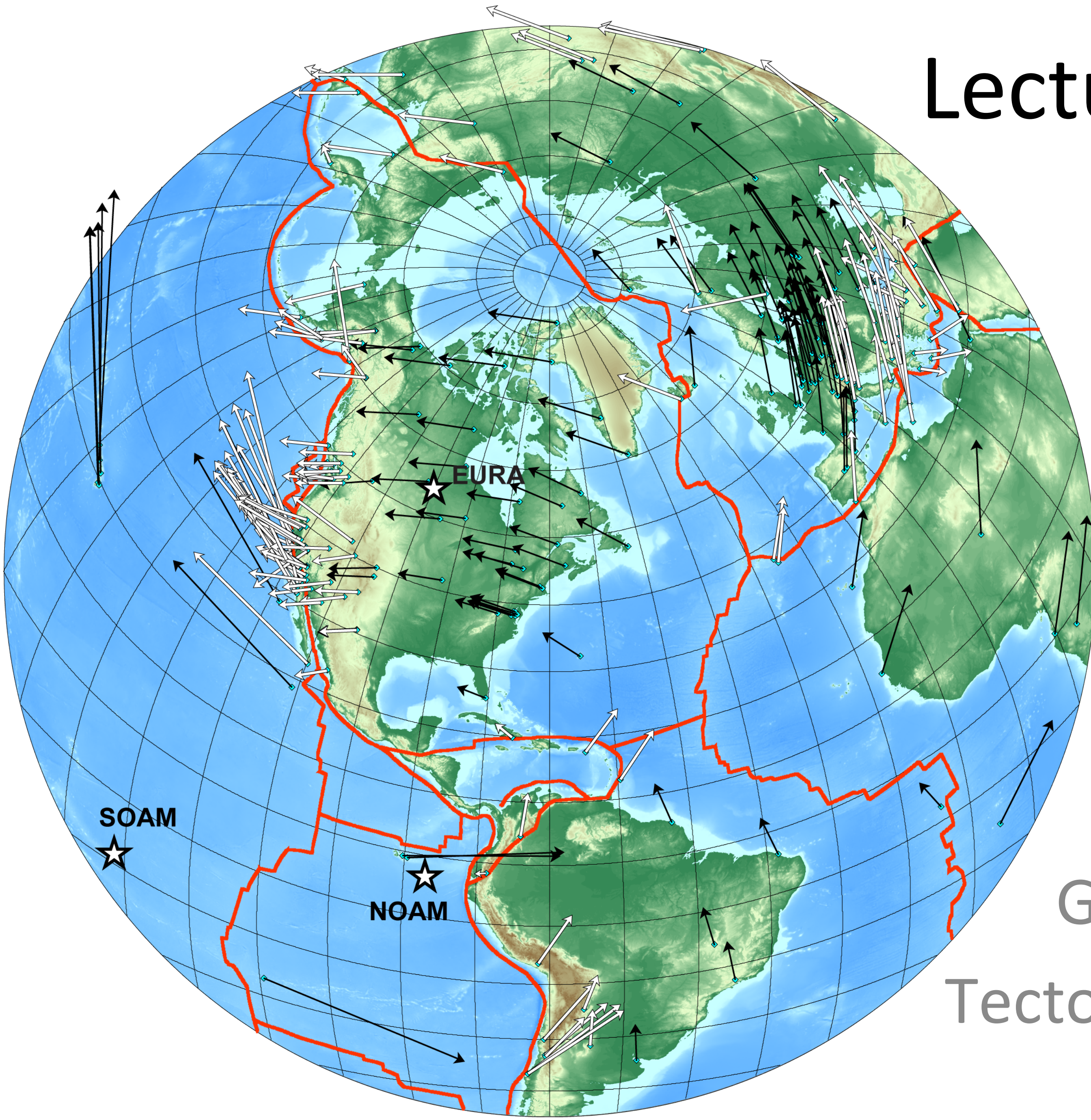
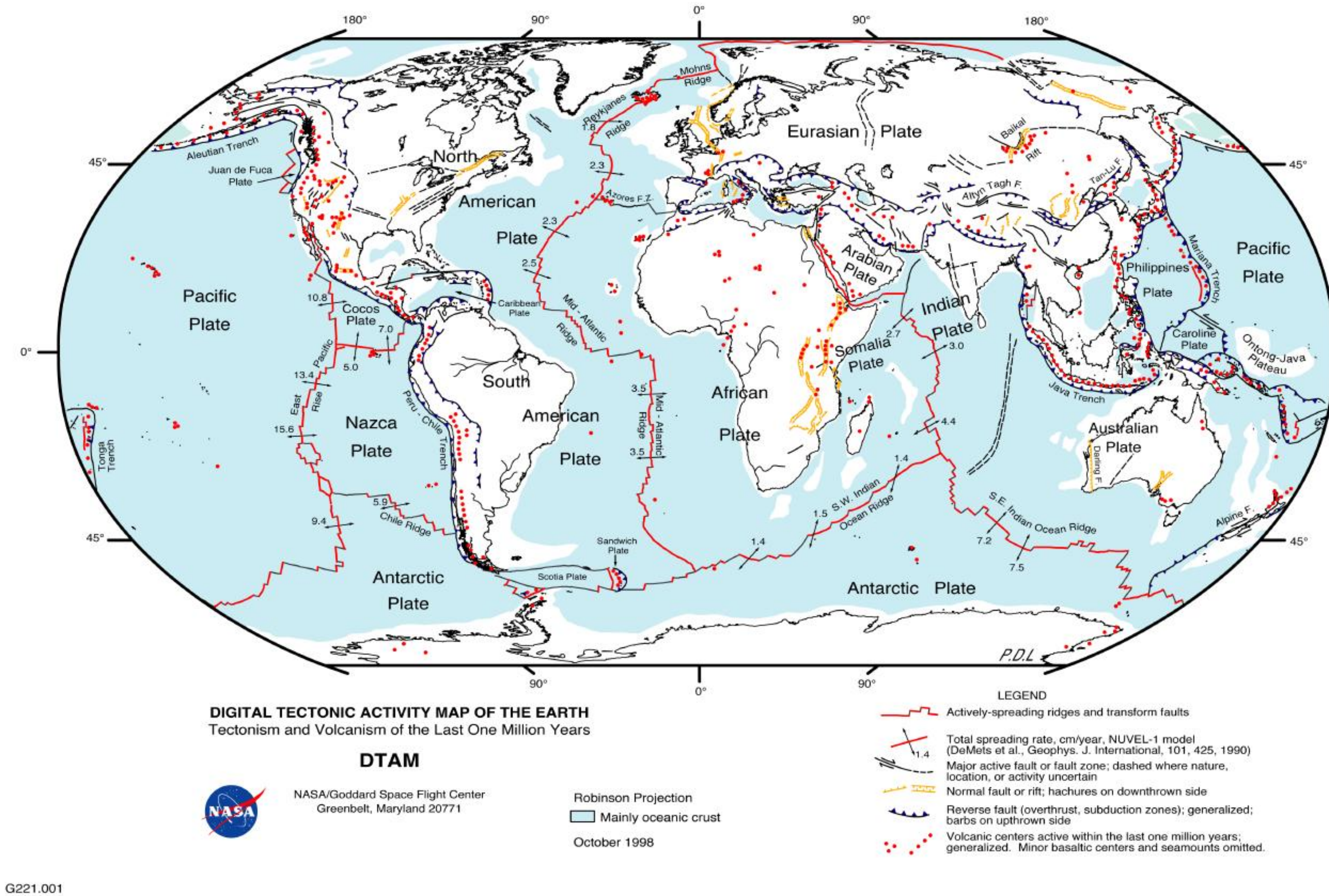


Lecture 8: Plate Kinematics

GEOS 655

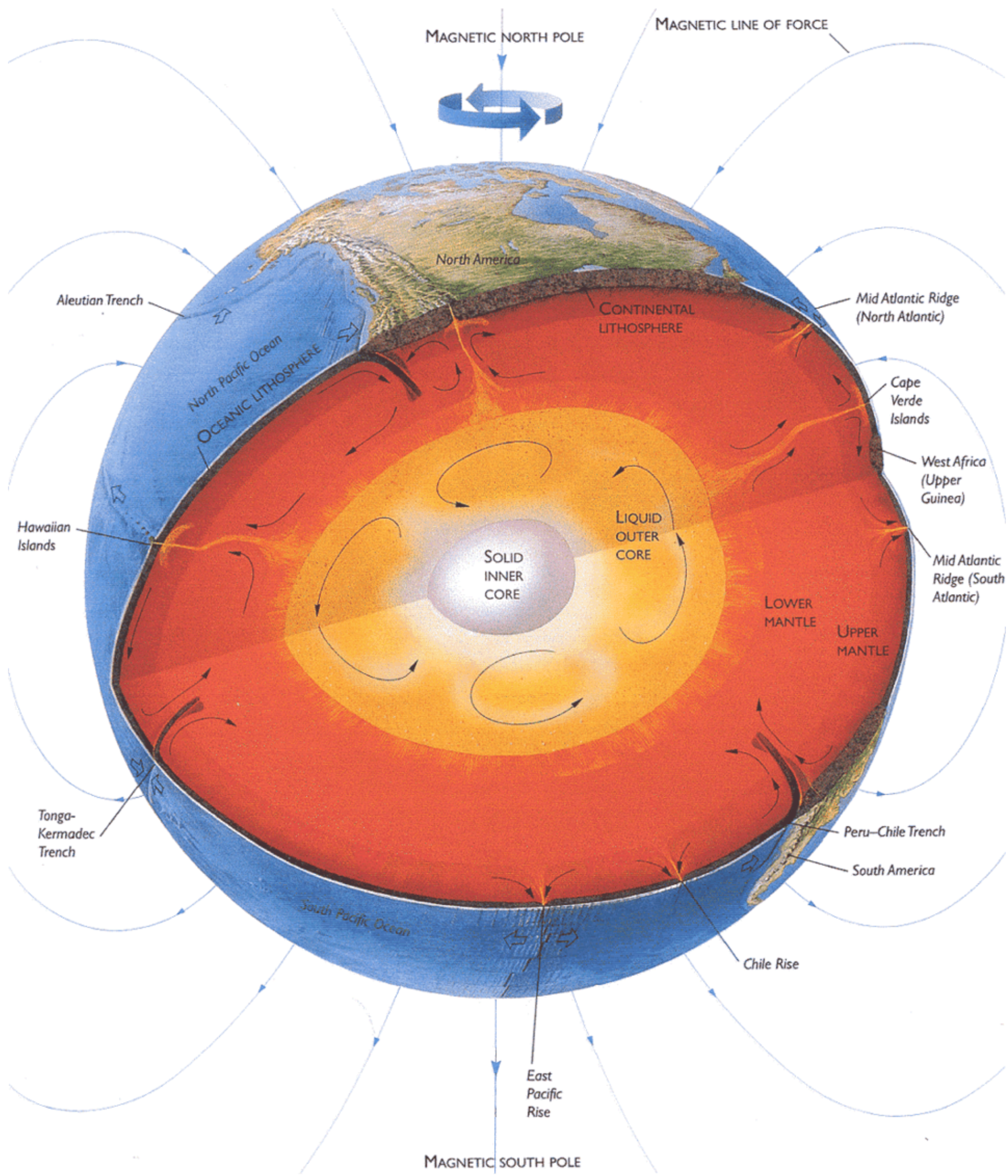
Tectonic Geodesy

Tectonic Activity



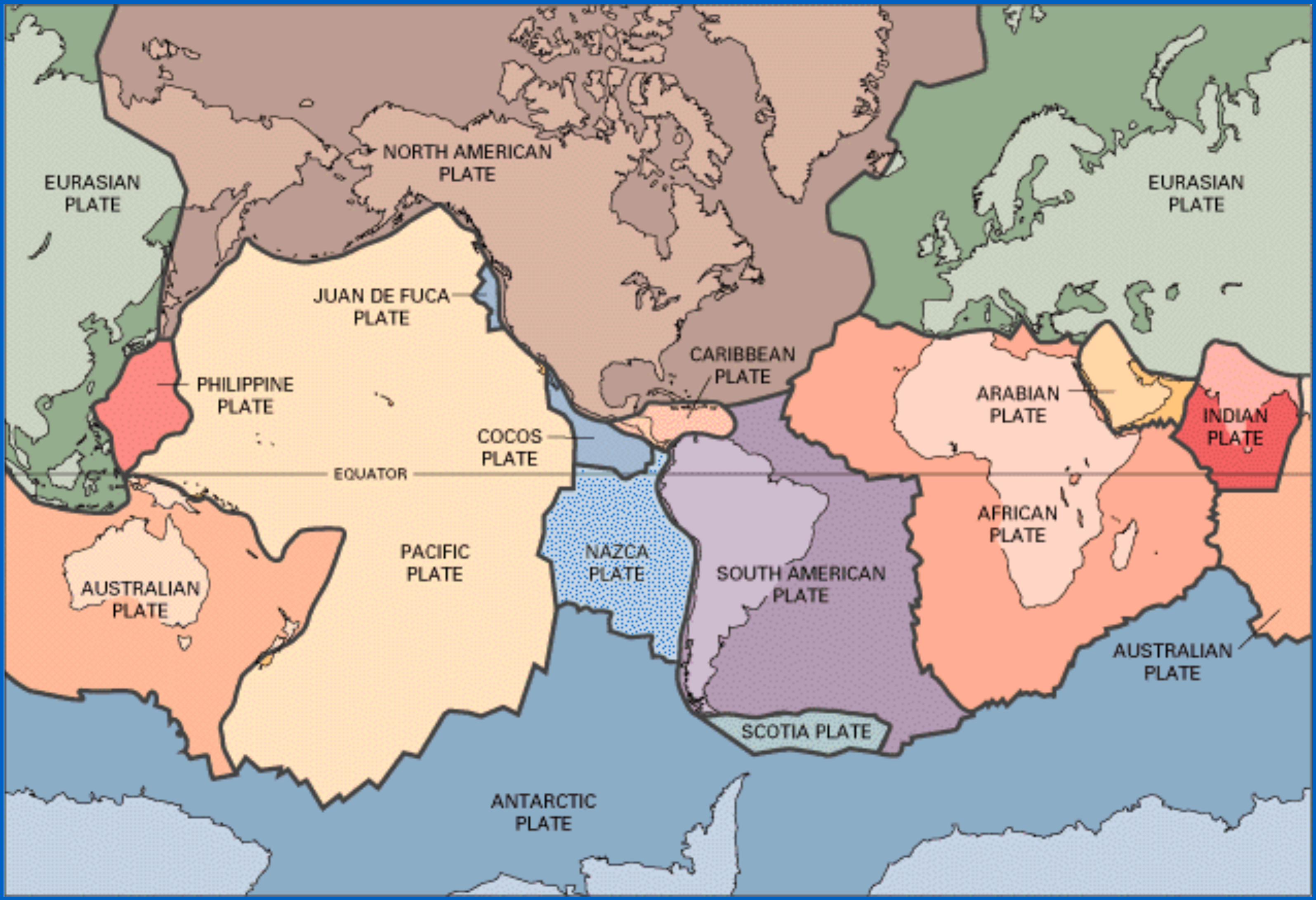
Basics of Plate Tectonics

- Review of Principles
  - Rigid plates, deforming only at boundaries (approx)
  - Types of plate boundaries
- Description of motions
  - Rigid body motion on a sphere is ***rotation about a geocentric axis***
  - Angular velocity, pole of rotation
- Quantification with Geodesy
  - Estimate site velocities from angular velocity
  - Estimate angular velocity from site velocities



Magnetic north pole
Magnetic line of force
North America
Aleutian Trench
North Pacific Ocean
Oceanic lithosphere
Continental lithosphere
Mid Atlantic Ridge (North Atlantic)
Cape Verde Islands
West Africa (Upper Guinea)
Hawaiian Islands
Liquid outer core
Solid inner core
Mid Atlantic Ridge (South Atlantic)
Lower mantle
Upper mantle
Tonga-Kermadec Trench
Peru–Chile Trench
South America
South Pacific Ocean
Chile Rise
East Pacific Rise
Magnetic south pole

Plate Tectonics



USGS

Plate Boundaries

- Plates are rigid, so relative motions between plates occur on their boundaries
- In reality, plate boundaries always have some finite width – **plate boundary zones**
  - Sometimes narrow, < 10 km
  - Sometimes very wide, 500-1000 km
- Relative motion occurs on **faults**, or breaks in the Earth's lithosphere.

Ridges and Transforms

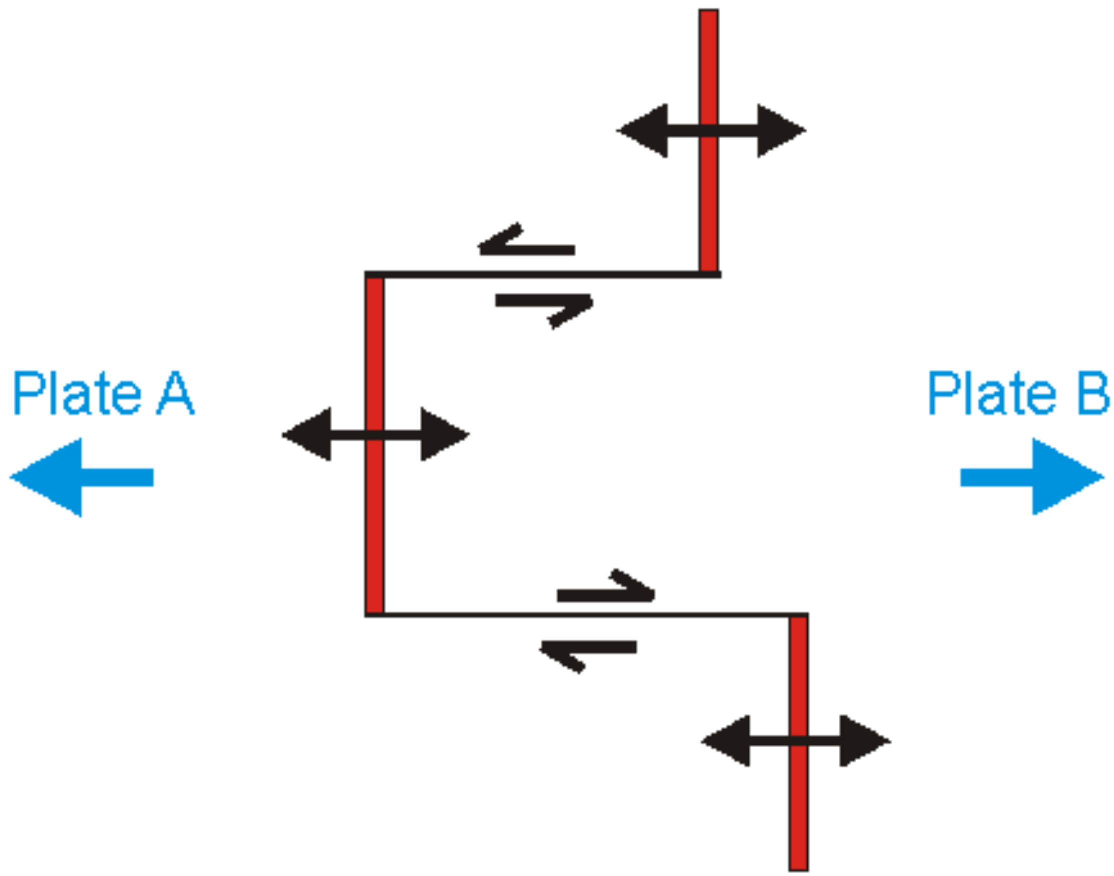
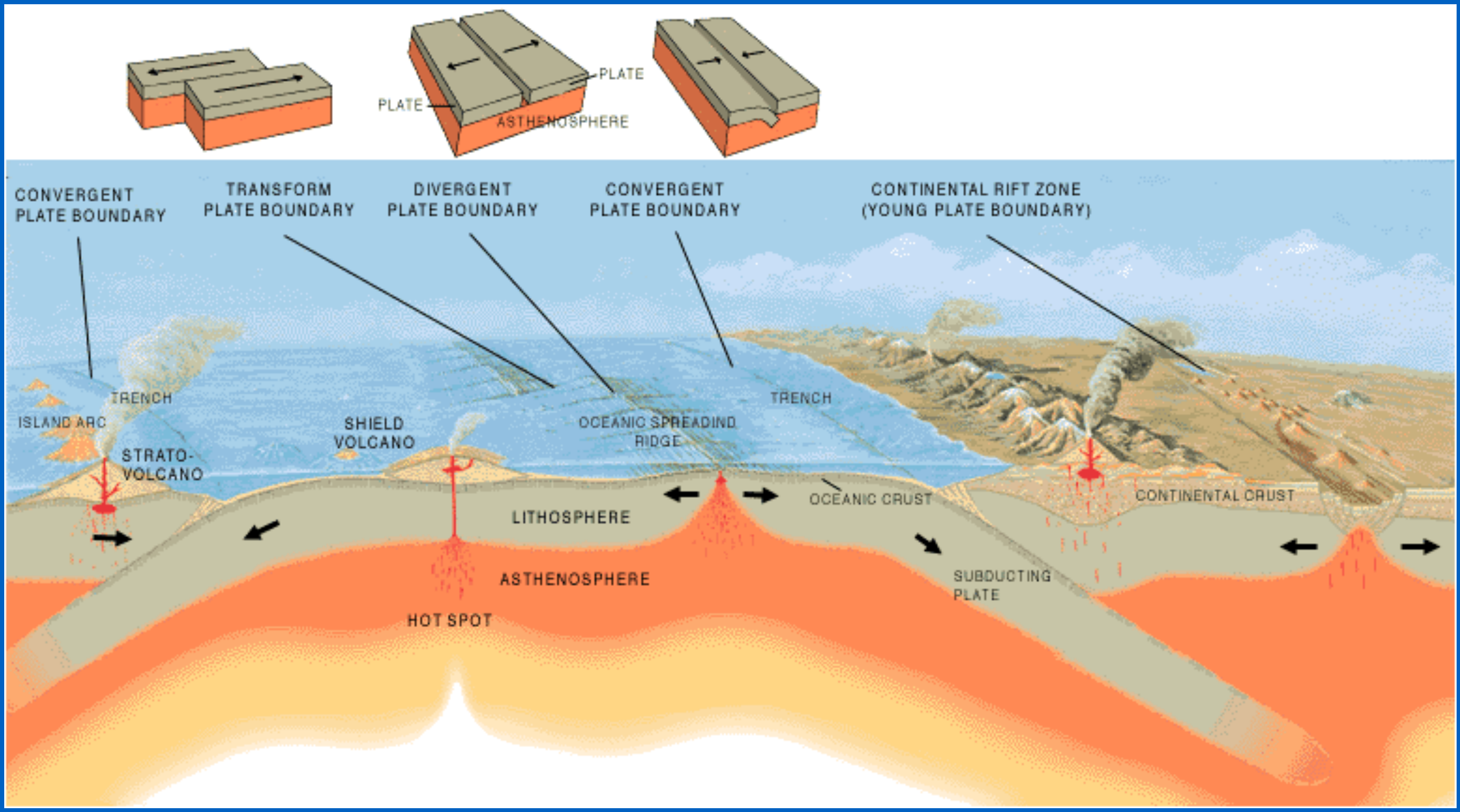


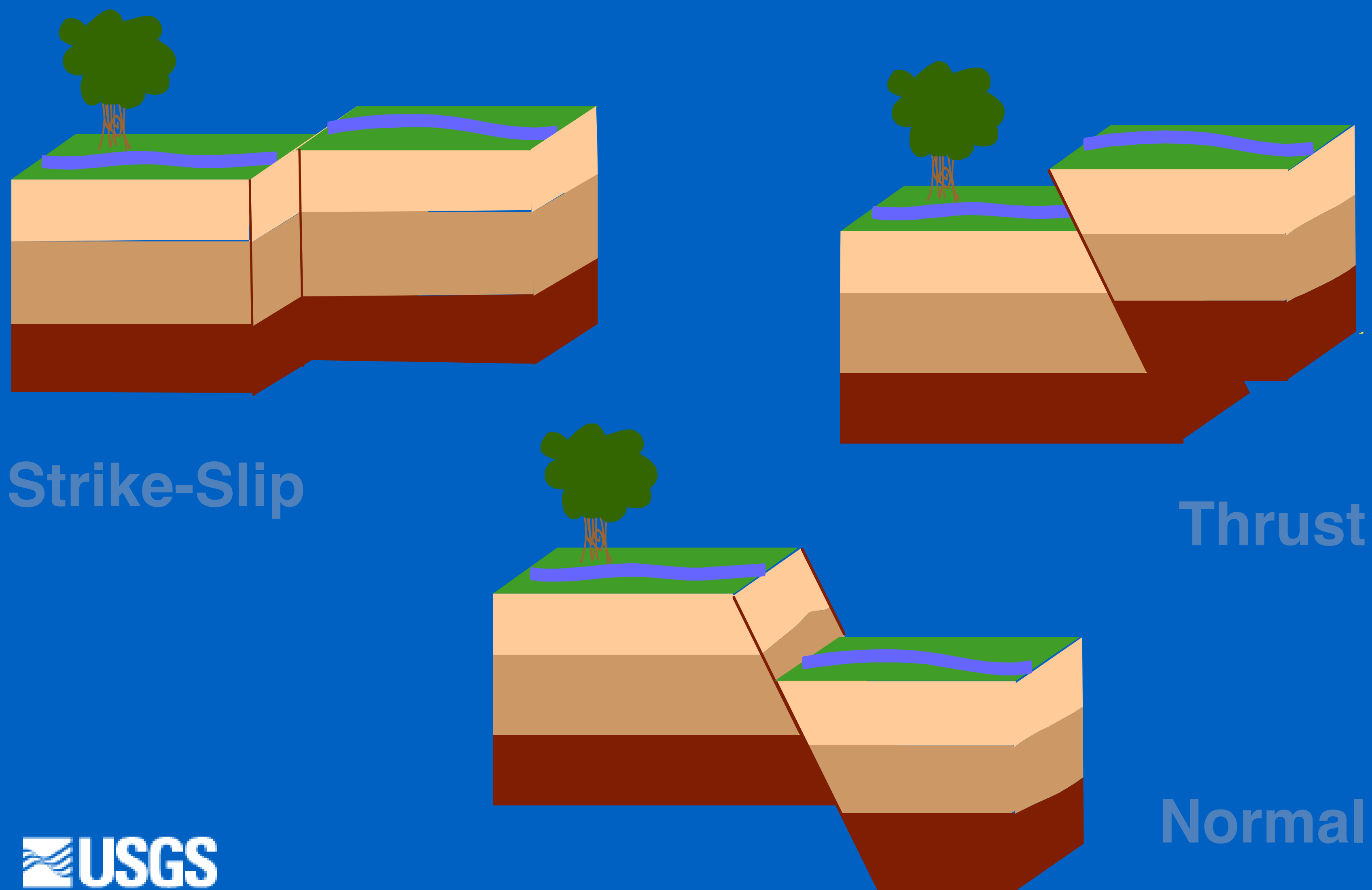
Plate Boundaries



Faults

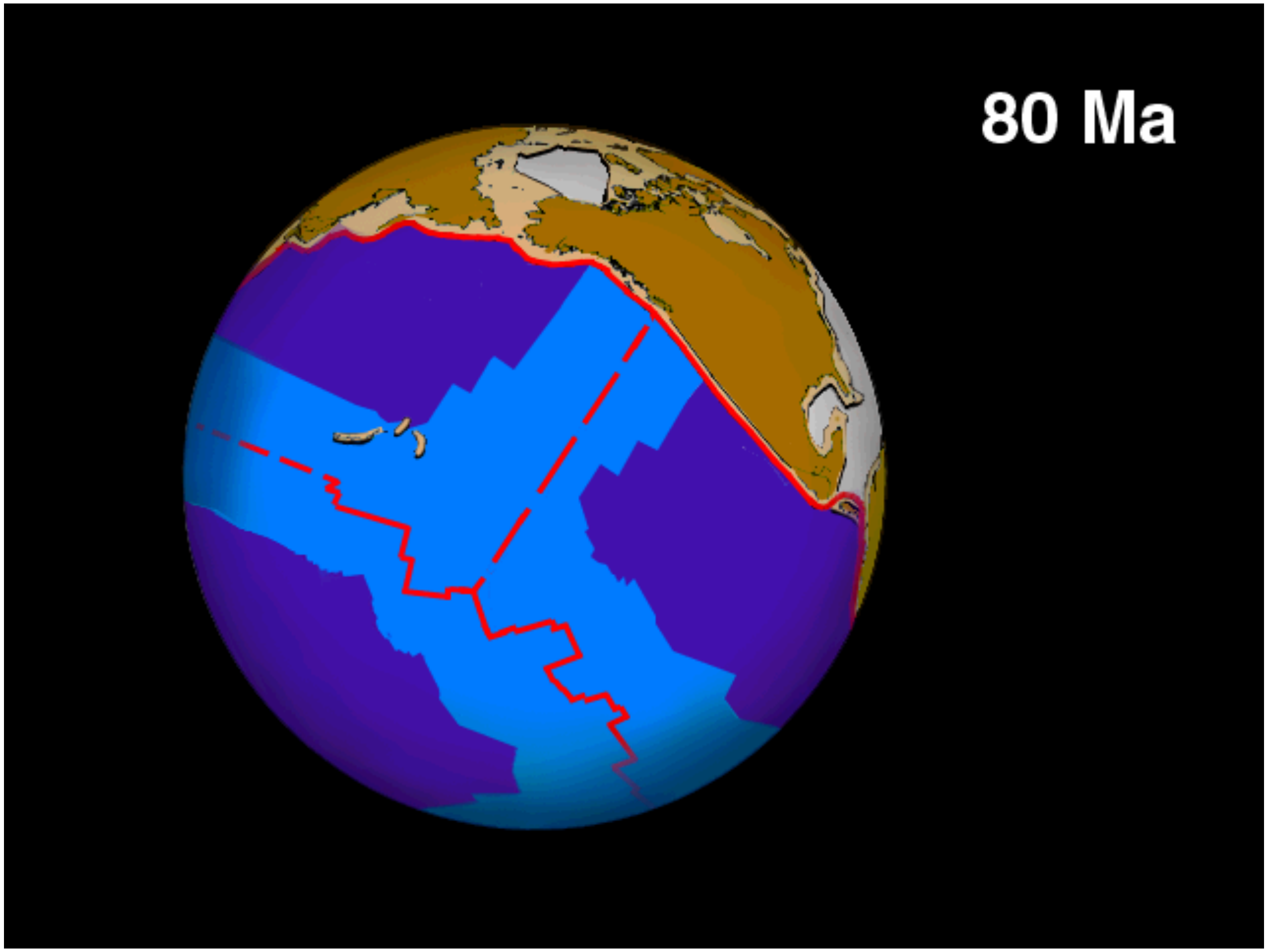
- Faults are surfaces, usually ~ planar, where the two sides move relative to each other.
  - Direction of motion == slip direction
- How slip occurs depends on depth
  - Shallow: sides are mostly stuck together by friction, but slips suddenly in earthquakes
  - Deeper: sides mostly slide past each other at a steady rate
- Plate tectonics drives the motion

Three Types of Faults

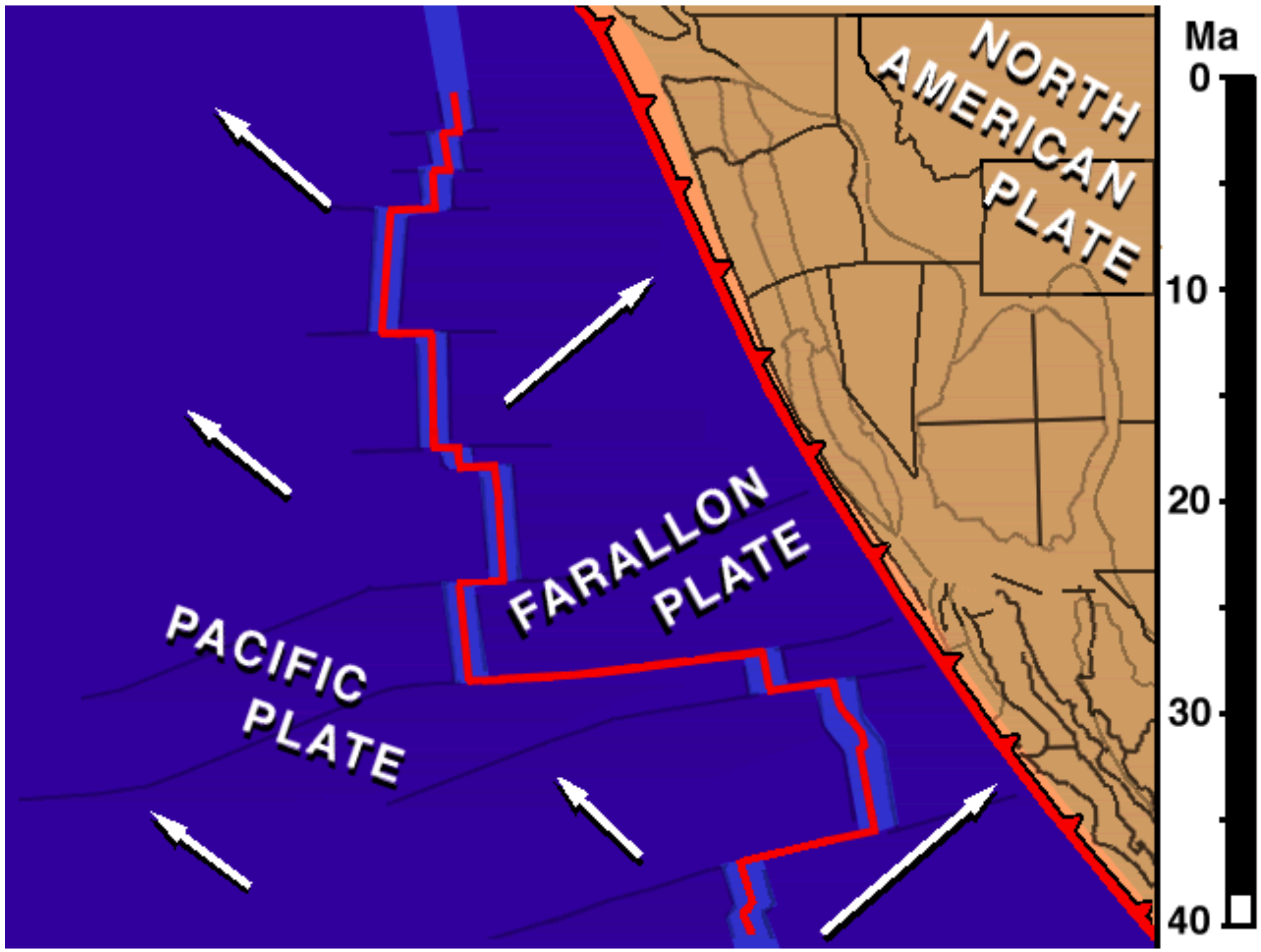


USGS

Plate Motion Movies

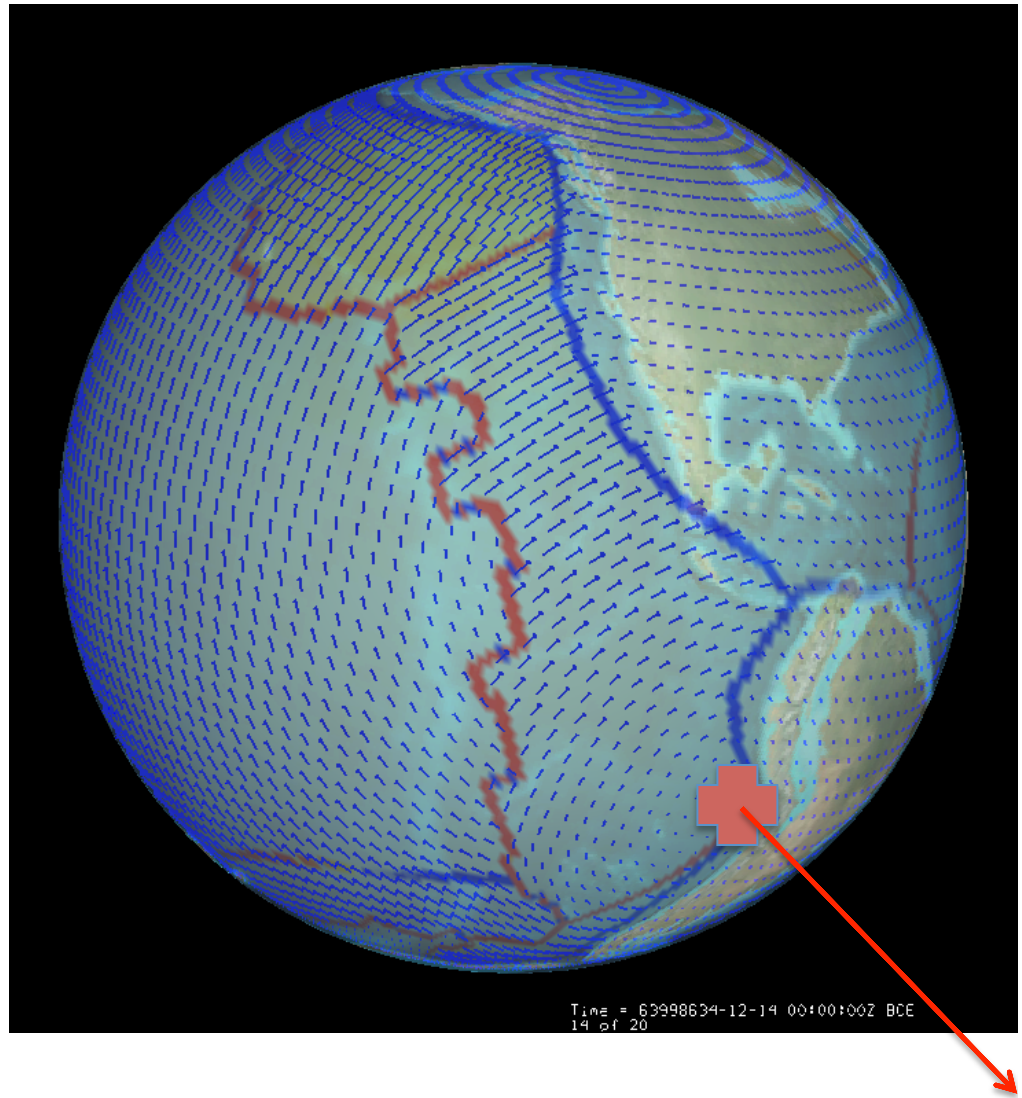


Watch Motion on Transform Faults

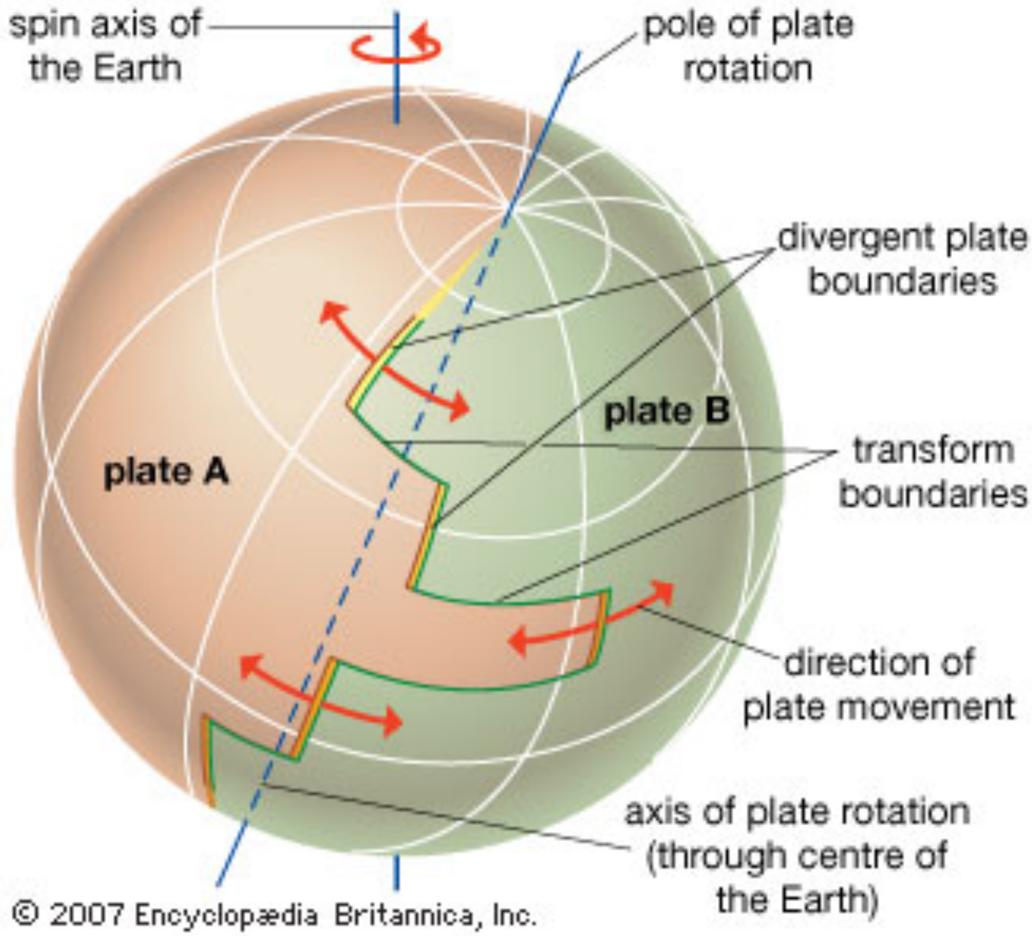


Rotation on a Sphere

- Any rigid motion on the surface of a sphere is a rotation about a geocentric axis.
  - All tectonic motions can be described in terms of rotations
- Two (equivalent) ways to describe rotation
  - Pole of rotation and angular speed
  - Angular velocity vector
- Can use this for any size plate or piece of crust



Pole of Rotation



Geologic Plate Motion Models

- Relative plate motion models based on some combination of
  - Spreading rates at mid-ocean ridges
    - From modeling of marine magnetic anomalies
  - Transform fault azimuths
  - Earthquake slip vectors
    - These are problematic
- Some plates have little or no data, for example the Caribbean and Philippine Sea Plates
- Commonly used: NUVEL-1, revised to NUVEL-1A
- Newer model: MORVEL (DeMets et al., 2010)

Absolute vs. Relative Motions

- Most evidence for plate motions are measures of relative plate motion – motion of B relative to A
  - Relative motion from geodesy
  - Plate boundary deformation
- Absolute plate motions depend on some externally defined reference frame
  - Hotspot reference frame
    - Except the hotspots move relative to each other
  - "No net rotation" == No net torque
- Plate motions defined in a geodetic reference frame

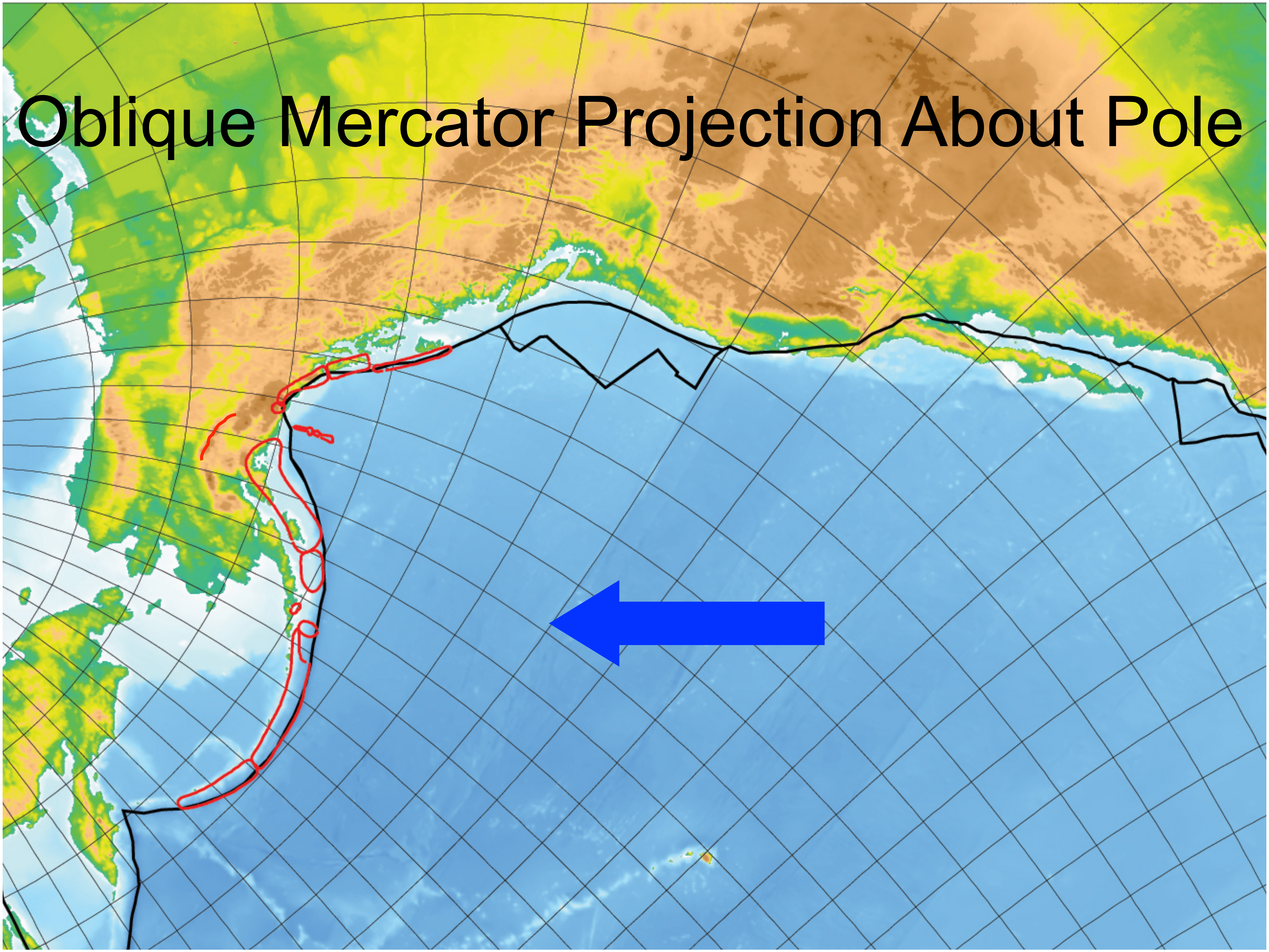
ITRF Orientation Time Evolution: No-Net-Rotation Condition

The NNRC is the null angular momentum h, defined in Tisserand mean Frame and given by:

$$h = \int_C X \times V \, dm = 0$$

If applied to rigid tectonic plates gives: $\boxed{h = \sum_{p \in P} Q_p \omega_p = 0}$

NNR-NUVEL-1A used: $\boxed{\omega_{PACIFIC} = -3/8\pi \sum_{p \in P} Q_p \Omega_p}$


Oblique Mercator Projection About Pole

Estimating Site Velocities

- It is easiest to compute the site velocities if you have the plate's angular velocity vector, because the site velocity is just the cross product of the site location vector with the plate angular velocity:

$$\underline{v} = \underline{\omega} \times \underline{r}$$

- You can compute it from the pole location as well, but that requires spherical trigonometry.

Estimating Plate Angular Velocity

- To get the angular velocity from site velocities, we need to invert the equation $\underline{v} = \underline{\omega} \times \underline{r}$

- Expand the cross product and rewrite it as a matrix equation

$$v = (z\omega_3 - y\omega_2)\hat{x} + (x\omega_3 - z\omega_1)\hat{y} + (y\omega_1 - x\omega_2)\hat{z}$$

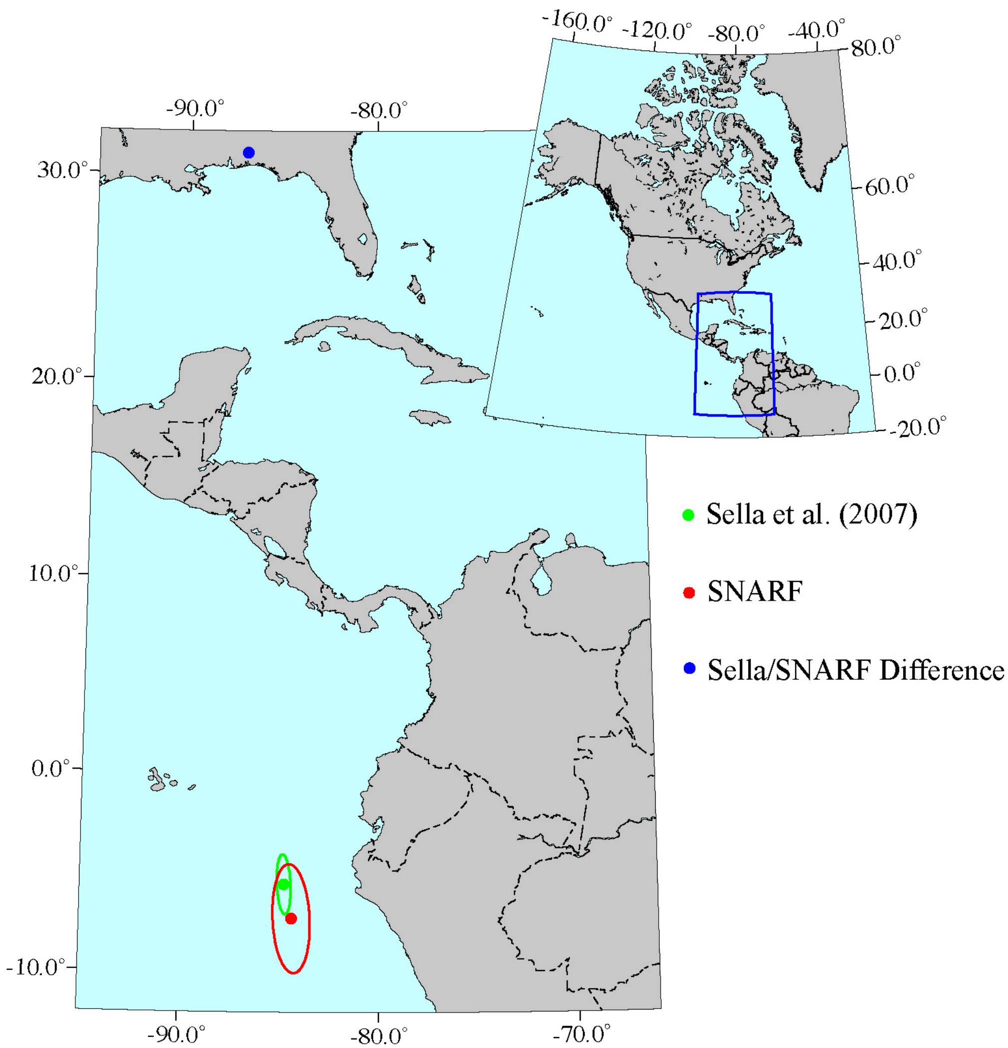
$$\begin{pmatrix} v_1 = z\omega_3 - y\omega_2 \\ v_2 = -z\omega_1 + x\omega_3 \\ v_3 = y\omega_1 - x\omega_2 \end{pmatrix}$$

$$\underline{\begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}} = \begin{bmatrix} 0 & z & -y \\ -z & 0 & x \\ y & -x & 0 \end{bmatrix} \cdot \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix}$$

How Many Sites Do You Need?

- There are 3 parameters in the plate angular velocity vector
- There are 3 data in each site velocity
  - But the plate model predicts no vertical, so only the horizontal velocity components count
- You need at least 2 sites to constrain the plate angular velocity vector
- The more sites, and the farther apart they are, the better the angular velocity is determined.

NOAM Poles



- With past studies, it is common that NOAM poles do not lie within 95% confidence ellipses of other studies
  - Systematic errors or missing uncertainty
- Difference between SNARF and Sella is a rotation about a pole in the SE United States.

What Part of Angular Velocity is Constrained by a single site's data?

- The least certain component of the plate' s angular velocity vector is a rotation about an axis through the centroid of the network.
- Consider the angular velocity vector of the plate expressed in the local east-north-up coordinates at a particular site:

$$\underline{\omega} = \omega_x \hat{x} + \omega_y \hat{y} + \omega_z \hat{z}$$

$$\underline{\omega} = \omega_e \hat{e} + \omega_n \hat{n} + \omega_r \hat{r}$$

The site's velocity is

0

$$\underline{v} = v_e \hat{e} + v_n \hat{n} = \underline{\omega} \times \underline{r}$$

$$v_e \hat{e} + v_n \hat{n} = (\omega_e \hat{e} \times R\hat{r}) + (\omega_n \hat{n} \times R\hat{r}) + (\omega_r \hat{r} \times R\hat{r})$$

$$v_e \hat{e} + v_n \hat{n} = R\omega_n \hat{e} - R\omega_e \hat{n} + 0\hat{r}$$

- Two components of the plate angular velocity are directly determined by the site's velocity, while the third (local vertical component) is completely undetermined.

$$\omega_e = -v_n / R$$

$$\omega_n = +v_e / R$$

$$\omega_r = ?$$

- **When sites span a small area, their local vertical directions will be similar, and this component of the angular velocity will be the least well determined.**

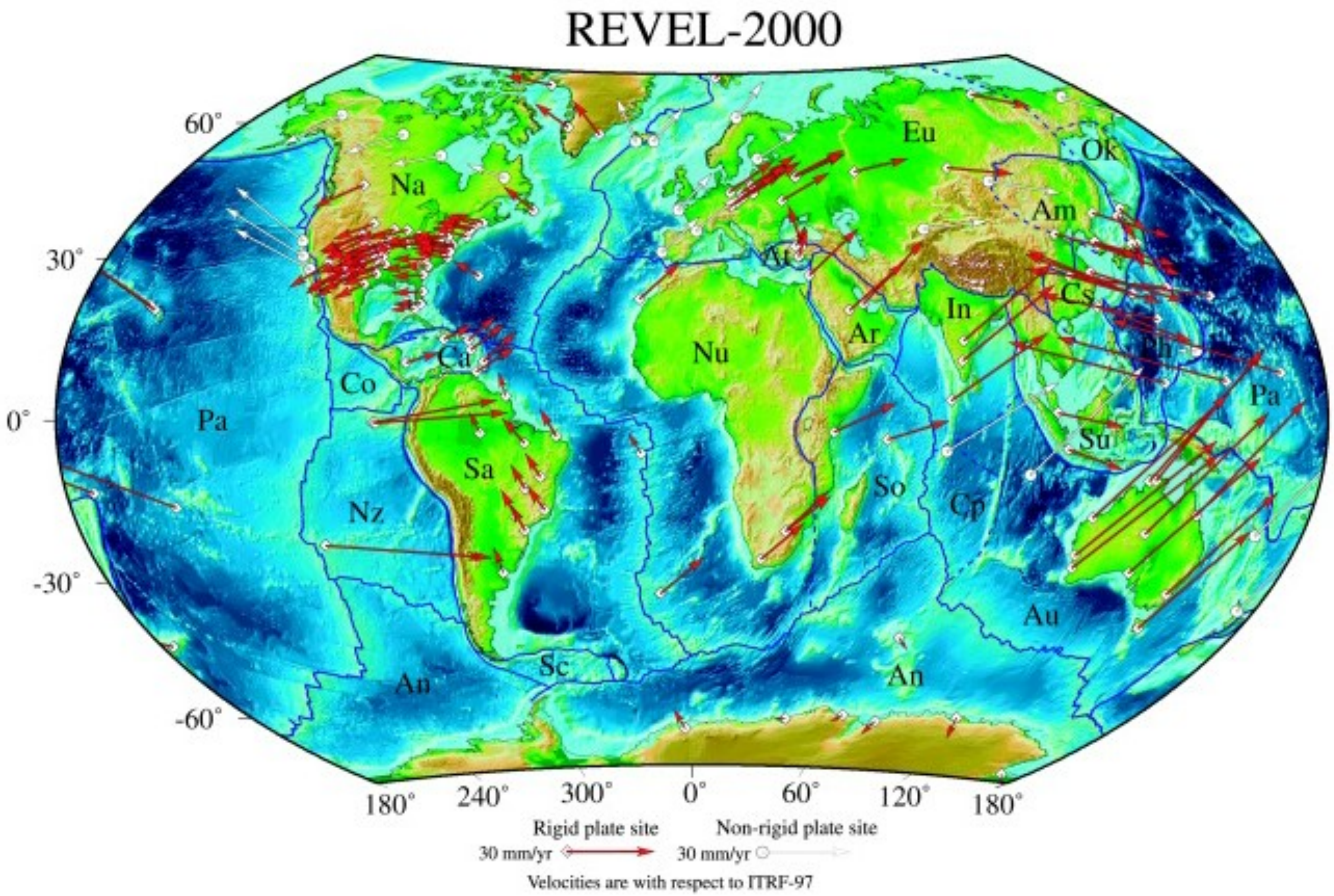
More About Angular Velocity

- We could resolve the undetermined component by taking a minimum norm solution:

$$\omega_r = 0 \;\; ; \;\; \therefore \underline{\omega} \cdot \underline{r} = 0$$

- In this case the pole is located 90° away from the site.
- The pole could also be located anywhere on the great circle that lies between this minimum-norm solution and the site itself.
- The component of the angular velocity in the average radial direction will naturally be the least constrained.

Example 1: The REVEL-2000 Model

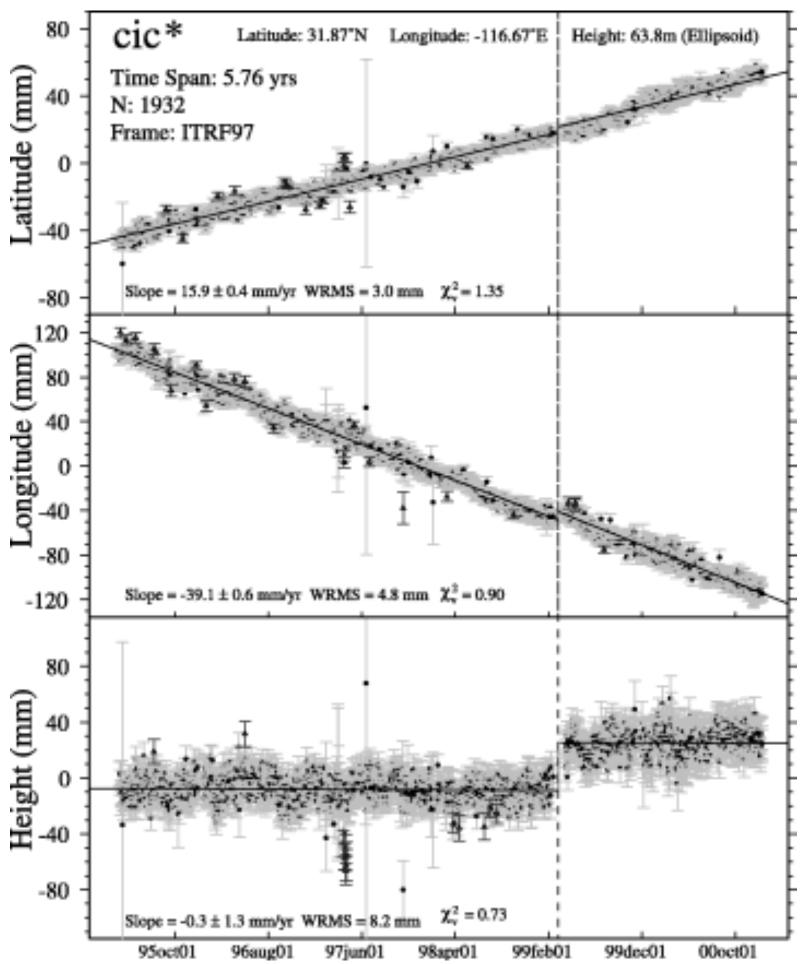


Sella et al. (2002, JGR, doi:10.1029/2000JB000033)

Details

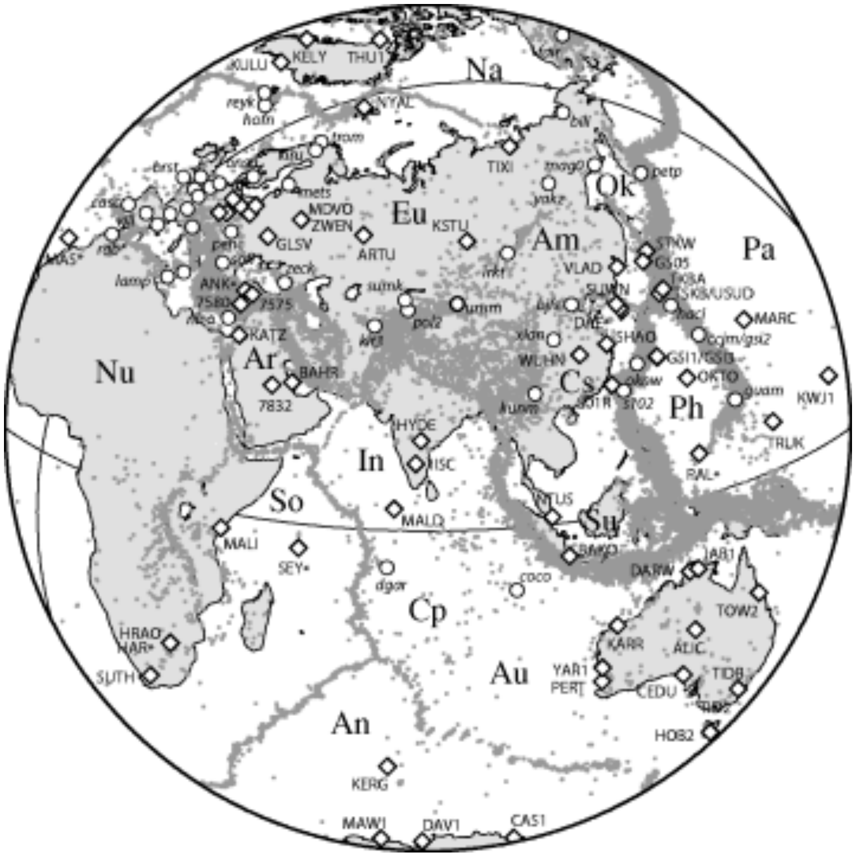
- Global plate motion model based entirely on GPS data
- Data span from early 1990s up through 2000.
- Combined many continuous sites and also repeated campaign survey data
- First model to have essentially complete global coverage.

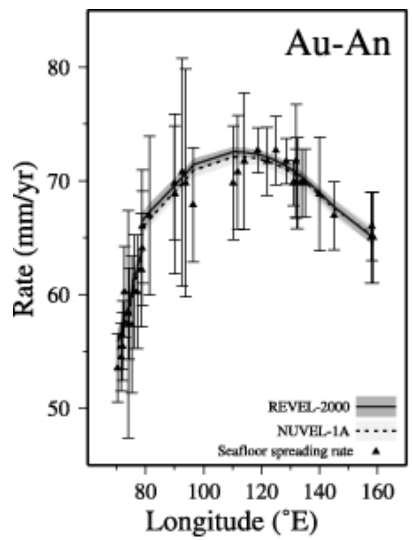
Data Used in Model

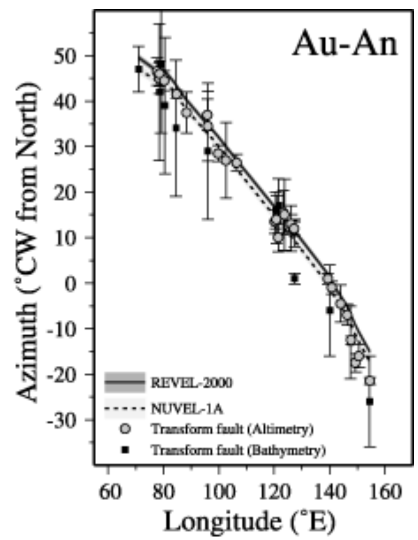


- Long time series of data in ***ITRF97*** frame, based on precise point positioning (PPP) solutions
- Fit linear trends plus offsets, combined co-located sites
- Outlier rejection and quality control

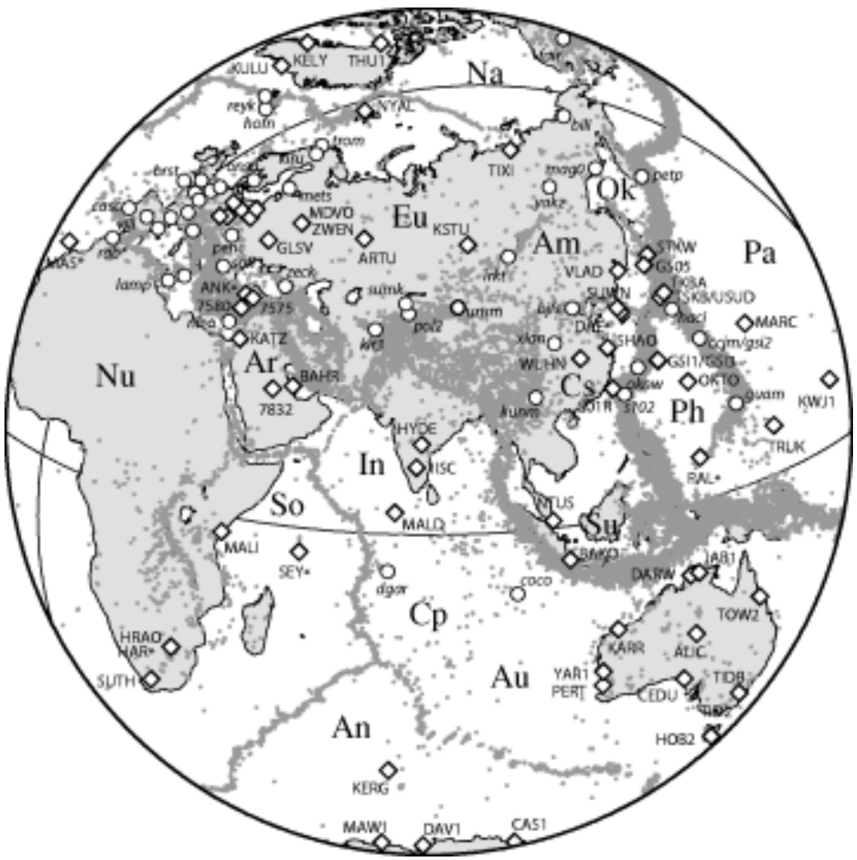
Australia–Antarctica

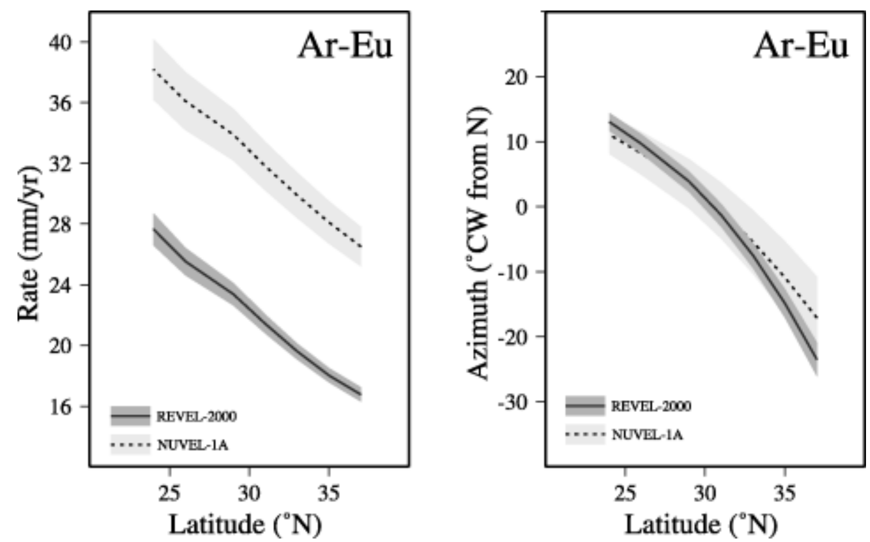




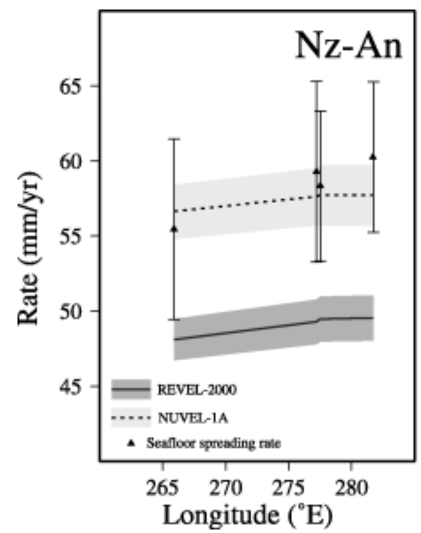


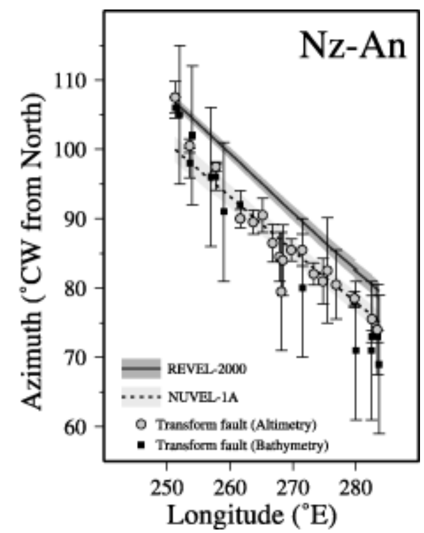
Arabia–Eurasia



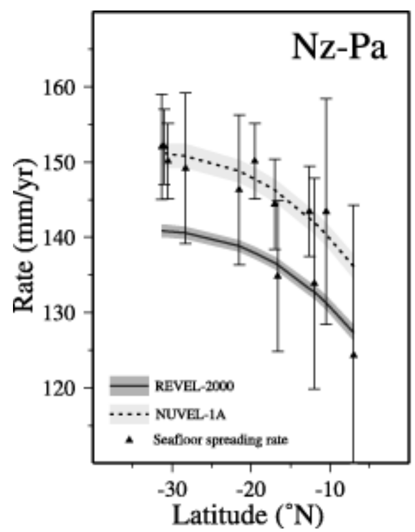


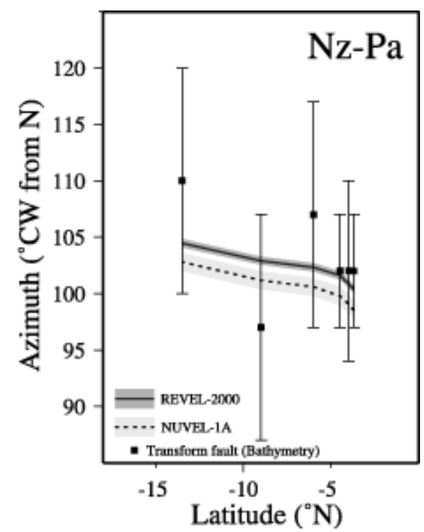
Nazca–Antarctica



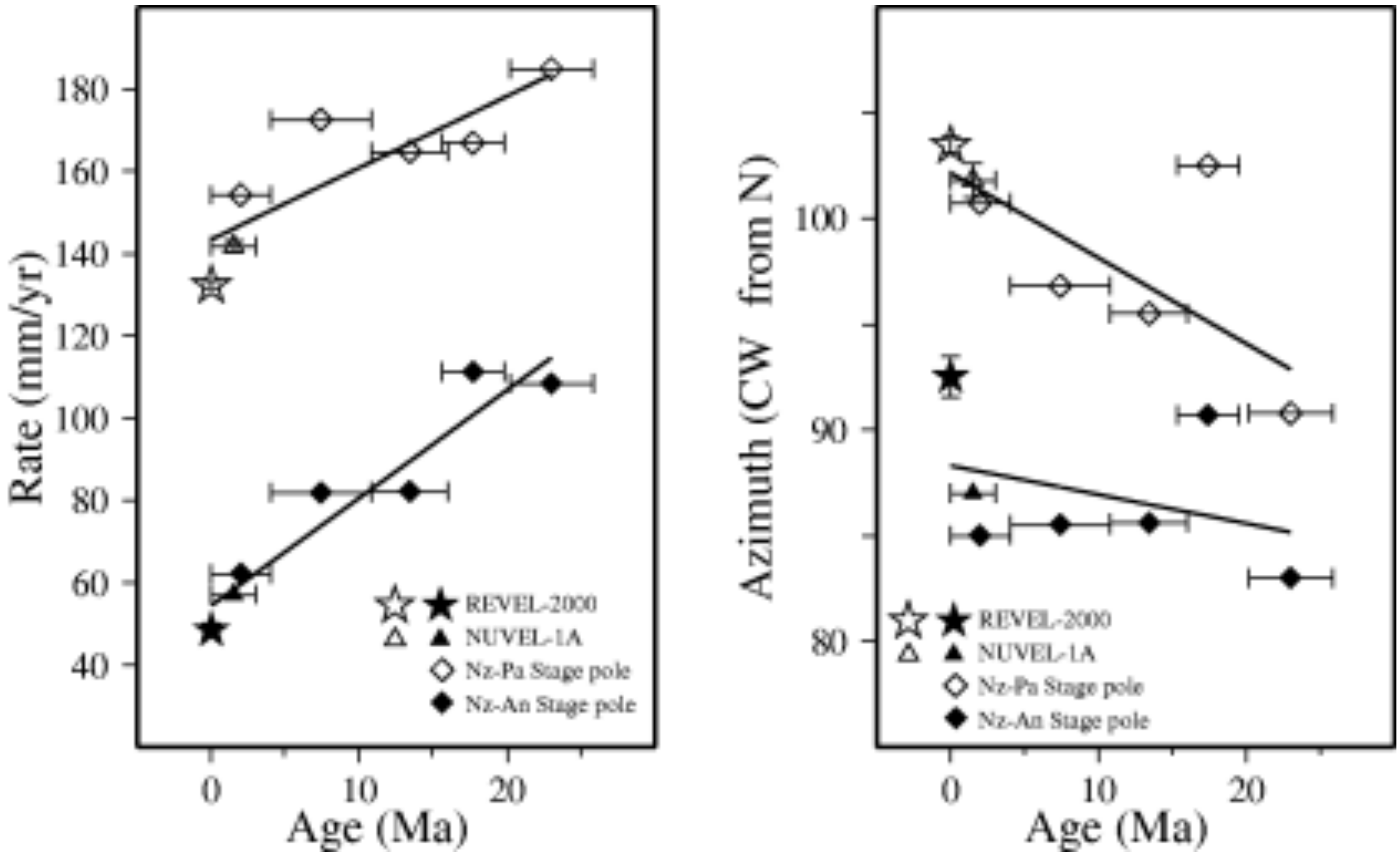


Nazca–Pacific

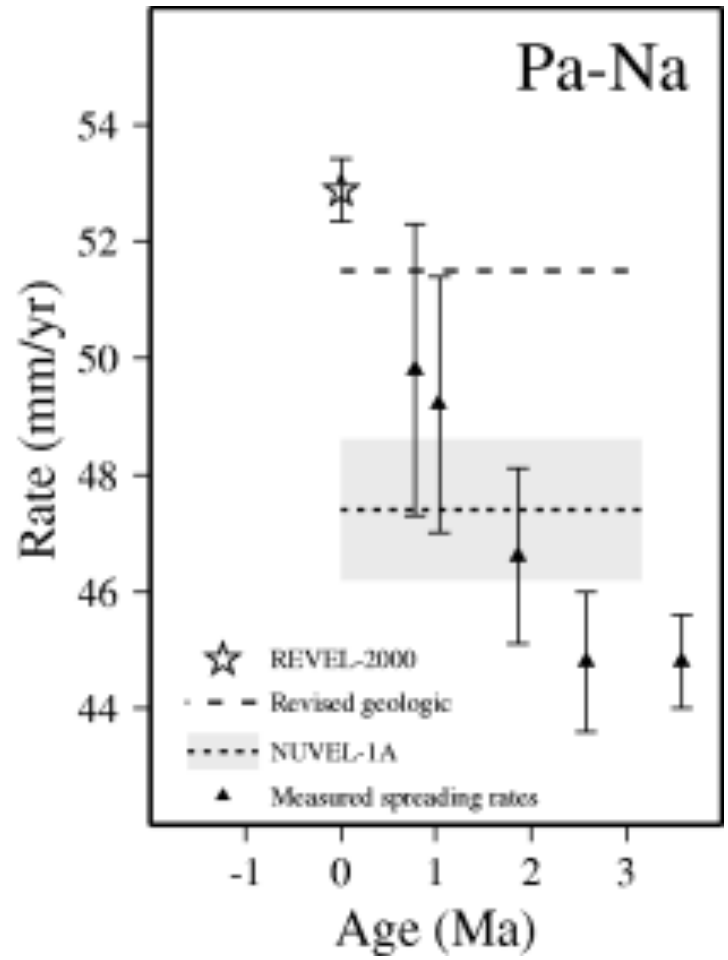




Nazca Plate Motion Over Time

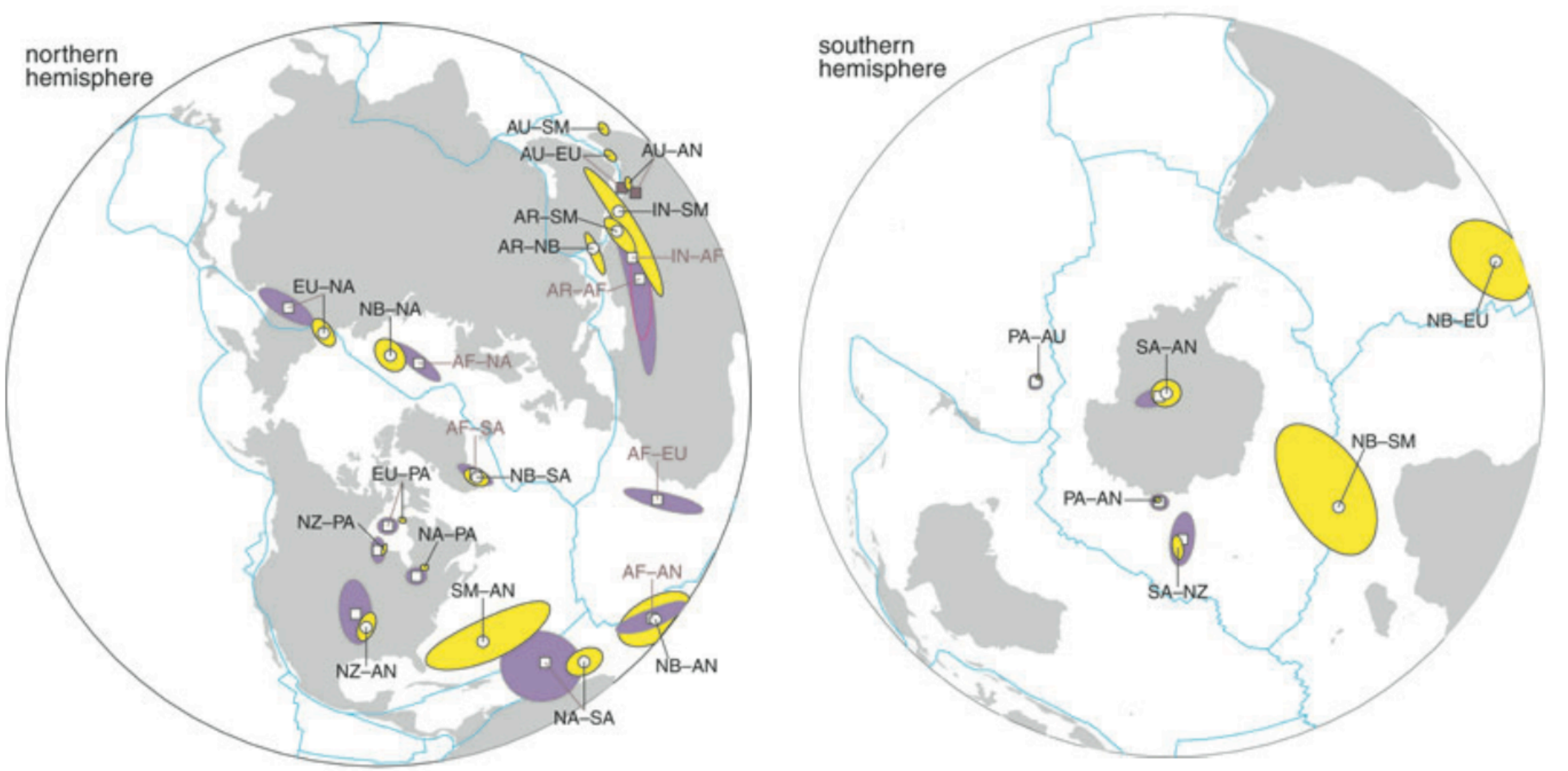


Pacific–North America



Example 2: GEODVEL

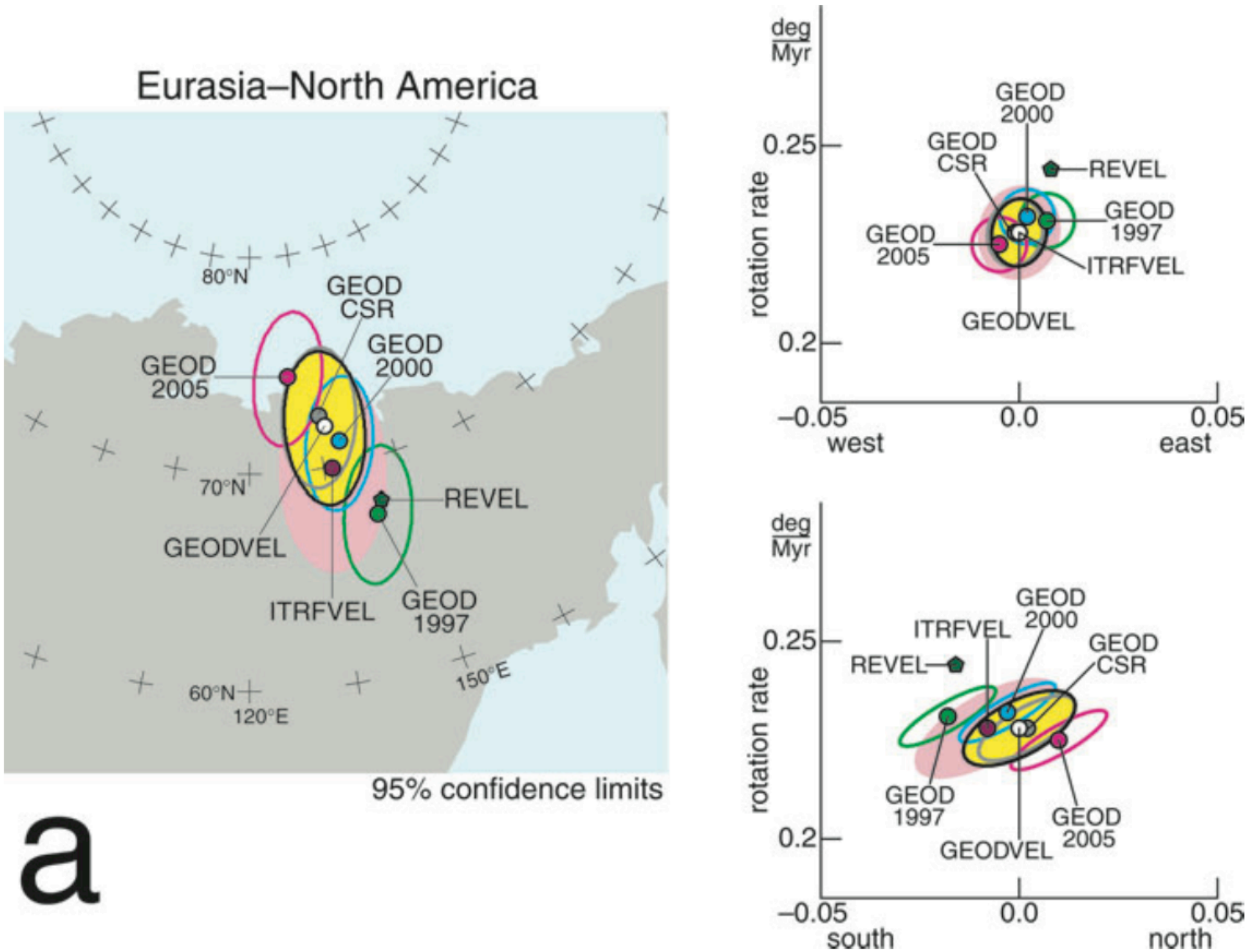
(Argus et al., 2010)



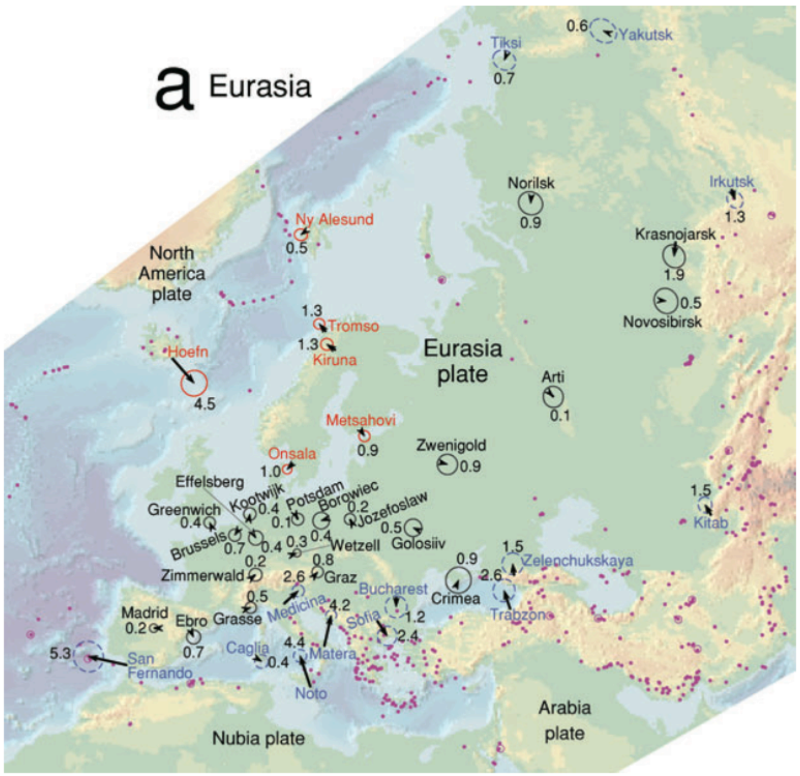
GEODVEL Details

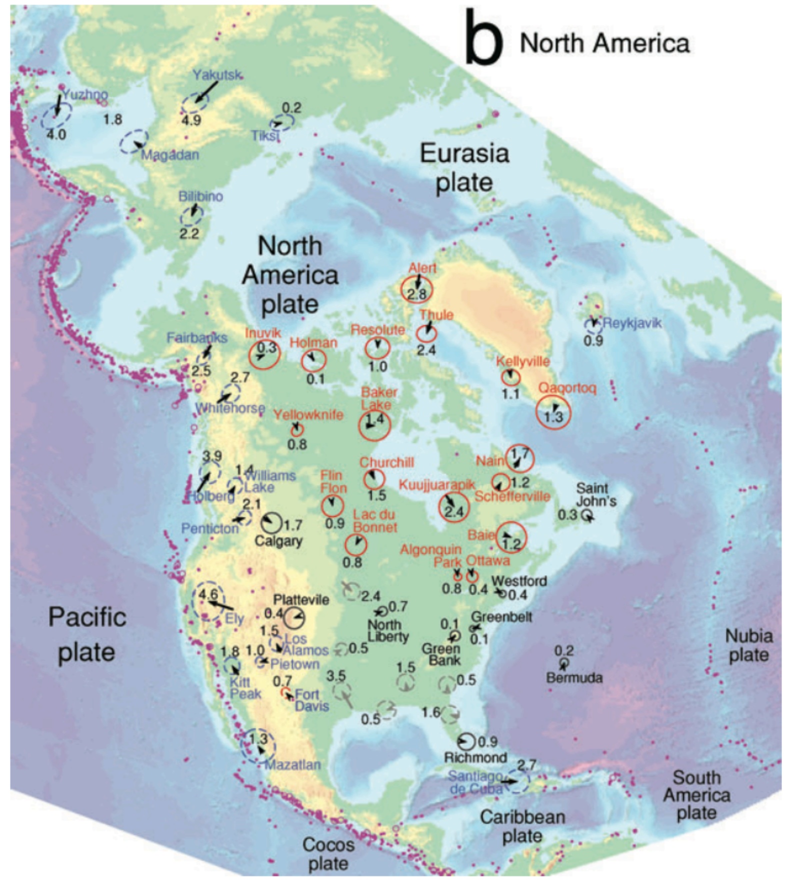
- Based on a combined solution of GPS, VLBI, SLR, DORIS, in ITRF2005.
- Includes an estimate of geocenter error in ITRF2005 (estimated error is about 1.2 mm/yr in Z direction).
- Relative plate angular velocities are estimated. Argus has also provided absolute plate poles suitable for comparison with ITRF velocities.

Comparison of Poles and Rates

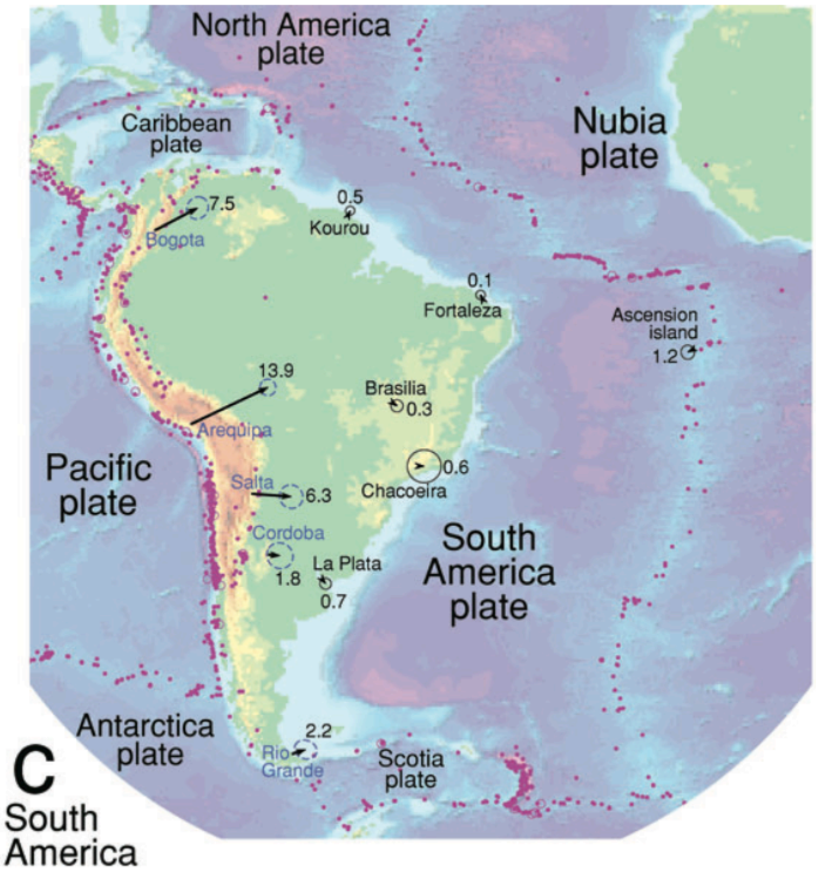


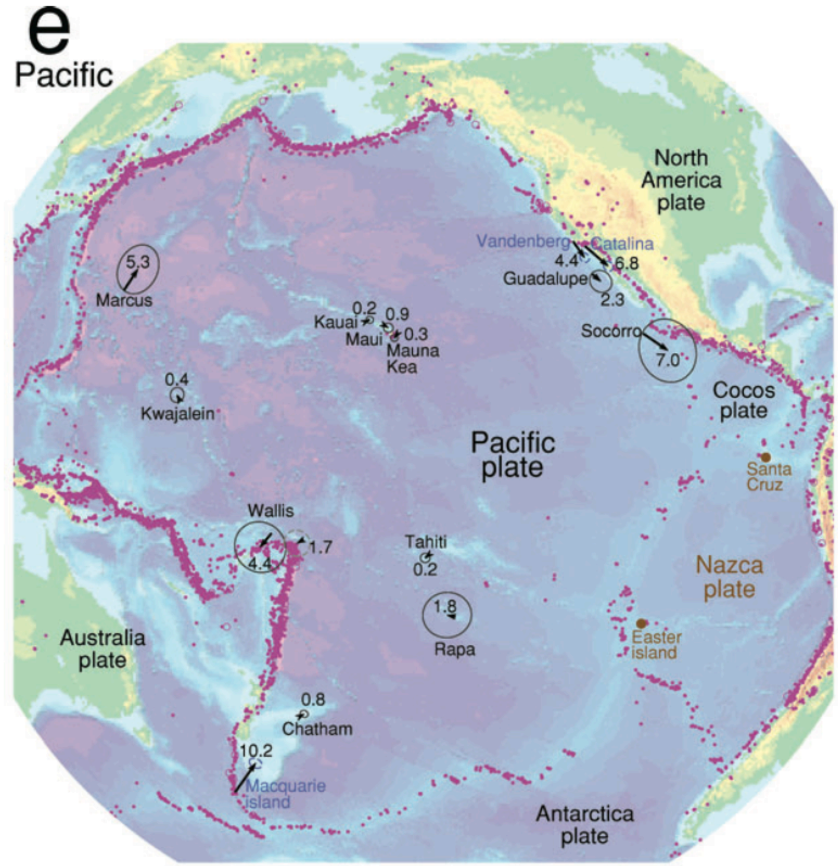
GEODVEL Residuals



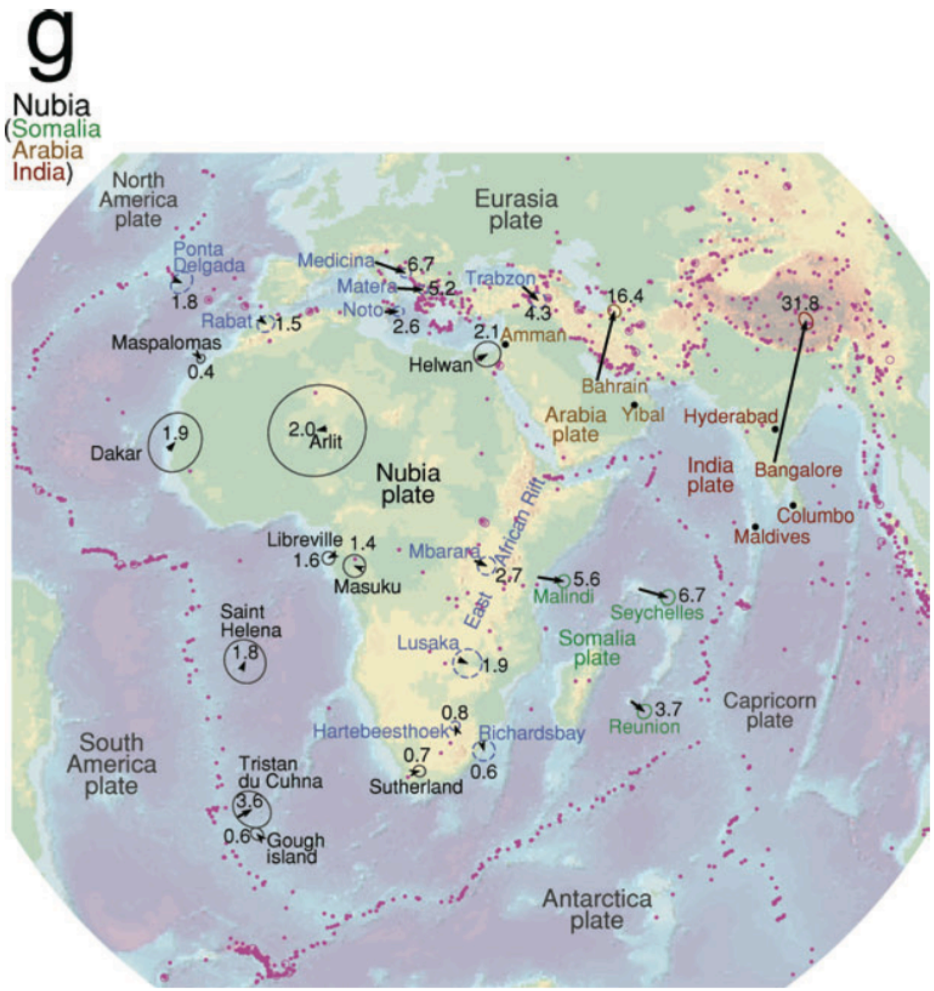


GEODVEL Residuals



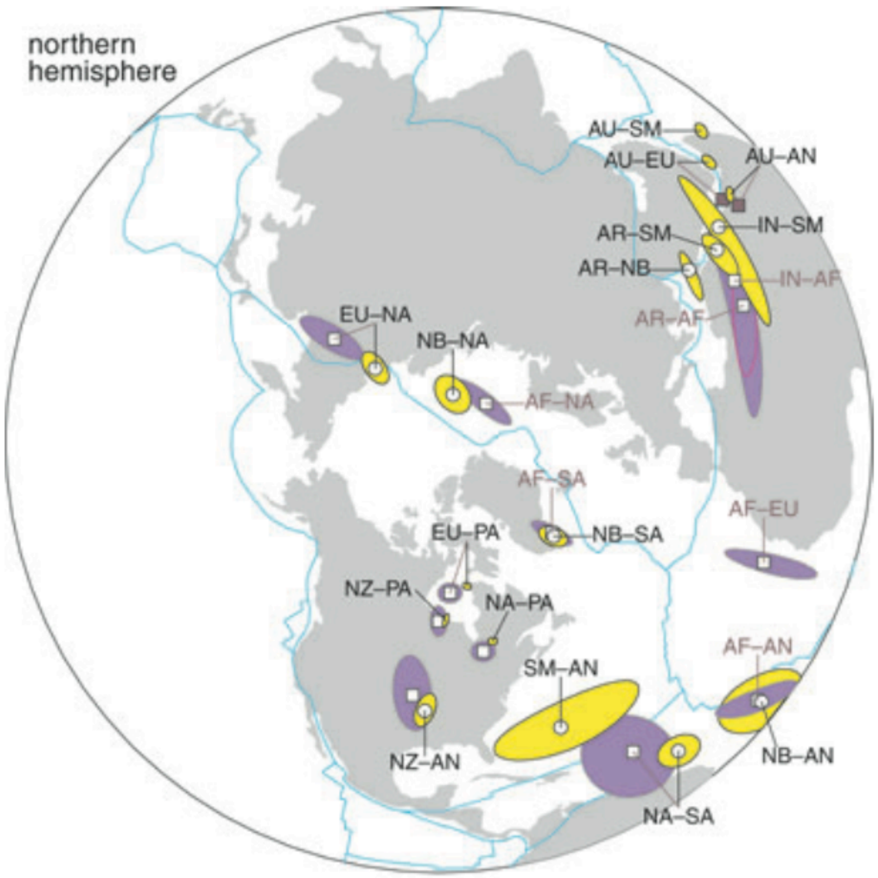


GEODVEL Residuals



- Former African plate split into two plates at East African Rift
  - Nubia
  - Somalia
- dd

GEODVEL Pole Locations



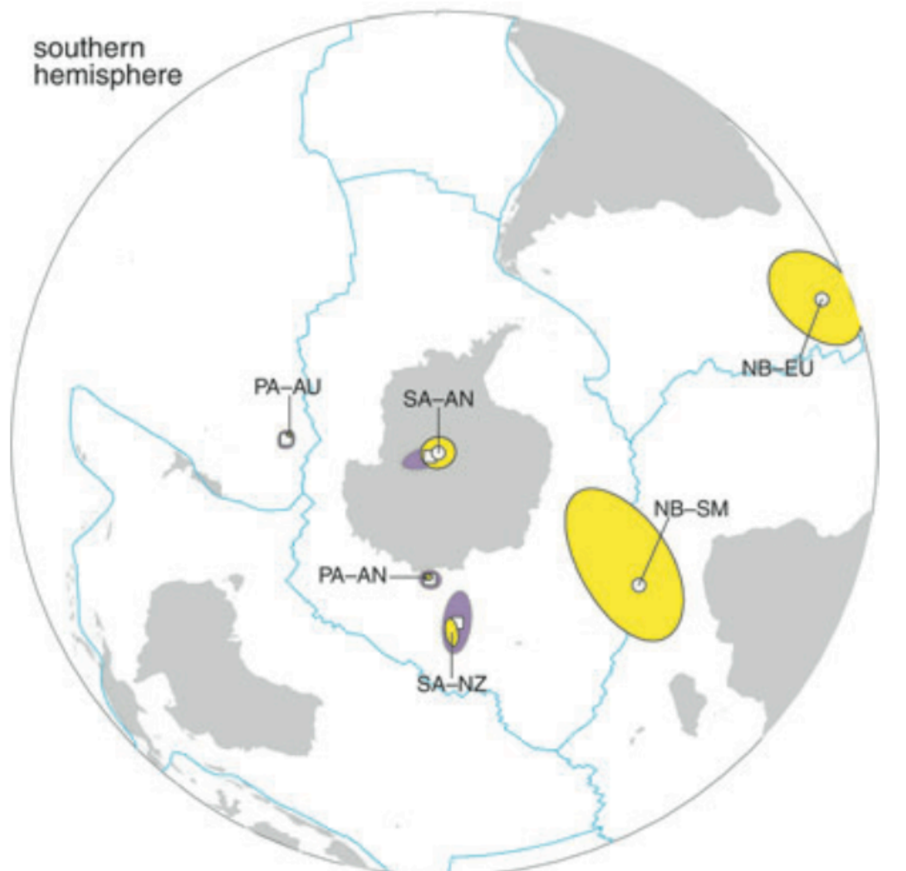
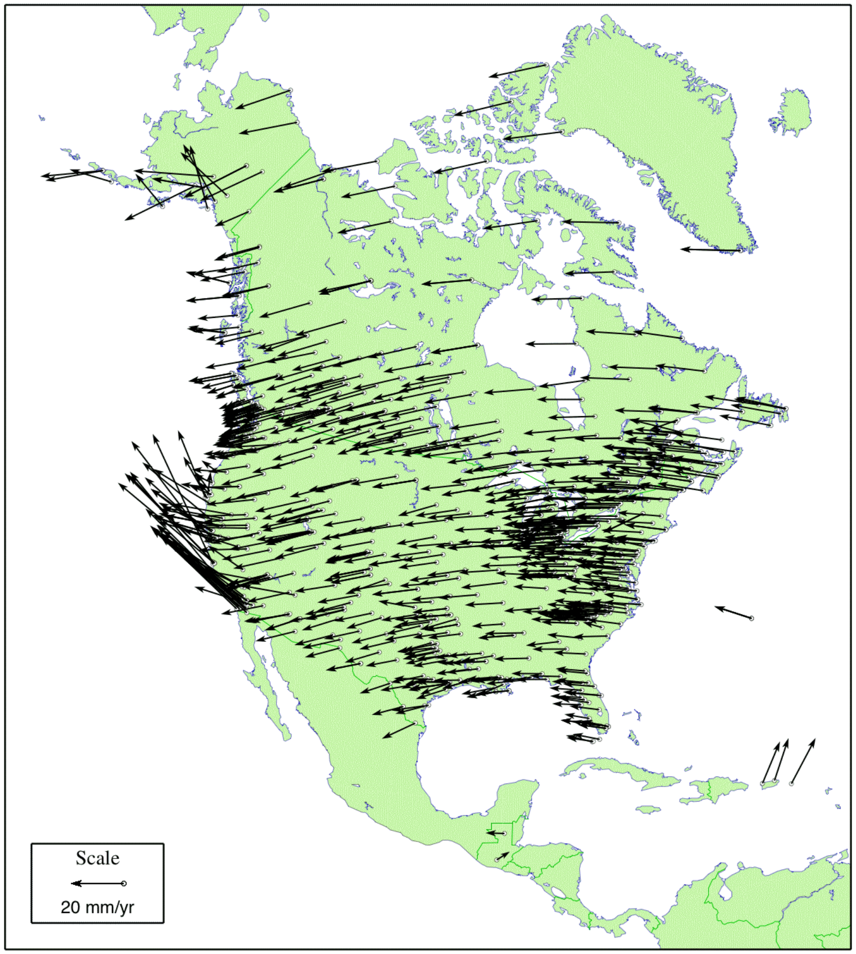
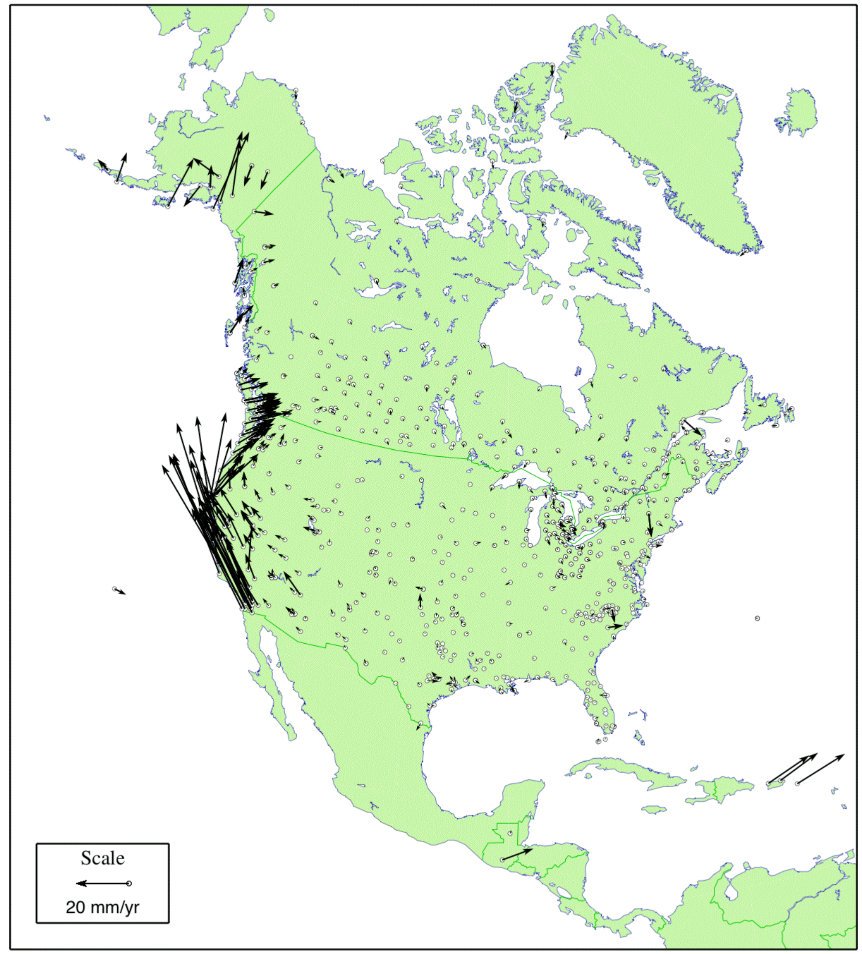


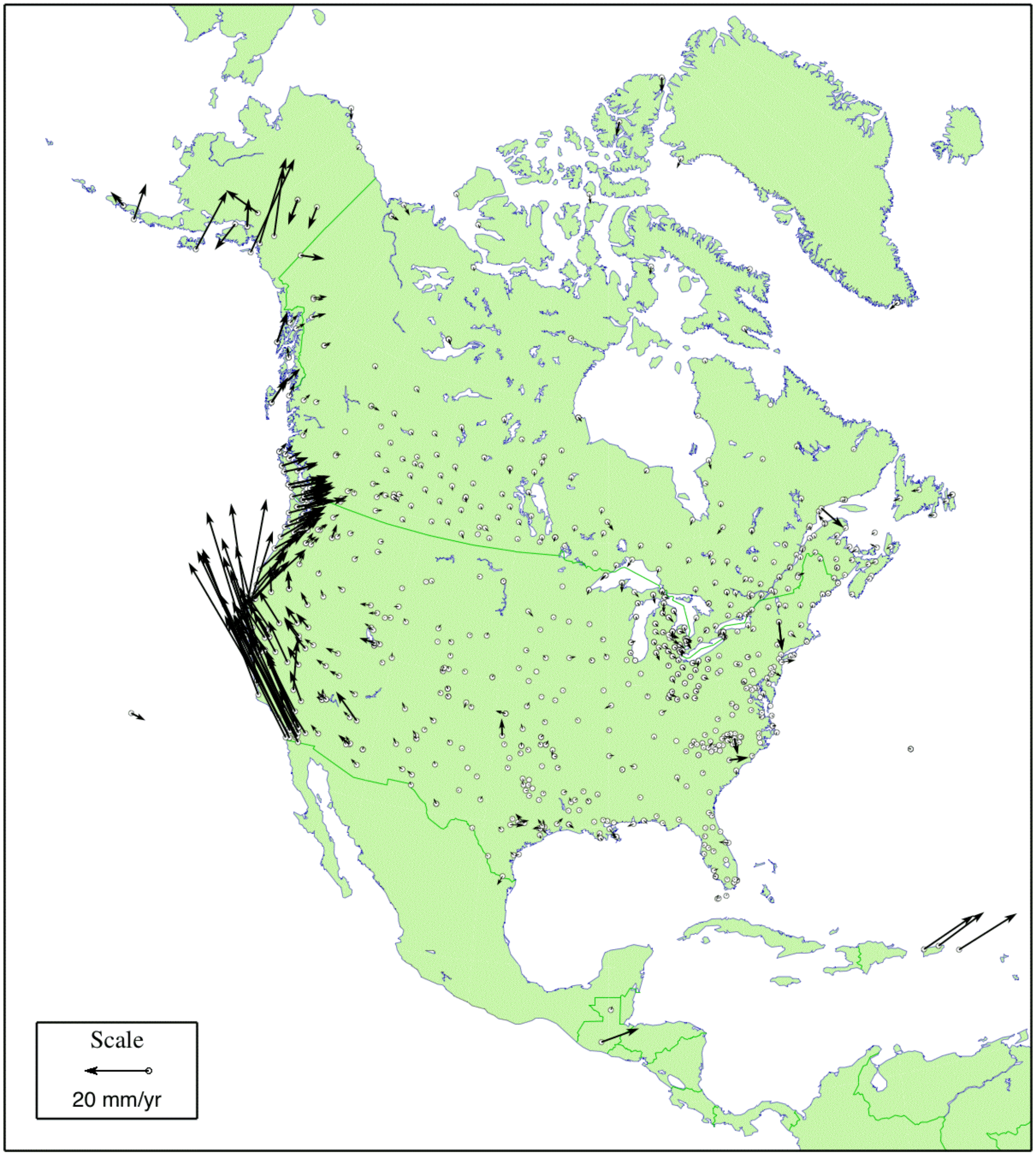
Plate-Fixed Reference Frame

- Plate-fixed reference frames are very convenient for visualizing and modeling tectonic deformation.
- To use a plate-fixed frame, we need to have an estimate of the plate motion in the same geodetic frame of our data.
- The transformation is simple. Just subtract the predicted motion based on the plate angular velocity from each site's observed velocity.

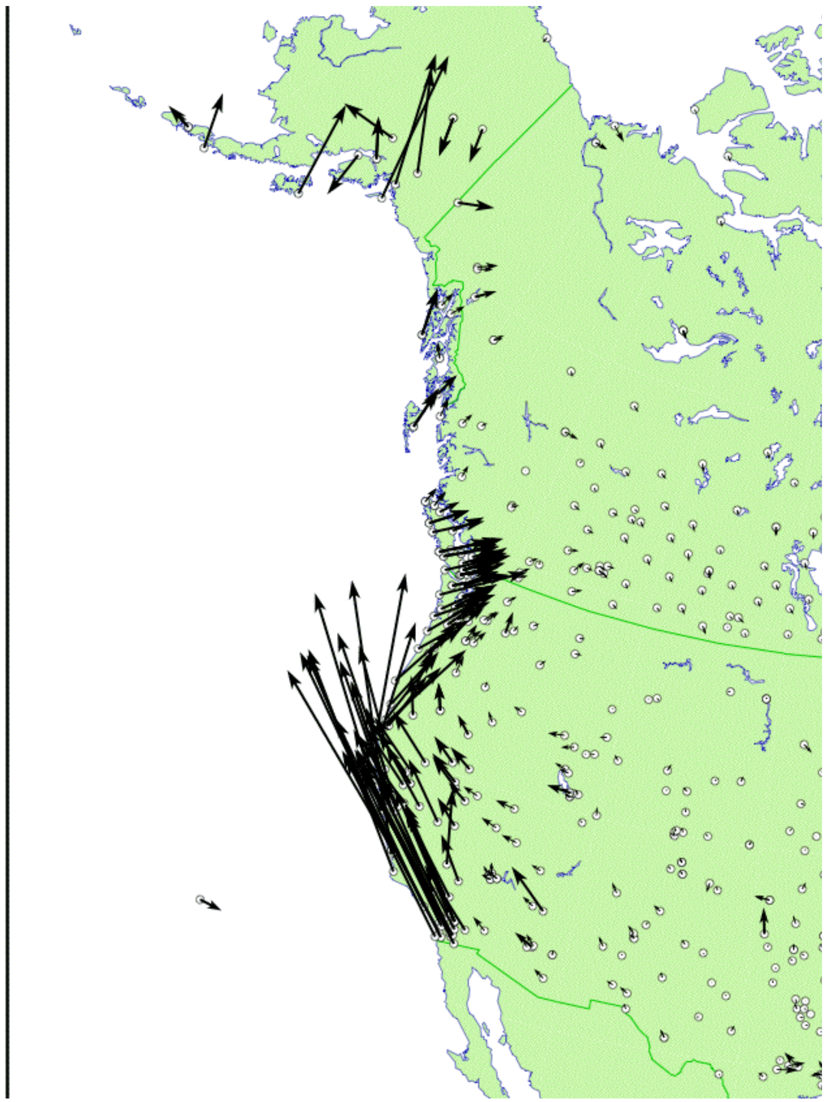
ITRF vs. Plate-fixed frame






Scale
20 mm/yr

Western North America

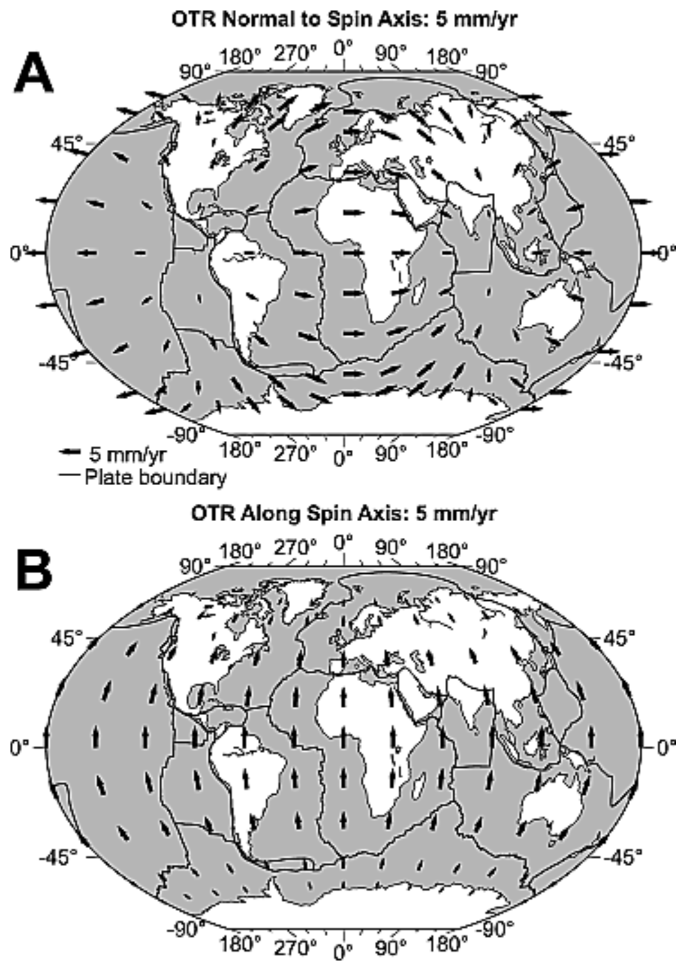


- Deformation of western North America results from a combination of:
  - Extension across Basin and Range
  - Shear on San Andreas fault system
  - Subduction strain in Cascadia and Alaska
  - Distributed deformation in N. Canada and Alaska

Back to Reference Frames

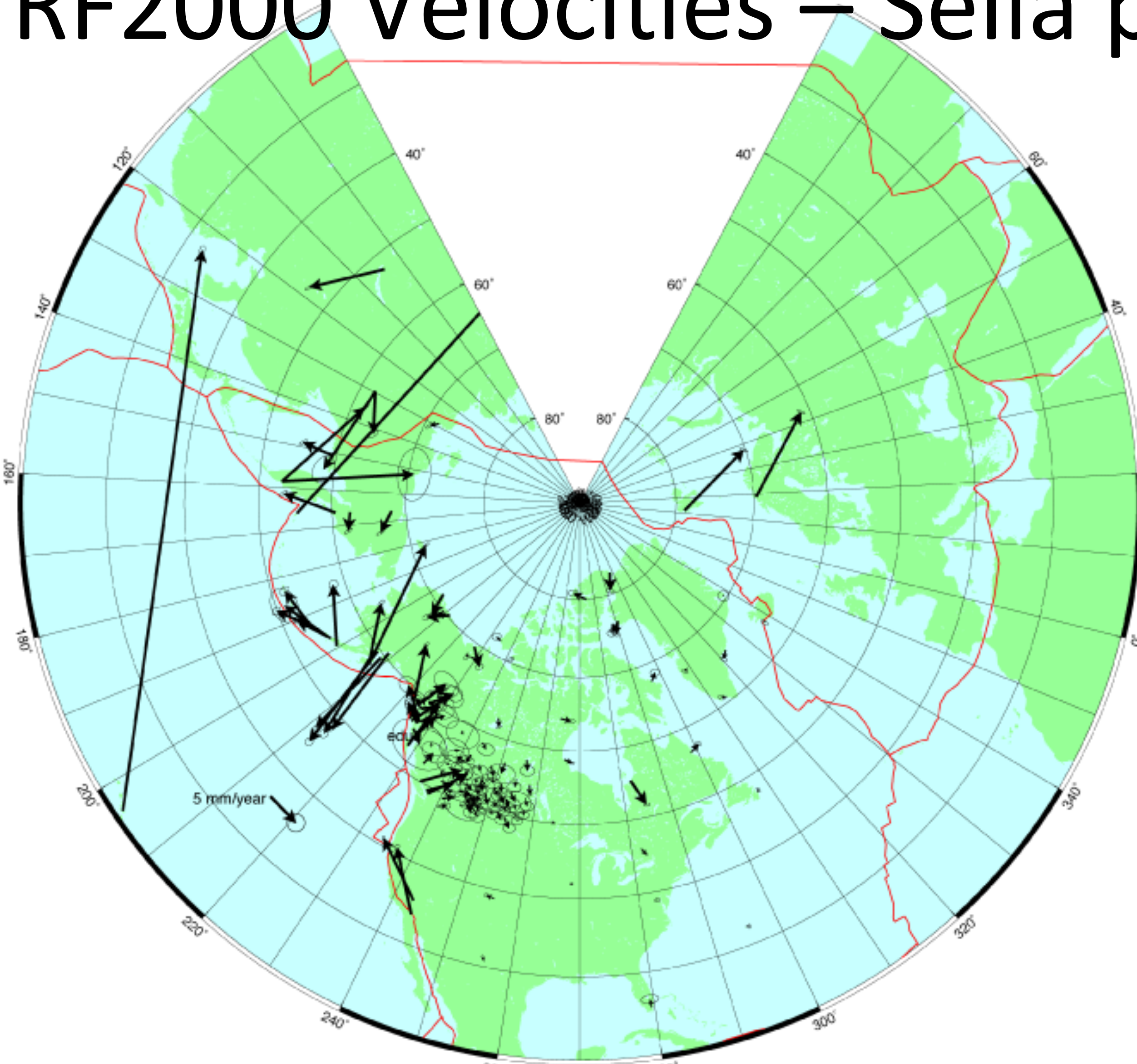
- Small differences between different versions of ITRF turn out to be big enough to affect estimated plate rotations.
  - Orientation differences (rotations) between frames affect absolute angular velocities, but affect all plates equally (relative plate velocities are not affected).
  - Geocenter differences (translations) affect both absolute and relative velocities.

Impact of Geocenter Error

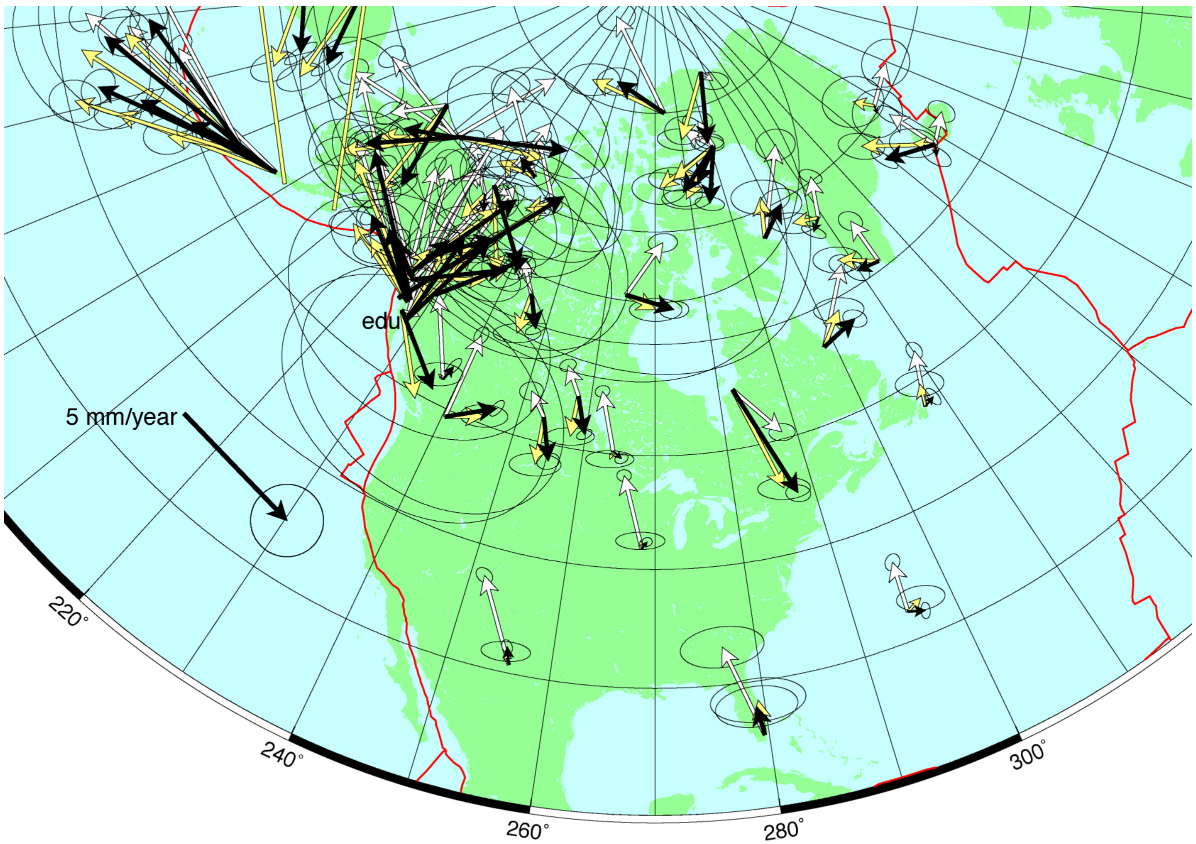


- Suppose our frame has an error in the geocenter. How are site velocities affected?
  - Such an error produces a combination of vertical and horizontal motion, depending on site location.
  - The error affects each plate differently
  - Impact on angular velocity depends on site distribution.

ITRF2000 Velocities – Sella pole



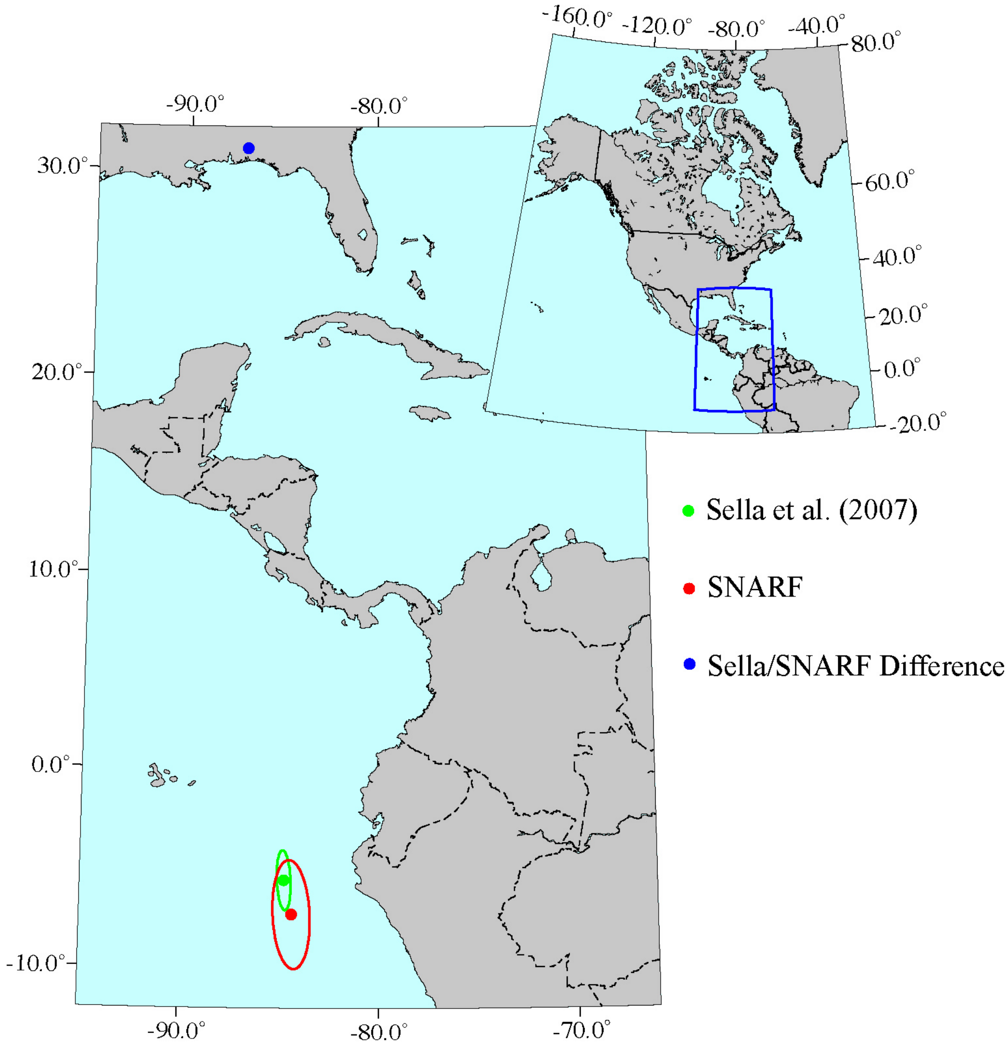
ITRF2000 Velocities – other poles



Black – Sella 2007
White – REVEL
Yellow – SNARF

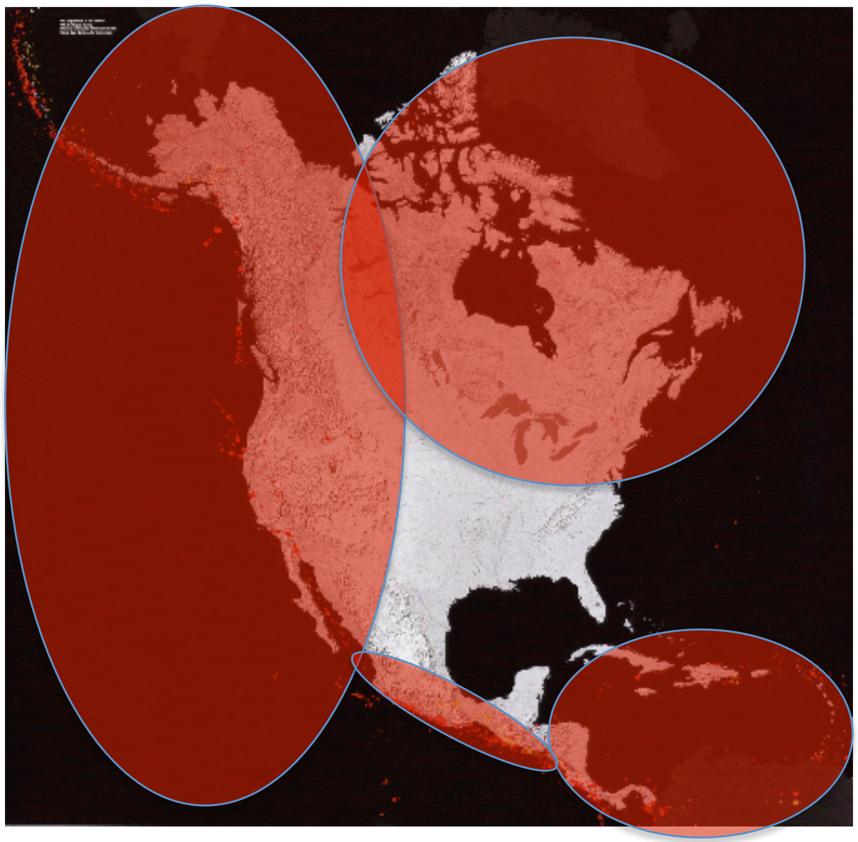
Note systematic residual in REVEL, 2-3 mm/yr. REVEL used ITRF97.

NOAM Poles



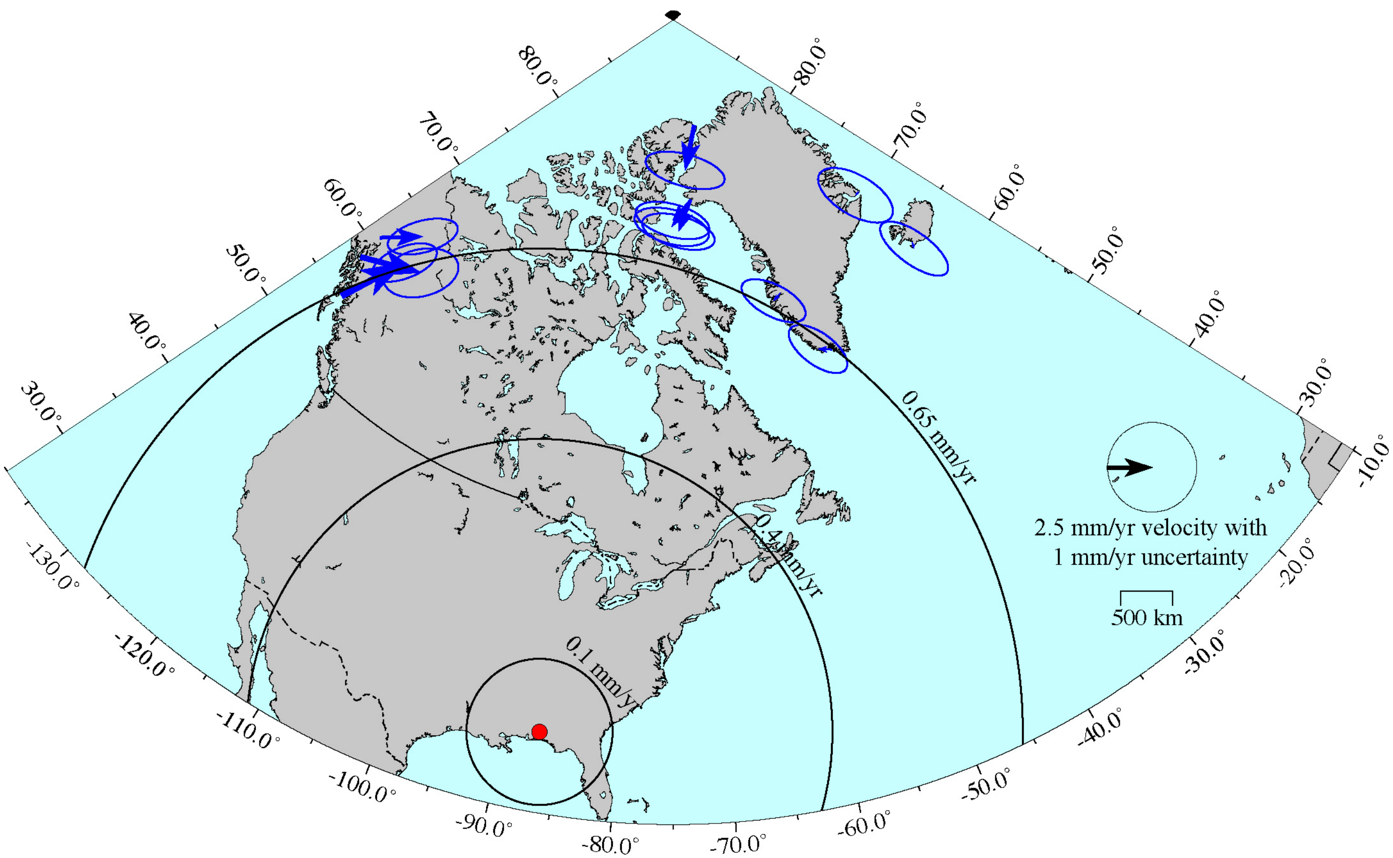
- With past studies, it is common that NOAM poles do not lie within 95% confidence ellipses of other studies
  - Systematic errors or missing uncertainty
- Difference between SNARF and Sella is a rotation about a pole in the SE United States.

Why is NOAM pole poorly determined?



- Active Tectonics in western North America
- Glacial Isostatic Adjustment in northern North America
- Only the SE part is stable both on geologic and geodetic timescales.
- Limited area for determination of plate angular velocity, and susceptible to bias.

Additional Uncertainty Rotation Only



Uncertainty in ITRF

- Uncertainty in ITRF commonly ignored.
- The TZ rate difference (1.8 mm/yr) between ITRF2005 and ITRF2000 has gotten a lot of attention.
- There may actually be a similar (or larger) difference between ITRF2000 and ITRF97
- If so, uncertainty in frame (geocenter origin) may be much larger than precision of GPS baseline rates.

How to define the 14 parameters ?
« Datum definition »

- Origin & rate: CoM (Dynamical Techniques)
- Scale & rate: depends on physical parameters
- Orientation: conventional
- Orient. Rate: conventional: Geophysical meaning (Tectonic Plate Motion)

- ==> Lack of information for some parameters:
  – Orientation & rate (all techniques)
  – Origin & rate in case of VLBI
  – ==> **Rank Deficiency** in terms of Normal Eq. System

Geocenter Motion

Translational motion of the tracking network due to variation of the CoM position induced by mass redistribution

- Likely involves periodic and secular components
- Satellite techniques have limited abilities to accurately measure this motion
- TRF origin from satellite techniques coincides with the CoM averaged over the period of the used observations

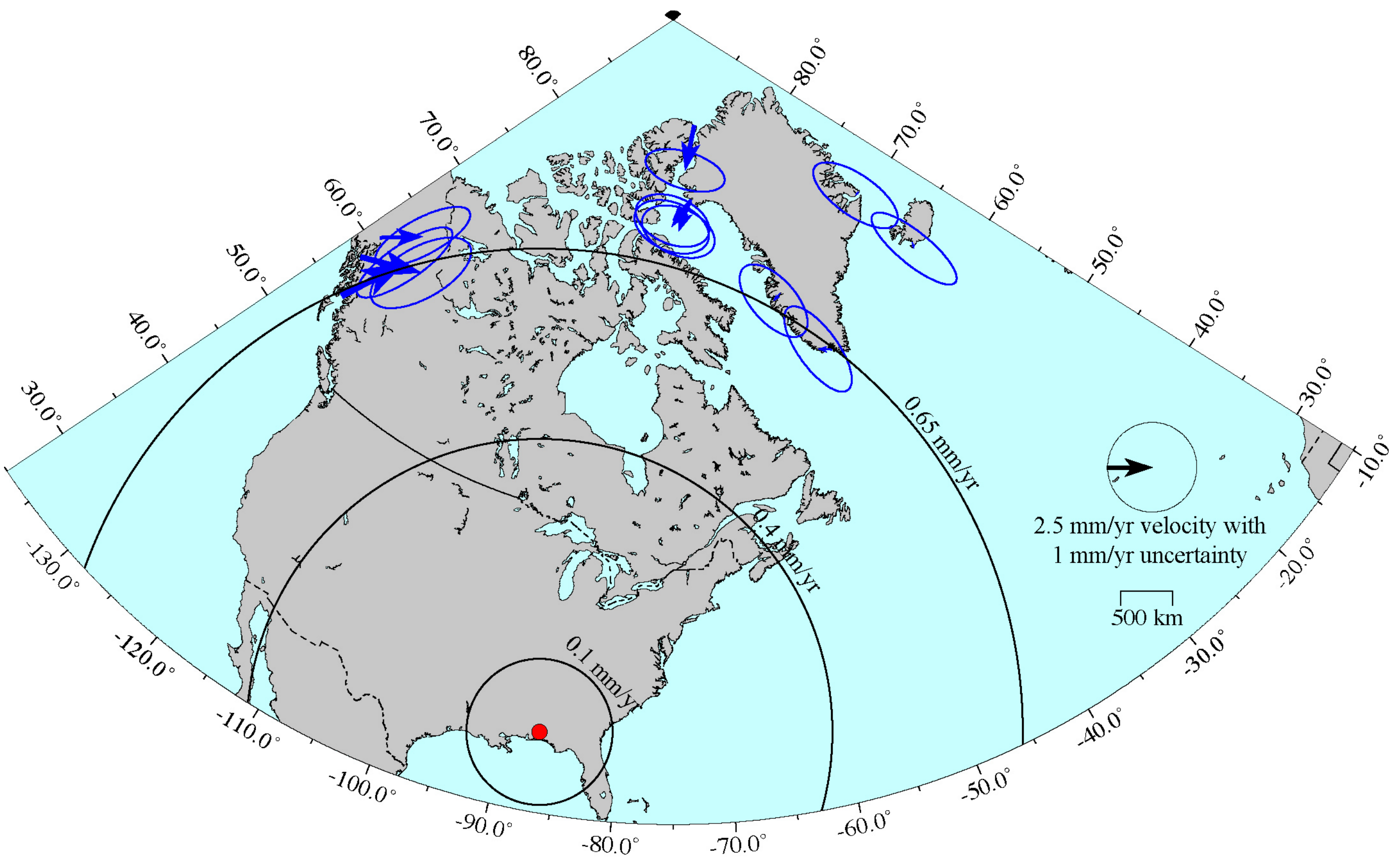
International Terrestrial Reference System (ITRS): Definition

- **Origin**: Center of mass of the whole Earth, including oceans and atmosphere
- **Unit of length**: meter SI, consistent with TCG (Geocentric Coordinate Time)
- **Orientation**: consistent with BIH (Bureau International de l' Heure) orientation at 1984.0.
- **Orientation time evolution**: ensured by using a No-Net-Rotation-Condition w.r.t. horizontal tectonic motions over the whole Earth

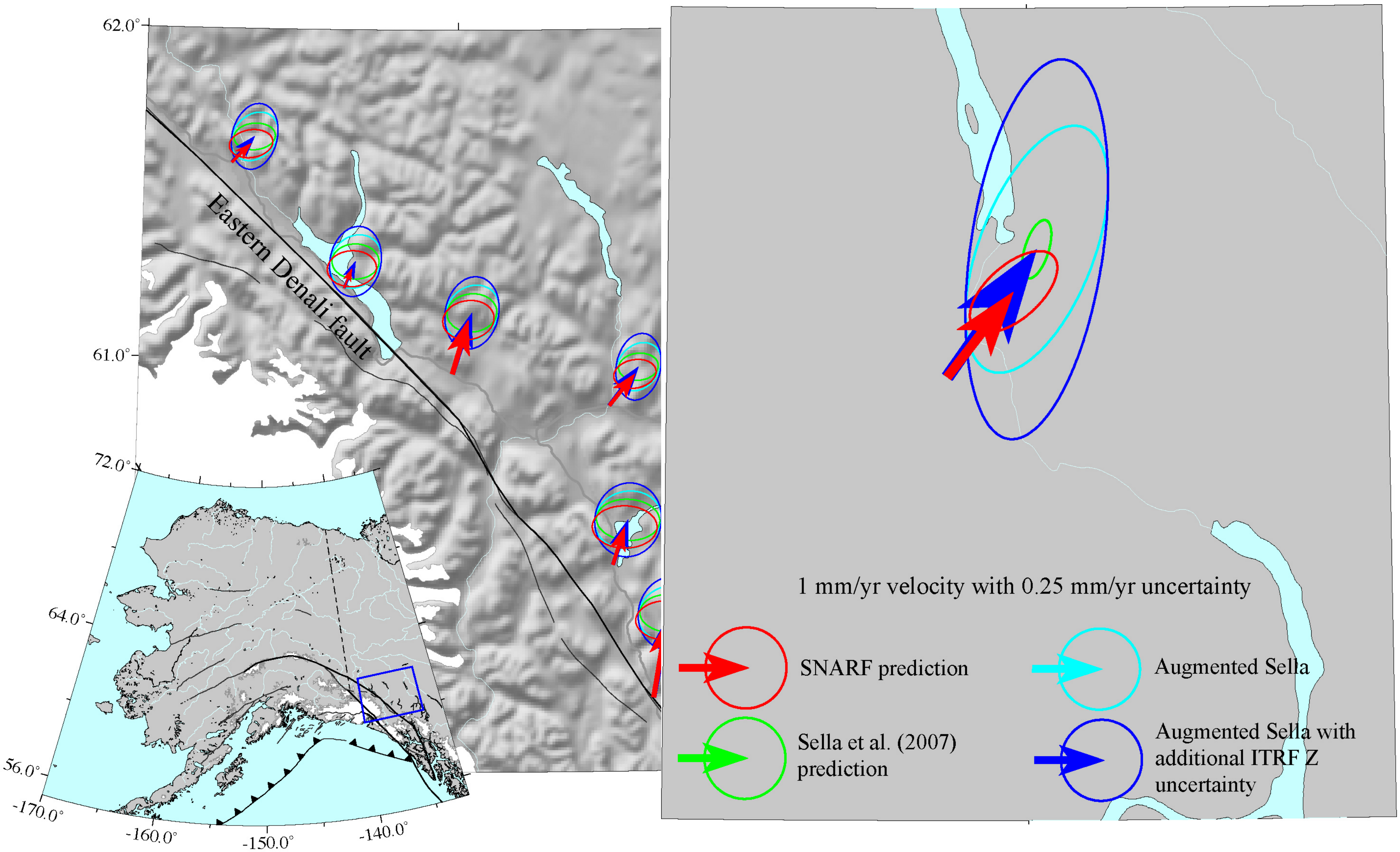
Strategy for Augmented Covariance

- Sella and SNARF differ by almost 1 mm/yr in Alaska, significant relative to CGPS site velocities, and we really can't tell which is "right"
- We thus augment the covariance in two ways:
  - Add an uncertainty corresponding to the difference in angular velocity between Sella and SNARF
  - Add an uncertainty in Zdot of 1.8 mm/yr as a conservative uncertainty in the ITRF.

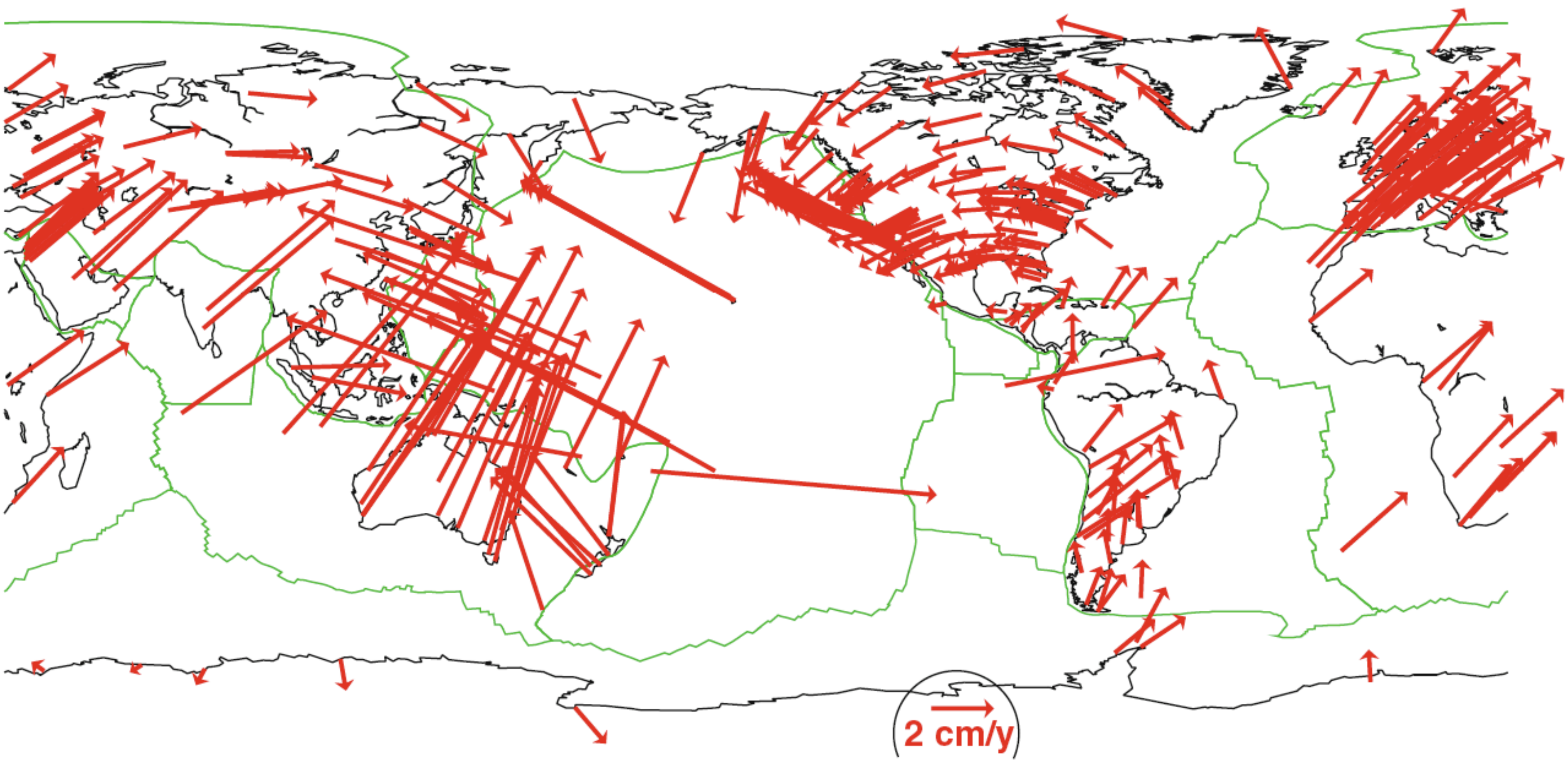
Additional Uncertainty Rotation + Zdot



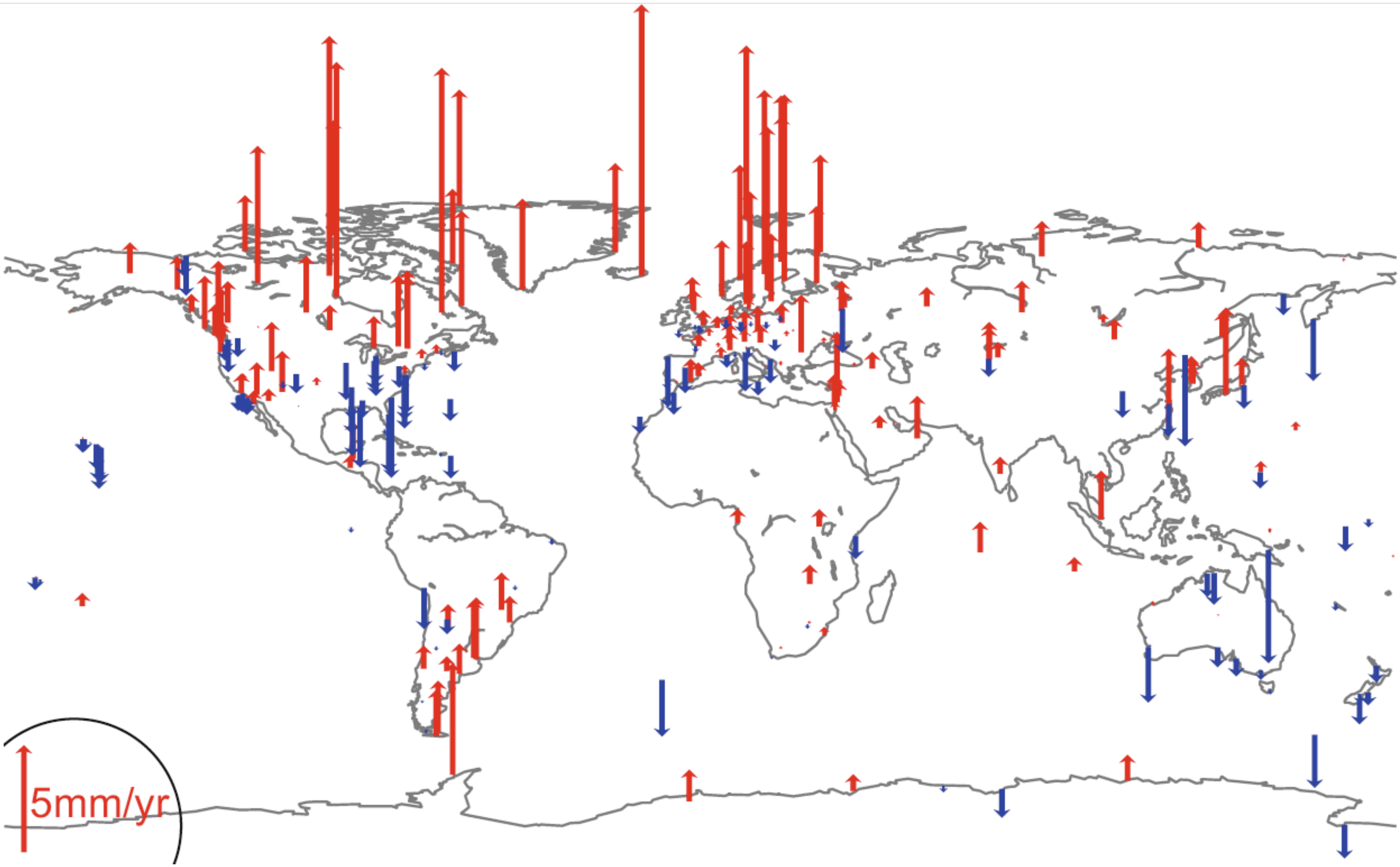
Augmented Covariance

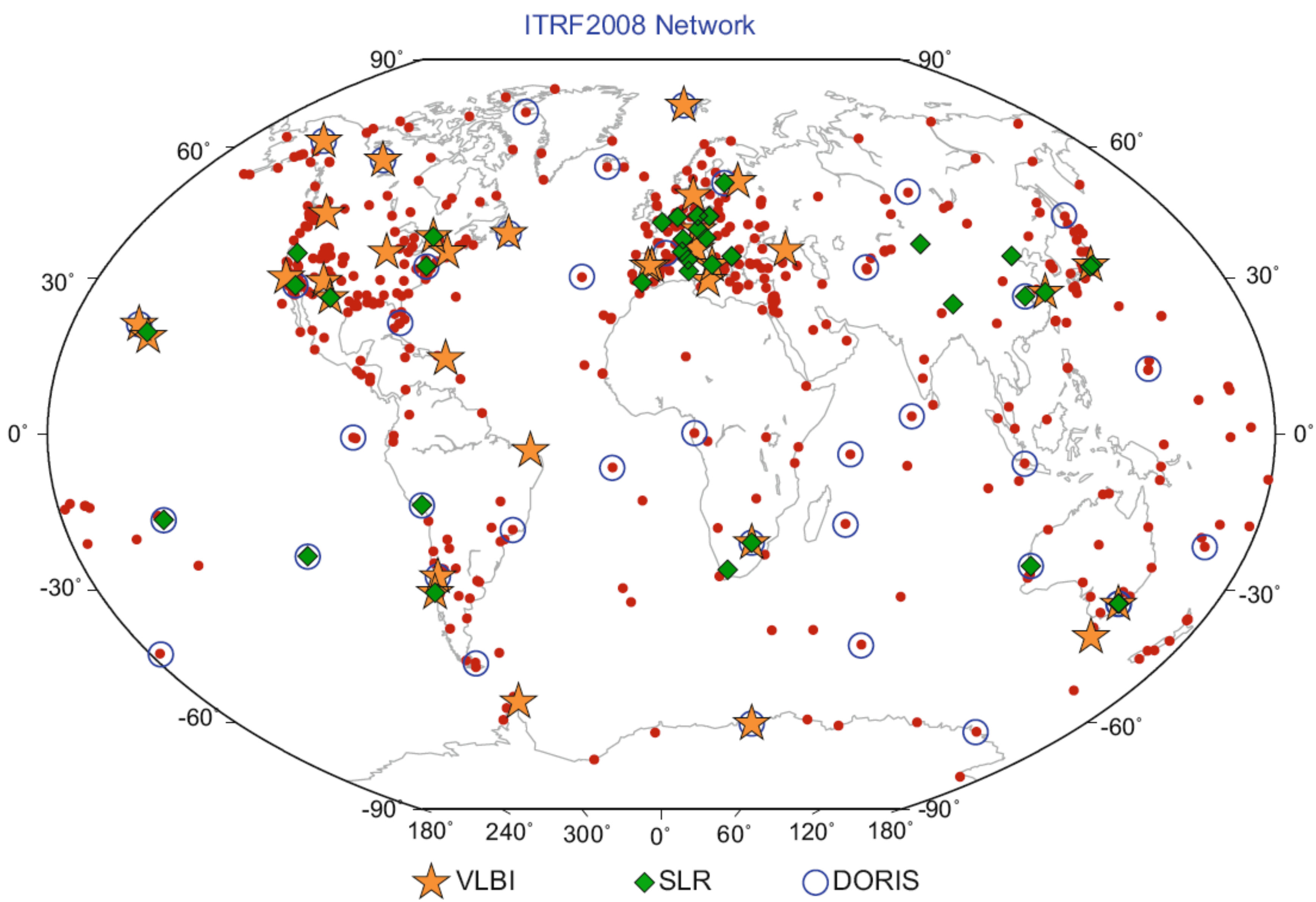


ITRF2008 horizontal velocities



ITRF2008 vertical site velocities





ITRF2008 Network
90°
90°
60°
60°
30°
30°
0°
0°
-30°
-30°
-60°
-60°
-90°
-90°
180°
240°
300°
0°
60°
120°
180°
VLBI
SLR
DORIS