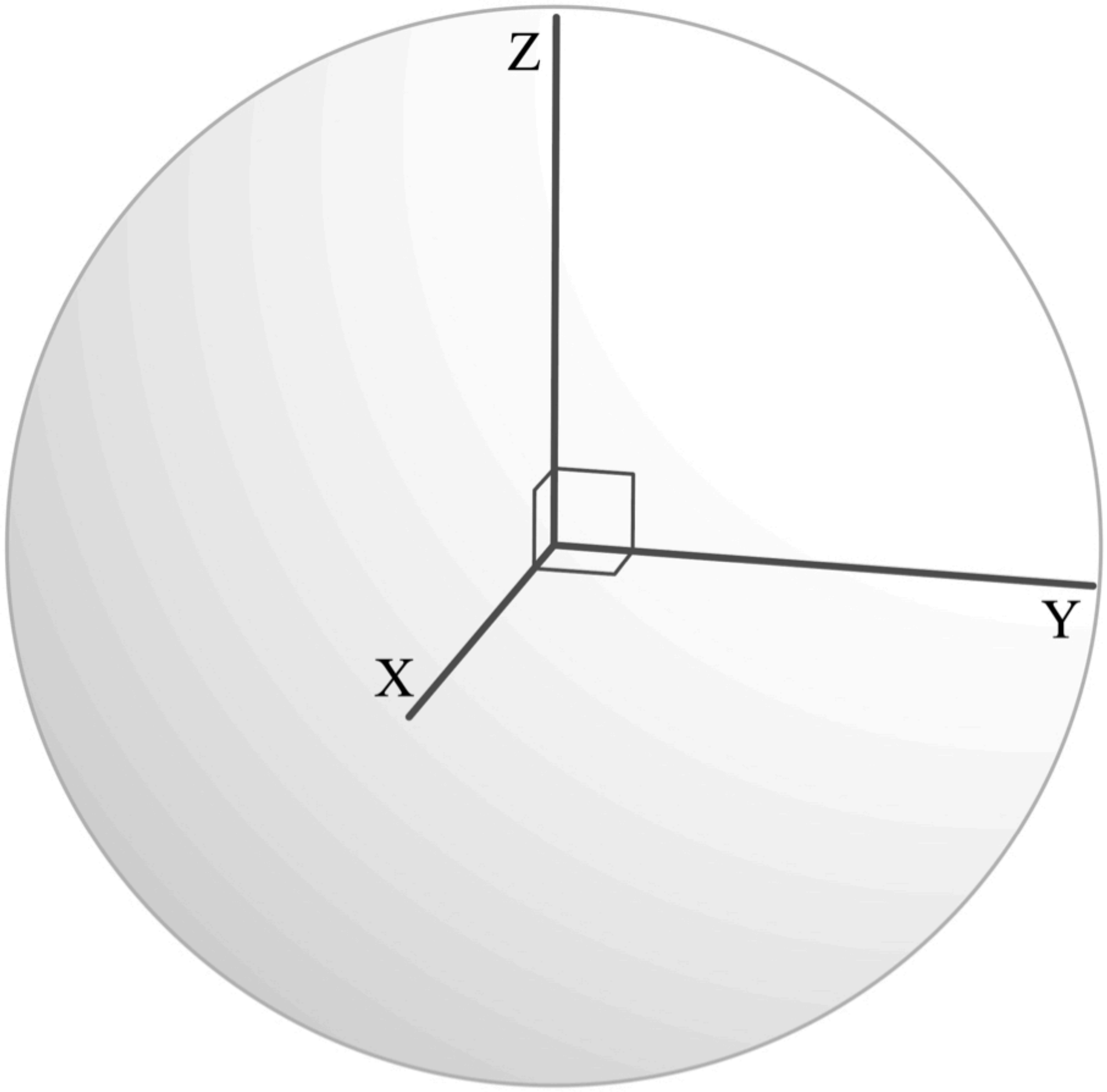
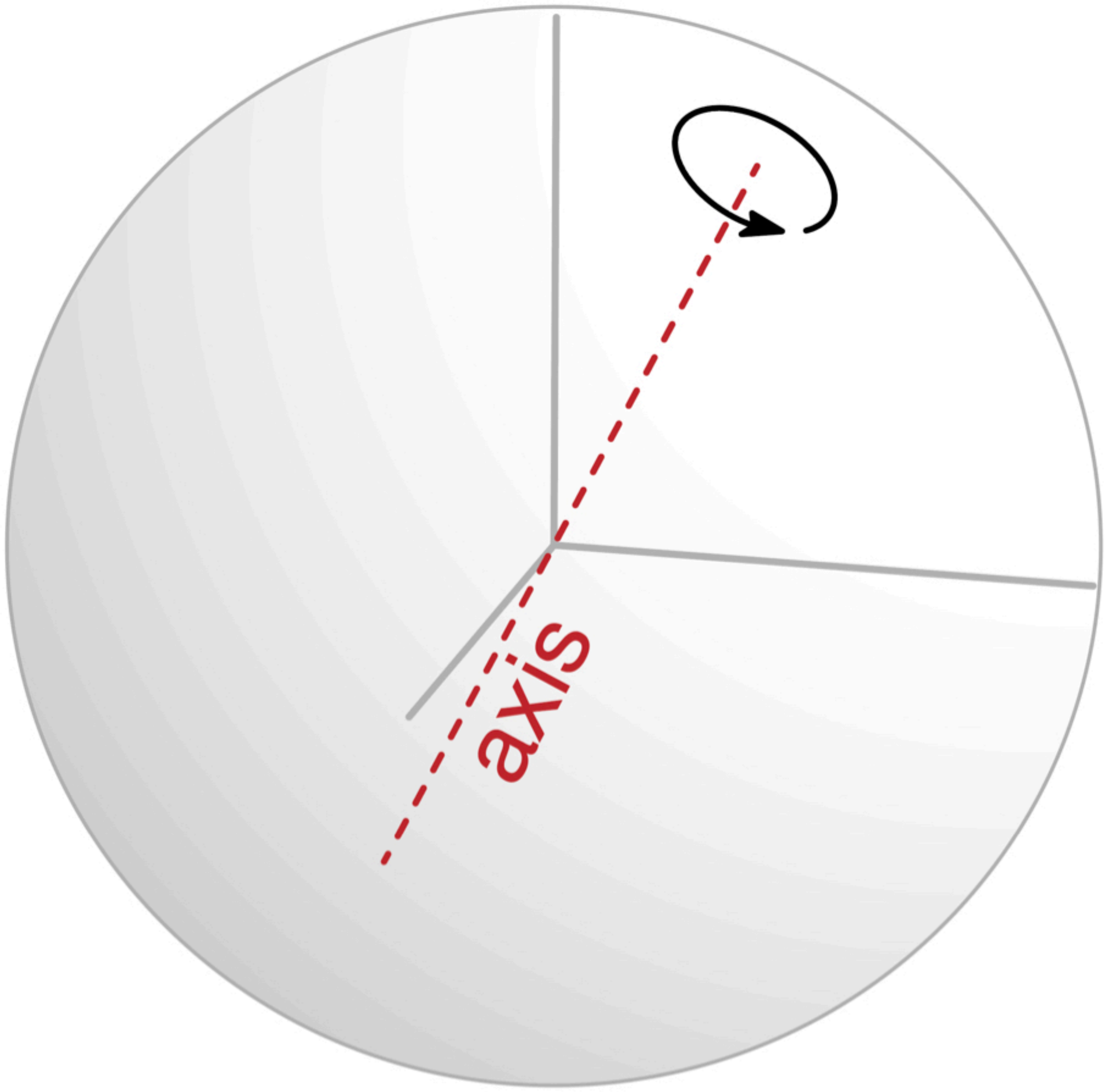
Kimberly, Australia, from Planet Snapshots, www.planet.com


Some Revisions After the
Plate Tectonic Revolution
https://CroninProjects.org/October2024/Revisions



Some Terms

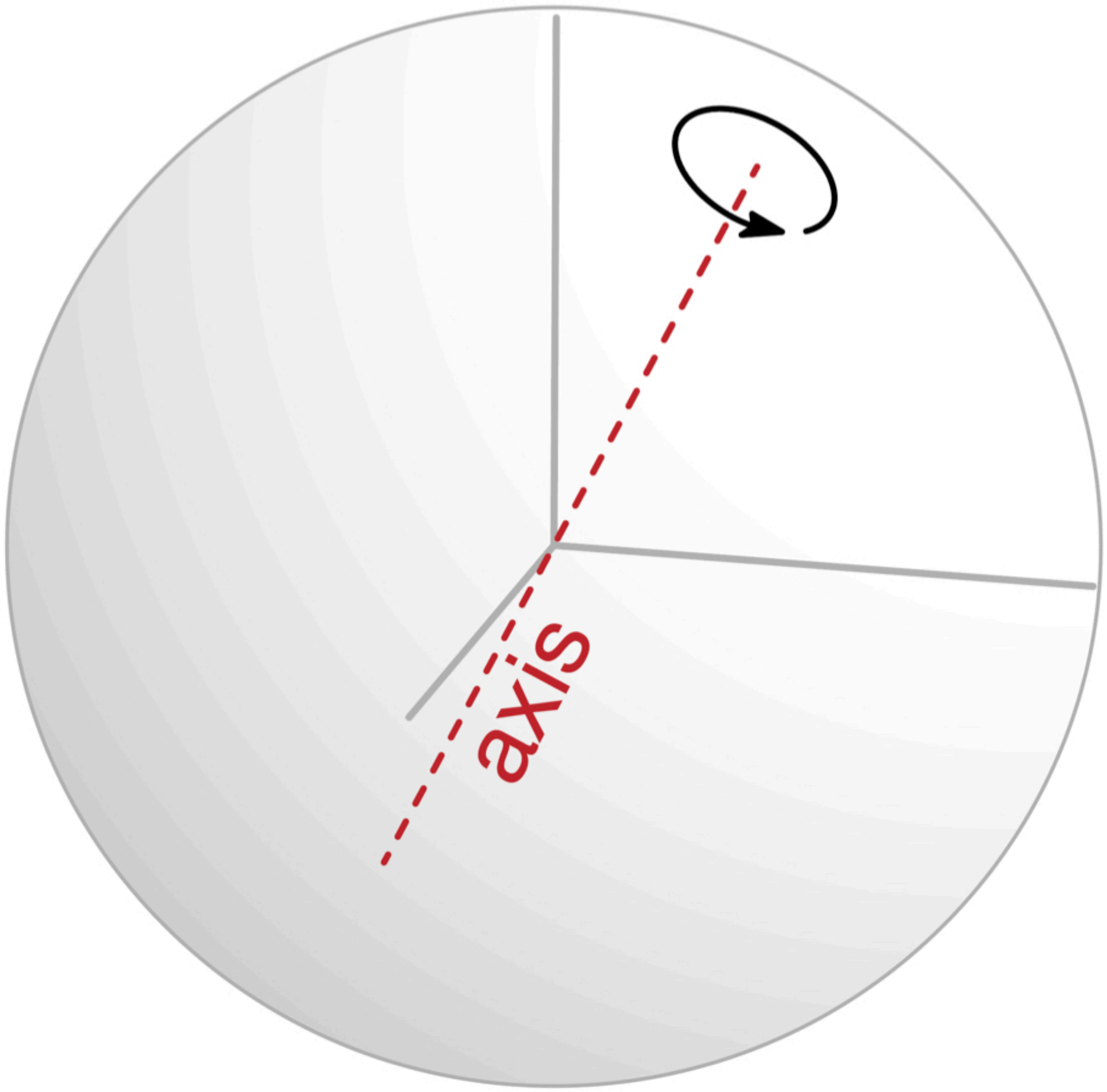
Cartesian coordinate axes of a geographic reference frame



Some Terms

Cartesian coordinate axes of a geographic reference frame

axis of rotation through the coordinate system origin

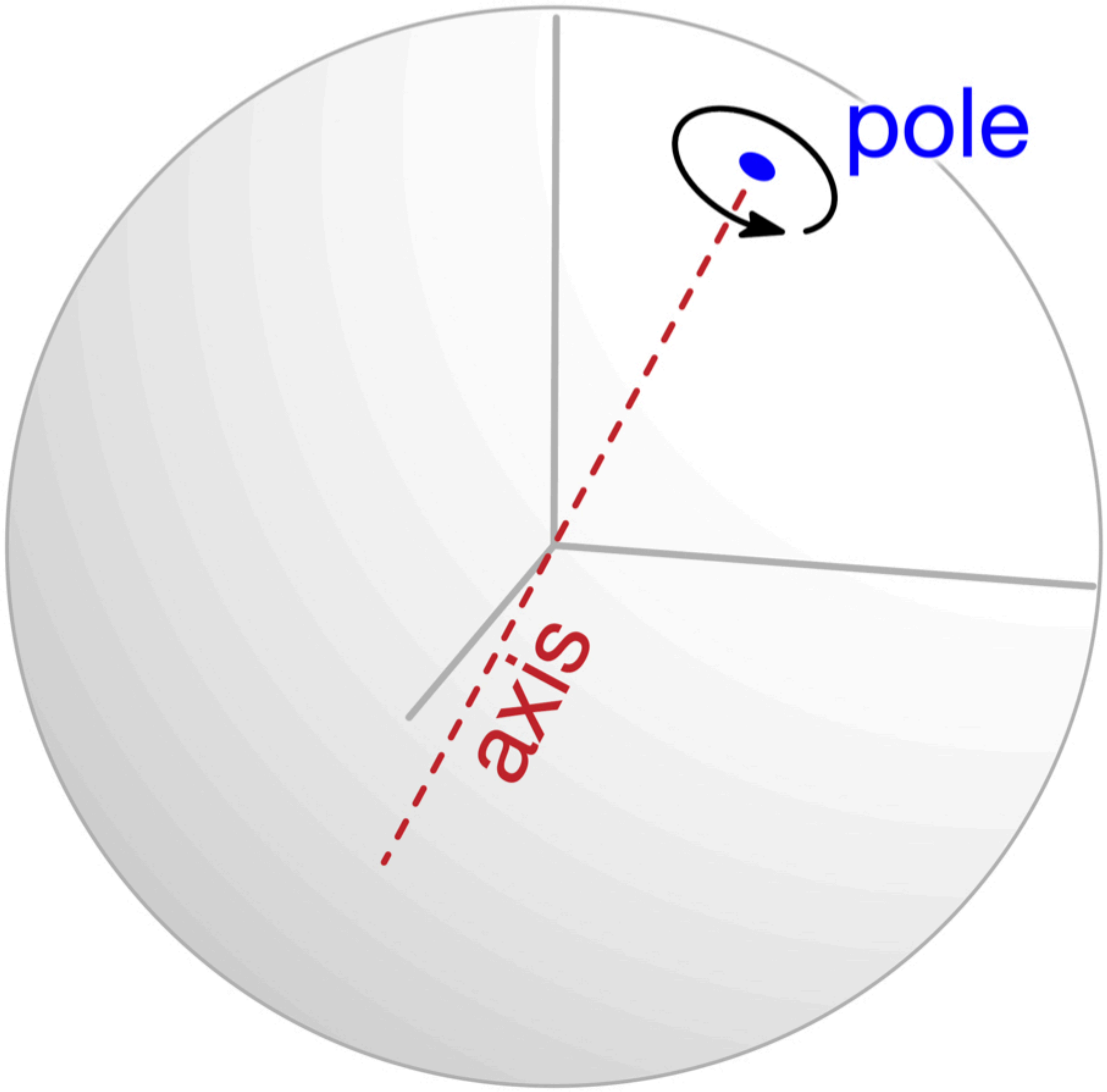


Some Terms

Cartesian coordinate axes of a geographic reference frame

axis of rotation through the coordinate system origin

(Sometimes called an Euler axis — Euler is pronounced the same as “oiler”)



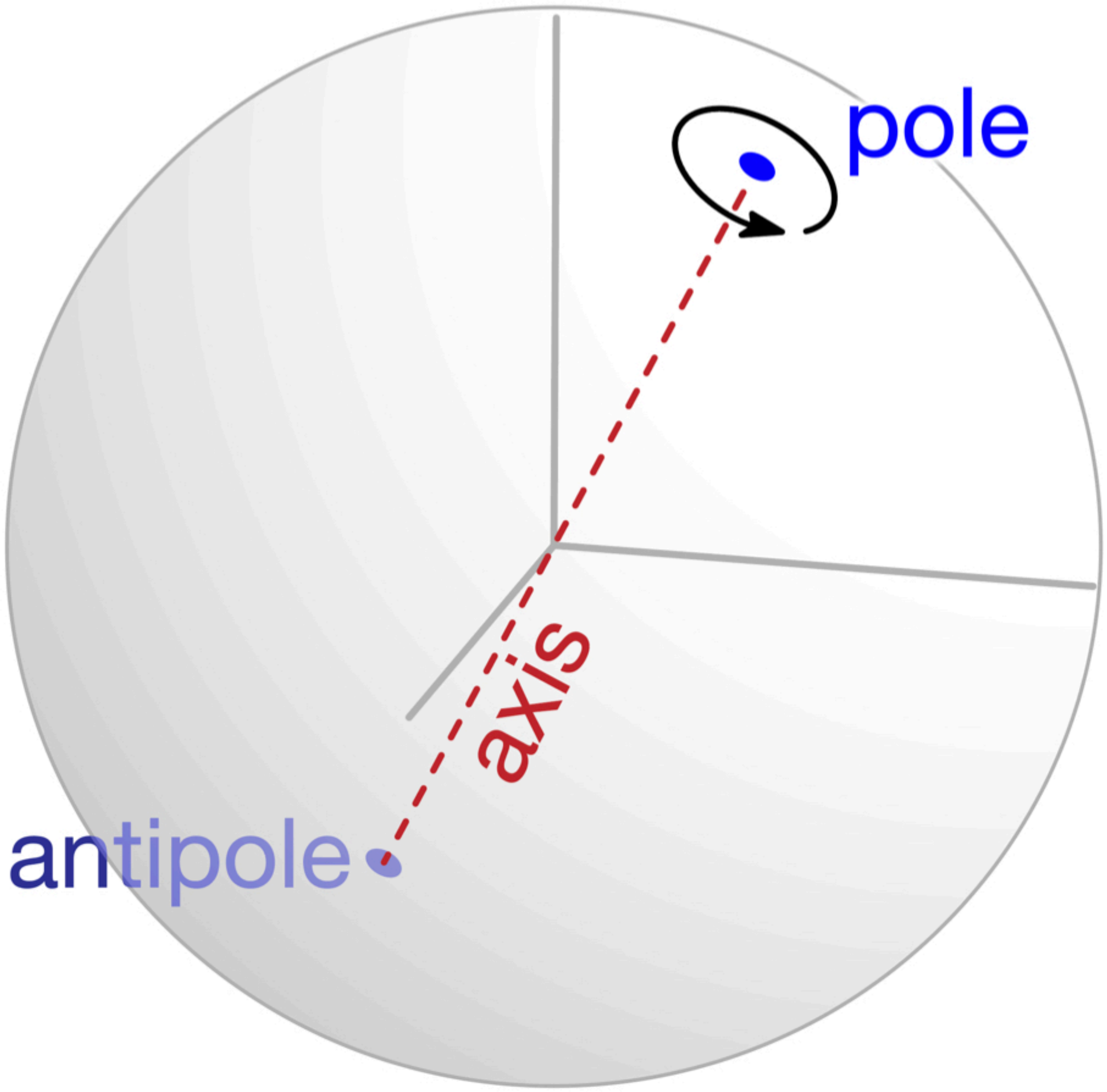
Some Terms

Cartesian coordinate axes of a geographic reference frame

axis of rotation through the coordinate system origin

pole of rotation
(+ve direction of rotation)

(Sometimes called an Euler pole — Euler is pronounced the same as “oiler”)



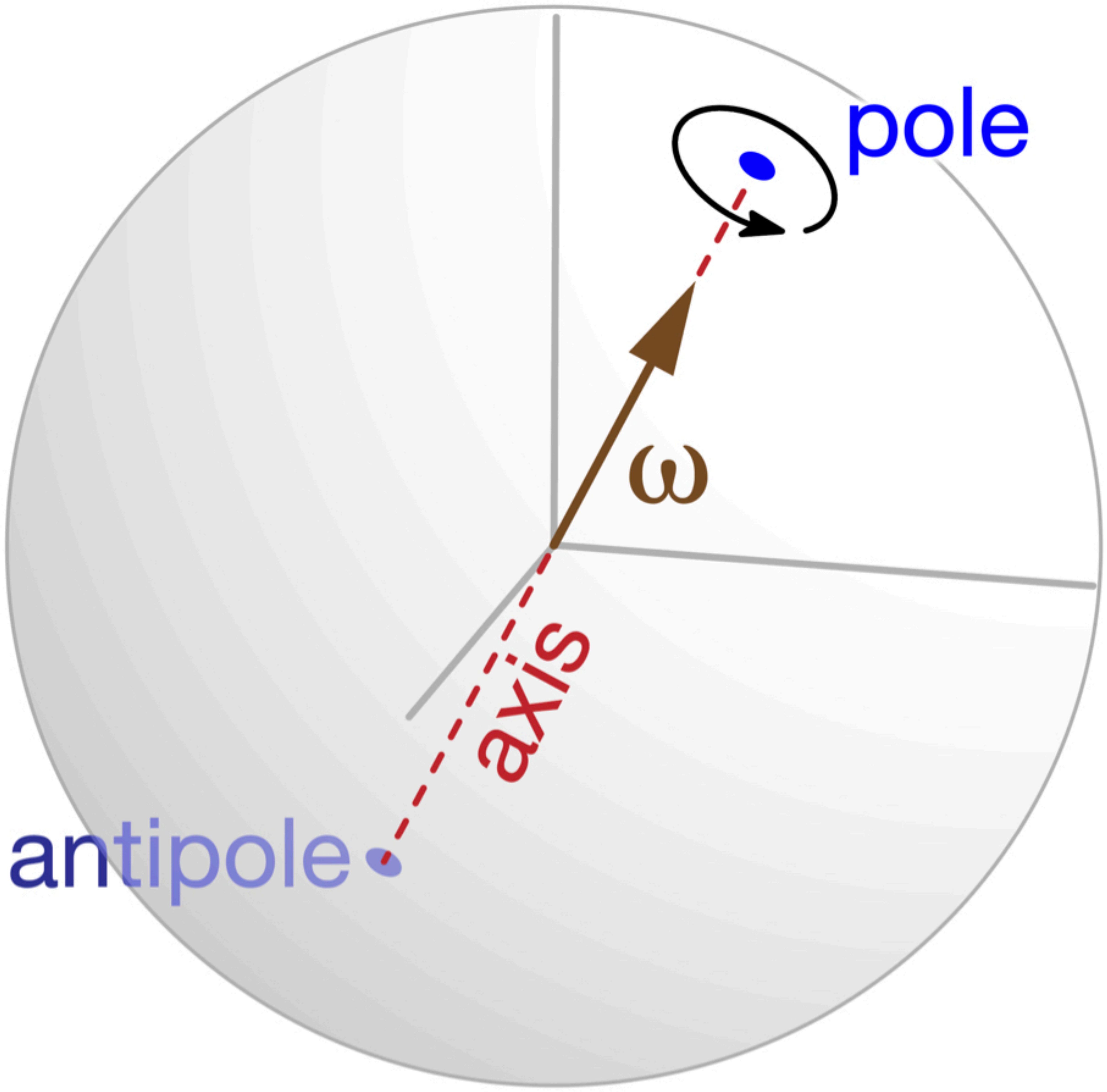
Some Terms

Cartesian coordinate axes of a geographic reference frame

axis of rotation through the coordinate system origin

pole of rotation (+ve direction of rotation)

antipole of rotation (-ve direction of rotation)



Some Terms

Cartesian coordinate axes of a geographic reference frame

axis of rotation through the coordinate system origin

pole of rotation (+ve direction of rotation)

antipole of rotation (-ve direction of rotation)

axial rotation vector

length = ω angle/time

V → conventional linear velocity, as in the tangential velocity

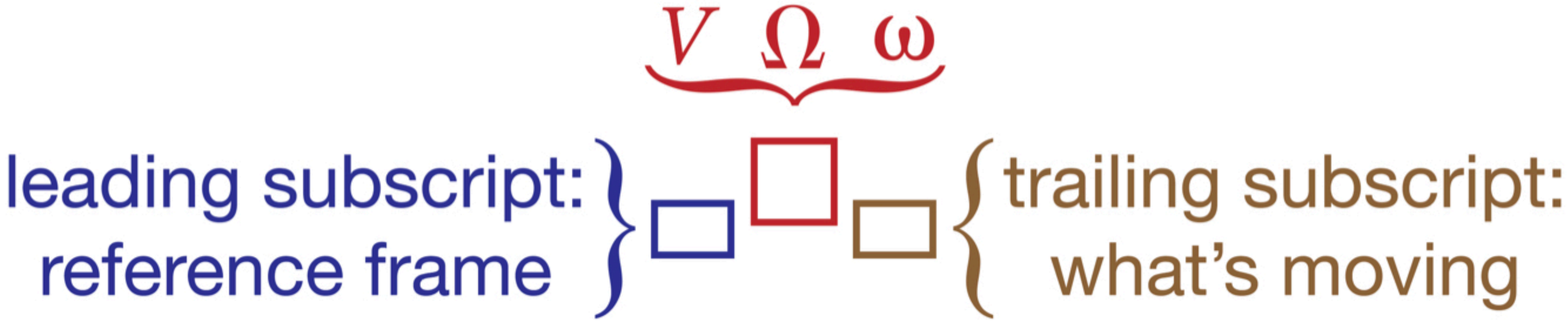
Ω → angular velocity vector; its length is the angular speed

ω → magnitude of angular velocity: angular speed

$V \rightarrow$ conventional linear velocity, as in the tangential velocity

$\Omega \rightarrow$ angular velocity vector; its length is the angular speed

$\omega \rightarrow$ magnitude of angular velocity: angular speed



V → conventional linear velocity, as in the tangential velocity

Ω → angular velocity vector; its length is the angular speed

ω → magnitude of angular velocity: angular speed

V Ω ω

leading subscript: reference frame } $_{\square}\square_{\square}$ { trailing subscript: what's moving

$${}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0$$

angular velocity vector of B as observed from A → ${}_{A}\Omega_{B}$

$${}_{A}\Omega_{B} = {}_{EX}\Omega_{B} - {}_{EX}\Omega_{A}$$

angular velocity vector of A as observed from an external frame of reference (EX), like ITRF → ${}_{EX}\Omega_{A}$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

$$ {}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0 $$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

$${}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0$$

$${}_{A}\Omega_{B} + {}_{B}\Omega_{EX} + {}_{EX}\Omega_{A} = 0$$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

$$ {}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0 $$

$$ {}_{A}\Omega_{B} + {}_{B}\Omega_{EX} + {}_{EX}\Omega_{A} = 0 $$

Note: $-{}_{B}\Omega_{EX} = {}_{EX}\Omega_{B}$

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$$ {}_{A}\Omega_{B} + \boxed{{}_{B}\Omega_{EX} - {}_{B}\Omega_{EX}} + {}_{EX}\Omega_{A} = {}_{EX}\Omega_{B} $$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

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$${}_A\Omega_B + {}_{EX}\Omega_A - {}_{EX}\Omega_A = {}_{EX}\Omega_B - {}_{EX}\Omega_A$$

$${}_A\Omega_B = {}_{EX}\Omega_B - {}_{EX}\Omega_A$$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

$$ {}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0 $$

...to the angular velocity vector circuit for the instantaneous motion of two plates relative to each other, and of each plate relative to an external reference frame.

$$ {}_{A}\Omega_{B} = {}_{EX}\Omega_{B} - {}_{EX}\Omega_{A} $$

From the angular velocity vector circuit for the instantaneous motion of three plates relative to each other...

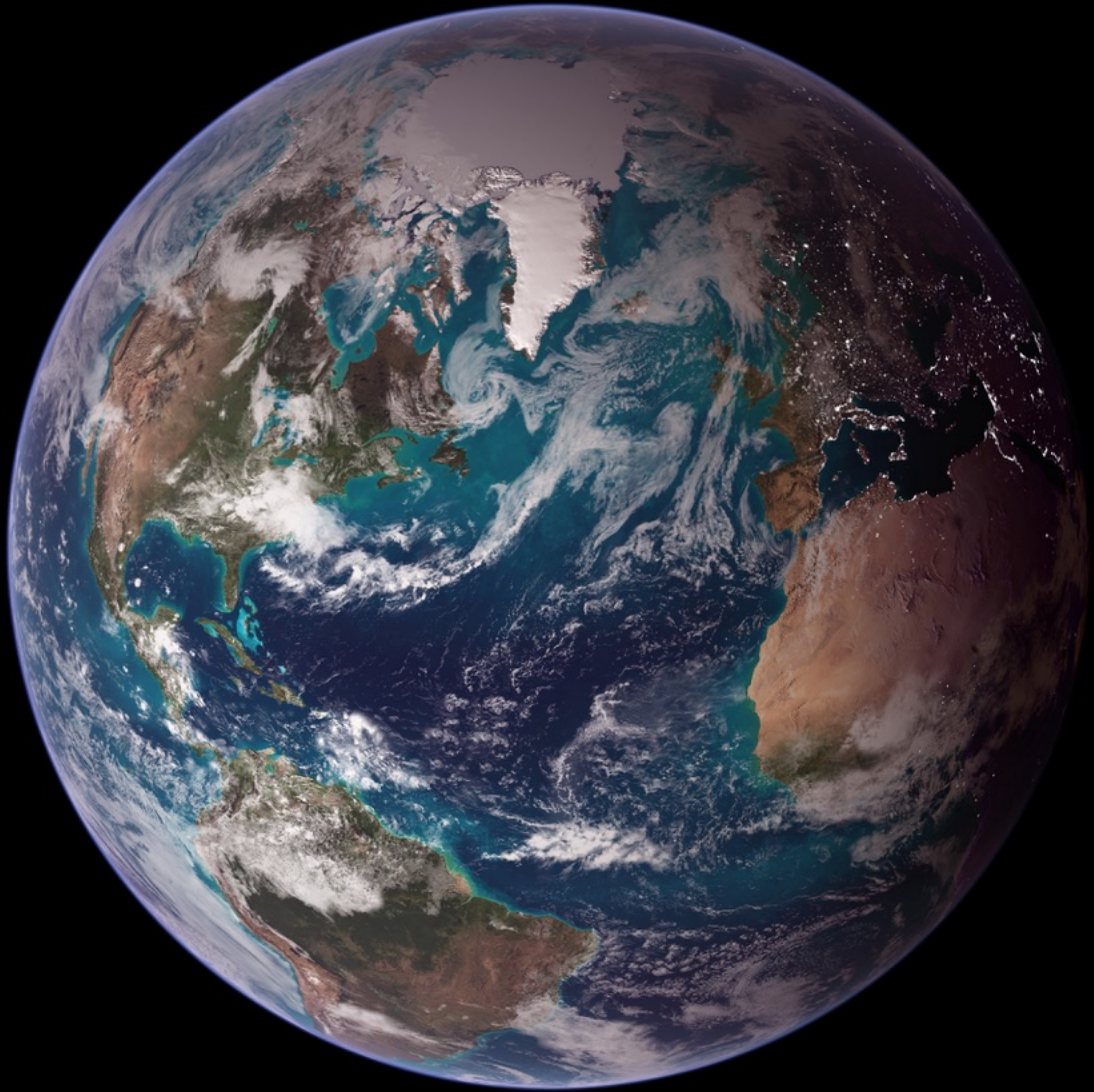
$$ {}_{A}\Omega_{B} + {}_{B}\Omega_{C} + {}_{C}\Omega_{A} = 0 $$

...to the angular velocity vector circuit for the instantaneous motion of two plates relative to each other, and of each plate relative to an external reference frame.

$$ {}_{A}\Omega_{B} = {}_{EX}\Omega_{B} - {}_{EX}\Omega_{A} $$

$$ {}_{B}\Omega_{C} = {}_{EX}\Omega_{C} - {}_{EX}\Omega_{B} $$

$$ {}_{C}\Omega_{A} = {}_{EX}\Omega_{A} - {}_{EX}\Omega_{C} $$



NASA Blue Marble
https://earthobservatory.nasa.gov/images/8108/twin-blue-marbles

Some Kinematics Terms

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instantaneous motion

motion modeled or observed over a short time interval that can be represented by a vector. GPS site velocities that might be averaged over decades of observation are considered instantaneous.

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simplest path between an initial and final position — not necessarily the trajectory along which the motion occurred.

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instantaneous motion

motion modeled or observed over a short time interval that can be represented by a vector. GPS site velocities that might be averaged over decades of observation are considered instantaneous.

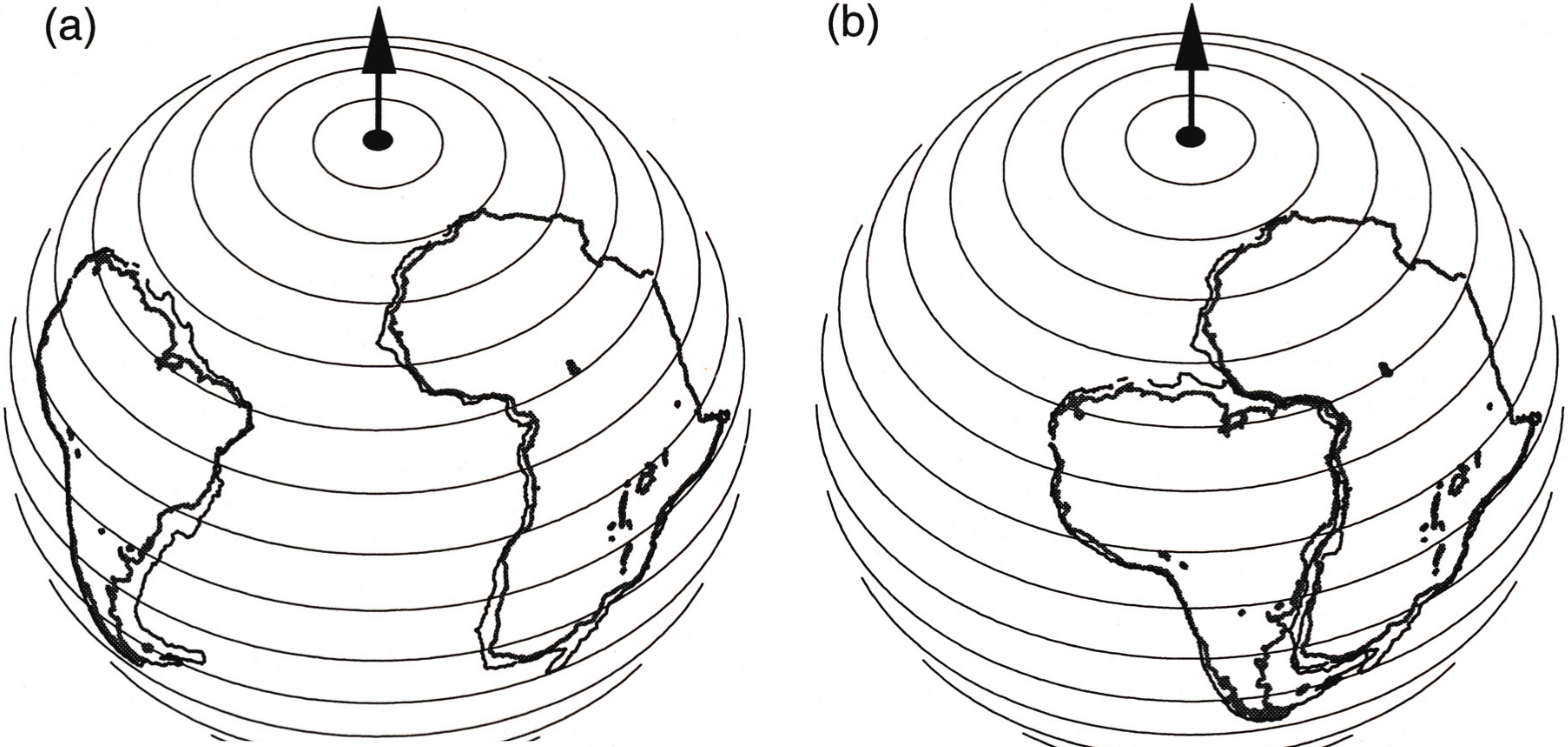
total motion

simplest path between an initial and final position — not necessarily the trajectory along which the motion occurred.

finite motion

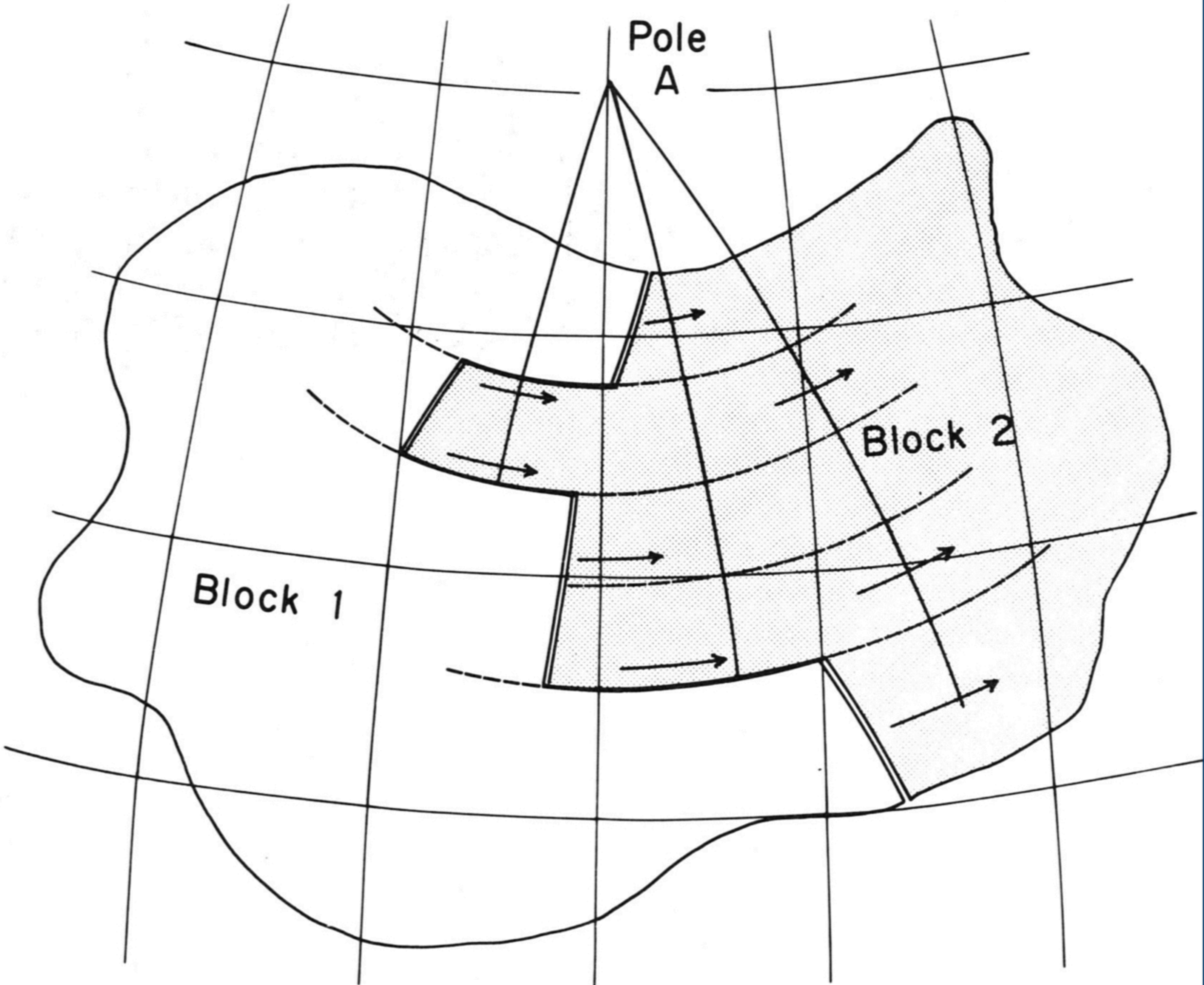
observed or modeled trajectory or path between an initial and final position over a finite time interval

Fit of South America and Africa by rotation around the total-opening Euler axis/pole



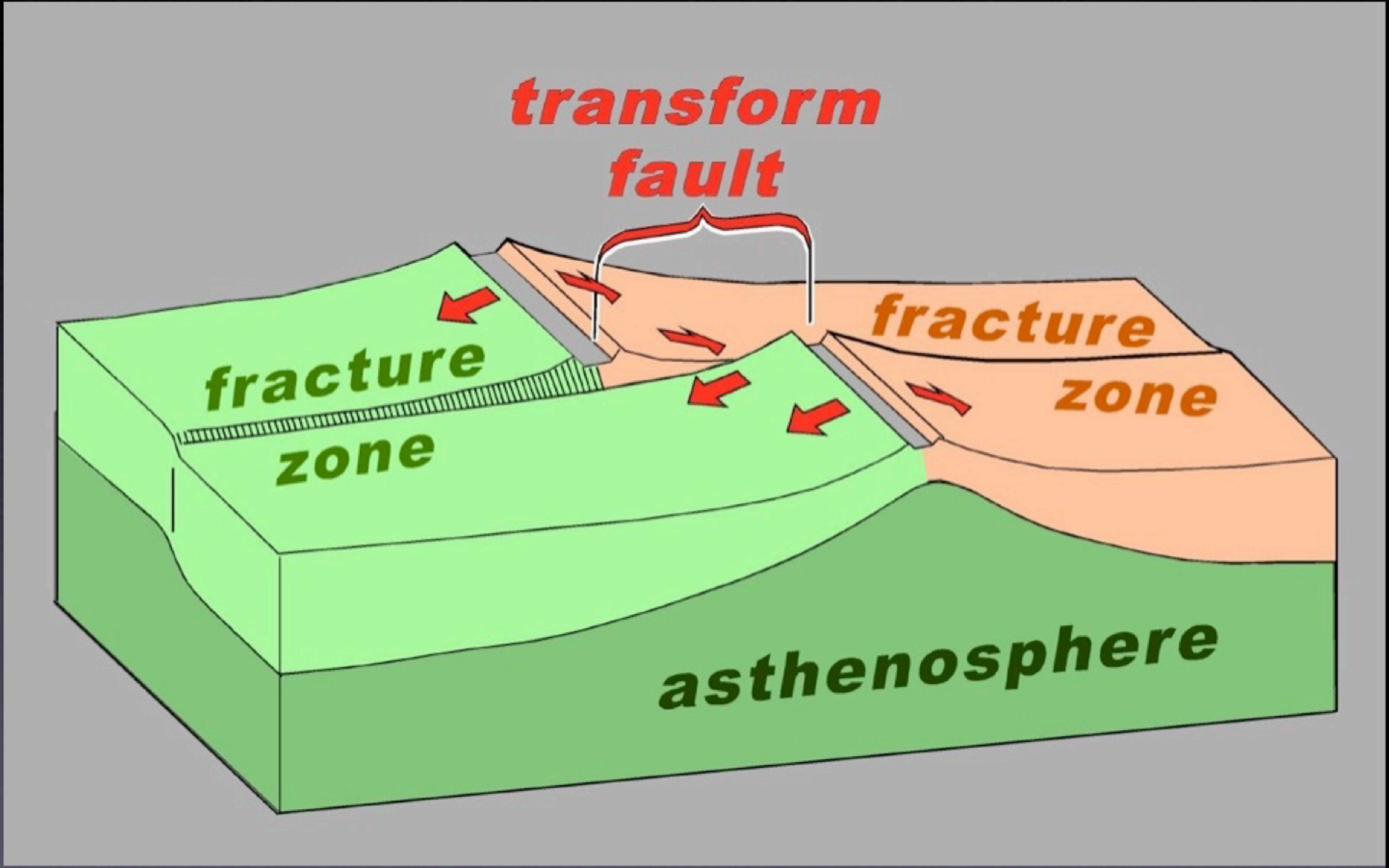
An example of “total motion”

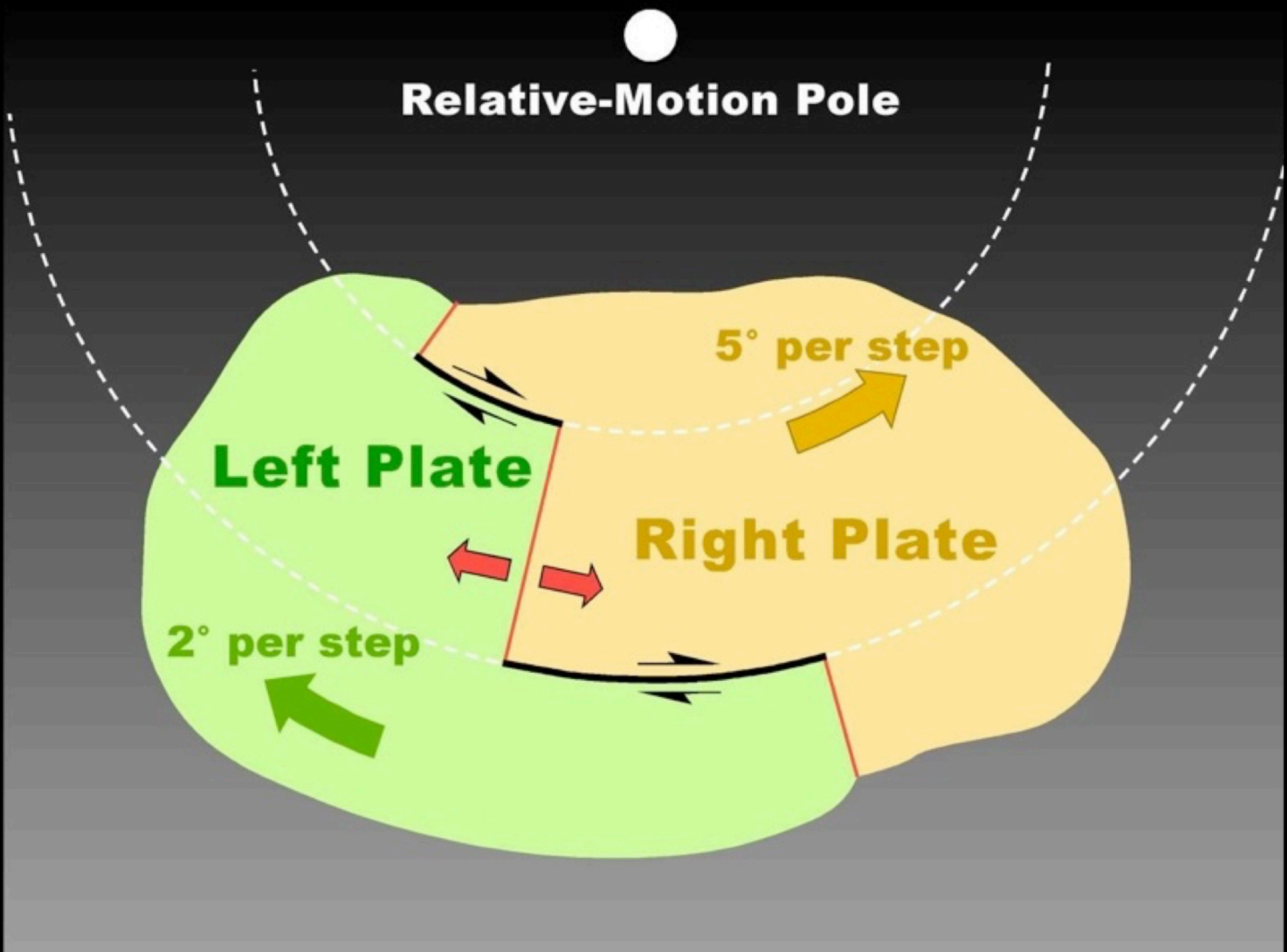
McKenzie, 2001, after Bullard et al., 1965

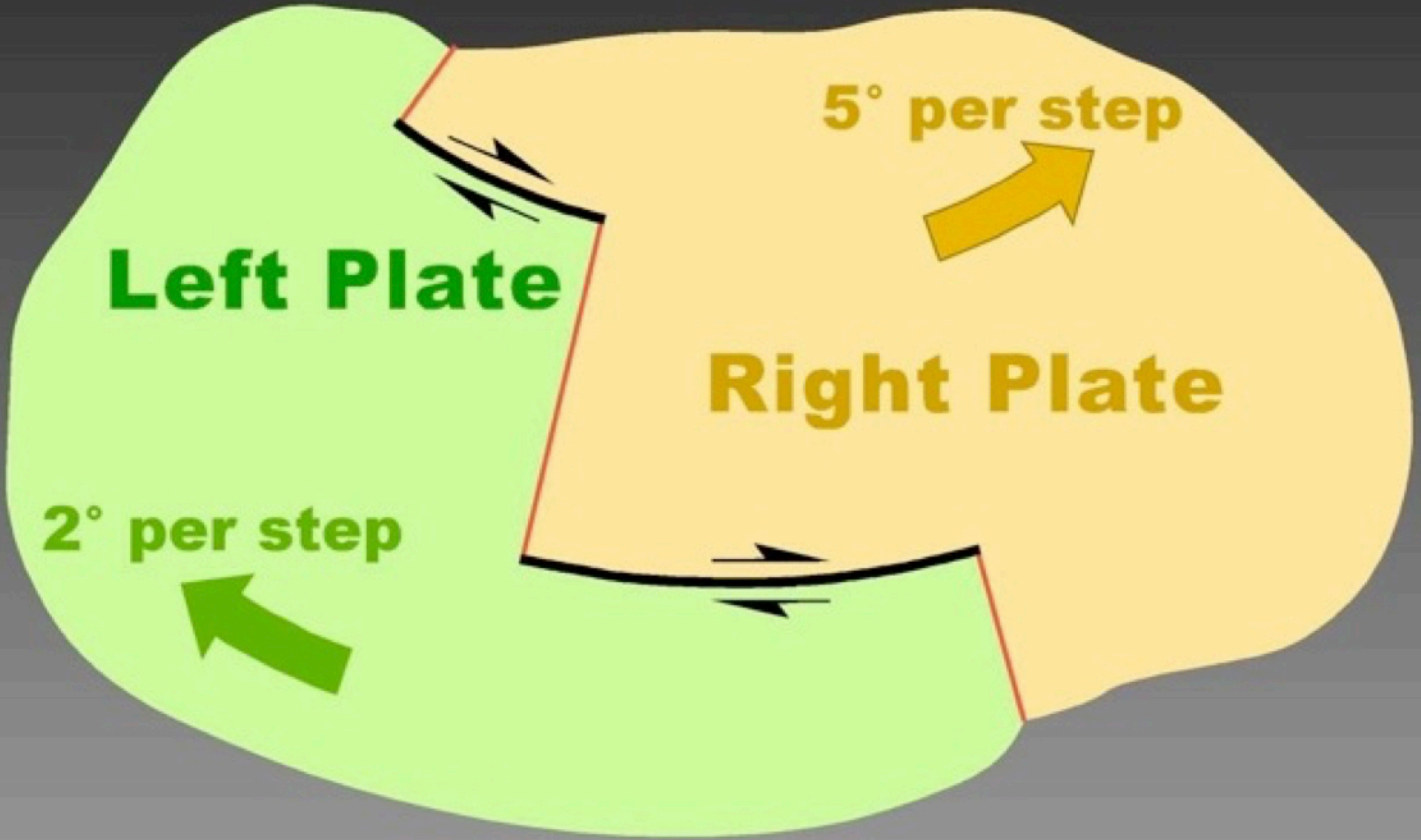


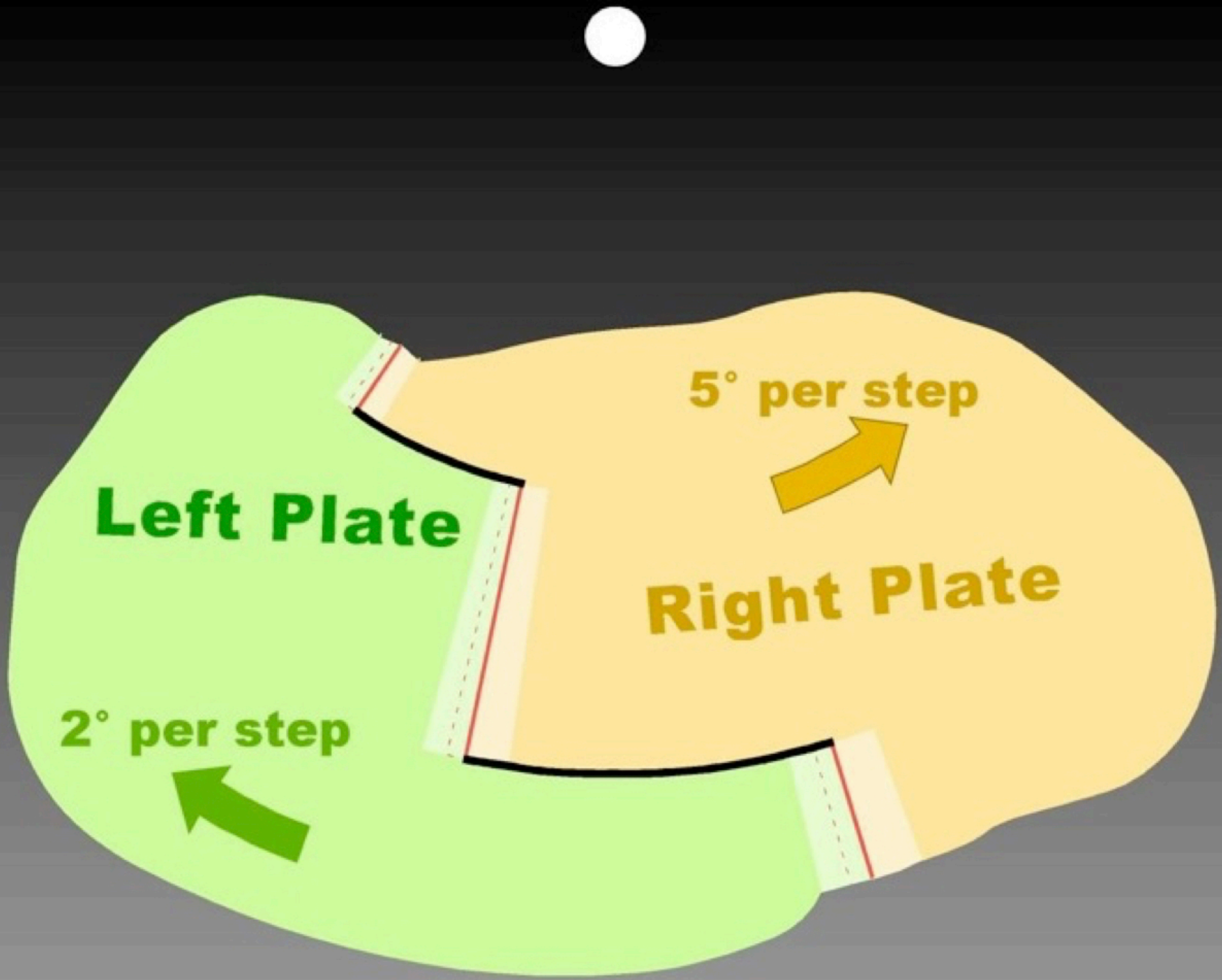
“On a sphere, the motion of block 2 relative to block 1 must be a rotation about some pole. All faults on the boundary between 1 and 2 must be small circles concentric around the pole A.”

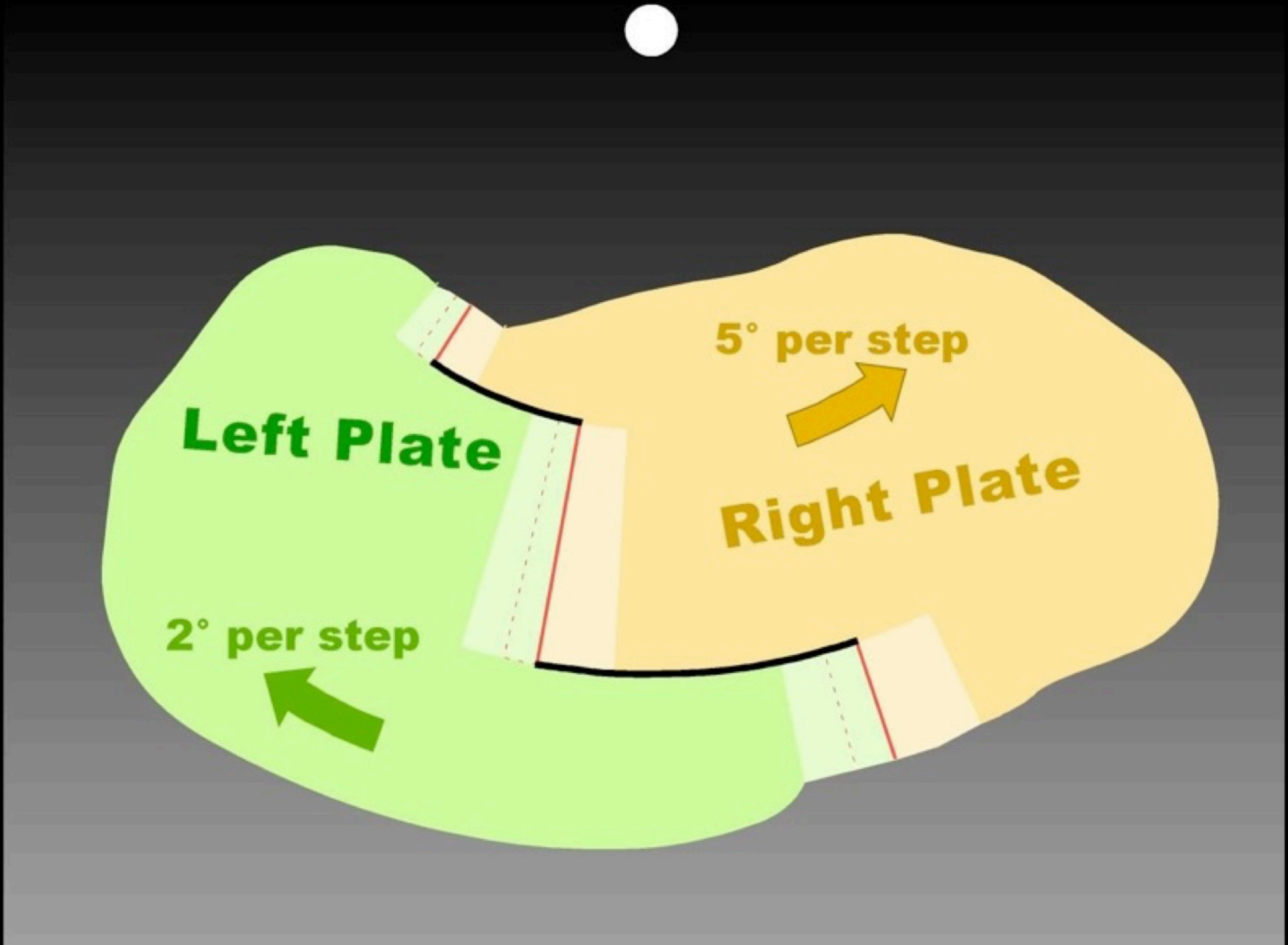
Jason Morgan, 1968


transform
fault
fracture
zone
fracture
zone
asthenosphere

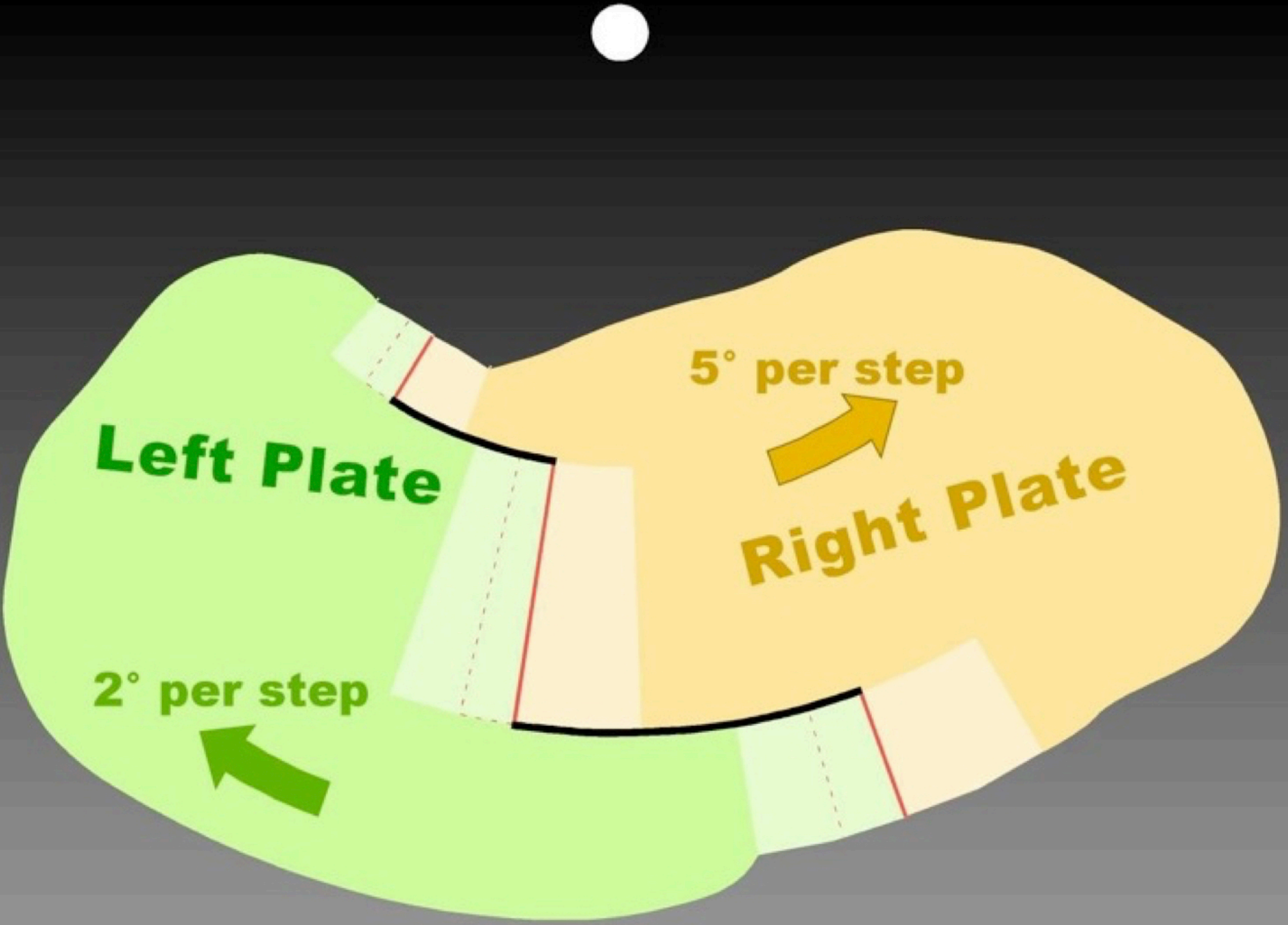

Relative-Motion Pole
5° per step
Left Plate
Right Plate
2° per step


5° per step
Left Plate
Right Plate
2° per step

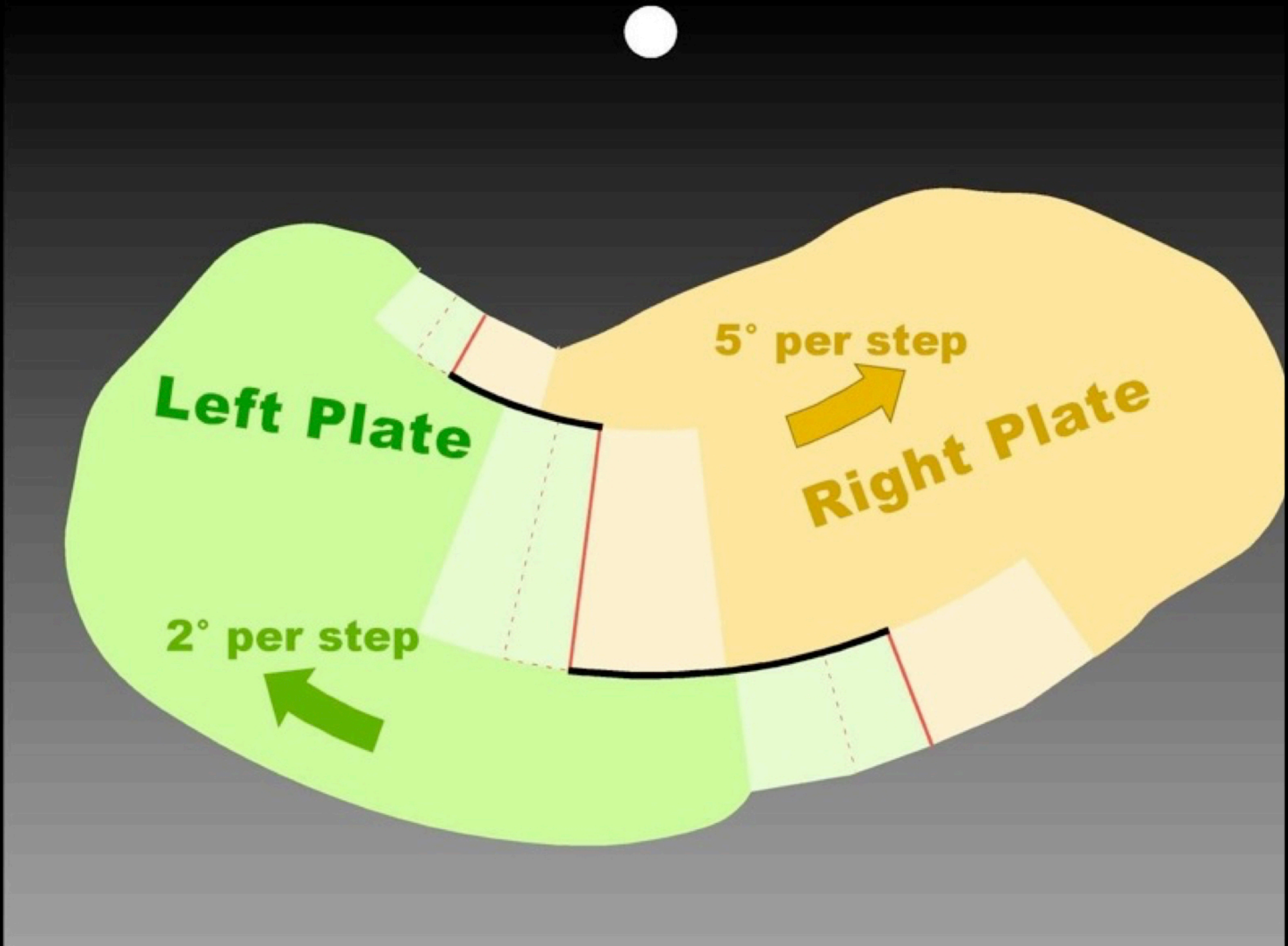

5° per step
Left Plate
Right Plate
2° per step



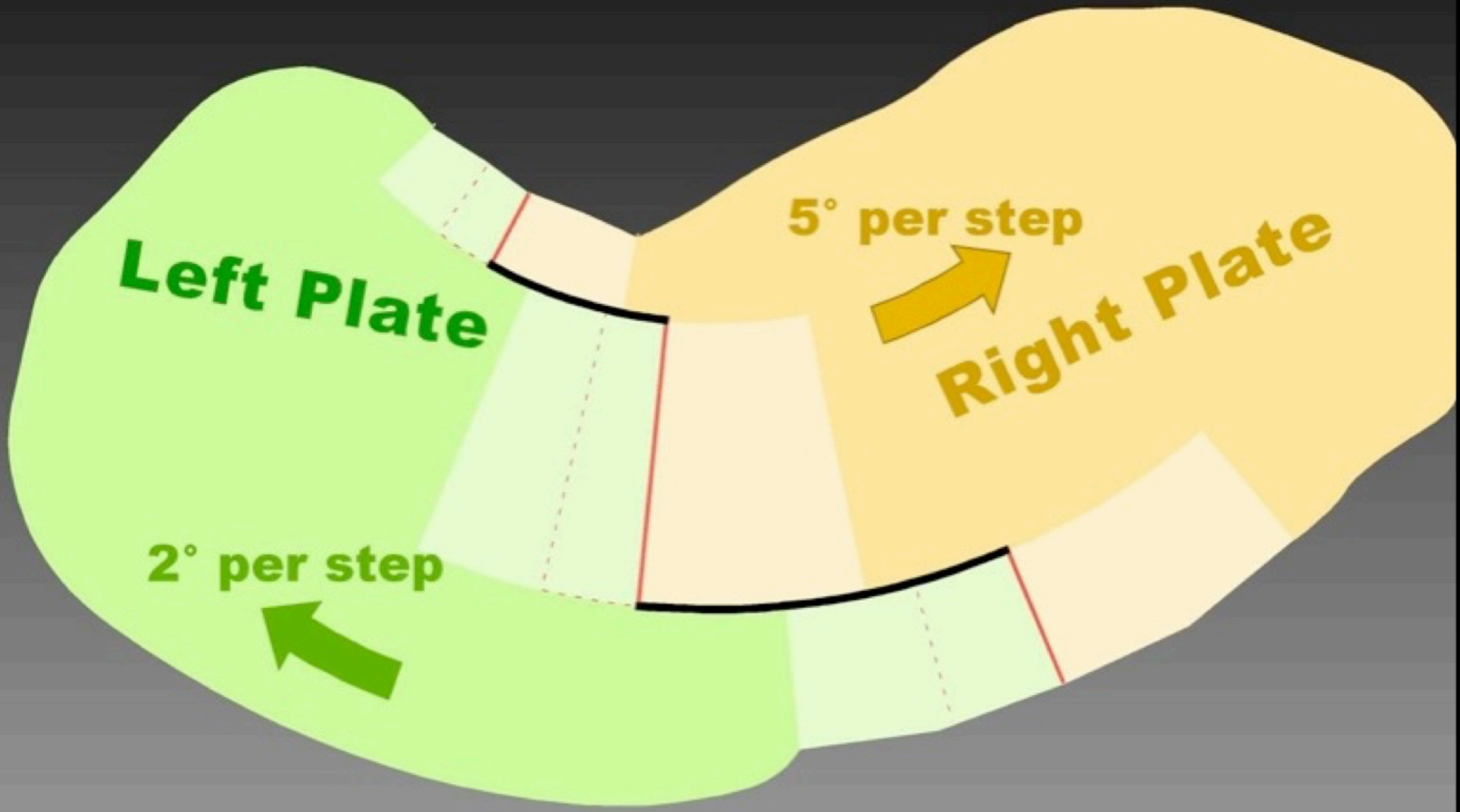
5° per step
Left Plate
Right Plate
2° per step

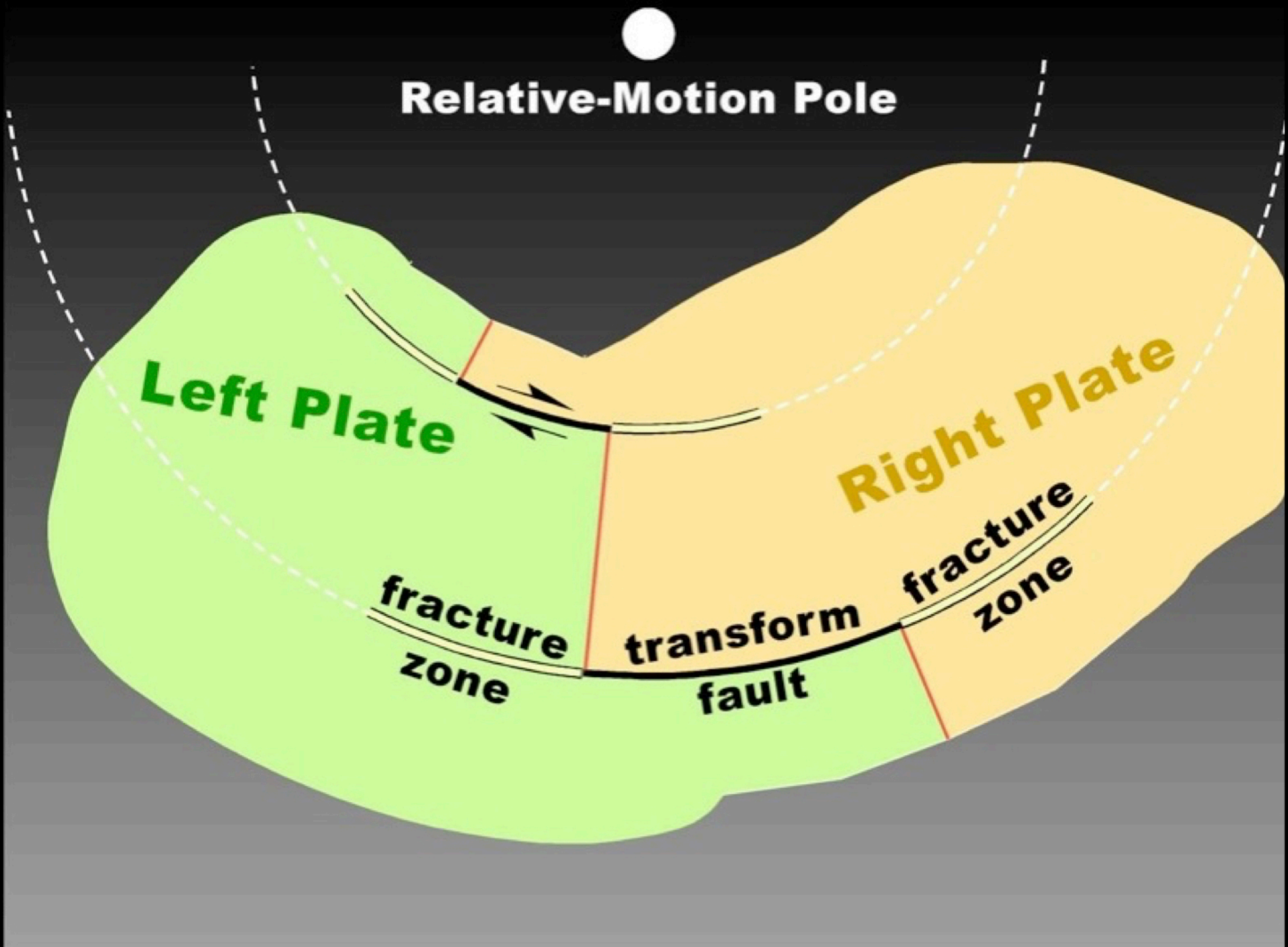


Left Plate
5° per step
Right Plate
2° per step



5° per step
Right Plate
Left Plate
2° per step


5° per step
Left Plate
Right Plate
2° per step


Relative-Motion Pole
Left Plate
Right Plate
fracture
zone
transform
fault
fracture
zone

As appealing as this idea of plates moving in circular arcs around fixed poles of relative motion was, **it is not valid**.

There is a fly in the ointment.

We have known about the fly in the ointment since 1969. But we've liked the simple model so much that we have ignored the fact that **it is not valid for finite plate motion**.

… Thus it is not possible for all three plates to rotate through finite angles about their instantaneous relative rotation axes.

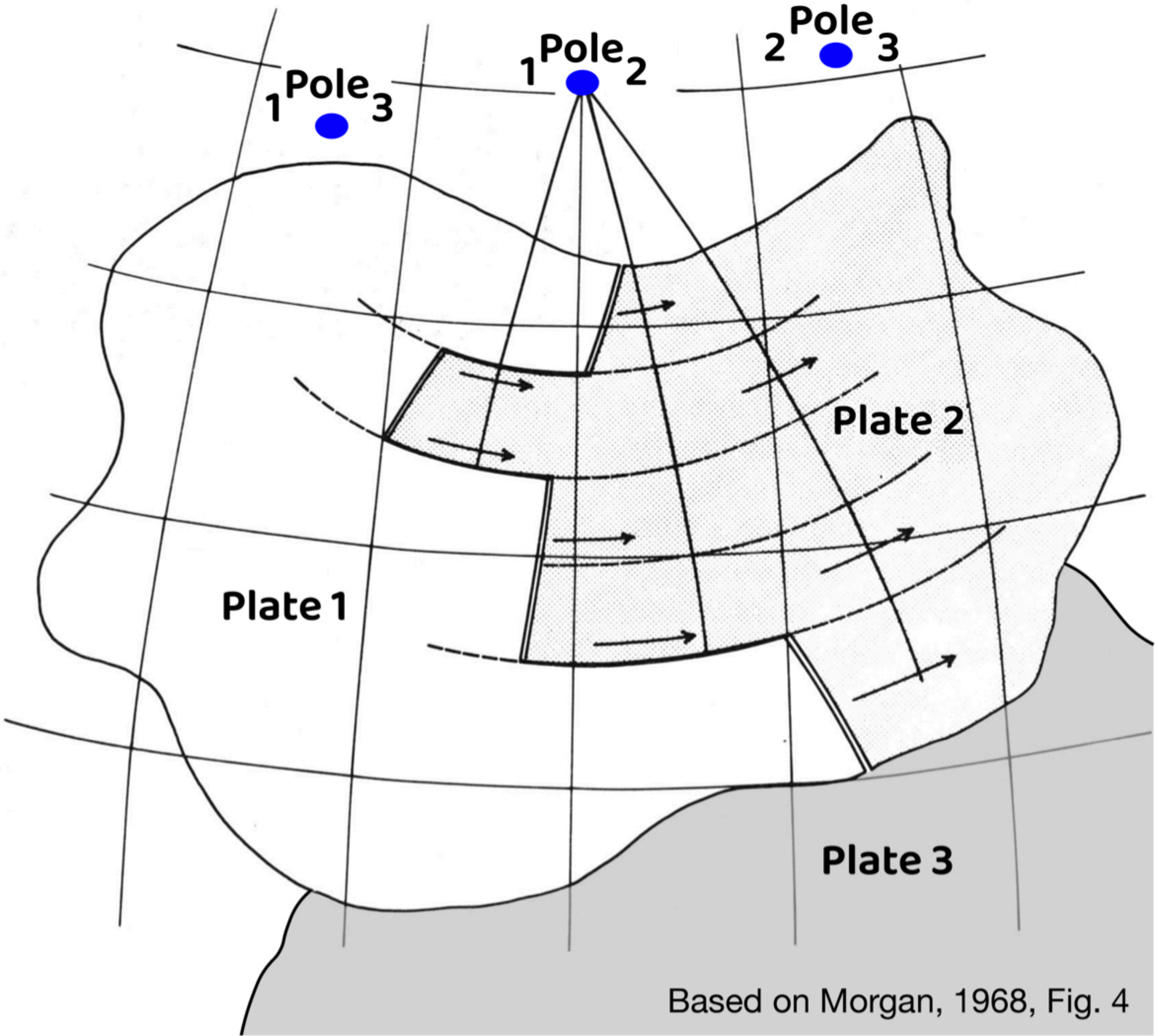
McKenzie and Morgan, 1969

The Three-Plate Problem

"If the earth's lithosphere were divided into only two plates, their pole [of instantaneous relative motion] could theoretically remain fixed relative to the two plates over long periods of time.

If, however, the earth's lithosphere is divided into three or more plates, this is no longer true.

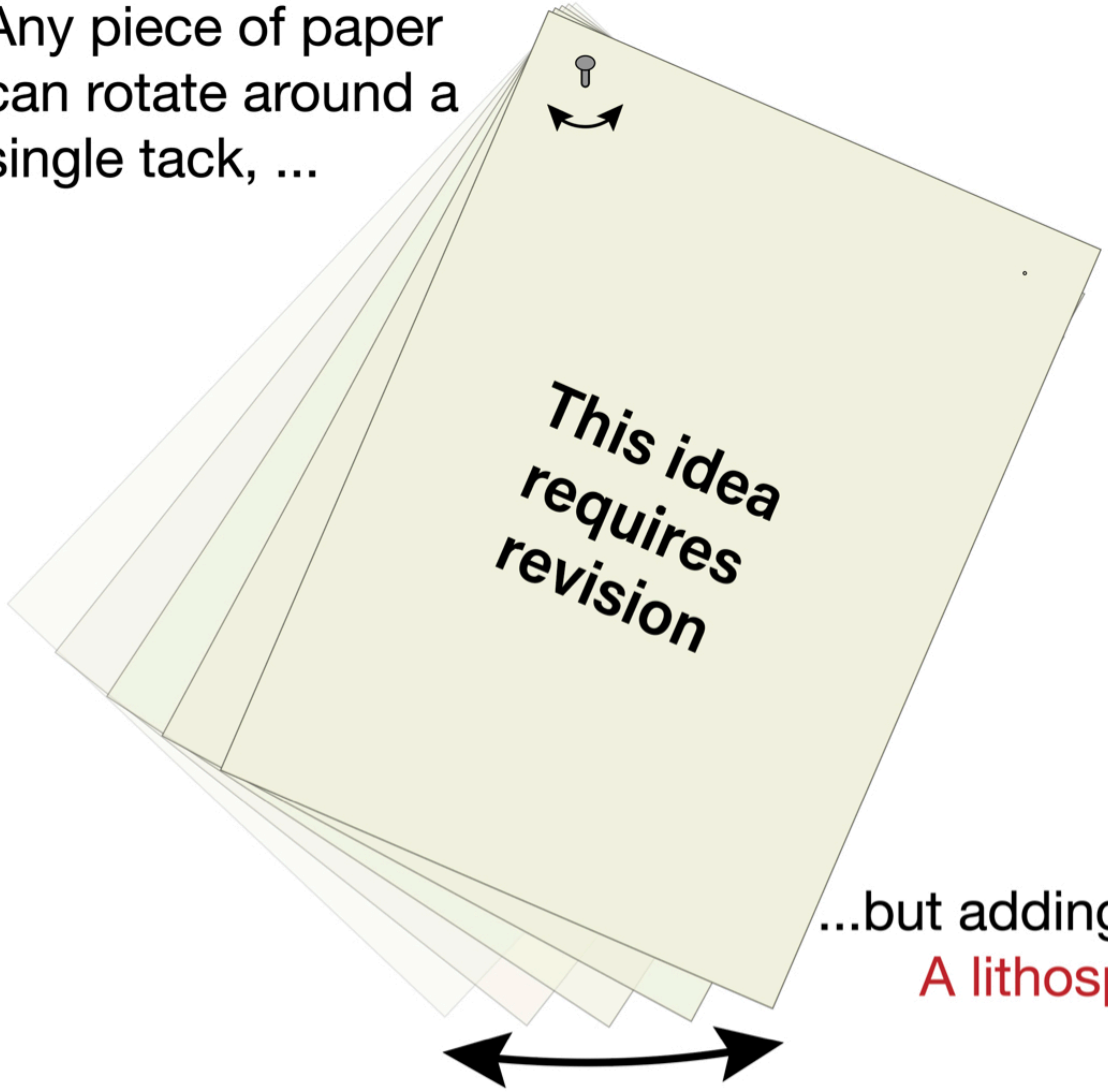
Allan Cox, 1973, p. 408



The 3-Plate Problem

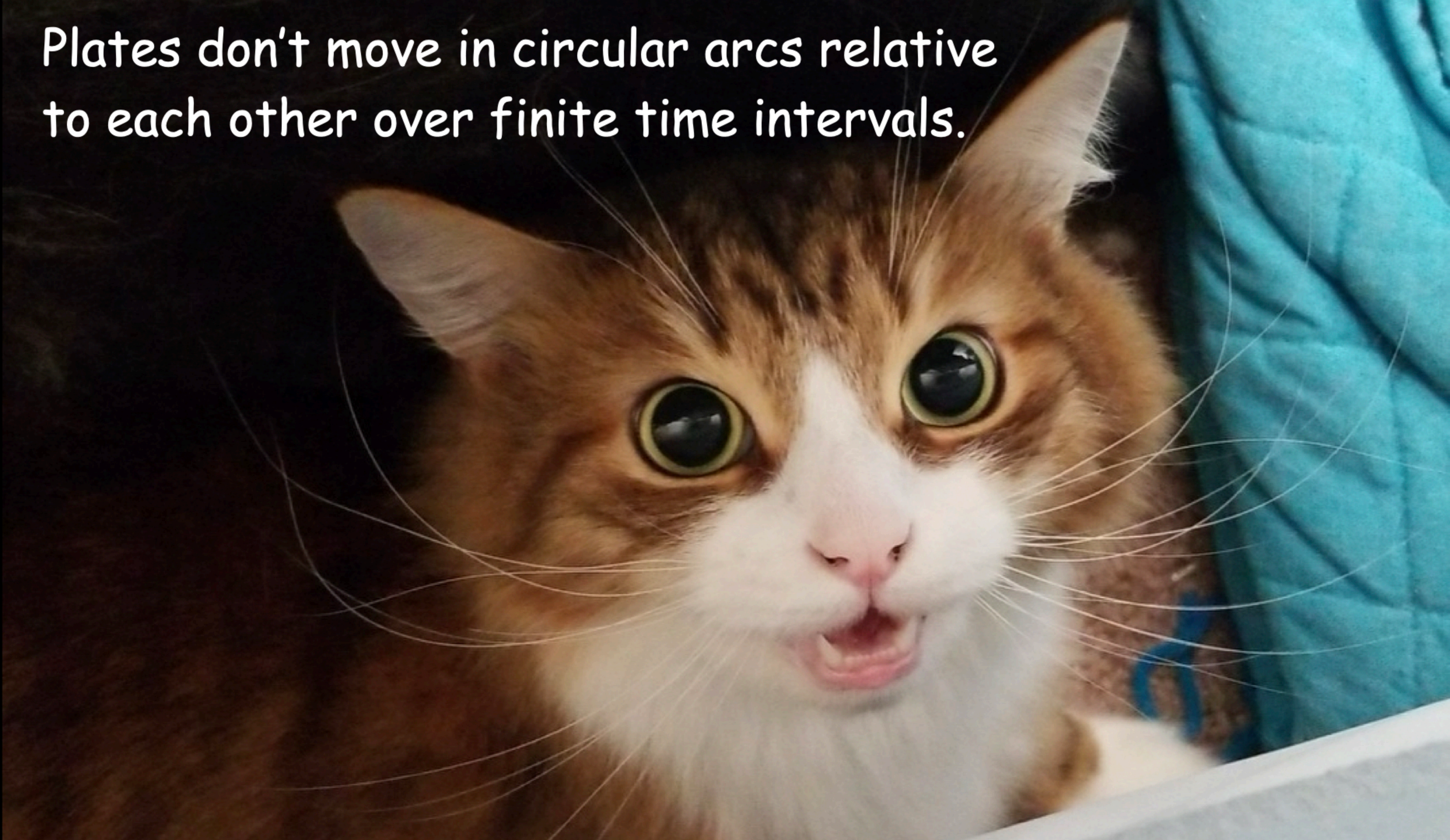
Plate 2 **cannot remain fixed** to both of its instantaneous relative motion poles ($_1$Pole$_2$ and $_2$Pole$_3$) over finite time intervals — during finite rotations.

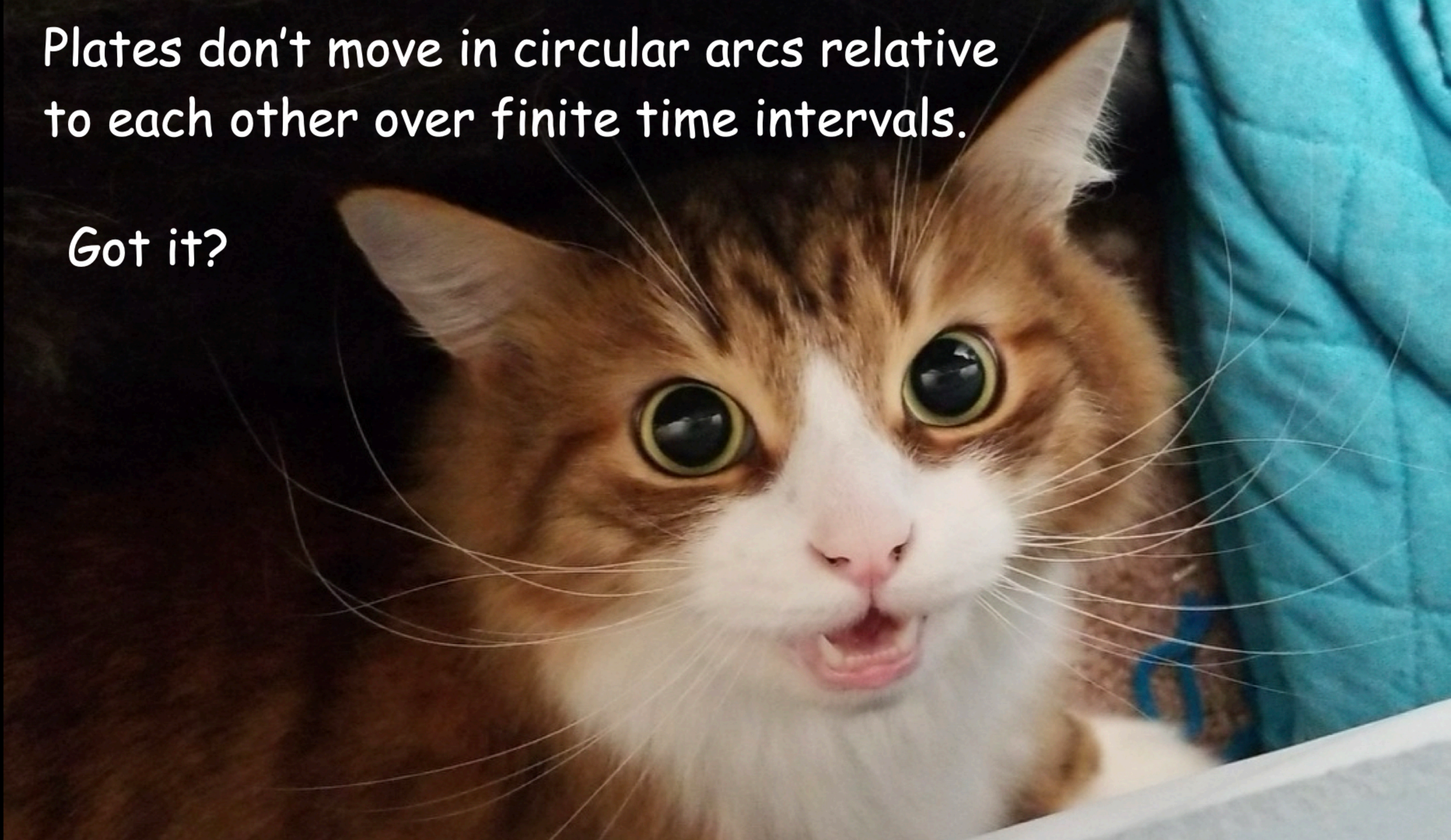
Any piece of paper can rotate around a single tack, ...

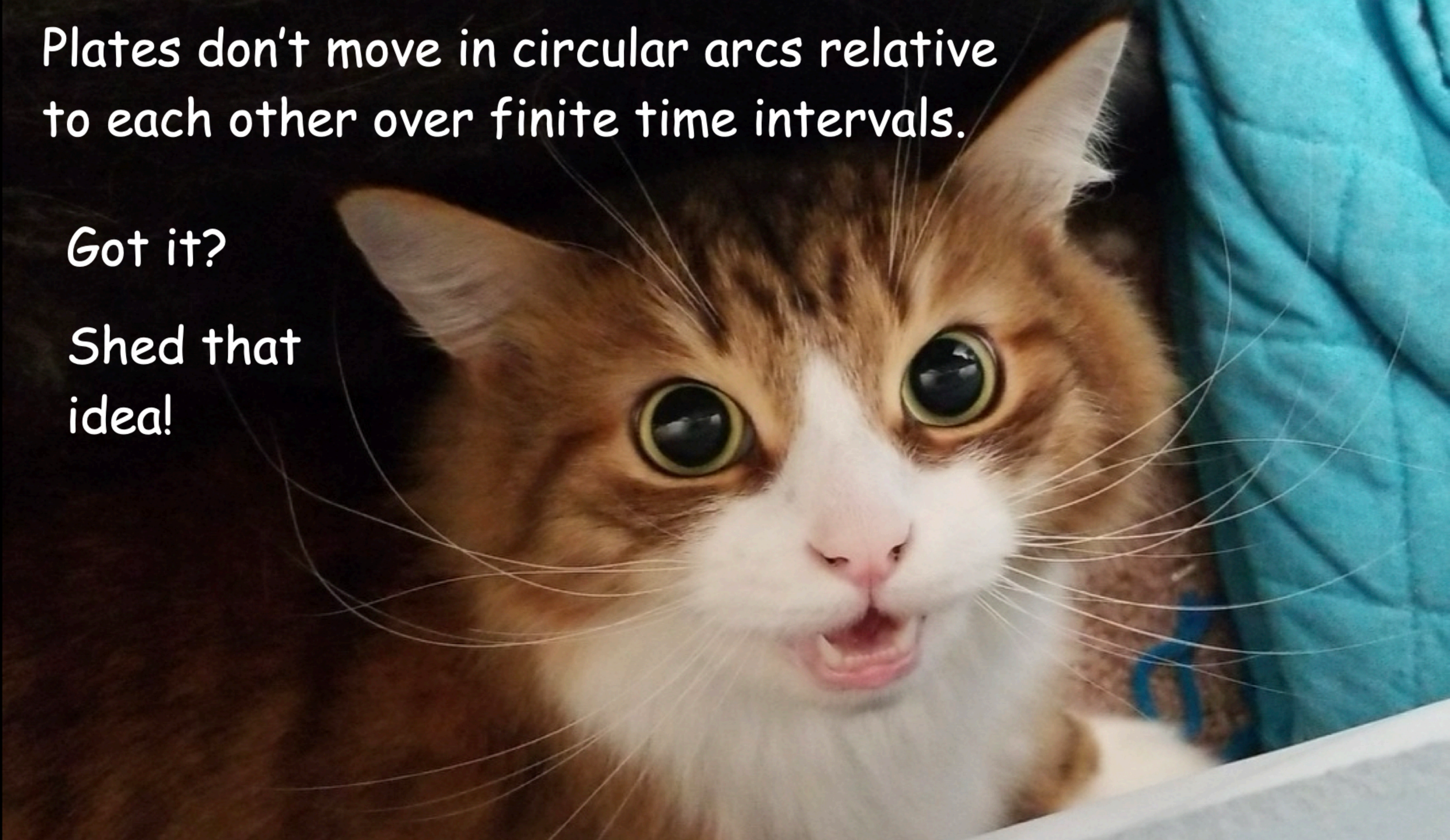


...but adding a second tack prohibits rotation.

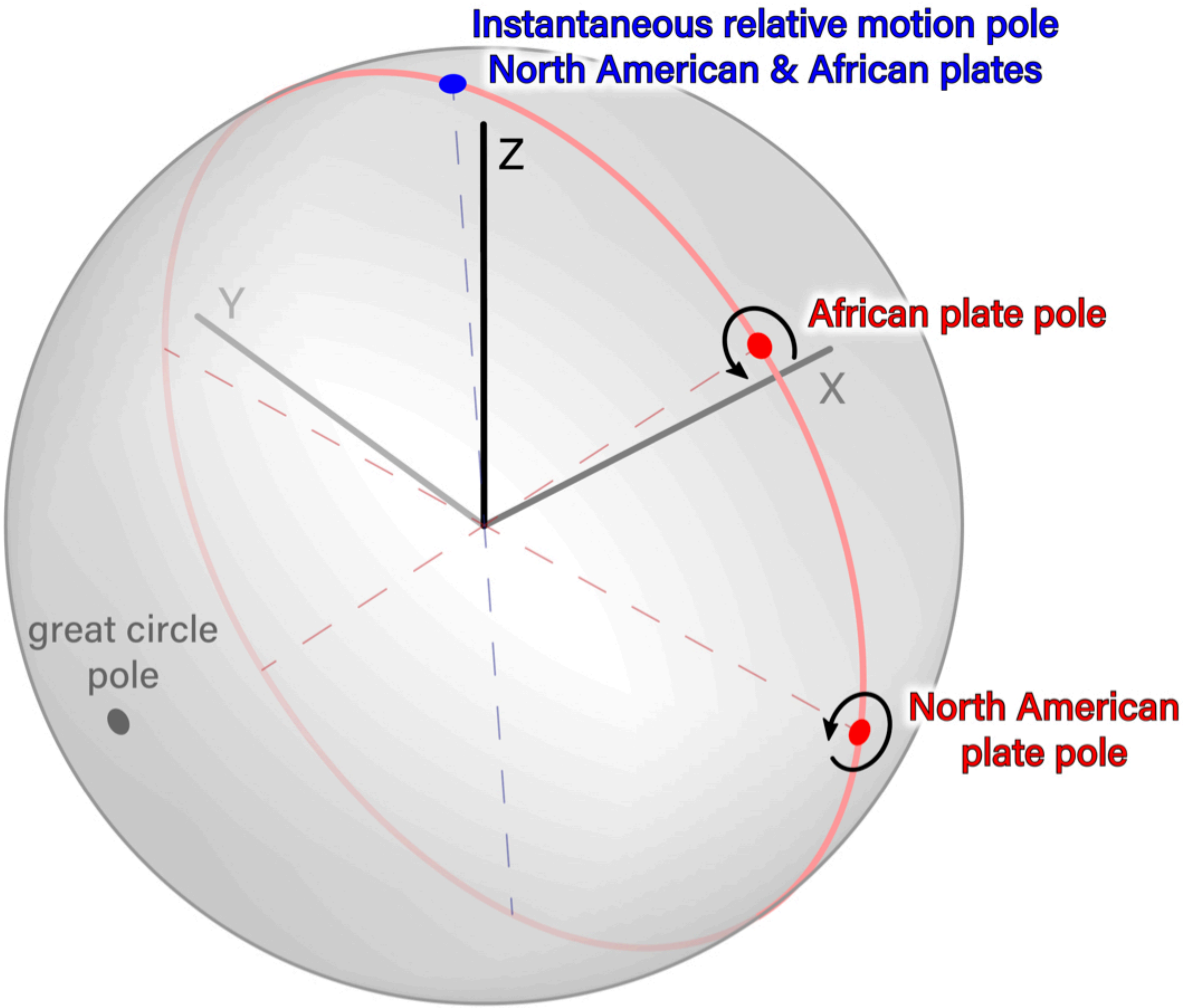
A lithospheric plate cannot rotate around two axes to which it is fixed.


Plates don't move in circular arcs relative to each other over finite time intervals.


Plates don't move in circular arcs relative to each other over finite time intervals.
Got it?


Plates don't move in circular arcs relative to each other over finite time intervals.
Got it?
Shed that idea!

A look at the instantaneous motion poles for a 3-plate system involving the North American, African (Nubian), and Eurasian plates.

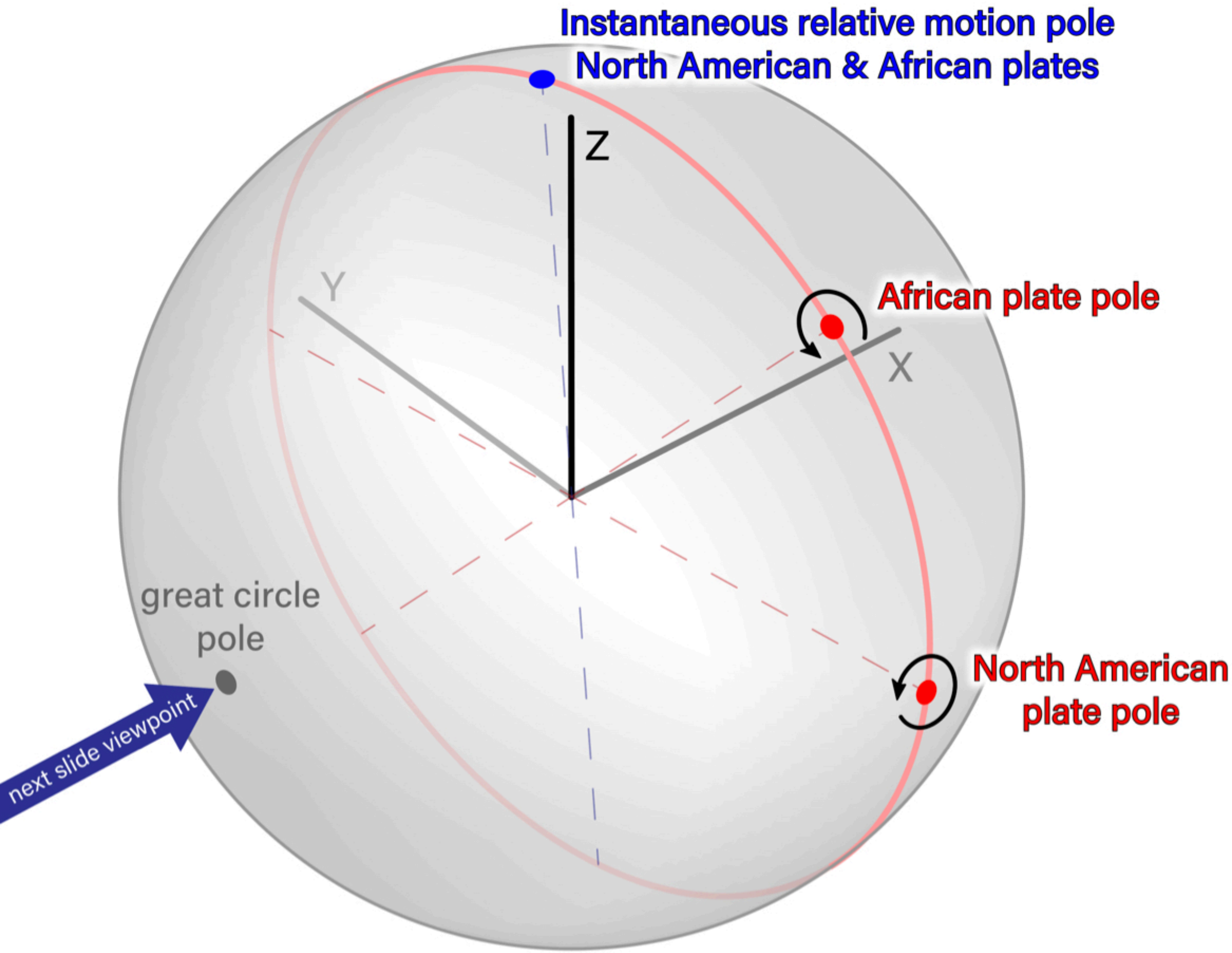


The instantaneous motion axes for any 2-plate system are all on the same plane (*i.e.*, they are coplanar) that passes through Earth's center.

Hence, the corresponding poles are all positioned along a great circle.

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213

NNR plate velocities from Kreemer et al., 2014, table S2



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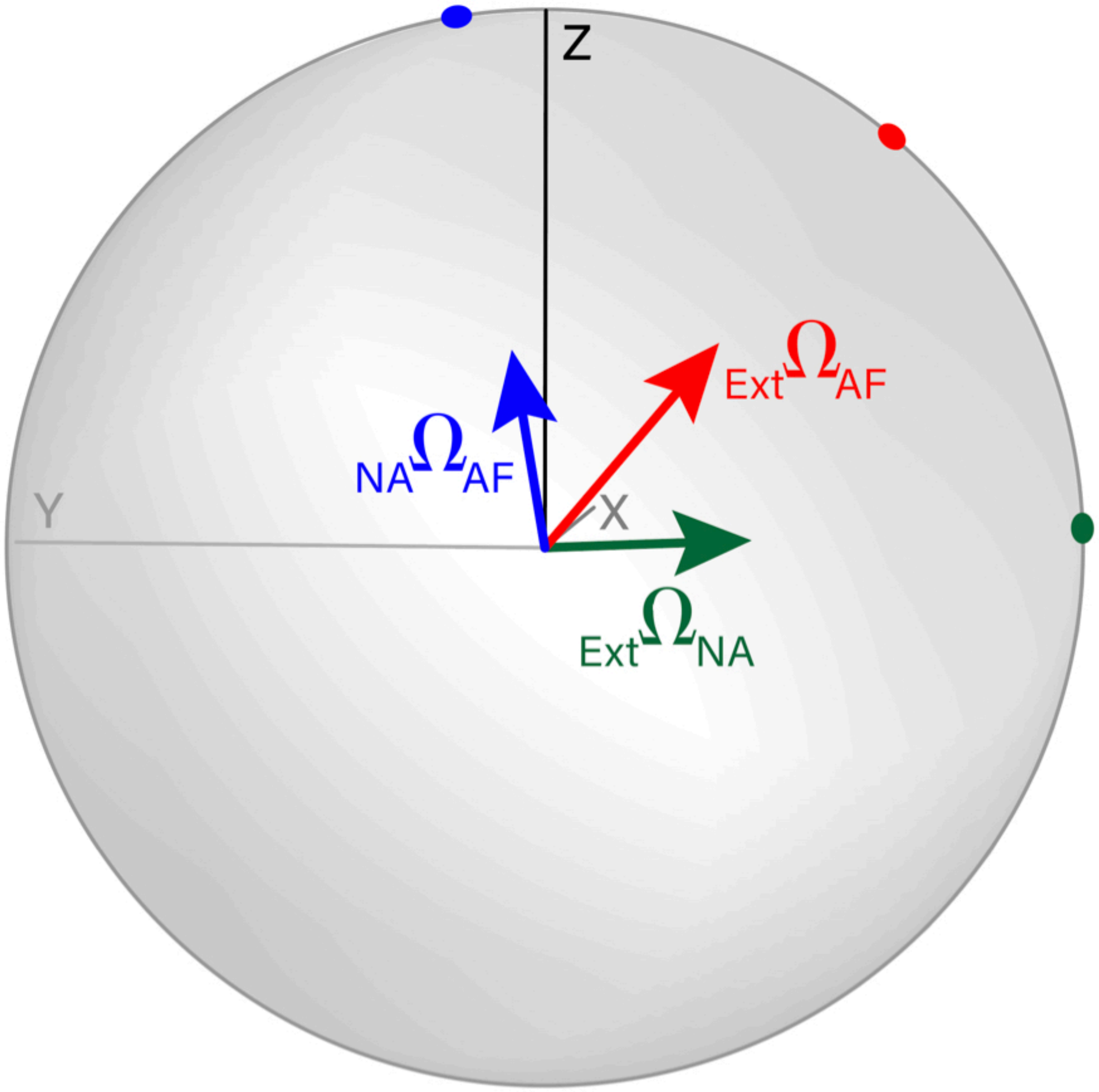
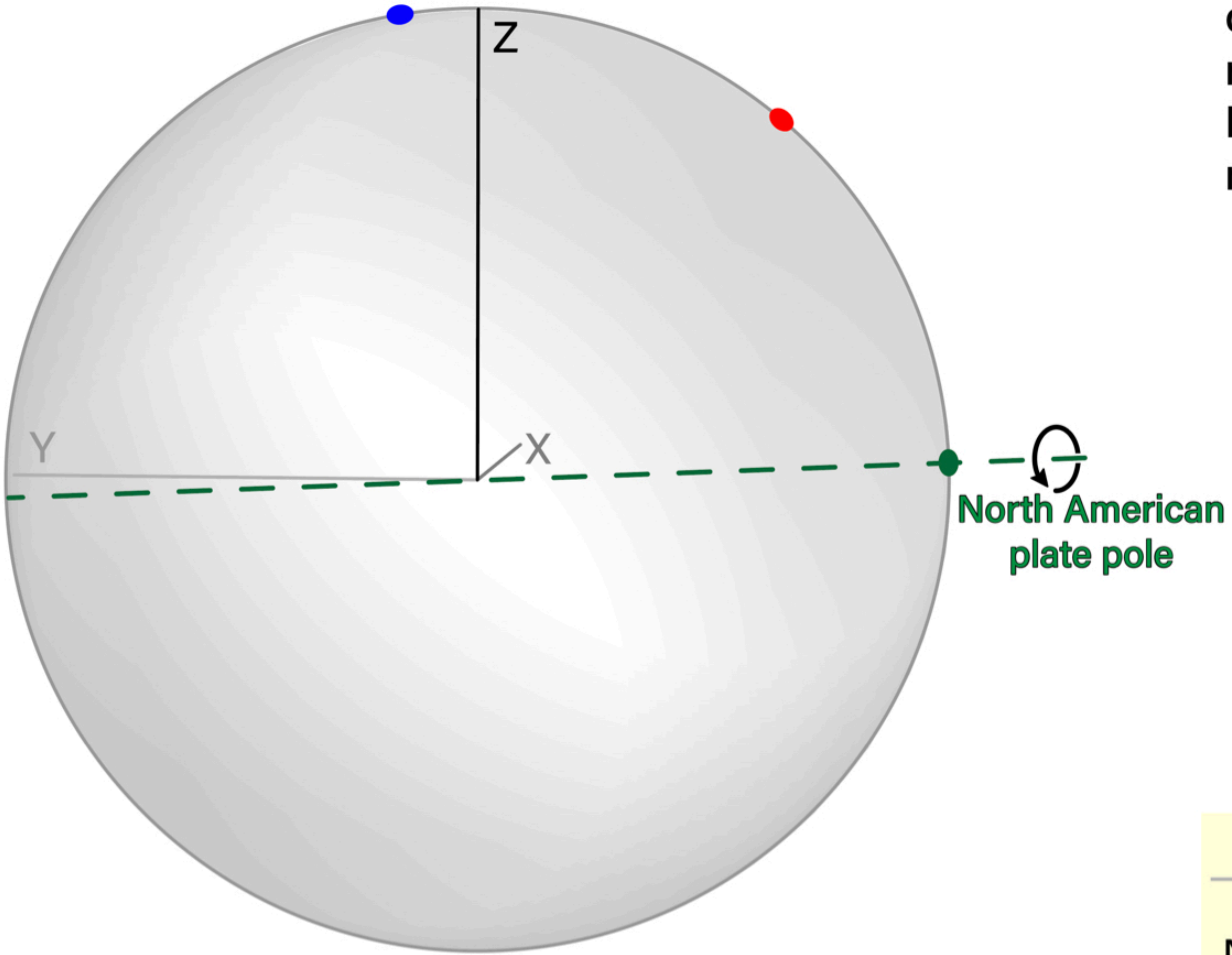


View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213



View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

Axis of rotation for the North American plate

	latitude	longitude	ω °/Ma
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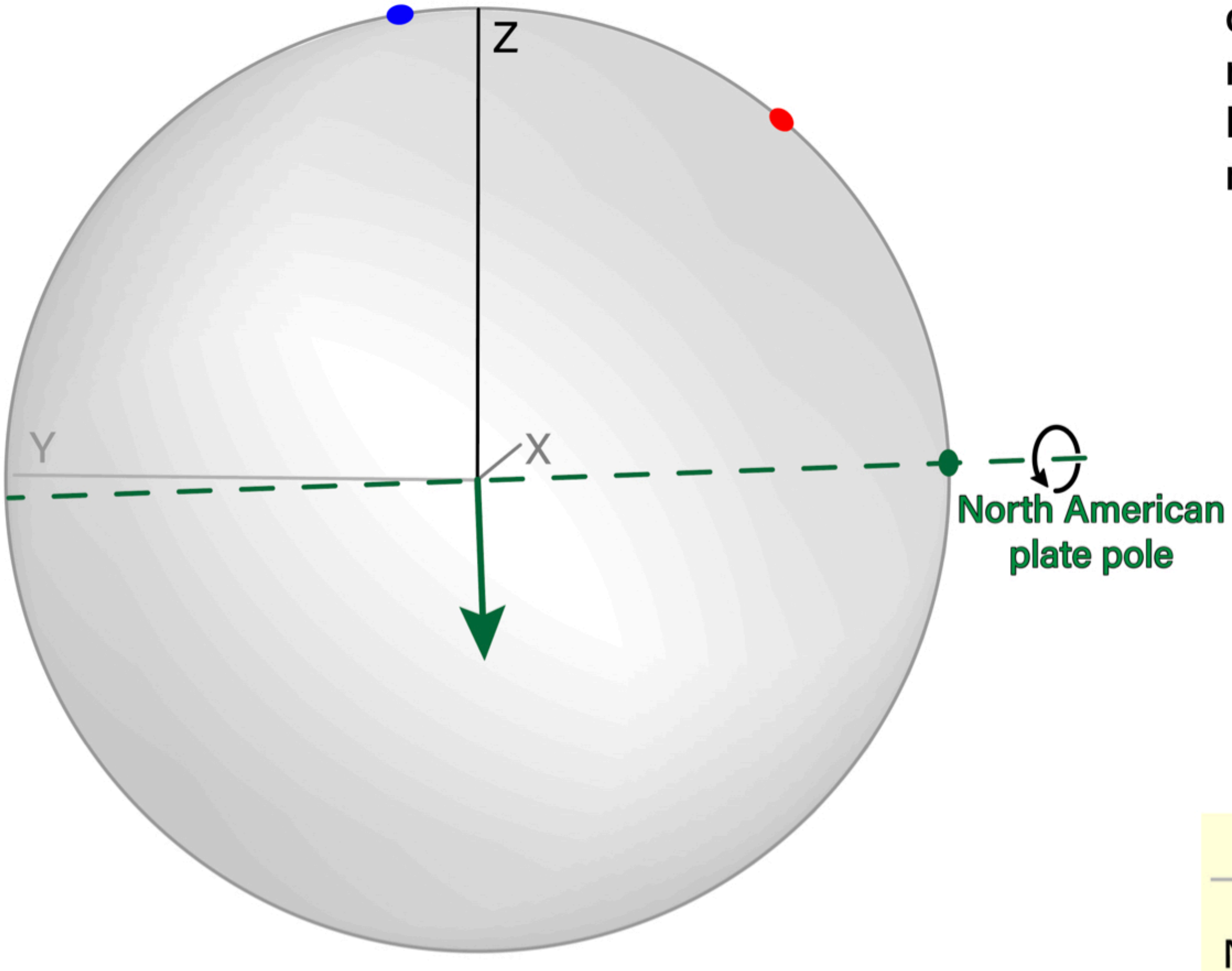
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213



View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

Axis of rotation for the North American plate and tangential velocity vector defined at the pole of the axial great circle

	latitude	longitude	ω °/Ma
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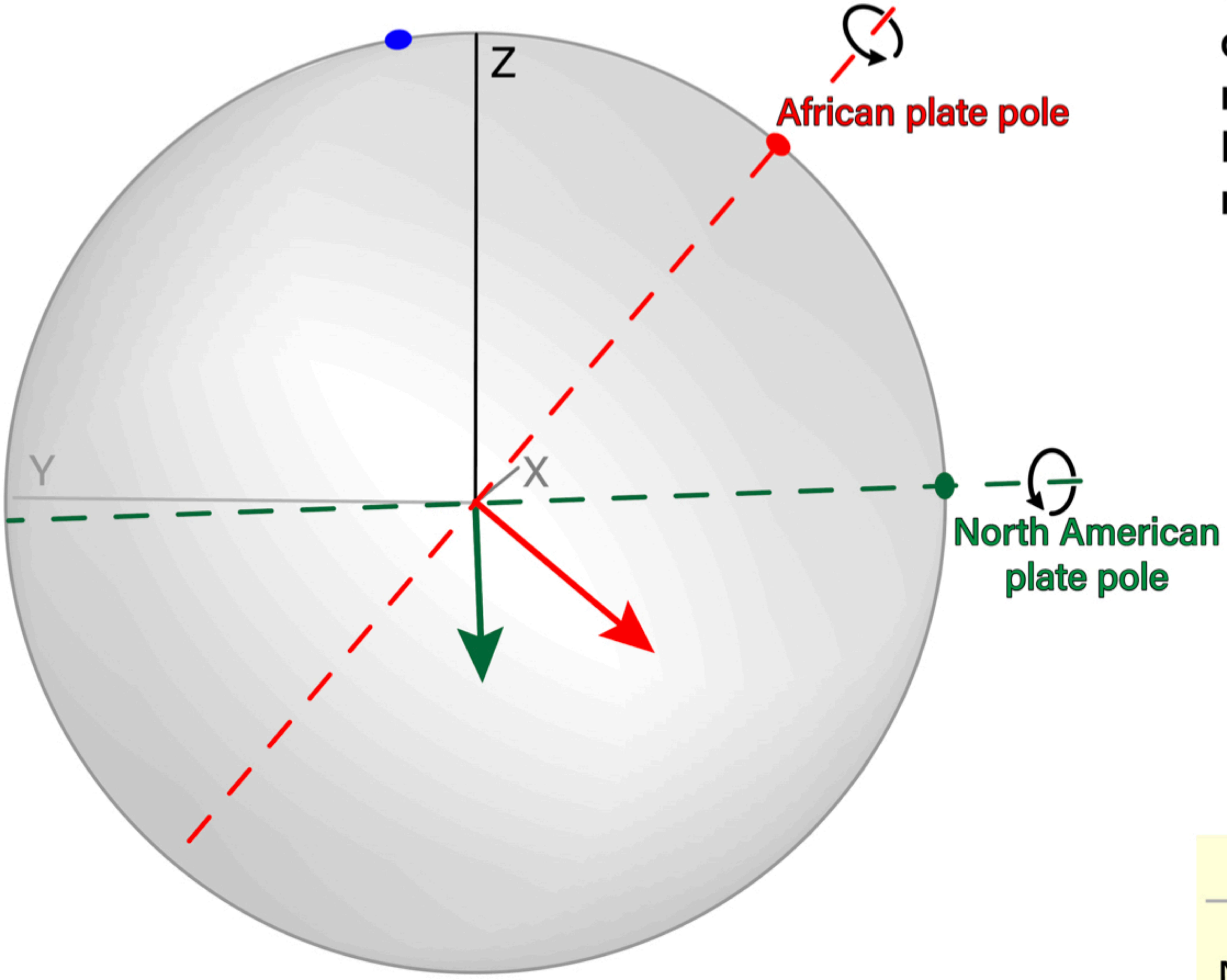
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213

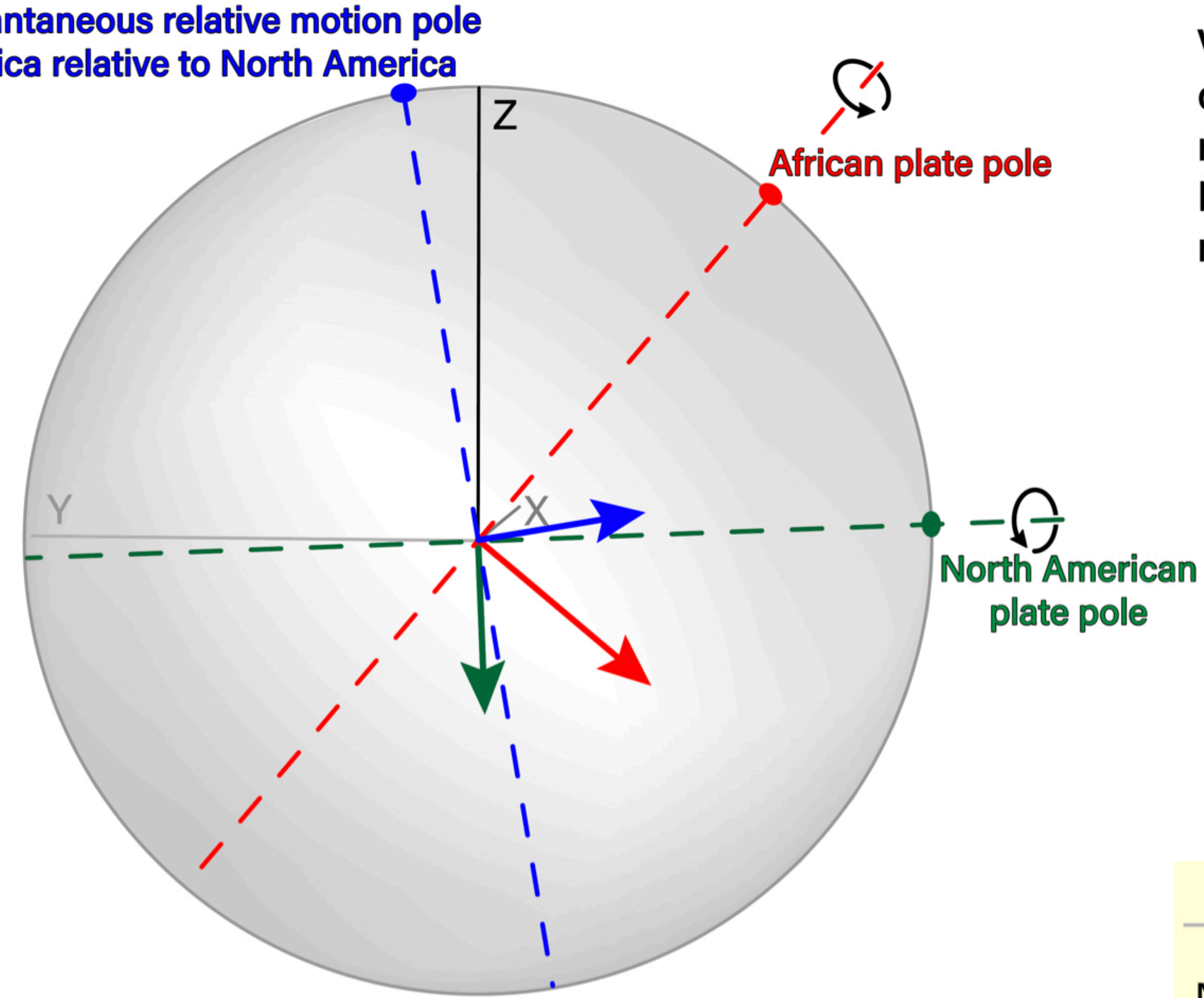


View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

Axis of rotation for the North American plate and tangential velocity vector defined at the pole of the axial great circle

Axis for the African plate and tangential velocity vector

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213



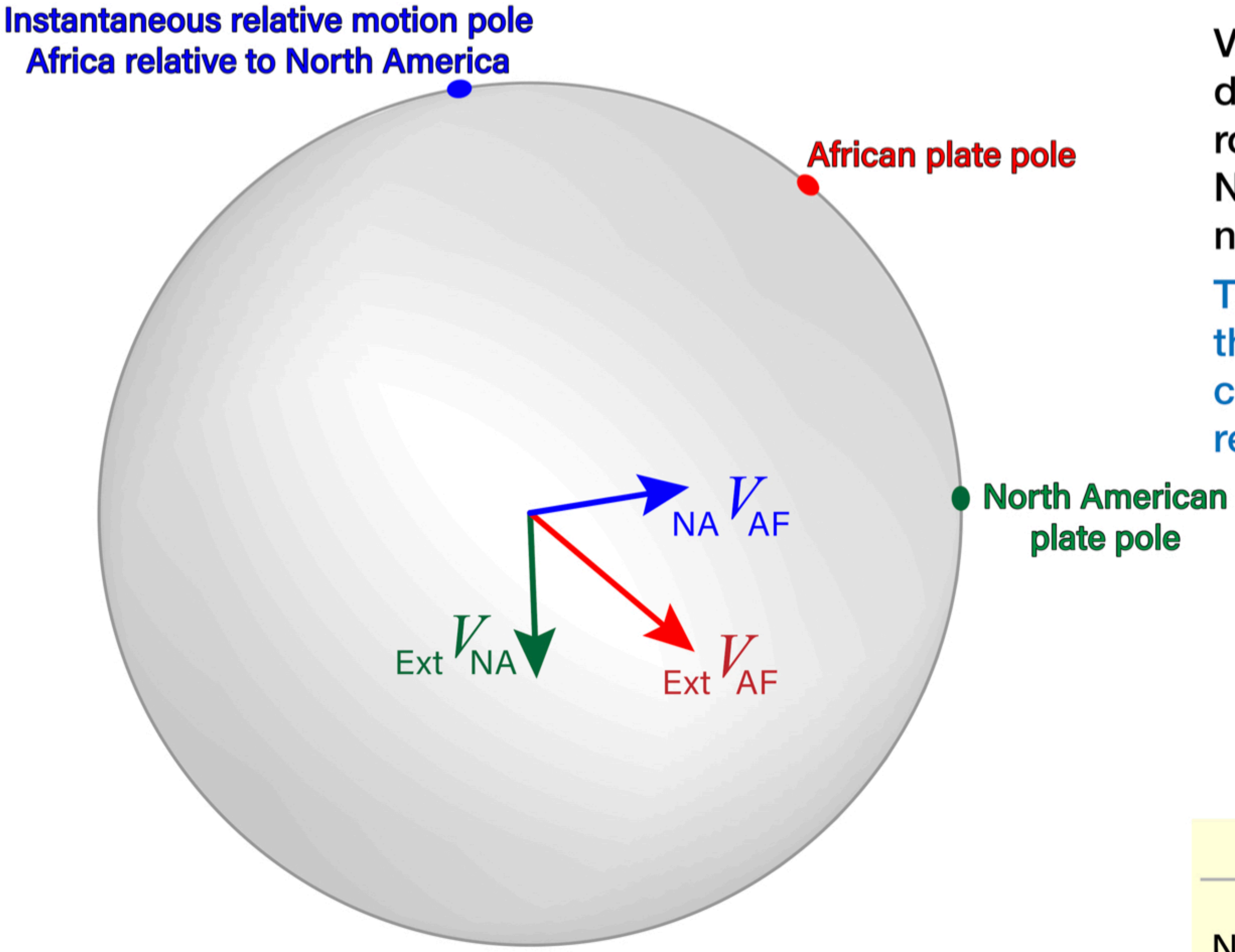
View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

Axis of rotation for the North American plate and tangential velocity vector defined at the pole of the axial great circle

Axis for the African plate and tangential velocity vector

Axis of instantaneous relative motion between the two plates and tangential velocity vector of Africa relative to North America

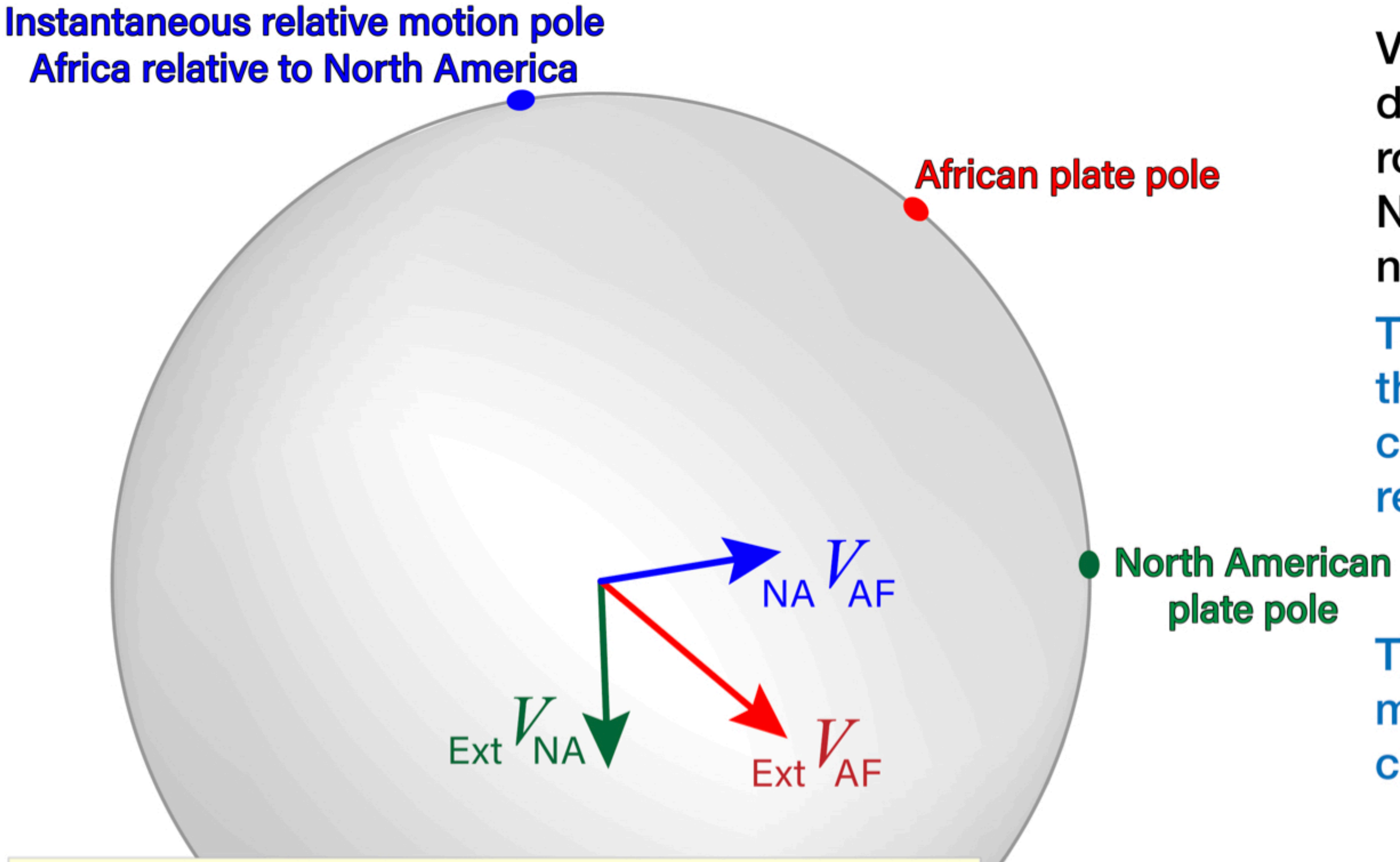
	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213



View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

The tangent vectors at the pole to the axial great circle display the correct proportional and angular relationships of the Euler vectors.

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213



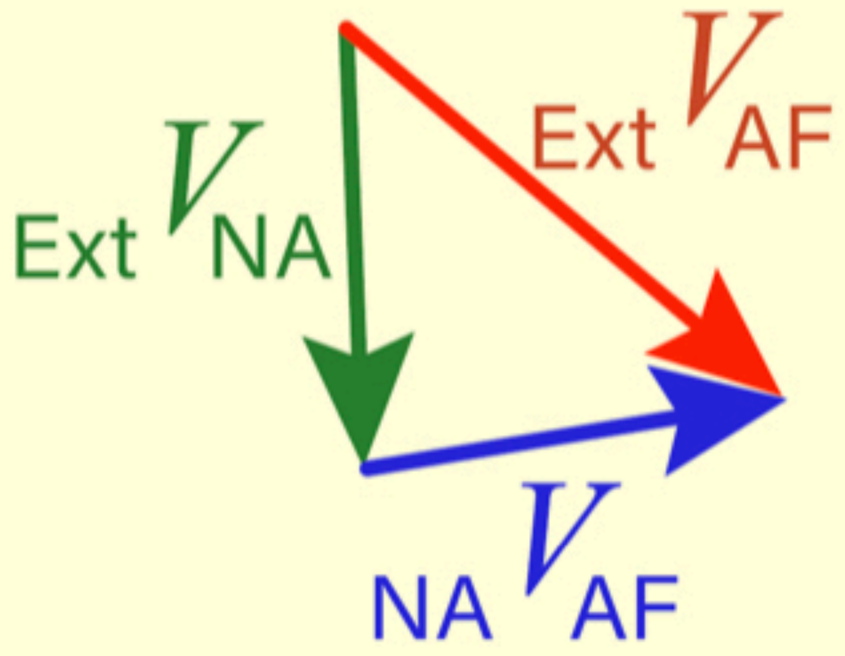
View perpendicular to the plane defined by the instantaneous rotational axes of the African and North American plate system in a no-net-rotation reference frame.

The tangent vectors at the pole to the axial great circle display the correct proportional and angular relationships of the Euler vectors.

The tangent vectors can be moved into a triangle forming a closed vector circuit.

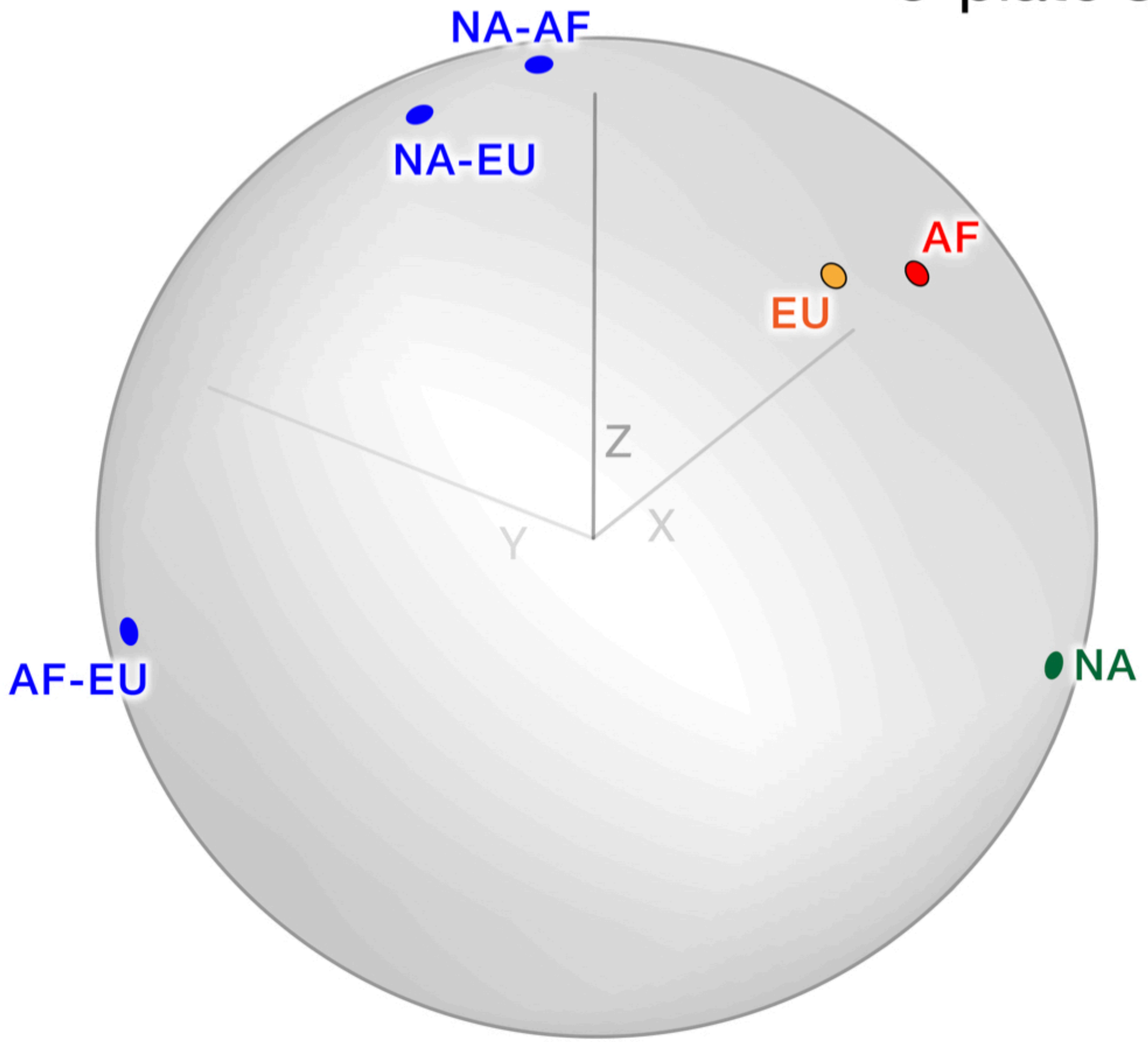
Tangential Velocity Vector Circuit

$$_{NA}V_{AF} = {}_{Ext}V_{AF} - {}_{Ext}V_{NA}$$



	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
NA-AF	79.24°	68.91°	0.213

3-plate system: N America, Africa, Eurasia

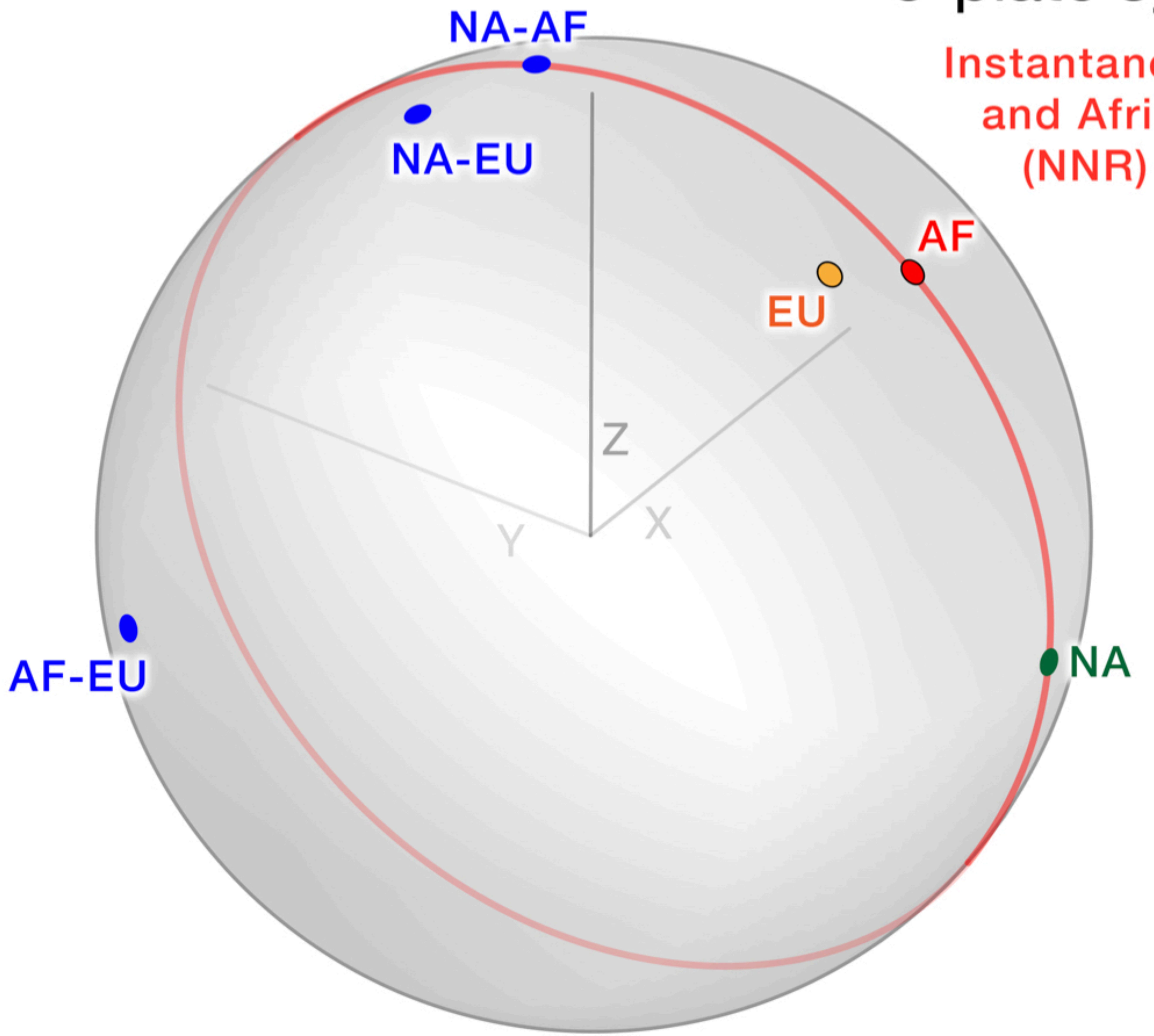


NNR plate velocities from Kreemer et al., 2014, table S2
Velocity of one plate relative to another computed by Vince Cronin

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
Eurasia	55.38°	-95.41°	0.271
NA-AF	79.24°	68.91°	0.213
NA-EU	70.78°	120.82°	0.227
AF-EU	5.58°	152.64°	0.060

3-plate system: N America, Africa, Eurasia

Instantaneous motion of the North American plate (NA) and African plate (AF) relative to a No-Net-Rotation (NNR) reference frame, and of Africa relative to North America (NA-AF)



	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
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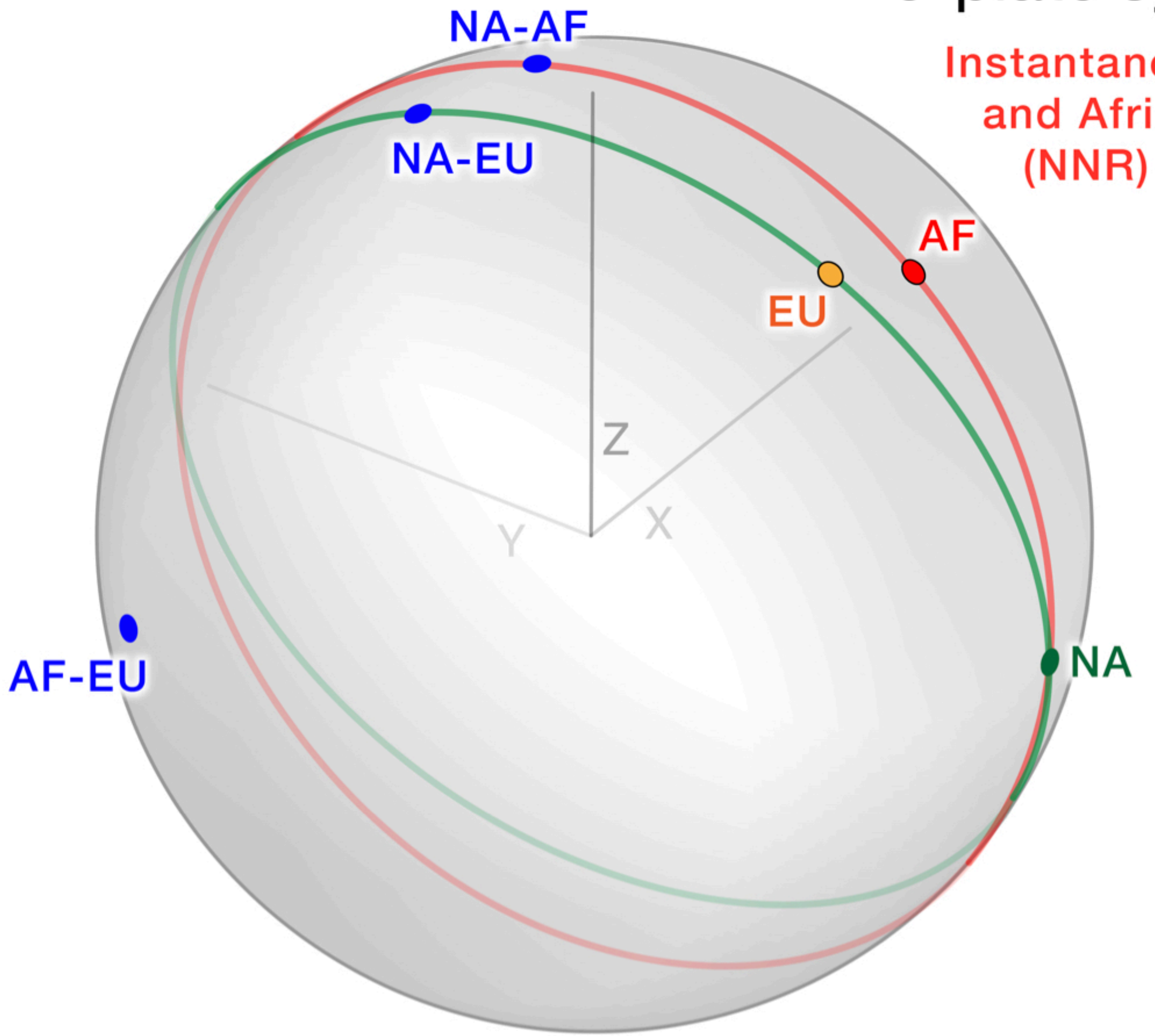
Velocity of one plate relative to another computed by Vince Cronin

3-plate system: N America, Africa, Eurasia

Instantaneous motion of the North American plate (NA) and African plate (AF) relative to a No-Net-Rotation (NNR) reference frame, and of Africa relative to North America (NA-AF)

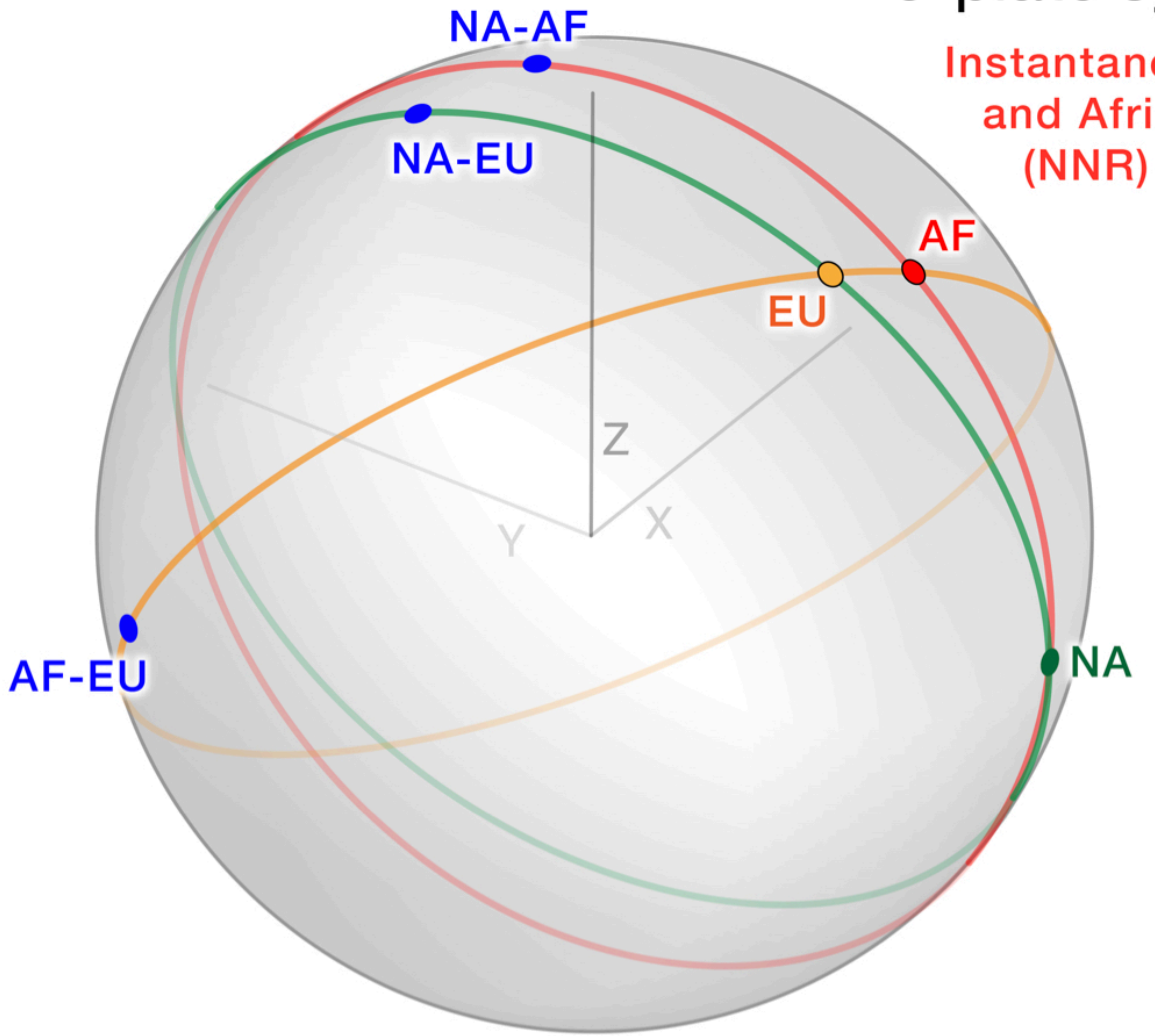
Instantaneous motion of NA and the Eurasian plate (EU) relative to NNR, and of EU relative to NA



	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
Eurasia	55.38°	-95.41°	0.271
NA-AF	79.24°	68.91°	0.213
NA-EU	70.78°	120.82°	0.227
AF-EU	5.58°	152.64°	0.060

NNR plate velocities from Kreemer et al., 2014, table S2
Velocity of one plate relative to another computed by Vince Cronin

3-plate system: N America, Africa, Eurasia



Instantaneous motion of the North American plate (NA) and African plate (AF) relative to a No-Net-Rotation (NNR) reference frame, and of Africa relative to North America (NA-AF)

Instantaneous motion of NA and the Eurasian plate (EU) relative to NNR, and of EU relative to NA

Instantaneous motion of AF and EU relative to NNR, and of EU relative to AF

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
Eurasia	55.38°	-95.41°	0.271
NA-AF	79.24°	68.91°	0.213
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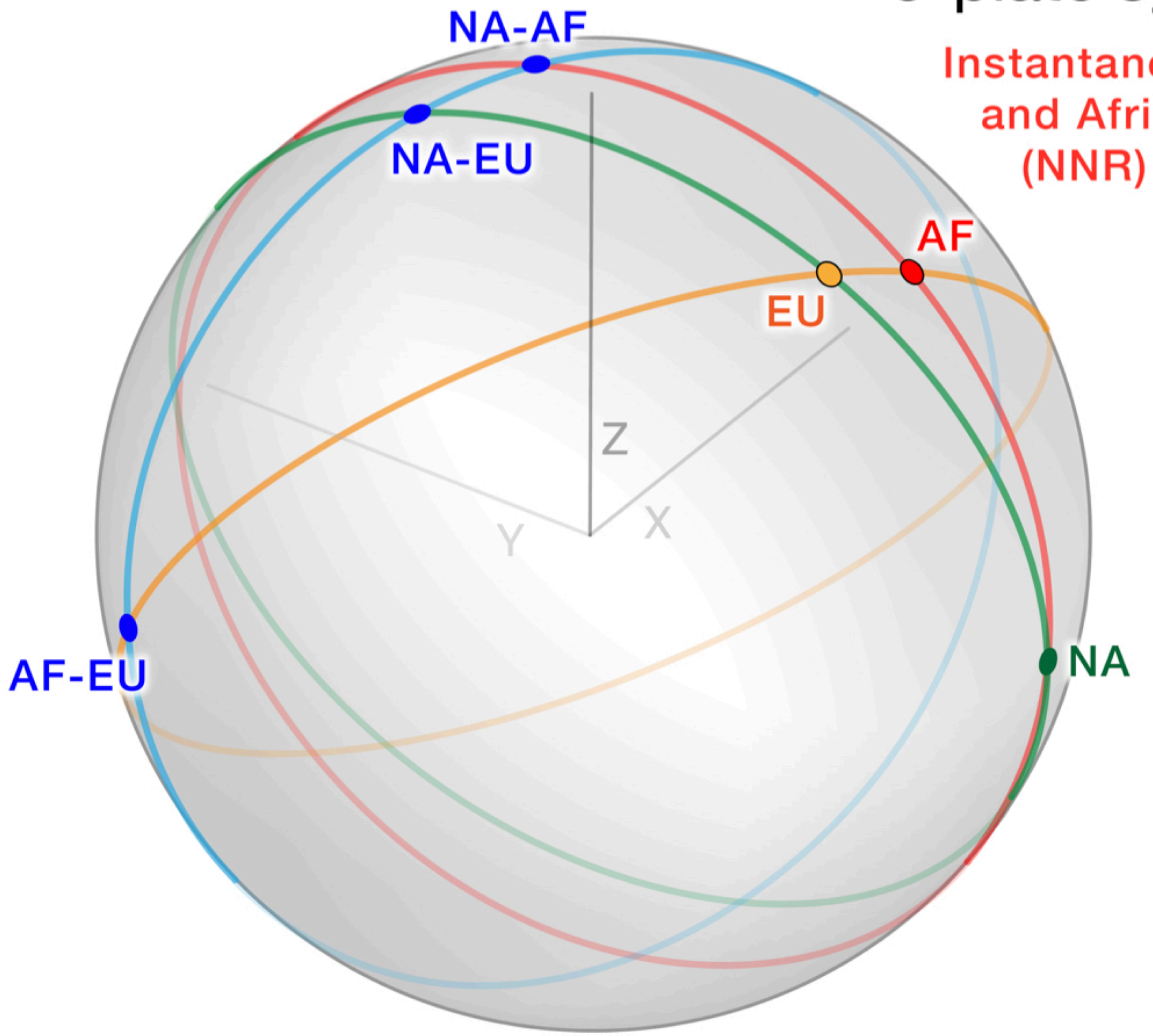
NNR plate velocities from Kreemer et al., 2014, table S2
Velocity of one plate relative to another computed by Vince Cronin

3-plate system: N America, Africa, Eurasia



Instantaneous motion of the North American plate (NA) and African plate (AF) relative to a No-Net-Rotation (NNR) reference frame, and of Africa relative to North America (NA-AF)

Instantaneous motion of NA and the Eurasian plate (EU) relative to NNR, and of EU relative to NA

Instantaneous motion of AF and EU relative to NNR, and of EU relative to AF

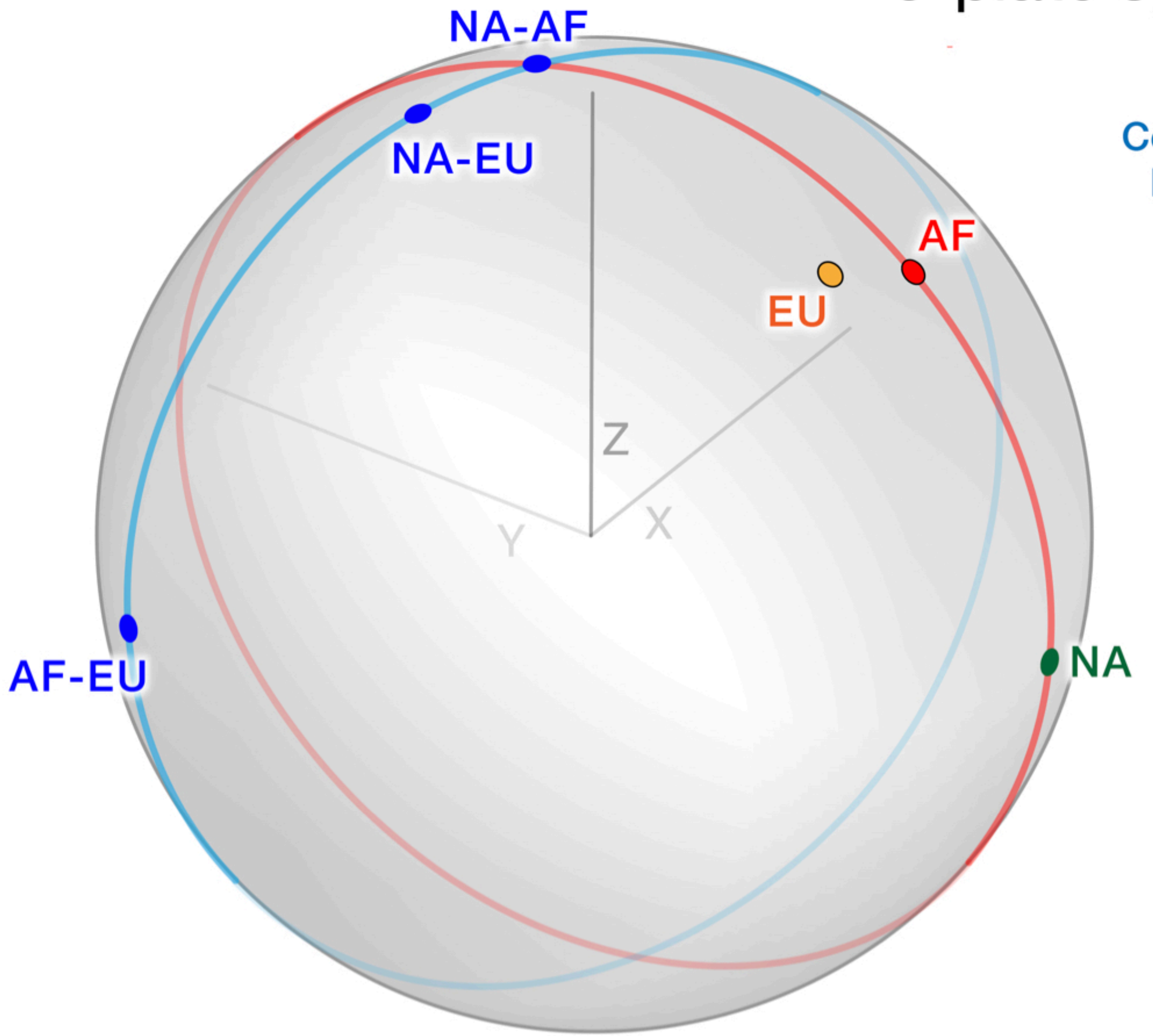
Great circle defined by $_{AF}\Omega_{EU}$, $_{NA}\Omega_{EU}$, and $_{NA}\Omega_{AF}$

	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
Eurasia	55.38°	-95.41°	0.271
NA-AF	79.24°	68.91°	0.213
NA-EU	70.78°	120.82°	0.227
AF-EU	5.58°	152.64°	0.060

NNR plate velocities from Kreemer et al., 2014, table S2
Velocity of one plate relative to another computed by Vince Cronin

As long as the **angular velocity vector** of each **plate is constant** relative to ITRF or some other external reference frame, the **position of each plate's pole is constant** in that reference frame.

3-plate system: N America, Africa, Eurasia



Computed Results

$$_{NA}\Omega_{AF} = {}_{Ext}\Omega_{AF} - {}_{Ext}\Omega_{NA}$$
$$_{NA}\Omega_{EU} = {}_{Ext}\Omega_{EU} - {}_{Ext}\Omega_{NA}$$
$$_{AF}\Omega_{EU} = {}_{Ext}\Omega_{EU} - {}_{Ext}\Omega_{AF}$$

Input Data

and

$$_{NA}\Omega_{EU} - {}_{AF}\Omega_{EU} - {}_{NA}\Omega_{AF} = 0$$

because

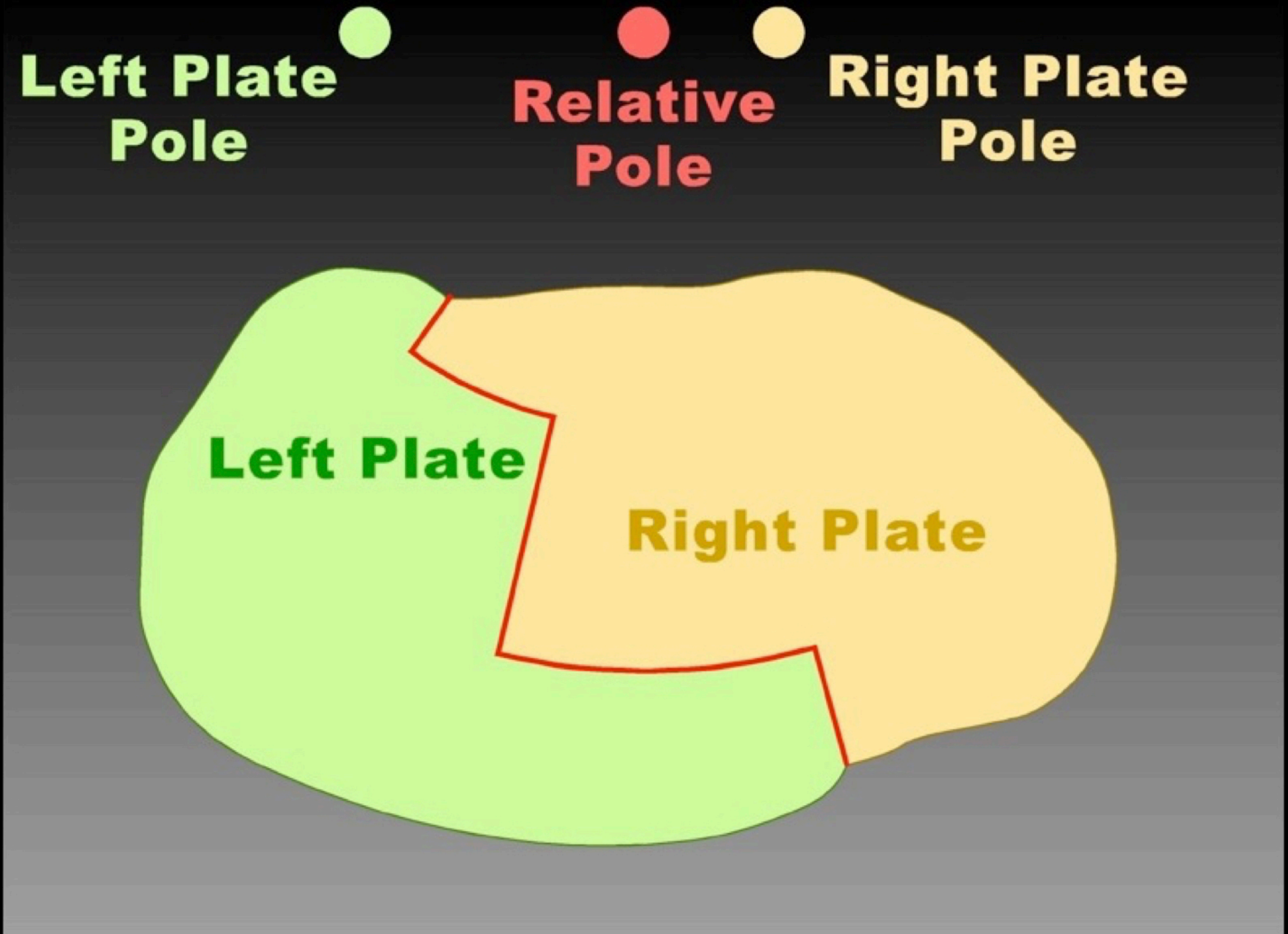
$$_{EU}\Omega_{AF} = (-{}_{AF}\Omega_{EU}),$$
$$_{AF}\Omega_{NA} = (-{}_{NA}\Omega_{AF}), \text{ and}$$
$$_{NA}\Omega_{EU} + {}_{EU}\Omega_{AF} + {}_{AF}\Omega_{NA} = 0$$

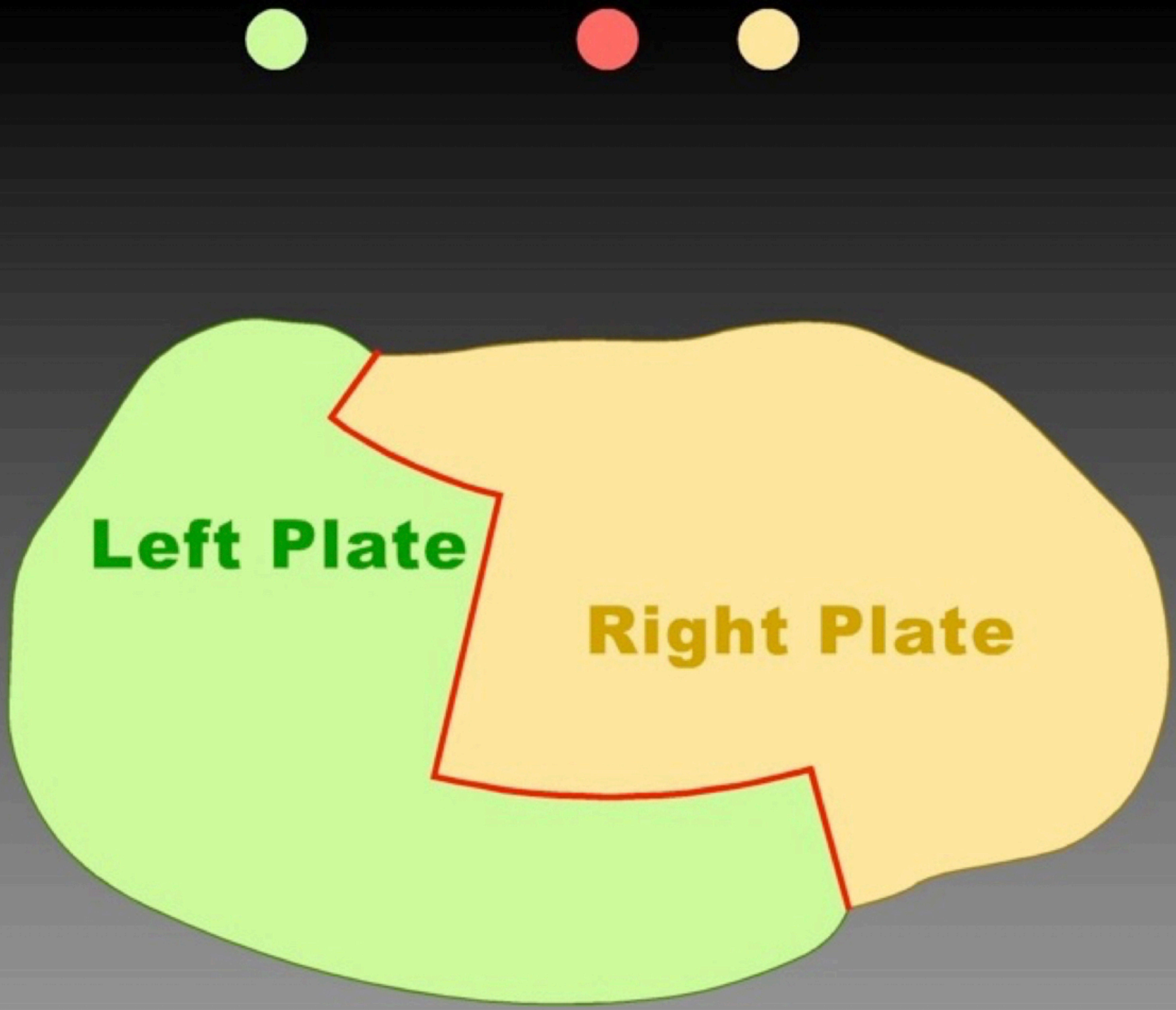
	latitude	longitude	ω °/Ma
Africa	49.66°	-78.08°	0.285
N America	2.19°	-83.75°	0.219
Eurasia	55.38°	-95.41°	0.271
NA-AF	79.24°	68.91°	0.213
NA-EU	70.78°	120.82°	0.227
AF-EU	5.58°	152.64°	0.060

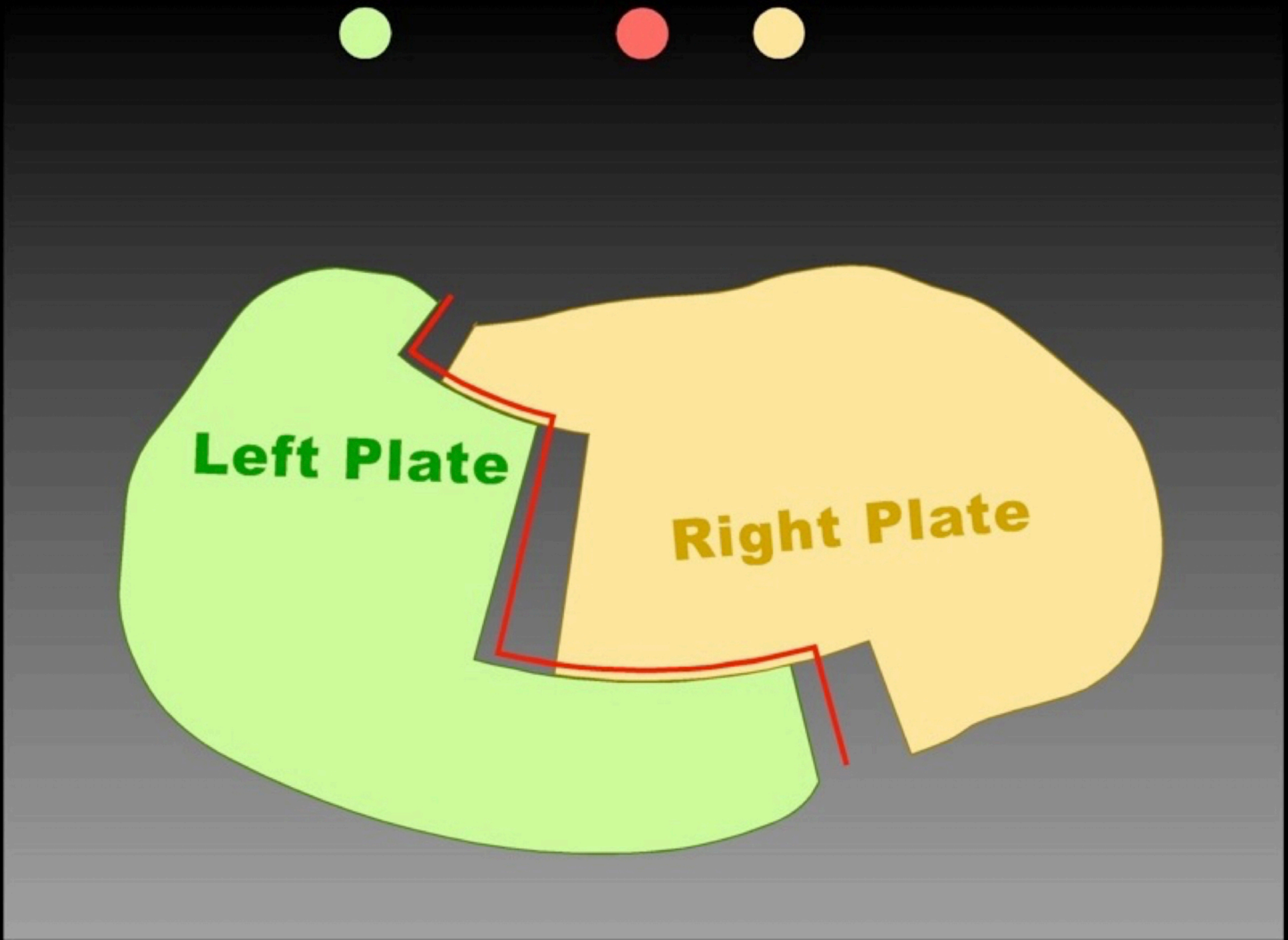
NNR plate velocities from Kreemer et al., 2014, table S2
Velocity of one plate relative to another computed by Vince Cronin

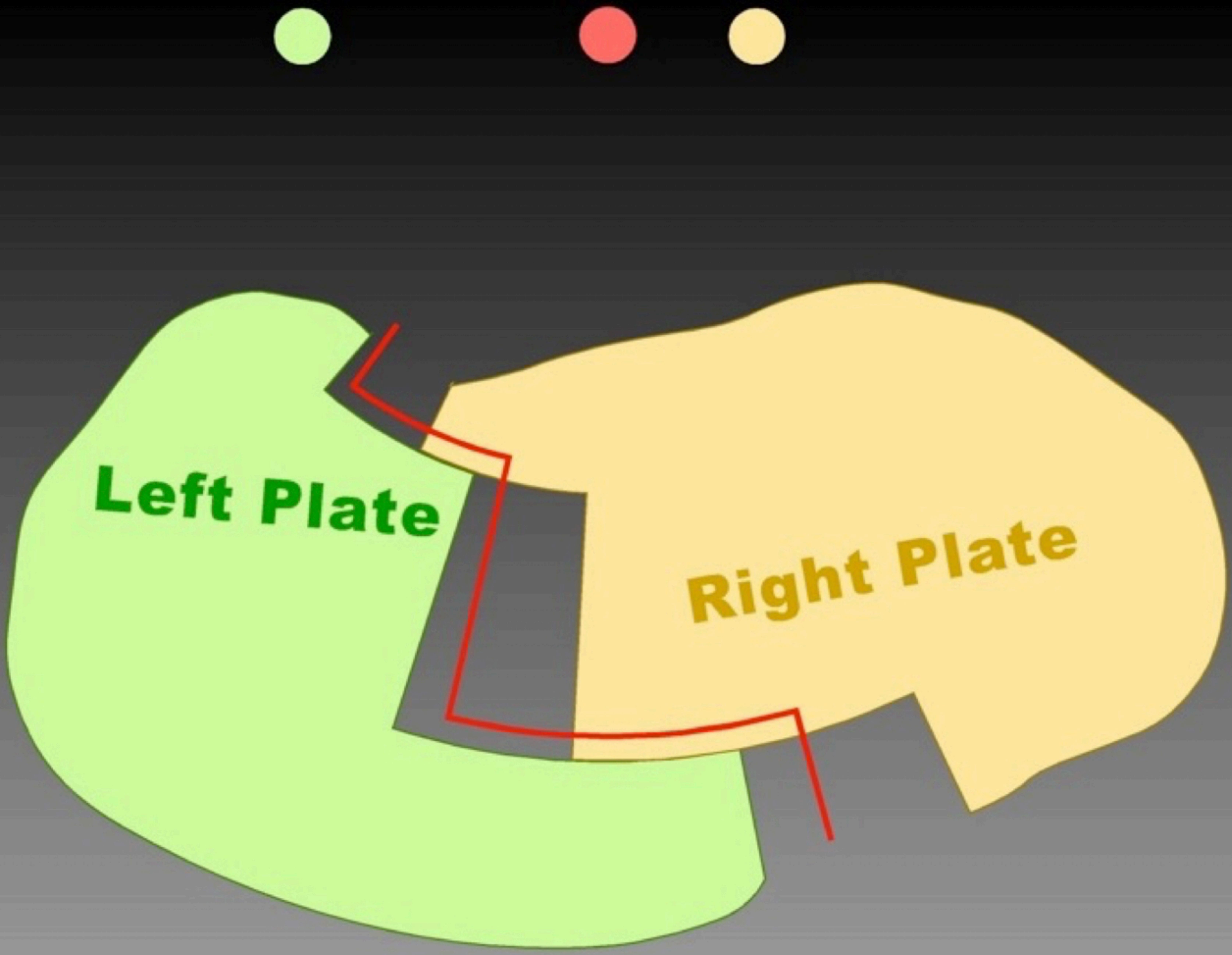
As a first-order model, we assume that the angular velocity vector for each plate is constant over a finite time period, in a stable reference frame external to the plates.

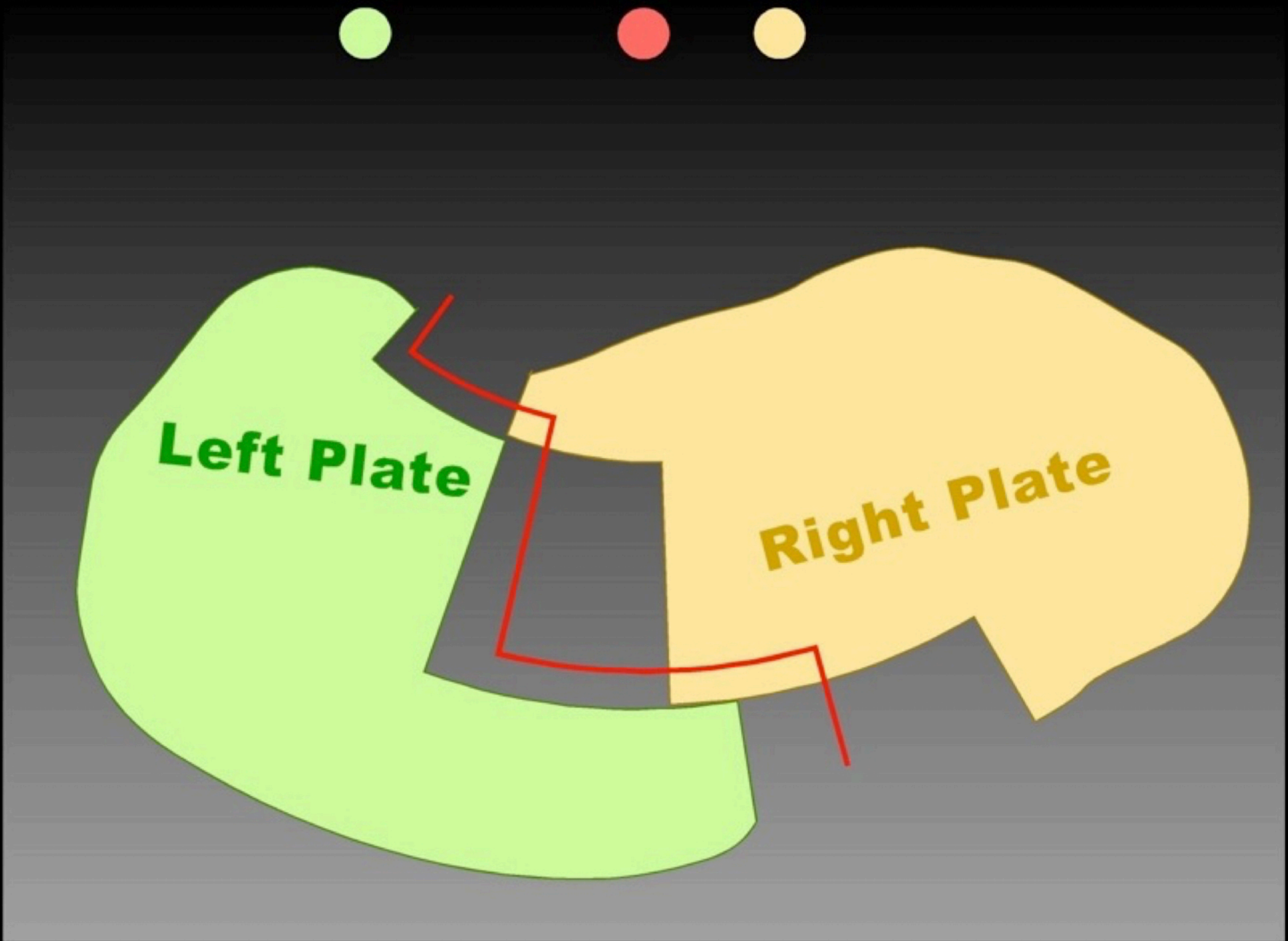
Our fundamental focus is on the motion of individual plates in the external reference frame.

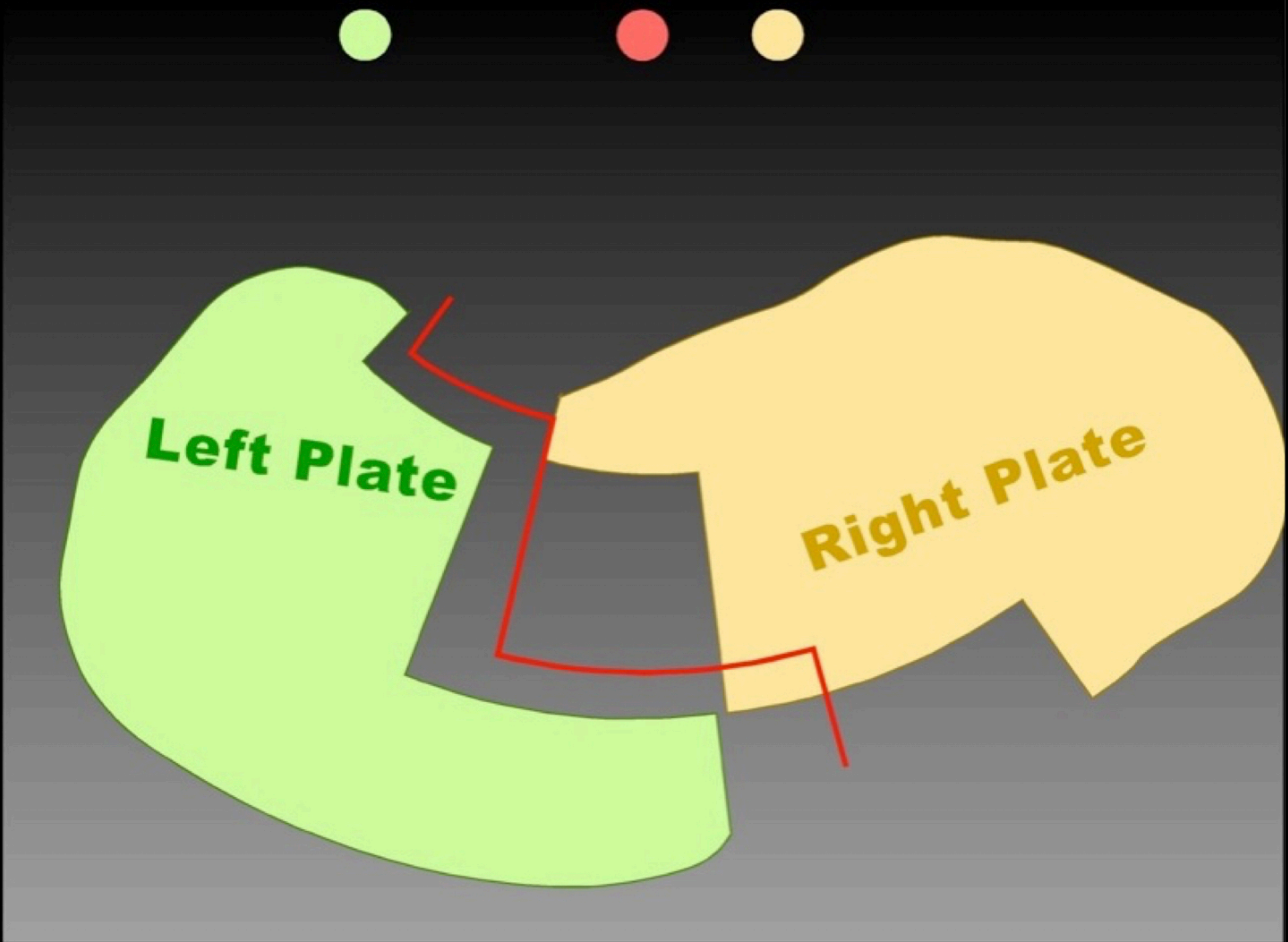

Left Plate
Pole
Relative
Pole
Right Plate
Pole
Left Plate
Right Plate

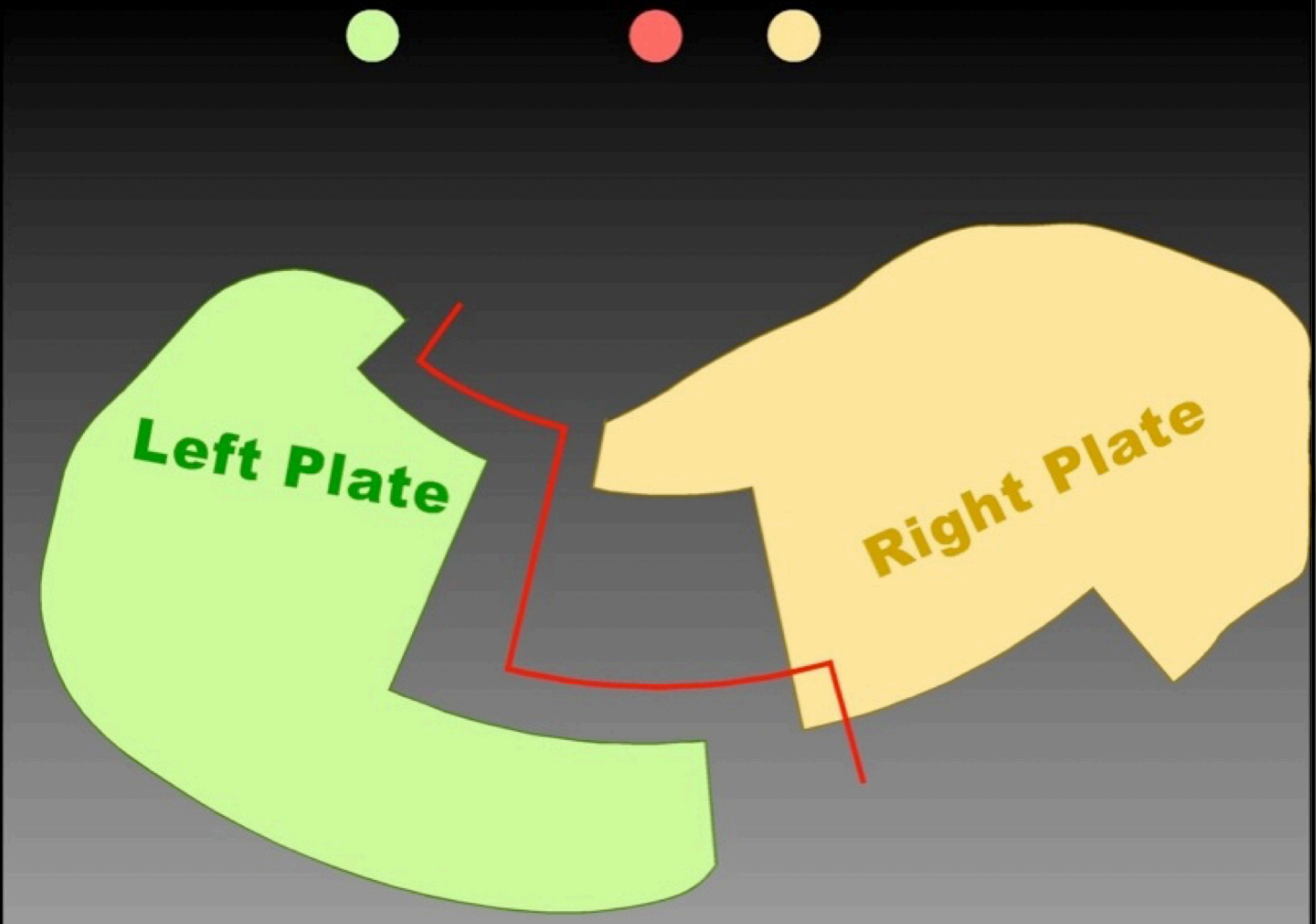

Left Plate
Right Plate

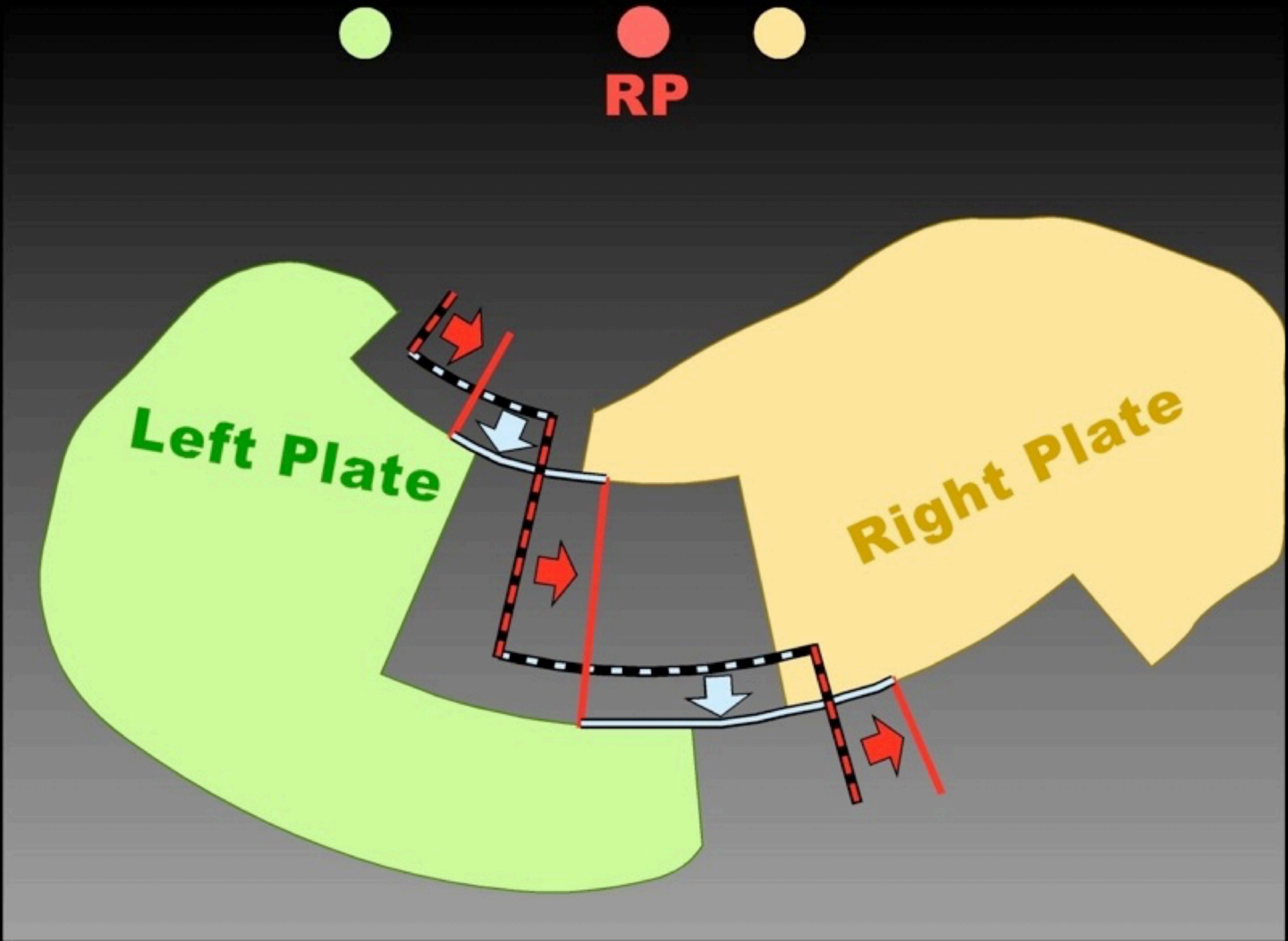

Left Plate
Right Plate

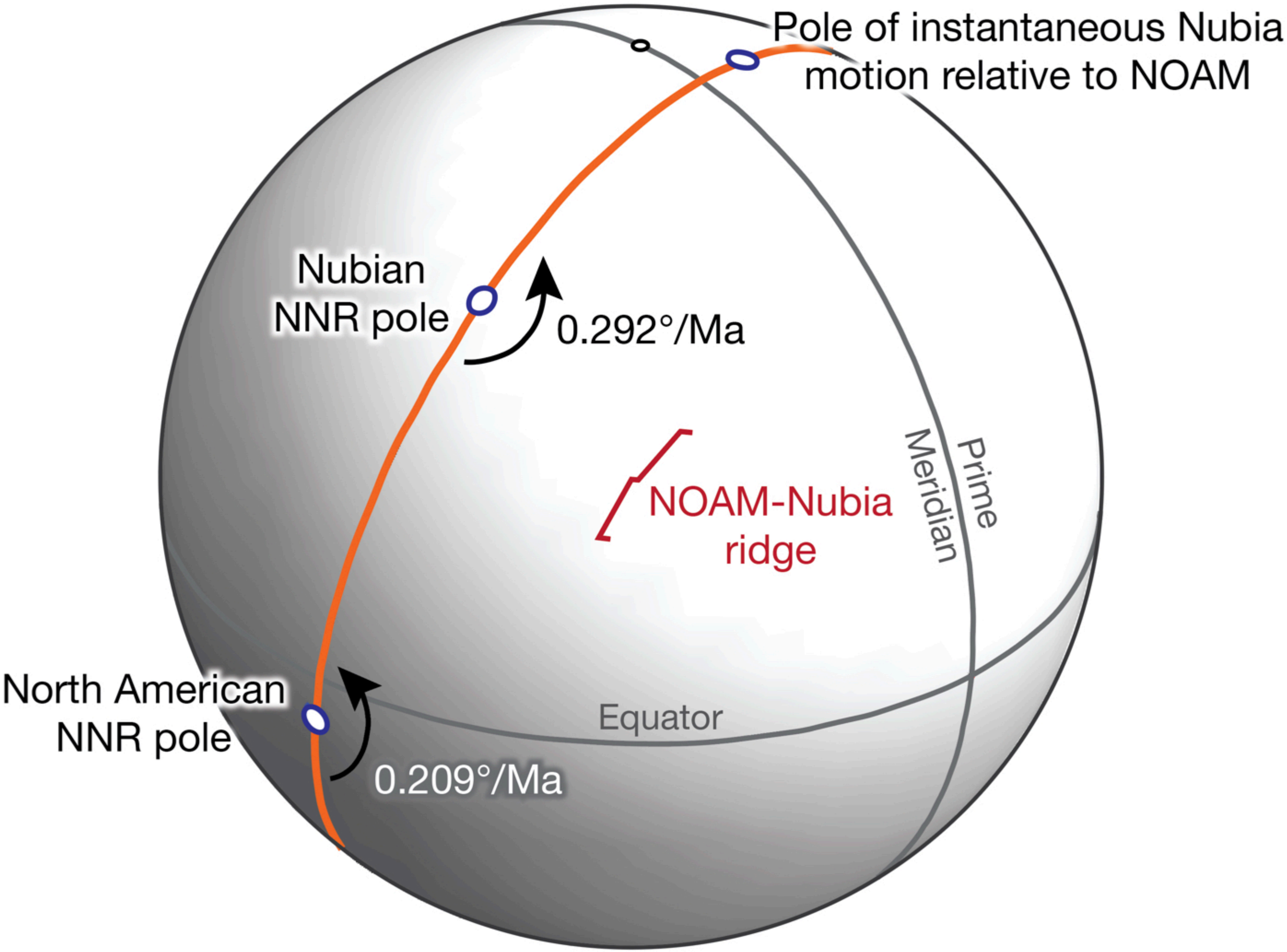

Left Plate
Right Plate


Left Plate
Right Plate

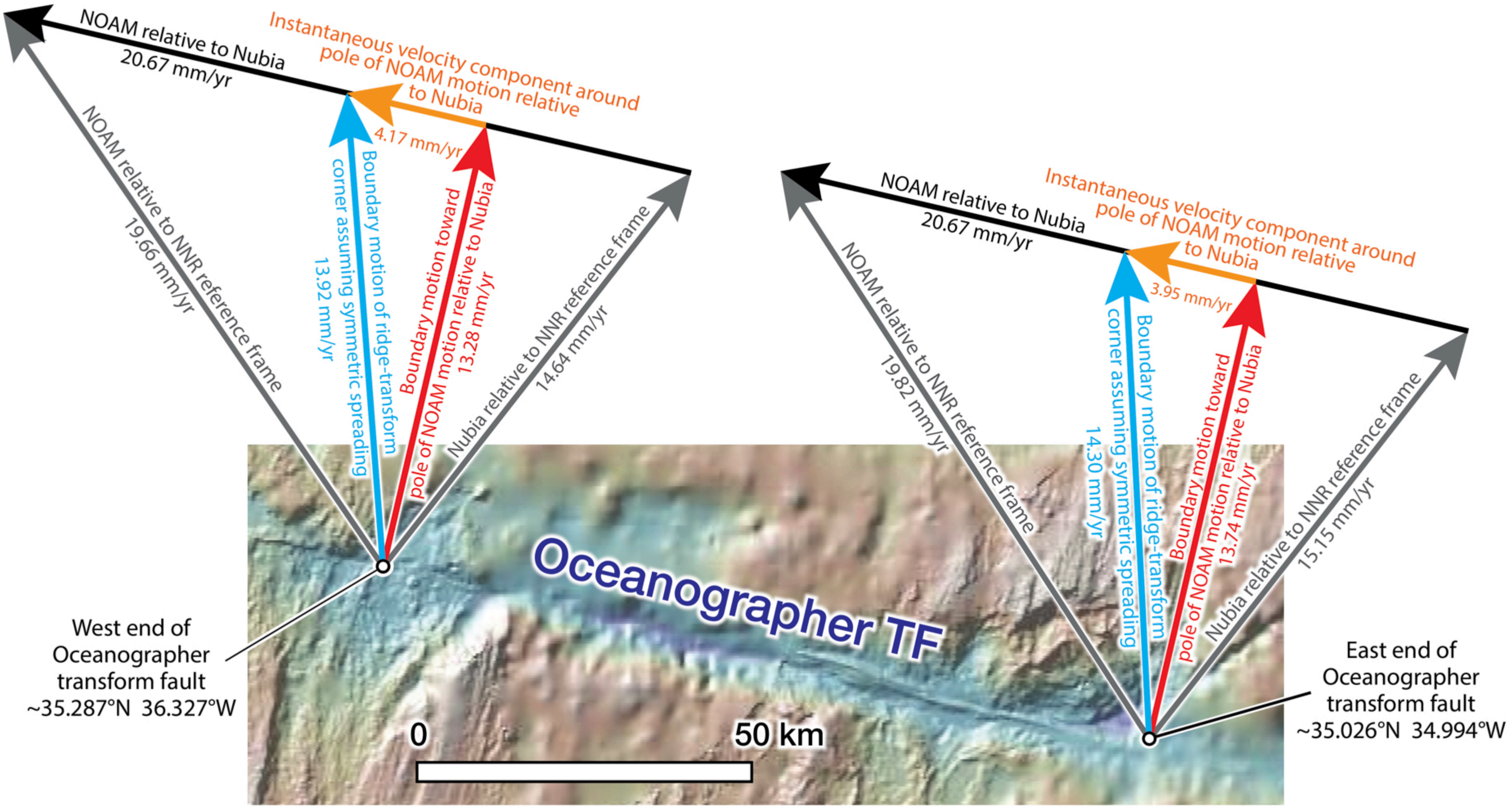

Left Plate
Right Plate

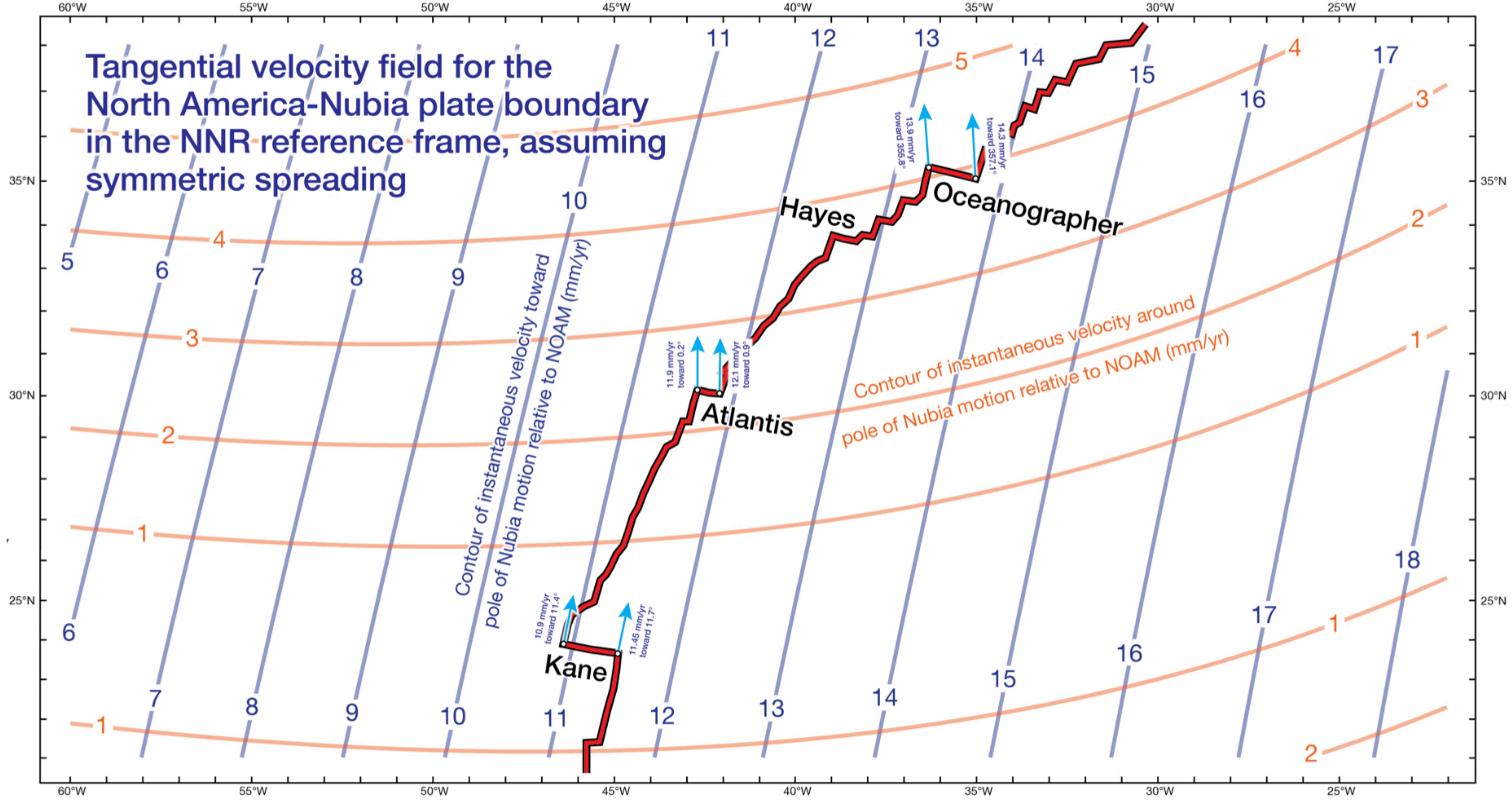

Left Plate
Right Plate


RP
Left Plate
Right Plate


Pole of instantaneous Nubia motion relative to NOAM
Nubian NNR pole
0.292°/Ma
NOAM-Nubia ridge
Prime Meridian
North American NNR pole
0.209°/Ma
Equator

Location of selected isochron segments along the Kane, Atlantis and Oceanographer fracture zones
North American plate
Nubian plate
Hayes
Oceanographer
Atlantis
Kane
C13n-y
C6n-o
C5ADn-o
C3n.4n-o
C5n.2n-o
C22n-o
60°W
55°W
50°W
45°W
40°W
35°W
30°W
25°W
35°N
30°N
25°N
Base map from GeoMapApp


NOAM relative to Nubia
20.67 mm/yr
Instantaneous velocity component around pole of NOAM motion relative to Nubia
4.17 mm/yr
NOAM relative to NNR reference frame
19.66 mm/yr
Boundary motion of ridge-transform corner assuming symmetric spreading
13.92 mm/yr
Boundary motion toward pole of NOAM motion relative to Nubia
13.28 mm/yr
Nubia relative to NNR reference frame
14.64 mm/yr
West end of
Oceanographer
transform fault
~35.287°N 36.327°W
Oceanographer TF
0
50 km
NOAM relative to Nubia
20.67 mm/yr
Instantaneous velocity component around pole of NOAM motion relative to Nubia
3.95 mm/yr
NOAM relative to NNR reference frame
19.82 mm/yr
Boundary motion of ridge-transform corner assuming symmetric spreading
14.30 mm/yr
Boundary motion toward pole of NOAM motion relative to Nubia
13.74 mm/yr
Nubia relative to NNR reference frame
15.15 mm/yr
East end of
Oceanographer
transform fault
~35.026°N 34.994°W

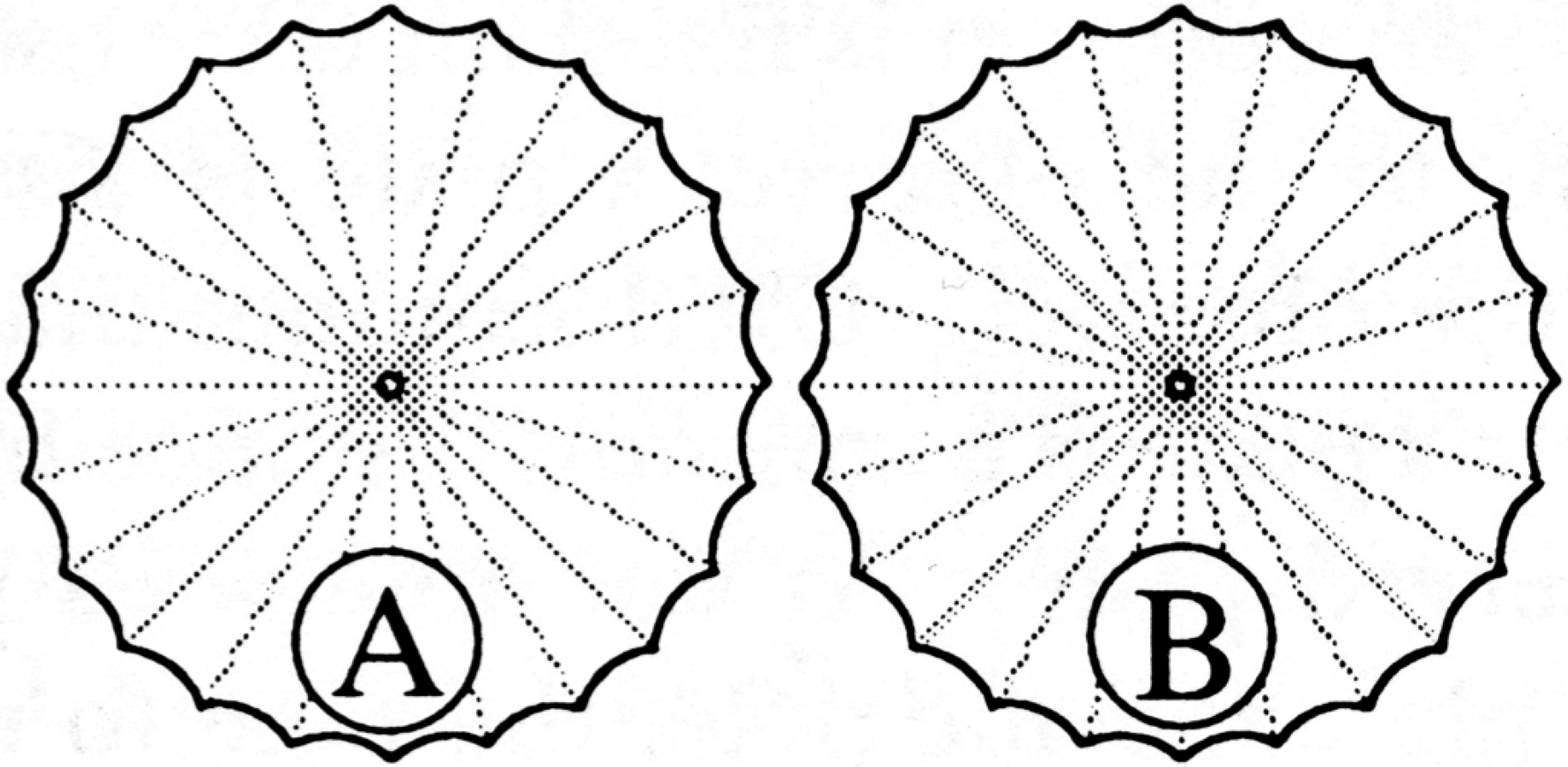


As the boundary moves in the NNR reference frame (Argus et al., 2011) over finite time intervals, the instantaneous velocity of each point along the boundary changes.

Our fundamental focus is on the motion of individual plates in the external reference frame.

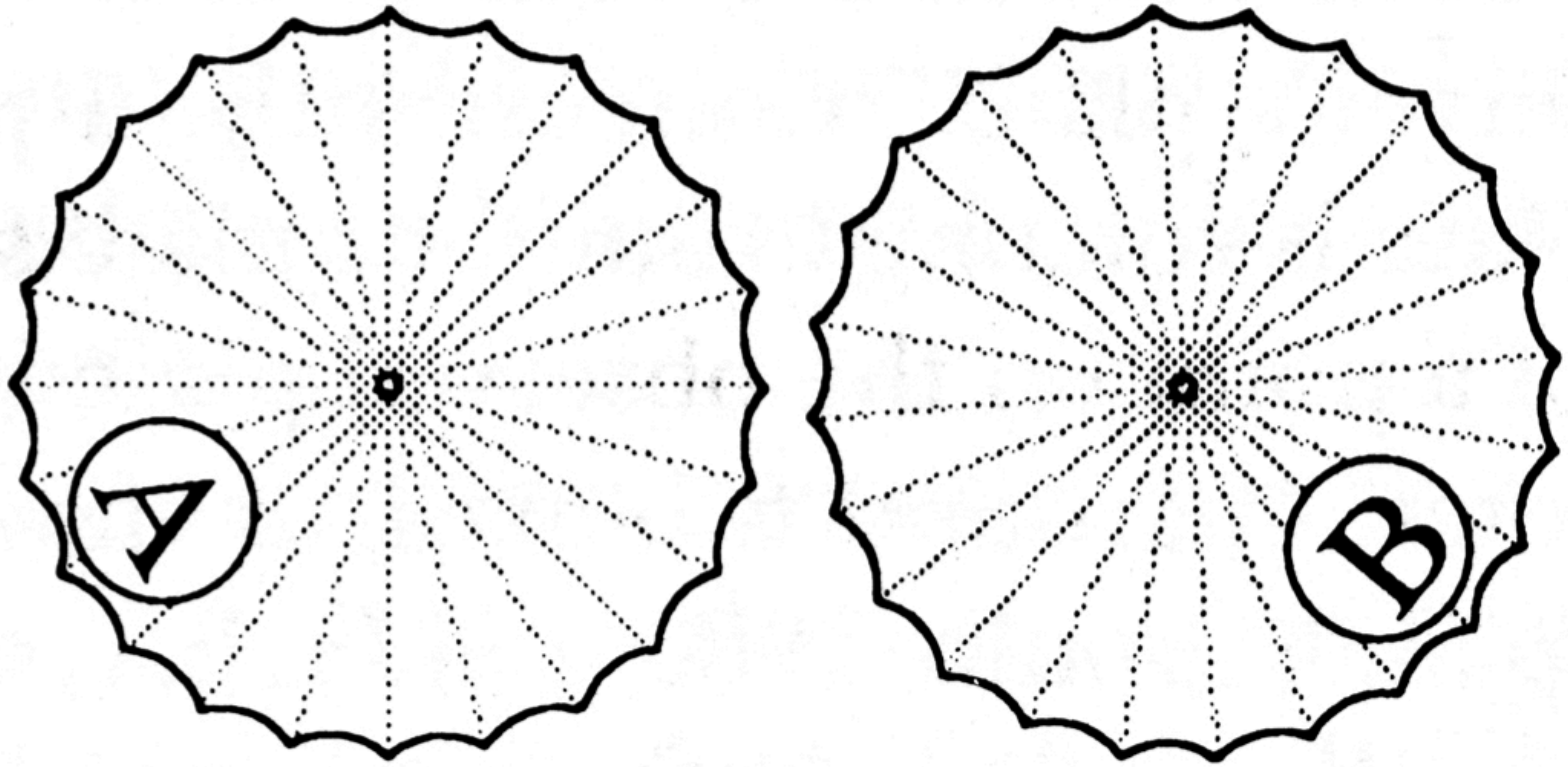
Given the (assumed constant) motion of individual plates, we can determine the motion of points on one plate as observed from another plate.

Initial state: two umbrellas with labeled reference points

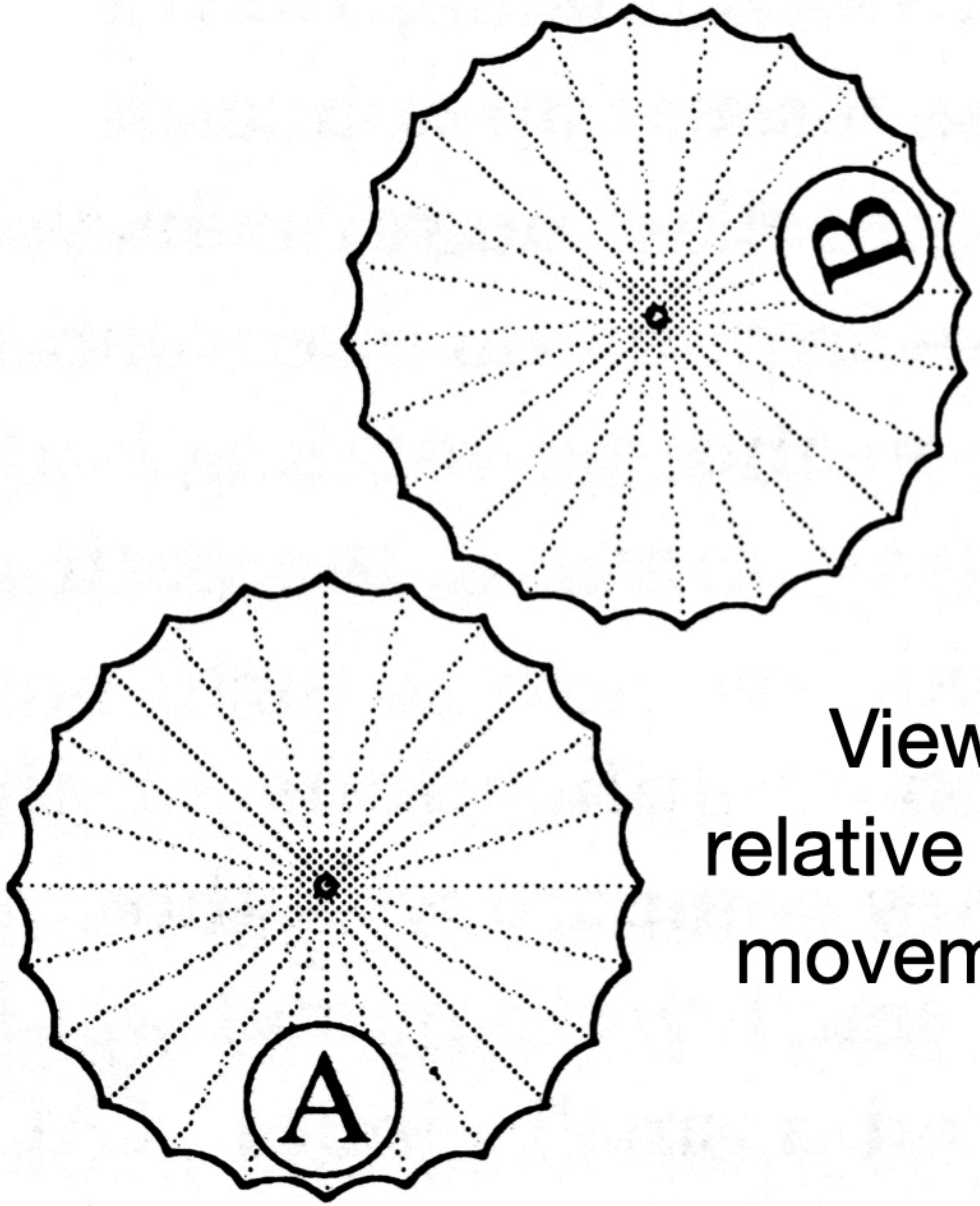


Cronin, 1992

View relative to an external reference frame, with umbrella A rotating 60° clockwise and umbrella B rotating 50° counter-clockwise

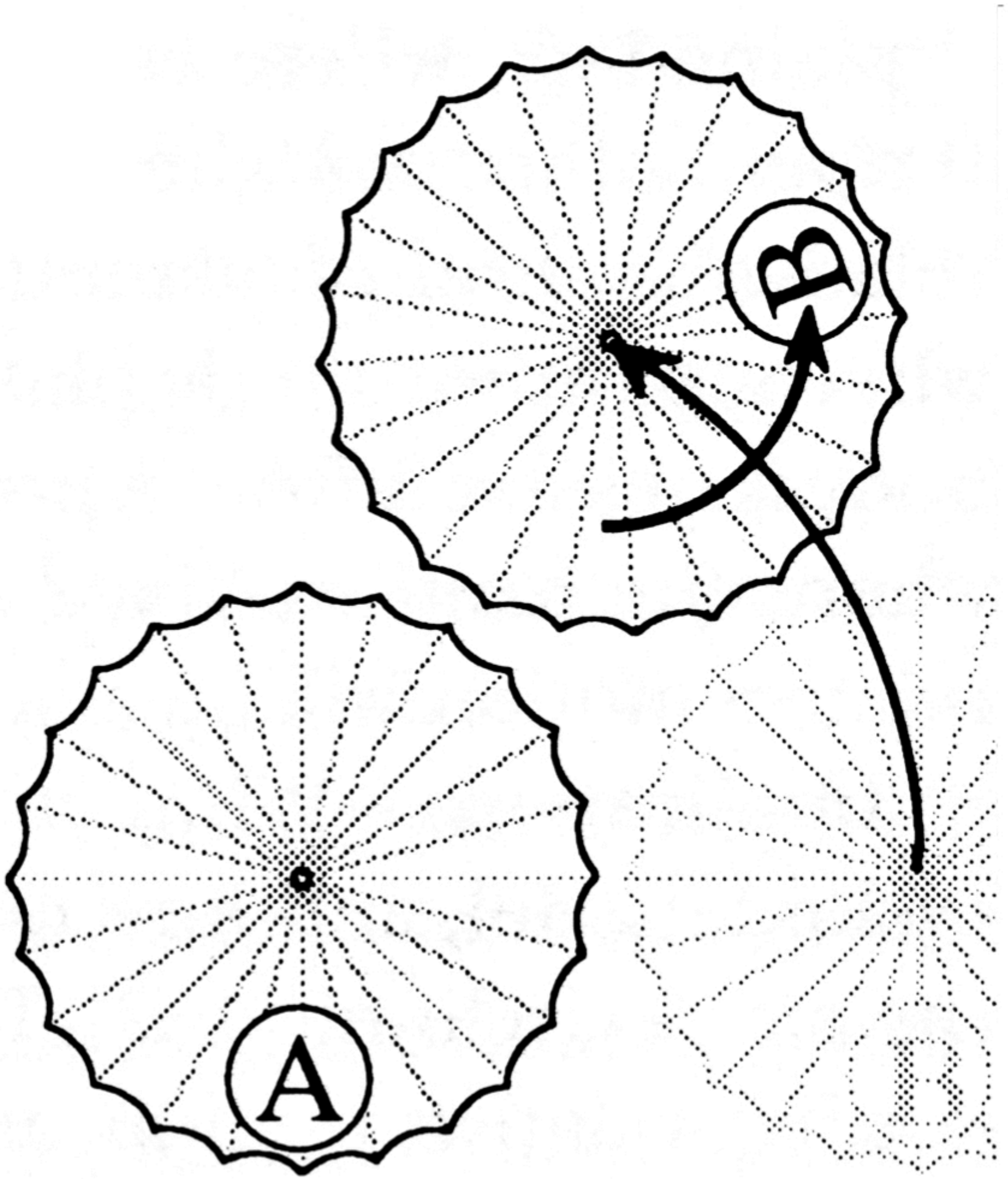


Cronin, 1992



View of umbrella B relative to umbrella A after movement from its initial position

Cronin, 1992

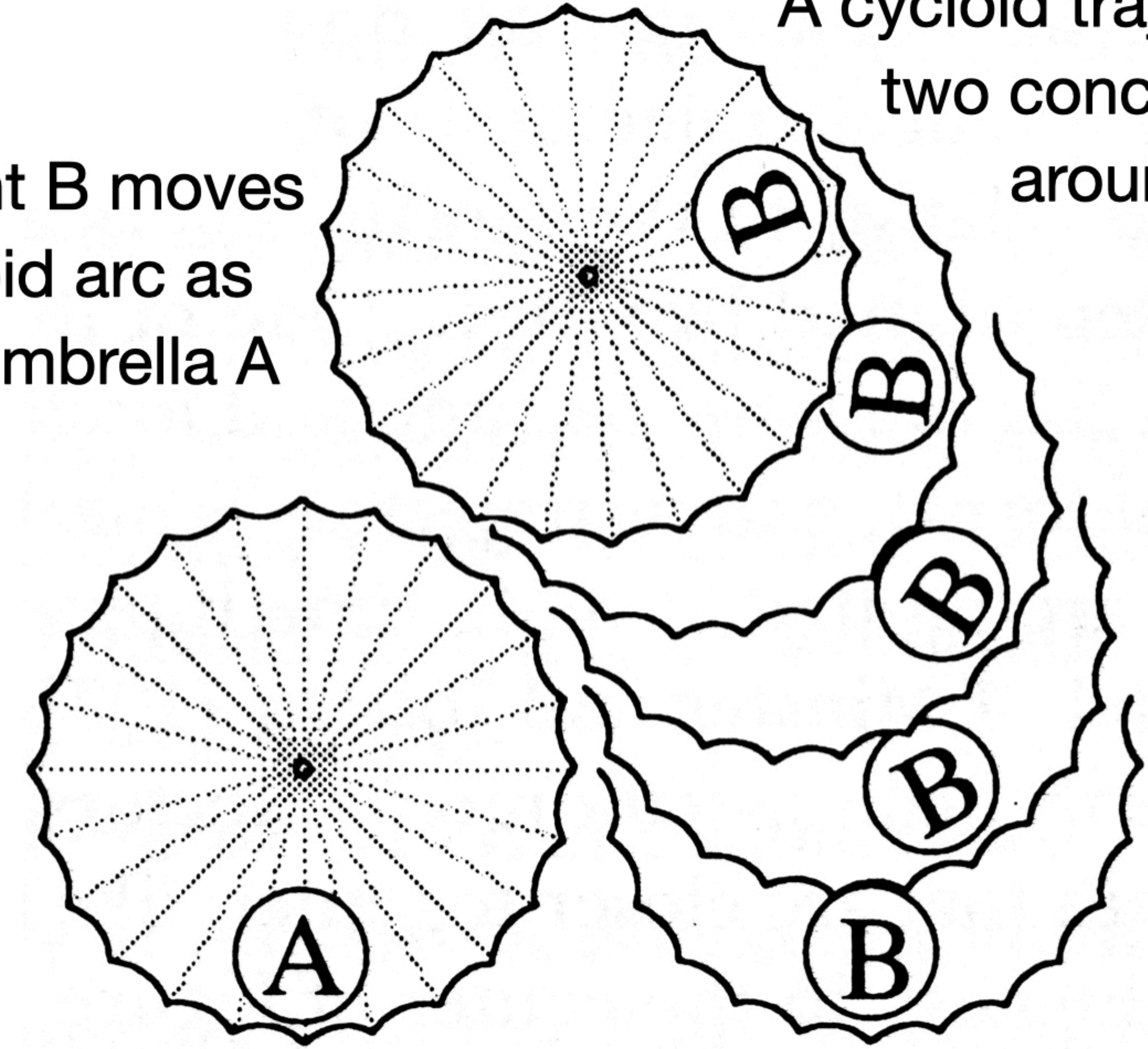


The axis of umbrella B moves 60° anti-clockwise around the axis of umbrella A, relative to umbrella A, at the same time that umbrella B rotates 50° clockwise around its axis

Cronin, 1992

A cycloid trajectory involves two concurrent rotations around two different axes

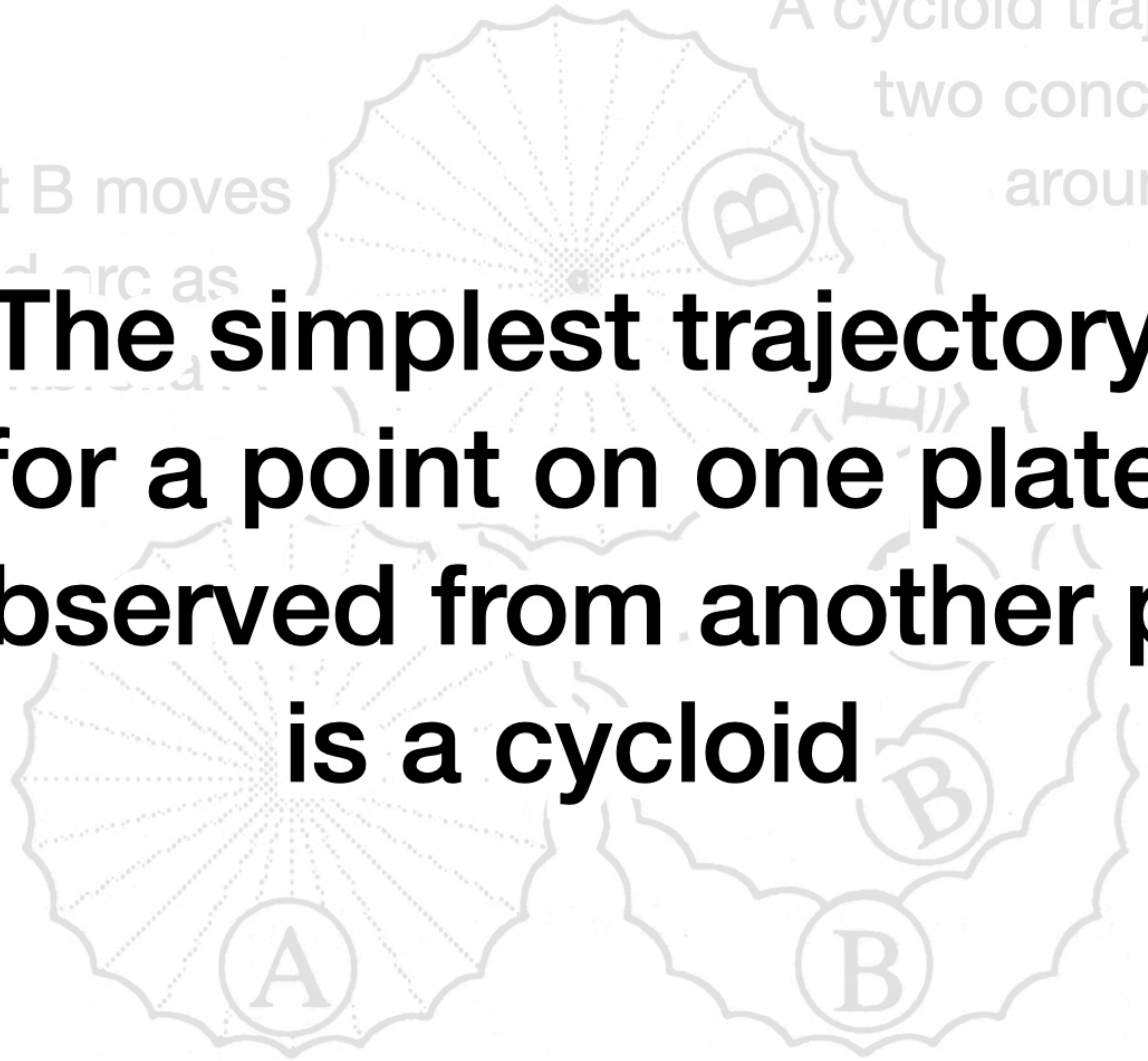
Reference point B moves along a cycloid arc as viewed from umbrella A



Cronin, 1992

A cycloid trajectory involves two concurrent rotations around two different axes

Reference point B moves along a cycloid arc as viewed from u[illegible]



The simplest trajectory for a point on one plate as observed from another plate is a cycloid

Cronin, 1992

Circular Motion Equation

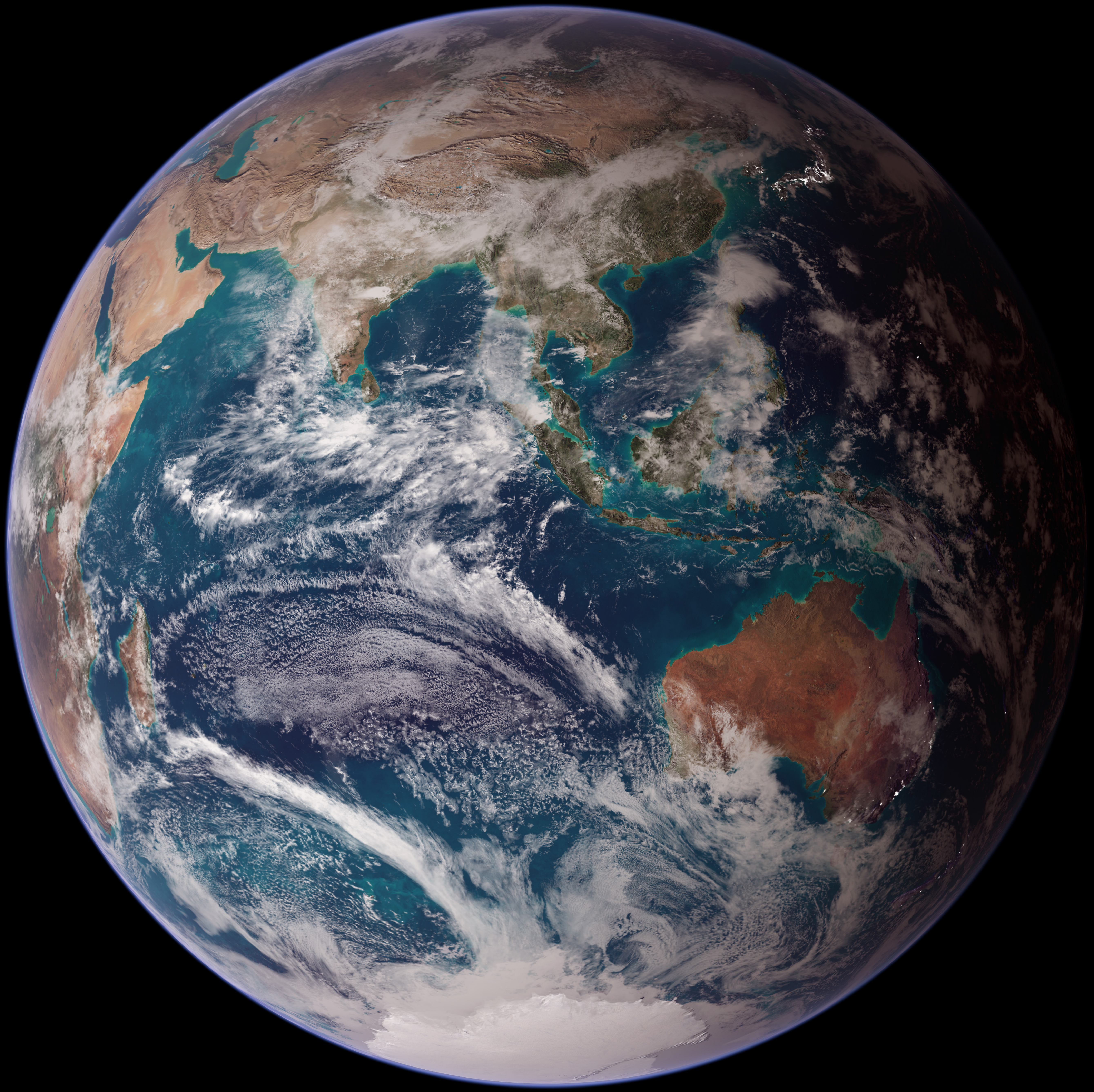
Used for motion of individual plates in an external reference frame like ITRF

$$\underbrace{\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}}_{\text{output position vector}} = \underbrace{\begin{bmatrix} \hat{i}\cdot\hat{i}' & \hat{i}\cdot\hat{j}' & \hat{i}\cdot\hat{k}' \\ \hat{j}\cdot\hat{i}' & \hat{j}\cdot\hat{j}' & \hat{j}\cdot\hat{k}' \\ \hat{k}\cdot\hat{i}' & \hat{k}\cdot\hat{j}' & \hat{k}\cdot\hat{k}' \end{bmatrix}}_{\text{transformation matrix}} \underbrace{\begin{bmatrix} \mathrm{Cos}[\omega\,\Delta t] & -\mathrm{Sin}[\omega\,\Delta t] & 0 \\ \mathrm{Sin}[\omega\,\Delta t] & \mathrm{Cos}[\omega\,\Delta t] & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{matrix for rotation around Z axis}} \underbrace{\begin{bmatrix} \hat{i}'\cdot\hat{i} & \hat{i}'\cdot\hat{j} & \hat{i}'\cdot\hat{k} \\ \hat{j}'\cdot\hat{i} & \hat{j}'\cdot\hat{j} & \hat{j}'\cdot\hat{k} \\ \hat{k}'\cdot\hat{i} & \hat{k}'\cdot\hat{j} & \hat{k}'\cdot\hat{k} \end{bmatrix}}_{\text{transformation matrix}} \underbrace{\begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}}_{\text{input position vector}}$$

Cycloidal Motion Equation

Used for plate motion relative to another plate

$$\underbrace{\begin{bmatrix} x_n \\ y_n \\ z_n \end{bmatrix}}_{\text{output position vector}} = \underbrace{\begin{bmatrix} \hat{i}\cdot\hat{i}' & \hat{i}\cdot\hat{j}' & \hat{i}\cdot\hat{k}' \\ \hat{j}\cdot\hat{i}' & \hat{j}\cdot\hat{j}' & \hat{j}\cdot\hat{k}' \\ \hat{k}\cdot\hat{i}' & \hat{k}\cdot\hat{j}' & \hat{k}\cdot\hat{k}' \end{bmatrix}}_{\text{transformation matrix}} \underbrace{\begin{bmatrix} \mathrm{Cos}[\omega_o\,\Delta t] & \mathrm{Sin}[\omega_o\,\Delta t] & 0 \\ -\mathrm{Sin}[\omega_o\,\Delta t] & \mathrm{Cos}[\omega_o\,\Delta t] & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{matrix for rotation around Z axis}} \underbrace{\begin{bmatrix} \mathrm{Cos}[\gamma] & 0 & -\mathrm{Sin}[\gamma] \\ 0 & 1 & 0 \\ \mathrm{Sin}[\gamma] & 0 & \mathrm{Cos}[\gamma] \end{bmatrix}}_{\text{matrix for rotation around Y axis}} \underbrace{\begin{bmatrix} \mathrm{Cos}[\omega_m\,\Delta t] & \mathrm{Sin}[\omega_m\,\Delta t] & 0 \\ -\mathrm{Sin}[\omega_m\,\Delta t] & \mathrm{Cos}[\omega_m\,\Delta t] & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{\text{matrix for rotation around Z axis}} \underbrace{\begin{bmatrix} \hat{i}'\cdot\hat{i} & \hat{i}'\cdot\hat{j} & \hat{i}'\cdot\hat{k} \\ \hat{j}'\cdot\hat{i} & \hat{j}'\cdot\hat{j} & \hat{j}'\cdot\hat{k} \\ \hat{k}'\cdot\hat{i} & \hat{k}'\cdot\hat{j} & \hat{k}'\cdot\hat{k} \end{bmatrix}}_{\text{transformation matrix}} \underbrace{\begin{bmatrix} x_o \\ y_o \\ z_o \end{bmatrix}}_{\text{input position vector}}$$



NASA Blue Marble
https://earthobservatory.nasa.gov/images/8108/twin-blue-marbles

Is there any physical basis for the first-order assumption that the angular velocity vector of a given plate might be constant over a finite time interval?

Is there any physical basis for the first-order assumption that the angular velocity vector of a given plate might be constant over a finite time interval?

Yes. The fundamental importance of subduction in plate motion.

Observed in a stable reference frame external to the lithosphere (e.g., ITRF), …

Observed in a stable reference frame external to the lithosphere (e.g., ITRF), …

1. Plates with subducting slabs move toward the subduction zone

Observed in a stable reference frame external to the lithosphere (e.g., ITRF), …

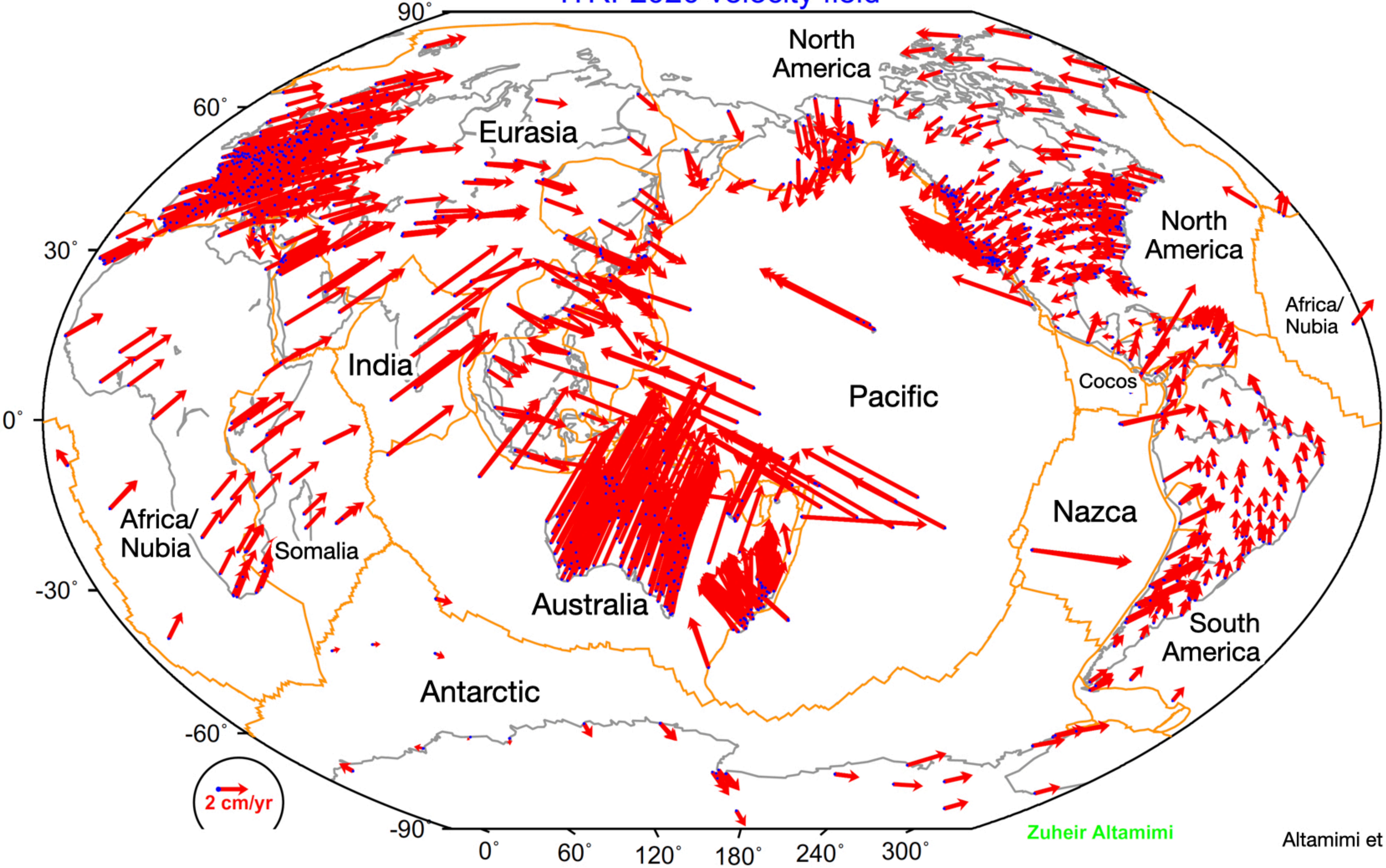
1. Plates with subducting slabs move toward the subduction zone

2. The overlying plate at a subduction zone moves toward the trench

Observed in a stable reference frame external to the lithosphere (e.g., ITRF), …

1. Plates with subducting slabs move toward the subduction zone
2. The overlying plate at a subduction zone moves toward the trench
3. Plates move away from mid-ocean ridge axes

ITRF2020 velocity field



Altamimi et al., 2023

Why do plates move?

Gravity provides the force responsible for plate motion.

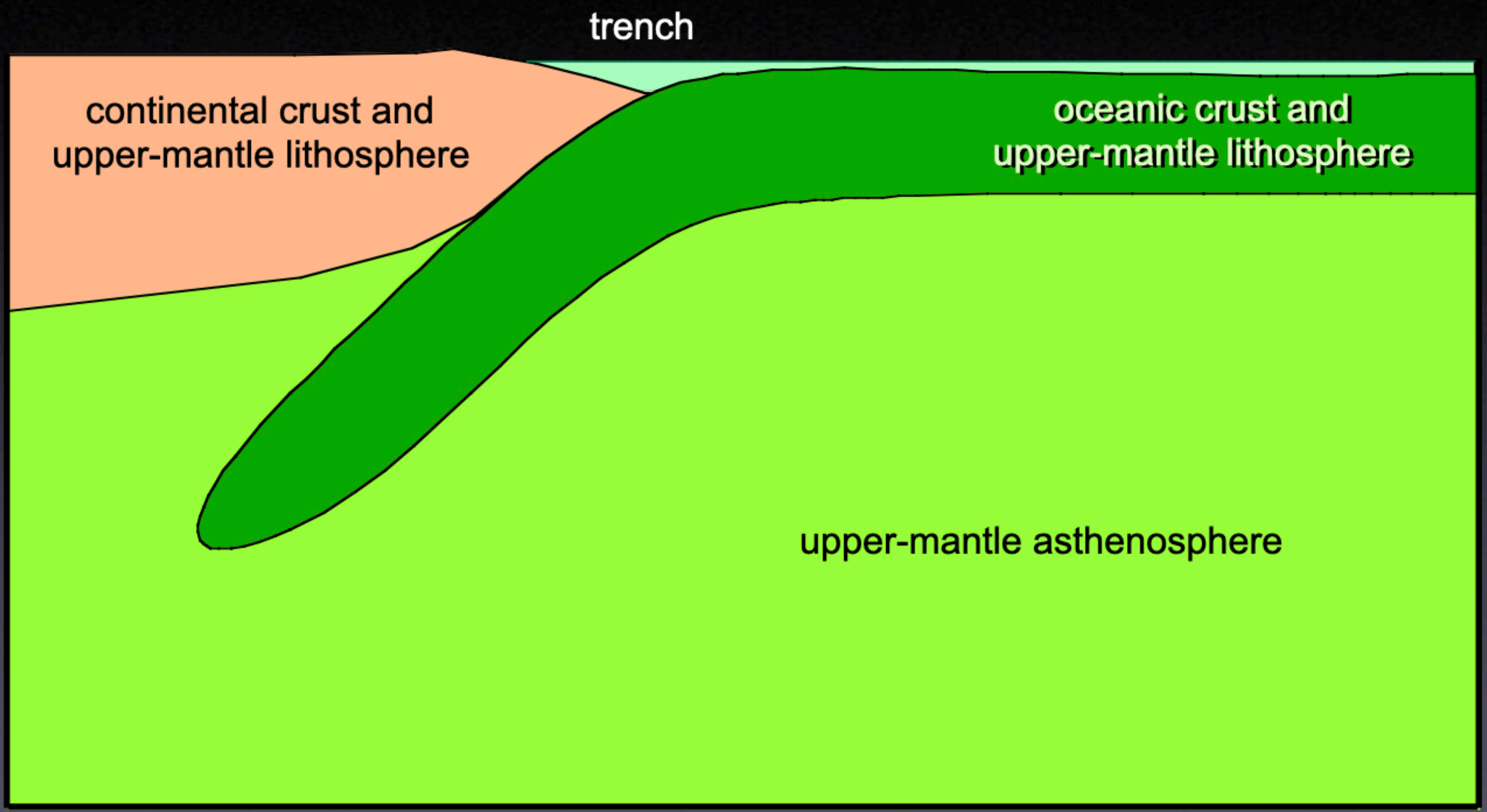
Some Other Important Variables:

- Density variations
- Strength
- Rheology

Why do plates move?

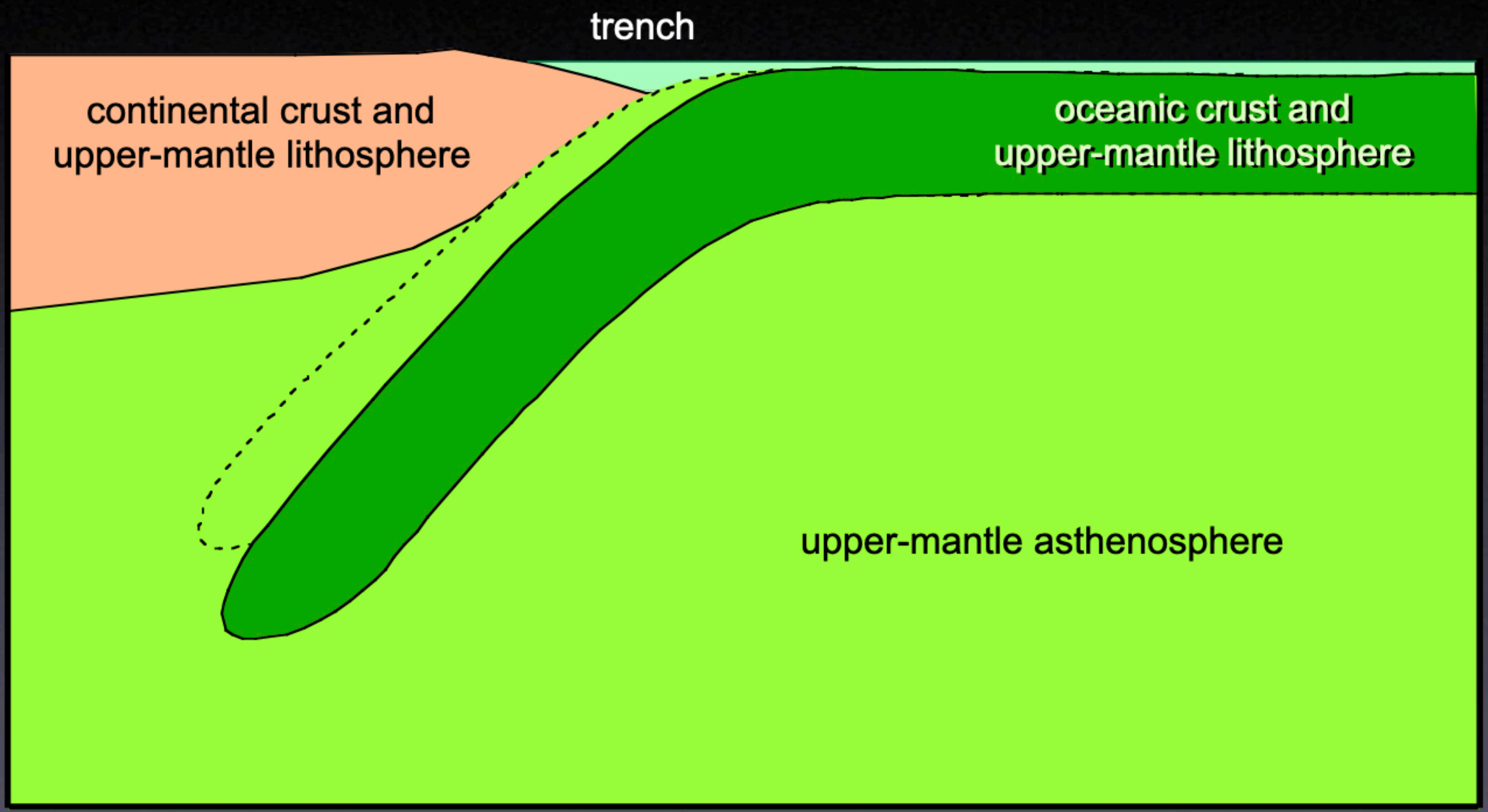
- **Slab pull** (most important)
- **Ridge push** (important)
- **Trench pull** or asthenosphere counterflow (locally import)
- **Convection**: viscous drag by a convecting mantle (?)
- Eötvös force, et cetera

Slab Pull

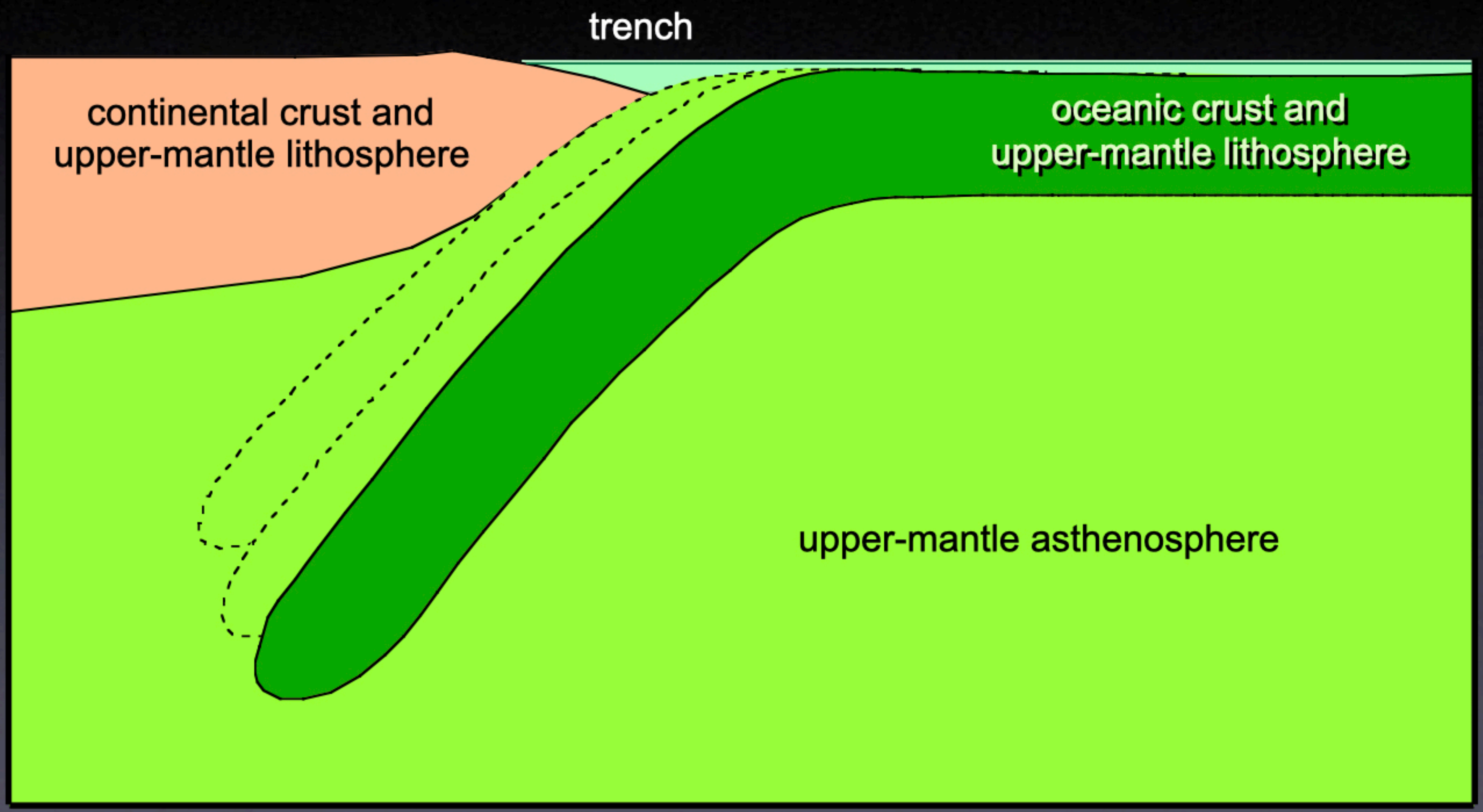


trench
continental crust and
upper-mantle lithosphere
oceanic crust and
upper-mantle lithosphere
upper-mantle asthenosphere

Slab Pull

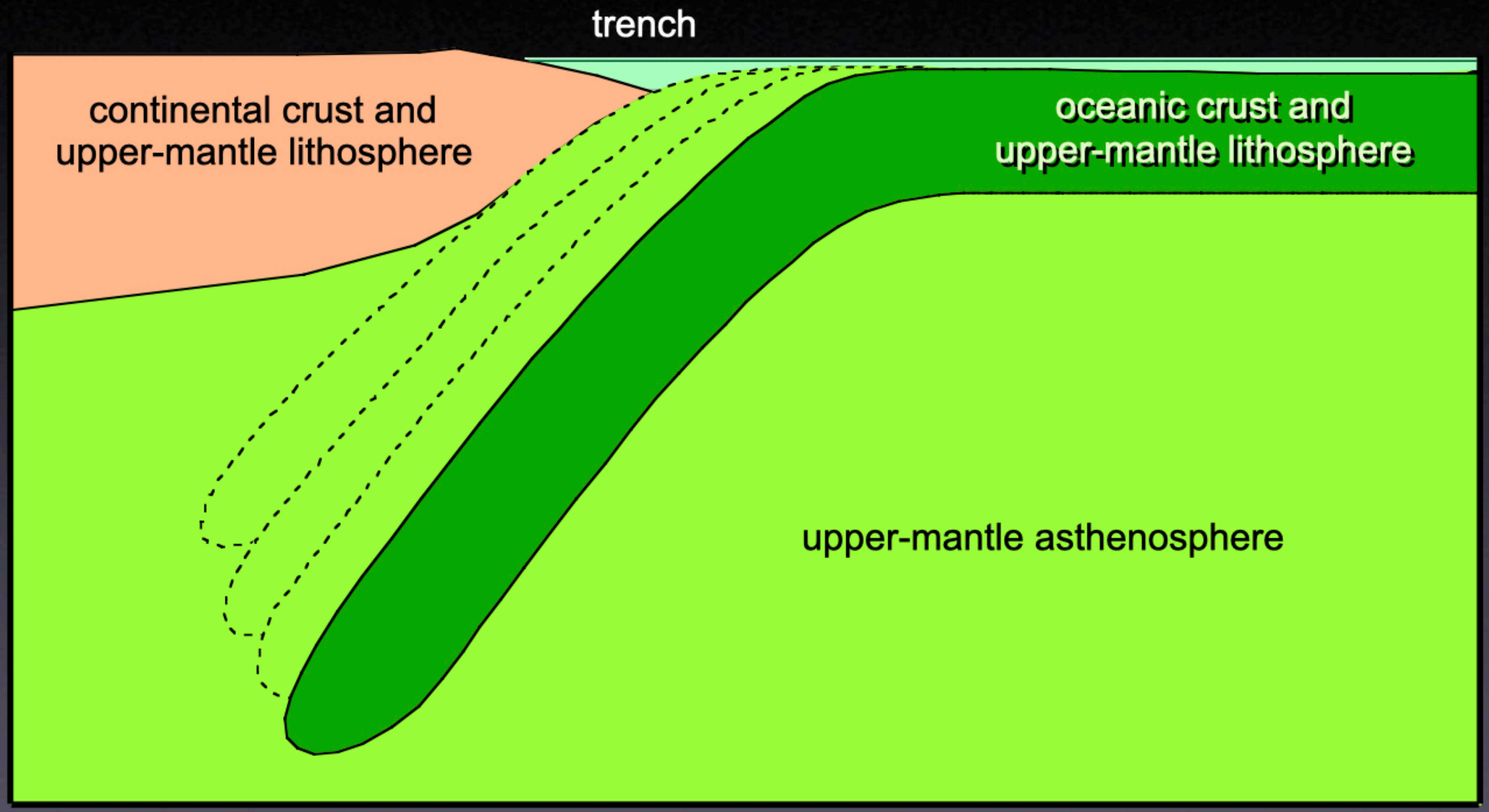

trench
continental crust and
upper-mantle lithosphere
oceanic crust and
upper-mantle lithosphere
upper-mantle asthenosphere

Slab Pull

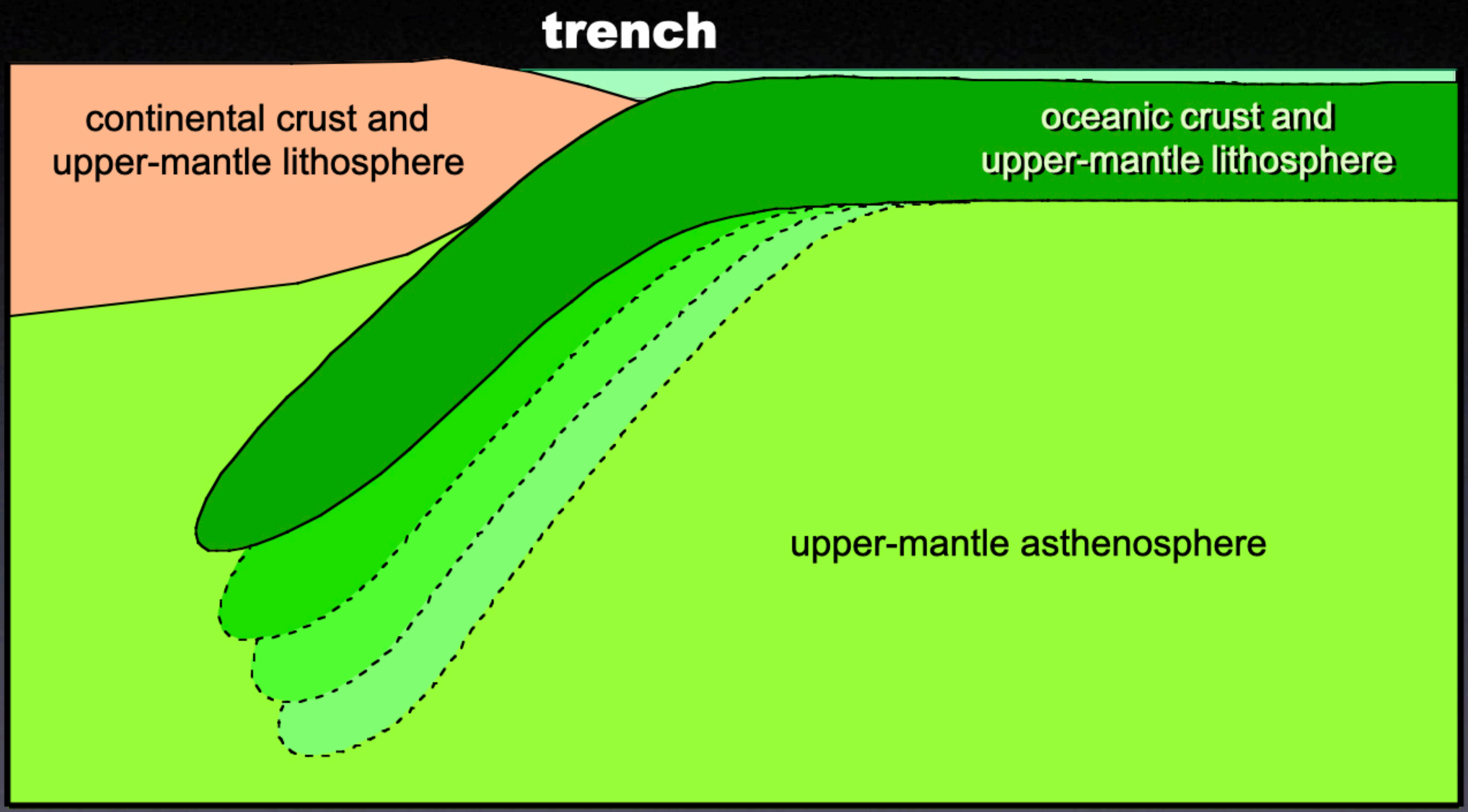


trench
continental crust and
upper-mantle lithosphere
oceanic crust and
upper-mantle lithosphere
upper-mantle asthenosphere

Slab Pull

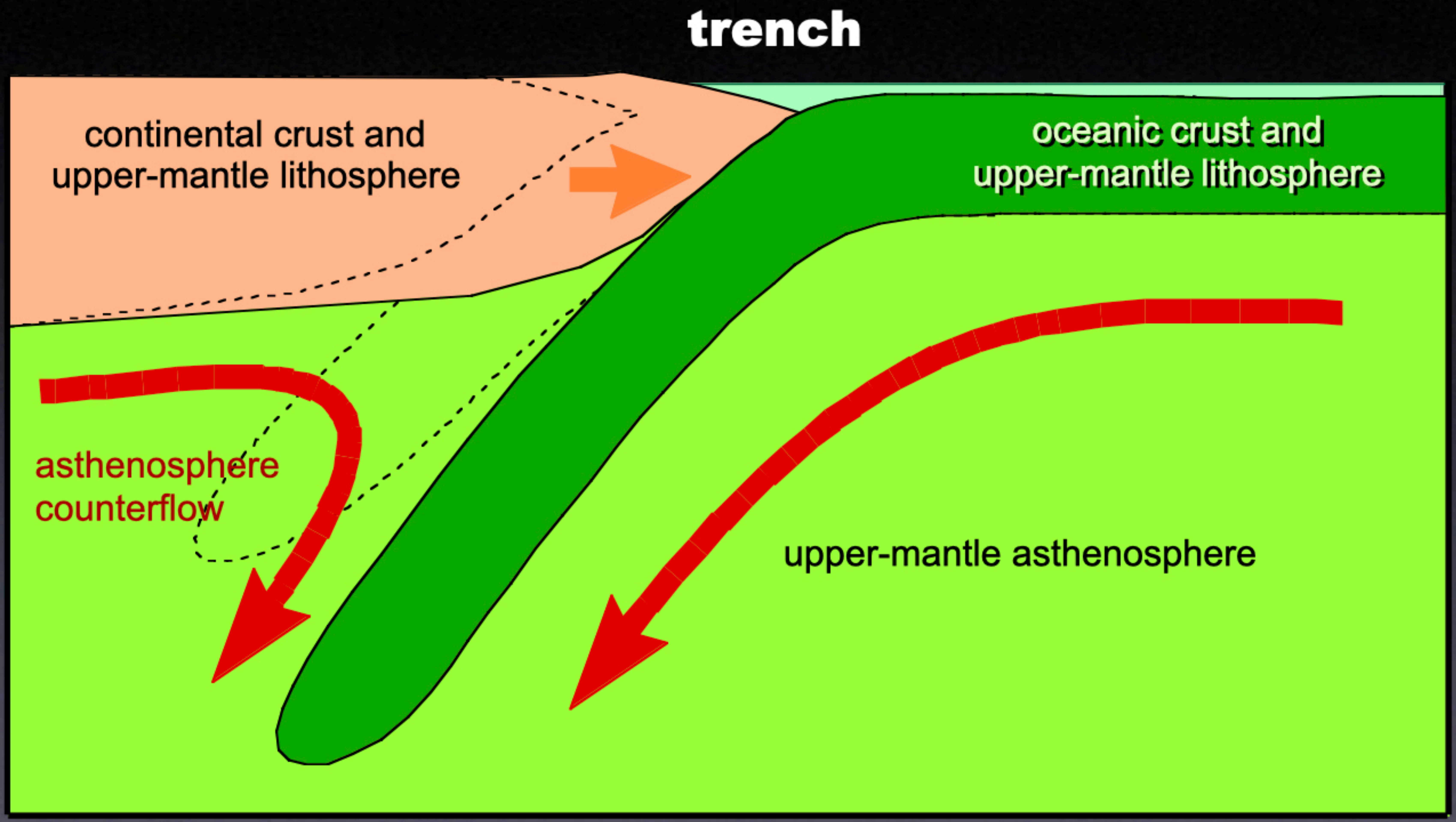

trench
continental crust and
upper-mantle lithosphere
oceanic crust and
upper-mantle lithosphere
upper-mantle asthenosphere

Trench Pull



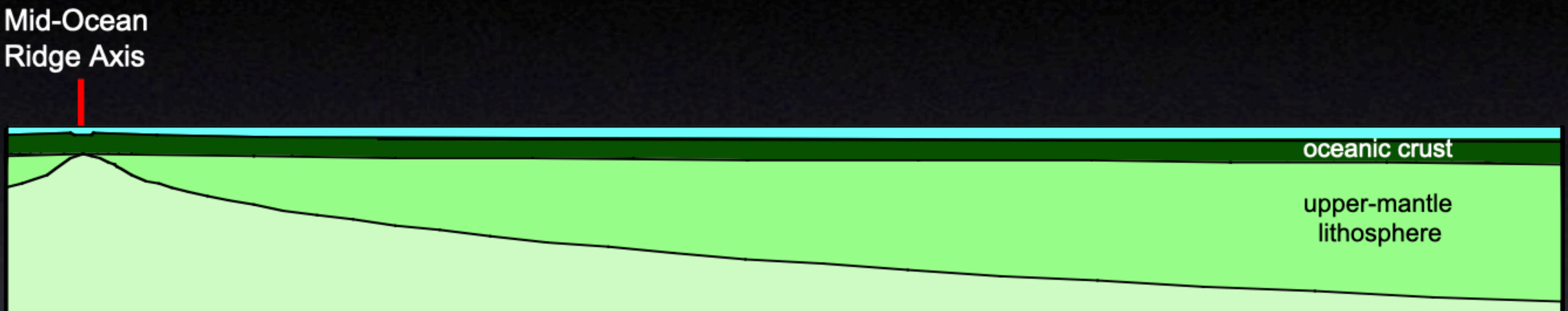
or Asthenospheric Counterflow

Trench Pull



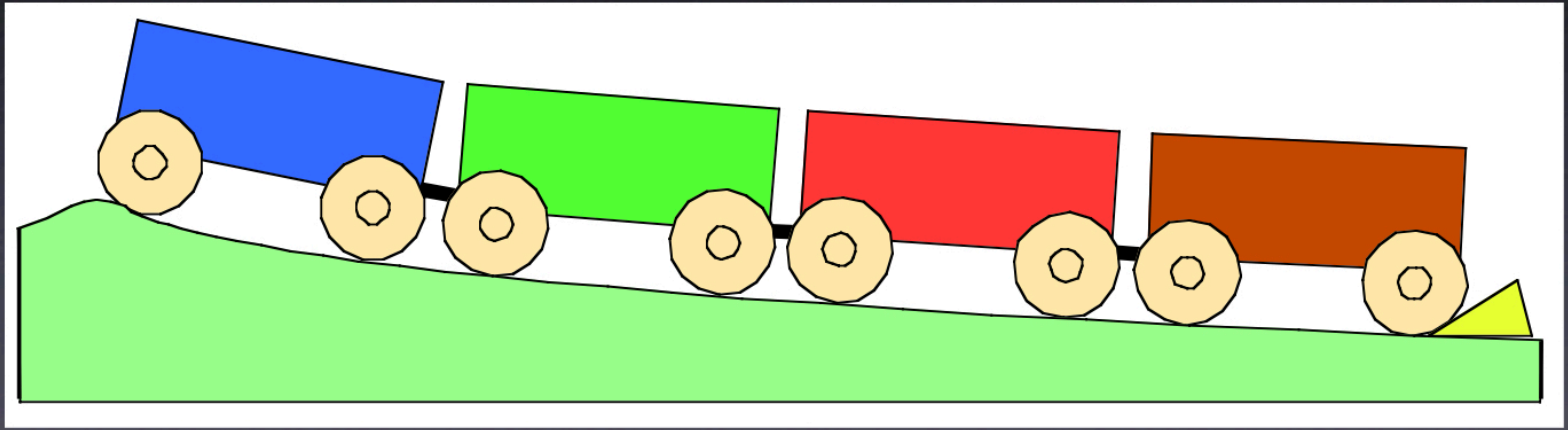
or Asthenospheric Counterflow

With increasing distance from the axis of the mid-ocean ridge, ...

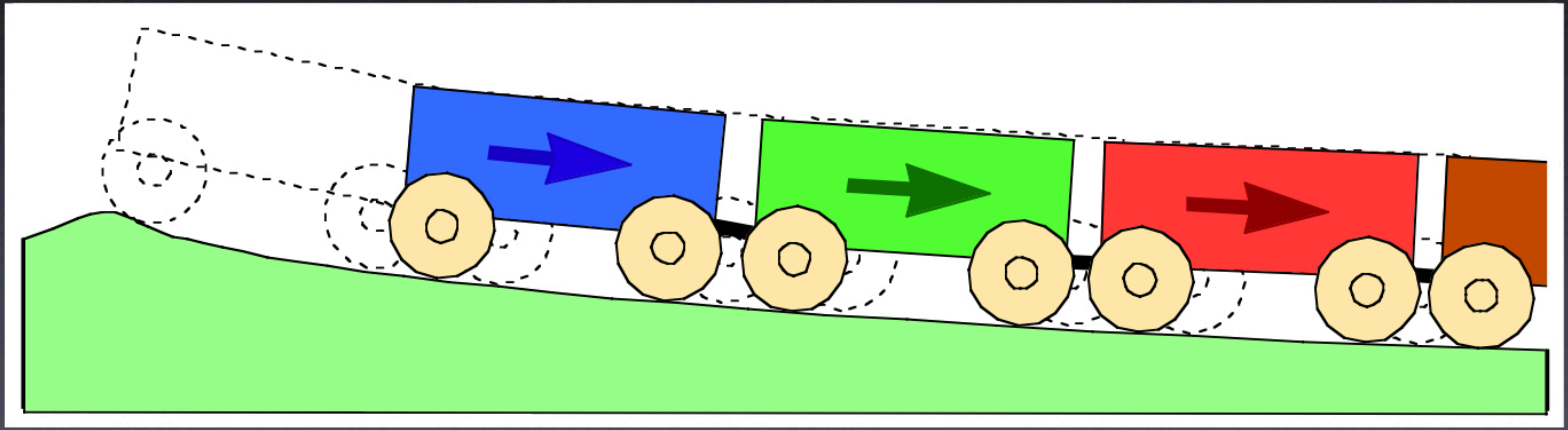


- the **age** of the lithosphere increases
- the **depth** to the sea floor increases
- the **thickness** of the upper-mantle lithosphere increases due to cooling and accretion from below, so
- **lithosphere thickness** increases

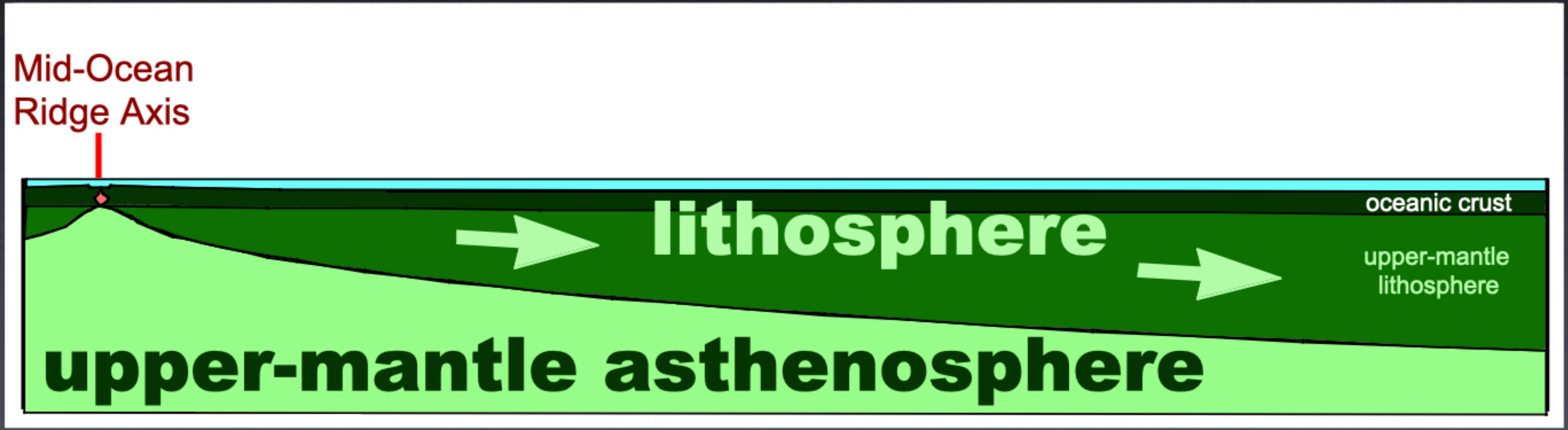
What will happen when the wedge is removed?



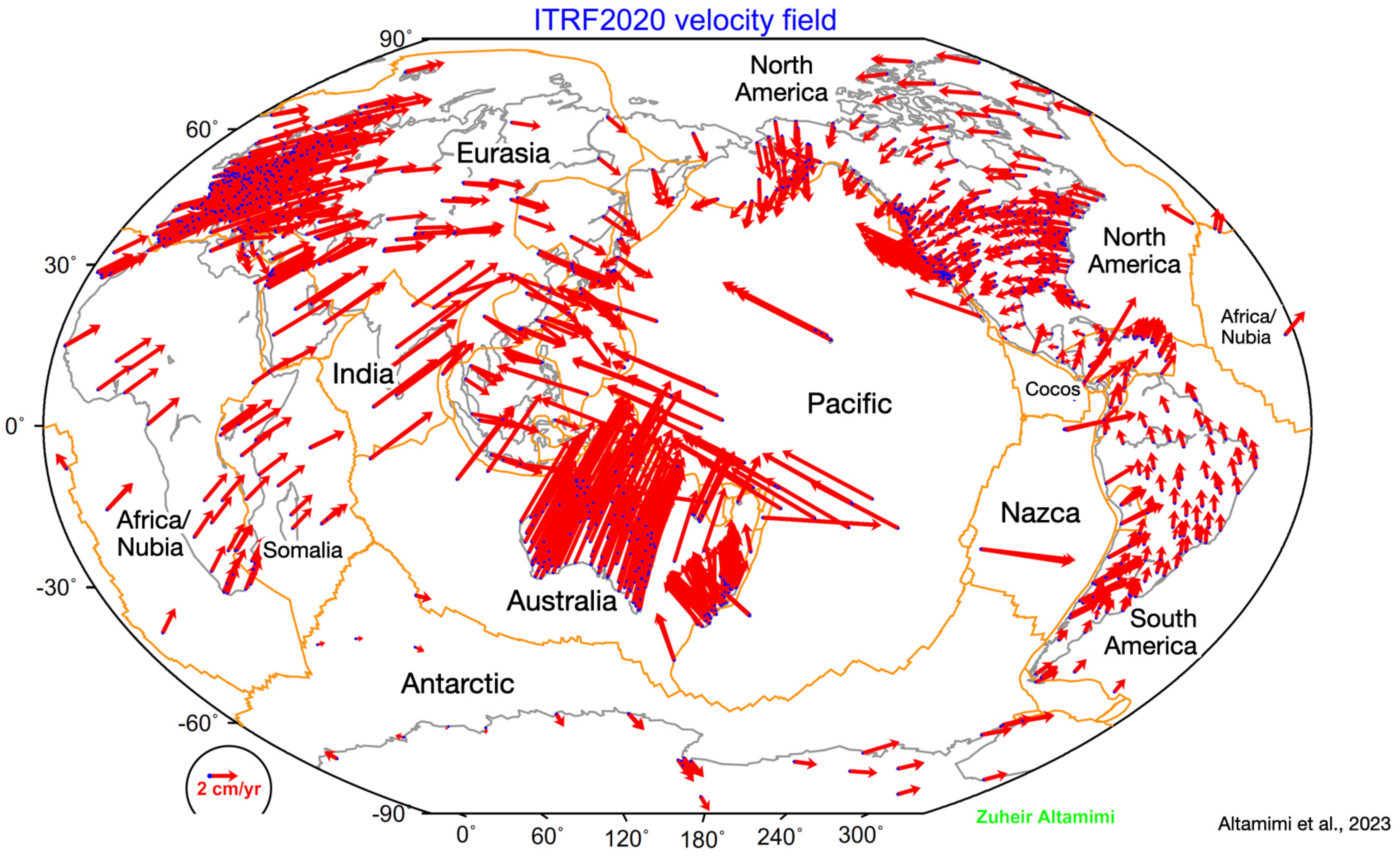
Gravity acts on the mass of the train, causing down-slope motion



Gravity acts on the mass of the lithosphere, causing motion away from the ridge



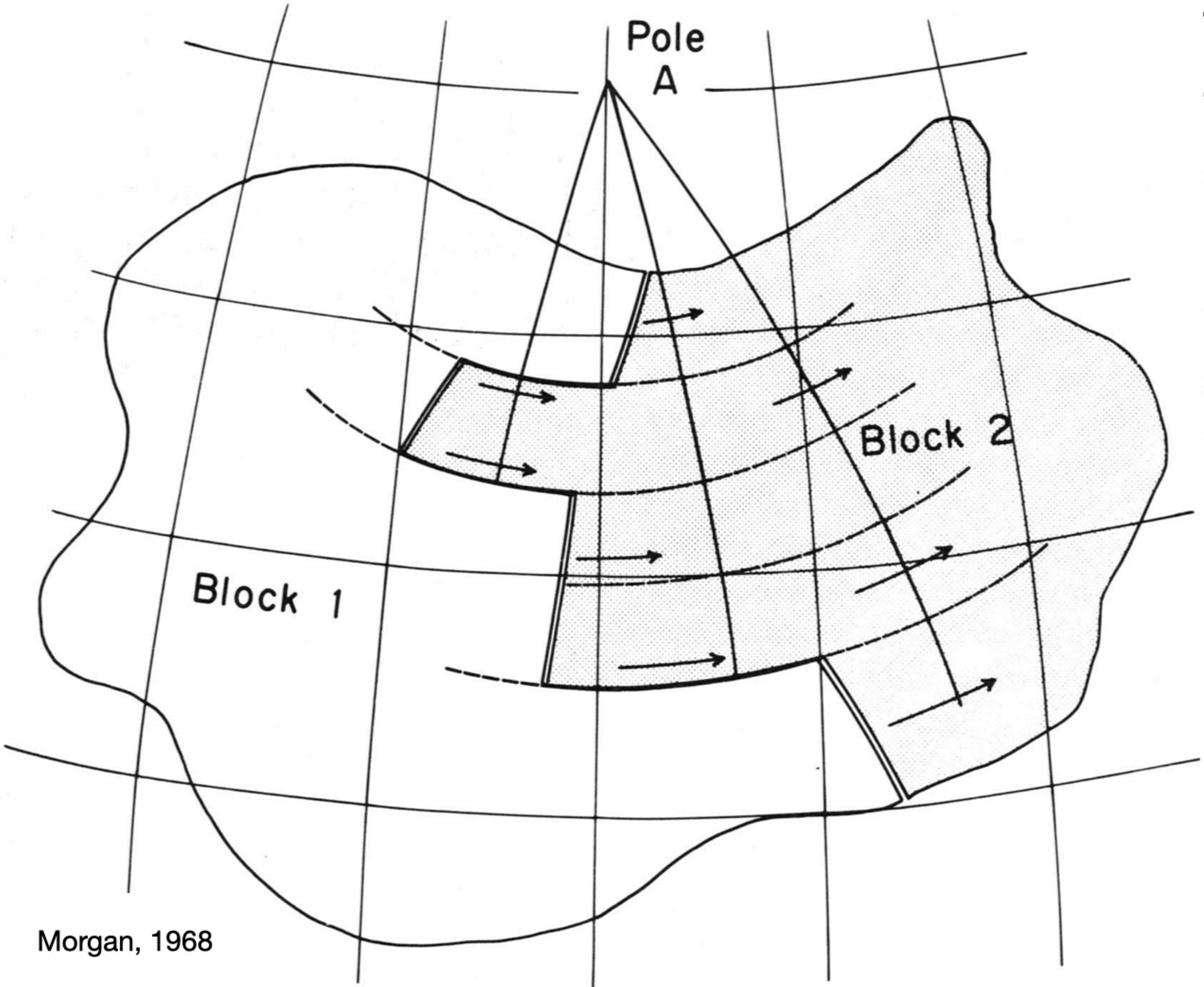
"Ridge push" is really more like "ridge slip"


ITRF2020 velocity field
90°
60°
30°
0°
-30°
-60°
-90°
0°
60°
120°
180°
240°
300°
North America
Eurasia
North America
Africa/ Nubia
India
Cocos
Pacific
Africa/ Nubia
Somalia
Nazca
Australia
South America
Antarctic
2 cm/yr
Zuheir Altamimi
Altamimi et al., 2023

Is there any physical evidence favoring a finite model in which the angular velocities of plates relative to a stable external reference frame are constant over a finite time interval?

Is there any physical evidence favoring a finite model in which the angular velocities of plates relative to a stable external reference frame are constant over a finite time interval?

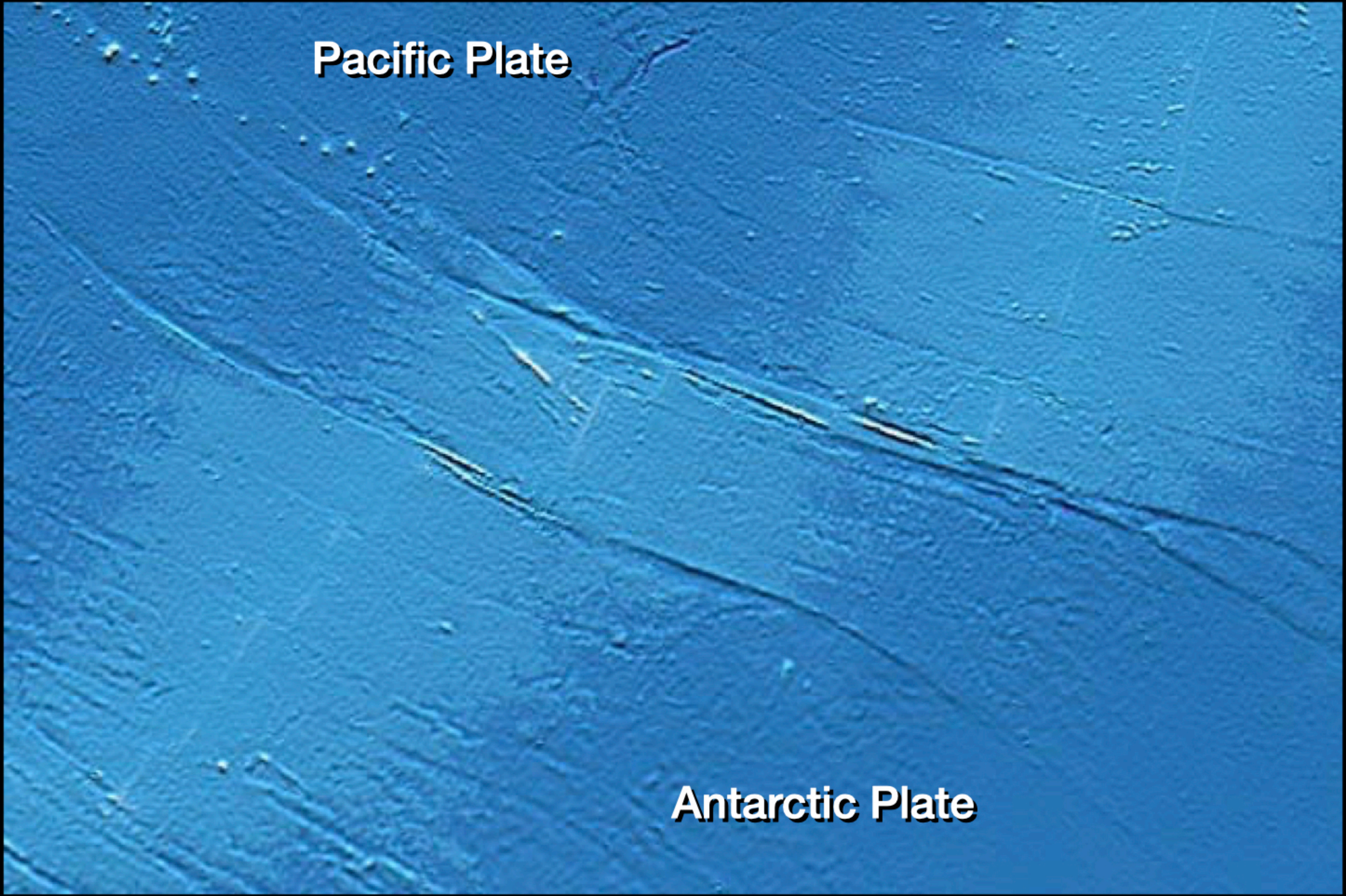
Yes. The long-wavelength shape of oceanic fracture zones.



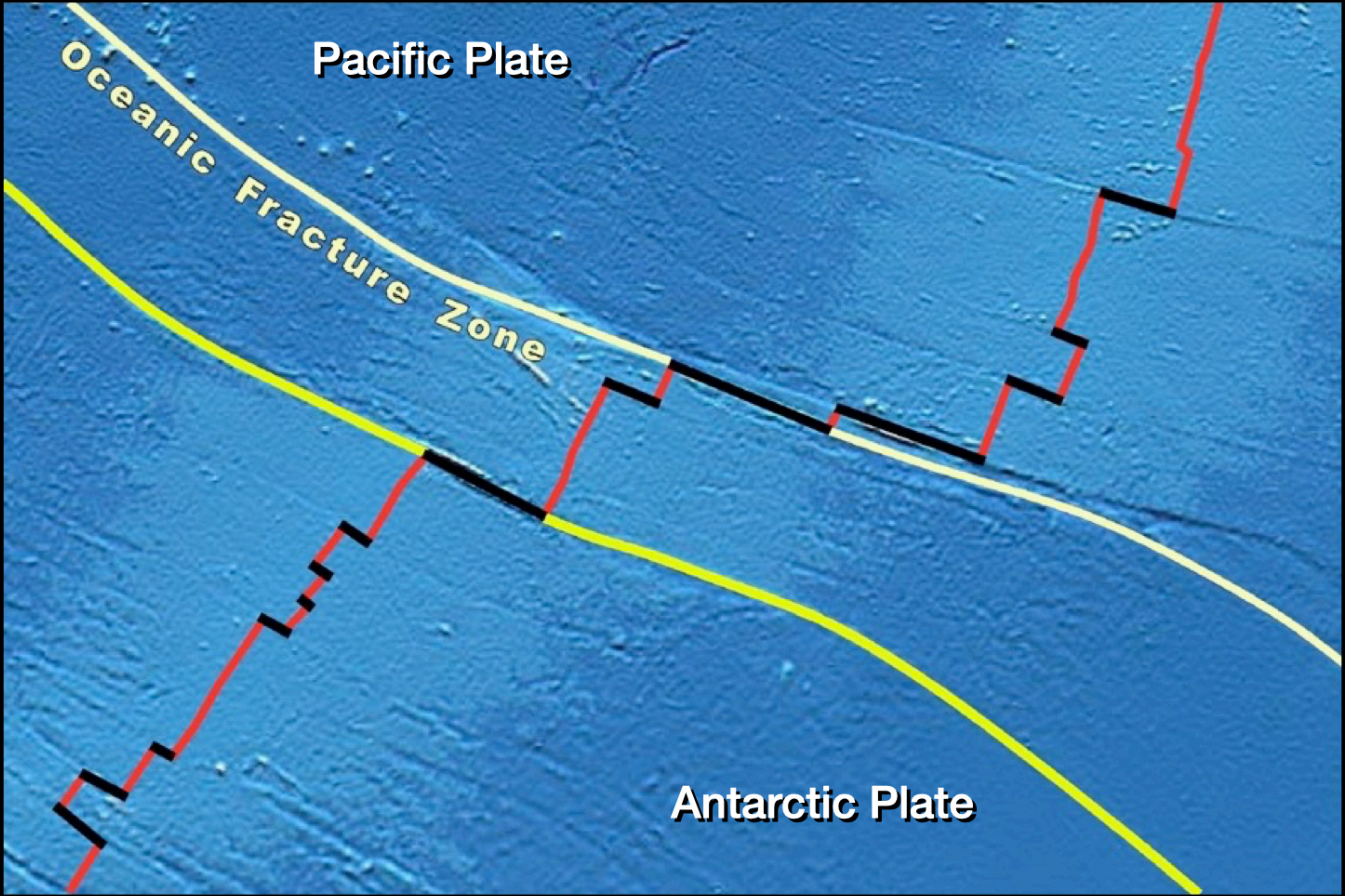
Morgan, 1968

The initial idea was that transform faults and oceanic fracture zones had the shape of small circle arcs that are concentric around the relative motion pole.

Grrrr… Don’t forget —
This model isn’t valid!



Observed oceanic fracture zone have more complex shapes.



Observed oceanic fracture zone have more complex shapes.

Jean Charcot Fracture Zone in the South Atlantic seafloor

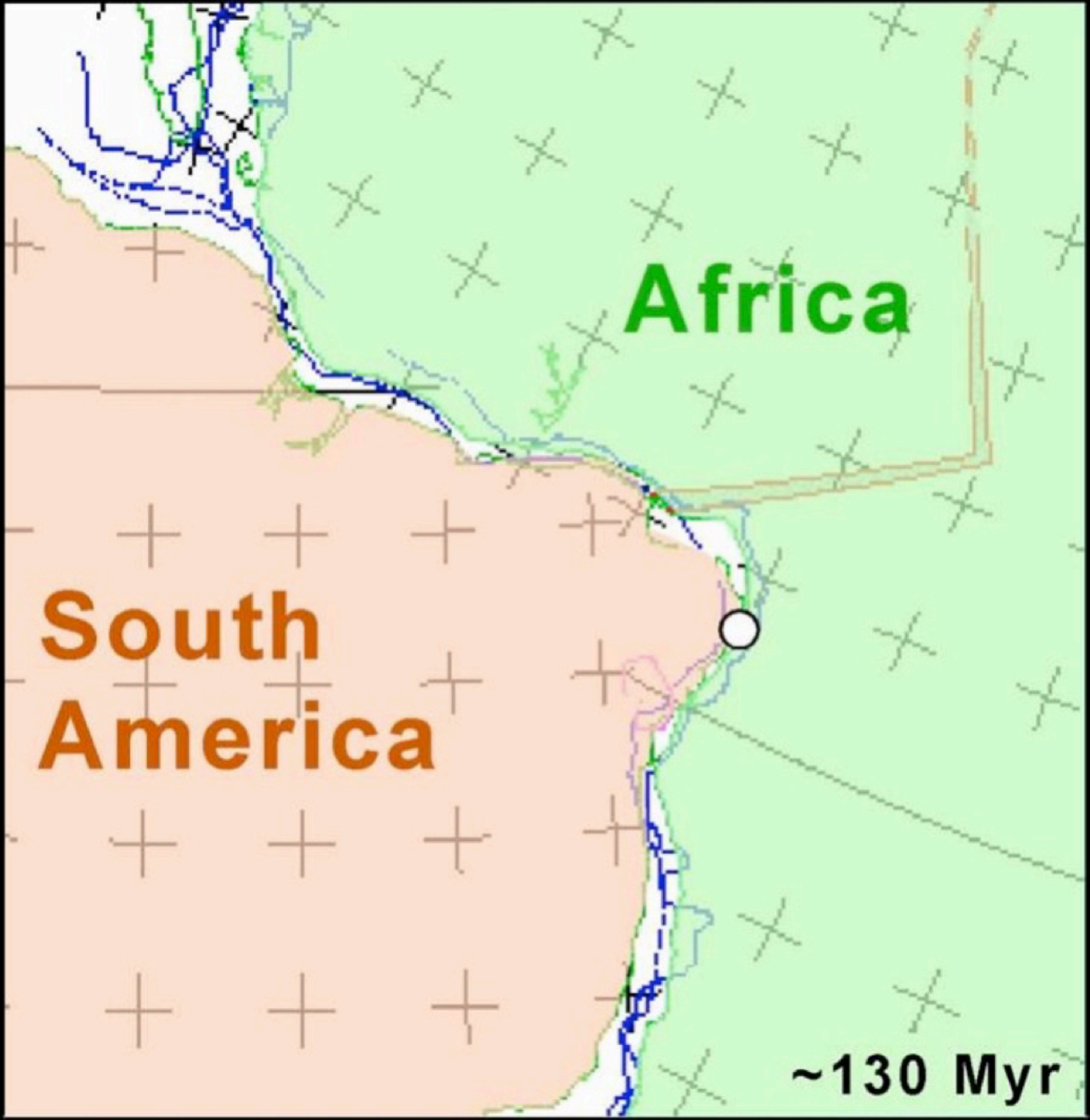
Shaw, 1987

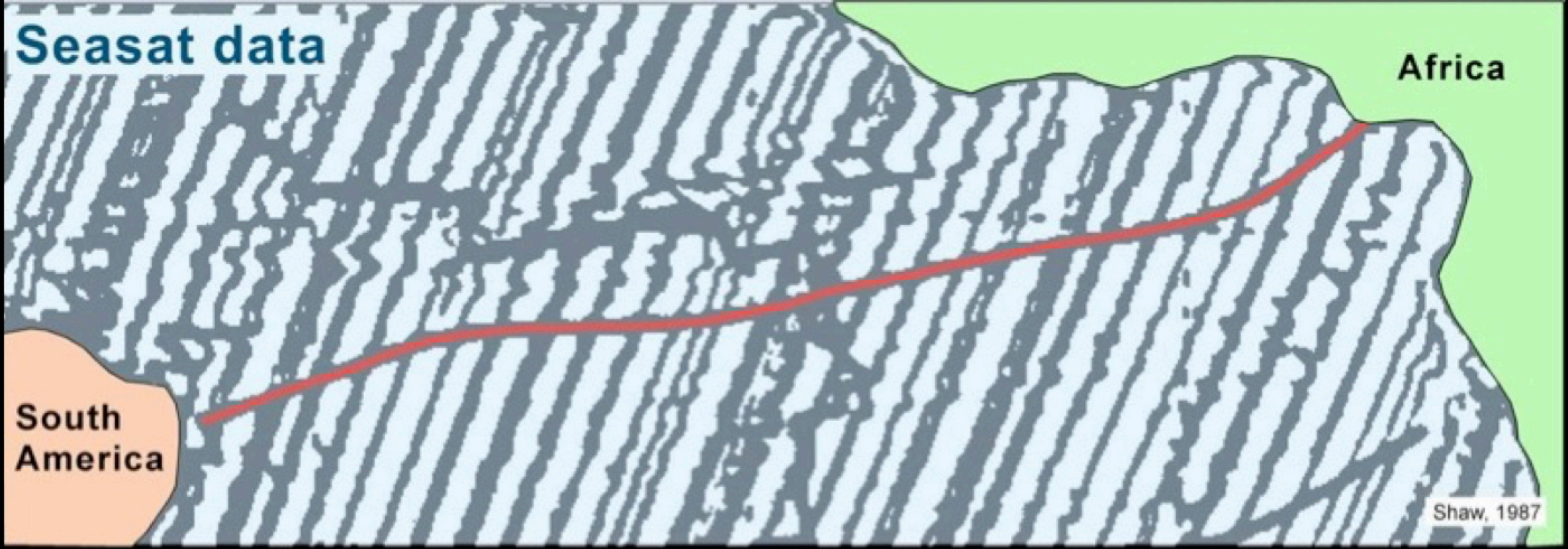
Vertical Gravity Gradient from Orbital Satellites

Sandwell et al., 2014

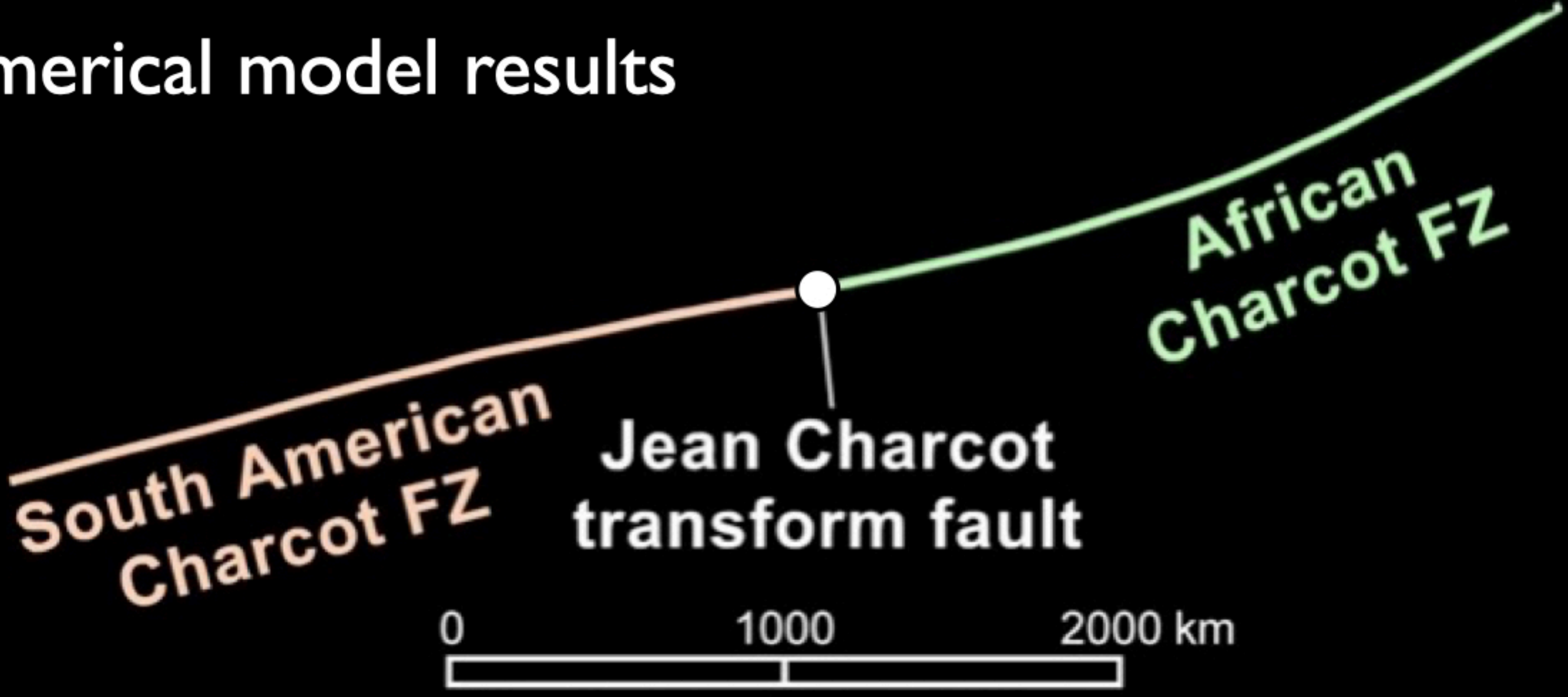
Jean Charcot Fracture Zone in the South Atlantic seafloor

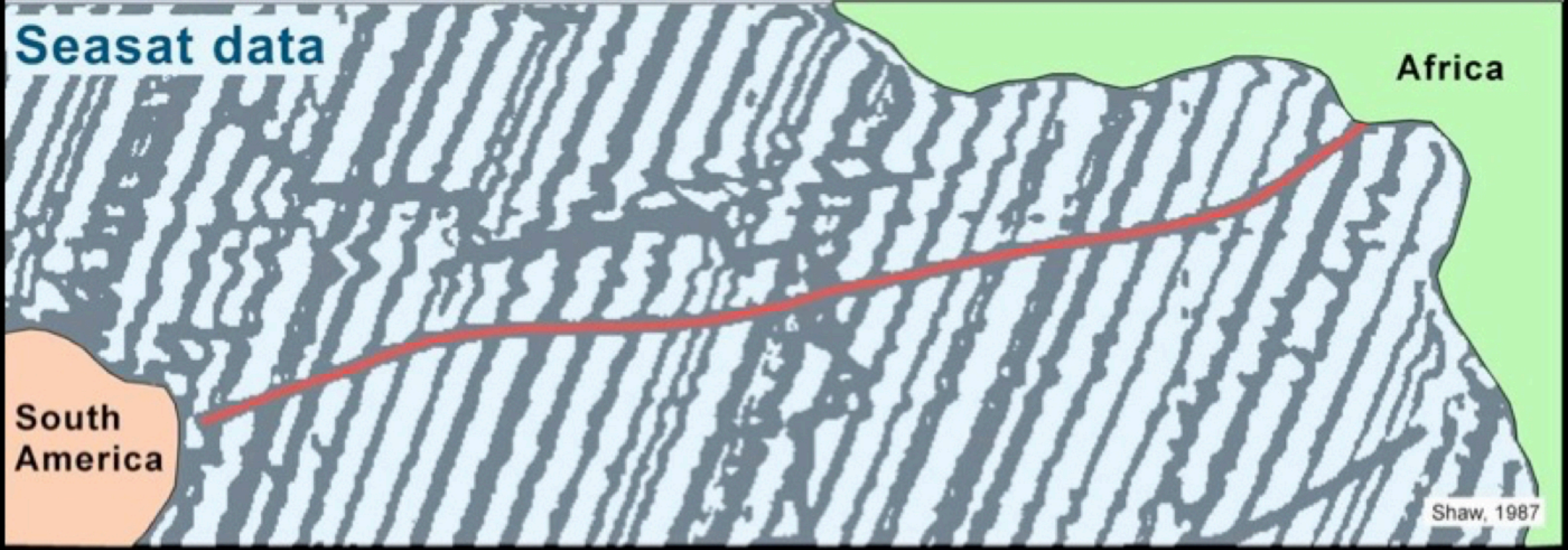
Sandwell et al., 2014


Africa
South
America
~130 Myr

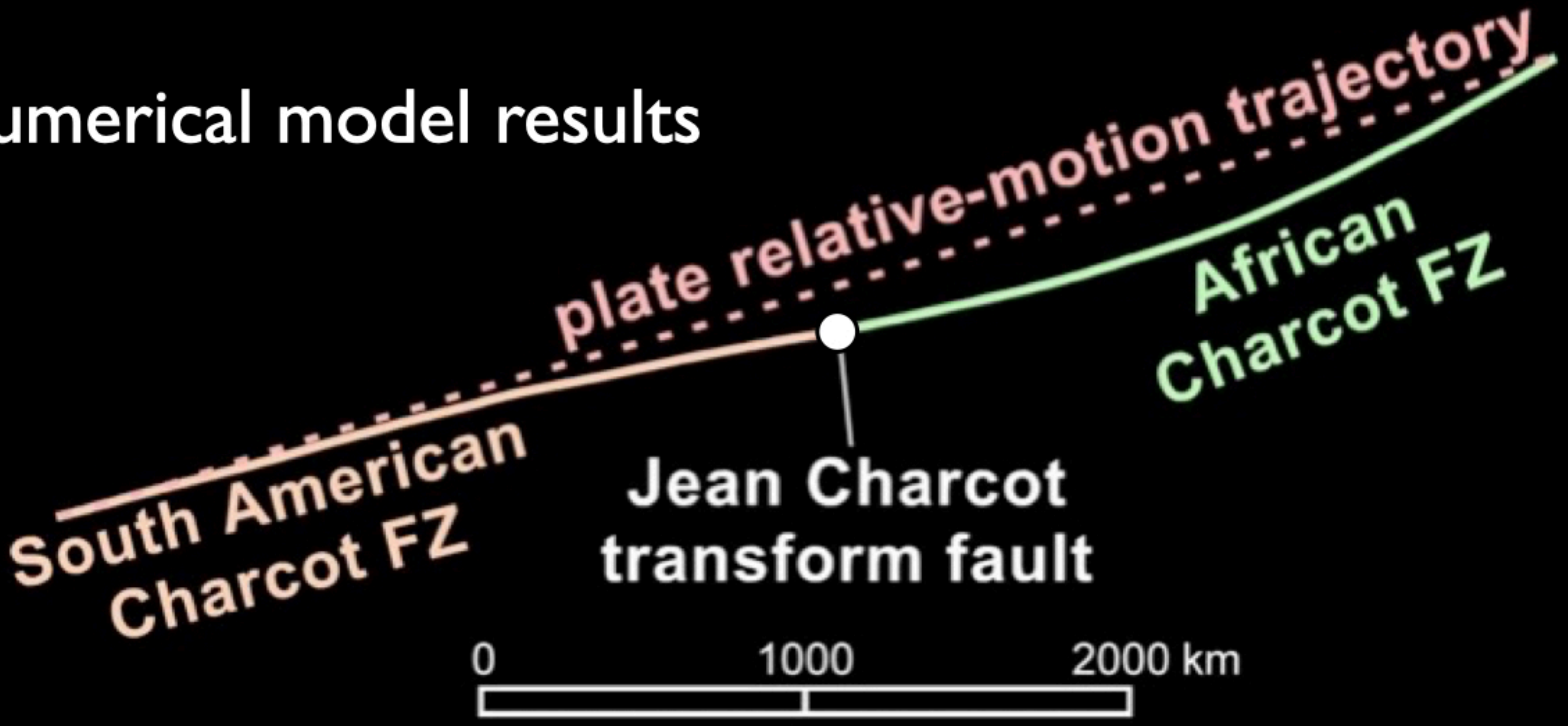


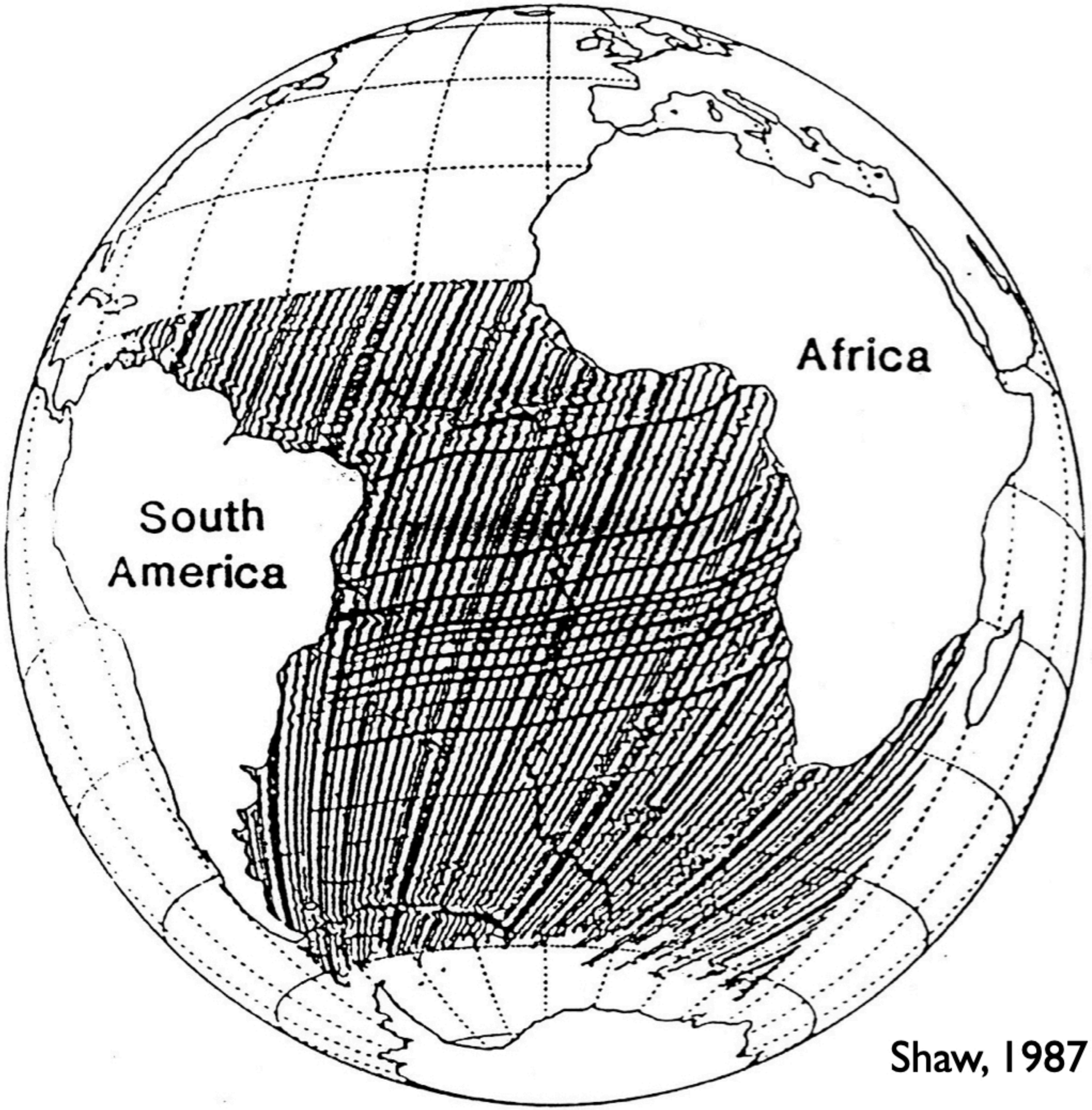
numerical model results



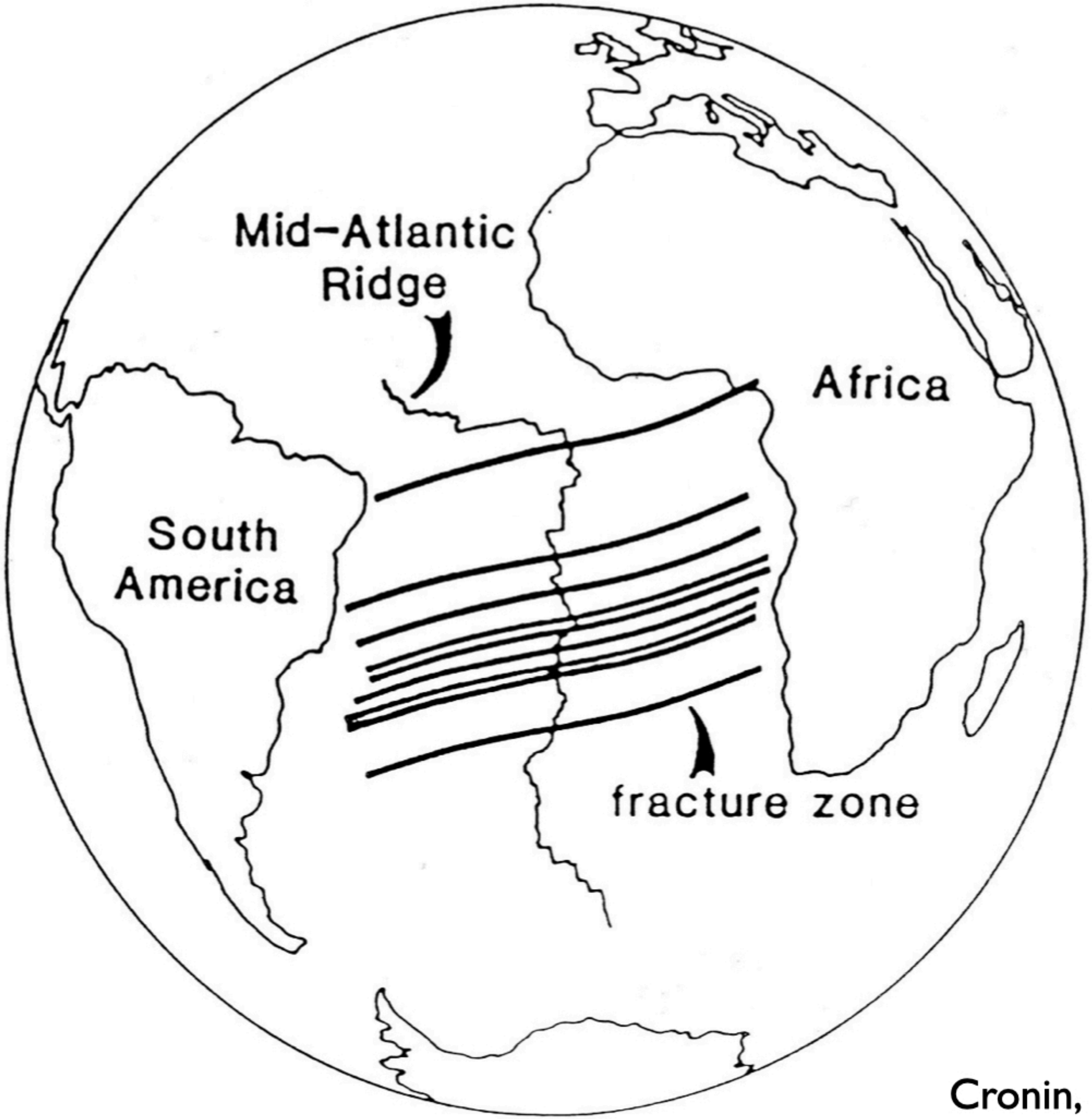


numerical model results





Shaw, 1987



Cronin, 1988

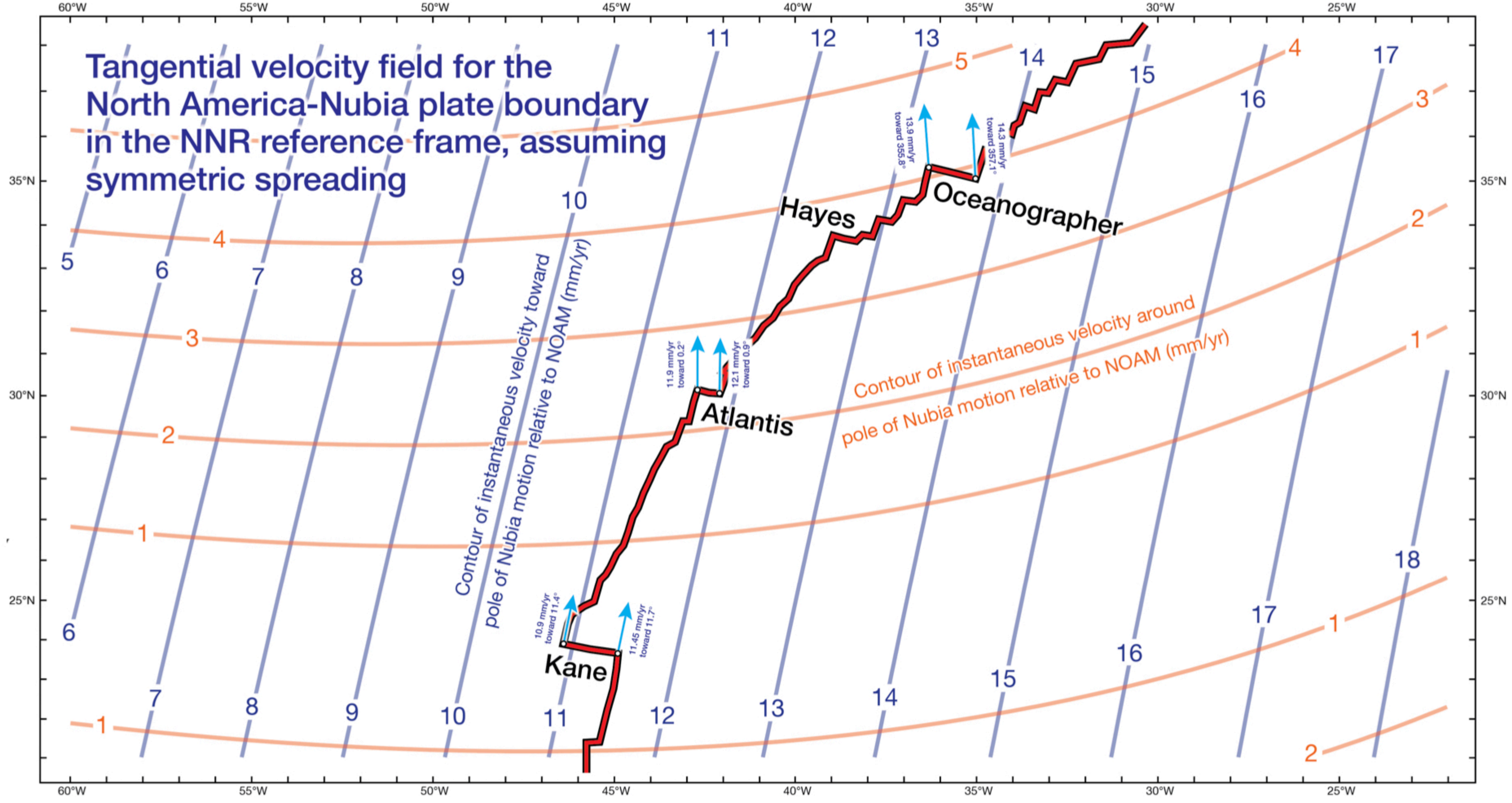
Ergo...

- An oceanic fracture zone on a given plate is the flow line of the end of a transform fault relative to that plate. It is not generally the flow line of any point on the adjacent plate.

- Oceanic fracture zones are not generally circular, contrary to common assumptions

Is there any physical evidence favoring a finite model in which the angular velocities of plates relative to a stable external reference frame are constant over a finite time interval?

Yes. The variation in length of ridge-ridge transform faults



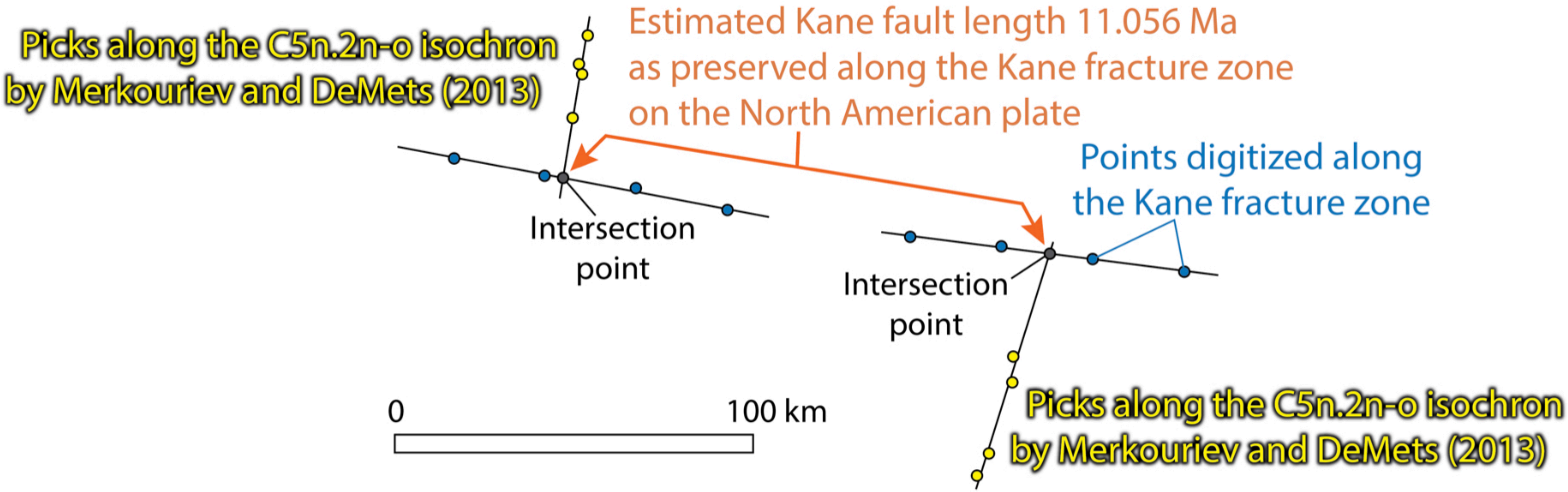
As the boundary moves in the NNR reference frame (Argus et al., 2011) over finite time intervals, the instantaneous velocity of each point along the boundary changes.

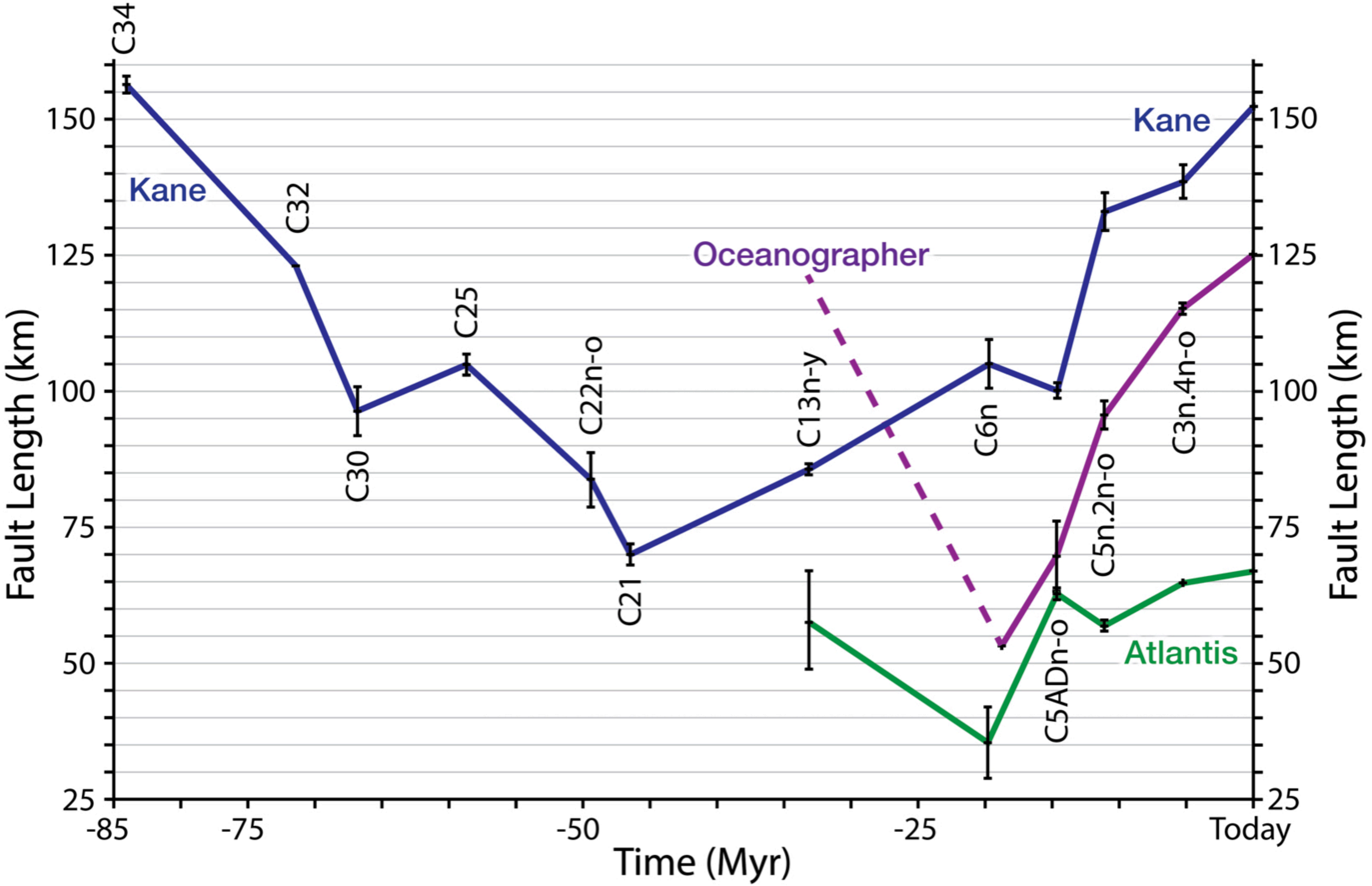
Location of selected isochron segments along the Kane, Atlantis and Oceanographer fracture zones
North American plate
Nubian plate
Hayes
Oceanographer
Atlantis
Kane
C13n-y
C6n-o
C5ADn-o
C3n.4n-o
C5n.2n-o
C22n-o
Base map from GeoMapApp
60°W
55°W
50°W
45°W
40°W
35°W
30°W
25°W
35°N
30°N
25°N

C13n-y
C6n-o
C5ADn-o
C3n.4n-o
C5n.2n-o
C6n-o
C13n-y
Hayes
Oceanographer

C13n-y
C6n-o
C5ADn-o
C3n.4n-o
C5n.2n-o
C6n-o
C13n-y
Atlantis


C22n-o
C13n-y
C6n-o
C5ADn-o
C3n.4n-o
C5n.2n-o
C6n-o
C13n-y
C22n-o
Kane

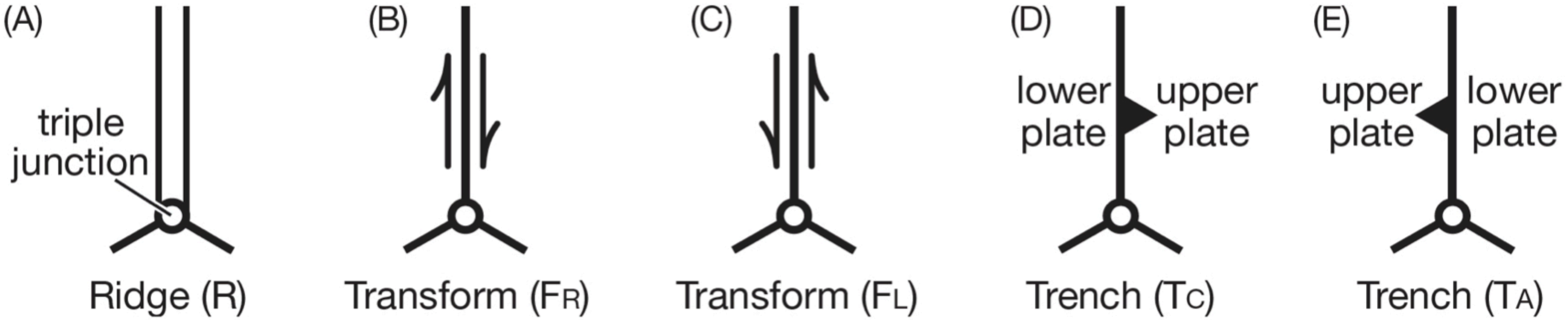

Picks along the C5n.2n-o isochron by Merkouriev and DeMets (2013)
Estimated Kane fault length 11.056 Ma as preserved along the Kane fracture zone on the North American plate
Points digitized along the Kane fracture zone
Intersection point
Intersection point
0
100 km
Picks along the C5n.2n-o isochron by Merkouriev and DeMets (2013)



C34
Kane
C32
C30
C25
C22n-o
C21
C13n-y
Oceanographer
C6n
C5ADn-o
C5n.2n-o
C3n.4n-o
Kane
Atlantis
Fault Length (km)
Fault Length (km)
150
125
100
75
50
25
-85
-75
-50
-25
Today
Time (Myr)

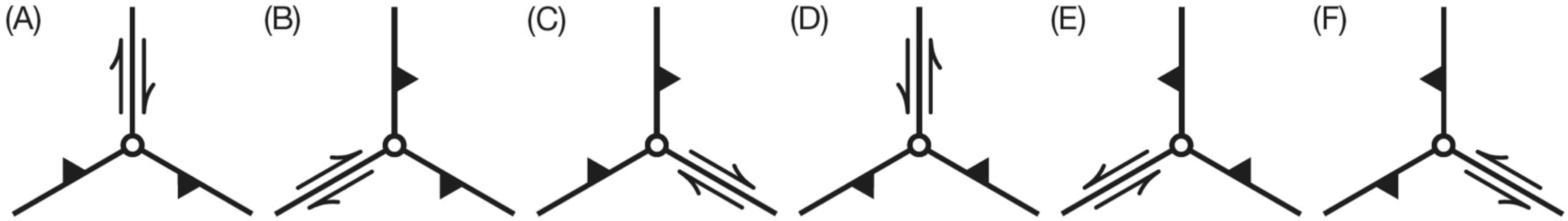
Revision of how we understand plate boundary triple junctions

Five Plate Boundaries



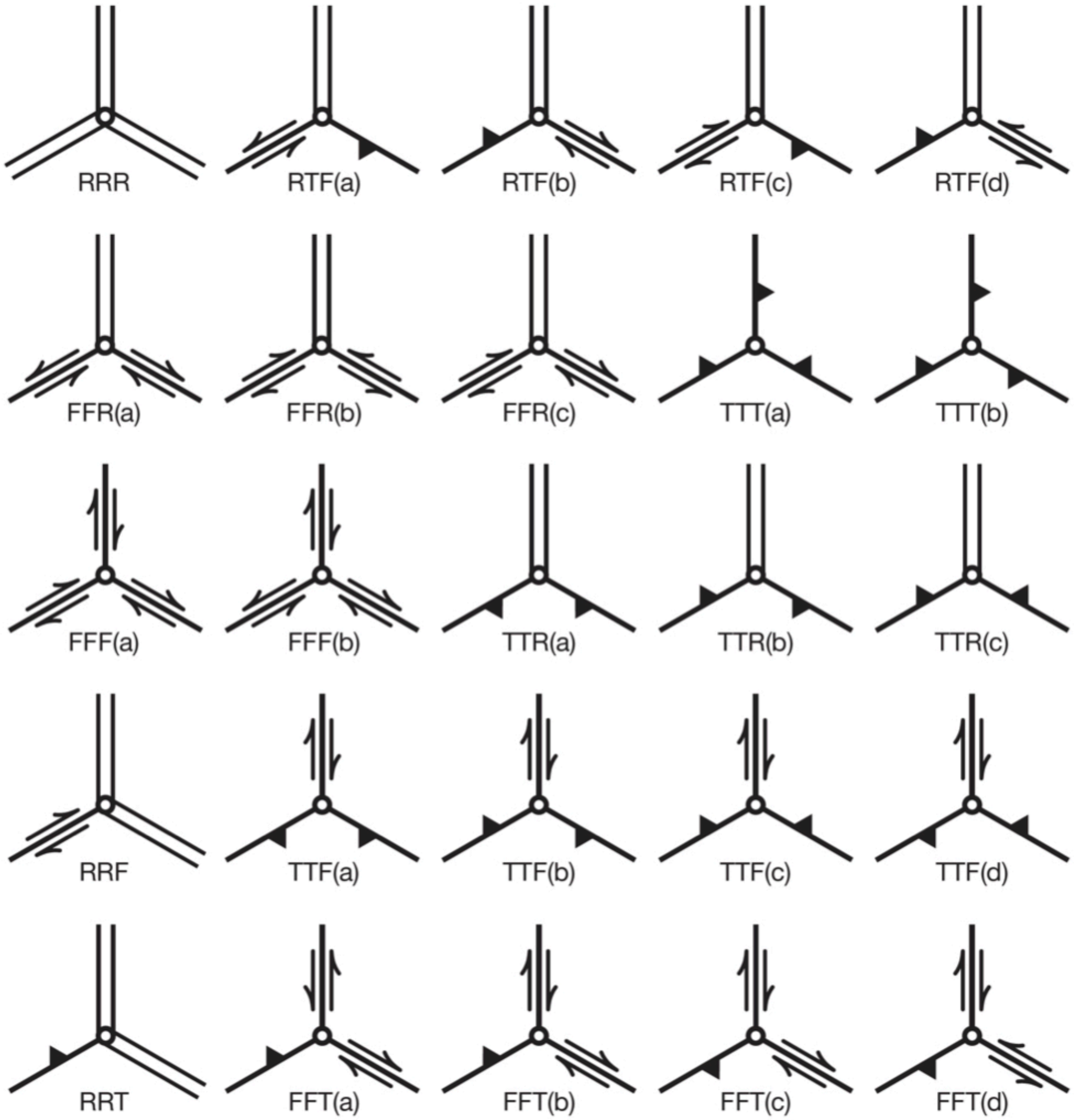
Cronin, 1988, 1992, 2021

The Same Triple Junction Rotated and Reflected



Cronin, 1988, 1992, 2021

The 25 Unique Types of Triple Junction



Cronin, 1988, 1992, 2021

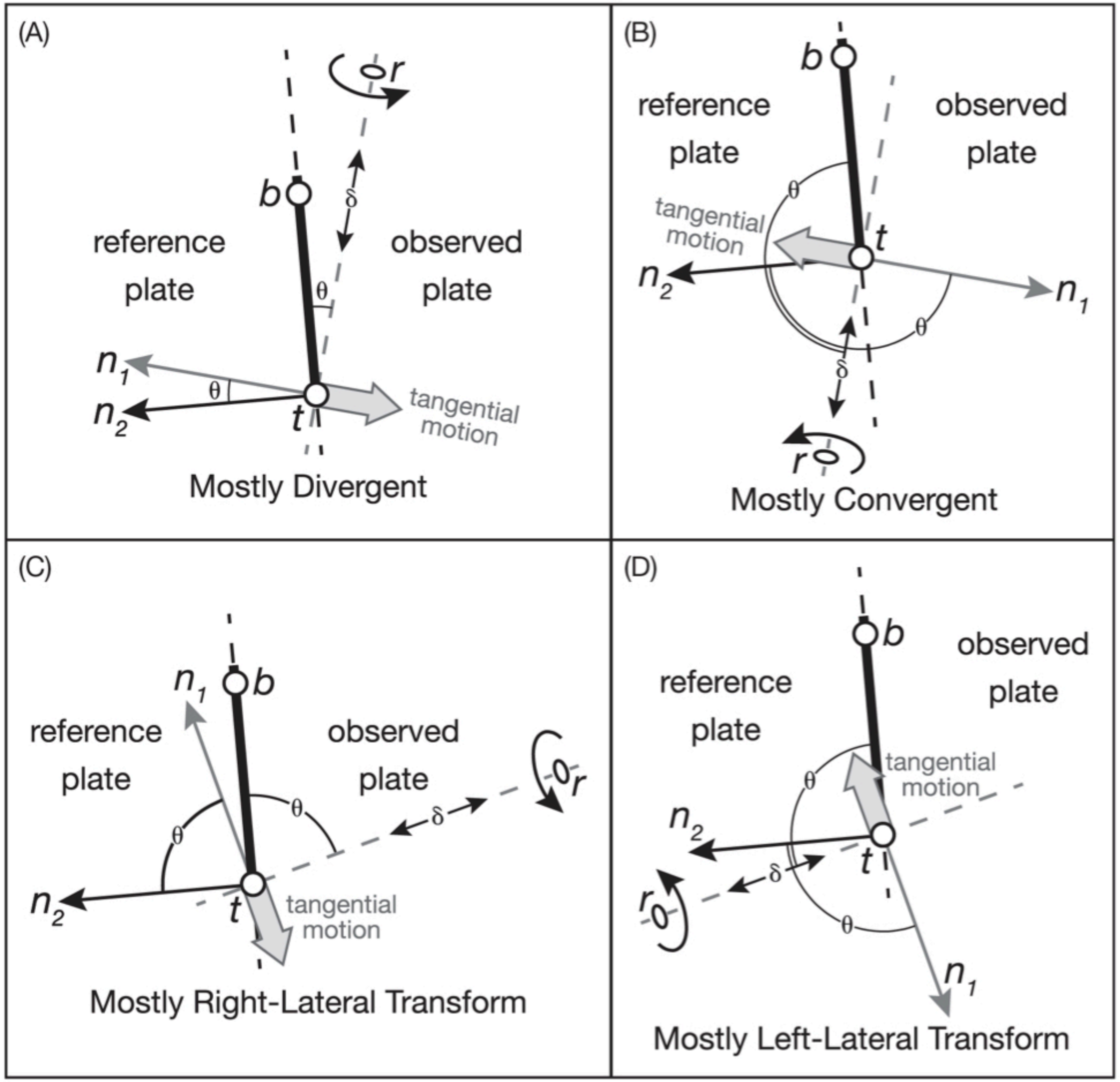


Fig. 5 The location of the triple junction (point *t*), a point along the plate boundary near the triple junction (point *b*), and the Euler pole (point *r*) around which the observed plate rotates anti-clockwise relative to the reference plate. The tangential speed varies with the angular distance (δ) from the triple junction to the Euler pole. (A) Scenario for a divergent boundary. (B) Scenario for a convergent boundary. (C) Scenario for a right-lateral transform fault. (D) Scenario for a left-lateral transform fault.

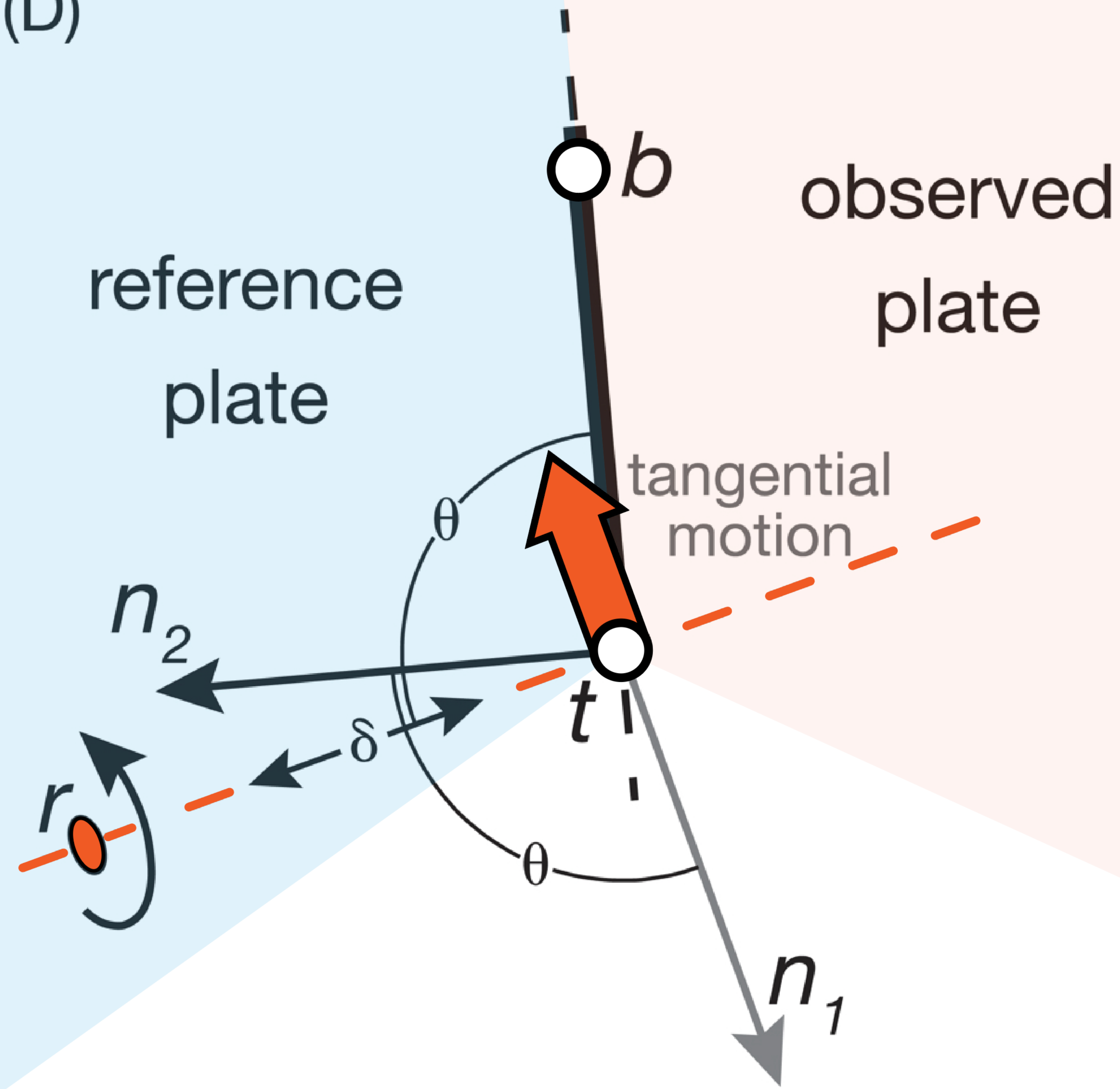
(A)
r
b
δ
reference
plate
observed
plate
θ
n_1
θ
n_2
t
tangential
motion
Mostly Divergent
Cronin, 2021


(B)
b
reference
plate
observed
plate
θ
tangential
motion
t
n_2
n_1
θ
δ
r
Mostly Convergent
Cronin, 2021

Mostly Right-Lateral Transform

Cronin, 2021

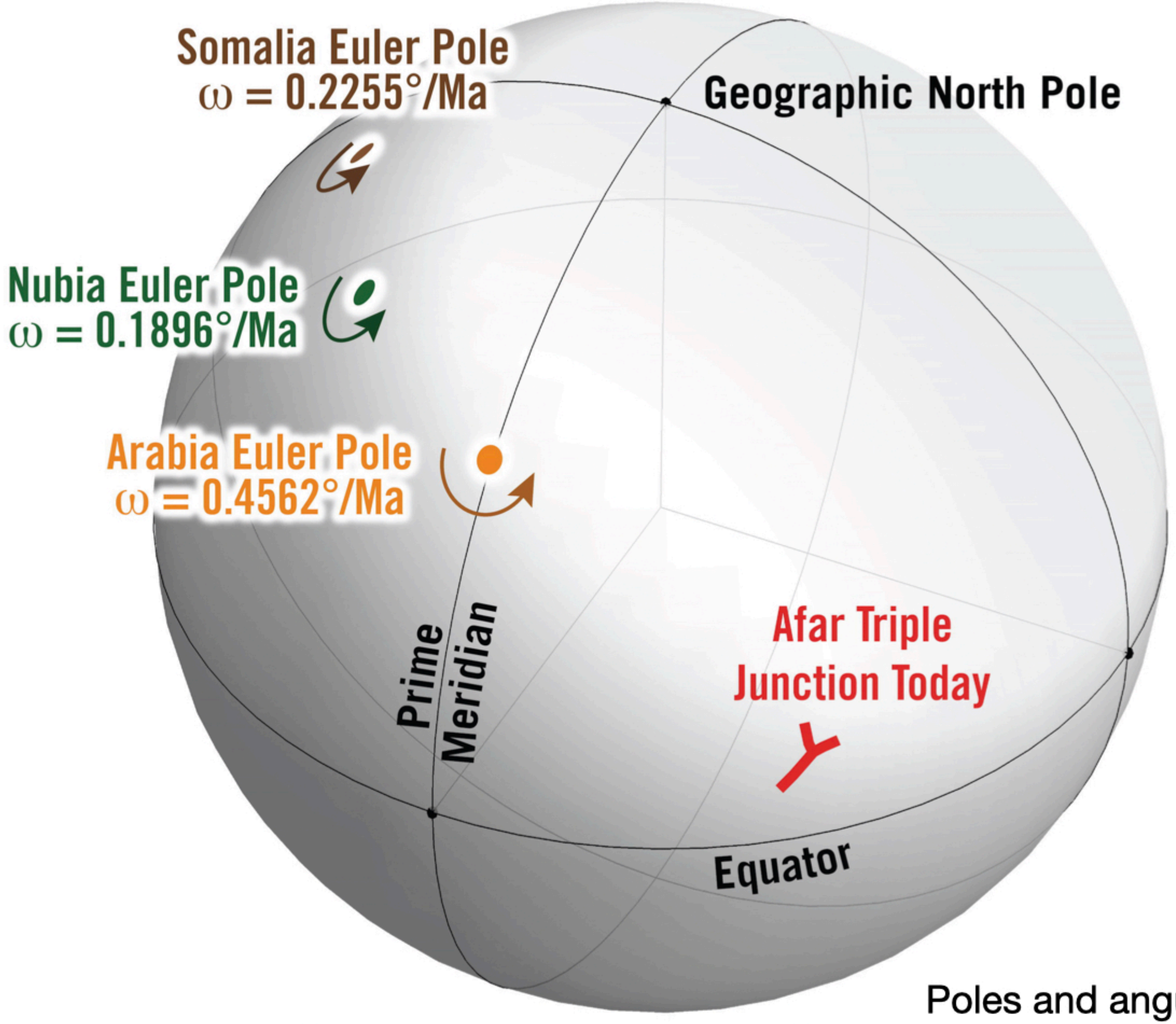
(D)



Mostly Left-Lateral Transform

Cronin, 2021

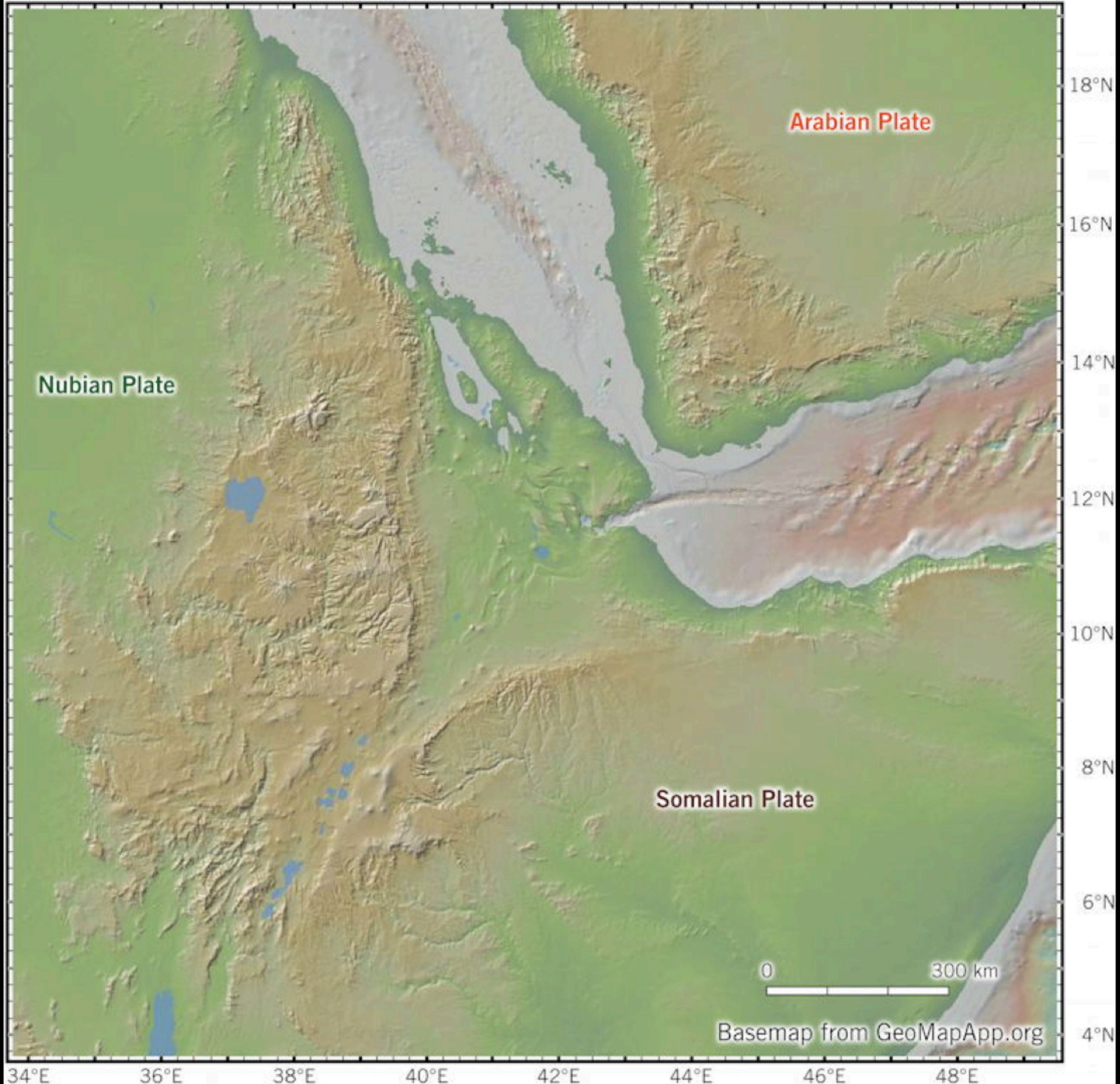
Google Earth



Instantaneous plate poles and angular speeds related to the Afar triple junction, expressed in a reference frame fixed to the Hawaiian hot spot

Ryley Collins, 2019, Preliminary Kinematic Model of Afar Triple Junction, -22 to 5 Ma: B.S. thesis, Baylor University, 71 p.

Poles and angular speeds are after Kreemer and others (2014) and Wang and others (2017).



Today

Collins, 2019
Fig. 1

The base map was made with GeoMapApp (www.geomapapp.org)

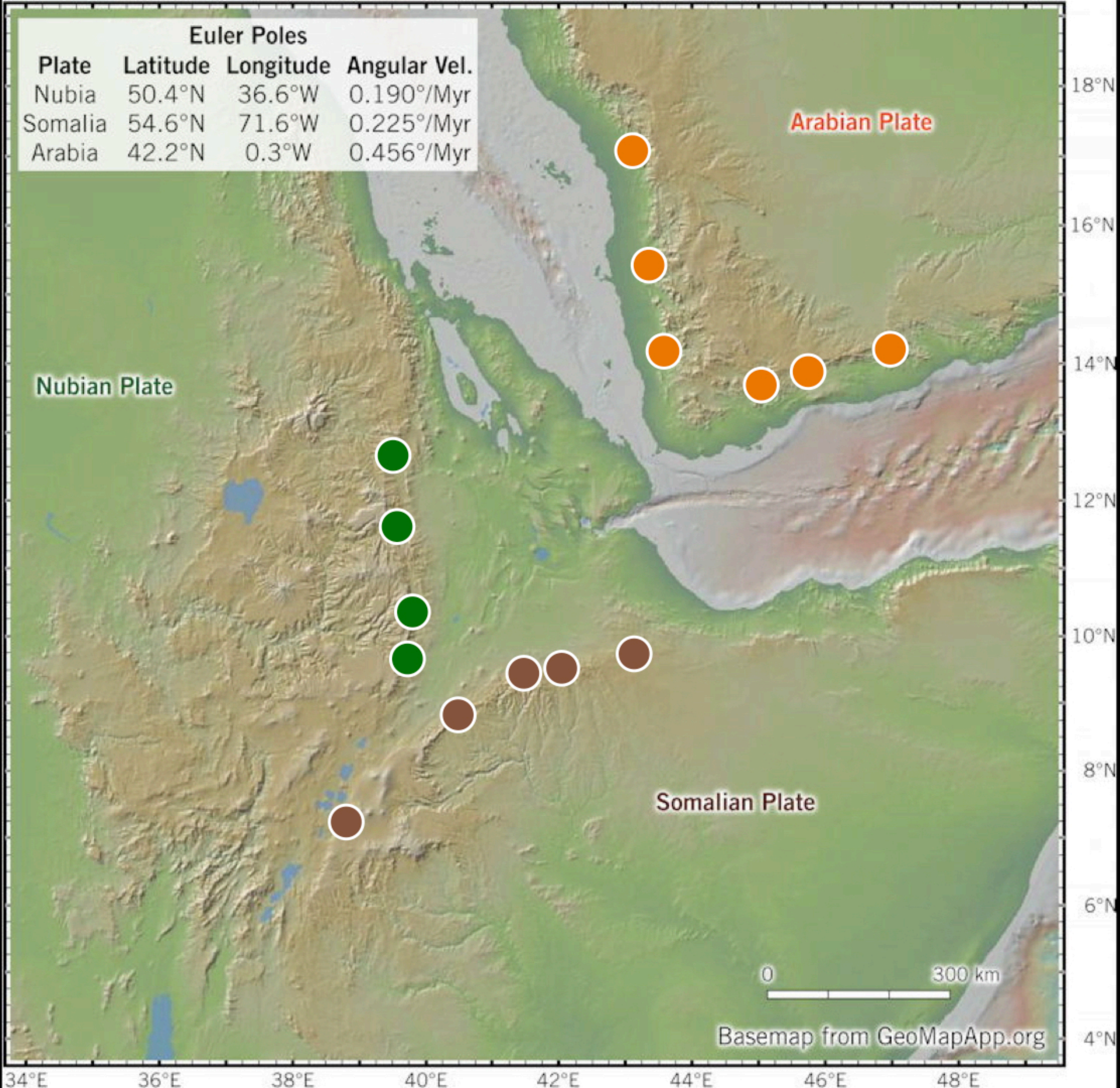


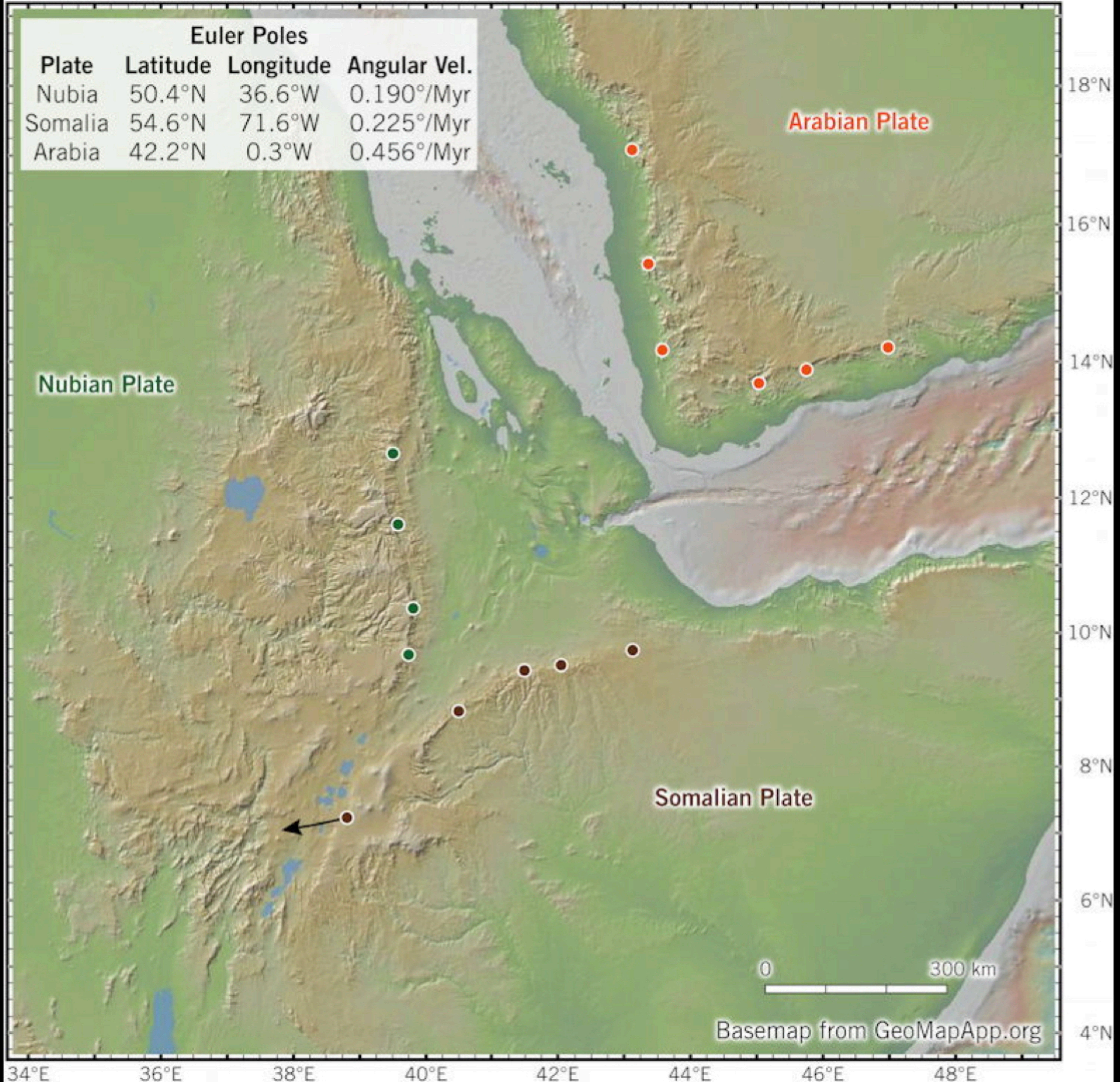
Plate	Latitude	Longitude	Angular Vel.
Nubia	50.4°N	36.6°W	0.190°/Myr
Somalia	54.6°N	71.6°W	0.225°/Myr
Arabia	42.2°N	0.3°W	0.456°/Myr

Selected control points along the undeformed edge of continental crust on the Arabian, Nubian (African) and Somalian plates

Collins, 2019
Fig. 3

The base map was made with GeoMapApp (www.geomapapp.org)

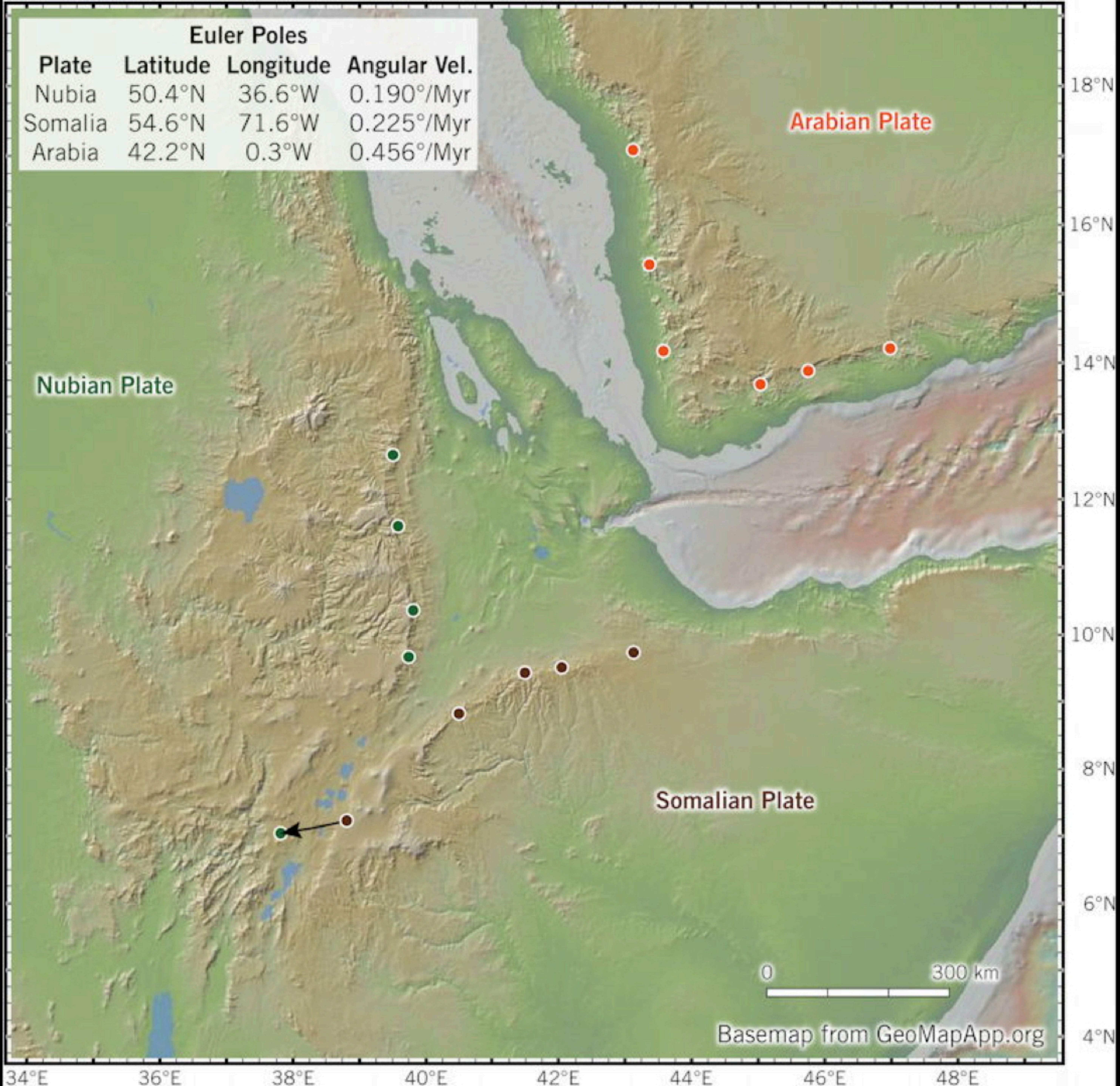
Projection of matching control points across the East African Rift



The base map was made with GeoMapApp (www.geomapapp.org)

Collins, 2019

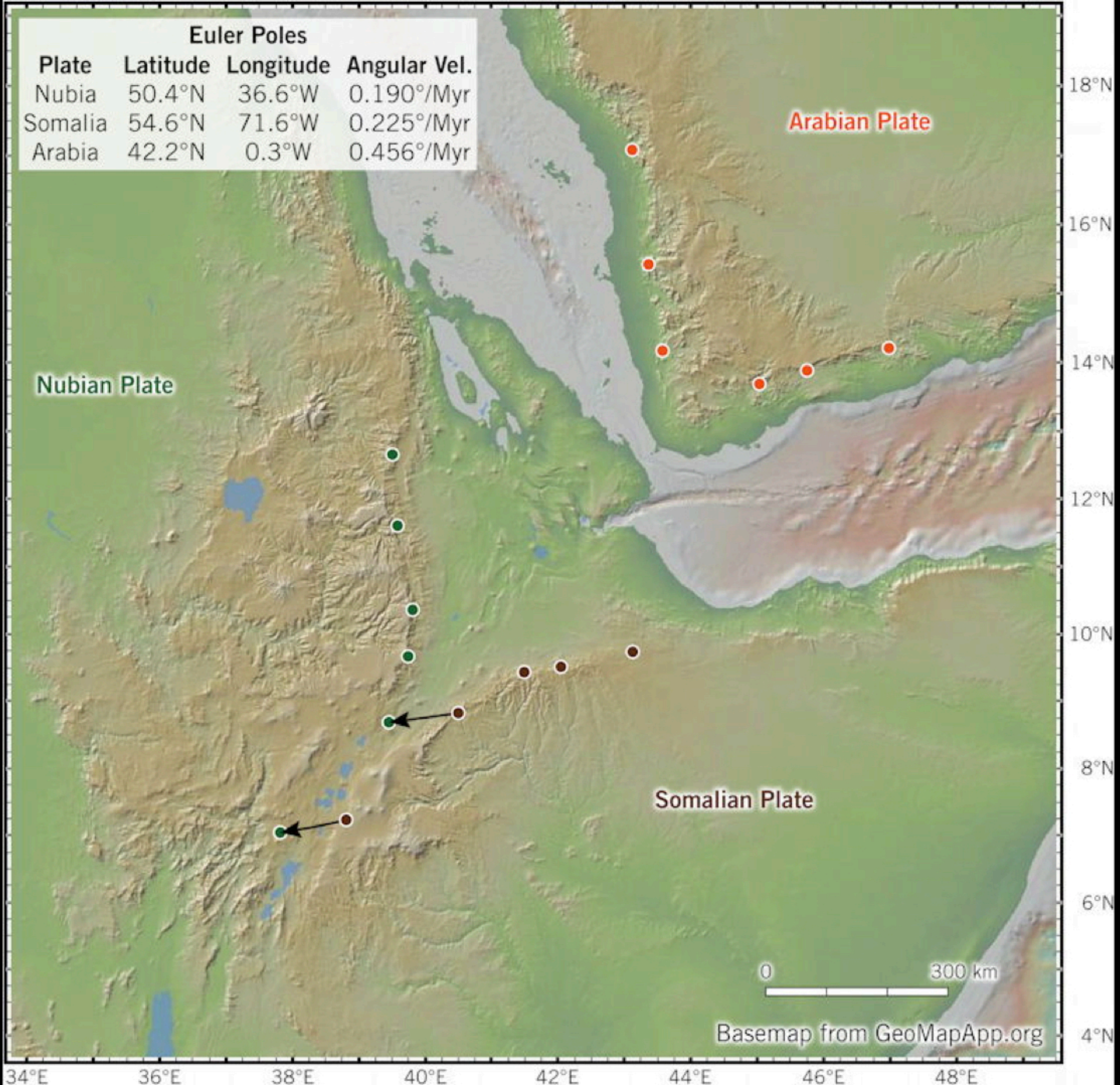
Projection of matching control points across the East African Rift



The base map was made with GeoMapApp (www.geomapapp.org)

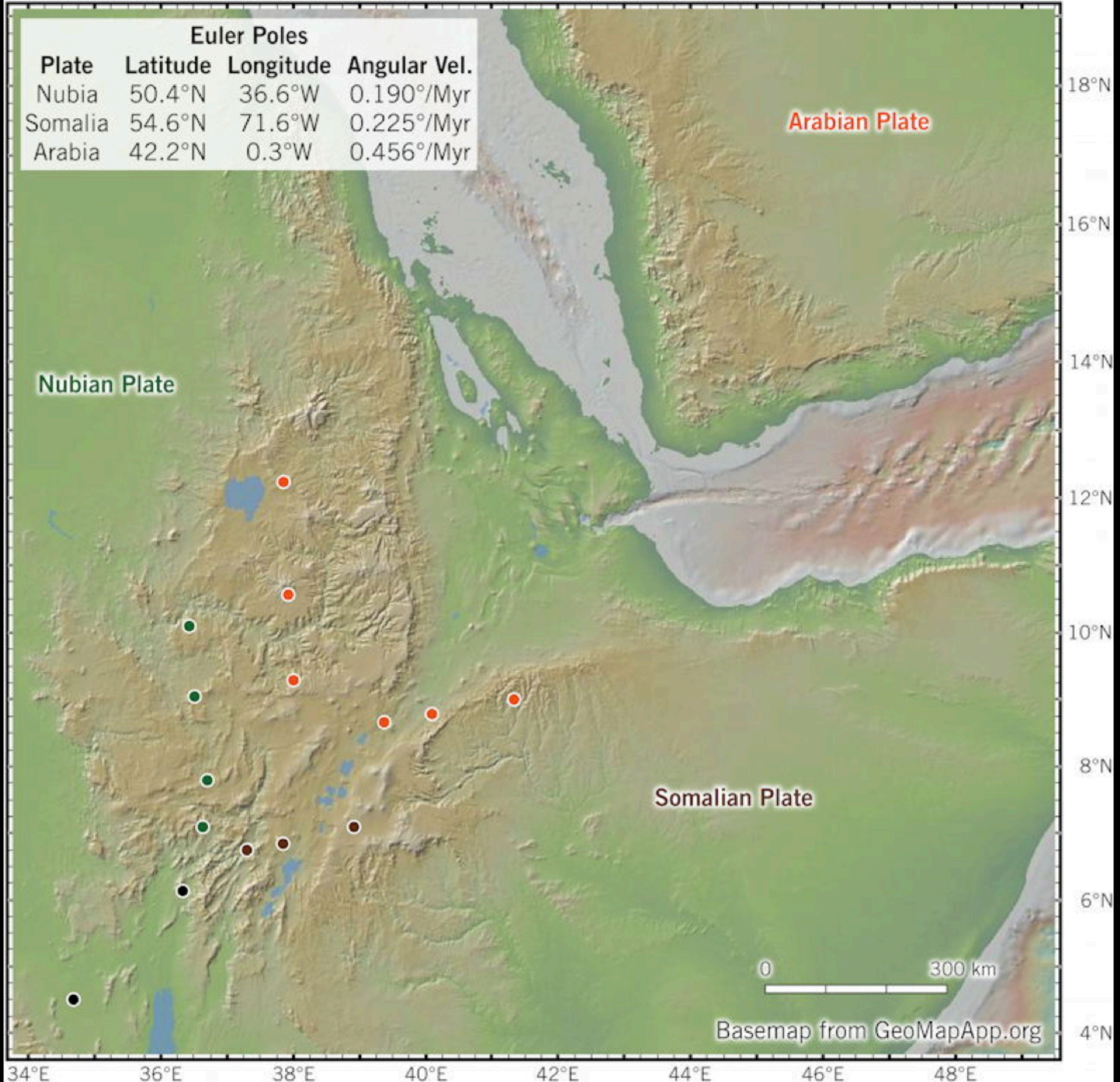
Collins, 2019

Projection of matching control points across the East African Rift



The base map was made with GeoMapApp (www.geomapapp.org)

Collins, 2019
Fig. 4

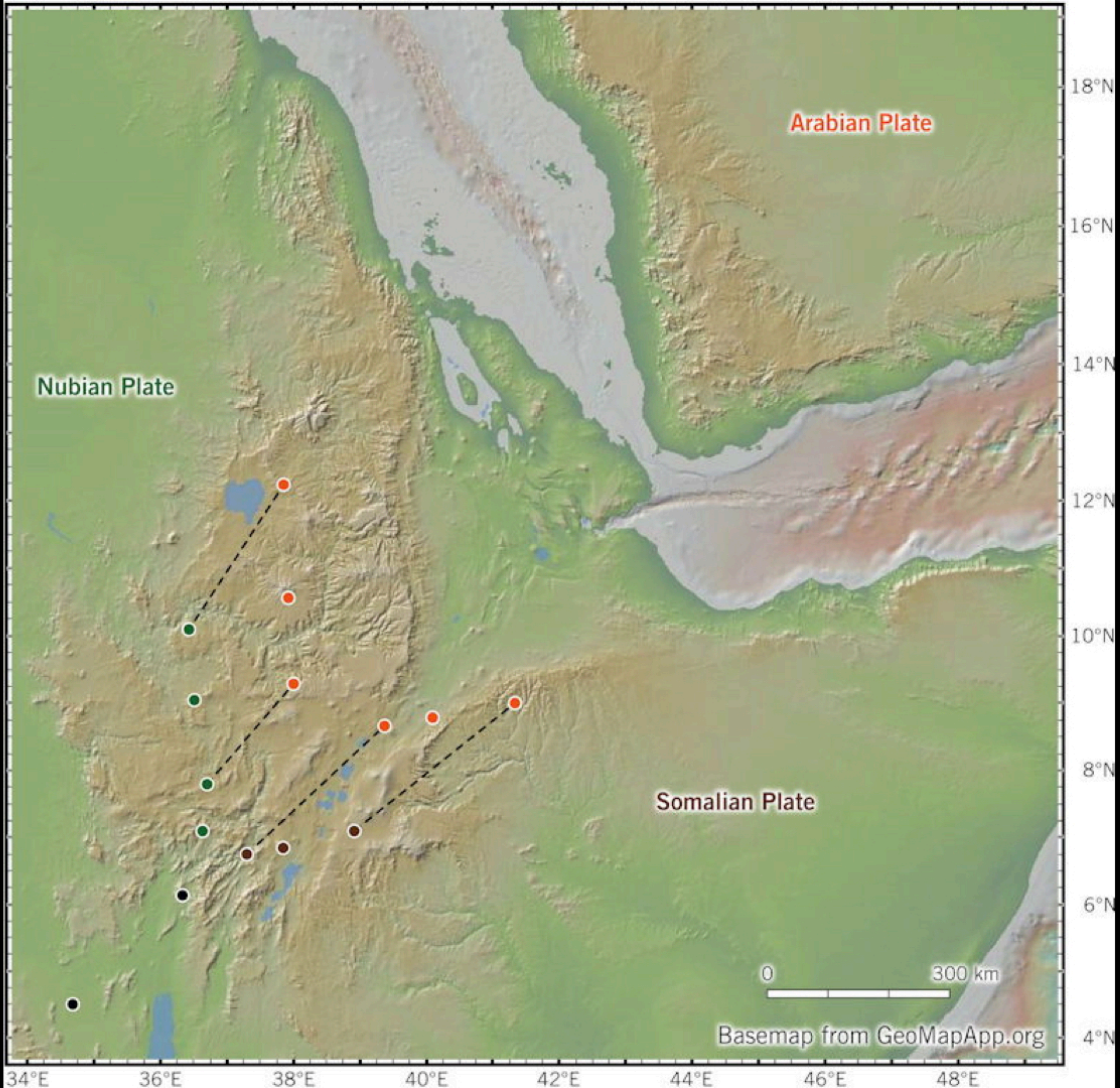


Closing of the East African Rift as represented by control points, -22 Ma

Collins, 2019
Fig. 5

The base map was made with GeoMapApp (www.geomapapp.org)

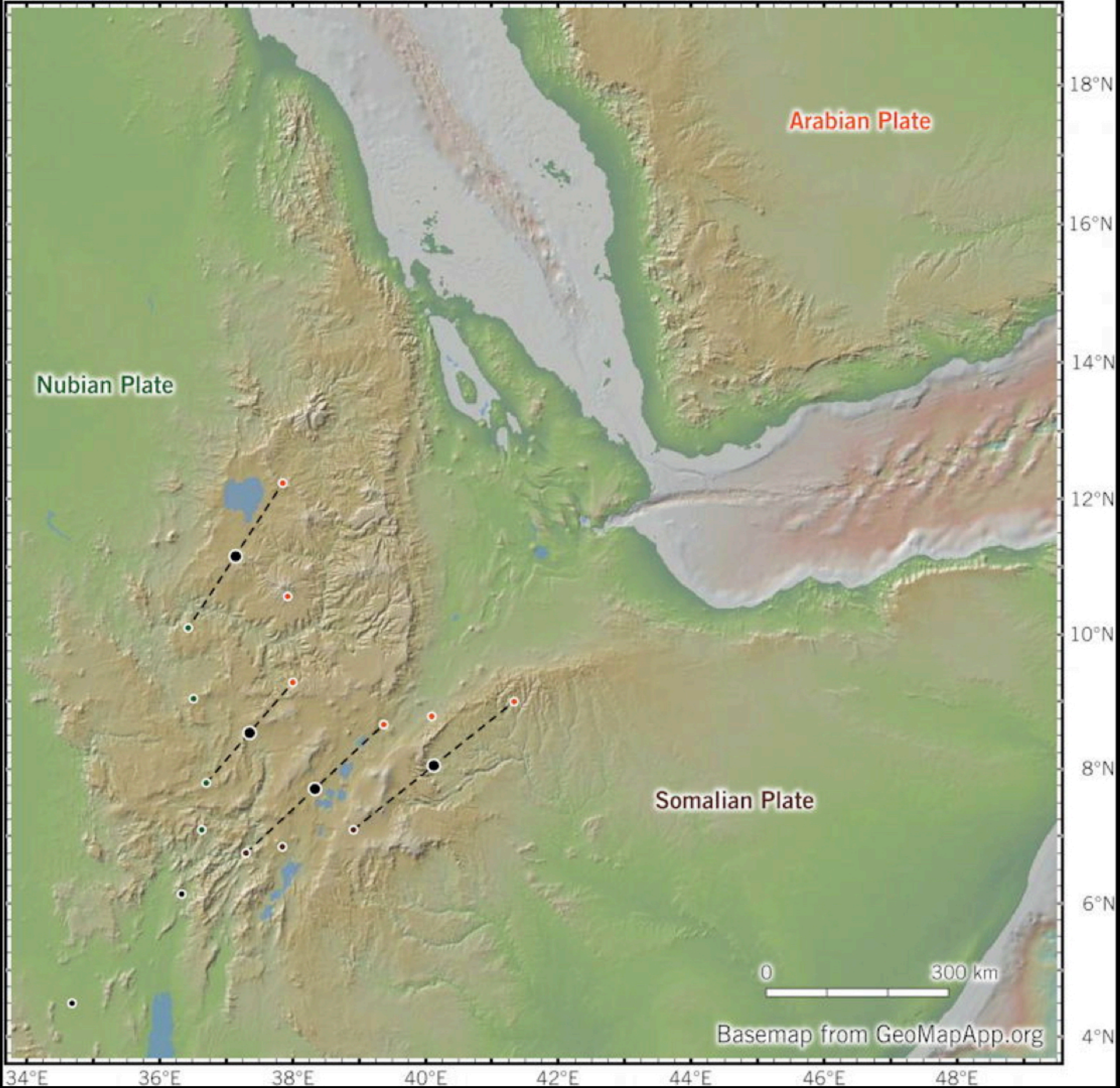
Great circle arcs between control points along the continental edges



The base map was made with GeoMapApp (www.geomapapp.org)

Collins, 2019
Fig. 6

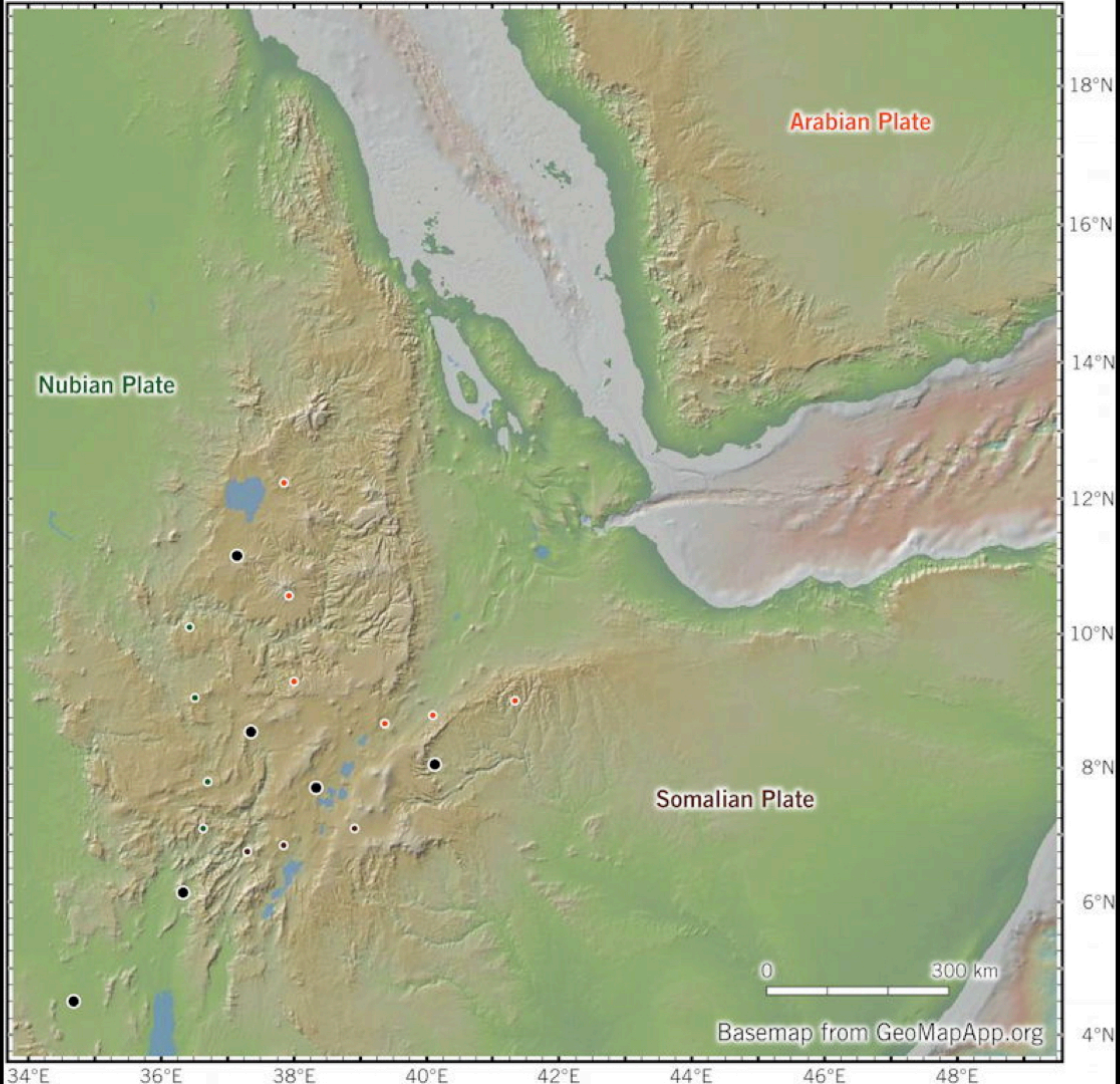
The base map was made with GeoMapApp (www.geomapapp.org)



Midpoints along great circle arcs between control points along the continental edges.

These represent the location of the Red Sea Rift and Aden Ridge prior to the initiation of the Afar triple junction.

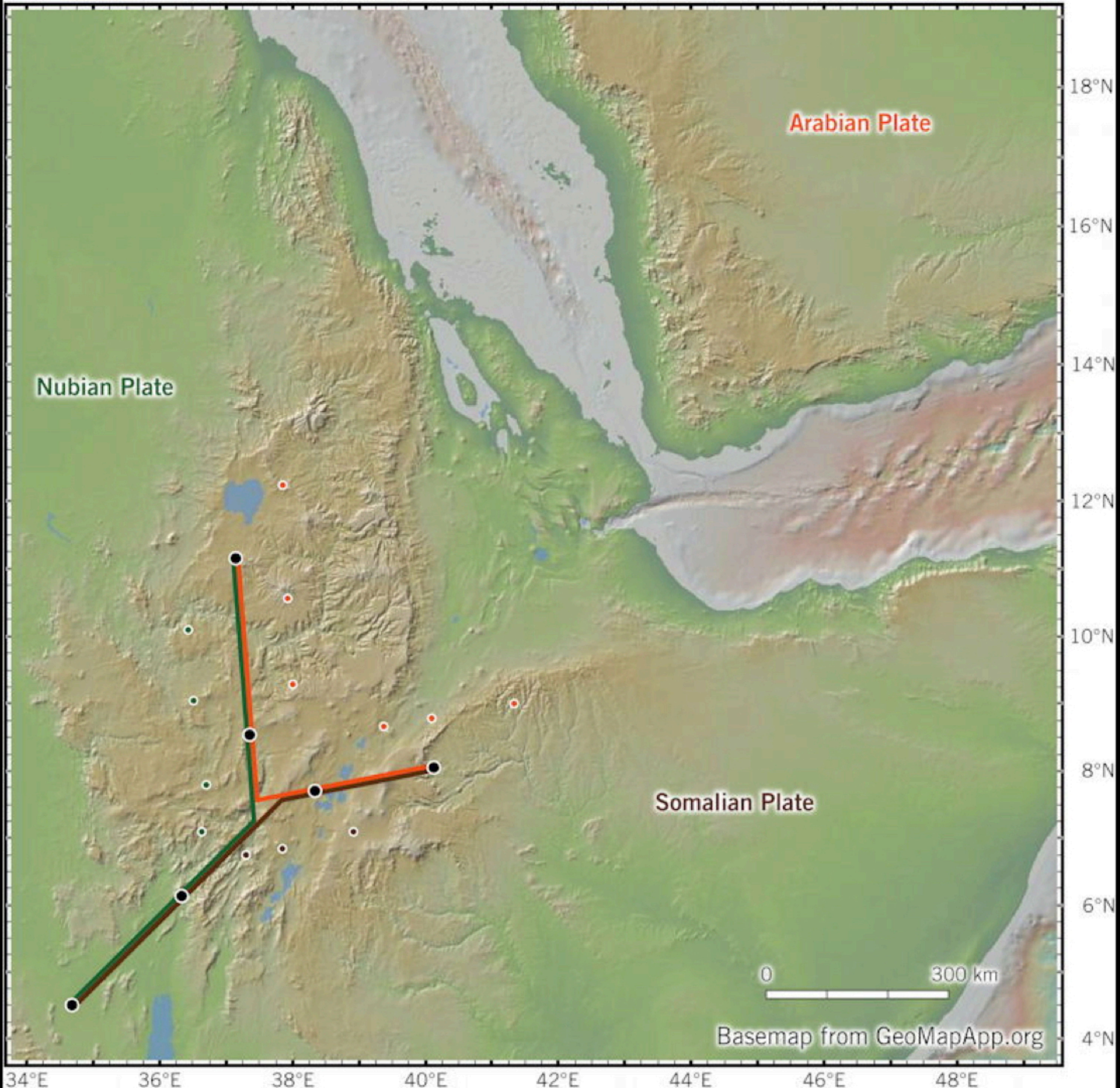
Collins, 2019
Fig. 6



The base map was made with GeoMapApp (www.geomapapp.org)

These represent the location of the Red Sea Rift and Aden Ridge prior to the initiation of the Afar triple junction.

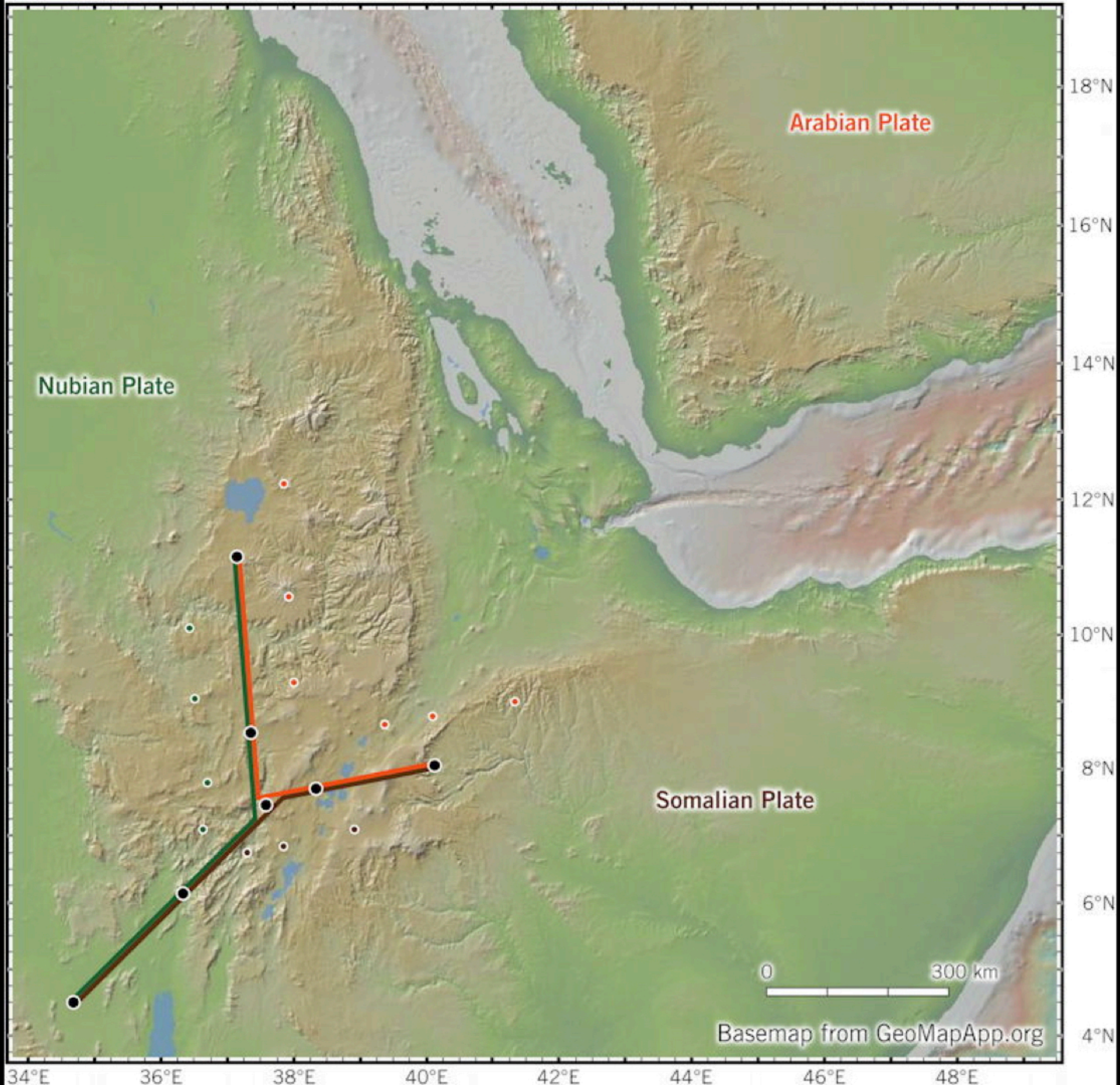
Collins, 2019 Fig. 1



The base map was made with GeoMapApp (www.geomapapp.org)

Great circle arcs defined by the rift midpoints delineate each rift system. Intersection of the three great circle arcs forms a triangle.

Collins, 2019 Fig. 7

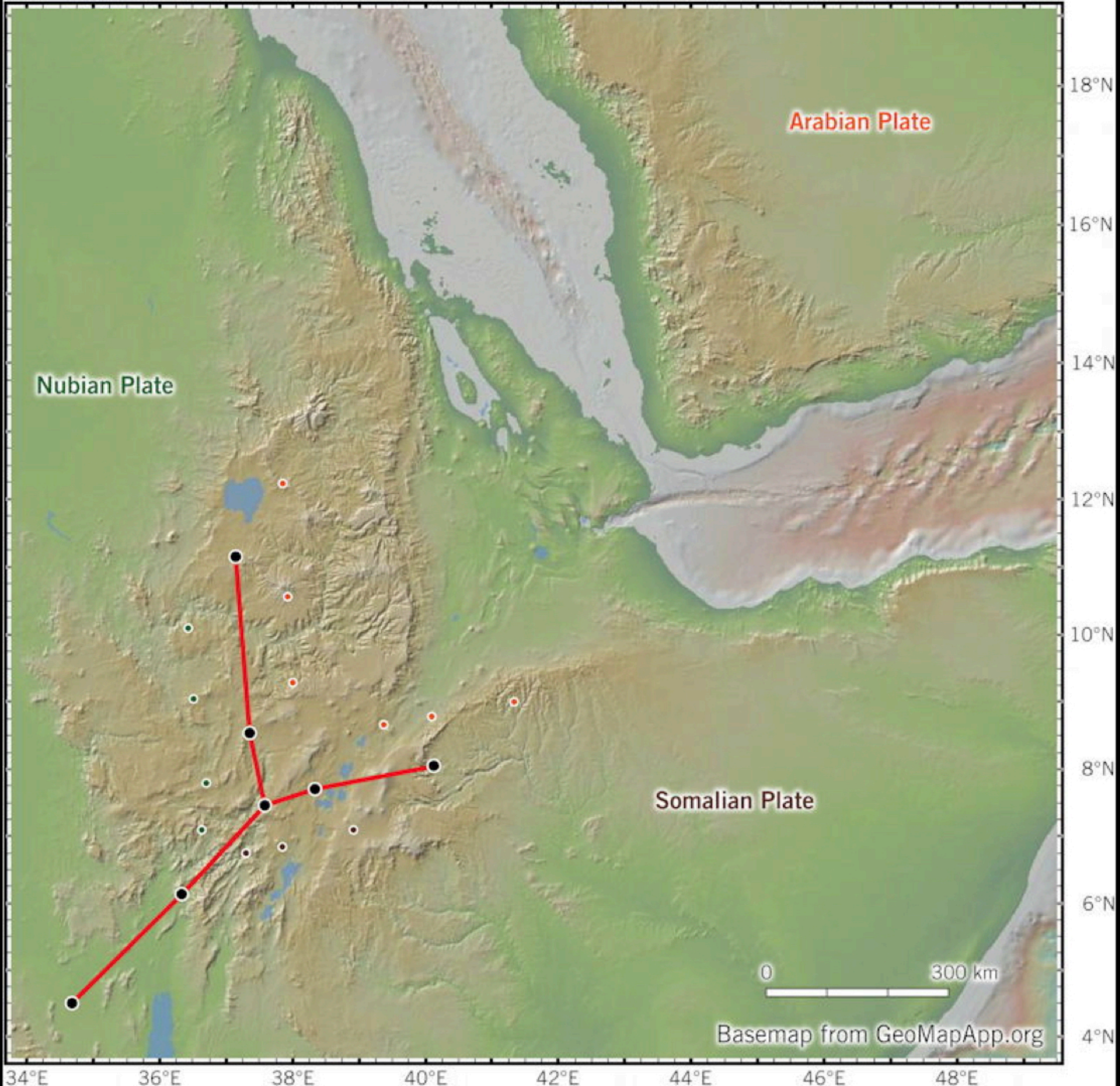


The triple junction is defined by the center of the triangle.

Collins, 2019 Fig. 8

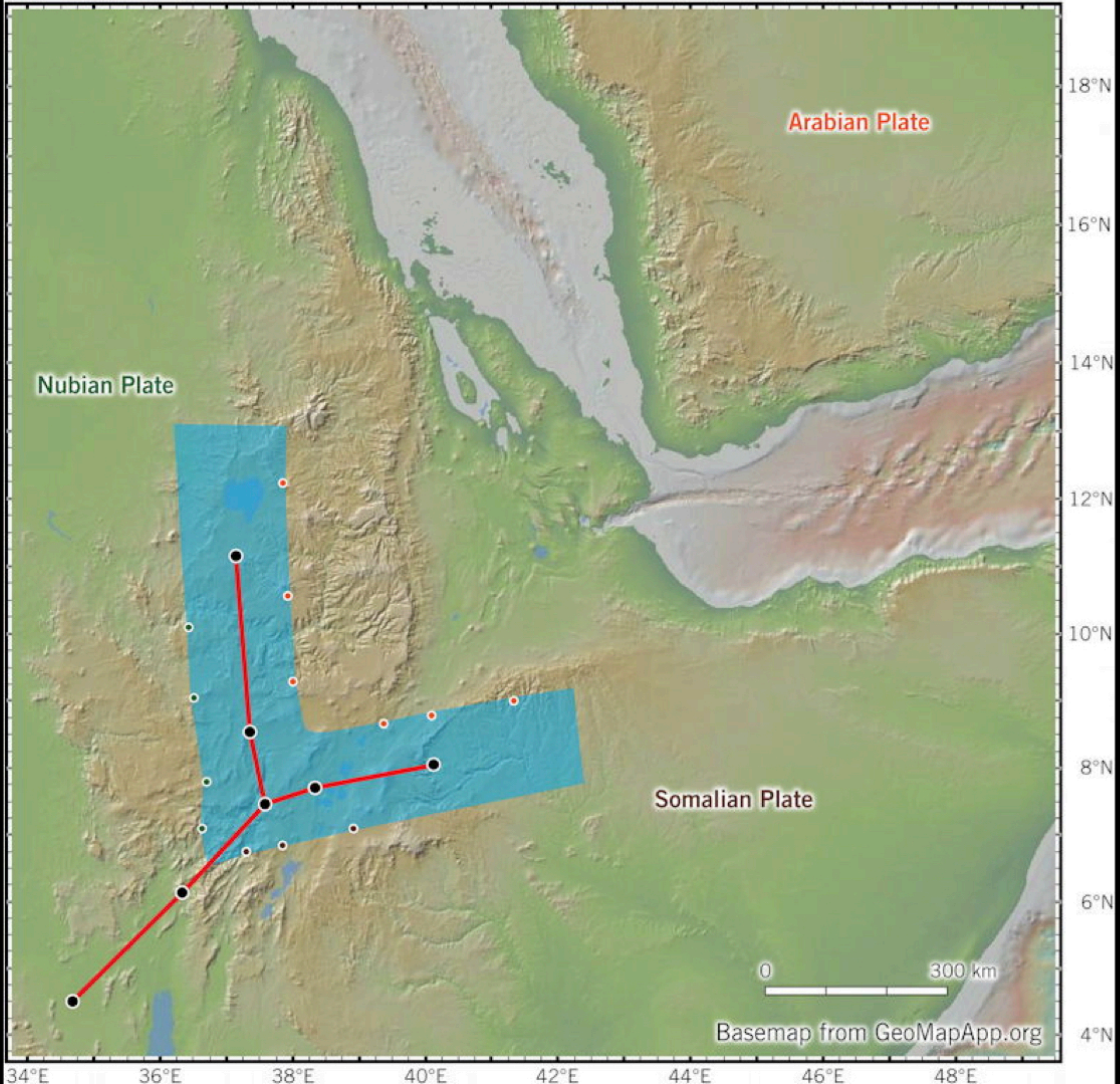
The base map was made with GeoMapApp (www.geomapapp.org)

Afar triple junction, modeled at -22 Ma



The base map was made with GeoMapApp (www.geomapapp.org)

Collins, 2019 Fig. 9

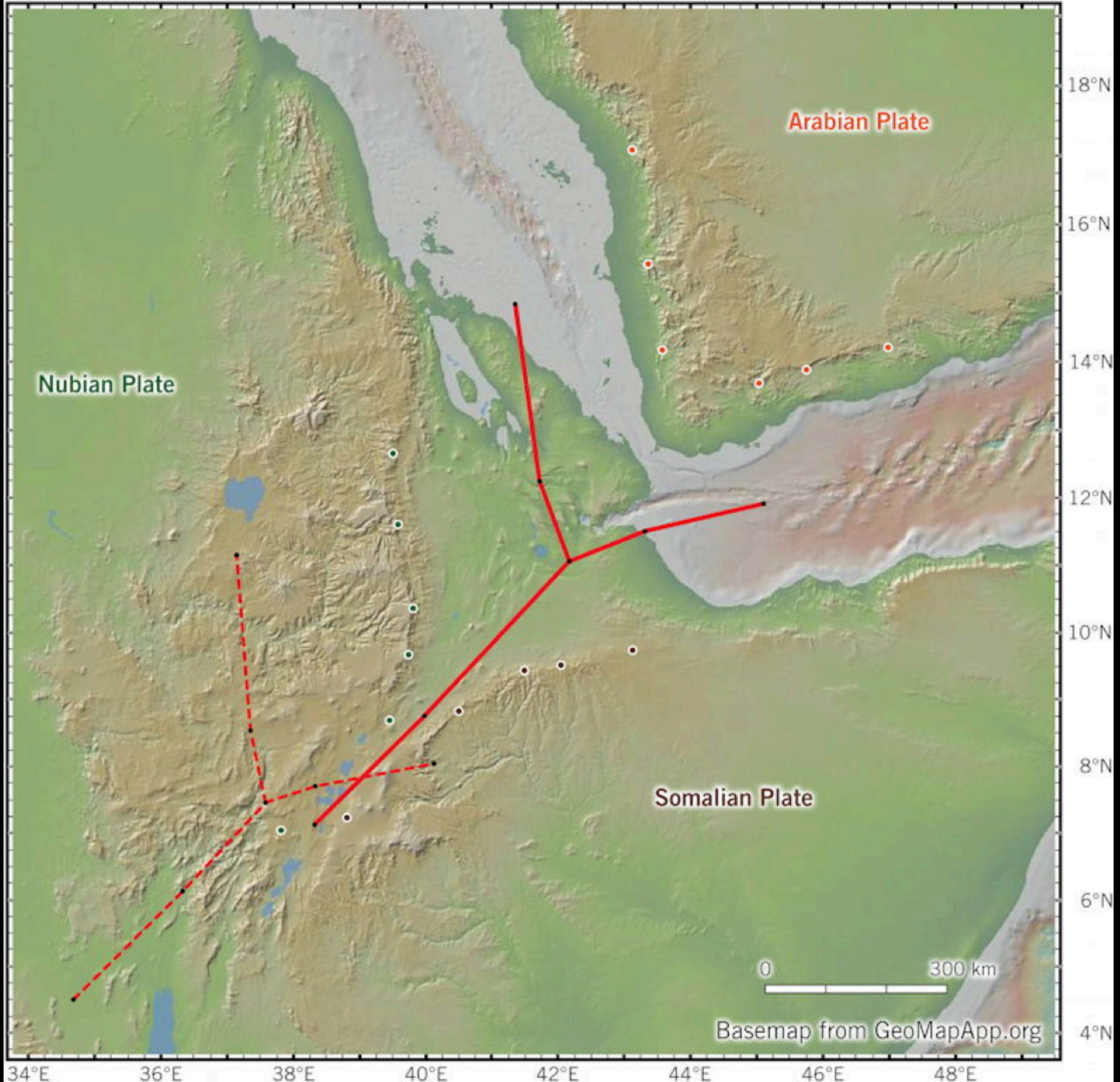


The base map was made with GeoMapApp (www.geomapapp.org)

The Red Sea and Afar Rifts might have been active prior to the initiation of the East African Rift, -22 Ma.

The blue area indicates the effects of early rifting and sea water inundation prior to -22 Ma.

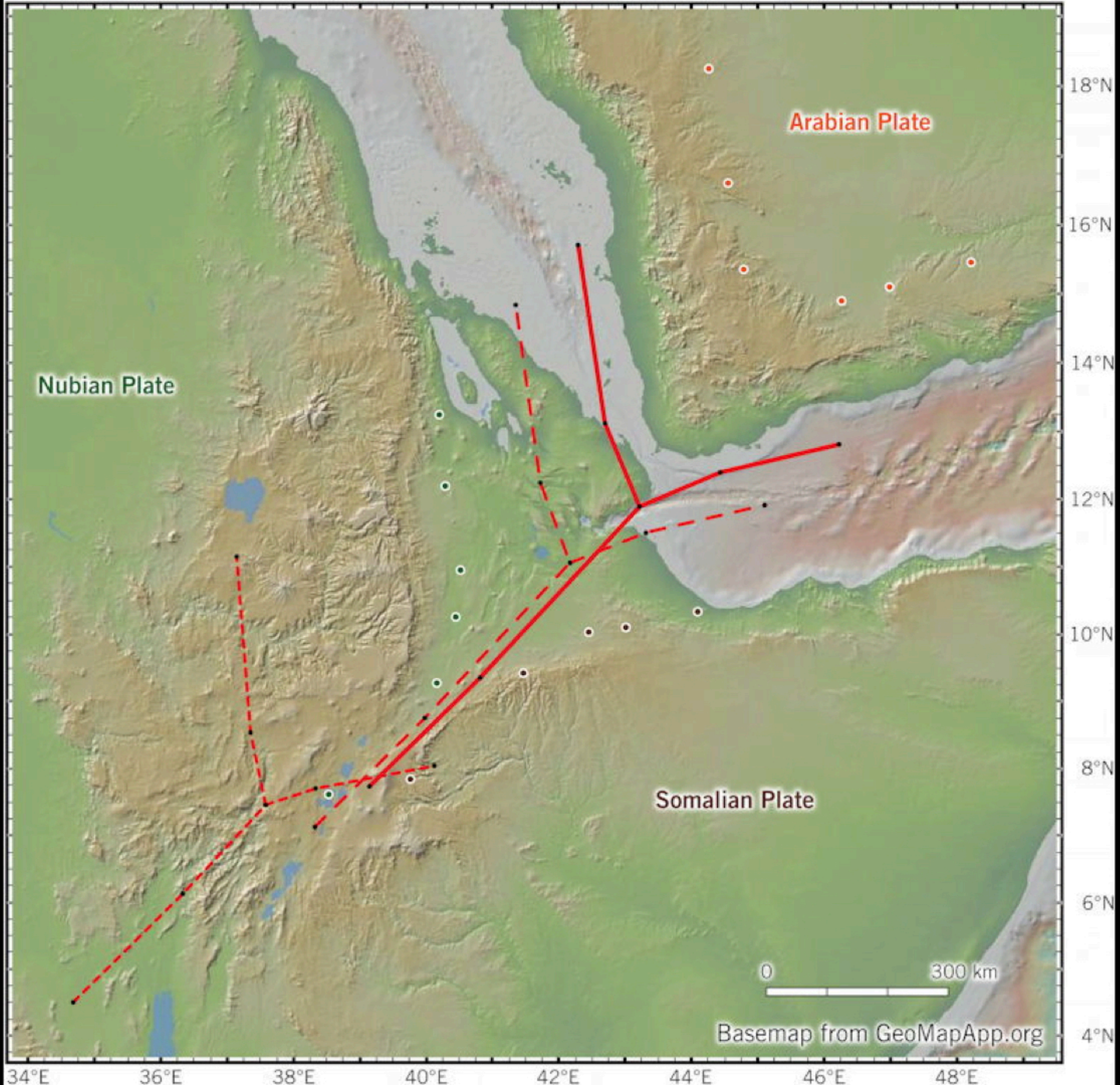
Collins, 2019 Fig. 10



Afar triple junction modeled at 0 Ma (today) based on model at -22 Ma.

The base map was made with GeoMapApp (www.geomapapp.org)

Collins, 2019 Fig. 11

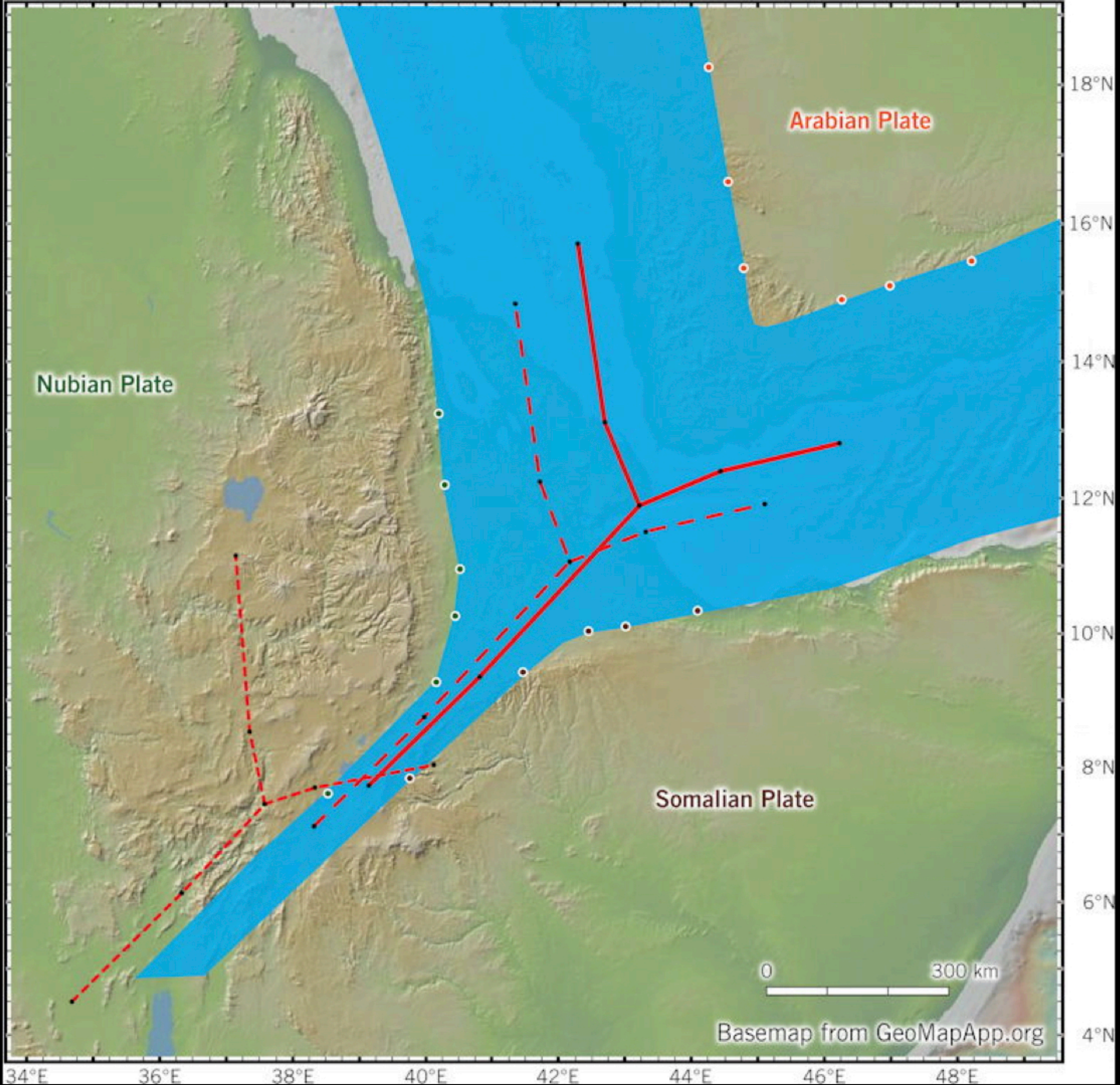


Afar triple junction projected 5 Ma in the future

Collins, 2019
Fig. 12

The base map was made with GeoMapApp (www.geomapapp.org)

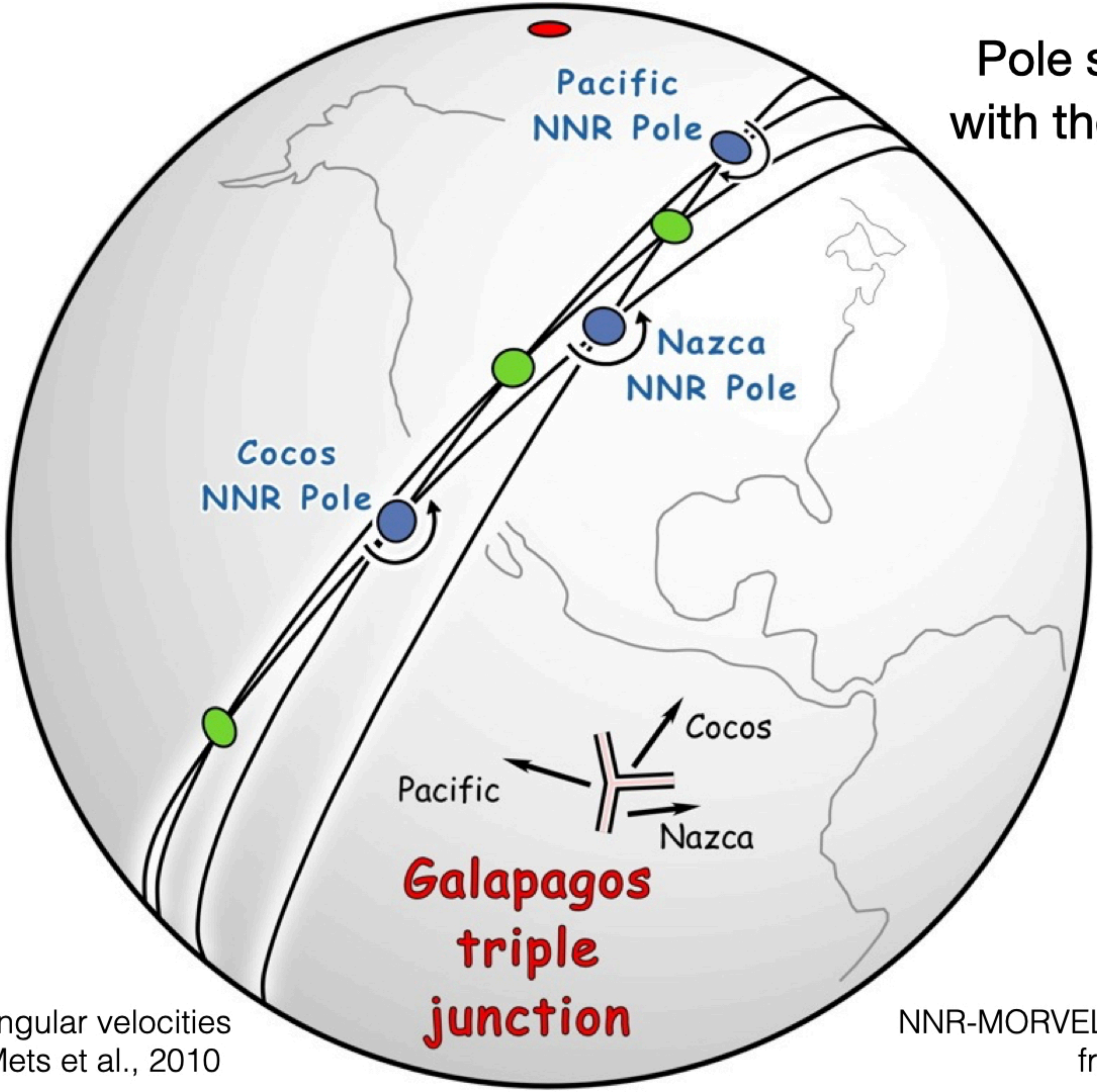
Extended rift zone at Afar triple junction, 5 Ma in the future



The base map was made with GeoMapApp (www.geomapapp.org)

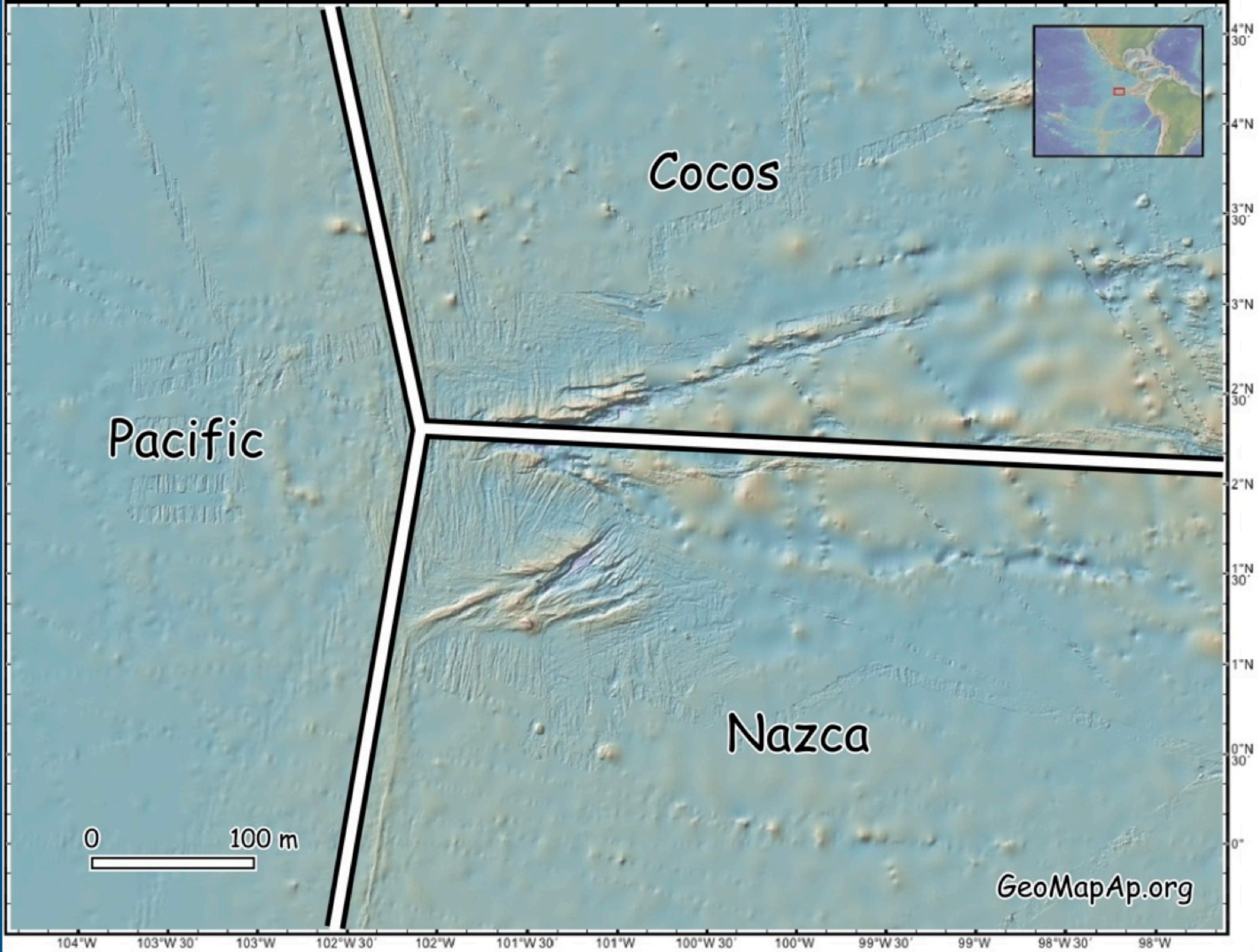
Collins, 2019 Fig. 13

Pole system associated with the Galapagos triple junction

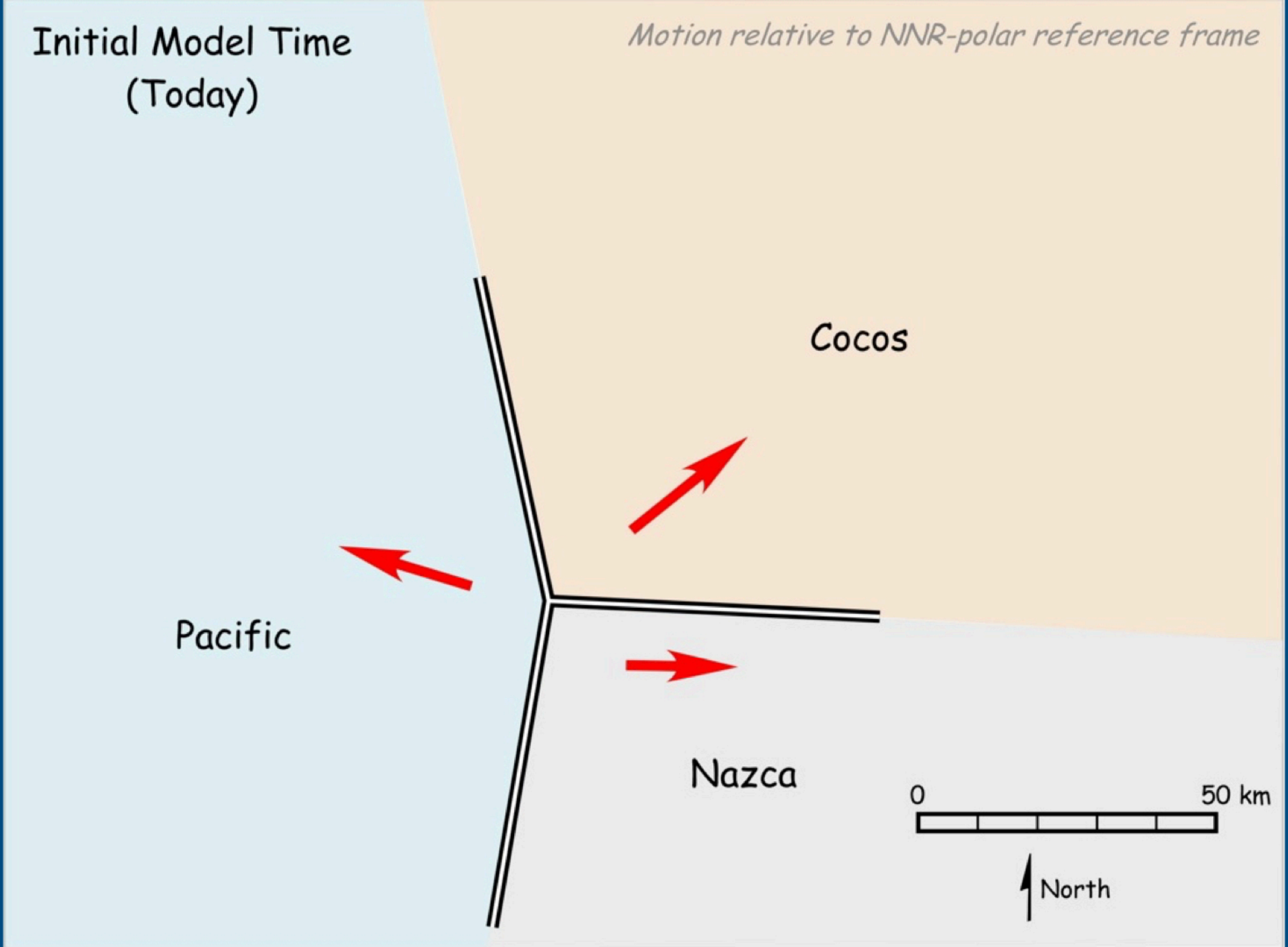


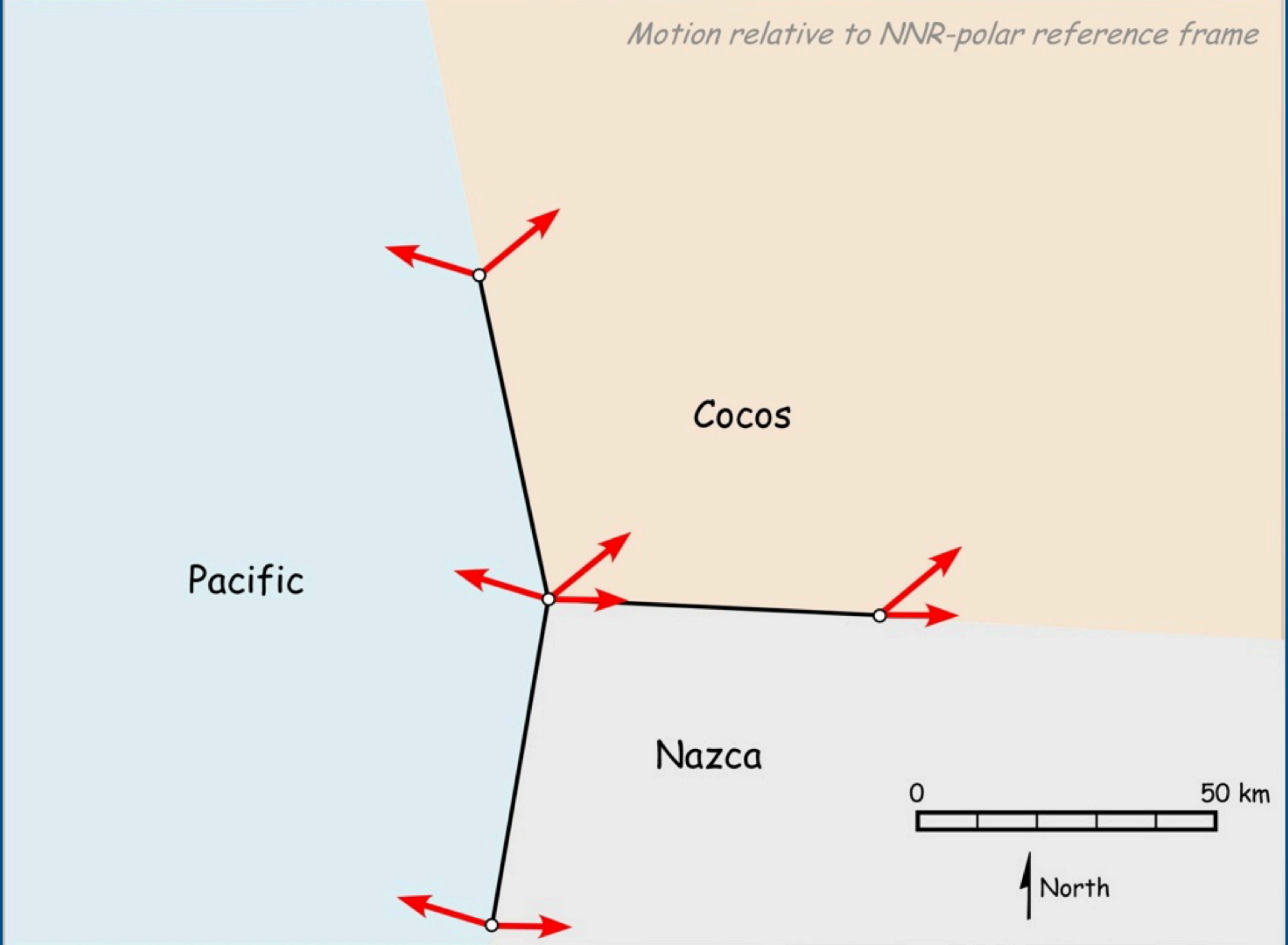
MORVEL angular velocities
from DeMets et al., 2010

NNR-MORVEL56 angular velocities
from Argus et al., 2011

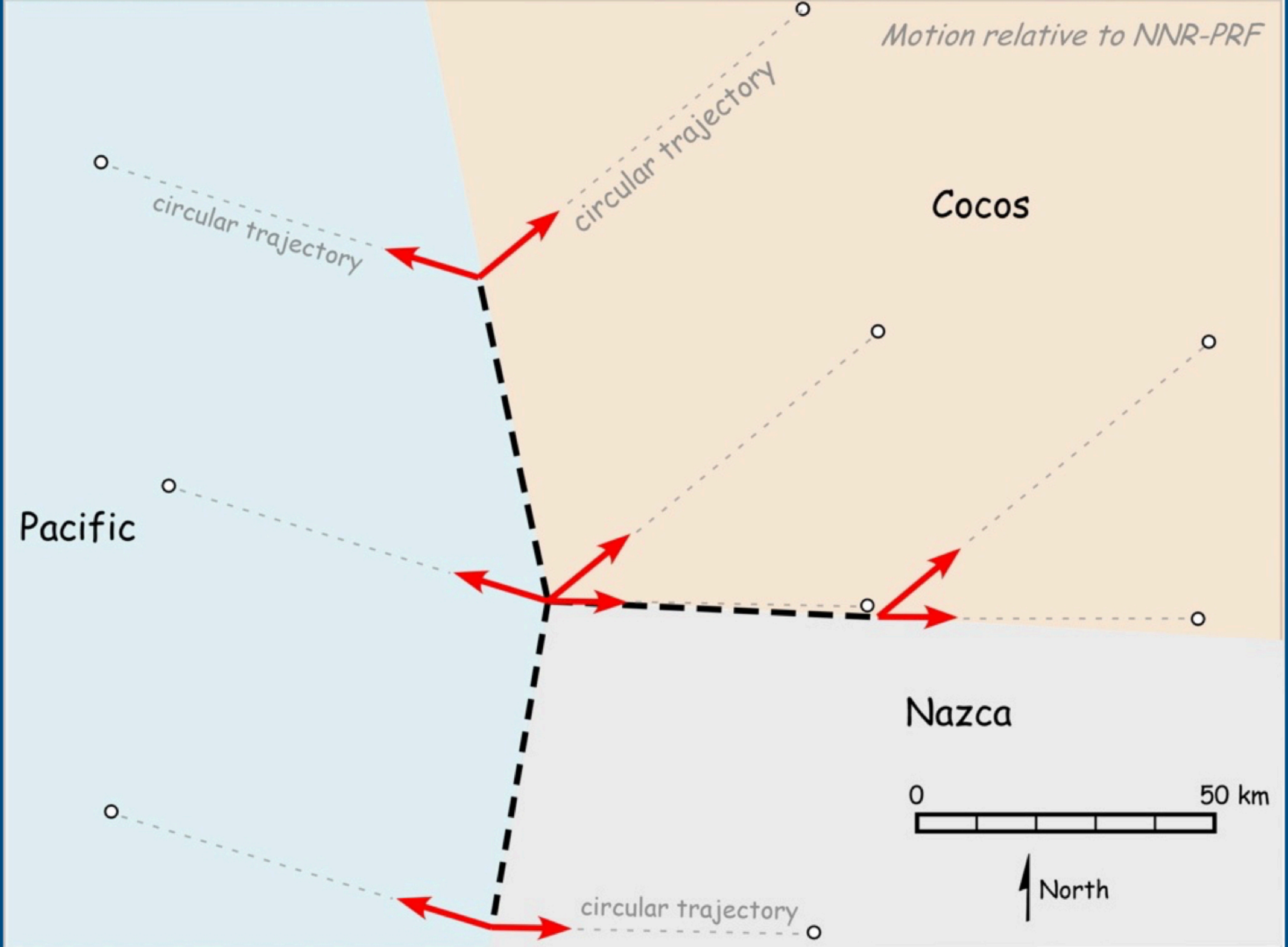


Cocos
Pacific
Nazca
0
100 m
GeoMapAp.org
4°N 30'
4°N
3°N 30'
3°N
2°N 30'
2°N
1°N 30'
1°N
0°N 30'
0°
104°W
103°W 30'
103°W
102°W 30'
102°W
101°W 30'
101°W
100°W 30'
100°W
99°W 30'
99°W
98°W 30'
98°W

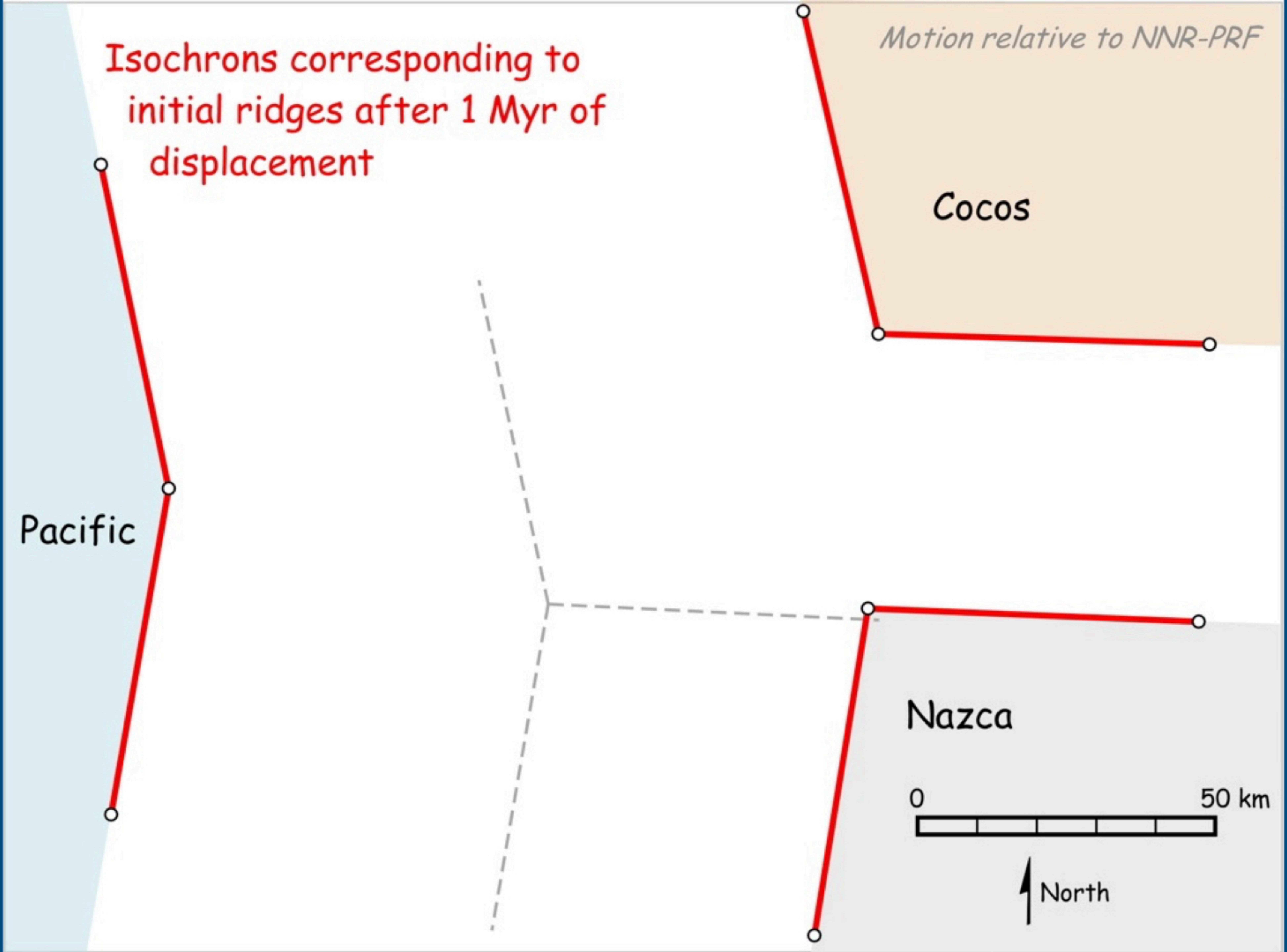

Initial Model Time
(Today)
Motion relative to NNR-polar reference frame
Cocos
Pacific
Nazca
0
50 km
North

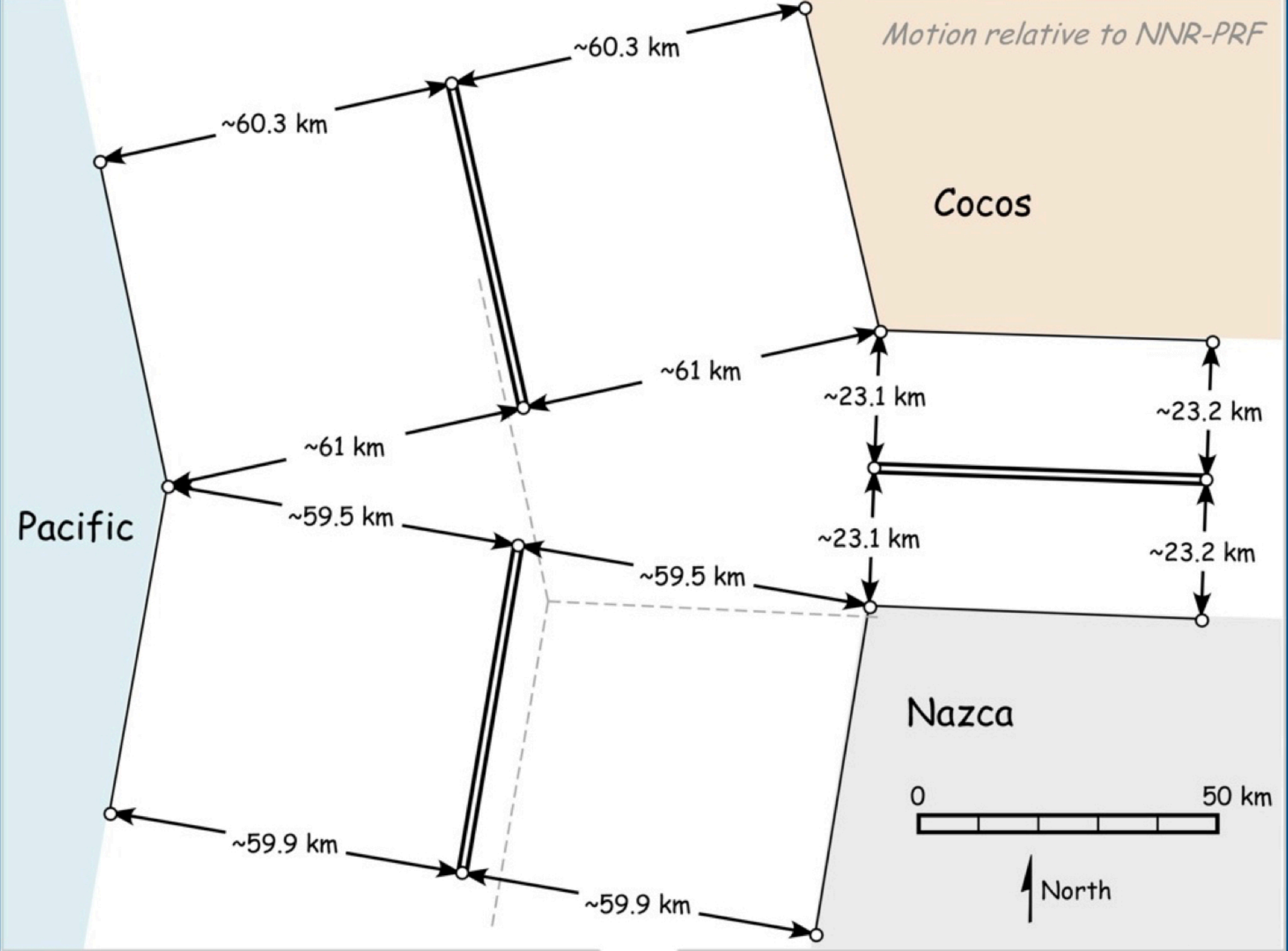


Motion relative to NNR-polar reference frame
Cocos
Pacific
Nazca
0
50 km
North

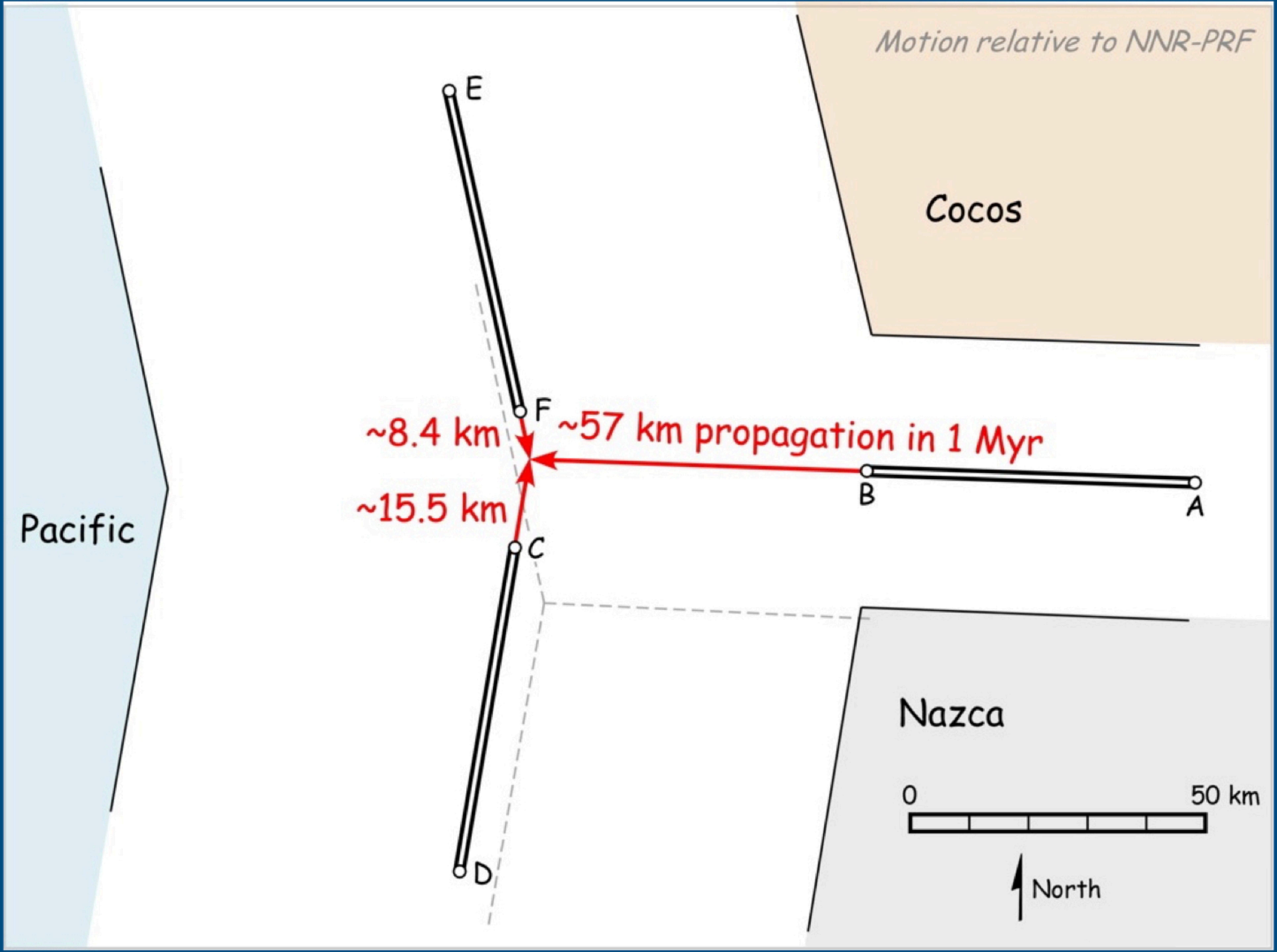


Motion relative to NNR-PRF
circular trajectory
circular trajectory
Cocos
Pacific
Nazca
0
50 km
North
circular trajectory

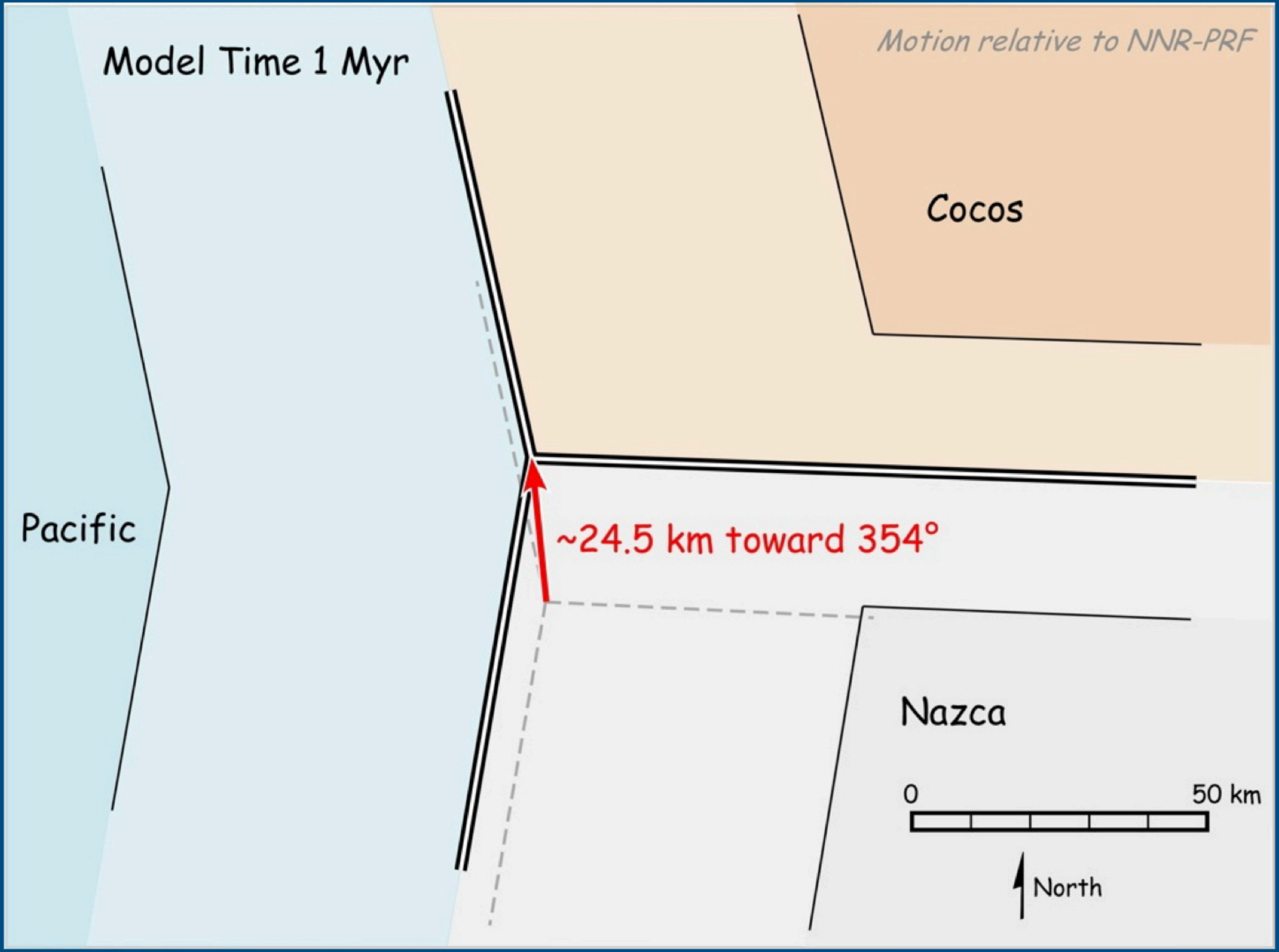

Isochrons corresponding to initial ridges after 1 Myr of displacement
Motion relative to NNR-PRF
Cocos
Pacific
Nazca
0
50 km
North

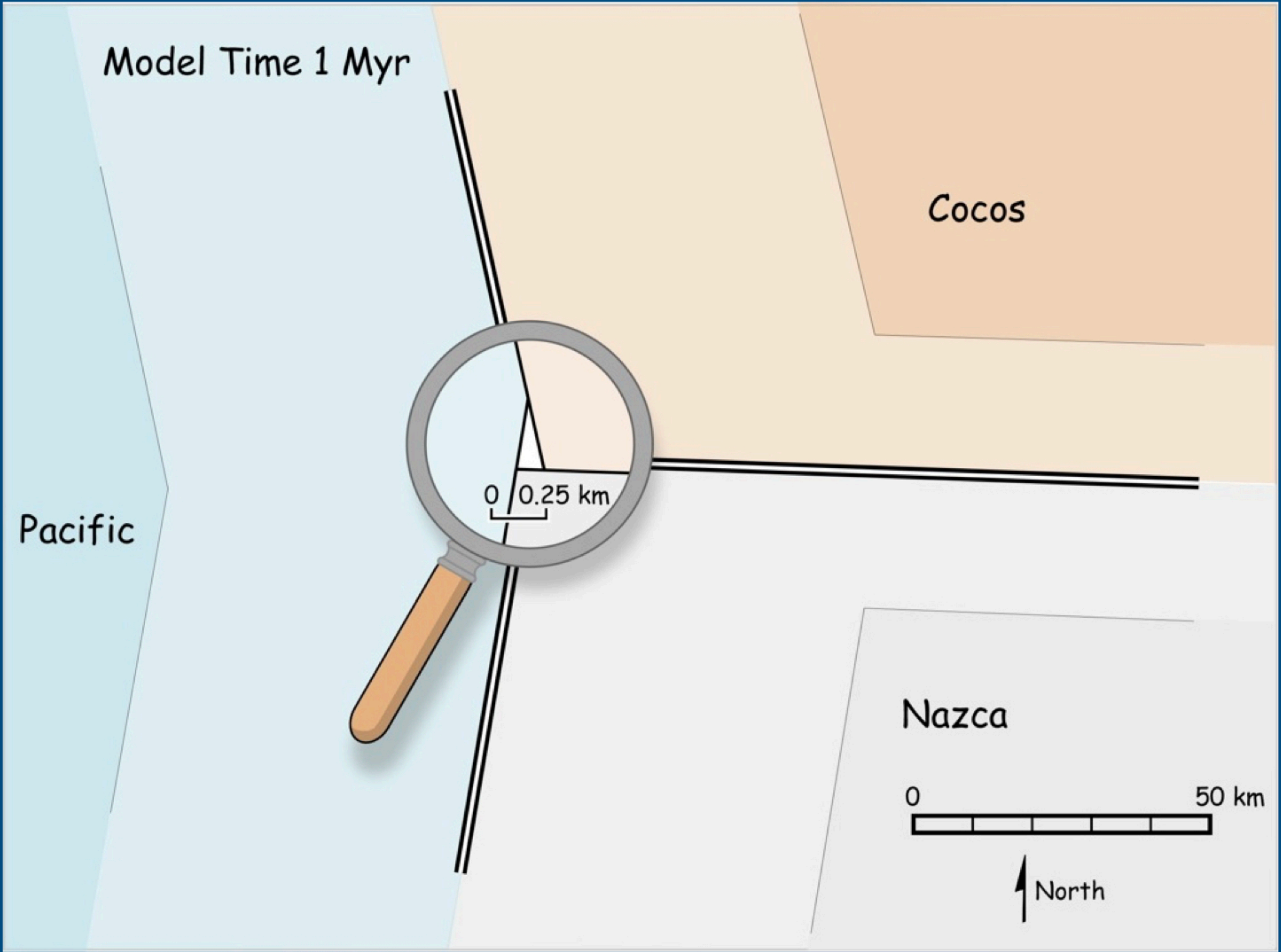


Motion relative to NNR-PRF
~60.3 km
~60.3 km
Cocos
~61 km
~61 km
~23.1 km
~23.2 km
Pacific
~59.5 km
~59.5 km
~23.1 km
~23.2 km
Nazca
0
50 km
~59.9 km
~59.9 km
North

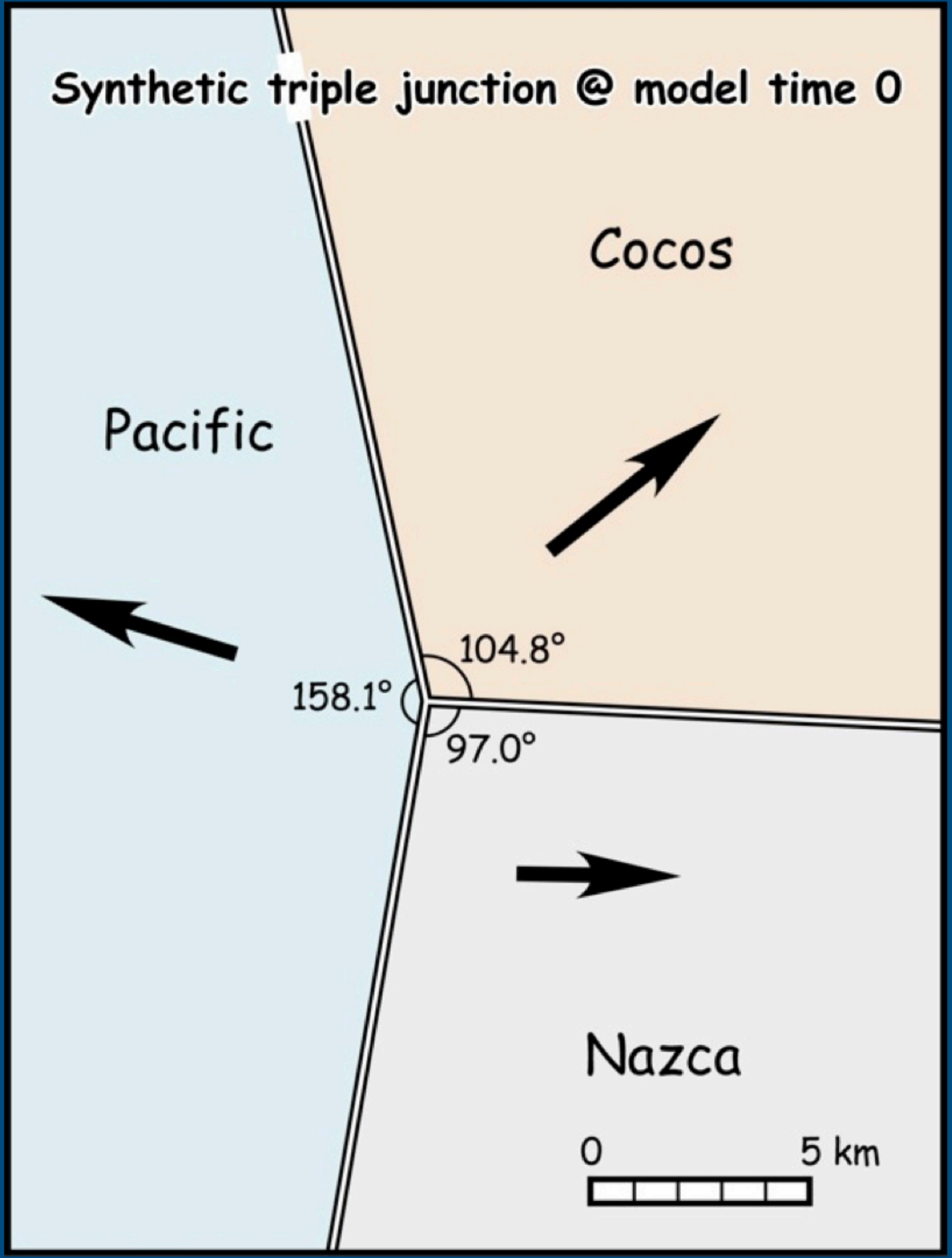


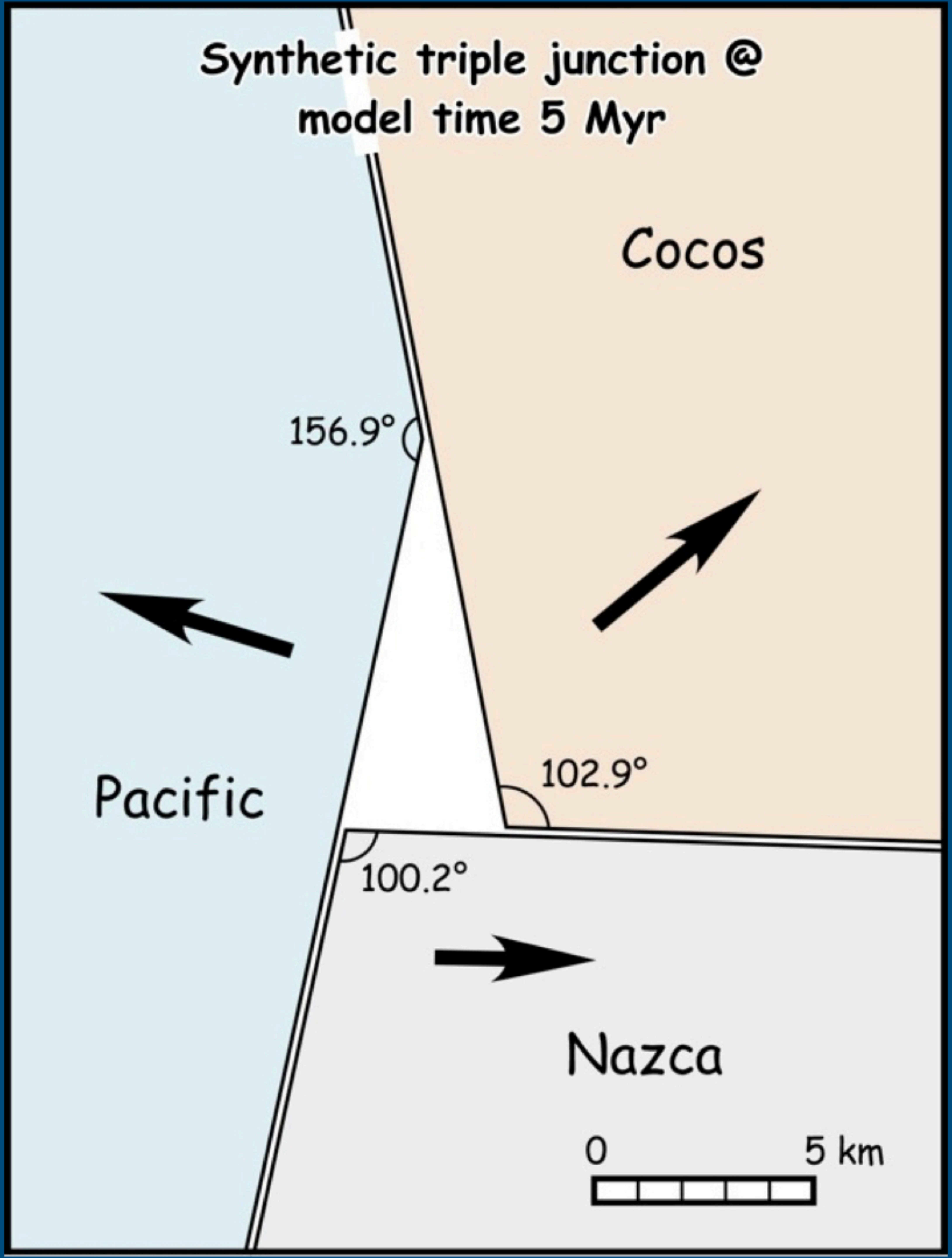
Motion relative to NNR-PRF
E
Cocos
F
~8.4 km
~57 km propagation in 1 Myr
B
A
~15.5 km
Pacific
C
Nazca
0
50 km
D
North

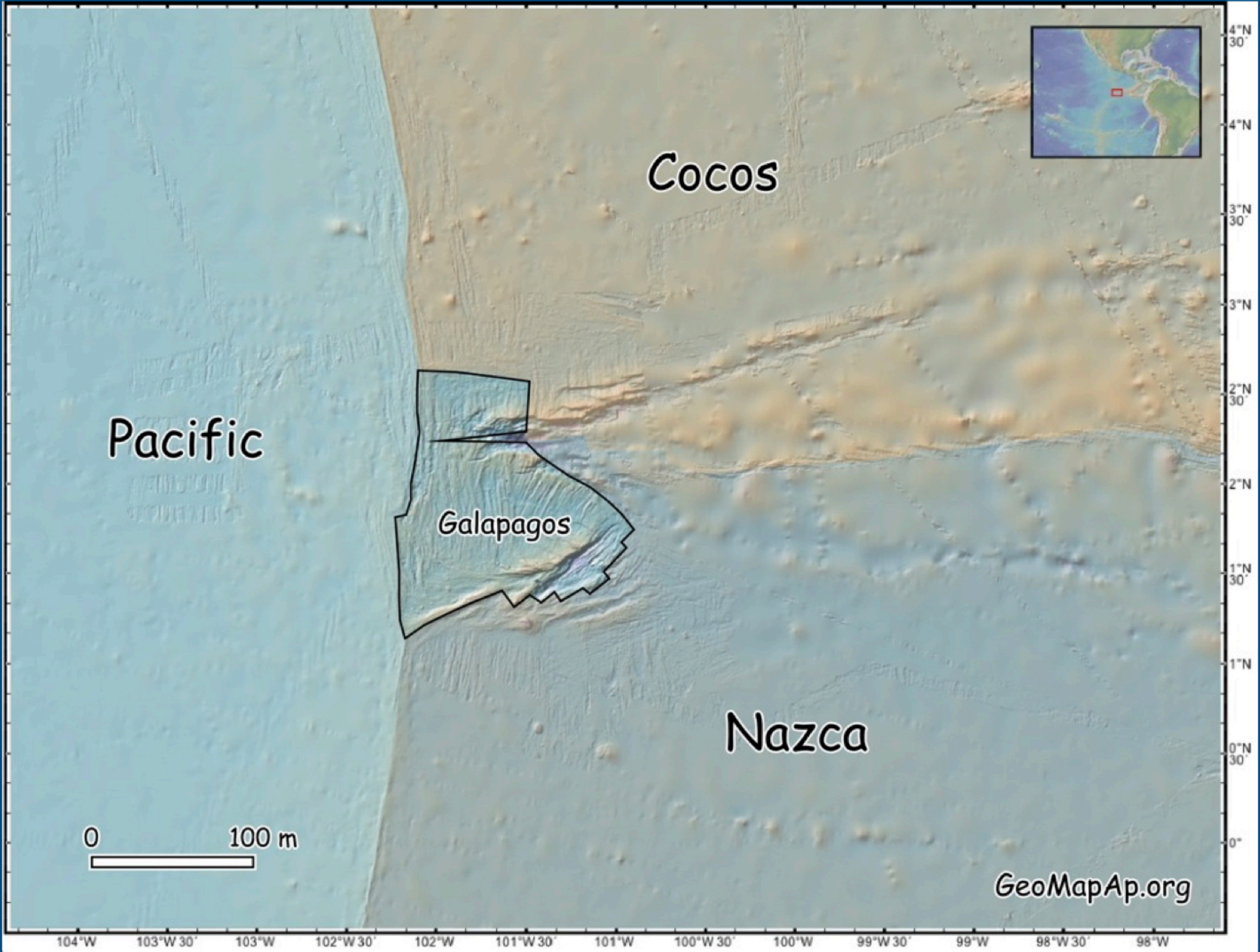

Model Time 1 Myr
Motion relative to NNR-PRF
Cocos
Pacific
~24.5 km toward 354°
Nazca
0
50 km
North

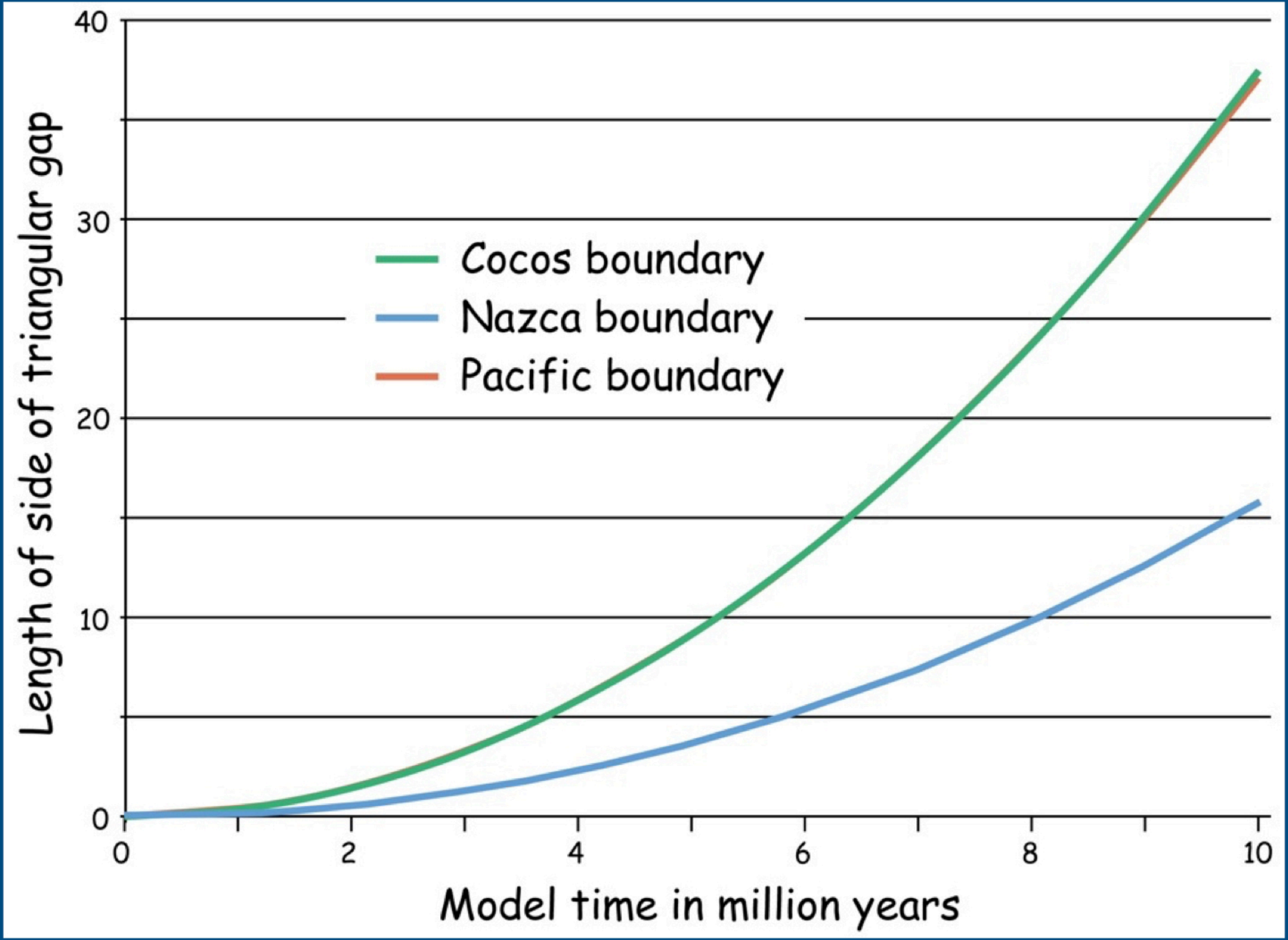


Model Time 1 Myr
Cocos
Pacific
0
0.25 km
Nazca
0
50 km
North


Synthetic triple junction @ model time 0
Cocos
Pacific
104.8°
158.1°
97.0°
Nazca
0
5 km

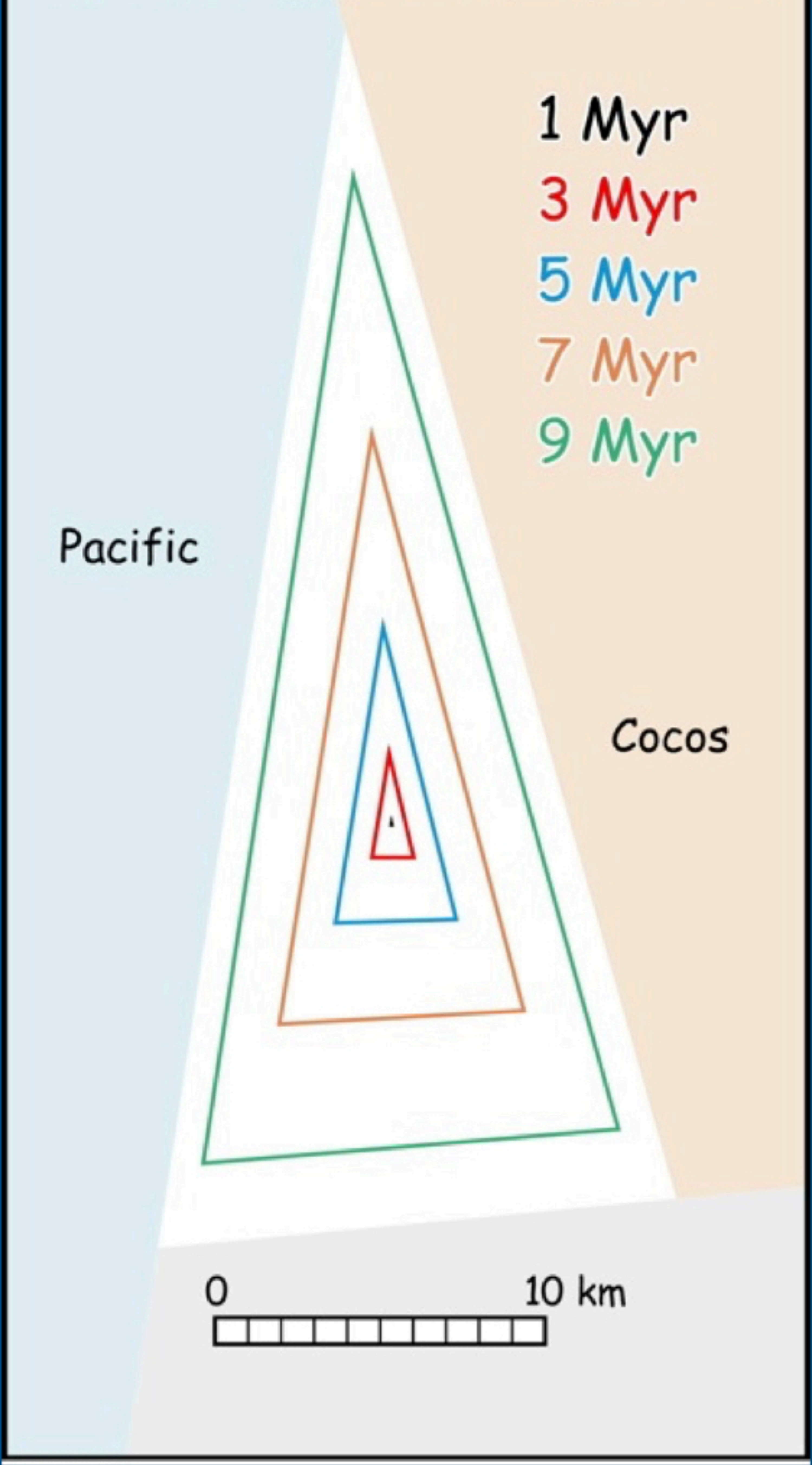

Synthetic triple junction @
model time 5 Myr
Cocos
156.9°
102.9°
Pacific
100.2°
Nazca
0
5 km


Cocos
Pacific
Galapagos
Nazca
0
100 m
GeoMapAp.org
4°N 30'
4°N
3°N 30'
3°N
2°N 30'
2°N
1°N 30'
1°N
0°N 30'
0°
104°W
103°W 30'
103°W
102°W 30'
102°W
101°W 30'
101°W
100°W 30'
100°W
99°W 30'
99°W
98°W 30'
98°W

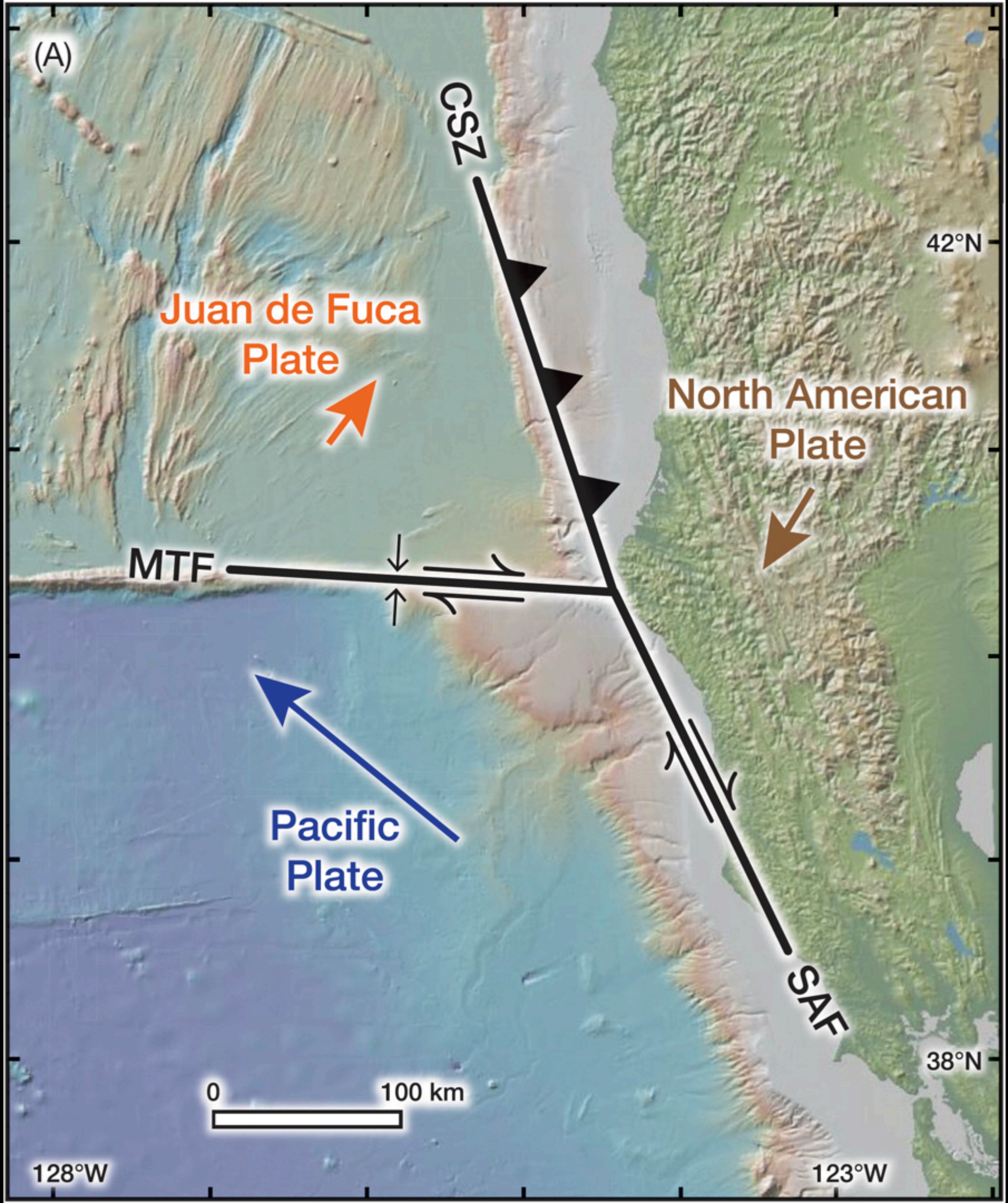


Cocos boundary
Nazca boundary
Pacific boundary
Length of side of triangular gap
0
10
20
30
40
0
2
4
6
8
10
Model time in million years

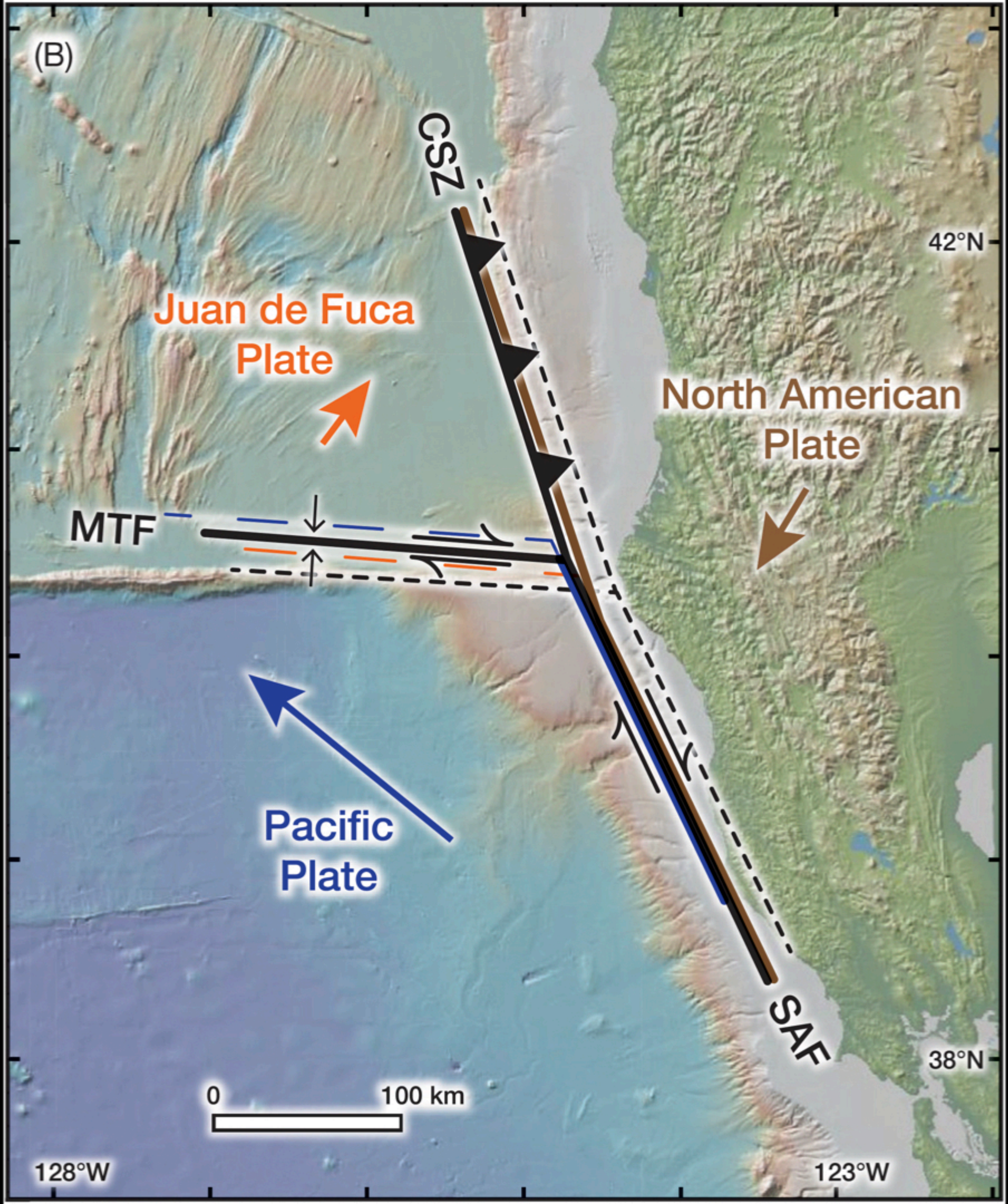
Growth of gap at triple junction




Google Earth



Cronin, 2021; GeoMapApp



Cronin, 2021; GeoMapApp

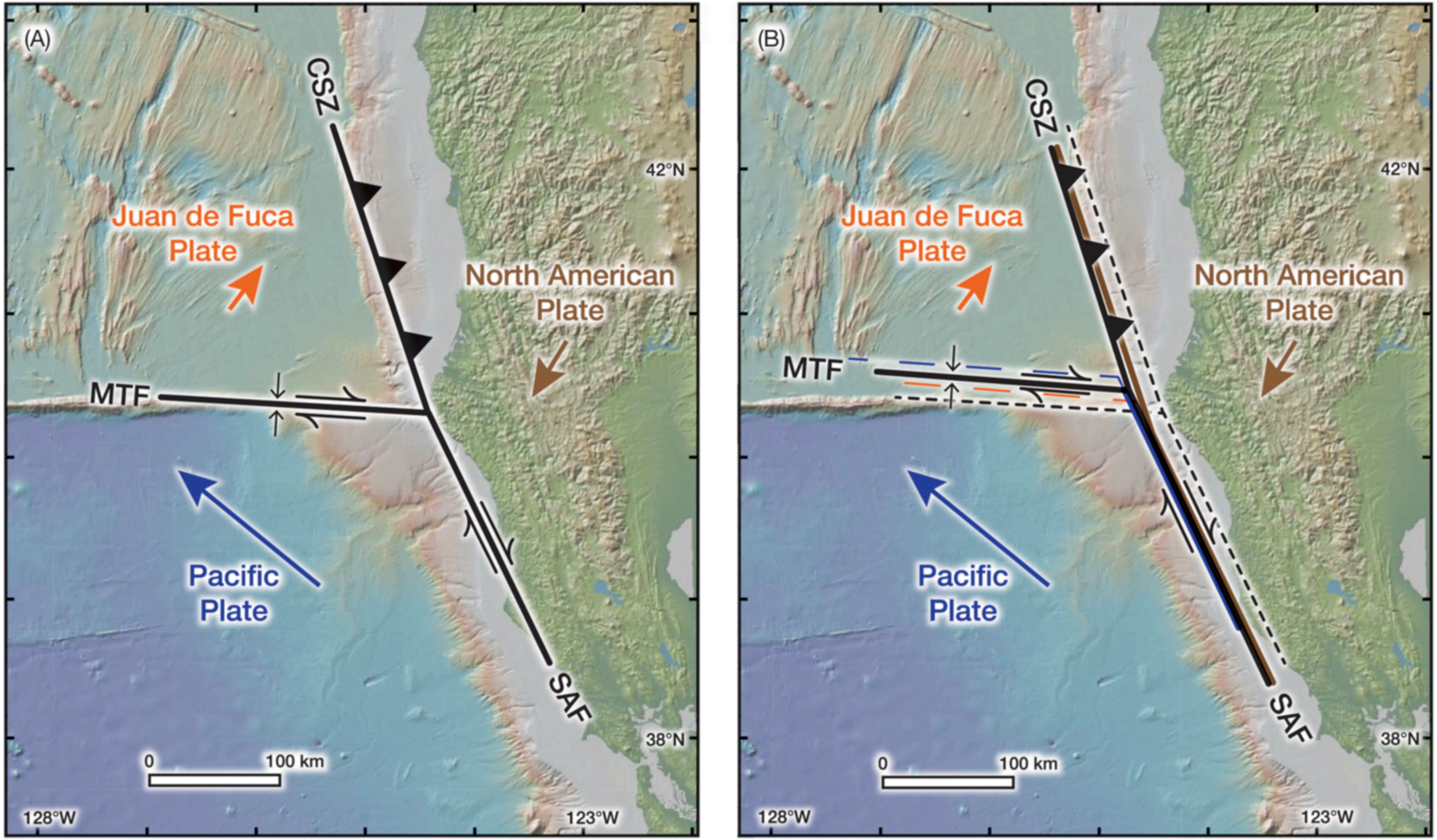


Fig. 7 (A) One trench and two transform boundaries (*black lines*) converge at the Mendocino (PA-NA-JF) triple junction today, simplified from Bird (2003). *Arrows* indicate direction each plate is moving relative to the hotspot reference frame of Wang et al. (2017). *CSZ*, Cascadia Subduction Zone; *MTF*, Mendocino Transform Fault; *SAF*, San Andreas Fault. Both shortening and right-lateral strike slip occur along the MTF. (B) Current plate boundaries (*colored lines*) and predicted location of the triple junction (*black lines*) after 1 Myr of displacement. Base maps are from GeoMapApp.org.