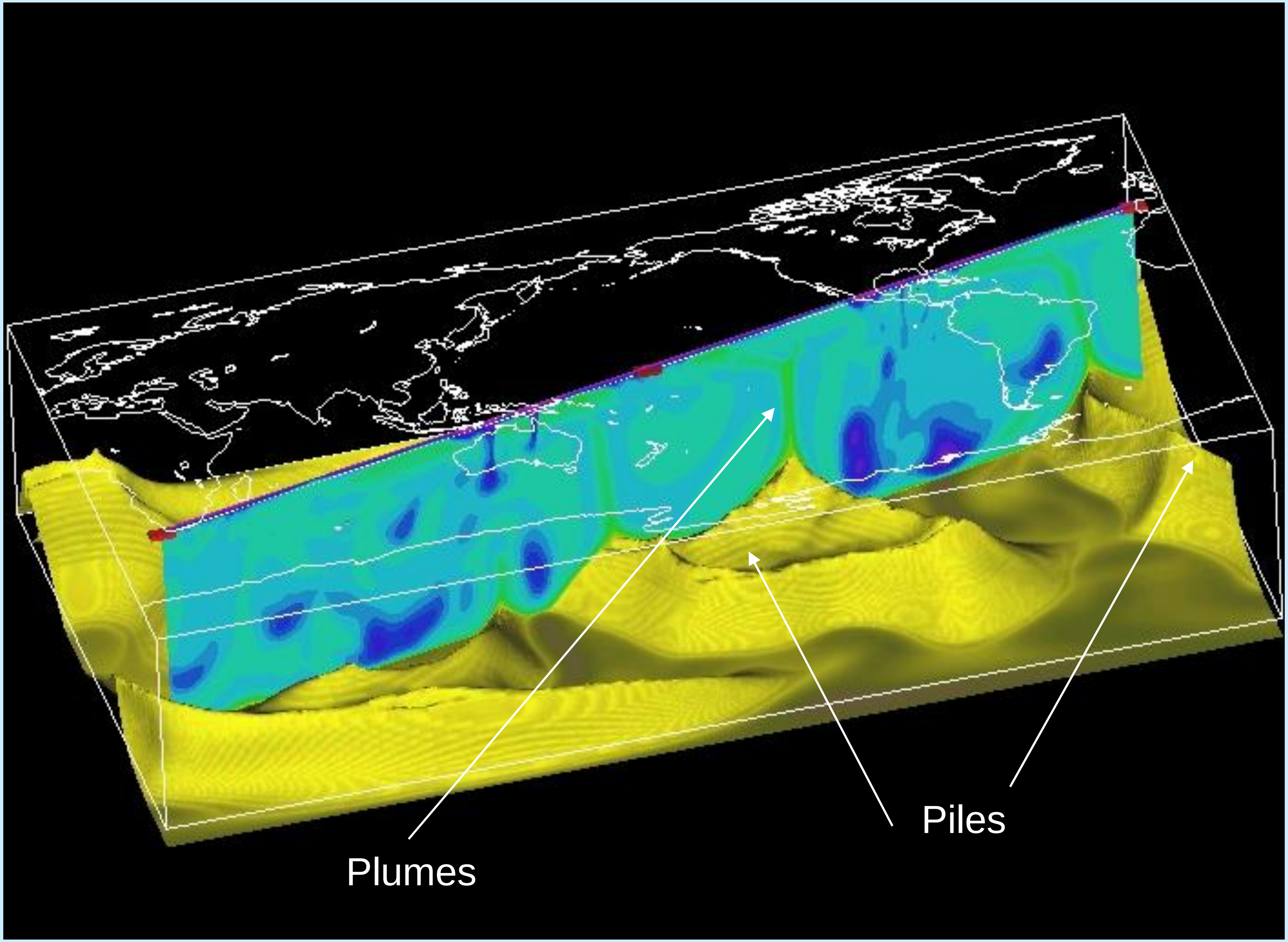


After 320 Ma



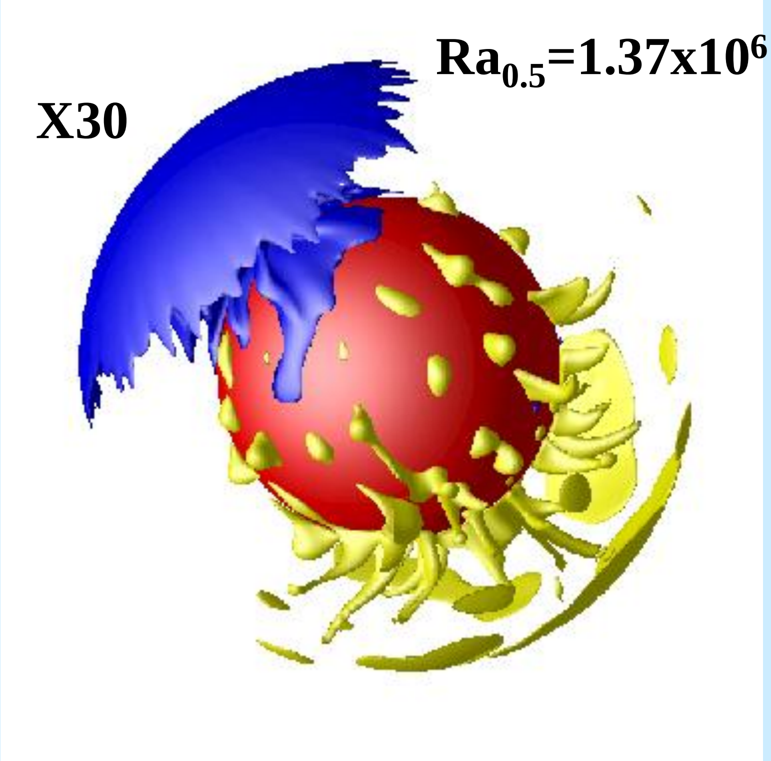
After 420 Ma

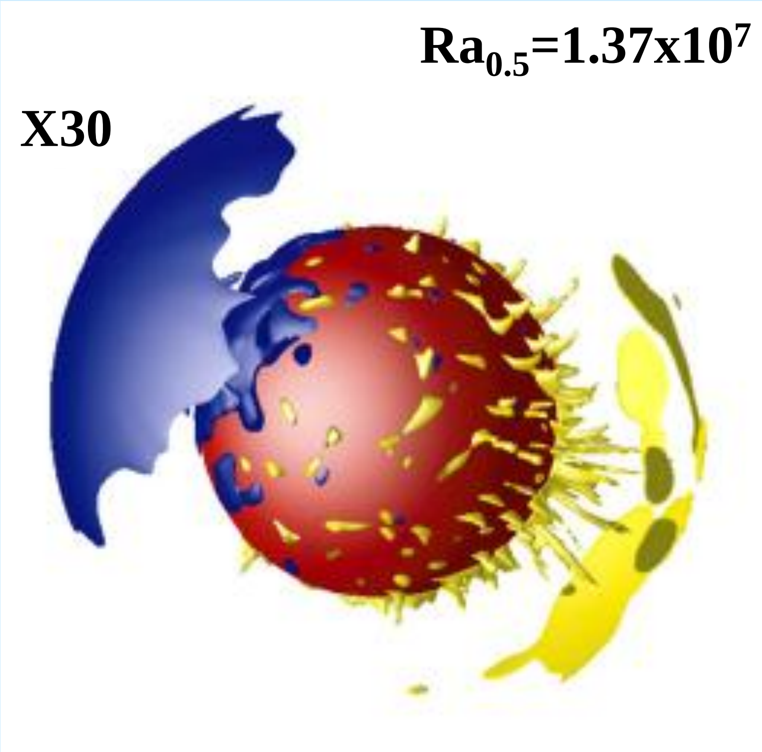




(figure courtesy of Chuck Meertens, GEON)

Independent of initial conditions, internal heating rate, and convective vigor

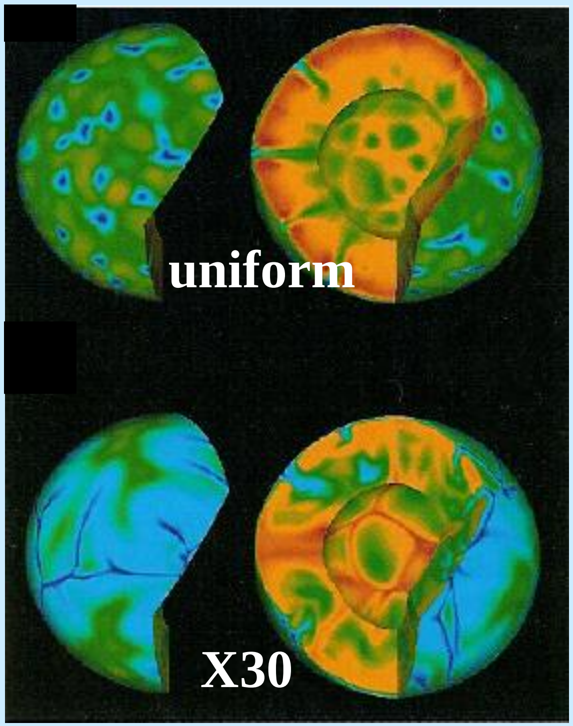




Average surface velocity:
~ 6 cm/year

Generation of long-wavelength mantle convection from radially stratified mantle viscosity

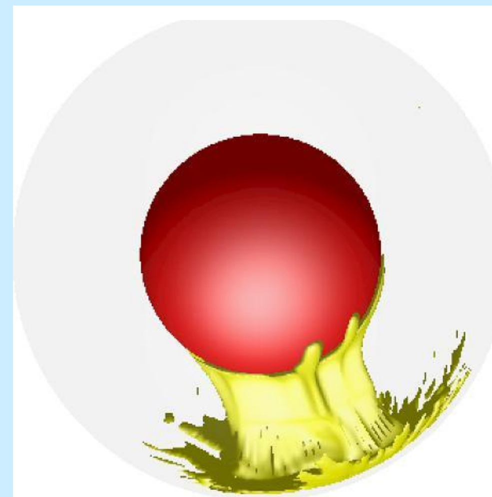
Suggested by Jaupart & Parsons [1985] and Zhang & Yuen [1995]



Bunge et al. [1996].

Largely at degree 6

Stagnant-lid convection for Mars

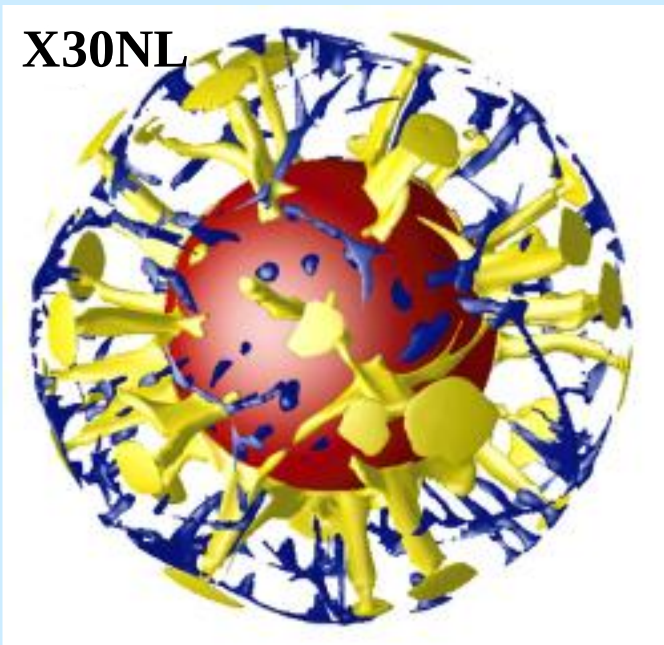


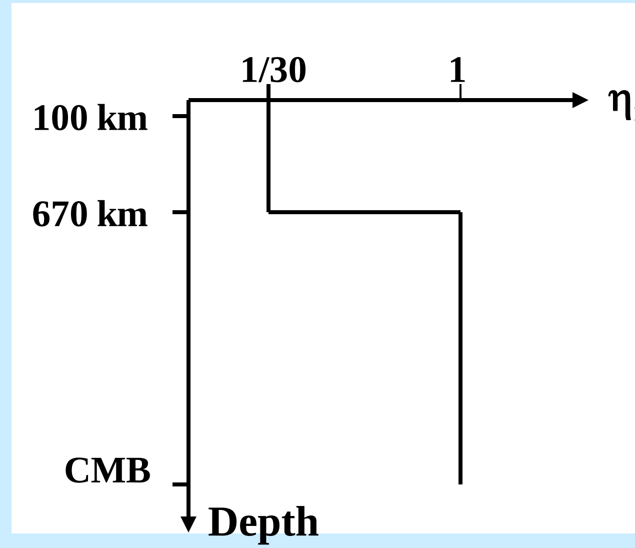
Roberts & Zhong [2004; 2006].

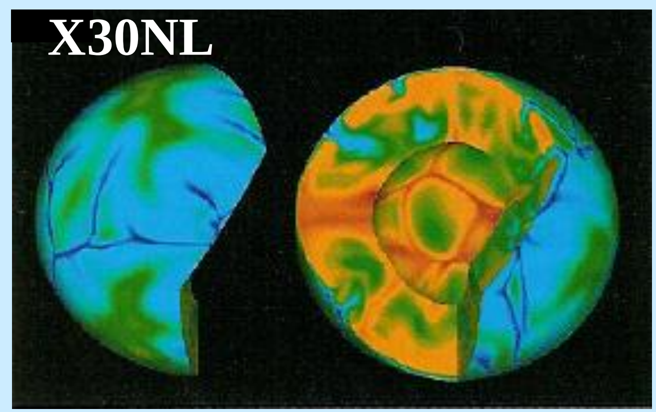
However, the exact mechanism is still an active research area [see Zhong & Zuber, 2001; Lenardic et al., 2006; Zhang & Zhong, 2007].

Lithospheric viscosity also plays an important role

X30 viscosity increase at 670 km depth but no lithosphere



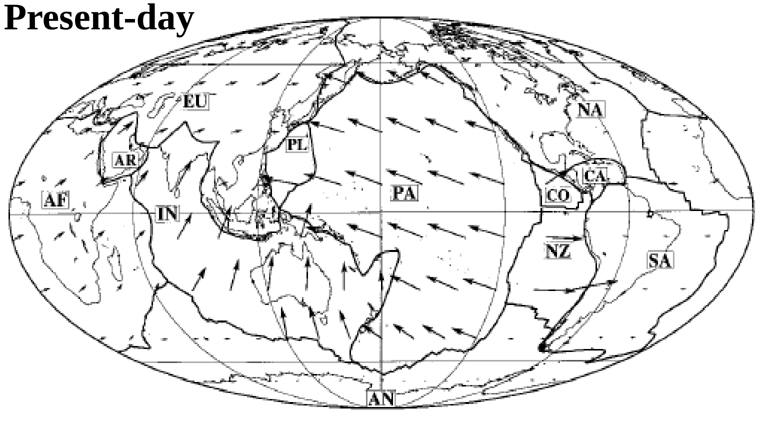




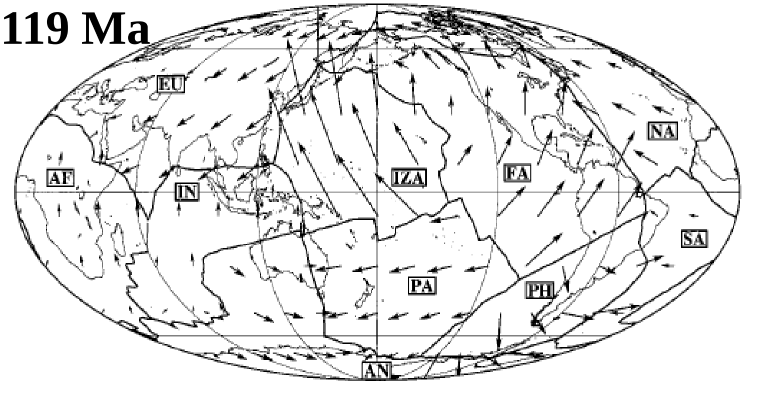
Largely at *l*=6 Bunge et al. [1996].

Previous explanation for the lack of TPW for the last 56 Ma

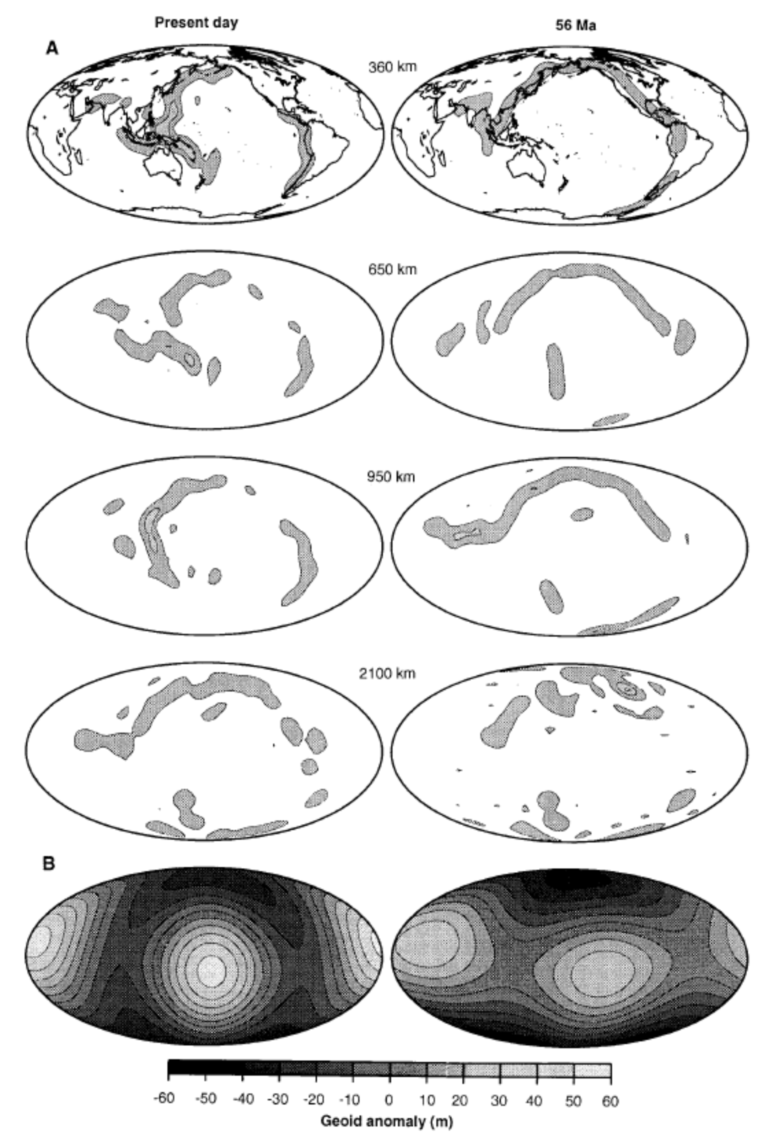
Present-day



119 Ma



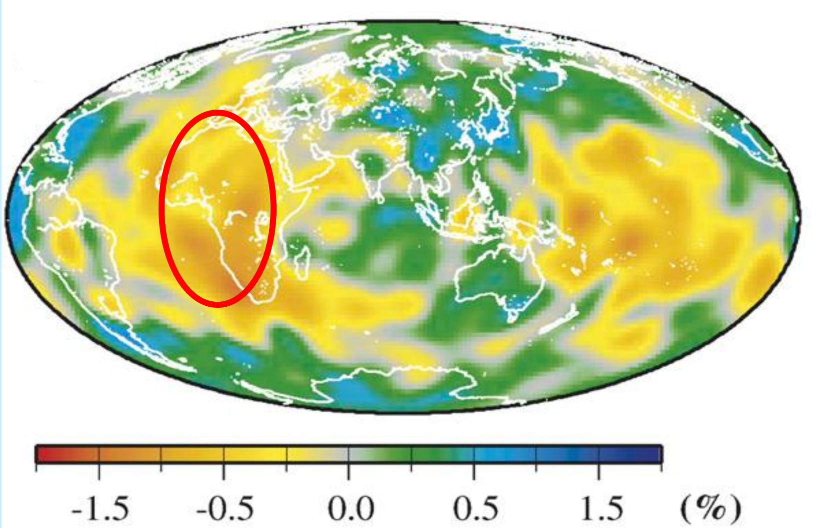
Engebretson et al. [1992]; Lithgow-Bertelloni & Richards [1998].



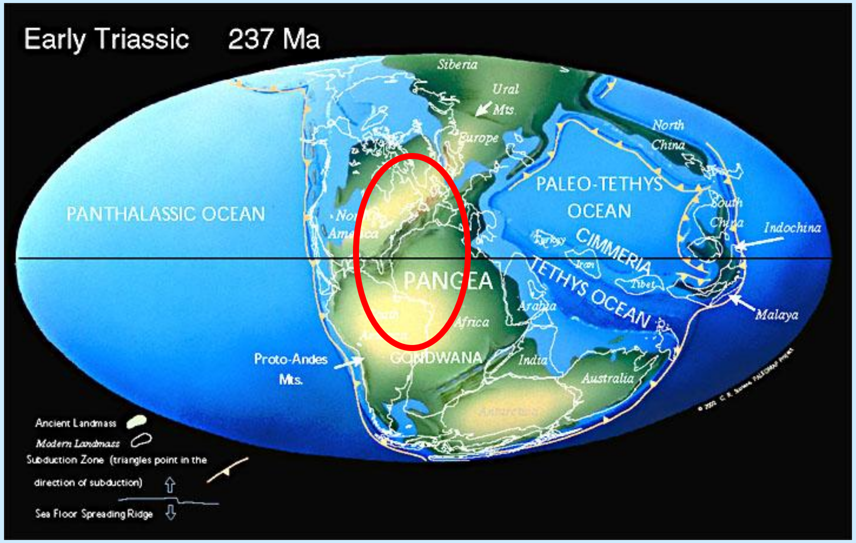
Richards et al. [1997]; Steinberger & O’Connell [1997]

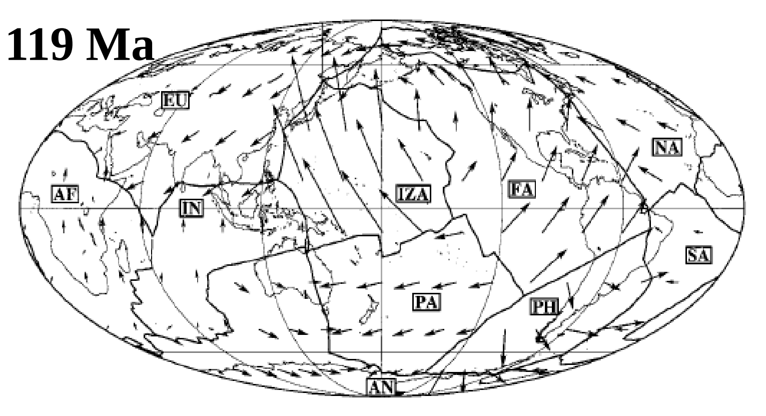
Mantle convection and structure and surface plate motion

African and Pacific super-plumes (antipodal) [Ritsema et al., 1999]



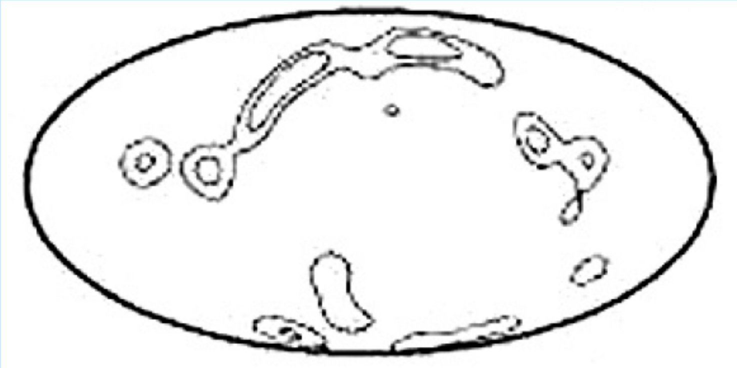
Pangea [Scotese, 1997]





Engebretson et al. [1992]; Lithgow-Bertelloni & Richards [1998].

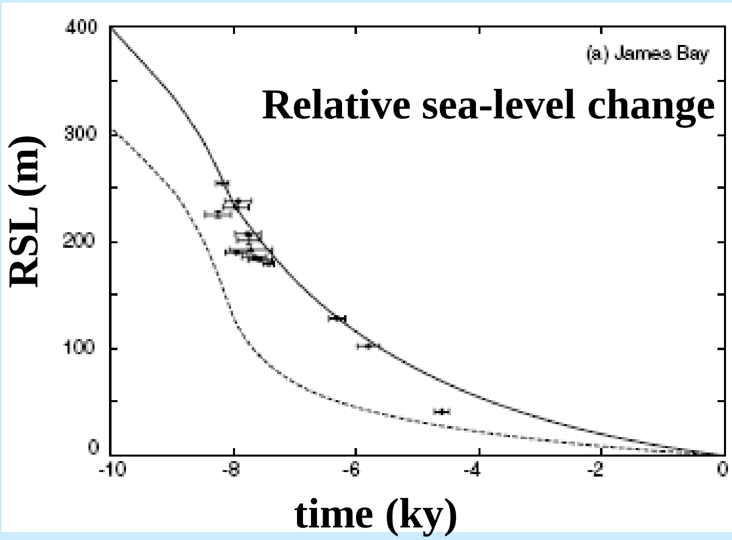
Slab distribution at 2105 km



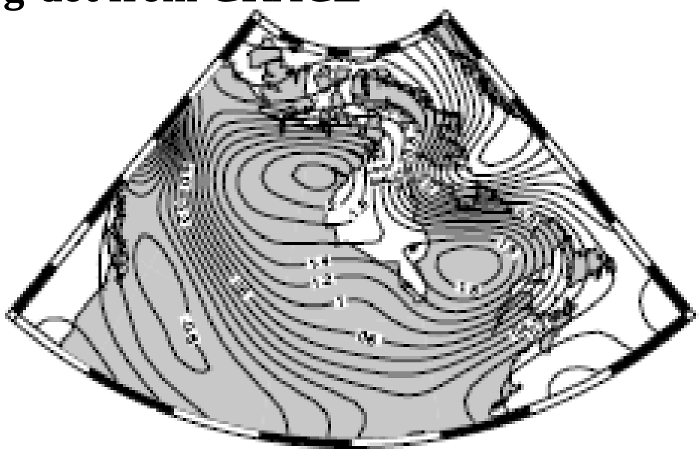
[Lithgow-Bertelloni & Richards, 1998].

Observational evidence for a weak asthenosphere

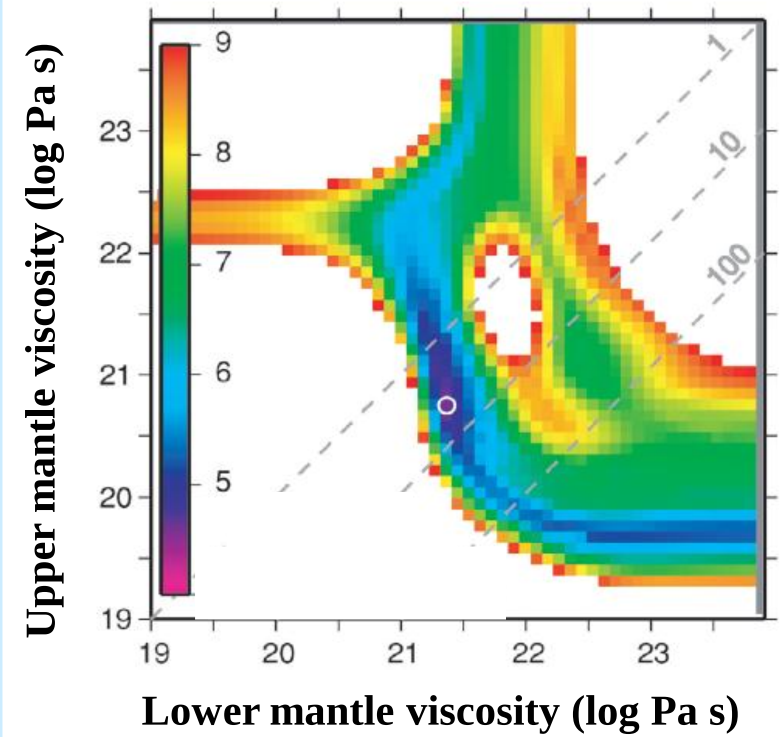
2) Post-glacial rebound [Peltier, 1976, 1998; Forte and Mitrovica, 1997].



g-dot from GRACE

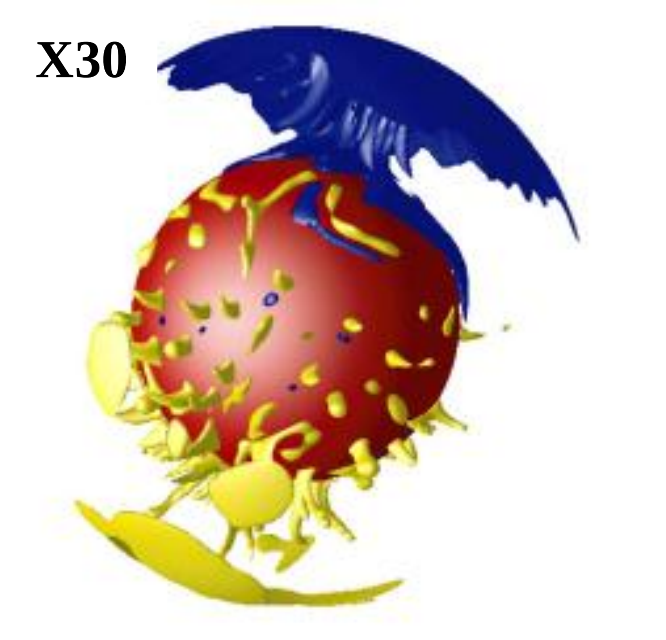


χ^2 misfit from a 2-layer inversion



Paulson, Zhong & Wahr [in press, 2007].

Degree-1 convection as a "ground" state?

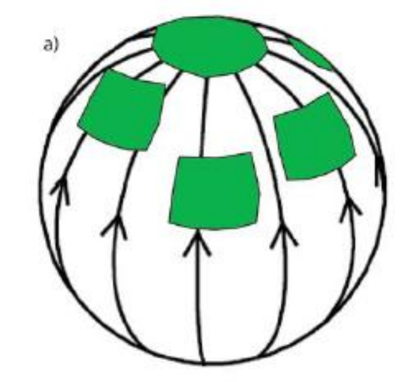


provided that the upper mantle is X30 less viscous than the lower mantle [Hager, 1984] and X200 less viscous than lithosphere [e.g., England & Molnar, 1997].

Degree-1 convection is a "ground" state that the mantle always tends to.

Since the models exclude continents, we propose that when continents are *sufficiently scattered* and do not affect global mantle flow, the mantle should go to this "ground" state.

Kinematic models

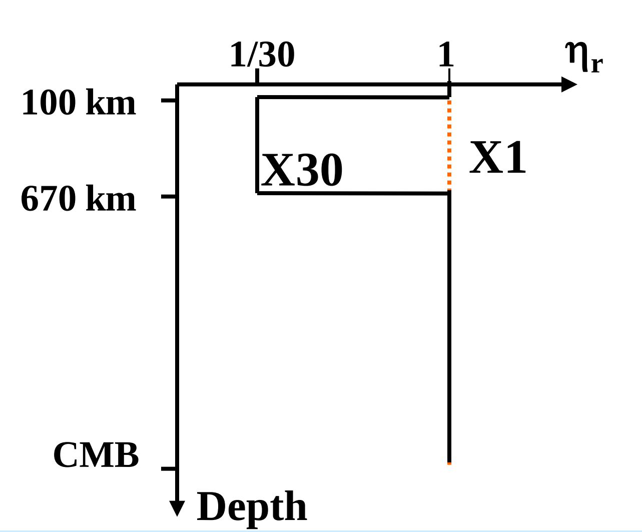


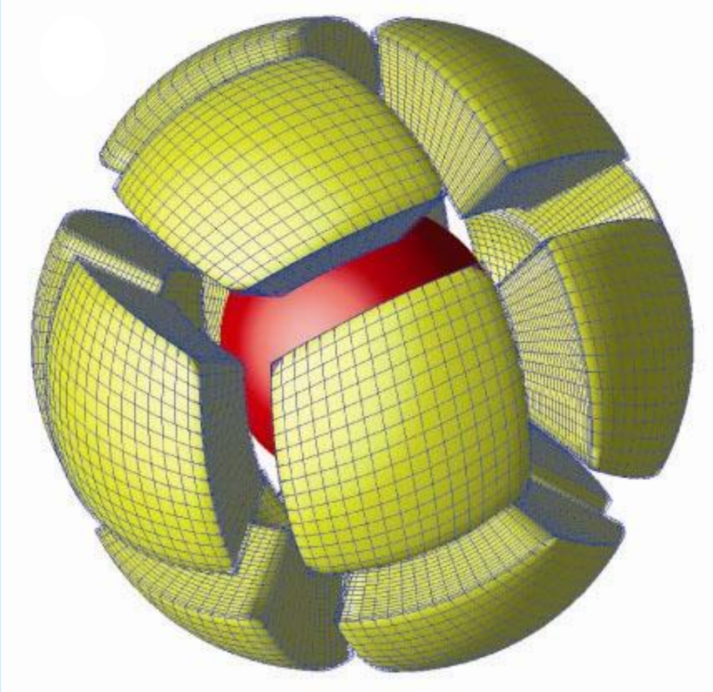
[Evans, 2003]

The degree-1 convection leads to supercontinent formation!

Mobile-lid mantle convection in 3-D spherical shell

1. **Heated both within the mantle (e.g., radiogenic heating) and from the below (i.e., core cooling).**
2. **Temperature- and depth-dependent viscosity: $\eta = \eta_r \exp[E(0.5-T)]$. Activation energy E is such that viscosity varies by 10^3 for non-dimensional temperature *T* varying from 0 at the surface to 1 at the CMB.**
3. **Use a 3D spherical convection code CitcomS that is extensively benchmarked [Zhong et al., 2000; also CIG].**





Supercontinent cycles, true polar wander, and very long-wavelength mantle convection

Shijie Zhong

Department of Physics
University of Colorado at Boulder
U.S.A.

See Zhong et al. [EPSL, 2007]

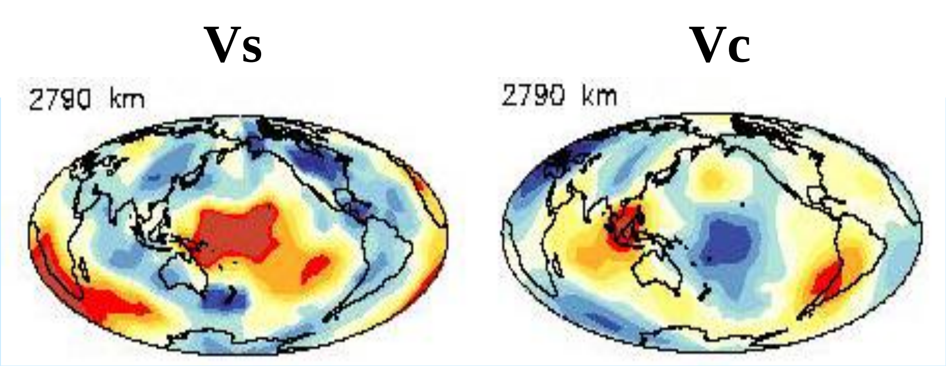
Time evolution of mantle structure for another case (higher Ra and initially random perturbation) (Movie 2)

Symmetric growth of the downwelling.

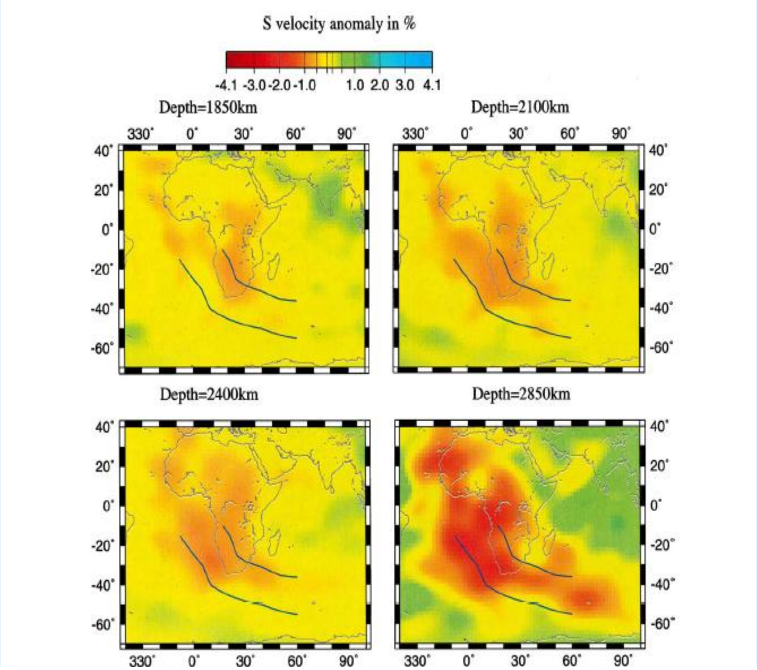
Evidence for compositional anomalies at the base of the mantle

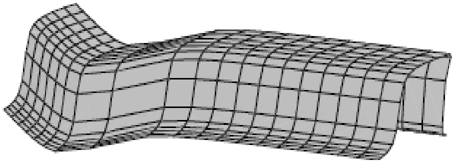
African chemical ridge?

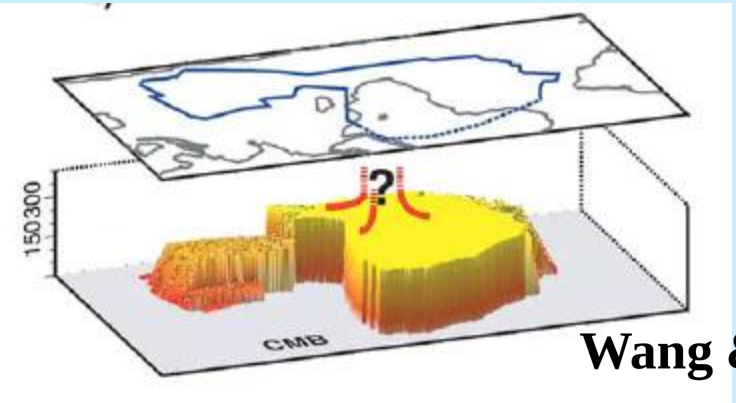
Anti-correlation between shear and bulk sound speeds



Masters et al. [2000];
also Su and Dziewonski [1997]







Wang & Wen [2004]

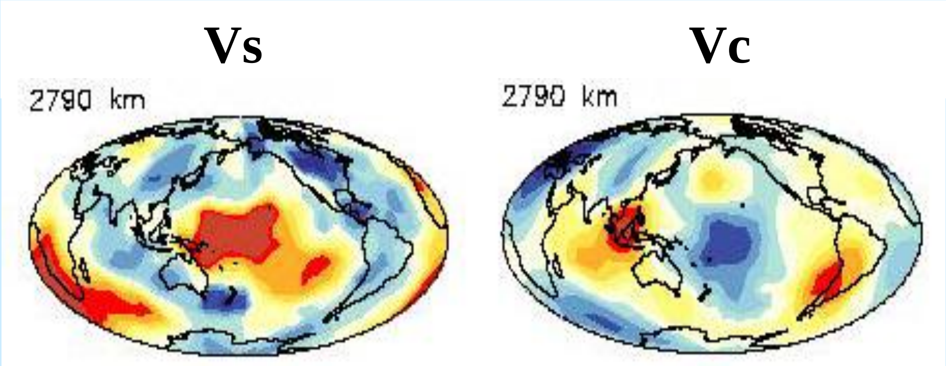
Ni & Helmberger [2003]

Distinct composition for African and Pacific superplumes

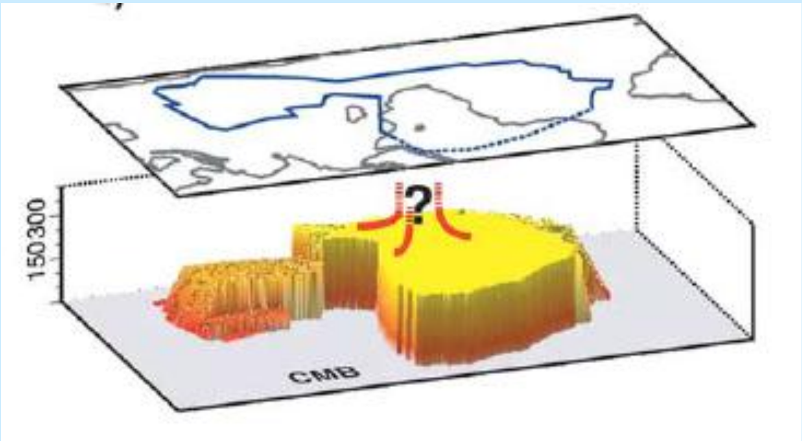
African chemical pile

Wen et al., [2001]; Ni et al., [2002]; He & Wen [2010].

Anti-correlation between shear and bulk sound speeds

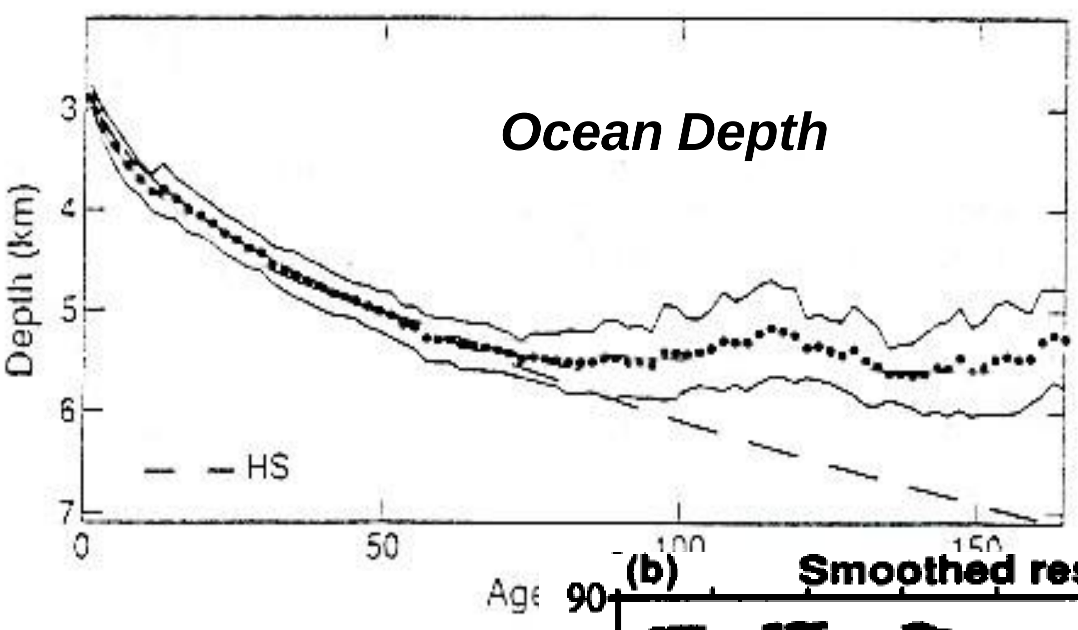


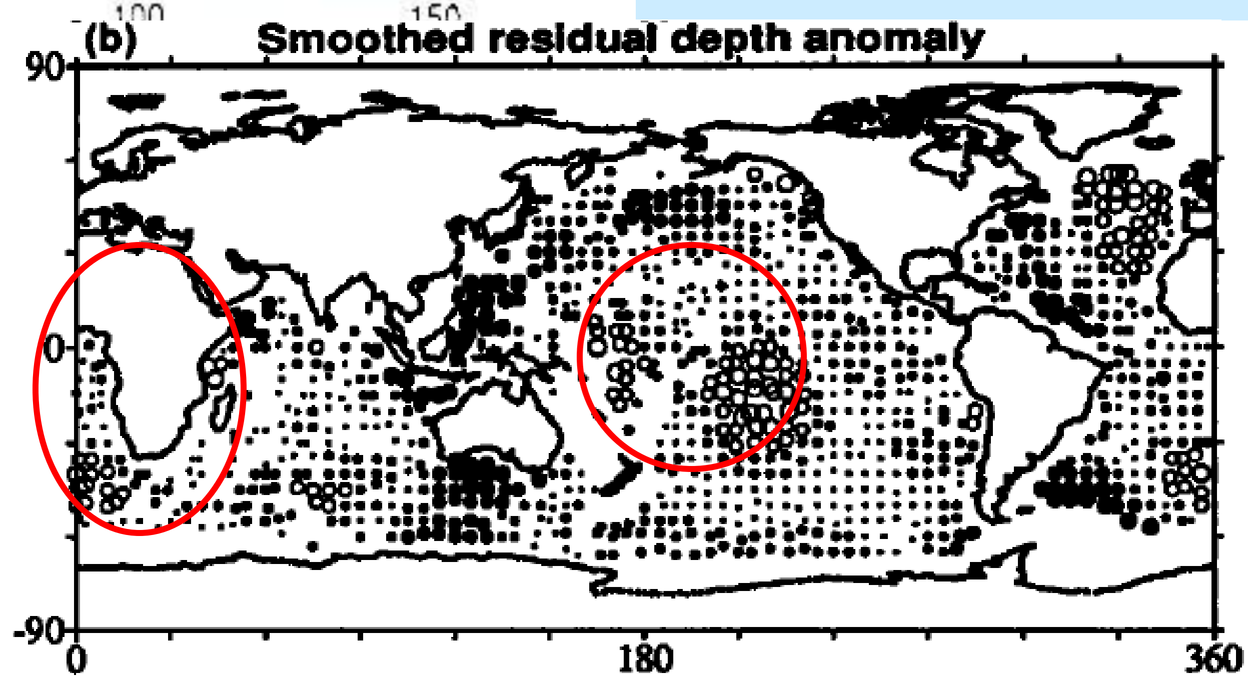
Masters et al. [2000];
also Su and Dziewonski [1997]



Wang & Wen [2004]

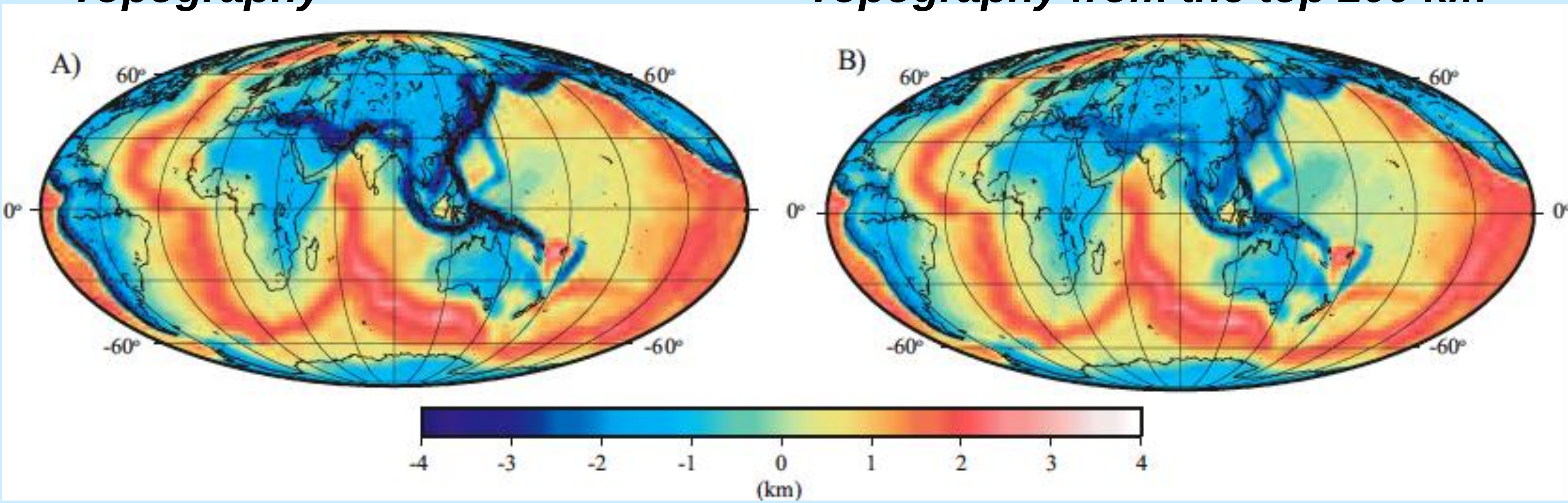
Topography and lithosphere age



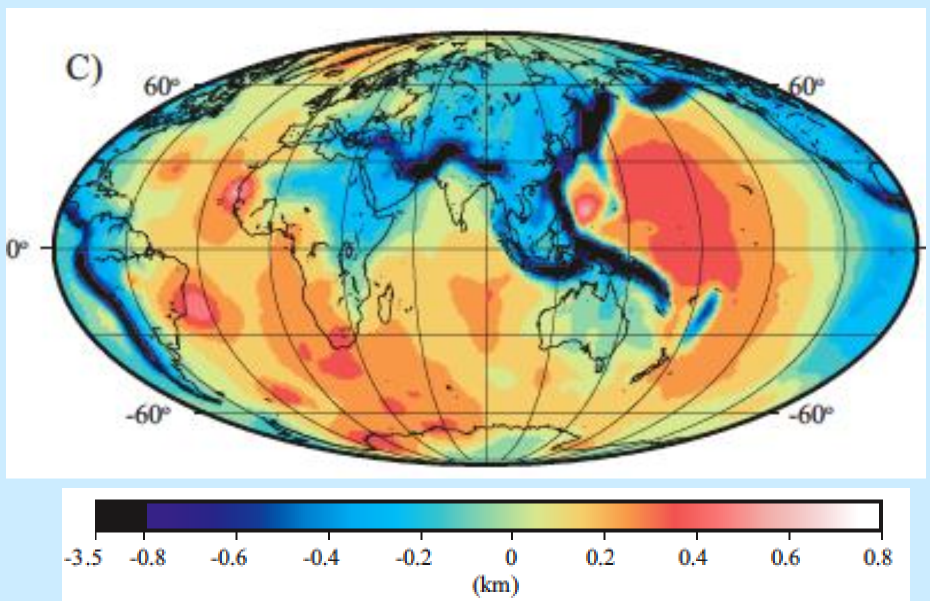


Model predictions of topography and dynamic topography

Topography | **Topography from the top 200 km**



Dynamic topography (i.e., from buoyancy below 200 km depth)

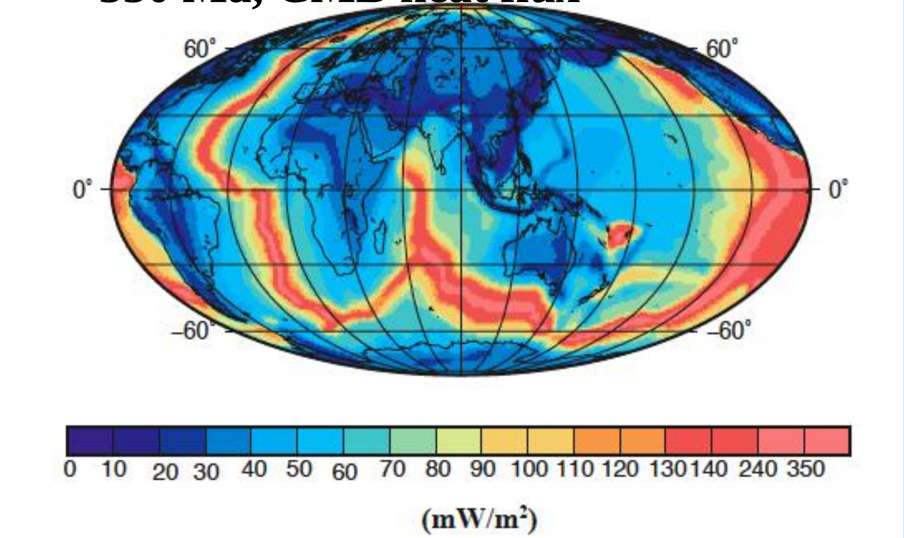


Zhang et al. (2011a)

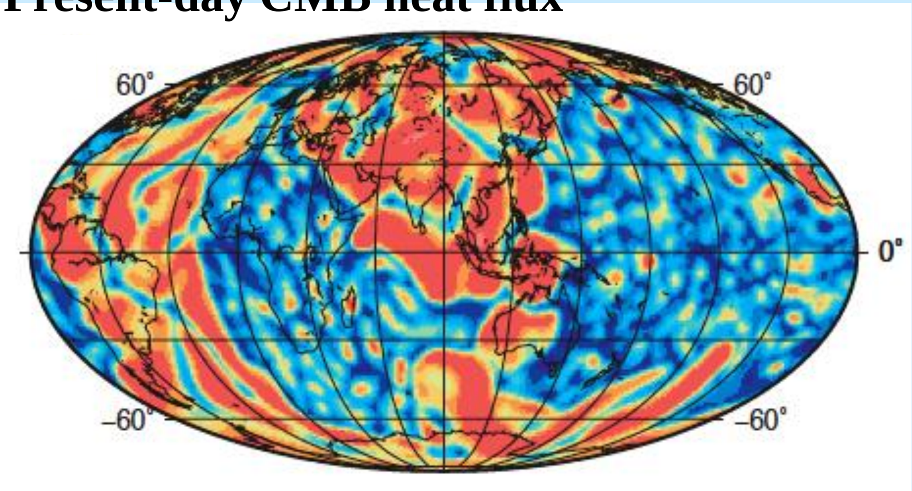
Global surface and CMB heat flux [Zhang & Zhong, 2011b]

Present-day surface heat flux

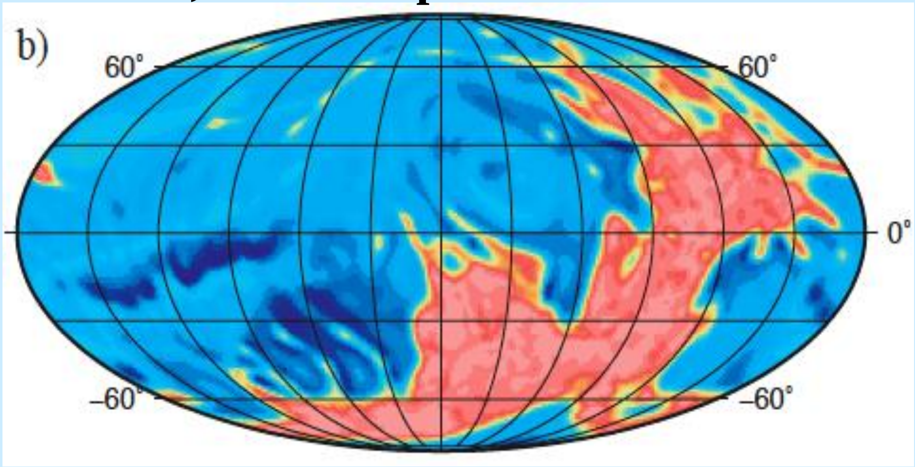
330 Ma, CMB heat flux



Present-day CMB heat flux



330 Ma, CMB temperature



Present-day CMB temperature