Lectures 3-5: Tectonics on a Sphere

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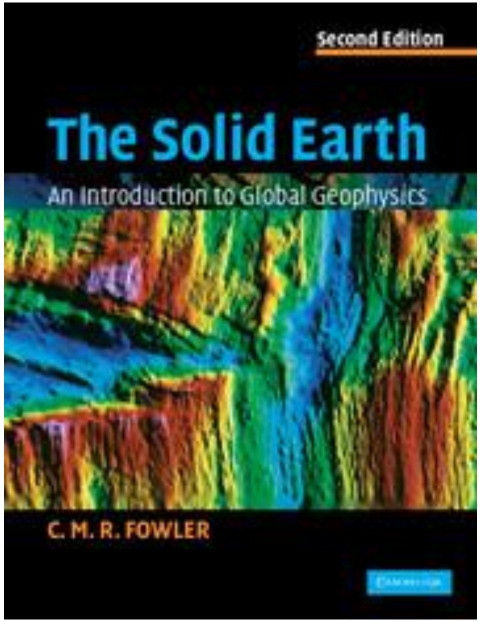
Lecture Schedule

Date	Day	Time	L/R	Broad Topic(s)
Module 1: Earth Structure and Plate Tectonics				
				Internal structure of the Earth
			L1	Plate Tectonics: kinematic Earth, analyzing plate boundaries
			L2	**Tectonics on a sphere: Geometry of Plate Tectonics**
			L3	**Triple Junction of plates: stability and significance**
			L4	**Absolute plate motion and plate driving forces**

Tectonics on a Sphere



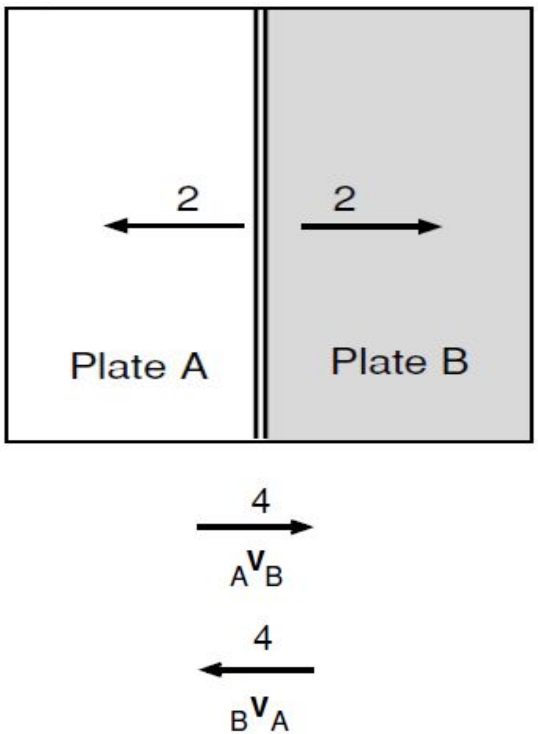
Chapter 2

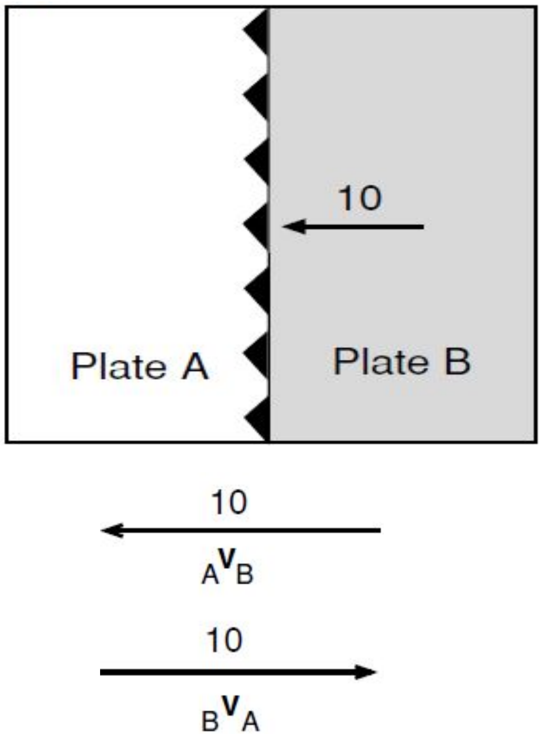
Geometry of Plate Tectonics

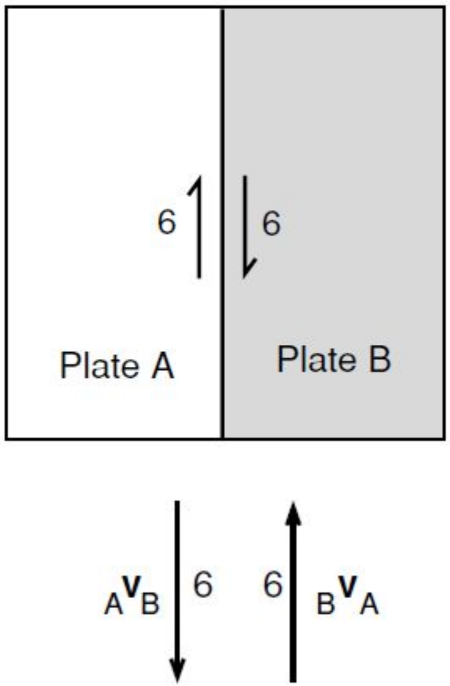
Geometry of Plate Tectonics

Representation of Plate boundaries on A Flat Earth

Ridge (R) **Trench** (T) **Transform Fault** (F)



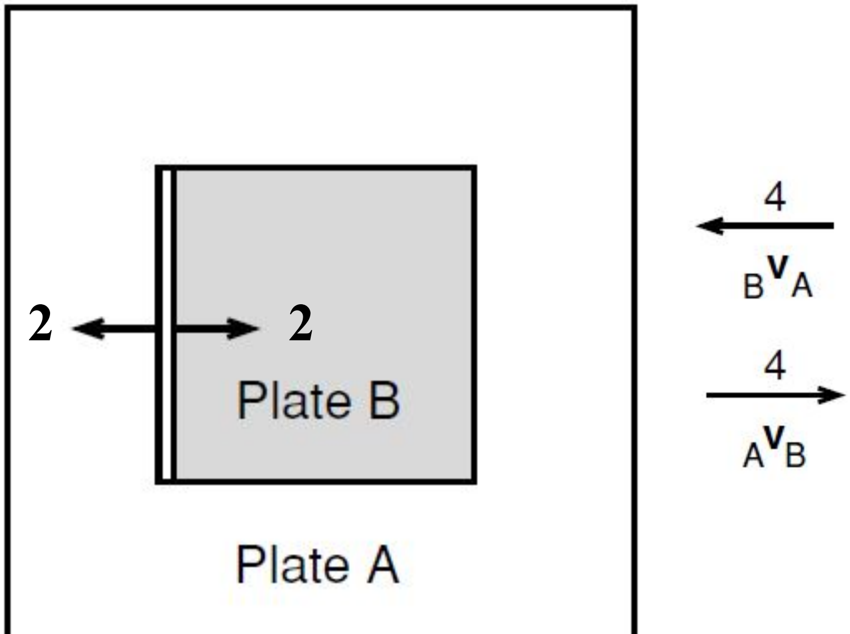


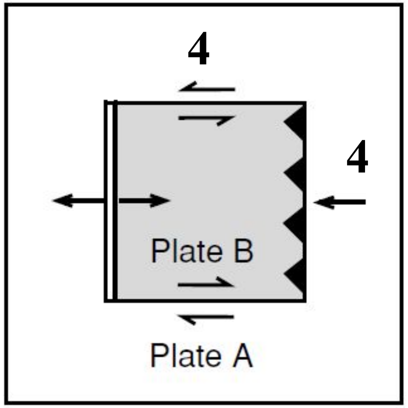


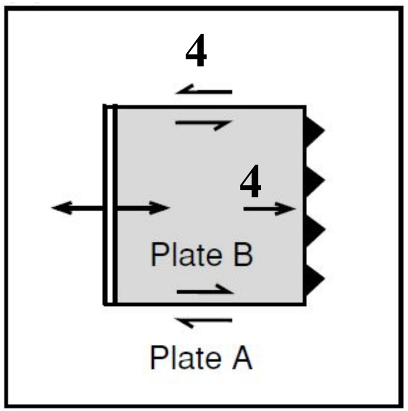
Relative Velocities along plate boundaries: The Velocity Vector

Relative Velocity of B w.r.t A : $_AV_B = V_B - V_A$ **and** $_AV_B = -\,_BV_A$

Two Plate Model





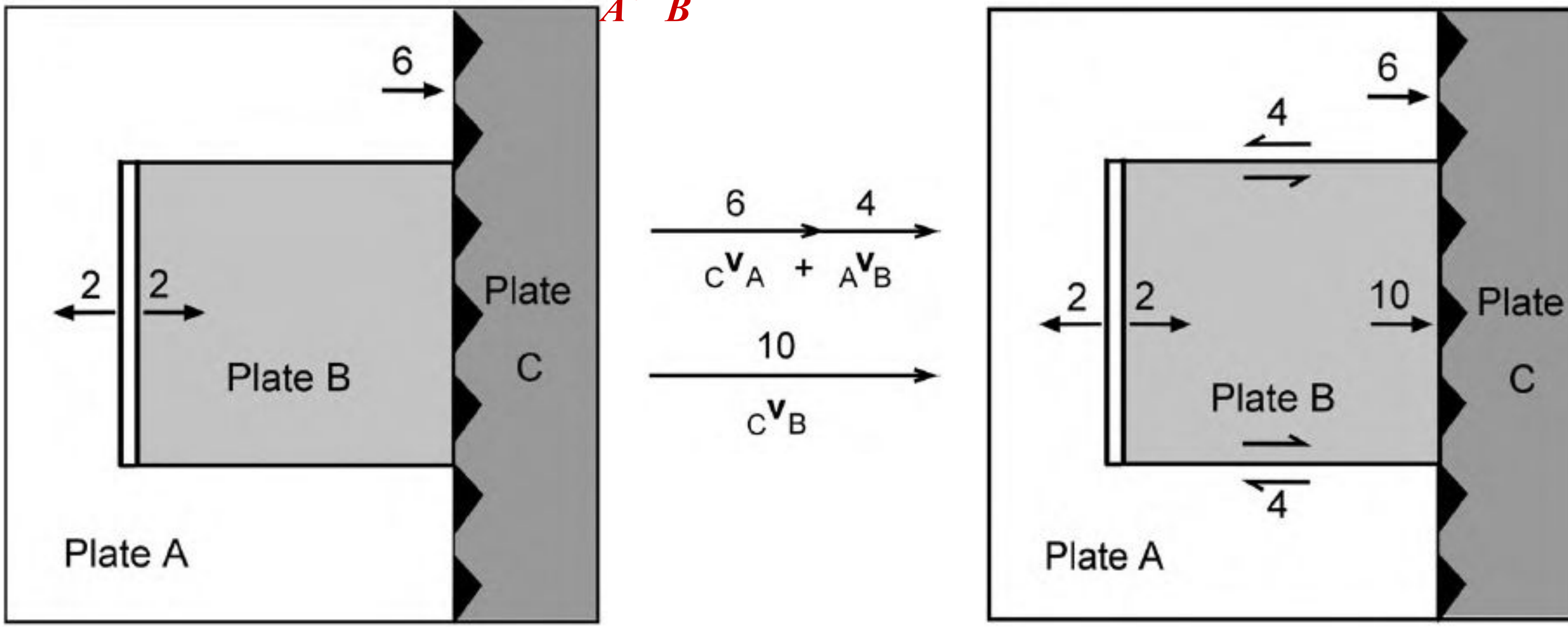


<u>Eastern Boundary of Plate B:</u> Subduction at a rate of 4 cm/yr

1. **A subducts (Plate B grows in size) or**
2. **B subducts (Plate B will be totally consumed after a while)**

Three Plate Model

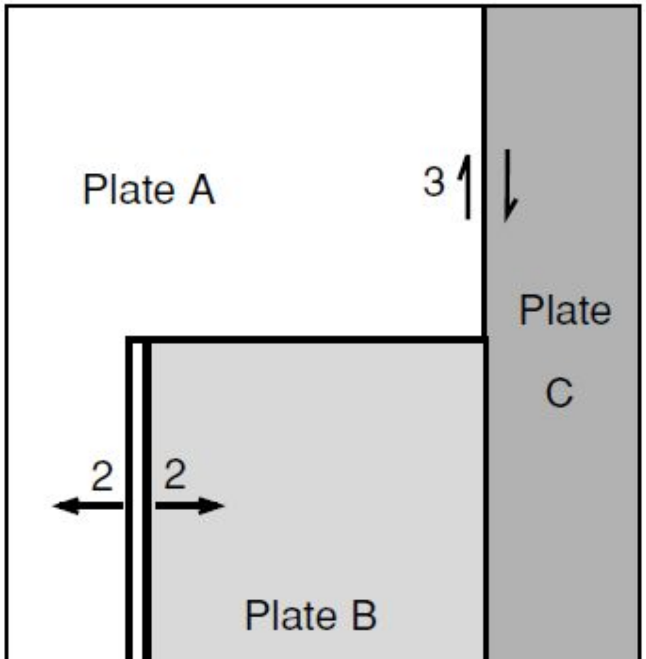
$${}_{C}V_{B} = {}_{C}V_{A} + {}_{A}V_{B}$$

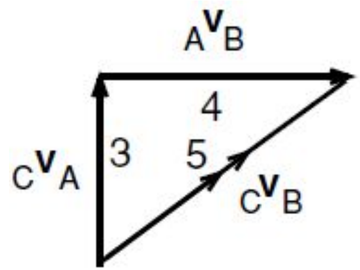


Net rate of destruction of Plate B = 10 – 2 = 8 cm/yr

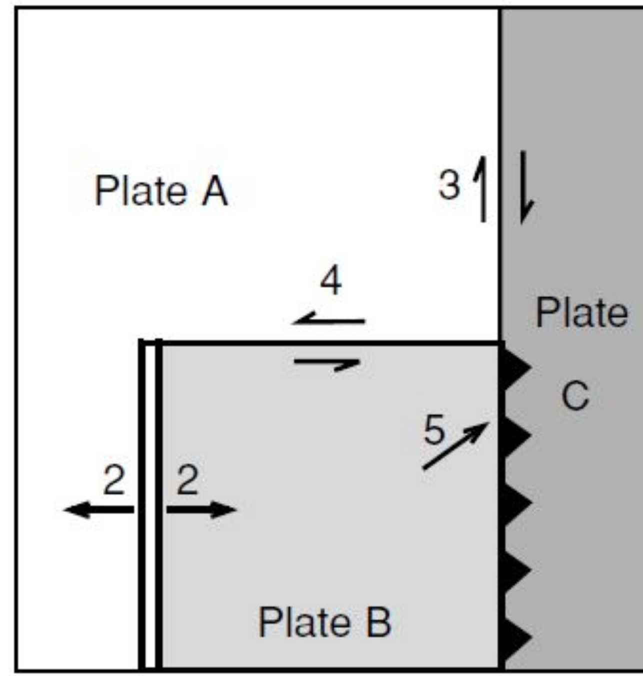
Three Plate Model

Oblique Subduction





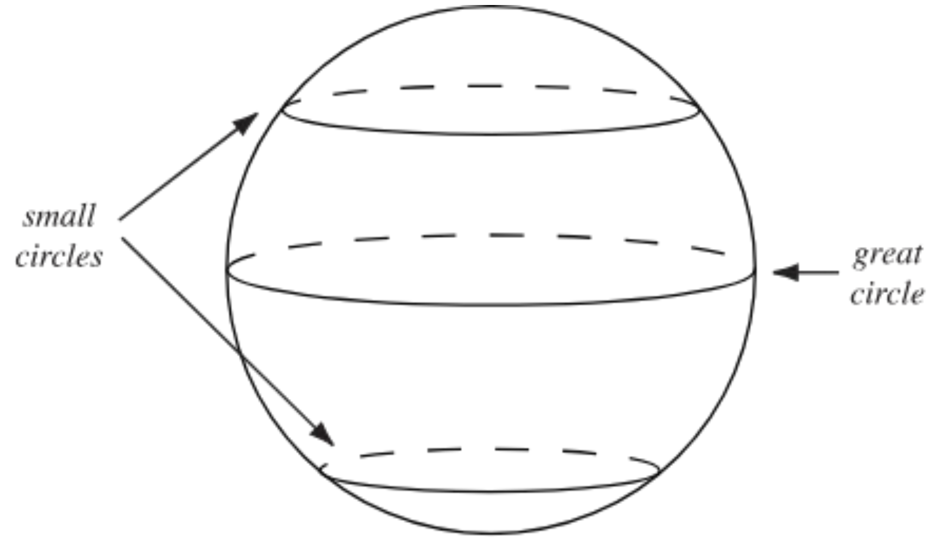
$${}_CV_B = {}_CV_A + {}_AV_B$$



Common Terms (which you already know)

Great Circle

Small Circle



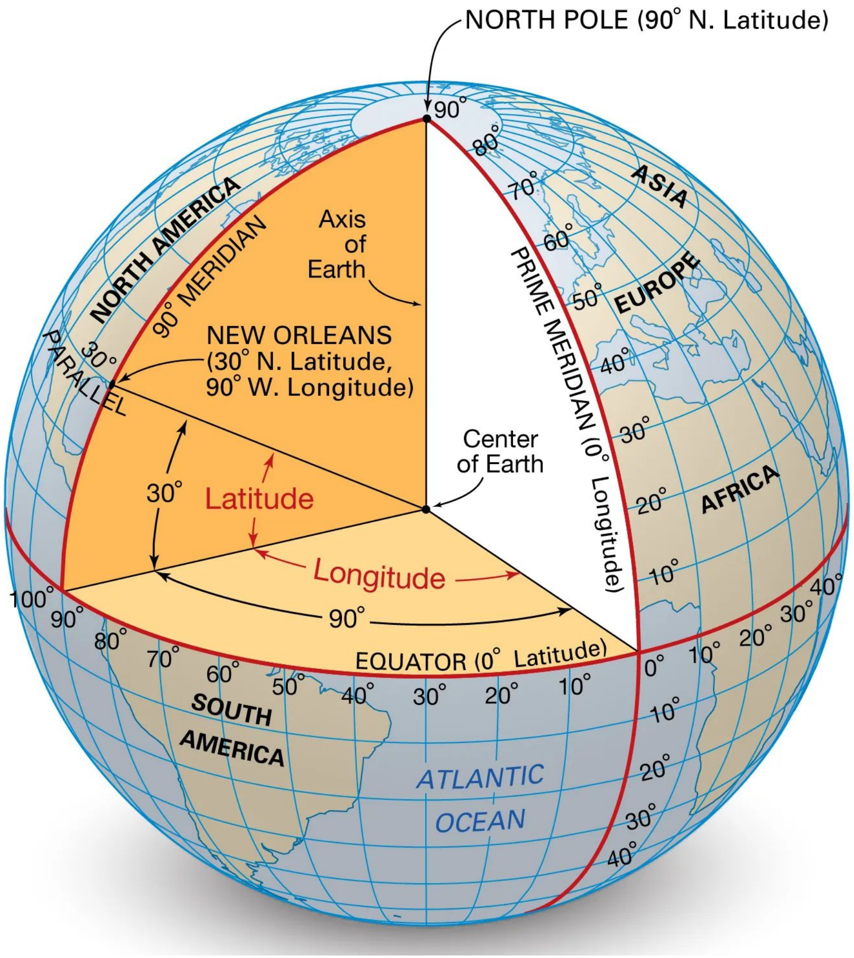
Common Terms (which you already know)

Great Circle

Small Circle

Latitude (λ)

Longitude (ϕ)



Common Terms (which you already know)

Great Circle

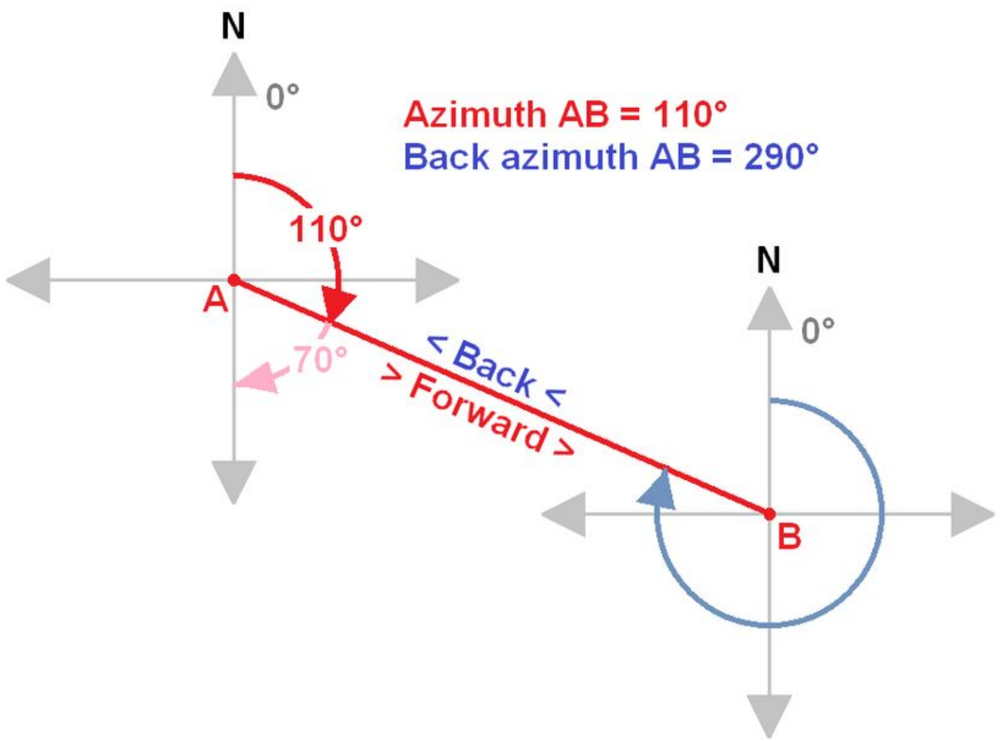
Small Circle

Latitude (λ)

Longitude (ϕ)

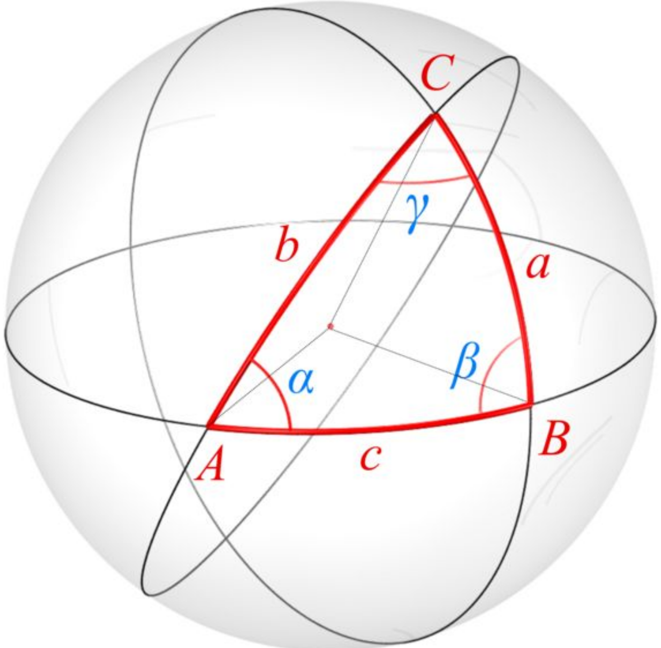
Azimuth (Az)

Back-Azimuth (BAz)

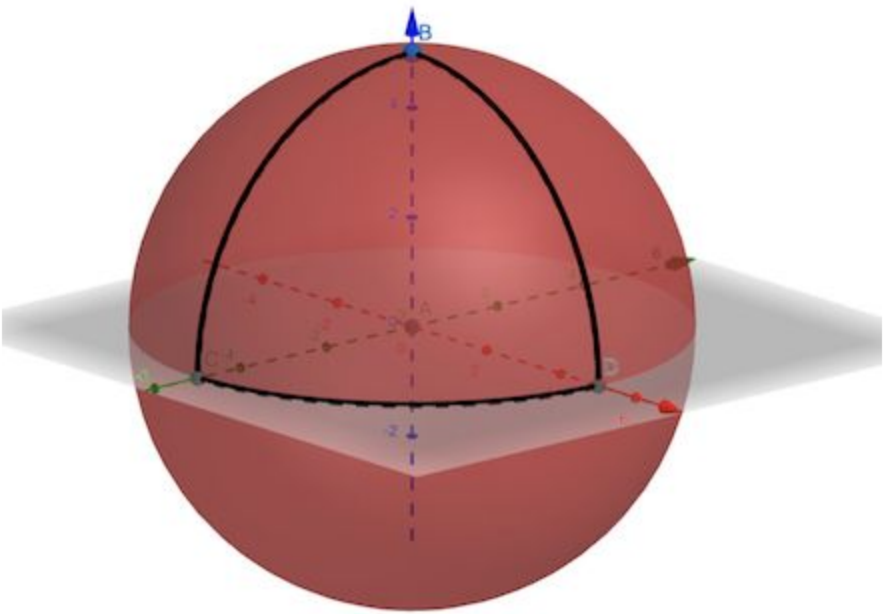


Spherical Trigonometry

Spherical Triangle?

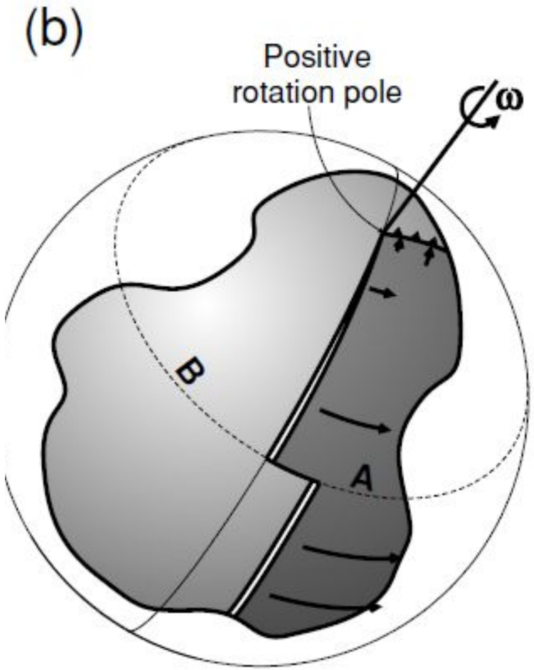


Sum of internal angles?



180 < SIA < 540

Rotation Vectors and Rotation Poles: (Spherical Earth)

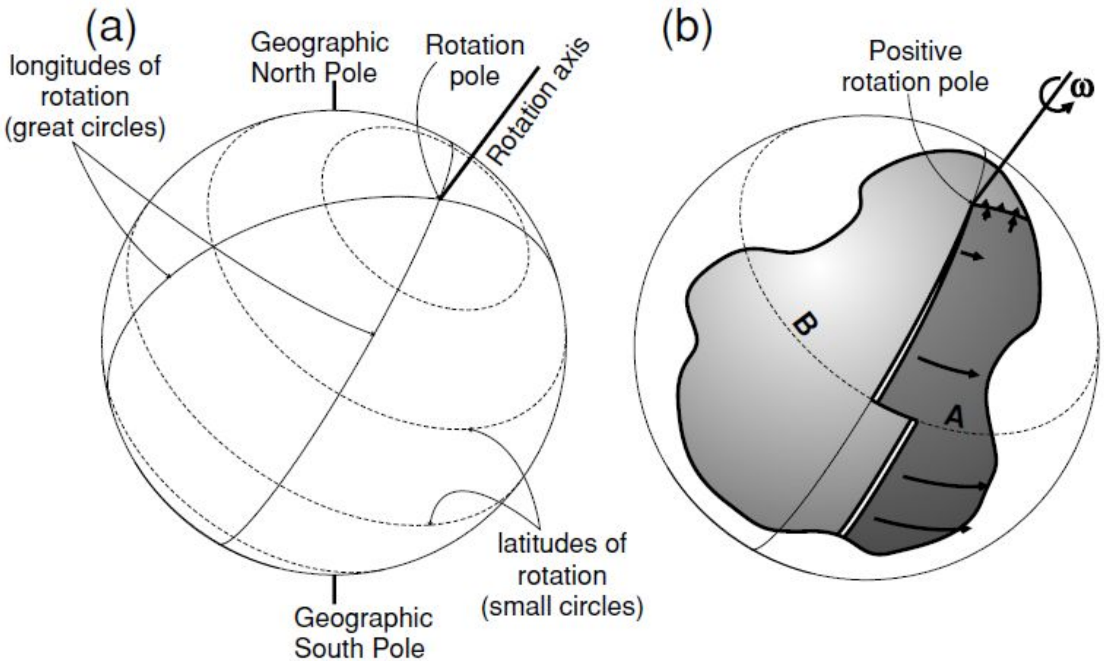


<u>Euler's fixed point theorem</u>

"The most general displacement of a rigid body (plates) with a fixed point (center of the Earth) is equivalent to a rotation about an axis through that fixed point"

Corollary: ***"Every displacement from one position to another on the surface of the Earth can be regarded as a rotation about a <u>suitably chosen axis</u>*** **(Rotation axis)** ***passing through the center of the Earth"***

Rotation Vectors and Rotation Poles: (Spherical Earth)



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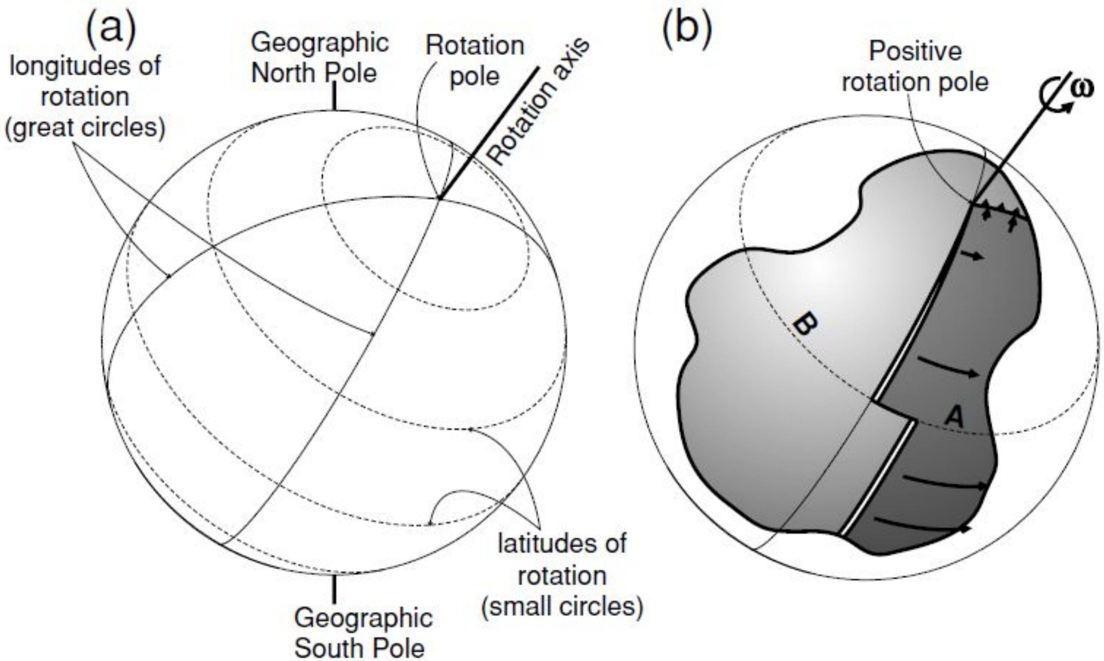
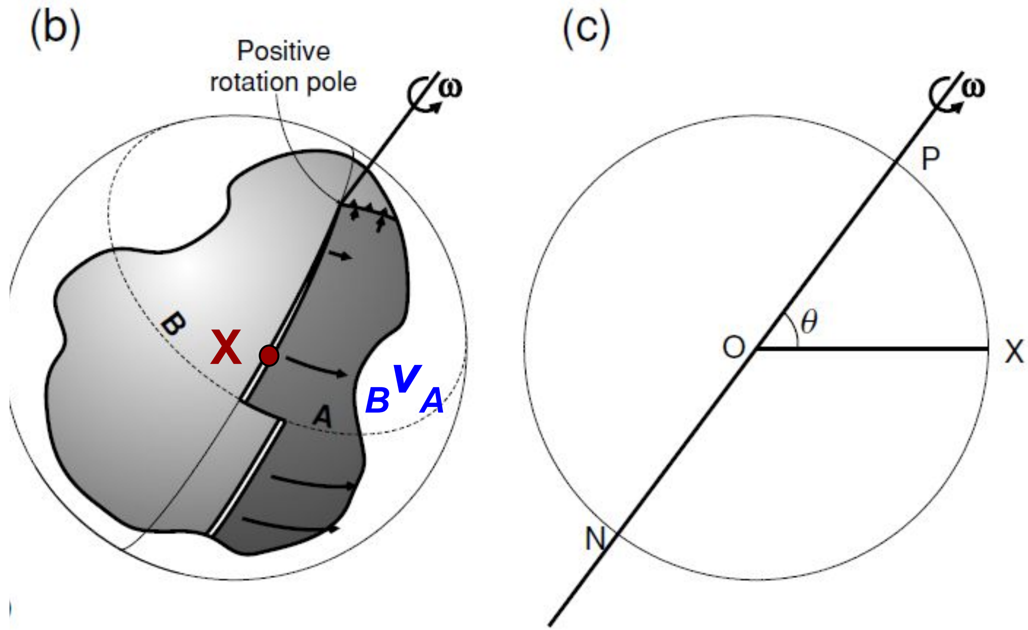
Rotation Vectors and Rotation Poles: (Spherical Earth)



The Rotation Axis cuts the surface of the Earth at two points called the Rotation Poles
+ve anti-clockwise rotation and -ve clockwise rotation when viewed from outside

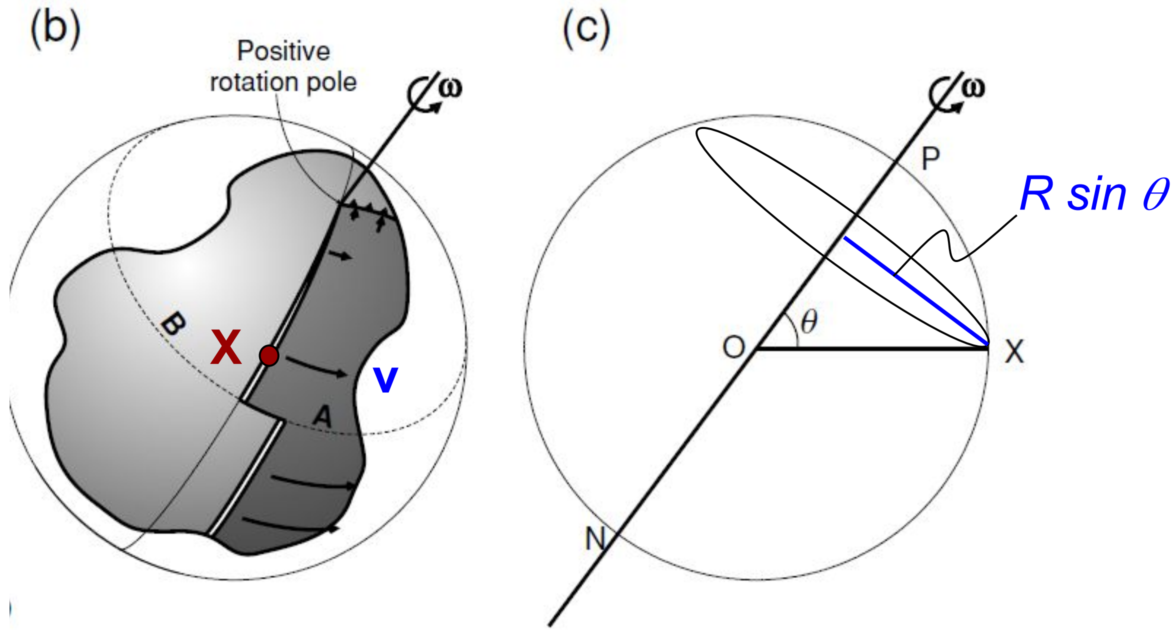
- **Their position describes the direction of motion of all points along the plate boundary**
- **The magnitude of angular velocity *(ω)* about the axis defines the magnitude of the relative motion between the two plates**

Rotation Vectors and Rotation Poles: (Spherical Earth)



Linear velocity: $_B v_A$ ***?***

Rotation Vectors and Rotation Poles: (Spherical Earth)



at θ = 90° (equator of rotation):
v = ω R (maximum)

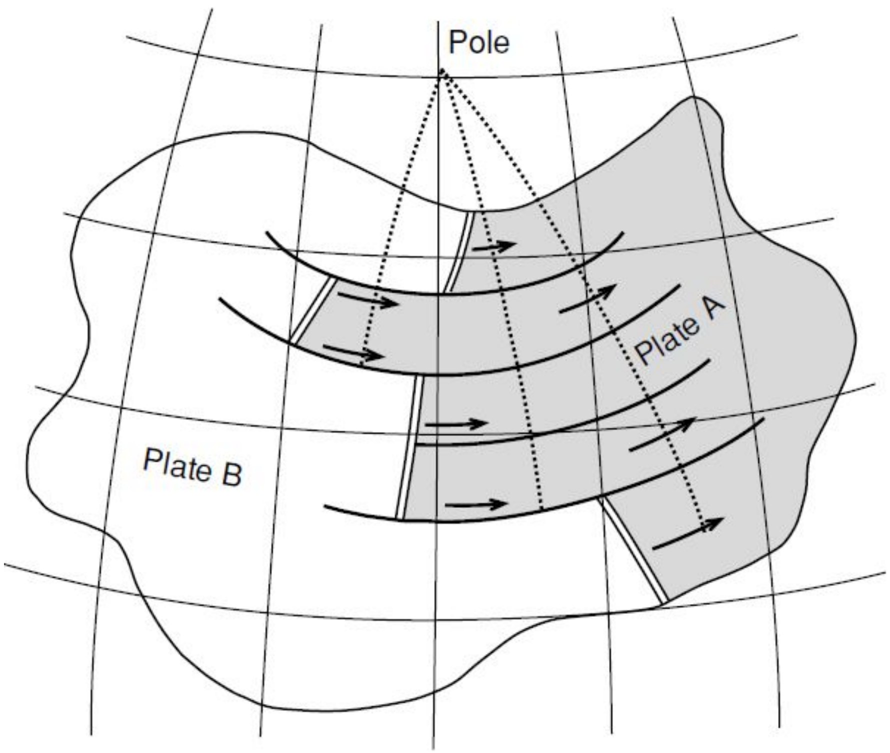
at θ = 0° (pole of rotation):
v = 0 (minimum)

Linear velocity: v = ω R sin θ

Varies along plate boundary

Present Day Plate Motions

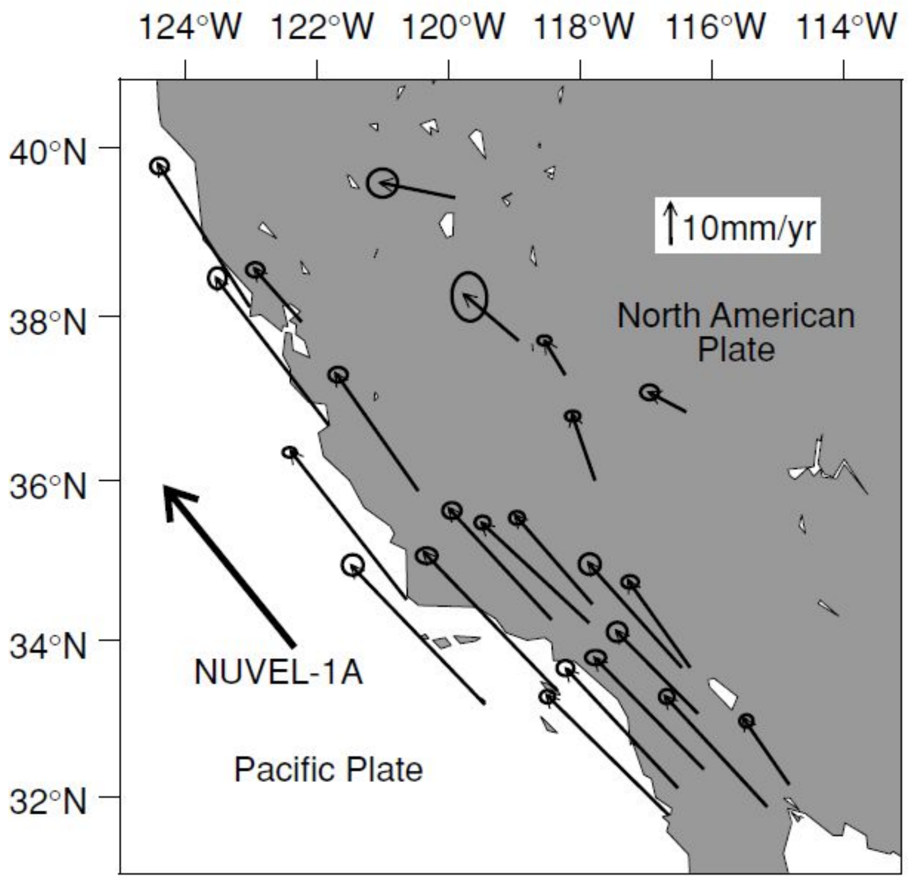
Determination of Rotation Poles and Rotation Vectors



- ❑ From strike of transform faults
- ❑ Spreading rate of accreting plate boundaries
- ❑ Fault plane solution for earthquakes along a plate boundary
- ❑ Plate boundaries crossing land by direct measurements

Present Day Plate Motions

Determination of Rotation Poles and Rotation Vectors



- GPS, satellite laser-ranging system, very long baseline interferometry (VLBI)

Calculation of Relative Motion at a Plate Boundary

Symbol	Meaning	Sign convention
λ_p	Latitude of rotation pole P	°N positive
λ_x	Latitude of point X on plate boundary	°S negative
ϕ_p	Longitude of rotation pole P	°W negative
ϕ_x	Longitude of point X on plate boundary	°E positive
$\mathbf{v}$	Velocity of point X on plate boundary	
v	Amplitude of velocity v	
β	Azimuth of the velocity with respect to north N	Clockwise positive
R	Radius of the Earth	
$\boldsymbol{\omega}$	Angular velocity about rotation pole P	

Calculation of Relative Motion at a Plate Boundary

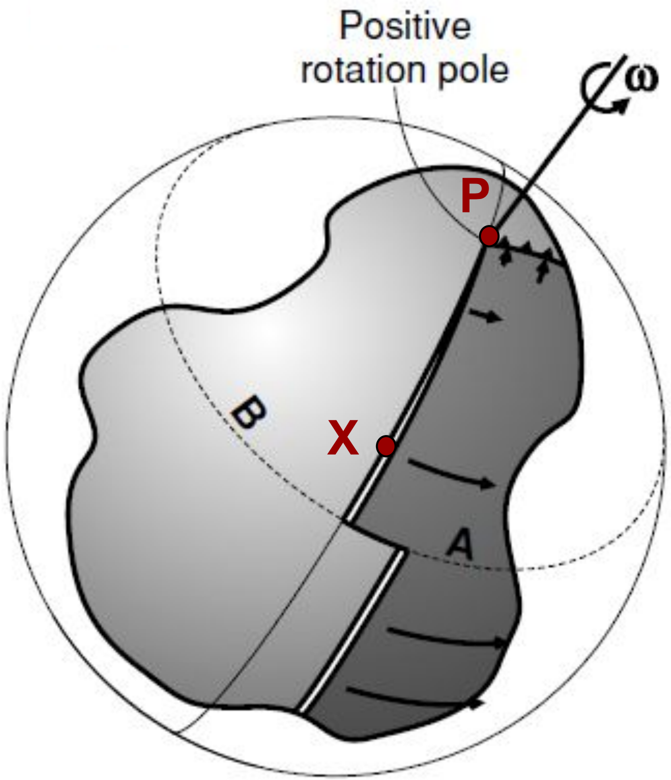
Given the Positive rotation pole (P) can you find the linear velocity (v) at X on the plate boundary?

P (λ_p, ϕ_p) & ${}_B\omega_A$

λ_p →Latitude of Rotation Pole

ϕ_p →Longitude of Rotation Pole

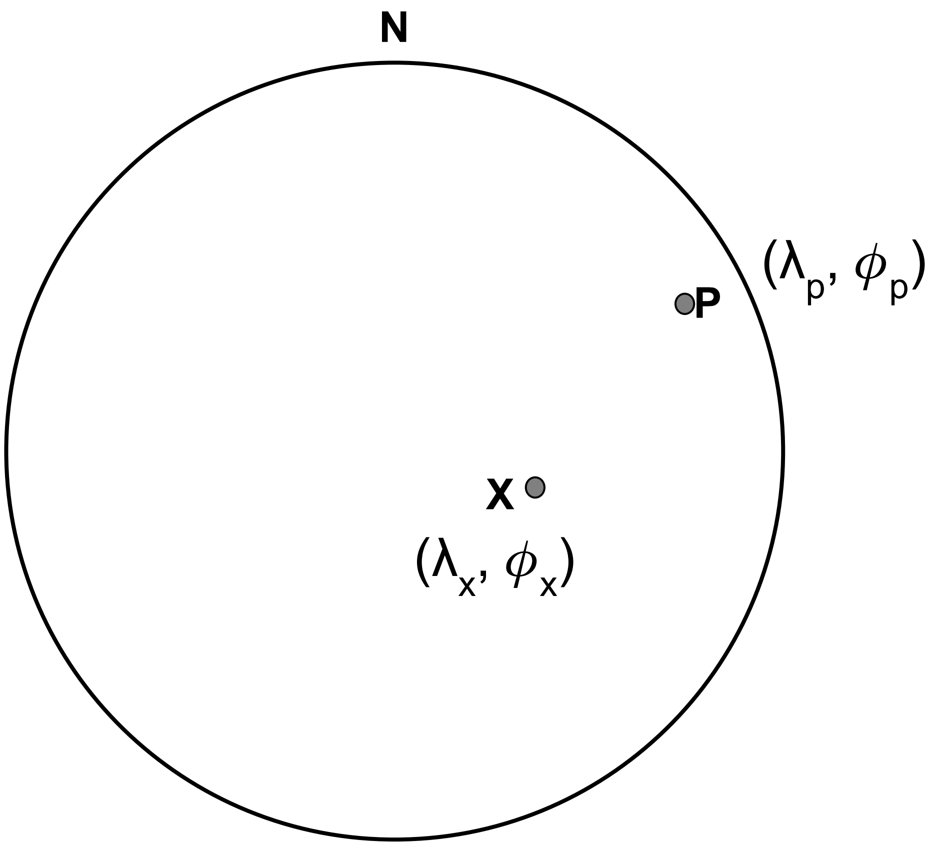
${}_B\omega_A$ →Angular velocity about rotation pole P

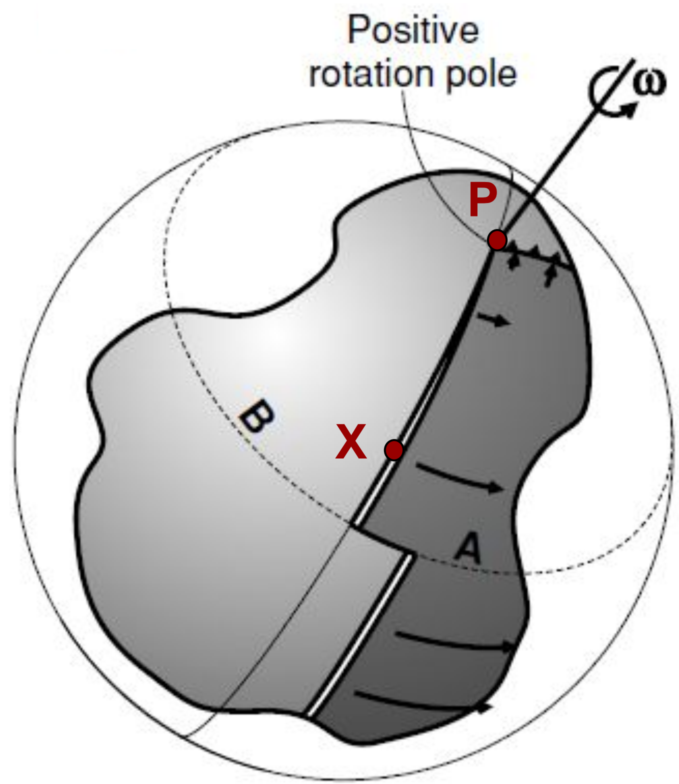


Step 1: Plot P, X and Geographic N pole on a sphere

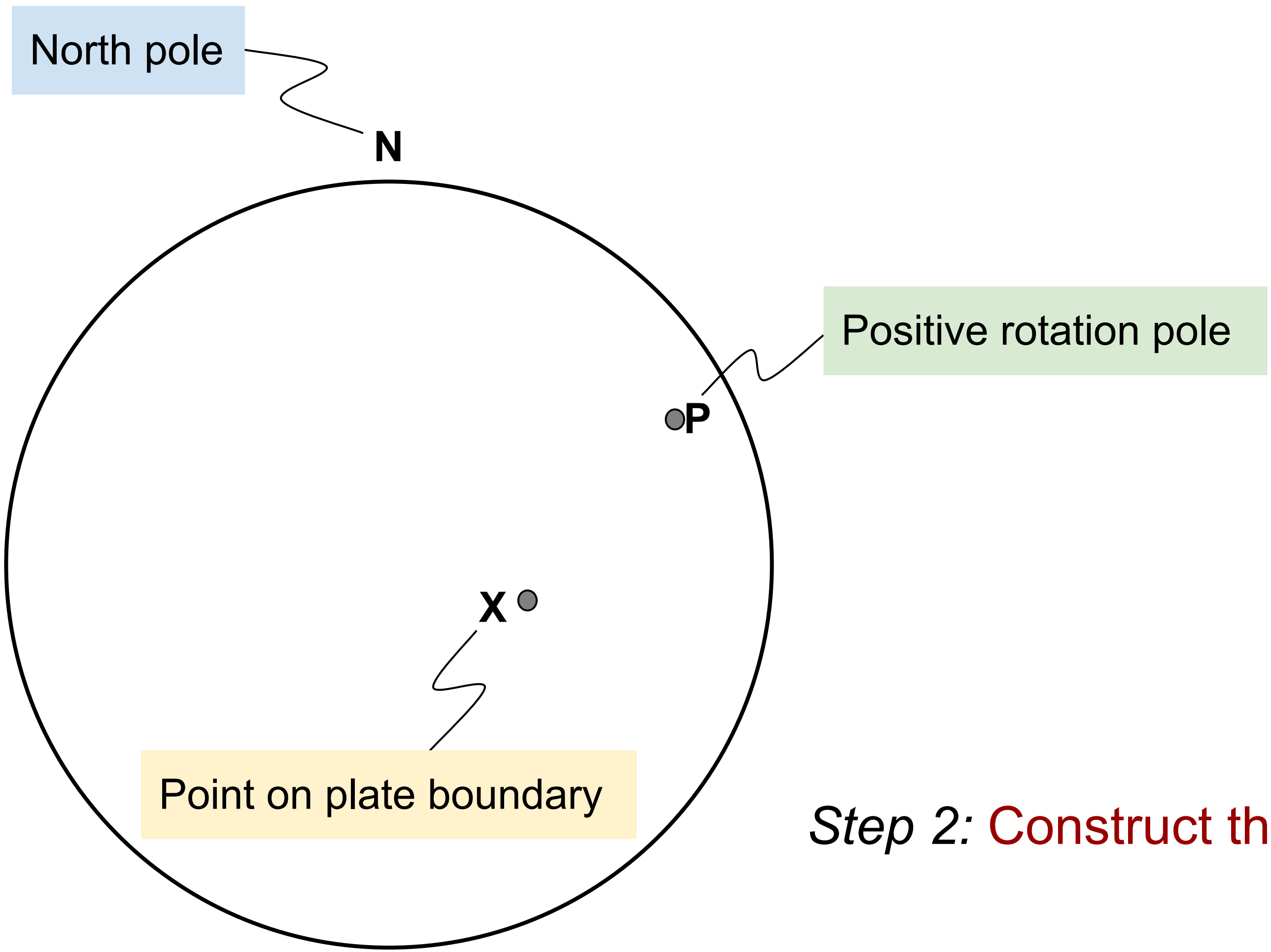
Calculation of Relative Motion at a Plate Boundary

Given the Positive rotation pole (P) can you find the linear velocity (v) at X on the plate boundary?



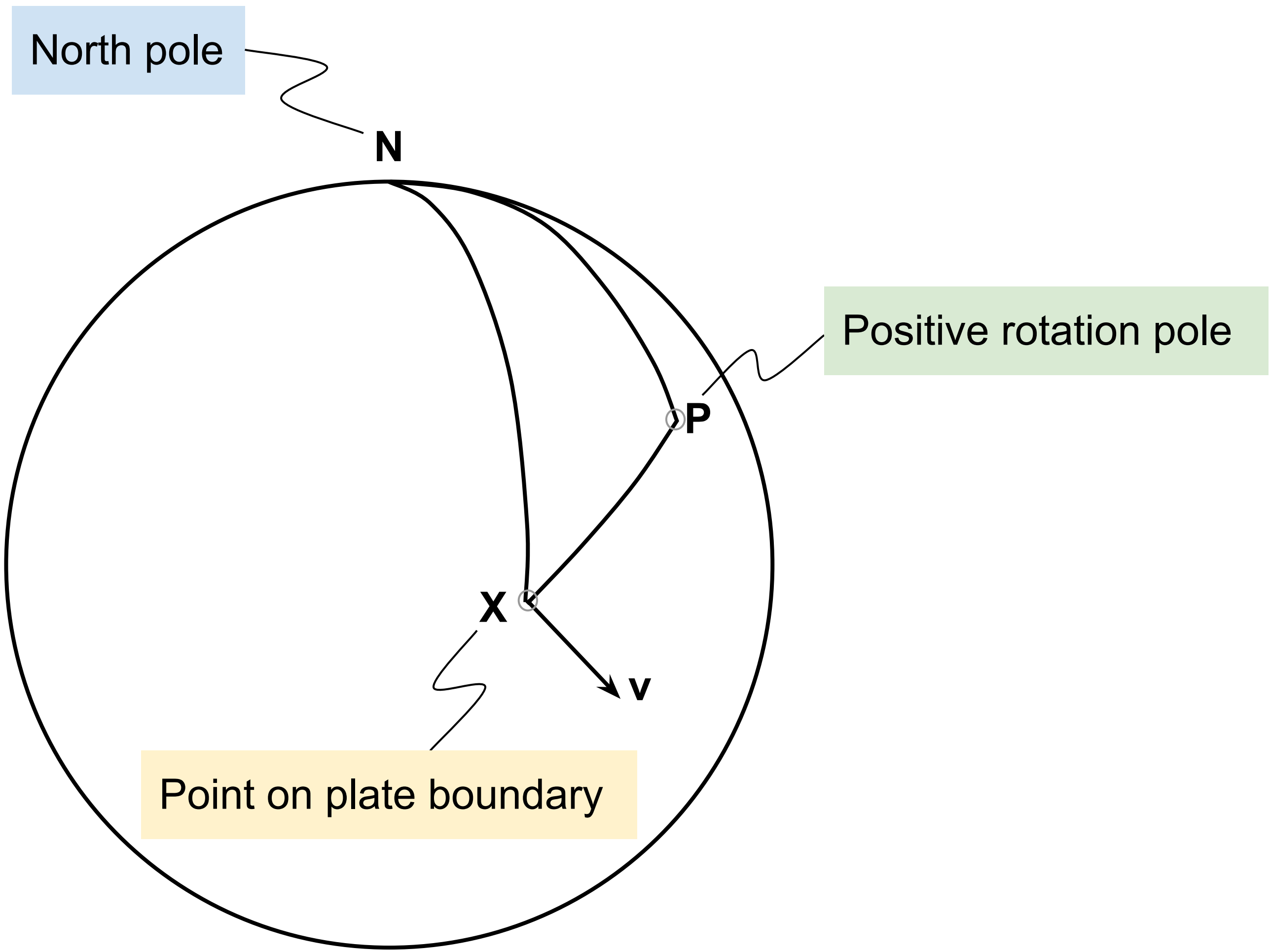


Calculation of Relative Motion at a Plate Boundary

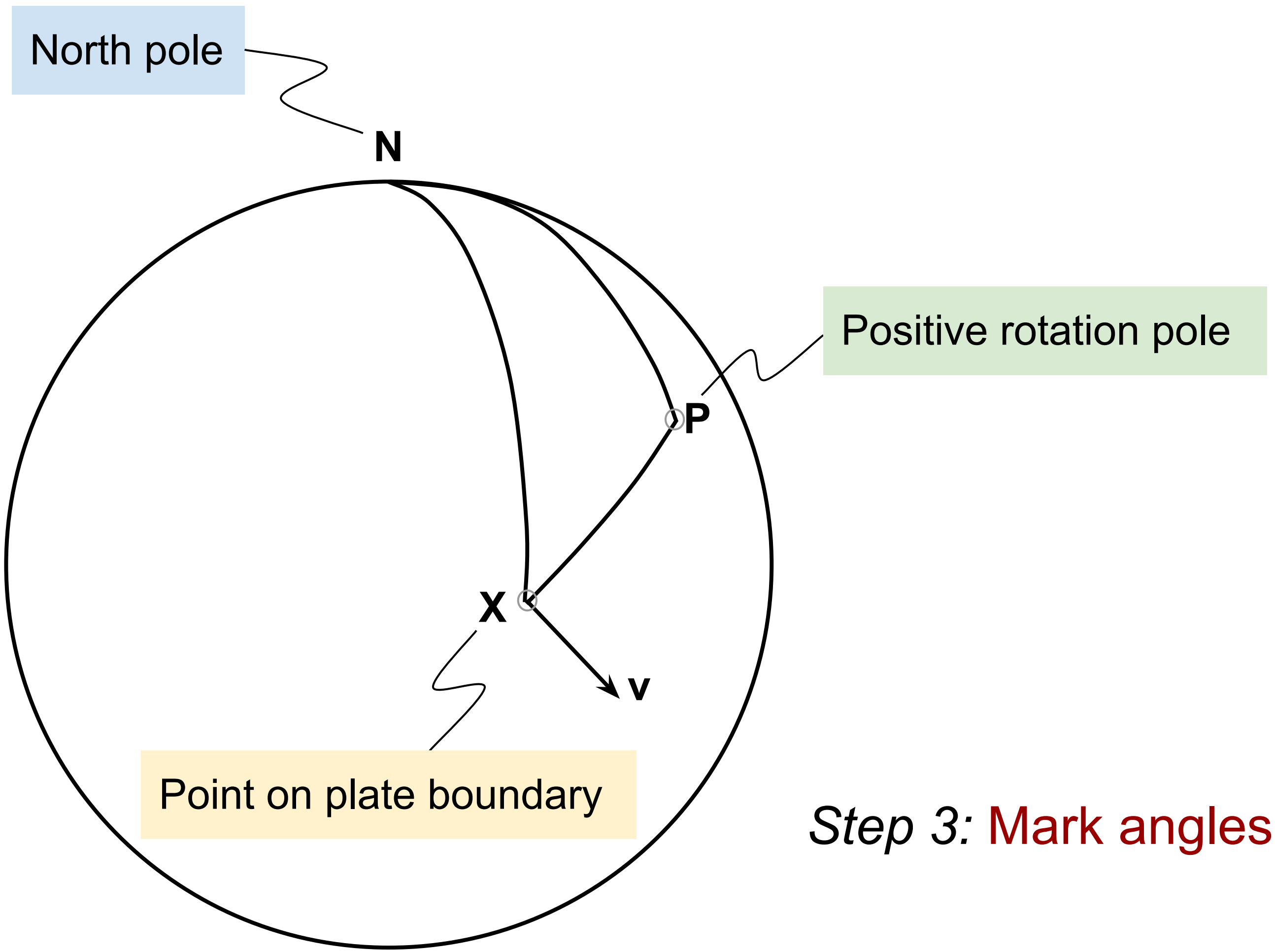


Step 2: Construct the spherical triangle

Calculation of Relative Motion at a Plate Boundary

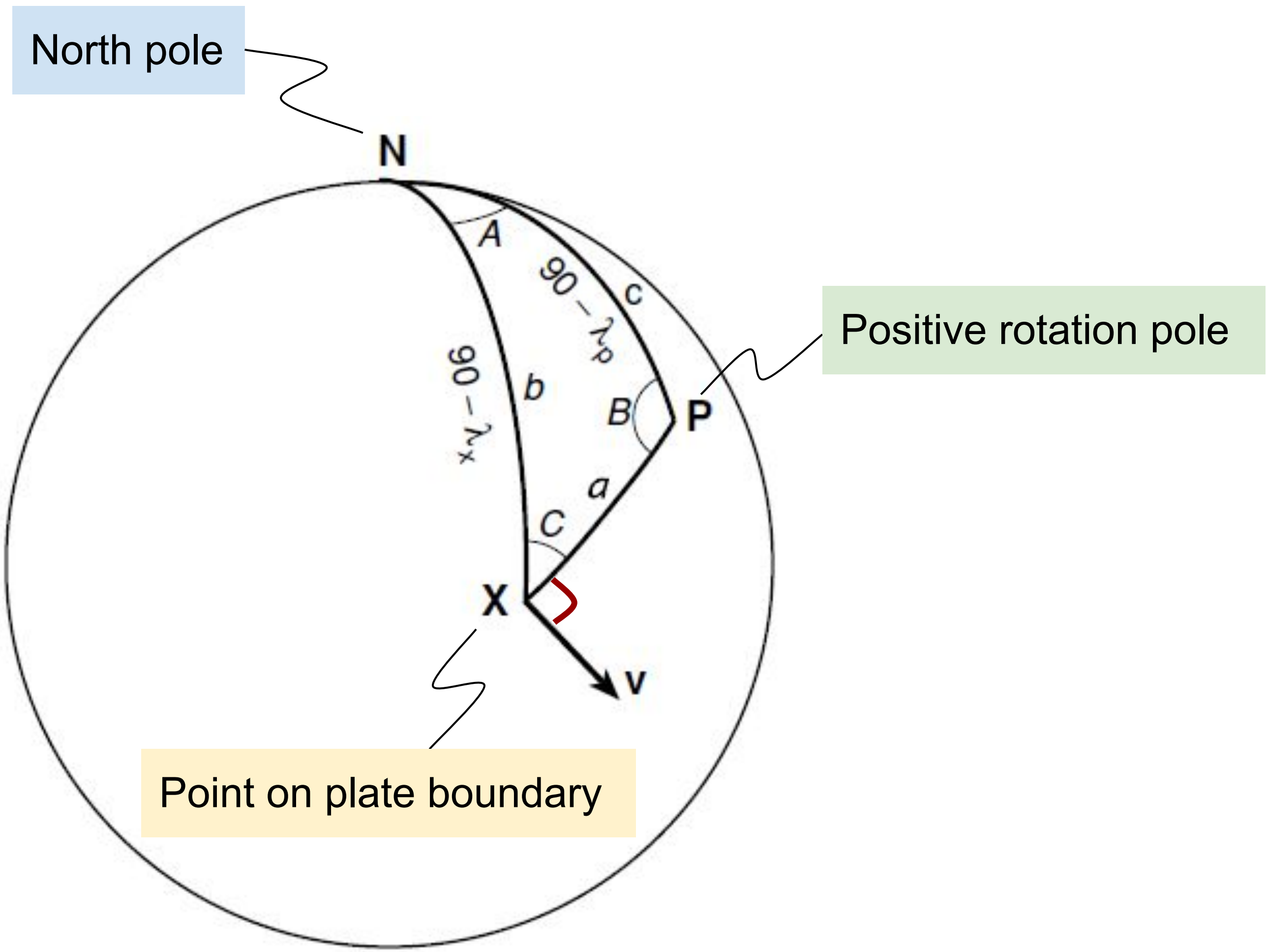


Calculation of Relative Motion at a Plate Boundary

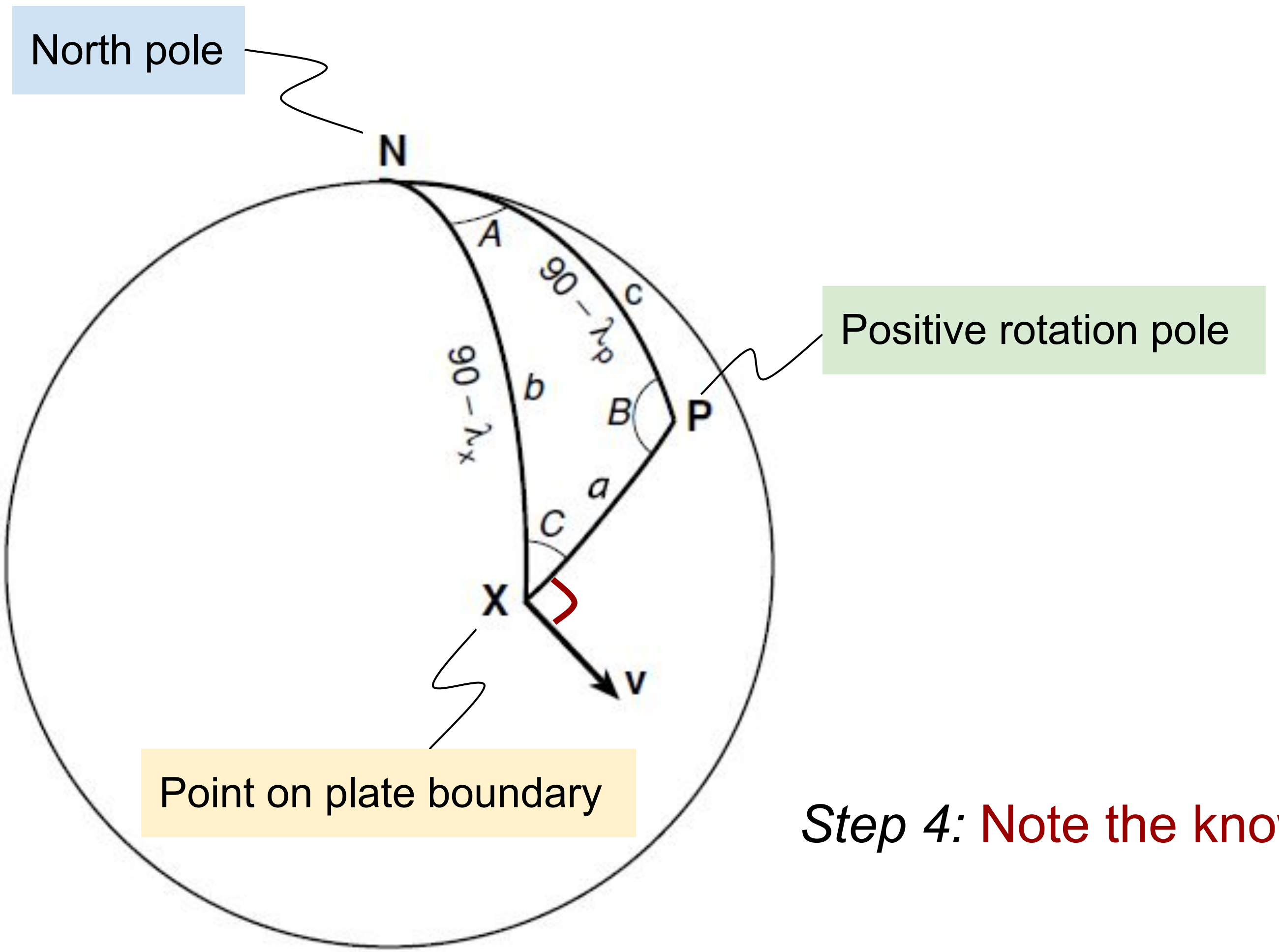


Step 3: Mark angles of spherical triangle

Calculation of Relative Motion at a Plate Boundary

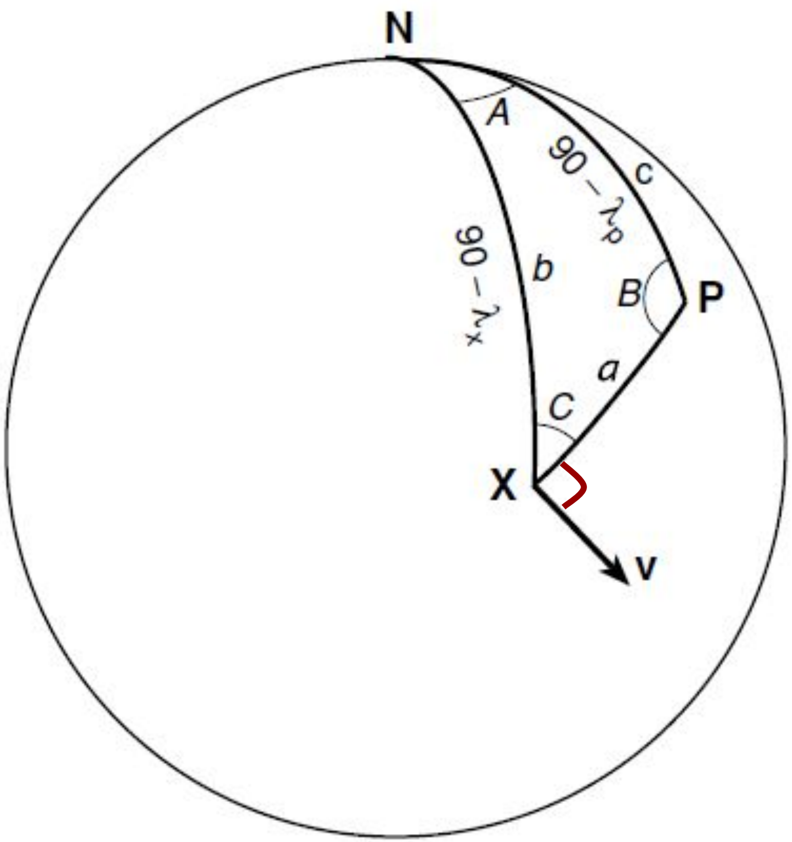


Calculation of Relative Motion at a Plate Boundary



Step 4: Note the known & unknown values

Calculation of Relative Motion at a Plate Boundary



NPX → Spherical triangle

<u>Angles of the Spherical Triangle</u>

A = XNP, *B = NPX*, *C = PXN*

<u>Angular lengths of sides of S Triangle</u>

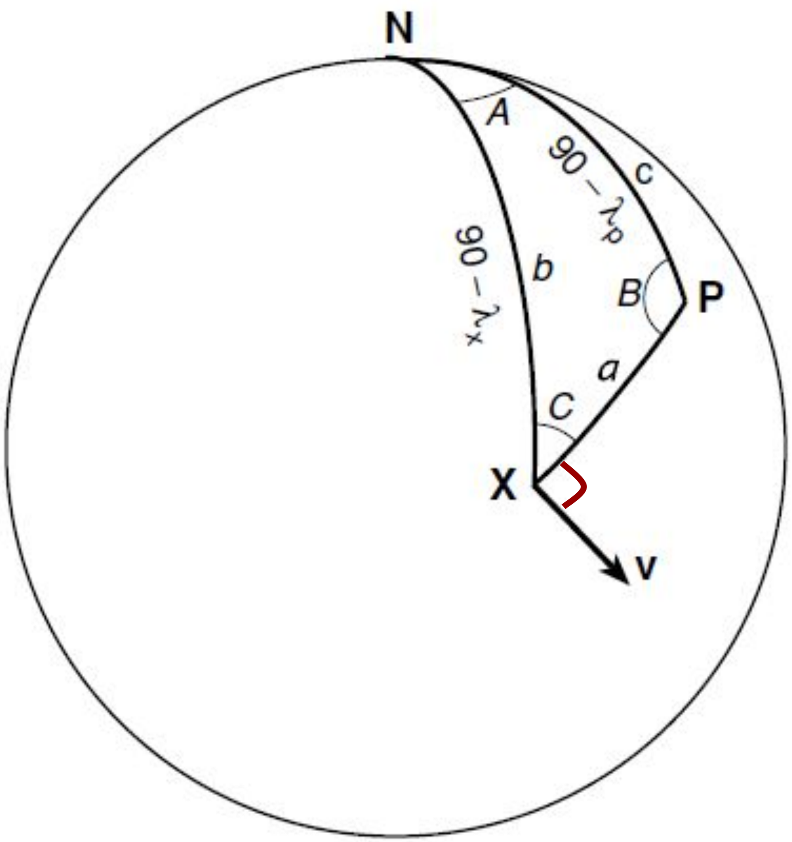
a = PX, *b = XN*, *c = NP*

Unknowns → *a, B, C*

Known values	Known relations
$b = 90 - \lambda_x$	1. $\upsilon = \omega R \sin a$
$c = 90 - \lambda_p$	2. $\beta = 90 + C$
$A = \phi_p - \phi_x$	

Calculation of Relative Motion at a Plate Boundary

Step 5: Find angles a & C



NPX → Spherical triangle

Angles of the Spherical Triangle

$A = XNP, \quad B = NPX, \quad C = PXN$

Angular lengths of sides of S Triangle

$a = PX, \; b = XN, \; c = NP$

Unknowns → a, B, C

Known values

$b = 90 - \lambda_x$

$c = 90 - \lambda_p$

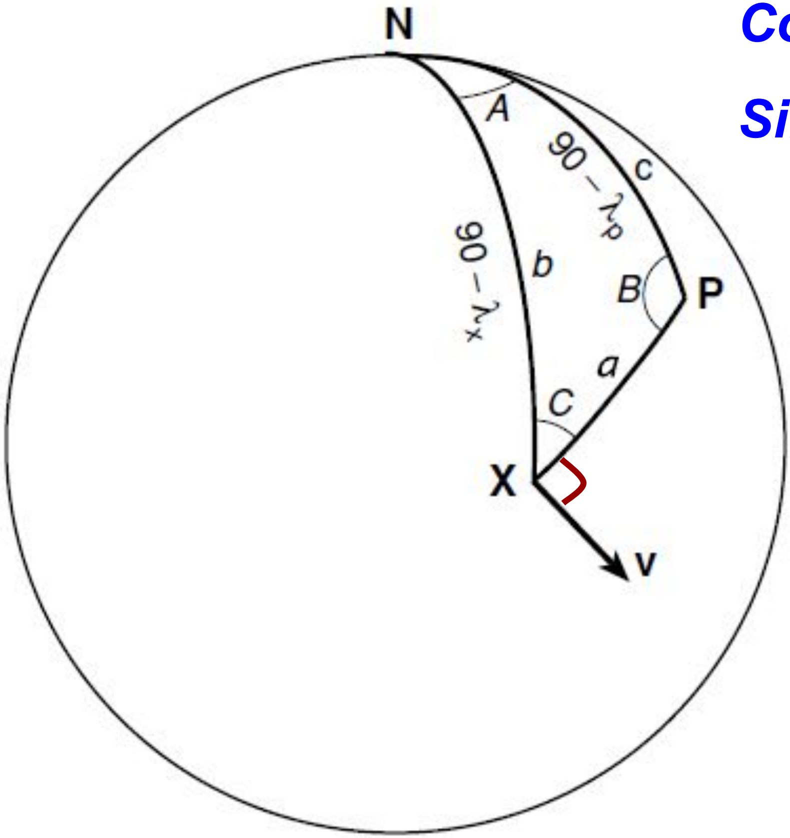
$A = \phi_p - \phi_x$

Known relations

1. $\upsilon = \omega R \sin a$
2. $\beta = 90 + C$

Calculation of Relative Motion at a Plate Boundary

To find angles *a* and ***C*** we use spherical trigonometry



Cos a = Cos b Cos c + Sin b Sin c Cos A

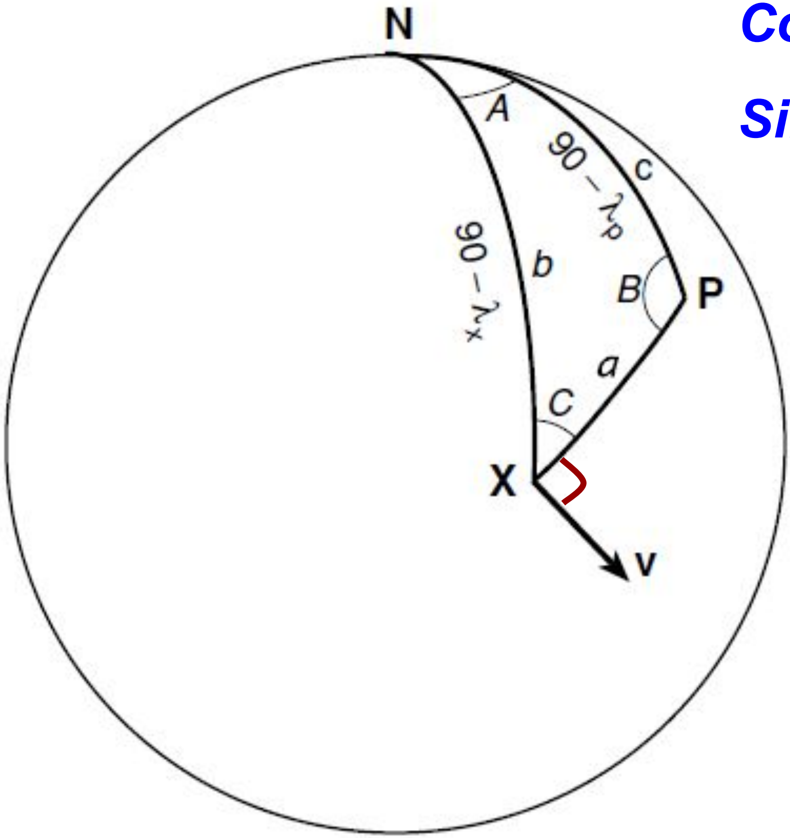
Sin a / Sin A = Sin c / Sin C

Calculation of Relative Motion at a Plate Boundary

To find angles *a* and ***C*** we use spherical trigonometry

Cos a = Cos b Cos c + Sin b Sin c Cos A

Sin a / Sin A = Sin c / Sin C

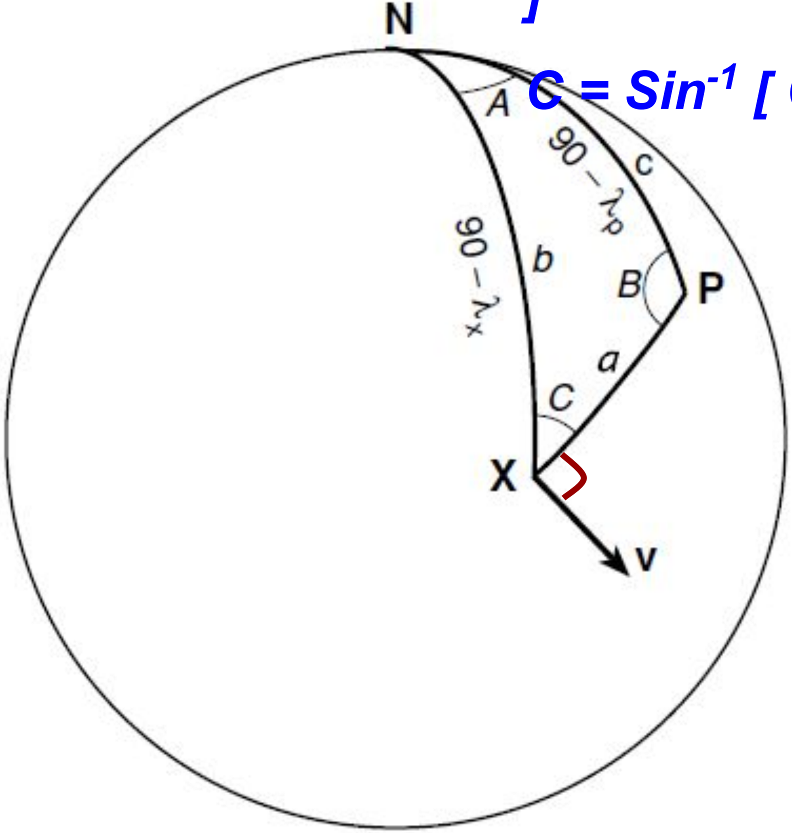


Step 6: Put the values from the S triangle

Calculation of Relative Motion at a Plate Boundary

$$a = \mathrm{Cos}^{-1}\left[\, \mathrm{Sin}\,\lambda_x\, \mathrm{Sin}\,\lambda_p + \mathrm{Cos}\,\lambda_x\, \mathrm{Cos}\,\lambda_p\, \mathrm{Cos}\,(\phi_p - \phi_x) \,\right]$$

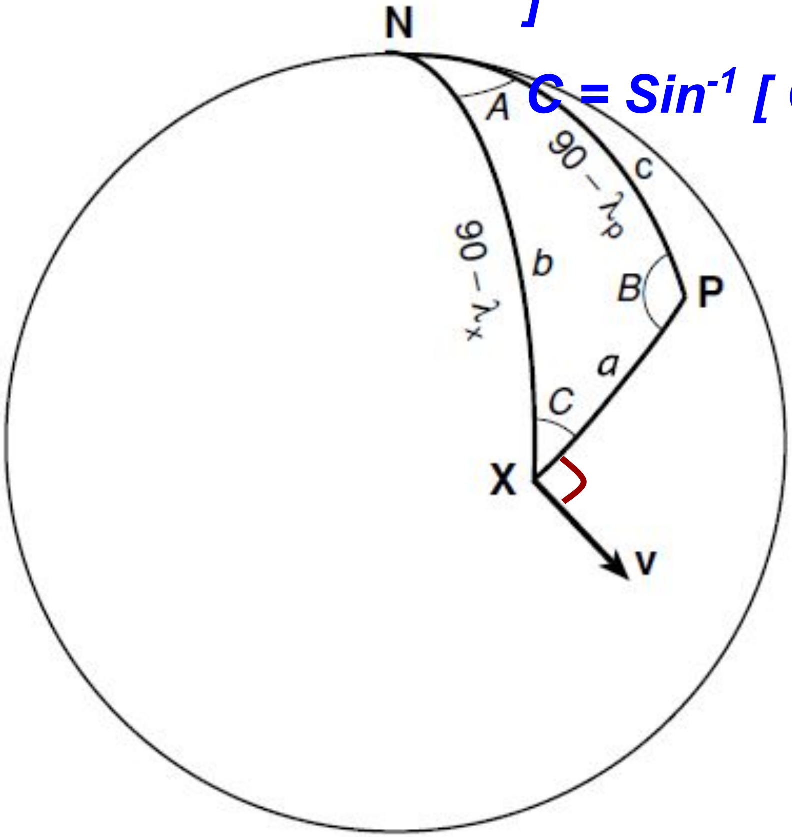
$$C = \mathrm{Sin}^{-1}\left[\, \mathrm{Cos}\,\lambda_p\, \mathrm{Sin}\,(\phi_p - \phi_x) \,/\, \mathrm{Sin}\, a \,\right]$$



Calculation of Relative Motion at a Plate Boundary

$$a = Cos^{-1}\,[\,Sin\,\lambda_x\,Sin\,\lambda_p + Cos\,\lambda_x\,Cos\,\lambda_p\,Cos\,(\phi_p - \phi_x)\,]$$

$$C = Sin^{-1}\,[\,Cos\,\lambda_p\,Sin\,(\phi_p - \phi_x)\,/\,Sin\,a\,]$$



Step 7:

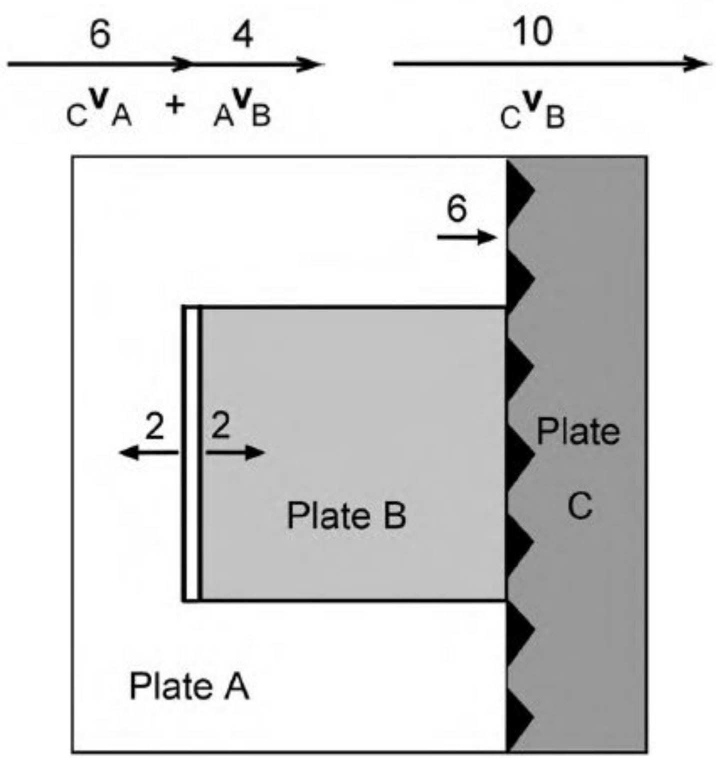
Substitute values of *a* & *C* in (1) and (2) to get values of *υ* and β.

1. $\upsilon = \omega R \sin a$
2. $\beta = 90 + C$

Combination of Rotation Vectors

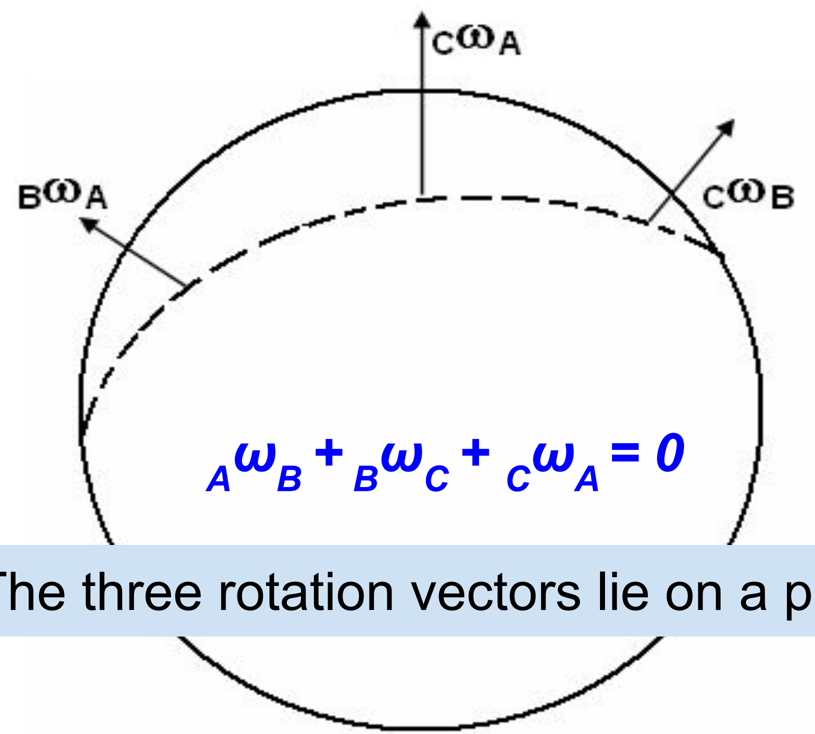
Flat Earth

$${}_{C}V_{B} = {}_{C}V_{A} + {}_{A}V_{B}$$



Spherical Earth

$${}_{C}\omega_{B} = {}_{C}\omega_{A} + {}_{A}\omega_{B}$$



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

The three rotation vectors lie on a plane

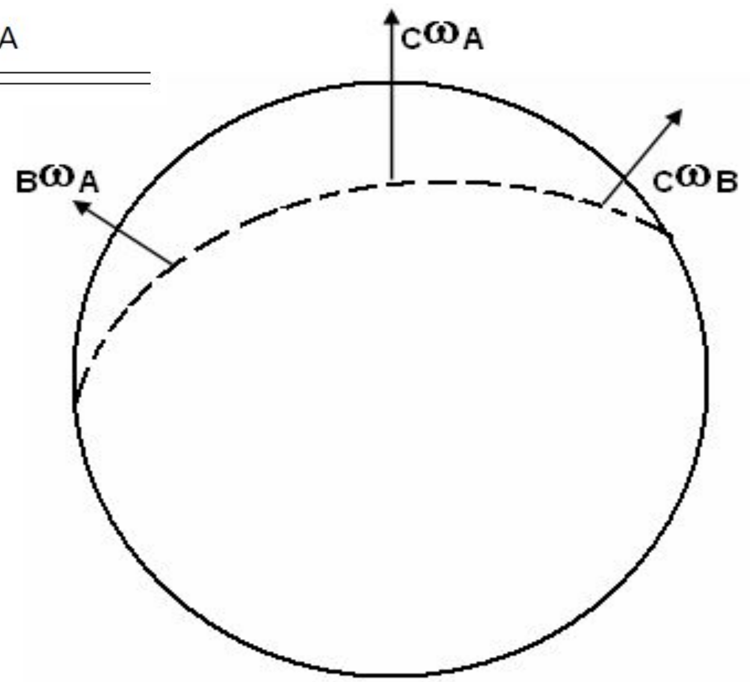
Combination of Rotation Vectors

Table 2.3 *Notation used in addition of rotation vectors*

Rotation vector	Magnitude	Latitude of pole	Longitude of pole
${}_B\boldsymbol{\omega}_A$	${}_B\omega_A$	λ_{BA}	ϕ_{BA}
${}_C\boldsymbol{\omega}_B$	${}_C\omega_B$	λ_{CB}	ϕ_{CB}
${}_C\boldsymbol{\omega}_A$	${}_C\omega_A$	λ_{CA}	ϕ_{CA}

Given ${}_C\omega_B$ **&** ${}_B\omega_A$

Find: ${}_C\omega_A$

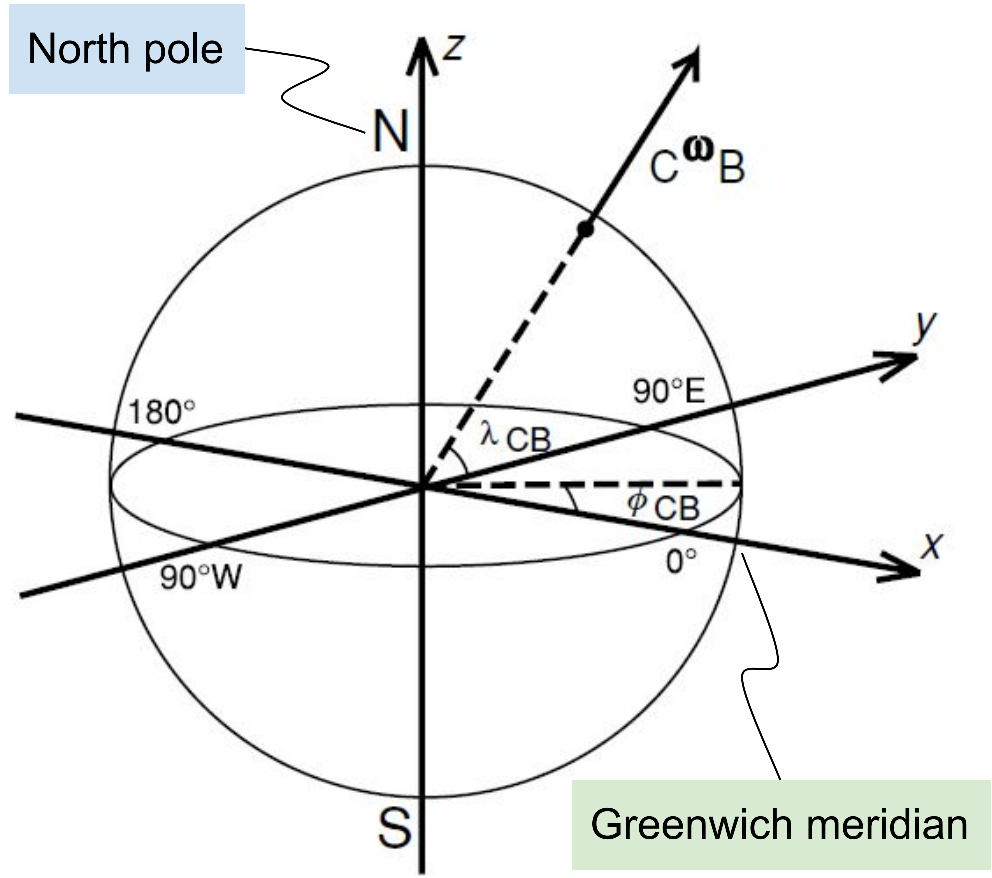


Combination of Rotation Vectors

We use rectangular coordinate system through the center of the earth
x-y plane → equatorial plane.

X-axis – passing through Greenwich meridian

Z-axis – passing through North pole



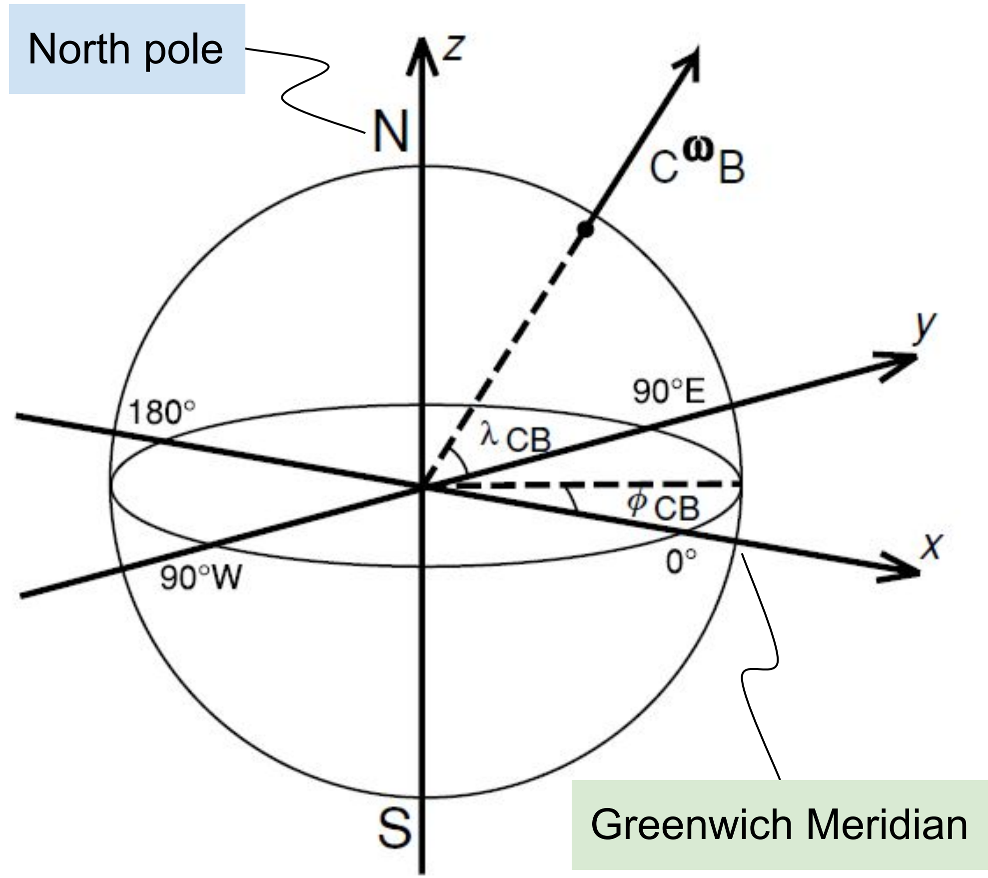
Combination of Rotation Vectors

We use rectangular coordinate system through the center of the earth
x-y plane → equatorial plane.

$$x_{\mathrm{CB}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \cos\lambda_{\mathrm{CB}} \cos\phi_{\mathrm{CB}}$$

$$y_{\mathrm{CB}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \cos\lambda_{\mathrm{CB}} \sin\phi_{\mathrm{CB}}$$

$$z_{\mathrm{CB}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \sin\lambda_{\mathrm{CB}}$$



Combination of Rotation Vectors

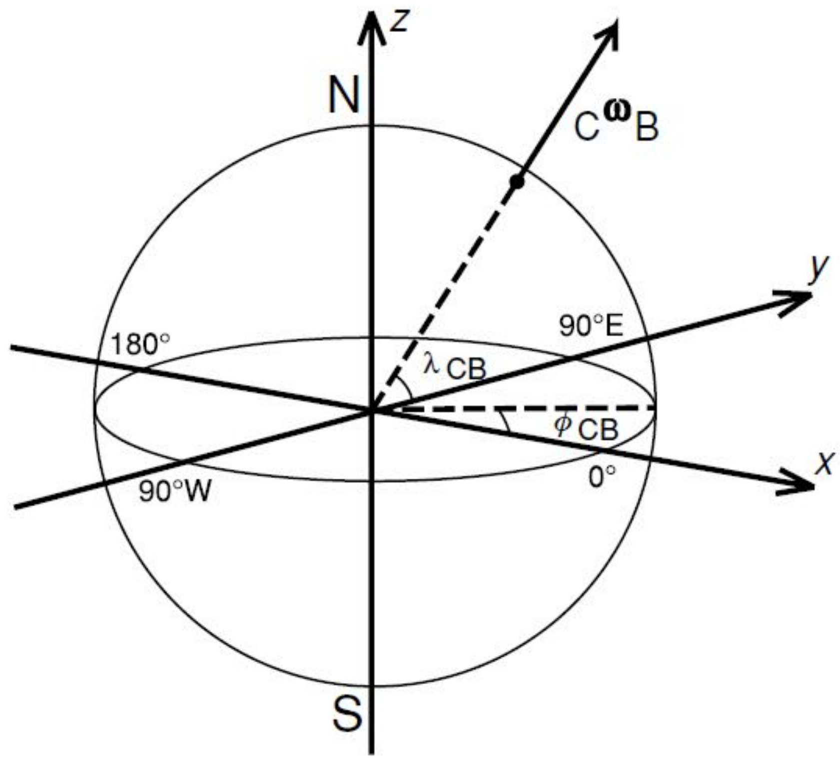
We use rectangular coordinate system through the center of the earth
x-y plane → equatorial plane.

$$ {}_A\omega_C = {}_C\omega_B + {}_B\omega_A $$

$$ x_{CA} = x_{CB} + x_{BA} $$

$$ y_{CA} = y_{CB} + y_{BA} $$

$$ z_{CA} = z_{CB} + z_{BA} $$



Combination of Rotation Vectors

We use rectangular coordinate system through the center of the earth

x-y plane → equatorial plane.

$$x_{\mathrm{CA}} = x_{\mathrm{CB}} + x_{\mathrm{BA}}$$

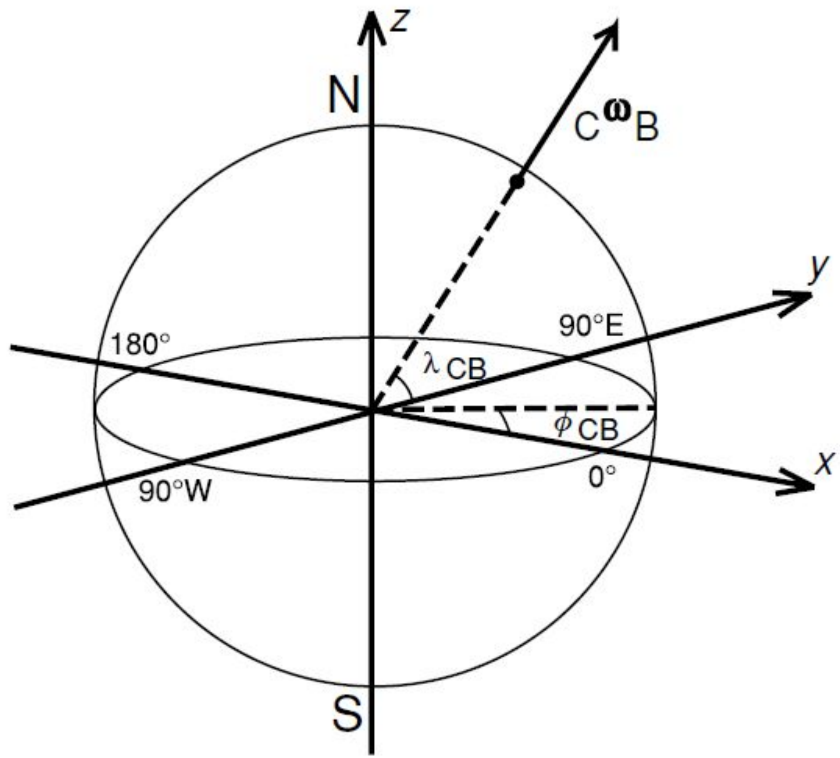
$$y_{\mathrm{CA}} = y_{\mathrm{CB}} + y_{\mathrm{BA}}$$

$$z_{\mathrm{CA}} = z_{\mathrm{CB}} + z_{\mathrm{BA}}$$

$$x_{\mathrm{CA}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \cos\lambda_{\mathrm{CB}} \cos\phi_{\mathrm{CB}} + {}_{\mathrm{B}}\omega_{\mathrm{A}} \cos\lambda_{\mathrm{BA}} \cos\phi_{\mathrm{BA}}$$

$$y_{\mathrm{CA}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \cos\lambda_{\mathrm{CB}} \sin\phi_{\mathrm{CB}} + {}_{\mathrm{B}}\omega_{\mathrm{A}} \cos\lambda_{\mathrm{BA}} \sin\phi_{\mathrm{BA}}$$

$$z_{\mathrm{CA}} = {}_{\mathrm{C}}\omega_{\mathrm{B}} \sin\lambda_{\mathrm{CB}} + {}_{\mathrm{B}}\omega_{\mathrm{A}} \sin\lambda_{\mathrm{BA}}$$



Combination of Rotation Vectors

We use rectangular coordinate system through the center of the earth

x-y plane → equatorial plane.

$$x_{CA} = x_{CB} + x_{BA}$$

$$y_{CA} = y_{CB} + y_{BA}$$

$$z_{CA} = z_{CB} + z_{BA}$$

$$X_{CA} = \underbrace{{}_{C}\omega_{B} \cos\lambda_{CB} \cos\phi_{CB}}_{X_{CB}} + \underbrace{{}_{B}\omega_{A} \cos\lambda_{BA} \cos\phi_{BA}}_{X_{BA}}$$

$$Y_{CA} = \underbrace{{}_{C}\omega_{B} \cos\lambda_{CB} \sin\phi_{CB}}_{Y_{CB}} + \underbrace{{}_{B}\omega_{A} \cos\lambda_{BA} \sin\phi_{BA}}_{Y_{BA}}$$

$$Z_{CA} = \underbrace{{}_{C}\omega_{B} \sin\lambda_{CB}}_{Z_{CB}} + \underbrace{{}_{B}\omega_{A} \sin\lambda_{BA}}_{Z_{BA}}$$

Combination of Rotation Vectors

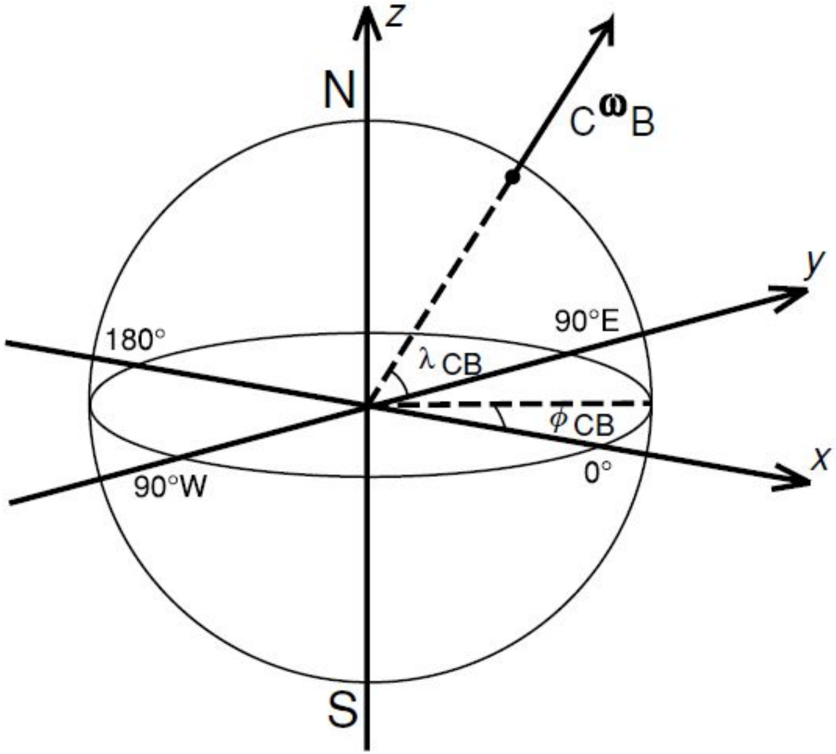
Magnitude of the resultant rotation vector $_C\omega_A$ is

$$_C\omega_A = [X_{CA}^{\,2} + Y_{CA}^{\,2} + Z_{CA}^{\,2}]^{1/2}$$

Pole position given by:

$$\lambda_{CA} = \sin^{-1}(Z_{CA} / {_C\omega_A})$$

$$\varphi_{CA} = \tan^{-1}(Y_{CA} / X_{CA})$$



Sign convection in φ_{CA}, ambiguity of 180°

i. e. $\tan 30^o = \tan 210^o = 0.5774$

$\tan 110^o = \tan 290^o = -2.747$

Resolve this by adding or subtracting 180°

$X_{CA} > 0$ **when** $-90° < \varphi_{CA} < +90°$

$X_{CA} < 0$ **when** $|\varphi_{CA}| > 90°$

Changes in Plate Boundaries with Time

Global Plate Boundary Change

- **Plates and Plate boundaries do not stay the same for all time.**

- **Formation of new Plates and destruction of existing Plates are obvious global reasons why Plate boundaries and relative motion changes**

- **Changes in position of rotation pole changes the relative motion between Plates: e.g 90º change in pole position: Transform fault → Ridges and vice versa.**

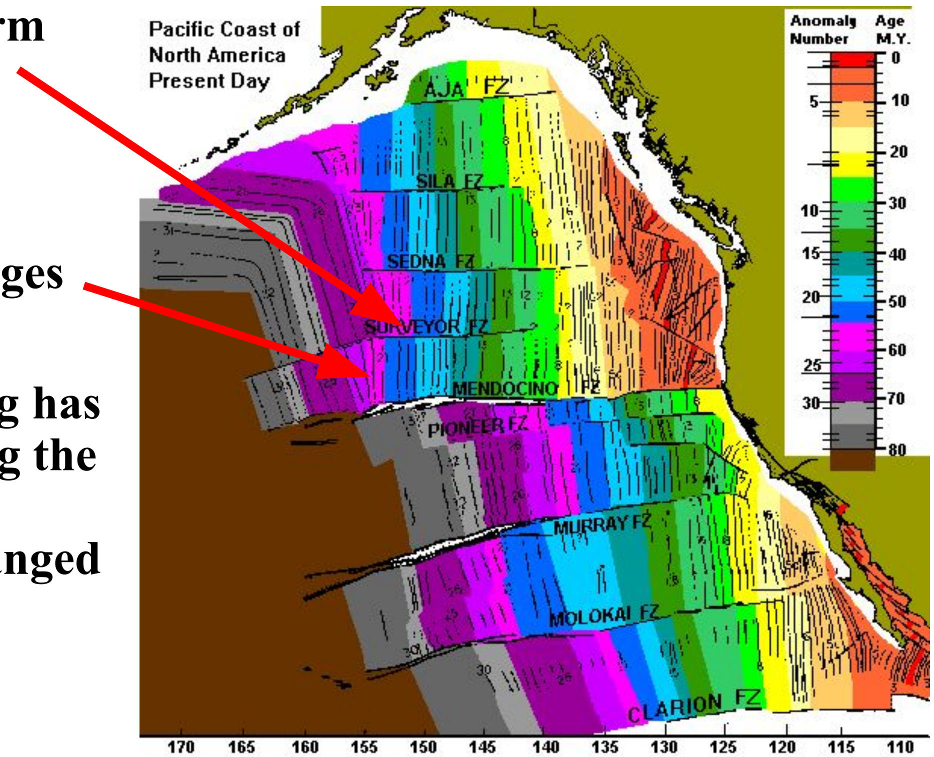
Indicators of Plate Boundary changes with Time

- Changes in the trends of Transform faults

- Magnetic anomalies pattern changes

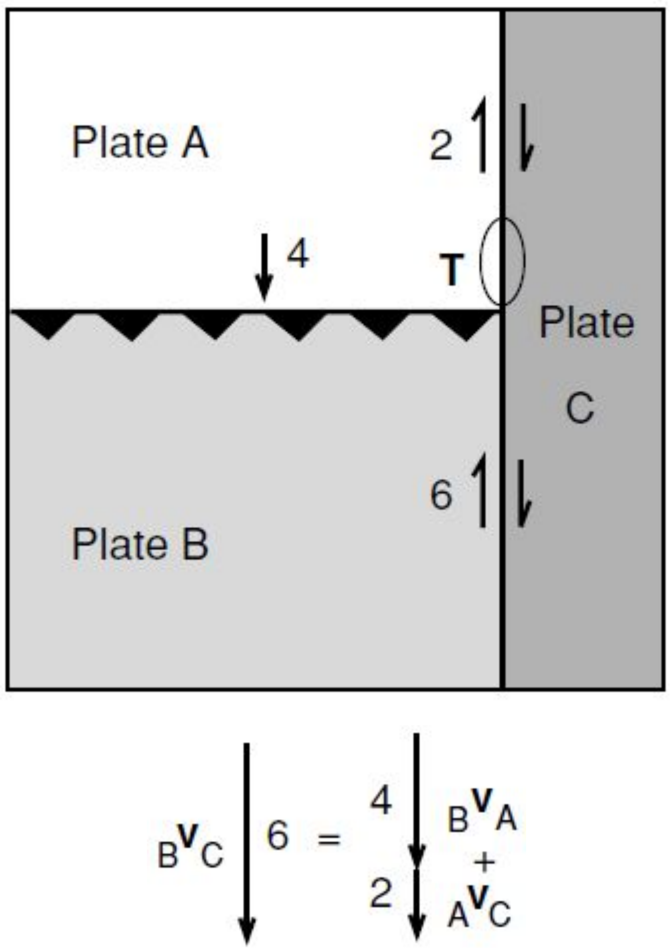
  E.g.:Pacific plate.

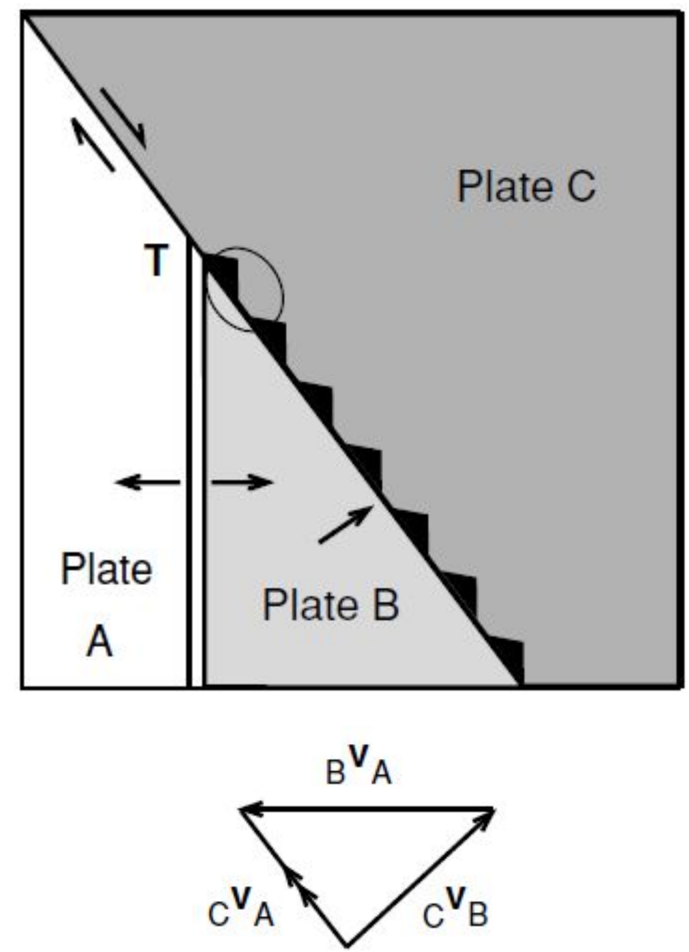
  The direction of seafloor spreading has changed a number of times during the tertiary.This indicates that the Pacific-Farallon pole position changed over time.



Parts of plate boundaries may change locally without any major Plate or pole event occurring.

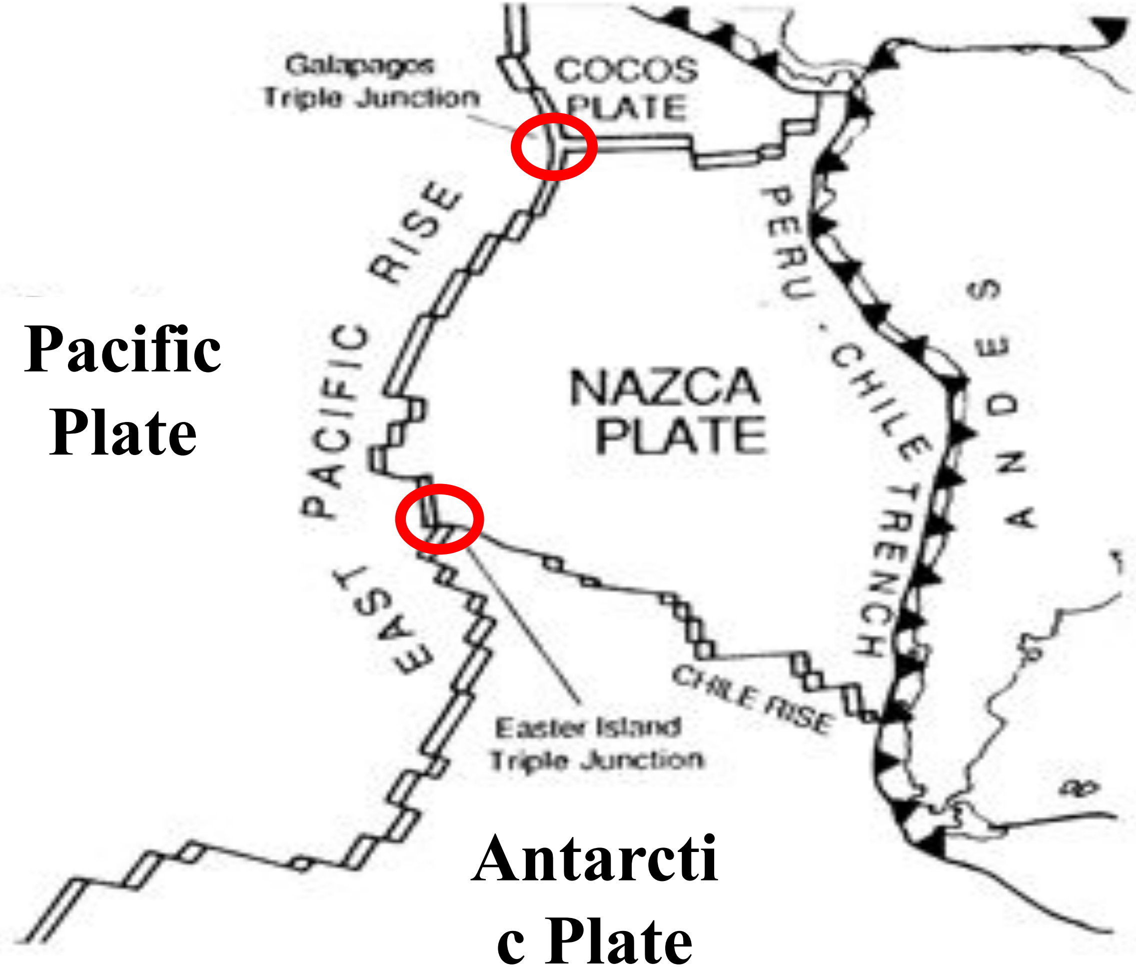
Local change in Plate Boundary





TRIPLE JUNCTIONS

* Point at which three plates meet.



Stable and Unstable Triple Junctions

Stable

Relative motion of the three plates and azimuth of their boundaries are such that the configuration of the junction does not change with time.

Unstable

Triple junction exists only momentarily before evolving to a stable geometry

Stable and Unstable Triple Junctions

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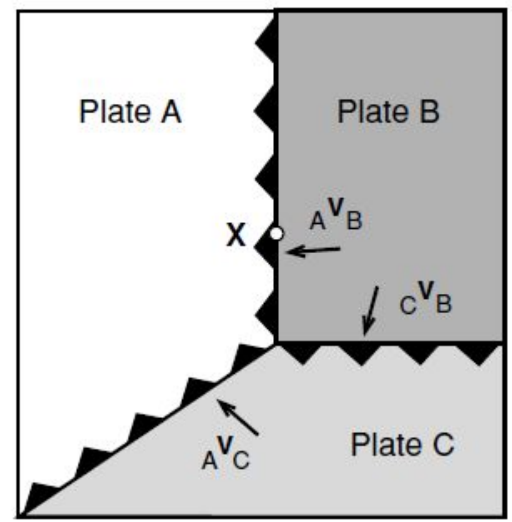
Relative motion of the three plates and azimuth of their boundaries are such that the configuration of the junction does not change with time.

Unstable

Triple junction exists only momentarily before evolving to a stable geometry

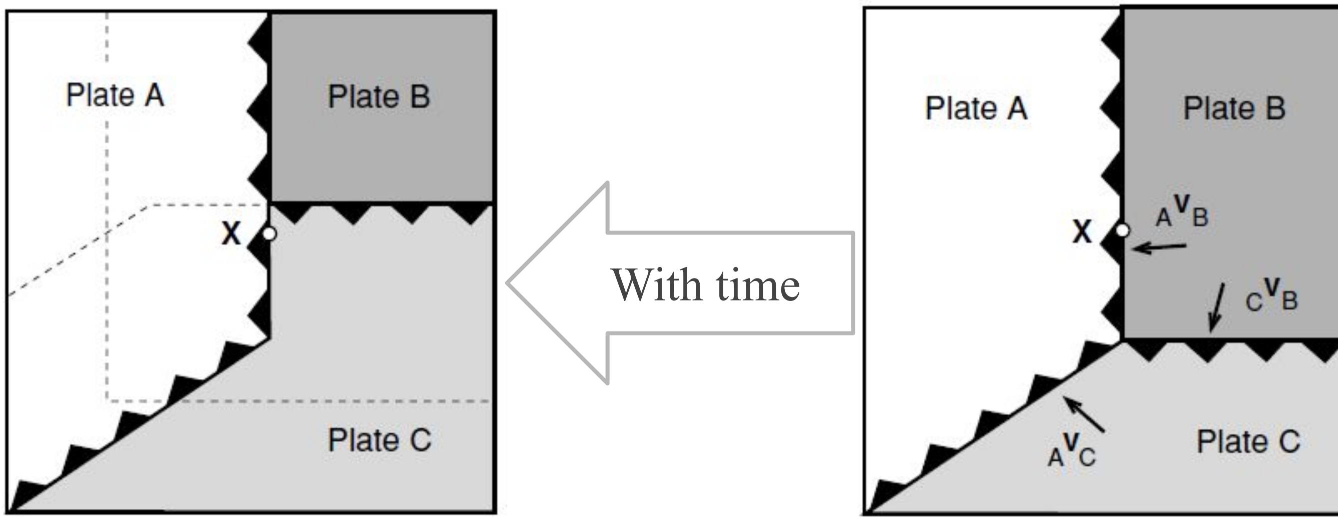
Example: Trench-Trench-Trench (TTT)



Stable or Unstable?

Stable and Unstable Triple Junctions

Example: Trench-Trench-Trench (TTT)



Stable or Unstable?

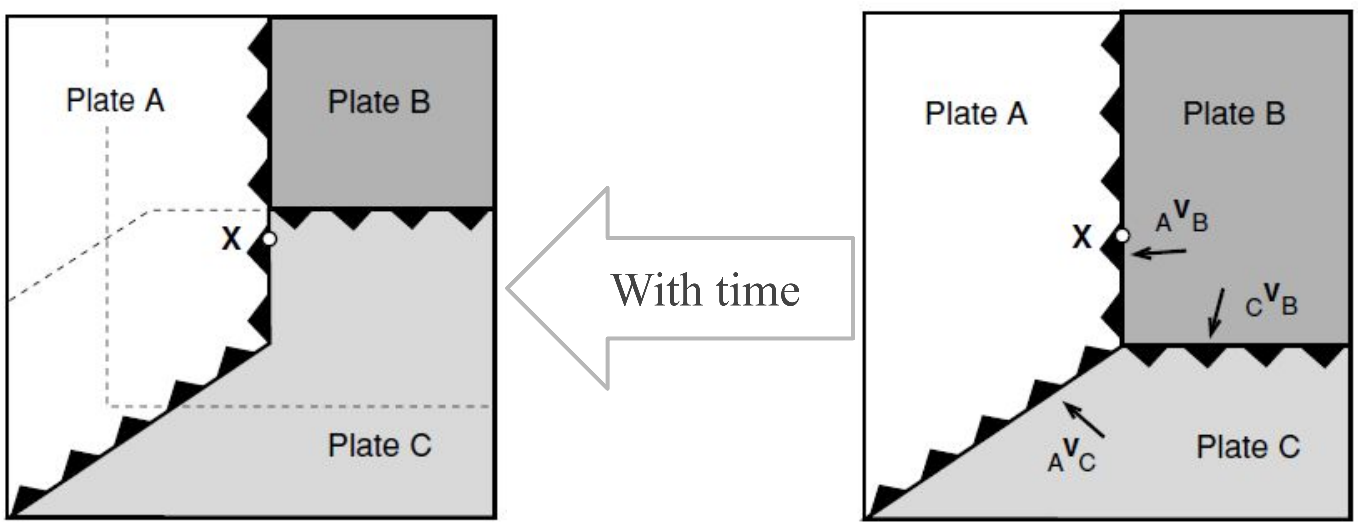
Evolution of a Stable Triple Junction from an unstable configuration

Conditions of Stability

1. If $_{A}V_{C}$ were parallel to the boundary between plates B and C.

   Boundary between B and C would not move in the N-S direction relative to plate A implies geometry of triple junction would not change with time.

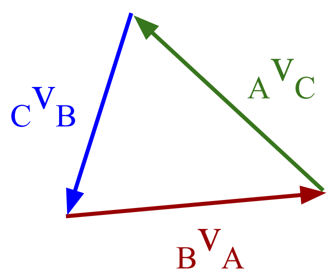
2. **Edges of plate A on both sides of the triple junction is straight.**

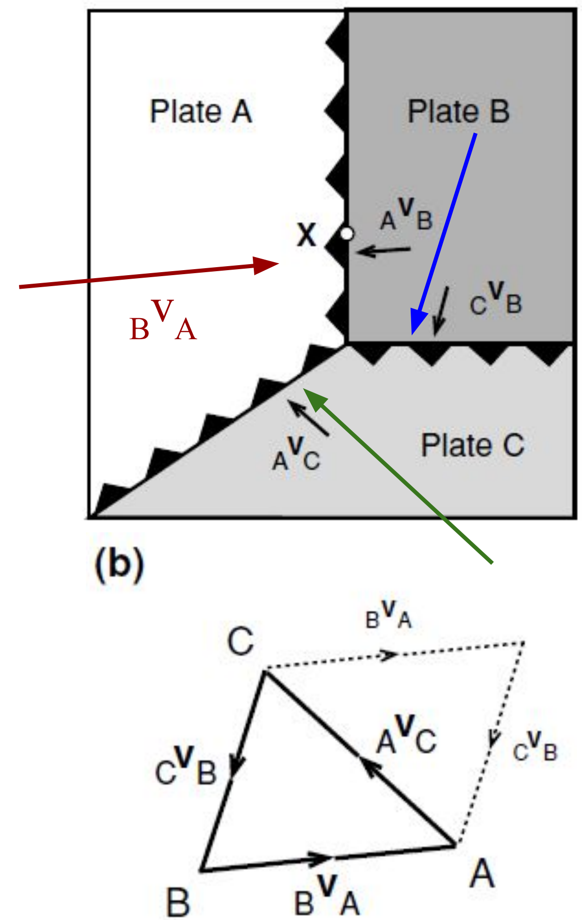


TTT

Stability of Triple Junctions - Rules using geometry

Step 1: Construct the Velocity Vector Triangle

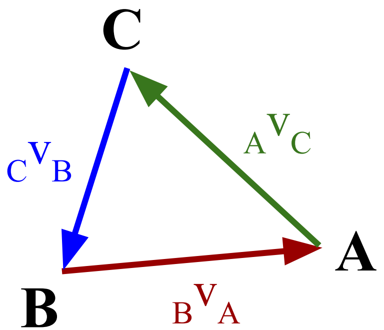


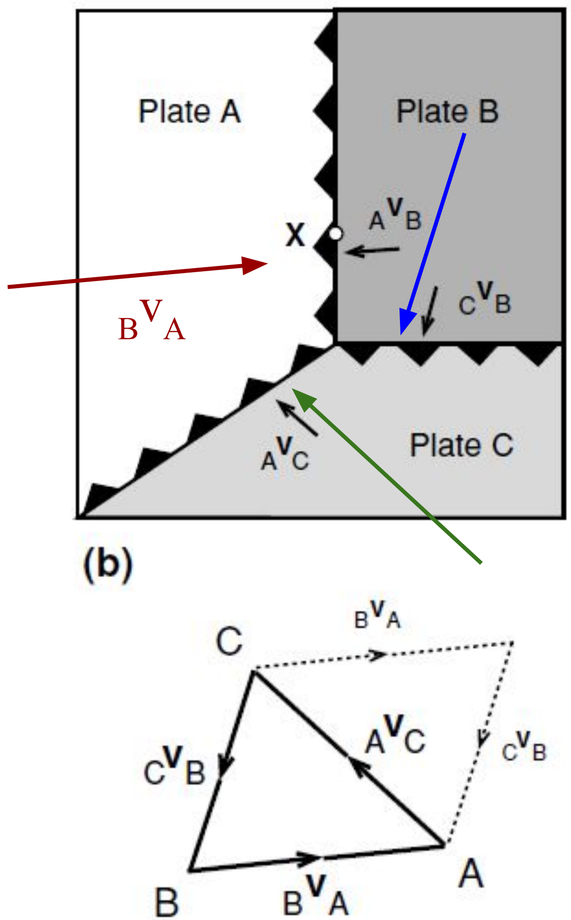


Stability of Triple Junctions - Rules using geometry

Step 1: Construct the Velocity Vector Triangle

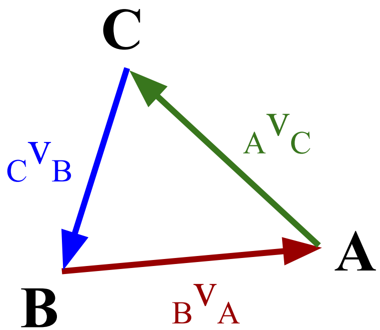
Step 2: Mark the Plates (common corners)

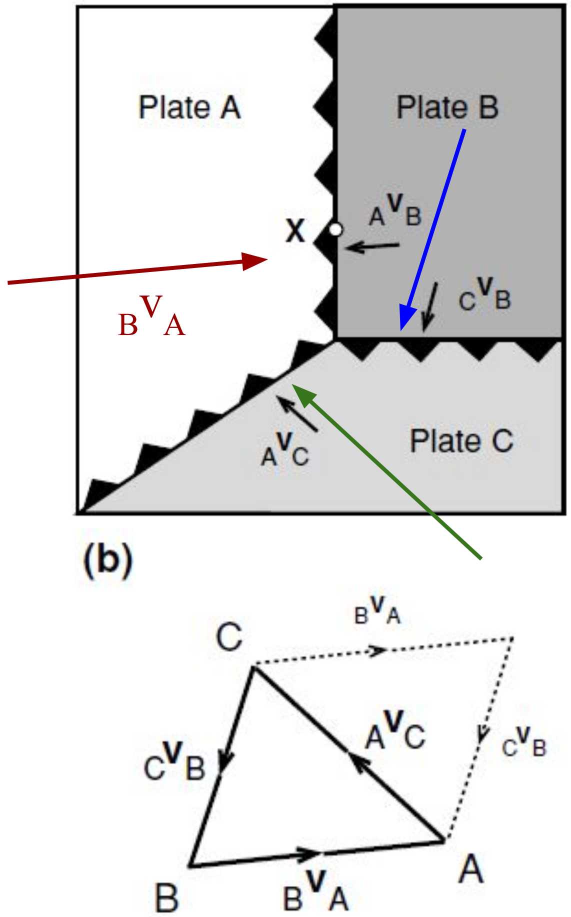




Stability of Triple Junctions - Rules using geometry

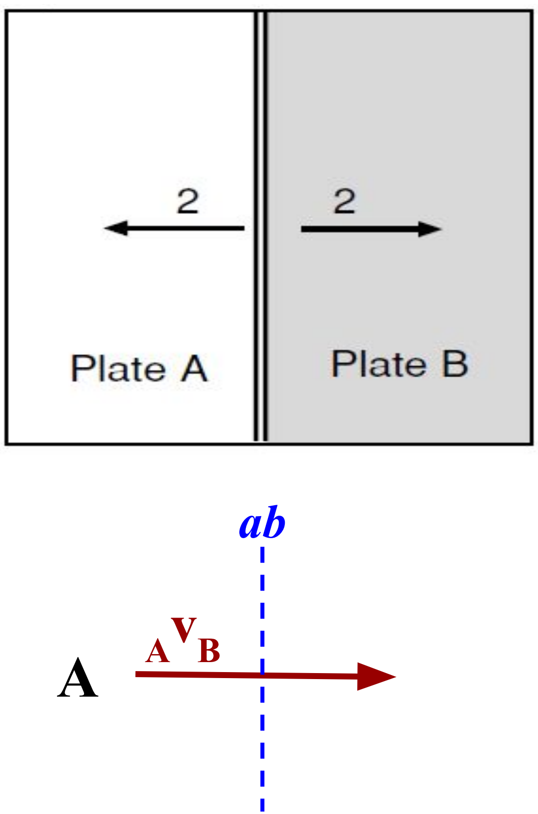
Step 3: Draw the Plate Boundaries



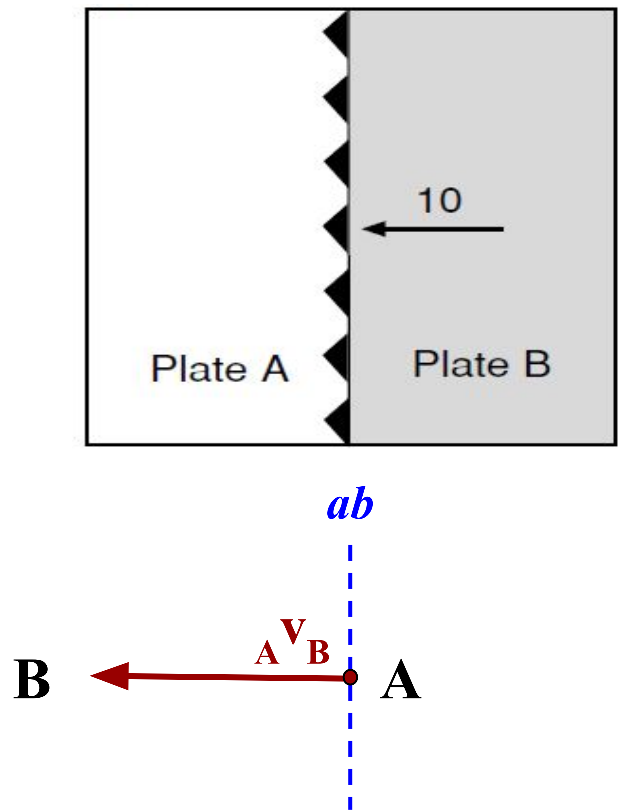


Stability of Triple Junctions - Rules using geometry

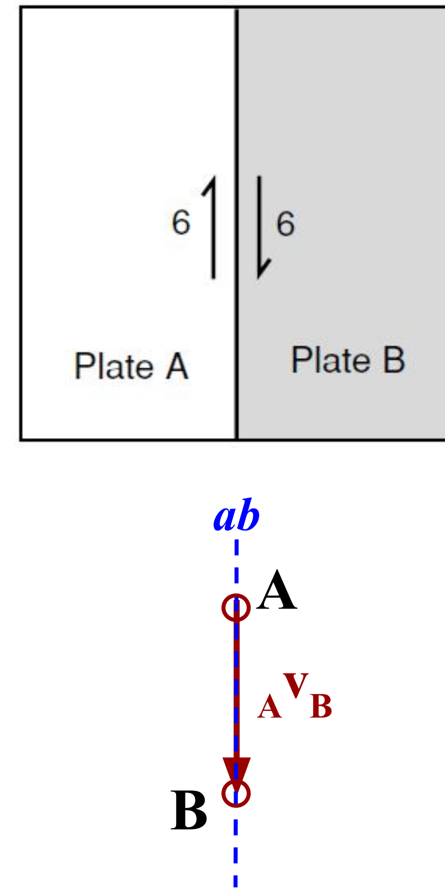
<u>Ridge</u> (R)



<u>Trench</u> (T)

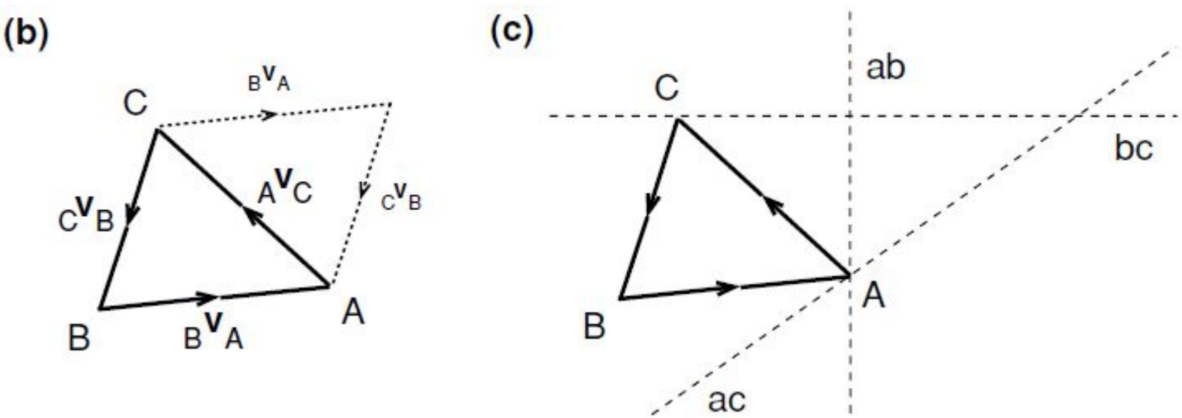


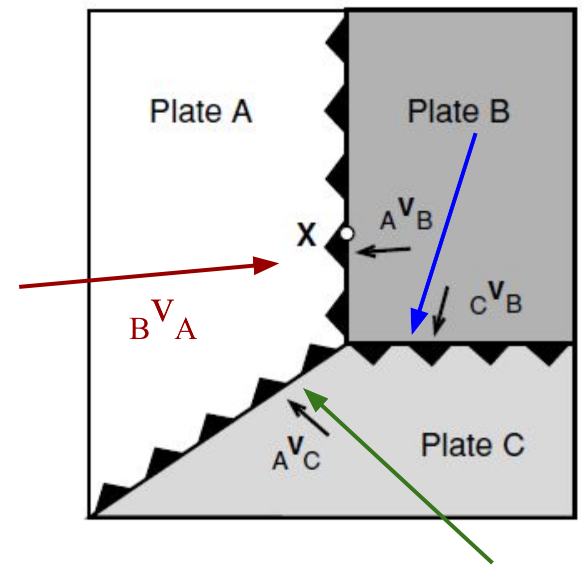
<u>Transform Fault</u> (F)



Stability of Triple Junctions - Rules using geometry

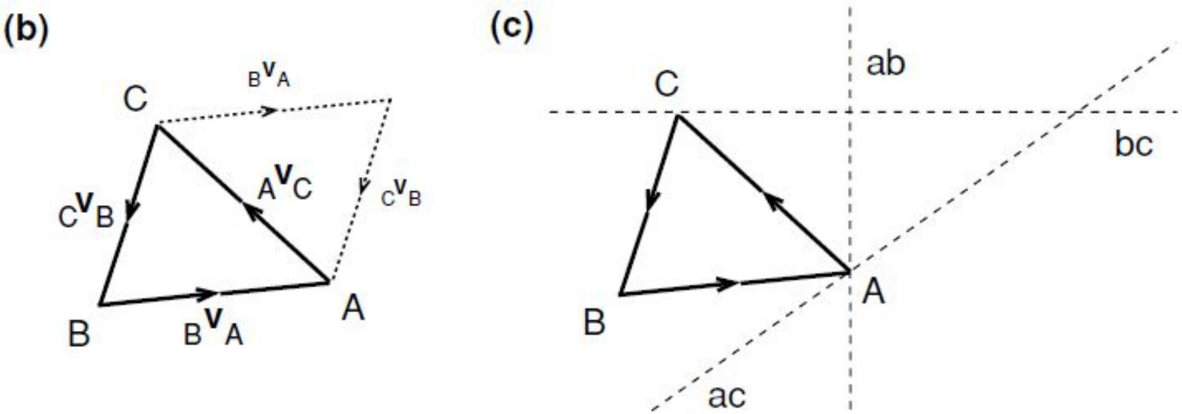
Step 3: Draw the Plate Boundaries

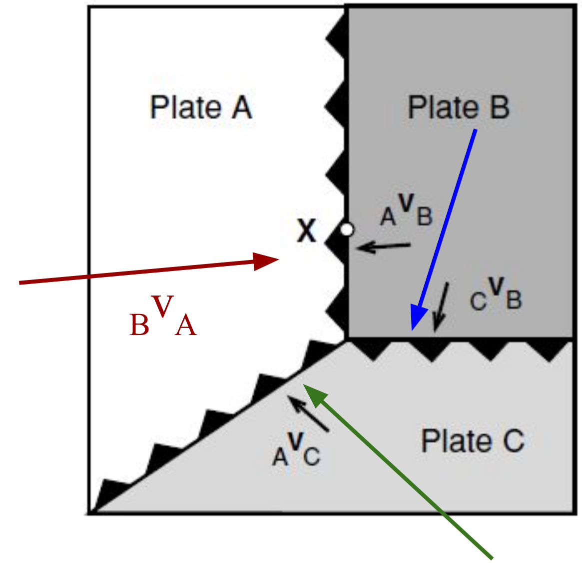




Stability of Triple Junctions - Rules using geometry

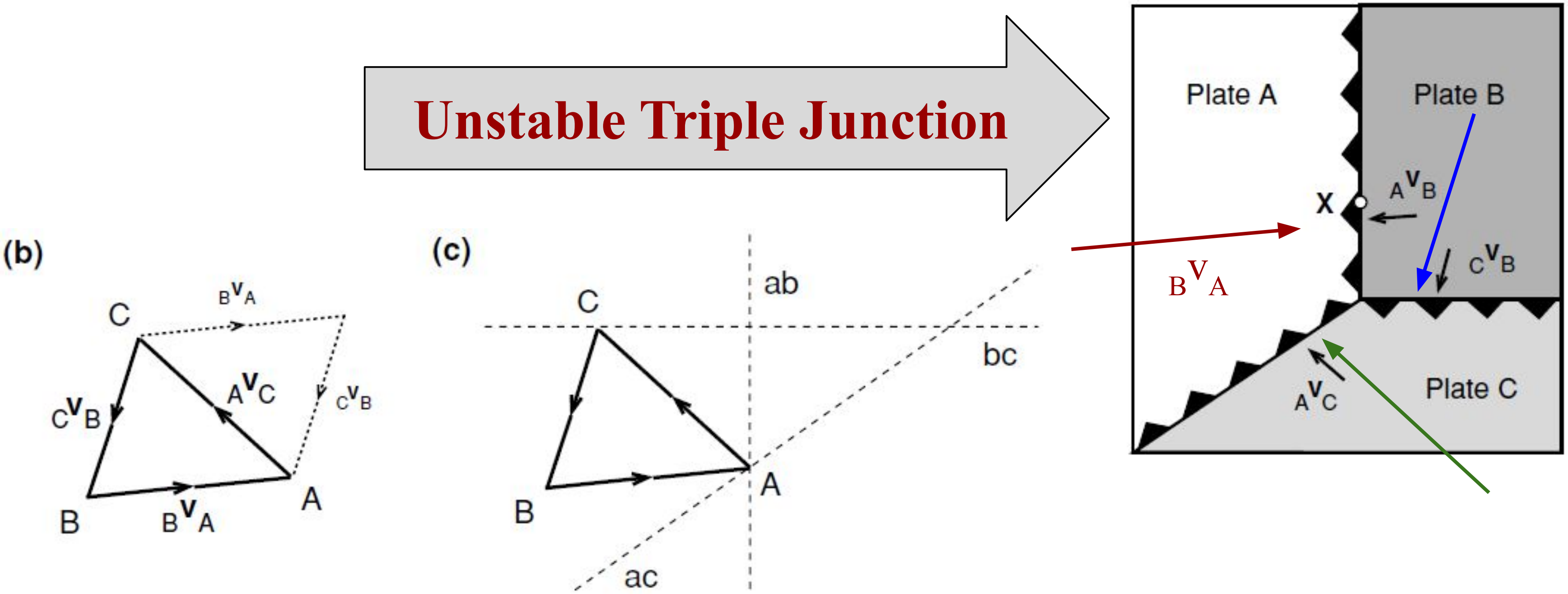
Step 4: Test for Stability?





If all the three lines pass through a point the Triple Junction is stable

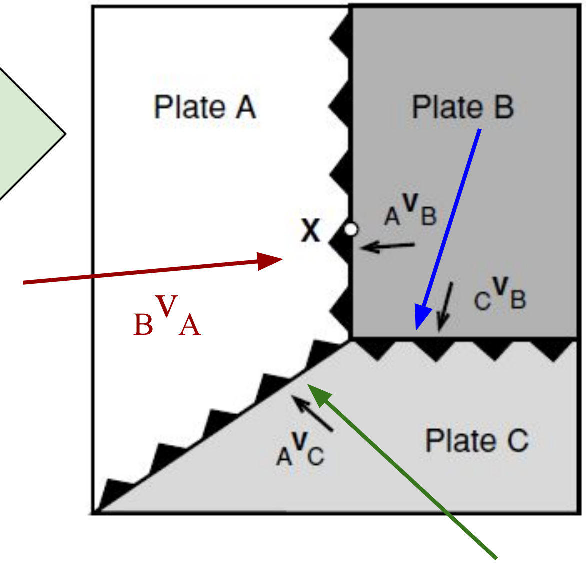
Stability of Triple Junctions - Rules using geometry

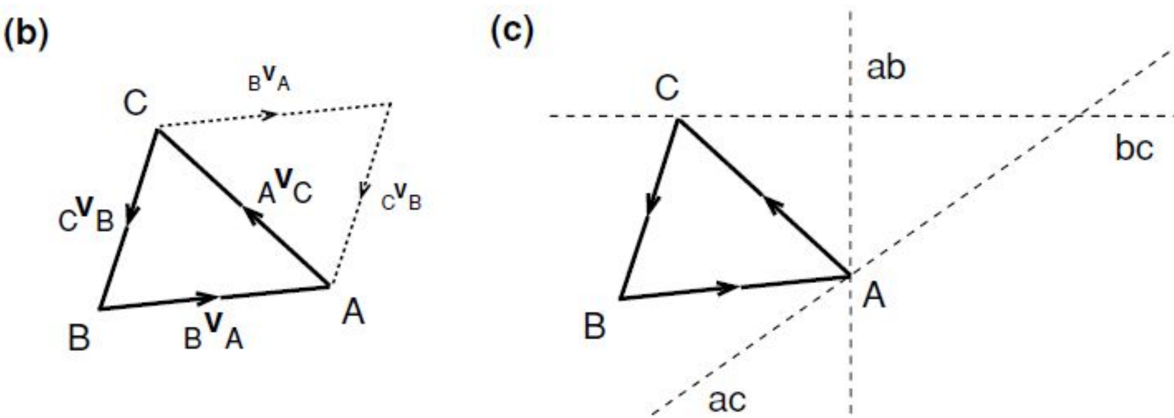


If all the three lines pass through a point the Triple Junction is stable

Examining Stability: Using Boundary Velocity Lines

How will it stabilise?



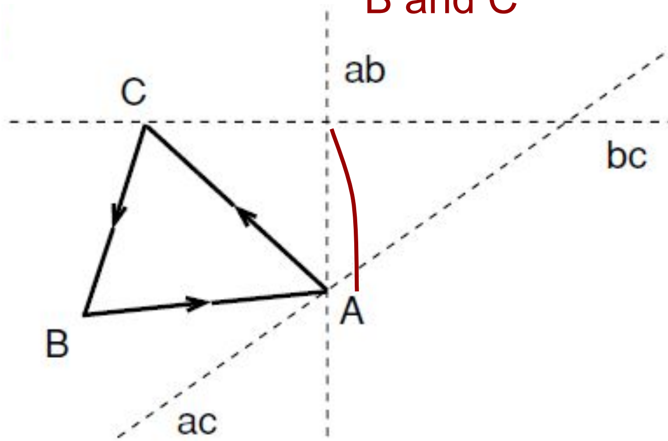


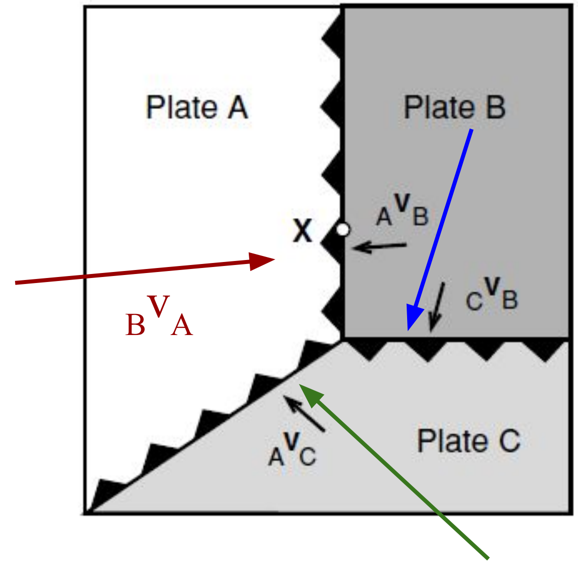
If all the three lines pass through a point the Triple Junction is stable

Examining Stability: Using Boundary Velocity Lines

Conditions of Stability

If $_{A}v_{C}$ were parallel to the boundary between plates B and C





If all the three lines pass through a point the Triple Junction is stable

Examining Stability: Using Boundary Velocity Lines

Conditions of Stability

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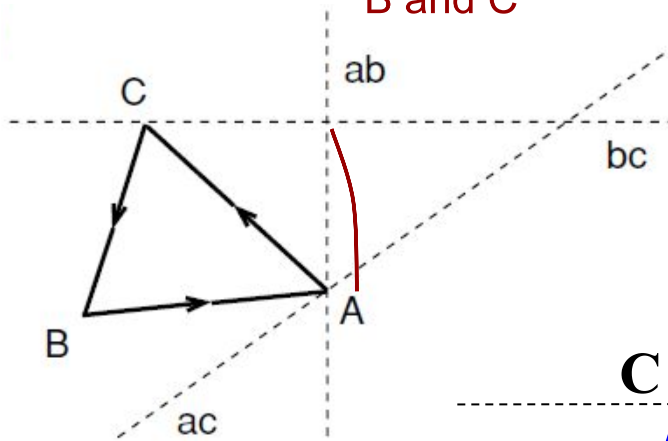
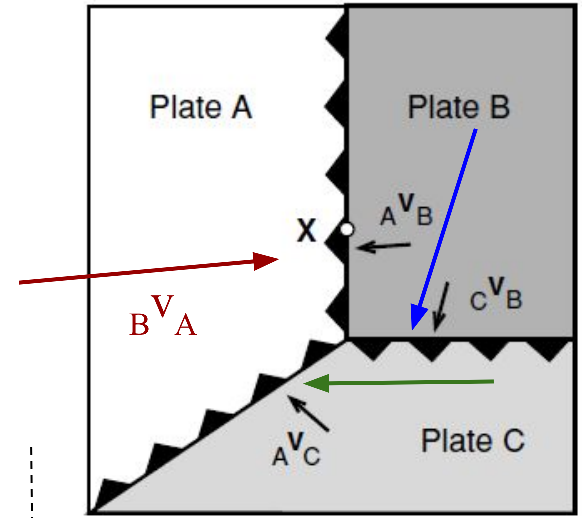
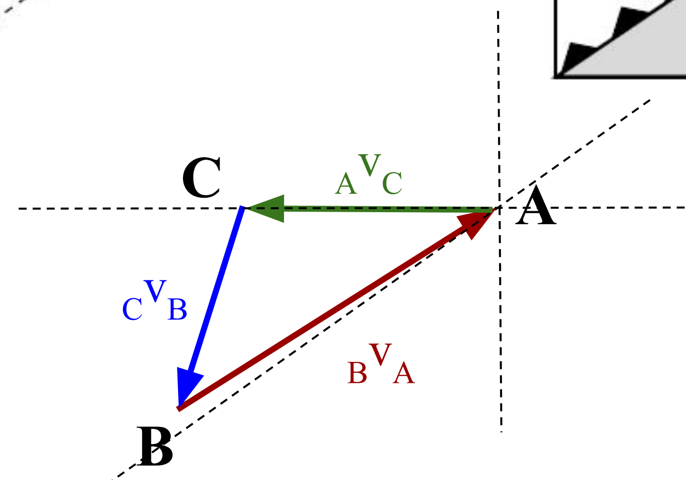


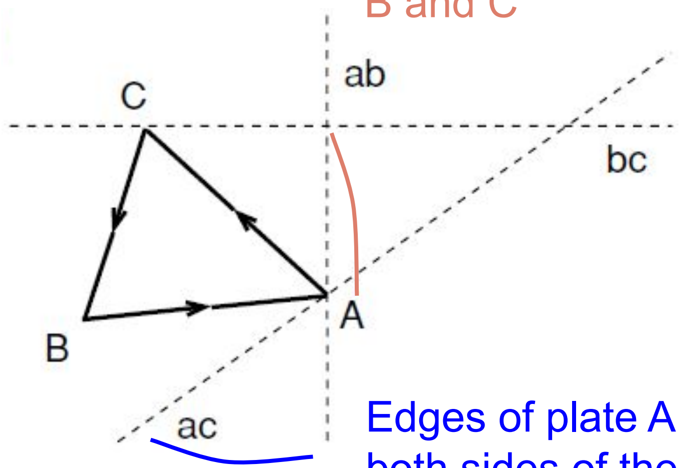




If all the three lines pass through a point the Triple Junction is stable

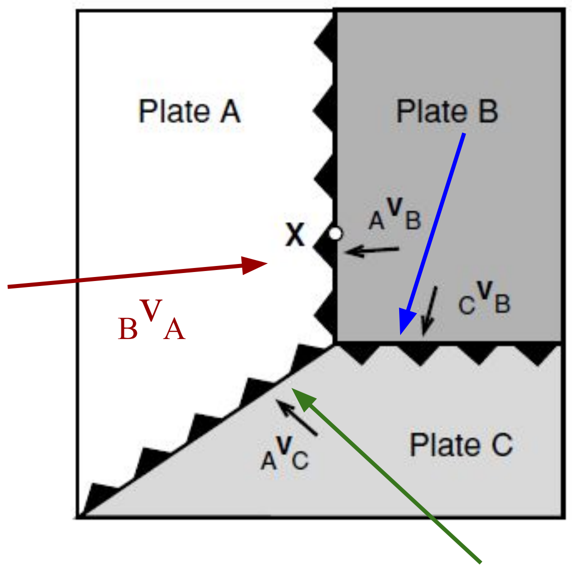
Examining Stability: Using Boundary Velocity Lines

Conditions of Stability



If ${}_{A}v_{C}$ were parallel to the boundary between plates B and C

Edges of plate A on both sides of the triple junction is straight

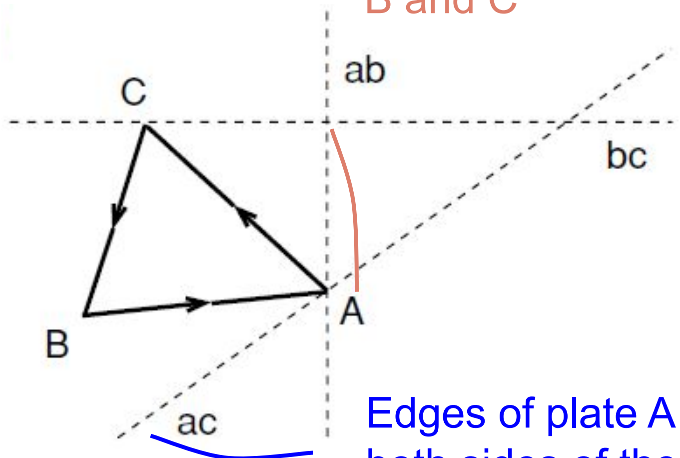


If all the three lines pass through a point the Triple Junction is stable

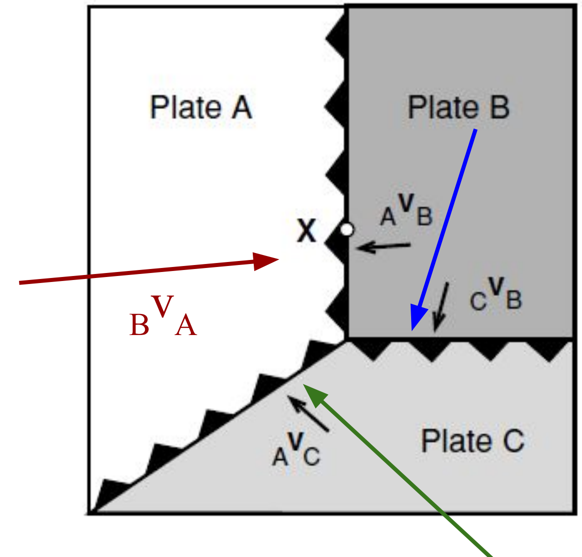
Examining Stability: Using Boundary Velocity Lines

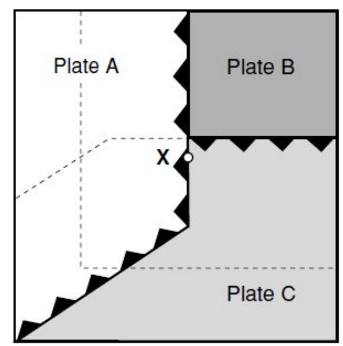
Conditions of Stability

If $_{A}v_{C}$ were parallel to the boundary between plates B and C



Edges of plate A on both sides of the triple junction is straight



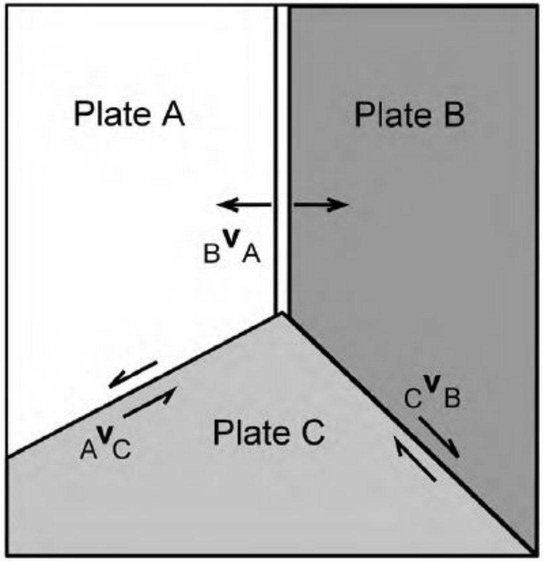


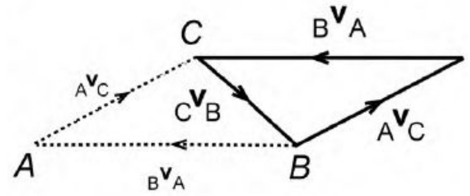
Boundaries between plates A&B and A&C become collinear

If all the three lines pass through a point the Triple Junction is stable

Examining Stability: Using Boundary Velocity Lines

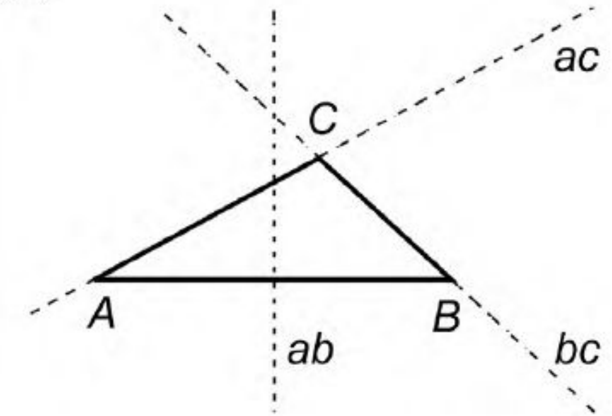
Example: Ridge-Ridge-Fault (RFF)





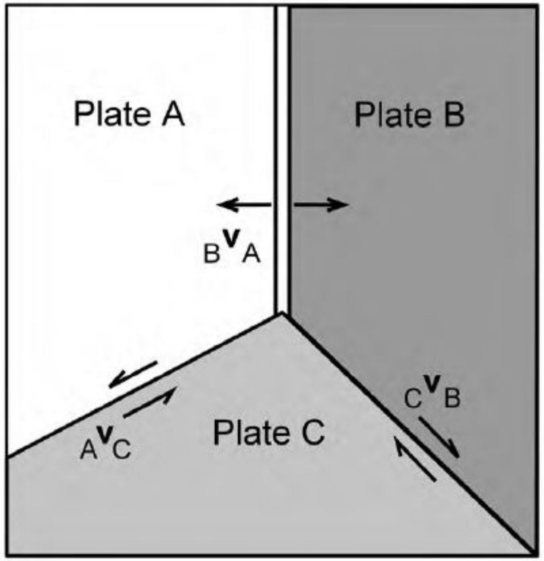
Condition-1

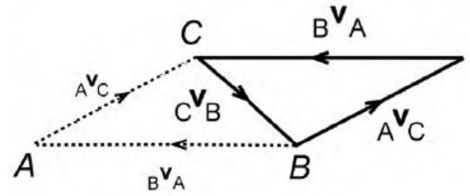
- **ab is the perpendicular bisector of AB**
  (i.e. Ridge spreads symmetrically & at right angles to its strike)
- **bc and ac are collinear with BC and AC**
  (i.e. represent motion along faults)



Examining Stability: Using Boundary Velocity Lines

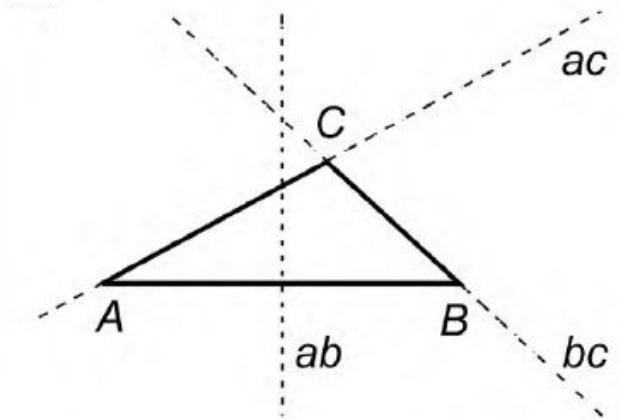
Example: Ridge-Ridge-Fault (RFF)



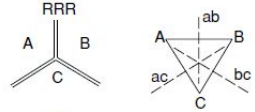
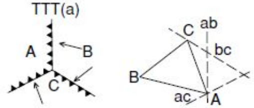
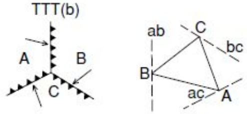
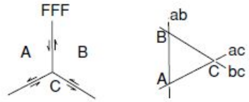
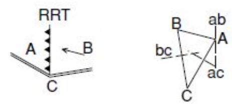
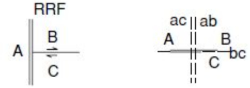
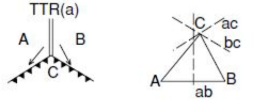
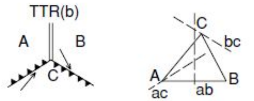
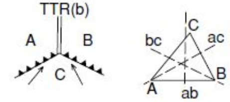
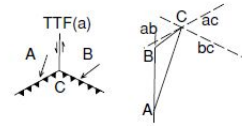
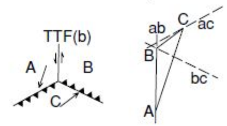
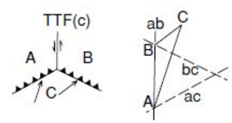
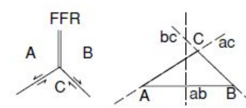
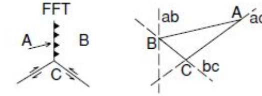
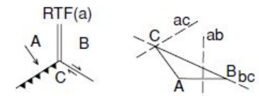
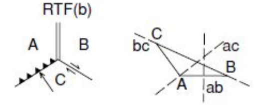


Condition-2

- ab goes through C
  (i.e both transform faults have the same slip rate)
- ac and bc are collinear
  (i.e the boundary of plate C is straight)



16 possible Combinations of Triple Junctions

Geometry	Velocity triangle	Stability	Possible Examples
RRR 		All orientations stable	East Pacific Rise and Galapagos Rift Zone, Indian Ocean Triple Junction
TTT(a) 		Stable if ab, ac form a straight line, or if bc is parallel to the slip vector CA	Central Japan
TTT(b) 		Stable if the complicated general condi-tion for ab, bc and ac to meeting at a point is satisfied	
FFF 		Unstable	
RRT 		ab must go through centroid of ABC	
RRF 		Unstable, evolves to FFR; but stable if ab and ac are perpendicular	
TTR(a) 		Stable if ab goes through C, or if ac, bc form a straight line	
TTR(b) 		Stable if com-plicated general conditions are satisfied	
TTR(b) 		Stable if the angles between ab and ac, bc, respectively, are equal, or if ac, bc form a straight line	
TTF(a) 		Stable if ac, bc form a straight line, or if C lies on ab	Intersection of the Peru–Chile trench and the Chile Rise
TTF(b) 		Stable if bc, ab form a straight line, or if ac goes through B	
TTF(c) 		Stable if ab, ac form a straight line, or if ab, bc do so	
FFR 		Stable if C lies on ab, or if ac, bc form a straight line	Owen fracture zone and the Carlsberg Ridge, Chile Rise and the East Pacific Rise
FFT 		Stable if ab, bc form a straight line, or if ac, bc do so	San Andreas Fault and Mendocino fracture zone (Mendocino triple junction)
RTF(a) 		Stable if ab goes through C or if ac, bc form a straight line	Mouth of the Gulf of California (Rivera triple junction)
RTF(b) 		Stable if ac, ab cross on bc	

Significance of Triple Junctions

- **To understand the past and predict the future evolution of plate configuration.**

- **To understand the evolution through time of the geodynamic setting of any given area on the Earth.**

Significance of Triple Junctions

<u>Example:</u>

Mendocino triple junction

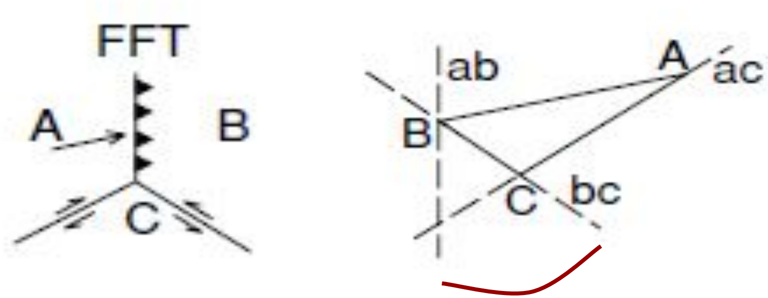
Fault-Fault-Trench (FFT)

Significance of Triple Junctions

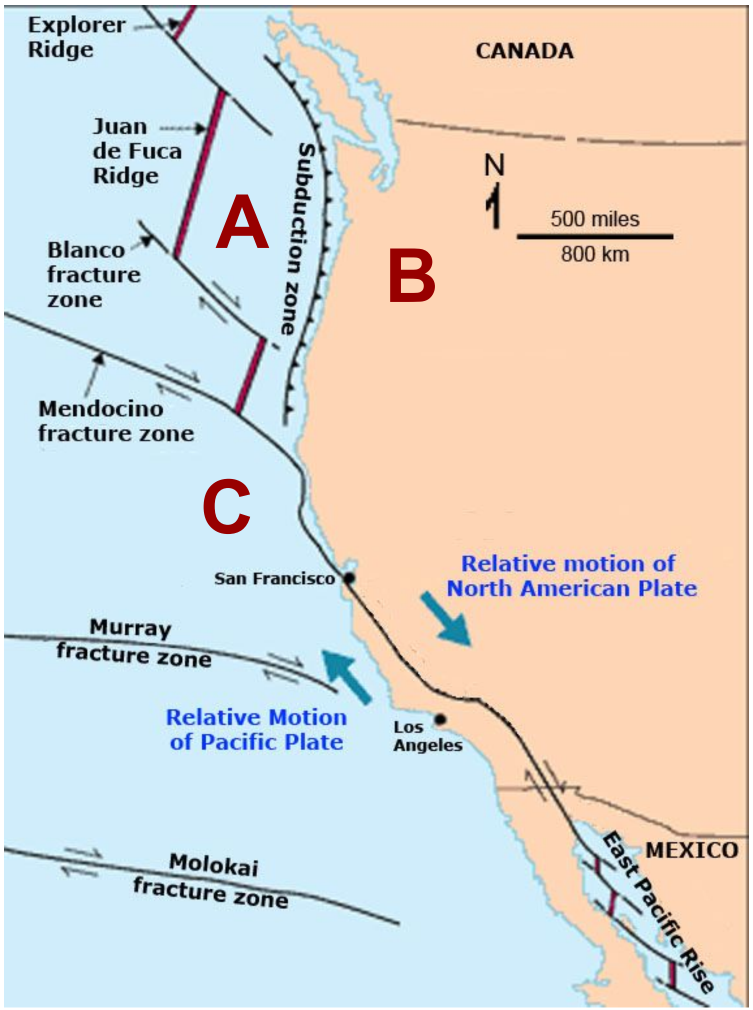
Example:

Mendocino triple junction

Fault-Fault-Trench (FFT)



Stable if ***ab*** and ***bc*** form a straight line

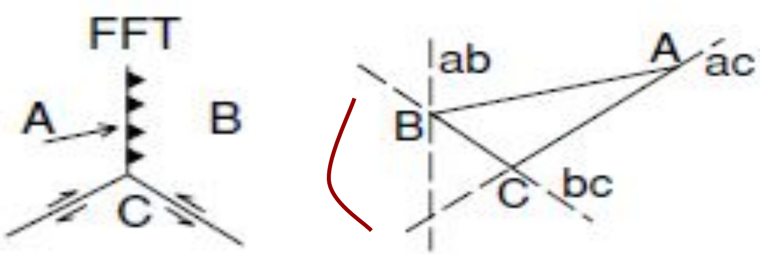


Significance of Triple Junctions

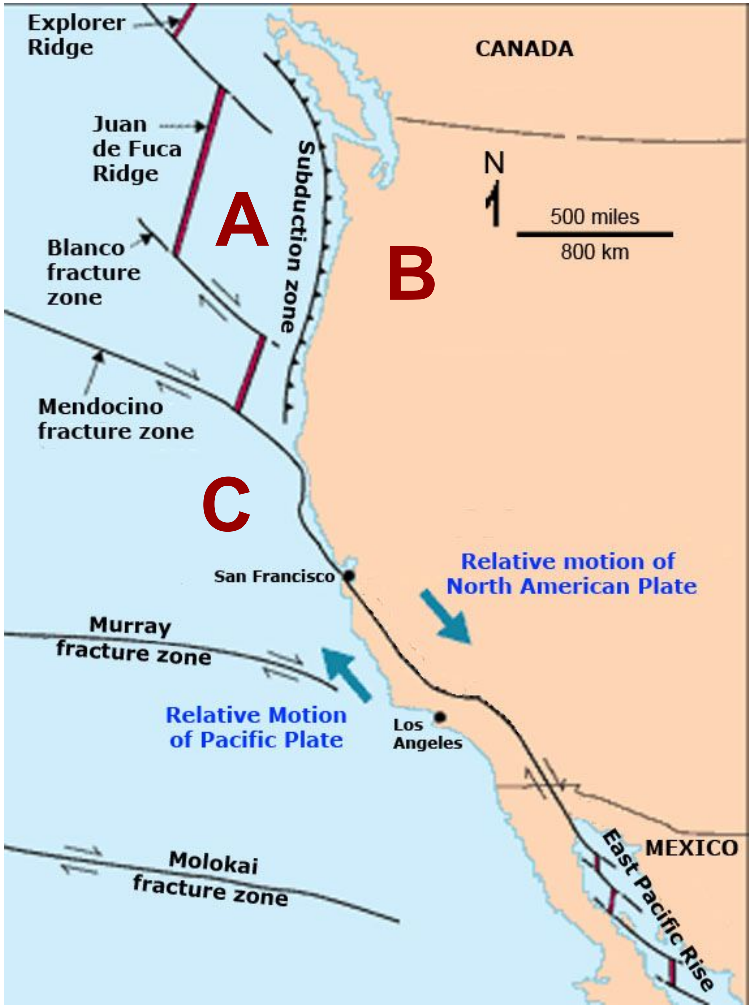
<u>Example:</u>

Mendocino triple junction

Fault-Fault-Trench (FFT)



Stable if ***ac*** and ***bc*** form a straight line

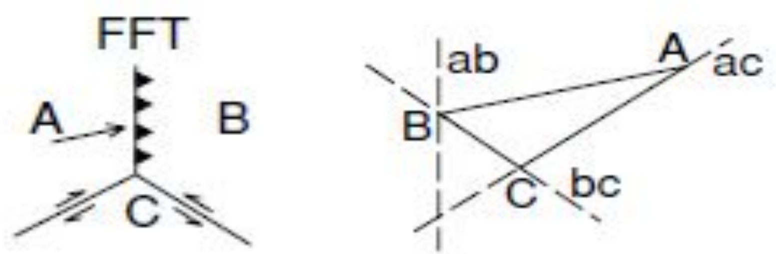


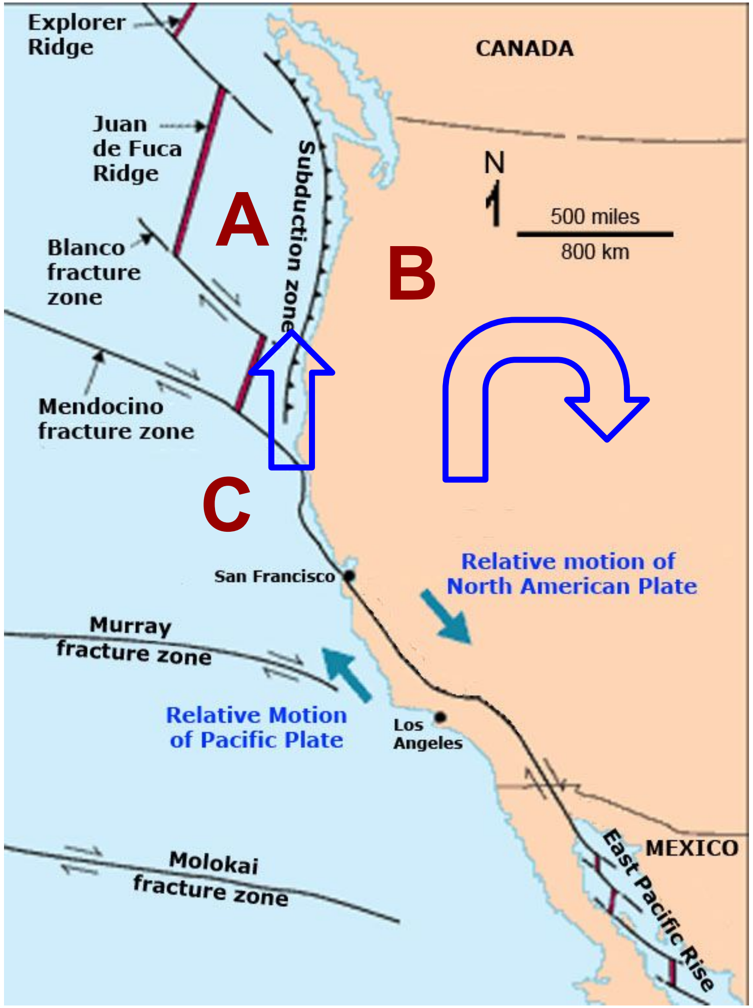
Significance of Triple Junctions

Example:

Mendocino triple junction

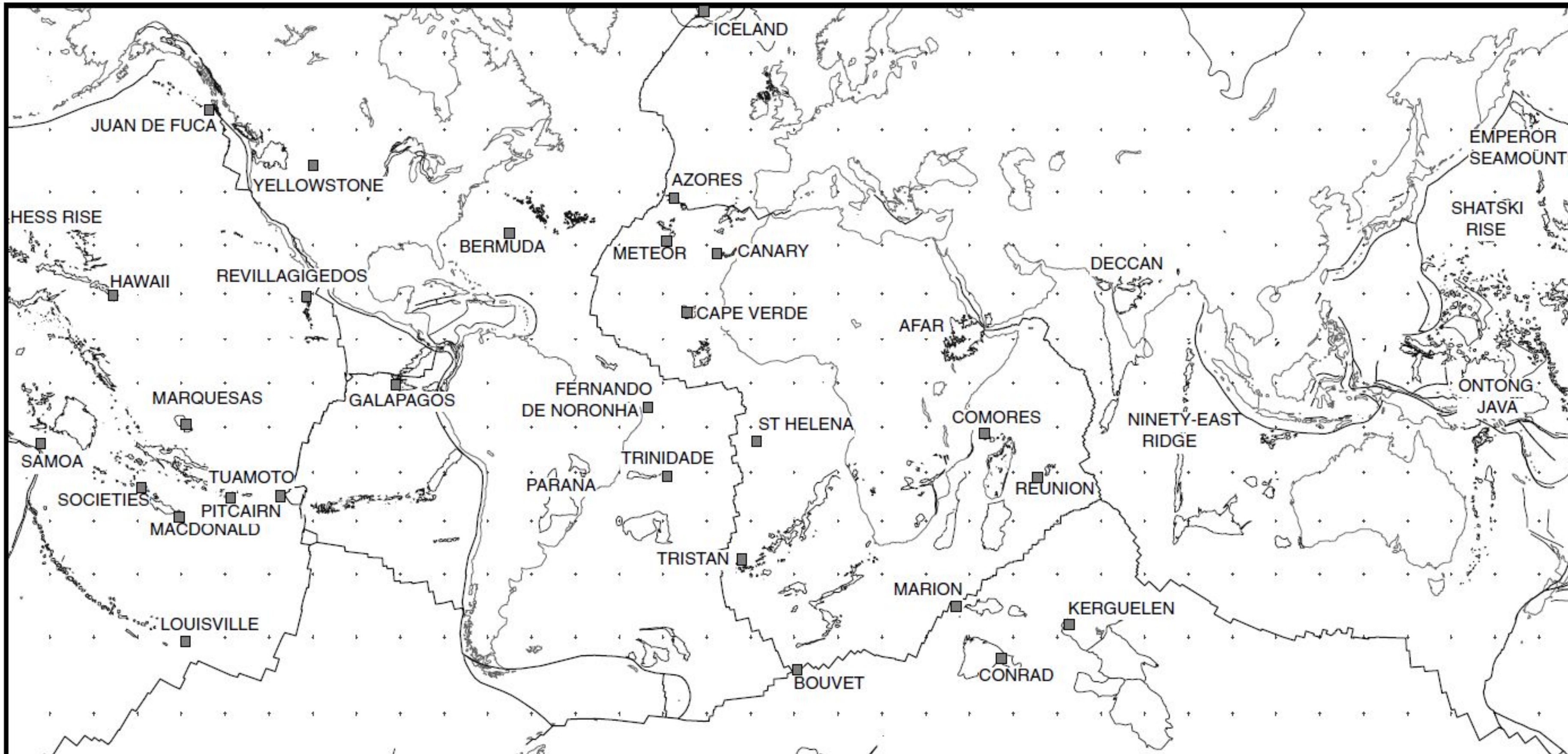
Fault-Fault-Trench (FFT)





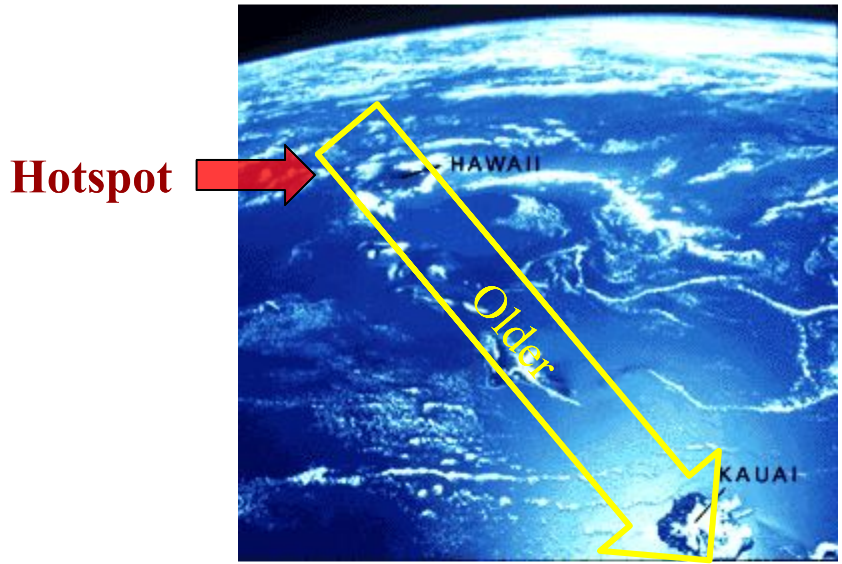
Result in northwards migration of the triple junction

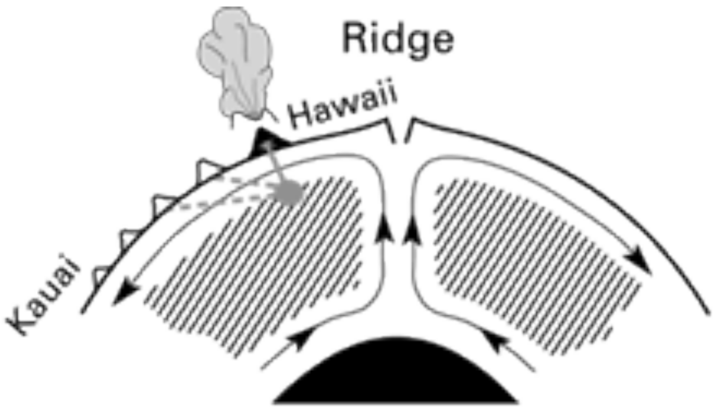
Absolute Plate Motions: hotspot reference frame



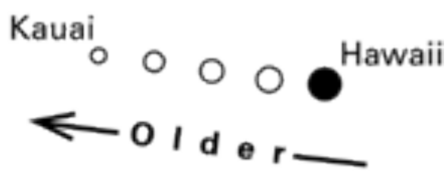
Absolute Plate Motions: The Hawaiian Plume

Measures with respect to Plumes/Hot Spots which are considered to be stationary



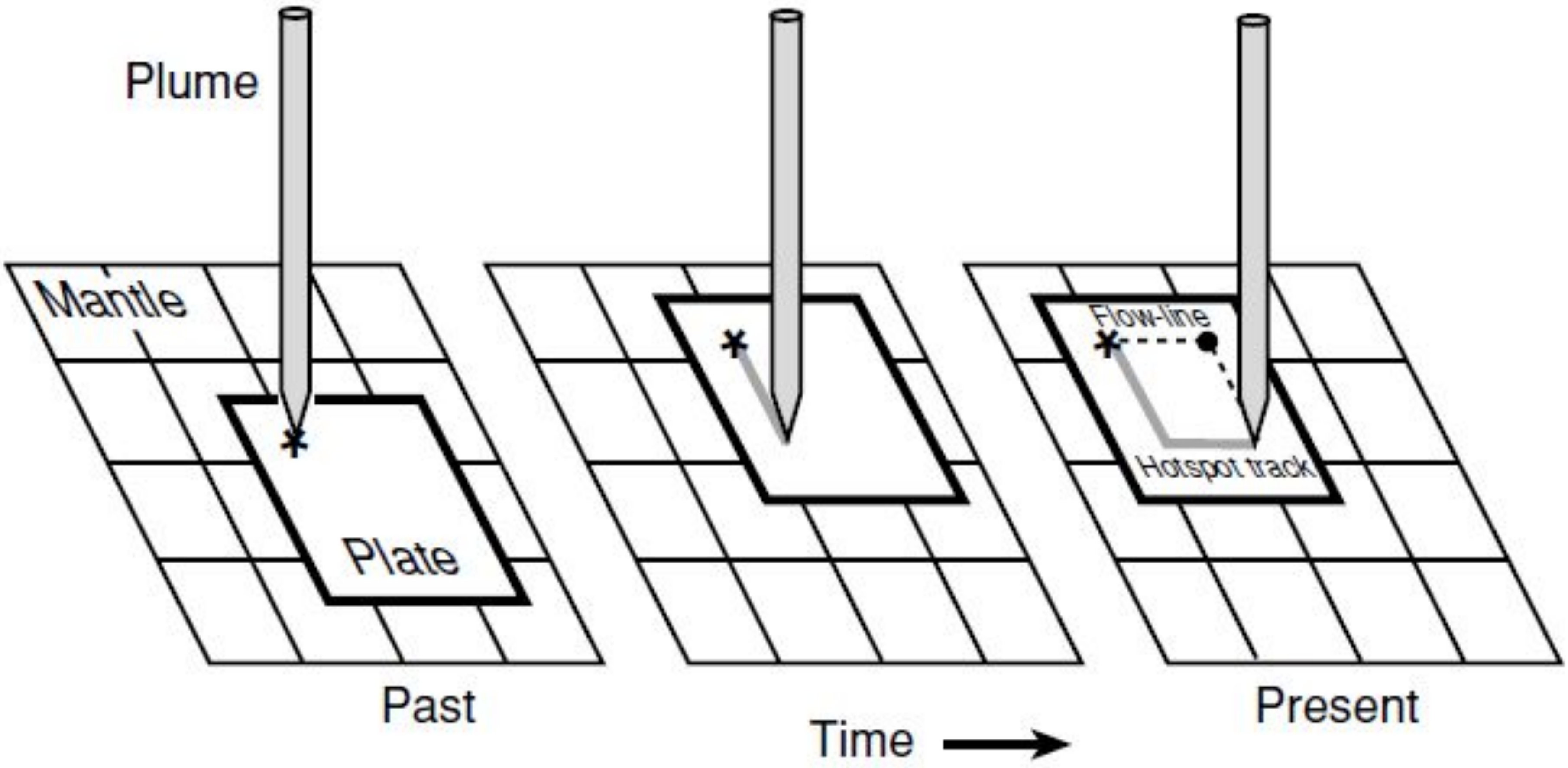


(a) Section

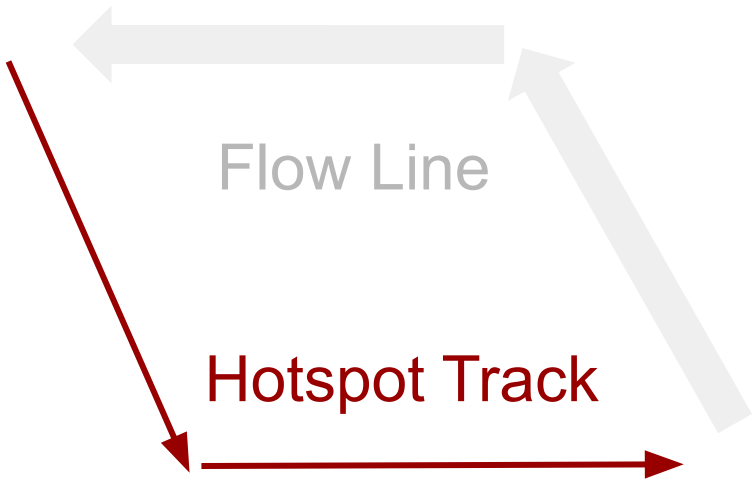


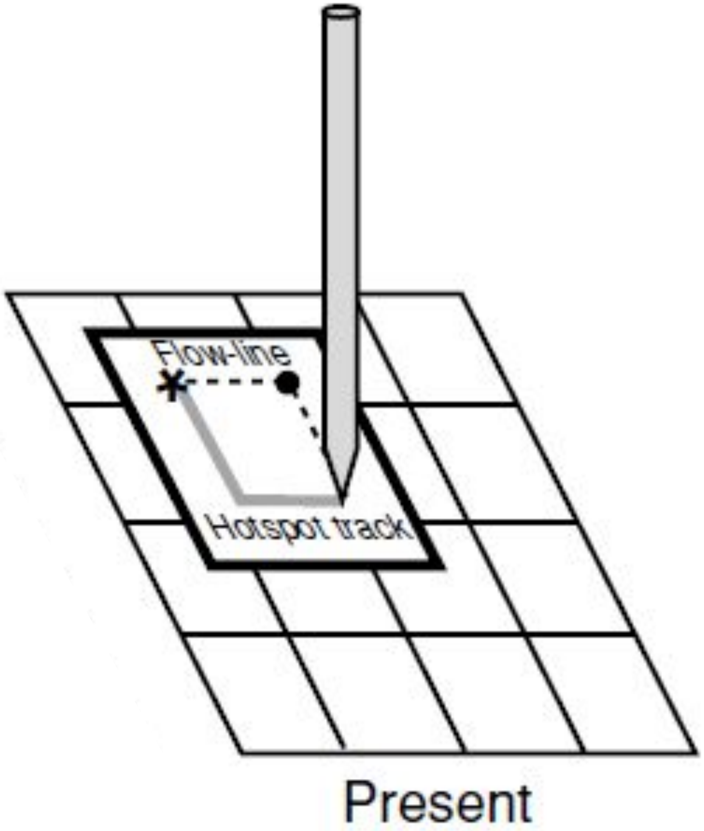
(b) Plan

Hot Spot Track and Flow Line



Hot Spot Track and Flow Line





What Drives the Plates?

1. ***Convection cell* or *Convective flow* ?**

Driven by the Earth's Heat Engine ?

2. ***Ridge Push ?***

3. ***Slab Pull ?***

The gravity-controlled sinking of a cold, denser oceanic slab into the subduction zone (called "slab pull") -- dragging the rest of the plate along with it -- is now considered to be the driving force of plate tectonics.