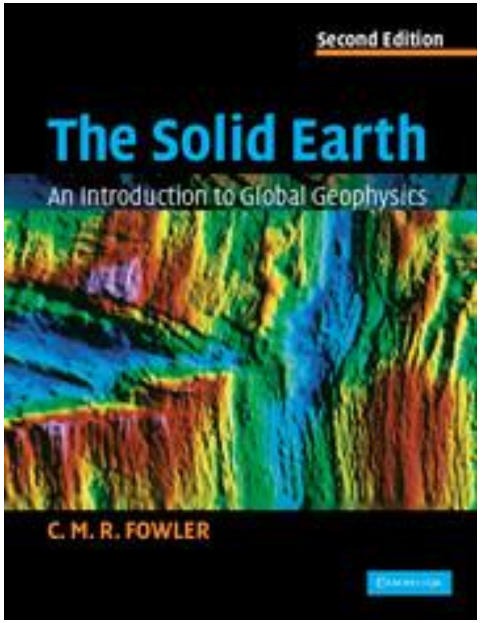
Past Plate Motions

Lecturer: Supriyo Mitra (IISER Kolkata)

Lecture Schedule

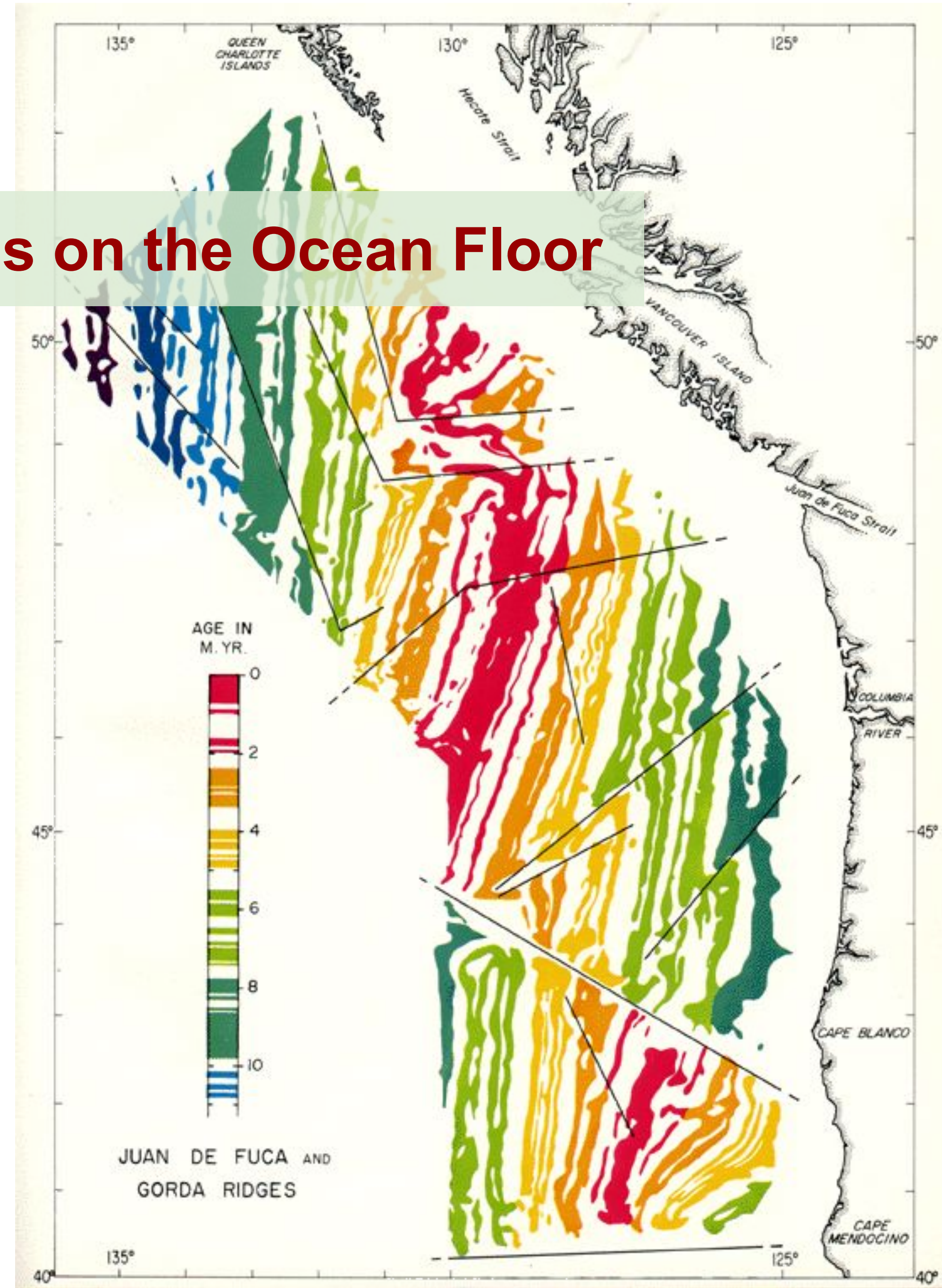
Module 2: Magnetic Field of the Earth and Past Plate Motions
Magnetic potential and field
Calculation of paleomagnetic latitude and pole positions
Magnetisation of rocks, paleomagnetism & polar wander path



Chapter 3

What is this Map?

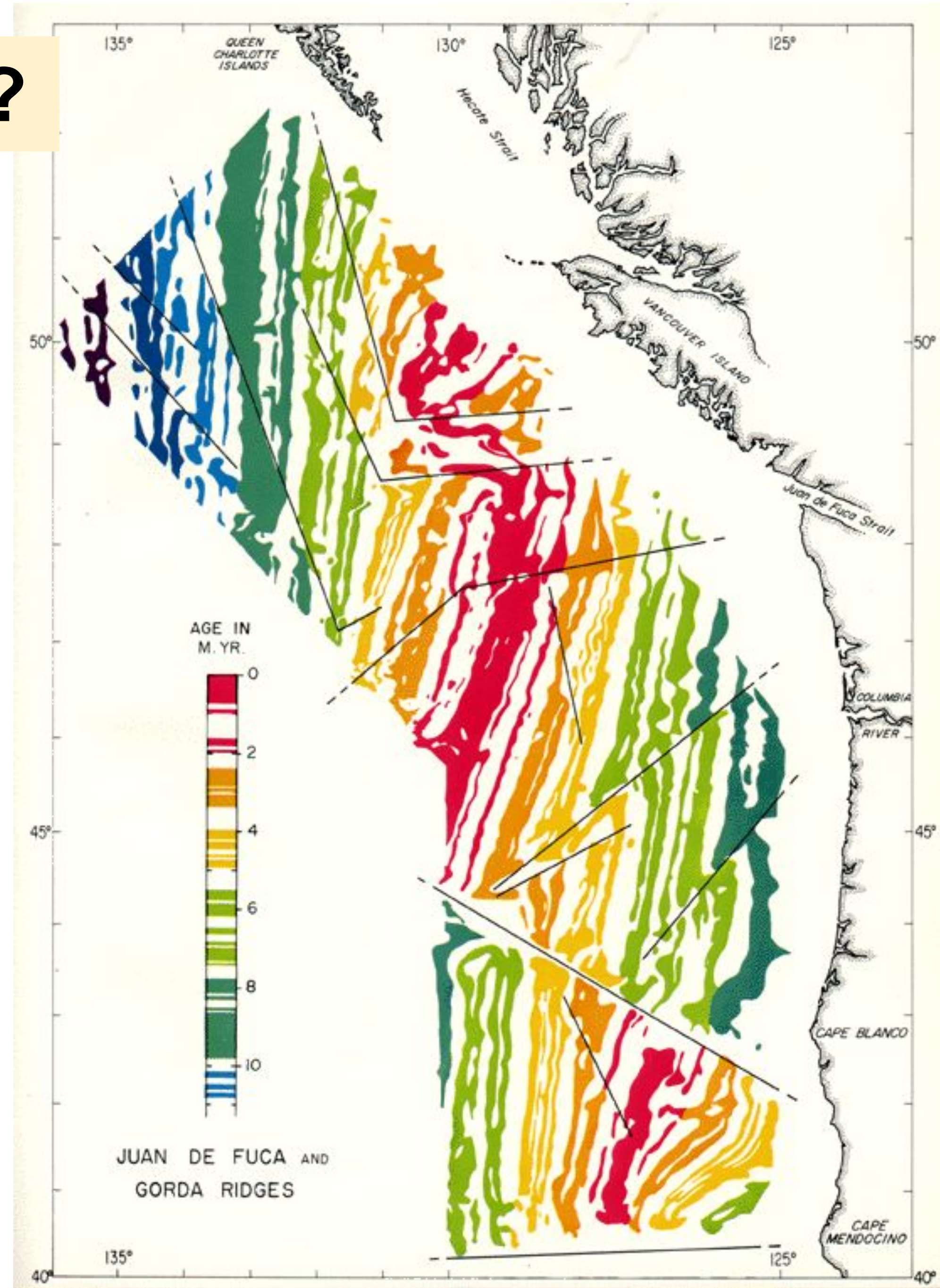
Magnetic anomaly patterns on the Ocean Floor



What does it tell you?

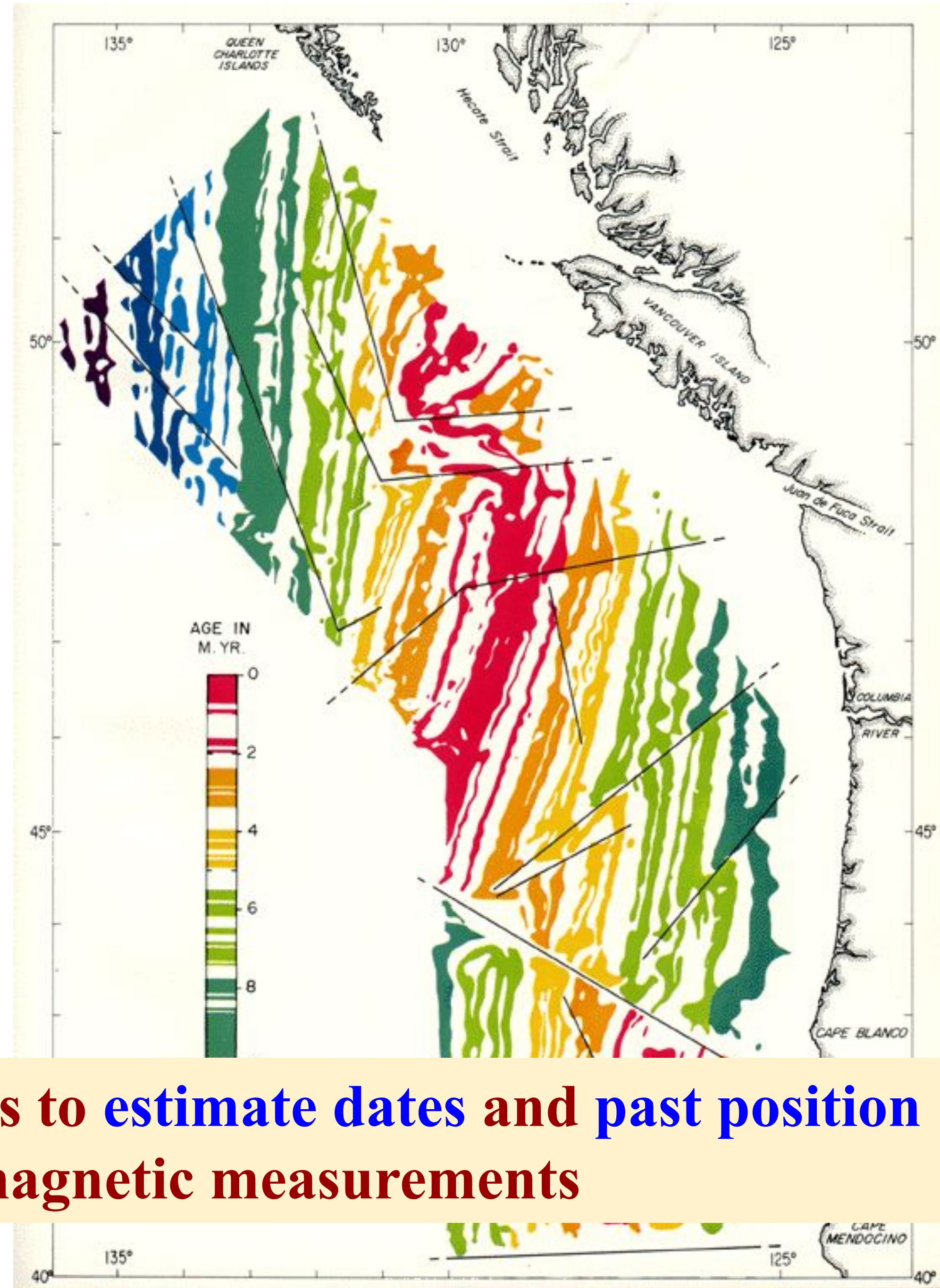
Two important facts:

- The earth's magnetic field has not always had its present (**normal**) polarity (Over geological history the magnetic field has intermittently **reversed**)
- Under certain circumstances (to be discussed later) rocks can record the earth's past ***(palaeo) magnetic*** field.



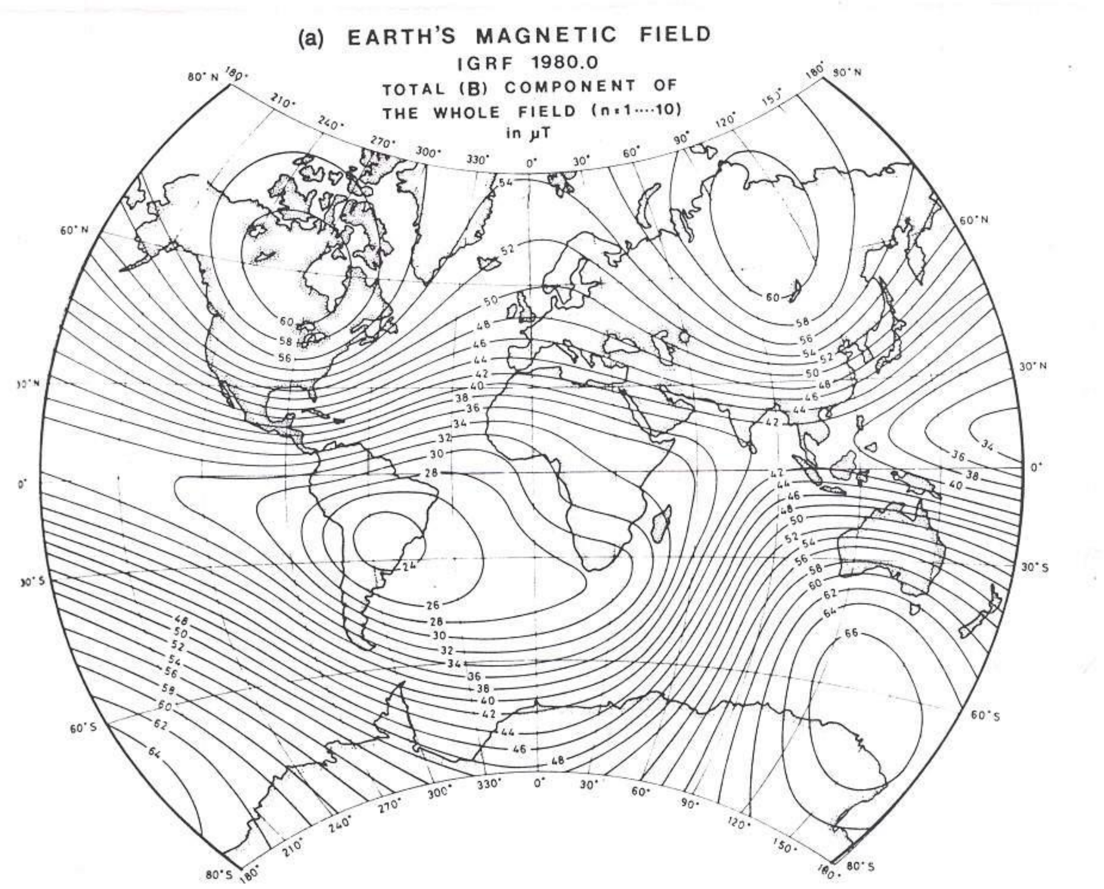
Two important facts:

- The earth's magnetic field has not always had its present (**normal**) polarity (Over geological history the magnetic field has intermittently **reversed**)
- Under certain circumstances (to be discussed later) rocks can record the earth's past ***(palaeo) magnetic*** field.



Together, these facts enable us to estimate dates and past position of plates from magnetic measurements

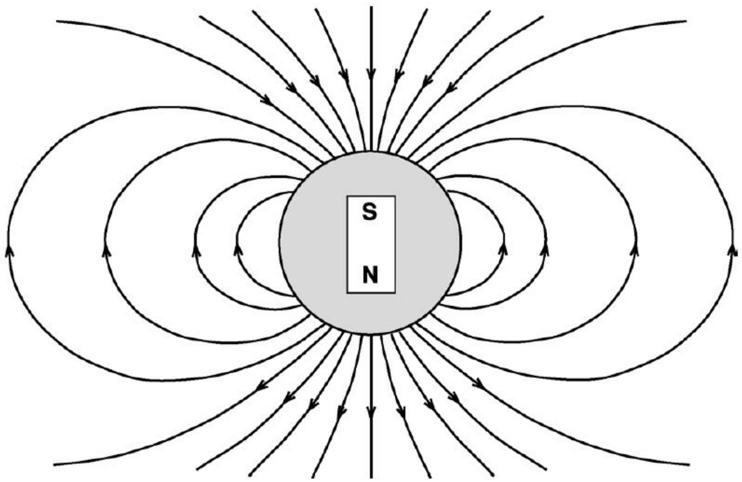
The Earth’s Magnetic Field

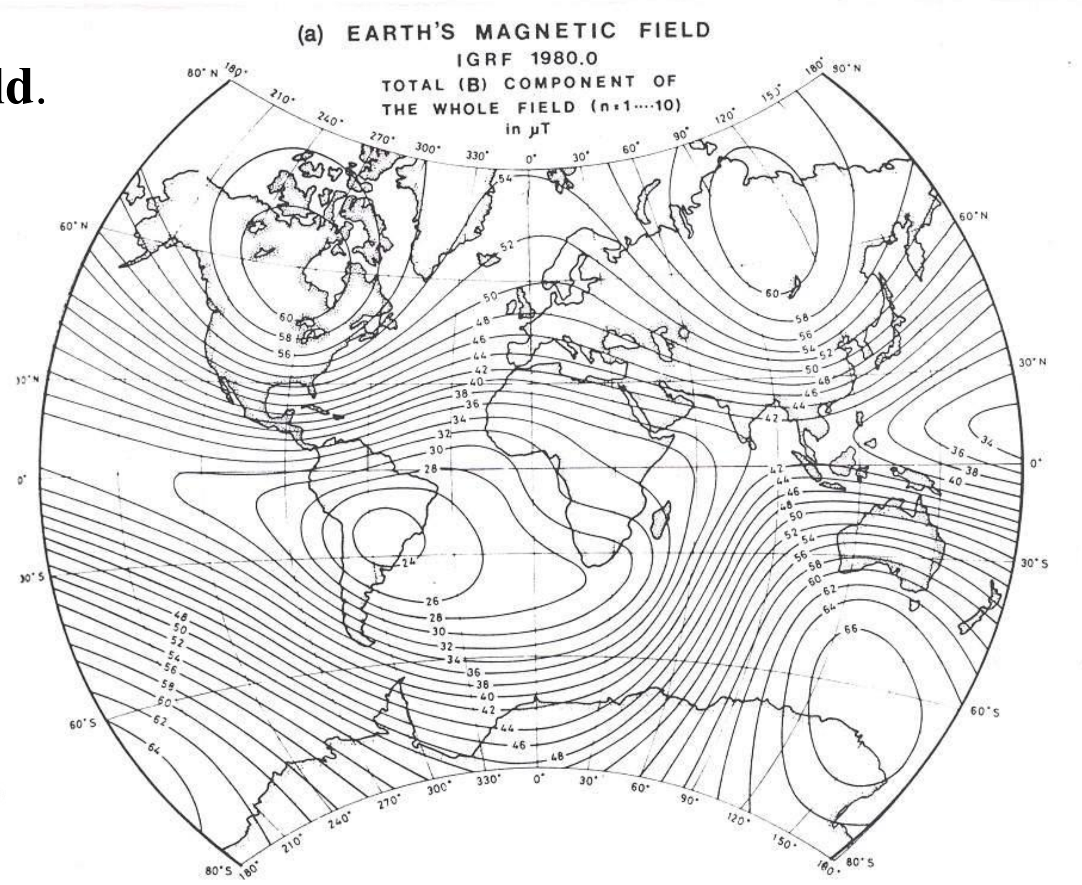


Is the Earth’s magnetic field a dipolar field?

The Earth's Magnetic Field

To a first approximation the **geomagnetic field** is a **dipole field**. (i.e. it can be represented by a magnetic dipole situated at the center of the earth).



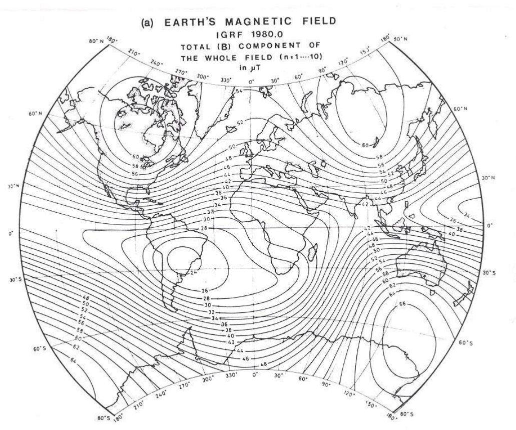


The Earth’s Magnetic Field

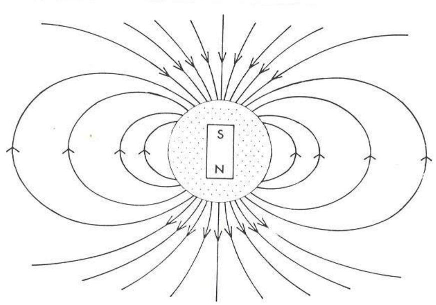
To a first approximation the **geomagnetic field** is a **dipole field**. (i.e. it can be represented by a magnetic dipole situated at the center of the earth).

At the earth’s surface the non-dipole field is small compared to the dipole field, though this is not the case at the core-mantle boundary.

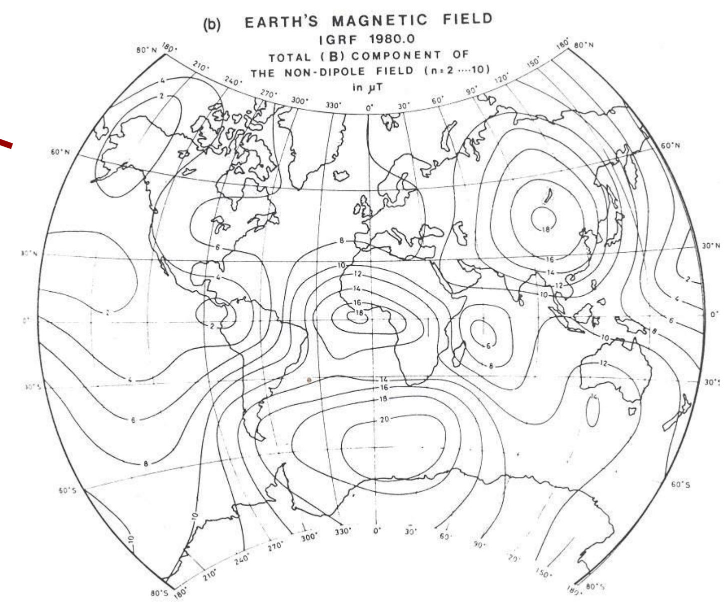
The difference between the earth’s magnetic field and the best dipole field is termed as the **non-dipole field**.



−



=



The Earth’s Magnetic Field: Terminologies

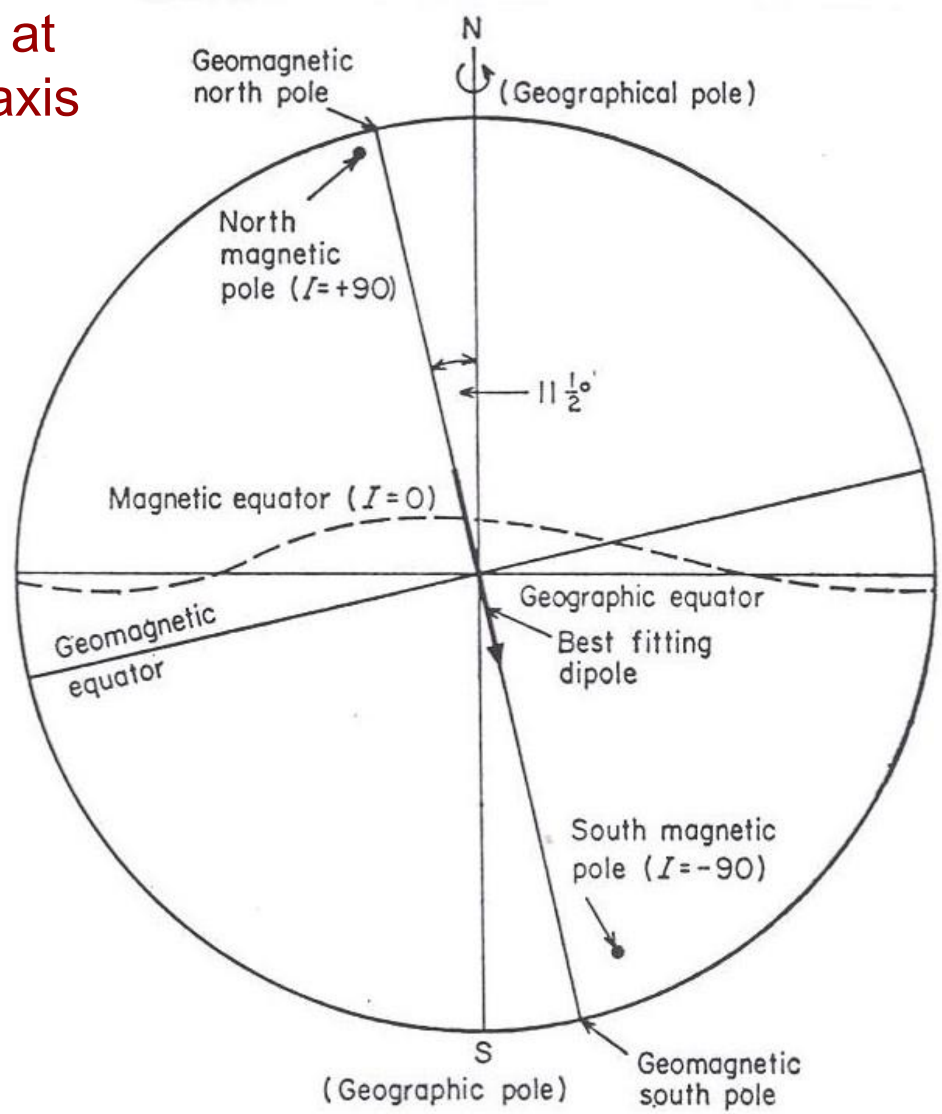
Today the best-fitting dipole is aligned at ~11.5º to the Earth’s geographic N-S axis

Geomagnetic Poles & Equator

The **geomagnetic poles** are the two points at which the axis of the best-fitting dipole intersect the Earth’s surface.

Now at:
79ºN, 71ºW (**geomagnetic north**) and
79ºS, 109ºE (**geomagnetic south**)

The **geomagnetic equator** is the equator of the best-fitting dipole axis



The Earth’s Magnetic Field: Terminologies

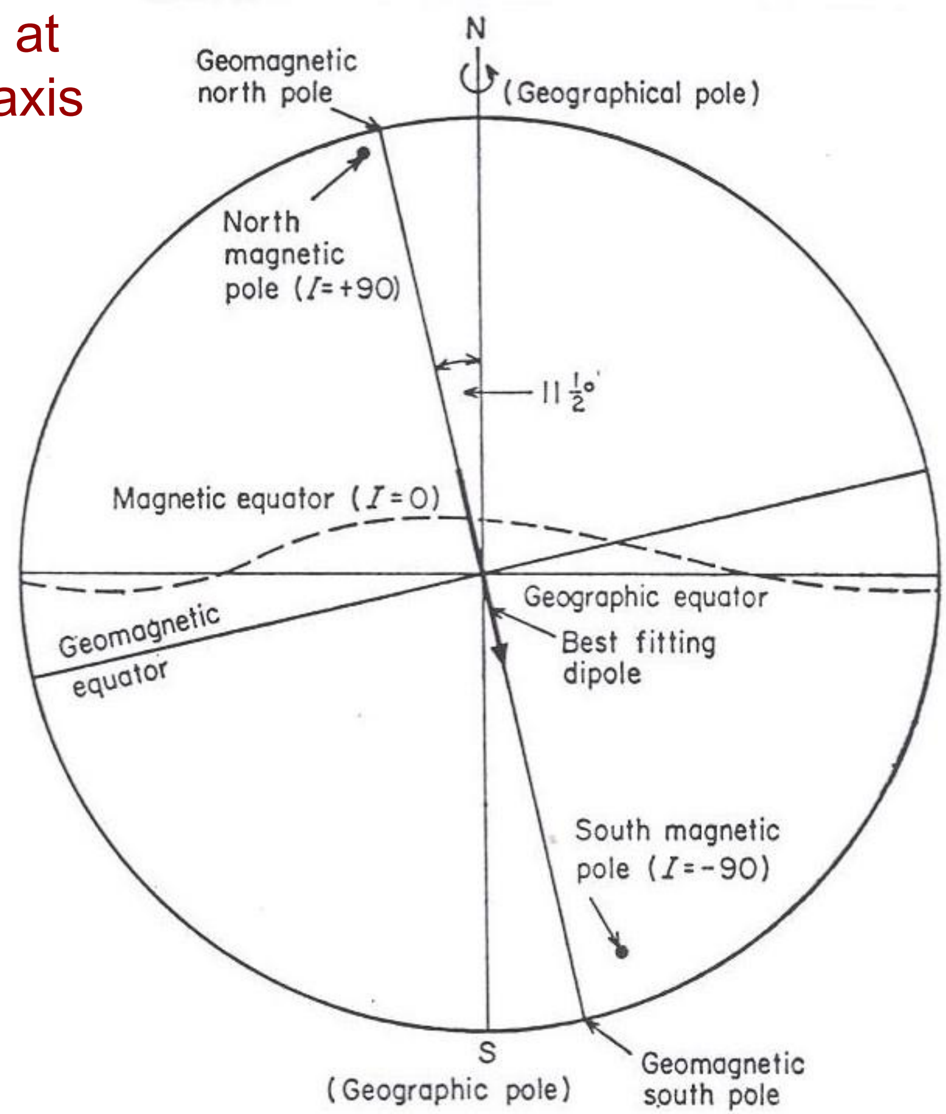
Today the best-fitting dipole is aligned at ~11.5º to the Earth’s geographic N-S axis

Magnetic Poles & Equator

The two points on the earth’s surface at which the magnetic field is vertical and has no horizontal component are called the **magnetic poles**, or **dip poles**

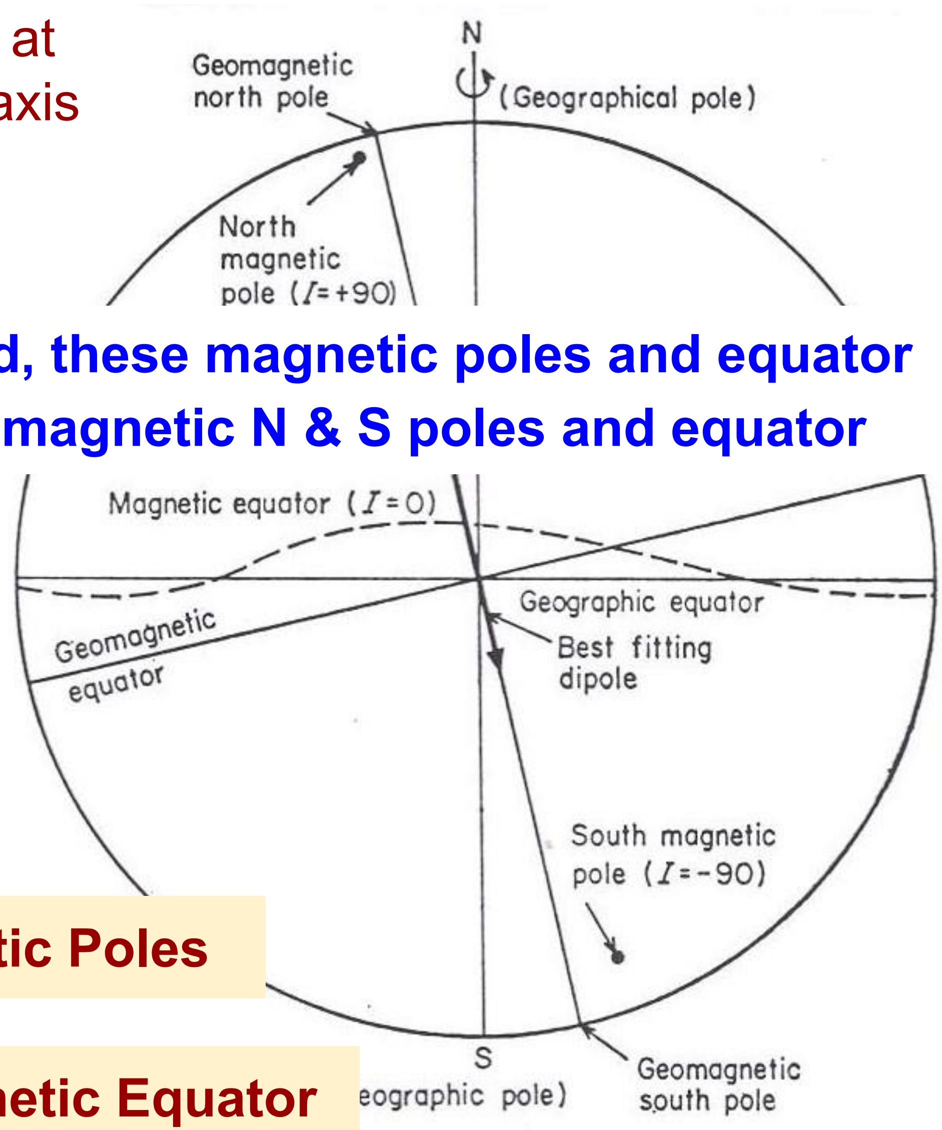
Present Location:
N magnetic pole 76ºN, 101ºW
S magnetic pole 66ºS, 141ºE

The **magnetic equator** is the line along which the magnetic field is horizontal and has no vertical component



The Earth's Magnetic Field: Terminologies

Today the best-fitting dipole is aligned at ~11.5º to the Earth's geographic N-S axis

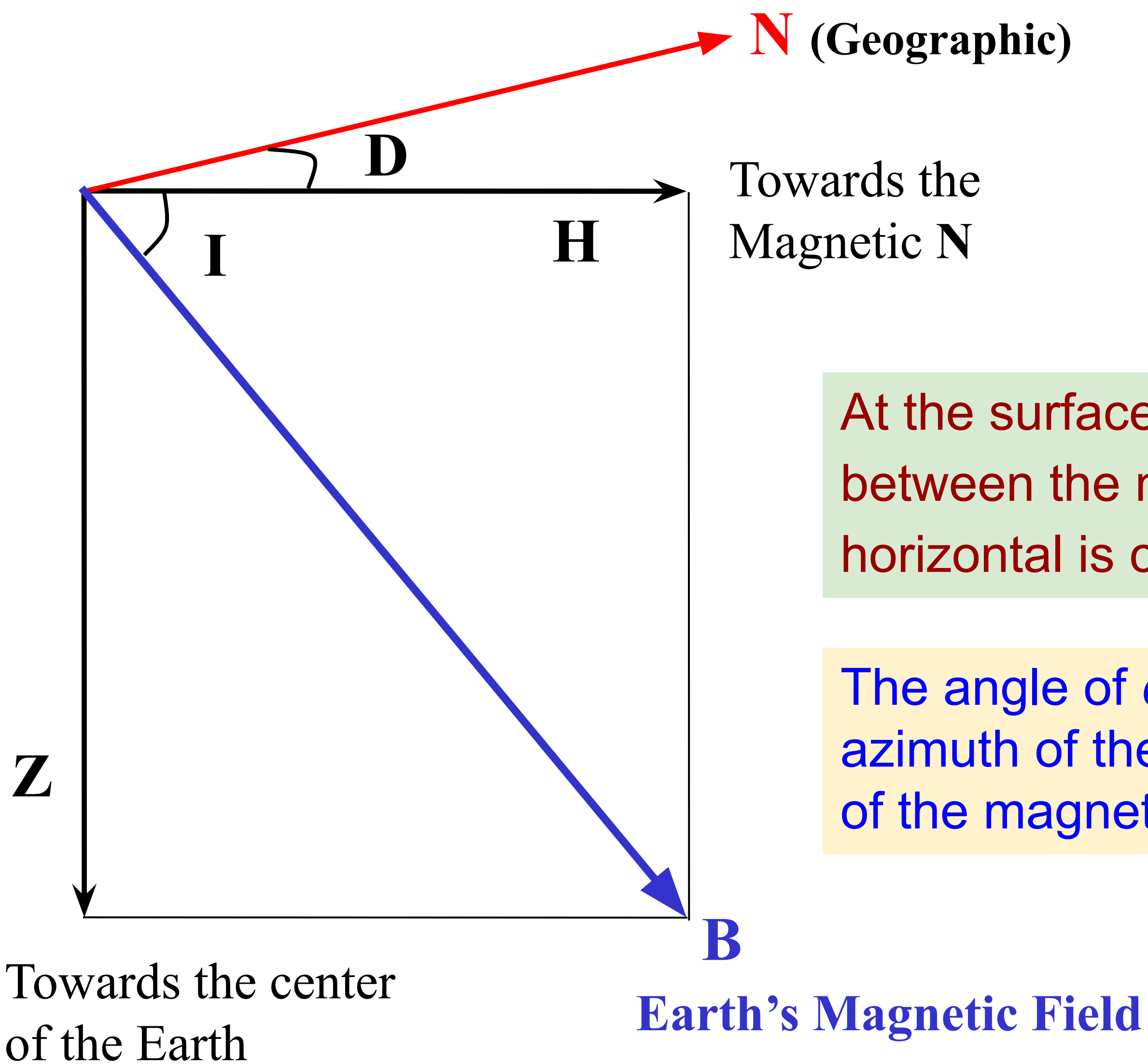


If the field was exactly a dipole field, these magnetic poles and equator would be coincident with the geomagnetic N & S poles and equator

Geomagnetic Poles ≠ **Magnetic Poles**

Geomagnetic Equator ≠ **Magnetic Equator**

Magnetic Inclination (I) & Declination (D)



At the surface of the Earth the angle between the magnetic field and the horizontal is called the ***inclination*** **(I)**

The angle of ***declination*** **(D)** is the azimuth of the horizontal component of the magnetic field

Calculation of the Earth's Magnetic Field

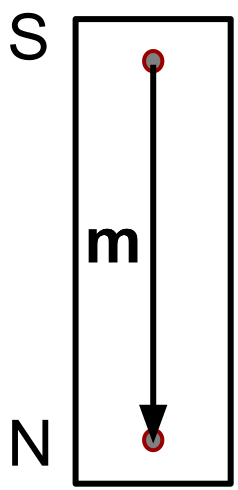
Magnetic Potential [$V(\mathbf{r})$] → Infinite series of spherical harmonic functions

↓

First term is the potential due to a dipole situated at the centre of the Earth

$$V(\mathbf{r}) = \frac{1}{4\pi r^3}\mathbf{m}\cdot\mathbf{r}$$

At any position **r** from a dipole



m is the dipole moment

(a vector aligned along the dipole axis)

For the Earth **m** is 7.94×10^{22} A m^2 in magnitude

Calculation of the Earth's Magnetic Field

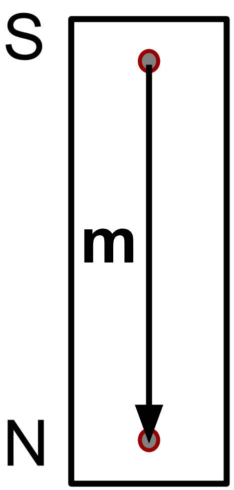
Magnetic Potential [$V(\mathbf{r})$]

Infinite series of spherical harmonic functions

First term is the potential due to a dipole situated at the centre of the Earth

$$V(\mathbf{r}) = \frac{1}{4\pi r^3}\mathbf{m}\cdot\mathbf{r}$$

At any position **r** from a dipole



Earth's Magnetic Field [$\mathbf{B}(\mathbf{r})$]

$$\mathbf{B}(\mathbf{r}) = -\mu_0 \nabla V(\mathbf{r})$$

At any position **r** can be determined by differentiating the magnetic potential

where $\mu_0 = 4\pi \times 10^{-7}$ kg m A^{-2} s^{-2} is the magnetic permeability of free space

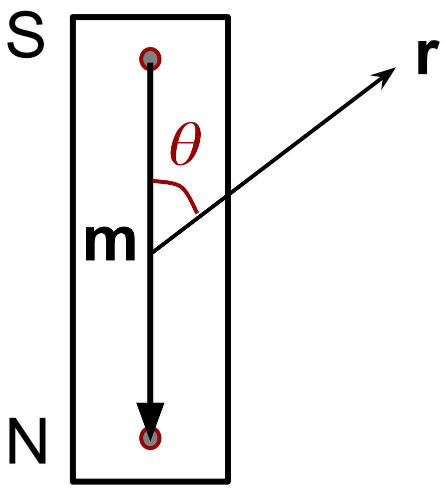
Calculation of the Earth's Magnetic Field

Magnetic Potential [$V(\mathbf{r})$]

$$V(\mathbf{r}) = \frac{1}{4\pi r^3}\mathbf{m}\cdot\mathbf{r}$$

Earth's Magnetic Field [$\mathbf{B}(\mathbf{r})$]

$$\mathbf{B}(\mathbf{r}) = -\mu_0 \nabla V(\mathbf{r})$$



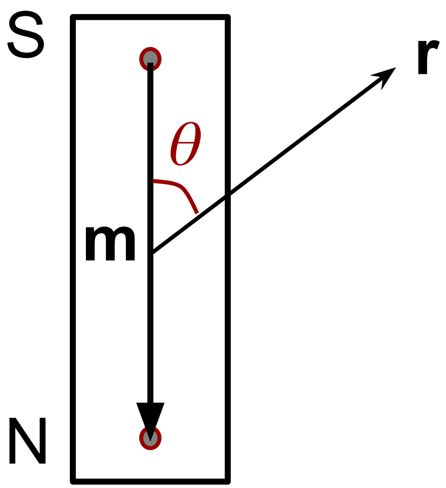
Use spherical polar coordinates (r, θ, φ)
r is the radius
θ the colatitude
φ the longitude or azimuth on the sphere

$\mathbf{B}(\mathbf{r}) = (B_r, B_\theta, B_\varphi)$ in this coordinate system
B_r is the radial component of the field
B_θ is the southerly component
B_φ is the easterly component

Calculation of the Earth's Magnetic Field

Magnetic Potential [$V(\mathbf{r})$]

$$V(\mathbf{r}) = \frac{1}{4\pi r^3}\mathbf{m}\cdot\mathbf{r}$$
$$= -\frac{mr\cos\theta}{4\pi r^3}$$
$$= -\frac{m\cos\theta}{4\pi r^2}$$



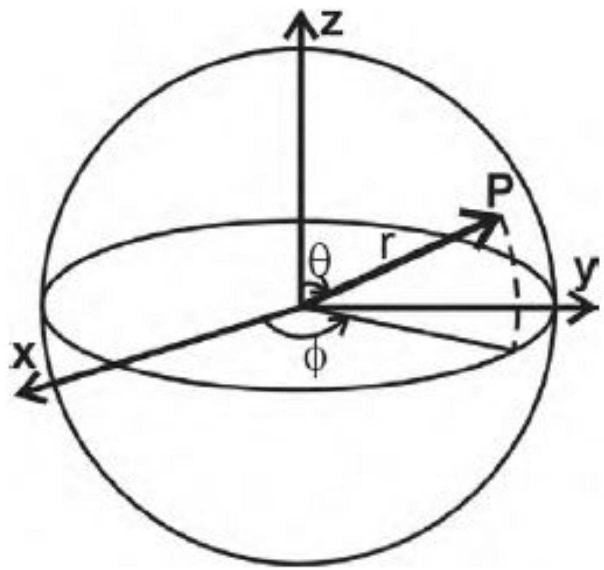
Substituting

$$\mathbf{B}(\mathbf{r}) = -\mu_0 \nabla V(\mathbf{r})$$

Calculation of the Earth's Magnetic Field

Earth's Magnetic Field [**B**(**r**)] → **B**(**r**) = (B_r, B_θ , B_φ)

$$B_r(r,\theta,\phi) = -\mu_0 \frac{\partial V}{\partial r}$$
$$= \frac{\mu_0 m \cos\theta}{4\pi} \frac{\partial}{\partial r}\left(\frac{1}{r^2}\right)$$
$$= -\frac{2\mu_0 m \cos\theta}{4\pi r^3}$$



$$B_\theta(r,\theta,\phi) = -\mu_0 \frac{1}{r} \frac{\partial V}{\partial \theta}$$
$$= \frac{\mu_0 m}{4\pi r^3} \frac{\partial}{\partial \theta}(\cos\theta)$$
$$= -\frac{\mu_0 m \sin\theta}{4\pi r^3}$$

$$B_\phi(r,\theta,\phi) = -\mu_0 \frac{1}{r\sin\theta} \frac{\partial V}{\partial \phi}$$
$$= 0$$

Note that, by symmetry, there can obviously be no field in the φ (east) direction.

Calculation of the Earth's Magnetic Field

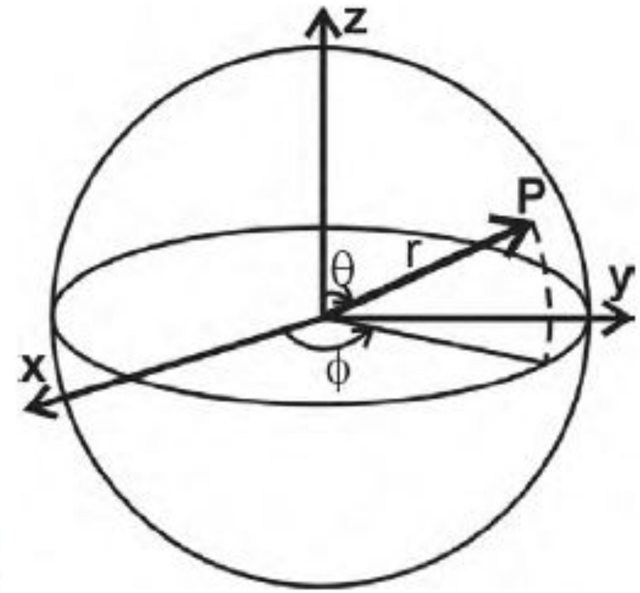
Earth's Magnetic Field [**B**(**r**)] → $\mathbf{B}(\mathbf{r}) = (B_r, B_\theta, B_\varphi)$

Total Field Strength at any point

$$B(r,\theta,\phi) = \sqrt{B_r^2 + B_\theta^2 + B_\phi^2}$$
$$= \frac{\mu_0 m}{4\pi r^3}\sqrt{1 + 3\cos^2\theta}$$

Calculation of the Earth's Magnetic Field

Total Field Strength at any point $$B(r,\theta,\phi) = \frac{\mu_0 m}{4\pi r^3}\sqrt{1+3\cos^2\theta}$$



Along the north-polar axis ($\theta = 0$) the field is

$$B_r(r,0,\phi) = -\frac{\mu_0 m}{2\pi r^3}$$

$$B_\theta(r,0,\phi) = 0$$

On the equator ($\theta = 90^\circ$) the field is

$$B_r(r,90,\phi) = 0$$

$$B_\theta(r,90,\phi) = -\frac{\mu_0 m}{4\pi r^3}$$

and along the south-polar axis ($\theta = 180^\circ$) the field is

$$B_r(r,180,\phi) = \frac{\mu_0 m}{2\pi r^3}$$

$$B_\theta(r,180,\phi) = 0$$

Earth's Magnetic Field at the poles is twice the equatorial field (in magnitude)

Calculation of the Earth's Magnetic Field

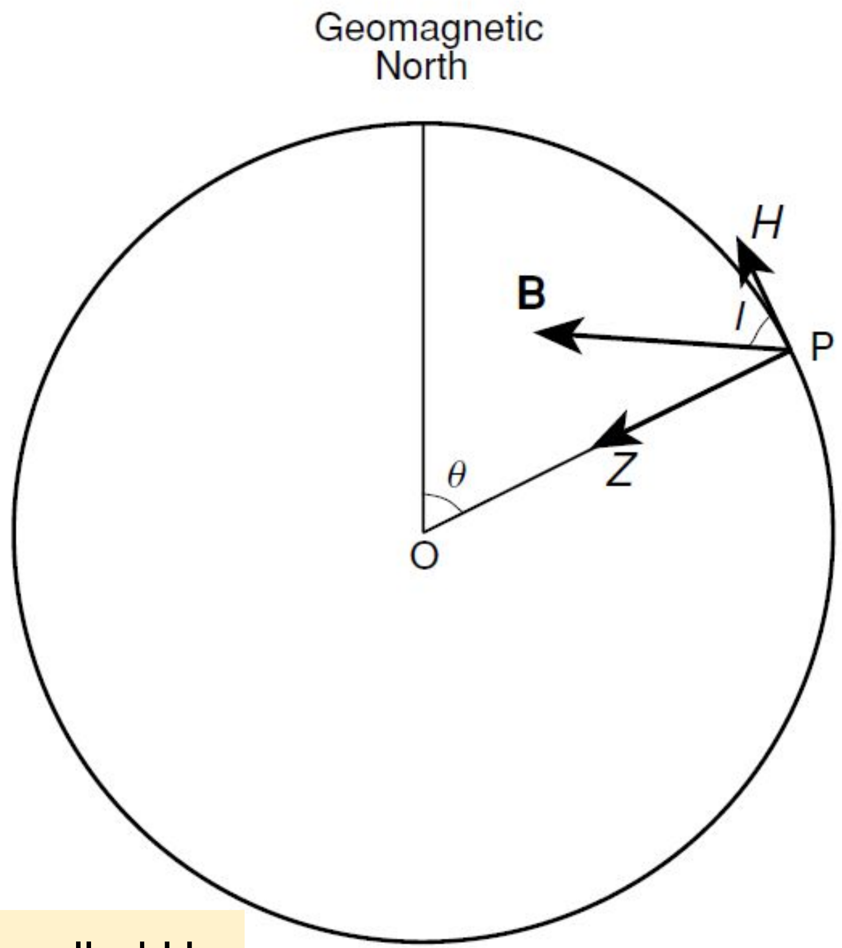
Total Field Strength at any point $$B(r,\theta,\phi) = \frac{\mu_0 m}{4\pi r^3}\sqrt{1+3\cos^2\theta}$$

If we define a constant B_0 as

$$B_0 = \frac{\mu_0 m}{4\pi R^3}$$

$$B_r(R,\theta,\phi) = -2B_0\cos\theta$$

$$B_\theta(R,\theta,\phi) = -B_0\sin\theta$$



In geomagnetic work, the inward radial component of the Earth's field is usually called Z (it is the downward vertical at the Earth's surface) and is positive.

The horizontal magnitude (always positive) is called H.

Calculation of the Earth's Magnetic Field

Total Field Strength at any point

$$B(r,\theta,\phi) = \frac{\mu_0 m}{4\pi r^3}\sqrt{1+3\cos^2\theta}$$

If we define a constant B_0 as

$$B_0 = \frac{\mu_0 m}{4\pi R^3}$$

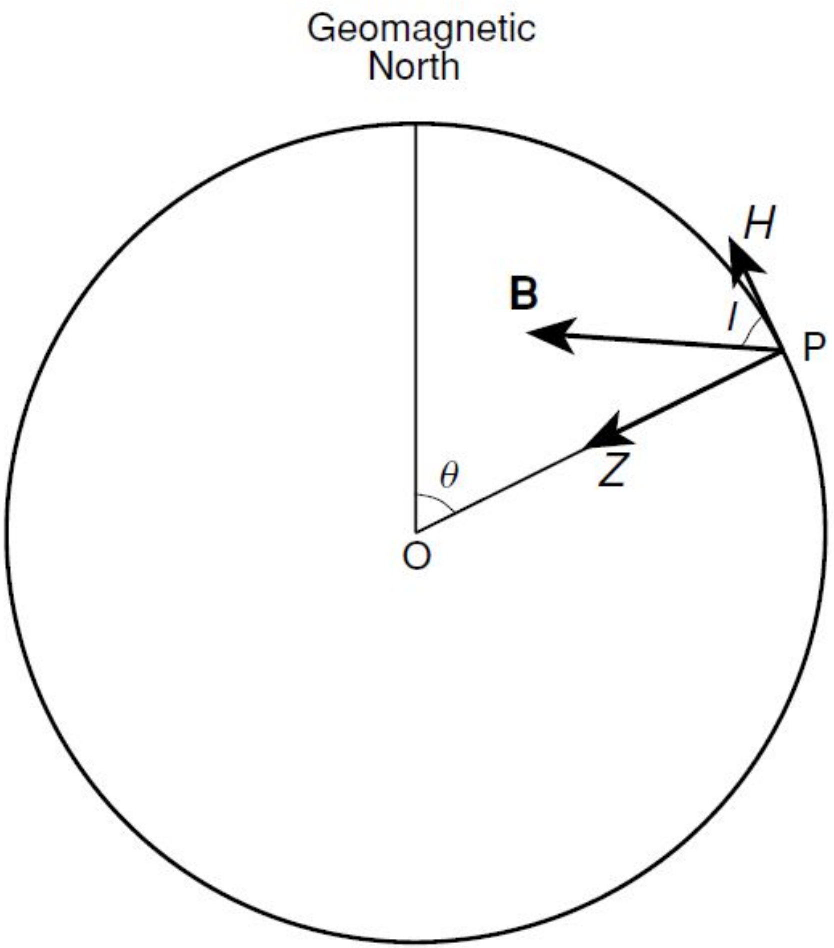
$$B_r(R,\theta,\phi) = -2B_0\cos\theta$$

$$B_\theta(R,\theta,\phi) = -B_0\sin\theta$$

$$Z(R,\theta,\phi) = -B_r(R,\theta,\phi)$$

$$H(R,\theta,\phi) = |B_\theta(R,\theta,\phi)|$$

$$\tan I = \frac{Z}{H}$$



Calculation of the Earth's Magnetic Field

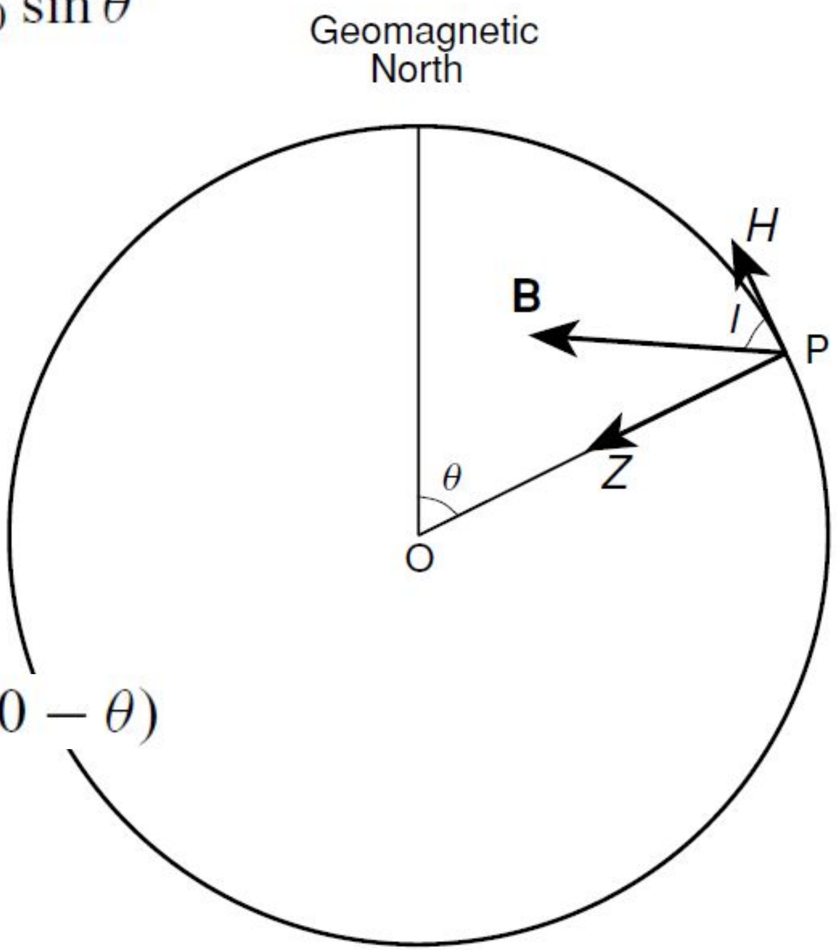
$$Z(R,\theta,\phi) = -B_r(R,\theta,\phi) \;=\; 2B_0\cos\theta$$

$$H(R,\theta,\phi) = |B_\theta(R,\theta,\phi)| \;=\; B_0\sin\theta$$

$$\tan I = \frac{Z}{H}$$

$$\begin{aligned}\tan I &= \frac{2\cos\theta}{\sin\theta}\\ &= 2\cot\theta\\ &= 2\tan\lambda\end{aligned}$$

where λ is the magnetic latitude ($\lambda = 90 - \theta$)



Earth’s Magnetic Field & Paleo Positions

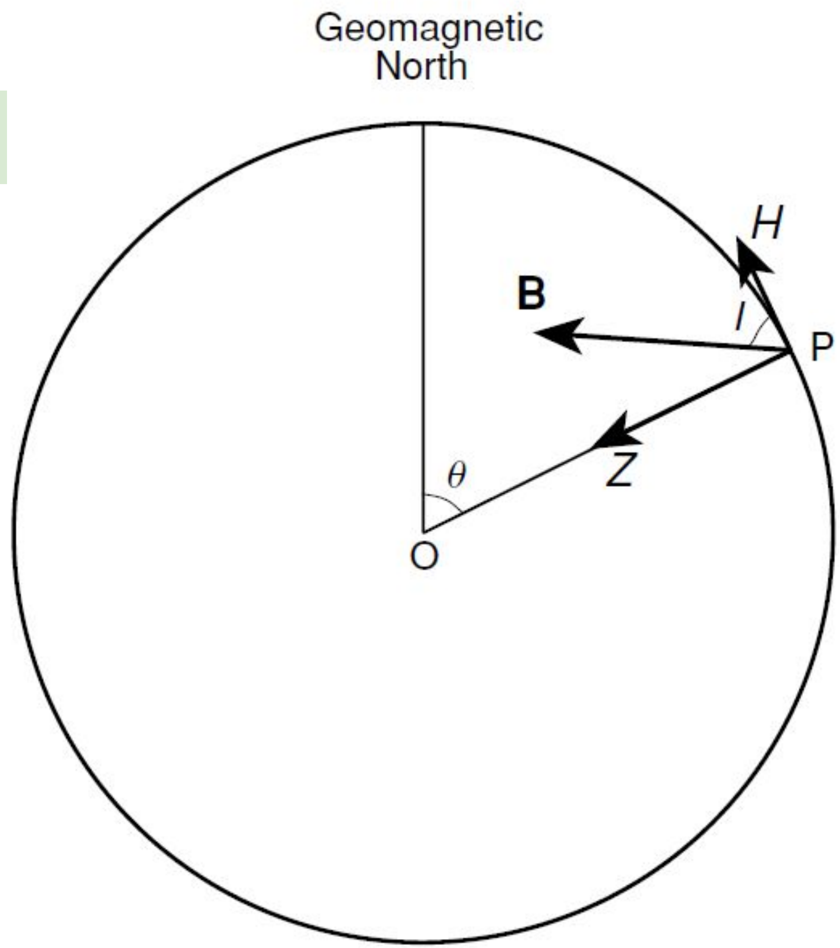
Angle of inclination ← Measure

↓

Magnetic Paleolatitude ← Calculate

↓

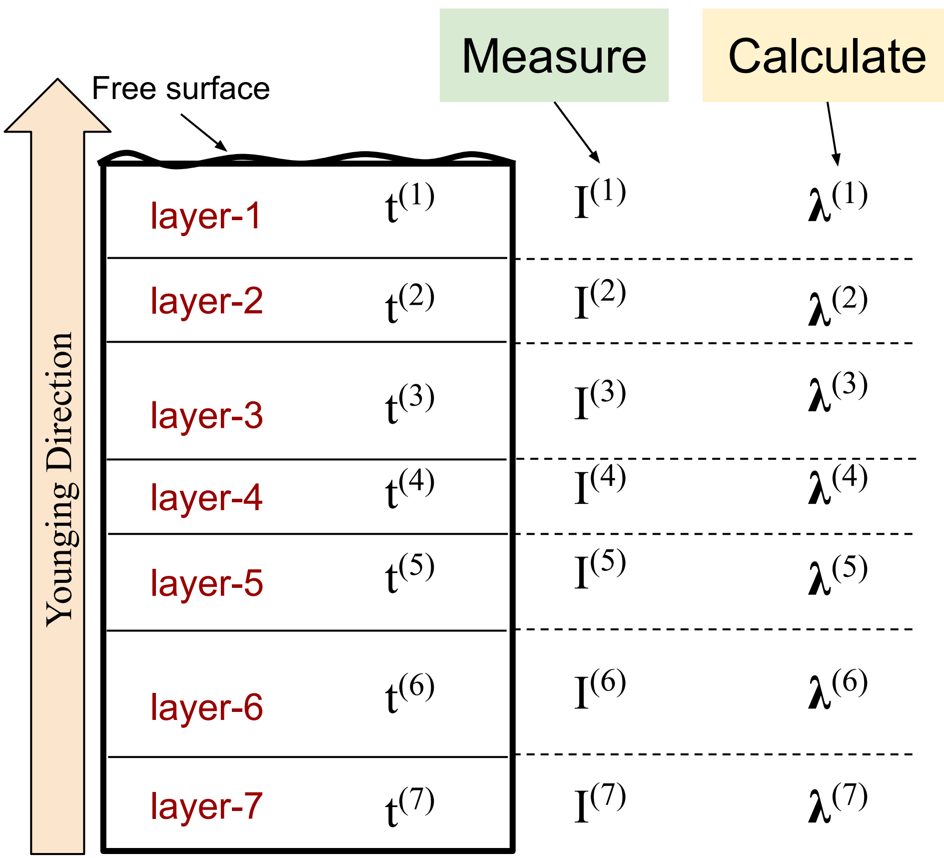
$$\tan I = 2 \tan \lambda$$

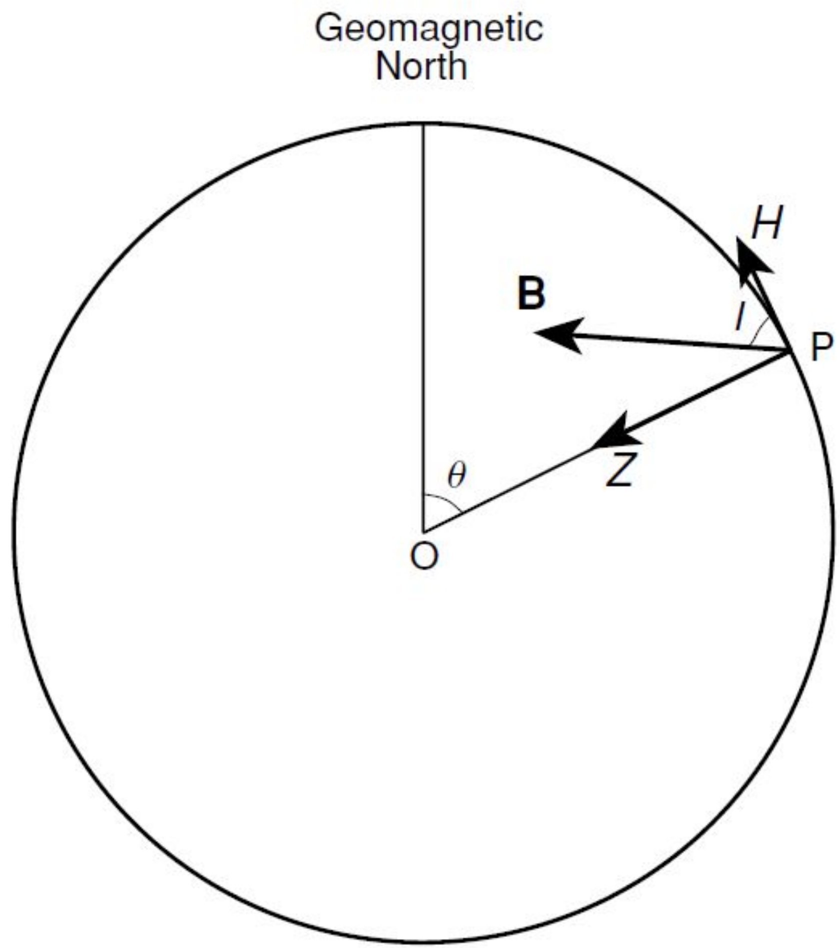


where λ is the magnetic latitude $(\lambda = 90 - \theta)$

Earth’s Magnetic Field & Paleo Positions

$$\tan I = 2 \tan \lambda$$



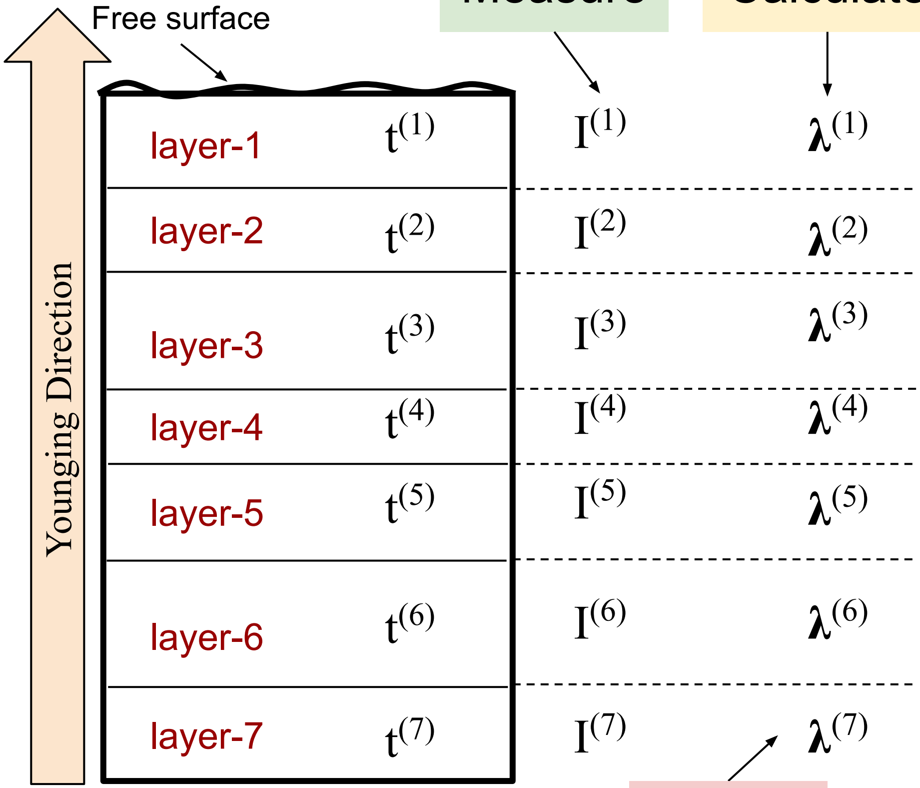


Earth's Magnetic Field & Paleo Positions

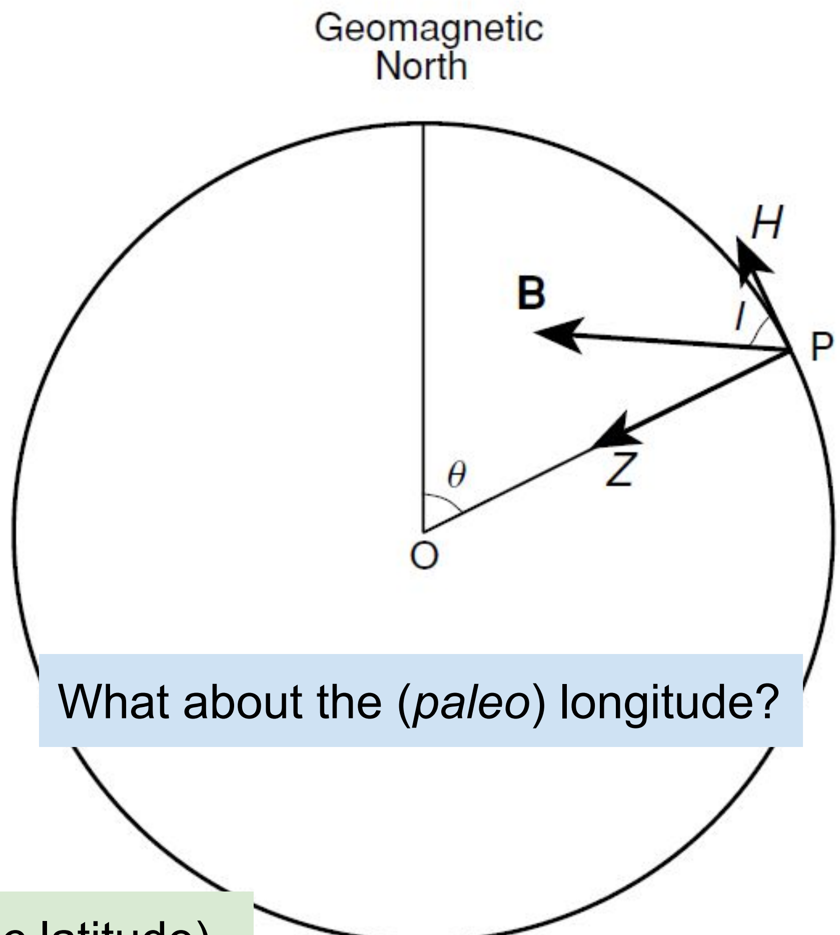
$$\tan I = 2 \tan \lambda$$

Measure

Calculate



Variation

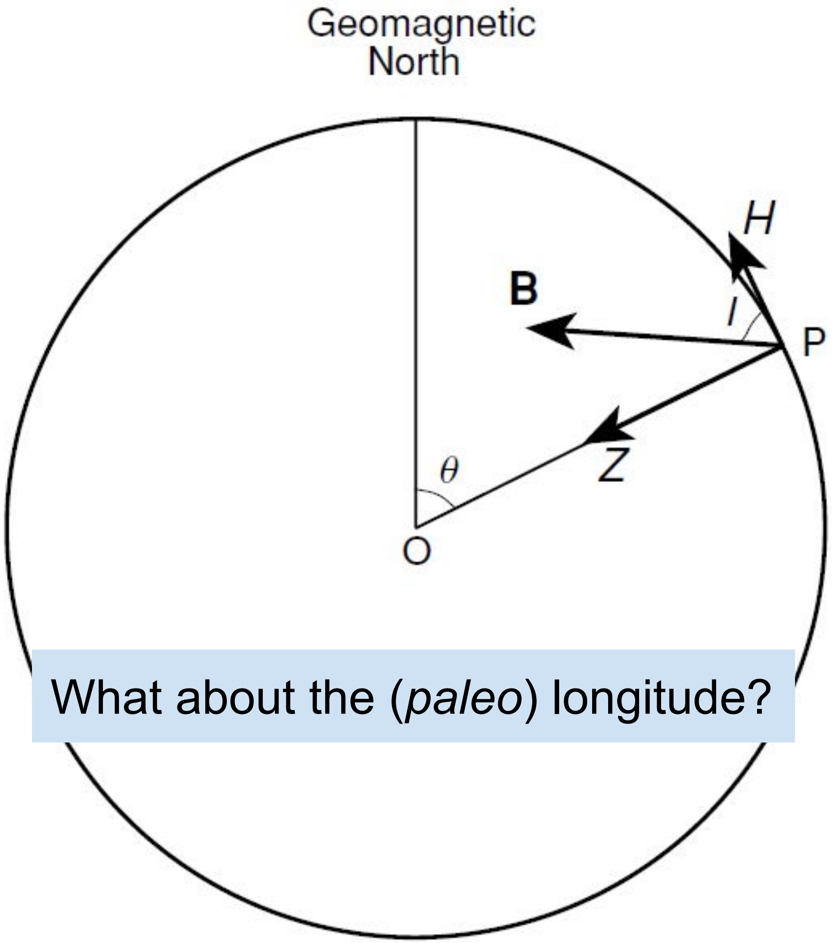


What about the (*paleo*) longitude?

Landmass/rocks have changed location (*paleo* latitude)

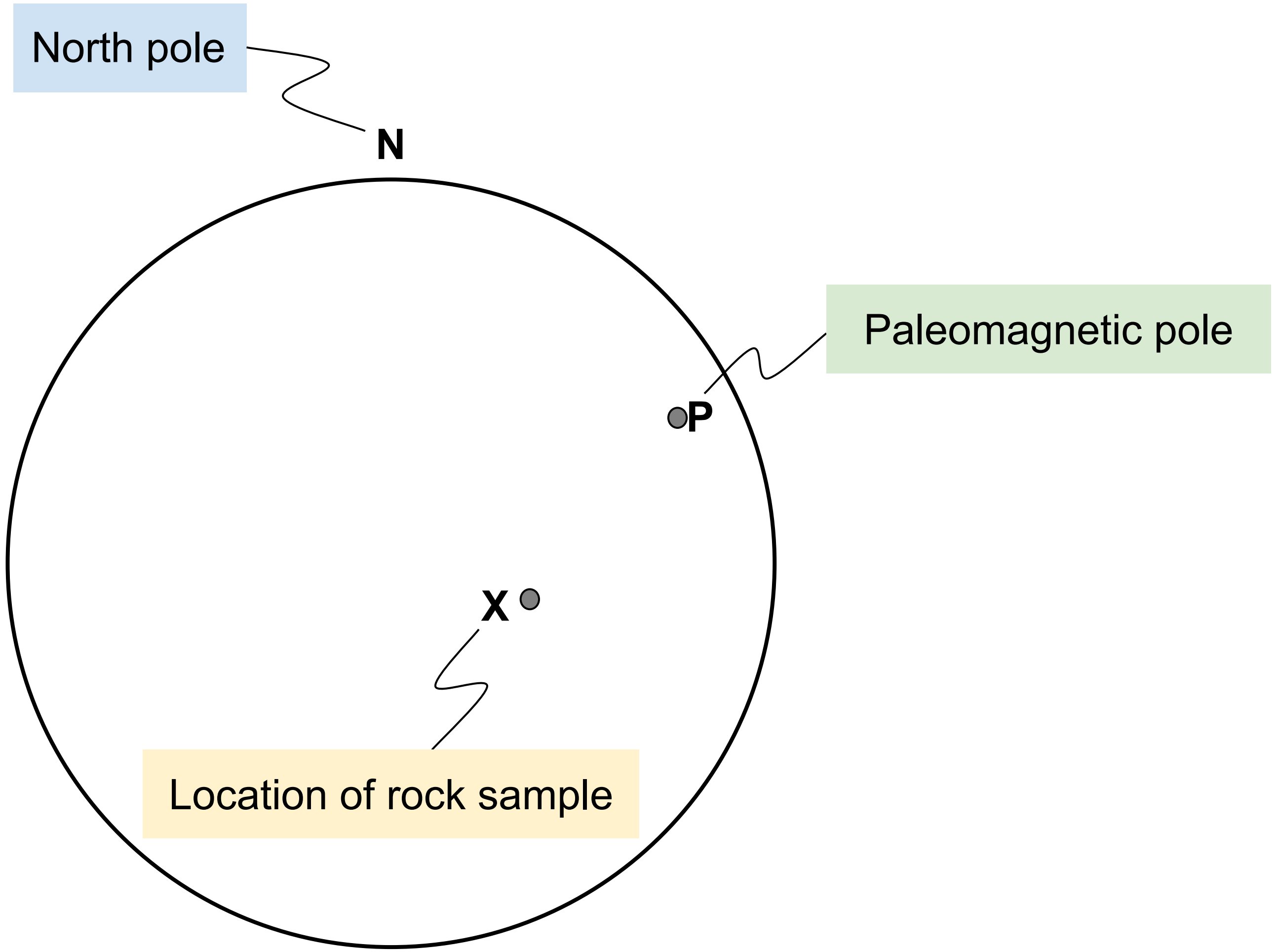
Earth's Magnetic Field & Paleo Positions

Find the position of the Paleomagnetic Pole

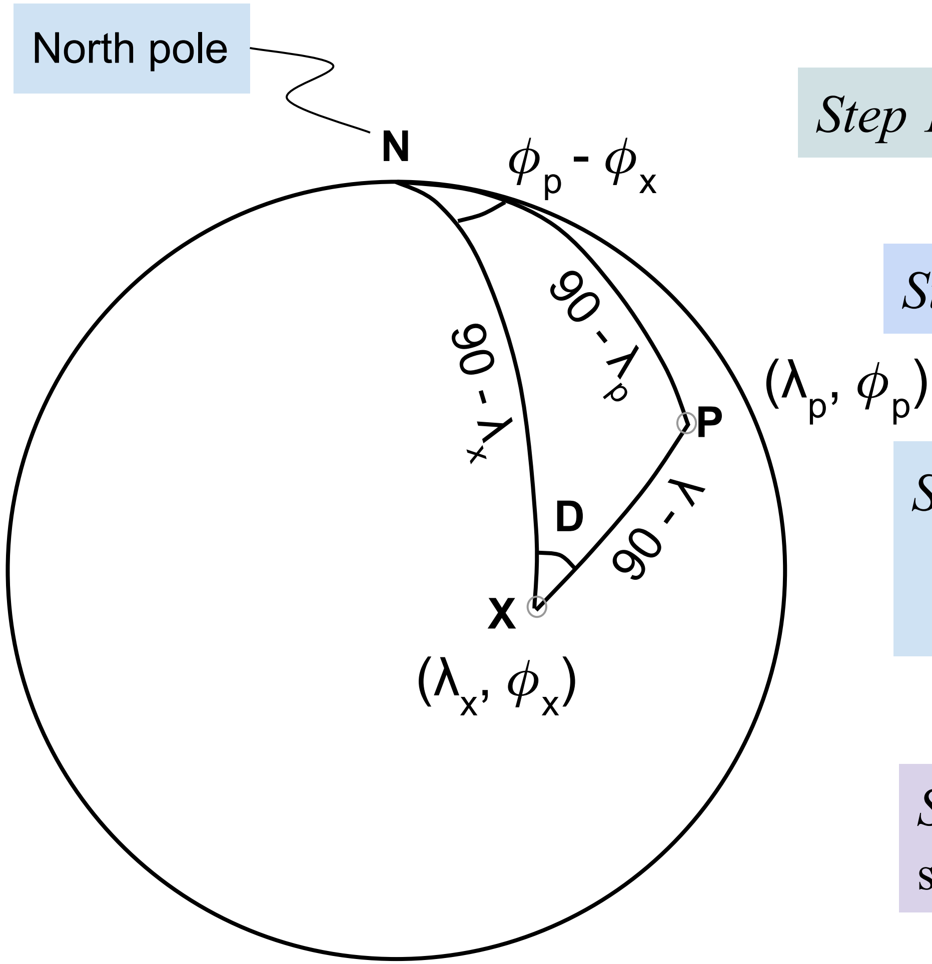


What about the (*paleo*) longitude?

Calculation of the Paleomagnetic Pole position



Calculation of the Paleomagnetic Pole position



Step 1: Measure I & D from the rock sample

Step 2: Calculate λ from I ($\tan I = 2 \tan \lambda$)

Step 3: Calculate λp using cosine formula

$$\cos(90-\lambda p) = \cos(90-\lambda x)\cos(90-\lambda) + \sin(90-\lambda x)\sin(90-\lambda)\cos D$$

Step 4: Calculate ϕp using sine formula

$$\sin(\phi p - \phi x) = [\sin(90-\lambda)\sin D] / \sin(90-\lambda p)$$

We obtain paleomagnetic pole position **(λp, ϕp)** for a rock sample magnetized in the past

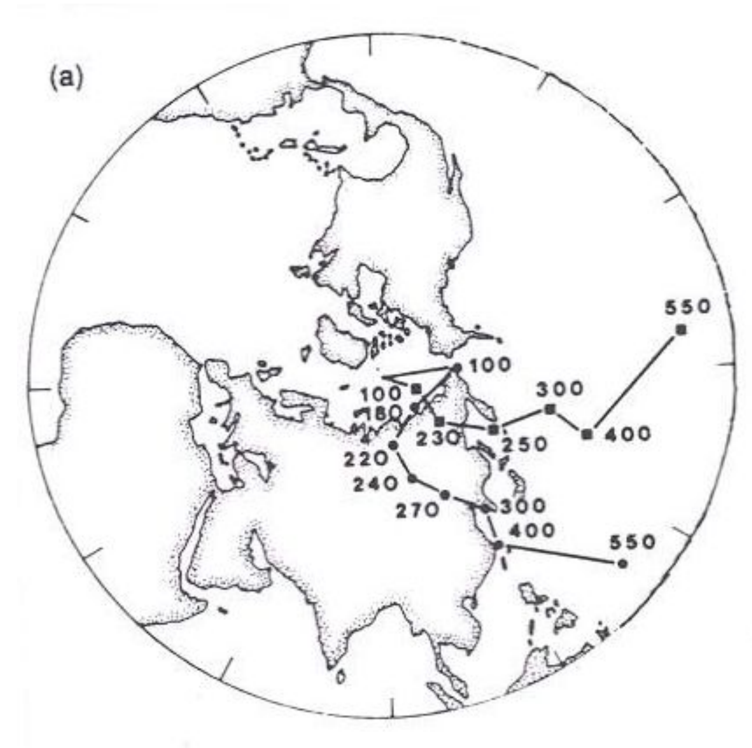
Paleomagnetic Pole position and Polar Wander Paths

Free surface

Younging Direction

		Measure		Calculate
layer-1	$t^{(1)}$	$I^{(1)}$	$D^{(1)}$	$\lambda p, \phi p^{(1)}$
layer-2	$t^{(2)}$	$I^{(2)}$	$D^{(2)}$	$\lambda p, \phi p^{(2)}$
layer-3	$t^{(3)}$	$I^{(3)}$	$D^{(3)}$	$\lambda p, \phi p^{(3)}$
layer-4	$t^{(4)}$	$I^{(4)}$	$D^{(4)}$	$\lambda p, \phi p^{(4)}$
layer-5	$t^{(5)}$	$I^{(5)}$	$D^{(5)}$	$\lambda p, \phi p^{(5)}$
layer-6	$t^{(6)}$	$I^{(6)}$	$D^{(6)}$	$\lambda p, \phi p^{(6)}$
layer-7	$t^{(7)}$	$I^{(7)}$	$D^{(7)}$	$\lambda p, \phi p^{(7)}$

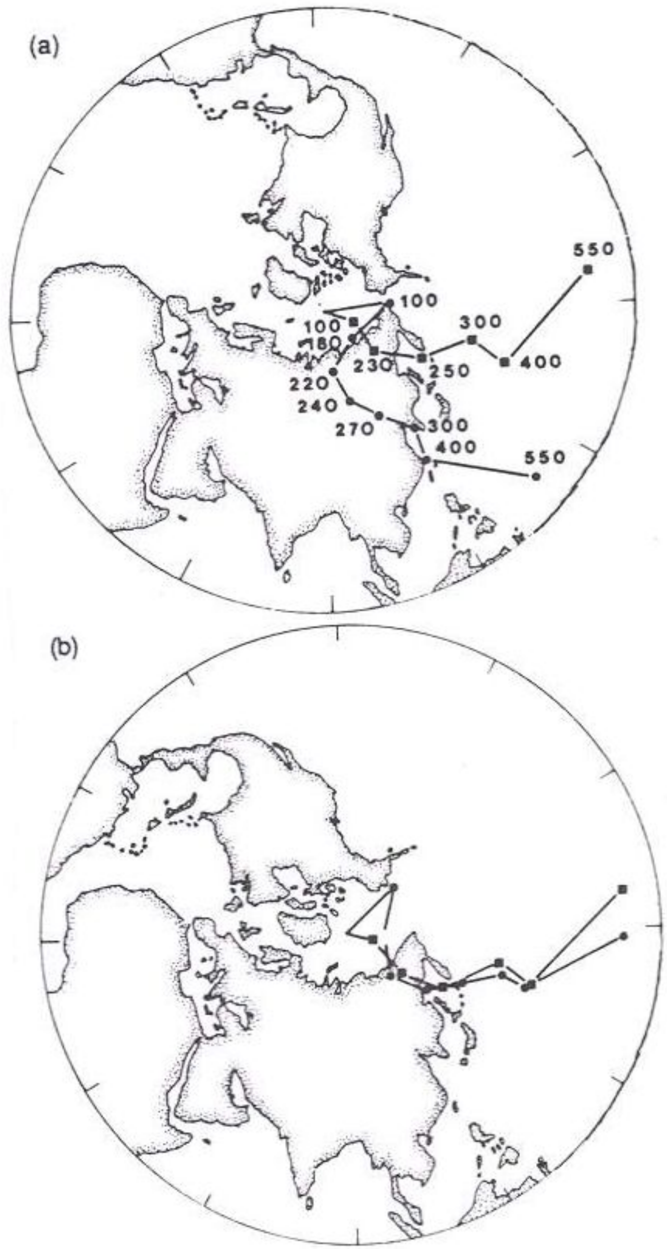
Polar Wander Path



Plot paleomagnetic pole positions **(λp, ϕp)** on a map

Polar Wander Paths

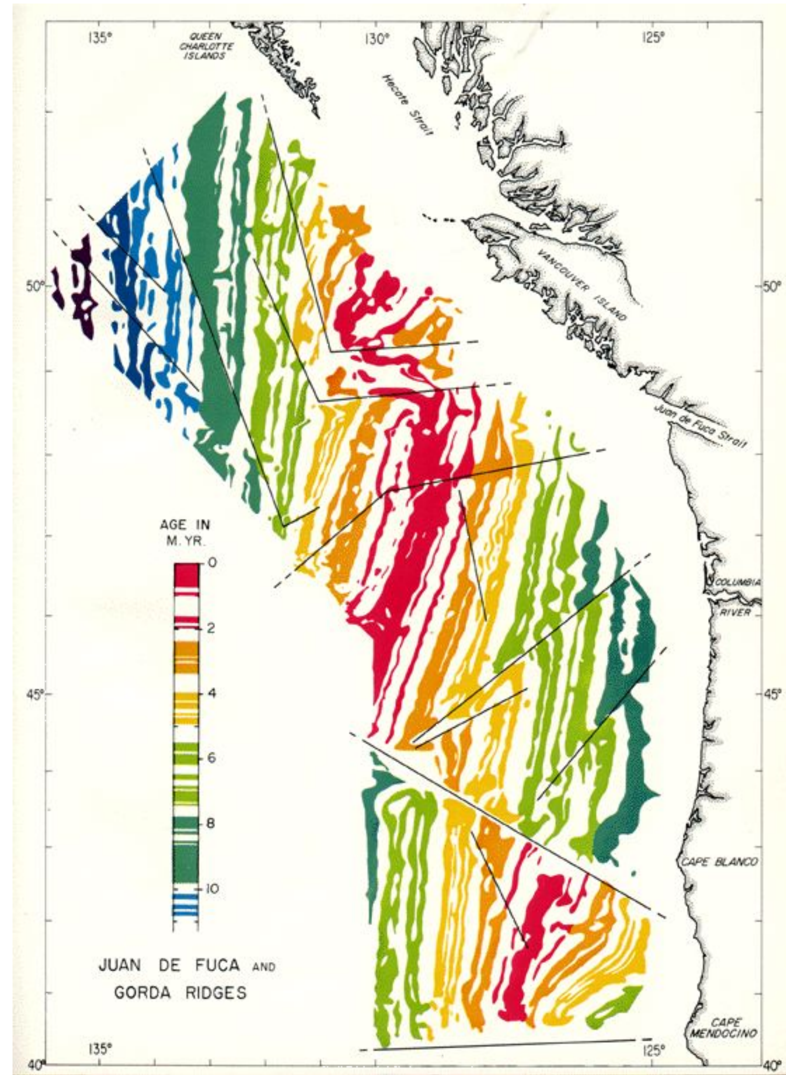
- Paleomagnetic pole positions are obtained from rocks of different ages on the same continent
- Poles plotted on a map → **Polar wander path**
- Shows the movement of the magnetic poles relative to the continent
- If such polar wander paths from two continents coincide, then the two continents haven't had relative motion w.r.t each during this time
- However, if the paths differ, there must have been relative motion of the continents
- Figure on the right shows polar wander paths for **Europe** and **North America** for the last **550 Ma**
- Paths have almost the same shape but they do not coincide
- When opening of the Atlantic is taken into account, the two paths rotate on top of each other



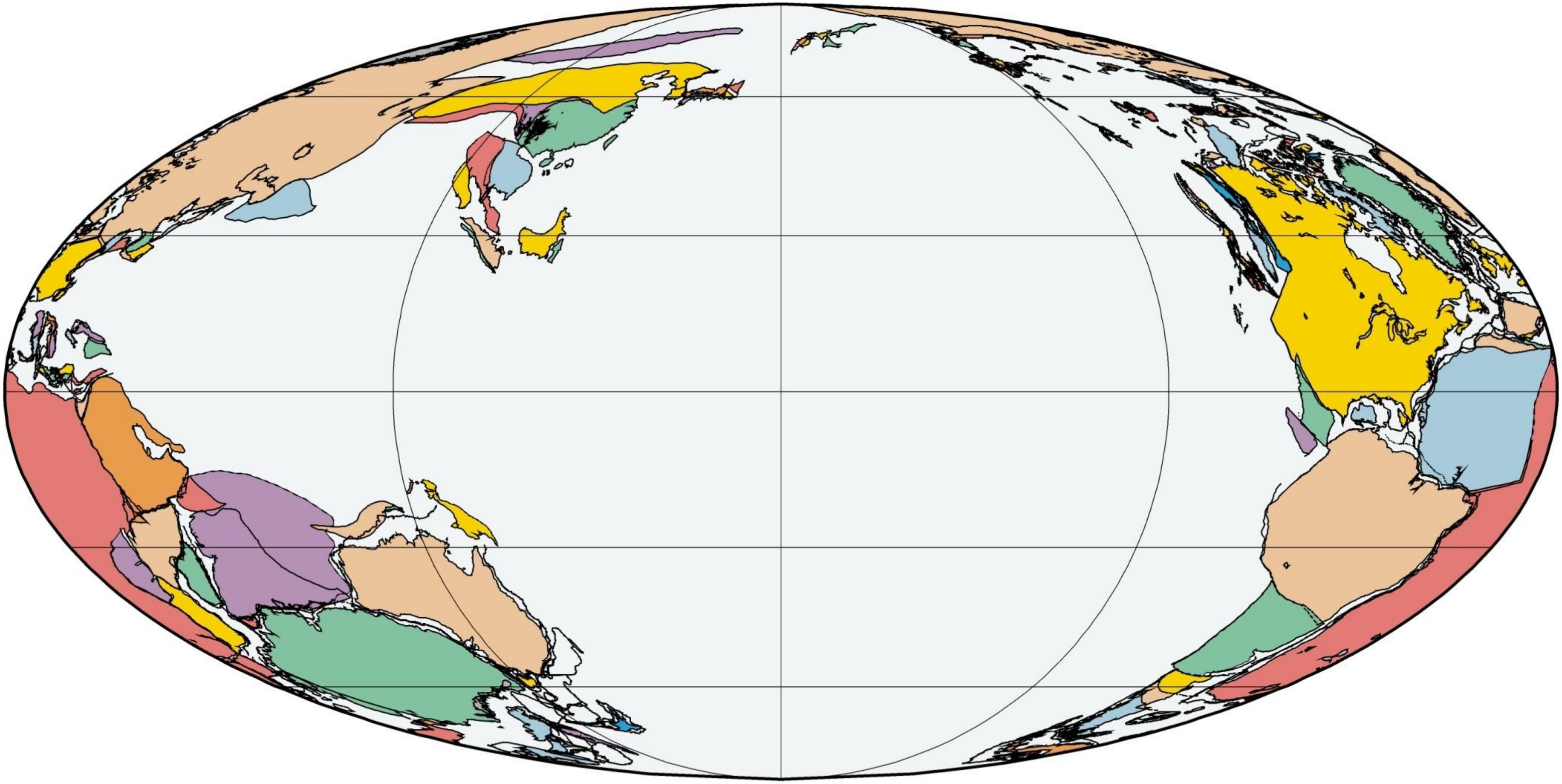
How do you take into account the opening of the Ocean?

Decode the Magnetic Anomaly Patterns

1. Establish a reversal time scale from continental lava piles / oceanic islands using dating techniques
2. Construct block models for this magnetic reversal time scale for a given oceanic region
3. Compute synthetic anomaly patterns for the region
4. Compare it with the observed magnetic anomaly patterns
5. Make the geologic and magnetic time scales as precise as possible
6. Combine Oceanic and Continental observations to form a detail map of the **Opening of the Ocean Floor** and **Past Plate Motions**



The Continents

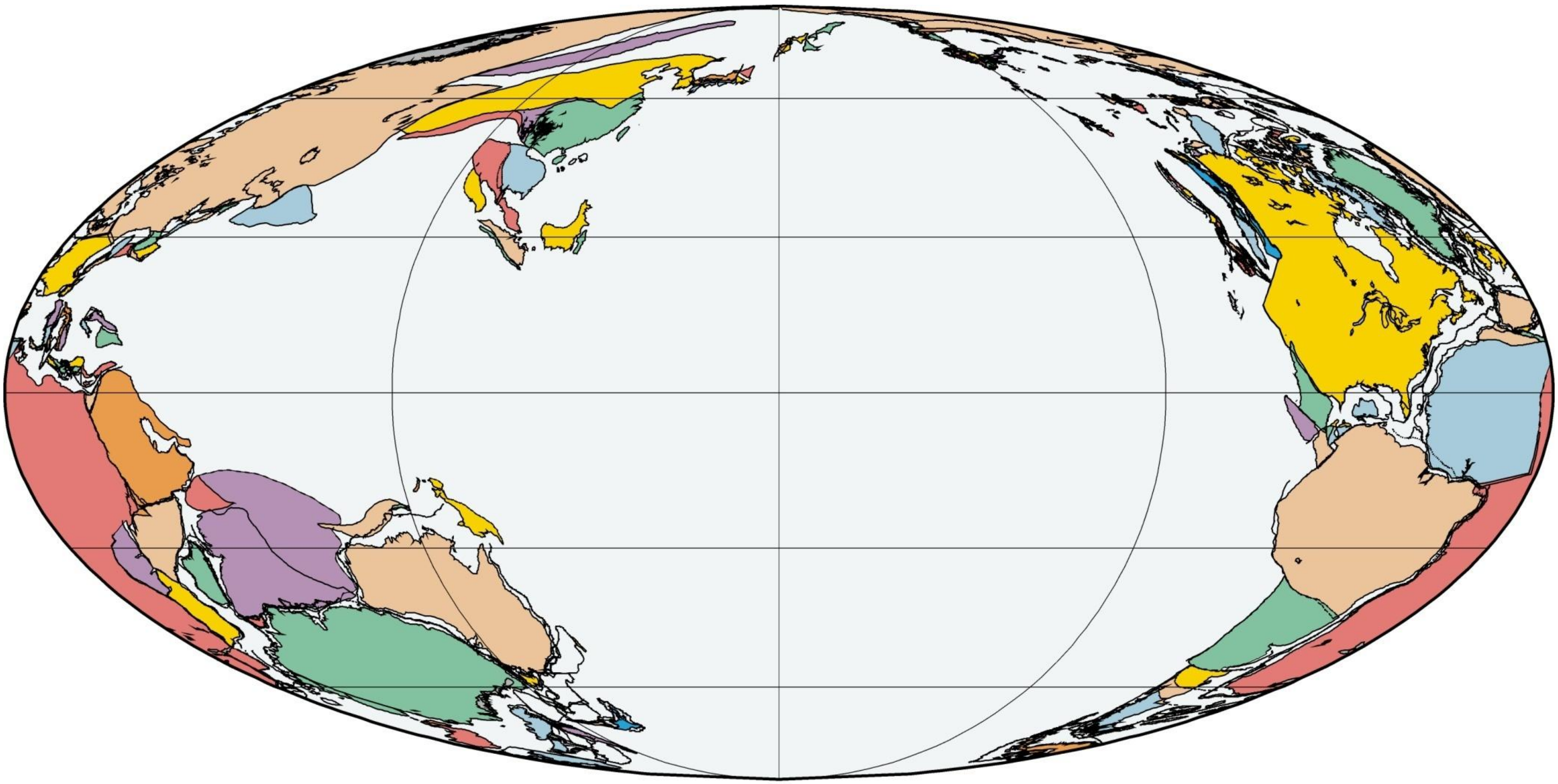


180 Ma

Aalenian (Middle Jurassic)

PLATES/UTIG

July 2003

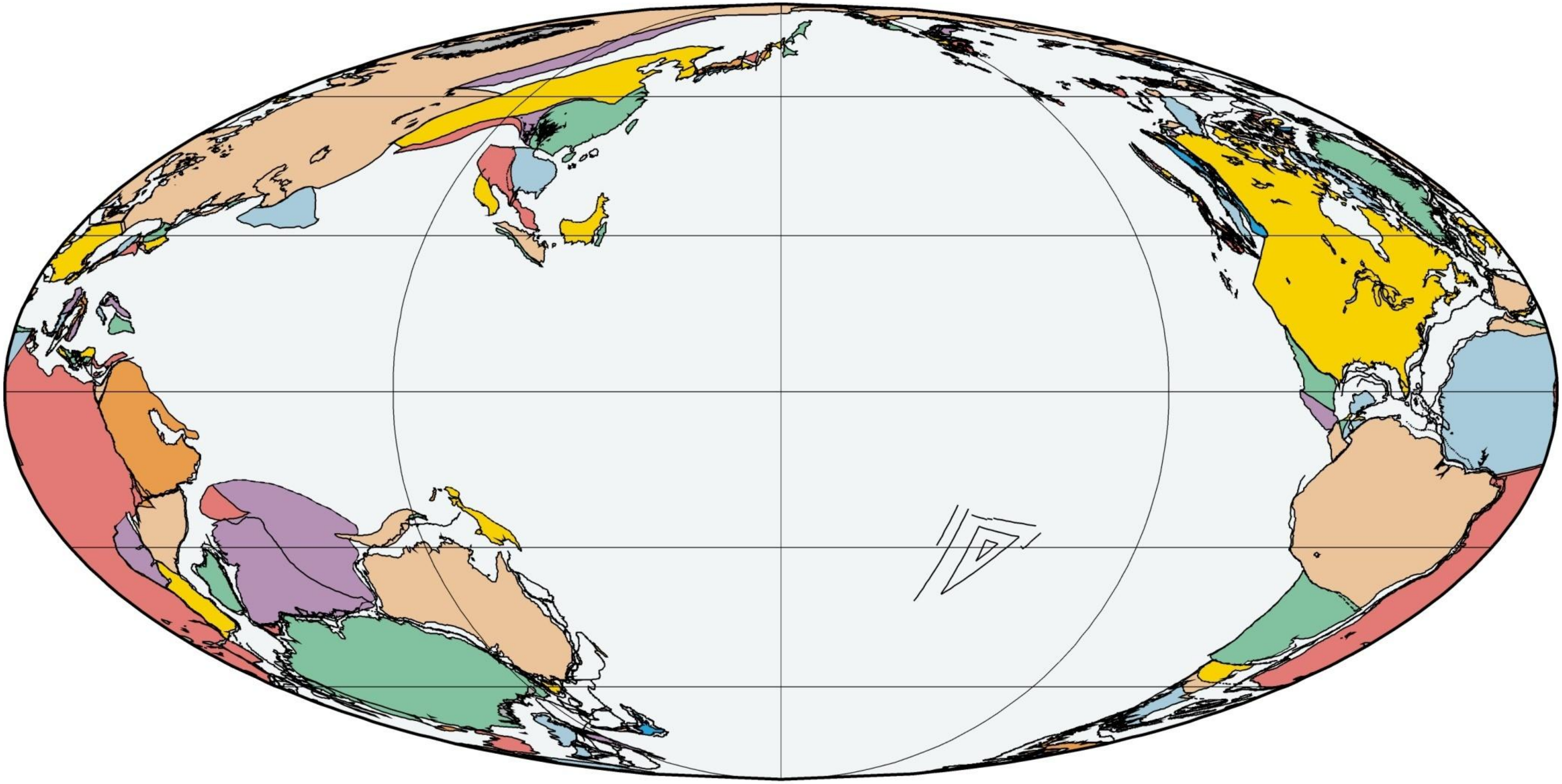


170 Ma

Bajocian (Middle Jurassic)

PLATES/UTIG

July 2003

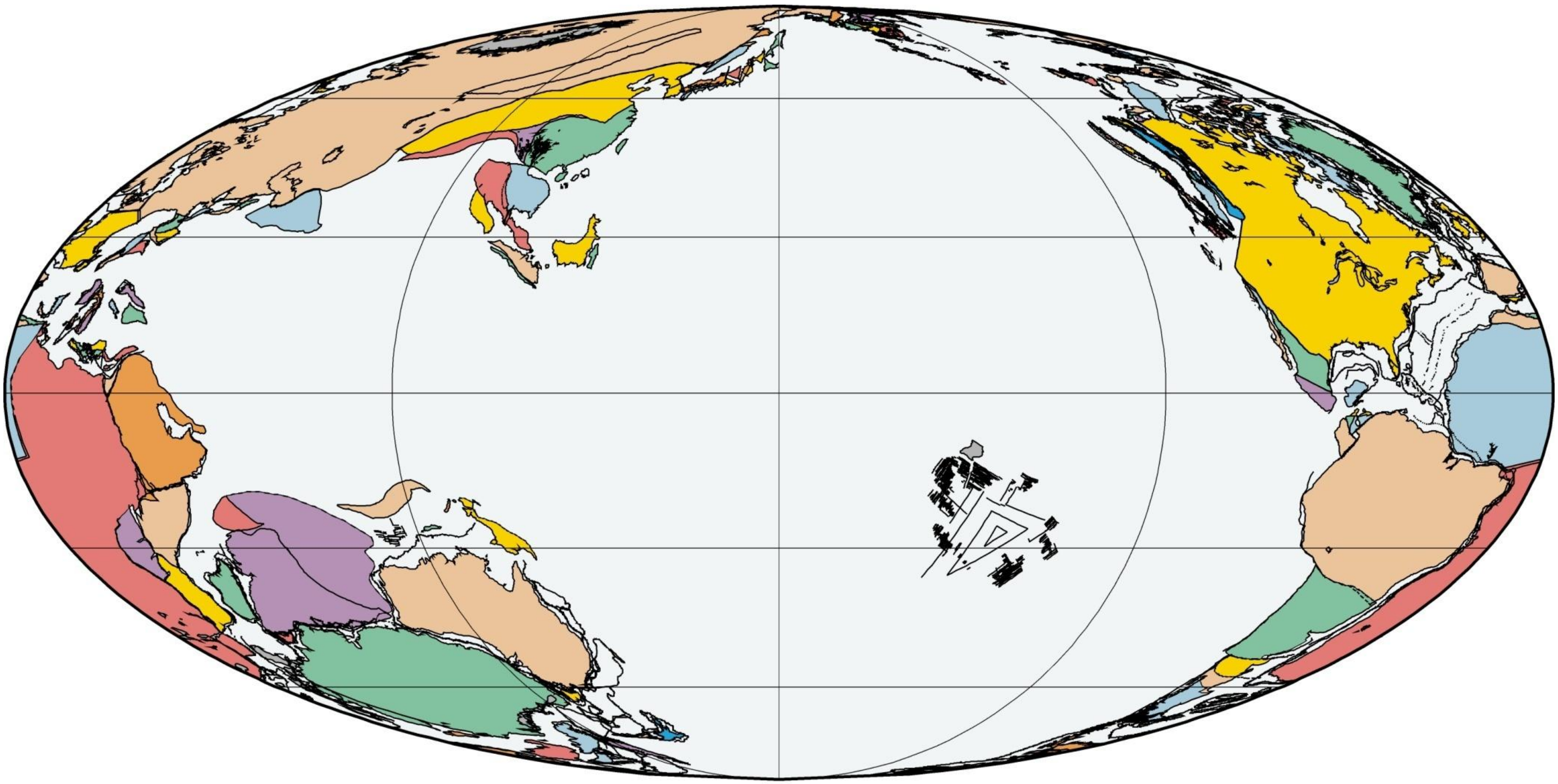


160 Ma

Callovian (Middle Jurassic)

PLATES/UTIG

July 2003

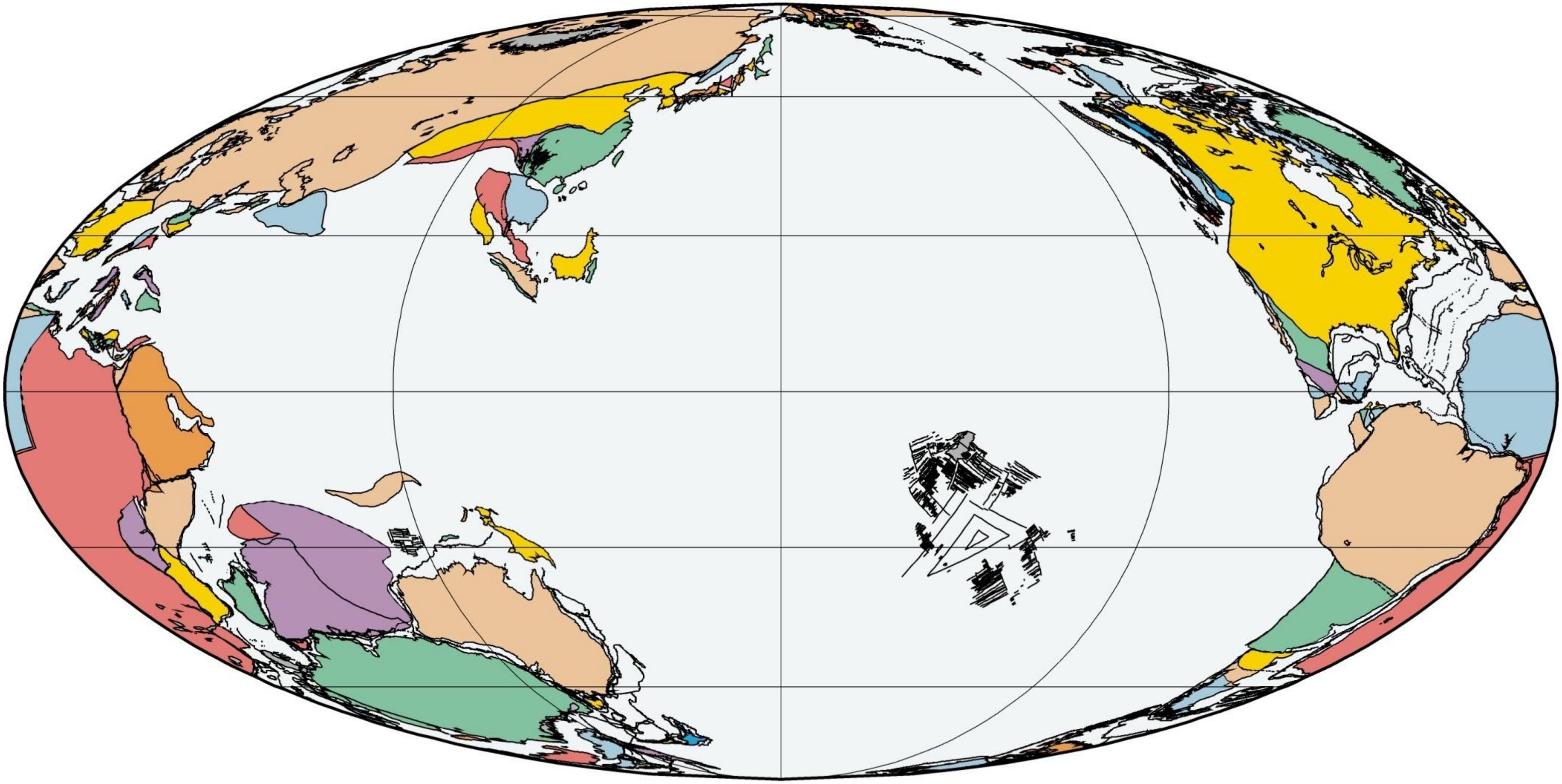


150 Ma

Volgian (Late Jurassic)

PLATES/UTIG

July 2003

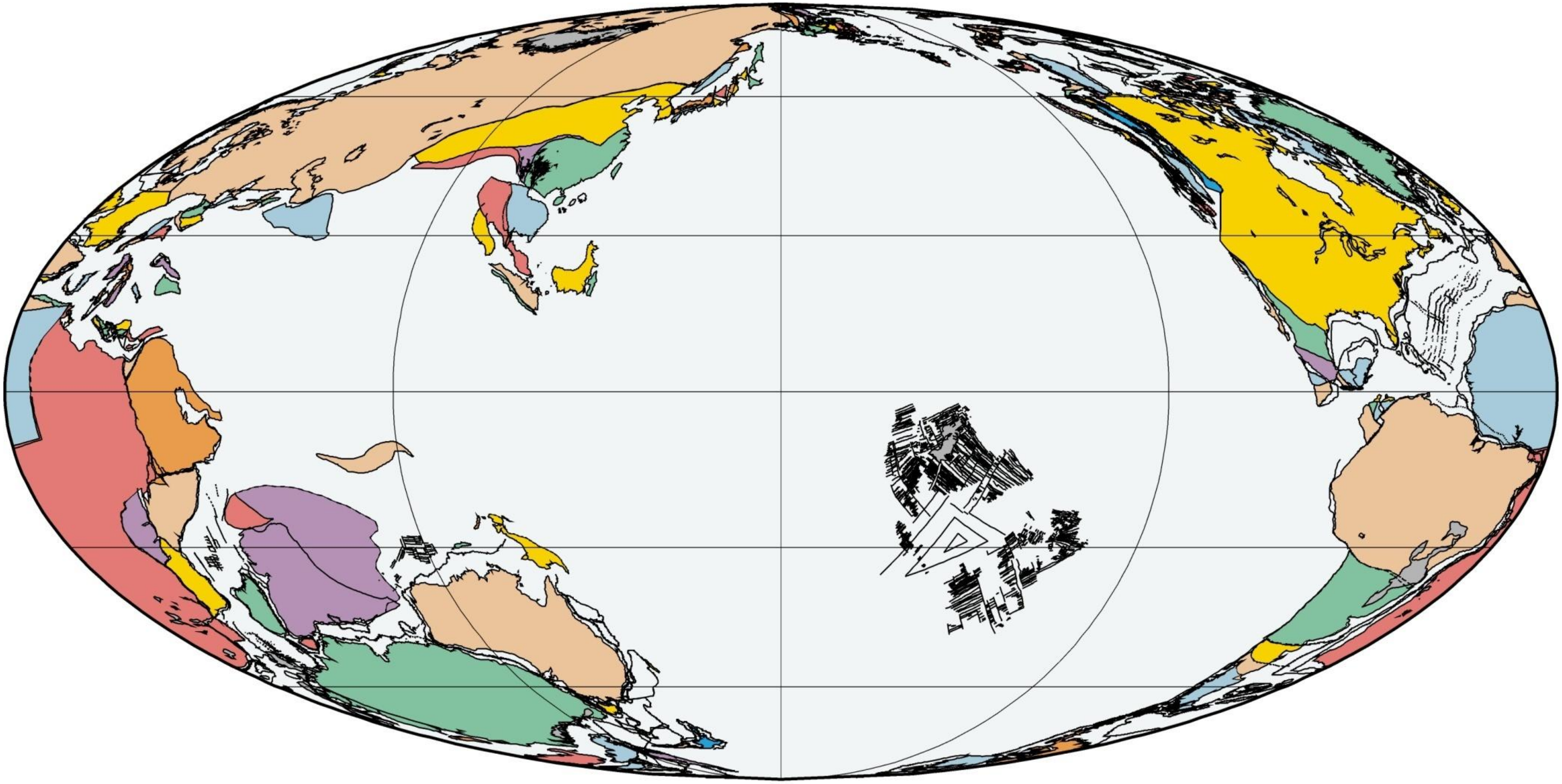


140 Ma

Ryazanian (Early Cretaceous)

PLATES/UTIG

July 2003

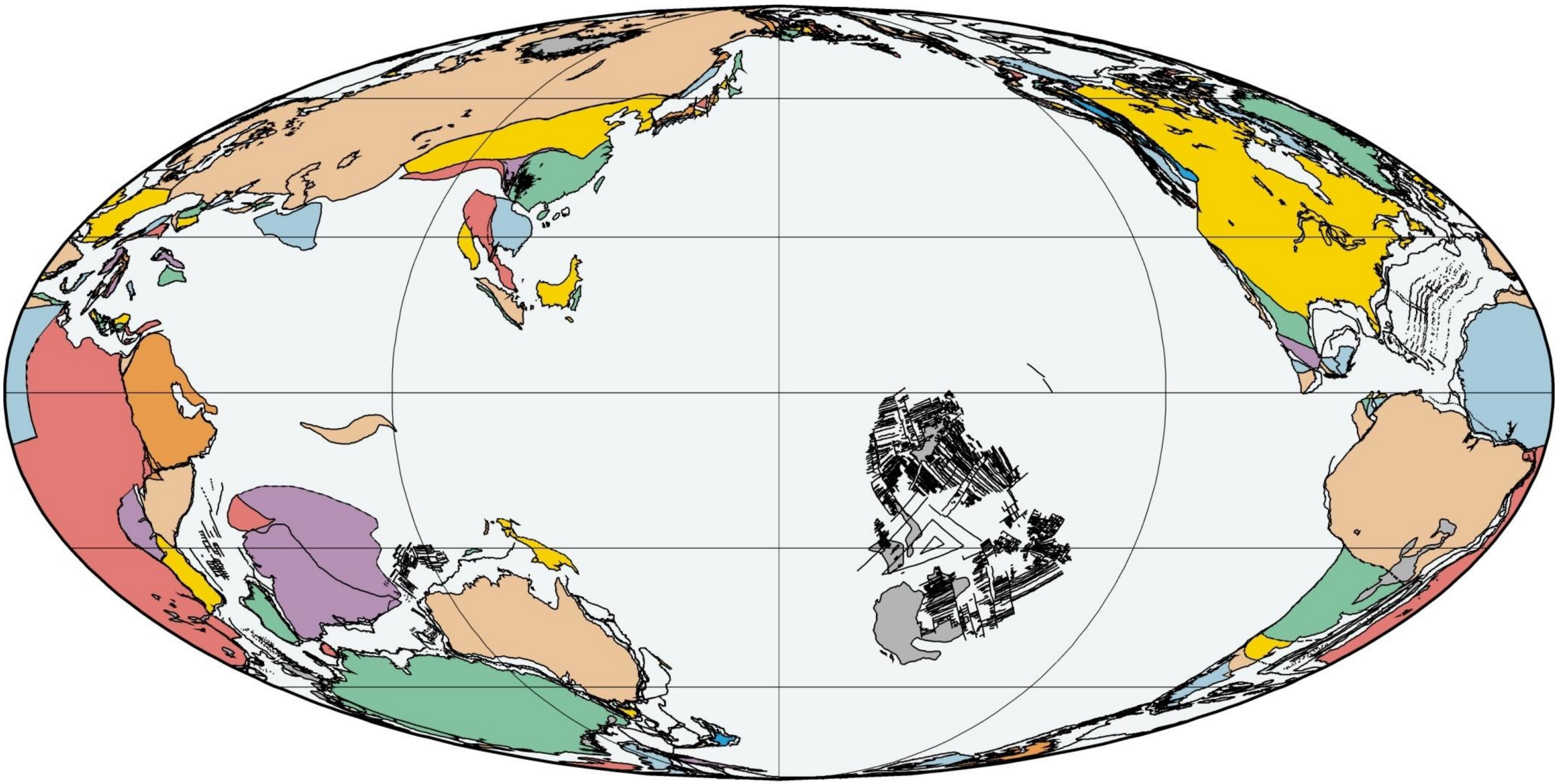


130 Ma

Hauterivian (Early Cretaceous)

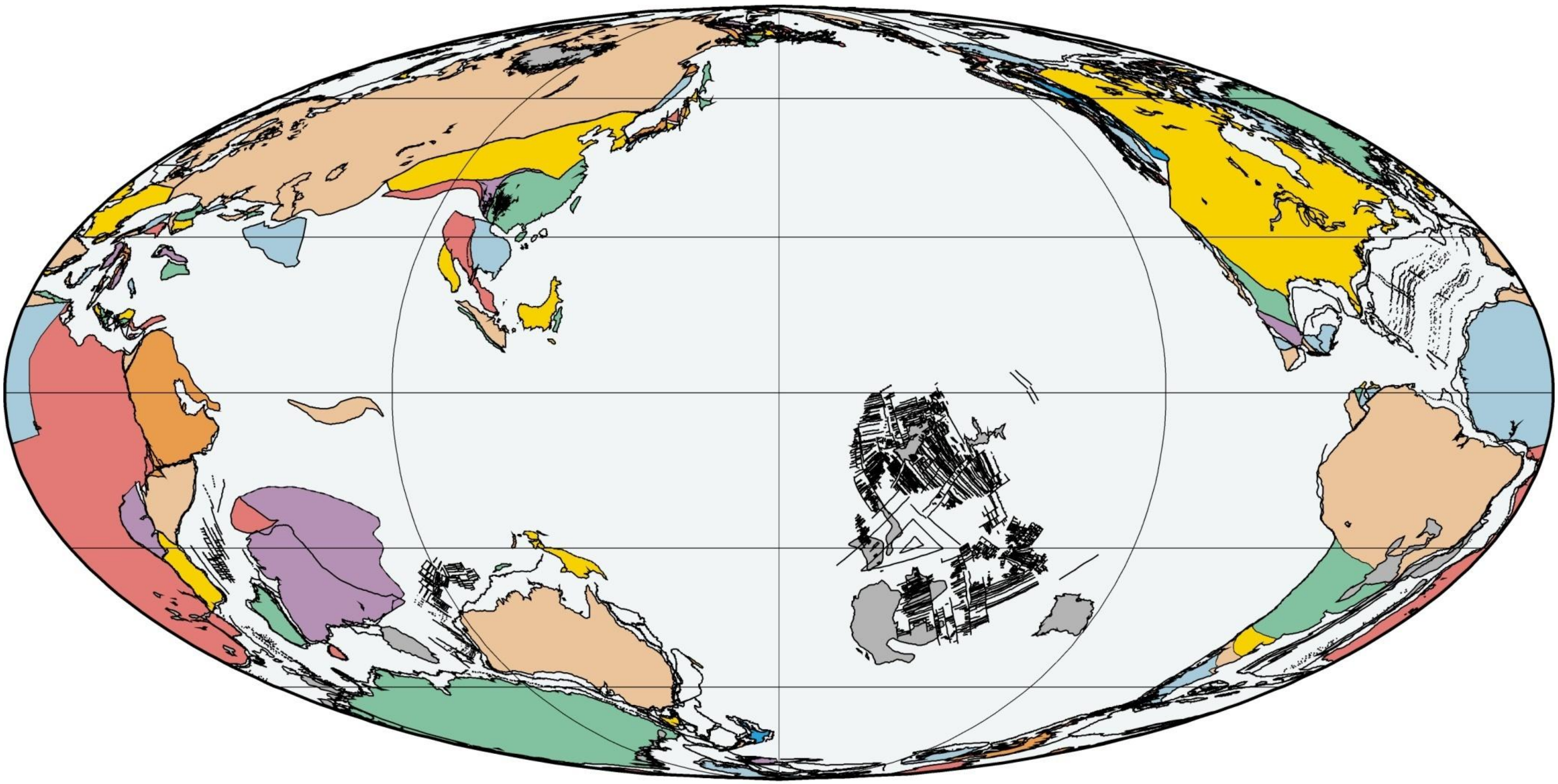
PLATES/UTIG

July 2003



120 Ma
Aptian (Early Cretaceous)

PLATES/UTIG
July 2003

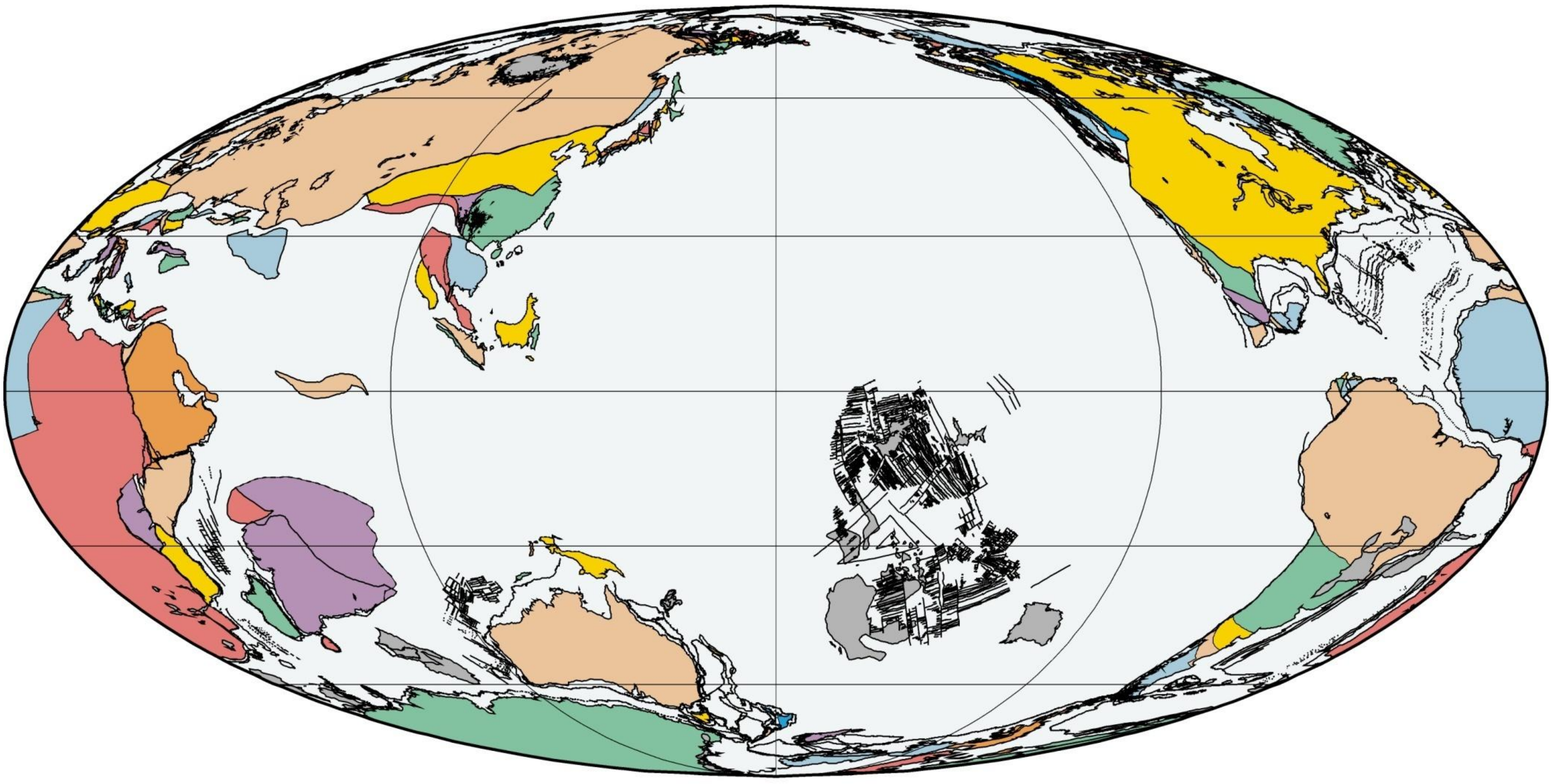


110 Ma

Early Albian (Early Cretaceous)

PLATES/UTIG

July 2003

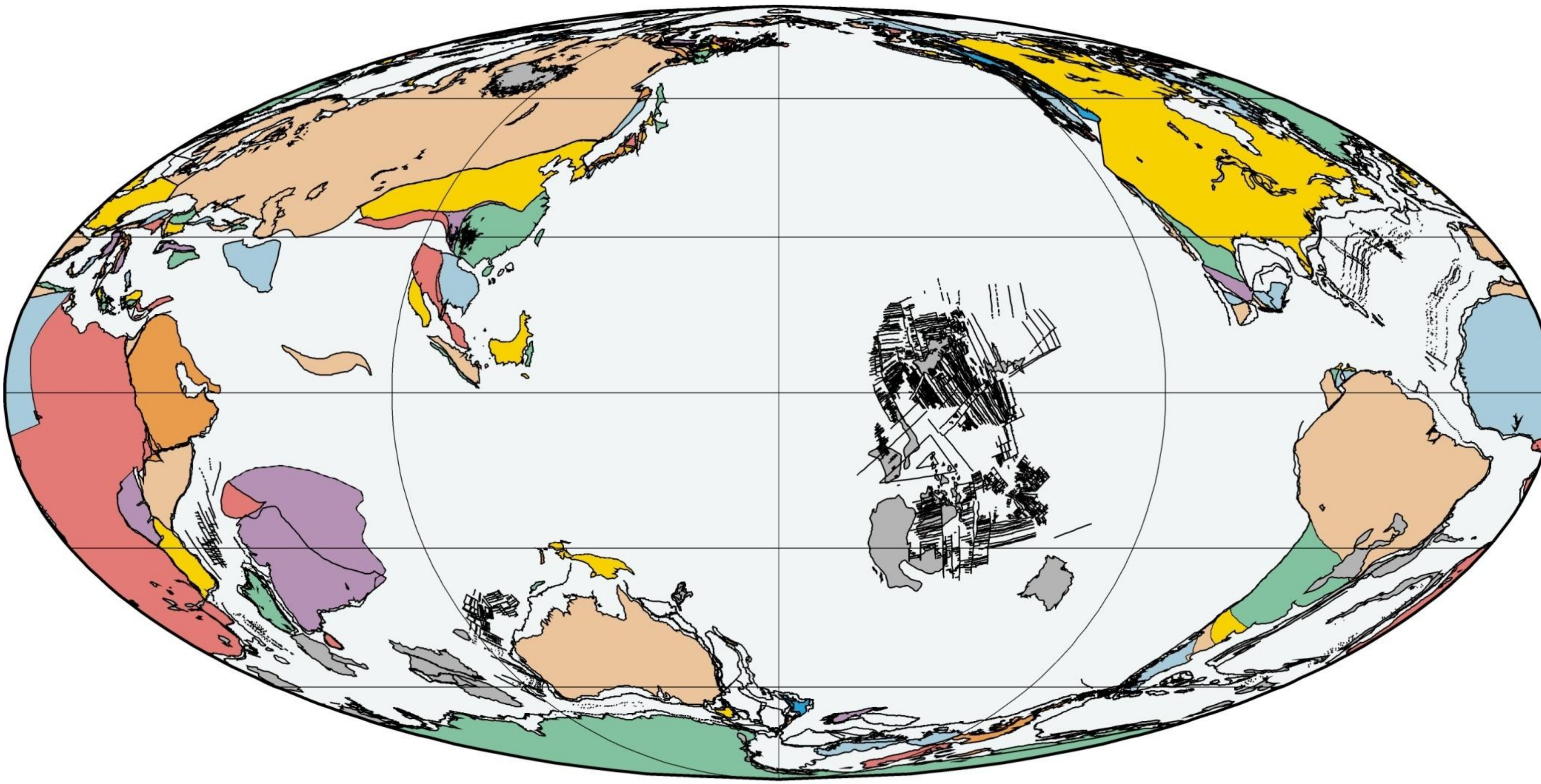


100 Ma

Late Albian (Early Cretaceous)

PLATES/UTIG

July 2003

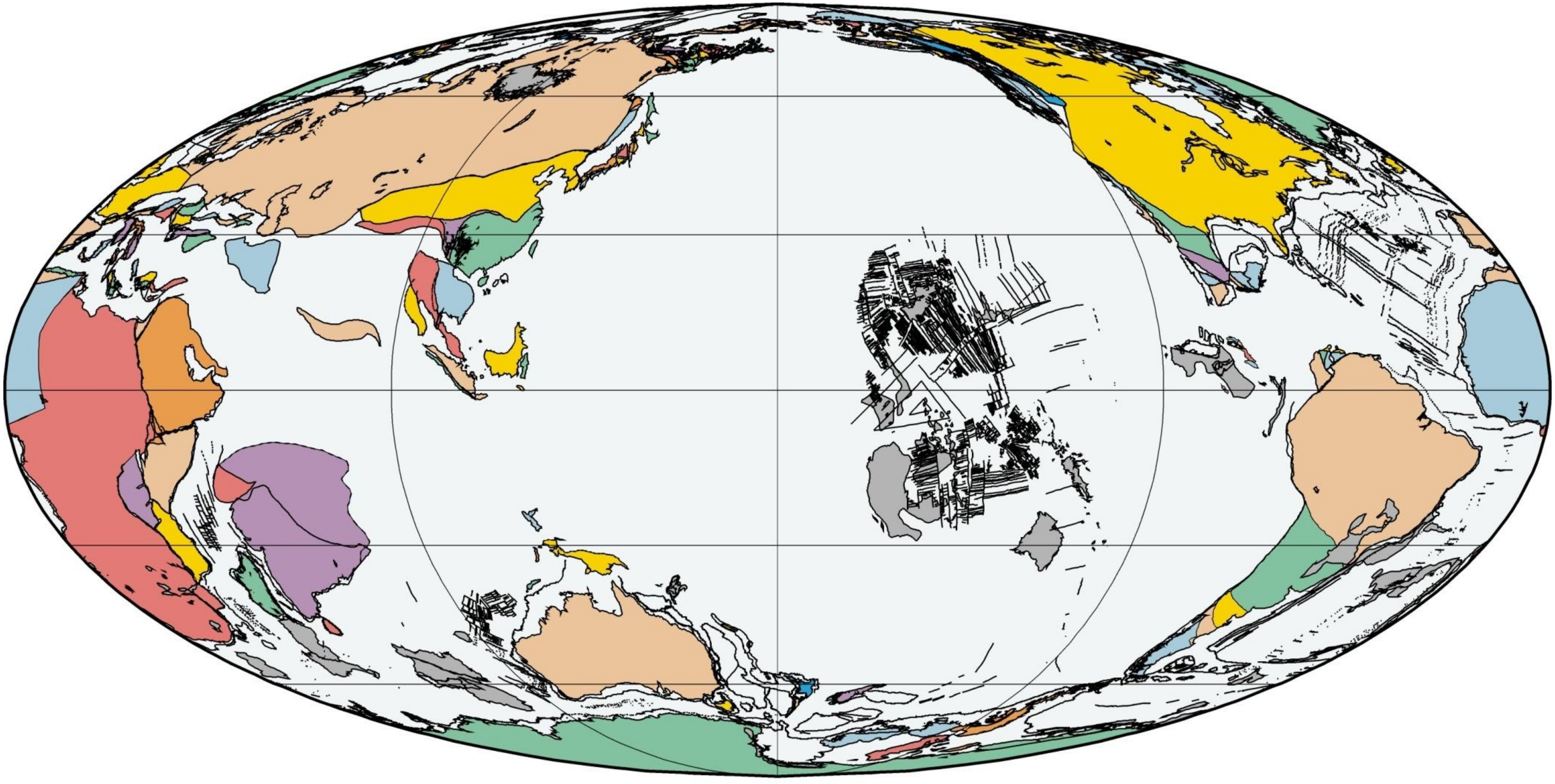


090 Ma

Turonian (Late Cretaceous)

PLATES/UTIG

July 2003

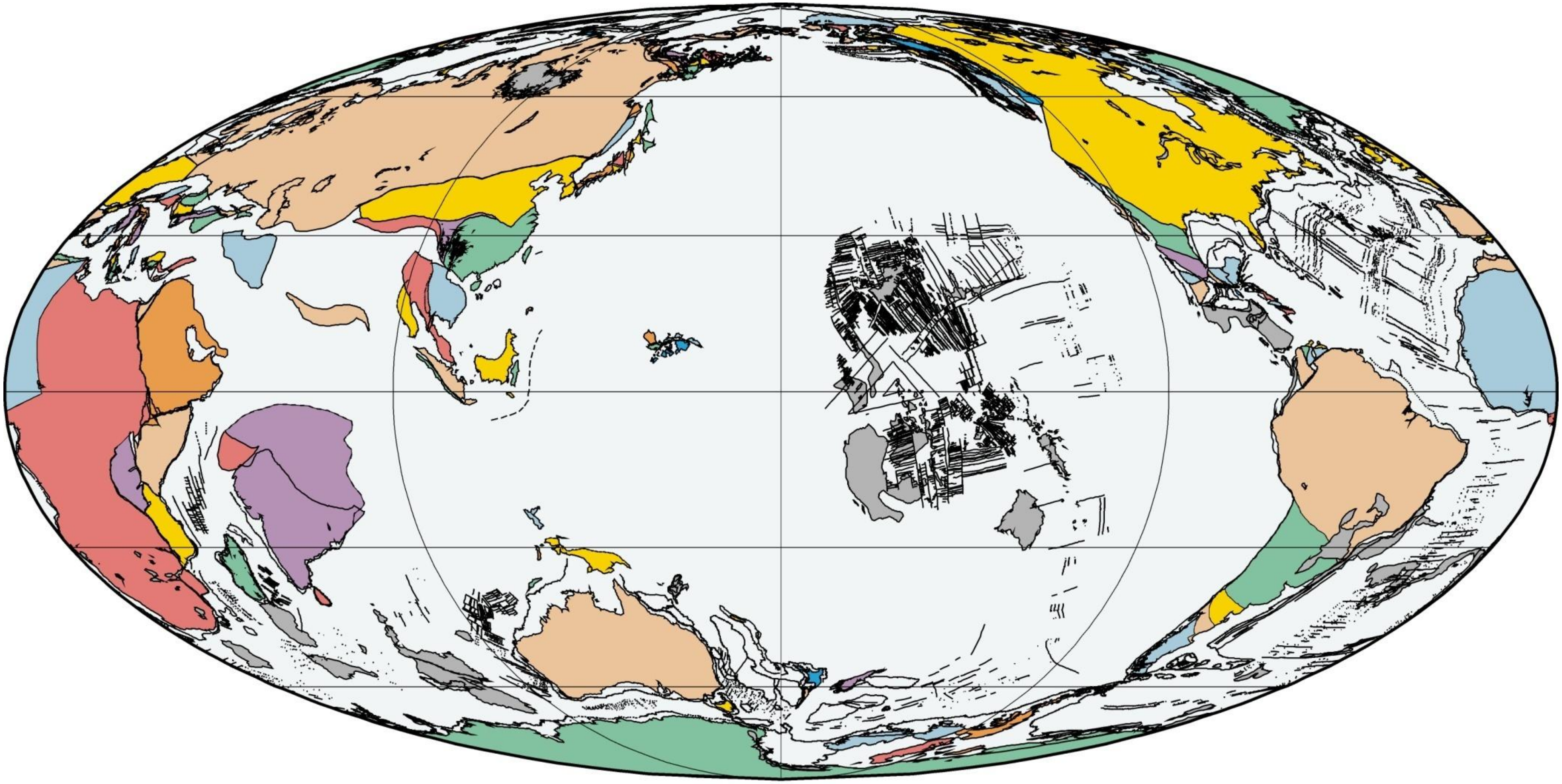


080 Ma

Campanian (Late Cretaceous)

PLATES/UTIG

July 2003

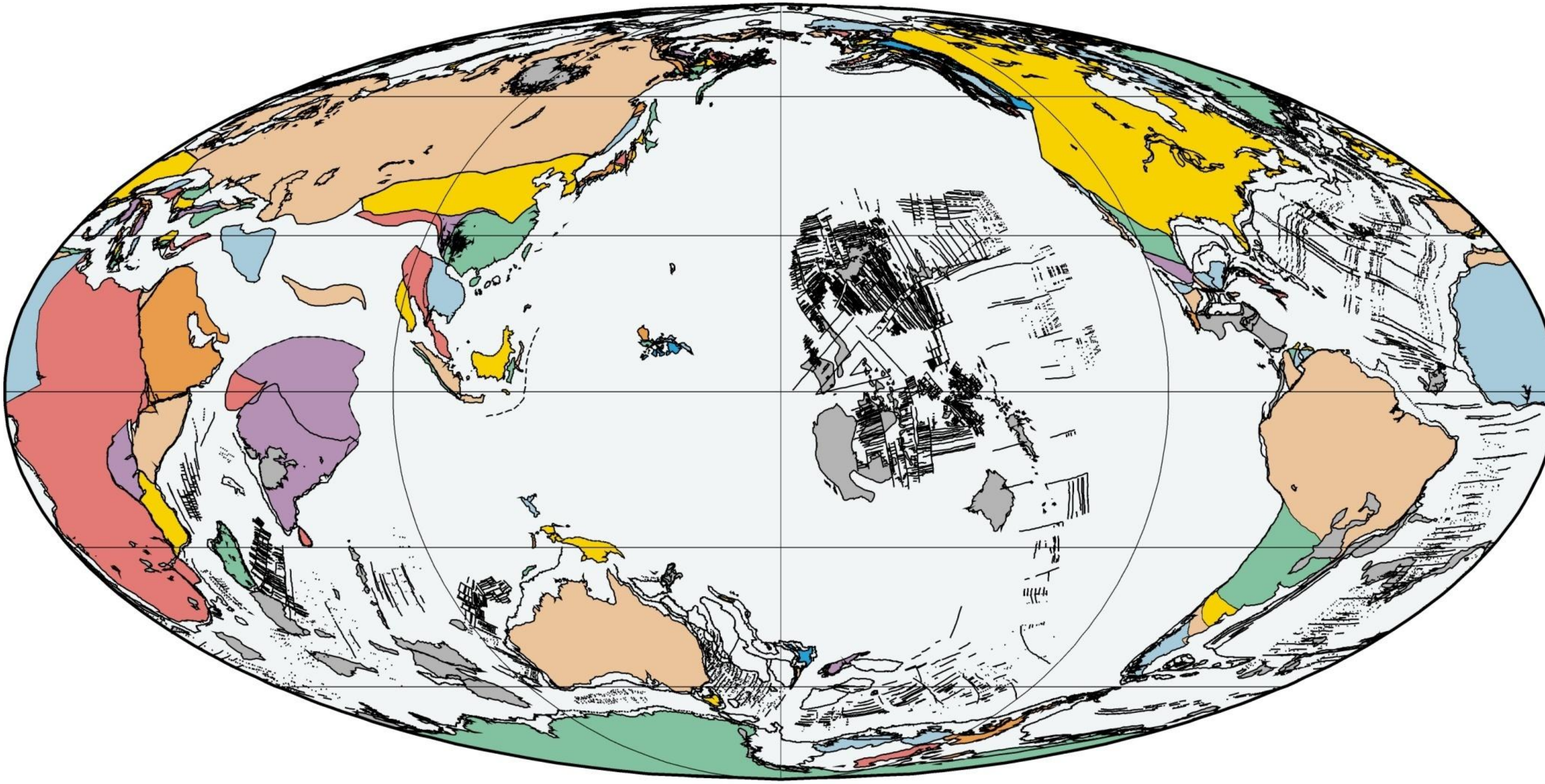


070 Ma

Maastrichtian (Late Cretaceous)

PLATES/UTIG

July 2003

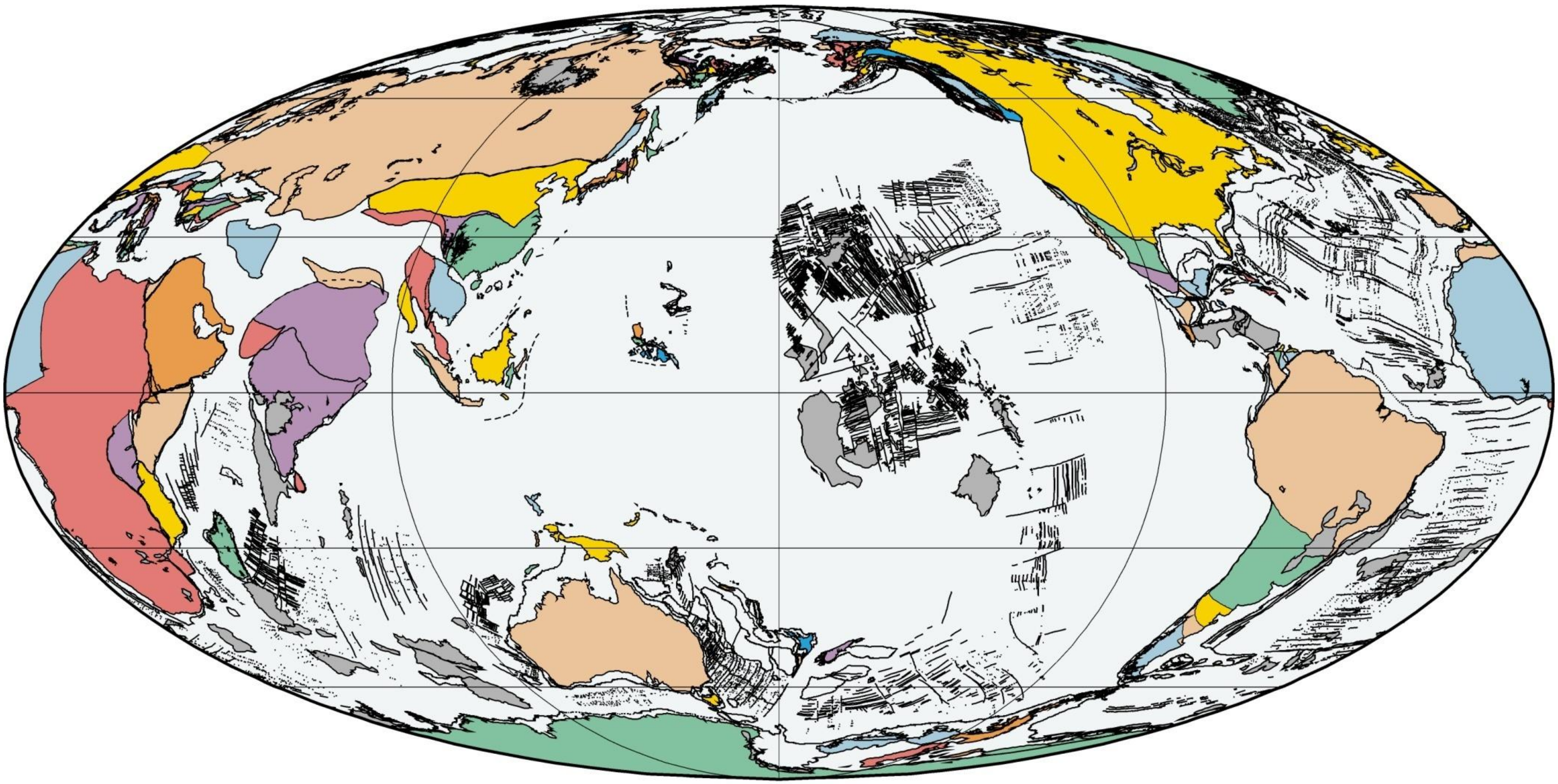


060 Ma

Late Paleocene

PLATES/UTIG

July 2003

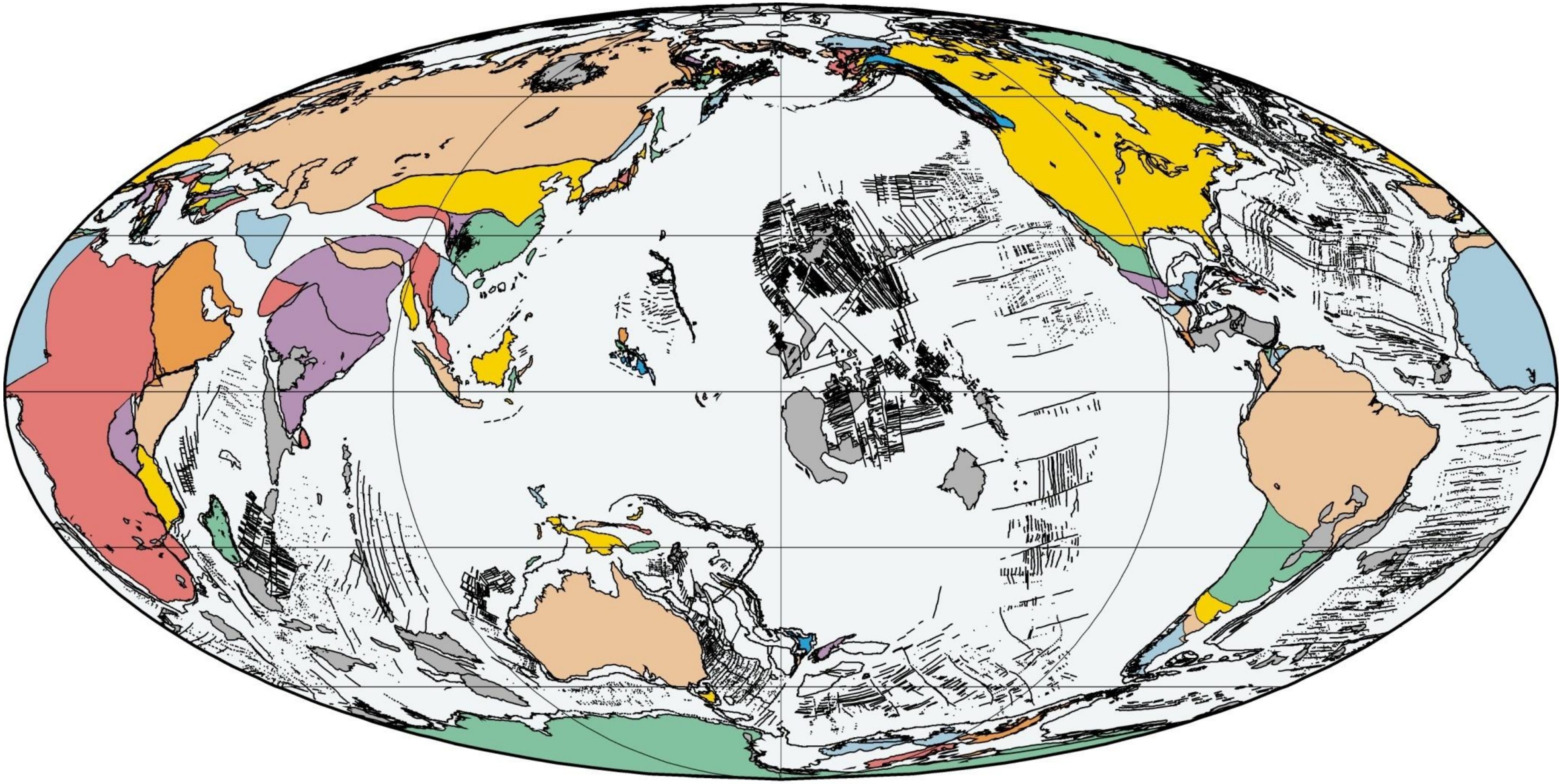


050 Ma

Early Eocene

PLATES/UTIG

July 2003

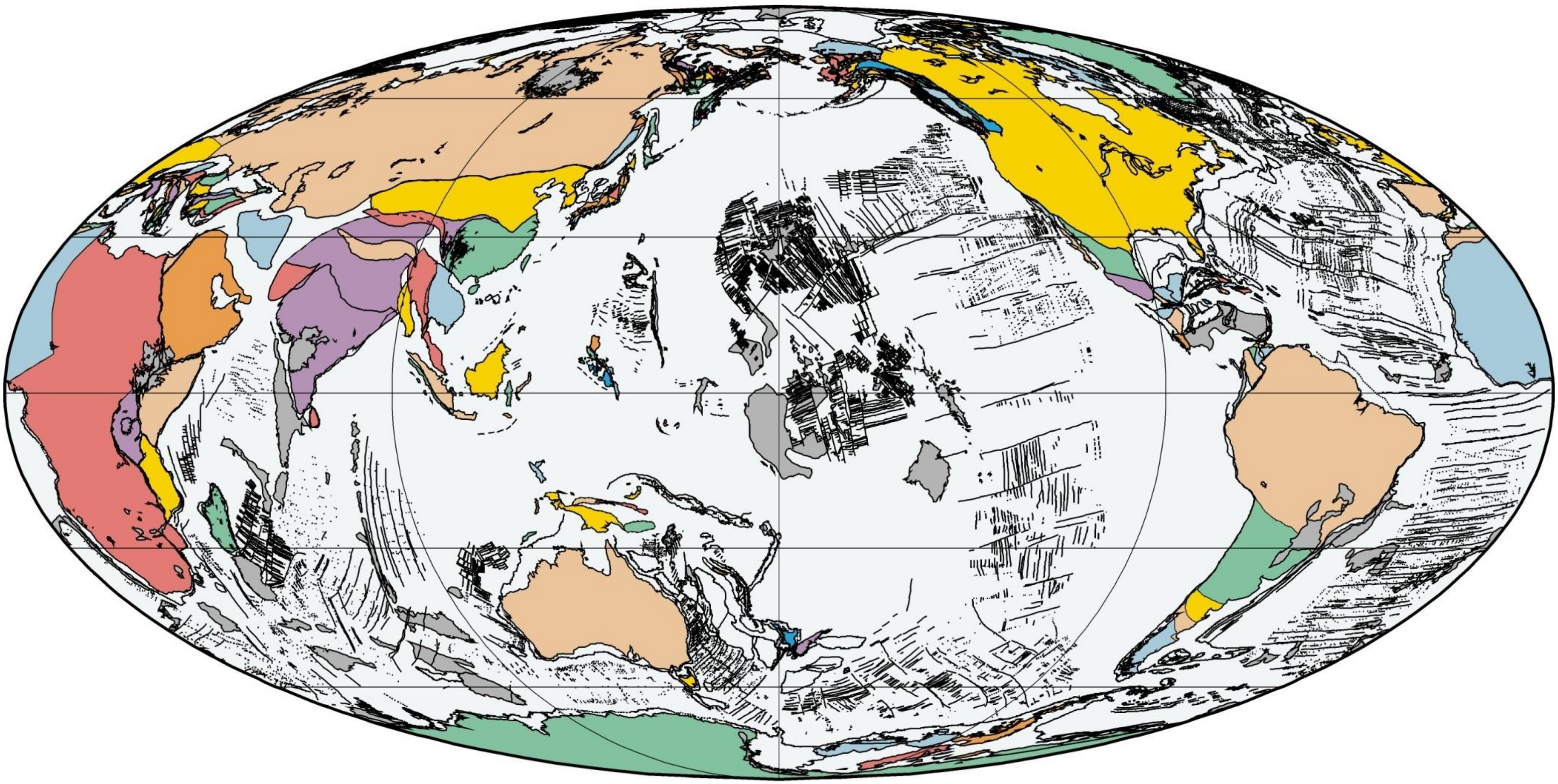


040 Ma

Middle Eocene

PLATES/UTIG

July 2003

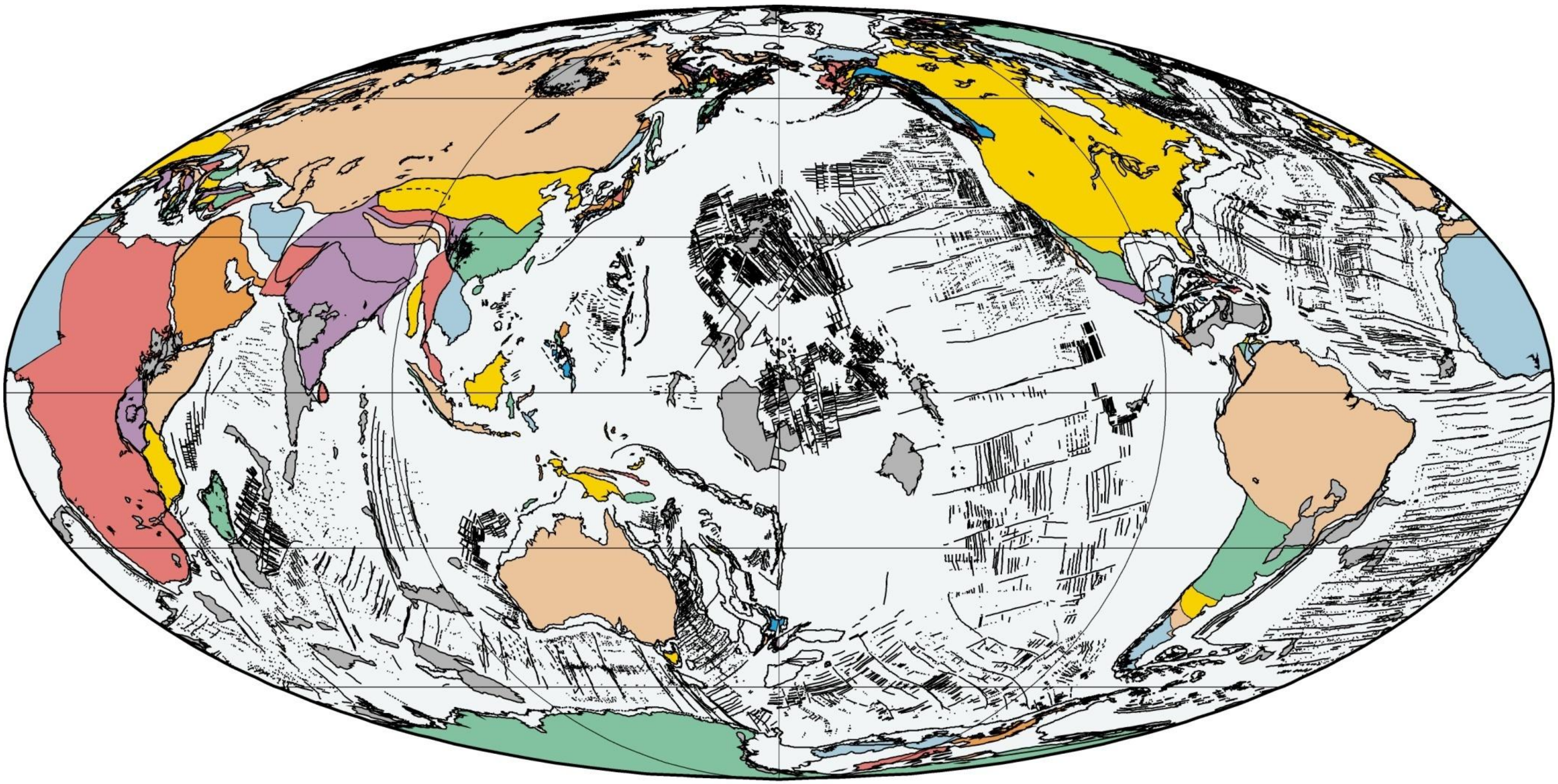


030 Ma

Early Oligocene

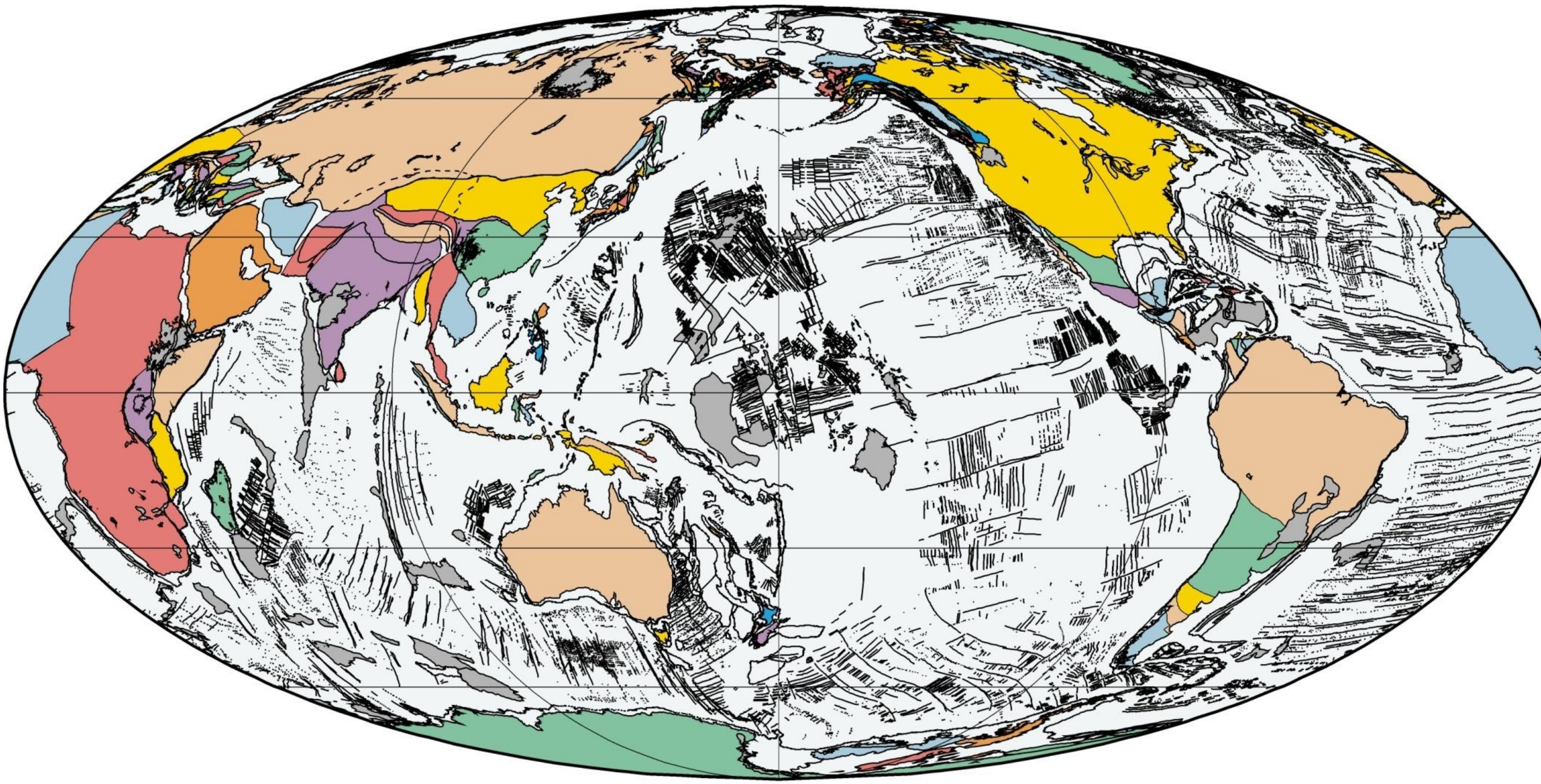
PLATES/UTIG

July 2003



020 Ma
Early Miocene

PLATES/UTIG
July 2003

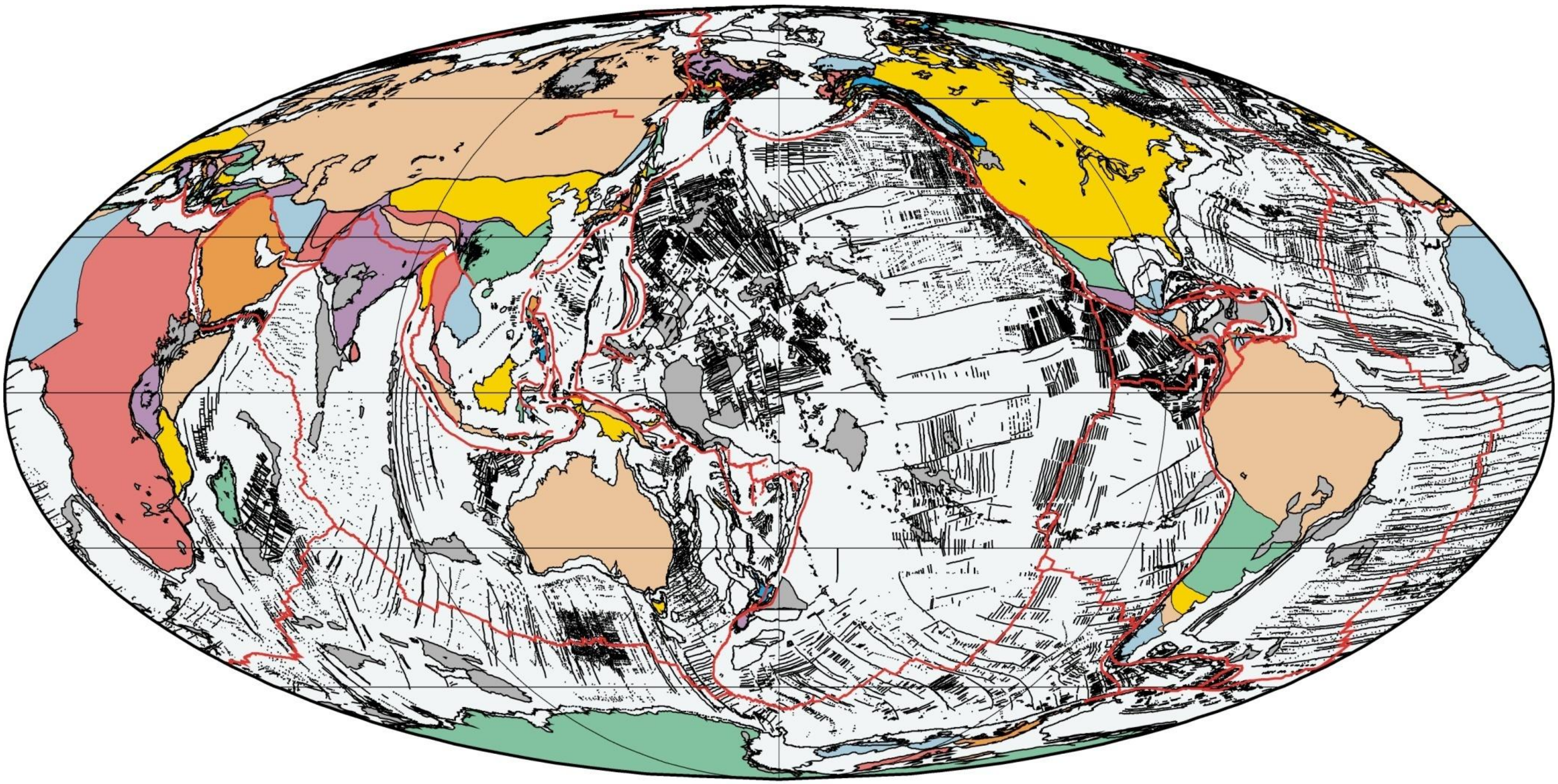


010 Ma

Late Miocene

PLATES/UTIG

July 2003



000 Ma

Present Day

PLATES/UTIG

July 2003

Summary

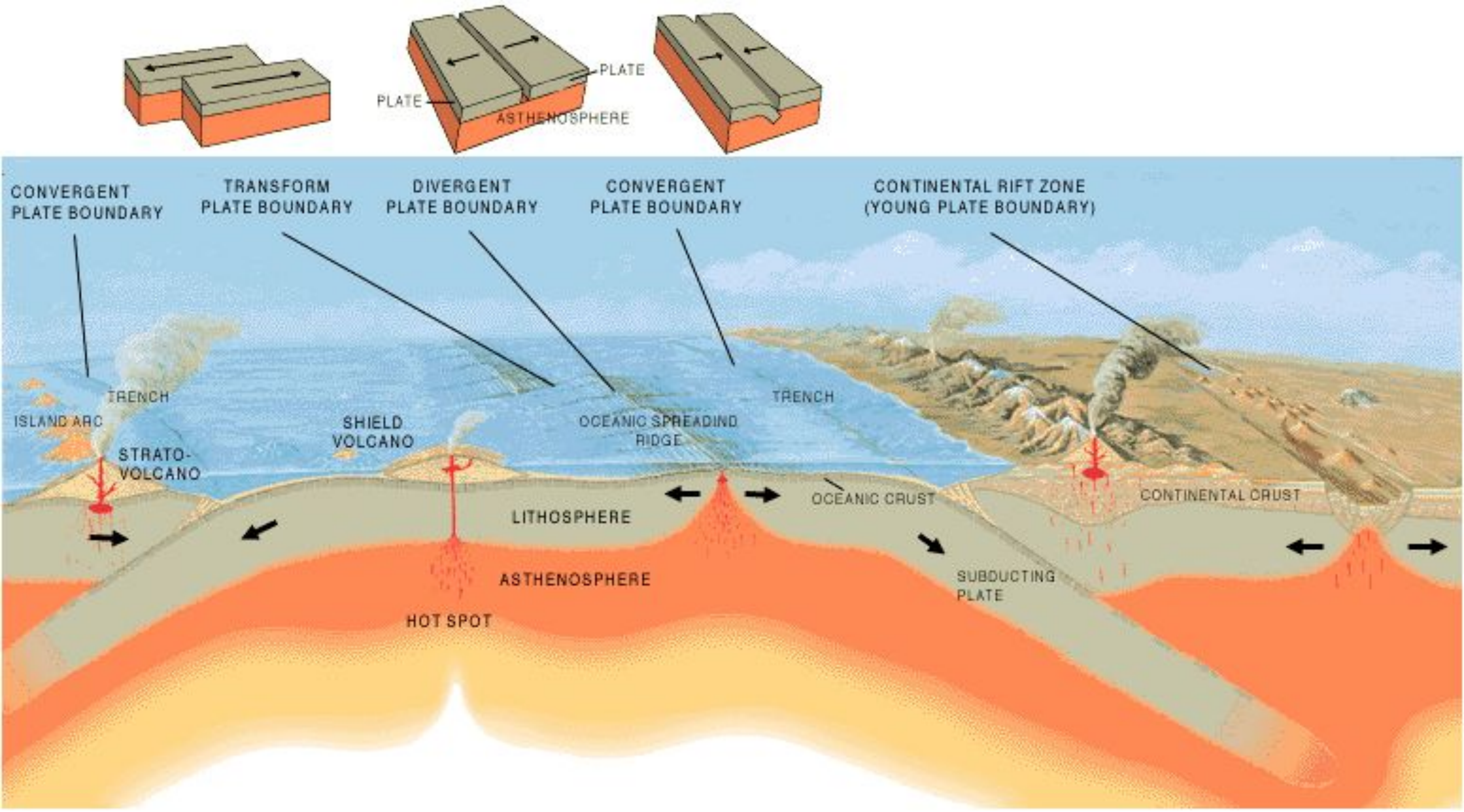


PLATE
PLATE
ASTHENOSPHERE
CONVERGENT PLATE BOUNDARY
TRANSFORM PLATE BOUNDARY
DIVERGENT PLATE BOUNDARY
CONVERGENT PLATE BOUNDARY
CONTINENTAL RIFT ZONE (YOUNG PLATE BOUNDARY)
TRENCH
ISLAND ARC
SHIELD VOLCANO
STRATO-VOLCANO
OCEANIC SPREADIND RIDGE
TRENCH
OCEANIC CRUST
CONTINENTAL CRUST
LITHOSPHERE
ASTHENOSPHERE
HOT SPOT
SUBDUCTING PLATE